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Relative behavior of notch-toughness tests for welded steel

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RELATIVE BEHAVIOR OF NOTCH-TOUGHNESS TESTS FOR WELDED STEEL

by

William D. McMullen

A THESIS

Presented to the Graduate Faculty
of Lehigh University
in Candidacy for the Degree of
Master of Science

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1961

CERTIFICATE OF APPROVAL

This thesis is accepted and approved in partial fulfillment of the requirements for the degree of Master of Science.

Date Nov 13, 1961

William J Murphy
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Head of the Department of
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ABSTRACT

Eleven structural steels in a variety of conditions were tested using the notched slow-bend (Kinzel), Naval Research Laboratory (NRL) drop-weight and V-notch Charpy tests in order to develop a basis of comparison for these tests.

In addition to determining the Kinzel 1% lateral contraction transition temperature, the nil-ductility transition temperature (NDT) and the Charpy 10 ft.lb. temperature, use was made of specimen fracture appearance after testing to help analyze the results of each test.

A correlation between the drop-weight NDT and the Kinzel 1% lateral contraction temperatures was found to exist when Kinzel specimen behavior reflected the ability of the base material to prevent cleavage crack propagation.

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INTRODUCTION

Brittle failures of welded ships during the last World War have led to extensive studies on the notch toughness of steels used in welded structures. Much helpful data have been accumulated from the various notch toughness tests; however, many points of confusion exist. These include interpretation of laboratory tests, correlation between the various laboratory tests and the correlation between laboratory tests and service performance. While all the tests show broad agreement in evaluating the notch toughness of steel, the use of the many specimen designs and the various test criteria have complicated the picture.

Most tests do not use a welded specimen which would be desirable when dealing with weld structure. The Charpy V-notch impact test does not incorporate a welded specimen, but it has the advantage of being easy to use and it readily measures the response of the transition temperature to the various heat treatments. Several different criteria have been used as a measure of the transition temperature in the Charpy test. The most widely accepted is the 10 foot-pound level which has been successfully correlated with service performance (1,2). This correlation was obtained from the study of the ship fractures, where it was found that a cleavage crack always started in a steel plate that could not absorb 10 foot-pound of energy at the temperature of failure.

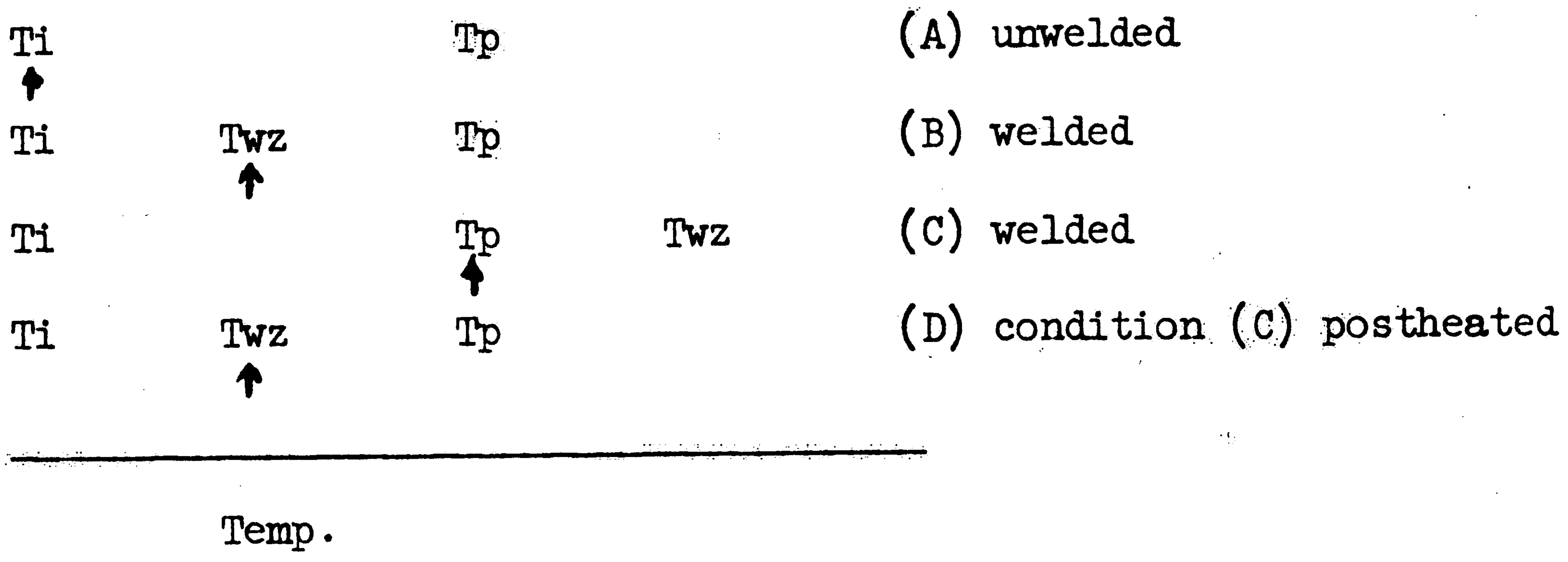
The Naval Research Laboratory (NRL) has developed a drop weight test using, essentially, an unwelded specimen (3,4,5,6). The test was developed to measure the "nil ductility temperature." The nil ductility temperature can be described as the temperature above which the amount of deformation required to "force" the propagation of fracture increases rapidly with temperature and below which the specimen cannot stand a small amount of deformation in the presence of the sharp notch used in the test. The actual specimen has a hard-facing weld deposit on the surface This is used only as a means of developing a running cleavage crack which is the sharpest obtainable notch. Pellini and co-workers feel that the heat affected zone under the weld does not affect the nil ductility temperature. They cite as evidence the ability to obtain the same nil ductility temperature before and after heat treating a series of specimens for one hour at 1100°F. Pellini has been able to relate the nil ductility temperature with the Charpy V-notch test (4). In rimmed steels, the Charpy energy level did not exceed 7 foot pounds at the NDT; in the semi-killed steels the Charpy energy level did not exceed 10 foot pounds at the NDT.

The last test considered is the Kinzel test (7,8). This test was developed to measure the effect of welding on the transition temperature of the steel specimen. Murphy and Stout give two important factors to consider when studying the effect of welding on the Kinzel test transition temperature. These two factors are:

(1) the tendency of the weld zone to initiate cleavage failure,

(2) the ability of the base metal to prevent propagation of cleavage failure.

This they show by the following schematic diagram.



In the above diagram the symbols are defined as follows:

Ti = Temperature at which cleavage is initiated easily in unwelded specimens. Defined here at 1% lateral contraction.

Tp = Lowest temperature at which the base material prevents easy propagation of a cleavage crack and thus raises the lateral contraction to 1%.

Twz = Highest temperature at which any area in the weld zone can initiate cleavage failure.

In Figure (A) the arrow indicates where the 1% lateral contraction transition temperature is located. This is for an unwelded specimen and here the transition temperature is determined by Ti. Since these are properties of the base metal they remain constant throughout the remaining figures. In the last figure, (D), this is not true but the change will usually not be appreciable.

In Figure (B) the weld zone is able to initiate a cleavage crack between Ti and Tp. In this case it controls the transition temperature.

For the case in Figure (C) the weld zone can indicate a cleavage crack at Twz and the crack propagates into the base material until further propagation is prevented by the base material. Therefore, shear rings are formed in the base material. Below Tp the propagation of the cleavage crack cannot be stopped by the base material. Therefore, Tp is the transition temperature. Postheating the specimen in Figure (C) lowers Twz below Tp and it again controls the transition temperature.

In the work of Murphy and Stout the above could be seen by looking at the fracture surfaces of the broken specimens, in which the condition illustrated in Figure (C) was demonstrated by rings of fibrous failure around the weld zone in the base metal from where the cleavage crack originates. As the test temperature is lowered these shear rings disappear and the lateral contraction drops below 1%.

In a few cases the influence of the weld zone was altered by the presence of a tough material surrounding a more brittle structure in the heat affected zone. In this case a cleavage crack could be stopped by the heat affected zone, raising the lateral contraction above 1%.

It was thought that the fracture surfaces might be of further interest so the study of the fracture patterns is continued in this paper. Also the disappearance of the shear rings or the "nil shear" temperature in Murphy and Stout's paper was thought to be similar to the nil ductility temperature of the drop weight test. This was investigated.

As a further study, a comparison between the 11-inch span Kinzel test and the 7-inch span Kinzel test was made.

The object of this paper is to try to correlate the different tests described above. Points of similarity as well as differences between the tests will be examined. It is hoped that the paper will lead to a better understanding of the tests and their interrelations.

MATERIAL

The steels used in this investigation were ordered to A.S.T.M. specifications except the 48S5, which has an American Bureau of Shipping specification, and the T-1, a steel developed by United States Steel Corporation.

The analyses and tensile properties are given in Tables I and II, respectively.

The E6010, E9010, E7015 and E12015 electrodes used were 3/16 inch in diameter and ordered to A.W.S. specifications. The Murex Hardex N is a special hard-facing electrode.

Apparatus and Procedure

The steels tested were received in large 1-inch thick plates. These were flame cut into smaller sections. A section, selected at random, was then cut into the desired test specimens.

The normalizing treatment, for the Kinzel and the drop weight specimens, was done in a reducing atmosphere at 1650°F for one hour. The normalized Charpy specimens were cut from the unstrained portion of a broken normalized Kinzel or drop weight specimen that had failed in a completely brittle fashion.

