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# A study of the effect of section thickness and strength level on the transition temperature of structural steels

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# A STUDY OF THE EFFECT OF SECTION THICKNESS AND STRENGTH LEVEL ON THE TRANSITION TEMPERATURE OF STRUCTURAL STEELS

by

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## CERTIFICATE OF APPROVAL

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

9 January 1967
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# TABLE OF CONTENTS

# LIST OF TABLES

1. Plate Analysis of Steels Used
2. Information on the Annealing of Test Specimens
3. Information on the Quenching Procedure of Test Specimens
4. Mechanical Properties of Steels Used in van der Veen Tests
5. Results of the van der Veen and Charpy Tests
6. Results of the Drop Weight Tests
7. Results of the Slow Bend Tests

# LIST OF FIGURES

# ABSTRACT

Three steels, in two heat treated conditions, were evaluated to determine the effect of section thickness and strength level on transition temperature. In addition to the conventional transition temperature plots, the thickness effect was also studied by utilizing two emperical parameters of thickness. By using these, straight line relationships were obtained and a possible extrapolation to infinite thickness transition temperature was suggested.

A further study was conducted to determine the effect of varying the amount of crack starter weld material on the NDT in the drop weight test. In conjunction with this, the loads necessary to cause failure in drop weight specimens tested in slow bending were also observed.

The drop weight tests, run on four weld configurations, showed no variation of NDT with varying amounts of crack starter material. In slow bending the loads showed a slight decrease for specimens with two weld beads, but the drop was not significant enough to indicate any major differences.

# INTRODUCTION

Brittle fracture in large, fabricated steel structures has been a major problem for a long time. This problem was recognized prior to World War II, and several investigators did some preliminary work in trying to explain the phenomenon (1, 2, 3). During World War II the brittle failure of the Liberty Ships caused much concern both here and in Europe, and initiated numerous investigations into finding the cause and a solution to brittle fracture (4, 5).

Out of all the work that has been done in this area in the last two decades, two major factors have been shown to be significant to brittle fracture in large steel structures: 1) a metallurgical effect, and 2) a geometric or size effect.

With the present emphasis on building larger structures, heavier loads are encountered and, hence, heavier section steel plates are required. Inherent in these thicker plates are metallurgical effects which are not found in thinner plates. Because of the higher finishing temperature after hot rolling and slower cooling rates of these plates, coarser grain sizes and more massive ferrite is formed. In addition to these factors, thicker plates undergo less reduction in rolling, and this results in a decrease in homogeneity. All of the above factors decrease the toughness of steel plates. Heat treatment of these plates, which sometimes proves beneficial, is also hindered by the slower cooling rates. It is possible, by lowering the carbon content and by adding beneficial alloying elements, to minimize these effects. It must be pointed out that any benefits achieved by these methods are offset by an increase in manufacturing costs. These effects of metallurgy on brittle fracture have been extensively studied, and the literature contains a large volume of data on this subject (6, 7, 8).

It has long been known that under identical test conditions a thick plate will show a greater tendency toward brittle fracture than a thin plate. This dimensional aspect of plate thickness is associated with the triaxial state of stress. In a plate under a triaxial state of stress, the stress in the thickness direction must fall to zero at the two free surfaces. Because of the surface effect, the maximum degree of triaxiality that can be attained will be greater the greater the plate thickness. As this stress rises, the constraint on plastic flow also rises and, hence, there is a greater tendency for brittle fracture.

The rate at which the triaxial stress rises with plate thickness is not constant. On reaching a given plate thickness, depending on the test method and steel, this rate decreases and eventually goes to zero. This means that for a given set of conditions there exists a plate thickness which will behave as though it were an infinitely thick plate. Hence, for a plate of this thickness, or thicker, the transition temperature should be essentially independent of thickness.

