

1. Report No. FHWA-RD-76-37	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle VARIABILITY OF FRACTURE TOUGHNESS IN A514/517 PLATE, EXECUTIVE SUMMARY		5. Report Date DECEMBER 1975	
		6. Performing Organization Code	
		8. Performing Organization Report No.	
7. Author(s) Hartbower, C.E. and Sunbury, R.D.		10. Work Unit No. (TRAIS) FCP 35F2-142	
9. Performing Organization Name and Address Office of Research and Development Division of Structures California Department of Transportation Sacramento, California 95807		11. Contract or Grant No. DOT-FH-11-8250 (T.O.7)	
		13. Type of Report and Period Covered Final Report	
12. Sponsoring Agency Name and Address Office of Research and Development Federal Highway Administration U. S. Department of Transportation Washington, D.C. 20590		14. Sponsoring Agency Code	
15. Supplementary Notes FHWA Contract Manager: C. H. McGogney (HRS-11)			
16. Abstract On June 13, 1970, a brittle fracture developed in one of the three tension flanges of a large steel box girder bridge under construction at Bryte Bend, California, as the concrete deck was being placed. This report presents a summary evaluation of the extensive fracture toughness and failure analysis data that were gathered by and for the California Department of Transportation in connection with the investigation of the cause of the brittle fracture. The study also included consideration of the steels used in a second bridge at Tuolumne River, California, which was simultaneously under construction and incorporated the same type of steel used in the Bryte Bend bridge. In addition, the characteristics of steels used to repair and reinforce these two bridges were also studied. The report recommends that bridges which have been fabricated from A514/517 Grade-F or Grade-H steels comparable to those used in the Bryte Bend and Tuolumne River Bridges be given frequent careful inspections as well as a realistic design review. The report also recommends that whenever A514/517 Grade-H steel is proposed for use in bridge construction, stringent test requirements should be imposed (depending upon thickness, redundancy, welding process, etc.) as a condition of use in main load carrying member components.			
17. Key Words fracture toughness A514/517 steel Bryte Bend bridge brittle fracture		18. Distribution Statement No Restrictions. This document is available to the public through the National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22161.	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page)	21. No. of Pages 34	22. Price

Preface

The report for which this Executive Summary was prepared contains 266 pages of text, including 34 tables, 122 figures, and 61 references. In addition there are four appendixes containing several tables and over 50 plots of data. For more detailed information on the scope of the report, the table of contents of the full report (Ref. 1) is appended to this the Executive Summary.

ACKNOWLEDGMENTS

This report was prepared under the general direction of Guy D. Mancarti, Office of Research and Development, Division of Structures, California Department of Transportation (Caltrans).

The authors are indebted to the engineers and technicians with Aerojet General Corporation, Effects Technology, Inc., Naval Research Laboratory, National Bureau of Standards, Caltrans Division of Structures, and Caltrans Laboratory who have participated in the development of data used in this report. They are particularly indebted to those with Caltrans Laboratory who under the direction of Eric Nordlin have over a period of 5 years developed, collected, and evaluated much of the data used in this report.

The authors also wish to express their appreciation to the Caltrans Legal Division and in particular to attorneys Orrin Finch and Fred Graebe who were assigned to the Bryte Bend Bridge and Tuolumne River Bridge litigation.

The contents of this report reflect the views and opinions of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

Variability of Fracture Toughness in A514/517 Plate

Introduction

On June 13, 1970, a large, steel, box-girder bridge under construction at Bryte Bend, west of Sacramento, California, developed a brittle fracture in one of three tension flanges as the concrete deck was being placed. The bridge comprises two, parallel, three-lane structures, each made up of a two-cell, trapezoidal, box-girder section with three separate top flanges (Figure 1). The flanges over piers 12, 13, and 14 were 30 inches (.762m) wide and 2 1/4 inches (57.2mm) thick. The failure occurred catastrophically across the full width of a 30-inch (.762m) wide flange and was arrested about 4 inches (101.6mm) down the web of the girder (Figure 2). The ambient temperature was +58°F (14.4°C). The steel was ASTM A517 Grade-H modified. By ASTM Specification, A514/517 Grade-H is limited to 2-inch (50.8mm) thickness; for this bridge, Grade H was allowed in thicknesses up to 2 1/4 inches (57.2mm). Following this failure, an extensive investigation of the cause was initiated by the California Department of Transportation. Some of the findings of that investigation form the basis of a 266-page report (Ref. 1) which is summarized herein.

At the time the Bryte Bend Bridge was designed and when the steel was purchased, toughness in A517 steel was taken for granted and was not a specification requirement. Of 76 bridges built in the United States prior to 1970 using A514/517 steel or comparable quenched-and-tempered proprietary steels, Charpy V-notch impact testing was specified in the plans of only three bridges. In 1970, ASTM A517-70a provided a Charpy V-notch impact test requirement of 15-mils (0.38mm) lateral expansion (at a temperature specified in the order but not higher than 32°F (0°C)). In 1974, AASHTO adopted a Charpy V-notch impact test requirement for A514 steel of 25 ft-lb (33.9J) at 30°F (-1.1°C) for service involving ambient temperatures down to 0°F (-17.8°C). Of twelve 2 1/4-inch (57.2mm) thick plate samples cut from the casualty bridge, only two would have been found acceptable if the ASTM A517-70a or the AASHTO Charpy specification had been in effect at the time the bridge steel was purchased.

While the Bryte Bend Bridge was being erected, a second bridge on State Highway 49 at Tuolumne River was being built of the same type of steel and from the same source. When the steel in the Bryte Bend Bridge was found to be seriously lacking in toughness, samples were taken from the Tuolumne River Bridge for testing; these also were found to be deficient in toughness. The heat/slab samples from this bridge were then added to the study summarized herein and reported in detail in reference (1).

Scope of the Study

The full report contains the fracture-toughness data and related failure analysis of the A517 Grade-H steel used in the Bryte Bend box-girder bridge. Also reported are the data from: (1) the Tuolumne River Bridge which contained A517 Grades F and H steel supplied by the producer of the Bryte Bend Bridge steel and (2) the A514/517 Grades F and H steel plates

procured for use in repair of both bridges. A total of 75 ingot-slabs of A514/517 steel were tested from 30 heats, involving two steel producers, two melting practices (open hearth and electric furnace) and two grades (ASTM A514/517 Grades H and F). The objective of the study was to provide bridge and materials engineers with (1) data on the fracture toughness of quenched-and-tempered, 100-ksi (689.47MN/m²) yield, A514/517 steel; and (2) information on the variability of the steel from type to type (A514 and 517), grade to grade (H and F), heat to heat, and slab to slab.

More specifically, the data were compiled, plotted and evaluated to determine the following:

- (1) the variation in tensile properties,
- (2) the variation in Charpy properties among: heats, ingots of a given heat, grades (H versus F), and types (A514 versus A517),
- (3) The variation in toughness with respect to position in the thickness direction in both Charpy impact and drop-weight NDT testing,
- (4) The variation in toughness as a function of rolling direction,
- (5) the variation in toughness as a function of tensile percent reduction of area and percent elongation,
- (6) the reproducibility of Charpy data from laboratory to laboratory (California Department of Transportation, National Bureau of Standards, Effects Technology, Inc., Aerojet General Corporation),
- (7) the usefulness of the precrack Charpy impact test for estimating NDT temperatures,
- (8) the effect of loading rate on transition temperature based on ASTM E399 compact tension versus Charpy impact testing, and
- (9) the effect of notch acuity on transition behavior in the standard Charpy V-notch (CVN) and precrack Charpy impact (PCI) testing.

Summary of Findings

The Charpy test results are particularly interesting considering the current AASHTO bridge-steel toughness requirement. Steel samples from the two bridges were tested using the Charpy V-notch impact test. Of 17 slabs of A517 Grade-H steel (involving six heats) tested at 0°F (-17.8°C),

not a single slab met the current AASHTO requirement of 25 ft-lb (33.9J) for group-2 service, and only one slab met the current ASTM A517-70a, CVN-impact requirement of 15-mils (0.38mm) lateral expansion.

The heats of A514/517 Grade-F steel which were supplied for repair of the Bryte Bend and Tuolumne River Bridges, with very few exceptions, not only met the current CVN-impact requirements (A517-70a) and AASHTO-74) but also generally exceeded these requirements by a wide margin (see Table I and Figures 3, 4, and 5).

A few heat/slabs were found where the precrack Charpy impact test showed the steel to be highly crack sensitive at the lowest anticipated service temperature (the LAST); whereas, the standard CVN-impact test indicated the steel to be acceptable according to AASHTO-74 and/or A517-70a (Figure 6).

The practice of assuming inherent toughness in A514/517 type steels is unsafe; fracture control demands testing to determine the toughness of each plate of steel.

A514/517 Grade-H steel in plate thicknesses of 2 inches (50.8mm) and greater, irrespective of melting practice, is prone to have low toughness. Even when Grade-H steel was supplied by a second steel producer with controlled sequential additions of aluminum, vanadium, titanium, and boron, there were 2-inches (50.8mm) thick, A514, Grade-H heats seriously lacking in toughness (Figures 7 and 8).

The present Charpy V-notch (CVN) impact requirements of ASTM A517-70a and the 1974 AASHTO Interim Specification for Bridges are sufficiently stringent to disqualify brittle steel such as the heat which triggered fracture in the Bryte Bend Bridge (Figure 9).

The precrack Charpy impact test result was demonstrated to be highly reproducible within a given laboratory and from laboratory to laboratory using a specified precracking and testing procedure.

A correlation was established between the fatigue-precracked Charpy impact test and static, fatigue-precracked, ASTM E399 compact-tension test results, viz.,

$$K_{IC}^{2/E} = 18 \text{ (PCI)},$$

where PCI is the precrack Charpy impact value in ft-lb for a nominal fatigue precrack depth of 35 mils (0.90mm), E is Youngs modulus in psi and K_{IC} is the static plane-strain fracture toughness in $\text{psi-in.}^{1/2}$

Bridges that were fabricated from A514/517 Grade-F or Grade-H steel melted by the practice used in making the steel of the Bryte Bend and Tuolumne River Bridges should be given extraordinary inspection on a scheduled basis, as well as a realistic design review.

The design review should cover all aspects related to fatigue crack growth to determine maximum size of cracks that can be tolerated with K_{IC} toughness levels in the range of 50 to 100 $\text{ksi-in.}^{1/2}$ (54.95 to 109.9 $\text{MNm}^{-3/2}$). In particular, emphasis should be placed on bridge members that constitute, or are part of, a one or two load-path system.

A design review and inspection may indicate the desirability of fracture testing samples obtained from any plates in question to determine the degree of brittleness that exists at the lowest anticipated service temperature (the LAST).

Fracture control involves protecting against catastrophic crack propagation from a pop-in crack and catastrophic propagation from a fatigue crack that has grown to critical size. Crack pop-in as a source of brittle fracture involves sudden crack growth with inherently high strain rate irrespective of the service loading (crack pop-in from an embrittled weld or weld heat-affected zone, an arc strike, an improperly made tack weld, etc.). Protection against this source of brittle fracture requires that the NDT temperature of the steel be at least 30°F (16.7°C) below the LAST or that the steel be capable of through-thickness yielding based on pre-crack Charpy impact testing at the LAST.

