C

Technical Report Documentation Page

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

7. Author(s)

Hartbower, C.E. and Sunbury, R.D.

8. Performing Organization Report No.

9. Performing Organization Name and Address

Office of Research and Development
Division of Structures
California Department of Transportation
Sacramento, California 95807

10. Work Unit No. (TRAIS) FCP 35F2-142

11. Contract or Grant No. DOT-FH-11-8250 (T.O.7)

12. Sponsoring Agency Name and Address

Office of Research and Development
Federal Highway Administration
U. S. Department of Transportation
Washington, D.C. 20590

13. Type of Report and Period Covered Final Report

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.

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 (14.4C). 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 Transporaation. 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 (0C)). In 1974, AASHTO adopted a Charpy V-notch impact test requirement for A514 steel of 25 ft-lb (33.9J) at 30°F (-1.1C) for service involving ambient temperatures down to 0°F (-17.8C). 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/m^2) 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 $0^{o}F$ (-17.8C), 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.,

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

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 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 realsitic 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 ksi-in.$^{1/2}$ (54.95 to 109.9MNm$^{-3/2}$). 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 (16.7C) 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.$^{1/2}$ (109.9MNm$^{-3/2}$). 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 (-40C) 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 ksi-in.$^{1/2}$ (16.48MNm$^{-3/2}$) with a maximum stress (39 ksi) (268.895MN/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 (379.212MN/m^2); most research has been performed with much lower maximum stress and lower stress ratios, even though most bridges with 100-ksi (689.476MN/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) +20°F (a)	0°F (b)	-30°F (b)	25 FT-LB TT (c)	LAT. EXPANS at LAST (d)
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.

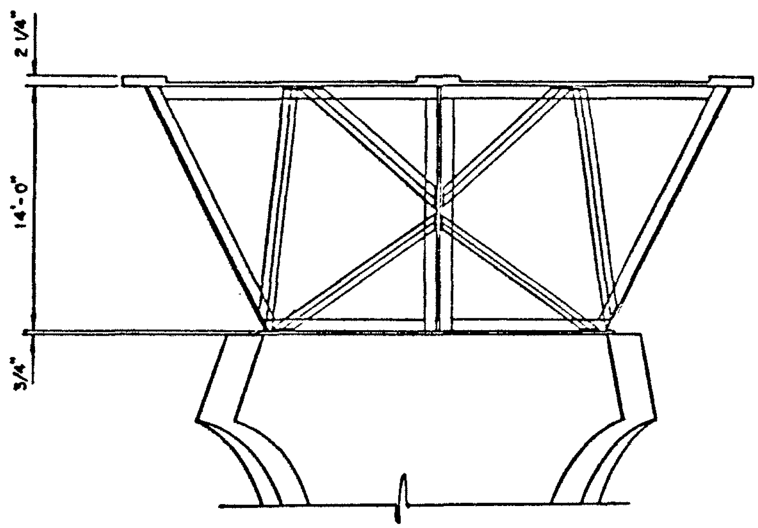
(d) Lateral expansion values at the lowest anticipated service temperature (LAST) correspond to the ft-lb values reported to the 1st decimal place. Thus, the lateral expansion value for plate AM was the average of three tests at +20°F whereas the value for plate G was the average of three tests at 0°F.

(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.

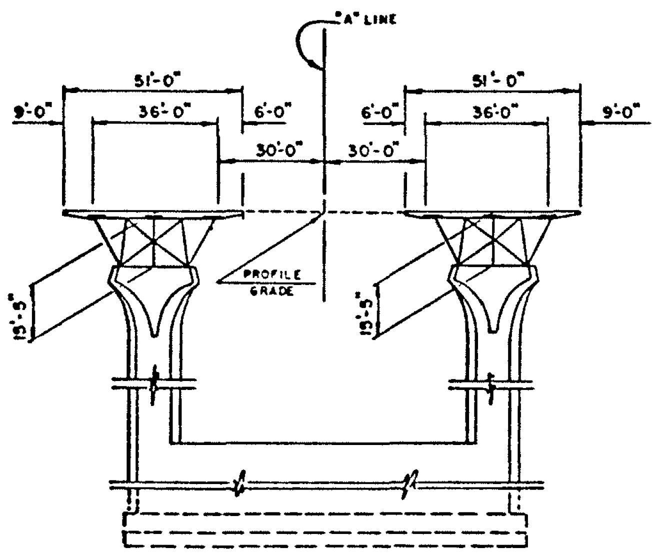
(f) Average CVN-impact value (ft-lb) of 81 tests made by the steel producers at -50°F.

Conversion Factors:

in. x 25.	=	mm
5/9 (°F - 32)	=	°C
ft-lb x 1 [illegible]6	=	J
mil x 0.0[illegible]4	=	mm

