Glossary of Symbols

CCT = Center-cracked tension specimen.
CLWL = Crack-line wedge-loaded specimen.
COS = Crack-opening stretch.
CT = Compact-tension specimen.
CVN = Charpy V-notch specimen.
EDM = Electrical-discharge-machine process.
LEFM = Linear-elastic fracture mechanics.
PTC = Partial-thickness-crack specimen.
RD = Rolling direction.
L-T = Orientation of full-thickness crack stressed parallel to RD and propagating perpendicular to RD.
R-curve = Plot of K_R vs Δa, where $\Delta a \equiv \Delta a_{phy}$.

a = Crack length; crack depth for PTC specimen.
a_{cr} = Critical crack length for the onset of a particular event.
a_{eff} = Effective crack length, including r_p.
a_n = Machined-notch crack length.
a_o = Initial crack length.
a_{phy} = Physical or actual crack length.
a_{act} = Actual or physical crack length.
Δa = Increment of crack extension.
Δa_c = Critical increment of stable crack extension at fracture instability, a property of the R-curve.
r_p = Plane-stress plastic-zone radius at the crack tip.
r_{Ip} = Plane-strain plastic-zone radius at the crack tip.
h = Hinge point, a distance measured from the load line, P.

B = Specimen thickness.
J-Integral = Path-independent integral of plastic strain-energy density surrounding the crack tip.
J_{Ic} = Critical J_I value at fracture under plane-strain conditions (analogous to G).
E = Modulus of elasticity.
G = Crack-extension force or strain-energy release rate.
G_R = Resistance to crack extension measured in terms of G.
H = One half of CT specimen height.
K = Stress-intensity factor.
K_c = Critical K value at fracture under plane-stress conditions.
K_I = Applied K value under opening-mode (Mode I) loading conditions.
K_{Ic} = Critical K_I value at fracture under plane-strain conditions.

K_{Icr} = A general critical K_I value corresponding to the onset of a specific event (K_c, K_{Ic}, K_{Id}, K_{Iscc}, etc.).

K_{Id} = Value of K_{Ic} measured under dynamic or impact loading conditions.

$K_{I,Gub}$ = Greatest-upper-bound K_I value for plane-strain conditions.

$K_{I,Lub}$ = Least-upper-bound K_I value for plane-strain conditions.

$K_{I,max}$ = Nominal K_I value at fracture calculated using initial crack length (a_o) and maximum load (P_{max}) on the basis of LEFM analysis.

K_Q = Questionable or invalid K_{Ic} value based on 5 percent secant-intercept method of analysis in fracture test record.

K_R = Resistance to crack extension measured in terms of K.

$K_{R,pl}$ = Plateau value of K_R from an R-curve.

ΔK_f = Stress-intensity range used in fatigue precracking.

P = Load or force.

P_{max} = Maximum load in a fracture test.

R = Stress ratio used in fatigue precracking.

T = Temperature.

V = Crack-opening displacement measured with a clip gage.

V_1 = Value of V measured at a distance 0.1576W from the load line, P, counter to the crack extension direction.

$V_{1\ abs}$ = Absolute value of V_1.

V_2 = Value of V measured at a distance 0.303W from the load line, P, in the same direction as crack extension.

$V_{2\ abs}$ = Absolute value of V_2.

$(V_1/V_2)_s$ = Slope of V_1 vs V_2 test record measured under elastic unloading conditions.

W = Specimen width.

β = Limit of plane-strain conditions at value of $\beta = 0.4$.

δ = Crack-opening stretch or crack-tip dislocation, used interchangeably with COS.

ε = Strain.

$\dot{\varepsilon}$ = Strain rate.

ε_{zz} = Through-thickness strain.

ε_{BS} = Back-surface strain measured on the free surface opposing the crack at a location that intersects with the crack plane.

ε_{ys} = Yield strain.

ρ = Root radius of a machined notch tip.

σ = Stress; also, standard deviation in a statistical sense.

σ_D = Design stress; alternatively, the gross, uniform tension stress applied to a CCT specimen remotely.

σ_{ys} = Yield stress.

σ_{zz} = Through-thickness stress (synonymous with "constraint").

Table I

Chemical Composition of A572 Steel Tested—Percent

Yield Strength, ksi	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Ti	Al*	Al**	N***	Cb	O
50	0.21	1.20	0.010	0.023	0.24	0.026	0.014	0.029	0.010	0.049	<0.005	0.021	0.023	0.006	<0.005	0.0031
62	0.22	1.21	0.014	0.022	0.25	0.021	0.014	0.020	0.005	0.070	<0.005	0.046	0.050	0.012	<0.01	ND

* Acid-soluble.

** Total.

*** Kjeldahl determination.

ND - Not determined.

Conversion Factor:

1 ksi = 6.895 MN/m^2

Table II

Mechanical Properties of A572 Steel Tested

Yield Strength, ksi	Orientation	Yield Strength (0.2% Offset), ksi	Tensile Strength, ksi	Elongation in 1 Inch, %		Reduction of Area, %		Charpy V-Notch Energy Absorption, ft-lb		
				At Maximum Load	At Fracture	At Maximum Load	At Fracture	+70 F	+40 F	0 F
50	Longitudinal	50	83	ND	30.0	ND	69.0	38	28	4
62	Longitudinal	62	92	14.0	27.0	15.1	65.1	26	11	7
50	Transverse	50	81	ND	26.0	ND	56.3	21	14	7
62	Transverse	63.5	94	13.4	23.4	14.0	50.3	16	10	7

Conversion Factors:

1 ksi = 6.895 MN/m^2
1 inch = 25.4 mm
1 ft-lb = 1.36 J

Table III

Overall R-Curve Study

σys, ksi	Specimen Thickness, Inches	No. of Spec	Spec Type⊛	Test Temperatures⊛⊛
50	B = 1.5	3	2T	T = ⊖40 F, +40 F + +72 F
"	"	3	4T⊛⊛⊛	" " "
"	"	4	4C⊛⊛⊛	" " "
"	"	4	7C	" " "
"	B = 0.5⊛⊛⊛⊛	4	2T	" " "
"	"	4	4T	" " "
		22 Total		
62	B = 1.5	2	7C	T = ⊖40 F + +72 F
		2 Total		

⊛ 2T and 4T specimens tested under "load-control" conditions, 4C and 7C specimens tested under "displacement-control" conditions.

⊛⊛ At least one specimen for each group of 3 or 4 was tested at each of the (nominal) test temperatures cited.

⊛⊛⊛ The cited 4T and 4C specimens provided an "overlapping" condition for each of the two different test techniques.

⊛⊛⊛⊛ All B = 0.5-inch specimens were taken from that portion of the plate closest to the center after the original 1.5-inch plate thickness was split.

Table IV

Summary of Test Conditions, Specimen Measurement Capacities, and Nominal Fracture Behaviors*

Item No.	Specimen No.**	Specimen Size and Type	B,*** inches	Test Temperature, F	σ_{ys},# ksi	$K_{I,lub}$,## ksi $\sqrt{inch}$	K_{MC},### ksi $\sqrt{inch}$	K_{BSY},+ ksi $\sqrt{inch}$	P_{max}, pounds	P_{frac}, pounds	$V_{1,max}$,++ inch	$V_{1,frac}$,+++ inches	$K_{I,max}$,++++ ksi $\sqrt{inch}$
				A. Full-Thickness Specimens (B = 1-1/2 Inches) of ASTM A572 Grade 50 (σ_{ys} = 50 ksi)									
1	7-1	2T	1.5	-35	55.4	42.8	57.4	74.3	39,900	39,900	0.047	0.047	110.1
2	7-2	2T	1.5	+34	51.3	39.6	54.0	70.3	45,850	45,850	0.114	0.114	122.8
3	7-3	2T	1.5	+67	50.3	38.9	53.3	69.7	34,650	34,650	0.034	0.034	91.3
4	7-2⊛	4T	1.5	-42	55.6	43.0	89.4	121.3	88,000	88,000	0.075	0.075	143.0
5	A7-4	4C	1.5	-40	55.6	43.0	85.7	112.8	55,900[1)]	55,900[1)]	0.044	0.044	102.8
6	7-3⊛	4T	1.5	+38	51.2	39.6	83.8	114.8	114,500	114,500	0.247	0.247	180.2
7	A7-1	4C	1.5	+40	51.2	39.6	78.0	102.1	66,400[2)]	66,400[2)]	0.085	0.085	124.0
8	A7-3	4C	1.5	+40	51.2	39.6	78.3	104.5	77,400[2)]	77,400[2)]	0.126	0.126	140.1
9	7-1⊛	4T	1.5	+72	50.2	38.8	79.5	106.9	106,500	97,500	0.334	0.476	177.2
10	A7-2	4C	1.5	RT	50.2	38.8	77.0	101.2	92,900[2)]	84,400[2)]	0.155	0.273	170.5
11	A572-1	7C	1.5	-44	55.7	43.1	112.8	149.6	41,600[1)]	41,600[1)]	0.031	0.031	54.8
12	A7-3	7C	1.5	-40	55.6	43.0	112.2	147.8	73,600[1)]	73,600[1)]	0.058	0.058	102.0
13	A7-4	7C	1.5	+40	51.2	39.6	103.2	135.8	116,200[1)]	116,200[1)]	0.111	0.111	161.3
14	A572-2	7C	1.5	RT	50.2	38.8	102.3	135.2	159,300[2)]	<86,900[2)]	0.262	0.599	208.5
				B. Full-Thickness Specimens (B = 1-1/2 Inches) of ASTM A572 Processed to σ_{ys} = 62 ksi									
15	A7-1	7C	1.5	-40	67.8	52.5	136.0	178.8	80,100[1)]	80,100[1)]	0.068	0.068	113.6
16	A7-2	7C	1.5	RT	62.2	48.2	126.4	167.8	134,100[2)]	123,400[2)]	0.200	0.326	184.8
				C. Subthickness Specimens (B = 1/2 Inch) of ASTM Grade 50 (σ_{ys} = 50 ksi)									
17	7-3	2T	0.5	-32	55.3	24.7	57.4	74.4	15,200	15,150	0.158	0.202	124.5
18	7-2	2T	0.5	+32	51.3	22.9	53.9	70.2	16,200	16,150	0.192	0.222	129.8
19	7-1	2T	0.5	+32	51.3	22.9	54.0	70.3	15,750	15,400	0.198	0.258	125.8
20	7-4	2T	0.5	+66	50.3	22.5	52.3	67.8	15,300	13,700	0.193	0.329	125.3
21	7-4⊛	4T	0.5	-40	55.6	24.9	90.2	122.6	30,700	30,700	0.077	0.077	146.5
22	7-3⊛	4T	0.5	+39	51.2	22.9	82.3	111.8	37,800	37,700	0.251	0.251	182.6
23	7-2⊛	4T	0.5	+72	50.2	22.5	82.3	112.8	38,700	<10,200[3)]	0.290	>>1.527	181.00
24	7-1⊛	4T	0.5	+72	50.2	22.5	81.6	111.2	37,700	3,300[4)]	0.313	>1.748	179.3

(Continued)

Table IV (Continued)

* All specimens were of the compact-tension (CT) with (H/W) = 0.600; all 2T and 4T specimens were tested (by U. S. Steel Corporation) under load-control conditions, and all 4C and 7C specimens were tested (by Armco Steel Corporation) under displacement-control conditions.

** All specimen numbers with an "A" prefix (4C or 7C specimen types) were tested (by Armco Steel Corporation) under displacement-control. conditions.