Parker (9), in his work on wide plates, indicated that this leveling off occurs at a plate thickness of one inch for plates tested in tension. Tipper (10), in her work on notched tensile bars, found no leveling off when going up to 4 inch plates. Epstein (8), in reporting data collected from Bagsar tests, found a marked rise in transition temperature in going from 3/4 inch to 2 inch plates, but then only a slight rise was reported found between the 2 inch and 4 inch plates. Agnew and Stout (11), in their work on the interrelationships between the dimensions of bend specimens, concluded that the effect of thickness on transition temperature was dependent on other geometrical variables. Essentially, they suggested that the effect of thickness cannot be determined unless the other dimension in the cross section be large enough so as to act as though it were infinite.

In more recent work, Roper and Stout (12) have shown, with the use of the van der Veen test, Bagsar test, and drop weight test, that by increasing the plate thickness from 1/2 inch to 2 inches the transition temperature will rise markedly, but above 2 inches the thickness has very little effect on the transition temperature. They also confirmed the earlier work of Agnew and Stout, showing that the thickness effect was dependent on the other cross sectional dimension.

In this investigation, it was decided to use the van der Veen test in testing plate thicknesses up to 4 inches. To insure that the thickness effect was being observed, all test dimensions but plate thicknesses were held constant. Also, to prevent metallurgical effects from masking any size effects, all plate thicknesses, of a given steel, were heat treated to constant microstructure. In addition to this, the effect of strength level on transition temperature was observed by using two different heat treatments on each steel.

An additional study was undertaken to determine the effect of the quantity of crack starting weld metal on the NDT in the drop weight test. For this study, one inch plates with differing weld configurations were studied. Further tests were run on the same configurations to determine the loads required to cause failure in static tests. It was hoped that the data obtained from these tests could be compared to data from the van der Veen tests through the use of fracture mechanics.

# EXPERIMENTAL PROCEDURE

## Steels Used

For the investigation of the effect of section thickness and strength level on transition temperature, three steels, each in three thicknesses, were used. Steel A517 grade F was used in 1/2, 1, and 2 inch thicknesses; A537 was used in 1, 2, and 4 inch thicknesses; and ABS class C was used in 3/4 inch, split from 1-1/2 inch plate, 1-1/2, and 3 inch thicknesses. The chemical compositions of these steels appear in Table 1. It should be noted that the laboratory heat treatments imposed on these steels caused them to depart from grade specifications. A more detailed description of these heat treatments appears in the next section.

The drop weight and slow bend tests were conducted on normalized A537. This steel was tested in full thickness one inch plates. The composition of this steel is the same as given in Table 1.

## Heat Treatment

In order to study the effect of section thickness alone on transition temperature, it was necessary to hold the metallurgical structure as nearly constant as possible in the three thicknesses. To study the effect of strength level on transition temperature, the steels were subjected to two different heat treatments such that two significantly different strength levels were obtained.

Because of the physical size of the 3 and 4 inch plates, it was decided to heat treat individual specimens rather than larger plates. To insure constant heating and cooling rates in the furnace used, an equal weight of steel was put in the furnace each time. In addition to this, thermocouples were put in the furnace at several locations and these were periodically checked to insure an even temperature in the furnace. The time of charging and removal from the furnace was matched as closely as possible for each heat.

The lower strength level was obtained by using a full anneal on all specimens. This heat treatment was done in a large circulating air furnace. The specimens were put in a cool furnace, heated to temperature, held for one hour per inch of plate thickness, and then furnace cooled. A summary of the conditions of this heat treatment appears in Table 2. Because all plate thicknesses were cooled in this manner, they had identical cooling rates.

The higher strength level was obtained by spray quenching the specimens. In this heat treatment, cooling rates had to be matched to get a constant microstructure in the three thicknesses. To do this the thickest specimen of each steel was spray quenched with a water delivery rate of 0.3 cubic inches of water per square inch of surface per side per second. The cooling rate which this produced then had to be matched in the two thinner thicknesses.

To measure the cooling rate, a thermocouple, in a ceramic protection tube, was inserted in a drilled hole down the length of the specimen to its center. This thermocouple was connected to an automatic recording potentiometer. In this way it was possible to record the half temperature time cooling rate during quenching. All cooling rate curves were run in duplicate.

