Consumers Power Company

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December 2, 1983 80-09 #12

50-329
50-330

Mr J G Keppler, Regional Administrator
US Nuclear Regulatory Commission
Region III
799 Roosevelt Road
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MIDLAND NUCLEAR ENERGY CENTER
DOCKET NOS 50-329 AND 50-330
LOW ALLOY QUENCHED AND TEMPERED BOLTING 1½ INCHES
AND GREATER IN SUPPORT OF SAFETY RELATED SYSTEMS
FILE: 0.4.9.46 SERIAL: 26594

References: J W Cook letters to J G Keppler, Same Subject:

(1) Serial 10996, dated January 9, 1981
(2) Serial 11526, dated March 31, 1981
(3) Serial 13690, dated September 29, 1981
(4) Serial 14666, dated January 15, 1982
(5) Serial 16149, dated April 2, 1982
(6) Serial 17354, dated May 17, 1982
(7) Serial 17542, dated July 9, 1982
(8) Serial 19085, dated October 29, 1982
(9) Serial 20711, dated February 22, 1983
(10) Serial 20747, dated April 5, 1983
(11) Serial 23774, dated August 19, 1983

This letter, as were the referenced letters, is an interim 10CFR50.55(e) report concerning the subject bolting. Attachment 1 provides a current status and the details of the LAQTS material evaluation that is currently taking place.

Another report, either interim or final, will be sent on or before March 16, 1984.

JAMooney for J.W. Cook

JWC/WRB/cd

OC1283-0001A-MP01

Serial 23774

80-09 #12

Attachment 1: MCAR 45A, Final Report Revised November 18, 1983
MCAR 45B, Interim Report 10, dated November 29, 1983

Attachment 2: APTECH Report, #AES 8010220, "Evaluation Procedure for Low Alloy Quenched and Tempered Bolting/Component Support Applications"

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Attachment 1
Serial 26594

Bechtel Associates Professional Corporation

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Mail Address: P.O. Box 1000, Ann Arbor, Michigan 48106

SUBJECT: MCAR 45A Final Report
MCAR 45B, Interim Report 10

DATE: November 29, 1983

PROJECT: Consumers Power Company
Midland Plant Units 1 and 2
Bechtel Job 7220

Introduction

The discrepancies discussed in this report concern the hardness values of the anchor and connecting studs for the reactor coolant pump (RCP) snubbers. MCAR 45A was issued as a Final Report on August 5, 1982. The MCAR 45A report has been reissued as an attachment to this report and will be carried as an attachment until this MCAR is complete.

Background

MCAR 45A: Final Report (see attachment)

MCAR 45B

On November 26, 1980, Consumers Power Company expanded the 10 CFR 50.55(e) report to include, as potentially reportable, all low-alloy quenched and tempered steel (LAQTS) bolting materials 1-1/2 inches in diameter and larger used in support of safety-related systems. In MCAR 45B, dated December 17, 1980, this scope was expanded to include review of 7/8-inch and larger safety-related LAQTS bolting material.

Investigative Action

MCAR 45A: Final Report (see attachment)

MCAR 45B

Consumers Power Company is leading the investigation required by this MCAR. Commonwealth Associates, Incorporated (CAI) of Jackson, Michigan, which is under contract to Consumers Power Company, has reviewed safety-related purchase orders and identified those purchase orders for LAQTS bolting and/or component support material. CAI has also gathered data that will be used in evaluating the LAQTS materials.

Most of the review being conducted on the LAQTS bolting and component support materials consists of field hardness testing. This testing is being performed by Consumers Power Company and CAI.

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Science Applications Incorporated (SAI) of Palo Alto, California, has been retained and has developed a sampling plan to determine the quantity of items to be tested. SAI has revised the sampling plan as a result of the additional materials identified by CAI.

Aptech Engineering Services has been retained to assist in evaluating the LAQTS materials purchased by identifying which materials are LAQTS and require testing. Aptech has developed a generic evaluation methodology (Report AES-8010220, dated July 1983) that establishes hardness limits for LAQTS materials. For bolting materials that exceed the established hardness limits, the methodology provides allowable stresses for preventing stress corrosion crack growth and brittle fracture. Guidelines are also given for evaluation of soft material for tensile-ductile failure.

Based on preliminary hardness test results, approximately 30 bolting material purchases were identified that appeared to contain material considerably softer than the hardness limits established by Aptech. Further evaluation and testing on a portion of these materials by the Consumers Power Company laboratory indicated that the bolting materials were actually within the acceptable hardness limits. The differences were determined to be due to the existence of a decarburized layer that had not been completely removed during field testing. The hardness test procedure has been modified to prevent future difficulties due to erroneous data. The retesting of the remaining portions of these 30 bolting material purchases with the decarburized layer removed has been completed.

The discovery of the erroneous hardness data resulting from decarburization raised the following two concerns for previously collected hardness data.

a. Bolting materials that had been tested and appeared to be below established hardness limits may actually be within the limits.

b. Bolting materials that had been tested and appeared to be above or within established hardness limits may actually be harder than the first hardness tests indicated.

As a result of these concerns, a retest sampling program was developed with SAI to identify previously collected hardness data that are suspect, including data for the RCP snubber anchor bolts. This retesting sampling program is complete and the results are currently being evaluated. The retest sampling program will identify bolting material purchases that require retesting to correct data errors due to decarburization.

Preliminary review of hardness test data indicates that, of 494 unique material deliveries that have been hardness tested to date, 247 contain material of hardness outside the ranges established by Aptech. These material deliveries have been identified on a nonconformance report and are being placed on hold pending final evaluation of test data and implementation of corrective action.

The majority of the hardness testing has been completed. However, some purchases of bolting material have not been located for hardness testing. To ensure location and testing of these items, a program is being developed to inventory all relevant applications that use bolting materials 7/8 inch in diameter or larger. The completed inventory lists will be used to identify safety-related locations of bolting requiring hardness testing. The inventory lists will also be used to locate remaining portions of safety-related materials tested that do not meet the established hardness limits.

Corrective Action

MCAR 45A: Final Report (see attachment)

MCAR 45B

The recommended corrective action for the bolting deliveries described under Investigative Action is to locate and replace the suspect bolting or verify by evaluation the acceptability of the material for each specific installation. This effort is being tracked under CPCo NCR M01-9-3-289.

Quality control receipt inspection includes hardness testing of LAQTS bolting/component support materials to preclude the use of defective materials.

Safety Implications

MCAR 45A: Final Report (see attachment)

MCAR 45B

Bolting purchases have been identified that contain material that hardness tested outside the ranges established by Aptech. Therefore, it must be assumed that these bolting materials could fail during operating or accident conditions. The disposition of the suspect materials will preclude any adverse safety implications.

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Bechtel Associates Professional Corporation

Reportability

This condition relative to the RCP snubber studs was identified as "potentially reportable" by Consumers Power Company to the NRC under 10 CFR 50.55(e) on November 25, 1980.

MCAR 45B

Submitted by: G.L. Richardson

Approved by: for E.B. Poser
Project Engineering Manager

Concurrence by: E.H. Smith
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Concurrence by: for M.A. Dietrich
Project Quality Assurance Engineer

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Attachment: MCAR 45A Final Report

Bechtel Associates Professional Corporation

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Mail Address: P.O. Box 1000, Ann Arbor, Michigan 48106

SUBJECT: MCAR 45A Final Report

DATE: August 5, 1983
(Reformatted and resigned November 18, 1983)

PROJECT: Consumers Power Company
Midland Plant Units 1 and 2
Bechtel Job 7220

Introduction

The discrepancies discussed in this report concern the hardness values of the anchor and connecting studs for the reactor coolant pump (RCP) snubbers.

Background

The RCP snubber anchor studs are 2-1/4, 2-1/2, 3, and 3-1/2 inches in diameter and vary in length from 3 feet, 5 inches to 7 feet, 1 inch. They are embedded in the secondary shield wall and the refueling canal wall. Also included are 2-inch and 2-1/4-inch-diameter connecting studs approximately 1 foot, 10 inches long that connect the snubbers to a structural steel transition piece. The anchor studs are in place. The snubbers restrain the RCPs during seismic and/or loss-of-coolant accident (LOCA) events. The studs were purchased from various vendors during 1977 and 1978 by Bechtel construction in accordance with either ASTM A 354, Grade BD, or ASTM A 540, Grade B23, Class 3. They were intended to be tensioned to a preload up to 96 ksi to maintain the specified snubber spring rates under all loading conditions. Prior to tensioning, to ascertain that the studs could withstand long-term loads of this magnitude without becoming susceptible to stress corrosion cracking, Consumers Power Company requested Teledyne Engineering Services (TES) to conduct hardness tests on the exposed end of the embedded and connecting studs. TES conducted these hardness tests from November 21 through November 23, 1980. The test results showed that 207 studs of 384 tested are outside the range of hardness specified by the ASTM specifications.

Investigative Action

Aptech Engineering Services of Palto Alto, California, was retained by Consumers Power Company to review the hardness data taken by TES, and to evaluate the effect of the measured hardnesses on the ability of the studs to withstand preload, operating, and accident loadings. Based on preliminary Aptech evaluations, it was decided to lower the required stud preload (to a maximum of 12 ksi) to preclude failure because of stress corrosion cracking. Subsequently, Aptech has provided Report AES-81-08-79 (which was transmitted to the NRC via Consumers Power Company letter, Serial 17354, 5/17/83). In the development of a generic evaluation methodology (in support of MCAR 45B), it was found that AES-81-08-79 was unconservative (by about 6%) in that development of fracture toughness limited allowable stresses; therefore, the allowable preload

and accident stresses of AES-81-08-79 have been reevaluated. Based on this reevaluation of allowable stresses, the lowest maximum allowable preload for any of the RCB snubber anchor bolts is 42.9 ksi. Therefore, the required 12 ksi preload is less than the allowables in the Aptech report and is acceptable. Instructions were issued to construction to preload the studs to 9 ksi, a value lower than the maximum permissible. A tolerance of ±3 ksi is allowed.

This preload value, when reduced by temperature and relaxation losses, exceeds 3 ksi, a value in excess of the minimum preload of 1.5 ksi required by Babcock & Wilcox (B&W) during operation. New spring rates have been submitted by Bechtel to B&W. B&W is proceeding with the new seismic and LOCA analysis of the reactor coolant system. ITT Grinnell, supplier of the snubbers, has also been informed of the change in the preload. Grinnell stated that there is no effect on the snubbers or on the spring rate of the snubbers themselves.

The Aptech report noted above also contains an assessment of the allowable accident stresses of the RCP snubber anchor bolts. Based on this report and on the reevaluated allowable accident stresses, the allowable stress limits for operation and short-duration loading are available. Calculations have been prepared and the results indicate that the bolt stresses, based upon the capacity of the snubbers, are acceptable when compared to the Aptech allowables.

Procurement documentation packages for these studs have been reviewed. All necessary corrective action was completed and a report issued. No additional action is required.

Corrective Action

Construction has been instructed to preload the snubber studs to 9 ± 3 ksi. A procedure was developed by B&W construction to ensure that the studs are tensioned as required. This work has been completed for Units 1 and 2. Engineering has made a comparison of the calculated anchor bolt stresses with the Aptech allowable stresses. These stresses, based on the capacity of the snubber, which limits the loading on the studs, are within the Aptech allowable limits. All corrective actions under MCAR 45A are considered to be complete.

Safety Implications

If the subject studs were tensioned according to the original design requirements, there may have been a safety deficiency in that some of the studs could have failed because of stress corrosion cracking. If uncorrected, this deficiency could have adversely affected the safety of Midland plant operations during the expected life of the plant.

Bechtel Associates Professional Corporation

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Reportability

This condition relative to the RCP snubber studs was identified as "potentially reportable" by Consumers Power Company to the NRC under 10 CFR 50.55(e) on November 25, 1980.

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EVALUATION PROCEDURE FOR LOW ALLOY QUENCHED AND TEMPERED BOLTING/COMPONENT SUPPORT APPLICATIONS

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EVALUATION PROCEDURE FOR LOW ALLOY QUENCHED AND TEMPERED BOLTING/COMPONENT SUPPORT APPLICATIONS

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July 1983

QUALITY ASSURANCE
VERIFICATION RECORD SHEET

Title: "Evaluation Procedure For Low Alloy Quenched and Tempered Bolting/ Component Support Applications" (AES 8010220)

Originated by: ______________________ 8/31/83
Russell C. Cipolla

Approved and Verified by: ______________________ 9-8-83
Geoffrey R. Egan

Quality Assurance Review by: ______________________ 9/2/83
Jeffrey D. Byron

Quality Assurance Approval: ______________________ 9/2/83
Jeffrey D. Byron

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ABSTRACT

A procedure for evaluating low alloy, quenched, and tempered materials is presented. The procedure utilizes the principles of fracture mechanics to assess the performance of potentially variable materials in environments and loading situations that may cause stress corrosion cracking or fracture. The output of the procedure are allowable stresses for preventing stress corrosion crack growth and brittle fracture. Guidelines are also presented in the evaluation of materials that may be soft and the concern for tensile-ductile failure becomes important.

The procedures are straightforward and are primarily focused on bolting applications. Guidelines for evaluating non-bolting applications are also included. The major analytical assumptions are discussed, and the technical basis and justification for the input parameters are presented. A form for completing the evaluation in an organized manner is provided in the appendices.