*** Nominal specimen thickness -

\# σ_{ys} = yield-strength (0.2% offset) values interpolated at the test temperatures shown using actual measurements made (as a function of temperature) under "static" test conditions ($\dot{\varepsilon} \cong 10^{-5}$ sec^{-1}).

\#\# $K_{I,lub}$ = plane-strain measurement capacity (least-upper-bound), given as: $K_{I,lub} = \sigma_{ys}\left(\frac{B}{2.50}\right)^{1/2}$.

\#\#\# K_{MC} = plane-stress measurement capacity (first conservative value - corresponding to $\sigma_N = \sigma_{ys}$ at the crack tip), given as:

$$K_{MC} = \sigma_{ys} \cdot W^{1/2}\left(\frac{f(X)\ (1-X)^2}{2(2+X)}\right) \text{ where } X = \left(\frac{a}{W}\right) \text{ and } f(X) = f\left(\frac{a}{W}\right) \text{ for the CT specimen.}$$

\+ K_{BSY} = plane-stress measurement capacity (second conservative value - corresponding to $\sigma_N = \sigma_{ys}$ at the back surface), given as:

$$K_{BSY} = -\sigma_{ys} \cdot W^{1/2}\left(\frac{f(X)\ (1-X)^2}{2(1+2X)}\right) \text{ where } X = \left(\frac{a}{W}\right) \text{ and } f(X) = f\left(\frac{a}{W}\right) \text{ for the CT specimen.}$$

\+\+ $V_{1,max} = V_1$ value at maximum load (@ $P = P_{max}$) in the P-V_1 record.

\+\+\+ $V_{1,frac} = V_1$ value at the unstable fracture load (@ $P = P_{frac}$) in the P-V_1 test record.

Note: The V_1 values for each of the two previous footnotes were either measured directly (in the case of the 10 4C and 7C specimens tested under deflection-control conditions) or interpolated values calculated assuming "rigid-body behavior" between the V_1 and V_2 (measured) clip-gage values (in the case of the 14 2T and 4T specimens tested under load-control conditions).

\+\+\+\+ $K_{I,max}$ = nominal K_I value at maximum load ($P = P_{max}$), calculated on the basis of the original specimen dimensions without any corrections to the original (physical) crack length (a_o) for plasticity (r_p) or stable crack extension (Δa), given as:

$$K_I = \left[\frac{P \cdot f\left(\frac{a}{W}\right)}{B \cdot W^{1/2}}\right]$$

@ Specimen was tested using the "load-total unload" procedure, with various physical measurements of the specimen being made intermediately under no-load (P = 0) conditions (U. S. Steel procedure).

1) Load, P, was calculated using a_{eff} [based on $\left(\frac{V_{1abs}}{V_{2abs}}\right)$ ratio] and the single-compliance calibration relationship $\left[\left(\frac{EBV_1}{P}\right) \text{ vs } \left(\frac{a}{W}\right)\right]$.

2) Load, P, was calculated indirectly using a_{eff} and K_R in combination with the elastic stress-intensity relationship, $K_I = \left[\frac{P \cdot f\left(\frac{a}{W}\right)}{B \cdot W^{1/2}}\right]$.

The a_{eff} value was calculated using the double-compliance calibration relationship $\left[\left(\frac{V_1}{V_2}\right) \text{ vs } \left(\frac{a}{W}\right)\right]$ as $a_{eff} = a_{phy} + A\left(\frac{K_R}{\sigma_{ys}}\right)^2$, where A is a constant determined at $\varepsilon_{BS} \cong \varepsilon_{ys}$ - that is, when a_{eff} and a_{phy} are both known simultaneously with the use of the $\left(\frac{V_{1abs}}{V_{2abs}}\right)$ and $\left(\frac{V_1}{V_2}\right)_s$ ratios, respectively, This indirect (and approximate) method is necessary since a_{eff} cannot be determined directly using $\left(\frac{V_{1abs}}{V_{2abs}}\right)$ for $\varepsilon_{BS} >> \varepsilon_{ys}$.

(Continued)

Table IV (Continued)

3) $P_{frac} \cong 6{,}200$ pounds, which occurred under increasing test-machine crosshead velocity and therefore at a crack-tip strain rate which is more rapid than that for "static" testing ($\dot{\varepsilon} >> 10^{-5}$ sec^{-1}).

4) $P_{frac} = 3{,}300$ pounds, which occurred under increasing test-machine crosshead velocity and therefore at a crack-tip strain rate which is more rapid than that for "static" testing ($\dot{\varepsilon} >> 10^{-5}$ sec^{-1}).

Conversion Factors:

1 inch = 25.4 mm
F = 9/5 C + 32
1 ksi = 6.895 MN/m^2
1 ksi $\sqrt{inch}$ = 1.099 $MNm^{-3/2}$
1 pound = 4.448 N

Table V

Summary of R-Curve and K_c Test Results for ASTM A572 Steels*

Item No.	Specimen No.	Specimen Size and Type	B,** inches	Test Temperature, F	Specimens Tested Under Load Control*** Meas a_o, inches	DC a_o, inches	Mismatch Δa, inch	Specimens Tested Under Deflection-Control*** Meas a_o, inches	DC a_o, inches	Mismatch Δa, inch	$K_{R,max}$,# ksi $\sqrt{inch}$	Analysis Technique for Calc of $K_{R,max}$	Δa_{max},## inches	K_c,### ksi $\sqrt{inch}$
				A. Full-Thickness Specimens (B = 1-1/2 Inches) of ASTM A572 Grade 50 (σ_{ys} = 50 ksi)										
1	7-1	2T	1.5	-35	1.784	1.720	-0.064	-	-	-	115.7	COS	0.044	116
2	7-2	2T	1.5	+34	1.739	1.728	-0.011	-	-	-	216.4	COS	0.034	216
3	7-3	2T	1.5	+67	1.714	1.603+	-0.111	-	-	-	87.4++	COS	0	>87++
4	7-2	4T	1.5	-42	2.988	2.797	-0.191	-	-	-	154.1	COS	0	154
5	A7-4	4C	1.5	-40	-	-	-	3.450	3.370	-0.080	101.9	LEFM	0	102
6	7-3	4T	1.5	+38	2.887	2.706	-0.181	-	-	-	313.7	COS	0.128	314
7	A7-1	4C	1.5	+40	-	-	-	3.530	3.440	-0.090	154.6	COS	0.020	155
8	A7-3	4C	1.5	+40	-	-	-	3.430	3.440	0.010	194.5	COS	0.125	195
9	7-1	4T	1.5	+72	3.077	2.894	-0.183	-	-	-	445.0	COS	0.477	445
10	A7-2	4C	1.5	RT	-	-	-	3.480	3.430	-0.050	318.3	COS	0.250	318
11	A572-1	7C	1.5	-44	-	-	-	5.750	5.750	0	56.8	LEFM	0	57
12	A7-3	7C	1.5	-40	-	-	-	5.830	5.730	-0.100	103.4	LEFM	0.020	103
13	A7-4	7C	1.5	+40	-	-	-	5.840	5.910	0.070	190.5	LEFM	0.120	191
14	A572-2	7C	1.5	RT	-	-	-	5.720	5.720	0	>477.3+++	COS	>0.868+++	>477+++
				B. Full-Thickness Specimens (B = 1-1/2 Inches) of ASTM A572 Processed to σ_{ys} = 62 ksi										
15	A7-1	7C	1.5	-40	-	-	-	5.860	5.820	-0.040	121.4	LEFM	0.030	121
16	A7-2	7C	1.5	RT	-	-	-	5.720	5.740	0.020	364.5	COS	0.480	365
				C. Subthickness Specimens (B = 1/2 Inch) of ASTM A572 Grade 50 (σ_{ys} = 50 ksi)										
17	7-3	2T	0.5	-32	1.775	1.895	0.120	-	-	-	315.5	COS	0	316
18	7-2	2T	0.5	+32	1.738	1.775	0.037	-	-	-	273.0	COS	0.127	273
19	7-1	2T	0.5	+32	1.735	1.838	0.103	-	-	-	312.6	COS	0.105	313
20	7-4	2T	0.5	+66	1.773	1.612	-0.161	-	-	-	308.4	COS	0.399	308
21	7-4	4T	0.5	-40	2.945	2.786	-0.159	-	-	-	149.6	COS	0.023	150
22	7-3	4T	0.5	+39	2.976	2.771	-0.205	-	-	-	304.8	COS	0.216	305
23	7-2	4T	0.5	+72	2.871	2.726	-0.145	-	-	-	>502.8	COS	>1.430	>503
24	7-1	4T	0.5	+72	2.933	2.773	-0.160	-	-	-	>379.6	COS	>0.922	>380

(Continued)

Table V (Continued)

* All specimens were of the compact-tension (CT) type [with (H/W) = 0.600] and were of the same RW crack orientation (a through-thickness crack subjected to stresses parallel to the rolling direction, R, and propagating across the orthogonal plate width direction, W). In addition, all specimens were tested under "static" crack-tip strain-rate conditions ($\dot{\varepsilon} = 10^{-4}$ to 10^{-5} sec^{-1}); the 2T and 4T specimens were tested under load-control conditions, and all 4C and 7C specimens were tested under deflection-control conditions.

** Nominal specimen thickness - see Table III for precise specimen measurements (W, 2H, B and a).

*** Meas a_o = initial specimen fatigue-crack length obtained as the average of physical measurements made through the specimen thickness.

DC a_o = initial specimen fatigue-crack length obtained from the Double-Compliance (DC) procedure using the initial $\left(\frac{V_1}{V_2}\right)_s$ ratio.

Mismatch Δa = the numerical difference between the Meas a_o and DC a_o values.

\# $K_{R,max}$ = the highest K_R value obtained in the test prior to catastrophic crack extension and calculated using either the COS or LEFM analysis technique listed in the next column; in the COS technique, the $K_{R,max}$ value was calculated using the final $\left(\frac{V_1}{V_2}\right)_s$ ratio prior to fracture.

\#\# Δa_{max} = the amount of stable crack extension occurring in the test prior to catastrophic extension of the crack at the $K_{R,max}$ value; thus, $\Delta a_{max} = a_f - a_o$, where a_o and a_f are the initial and final a_{phy} values, respectively, determined using the initial and final $(V_1/V_2)_s$ ratios in combination with the double-compliance (DC) calibration relationship

$$\left[\left(\frac{V_1}{V_2}\right) vs \left(\frac{a}{W}\right)\right].$$

\#\#\# K_c = the K_c value observed at instability for the specified test conditions (including T, $\dot{\varepsilon}$, B, and a_o).

\+ Estimated value only - due to premature fracture prior to the scheduled first unloading step.

\+\+ Value based on an estimated $(V_1/V_2)_s$ ratio - an approximation necessary due to premature fracture prior to the scheduled first unloading step. Premature fracture resulted in part from a more rapid crack-tip strain rate ($\dot{\varepsilon}$) than normal for "static" loading; thus, the K_c value observed is much lower than would be expected normally on account of a slightly cooler temperature (67 F compared with 72 F) and a shorter crack length (2T specimen with a_o = 1.714 inches).

\+\+\+ The $K_{R,max}$, Δa_{max}, and K_c values cited are minimum values since they correspond to the point at which the allowable deflection capability (physical limit) was exceeded (without specimen failure) in the deflection-control testing machine.

(#) For an unknown reason no crack extension (Δa_{phy} = 0) was indicated at fracture by the V_1 vs V_2 test record, even though a stable extension of Δa_{phy} = 0.125 inch actually occurred on the fracture surface (see Figure 16); consequently, an initial negative error of 7.5 percent in K_R at low load levels due to a Mismatch Δa = +0.120 inch was fully cancelled at $K_R = K_{R,max}$ by an equivalent positive error of 7.5 percent in K_R arising from the actual crack extension, Δa_{phy} = 0.125 inch.