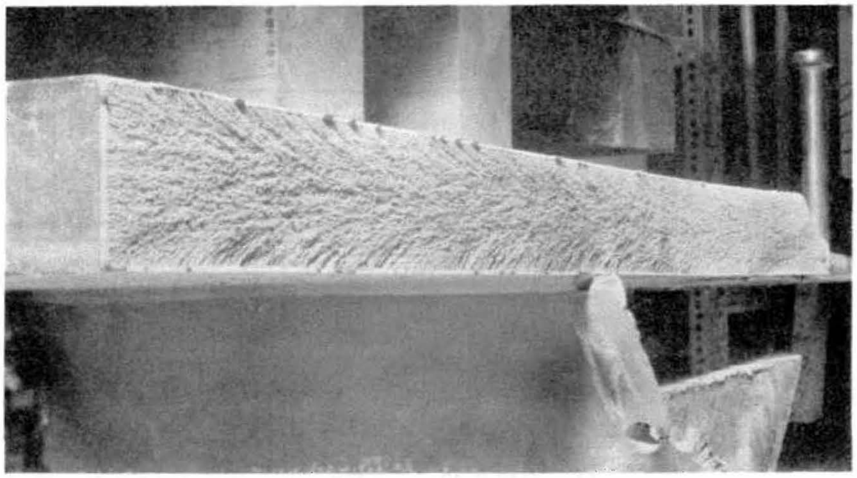


TYPICAL SECTION OF STEEL BOX GIRDERS

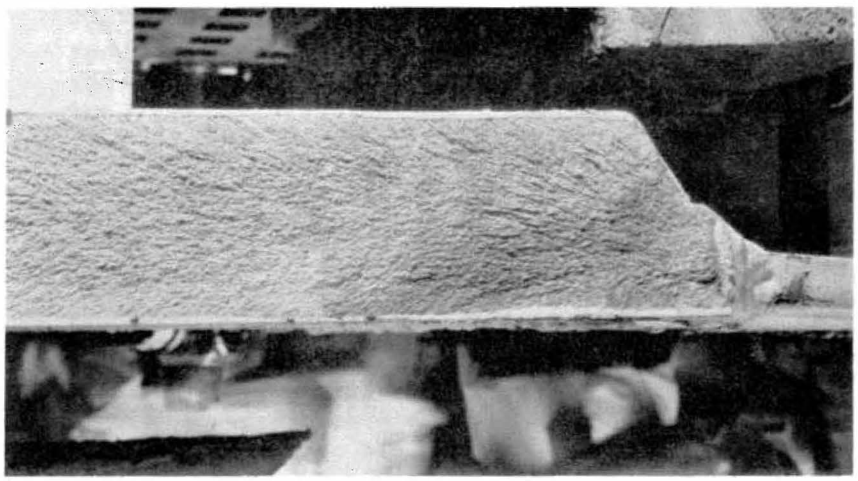


TYPICAL SECTION AT PIERS 12, 13 & 14

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

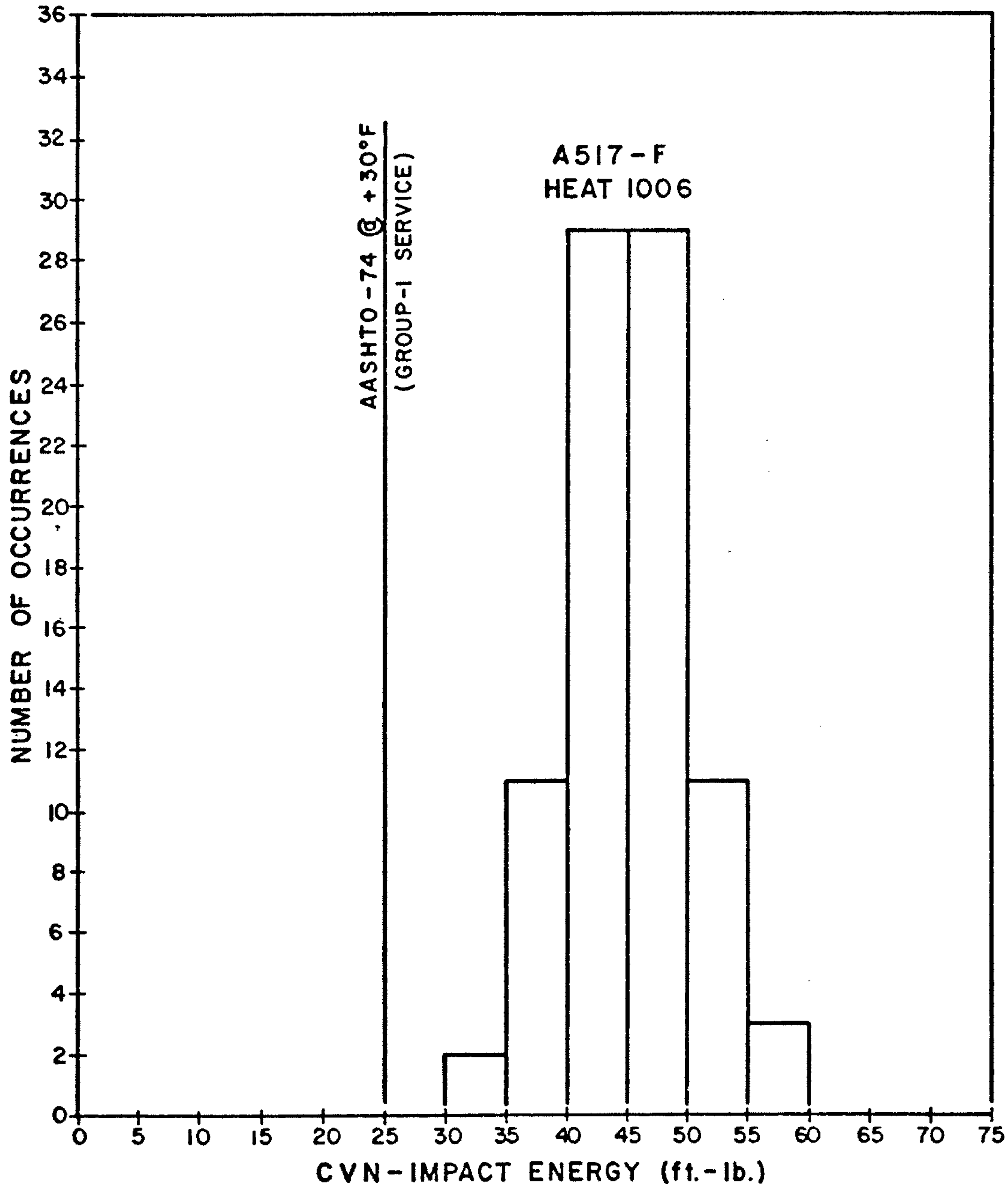


Figure 3 - Histogram of CVN-Impact Energy Values from 29 A517 Grade-F Slabs from Heat 1006 Tested at +20°F