Once the cooling rate was established for the thickest specimen, it was then necessary to match this cooling rate in the center of the thinner specimens. This was accomplished by adjusting the nozzle size and water pressure for quenching to get the desired cooling rate. The results of these heat treatments are summarized in Table 3.

To determine how effective these heat treatments were in producing a constant microstructure, photomicrographs were prepared as shown in Figures 2 through 4. In addition, mechanical properties and hardness traverses were determined, and these appear in Table 4 and Figure 5, respectively.

## Van der Veen Test (13)

The van der Veen test is a slow bend test on a notched beam type test coupon. Figure 6 shows the dimensions and orientation of the specimen.

All specimens were sawcut previous to heat treatment, and all longitudinal sawcuts were at least one inch from a flamecut surface. The longitudinal dimension (9.5 inches) of the specimen was parallel to the rolling direction and the thickness was equal to the plate thickness. The height of 2.75 inches was the same for all specimens.

During all spray quenching operations, the two sawcut surfaces were protected from the direct spray by means of side plates. This also insured a more uniform cooling rate across the thickness dimension. After heat treatment the specimens were wire brushed and then notched prior to testing.

The specimens were notched by pressing a tool steel die into the specimen. The notch was .118 inches (3mm) deep, had an included angle of 45°, and terminated in a 0.0015 inch radius. This notch was located on one of the sawcut surfaces at midspan and traversed the entire thickness dimension of the specimen. Because of this geometry, the notch was perpendicular to the plate surface and the resulting crack propagated parallel to the plate surfaces.

A van der Veen series consisted of fifteen specimens of identical dimensions tested over a temperature range such that completely ductile (shear) to completely brittle (cleavage) fractures were obtained. A typical transition is shown in Figure 7. The specimens were cooled to the desired temperature by immersing them in an ethyl alcohol bath in which the temperature was controlled by dry ice additions. The specimens were held at temperature for a sufficient time to produce a constant temperature throughout.

For testing, the specimen was removed from the bath, centered on the testing jig, and the load applied at the rate of one inch per minute cross head travel in a universal testing machine. It took approximately 10 seconds to begin testing after the specimen had been removed from the bath. Figure 8 shows a specimen ready to be tested. During testing, the deflection was recorded by means of an Ames dial gauge which measured cross head separation. The maximum load and the breaking load were also recorded.

After testing the specimens were inspected to determine the amount of the shear occurring in the fracture and the deformation before fracture. The criteria which were selected to establish transition temperatures were 50% shear (fracture appearance) and 2% lateral contraction (ductility). The 50% shear criteria was obtained by measuring the length of the ductile (shear) fracture below the root of the notch, and this was recorded as a percent of the total height. The lateral contraction was obtained by measuring the width of the specimen, at the root of the notch, both before and after testing.

## Charpy Tests

In addition to the photomicrographs, mechanical properties, and hardness surveys, a Charpy V-notch series was run on each plate thickness and heat treatment used in the van der Veen tests. The purpose of these tests was twofold. First, they provided another criteria by which the uniformity of the heat treatments could be evaluated. Second, these tests would provide a means for making first order corrections to variations in van der Veen results introduced by metallurgical non-uniformity in the plates. This last statement will be explained in more detail in a later section.

All Charpy specimens were cut from the quarter plate thickness position and were parallel to the rolling direction. The notch was cut perpendicular to the plate surface. A Charpy series consisted of fifteen specimens tested over a temperature range to yield data for both fracture appearance and ductility criteria.

## Drop Weight Test (14)

The standard drop weight specimen is a beam type test coupon which has a brittle weld bead deposited parallel to the length; the weld bead is superficially notched for testing. Figure 9 shows a standard drop weight specimen.

The specimens for these tests were sawcut with the longitudinal axis parallel to the rolling direction, and all sawcuts were at least one inch from a flamecut edge. The thickness of the specimens corresponded to the one inch plate thickness and the width was 3-1/2 inches.