The A-302 steel was welded with E9010 electrodes, the 48S5 steel welded with E7015 electrodes, and the T-1 steel welded with E12015 electrodes. The balance of the steels were welded with E6010 electrodes. The weld bead was always parallel to the rolling direction and was deposited using 170 amps and 28 volts, with the exception of the E7015 and E12015 electrodes, which deposited weld beads using 190-200 amps and 22-24 volts. The welding speed was approximately 6 inches a minute. The Murex Hardex N electrodes were used for the weld bead on the drop weight specimens. This was deposited in the longitudinal direction using a current of 190-200 amps with 22 volts and a welding speed of 5 inches per minute. This left a moderately high weld deposit 2 inches long with a hardness of Rc46. All welded specimens were then set aside for 7 days to age before testing.

The Charpy specimens were ground to standard dimensions and notched with the regular Charpy V-notch. The longitudinal axis of the specimen was always parallel to the rolling direction of the plate and the notch machined perpendicular to the plate surface. Testing temperatures below room temperature were obtained by placing the sample in an alcohol bath and cooling the bath with dry ice to the desired temperature. Temperatures above room temperature were obtained by placing the sample in water or glycerin and heating on an electric burner. After the specimen had reached the desired temperature it was quickly placed in the impact machine and tested The energy required to break the specimen was recorded.

The Kinzel specimens were machined and notched as shown in Figure 1 in the appendix. A testing span of 11 inches was used. Five series of the regular 7-inch span were also tested. The testing temperatures were obtained by methods described above. The only difference being a larger bath and, for the unwelded specimens, where the extra low temperatures were obtained by using petroleum and liquid nitrogen. Measurements were taken of the lateral distance 1/32nd inch below the notch for each specimen before and after testing. Any lateral contraction less than 1% was considered to indicate a brittle failure. The temperature of the complete disappearance of shear rings in the weld zone or base metal was taken as the "nil shear" temperature. A load-deflection curve was obtained for each specimen tested.

After testing, the fracture surface was examined and drawings made of the shear and cleavage areas. An example is shown in Figure 3. The top of the drawing represents the bottom of the notch. The first arc at the top in the center represents the weld metal. Between the first and second arc represents the heat affected zone. Shear is indicated by cross-hatching; the cleavage is the open portion (the rest of the surface). The percent lateral contraction is given in the lower right corner. The temperature at which the specimen was tested is placed at the side.

The drop weight specimens were tested in an apparatus similar to that developed at the Naval Research Laboratory, the major difference being in the height. The height of the drop was limited to a little over 8 feet because of the low ceiling. The falling weight was 100 pounds. This could be increased to 150 pounds by the addition of two lead blocks placed on the top of the weight. The drop weight specimens were of the same dimensions as used by the Naval Research Laboratory (Figure 2), a testing span of 12 inches and 3-1/2 inches wide. All specimens were 1 inch thick. The notch was cut with a milling cutter used in the Charpy V-notch. The cleavage crack was developed by bending the hard weld deposit in tension. The apex of the notch was always 0.070 inch above the base metal. The carbon steel specimens were allowed to bend a maximum of 0.30 inch when the falling weight struck them. The higher strength alloy steels (48S5 and T-1) were allowed to bend 0.5 inch because the running cleavage crack was harder to start in those steels of high yield strength. The testing temperature was obtained as in the Kinzel test, by dry ice and an alcohol bath.

By varying the testing temperature, the nil ductility temperature (NDT) was obtained. If the running cleavage crack, developed at the start of bending, ran through the specimen, the testing temperature was below the NDT If the crack stopped in the material and could not be broken by hand the testing temperature was above the NDT.

After the specimens were tested they were set aside for a day. The ductile specimens were then broken apart and the fracture surfaces were examined. A thin rust film indicated where the running cleavage crack stopped. These were recorded in a manner similar to the fracture patterns of the Kinzel specimens. The top of the drawing represents the top of the specimen and not the bottom of the notch as in the drawings of the Kinzel fracture surfaces. The line drawn around the weld zone is where the cleavage crack was stopped. The testing temperature is indicated at the side of the drawing.

Three series of regular drop weight specimens were tested in the 11-inch span Kinzel apparatus as a further comparison between the two tests. In order to maintain the same criterion as used in the drop weight test, the specimens were assumed to have failed only when they fractured completely before 0.3 inch deflection was reached. The loading rate was 2 inches per minute. The percent lateral contraction and the nil shear were obtained as in the Kinzel test.

RESULTS AND DISCUSSION

The various individual tests are plotted on graphs in the appendix. Table III is a compilation of the transition temperatures for all the steels in all conditions as determined by the three testing methods.

Correlation Between the NDT and the Kinzel Transition Temperature

In Figure 3 in the appendix the fracture patterns of the Kinzel and drop weight specimens are drawn for a representative steel. In the Kinzel test at -20°F, the cleavage crack, initiated in the weld zone, propagated through the entire specimen while in another Kinzel specimen, at the same temperature, the cleavage crack did not propagate completely through the specimen but changed into a region of shear. The region of shear in the base metal caused the lateral contraction to rise above 1%. The 1% lateral contraction and the nil shear transition temperature for this Kinzel series are both at -20°F.

In the drop weight tests, at and below -10°F, the cleavage crack initiated in the hard-surfacing weld ran completely through the specimen. One specimen at -10°F and those above this temperature stopped the propagation of the crack in the base metal. The NDT for this series is -10°F. It must be remembered that the fibrous areas are produced after testing when the specimens are broken apart.

There was an obvious similarity between the fracture patterns. In both series the resistance of the base metal to the propagation of a cleavage crack was measured. There was also a high degree of correlation between the two tests as shown in Figures 4 and 5 in the appendix where the two regression lines* almost coincide. This similarity was valid only for the particular steels plotted where the 1% lateral contraction was controlled by the ability of the base material to prevent cleavage crack propagation.

Correlation Between the Charpy V Transition, the NDT, and the Kinzel Transition

In Figure 6, the correlation between the Charpy V-notch 10 foot pound transition temperature and the NDT is shown. In Figures 7 and 8, the correlations between the Charpy V-notch 10 foot pound transition temperature and the transition temperatures measured by the Kinzel test are shown. The curve for NDT vs. the 10 foot pound transition temperature for these particular steels shows an excellent correlation; the two regression lines almost coincide. The slopes of the lines are not close to 45°; the Charpy V-notch transition temperatures fall faster than the NDT as the notch toughness increases. The relative effect of increasing the notch toughness is shown in Figure 9. In all cases the normalizing treatment decreased the Charpy transition temperature by at least 25°F in the steels tested and the decrease was always more than the NDT. In the A7 (RW) steel the NDT did not change. The Kinzel 1% lateral contraction is even less consistent. In two cases A-7 (W) and A-201 (RB), normalizing increased the transition temperature and for the A-201 (Y) and the A-285 steels there was no change.

There is considerable spread in the point on the scatter diagrams of the Charpy transition temperatures vs. the 1% lateral contraction

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*See Appendix I.

transition temperature and the nil shear temperature. The angle between the regression lines is very large as compared to that between the Charpy transition temperature vs. the NDT and the NDT vs. the Kinzel transition temperatures. There is, however, a definite correlation between the two tests.

Effect of Increasing the Test Span on Kinzel Transition Temperature Correlation Between 7-inch and 11-inch Kinzel Specimens

The difference in the transition temperatures obtained by the 7-inch span and by the 11-inch span Kinzel tests (see Table IV) can possibly be explained by two factors. First, the energy available to propagate the cleavage crack is greater in the 7-inch span than in the 11-inch span. The moments in inch pounds, measured to the center of the span, are almost the same in each test. To obtain the same moment the 7-inch span will require a greater force exerted by the testing machine; therefore, more energy is stored in the machine and in the specimen to propagate the cleavage crack. Second, the constraint is greater in the 7-inch than in the 11-inch span. This will tend to increase the severity of the test which will increase the transition temperature.

Effect of Loading Rate on NDT

Tests were conducted on several steels to determine the effect of loading rate on the nil ductility temperature. Standard drop weight specimens were tested in slow bending in the same manner the Kinzel specimens were tested. In order to maintain the same transition criterion for the slow bend tests as the drop weight tests, the specimens were assumed to have failed only when complete brittle fracture resulted before a deflection of 0.3 inch was reached. Results of these tests and the standard drop weight tests are reported in Table V. The slow bending of the drop weight specimens decreased the transition temperature 40 to 65°F below the standard NDT.

Conclusions

(1) There is a very good correlation between the nil ductility transition as determined by the crack starter drop weight test and the Kinzel 1% lateral contraction. The two regression lines almost coincide with an approximate one-to-one correlation. This correlation is valid only for those steels in which the behavior of the Kinzel specimen tested above the transition temperature is one in which the propagation of a cleavage crack, initiated in the weld zone, is inhibited by the base material.

(2) For most of the structural steels tested, the Kinzel 1% lateral contraction transition temperature was a manifestation of the ability of the base material to inhibit propagation of a weld-zone-initiated cleavage crack.

(3) For the steels tested here, fracture examination of standard drop weight specimens indicated that the NDT was a true measure of the base material notch toughness and was not affected by the heat-affected zone beneath the weld.

(4) The correlation between the nil ductility transition and the Charpy 10 foot pound is excellent, but is not a one-to-one correlation. The Charpy 10 foot pound transition temperatures fall faster than the NDT as the toughness of the steels improves.

(5) There is not a good correlation between the Kinzel 1% lateral contraction transition temperature and the nil shear temperature with the Charpy 10 foot pound transition temperature. Both exhibit the same general trend but there is considerable scatter in the points.

(6) Decreasing the loading rate by testing drop weight specimens in slow bending lowered the NDT by 40 to 65°F.

(7) The 7 inch span Kinzel specimen increases the 1% lateral contraction transition temperature over that measured with an 11 inch span specimen. This may be explained by the increase in constraint and the added energy stored in the test system which is available to propagate the cleavage crack.

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APPENDIX I

Graphical and Numerical Correlation

Between the Various Tests

The correlations between the various tests were analyzed statistically. The method is outlined below for the correlation between the Kinzel 1% lateral contraction transition temperature and the nil ductility temperature (NDT).