(##) The $K_{R,max}$, Δa_{max}, and K_c values cited are minimum values of behavior since they correspond to the highest values measured prior to the onset of erratic clip-gage behavior (V_1 and V_2) and occurred well before complete (catastrophic) specimen fracture. The erratic clip-gage behavior resulted, specifically, from a combination of circumstances including 1) exceeding the available clip-gage linearity range, 2) the occurrence of out-of-plane specimen buckling, and 3) concomitant misalignment of the clip-gage holders attached to the specimen. The cited Δa_{max} values (1.430 and 0.920 inches for specimens 7-2 and 7-1, respectively) can be seen to be only a small fraction of the total stable crack extension that took place on the fracture surfaces of each specimen prior to catastrophic crack extension, Δa_{max} = 3.471 and 3.954 inches for specimens 7-2 and 7-1, respectively (Figure 17).

Conversion Factors:

1 inch = 25.4 mm 1 ksi $\sqrt{inch}$ = 1.099 $MNm^{-3/2}$

F = 9/5 C + 32 1 ksi = 6.895 MN/m^2

Table VI

Analysis of K_c Results for Duplicate Specimen Tests

Item No.	No. of Specimens Tested	Specimen Size and Type	B, inches	Test Temperature, F	K_c, ksi $\sqrt{inch}$	Average K_c and Range, ksi $\sqrt{inch}$	Range of K_c Results,* percent
7&8	2	4C	1.50	+40	155 195	175±20	±11.4
11&12	2	7C	1.50	-40	57 103	80±23	±28.8
18&19	2	2T	0.50	+40	273 313	293±20	±6.8
23&24	2	4T	0.50	+72	>503 >380	>442±62	±14.0

* Range expressed of percent relative to the average K_c value cited in the previous column.

Conversion Factors:

1 inch = 25.4 mm

F = 9/5 C + 32

1 ksi $\sqrt{inch}$ = 1.099 $MNm^{-3/2}$

Table VII

Analysis of K_c Results for Different Test Procedures

Item No.	Specimen Size and Type*	Nominal Test Temperature, F	K_c, ksi $\sqrt{inch}$	Extent to Which K_c for 4T Exceeds That for 4C**
4	4T	-40	154	+51.0%
5	4C	-40	102	-
6	4T	+40	314	+79.5%
7	4C	+40	155	-
8	4C	+40	195	-
9	4T	+72	445	+40.0%
10	4C	+72	318	-

* 4T specimens tested by load-control test method.
4C specimens tested by deflection-control test method.

** Expressed as a percentage of the listed (or average) K_c value for the corresponding 4C specimen.

Conversion Factors:

$$F = 9/5\ C + 32$$

$$1\ \text{ksi}\ \sqrt{\text{inch}} = 1.099\ \text{MNm}^{-3/2}$$

Table VIII

Comparisons of Studies Conducted to Evaluate K_C Behavior Measured Using the Load-Control and Displacement-Control Test Techniques

	Earlier Studies by Heyer & McCabe*		Present Study**
Materials	High-Strength Aluminum & Titanium Alloys	vs	Low-Strength Steel
Material thickness, inches	$B \leq 0.066$	vs	$B = 1.50$
K_C Repeatability	Excellent (±5%)	vs	Fair (±15 to ±30%)
Strain-rate Sensitivity (on K_C)	NIL	vs	High
Method of Analysis @ K_C	LEFM	vs	COS

* Complete Equivalence of K_C behavior demonstrated in tests conducted with load-control and displacement-control testing techniques.

** K_C for load-control = 40% to 80% higher than K_C for displacement-control.

Table IX

Effects of Thickness (B = 1.5 inch vs B = 0.5 inch) on K_c Behavior from Load-Control Tests on 50-ksi Yield-Strength A572 Grade 50 Steel

Item No.	Specimen Size	Nominal Test Temperature, F	K_c for B = 1.50 inch Specimen, ksi $\sqrt{inch}$	K_c for B = 0.50 inch Specimen, ksi $\sqrt{inch}$
		A. 2T Specimen Size		
1	2T	-40	116	-
17	2T	-40	-	316
2	2T	+40	216	-
18	2T	+40	-	273
19	2T	+40	-	313
3	2T	+72	>87+	-
20	2T	+72	-	308
		B. 4T Specimen Size		
4	4T	-40	154	-
21	4T	-40	-	150
6	4T	+40	314	-
22	4T	+40	-	305
9	4T	+72	445	-
23	4T	+72	-	>503+
24	4T	+72	-	>380+

+ See appropriate footnote for detailed behavior in Table V.

Conversion Factors

1 inch = 25.4 mm.

F = 9/5C + 32.

1 ksi $\sqrt{inch}$ = 1.099 $MNm^{-3/2}$.

Table X

Summary of CVN Test Results From Selected CT Specimens of A572 Steel

Item No.	Specimen No.	Specimen Size and Type	B, inches	Test Temperature, F	K_c, ksi $\sqrt{inch}$	CVN Energy Absorption, ft-lb											
						+72 F				+40 F			0 F			-40 F	
3	7-3	2T	1.50	+67	>87	45.0	45.0	37.0	53.0	27.0	21.0	26.0	9.0	15.0	9.0	-	-
5	A7-4	4C	1.50	-40	102	49.5	38.5	56.0	44.5	49.0	-	35.0	-	-	-	12.0	17.0
7	A7-1	4C	1.50	+40	155	45.0	38.0	53.5	52.0	32.0	-	30.5	-	-	-	5.0	9.0
8	A7-3	4C	1.50	+40	195	50.0	41.0	47.0	38.0	42.0	-	29.0	-	-	-	2.5	7.0
9	7-1	4T	1.50	+72	445	41.0	41.0	56.0	-	26.0	30.0	26.0	24.0	-	23.0	-	-
10	A7-2	4C	1.50	RT	318	42.0	51.0	47.0	60.5	32.0	-	38.5	-	-	-	3.5	5.5
11	A572-1	7C	1.50	-44	57	47.0	47.5	74.0	54.0	40.0	-	39.5	-	-	-	3.0	6.0
12	A7-3	7C	1.50	-40	103	51.5	43.5	54.0	42.0	14.5	-	20.5	-	-	6.0	-	5.5
13	A7-4	7C	1.50	+40	191	43.0	45.5	30.0	41.0	25.0	-	32.0	-	-	-	3.5	2.5
17	7-3*	2T	0.50	-32	316	60.0	47.0	-	-	33.0	-	32.0	25.0	-	35.0	16.0*	18.0*
21	7-4#	4T	0.50	-40	150	60.0	52.0	-	-	42.0	-	33.0	29.0	-	28.0	10.0#	18.0#
						Corresponding CVN Lateral Expansion (LE), mils											
3	7-3	2T	1.50	+67	>87	46.0	44.0	37.0	52.0	29.0	24.0	28.0	12.0	16.0	12.0	-	-
5	A7-4	4C	1.50	-40	102	38.0	31.5	42.0	37.5	38.5	-	27.0	-	-	-	6.5	10.0
7	A7-1	4C	1.50	+40	155	39.5	31.0	42.0	38.5	23.5	-	25.5	-	-	-	0.5	3.5
8	A7-3	4C	1.50	+40	195	37.0	33.5	38.0	34.5	31.5	-	21.0	-	-	-	0	4.0
9	7-1	4T	1.50	+72	445	41.0	38.0	47.0	-	24.0	27.0	27.0	21.0	-	21.0	-	-
10	A7-2	4C	1.50	RT	318	35.0	44.0	38.0	48.0	24.5	-	29.0	-	-	-	2.0	0.5
11	A572-1	7C	1.50	-44	57	39.0	40.5	58.0	41.0	33.0	-	29.0	-	-	-	0	1.0
12	A7-3	7C	1.50	-40	103	41.0	36.0	41.5	35.0	13.0	-	15.0	-	-	-	1.0	1.5
13	A7-4	7C	1.50	+40	191	33.0	34.0	29.0	39.5	20.0	-	26.0	-	-	-	0	1.0
17	7-3*	2T	0.50	-32	316	51.0	40.0	-	-	31.0	-	32.0	24.0	-	32.0	14.0*	15.0*
21	7-4#	4T	0.50	-40	150	50.0	45.0	-	-	39.0	-	33.0	25.0	-	24.0	10.0#	15.0#

Note: * Additional results at -80 F were CVN energy = 6.0 and 4.0 ft-lb with corresponding LE = 3.0 and 2.0 mils.
Additional result at -80 F was CVN energy = 7.0 ft-lb and LE = 3.0 mils.

Conversion Factors:

1 inch = 25.4 mm
F = 9/5 C + 32
1 ksi $\sqrt{inch}$ = 1.099 $MNm^{-3/2}$
1 ft-lb = 1.36 J
1 mil = 0.0254 mm

Table XI

Summary of Static K_{Ic} Tests* on A572 Grade 50 (σ_{ys}=50 ksi) Steel

Item No.	Spec No.	Test Temp, F	σ_{ys}, ksi	Specimen Measurement Capacities $K_{I,Lub}$,** ksi $\sqrt{inch}$	$K_{I,Gub}$ *** ksi $\sqrt{inch}$	K_Q, ksi $\sqrt{inch}$	$\left(\frac{K_Q}{K_{I,Gub}}\right)$	$K_{I,max}$,+ ksi $\sqrt{inch}$	K_{Ic}, ksi $\sqrt{inch}$	Comments
1	7-1	-320	138	105	166	32.3	0.19	32.3	32.3	Valid
2	7-11	-320	138	106	168	25.7	0.16	26.2	25.7	Valid
3	7-8	-240	101	77	122	31.2	0.26	31.2	31.2	Valid
4	7-3	-220	94	72	114	36.2	0.32	36.2	36.2	Valid
5	7-13	-200	87	66	104	28.9	0.28	28.9	28.9	Valid
6	7-10	-180	81	62	98	38.3	0.39	38.3	38.3	Valid
7	7-4	-165	77	59	93	63.8	0.69	63.8	63.8	Essentially valid
8	7-8	-156	75	57	90	58.5	0.65	58.5	58.5	Essentially valid
9	7-9	-149	74	56	88	44.8	0.51	44.8	44.8	Valid
-	-	-	-	-	-	-	-	-	-	-
10	7-12	-120	67	51.5	81.5	76.5++	0.94	105.1	>51.5	Invalid
11	7-5	-104	64	49.0	77.5	74.2++	0.96	74.2	>49.0	Invalid
12	7-7	-55	57	43.2	68.3	73.6++	1.08	99.1	>43.2	Invalid
13	7-6	+7	52	39.9	63.1	71.9++	1.14	117.0	>39.9	Invalid
14	7-2	+75	50	38.0	60.1	63.4++	1.06	113.3	>38.0	Invalid

* 3-Point bend specimens: span = 24.0 inches [S/W = 4.0/1]; nominal specimen dimensions:

W = 6.00 inches
B = 1.47 inches
a = 2.90 inches

** Least-upper-bound measurement capacity, given as $K_{I,Lub} = \sigma_{ys}\left(\frac{B}{2.50}\right)^{1/2}$.

(Continued)

Table XI (Continued)

*** Greatest-upper-bound measurement capacity, given as $K_{I,Gub} = \sigma_{ys} \left(\frac{B}{1.00}\right)^{1/2}$.

+ Nominal K_I value at maximum load ($P = P_{max}$) calculated on the basis of LEFM and the original specimen dimensions, without any plasticity corrections to the original crack length, a.

++ K_Q value reflects <u>severe K_I-suppression effects</u> due to grossly inadequate specimen dimensions.