NOMENCLATURE

Symbol	Definition
a	Crack depth
a_c	Critical crack depth
a_r	Crack depth for a postulated "reference" flaw
a/ℓ	Crack aspect ratio
A	Cross-sectional (shank) area
A_s	Net tensile area or "stress" area
C_f	Yield strength reduction factor for temperature
D	Nominal (major) diameter
d	Minor diameter
F_y	Specified minimum yield strength
F_u	Specified minimum ultimate tensile strength
h	Hardness
h_{max}	Statistically based maximum hardness limit
h_{min}	Statistically based minimum hardness limit
K	Stress intensity factor
$\tilde{K}_I$	Stress intensity factor for Mode I loading for a unit stress
$\tilde{K}_{II}$	Stress intensity factor for Mode II loading for a unit stress
K_{Ic}	Plane strain fracture toughness for Mode I loading
K_{IIc}	Plane strain fracture toughness for Mode II loading
K_{Ic}^-	Conservative bound to K_{Ic} data
K_{Iscc}	Threshold stress intensity factor for crack propagation by stress corrosion cracking
K_{Iscc}^-	Conservative bound to K_{Iscc} data
K_t	Stress concentration factor

Symbol	Definition
ℓ	Crack length
L	Leeb-scale units for hardness
n	Number of threads per inch
p	Thread pitch (p = 1/n)
P	Axial load
$P_a^{\ell t}$	Allowable tension load for long-term (normal) loading conditions
P_a^{st}	Allowable tension load for short-term (accident) loading conditions
R_b	Rockwell-B scale units for hardness (also HRB)
R_c	Rockwell-C scale units for hardness (also HRC)
S_y	Specified minimum yield strength (ASME Code)
S_u	Specified minimum ultimate tensile strength (ASME Code)
σ	Nominal applied stress
σ_a	Allowable stress
σ_a^f	Allowable stress based on fracture toughness
σ_a^s	Allowable stress based on strength
σ_a^{scc}	Allowable stress based on stress corrosion cracking
$\sigma_a^{\ell t}$	Allowable stress for long-term loading conditions
σ_a^{st}	Allowable stress for short-term (accident) loading condition
σ_y	Yield strength
σ_{ym}	Minimum yield strength
σ_{ymax}	Maximum yield strength limit based on h_{max}
σ_{ymin}	Minimum yield strength limit based on h_{min}
σ_u	Ultimate tensile strength
σ_{um}	Minimum ultimate tensile strength
σ_{umax}	Maximum tensile strength limit based on h_{max}

Symbol	Definition
σ_{umin}	Minimum tensile strength limit based on h_{min}
τ	Nominal applied shear stress
τ_a	Allowable shear stress
τ_a^f	Allowable shear stress based on fracture toughness
τ_a^s	Allowable shear stress based on strength
τ_a^{scc}	Allowable shear stress based on stress corrosion cracking
$\tau_a^{\ell t}$	Allowable shear stress based on long-term (normal) loading conditions
V_a^f	Allowable shear load based on fracture
V_a^{scc}	Allowable shear load based on stress corrosion cracking
$V_a^{\ell t}$	Allowable shear load for long-term (normal) loading conditions
V_a^{st}	Allowable shear load for short-term (accident) loading conditions

Section 1
INTRODUCTION

In May 1982, Aptech Engineering Services, Inc., issued a report (1) that presented the results of an integrity evaluation for the reactor coolant pump (RCP) snubber anchor studs (SAS) for the Midland Project of Consumers Power Company (CPCo). The objective of that evaluation was to assess the structural integrity for both long-term and short-term loading situations. Specifically, the assessment involved detailed computations to:

(1) Determine the potential for stress corrosion cracking (SCC) in the materials purchased

(2) Evaluate the effects of low toughness properties

(3) Evaluate the potential for ductile failure for the situation when the material may be soft

(4) Calculate the allowable loads under long- and short-term loading conditions

The purpose of this report is to present an evaluation procedure for general application to bolting and component supports that are fabricated from low alloy, quenched, and tempered (LAQT) materials. Where possible, this report has expanded the work presented in (1) in order to allow for general use. For completeness, all of the basic assumptions and description of the input parameters are presented herein.

Section 2
EVALUATION METHOD

2.1 STRATEGY

The basic approach of the evaluation method is summarized in this section. It is the intent to outline an evaluation procedure in a generic fashion to allow for a uniform or standardized approach for which the completed RCP-SAS evaluation would be a subset. The procedure employs fracture mechanics concepts to quantify the allowable bolt loads based on the fracture properties of the material. In addition, the minimum strength of the material is estimated in order to compare with the design requirements based on strength.

A flowchart showing the integration of the required input information with the calculational steps is shown in Figure 1. In applying the principles of linear elastic fracture mechanics (LEFM), a philosophy has been adopted which involves the use of a "reference flaw" to calculate the allowable bolt loads. In the assessment strategy, this reference flaw is postulated at the thread root and represents a flaw which is large enough to be unlikely to exist in a bolt. The material behavior (i.e., mechanical strength, fracture resistance, and SCC resistance) are estimated from an analysis of the field hardness measurements. Hence, a key step in the evaluation is the determination of the hardness for the material for a reasonable sample size so that statistical limits can be established. Once the material properties are established, the remaining calculational steps are straightforward and simple.

2.2 ASSUMPTIONS

Many assumptions were made in establishing the procedures. The important assumptions are discussed in detail in the RCP-SAS Report (1). For completeness, the major assumptions and areas of conservatism are outlined below:

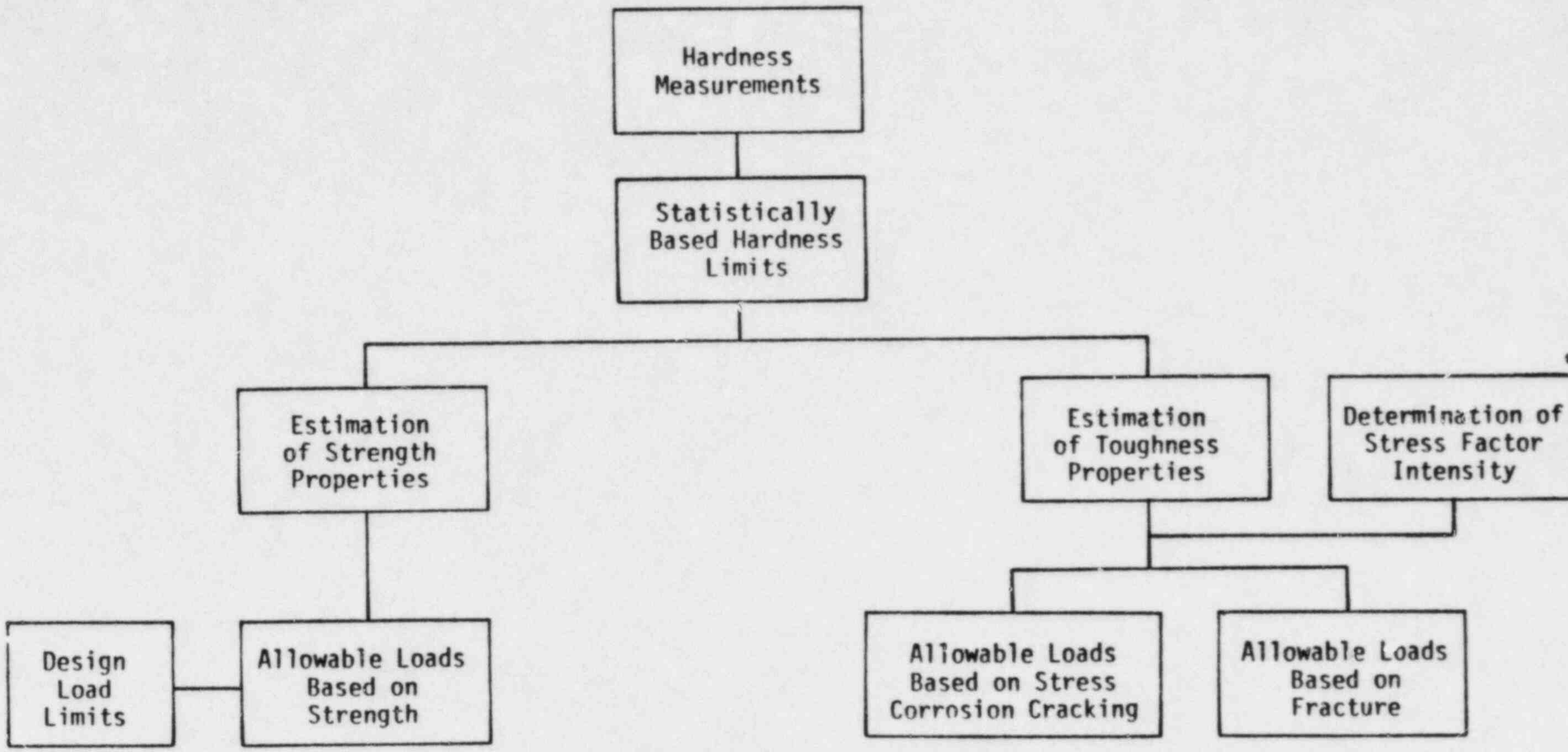

Figure 1 - Strategy of Evaluation Methodology.

(1) A flaw with a depth of 0.02 inches with an aspect ratio, a/ℓ, of 1-to-4 is assumed to exist at the thread root

(2) A lower bound curve to fracture toughness data was used to establish K_{Ic} for the material

(3) A lower bound curve to threshold stress intensity factor data was used to establish K_{Iscc} for the material

(4) The variability in hardness within a component (e.g., bolt) was assumed to be no better than the variability in hardness within the heat

(5) A 90% probability of occurrence with 95% confidence was used as the statistical criterion for determining the tolerance limits for the bolt population

Some of the assumptions above have the potential of being very conservative. Future improvements or refinements may be warranted for materials that cannot meet these criteria and are difficult to replace. The areas where this potential exists are summarized below:

(1) The assumption that the material variability within a component is equal to the material variability determined for the entire heat may be very unrealistic especially for short bolts. The variability in hardness with respect to axial position could be quantified by testing.

(2) Lower bound curves for K_{Ic} and K_{Iscc} could be very conservative. Statistically based curves may provide improvements.

(3) The 0.02 inch flaw depth assumed as the "reference flaw" was excessive when compared to the flaw sizes which have been observed to initiate the failures in component support bolting summarized in

(1). In fact, failure analyses for these instances did not identify pre-existing flaws which initiated SCC.

2.3 OUTLINE OF PROCEDURE

2.3.1 Description

The outline presented below summarizes the steps required to perform the evaluation. The strategy shown in Figure 1 is divided into five parts as follows:

Part 1 - Determination of Hardness Limits

Part 2 - Estimation of Material Properties

Part 3 - Determination of K

Part 4 - Calculation of Allowable Bolt Loads Based on Stress Corrosion Cracking (Long-Term Conditions)

Part 5 - Calculation of Allowable Bolt Loads Based on Fracture (Short-Term Conditions)

Each analysis part is described in detail in the subsections that follow. A calculational form is provided in Appendix I that outlines each analysis step. There is space provided on the form for all relevant information with regard to the evaluation as well as recording the results.

2.3.2 Part 1 - Establishment of the Hardness Limits

The minimum and maximum hardness limits for the lot of bolts must be established to provide a quantitative estimate of material properties. To determine the minimum and maximum limits, hardness testing is required to establish a data base for the lot. For statistical purposes, we will define

this bolt lot a stratum. If possible, the lot of bolts should be defined as an individual heat of material or a single size of bolt. The following steps should then be followed:

(1) Establish a data base of hardness measurements by stratum, by implementing a suitable test sampling plan.

(2) Establish the probability function that best represents the frequency of the data. A normal distribution function may provide a reasonable fit for hardness data directly or when the hardness data have been first converted to their equivalent value in tensile strength units in accordance with ASTM A370 (2) and the normal function is applied to the tensile strength data set. If a sufficient number of data points exist, a nonparametric approach will allow statistical limits to be determined without the need to assume a particular distribution function.

(3) Determine the two-sided tolerance limits for the bolt population that provides a 90% probability that measurements will fall between these limits with 95% confidence (see Reference 1 for the definition of a two-sided tolerance limit and the basis for the statistical criterion).

(4) Compare the two-sided hardness limits with the appropriate specification requirements (see Appendix II for a listing of hardness limits by specification). If the computed limits satisfy the requirements for which the material was purchased, then compliance with the intent of the original purchase specification is achieved and no additional evaluation would be required.

(5) If additional analysis is required beyond Step 4, compute the one-sided tolerance limits for minimum and maximum hardness level (or strength level) with the same 90-95% criteria (see Reference 1 for the definition of a one-sided tolerance limit).

The above procedure can be repeated for each material group or stratum that was identified as requiring evaluation. The computed one-sided tolerance limits for minimum and maximum hardness will be used in Part 2 of the procedure.

2.3.3 Part 2 - Estimation of Material Properties

The procedures outlined below are the steps that will define conservative estimates of yield and ultimate strength, SCC threshold, and fracture toughness based on the one-sided minimum and maximum tolerance limits from Part 1:

(1) Define the specified minimum yield strength, F_y, and the specified minimum ultimate tensile strength, F_u, for the governing material specification.

(2) Convert the minimum hardness (or tensile strength) limit from Step 5 of Part 1 to material yield strength, σ_{ymin}, with the curve provided in Figure 2 (1).

(3) Convert the minimum hardness limit from Step 5 of Part 1 to equivalent tensile strength units with the tables in ASTM A370 (2). This defines σ_{umin}.

(4) Define the minimum yield strength value at room temperature, σ_{ym}, as either σ_{ymin} from Step 2 above or the specified minimum yield strength for the material at room temperature, F_y, whichever is lower.

(5) Define the minimum tensile strength value at room temperature, σ_{um}, as either σ_{umin} from Step 3 above or the specified minimum tensile strength for the material at room temperature, F_u, whichever is lower.

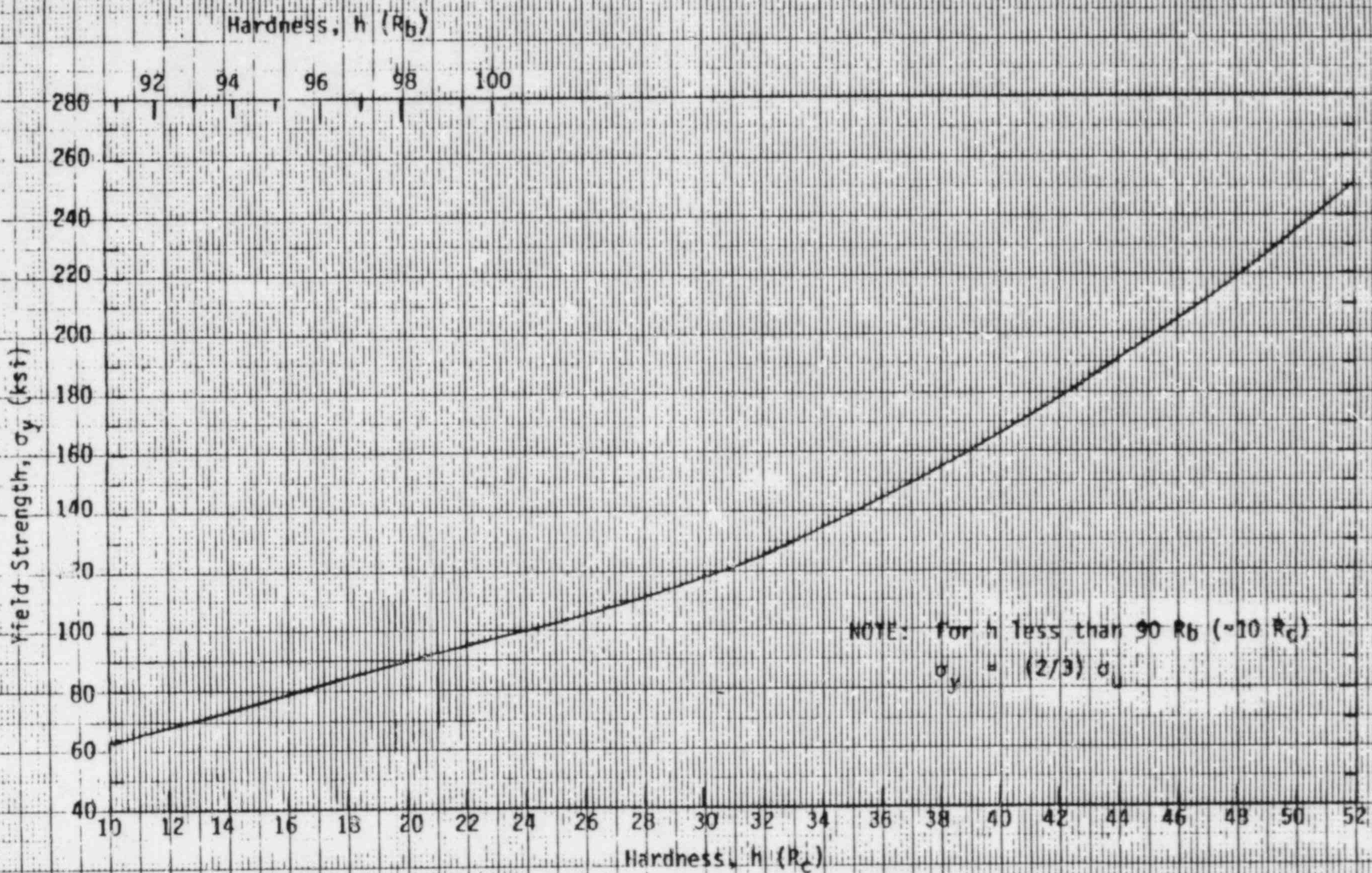

Figure 2 - Yield Strength Versus Hardness For LAQT Steels (1).