Since either the 1% lateral contraction transition temperature, or the nil ductility temperature (Figure 5) can be the variable and the other the dependent variable, there are two regression lines. The two regression lines are also plotted on the diagram. Regression lines are least square lines, one minimizes the error in the Y direction ($y = 1.6 + 1.19x$) and the second minimizes the error in the X direction ($x = -0.4 + 0.70y$). If there were a perfect correlation between the two transition temperatures the two regression lines would become one line. Therefore, the slopes of the two regression lines are a measure of their correlation. The coefficient of correlation is given by the following equation (12):

$$r = (b \cdot b')^{1/2}$$

where b and b' are the slopes of the two regression lines. A perfect correlation would be $r = \pm 1$. The significance of r can be obtained from a statistical table which also takes into account the number of samples used.

In this case, $r = 0.914$. The significance of correlation is greater than 99.9% which is highly significant.

TABLE I

Steels and Chemical Composition

			% Composition								
Spec.	Steel Grade	Code	C	Mn	P	S	Si	Ni	Cr	Mo	Other
A-7	-	RW	.20	.75	.009	.030	-	-	-	-	-
A-7	-	W	.27	.60	.014	.031	-	-	-	-	-
A-201	A	RB	.12	.48	.010	.022	.18	-	-	-	-
A-201	A	Y	.11	.51	.020	.024	.20	-	-	-	-
A-212	B	KC	.25	.66	.020	.022	.19	-	-	-	-
A-285	B	RG	.09	.49	.010	.031	-	-	-	-	-
A-302	B	H	.18	1.12	.035	.033	.23	-	-	.45	-
A-302	B	B	.20	1.32	.022	.030	.25	-	-	.42	-
48s5	-	E	.15	1.09	.033	.028	.18	.06	.06	.02	V - .09 Ti - .009 Cu - .11
T-1	-	R	.15	.93	.015	.022	.27	.89	.48	.44	V - .06 B - .0031

TABLE II

Tensile Properties of Steels

Steel	Condition	Y.P.	T.S.	% Elong. (2")	% R.A.
A-7	A.R.	28,200	68,800	33.3	63.2
	N.	38,700	58,900	37.0	67.8
A-7 (W)	A.R.	39,500	80,200	22.8	52.3
	N.	41,400	79,000	23.0	43.4
A-201 (RB)	A.R.	28,700	56,400	36.0	67.4
	N.	36,800	57,800	36.0	68.8
A-201 (Y)	A.R.	27,600	56,300	36.3	76.8
	N.	38,000	58,700	36.0	69.2
A-212 (KC)	A.R.	36,400	71,700	31.7	61.5
	N.	44,400	72,900	31.7	63.5
A-212 (T)	A.R.	42,100	83,300	22.6	45.8
A-285	A.R.	21,200	50,100	37.0	66.8
	N.	33,000	51,600	38.2	69.5
A-302 (H)	A.R.	67,000	95,400	20.2	66.2
	N.	47,700	85,600	26.8	62.2
A-302 (B)	M.N.	52,000	83,300	22.1	55.8
48s5	M.N.	47,300	68,300	29.8	67.2
T-1	Q.&T.	114,000	123,600	13.9	57.5

A.R. - As rolled
N. - Lab. normalized

M.N. - Mill normalized
Q.&T. - Quenched and tempered

TABLE III

Transition Temperatures Obtained by Four Testing Methods

Steel	Condition	Kinzel		Drop weight N.D.T.	V-Charpy 10 ft.lb.
		1% Lat. cont.	Nil-shear		
A-7 (RW)	A.R.	+20°F	+15°F	+ 5°F	+15°F
	N.	+ 5	+ 5	+ 5	-10
A-7 (W)	A.R.	+20	+20	+35	+60
	N.	+25	+10	+25	+35
A-201 (RB)	A.R.	-30	-30	- 5	+15
	N.	-20	-20	-10	-30
A-201 (Y)	A.R.	+10	+10	+10	+10
	N.	-	-	-20	-25
A-212 (KC)	A.R.	+25	+15	+15	+10
	N.	+ 5	+ 5	+ 5	-20
A-212 (T)	A.R.	+60	+25	+35	+60
A-285	A.R.	-15	-15	+ 5	+35
	N.	-15	-15	-15	+10
A-302 (H)	A.R.	+100	+100	-	+10
	N.	-	-	-20	-25
A-302 (B)	M.N.	+ 20	-	+ 5	-35
48s5	M.N.	-20	-	-15	-60
T-1	Q.&T.	-80	-80	-85	-210

A.R. - As rolled
N. - Lab. normalized

M.N. - Mill normalized
Q.&T. - Quenched and tempered

TABLE IV

Comparison Between Kinzel Specimens of Different Spans

	11 Inch Span			7 Inch Span		
Steel	Load* lbs	Moment in-lb	Trans Temp °F	Load* lbs	Moment in-lb	Trans Temp °F
A-7 (W)	13,200	73,000	+20	22,300	78,000	+45
A-201 (Y)	13,200	73,000	+10	24,000	84,000	+20
A-212 (KC)	14,800	81,000	+15	28,800	101,000	+60
A-212 (T)	13,300	73,000	+25	22,300	78,000	+55
A-302 (H)	24,500	132,000	+100	39,400	138,000	+125

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*Load at which the cleavage starts

TABLE V

Effect of Loading Rate on NDT

Steel	Condition	Standard NDT °F	Slow Bend NDT °F
A-7 (RW)	As Received	+5	-35
A-201 (RB)	As Received	-5	-60
A-285	As Received	+5	-60

TABLE VI

Experimental Data for Steel: A-201 (Y)

Series: As-Received Welded 11 in Kinzel

Test Temp °F	% Lateral Contraction	Maximum Load	Shear Rings
30	2.6	17,700	Yes
20	1.1	14,200	Yes
20	1.2	15,100	Yes
20	1.2	14,300	-
10	1.3	12,300	Yes
10	0.8	14,200	-
10	0.7	13,200	-
0	0.3	12,200	-
0	0.4	13,200	-
0	0.9	14,000	-
-10	1.5	12,600	Yes
-10	0.7	13,600	-
-20	0.4	13,100	-

1% Trans Temp +10°F
Nil Shear Temp +10°F

Series: As-Received Drop Weight

Test Temp °F	Propagation of Crack Stopped
20	Yes
20	Yes
10	Yes
10	Yes
10	No
0	No
-10	No

NDT +10°F

Series: Normalized Drop Weight

Test Temp °F	Propagation of Crack Stopped
0	Yes
-10	Yes
-10	Yes
-10	Yes
-20	No
-20	Yes
-20	Yes
-30	No

NDT -20°F

Continued

TABLE VI
(Continued)

Experimental Data for Steel: A-201 (Y)

Series: As-Received Charpy

Test Temp °F	Energy Ft Lb
78	104
70	162
60	102
60	80
50	38
50	30
50	21
40	22
40	18
30	16
30	15
20	10
20	12
20	14
10	10
10	10
0	7
0	7
-20	5

10 ft lb level + 10°F

Series: Normalized Charpy

Test Temp °F	Energy Ft Lb
20	168
10	130
10	110
0	15
0	30
0	32
0	33
-10	11
-10	12
-10	13
-20	11
-20	13
-30	8
-30	9
-40	5
-40	10
-50	3
-60	3

10 ft lb level -20°F

TABLE VII

Experimental Data for Steel: A-212 (T)

Series: As-Received Welded 11 in Kinzel

Test Temp °F	% Lateral Contraction	Maximum Load	Shear Rings
70	1.6	14,000	Yes
70	0.9	15,100	Yes
60	1.4	14,200	Yes
60	0.4	14,200	Yes
60	0.7	14,000	Yes
60	1.2	14,300	Yes
60	1.1	15,000	Yes
50	0.9	12,700	Yes
50	0.8	14,300	Yes
50	0.9	13,600	Yes
40	0.7	13,100	Yes
40	0.8	12,900	Yes
30	0.7	13,700	Yes
30	0.8	13,400	-
20	0.6	13,300	-
20	0.6	13,600	Yes

1% Trans Temp 60°F
Nil Shear Temp 25°F

Series: As-Received Charpy

Test Temp °F	Energy Ft Lb
175	48
146	38
125	23
103	17
100	20
90	17
90	13
80	13
80	12
68	12
60	11
60	9
54	8
50	7
40	5

10 ft lb level 60°F

Series: As-Received Drop Weights

Test Temp °F	Propagation of Crack Stopped
50	Yes
40	No
40	Yes
40	Yes
30	No
30	Yes
20	No
20	No

NDT 15°F

TABLE VIII

Experimental Data for Steel: A-212 (KC)

Series: As-Received Welded 11 in Kinzel

Test Temp °F	% Lateral Contraction	Maximum Load	Shear Rings
40	1.5	16,200	Yes
40	2.5	15,000	Yes
40	2.3	17,200	Yes
30	0.9	15,800	-
30	1.0	15,600	Yes
30	1.3	15,300	Yes
20	0.9	14,700	Yes
20	1.5	15,800	Yes
20	0.8	14,900	-
10	0.3	14,900	-
10	0.3	15,100	-
0	0.2	14,800	-

1% Trans Temp +25°F
Nil Shear Temp +15°F

Series: Normalized Welded 11 in Kinzel

20	1.6	15,600	Yes
10	1.5	15,000	Yes
10	1.2	15,100	Yes
10	1.6	15,600	Click
10	1.7	15,500	Click
0	0.3	14,100	-
0	0.5	14,800	-
0	0.4	15,700	-
-10	0.2	15,000	-
-10	0.1	14,700	-

15 Trans Temp +5°F
Nil Shear Temp +5°F

Continued

TABLE VIII
(Continued)

Experimental Data for Steel: A-212 (KC)