<u>Conversion Factors</u>:

$$C = 5/9(F - 32)$$
$$1 \text{ ksi} = 6.895 \text{ MN/m}^2 = 6.895 \text{ N/mm}^2$$
$$1 \text{ ksi} \sqrt{\text{inch}} = 1.099 \text{ MNm}^{3/2}$$
$$1 \text{ inch} = 25.4 \text{ mm}$$

Table XII

Fracture Behavior of A572 Grade 50 Steel (σys = 50 ksi)

	Invalid K_{Ic} Test Results		Estimated K_{Ic} Values, ksi $\sqrt{inch}$	
Test Temp	K_Q, ksi $\sqrt{inch}$	$\left(\frac{K_Q}{K_{I,Gub}}\right)$	From K_I-Suppression Effect*	From J-Integral**
⊖120 F	76.5	0.94	148⊖	100-130
⊖104 F	74.2	0.96	148⊖	-
⊖55 F	73.6	1.08	148+	-
+7 F	71.9	1.14	148+	-
+75 F	63.4	1.06	148+	160-200

* $K_{Ic} \cong 2.0\ K_Q$ @ $\left(\frac{K_Q}{K_{I,Gub}}\right) = 1.00$ where $K_{I,Gub} = \sigma ys\left(\frac{B}{1.0}\right)^{1/2}$

$\therefore K_{Ic} \cong 2 \times 74 = 148$ ksi $\sqrt{inch}$ @ T = -80 F

** "One-shot" J_{Ic} equation.

Table XIII

Summary of Minimum Plane-Stress Fracture Toughness for Two Thicknesses of A572 Grade 50 Steel Under Static Loading Condiitons ($\varepsilon \approx 10^{-5}$ sec^{-1})

Temperature, F	Minimum K_c, ksi $\sqrt{inch}$	σ_{ys}, ksi	Minimum a_{cr} for Infinite CCT Spec* @ $\sigma_D = 3/4\ \sigma_{ys}$, inches
A. For B = 1-1/2-Inch-Thick Plate and σ_{ys} = 50 ksi			
-40	57**	56	0.58 (180)**
+40	155	51	5.22
+72	318	50	22.9
B. For B = 1/2-Inch-Thick Plate and σ_{ys} = 50 ksi			
-40	150	56	4.06
+40	273	51	16.2
+72	>380	50	>32.7
C. For B = 1-1/2-Inch-Thick Plate and σ_{ys} = 62 ksi			
-40	121	68	1.80
+72	365	62	19.6

* For an infinite center-cracked tension (CCT) specimen:

$$K = \sigma \sqrt{\pi a} \tag{1}$$

Rearranging (1): $\therefore\ a_{cr} = \frac{1}{\pi}\left(\frac{K_c}{\sigma_D}\right)^2$ (2)

and for

$$\sigma_D = 3/4\ \sigma_{ys}$$

we get

$$a_{cr} = \frac{16}{9 \cdot \pi}\left(\frac{K_c}{\sigma_{ys}}\right)^2 = 0.566\ \left(\frac{K_c}{\sigma_{ys}}\right)^2 \tag{3}$$

** If the minimum representative fracture toughness is taken to be K_c = 100 ksi $\sqrt{inch}$; The corresponding value of critical flaw size would be a_{cr} = 1.80 inches.

Conversion Factors:

$F = 9/5\ C + 32$

1 ksi $\sqrt{inch}$ = 1.099 MNm$^{-3/2}$

1 ksi = 6.895 N/mm^2 = 6.895 MN/m^2

1 inch = 25.4 mm

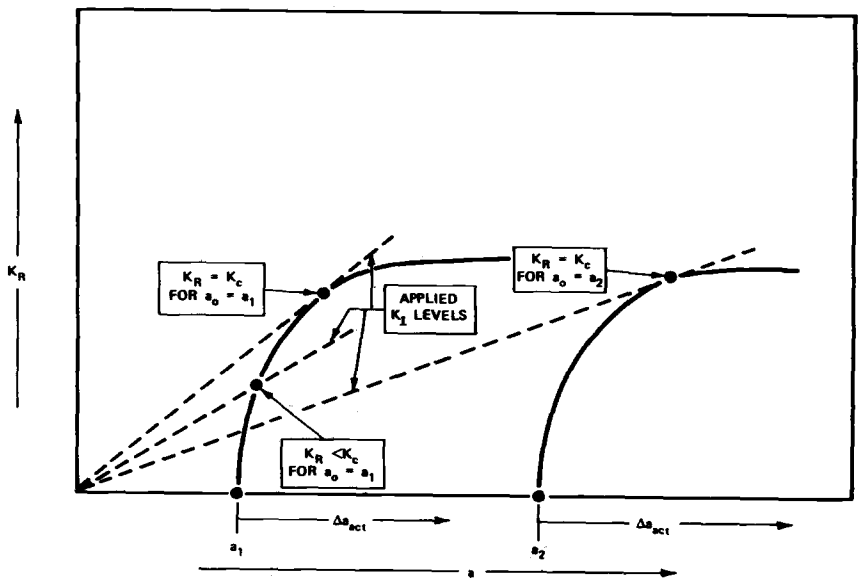

FIG. 1—*Basic principle of R-curves for use in determining K_c under different conditions of initial crack length, a_o.*

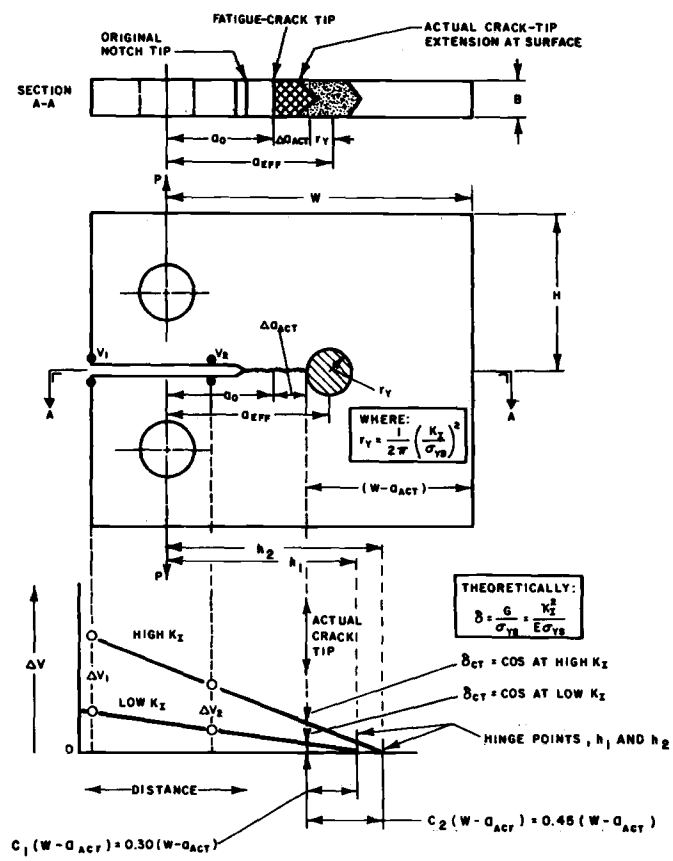

FIG. 2—*Schematic of procedure for measuring δ_{ct} or cos at the actual crack tip (σ_{qct}) relative to applied load level (K_I) under plane-stress conditions.*

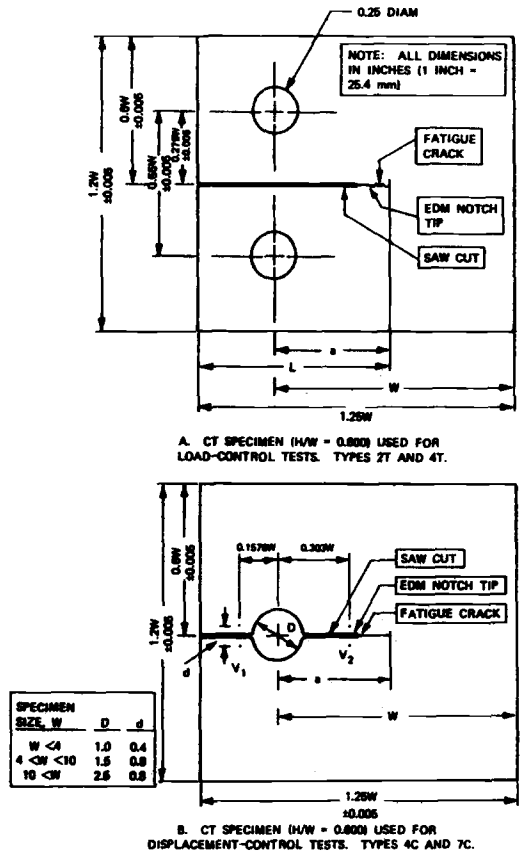

FIG. 3—*CT specimens used for load-control and displacement-control tests.*

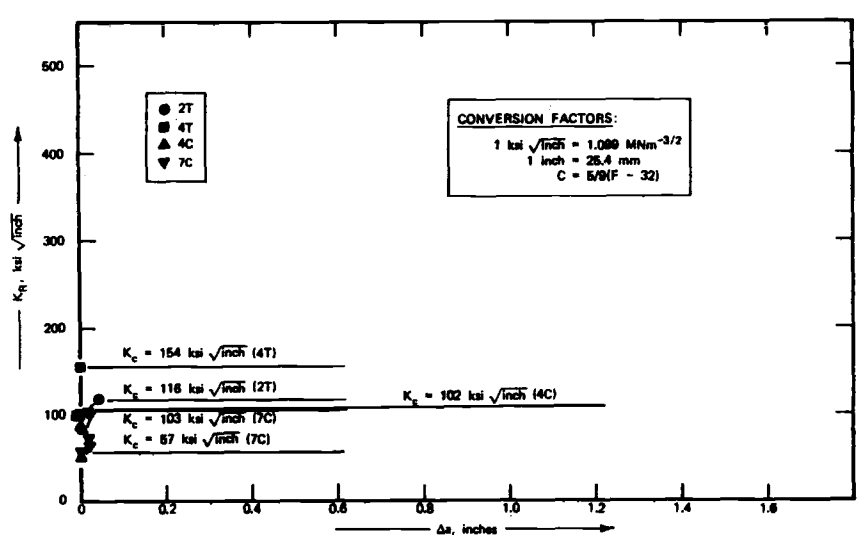

FIG. 4—*R-curve and K_c results of full-thickness (B = 1.5 in.) specimens of A572 Grade 50 steel tested at −40°F.*

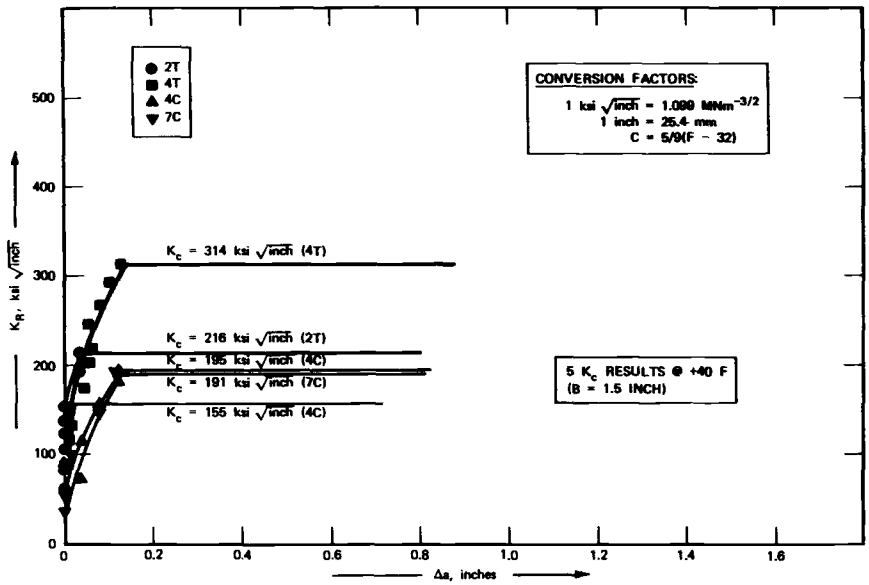

FIG. 5—*R-curve and K_c results for full-thickness (B = 1.5 in.) specimens of A572 grade 50 steel tested at +40°F.*