(6) Define a conservative bounding value for K_{Iscc} called $\overline{K}_{Iscc}$ from Figure 3 (1) for the value of maximum hardness from Step 5 of Part 1.

(7) Define a conservative bounding value for K_{Ic} called $\overline{K}_{Ic}$ from Figure 4 (1) for the value of maximum hardness from Step 5 of Part 1.

It should be noted that since both $\overline{K}_{Iscc}$ and $\overline{K}_{Ic}$ reach a conservative "threshold" value with respect to increasing material yield strength of 8 ksi $in^{1/2}$ and 34 ksi $in^{1/2}$, respectively, the Part 1 evaluation could be deleted by conservatively assuming the conservative bound threshold levels for materials with trends that appear on the hard side. Provided one is assured that there is no difficulty in meeting the specified minimum strength requirements, the analysis would be simplified significantly if Part 1 can be eliminated. However, if the maximum hardness limit is greater than 48 R_c, then the effect of residual stress due to quenching may need to be considered in the analysis for allowable bolt stress.

2.3.4 Part 3 - Determination of K

The following is the procedure to determine the applied stress intensity factors for a unit applied stress. The tables in Appendix III for K are based upon calculations which assume a reference flaw at the root of a thread with depth of 0.02 inches and a flaw aspect ratio (a/ℓ) equal to 1/4.

(1) Define the geometry of the fastener in terms of the following parameters:

(a) Nominal diameter, D

(b) Thread pitch p = 1/n where n is the number of threads per inch

(c) Shank or nominal cross-sectional area, A

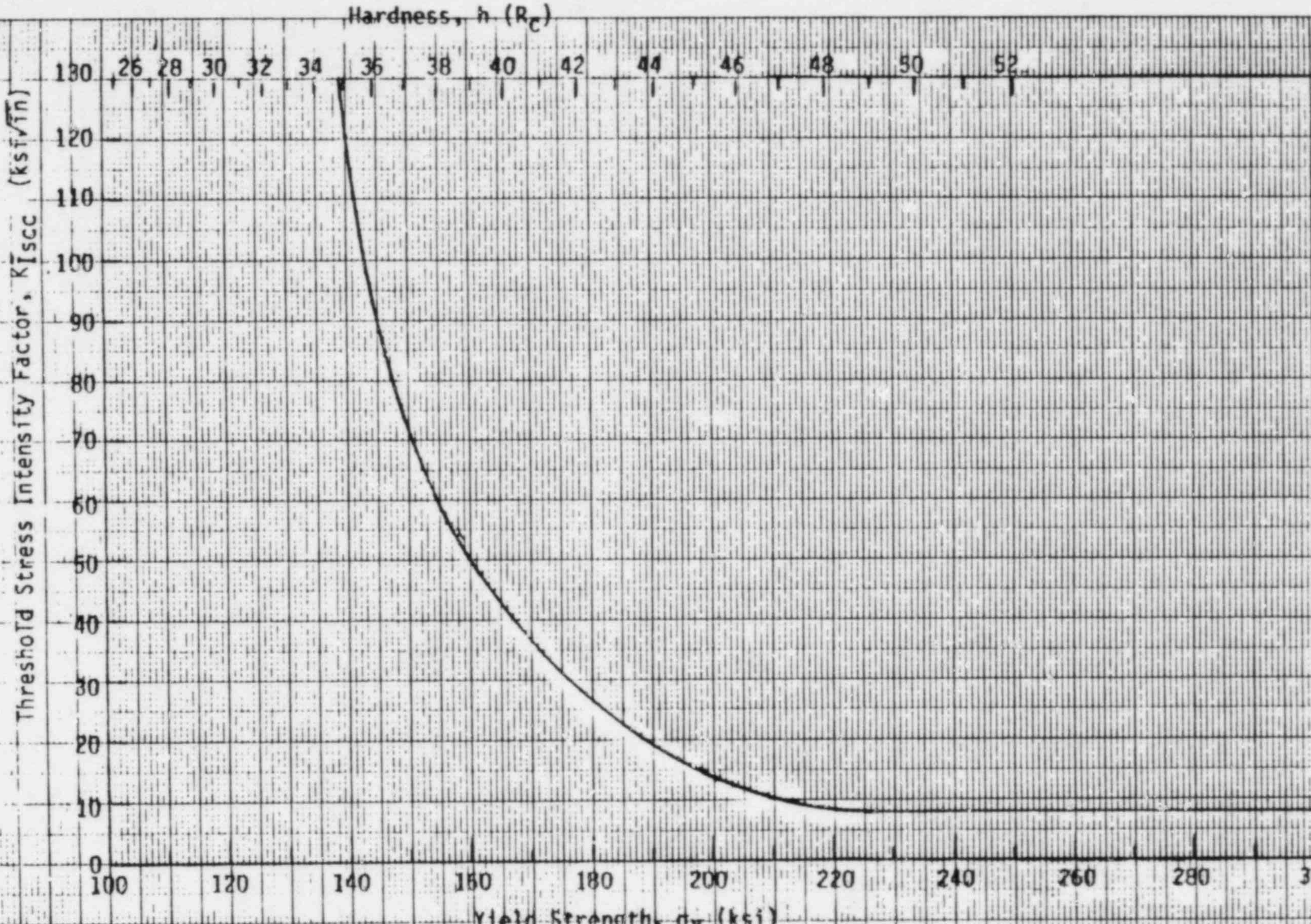

Figure 3 - Conservative Bound For SCC Threshold Versus Strength (1).

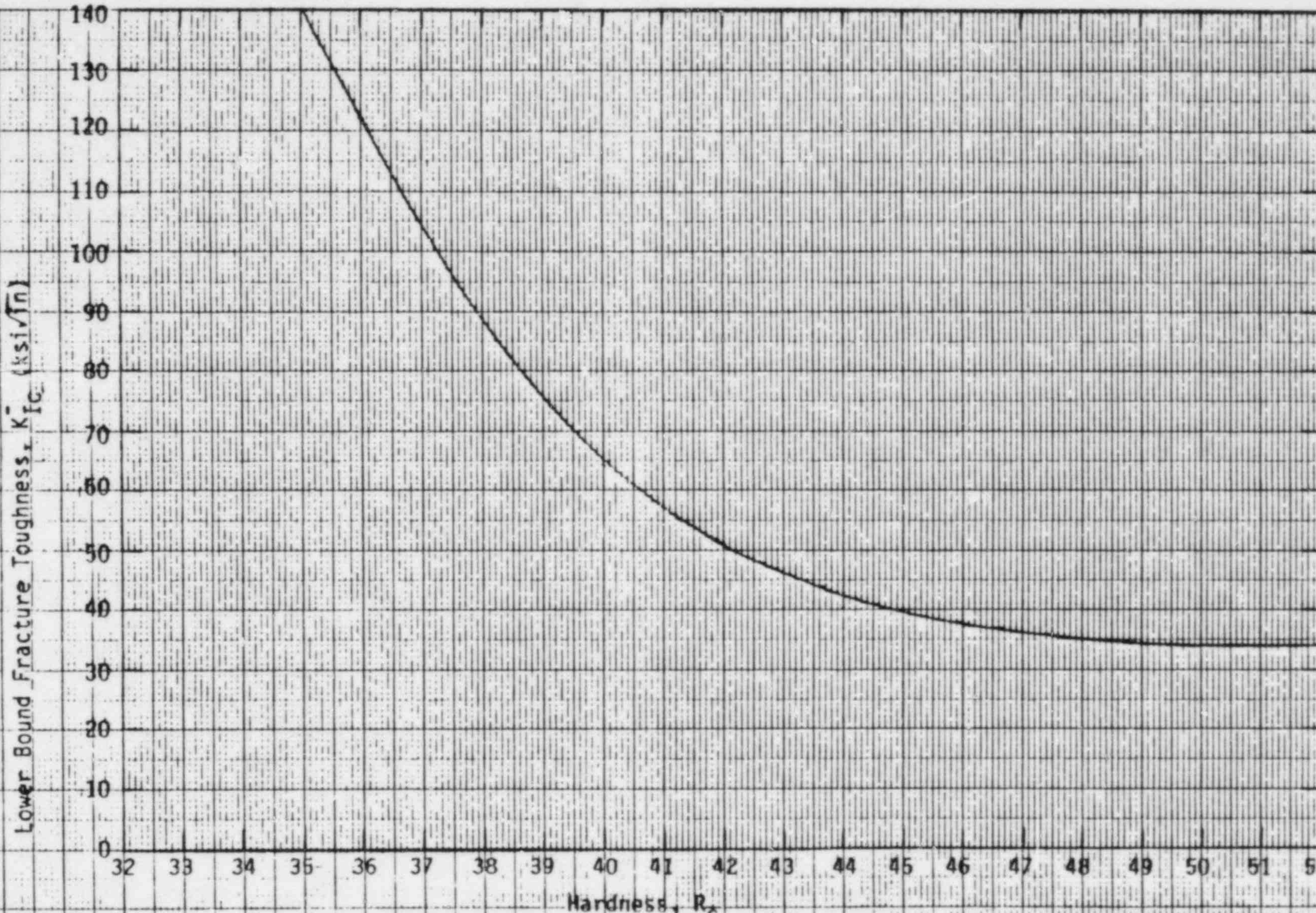

Figure 4 - Conservative Bound For Fracture Toughness Versus Hardness (1).

(d) Net tensile or stress area, A_s

(2) For the threaded fasteners including studs and bolts, the value of $\tilde{K}_I$ is determined by the following procedure:

(a) For the given fastener geometry (i.e., diameter, D, and thread pitch, p) use tables in Appendix III to define the stress intensity factor for a unit applied stress, $\tilde{K}_I$.

(b) If the exact bolt diameter or thread pitch is not listed in the tables, then use linear interpolation to determine the value of $\tilde{K}_I$.

(3) For solid pins that are subjected to pure shear loading, the value of stress intensity for uniform shear stress (Section 3.5.3) is determined from

$$K_{II} = 0.232\tau \tag{2-1}$$

Hence, the unit applied stress intensity factor $\tilde{K}_{II}$ for shear pins is $\tilde{K}_{II} = 0.232$ for use later in Parts 4 and 5.

2.3.5 Part 4 - Calculation of Allowable Bolt Load Based on SCC

The allowable bolt load for prevention against SCC for long-term loading under normal operating condition is determined by the following procedure:

(1) For threaded fasteners, calculate the allowable stress based on considerätion for SCC from the expression

$$\sigma_a^{SCC} = (1/\tilde{K}_I)\, K^-_{ISCC} \tag{2-2}$$

where $\bar{K}_{Iscc}$ is the conservative bound for K_{Iscc} established under Step 6 of Part 2, and $\tilde{K}_I$ is the stress intensity factor for the postulated reference flaw and unit applied stress from Step 2 of Part 3. The allowable bolt load based on SCC can be computed from

$$P_a^{scc} = \sigma_a^{scc} A_s \quad (2\text{-}3)$$

where A_s is the net tensile or stress area for the bolt.

(2) For shear pins, the allowable shear stress based on consideration for SCC is calculated from

$$\tau_a^{scc} = (1/\tilde{K}_{II})\, \bar{K}_{Iscc} = 4.31\, \bar{K}_{Iscc} \quad (2\text{-}4)$$

where $\bar{K}_{Iscc}$ is the conservative bound for K_{Iscc} established under Step 6 of Part 2, and $\tilde{K}_{II} = 0.232$ from Step 3 of Part 3. The allowable shear load based on SCC is

$$V_a^{scc} = \tau_a^{scc} A \quad (2\text{-}5)$$

where A is the cross-sectional area of the pin.

It should be noted that fracture toughness is not considered in the determination of allowable bolt stress for long-term load since K_{Iscc} will be less than K_{Ic} and, therefore, limiting.

2.3.6 Part 5 - Calculation of Allowable Bolt Loads Based on Fracture

The allowable bolt load based on fracture for short-term or accident loading conditions is determined according to the following procedure:

(1) For threaded fasteners, compute the allowable stress for preventing fracture from

$$\sigma_a^f = (1/\tilde{K}_I)K_{Ic}^- \tag{2-6}$$

where $\tilde{K}_I$ is determined from Step 2 of Part 3, and $\bar{K}_{Ic}$ is the conservative bound for fracture toughness from Step 7 of Part 2. The allowable bolt load based on fracture can be computed from

$$P_a^f = \sigma_a^f A_s \tag{2-7}$$

where A_s is the net tensile or stress area for the bolt.

(2) For shear pins, the allowable shear stress based on fracture is calculated from:

$$\tau_a^f = (1/\tilde{K}_{II}) K_{Ic}^- = 4.31 K_{Ic}^- \tag{2-8}$$

where $\tilde{K}_{II}$ is given in Step 3 of Part 3, and $\bar{K}_{Ic}$ is the conservative bound for fracture toughness from Step 7 of Part 2. The allowable shear load based on fracture is

$$V_a^f = \tau_a^f A \tag{2-9}$$

where A is the cross-sectional area of the pin.

This completes the details of evaluation. At the end of the Parts 4 and 5, the allowable bolt stress (or loads) for SCC and fracture considerations have been quantified. Some guidelines are presented next as to how to use these results to establish allowable bolt loads that would be the limiting case for the specific bolting application.