Series: As-Received Drop Weight

Test Temp °F	Propagation of Crack Stopped
30	Yes
20	Yes
20	Yes
20	Yes
10	No
10	No
10	No
0	No

NDT 15°F

Series: Normalized Drop Weight

Test Temp °F	Propagation of Crack Stopped
20	Yes
10	Yes
10	Yes
10	Yes
0	No
0	No
0	No

NDT 5°F

Series: As-Received Charpy

Test Temp °F	Energy Ft Lb
185	93
165	80
140	77
125	52
100	69
75	47
53	18
40	33
40	16
30	12
30	35
30	13
20	15
20	15
20	14
10	9
10	11
10	8
0	6

10 ft lb level 10°F

Series: Normalized Charpy

Test Temp °F	Energy Ft Lb
165	105
140	98
125	92
100	83
75	78
53	56
30	38
20	36
10	18
10	27
0	18
0	13
-10	12
-10	17
-10	12
-20	12
-20	9
-30	8
-30	9

10 ft lb level -25°F

TABLE IX

Experimental Data for Steel: T-1

Series: Quenched and Tempered Drop Weight

Test Temp °F	Propagation of Crack Stopped
-70	Yes
-80	Yes
-80	Yes
-80	Yes
-80	Yes
-90	No
-90	No
-90	No
-100	No

NDT -85°F

TABLE X

Experimental Data for Steel: 48S5

Series: Mill Normalized Drop Weight

Test Temp °F	Propagation of Crack Stopped
0	Yes
-10	Yes
-10	Yes
-20	No
-20	No

NDT -15°F

TABLE XI

Experimental Data for Steel: A-302 (B)

Series: Mill Normalized Drop Weight

Test Temp °F	Propagation of Crack Stopped
+20	Yes
+10	Yes
+10	Yes
+10	Yes
0	No
0	No
0	Yes
-20	Yes

NDT +5°F

TABLE XII

Experimental Data for Steel: A-285

Series: As-Received Welded 11 in Kinzel

5

Test Temp °F	% Lateral Contraction	Maximum Load	Shear Rings
20	2.8	16,100	-
20	1.7	14,200	Yes
10	1.7	14,100	Yes
10	1.4	13,600	Yes
0	1.5	13,500	Yes
0	1.5	11,700	Yes
-10	1.3	11,600	Yes
-10	0.9	13,400	-
-20	0.5	11,800	-
-20	1.0	11,200	Yes
-30	0.8	12,900	-
-30	0.4	11,700	-

1% Trans Temp -15°F
Nil Shear Temp -15°F

Series: Normalized Welded 11 in Kinzel

10	1.2	13,200	Yes
10	2.3	15,400	-
0	1.0	12,000	-
0	2.2	15,100	Yes
-10	3.1	12,200	Yes
-10	1.1	11,400	Yes
-10	1.1	11,200	Yes
-10	0.9	12,100	-
-10	3.3	12,200	Yes
-20	0.8	12,300	-
-20	0.6	12,600	-
-20	0.6	11,100	Yes
-20	0.3	12,200	-
-30	0.3	12,900	-
-30	0.5	12,700	-
-50	0.5	12,200	-

1% Trans Temp -15°F
Nil Shear Temp -15°F

Continued

Table XII
(Continued)

Experimental Data for Steel: A-285

Series: As-Received Drop Weight

Test Temp °F	Propagation of Crack Stopped
20	Yes
20	Yes
20	Yes
10	No
10	No
10	No
10	Yes
0	Yes
0	Yes
0	No
0	No
-10	No
-10	No
-10	No

NDT 5°F

Series: Normalized Drop Weight

0	Yes
0	Yes
-10	Yes
-10	Yes
-10	Yes
-10	No
-20	No
-20	No
-20	No

NDT -15°F

TABLE XII
(Continued)

Experimental Data for Steel: A-285

Series: Normalized Charpy

Test Temp °F	Energy Absorbed Ft Lbs
125	152
110	104
95	89
83	67
75	59
57	28
45	28
30	19
30	21
30	17
20	14
20	13
10	10
10	9
10	10
0	9
0	8
-10	6
-20	5
-30	4

Series: As-Received Charpy

155	99
140	85
132	87
120	55
96	33
65	21
60	18
60	15
50	18
50	13
40	9
40	12
40	12
30	8
30	7
30	10
20	7
10	6
10	7
0	4
-10	3

TABLE XIII

Experimental Data for Steel: A-302 (H)

Series: As-Received Welded 11 in Kinzel

Test Temp °F	% Lateral Contraction	Maximum Load	Shear Rings
115	1.2	23,800	-
110	1.3	24,900	Yes
105	1.5	24,600	Yes
100	0.9	25,000	-
100	0.7	24,900	-
92	0.4	22,800	-
83	0.7	23,000	-
80	0.7	23,600	-
50	0.3	22,400	-
30	0.5	22,800	-

1% Trans Temp 100°F
Nil Shear Temp 100°F

Series: Normalized Drop Weights

Test Temp °F	Propagation of Crack Stopped
20	Yes
0	Yes
-10	Yes
-20	Yes
-20	No
-30	No
-30	No
-40	No

NDT -20°F

Continued

TABLE XIII
(Continued)

Experimental Data for Steel: A-302 (H)

Series: As-Received Charpy

Test Temp °F	Energy Ft Lb
175	58
146	48
120	37
104	29
90	27
80	35
80	18
68	23
60	17
50	12
50	11
40	20
40	14
30	20
30	15
30	13
20	20
20	15
20	10
10	17
10	11
10	7
0	8
0	7
0	6

10 ft lb level +10°F

Series: Normalized Charpy

Test Temp °F	Energy Ft Lb
90	47
74	40
70	38
60	42
50	36
30	30
20	26
0	20
0	16
-10	15
-20	13
-20	6
-30	9
-40	9
-50	8
-50	7

10 ft lb level -25°F

TABLE XIV

Experimental Data for Steel: A-7 (W)

Series: As-Received Welded 11 in Kinzel

Test Temp °F	% Lateral Contraction	Maximum Load	Shear Rings
60	0.9	14,400	Yes
60	0.9	13,700	Yes
50	0.9	14,400	Yes
50	1.3	14,200	-
40	1.1	12,600	Yes
30	1.0	13,400	Yes
20	0.3	13,000	-
20	1.0	13,400	Yes
10	0.5	13,500	-
10	0.1	13,000	-
0	0.0	12,900	-
0	0.1	13,700	-

1% Trans Temp +20°F
Nil Shear Temp +20°F

Series: Normalized Welded 11 in Kinzel

40	1.3	13,500	Yes
40	1.2	12,600	Yes
30	1.1	13,000	Yes
30	1.2	13,500	Yes
20	0.7	12,800	Yes
20	1.0	14,200	Yes
10	0.7	12,400	Yes
10	0.4	13,600	-
0	0.1	13,400	-
0	0.4	13,700	-

1% Trans Temp +25°F
Nil Shear Temp +10°F

Continued

TABLE XIV
(Continued)

Experimental Data for Steel: A-7 (W)

Series: As-Received Drop Weight

Test Temp °F	Propagation of Crack Stopped
40	Yes
40	Yes
40	Yes
30	No
30	No
20	No

NDT +35°F

Series: Normalized Drop Weight

Test Temp °F	Propagation of Crack Stopped
30	Yes
30	Yes
30	Yes
20	No
20	No
10	No

NDT +25°F

Series: As-Received Charpy

Test Temp °F	Energy Ft Lb
175	58
145	43
125	30
100	25
100	22
90	16
90	17
80	15
80	13
68	12
60	11
60	10
54	8
50	8
38	6

Series: Normalized Charpy

Test Temp °F	Energy Ft Lb
70	24
60	11
60	21
60	30
50	16
50	13
50	14
40	8
40	14
40	10
30	11
30	12
30	9
20	7
20	8
10	4
10	7
0	4
0	4

TABLE XV

Experimental Data for Steel: A-201 (RB)

Series: As-Received Welded 11 in Kinzel

Test Temp °F	% Lateral Contraction	Maximum Load	Shear Rings
40	Did not break		
0	Did not break		
-10	2.2	17,300	Yes
-10	1.6	12,700	Yes
-20	0.6	13,700	Yes
-20	0.4	12,100	Yes
-20	1.5	12,400	Yes
-30	1.1	12,000	Yes
-30	4.0	21,000	-
-30	1.1	13,500	Yes
-40	0.6	13,800	No
-40	0.3	13,400	No

1% Trans Temp -30°F
Nil Shear Temp -30°F

Series: Normalized Welded 11 in Kinzel

20	2.7	18,400	Yes
0	5.4	13,800	Yes
0	5.0	14,800	Yes
-10	3.8	--	Yes
-10	5.1	14,100	Yes
-10	4.7	13,500	Yes
-20	0.3	13,400	-
-20	4.4	13,600	Yes
-20	0.3	13,200	-
-30	0.2	14,200	-
-30	0.4	13,600	-
-40	0.1	13,900	-

1% Trans Temp -20°F
Nil Shear Temp -20°F

Continued

TABLE XV
(Continued)

Experimental Data for Steel: A-201 (RB)

Series: As-Received Charpy

Test Temp °F	Energy Ft Lb
73	122
60	162
50	22
50	82
40	20
40	17
30	11
30	17
20	13
20	10
10	9
10	9
0	9
0	7
-10	5

10 ft lb level +15°F

Series: Normalized Charpy

Test Temp °F	Energy Ft Lb
57	204
30	207
30	207
20	116
10	39
0	22
-10	21
-10	29
-20	17
-20	16
-20	12
-30	7
-30	9
-30	12
-40	9
-40	8
-50	5

10 ft lb level -30°F

TABLE XV
(Continued)

Experimental Data for Steel: A-201 (RB)