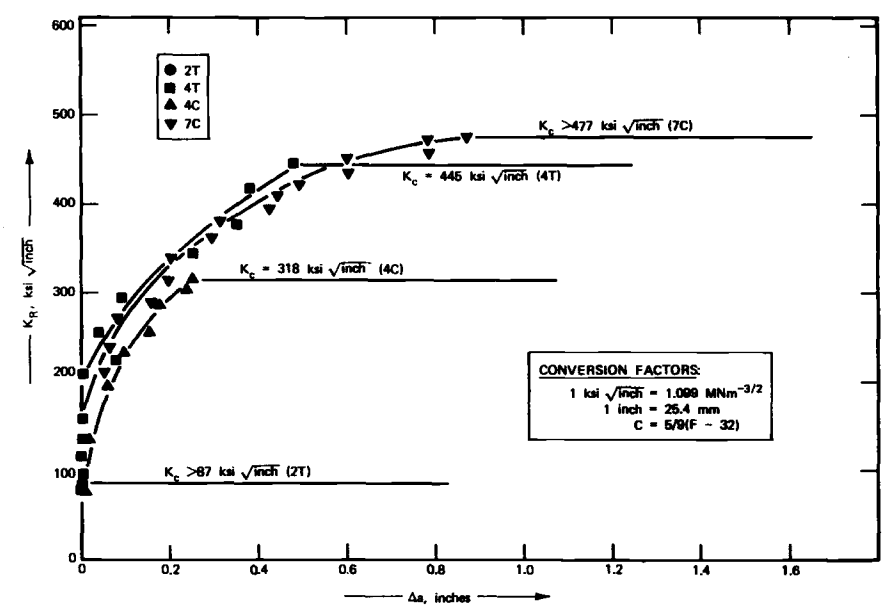

FIG. 6—*R-curve and K_c results for full-thickness (B = 1.5 in.) specimens of A572 grade 50 steel tested at +72°F.*

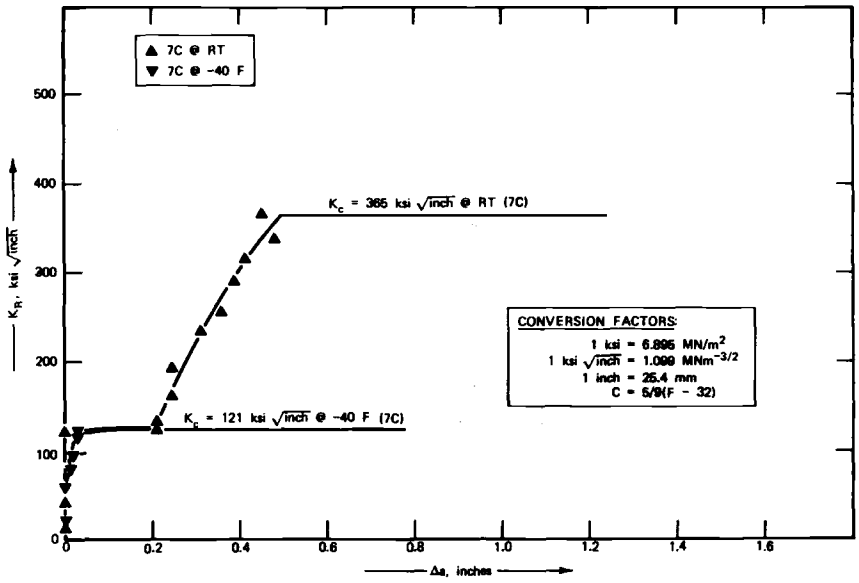

FIG. 7—*R-curve and K_c results for full-thickness (B = 1.5 in.) specimens of A572 steel processed to 62-ksi strength level at two different temperatures.*

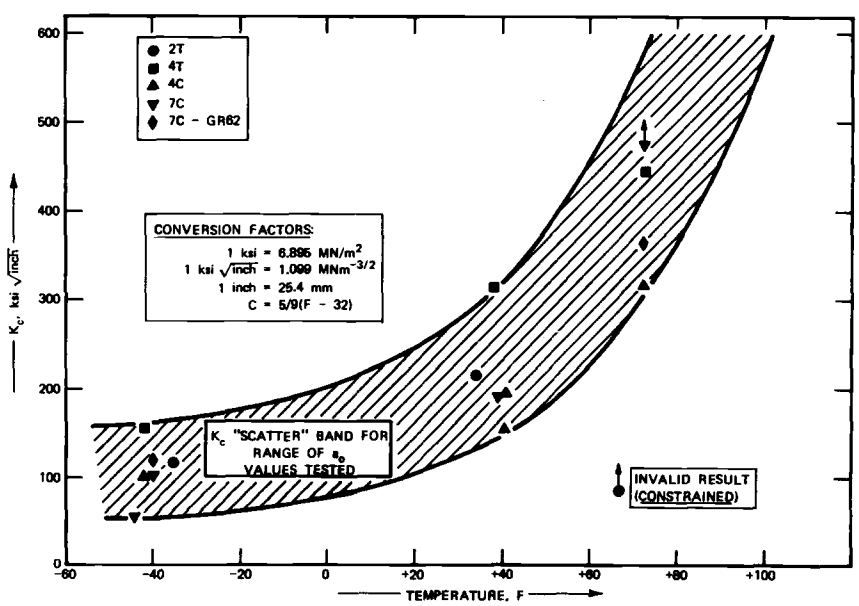

FIG. 8—*Summary of K_c results for full-thickness (B = 1.5 in.) specimens of A572 grade 50 steel and A572 steel processed to 62-ksi strength level.*

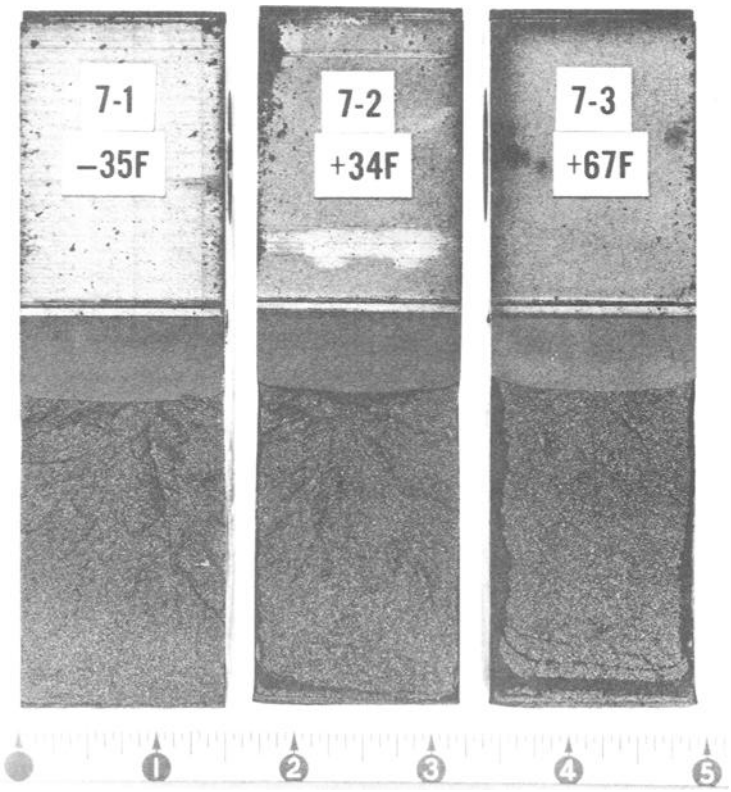

FIG. 9—*Fracture surfaces of full-thickness (B = 1.5 in.) 2T CT specimens of A572 grade 50 steel tested under load-control conditions using an essentially monotonic loading sequence (Armco procedure).*

FIG. 10—*Fracture surfaces of full-thickness (B = 1.5 in.) 4T CT specimens of A572 Grade 50 steel tested under load-control conditions using a total unload/reload loading sequence (U. S. Steel procedure).*

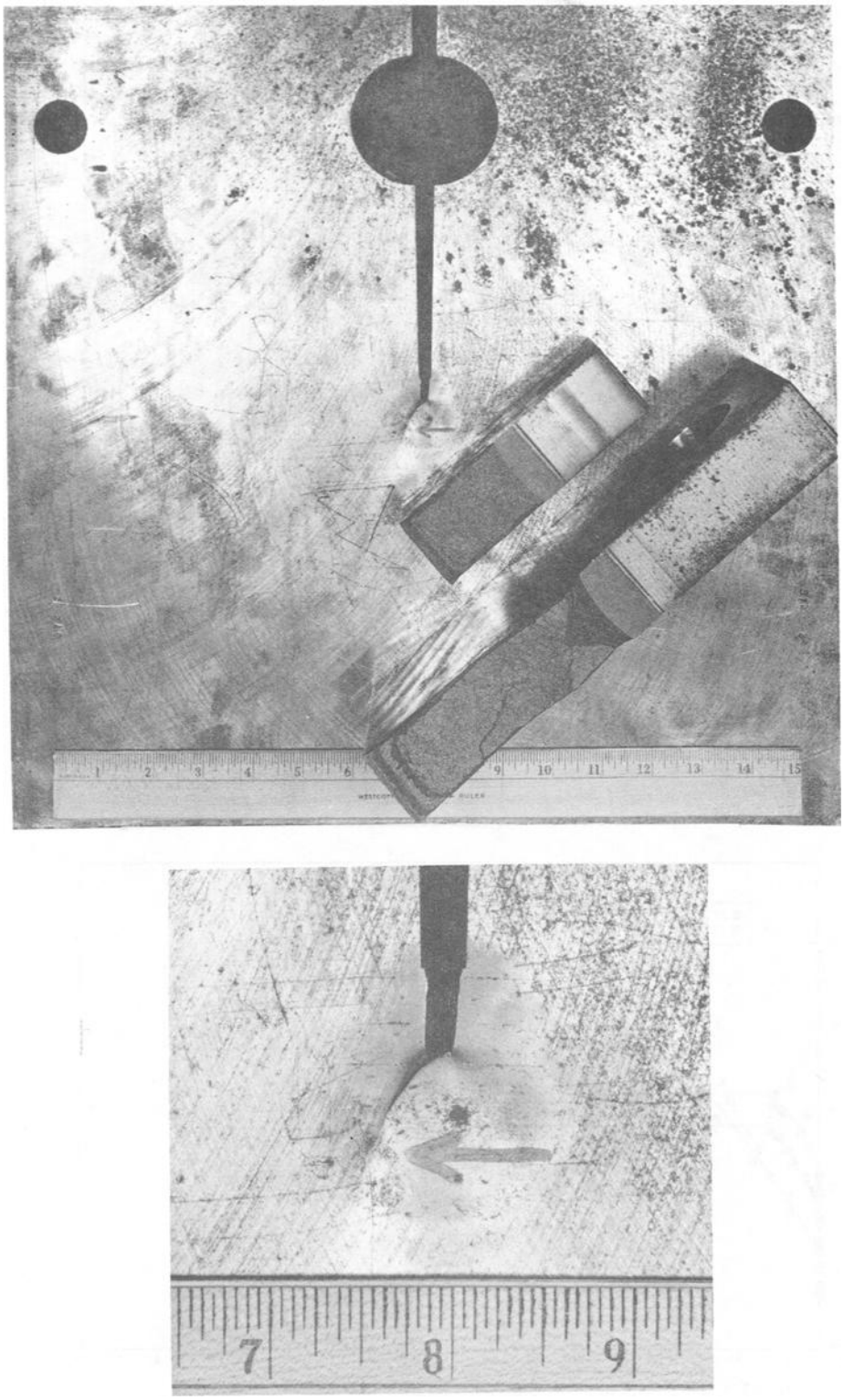

FIG. 11—*R-curve specimens of A572 Grade 50 steel tested at ambient temperature (~ 72°F). The 2T and 4T specimens were tested to fracture under load-control conditions, and the 7C specimen was tested to the limit of available capacity under displacement-control conditions. Note:* $\Delta a = a_f - a_o \cong 0.50$ *in. on the specimen surface for the 7C specimen at the end of the test.*