2.4 GUIDELINES FOR DETERMINING MATERIAL ACCEPTANCE

The criteria for acceptance is based on a fitness-for-purpose philosophy such that if the applied stress is less than the allowable stress, then the material is suitable for service. Hence, the criteria are established as

$$\sigma^{st} < \sigma_a^{st} \qquad (2\text{-}10)$$

$$\sigma^{\ell t} < \sigma_a^{\ell t} \qquad (2\text{-}11)$$

where σ^{st} and $\sigma^{\ell t}$ are the calculated short-term and long-term stress conditions, respectively, for the design, and σ_a^{st} and $\sigma_a^{\ell t}$ are respective allowable stresses. A similar set of criteria can be established for shear carrying members, such as shear pins. The allowable stress is the minimum value of the allowable stresses determined from consideration of fracture, SCC, and tensile-ductile failure modes. Therefore,

$$\sigma_a^{st} = \sigma_a^f \text{ or } \sigma_a^s \qquad (2\text{-}12)$$

whichever is minimum and where σ_a^s is the allowable stress based on strength. The allowable stress, σ_a^s, is calculated in accordance with

applicable conventional desi^n procedures and based on σ_{ym} and σ_{um} determined in Part 2. Similarly for long-term stresses

$$\sigma_a^{\ell t} = \sigma_a^{scc} \text{ or } \sigma_a^{s} \qquad (2\text{-}13)$$

whichever is minimum. In order to test for acceptance, the allowable stress based on strength must be established given the anticipated design conditions and safety factors. Provided it is accepted tha+ the design is sufficient when the specified minimum strength requirements are achieved, then σ_a^s need not be quantified, and the long- and short-term allowables based on σ_a^{scc} and σ_a^f need only be compared with the applied stress. Again, this is true without question as to the type of design or design criteria when

$$\sigma_{ymin} \geq F_y \qquad (2\text{-}14)$$

and

$$\sigma_{umin} \geq F_u \qquad (2\text{-}15)$$

Knowledge of the design criteria and inherent design safety factors will be required if the design basis is not satisfied by the appropriate equations above. If both Eq. (2-14) and Eq. (2-15) are true as determined during the evaluation, then the only required check for acceptance is that Eq. (2-10) and Eq. (2-11) are satisfied as written below:

$$\sigma^{st} < \sigma_a^f \qquad (2\text{-}16)$$

$$\sigma^{\ell t} < \sigma_a^{scc} \tag{2-17}$$

If Eq. (2-14) or Eq. (2-15) is not satisified, then a review of the design calculations and allowables may be required to insure that σ_a^s is not limiting. If this becomes the case, then those parameters that effect strength must be considered. If the material is subjected to elevated temperatures during service, then a reduced strength should be used. A yield strength reduction factor, C_f, was developed for common bolting materials from (4). These factors are given in Section 3.4 for a range of temperatures between 100°F to 600°F and apply to yield strength only. In this temperature range, no reduction in the ultimate tensile strength is assumed.

Section 3
ANALYSIS ASSUMPTIONS AND RESTRICTIONS

3.1 INTRODUCTION

In order for this report to be self supporting, this section has been prepared to provide the technical basis for the evaluation procedures. Reference will be made to the RCP-SAS report as required to justify assumptions and information implemented herein from (1). In the areas that are expansions of the RCP-SAS analysis, background information is also provided herein. The final objective of this section is to identify the key assumptions in order to define the applications where the evaluation procedures are valid.

3.2 FAILURE MODES

In the evaluation procedure contained herein, the acceptability requirements for service have been established based on assuring against service failure from three potential failure modes. These modes of failure are

(1) Ductile rupture by plastic instability (limit load failure)

(2) Crack propagation in a subcritical manner by intergranular stress corrosion cracking

(3) Brittle or fast fracture due to crack instability under monotonically increasing load

In many respects, each failure condition is unique so that assuring failure prevention for one mode does not guarantee safe conditions for the others.

When applying the evaluation method, the failure mode or modes to be prevented must be described by one of the above failure models; otherwise, irrelevant conclusions will be achieved. Specific failure modes that are not covered by the procedure but are relevant to bolts in general, include general corrosion failure or wastage, fatigue, and corrosion-assisted fatigue. The procedures would require revision in order to expand the method to cover other modes of failure.

3.3 MATERIALS

3.3.1 Chemistry and Heat Treatment

The material properties curves for SCC susceptibility and fracture toughness behavior were derived from a data base of laboratory tests for steels that can be classified as low alloy quenched and tempered. For consistency with the Consumers Power Company commitment to review safety related LAQT steels, we have adopted herein the same definition as was set forth in (3). Specifically, a steel will be considered a low-alloy steel "when the maximum range specified for the content of alloying elements exceeds one or more of the following limits: manganese 1.65%; silicon 0.60%; copper 0.60%; or in which a definite range or a definite minimum quantity is specified or required within the recognized commercial field of alloy steels; aluminium, boron, and chromium up to 3.99%, cobalt, columbium, molybdenum, nickel, titanium, tungsten, vanadium, zirconium, or any other alloying element added to obtain a desired alloying effect". In addition, the total content of alloying elements when summed shall not exceed 5% with the exclusion of carbon and commonly encountered amounts of manganese (up to 0.65%), silicon (up to 0.15%), and copper (up to 0.10%). This definition, although not very precise, was sufficient to identify those items purchased to specifications which require consideration in the CPCo LAQT review program.

A low alloy steel will be considered quenched and tempered if it has experienced a heat treatment that can result in heating to a temperature of 1500°F or greater, followed by rapid cooling, usually in a fluid medium, and

subsequent heating to a temperature in the range of 650-1250°F for a period of 1 to 3 hours (or for thick sections, approximately 1 hour per inch of thickness), followed by cooling to room temperature.

Materials that satisfy the above conditions for chemistry and heat treatment can be evaluated by the methods described in this report. A listing of the ASTM and ASME material designations compiled from Midland field purchase records that could have LAQT steels supplied is given in (3).

3.3.2 Ratio of Yield to Ultimate Strength Correlation

The yield to ultimate strength correlation was developed in the RCP-SAS report based on specific data for the supplied materials and reported "typical" behavior for LAQT steels. The study covered a range of material hardness from 21 R_c to 52 R_c. This correlation is given graphically in Figure 2 and is based on Eq. (4-1) in (1). In anticipation of very soft material behavior, this correlation was expanded to 90 R_b (~10R_c). The expansion of the original curve was accomplished by using, as guidance, the expected value and typical scatter for σ_y and σ_u for quenched and tempered steels reported in (5). Below 21 R_c, the curve given in Figure 2 was developed graphically staying within the limits of the reported data band (5). The curve was drawn to approach a constant ratio between σ_y and σ_u equal to 2/3 at 90 R_b. For hardness limits below 90 R_b, it is assumed that the equation, $\sigma_y = (2/3)\ \sigma_u$, is a reasonable approximation for yield strength.

3.4 ENVIRONMENT

3.4.1 Stress Corrosion Cracking

The SCC susceptibility of LAQT steels is very sensitive to the environmental conditions: specifically, the corrosive medium and service temperature. The SCC threshold curve shown in Figure 3 was derived from K_{Iscc} data measured in the laboratory with either moist air, distilled water, aqueous NaCl solutions or seawater environments. Although not indicated in all cases, the

testing temperature was typically at room temperature levels. However, a review of K_{Iscc} data given in Appendix IV as a function of test temperature indicated K_{Iscc} is temperature invariant for aqueous solutions. Based on this background information, the following restriction for the SCC evaluation for computing the allowable stress level σ_a^{scc} is applied:

(1) Service environments are restricted to moist air or aqueous NaCl environments, or environments that are viewed as being less aggressive than those from which the test data were developed.

(2) Highest service temperature for the bolting application in consideration of SCC limits should be limited to 250°F when no attention is given to the use of thread lubricating compounds, etc. (see below).

Caution should be exercised when extending the scope of the K_{Iscc} evaluation to other environments or elevated temperatures. Application to temperatures greater than 250°F are allowed, since the aqueous environment will not be present provided that the creation of more aggressive environments such as those caused by the breakdown of thread lubricants or coatings is prevented.

3.4.2 Fracture Toughness

For structural applications, the effect of environment on fracture toughness behavior can be neglected in that there will be no toughness degradation due to service exposure. The effect of temperature on toughness will tend to increase fracture resistance as temperature is elevated. Since the data base that validated the lower bound K_{Ic} curve in Figure 4 is based on room temperature behavior, any applications above this temperature will be conservatively treated by the evaluation procedure.

3.4.3 Yield and Ultimate Strength

If the expected service temperature is low (i.e., ambient conditions), then the effect of temperature on strength can be neglected. Guidelines for quantifying the reduction in strength are given in Section 2.4 and Table 1. The yield strength based on room temperature conditons is not significantly affected until temperatures in excess of 200 °F are reached. This is observed in Table 1. The strength reduction factors in Table 1 were developed from Section III of the ASME Code (4). The yield strength reduction factors were determined from the yield strength values, S_y, given in Table I-13.3 for bolting materials under Class 1, 2, 3, and MC components classification. Although only four material specifications are listed in the Code (and Table 1), reduction factors for other LAQT materials can be estimated by comparing material chemistry and mechanical strength properties with those of the materials listed in Table 1.

With regard to ultimate tensile strength, S_u for Code design limit for LAQT materials is generally insensitive to temperature. In most cases, the tensile strength is constant up to temperatures of 600°F or within 98% of their level at room temperature. It is therefore reasonable to assume room temperature values for S_u up to 600°F.

3.5 BOLT GEOMETRY

3.5.1 Thread-Root Region

The bolt geometry and thread-root characteristics are consistent with the Unified Inch Screw Thread Standards of ANSI B1.1 (6). The stress concentration effect of the threads and the stress attenuation with distance across the bolt diameter were approximated by literature solutions that describe the stress distribution in single-grooved bars under uniaxial tension. The capabilities of the evaluation method to handle different bolt geometries has been expanded since the first evaluation performed on the RCP snubber anchor studs. This was accomplished through the work performed under RP 1757-2 and RP 2055-5 for the Electric Power Research Institute (EPRI) (7)

Table 1

REDUCTION IN YIELD STRENGTH DUE TO TEMPERATURE

ASTM Specification	Type or Grade	Class	Thickness	Minimum Yield Strength (ksi)	Yield Strength Reduction Factor, C_f Temperature (^oF) Not to Exceed: 100	200	300	400	500	600
A193	B7	--	--	105	1.000	0.933	0.896	0.871	0.843	0.812
				95	1.000	0.931	0.896	0.866	0.843	0.812
				75	1.000	0.932	0.896	0.872	0.843	0.812
	B16	--	--	105	1.000	0.971	0.949	0.929	0.909	0.881
				95	1.000	0.969	0.947	0.928	0.909	0.881
				85	1.000	0.971	0.949	0.928	0.907	0.882
A320	L7	--	--	105	1.000	0.933	0.896	0.871	0.843	0.812
	L43	--	--	105	1.000	0.943	0.911	0.874	0.843	0.803
	L7A	--	≤2½"	105	1.000	0.933	0.896	0.871	--	--
A354	BC	--	≤2½"	109	1.000	0.936	0.904	0.877	0.851	0.814
	BC	--	>2½" < 4"	99	1.000	0.934	0.903	0.878	0.852	0.813
	BD	--	≤1½"	125	1.000	0.935	0.903	0.878	0.852	0.814
A540	B21-B24	1	--	150	1.000	0.956	0.924	0.896	0.868	0.828
	B21-B24	2	--	140	1.000	0.956	0.924	0.896	0.868	0.829
	B21-B24	3	--	130	1.000	0.955	0.927	0.895	0.868	0.829
	B21-B24	4	--	120	1.000	0.955	0.923	0.898	0.868	0.828
	B21-B24	5	--	105	1.000	0.954	0.926	0.894	0.866	0.829
	B21-B24	5	--	100	1.000	0.954	0.927	0.894	0.867	0.828

NOTE: Developed from (4). Linear interpolation is permitted.

and other plant specific work performed for the Tennessee Valley Authority (TVA) (8).

The areas of applicability are summarized below:

(1) The method is directly applicable to the thread-root region over the span of unengaged threads for studs and bolts.

(2) The procedure will be reasonable for evaluating the thread-root region of engaged threads within nuts or internally threaded connectors.

Engineering judgement was used to establish item 2 above; that judgement is based on a comparison between engaged and unengaged regions as to the nature of the stress distributions and the magnitude of the stress concentration. Although it is recognized that the stress concentration factor would tend to be higher for load carrying threads, the loading will be shared over several threads. Results from photoelastic tests on threaded models loaded through nuts (9) indicate that most of the load is carried by the first three engaged threads and that the nominal stress at the first thread is approximately 80% of the total net stress. Hence the nominal stress would be approximately 20% less at the highest stress engaged thread than at an unengaged thread plane due to load sharing. Furthermore, the assumption that the stress concentration factor (K_t) for a single groove bar represents a multiple-grooved bar such as a threaded stud is conservative. A single notch represents a higher degree of stress concentration than a series of closely spaced notches of similar geometry as the single notch. Results from photoelastic tests on multiple-grooved plates reported in (10) indicate about 25% reduction in K_t for multiple notches typical of a threaded fastener when compared to the K_t of a single notch. These effects of load sharing and K_t reduction could accommodate a 50% decrease in local stress along an engaged thread plane. These findings have been judged to be sufficient to allow the method to also be applicable to engaged thread regions as well. For

these reasons, the procedure is deemed general in application to standard ANSI threads in both engaged and unengaged thread regions.

3.5.2 Head-to-Shank Region

For headed bolts, another region of high local stress exists at the head-to-shank transition region. Although there is a potential for SCC to initiate at this location as well, for most situations, it has been judged that the thread root region will be the limiting region from the standpoint of local stress and crack driving force. This judgement is partially based on reported experience with bolting problems (11). Bolt failures have been associated more with the thread-root region as compared with the head-to-shank region in common bolt uses. Specifically, 65% of bolt problems are thread-related, whereas, 15% are related to the head-to-shank transition region with the remainder of the problems not associated with either the head-to-shank or thread-root regions. An analysis of a socket head bolt with 12UNF threads resulted in a higher stress intensity factor for the head-to-shank transition region than for the thread-root (8). Review of other work involving stress determinations at the bolt head transition suggest that stress concentration effect at the head may be comparable or less than that for the thread. Hence, the use of the thread-root region as the area of concern seems reasonable.

Finally, since it is also believed that the assumptions on flaw size and material properties are conservative, in the final analysis, satisfying the evaluation procedure will be sufficient to assure overall bolt integrity even though only the thread root was examined.

3.5.3 Shear Pins

For components that carry pure shear load, such as shear pins in clevis-trunnion attachments, the RCP-SAS procedure was expanded to include an SCC and fracture assessment. Although the contribution of shear stress to either Mode I or Mode II stress intensity factors will be small as discussed

In (1), a conservative treatment of shear stress on K_{II} is included for shear pins in order to provide assurance against SCC and fracture for these specialized components. The stress intensity factor for uniform shear loading in a semi-infinite body (12) is:

$$K_{II} = 1.122\tau\sqrt{\pi a/\Phi^2} \tag{3-1}$$

where τ is the uniform applied shear stress across the section and Φ is the elliptical integral. A reasonable approximation for Φ is given in (13) as

$$\Phi^2 = 1 + 4.593\,(a/\ell)^{1.65} \tag{3-2}$$

For a 0.02 inch reference flaw depth and 1-to-4 aspect ratio, the Mode II stress intensity factor is

$$K_{II} = 0.232\tau \tag{3-3}$$

In the procedure, K_{II} is to be compared with $\bar{K}_{Iscc}$ and $\bar{K}_{Ic}$ in order to de⁺ermine the allowable shear stresses. It is reported in (14) that K_{IIc} is app oximately equal to K_{Ic} for LAQT steels so that the use of Mode I prop rties is a reasonable approach.