Series: As-Received Drop Weights

Test Temp °F	Propagation of Crack Stopped
+10	Yes
0	Yes
0	Yes
0	Yes
-10	Yes
-10	No
-10	No
-10	No
-20	No
-20	No
-30	No
-50	No

NDT -5°F

Series: Normalized Drop Weights

0	Yes
0	Yes
0	Yes
-10	Yes
-10	Yes
-10	No
-10	No
-20	No
-20	No
-20	No

NDT -10°F

Series: As-Received - Slow Drop Weights

-20	Yes
-40	Yes
-40	Yes
-50	Yes
-50	Yes
-60	No
-60	Yes
-70	No

NDT -60°F

TABLE XVI

Experimental Data for Steel: A-7 (RW)

Series: As-Received Welded 11 in Kinzel

Test Temp °F	% Lateral Contraction	Maximum Load	Shear Rings
61	1.6	15,600	Yes
50	1.5	14,100	Yes
40	1.3	16,600	-
40	1.5	16,300	Yes
30	0.7	15,000	-
30	1.1	13,400	Yes
30	1.8	18,200	-
20	2.1	12,800	Yes
20	1.7	12,700	Yes
20	0.9	15,000	Yes
20	1.1	13,000	Yes
10	0.5	13,800	-
10	0.5	13,600	-
0	0.3	13,500	-
0	0.4	13,200	-

1% Trans Temp +20°F
Nil Shear Temp +15°F

Series: Normalized Welded 11 in Kinzel

Test Temp °F	% Lateral Contraction	Maximum Load	Shear Rings
40	4.1	15,500	Yes
20	2.0	13,500	Yes
20	2.3	13,800	Yes
20	3.0	13,500	Yes
10	1.1	15,600	Yes
10	2.2	13,700	Yes
10	0.8	14,000	-
10	1.8	13,800	Yes
10	2.4	13,700	Yes
0	0.3	13,900	-
0	0.7	13,700	-
0	0.3	13,300	-

1% Trans Temp +5°F
Nil Shear Temp +5°F

TABLE XVI
(Continued)

Experimental Data for Steel: A-7 (RW)

Series: As-Received Drop Weight

Test Temp °F	Propagation of Crack Stopped
40	Yes
20	Yes
10	Yes
10	Yes
10	Yes
0	No
0	No
0	No
-10	No

NDT +5°F

Series: Normalized Drop Weight

20	Yes
10	Yes
10	Yes
10	Yes
0	No
0	No
0	No
-10	No

NDT +5°F

Continued

TABLE XVI
(Continued)

Experimental Data for Steel: A-7 (RW)

Series: Normalized Charpy

Test Temp °F	Energy Ft Lb
150	107
125	93
105	112
83	80
75	90
57	54
45	53
30	45
30	20
30	30
20	17
20	17
10	13
10	14
0	17
0	11
-10	8
-10	10
-10	10
-20	7
-20	8
-30	8

10 ft lb level -10°F

Series: As-Received Charpy

Test Temp °F	Energy Ft Lb
171	100
150	92
125	92
105	79
83	52
75	50
61	46
50	18
40	20
40	14
30	14
30	12
20	8
20	12
20	11
10	7
10	8
0	6
0	8

10 ft lb level +15°F

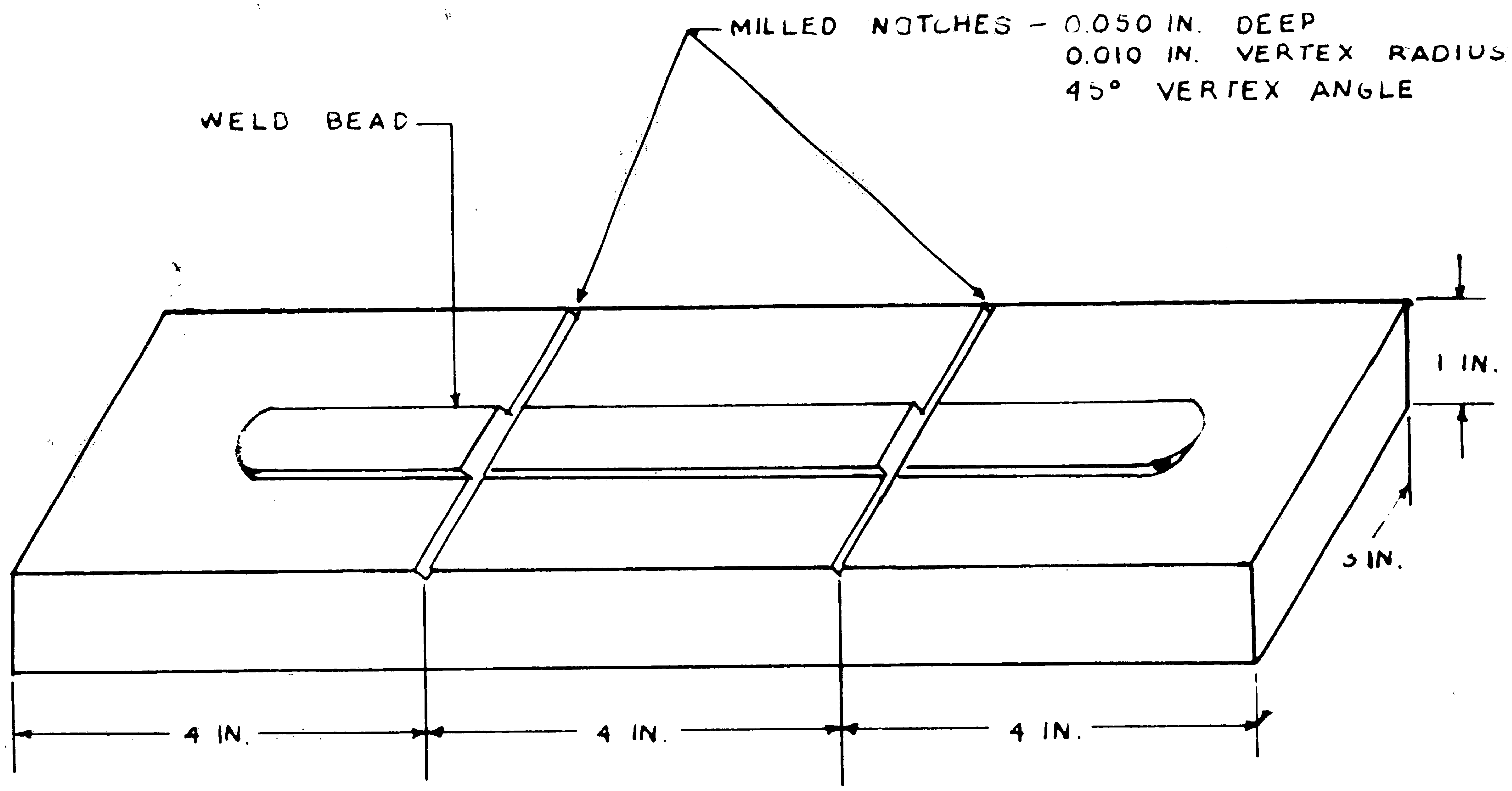


FIG. 1 MODIFIED KINZEL NOTCH-BEND SPECIMEN.

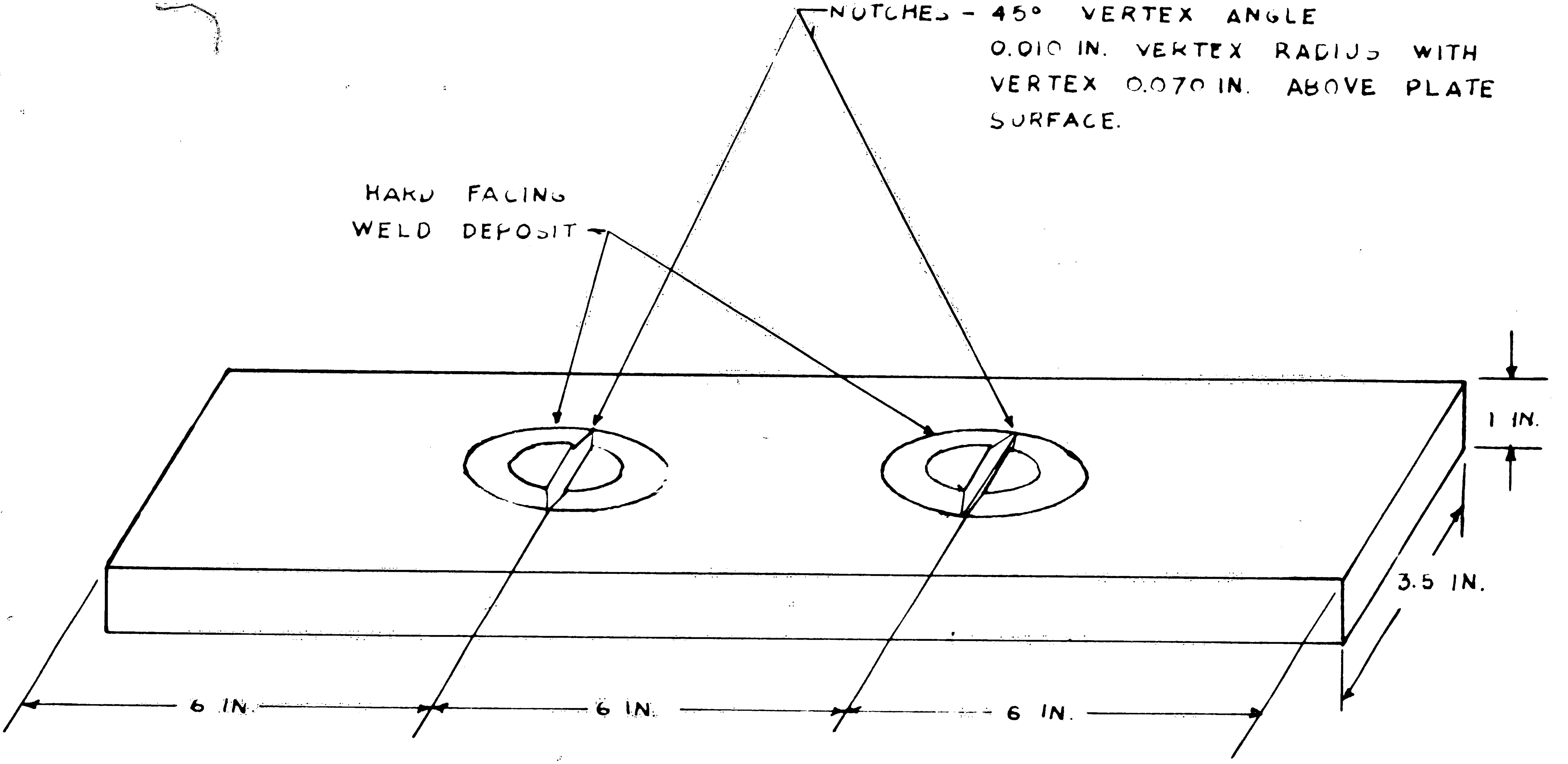


FIG. 2 DROP WEIGHT SPECIMEN.