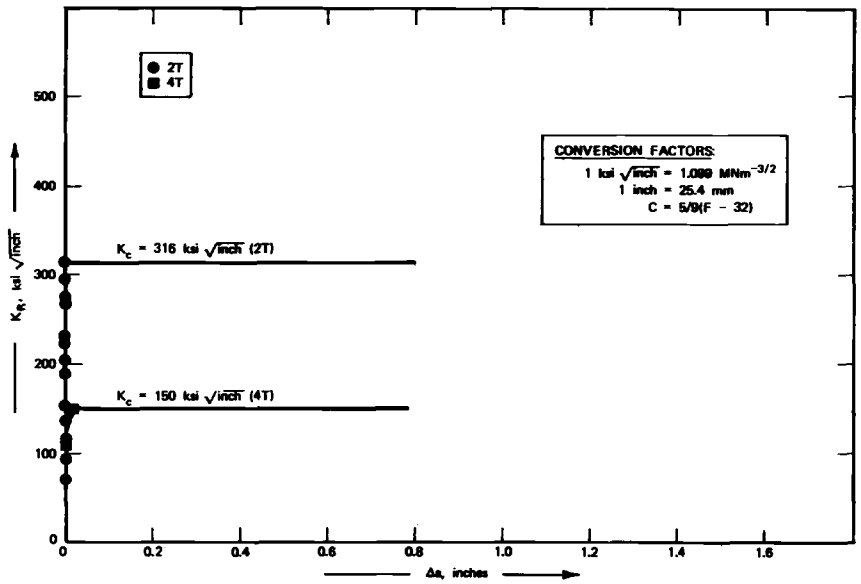

FIG. 12—*R-curve and K_c results for subthickness ($B = 0.5$ in.) specimens of A572 Grade 50 steel tested at −40°F.*

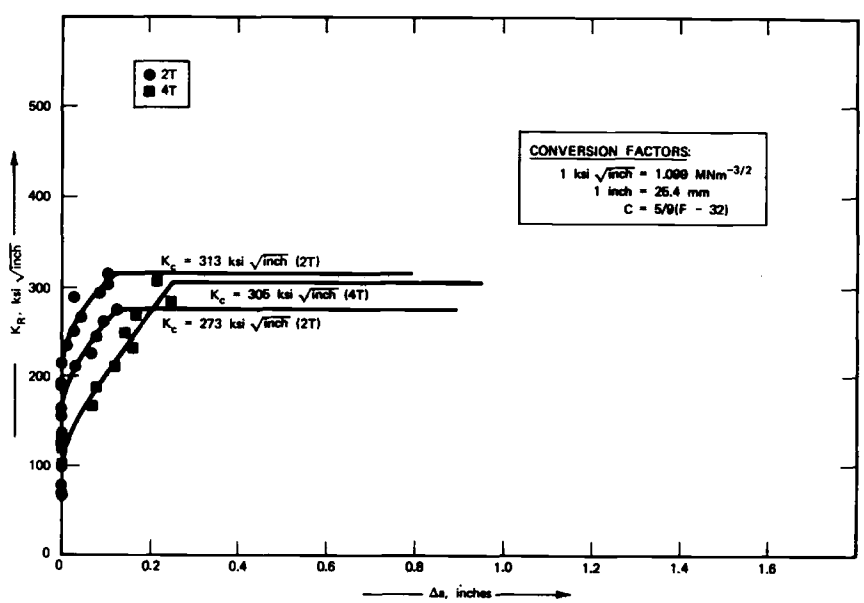

FIG. 13—*R-curve and K_c results for subthickness ($B = 0.5$ in.) specimens of A572 Grade 50 steel tested at +40°F.*

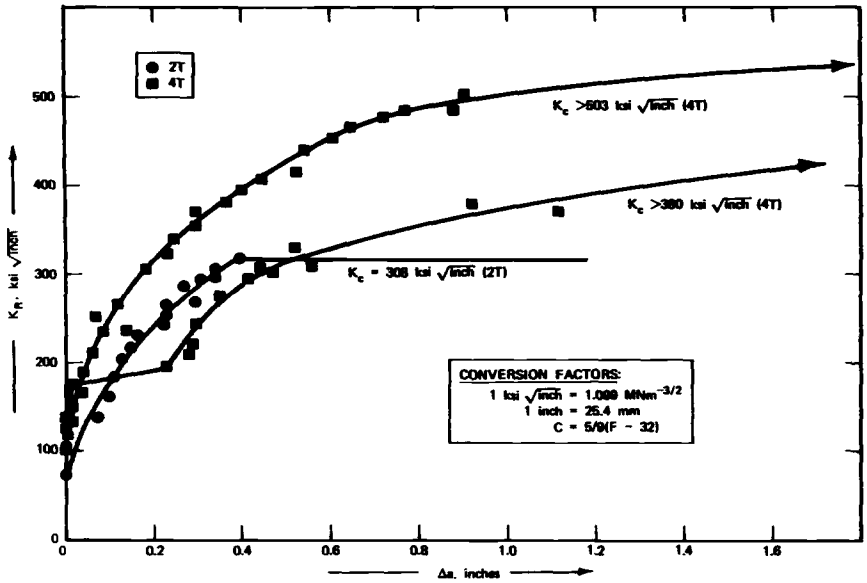

FIG. 14—*R-curve and K_c results for subthickness (B = 0.5 in.) specimens of A572 Grade 50 steel tested at +72°F.*

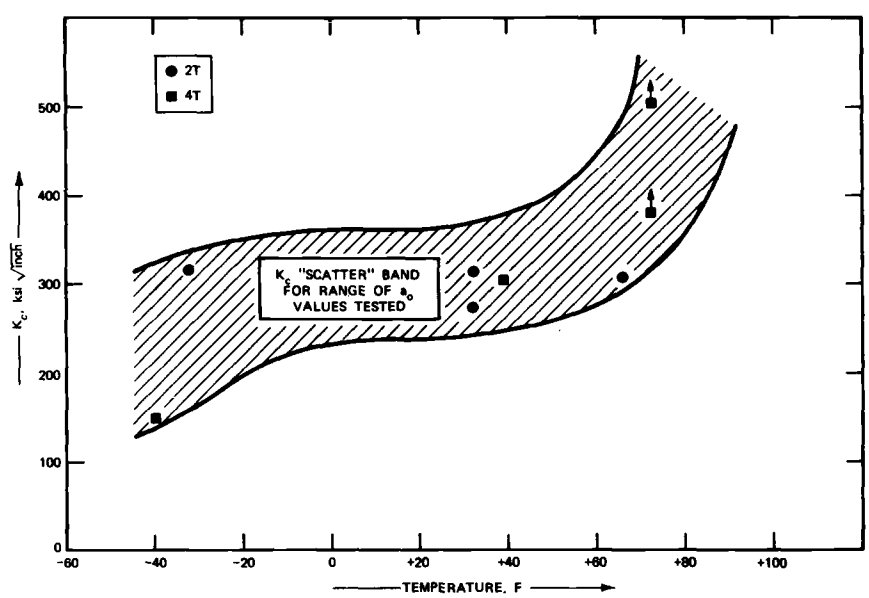

FIG. 15—*Summary of K_c results for subthickness (B = 0.5 in.) specimens of A572 Grade 50 steel.*

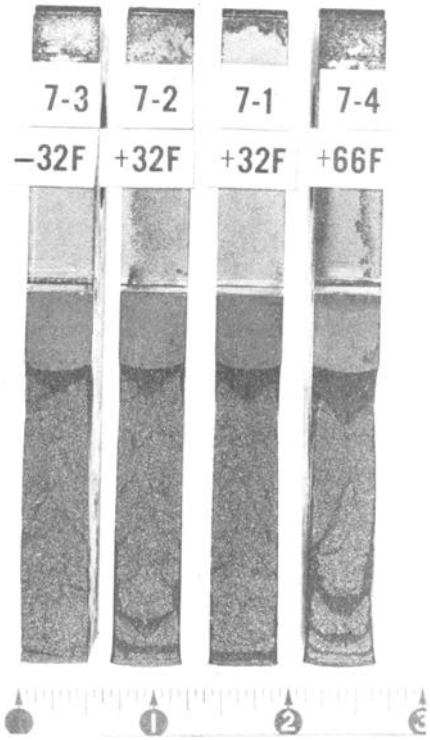

FIG. 16—*Fracture surfaces of subthickness (B = 0.5 in.) 2T CT specimens of A572 Grade 50 steel tested under load-control conditions using an essentially monotonic loading sequence (Armco procedure).*

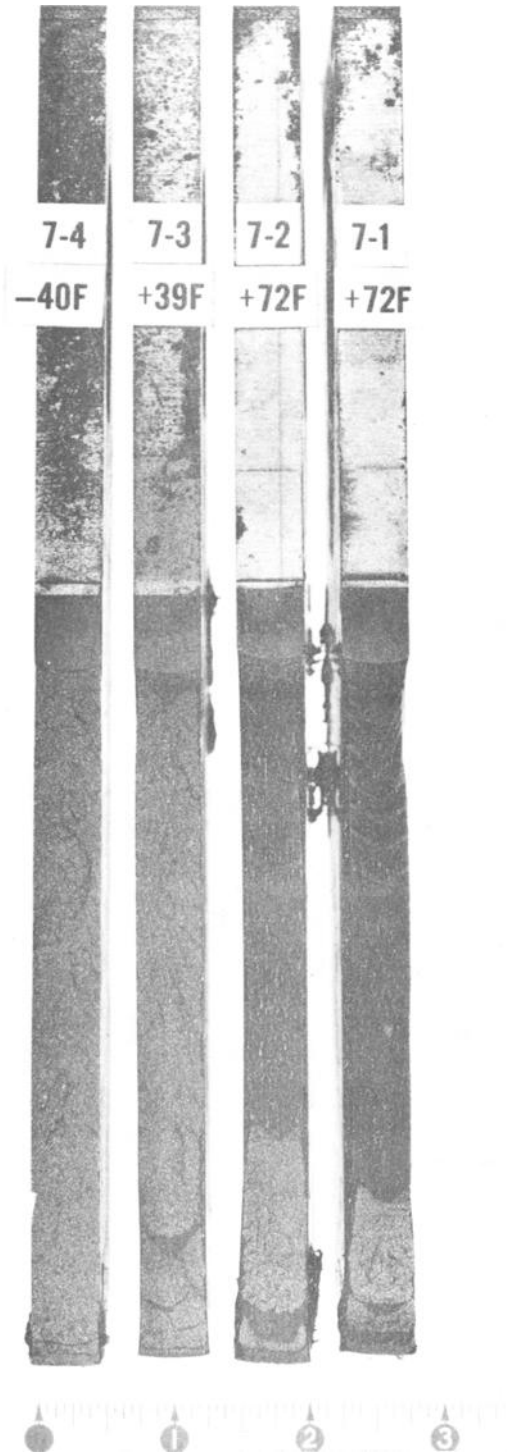

FIG. 17—*Fracture surfaces of subthickness (B = 0.5 in.) 4T CT specimens of A572 Grade steel tested under load-control conditions using a total unload/reload loading sequence (U. S. Steel procedure).*