3.6 LOADINGS

It is assumed in the evaluation methodology that the predominant loading mode is uniaxial tension. The source of the uniaxial stress can be preload, actively applied mechanical loads, or thermally-induced loading due to expansion. For the situation where shear loads are to be carried by the bolts, it was judged in the RCP-SAS report that for SCC and fracture, shear stresses other than torsion, will not significantly contribute to the crack driving force of the postulated reference flaw as described in (1).

Bending stresses have been neglected in the procedure, so any applications where bolts will experience cross-sectional bending loads cannot be handled

directly by the method in its present form. A conservative method to account for any bending loads is to add the bending stress magnitude to the tension stress, or

$$\sigma = \sigma_m + \sigma_b \tag{3-4}$$

where σ_m is the membrane or tensile component and σ_b is the bending stress.

Section 4
LIMITATIONS OF THE PRESENT METHODOLOGY

4.1 GENERAL OVERVIEW

The primary objective of Section 3 was to outline the major assumptions of the RCP-SAS report and to provide background information. The purpose of this section is to address the important limitations of the procedures, and to discuss the assumptions that are the most restrictive to the general application of the method. Clearly, the method can be improved in many ways. The important limitations of the method can be categorized into two areas; those assumptions that resulted in the restricted application of the method due to limited data, information, or details, and those assumptions that caused the analysis method itself to be conservative. The limitations to the general application of the procedure include:

(1) The focusing of the method to bolts, studs, threaded bars, and shear pins only

(2) The qualified restriction of the procedure to service temperatures below 250°F (see Section 3.4)

(3) The limitation to the bolt geometries described

Some of the more restrictive analysis assumptions include:

(1) The conservative use of linear elastic analysis when local yielding will cause lower stresses than those computed under linear conditions.

(2) The definition of a reference flaw that may be much larger than that expected for bolts that have not been subjected to SCC.

(3) Defining conservative threshold curves rather than statistically based criteria for K_{Ic} and K_{Iscc}.

(4) The conservative treatment of the SCC and fracture analysis for shear pins.

Two items listed above that have the greatest impact to the general application of the method are (1) the limitation of the present method to focus only on bolting, and (2) the restriction on service temperature. The remaining subsections discuss these two topics and provide guidance and recommendations for evaluating cases that would be otherwise limited by these two restrictions.

4.2 APPLICATION FOR OTHER COMPONENT SUPPORTS

In its most general application, the methodology must be capable of evaluating all types of component supports and threaded fasteners that are fabricated from LAQT steels and are utilized in a safety related function. There are essentially two categories of component supports: linear type supports in which threaded fasteners are members, and plate and shell type supports. Linear type supports are defined as those support elements that are acting essentially under a single component of direct stress or shear stress. Besides threaded fasteners, other linear supports would include shear pins, clevises, eye bolts and other types of clamping devices. The evaluation of shear pins has been included in the method and with slight additions or modifications, the present method can be revised to handle other types of linear supports. It is recommended that specific procedures for other linear support elements be added on a case-by-case basis.

Plate and shell type component supports are supports that are fabricated from plate and shell elements and are normally subjected to biaxial stress field. To evaluate these types of supports, two major complications to the method formulation would have to be resolved. First, the stress intensity factor curves would have to be revised for the different type of geometries and

stress states that would be encountered. This is actually not a difficult problem, in that a Code procedure already exists to do this; Appendix A of Section XI to the ASME Code (15) contains procedures to calculate K_I for the type of stress states that occur in plate and shell structures.

One area that must be addressed is the design factors and rules used to design the component supports in order to develop a consistent set of criteria for acceptances to design rules. In general, they are more complicated than for linear supports and it will be difficult to state in simple terms the relationship that provides the allowable stress consistent with all the rules of the design. This does not preclude a procedure where the impact of a soft material is assessed by simply returning to the original design calculations in a review mode. Clearly, the only time a concern on the design parameters would occur is when the minimum hardness limits give a value of σ_{ym} or σ_{um} that is less than the specified minimum values: F_y or F_u respectively.

Recent efforts have been expended to document the technical basis and background to these analytical procedures (13), as well as the development of a computational tool to perform the Appendix A procedure (16).

Section 5
SUMMARY

General evaluation procedures were developed around the Reactor Coolant Pump (RCP) Snubber Anchor Stud (SAS) assessment report. These procedures can be applied to other bolting applications to assess material acceptance in situations where material variability in hardness suggests a concern may exist in material resistance to SCC, fracture or tensile-ductile failure. The evaluation procedure may also be applied to evaluate materials that fail to meet purchase specification requirements in hardness. A calculational form for documenting and recording the evaluation results is provided.

The report dedicates considerable discussion to the assumptions and limitations of the method. The major restrictions of the original method presented in the RCP-SAS report were eliminated; specifically the limitation on maximum service temperature and restricted geometries. Guidance is provided on how other shortcomings in the method can be overcome, and recommendations are made on methodology improvements.

REFERENCES

1. Cipolla, R.C., R.L. Cargill and J.M. Bersin, "Assessment of Stud Integrity for the Reactor Coolant Pump Snubber Anchor Bolting", APTECH Report No. AES-81-08-79 (May 1982).

2. ASTM Annual Standards, Part 4, A370, "Mechanical Testing of Steel Products" (1979).

3. Hayes, D.J. and R.C. Cipolla, "Proposed Screening Procedure For Review of Low Alloy Quenched and Tempered Steel in Midland Plant Units 1 and 2," APTECH Report No. AES-81-05-68 (October 1981).

4. ASME Boiler and Pressure Vessel Code, Section III, "Rules for Construction of Nuclear Power Plant Components, Division 1 - Appendices," 1977 Edition.

5. ASM Metals Handbook, Volume 1, <u>Properties and Selection: Iron and Steels</u>, 9th Edition (1979).

6. American National Standards, "Unified Inch Screw Threads (UN and UNR Thread Form)," ANSI B1.1-1974, American Society of Mechanical Engineers (1974).

7. Cipolla, R.C., et al., "Review of Requirements and Guidelines for Evaluation of Component Supports and Bolting Under Unresolved Safety Issue A-12," EPRI RP 1757-2, APTECH Draft Final Report AES-8008203 (September 1982).

8. Cipolla, R.C. and W.P. McNaughton, "Calculation of Stress Intensity Factor for Elliptically-Shaped Cracks in Bolts," APTECH Report AES FR8202313 (Rev. 1) (July 1983).

9. Chalupnik, J.D., "Stress Concentrations in Bolt-Thread Roots," <u>Experimental Mechanics</u>, SESA, p. 398-404 (September 1968).

10. Peterson, R.E., <u>Stress Concentration Factors</u>, J. Wiley & Sons (1974).

11. Bickford, J.H., <u>An Introduction to the Design and Behavior of Bolted Joints</u>, Marcel Dekker Inc. (1981).

12. Tada, H., P.C. Paris, and G.R. Irwin, <u>The Stress Analysis of Cracks Handbook</u> (June 1973).

13. Marston, T.U. (ed.), "Flaw Evaluation Procedures - Background and Application of ASME Section, XI Appendix A," EPRI Special Report NP-719-SR (August 1976).

14. Snaider, R.P., J.M. Hodge, H.A. Levin, and J.J. Zudans, "Potential for Low Fracture Toughness and Lamellar Tearing on PWR Steam Generator and Reactor Coolant Pump Supports - Resolution of Generic Technical Activity A-12, NUREG-0577 (for comment) (October 1979).

15. ASME Boiler and Pressure Vessel Code, Section XI, "Rules for the Inservice Inspection of Nuclear Power Plant Components - Division 1," Appendix A, 1977 Edition.

16. Cipolla, R.C., "Computational Method to Perform the Flaw Evaluation Procedure as Specified in the ASME Code, Section XI, Appendix A - Part 1: General Description and Background", EPRI RP 700-1 Key Phase Report NP-1181 (September 1979).

Appendix I
BOLTING EVALUATION FORM

A calculational form has been developed to assist in completing the evaluation procedures. The form is provided for guidance and modifications or improvements to the form to suit individual organizations are encouraged. All important input data are recorded on the form, as well as the results of the analysis. Space is provided on each form for the stratum number, originator of the calculations, the verifier, and general remarks. The remainder of the form follows the procedural outline given in Section 2. It is recommended that the form be used while following the individual steps of the procedure.

One form should be prepared for each stratum where at least the bolt diameter, thread pitch and support category are the same for all bolts. Substratum categories may be required to assure commmon input parameters for the evaluation.

STRATUM NO. ______________________

ORIGINATOR ______________________

DATE ______________________

VERIFIER ______________________

DATE ______________________

4. ESTIMATION OF MATERIAL TOUGHNESS PROPERTIES (PART 2 - CONTINUED)

A. THRESHOLD STRESS INTENSITY FACTOR, K^*_{ISCC} ______________________
(USE FIGURE 3 AND h_{MAX} FROM 2C)

B. FRACTURE TOUGHNESS, K^*_{IC} ______________________
(USE FIGURE 4 AND h_{MAX} FROM 2C)

5. STRESS INTENSITY FACTOR, K (PART 3)

A. THREADED FASTENERS (TENSION) $\tilde{K}_I =$ ______________________
(FROM APPENDIX III)

B. SHEAR PINS (SHEAR ONLY) $\tilde{K}_{II} =$ 0.232

6. ALLOWABLE STRESSES FOR SCC AND FRACTURE (PARTS 4 AND 5)

A. ALLOWABLE STRESS (SCC)

$\sigma_A^{SCC} = (1/\tilde{K}_I)K^*_{ISCC}$ = ________ X ________ = ________

$\tau_A^{SCC} = (1/\tilde{K}_{II})K^*_{ISCC}$ = 4.31 X ________ = ________

$P_A^{SCC} = \sigma_A^{SCC} A_S$ OR $V_A^{SCC} = \tau_A^{SCC} A$ = ________ X ________ = ________

B. ALLOWABLE STRESS (FRACTURE)

$\sigma_A^F = (1/\tilde{K}_I)\, K^*_{IC}$ = ________ X ________ = ________

$\tau_A^F = (1/\tilde{K}_{II})\, K^*_{IC}$ = 4.31 X ________ = ________

$P_A^F = \sigma_A^F A_S$ OR $V_A^F = \tau_A^F A$ = ________ X ________ = ________

7. REMARKS

____

____

____

____

LAQTS EVALUATION FORM

STRATUM NO. ____________________ ORIGINATOR ______________________________

DATE ______________________________

VERIFIER ______________________________

DATE ______________________________

1. GENERAL INFORMATION

   A. MATERIAL ____

   B. COMPONENT TYPE BOLT_____ STUD_____ SHEAR PIN_____ OTHER_____

   C. DIAMETER, D_______________ D. THREADS/INCH, N_______________

   E. TENSILE AREA, A_S_______________ F. NOMINAL AREA, A_______________

2. HARDNESS LIMITS (PART 1)

	A. SPECIFICATION (APP II)	B. TWO-SIDED (90-95%)	C. ONE-SIDED (90-95%)
h_{MIN} =	____________	____________	____________
h_{MAX} =	____________	____________	____________

   D. TWO-SIDED LIMITS FALL WITHIN SPECIFICATION? YES____ NO____
   (IF YES, EVALUATION IS COMPLETE)

3. ESTIMATION OF MATERIAL STRENGTH PROPERTIES (PART 2)

   A. SPECIFIED MINIMUM YIELD STRENGTH, F_y ____________

   B. SPECIFIED MINIMUM TENSILE STRENGTH, F_u ____________

   C. ESTIMATE YIELD STRENGTH, σ_{YMIN} ____________
   (USE FIGURE 2 AND h_{MIN} FROM 2C)

   D. ESTIMATE TENSILE STRENGTH, σ_{UMIN} ____________
   (USE ASTM A370 TABLE 3A AND h_{MIN} FROM 2C)

   E. MINIMUM YIELD STRENGTH, σ_{yM} ____________
   (LOWER OF 3A AND 3C)

   F. MINIMUM TENSILE STRENGTH, σ_{uM} ____________
   (LOWER OF 3B AND 3D)

Appendix II
RECOMMENDED HARDNESS LIMITS FOR SATISFYING ASTM/ASME SPECIFICATIONS

II-1 SUMMARY

Hardness limits were established for candidate LAQT materials supplied to the Midland Site. These limits are provided in Table II-1 and give the minimum and maximum hardnesses in Rockwell-scale and Leeb-scale units. The technical basis for the limits is documented in (II-1 through II-3). Specifically, the limits were established under the following conditions:

(1) When a hardness limit (either minimum or maximum) is given as a requirement in the material specifications, then this limit is given in Table II-1. If the hardness limit is given in units other than those listed in Table II-1, then the hardness limit was converted to equivalent Rockwell-scale units according to ASTM A370 (II-4).

(2) When a hardness limit (either minimum or maximum) is not specified, then engineering judgement was used to establish a limit based upon consideration of specified material yield strength, tensile strength, and product thickness.

The limits that were established by engineering judgement are identified in Table II-1 by an asterisk (*).

II-2 REFERENCES

II-1 Letter to J.A. Pastor (CPCo) from R.C. Cipolla (APTECH) entitled, "Hardness Limits for Receipt Inspection Program," (January 14, 1982).

II-2 Letter to J.A. Pastor (CPCo) from R.C. Cipolla (APTECH) entitled, "Revised Hardness Limits for CPCo Receipt Inspection Program," (September 17, 1982).

II-3 Letter to J.A. Pastor (CPCo) from R.C. Cipolla (APTECH) entitled, "Response to Questions on LAQT Determinations and Hardness Limits," (October 28, 1982).

II-4 ASTM Annual Standards, Part 4, A370, "Mechanical Testing of Steel Products," (1979).