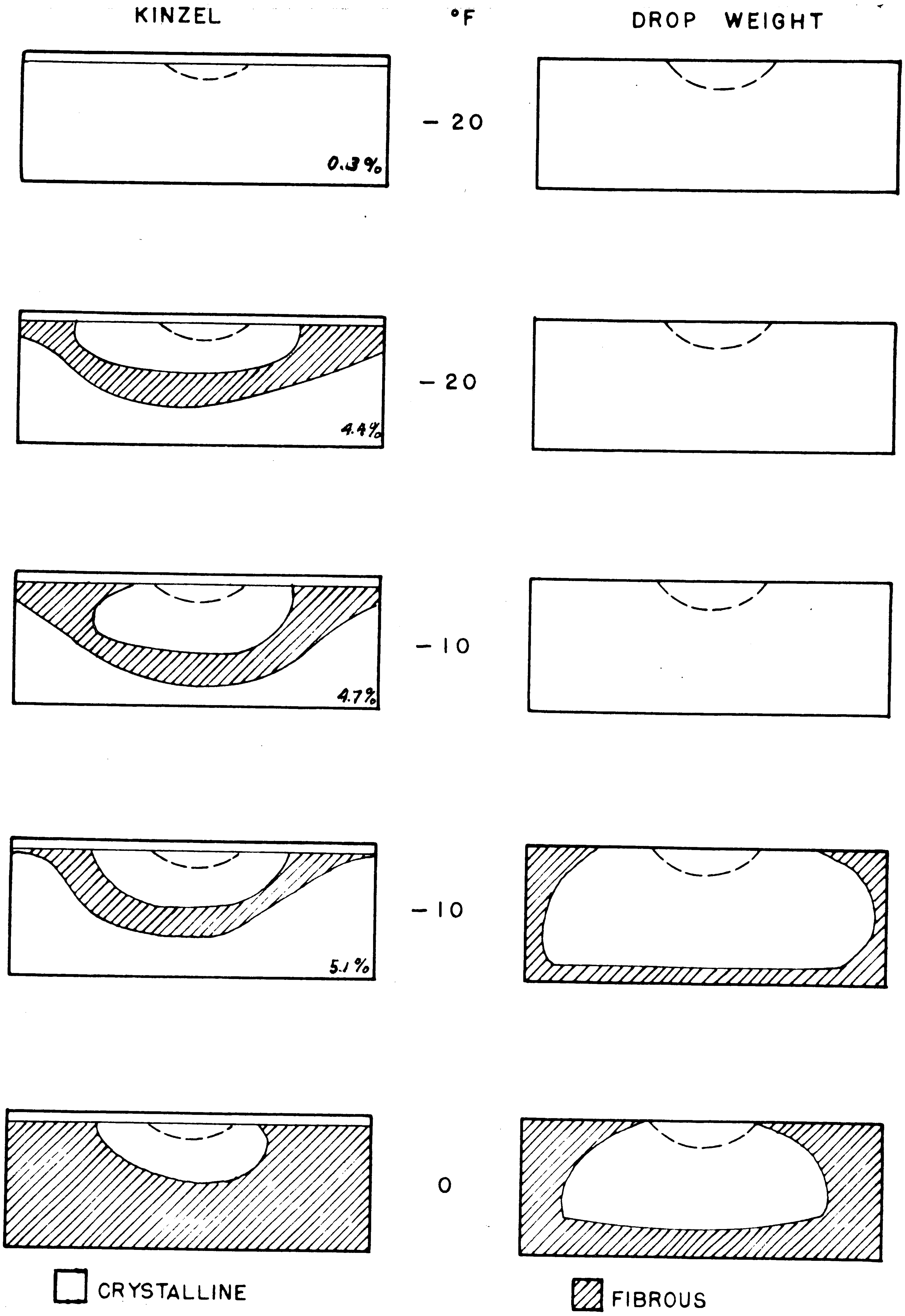


FIG. 3 TYPICAL FRACTURE PATTERNS FOR KINZEL AND DROP-WEIGHT SPECIMENS TESTED THROUGH THE TRANSITION RANGE.

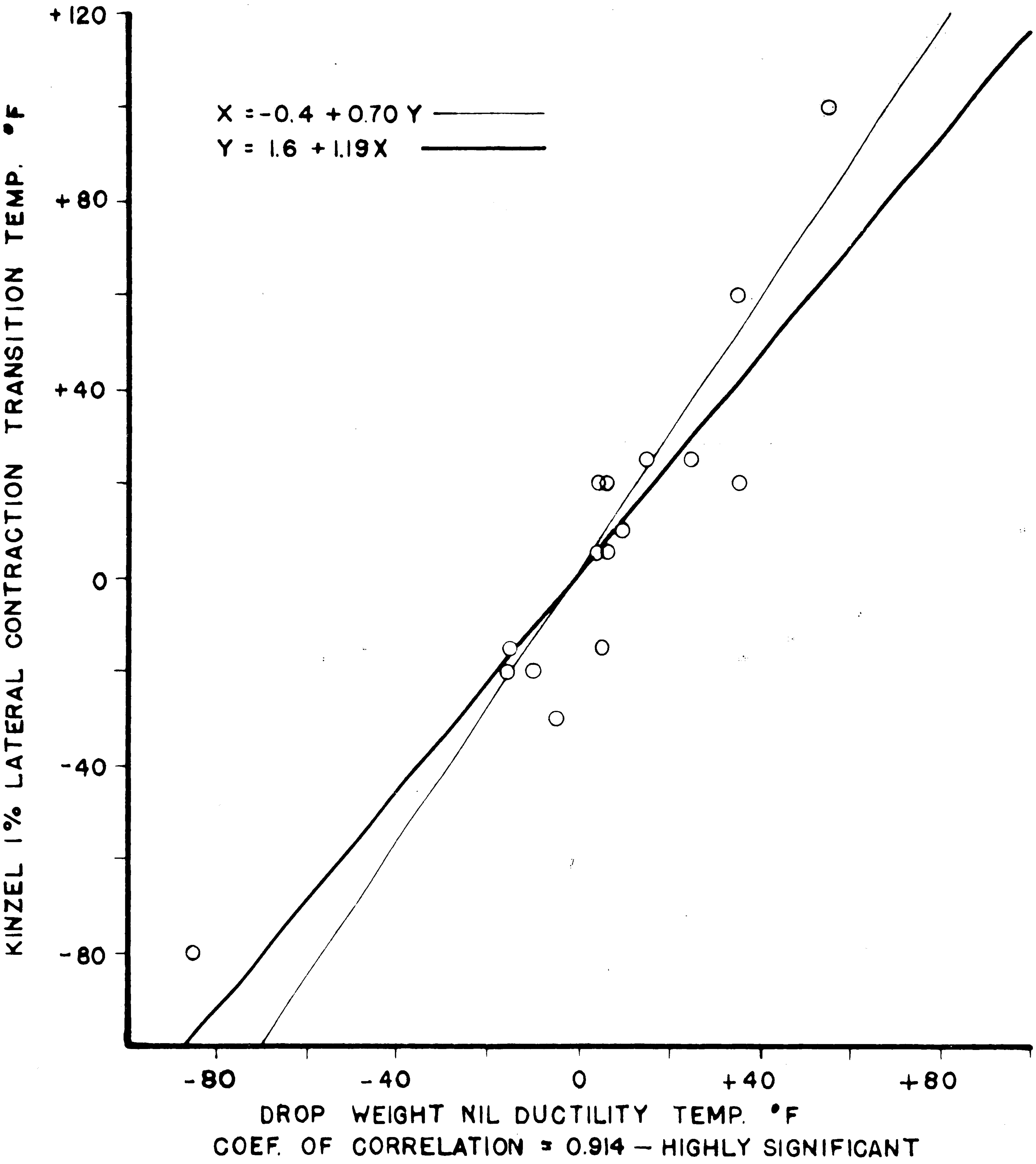


FIG. 4 CORRELATION BETWEEN THE KINZEL 1% LATERAL CONTRACTION TRANSITION TEMPERATURE AND THE NIL DUCTILITY TEMPERATURE.