ft-lb x 1.356 = J

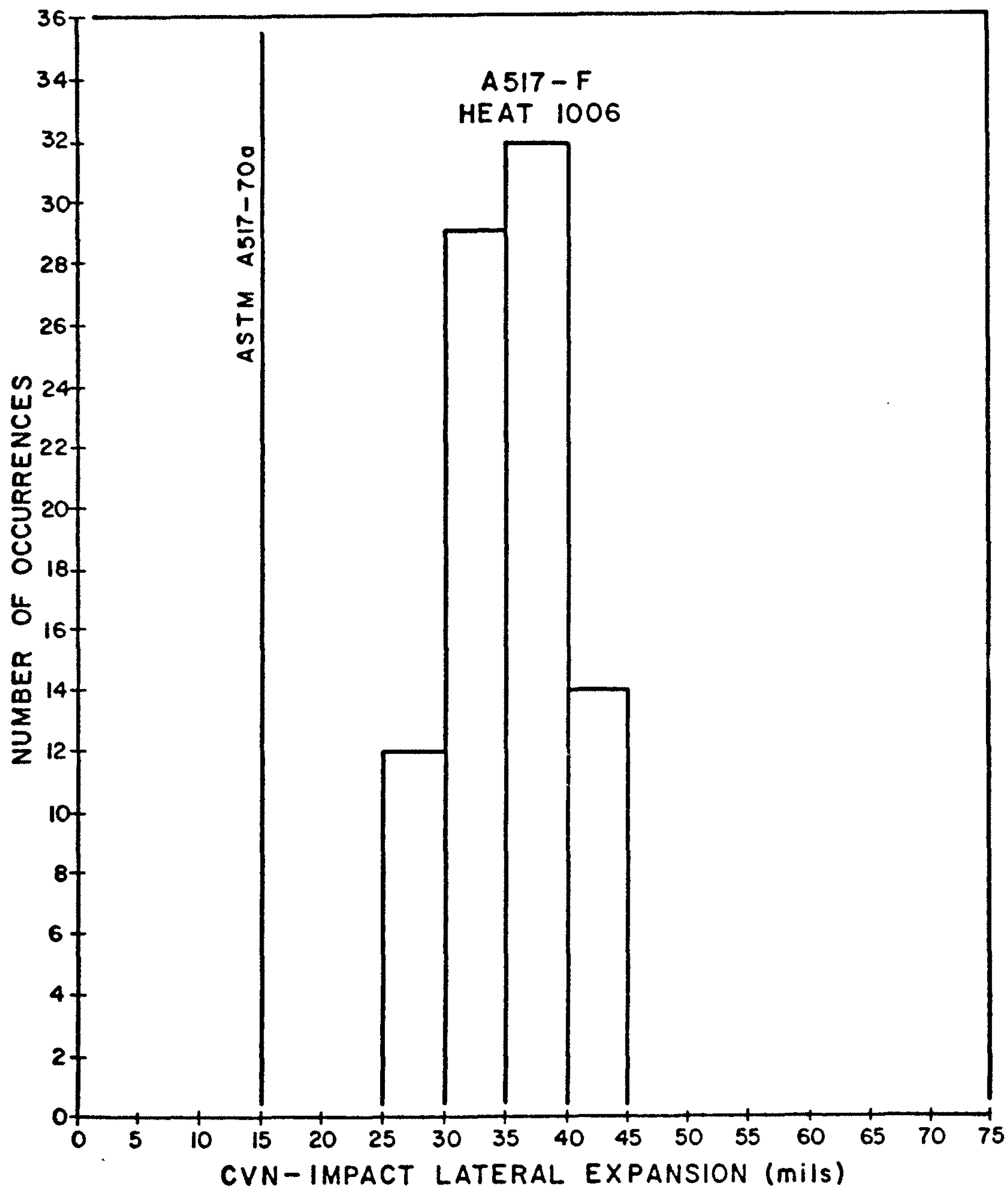


Figure 4 - Histogram of CVN-Impact Lateral Expansion Values from 29 A517 Grade-F Slabs from Heat 1006 Tested at +20°F