Table II-1

RECOMMENDATIONS ON HARDNESS LIMITS FOR LAQT
Materials

ASTM/ASME SPECIFICATION	GRADE AND/ OR CLASS	DIAMETER OR THICKNESS	HARDNESS LIMITS (7) ROCKWELL-SCALE MIN.	ROCKWELL-SCALE MAX.	LEEB-SCALE (L) MIN.	LEEB-SCALE (L) MAX.
A7-66	(see Note 1)	-	-	-	-	-
A36-77a	(see Note 1)	-	-	-	-	-
A125-73	(see Note 2)	-	38HRC*	50HRC	634L*	731L
SA155-75	CMSH-80 (3)	≤2½" thick	86HRB* (~4HRC)	22HRC*	434L*	514L*
		Over 2½" to 4"	83HRB* (~1HRC)	22HRC*	421L*	514L*
A182-78/SA182-78	F1	-	78HRB	91HRB (~10HRC)	400L	462L
	F2	-	78HRB	91HRB (~10HRC)	400L	462L
	F11	-	78HRB	94HRB (~14HRC)	400L	479L
	F12	-	78HRB	94HRB (~14HRC)	400L	479L
	F21	-	82HRB	94HRB (~14HRC)	418L	479L

(TABLE II-1 - Continued)

ASTM/ASME SPECIFICATION	GRADE AND/ OR CLASS	DIAMETER OR THICKNESS	HARDNESS LIMITS (7) ROCKWELL-SCALE MIN.	ROCKWELL-SCALE MAX.	LEEB-SCALE (L) MIN.	LEEB-SCALE (L) MAX.
A182-78/SA182-78 (Continued)	F22	-	82HRB	94HRB (~14HRC)	418L	479L
	F22a	-	69HRB*	86HRB (~4HRC)	372L*	435L
A193-78a/ SA193/78a	B7	≤2½" Dia.	26HRC*	36HRC*	544L*	618L*
		Over 2½" to 4"	22HRC*	33HRC*	514L*	596L*
		Over 4" to 7"	95HRB* (~16HRC)	28HRC*	485L*	558L*
	B7M	≤2½" Dia.	94HRB (~14HRC)	22HRC	473L	514L
	B16	≤2½" Dia.	26HRC*	36HRC*	544L*	618L*
		Over 2½" to 4"	20HRC*	31HRC*	500L*	581L*
		Over 4" to 7"	95HRB* (~16HRC)	28HRC*	485L*	558L*
A194-80a/ SA194-80a	4	All	24HRC	38HRC	529L	634L
	7	All	24HRC	38HRC	529L	634L
	7M	All	83HRB (~1HRC)	22HRC	421L	514L
A234-80/ SA234-78	WP1	All	65HRB*	92HRB (~12HRC)	361L*	468L
	WP12	All	69HRB*	92HRB (~12HRC)	372L*	468L
	WP11	All	69HRB*	92HRB (~12HRC)	372L*	468L

(TABLE II-1 - Continued)

ASTM/ASME SPECIFICATION	GRADE AND/ OR CLASS	DIAMETER OR THICKNESS	HARDNESS LIMITS (7) ROCKWELL-SCALE MIN.	ROCKWELL-SCALE MAX.	LEEB-SCALE (L) MIN.	LEEB-SCALE (L) MAX.
A234-80/ SA234-78 (continued)	WP22	All	69HRB*	92HRB (~12HRC)	372L*	468L
	WPR	All	72HRB*	96HRB (~17HRC)	382L*	490L
A304-79	(see Note 4)	-	-	-	-	-
A320-80b/ SA320-78 (5)	L1	≤1" Dia.	26HRC*	36HRC*	544L*	618L*
	L7, L7A, L7B, L7C	≤2½" Dia.	26HRC*	36HRC*	544L*	618L*
	L7M	≤2½"Dia.	94HRB (~14HRC)	22HRC	473L	514L
	L43	≤4" Dia.	26HRC*	37HRC*	544L*	626L*
A322-80	(see Note 4)	-	-	-	-	-
A325-78a/ SA325-78a	2, 3 (see Note 6)	½" to 1" Dia.	24HRC	35HRC	529L	611L
		1 1/8" to 1½" Dia.	19HRC	31HRC	497L	581L
A331-74	(see Note 4)	-	-	-	-	-
A333-79	8	-	95HRB* (~16HRC)	28HRC*	485L*	558L*
A354-78a/ SA354-78a	BC	¼" to 2½" Dia.	26HRC	36HRC	544L	618L
		Over 2½" Dia.	22HRC	33HRC	514L	596L
	BD	¼" to 2½" Dia.	33HRC	38HRC	596L	634L
		Over 2½" Dia.	31HRC	38HRC	581L	634L

(TABLE II-1 - Continued)

ASTM/ASME SPECIFICATION	GRADE AND/ OR CLASS	DIAMETER OR THICKNESS	HARDNESS LIMITS(7) ROCKWELL-SCALE MIN.	ROCKWELL-SCALE MAX.	LEEB-SCALE (L) MIN.	LEEB-SCALE (L) MAX.
SA420-78	WPL3	Plate (≤4 inches)	74HRB*	95HRB* (~17HRC)	389L*	490L*
		Forgings (All sizes)	79HRB*	25HRC*	405L*	536L*
	WPL9	Forgings (All sizes)	72HRB*	22HRB*	382L*	514L*
A434-76	BB	1½" Dia. and less	20HRC*	31HRC*	500L*	581L*
		Over 1½" to 2½"	97HRB* (~19HRC)	28HRC*	496L*	558L*
		Over 2½" to 4"	95HRB* (~16HRC)	28HRC*	485L*	558L*
		Over 4" to 7"	93HRB* (~13HRC)	25HRC*	471L*	536L*
		Over 7" to 9½"	91HRB* (~10HRC)	22HRC*	460L*	514L*
	BC	1½" Dia. and less	28HRC*	38HRC*	558L*	634L*
		Over 1½" to 2½"	26HRC*	36HRC*	544L*	618L*
		Over 2½" to 4"	22HRC*	33HRC*	514L*	596L*
		Over 4" to 7"	20HRC*	32HRC*	500L*	588L*
		Over 7" to 9½"	97HRB* (~19HRC)	30HRC*	496L*	573L*
	BD	1½" Dia. and less	34HRC*	40HRC*	603L*	649L*
		Over 1½" to 2½"	33HRC*	38HRC*	596L*	634L*
		Over 2½" to 4"	31HRC*	38HRC*	581L*	634L*
		Over 4" to 7"	29HRC*	38HRC*	566L*	634L*

(TABLE II-1 - Continued)

ASTM/ASME SPECIFICATION	GRADE AND/ OR CLASS	DIAMETER OR THICKNESS	HARDNESS LIMITS(7) ROCKWELL-SCALE MIN.	ROCKWELL-SCALE MAX.	LEEB-SCALE (L) MIN.	LEEB-SCALE (L) MAX.
A434-76 (Continued)	BD	Over 7" to 9½"	28HRC*	37HRC*	558L*	626L*
A487-80	1Q,2Q	-	91HRB* (∿10HRC)	22HRC*	460L*	514L*
	4Q,11Q,12Q,13Q	-	97HRB* (∿19HRC)	34HRC*	496L*	603L*
	4QA	-	22HRC*	33HRC*	514L*	596L*
	6Q	-	24HRC*	34HRC*	529L*	603L
	7Q	2½" thick	22HRC*	33HRC*	514L*	596L*
	8Q,9Q	-	95HRB* (∿16HRC)	29HRC*	485L*	566L*
	10Q	-	25HRC*	34HRC*	536L*	603L*
	14Q	-	24HRC*	38HRC*	529L*	634L*
A490-80a	All Grades	½" to 1½" Dia.	33HRC	38HRC	596L	634L
A514-77	All Grades	to 3/4" thick	22HRC	31HRC	514L	581L
		over 3/4" to 2½"	22HRC*	32HRC*	514L*	588L*
		over 2½" to 6"	95HRB* (∿16HRC)	33HRC*	485L*	596L*
A519-80	(see Note 4)	-	-	-	-	-
A521-76	CG	≤4" Solid Dia. or Thick or ≤2" Bored Wall Thick	90HRB* (∿10HRC)	22HRC	456L*	514L*
		>4" to 7" (Solid) or >2" to 3½" (Bored)	88HRB* (∿7HRC)	96HRB* (∿17HRC)	440L*	490L*
		>7" to 10" (Solid) or >3½" to 5" (Bored)	88HRB* (∿7HRC)	96HRB* (∿17HRC)	440L*	490L*

(TABLE II-1 - Continued)

ASTM/ASME SPECIFICATION	GRADE AND/ OR CLASS	DIAMETER OR THICKNESS	HARDNESS LIMITS (7) ROCKWELL-SCALE MIN.	ROCKWELL-SCALE MAX.	LEEB-SCALE (L) MIN.	LEEB-SCALE (L) MAX.
A521-76 (Contd.)	CG	>5" to 10" (Bored)	88HRB* (∼7HRC)	96HRB* (∼17HRC)	440L*	490L*
	AD	≤7" Solid Dia. or Thick or ≤3½" Bored Wall Thick	92HRB* (∼12HRC)	25HRC*	468L*	536L*
		>7" to 10" (Solid) or >3½" to 10" (Wall)	90HRB* (∼10HRC)	22HRC*	456L*	514L*
	AE	≤7" Solid Dia. or Thick or ≤3½" Bored Wall Thick	95HRB* (∼16HRC)	29HRC*	485L*	566L*
		>7" to 10" (Solid) or >3½" to 5" (Bored)	94HRB* (∼14HRC)	29HRC*	479L*	566L*
		>10" to 20" (Solid) or >5" to 8" (Bored)	92HRB* (∼12HRC)	25HRC*	468L*	536L*
	AF	≤4" Solid Dia. or Thick or ≤2" Bored Wall Thick	25HRC*	34HRC*	536L*	603L*
		>4" to 7" (Solid) or >2" to 3½" (Bored)	22HRC*	32HRC*	514L*	588L*
		>7" to 10" (Solid) or >3½" to 5" (Bored)	97HRB* (∼19HRC)	31HRC*	497L*	581L*
	AG	≤4" Solid Dia. or Thick or ≤2" Bored Wall Thick	31HRC*	38HRC*	581L*	634L*
		>4" to 7" (Solid) or >2" to 3½" (Bored)	30HRC*	37HRC*	573L*	626L*
		>7" to 10" (Solid) or >3½" to 5" (Bored)	28HRC*	36HRC*	558L*	618L*

(TABLE II-1 - Continued)

ASTM/ASME SPECIFICATION	GRADE AND/ OR CLASS	DIAMETER OR THICKNESS	HARDNESS LIMITS (7) ROCKWELL-SCALE MIN.	ROCKWELL-SCALE MAX.	LEEB-SCALE (L) MIN.	LEEB-SCALE (L) MAX.
A521-76 (Contd.)	AH	≤4" Solid Dia. or Thick or ≤2" Bored Wall Thick	36HRC*	43HRC*	618L*	673L*
		>4" to 7" (Solid) or >2" to 3½" (Bored)	36HRC*	43HRC*	618L*	673L*
		>7" to 10" (Solid) or >3½" to 5" (Bored	34HRC*	42HRC*	603L*	665L*
SA537-78	2	≤2½" thick	86HRB* (~4HRC)	22HRC*	434L*	514L*
		over 2½" to 4"	83HRB* (~1HRC)	22HRC*	421L*	514L*
A540-77a/ SA540-77a	B21, CL5	≤2½" thick	23HRC	30HRC	522L	573L
		over 2" to 6"	24HRC	32HRC	529L	588L
		over 6" to 8"	25HRC	33HRC	536L	596L
	B21, CL4	≤3" thick	28HRC	36HRC	558L	618L
		over 3" to 6"	29HRC	38HRC	55[illegible]L	634L
	B21, CL3	≤3" thick	31HRC	38HRC	581L	634L
		over 3" to 6"	32HRC	40HRC	588L	649L
	B21, CL2	≤4" thick	33HRC	43HRC	596L	673L
	B21, CL1	≤4" thick	34HRC	46HRC	603L	698L
	B22, CL5	≤2" thick	24HRC	31HRC	529L	581L

(TABLE II-1 - Continued)

ASTM/ASME SPECIFICATION	GRADE AND/ OR CLASS	DIAMETER OR THICKNESS	HARDNESS LIMITS (7) ROCKWELL-SCALE MIN.	MAX.	LEEB-SCALE (L) MIN.	MAX.
A540-77a/SA540-77a (continued)	B22, CL5	Over 2" to 4"	25HRC	32HRC	536L	588L
	B22, CL4	<1" thick	28HRC	37HRC	558L	626L
		Over 1" to 4"	29HRC	39HRC	566L	642L
	B22, CL3	≤2" thick	31HRC	39HRC	581L	642L
		Over 2" to 4"	32HRC	40HRC	588L	649L
	B22,CL2	≤3" thick	33HRC	43HRC	596L	673L
	B22,CL1	≤1½" thick	34HRC	43HRC	603L	673L
	B23,CL5	≤6" thick	24HRC	33HRC	529L	596L
		Over 6" to 8"	25HRC	34HRC	536L	603L
		Over 8" to 9½"	27HRC	34HRC	551L	603L
	B23, CL4	≤3" thick	28HRC	37HRC	558L	626L
		Over 3" to 6"	29HRC	38HRC	566L	634L
		Over 6" to 9½"	30HRC	39HRC	573L	642L
	B23, CL3	≤3" thick	31HRC	39HRC	581L	642L
		Over 3" to 6"	32HRC	40HRC	588L	649L
		Over 6" to 9½"	33HRC	42HRC	596L	665L
	B23, CL2	≤3" thick	33HRC	42HRC	596L	665L
		Over 3" to 6"	33HRC	43HRC	596L	673L
		Over 6" to 9½"	34HRC	45HRC	603L	689L

(TABLE II-1 - Continued)

ASTM/ASME SPECIFICATION	GRADE AND/ OR CLASS	DIAMETER OR THICKNESS	HARDNESS LIMITS (7) ROCKWELL-SCALE MIN.	HARDNESS LIMITS (7) ROCKWELL-SCALE MAX.	LEEB-SCALE (L) MIN.	LEEB-SCALE (L) MAX.
A540-77a/SA540-77a (continued)	B23; CL1	≤3" thick	34HRC	45HRC	603L	689L
		Over 3" to 6"	36HRC	46HRC	618L	698L
		Over 6" to 8"	37HRC	47HRC	626L	707L
	B24, CL5	≤6" thick	24HRC	33HRC	529L	596L
		Over 6" to 8"	25HRC	34HRC	536L	603L
		Over 8" to 9½"	27HRC	34HRC	551L	603L
	B24, CL4	≤3" thick	28HRC	37HRC	558L	626L
		Over 3" to 6"	29HRC	38HRC	566L	634L
		Over 6" to 8"	30HRC	39HRC	573L	642L
	B24, CL3	≤3" thick	31HRC	39HRC	581L	642L
		Over 3" to 8"	32HRC	42HRC	588L	665L
		Over 8" to 9½"	33HRC	42HRC	596L	665L
	B24, CL2	≤7" thick	33HRC	43HRC	596L	673L
		Over 7" to 9½"	34HRC	45HRC	603L	689L
	B24, CL1	≤6" thick	34HRC	45HRC	603L	689L
		Over 6" to 8"	36HRC	46HRC	618L	698L
	B24V, CL3	≤4" thick	31HRC	39HRC	581L	642L
		Over 4" to 8"	32HRC	40HRC	588L	649L
		Over 8" to 11"	33HRC	42HRC	596L	665L