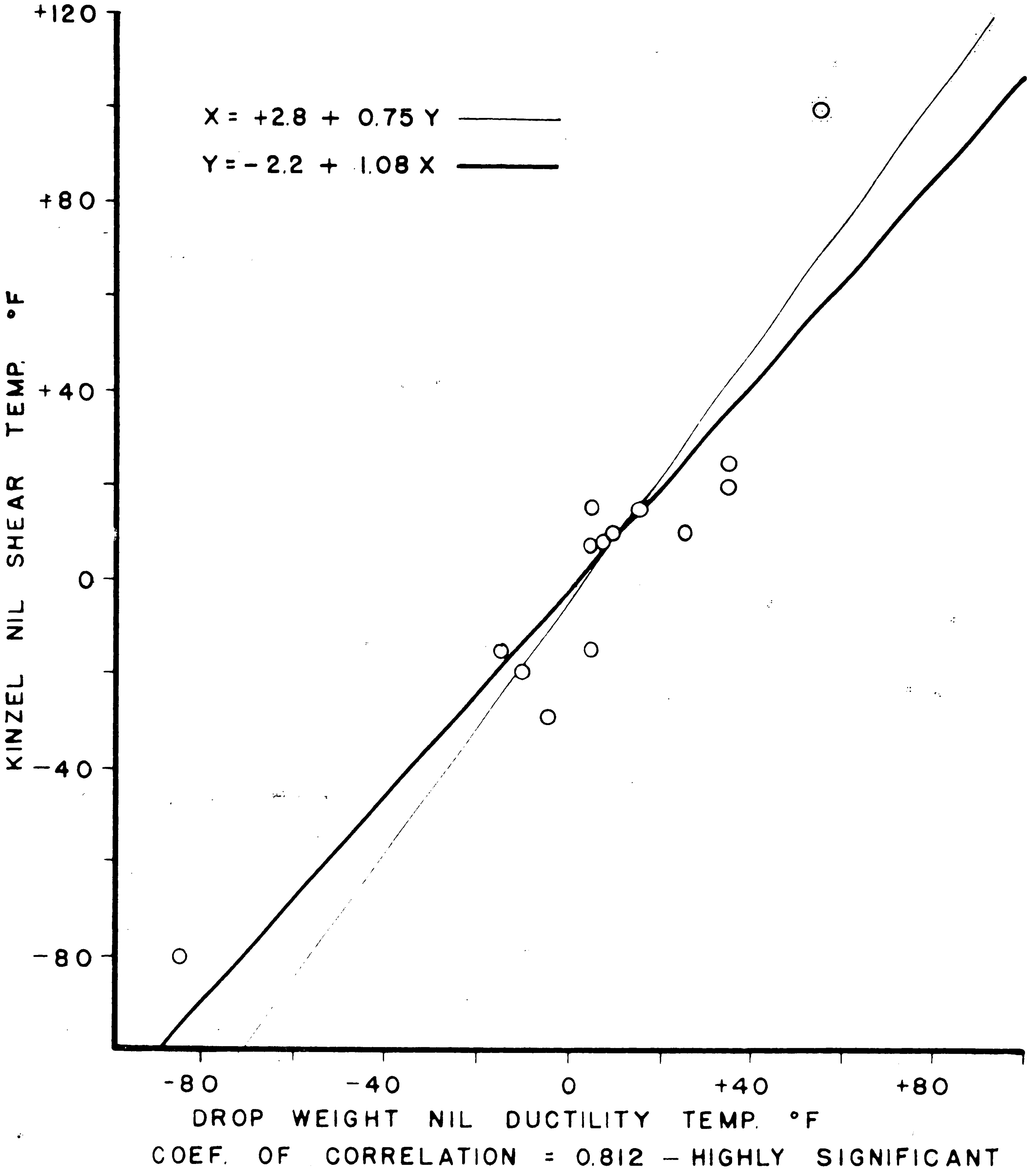


FIG. 5 CORRELATION BETWEEN THE KINZEL NIL SHEAR TEMPERATURE AND THE NIL DUCTILITY TEMPERATURE.