mil x 0.0254 = mm

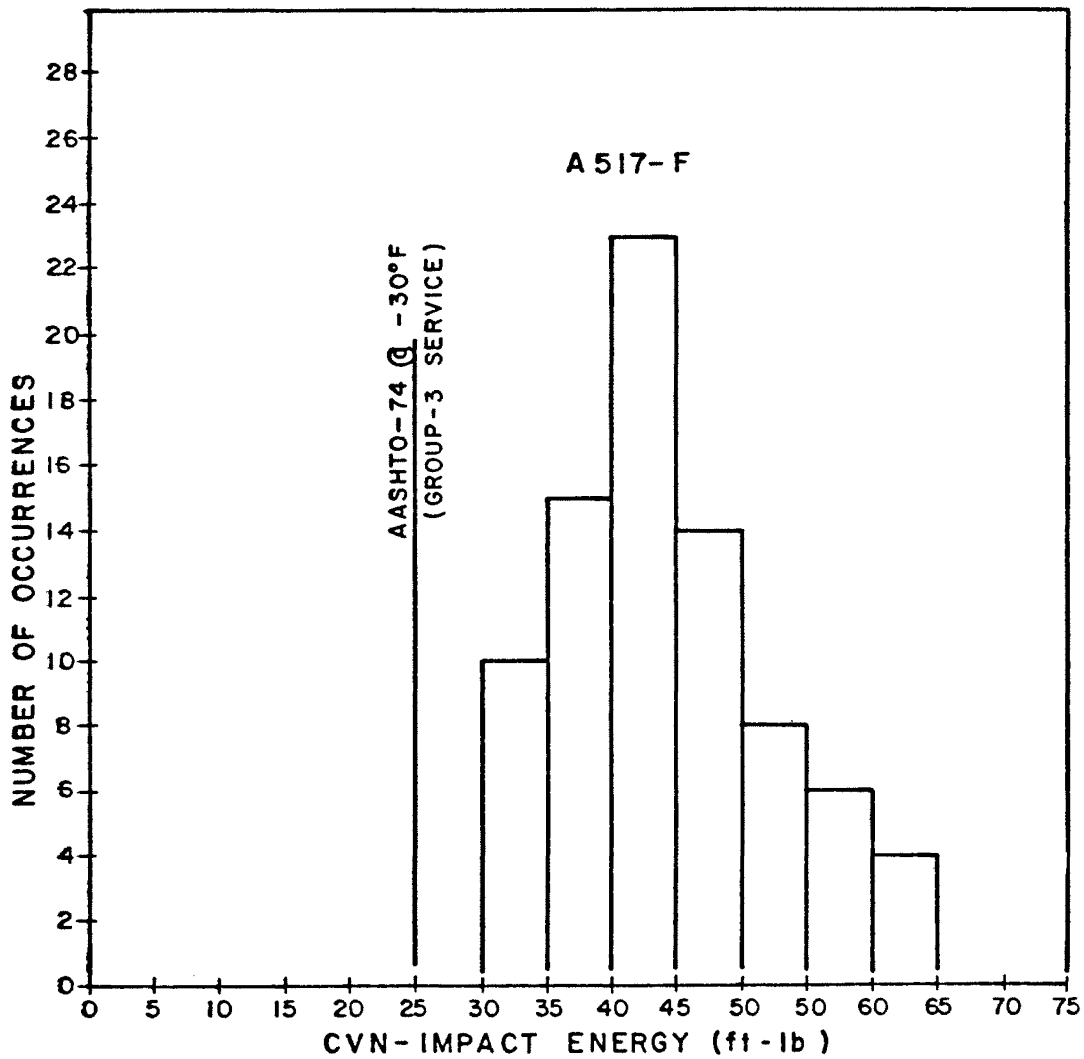


Figure 5 - Histogram of CVN-Impact Energy Values from 27 A517 Grade-F Slabs from Heat 1006 Tested by the Steel Producer at -50°F