These tests were conducted on three different weld configurations. The configurations differed in the amount of weld metal deposited to act as a crack starter. The first series consisted of plates with two weld beads, side by side, located in the center of the plate. The second series consisted of plates with two weld beads, one on top of the other, laid in a channel 3 inches long, 1/2 inch wide, and 1/8 inch deep, located in the center of the plate. The third series consisted of four weld beads, two wide and two deep, laid in a channel 3 inches long, 7/8 inches wide, and 1/8 inch deep, located in the center of the plate. Figure 10 shows the cross sections of these drop weight specimens.

All of the specimens were welded under the same set of conditions. The weld rod was 3/16 inch Murex Hardex N covered electrode which was welded at 170 amps, 22 volts, and 11.25 ipm travel. Subsequent weld passes were not deposited until the plate had cooled back to room temperature. These conditions were sufficient to produce a hardness of Rockwell C 38 to 40 in the weld bead which was necessary to initiate a brittle fracture.

After welding each specimen had a notch cut in the weld bead at center span. The notch was cut with a standard Charpy V-notch cutter so that the bottom of the notch was .070 inch above the surface of the plate. The notch initiates a brittle crack which either blunts out or propagates through the base plate, depending on its temperature.

The drop weight series consisted of five to ten identical specimens tested over a temperature range to get the nil-ductility-transition temperature (NDT). The specimens were cooled in an ethyl alcohol and dry ice bath. The specimen was removed from the bath, placed on supports 12 inches apart, with the notch down, and then impact-loaded by a weight dropped on it from a height sufficient to deflect it 0.3 inch. This deflection is controlled by means of a stop which is initially 0.3 inch below the specimen at its midspan.

The test results are based on a simple "go-no go" basis. A "go" specimen is one which is deflected 0.3 inch, the weld bead is cracked, and the initiated crack propagates to one or both of the specimen edges. A "no-go" specimen is one which is deflected 0.3 inch, the weld bead is cracked, but the initiated crack blunts out in the base plate before reaching a specimen edge. The test is invalid if the weld bend does not crack or if the specimen does not deflect the 0.3 inch required. On this basis, the NDT is defined as the highest temperature at which there is at least one "go" specimen, provided there are duplicate "no-go" specimens obtained at a temperature 10°F. warmer.

## Slow Bend Test

Slow bend tests were conducted, in duplicate, on specimens which were identical to the drop weight specimens. In addition, tests were run on specimens with a single weld bead and with three weld beads side by side. A specimen, without a weld bead, was also tested to determine the yielding load for a specimen tested in this manner. These tests were conducted at two designated temperatures, -95°F. and -150°F., selected because they should be far enough below the NDT of the steel to give completely brittle failures. These specimens were tested by the same technique as that used for the van der Veen tests. In these tests, only the load required for failure was recorded.

# EXPERIMENTAL RESULTS

The three steels were evaluated by the van der Veen test in the annealed and quenched conditions except for the spray quenched A517 grade F. Because of the high hardness produced in this steel, it was difficult to press acceptable notches into it, and very high loads were required to cause failure. Therefore, it was decided to omit testing this material rather than to jeopardize the testing equipment.

The results of the van der Veen and Charpy tests are given in Table 5. Typical transition curves for these tests appear in Figures 11 and 12. The values recorded for the adjusted van der Veen transition temperature were obtained in the following manner.

If all thicknesses for a given steel did, in fact, have a constant microstructure, the Charpy results for these plates would be identical. Since the transition temperatures were not identical, it was assumed that the difference was due to a metallurgical effect since the Charpy test is a constant dimension test.

As an example of the method used for adjusting van der Veen temperatures, take the annealed A537 steel. In applying the correction, the thickest plate in the series was taken as the base so that its result was not altered. The correction applied was the average deviation of the 20 mil and 50% shear Charpy values.