ASTM/ASME SPECIFICATION	GRADE AND/ OR CLASS	DIAMETER OR THICKNESS	HARDNESS LIMITS (7) ROCKWELL-SCALE MIN.	MAX.	LEEB-SCALE (L) MIN.	MAX.
A540-77a/SA540-77a (continued)	B24V, CL2	≤4" thick	33HRC	42HRC	596L	665L
		Over 4" to 8"	33HRC	43HRC	596L	673L
		Over 8" to 11"	34HRC	45HRC	603L	689L
	B24V, CL1	≤4" thick	34HRC	45HRC	603L	689L
		Over 4" to 8"	36HRC	46HRC	618L	698L
		Over 8" to 11"	36HRC	47HRC	618L	707L
A574-80	- -	≤½" Dia.	39HRC	45HRC	642L	689L
		≤5/8" Dia.	37HRC	45HRC	626L	689L
A563-78a	DH3	¼" to 4" size	24HRC	38HRC	529L	634L
	C3	¼" to 4" size	78HRB	38HRC	400L	634L
A668-79a	F, FH	<4" thick	90HRB (∿10HRC)	22HRC	456L	514L
		Over 4" to 7"	88HRB (∿7HRC)	96HRB (∿17HRC)	440L	490L
		Over 7" to 10"	88HRB (∿7HRC)	96HRB (∿17HRC)	440L	490L
		Over 10" to 20"	88HRB (∿7HRC)	96HRB (∿17HRC)	440L	490L
	J, JH	≤7" thick	92HRB (∿12HRC)	25HRC	468L	536L
		Over 7" to 10"	90HRB (∿10HRC)	22HRC	456L	514L
	K, KH	≤7" thick	95HRB (∿16HRC)	28HRC	485L	558L

(TABLE II-1 - Continued)

ASTM/ASME SPECIFICATION	GRADE AND/ OR CLASS	DIAMETER OR THICKNESS	HARDNESS LIMITS (7) ROCKWELL-SCALE MIN.	MAX.	LEEB-SCALE (L) MIN.	MAX.
A668-79a (Contd.)	K, KH	Over 7" to 10"	94HRB (~14HRC)	28HRC	479L	558L
	L, LH	≤4" thick	25HRC	34HRC	536L	603L
		Over 4" to 7"	22HRC	32HRC	514L	588L
		Over 7" to 10"	97HRB (~19HRC)	31HRC	497L	581L
	M, MH	≤4" thick	31HRC	38HRC	581L	634L
		Over 4" to 7"	30HRC	37HRC	573L	626L
		Over 7" to 10"	28HRC	36HRC	558L	618L
	N, NH	≤4" thick	36HRC	43HRC	618L	673L
		Over 4" to 7"	36HRC	43HRC	618L	673L
		Over 7" to 10"	34HRC	42HRC	603L	665L
A687-79	All Grades	-	26HRC*	34HRC*	543L*	603L*
A739-76 SA739-76	B11	-	79HRB*	25HRC*	405L*	536L*
	B22	-	82HRB*	25HRC*	417L*	536L*
F568-79	8.8	-	23HRC	34HRC	522L	603L
	8.8.3	-	23HRC	34HRC	522L	603L
	9.8	-	27HRC	36HRC	551L	618L
	10.9	-	33HRC	39HRC	596L	642L
	10.9.3	-	33HRC	39HRC	596L	642L
	12.9	-	38HRC	44HRC	634L	682L

(TABLE II-1 - Continued)

NOTES

[1]Bolts or nuts when included with material purchases can be supplied to A325.

[2]The specified or indicated minimum hardness must be sufficient to develop the required strength to withstand the solid stresses of the spring design.

[3]Same material grade as A537 Class 2.

[4]Maximum surface Brinell hardness, if specified by purchaser as a supplementary requirement, shall be agreed upon between the manufacturer and the purchaser. Mechanical strengths are not specified.

[5]SA320-78 is identical to A320-76 except for the deletion of Grade L1.

[6]Bolts shall not exceed maximum hardness specified. Bolts less than three diameters in length shall have a hardness value not less than the minimum nor more than the maximum in hardness limits, as hardness is the only requirement.

[7]Hardness values supplied are in HRC and L-scale numbers unless otherwise noted. Mechanical strengths are not specified.

*These limits are not ASTM or ASME specified limits but based upon a review of yield and tensile strength requirements and a comparison with other ASTM materials with specified hardness requirements.

Appendix III

TABULATION OF STRESS INTENSITY FACTORS ($\tilde{K}_I$)

Table III-1

BASIC DIMENSIONS AND $\tilde{K}_I$ FOR EXTERNAL FOUR-THREAD SERIES (4-UN/4-UNR)

Primary Size (Inches)	Basic Major Diameter, D (Inches)	Minor Diameter, d (Inches)	Tensile Stress Area, A_s (Inches^2)	Stress Intensity Factor, $\tilde{K}_I$ (Inches$^{1/2}$)
2-1/2	2.5000	2.1933	4.00	0.5701
2-3/4	2.7500	2.4433	4.93	0.5817
3	3.0000	2.6933	5.97	0.5903
3-1/4	3.2500	2.9433	7.10	0.6002
3-1/2	3.5000	3.1933	8.33	0.6076
3-3/4	3.7500	3.4433	9.66	0.6142
4	4.0000	3.6933	11.08	0.6200
4-1/4	4.2500	3.9433	12.61	0.6252
4-1/2	4.5000	4.1933	14.23	0.6299
4-3/4	4.7500	4.4433	15.90	0.6341
5	5.0000	4.6933	17.80	0.6379
5-1/4	5.2500	4.9433	19.70	0.6414
5-1/2	5.5000	5.1933	21.70	0.6446
5-3/4	5.7500	5.4433	23.80	0.6475
6	6.000	5.6933	26.00	0.6502

Table III-2

BASIC DIMENSIONS AND $\tilde{K}_I$ FOR EXTERNAL SIX-THREAD SERIES (6-UN/6-UNR)

Primary Size (Inches)	Basic Major Diameter, D (Inches)	Minor Diameter, d (Inches)	Tensile Stress Area, A_s (Inches^2)	Stress Intensity Factor, $\tilde{K}_I$ (Inches$^{1/2}$)
1-3/8	1.3750	1.1705	1.155	0.4895
1-1/2	1.5000	1.2955	1.405	0.5003
1-5/8	1.6250	1.4205	1.680	0.5098
1-3/4	1.7500	1.5455	1.980	0.5181
1-7/8	1.8750	1.6705	2.300	0.5254
2	2.0000	1.7955	2.650	0.5319
2-1/4	2.2500	2.0455	3.420	0.5431
2-1/2	2.5000	2.2955	4.290	0.5522
2-3/4	2.7500	2.5455	5.260	0.5598
3	3.0000	2.7955	6.330	0.5663
3-1/4	3.2500	3.0455	7.490	0.5718
3-1/2	3.5000	3.2955	8.750	0.5766
3-3/4	3.7500	3.5455	10.110	0.5808
4	4.0000	3.7955	11.570	0.5845
4-1/4	4.2500	4.0455	13.120	0.5878
4-1/2	4.5000	4.2955	14.780	0.5907
4-3/4	4.7500	4.5455	16.500	0.5934
5	5.0000	4.7955	18.400	0.5958
5-1/4	5.2500	5.0455	20.300	0.5979
5-1/2	5.5000	5.2955	22.400	0.5999
5-3/4	5.7500	5.5455	24.500	0.6017
6	6.0000	5.7955	26.800	0.6034

Table III-3

BASIC DIMENSIONS AND $\tilde{K}_I$ FOR EXTERNAL EIGHT-THREAD SERIES (8-UN/8-UNR)

Primary Size (Inches)	Basic Major Diameter, D (Inches)	Minor Diameter, d (Inches)	Tensile Stress Area, A_s (Inches^2)	Stress Intensity Factor, $\tilde{K}_I$ (Inches$^{1/2}$)
1	1.0000	0.8466	0.606	0.4253
1-1/8	1.1250	0.9716	0.790	0.4405
1-1/4	1.2500	1.0966	1.000	0.4504
1-3/8	1.3750	1.2216	1.233	0.4603
1-1/2	1.5000	1.3466	1.492	0.4691
1-5/8	1.6250	1.4716	1.780	0.4741
1-3/4	1.7500	1.5966	2.080	0.4775
1-7/8	1.8750	1.7216	2.410	0.4830
2	2.0000	1.8466	2.770	0.4879
2-1/4	2.2500	2.0966	3.560	0.4941
2-1/2	2.5000	2.3466	4.440	0.5004
2-3/4	2.7500	2.5966	5.430	0.5075
3	3.0000	2.8466	6.510	0.5129
3-1/4	3.2500	3.0966	7.690	0.5190
3-1/2	3.5000	3.3466	8.960	0.5254
3-3/4	3.7500	3.5966	10.340	0.5280
4	4.0000	3.8466	11.810	0.5317
4-1/4	4.2500	4.0966	13.380	0.5345
4-1/2	4.5000	4.3466	15.100	0.5379
4-3/4	4.7500	4.5966	16.800	0.5400
5	5.0000	4.8466	18.700	0.5417
5-1/4	5.2500	5.0966	20.700	0.5445
5-1/2	5.5000	5.3466	22.700	0.5466
5-3/4	5.7500	5.5966	24.900	0.5485
6	6.0000	5.8466	27.100	0.5504

Table III-4

BASIC DIMENSIONS AND $\bar{K}_I$ FOR EXTERNAL
12-THREAD SERIES (12-UN/12-UNR)

Primary Size (Inches)	Basic Major Diameter, D (Inches)	Minor Diameter, d (Inches)	Tensile Stress Area, A_s (Inches^2)	Stress Intensity Factor, $\bar{K}_I$ (Inches$^{1/2}$)
7/8	0.8750	0.7728	0.495	0.4148
1	1.0000	0.8978	0.663	0.4258
1-1/8	1.1250	1.0228	0.856	0.4346
1-1/4	1.2500	1.1478	1.073	0.4419
1-3/8	1.3750	1.2728	1.315	0.4479
1-1/2	1.5000	1.3978	1.580	0.4531
1-5/8	1.6250	1.5228	1.870	0.4574
1-3/4	1.7500	1.6478	2.190	0.4613
1-7/8	1.8750	1.7728	2.530	0.4646
2	2.0000	1.8978	2.890	0.4675
2-1/4	2.2500	2.1478	3.690	0.4725
2-1/2	2.5000	2.3978	4.600	0.4765
2-3/4	2.7500	2.6478	5.590	0.4798
3	3.0000	2.8978	6.690	0.4826
3-1/4	3.2500	3.1478	7.890	0.4849
3-1/2	3.5000	3.3978	9.180	0.4870
3-3/4	3.7500	3.6478	10.570	0.4887
4	4.0000	3.8978	12.060	0.4903
4-1/4	4.2500	4.1478	13.650	0.4916
4-1/2	4.5000	4.3978	15.300	0.4929
4-3/4	4.7500	4.6478	17.100	0.4940
5	5.0000	4.8978	19.000	0.4949
5-1/4	5.2500	5.1478	21.000	0.4959
5-1/2	5.5000	5.3978	23.100	0.4967
5-3/4	5.7500	5.6478	25.200	0.4974
6	6.0000	5.8978	27.500	0.4981

*Sizes less than 7/8 inch are not listed.

Table III-5

BASIC DIMENSIONS AND $\bar{K}_I$ FOR EXTERNAL COARSE THREADS (UNC/UNRC) WITH 4-1/2, 5, 7, AND 9 THREADS PER INCH

Size (Inches)	Threads Per Inch	Basic Major Diameter, D (Inches)	Minor Diameter, d (Inches)	Tensile Stress Area, A_s (Inches^2)	Stress Intensity Factor, $\bar{K}_I$ (Inches$^{1/2}$)
7/8	9	0.8750	0.7387	0.419	0.4272
1-1/8	7	1.1250	0.9497	0.693	0.4612
1-1/4	7	1.2500	1.0747	0.890	0.4740
1-3/4	5	1.7500	1.5046	1.740	0.5219
2	4-1/2	2.0000	1.7274	2.500	0.5405
2-1/4	4-1/2	2.2500	1.9774	3.250	0.5553

Appendix IV

EFFECT OF TEMPERATURE ON THE THRESHOLD STRESS CORROSION CRACKING STRESS INTENSITY VALUES OF LOW ALLOY QUENCHED AND TEMPERED STEELS

IV-1 INTRODUCTION

The potential deleterious effect of temperature on SCC susceptibility has been observed in high strength materials in the form of increased cracking velocities. For AISI 4320 and H11 steel crack growth rates in aqueous solutions increase sharply with temperature (IV-1, IV-2). Similar effects have been observed in environments saturated with water vapor, but in the absence of complete saturation, crack velocity has been observed to decrease with increasing temperature (IV-2).

More relevant are the observations in the data derived from tests of precracked specimens that show that the threshold stress intensity factor is insensitive to temperature in high strength steels. It is reported in IV-2 that K_{Iscc} is remarkably constant. In aqueous solutions containing 150 and 3000 ppm of H_2S, K_{Iscc} has been known to increase with temperature, approximately doubling the value of K_{Iscc} of a 132 ksi yield strength steel. Such trends suggest that the room temperature behavior for the test data can be used as a conservative estimate for behavior under elevated temperature conditions. A possible upper limit for the K_{Iscc} could be established at the point where the aqueous solution environment would be lost, that is a temperature in excess of 200°F.

The purpose of this appendix is to confirm the trends for K_{Iscc} reported in the above mentioned review papers. The original cited references were obtained and reviewed and a summary of the review is presented next.

IV-2 H_2S ENVIRONMENT

In 1952, Fraser and Treseder (IV-3) found an "increasing tendency to cracking" with a decrease in temperature from experiments on unnotched high strength steels strained in 3 point bending and placed in 0.5% CH_3COOH/H_2S (acetic acid and hydrogen sulfide) solutions. This temperature effect was substantiated by Warren and Beckman (IV-4) in their study of sulfide corrosion cracking of high strength bolting material. In 1971, Townsend (IV-5) observed that the time to failure of free corroding, bent, high strength carbon steel wires immersed in H_2S solutions was a minimum at room temperature - increasing failure periods being observed both above and below room temperature.

If stress corrosion crack growth rates are measured as a function of opening mode stress intensity factor values, then three distinct cracking velocity regimes (da/dt) may be observed. Region I crack growth is the first stage of growth where the applied K level is low and where there is a significant stress dependence on crack velocity. Region II follows Region I where there is a change in slope on da/dt so that the crack growth is nearly independent of stress. Finally, Region III represents a final slope change in da/dt versus K where the slope rapidly increases. At a very slow crack growth rate, an apparent threshold value of stress intensity is reached, below which crack growth rates become immeasurably small. The value of stress intensity where this occurs is referred to as the critical stress corrosion cracking threshold stress intensity value, K_{Iscc}. In the experiments mentioned previously, it is not clear whether the effects observed were actually depicting changes in K_{Iscc} versus temperature, or changes in the combined crack growth rates experienced in Regions I, II and III. However, in a study of H_2S stress corrosion cracking of steels by Dvoracek (IV-6), measured values of K_{Iscc} were observed to increase with increasing temperature.