Fatigue crack growth as a source of brittle fracture involves two considerations in fracture testing: (1) static plane-strain fracture toughness (K_{IC}) measurements to determine the critical crack size at the maximum stress and the lowest temperature anticipated in service; and (2) fatigue crack-growth-rate (da/dN) measurements to permit a determination of the number of cycles for a fatigue crack to reach critical size.

A computer program to perform numerical integration of the crack growth rate expression from Barsom⁽²⁾

$$da/dN = 0.0066 \times 10^{-6} (\Delta K)^{2.25}$$

and laboratory testing of the heat of steel causing fracture in the Bryte Bend Bridge (Figures 10 and 11) indicated that there may be a serious problem in getting 500,000 cycles of fracture-safe service in bridges with stresses of the magnitude of those of the Bryte Bend Bridge where the plane-strain fracture toughness is less than 100 ksi-in.^{1/2} (109.9 MNm^{-3/2}). This observation is based in part on generally inadequate quality control in welding, and consequently, undetected weld cracks at the outset of bridge service.

The A514/517 Grade-F, Charpy-impact energy and lateral expansion values in the AASHTO-74 and ASTM A517-70a specifications are lower than what can be supplied by the steel industry as shown by the histograms on pages 10 to 12. Greater toughness can and should be required to avoid accelerated fatigue crack-growth-rate behavior; for example, thirty (30) ft-lb (40.68J) CVN-impact for AASHTO service groups 1, 2, and 3, and twenty-five (25) mils (0.64mm) of lateral expansion for ASTM A514/417 steel can easily be met in A514/517 Grade-F steel at temperatures down to -40°F (-40°C) for thicknesses to at least 1 1/2 inches (38.2mm).

Recommendations

It is recommended that research be funded to explore further the effect of stress ratio, maximum stress, and fracture toughness on fatigue crack growth rate and, in particular, on the initiation of accelerated fatigue

crack-growth-rate behavior. The A517, Grade-H heat of steel involved in the Bryte Bend Bridge failure appeared to suffer accelerated fatigue crack growth rate starting at a ΔK of about $15 \text{ ksi-in.}^{1/2}$ ($16.48 \text{ MNm}^{-3/2}$) with a maximum stress (39 ksi) (268.895 MN/m^2) and a stress ratio (0.75) of the order of magnitude expected in the bridge (see Figure 11). AASHTO allows a maximum stress of up to 55 ksi (379.212 MN/m^2); most research has been performed with much lower maximum stress and lower stress ratios, even though most bridges with 100-ksi (689.476 MN/m^2) yield steel inherently have stress ratios of the order of 0.7. Research is needed to confirm the effect of maximum stress and stress ratio on da/dN in a variety of steels (say A36, A441, A588, and A514) at various toughness levels.

It is recommended wherever A514/517 Grade-H steel is proposed for use in bridge construction, that there be extraordinary test requirements imposed (depending upon thickness, redundancy, welding process, etc.) as a condition of use in main load carrying member components.

It is recommended that consideration be given to increasing the AASHTO-74 CVN-impact requirement for A514/517 steels from 25 to 30 ft-lb (33.9 to 40.7J) and the ASTM A517-70a CVN-impact requirement from 15 to 25 mils (0.38 to 0.64mm).

References

- (1) Carl E. Hartbower and Roger D. Sunbury, "Variability of Fracture Toughness in A514/517 Plate," Final Report to the U.S. Department of Transportation under Phase I of State of California Contract DOT-FH-11-8250, Task Order No. 7, 266 pages, December 1975. (Unpublished)
- (2) J. M. Barsom, E. J. Imhof, Jr., and S. T. Rolfe, "Fatigue-Crack Propagation in High-Strength Steels." Engineering Fracture Mechanics, 1971, Vol. 2, pp. 301-317.

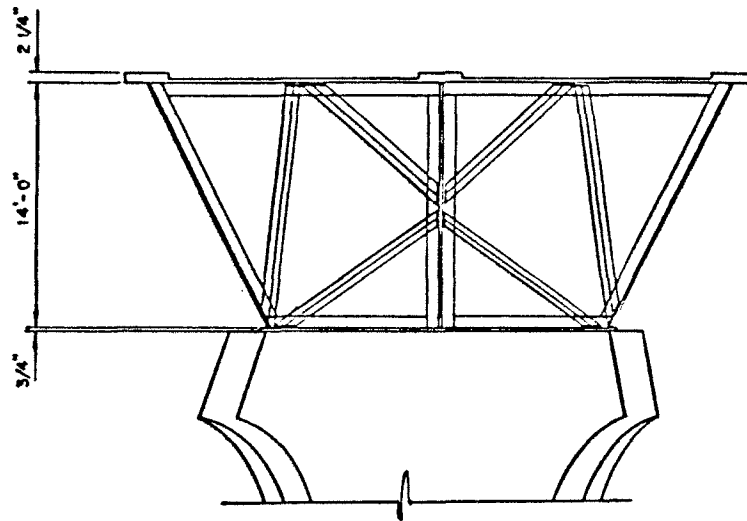
TABLE 1
SUMMARY OF A514/517 GRADE-F CVN-IMPACT TEST RESULTS

ASTM TYPE-GRADE	REPORT CODE HEAT/SLAB	THICK. (IN.)	CVN-IMPACT (FT-LB)			25 FT-LB TT	LAT. EXPANSION at LAST
			+20°F (a)	0°F (b)	-30°F (b)		
A517-F	1005/22BX	1-3/8	35.1	34	32	> -60	26.3
A517-F	1009/40BH	1-3/8	65.2	66	66	> -60	48.7
A517-F	1010/AP	1-3/8	53.7	54	54	> -60	39.0
A517-F	1011/CA	1-3/8	50.0	43	31	-45	38.8
A517-F	1001/82AD	1-1/2	61	60.4	58	> -60	44.7
	1001/83AE	1-1/2	62	63.6	61	> -60	44.2
	1001/84AF	1-1/2	51	50.6	48	> -60	37.3
A517-F	1002/82AB	1-1/2	49	49.1	50	> -60	35.8
	1002/38AC	1-1/2	48	48.4	46	> -60	35.3
A517-F	1004/44AG	1-1/2	66	65.8	66	> -60	45.8
	1004/96AH	1-1/2	70	67.4	70	> -60	47.8
	1004/98AJ	1-1/2	60	60.6	60	> -60	42.5
A517-F	1012/99AK	1-1/2	60	61.3	59	> -60	44.2
A514-F	1003/29CB	2-1/4	37.5	28	14	-5	25.3
A514-F	1013/32J	2-1/4	22.3	19	15	+25	15.3
A514-F	1014/02M	2-1/4	65.7	65	56	> -60	47.0
A514-F	1017/62L	2-1/4	71.7	67	47	-60	45.7
A517-F	1026/92A	2-1/4	16	15.8	14	+130	10.0
A517-F	1008/76D	2-1/2	53	48.6	38	> -60	36.3
A517-F	1028/64B	2-1/2	31	20.7	20	-5	14.7
A517-F	1006/(e)	1-3/8	45.5	43	43	43.6(f)	33.0

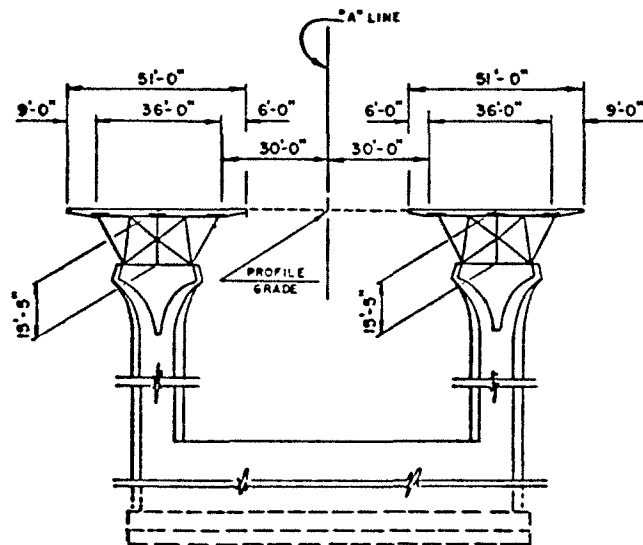
- (a) Data reported to one decimal place are averages of three tests by CALTRANS.
- (b) Rounded-off ft-lb values are interpolated from the transition-curve plots.
- (c) Temperature (°F) corresponding to 25 ft-lb CVN-impact energy.
- (d) Lateral expansion values at the lowest anticipated service temperature (LAST) correspond to the ft-lb values reported to the 1st decimal place. Thus, the lateral expansion value for plate AM was the average of three tests at +20°F whereas the value for plate G was the average of three tests at 0°F.
- (e) Twenty-nine slabs from heat 1006 were tested in triplicate; values reported for this heat to one decimal place were the average of 87 tests.
- (f) Average CVN-impact value (ft-lb) of 81 tests made by the steel producers at -50°F.

Conversion Factors:

in. x 25.4 = mm
 $5/9 (°F - 32) = °C$
ft-lb x 1.356 = J
mil x 0.0254 = mm

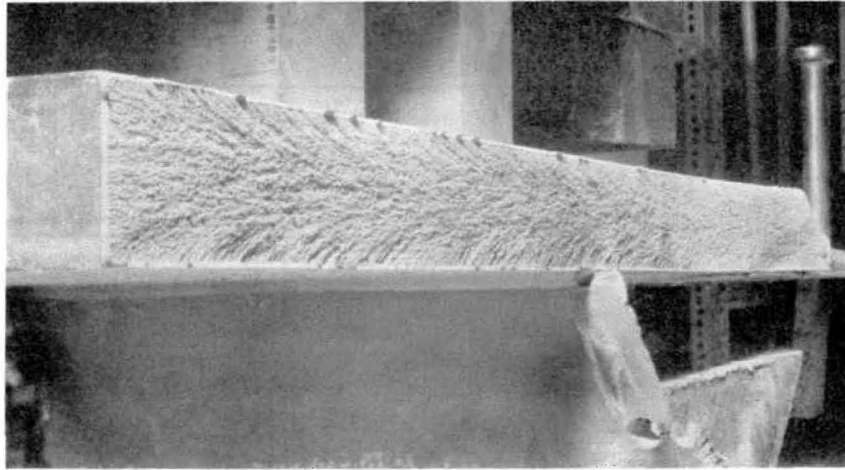


TYPICAL SECTION OF STEEL BOX GIRDERS

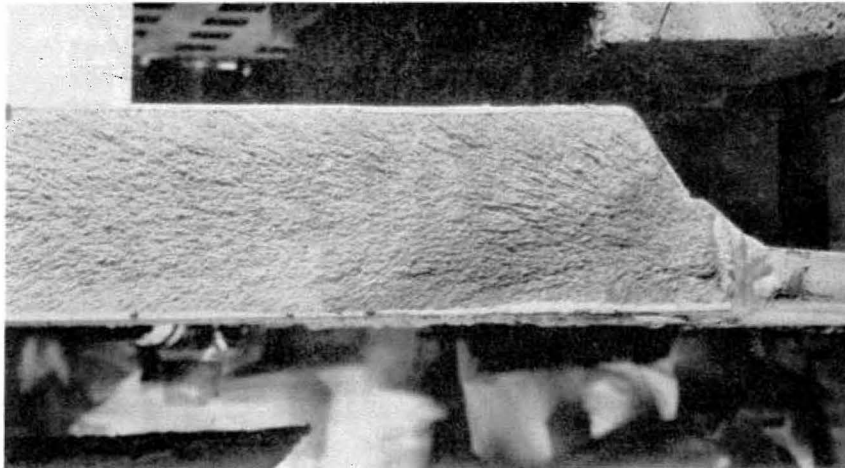


TYPICAL SECTION AT PIERS 12, 13 & 14

Figure 1 - Bryte Bend Bridge at Sacramento, California
ft x 0.3048 = m



2-1/4-IN.-THICK, 30-IN.-WIDE, FRACTURED FLANGE



FRACTURE ORIGIN AT WELD BETWEEN FLANGE AND
CROSS BRACING

Figure 2 - Fracture Surface of the Casualty Flange in
the Bryte Bend Bridge

in. x 25.4 mm

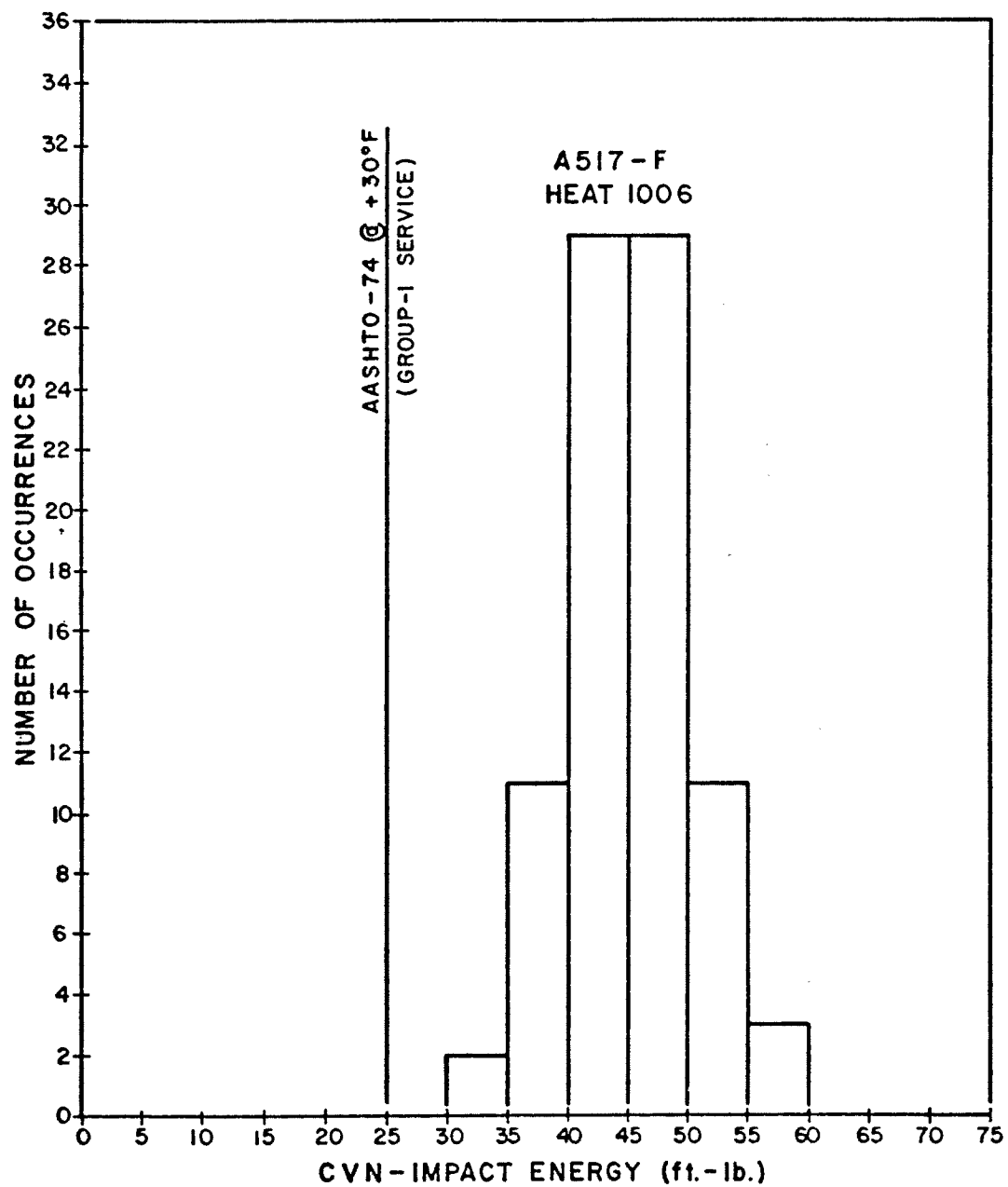


Figure 3 - Histogram of CVN-Impact Energy Values from 29 A517 Grade-F Slabs from Heat 1006 Tested at +20°F

$$\text{ft.-lb} \times 1.356 = \text{J}$$

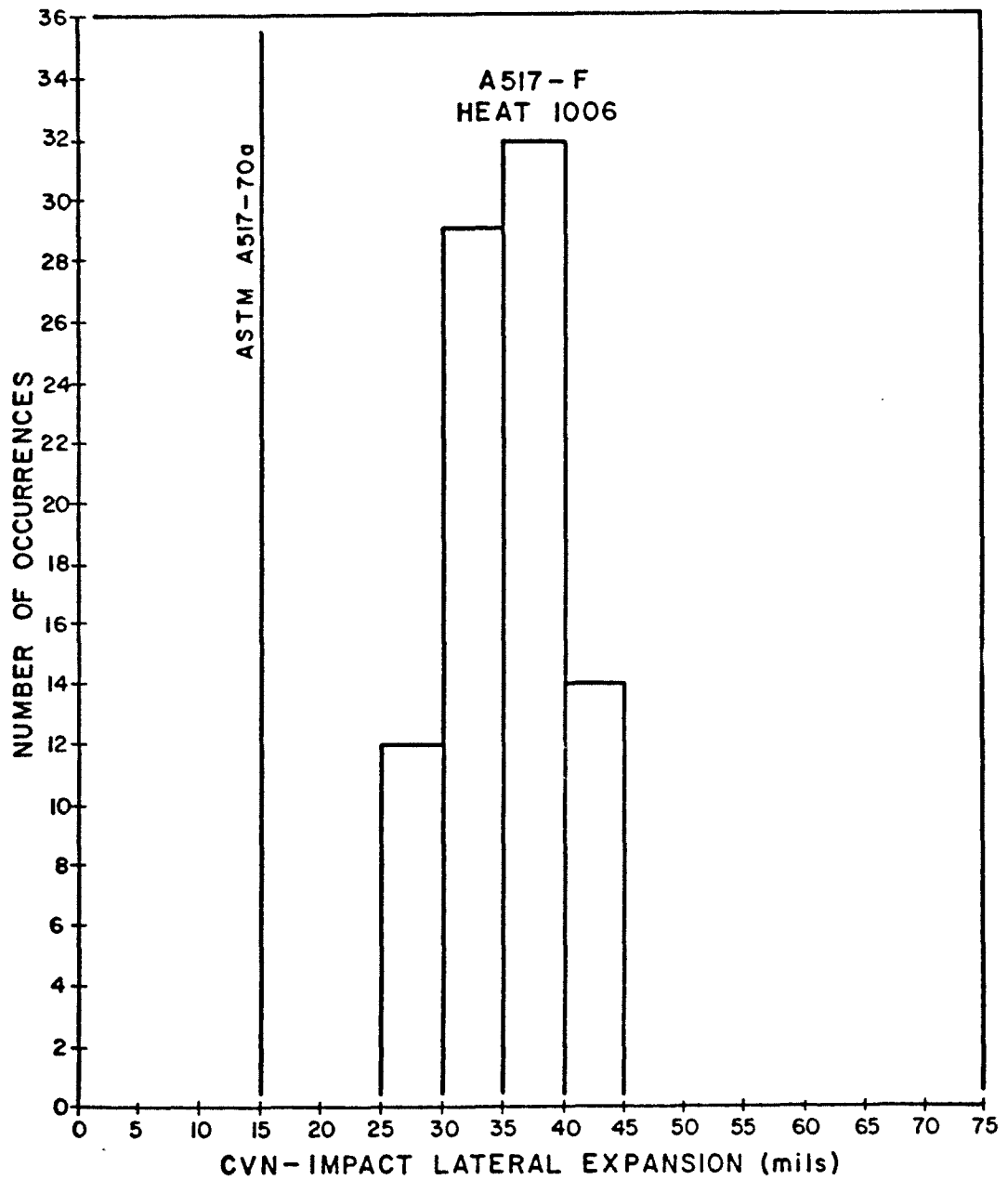


Figure 4 - Histogram of CVN-Impact Lateral Expansion
Values from 29 A517 Grade-F Slabs from
Heat 1006 Tested at +20°F
mil x 0.0254 = mm