ft-lb x 1.356 = J

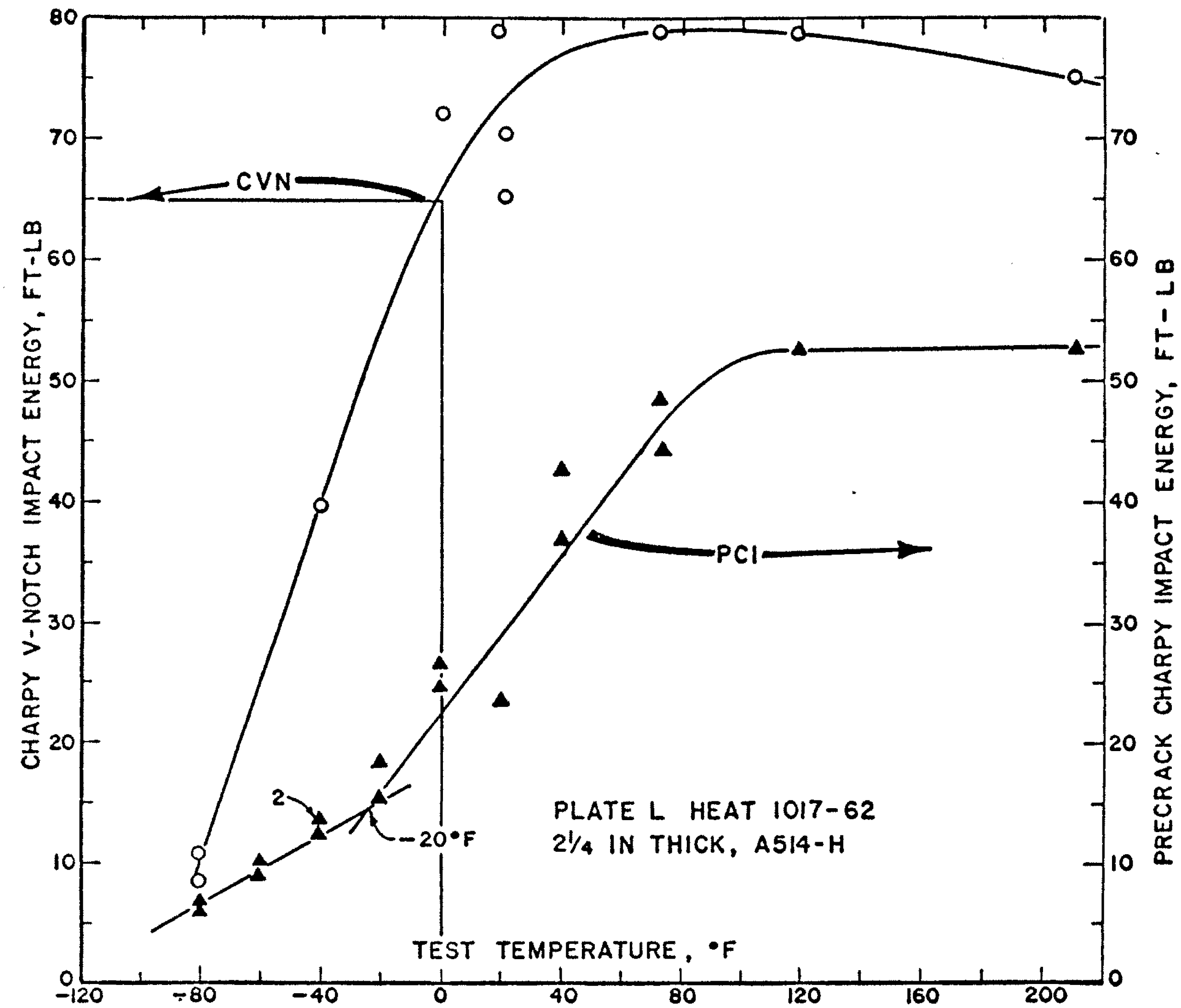


Figure 6 - CVN-Impact and Precrack Charpy Impact Transition Curves for A514 