IV-3 WATER AND OTHER ENVIRONMENTS

In 1965, Johnson and Wilner (IV-7) measured threshold stress intensity values on H11 steel in water at various temperatures and found the threshold stress

intensity value, K_{Iscc}, to be constant over a temperature range from 30°F to 150°F. These results are shown in Figure IV-1.

More recently, in a study by Nelson and Williams (IV-8) with 4130 steel, it was shown that K_{Iscc} was indeed invariant throughout the temperature range of 33°F to 190°F when placed in a distilled H_2O environment. These test data are shown in Figure IV-2. During this study, measurements of K_{Iscc} in molecular hydrogen environments as a function of temperature were also made. The results are shown in Figure IV-3 for 4130 steel with two different yield strengths. These data also depict an increase in threshold stress intensity values with increases in temperature. Furthermore, the reversibility of this temperature effect was shown in an experiment in which lowering the temperature of a specimen which was previously experiencing slow crack growth (1×10^{-7} m/sec), resulted in an immediate increase in crack growth rate.

IV-4 SUMMARY OF FINDINGS

The data relevant to the determination of K_{Iscc} are plotted in Figure IV-4. Based on the data obtained during this review, the following conclusions are established:

(1) K_{Iscc} of high strength steels in distilled water is invariant with temperature over the temperature range of 30°F to 190°F.

(2) K_{Iscc} of high strength steels in molecular hydrogen increases with increased temperatures over the temperature range of -45°F to 260°F.

(3) K_{Iscc} of HSLA steel in H_2S environments increases with increased temperatures within the temperature range 75°F to 300°F.

(4) Based on these findings, the effect of temperature on K_{Iscc} derived from room temperature tests seems not important for structural

bolt applications where aqueous environments are involved. This observation seems valid up to temperatures of 190°F and possibly higher.

IV-5 REFERENCES

IV-1 Fujita, T. and Y. Yamada, "Physical Metallurgy and SCC in High Strength Steels," Firminy Conference, NACE-5 (1973).

IV-2 Carter, C.S. and M.V. Hyatt, "Review of Stress Corrosion Cracking in Low Alloy Steels with Yield Strengths Below 150 ksi," Firminy Conference, NACE-5 (1973).

IV-3 Frayer, J.T. and R.S. Treseder, "Cracking of High Strength Steels in Hydrogen Sulfide Solution," Corrosion, Volume 8, p. 342 (1952).

IV-4 Warren, D. and G.W. Beckman, "Sulfide Corrosion Cracking of High Strength Bolting Material," Corrosion, Volume 13, p. 631t (1957).

IV-5 Townsend, H.E., "Hydrogen Sulfide Stress Corrosion Cracking of High Strength Steel Wire," Corrosion, Volume 28, p. 39 (1972).

IV-6 Dvoracek, L.M., "Sulfide Stress Corrosion Cracking of Steels," Corrosion, Volume 26, p. 177 (1970).

IV-7 Johnson, H.H. and A.M. Wilner, "Moisture and Stable Crack Growth in a High Strength Steel," Appl. Matl. Res., Volume 4, p. 33 (1965).

IV-8 Nelson, H.G. and D.P. Williams, "Quantitative Observations of Hydrogen-Induced Slow Crack Growth in a Low Alloy Steel," Firminy Conference, NACE-5 (1973).

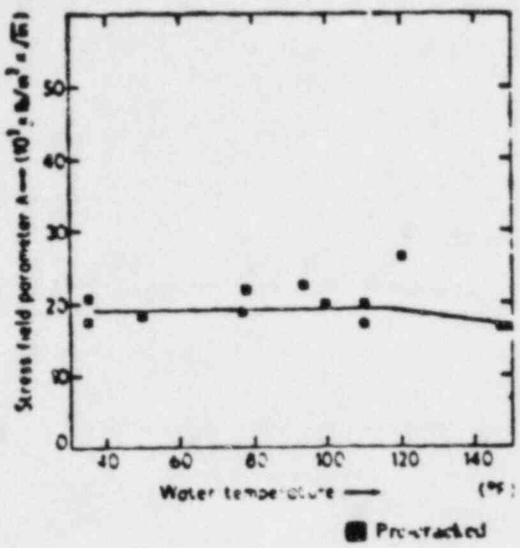

Figure IV-1 - Influence of Water Temperature Upon Threshold Stress, Intensity Values (After Johnson and Willner, Reference (IV-7)).

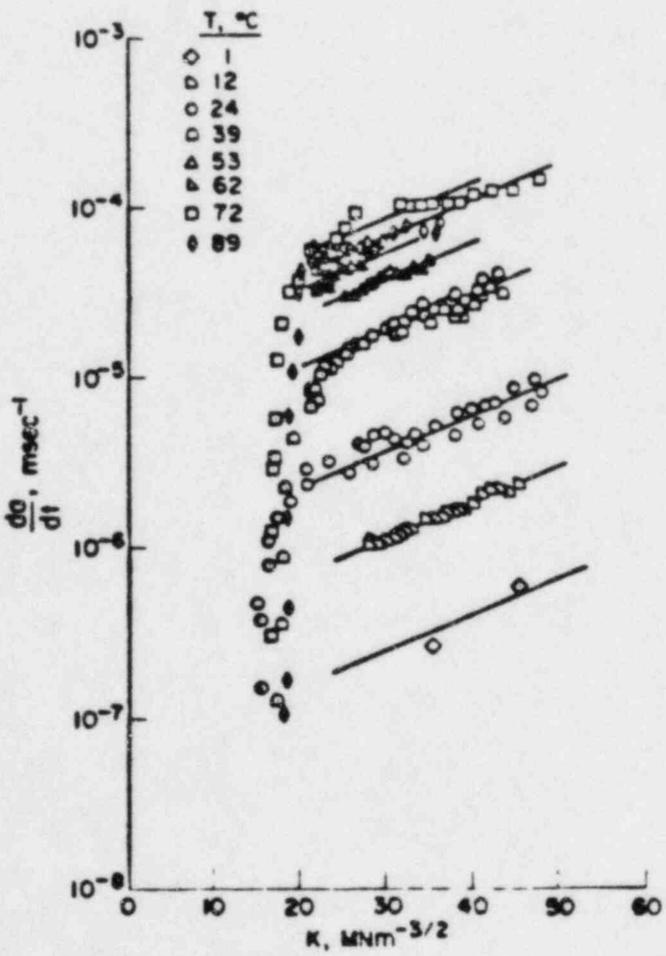

Figure IV-2 - The Stress Intensity K_I, Dependence of Crack Growth Rate, da/dt at Various Temperatures in Distilled Water For 4130 Steel With a Yield Strength of 1330 MN/m^2 (After Nelson and Williams, Reference (IV-8)).

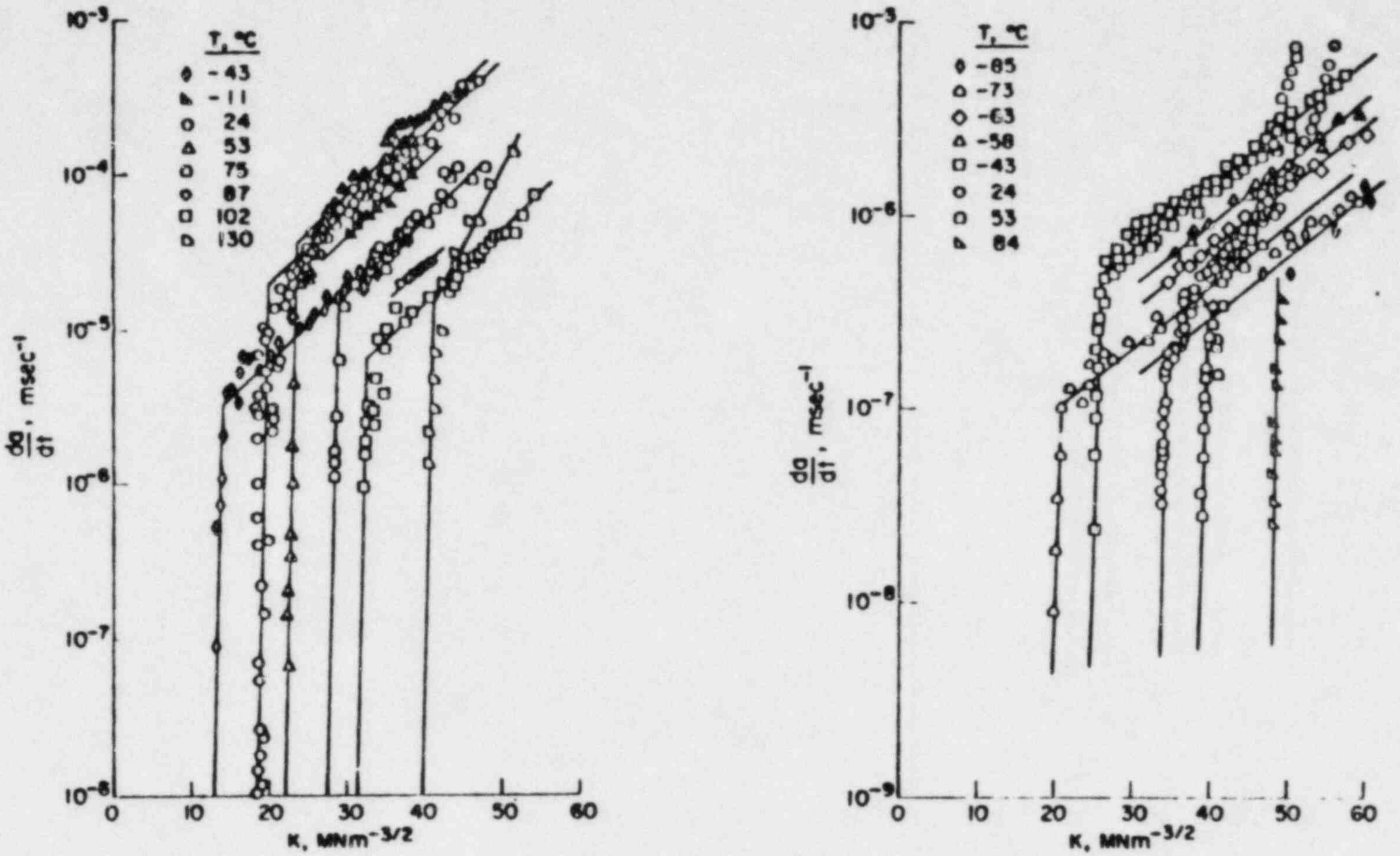

Figure IV-3 - The Stress Intensity, K_I, Dependence of Crack Growth Rate, da/dt, at Various Temperatures In 77.3 kN/m^2 Hydrogen For 4130 Steel With the Two Listed Yield Strengths (After Nelson and Williams, Reference (IV-8)).

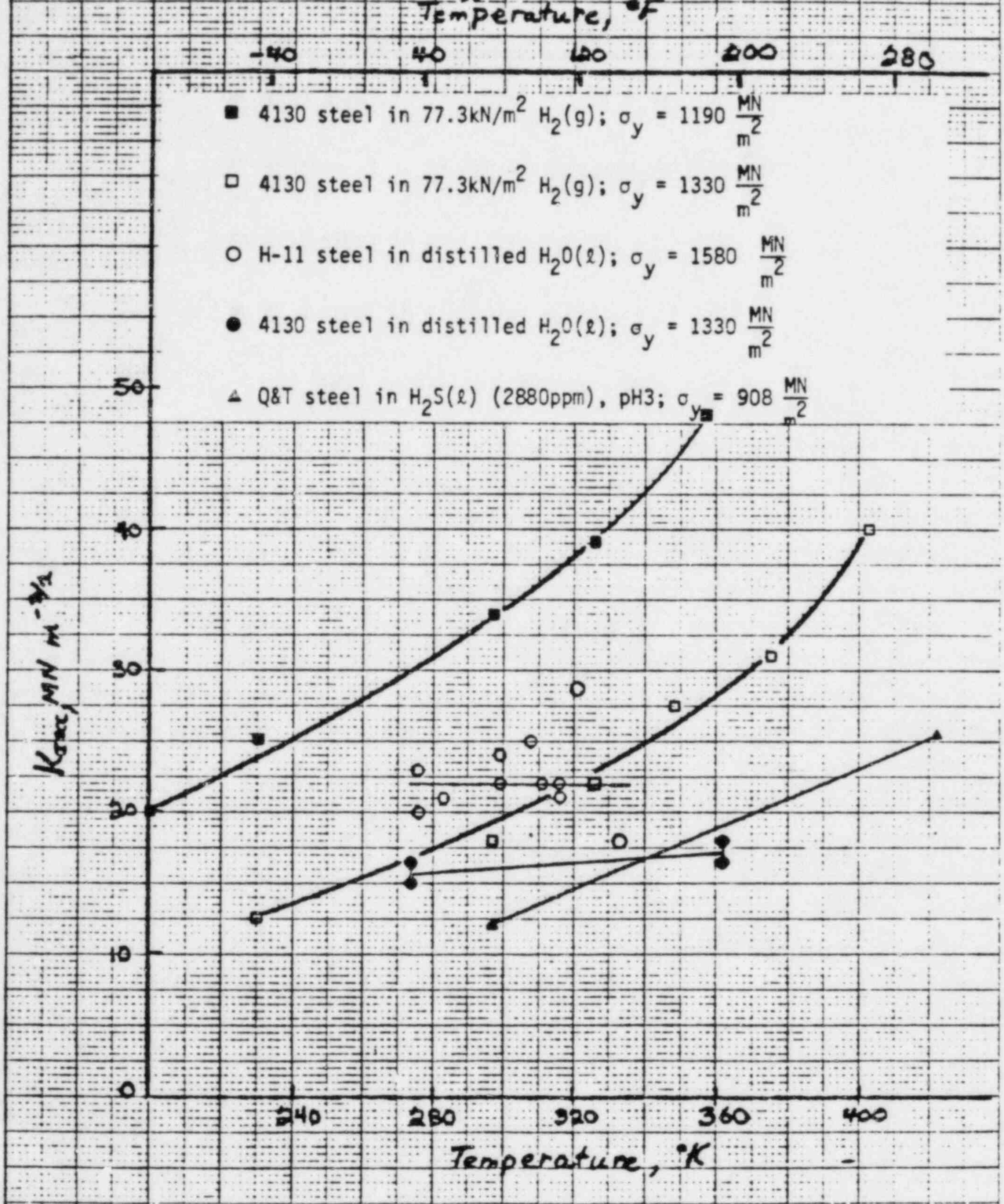

Figure IV-4 - Dependence of the Threshold Stress Corrosion Cracking Stress Intensity Value, K_{Iscc}, with Temperature For Various Steels and Environments.