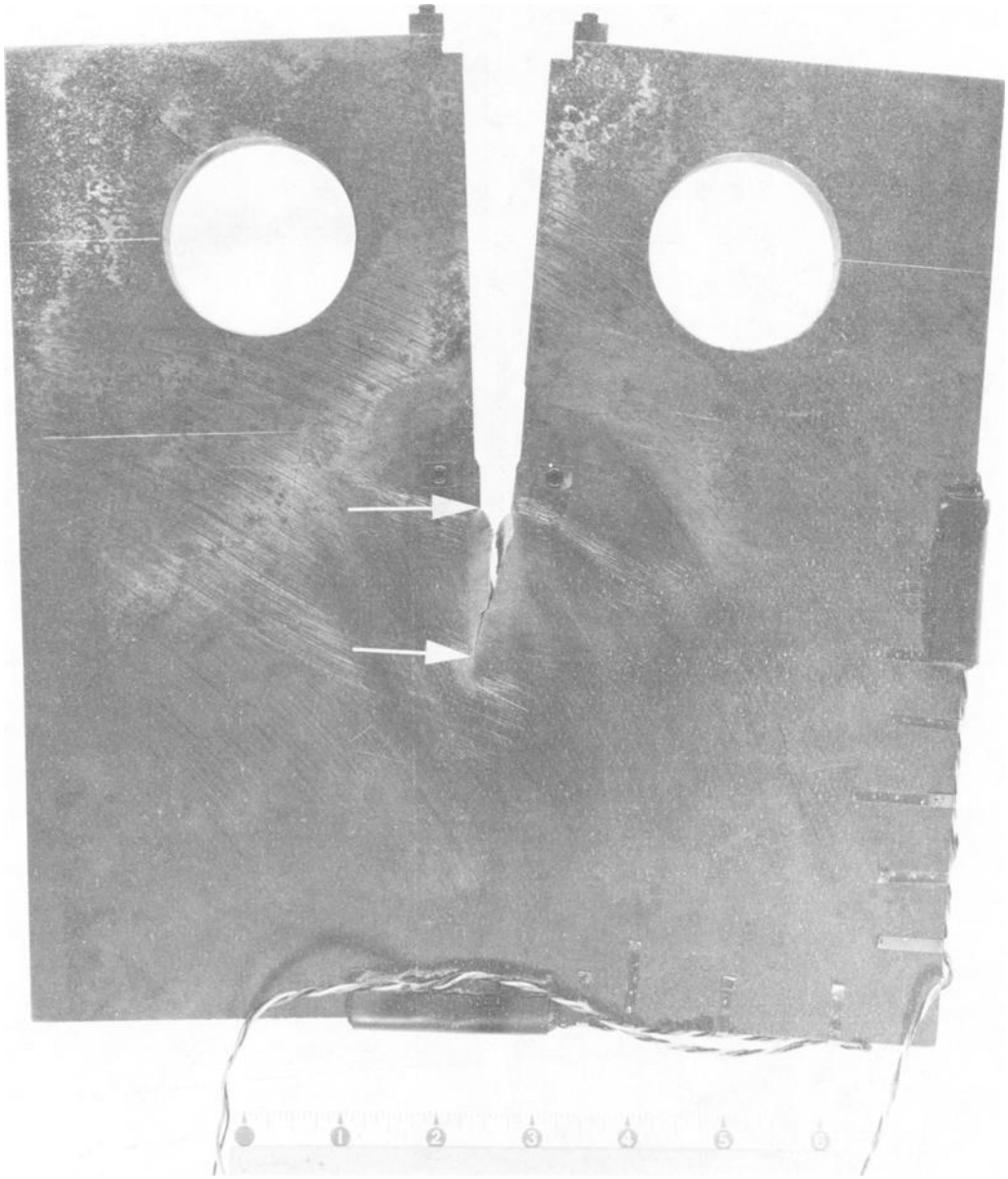

FIG. 18—*Subthickness ($B = 0.5$ in.) 4T CT specimen 7-2 tested at +72°F. Photograph was taken after unload 33 and just prior to complete fracture (intentional). Note the extent of stable crack extension visible on the specimen surface ($\Delta a = a_f - a_o \cong 1.60$ in.).*

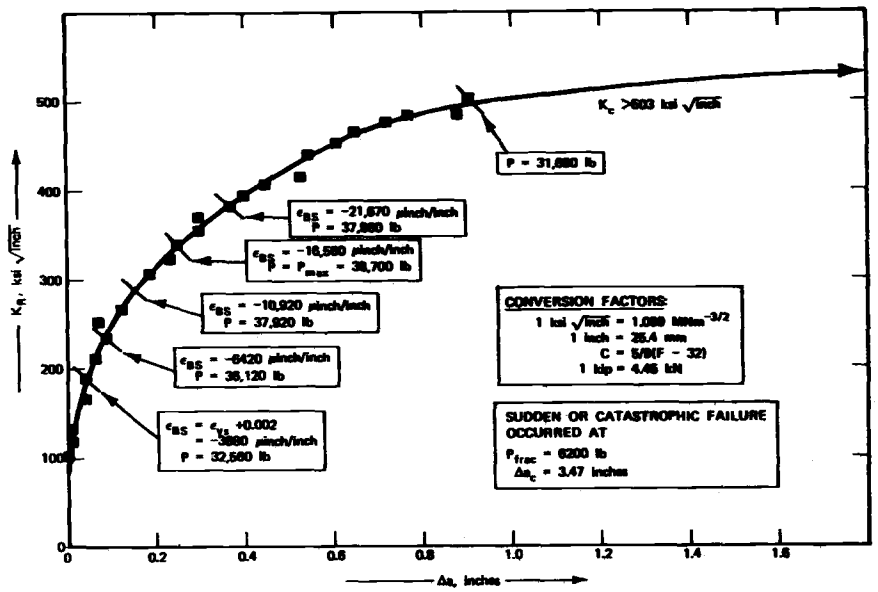

FIG. 19—*Superposition of ϵ_{BS} and P in the development for the 4T subthickness (B = 0.5 in.) specimen of A572 Grade 50 steel tested at +72°F.*

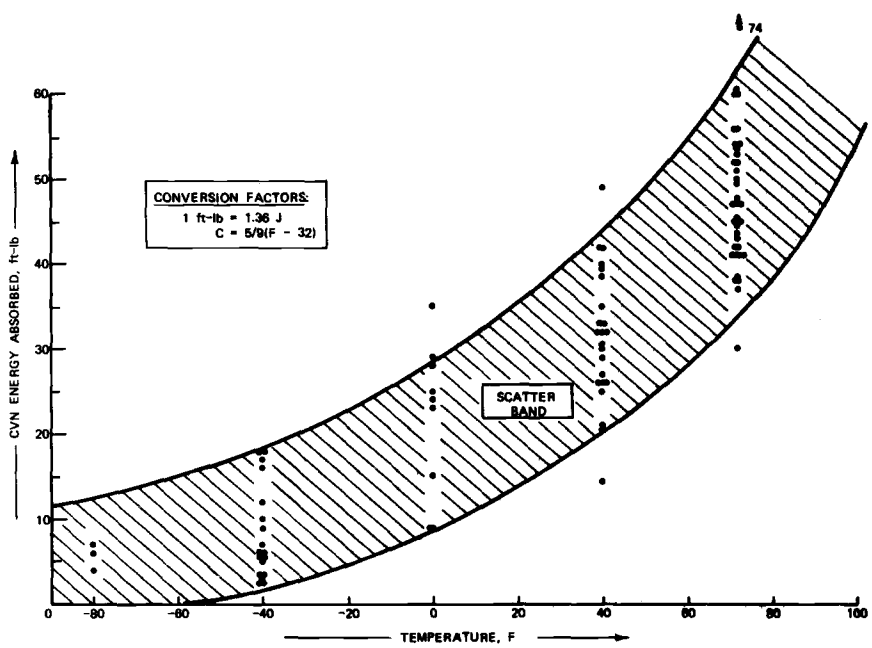

FIG. 20—*Combined CVN energy-absorption behavior of A572 Grade 50 steel as determined from the broken halves of 11 CT specimens used to establish R-curve behavior.*

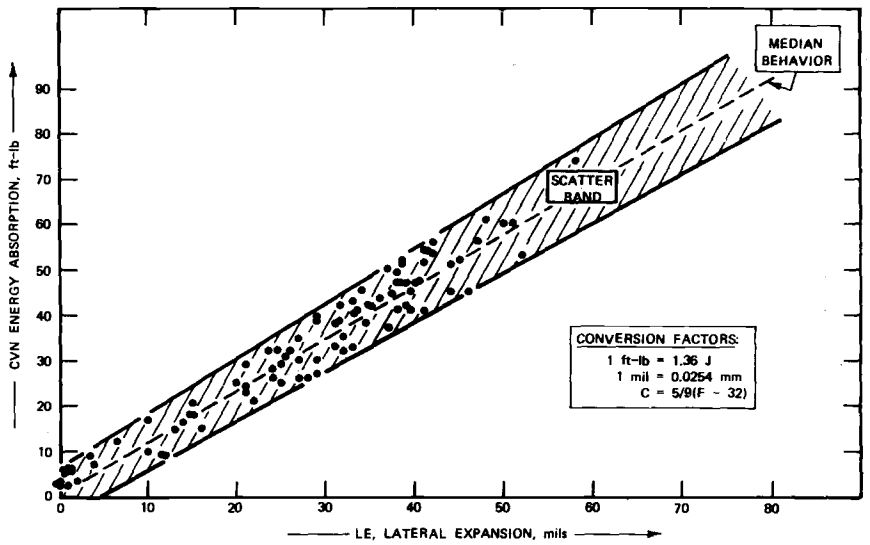

FIG. 21—*Correlation between CVN energy absorption and lateral expansion (LE) for A572 Grade 50 steel at all temperatures (−80 to +72°F) as determined from the broken halves of 11 CT specimens used to establish R-curve behavior.*

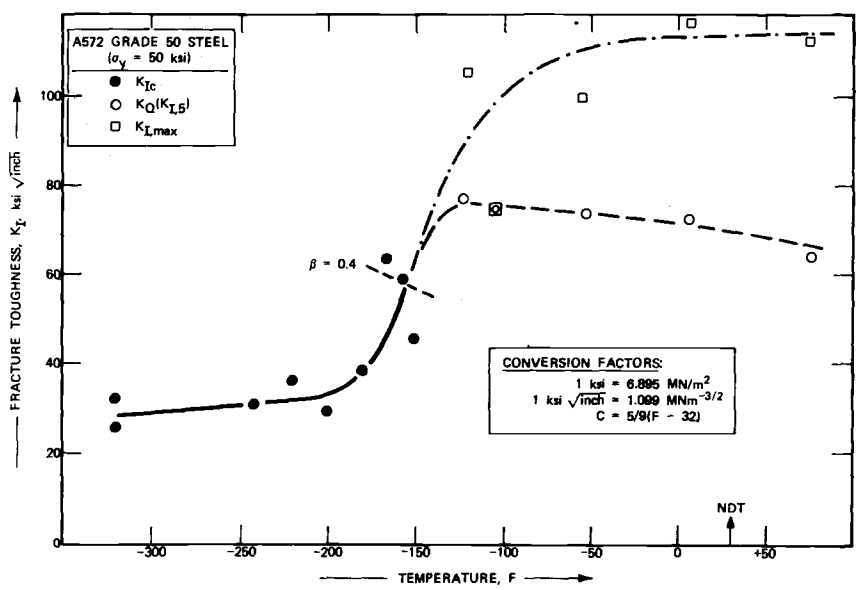

FIG. 22—*Results of static fracture-toughness tests of A572 Grade steel (σ_y = 50 ksi).*