Grade-F Heat 1017-62

ft-lb x 1.356 = J

5/9(F-32) = C

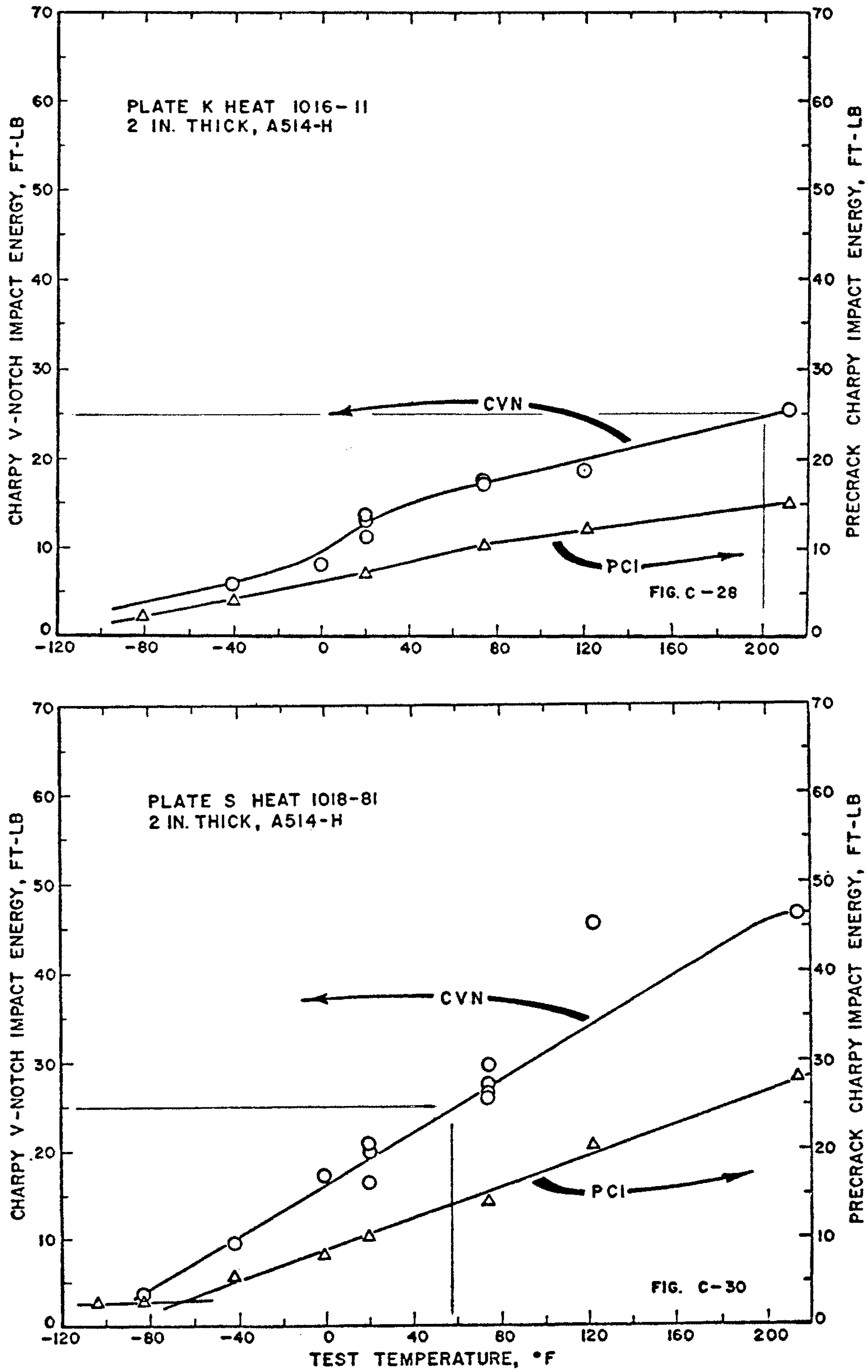
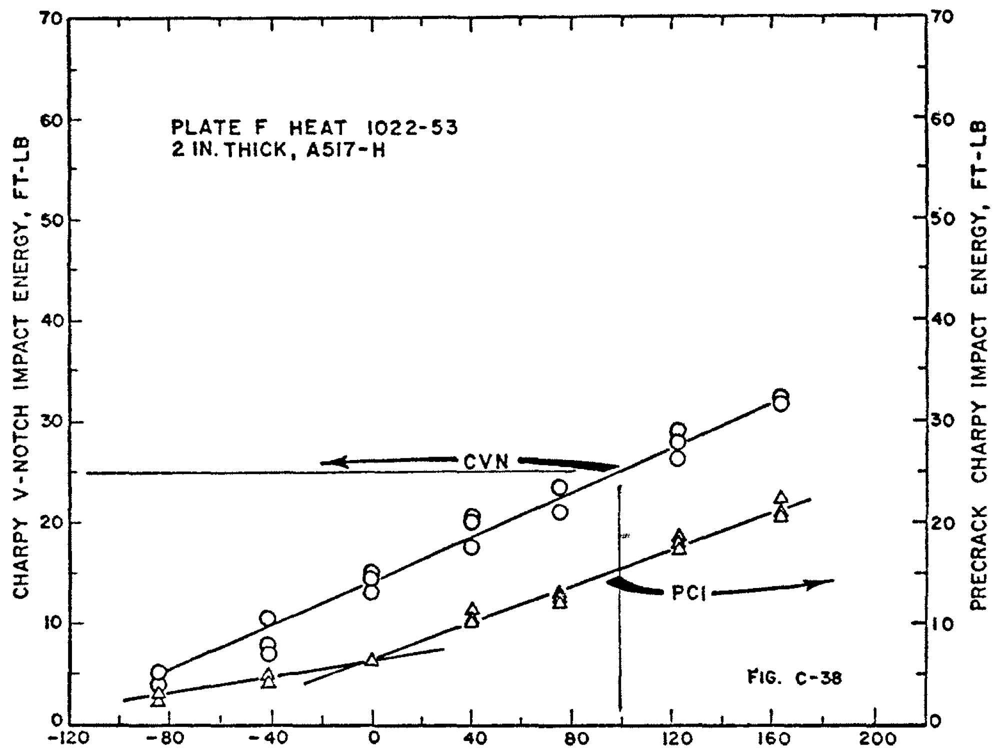