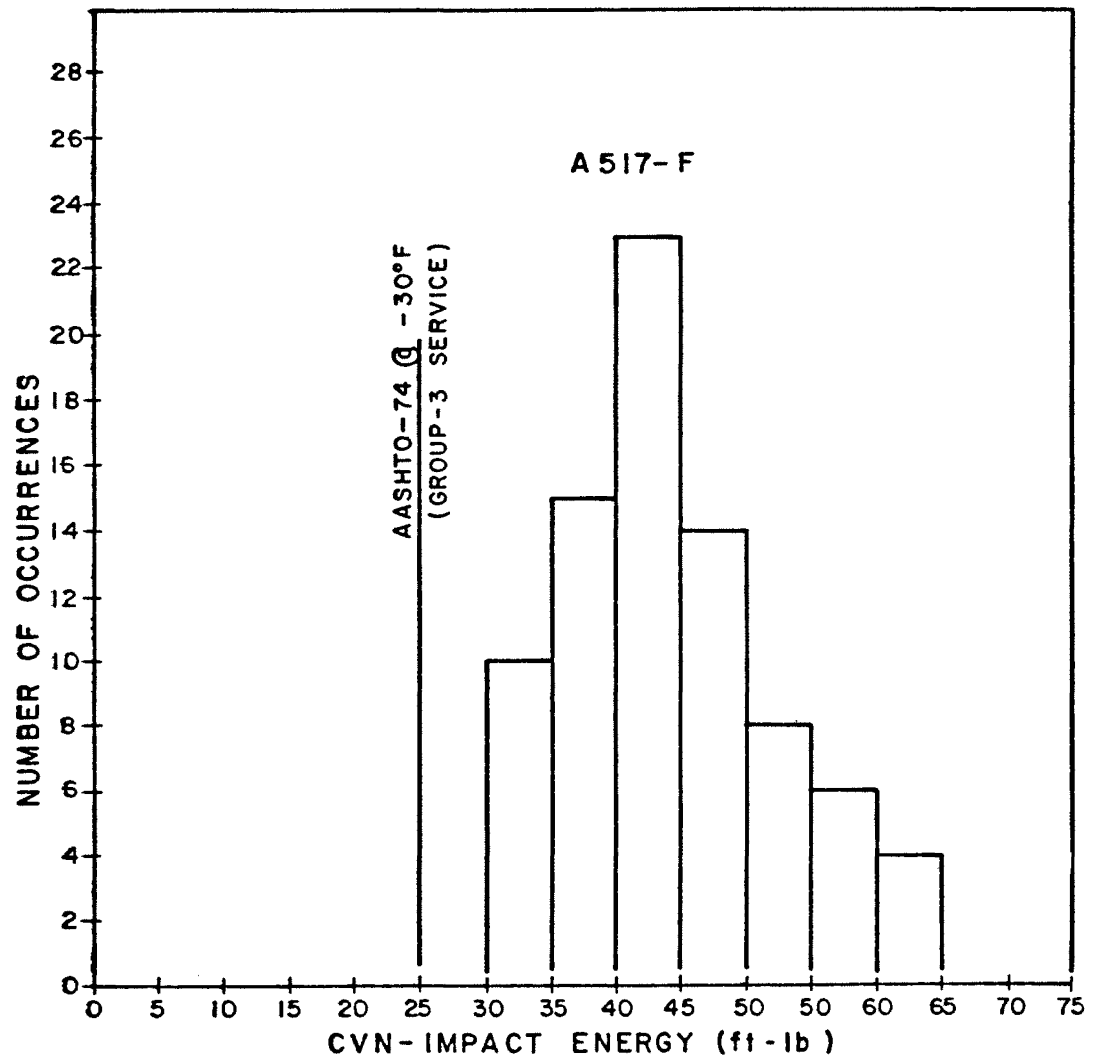


Figure 5 - Histogram of CVN-Impact Energy Values from
27 A517 Grade-F Slabs from Heat 1006 Tested
by the Steel Producer at -50°F
 $\text{ft-lb} \times 1.356 = \text{J}$

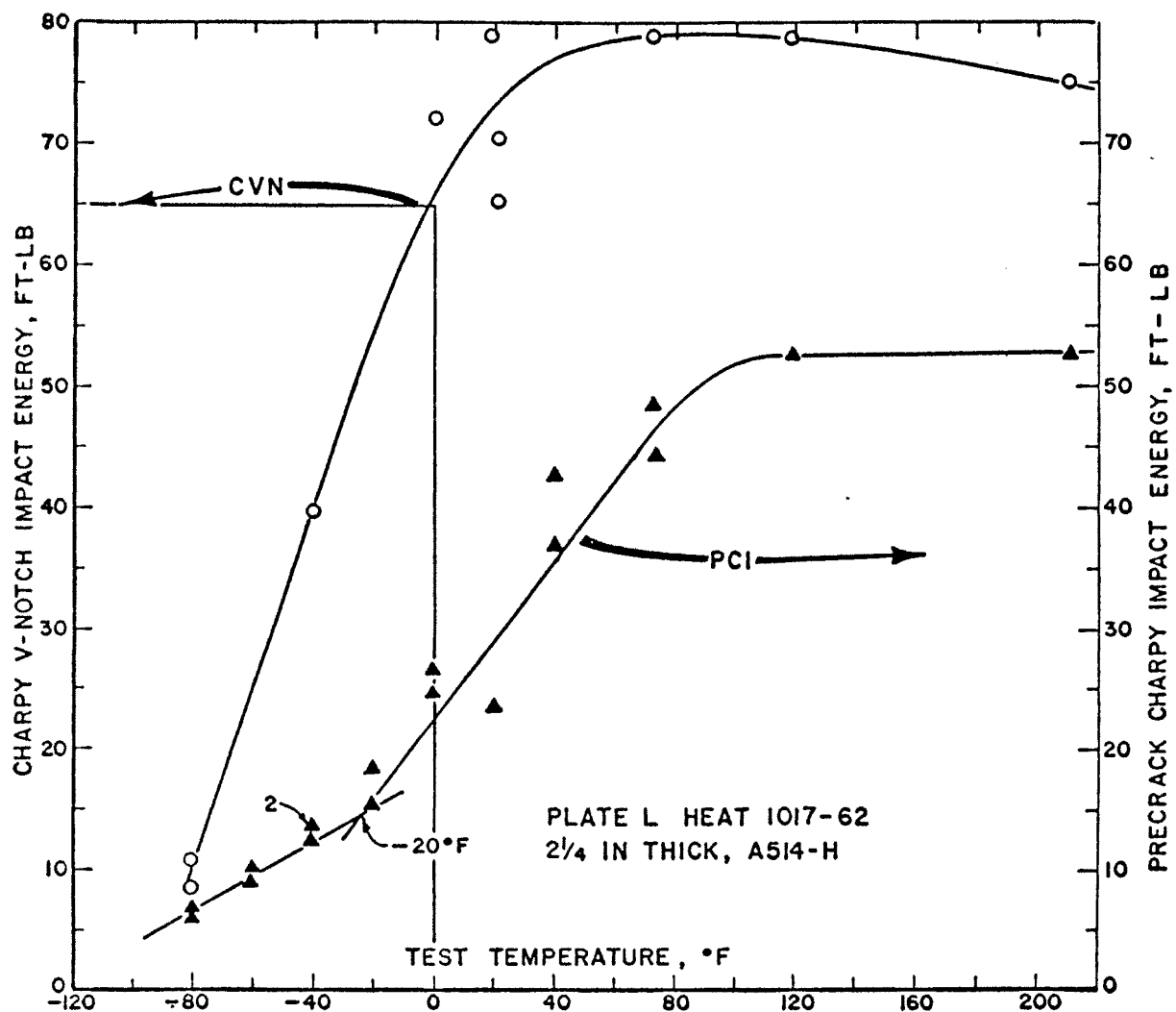


Figure 6 - CVN-Impact and Precrack Charpy Impact
Transition Curves for A514 Grade-F Heat 1017-62

$$\text{ft-lb} \times 1.356 = \text{J}$$

$$5/9(\text{F}-32) = \text{C}$$

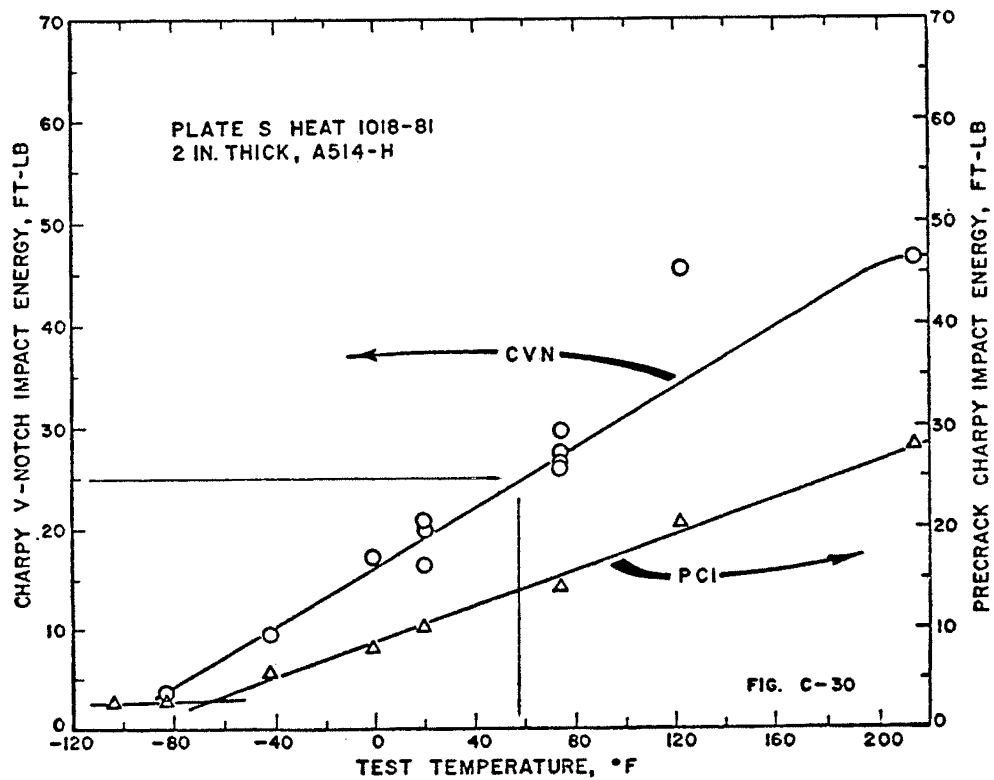
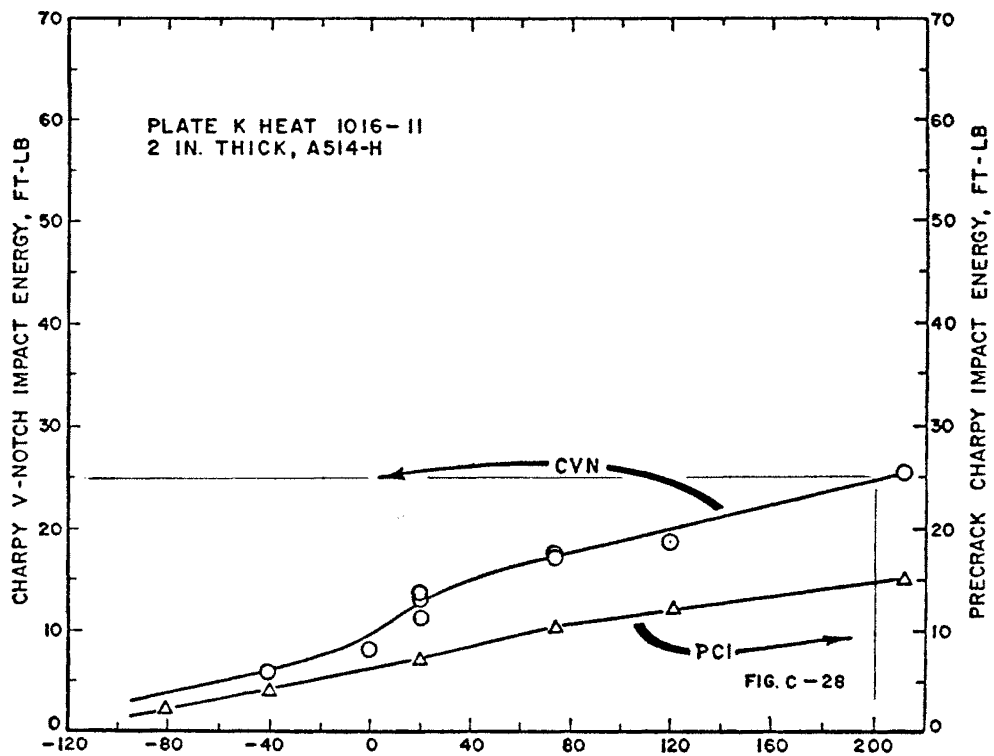