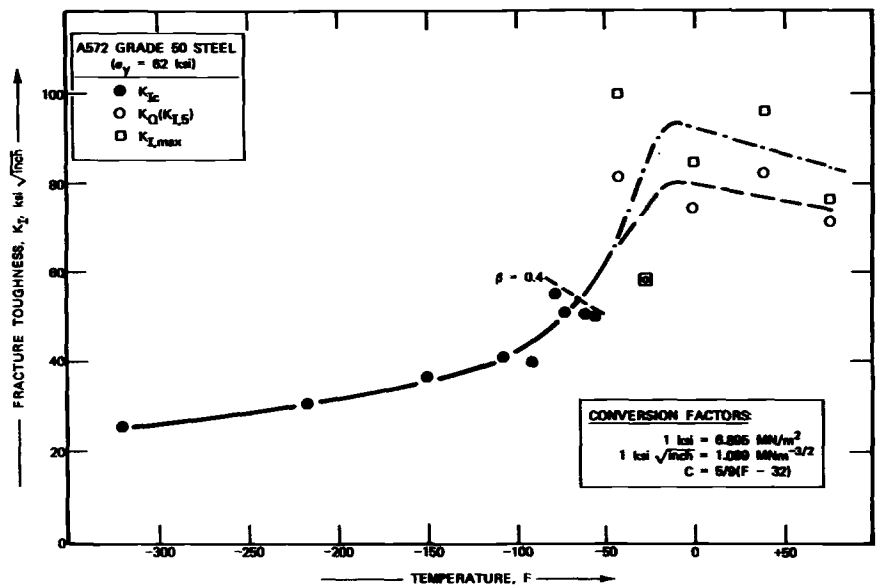

FIG. 23—*Results of static fracture-toughness tests of A572 Grade 50 steel (σ_y = 62 ksi).*

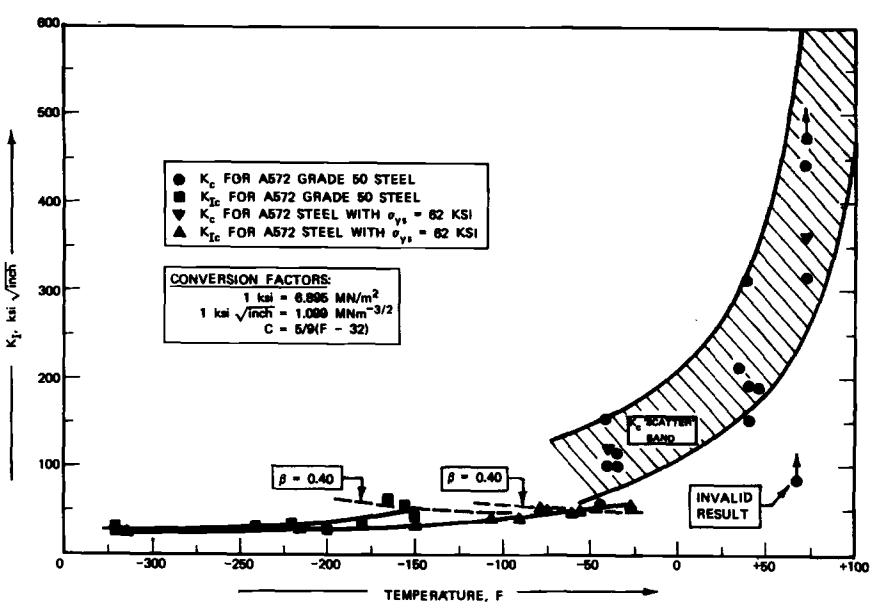

FIG. 24—*Summary comparisons of K_c and K_{Ic} behavior obtained from 1.5-in.-thick plates of A572 steel.*

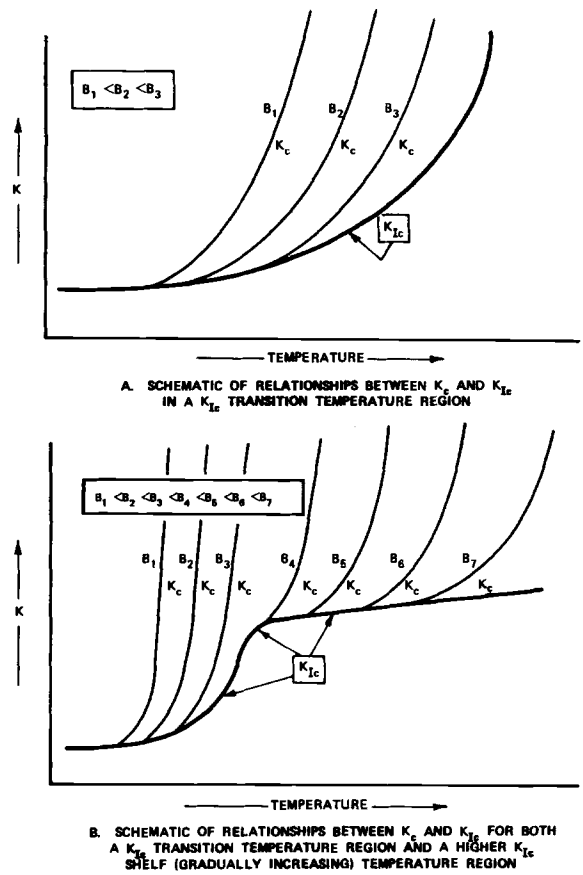

FIG. 25—*Schematics of relationships between K_c and K_{Ic}.*

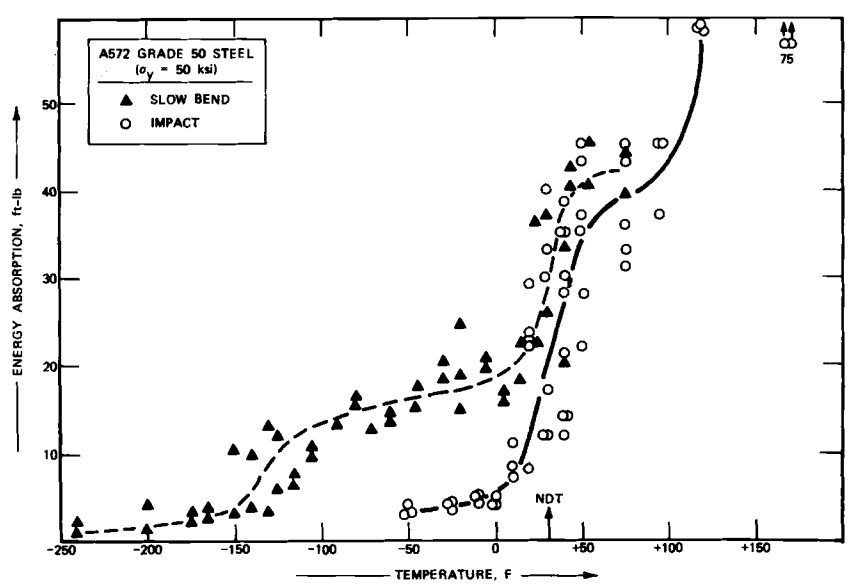

FIG. 26—*Longitudinal Charpy V-notch energy absorption for impact and slow-bend tests of standard CVN specimens.*

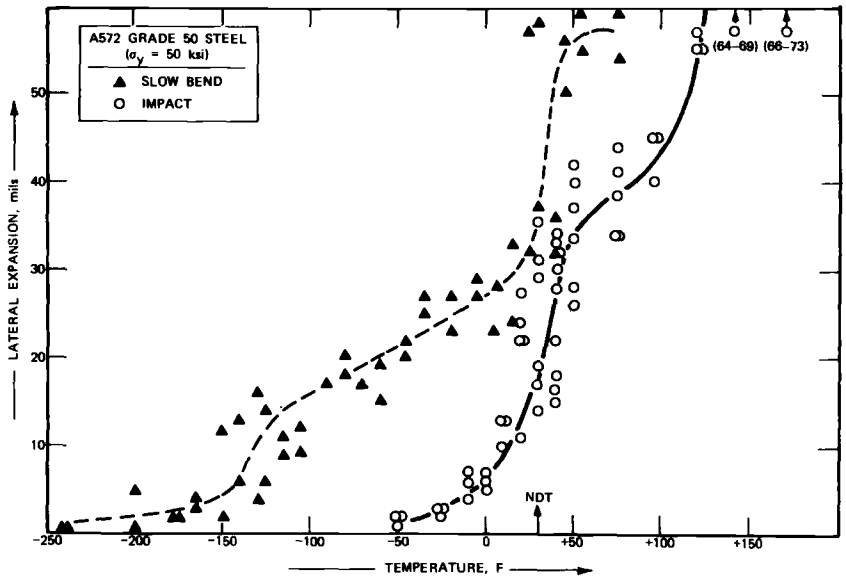

FIG. 27—*Longitudinal Charpy V-notch lateral expansion for impact and slow-bend tests of standard CVN specimens.*

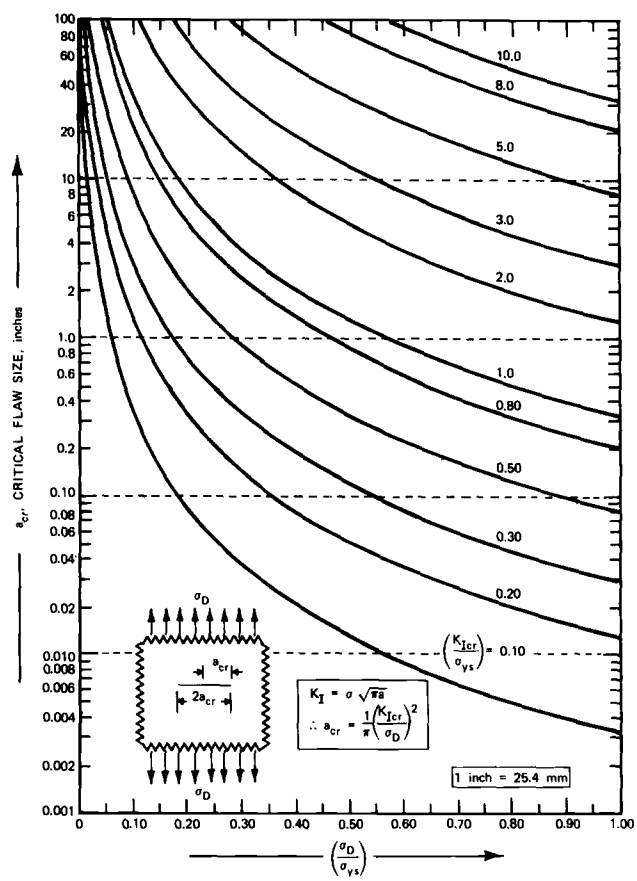

FIG. 28—*Critical flaw size (a_{cr}) requirements for the initiation of a critical event (K_{Icr}) for cracks contained in an infinite center-cracked tension (CCT) specimen and subjected to a uniform tension stress (σ_D) applied remotely.*