Figure 7 - Two-Inch-Thick ASTM A514 Grade-H Steel, Open-Hearth Practice

ft-lb x 1.356 = J

5/9(F-32) = C

in. x 25.4 = mm



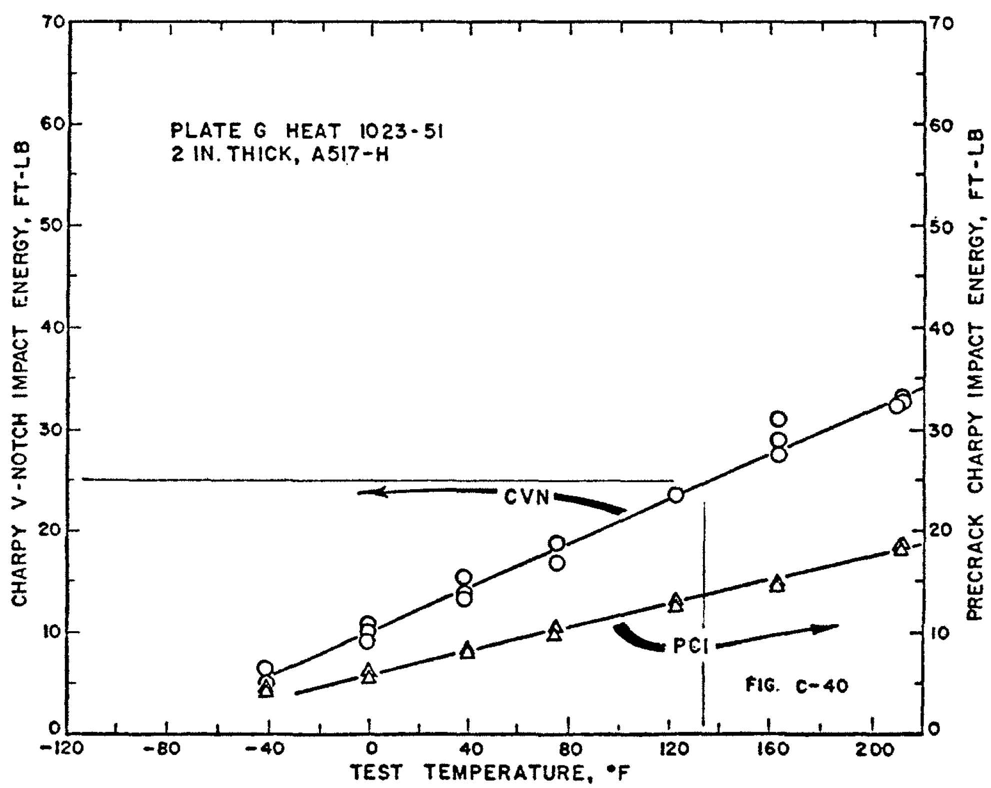


Figure 8 - Two-Inch-Thick ASTM A517 Grade-H Steel, Electric-Furnace Practice

ft-lb x 1.356 = J

5/9(F-32) = C

in. x 25.4 = mm

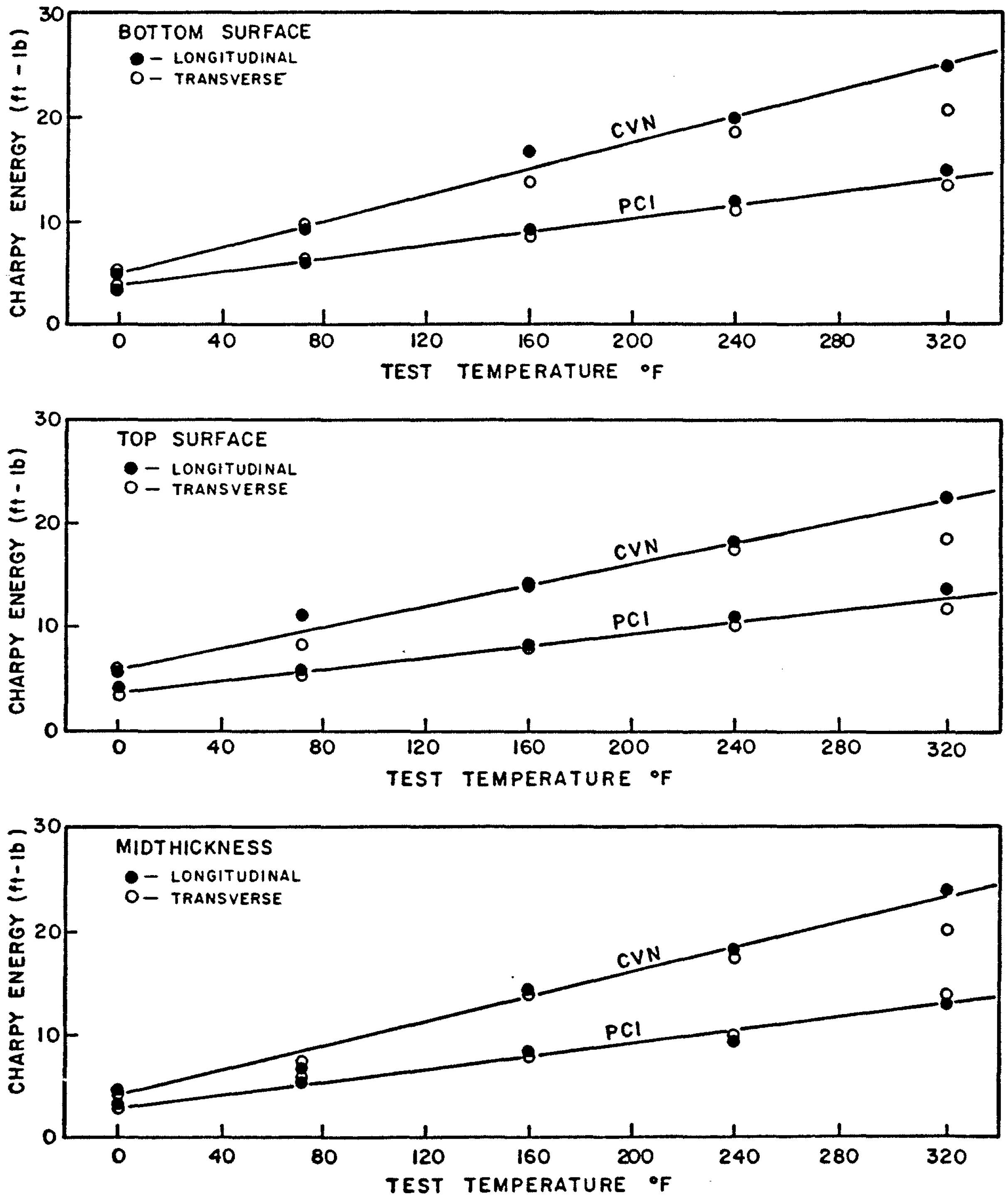


Figure 9 - CVN-Impact and Precrack Charpy Impact Transition Curves for A517 Grade-H Heat 1027-44CK Which Fractured in the Bryte Bend Bridge