Figure 7 - Two-Inch-Thick ASTM A514 Grade-H Steel, Open-Hearth Practice

$$\text{ft-lb} \times 1.356 = \text{J}$$

$$5/9(\text{F}-32) = \text{C}$$

$$\text{in.} \times 25.4 = \text{mm}$$

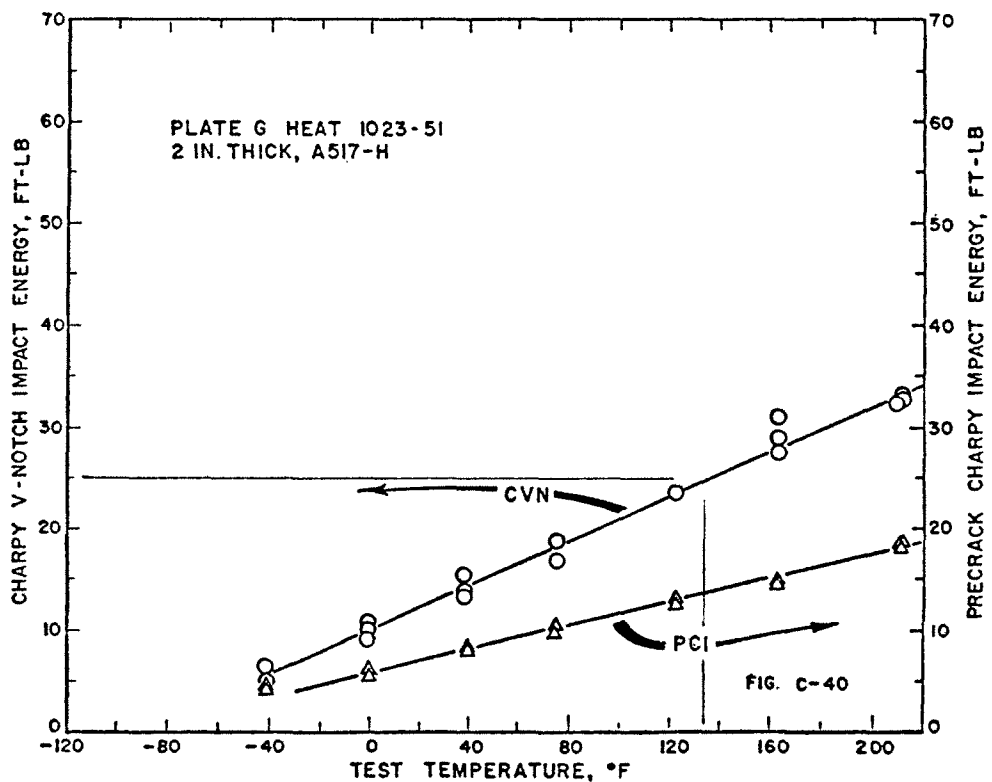
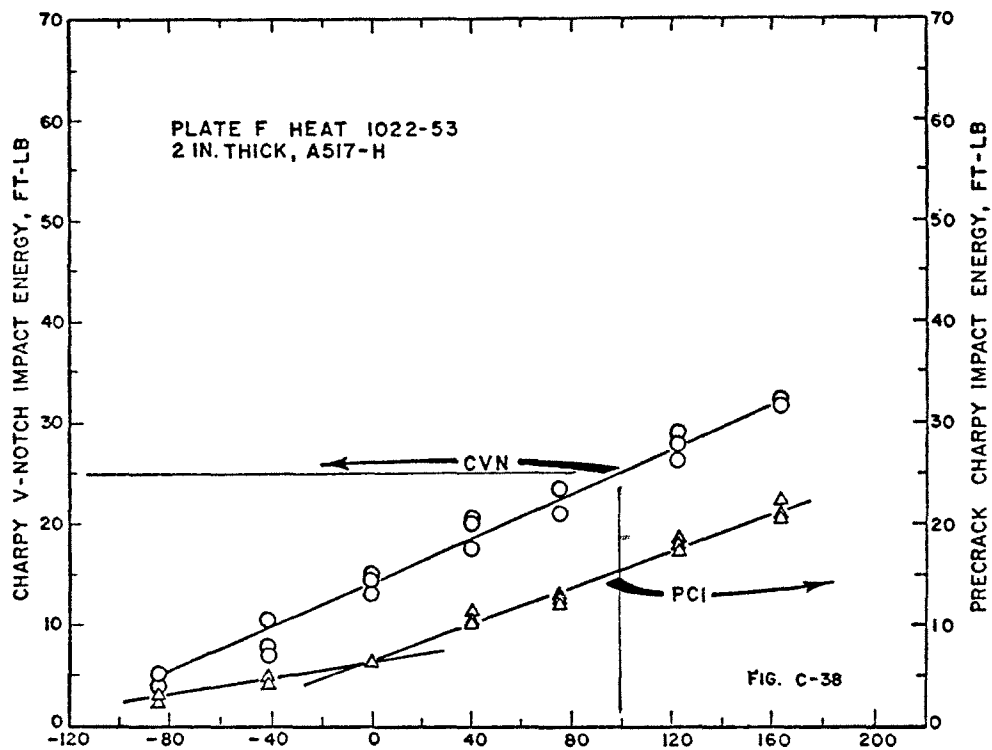


Figure 8 - Two-Inch-Thick ASTM A517 Grade-H Steel,
Electric-Furnace Practice

$$\text{ft-lb} \times 1.356 = \text{J}$$

$$5/9(F-32) = C$$

$$\text{in.} \times 25.4 = \text{mm}$$

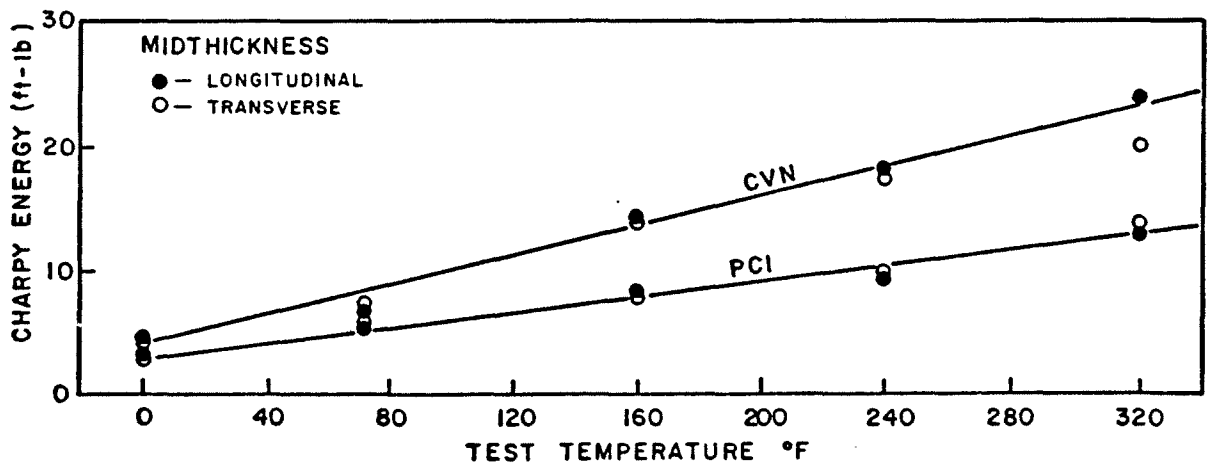
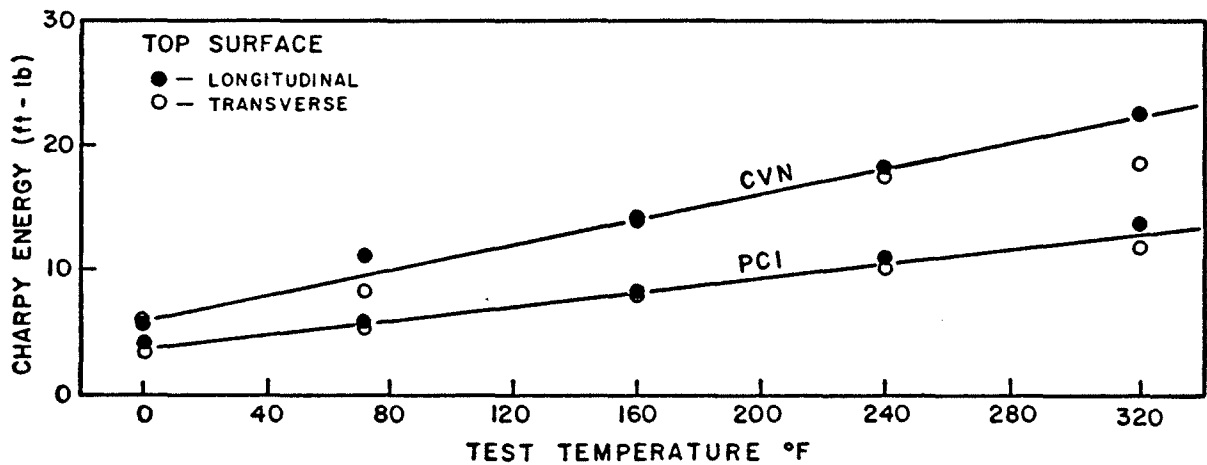
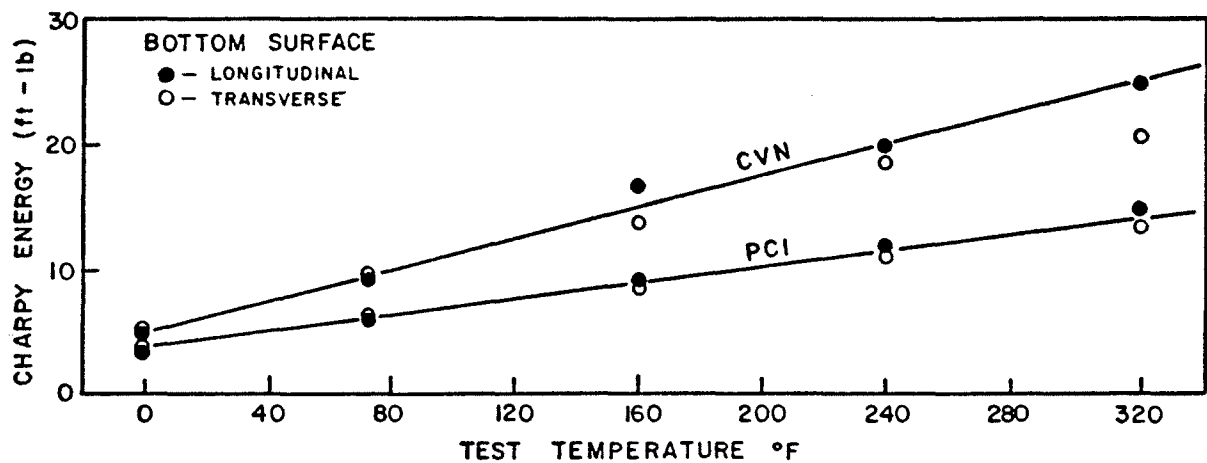