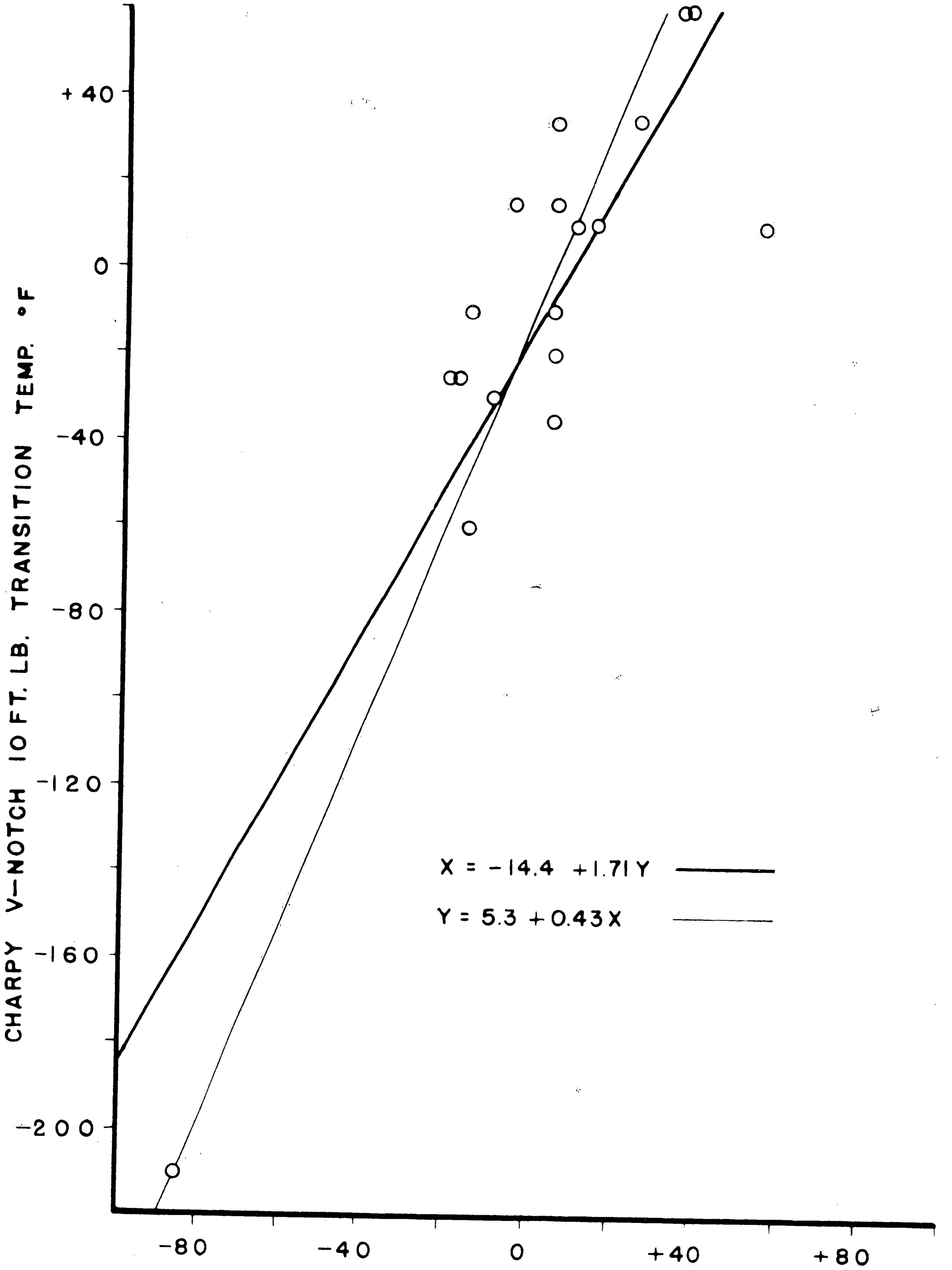


FIG. 6 CORRELATION BETWEEN THE CHARPY V–NOTCH 10FT. LB. TRANSITION TEMPERATURE AND THE NIL DUCTILITY TEMPERATURE

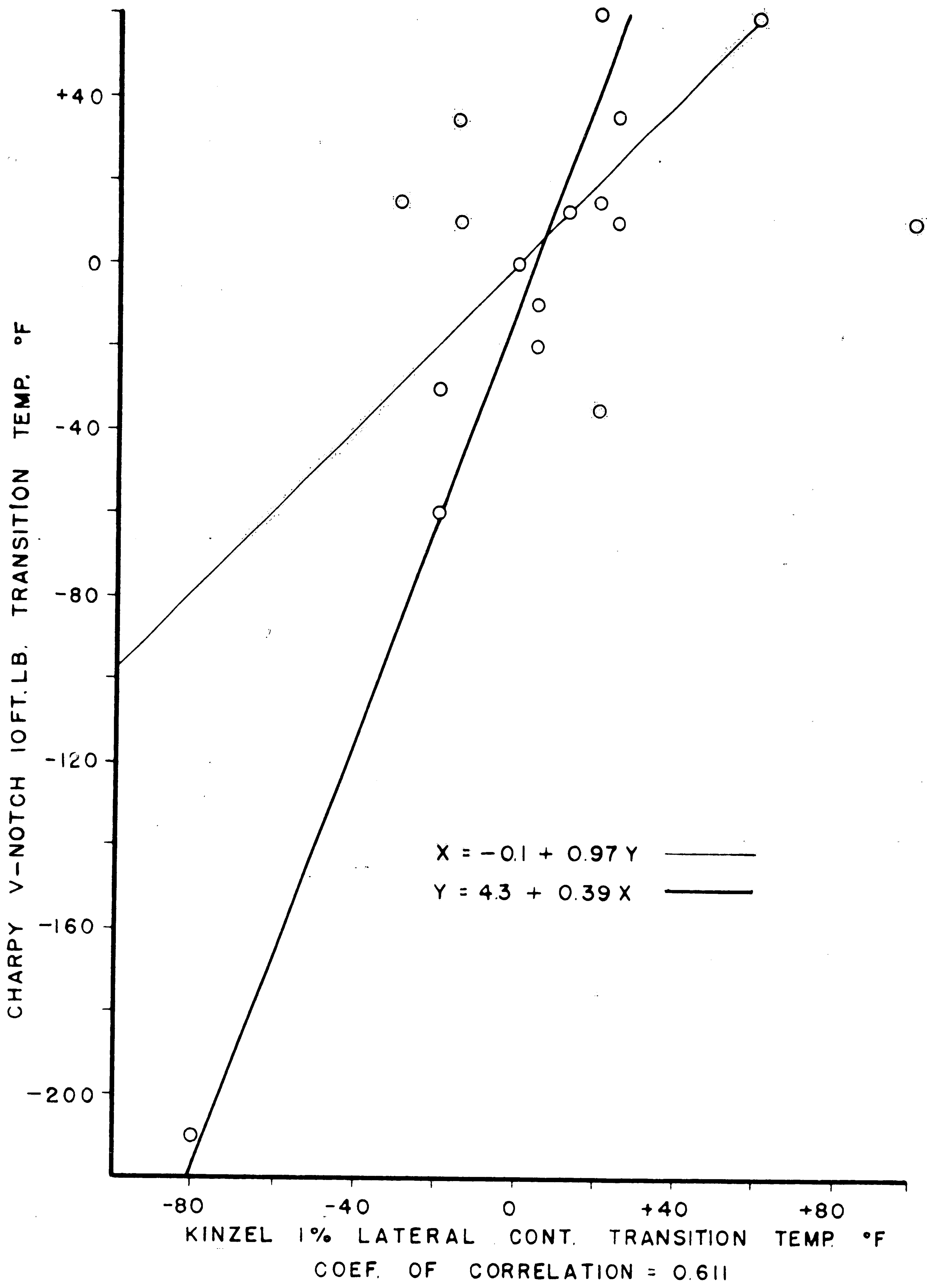
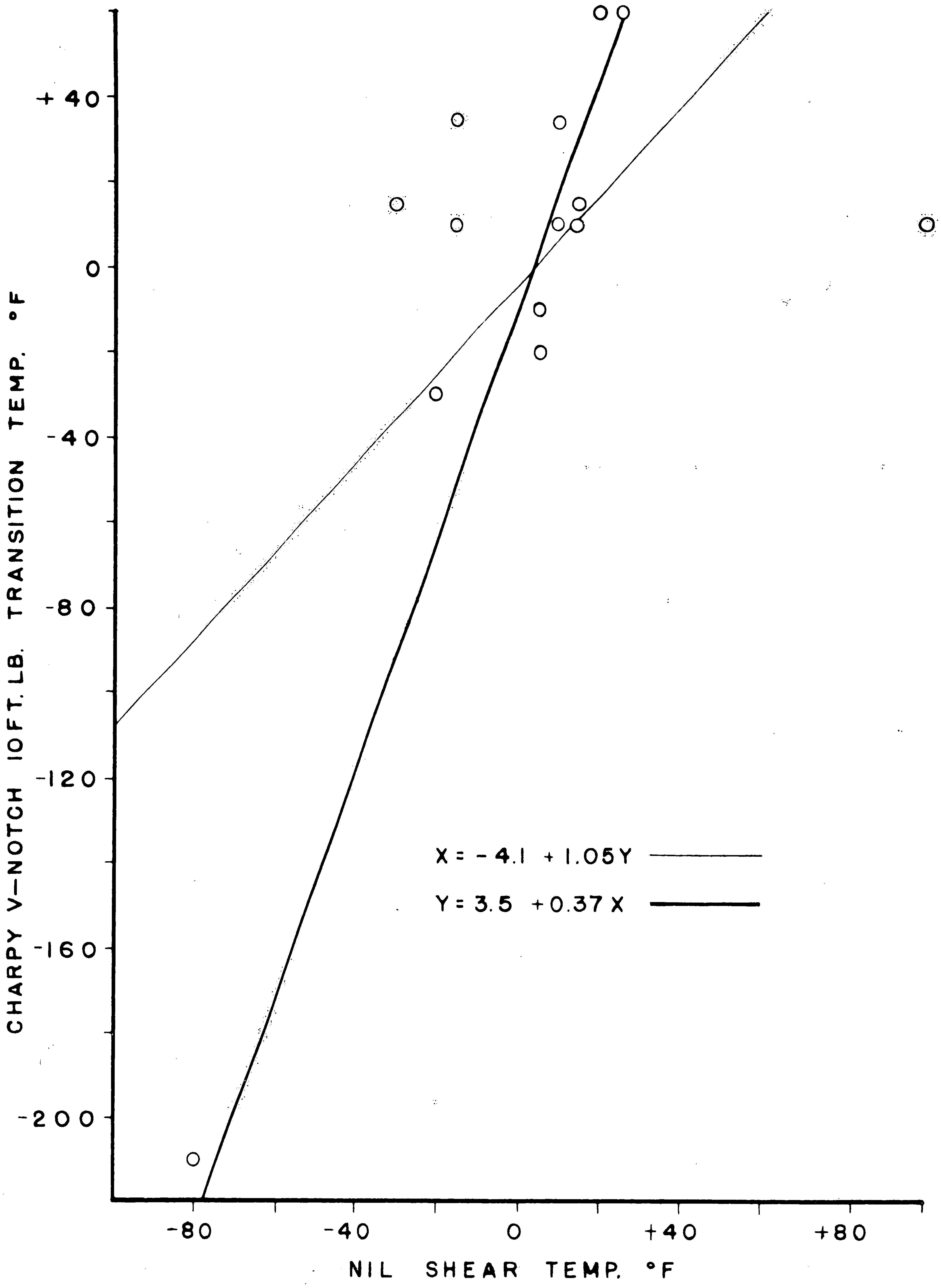


FIG. 7 CORRELATION BETWEEN THE CHARPY V—NOTCH 10 FT. LB. TRANSITION TEMPERATURE AND THE KINZEL 1% LATERAL CONTRATION TRANSITION TEMPERATURE.



COEF. OF CORRELATION = 0.622

FIG. 8 CORRELATION BETWEEN THE CHARPY V-NOTCH 10 FT. LB. TRANSITION TEMPERATURE AND THE NIL SHEAR TEMPERATURE.

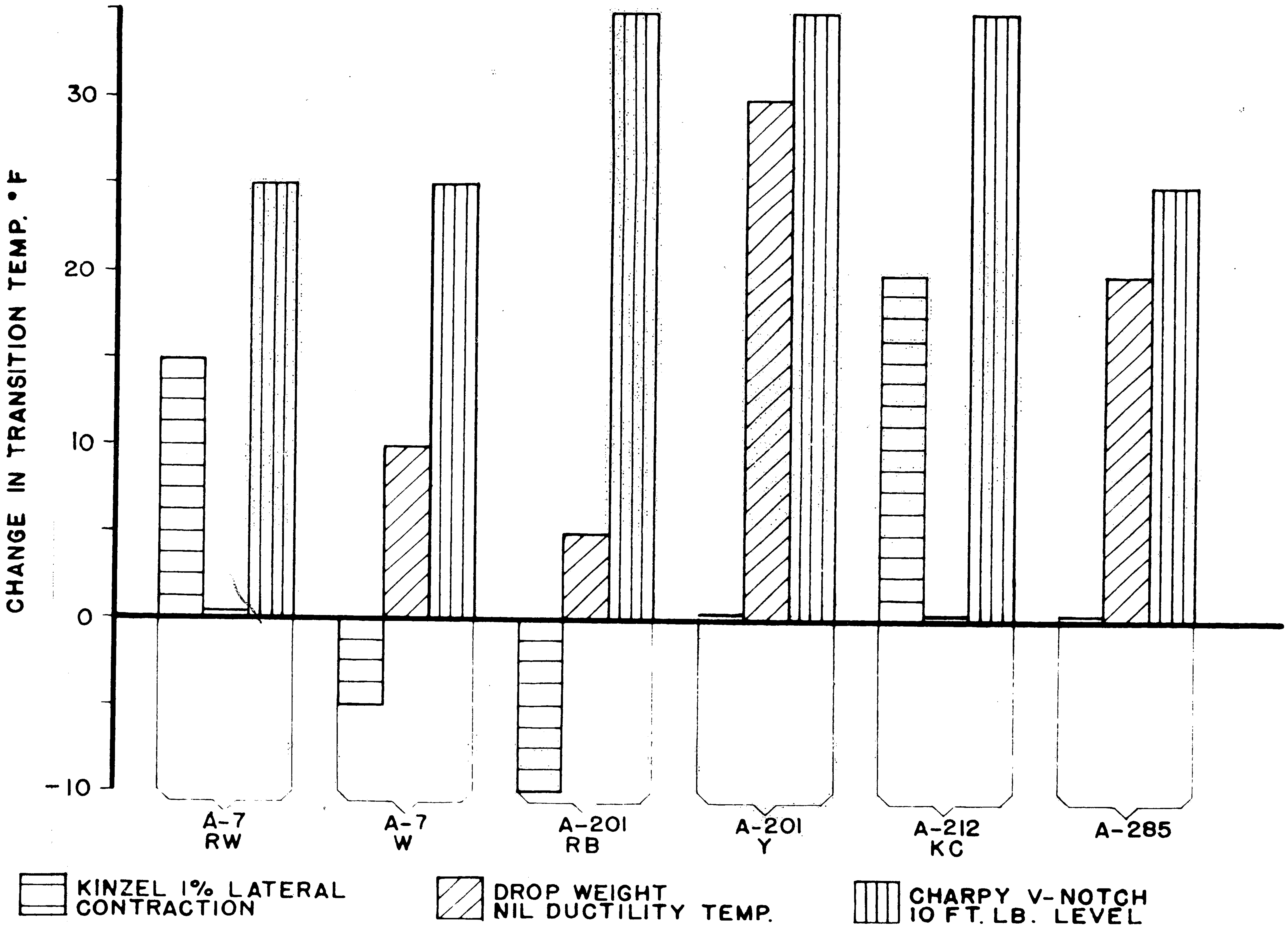


FIG. 9 THE CHANGE IN TRANSITION TEMPERATURE DUE TO NORMALIZING