ft-lb x 1.356 = J
5/9(F-32) = C

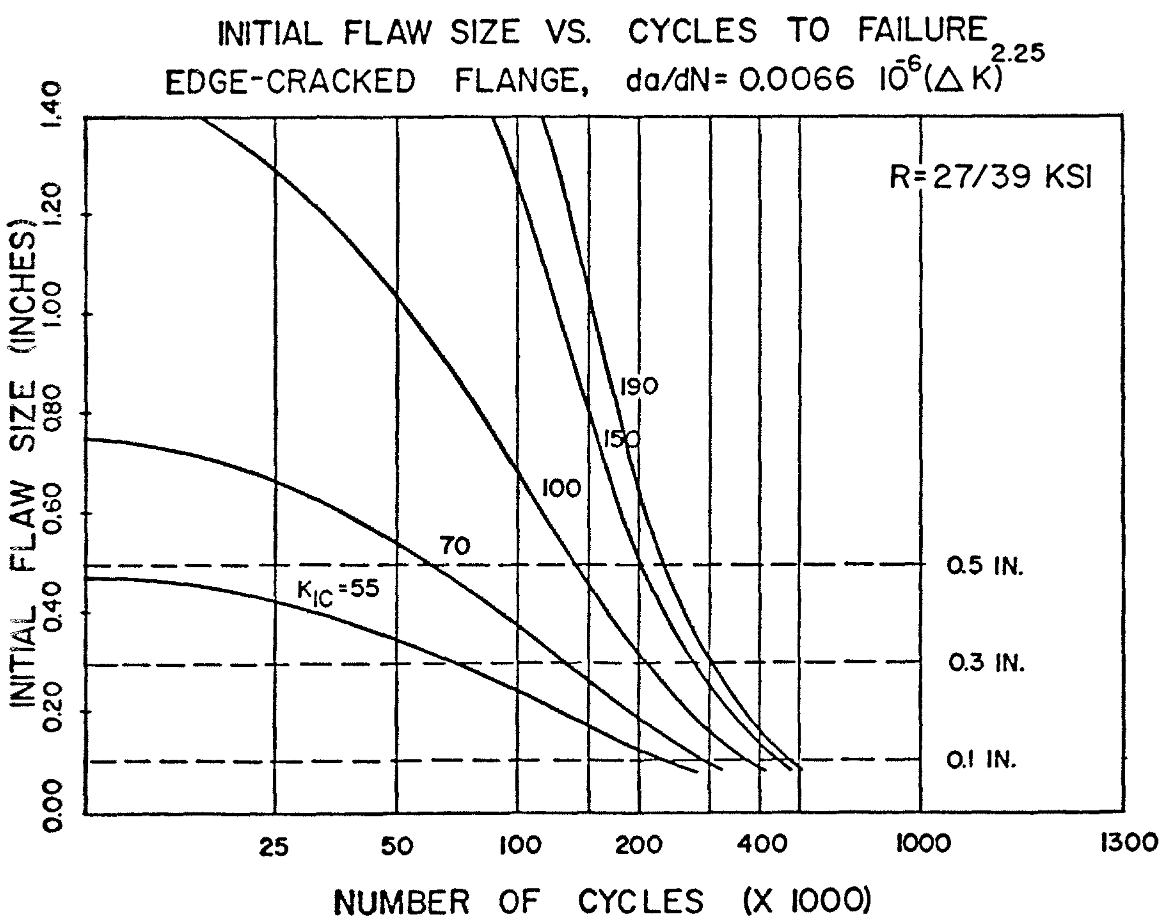


Figure 10 - Computer-Plotted Curves Providing and Estimate of Fatigue Life in an Edge-Cracked, 30-inch-wide Flange Subjected to a Stress Ratio of 27/39 ksi (R=0.7)

ksi x 6.895 = MN/m^2

ksi-in.$^{1/2}$ x 1.099 = $MNm^{-3/2}$

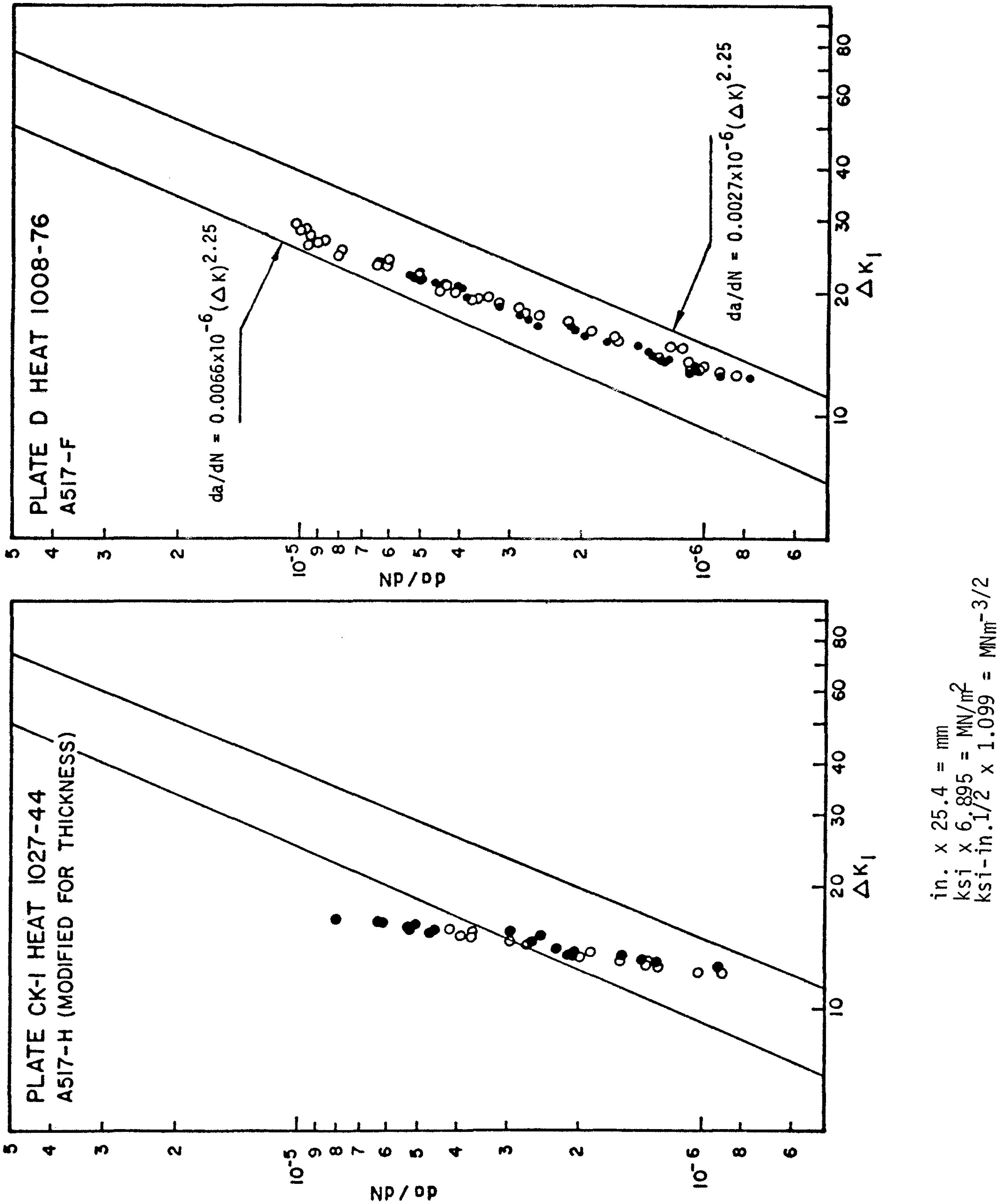


Figure 11 - Fatigue-Crack Growth-Rate Tests of A517 Grade-F Plate D and A517 Grade-H Plate CK Tested at 45 ksi Maximum Stress and R-0.7 (bands correspond to martensitic-steel data collected by Barsom).

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

TABLE OF CONTENTS (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF TABLES (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)