Figure 9 - CVN-Impact and Precrack Charpy Impact Transition Curves for A517 Grade-H Heat 1027-44CK Which Fractured in the Bryte Bend Bridge

$$\text{ft-lb} \times 1.356 = \text{J}$$

$$5/9(\text{F}-32) = \text{C}$$

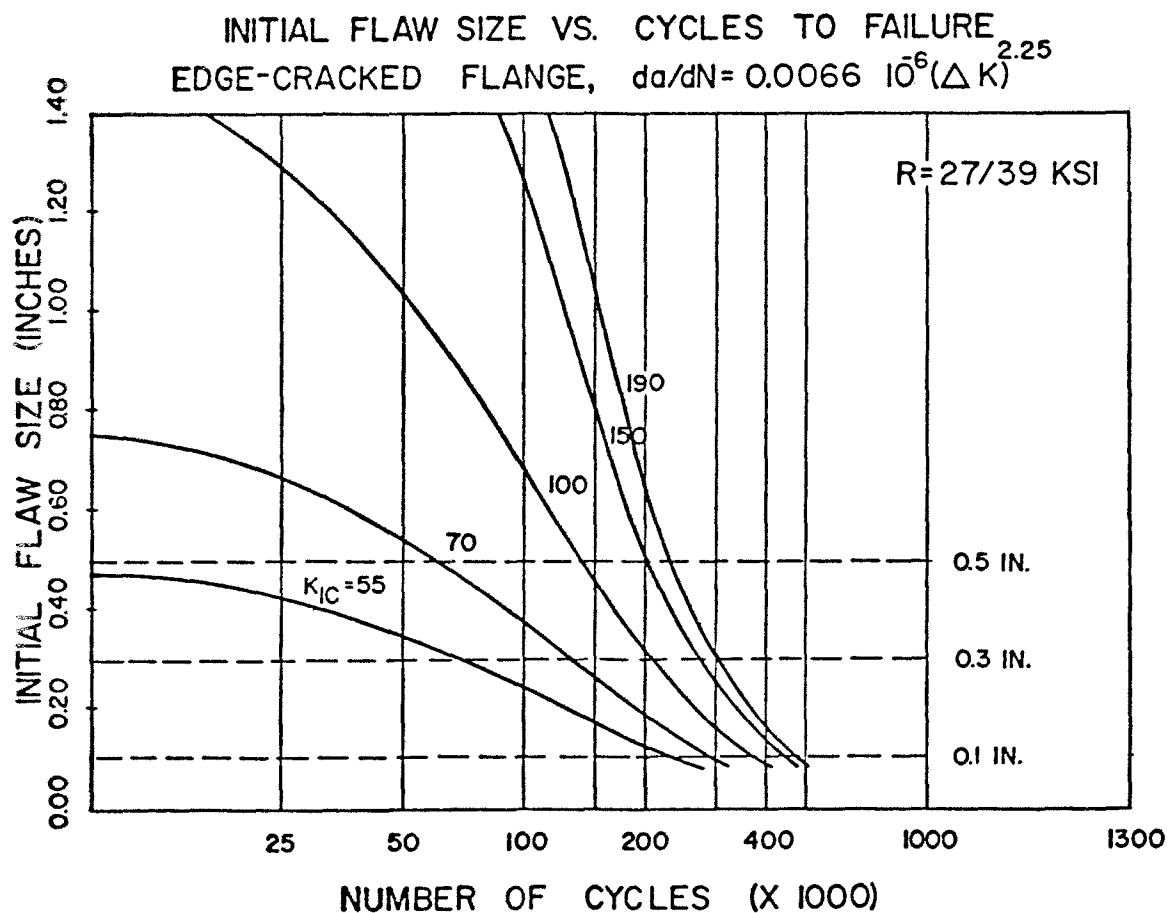
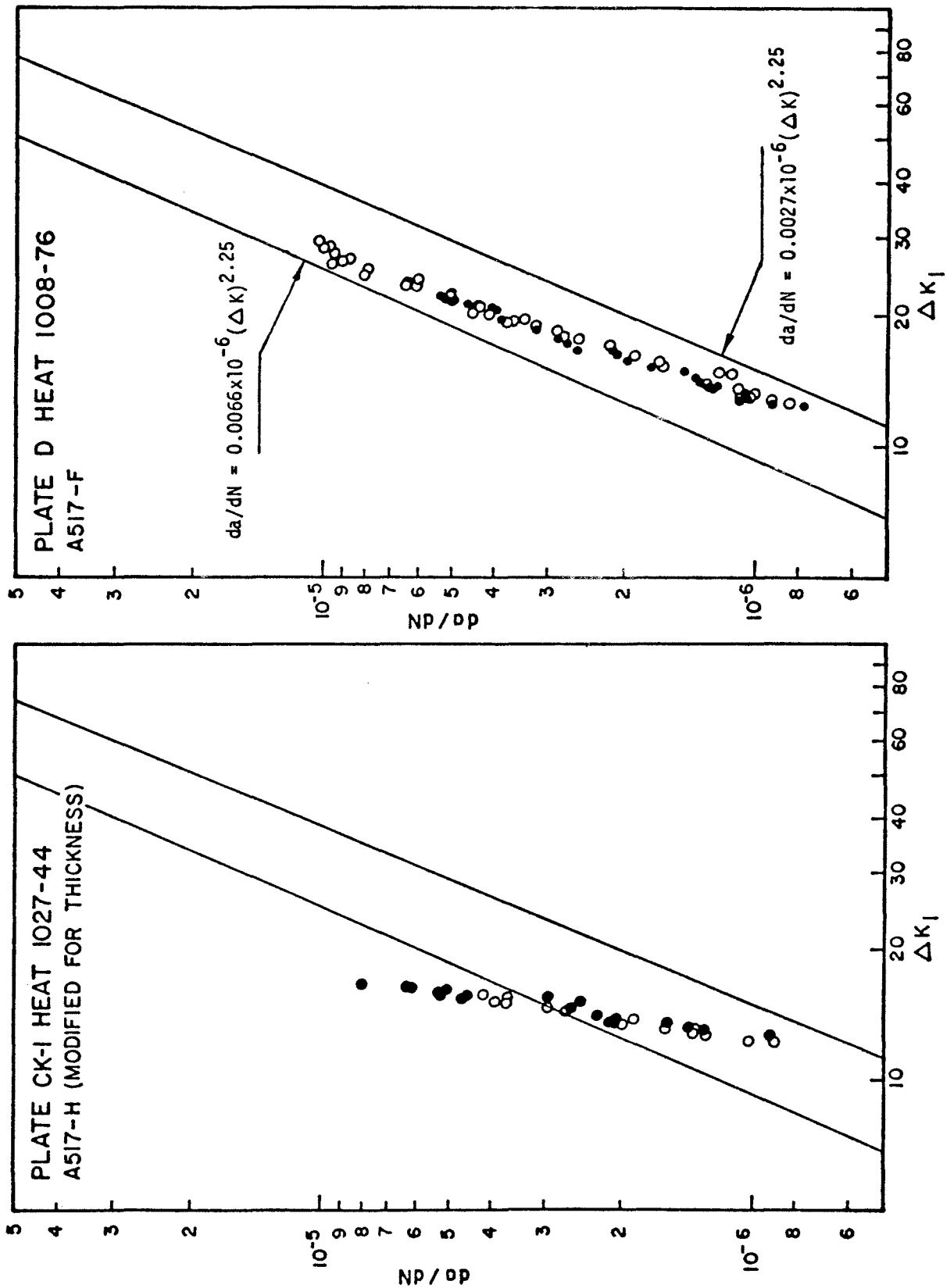


Figure 10 - Computer-Plotted Curves Providing and Estimate of Fatigue Life in an Edge-Cracked, 30-inch-wide Flange Subjected to a Stress Ratio of 27/39 ksi (R=0.7)

$$\text{ksi} \times 6.895 = \text{MN/m}^2$$

$$\text{ksi-in.}^{1/2} \times 1.099 = \text{MNm}^{-3/2}$$



in. x 25.4 = mm
 ksi x 6.895 = MN/m²
 ksi-in.^{1/2} x 1.099 = MNm^{-3/2}

Figure 11 - Fatigue-Crack Growth-Rate Tests of A517 Grade-F Plate D and A517 Grade-H Plate CK Tested at 45 ksi Maximum Stress and R-0.7 (bands correspond to martensitic-steel data collected by Barsom).

TABLE OF CONTENTS
of

Reference 1

"Variability of Fracture Toughness in A514/517 Plate"
Final Report to the U.S. Department of Transportation
under Phase I of State of California Contract
DOT-FH-11-8250 Task Order No. 7, 266 pages, December 1975.

TABLE OF CONTENTS

	<u>Page</u>
1.0 Introduction	1
1.1 Purpose of Study	1
1.2 Background	1
1.3 Source of the Material Investigated	5
1.4 Scope of the Investigation	11
2.0 Materials Investigated	13
2.1 Identification of the 76 Plates	13
2.2 Tensile Properties	13
2.3 Chemistry of the Plates	14
3.0 Test Method	21
3.1 Standard Charpy V-Notch Impact Test	21
3.2 Precrack Charpy Impact Tests	21
3.2.1 Instrumented Precrack Charpy Impact	23
3.2.2 Temperature Measurement	25
3.2.3 Impact Machine Calibration	27
3.2.4 Raw Data Reduction	27
3.2.5 Calculation of Strength and Toughness	31
3.3 ASTM E399 Compact Tension Testing	35
3.3.1 Computer Program	39
3.4 ASTM E208 NDT Temperature Test	44
3.5 Military Standard Method for 5/8 in. Dynamic Tear Testing (MIL-STD-1601 SHIPS) 8 May 1973	45
4.0 Test Results	50
4.1 Charpy Impact Test Results	50
4.1.1 Transition-Temperature Concepts	50
4.1.2 Fatigue Precracked Charpy Testing	53
4.1.3 Current Developments in Precracked Charpy Testing	59
4.1.4 A514/517 Charpy Data Plotting	62
4.1.5 Effect of Notch Acuity	75
4.1.6 Lab to Lab Reproducibility of Charpy Data	79
4.1.7 Slab to Slab Variability	91
4.1.8 Variation in Toughness with Respect to Rolling Direction	114
4.1.9 Correlation of Toughness and Tensile Test Data	117
4.2 Charpy Impact Correlations	120
4.2.1 Background	120
4.2.2 Charpy Test Results	136
4.2.3 Upper Shelf K_{IC} - CVN Correlation	145
4.2.4 Lower Shelf K_{IC} - PCI Correlation	147
4.2.5 Through-Thickness Yielding Criteria	151
4.2.6 Inhomogeneity of Plate in the Thickness Direction	161

TABLE OF CONTENTS (Continued)

	<u>Page</u>
4.3 Summary of CVN - Impact Test Results	169
4.3.1 Procedure for Data Presentation	169
4.3.2 Frequency Tables	169
4.3.3 Frequency Distribution Histograms	170
4.3.4 Frequency Distribution in 29 Slabs from a Single Heat	180
4.4 ASTM E399 Compact Tension Test Results	194
4.4.1 Effect of "Invalid" K_{IC} tests	204
4.4.1.1 Effect of Fatigue Precracking Discrepancies	204
4.4.1.2 Effect of Specimen Size Discrepancies	211
4.4.2 Plate to Plate Variability in K_{IC}	212
4.4.3 Discussion of the K_{IC} Test Results	214
4.4.4 Subcritical Crack Growth in Plate CK	219
4.4.5 Effect of Regions II and III on Fatigue Life	222
4.5 Drop-Weight NDT and Dynamic Test Test Results	230
4.5.1 A517 Grade-H Heat 1027/44CK	231
4.5.2 Heats 1008/76D, 1020/46AL, 1024/91Y and 1026/92A	235
4.5.3 ASTM E208-69 Drop Weight NDT Temperature	243
4.5.4 A517 Grade-H Heat 1027/44CK NDT Temperature	244
4.5.5 Heats 1008/76D, 1020/46AL, 1024/91Y and 1026/92A	246
4.6 Effect of Microstructure on Fatigue	257
5.0 References	260
6.0 Appendices	266
A. Tensile Properties of 76 Slabs from 30 Heats of A514/517 Steel as Recorded in the Mill Test Report and as Determined by Caltrans Lab.	A1 thru A11
B. Chemistry of 30 Heats of A514/517 Steel as Recorded in the Mill Test Reports and as Determined by Caltrans Lab.	B1 thru B6
C. Charpy V-Notch and Precrack Charpy Impact Test Results of 76 Slabs from 30 Heats of A514/517 Steel.	C1 thru C63
D. Effects Technology, Inc. Charpy Impact Test Results on Seven Heats of A514/517 Steel.	D1 thru D17
E. National Bureau of Standards Charpy Impact Test Results of Selected Heats of A514/517 Steel.	E1 thru E18

LIST OF TABLES

<u>Table</u>		<u>Page</u>
1.1	A514/517 Plates Investigated in Recent Researches	6
2.1.1	Identification of Steels by Type, Grade, Heat, Slab & Thickness Indexed by Plate Identification	15
2.1.2	Identification of Steels by Type, Grade, Heat, Slab & Thickness Indexed by Heat & Slab	18
4.1	Test Plan for NBS Charpy Impact Testing and Computer Evaluation of A517-H Heat 1027/44	80
4.2	Charpy V-Notch Impact Data from Seven Slabs of A517-F Heat 1006	92
4.3	Precracked Charpy Impact Data from Seven Slabs of A517-F Heat 1006	93
4.4	Precracked Charpy Impact Energy and Lateral Expansion Values from Twenty-Nine Slabs of A517-F Heat 1006 Tested at Plus 20°F	95
4.5	Standard CVN - Impact Tests Showing the Effect of Specimen Orientation	116
4.6	Increase in Transition Temperature as a Result of Impact Loading (Reference 3)	128
4.7	U. S. Steel Plane-Strain Fracture-Toughness Data for A517-F Heat 73A377	146
4.8	Plane-Strain Fracture Toughness Calculated from Charpy V-Notch Upper-Shelf Energy	146
4.9	Transition-Range Charpy- K_{IC} Correlation Data	149
4.10	Charpy Energy Requirements for Through-Thickness Yielding	154
4.11	Standard Charpy V-Notch Impact Properties from Twenty-Nine Slabs of A517-F Heat 1006 (Mill Test Data)	185

LIST OF TABLES (Continued)

<u>Table</u>		<u>Page</u>
4.12	Standard Charpy V-Notch Impact Properties from Sixteen Heats, Twenty-Four Slabs of A514/517 Grade-F Steel	186
4.13	Standard Charpy V-Notch Impact Properties from Twelve Heats, Twenty-Five Slabs of A514/517 Grade-H Steel	187
4.14	Frequency Distribution for CVN-Impact Energy and Lateral Expansion in 74 Slabs of A514/517 Grade-F and Grade-H Steel at Selected Test Temperatures	188
4.15	Arithmetic Mean Values of CVN-Impact Energy and Lateral Expansion in A514/517 Grade-H and Grade-F Steels Tested at Selected Temperatures	189
4.16	Summary of A514/517 Grade-F CVN-Impact Test Results	190
4.17	Summary of A514/517 Grade-H CVN-Impact Test Results	191
4.18	Slab-to-Slab Variability in Selected Heats A514/517 Grade-F	192
4.18a	Slab-to-Slab Variability in Selected Heats A514/517 Grade-H	193
4.19	Summary of One-Inch-Thick Compact Tension Test Results for Seven A514/517 Steels	195
4.20	Summary of two-Inch-Thick Compact-Tension Test Results for Seven A514/517 Steels	196
4.21	Transition-Temperature Shift Due to Rate of Loading (Static K_{Ic} vs PCI)	205
4.22	Fatigue Precracking Discrepancies in Compact-Tension Tests	206
4.23	Summary of Compact-Tension Test Results from A517 Grade-H Plate CK-2	213
4.24	Temperature at the onset of Elastic-Plastic Behavior Under Plane-Strain Static Loading and Calculated Critical Crack Sizes at the LAST for AASHTO-74 Group-1 Service	216

LIST OF TABLES (Continued)

<u>Table</u>		<u>Page</u>
4.25	Predicted Life in a 30-Inch-Wide Flange as a Function of Edge Crack Depth, Fracture Toughness and Stress Range	228
4.26	Dynamic Tear Test Results from A517 Grade-H Heat 1027/44 CK as a Function of Thickness Position	231
4.27	Dynamic Tear Test Results from Selected Heats of A514/517 Grade-F and Grade-H Steels	235
4.28	ASTM E208 Drop-Weight NDT Temperatures for A517 Grade-H Heat 1027/44 CK	245
4.29	ASTM E208 Drop-Weight NDT Temperatures for Selected Heats of A514/517 Grade-F and Grade-H Steels	247
4.30	Summary of E208 NDT Temperatures and Dynamic Tear Test and Precrack Charpy Impact NDT Estimates	250

LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
1.1	Typical Section of the Bryte Bend Bridge	2
1.2	Fracture Surface of Casualty Flange in Bryte Bend Bridge	3
1.3	Location of Heats and Slabs in the Bryte Bend Bridge	8
1.4	Location of Heats and Slabs in the Tuolumne River Bridge	9
3.1	Physmet (ManLabs) Charpy Impact Testing Machine (Photograph)	22
3.2	Instrumented Charpy Impact Testing System(<u>13</u>)	24
3.3	Typical Raw-Data Record from Instrumented Charpy Impact Testing System(<u>13</u>)	26
3.4	Idealized Load-Deflection Record(<u>13</u>)	29
3.5	Typical Raw-Data Tabulation(<u>13</u>)	30
3.6	Relationship of Equivalent Energy Fracture Load P^* to the Actual Fracture Load(<u>13</u>)	34
3.7	Typical Fracture Toughness Results Tabulation(<u>13</u>)	36
3.8	Two-Inch-Thick Compact-Tension Specimen Dimensions and Tolerances	38
3.9	Double-Cantilever Displacement Gage	42
3.10	Computer-Printed Tabulation of Compact-Tension-Test Results	43
3.11	Double-Pendulum Machine of 2000 ft-lb Capacity for Testing 5/8-DT Specimens (Reference 22)	47
3.12	DT Test Results from Two Laboratories, Testing 5/8 in. Thick A514/517 Grade D Plate	49

LIST OF FIGURES (Continued)

<u>Figure</u>		<u>Page</u>
4.1	Charpy-Test Transition Temperatures Including Fracture Mode Transition	53
4.2	Comparison of Static, Dynamic and Instrumented Precracked Charpy Impact Fracture Toughness as a Function of Temperature	57
4.2.1	Comparison of V-Notch and Precracked Charpy Data with 5/8 in. Dynamic Tear Data on A533-B Steel(27)	58
4.3	ASTM E24.03.03 Precracked Charpy Round-Robin Phase-I Test Matrix (NBS)	61
4.4	Precrack Charpy Impact Transition Curve for A517-F Plate B Based on Energy Absorption and Lateral Expansion	64
4.5	Relationship Between Energy Absorption and Lateral Expansion in Precrack Charpy Impact Tests of A514/517 Grade F Steels	66
4.6	Relationship Between Energy Absorption and Lateral Expansion in Precrack Charpy Impact Tests of A514/517 Grade H Steels	67
4.7	Relationship Between Energy Absorption and Lateral Expansion in Standard Charpy V-Notch Impact Tests of A514/517 Grade F Steels	68
4.8	Relationship Between Energy Absorption and Lateral Expansion in Standard Charpy V-Notch Impact Tests of A514/517 Grade H Steels	69
4.9	CVN-Impact Energy Absorption and Lateral Expansion Transition Curves for A517-F Plate B	70
4.10	CVN-Impact and PCI Transition Curves for A517-F Plate A	72
4.11	Effects Technology, Inc. PCI W/A - versus - Temperature Plot for A517-F Plate A	74
4.12	CVN-Impact and PCI Transition Curves for A514-H Plate L	76

LIST OF FIGURES (Continued)

<u>Figure</u>		<u>Page</u>
4.13	CVN-Impact and PCI Transition Curves for A514-F Plate J	77
4.14	CVN-Impact and PCI Transition Curves for A514-F Plate CB	78
4.15	Lab-to-Lab Variability in CVN-Impact and PCI Tests of A517-H Plate CK	84
4.16	Super Position of Effects Technology Inc. Precrack Charpy Impact Data on Aerojet General Corp. Data for A517-F Plate A	85
4.17	Super Position of Effects Technology, Inc. Precrack Charpy Impact Data on Aerojet General Corp. Data for A517-H Plate AL	86
4.18	Super Position of Effects Technology, Inc. Precrack Charpy Impact Data on Aerojet General Corp. Data for A514-H Plate L	87
4.19	Super Position of Effects Technology, Inc. Precrack Charpy Impact Data on Aerojet General Corp. Data for A514-F Plate M	88
4.20	Super Position of Effects Technology, Inc. Precrack Charpy Impact Data on Aerojet General Corp. Data for A514-H Plate R	89
4.21	Super Position of Effects Technology, Inc. Precrack Charpy Impact Data on Aerojet General Corp. Data for A517-H Plate Z	90
4.22	Histogram of PCI Values at +20°F from 29 Slabs of A517-F Heat 1006	96
4.23	PCI Tests of Four Slabs from A517-H Heat 1020	98
4.24	PCI Tests of Three Slabs from A517-H Heat 1024	99
4.24.1	CVN-Impact Tests of Three Slabs from A517-H Heat 1024	100
4.25	PCI Tests of Three Slabs from A517-H Heat 1027	101
4.26	Lateral Expansion Data from CVN-Impact and PCI Tests of Seven Slabs from Heat 1006	103

LIST OF FIGURES (Continued)

<u>Figure</u>		<u>Page</u>
4.27	Lateral Expansion Transition Behavior from CVN-Impact Tests of Seven Slabs of A517-F Heat 1006	104
4.27.1	Lateral Expansion Transition Behavior from PCI Tests of Seven Slabs of A517-F Heat 1006	105
4.28	Lateral Expansion Transition Behavior from CVN-Impact Tests of Three Slabs of A517-F Heat 1001	106
4.28.1	Lateral Expansion Transition Behavior from PCI Tests of Three Slabs of A517-F Heat 1001	107
4.29	Lateral Expansion Transition Behavior from CVN-Impact Tests of Three Slabs of A517-F Heat 1004	108
4.29.1	Lateral Expansion Transition Behavior from PCI Tests of Three Slabs of A517-F Heat 1004	109
4.30	Lateral Expansion Transition Behavior from CVN-Impact Tests of Four Slabs of A517-H Heat 1020	110
4.30.1	Lateral Expansion Transition Behavior from PCI Tests of Four Slabs of A517-H Heat 1020	111
4.31	Lateral Expansion Transition Behavior from CVN-Impact Tests of Three Slabs of A517-H Heat 1022	112
4.31.1	Lateral Expansion Transition Behavior from PCI Tests of Three Slabs of A517-H Heat 1022	113
4.31.2	Longitudinal and Transverse CVN-Impact and PCI Transition Curves for A514-H Heat 1027-44 CK	115
4.31.3	Correlation of CVN Impact Energy and % Reduction of Area of A514/517 Grades F and H	118
4.31.4	Correlation of CVN Impact Energy and % Elongation of A514/517 Grade F and H.	119
4.32	Limiting Yielding Strength, Plate Thickness and Fracture Toughness for Valid K_{IC} Determinations Per ASTM E399	121
4.33	K_{IC} Temperature Transition for A517-F Steel (Reference 32)	123
4.34	Energy, Lateral-Expansion and Fracture- Appearance Transition Curves from Standard CVN- Impact Tests of A517-F Heat 73B320 (Reference 32)	124

LIST OF FIGURES (Continued)

<u>Figure</u>		<u>Page</u>
4.35	Energy, Lateral-Expansion and Fracture-Appearance Transition Curves from PCI Tests of A517-F Heat 73B320 (Reference 32)	125
4.36	K_{IC} and PCI Temperature Transition Based on Data from Reference 32	126
4.37	Prediction of Dynamic K_{IC} Based on Precrack Charpy PCI and PCSB Tests (Reference 4)	129
4.38	Static and Dynamic K_{IC} Predictions Based on PCSB and PCI Testing	130
4.39	Upper-Shelf CVN-Impact K_{IC} Correlation (Reference 31)	132
4.40	CVN-Impact and PCI Transition Curves for A517-F Heat-Slab 1026-92	137
4.41	CVN-Impact and PCI Transition Curves for A517-H Heat-Slab 1020-46	138
4.42	CVN-Impact and PCI Transition Curves for A517-H Heat-Slab 1027-44	139
4.43	CVN-Impact and PCI Transition Curves for A514-F Heat-Slab 1017-62	140
4.44	CVN-Impact and PCI Transition Curves for A514-F Heat-Slab 1014-02	141
4.45	CVN-Impact and PCI Transition Curves for A514-H Heat-Slab 1019-31	142
4.46	CVN-Impact and PCI Transition Curves for A517-H Heat-Slab 1024-94	143
4.47	Reinforcement of the Energy-Temperature Plot with Lateral Expansion in A517-F Plates A and B	144
4.48	Upper-Shelf CVN-Impact Estimate of K_{IC} Fracture Toughness (<u>solid</u> symbols are ASTM E399 valid K_{IC} values; open symbols are CVN- K_{IC} estimated values)	148

LIST OF FIGURES (Continued)

<u>Figure</u>		<u>Page</u>
4.49	Transition - Range CVN-Impact Correlation with Static Compact Tension K_{IC} Test Results (valid K_{IC} data from Table 4.9)	150
4.50	Transition - Range Precrack Charpy Impact Correlation with ASTM E399 Valid K_{IC} Data (valid K_{IC} data from Table 4.9)	152
4.51	CVN-Impact Requirement at 0°F for Through-Thickness Yielding Based on the U.S.Steel Transition Temperature CVN- K_{IC} Correlation (Equation 4.12)	156
4.52	CVN-Impact Requirements at 0°F for Through-Thickness Yielding Based on the Upper-Shelf Correlation (Equation 4.3) and the Transition-Range Correlation (Equation 4.12-dashed lines)	158
4.53	PCI Requirements at 0°F for Through-Thickness Yielding Based on the Precrack Charpy Impact PCI- K_{IC} Correlation (Equation 4.13)	160
4.54	PCI Transition Curve for the Quarter-Point Position in A517-F Plate A	162
4.55	PCI Transition Curve for the Quarter-Point Position in A517-F Plate B	163
4.56	PCI Transition Curve for the Quarter-Point Position in A517-H Plate AL	164
4.57	PCI Transition Curve for the Quarter-Point Position in A517-H Plate Y	165
4.58	PCI Transition Curve for the Quarter-Point Position in A517-H Plate Z	166
4.59	CVN-Impact and PCI Transition Curves for the Surface, Midthickness and 1/4 Point Positions in A517-H Plate AL	168
4.60	Histogram of CVN-Impact Energy Values from 74 Slabs Tested at +20°F	171
4.61	Histogram of CVN-Impact Energy Values from 20 A514/517 Grade-H Slabs and 53 A514/517 Grade-F Slabs Tested at +20°F	173

LIST OF FIGURES (Continued)

<u>Figure</u>		<u>Page</u>
4.62	Histogram of CVN-Impact Lateral Expansion Values from 20 A514/517 Grade-H Slabs and 53 A514/517 Grade-F Slabs Tested at +20°F	175
4.63	Histogram for CVN-Impact Energy Values from 25 A514/517 Grade-H Slabs and 32 A514/517 Grade-F Slabs Tested at 0°F	176
4.64	Histogram for CVN-Impact Lateral Expansion Values from 25 A514/517 Grade-H Slabs and 32 A514/517 Grade-F Slabs Tested at 0°F	177
4.65	Histogram for CVN-Impact Energy Values from 25 A514/517 Grade-H Slabs and 34 A514/517 Grade-F Slabs Tested at -40°F	178
4.66	Histogram for CVN-Impact Lateral Expansion Values from 25 A514/517 Grade-H Slabs and 34 A514/517 Grade-F Slabs Tested at -40°F	179
4.67	Histogram for CVN-Impact Energy Values from 29 A517 Grade-F Slabs of Heat 1006 Tested at +20°F	181
4.68	Histogram for CVN-Impact Lateral Expansion Values from 29 A517 Grade-F Slabs of Heat 1006 Tested at +20°F	182
4.69	Histogram for CVN-Impact Energy Values from 27 A517 Grade-F Slabs of Heat 1006 Tested by The Steel Producer at Minus 50°F	183
4.70	Static Compact-Tension and Precrack Charpy Impact Test Results for A517-F Plate A	197
4.71	Static Compact-Tension and Precrack Charpy Impact Test Results for A517-H Plate AL	198
4.72	Static Compact-Tension and Precrack Charpy Impact Test Results for A514-F Plate L	199
4.73	Static Compact-Tension and Precrack Charpy Impact Test Results for A514-F Plate M	200

LIST OF FIGURES (Continued)

<u>Figure</u>		<u>Page</u>
4.74	Static Compact-Tension and Precrack Charpy Impact Test Results for A517-H Plate CK-1	201
4.75	Static Compact-Tension and Precrack Charpy Impact Test Results for A514-H Plate R	202
4.76	Static Compact-Tension and Precrack Charpy Impact Test Results for A517-H Plate Z	203
4.76.1	Compact Tension Test Results Showing Scatter Produced by Deviating from ASTM E399 Test Requirement - Plates Z and L	209
4.76.2	Compact Tension Test Results Showing Scatter Produced by Deviating from ASTM E399 Test Requirement - Plates AL and R	210
4.77	Static Compact-Tension Test Results for A517 Grade-H Plates CK-1 and CK-2 from Heat/Slab 1027-44	215
4.78	Schematic Representation of Fatigue-Crack Growth in Steel (Reference 46)	218
4.79	Log-Log dA/dN vs ΔK Plots for Two 1-inch-WOL Fatigue Crack Growth Rate Tests of Each of Two Plates - A517-F Plate D and A517-H Plate CK Tested at 45 ksi Maximum Stress and a 0.73 Stress Ratio	220
4.79.1	Computer Plotted Curves Showing Fatigue Life of an Edge Cracked 30" Wide Flange with $R = 33 \text{ ksi}/45 \text{ ksi}$	224
4.79.2	Computer Plotted Curves Showing Fatigue Life of an Edge Cracked 30" Wide Flange with $R = 27 \text{ ksi}/39 \text{ ksi}$	225
4.79.3	Computer Plotted Curves Showing Fatigue Life of an Edge Cracked 30" Wide Flange with $R = 33 \text{ ksi}/39 \text{ ksi}$	226
4.80	Dynamic Tear Test Results from A517 Grade-H Heat 1027/44 CK for Surface and Midthickness Positions	232
4.81	Force-Time Traces Corresponding to Selected Temperatures in Figure 4.80 Midthickness Position	234

LIST OF FIGURES (Continued)

<u>Figure</u>		<u>Page</u>
4.82	Dynamic Tear and Precrack Charpy Impact Test Results from Two Heats of A517 Grade-F Steel By Different Melting Practices	237
4.83	Dynamic-Tear-Test Force-Time Traces of A517 Grade-F Plate A	238
4.84	Dynamic Tear and Precrack Charpy Impact Test Results from A517 Grade-H Heat 1024/44 CK	239
4.85	Dynamic Tear and Precrack Charpy Impact Test Results from A517 Grade-H Heat 1020/46 AL	240
4.86	Dynamic Tear and Precrack Charpy Impact Test Results from A517 Grade-H Heat 1024/91Y	241
4.87	Summary of Dynamic Tear Test Results on Selected Heats of A514/517 Steel with ASTM E208 NDT Temperatures Indicated	242
4.88	ASTM E208 Drop-Weight NDT Temperature Test Results for A517 Grade-F Plates of Two Melting Practices and Bryte Bend Bridge Casualty Plate A517 Grade-H Heat 1027/44 CK	248
4.89	ASTM E208 Drop-Weight NDT Temperature Test Results for A517 Grade-H Plates Y and AL	249
4.90	Specimen Positions Relative to Hardness and Microstructure in Plate-A Thickness	252
4.91	E208 NDT Specimens Heat Tinted and Broken Apart to Show the Extent of Fracture in the NDT Testing (The E208 NDT Temperature was 0°F)	255
4.92	Crack Arrest in the Weld Heat-Affected Zone of Plate A ASTM E208 NDT Test of Specimen A-5	256
4.93	Fracture Surface in 2 inch Compact Tension Specimen from Plate AL	258
4.94	Fracture Surfaces in 2 inch Compact Tension Specimens from Plates R, M, L, Z, AL and A	259