Inspection of the one and 4 inch Charpy results shows that they are identical within experimental error. Therefore, no correction was applied to the one inch annealed A537 van der Veen result. From comparison of the 2 and 4 inch Charpy results, it is seen that for both the 20 mil and 50% shear transition temperatures the 4 inch plate exhibits a lower transition temperature by 25°F. Therefore, it can be said that due to metallurgical effects the 4 inch plate will exhibit a better transition temperature than the 2 inch plate. To compensate for this 25°F. was subtracted from the 2 inch annealed A537 van der Veen result to give an adjusted transition temperature of +40°F. An adjustment factor was applied wherever justified by the Charpy results.

The results of the drop weight tests appear in Table 6. The NDT for the standard one inch A537 specimen was available from Roper and Stout (15), who conducted a series of tests on the same heat. The results of the slow bend tests on the drop weight specimens appear in Table 7.

## DISCUSSION OF RESULTS

The adjusted values from the van der Veen tests were plotted and appear in Figure 12. It should be mentioned here that, except for the 2 inch annealed and spray quenched A537, omitting these corrections would not alter significantly the resulting conclusions.

It can be seen that in all cases the effect of increasing plate thickness is to raise the transition temperature. In addition to this, the effect of plate thickness tends to level off in the A537 above 2 inches, in the ABS class C above 1-1/2 inches, and in the A517 grade F above one inch. These results, then, agree with the data discussed earlier in the text. The published data indicate that changes in thickness below one inch exert a strong influence on transition temperature, while above 2 inches in thickness the effect of thickness is moderate. Inspection of the curves in Figure 12 would suggest that a better parameter might be used to express the plate thickness. From the shape of these curves it would seem that a power function may be appropriate. Several parameters were tried, and it was found that this behavior could be better described if the plate thickness were expressed as a reciprocal square root or as a logarithmic function. If this is done for both the data from the literature and the data obtained from this investigation, plots such as Figures 13 and 14 are obtained.

Inspection of the curves shows that a reasonably linear relation is obtained for both parameters for a variety of steels and testing methods. This would indicate, for the reciprocal square root plot, that it may be possible to extrapolate the curves to zero, i.e., infinite thickness, and obtain the transition temperature for an infinitely thick plate of the given steel and testing conditions. On comparing the slopes in Figure 13 to those in Figure 14, it is seen that each testing method seems to give a characteristic slope. It is suggested here that this slope may depend on the acuity of notch and testing method used. If this is true, it would then be possible to correlate transition temperatures based on test method and notch acuity. Before any such comparisons can be made, however, more work would have to be done in this area.

From the results obtained it is impossible to draw any conclusions concerning the effects of strength level on the transition temperature. The ABS class C results indicate that the stronger spray quenched plate exhibits a much better transition temperature than the annealed plates. In contrast to this, the annealed A537 shows a slight superiority in transition temperature over the spray quenched material.

## Drop Weight Test

From Table 6 it can be seen that varying the amount of crack starter material did not change the NDT of the steel. The 10°F. difference between the single weld bead and multiple bead specimens is within the acceptable scatter band.

It is not surprising to find that the NDT did not change with varying amounts of crack starter material. In all cases the width of the crack starter zone was only increased by one weld bead. This would not seriously change the ratio of weld bead width to plate width or the distance that the initiated crack has to propagate to a specimen edge. Therefore, this small increase in crack starter width should not alter the test results appreciably.

## Slow Bend Tests

The results in Table 7 indicate that the loads causing failure in the slow bend drop weight specimens did not change appreciably with volume of the crack starting weld metal. For the two weld beads side by side the load fell off slightly, but not enough to indicate any major differences. The specimens with three or four weld beads had fracture surfaces which were considerably rougher than the other configurations, indicating that these were slightly higher energy fractures. This may be attributed to the annealing and dilution effects that the additional weld passes had on the previously laid weld beads.

In essence, the results of the tests on crack starter volume were negative. It was hoped that the effect of flow size could be demonstrated at temperatures below the NDT, but all failures occurred close to the load required to produce yielding. Apparently much lower temperatures would be needed or crack like flows rather than brittle weld metal should be used to initiate the fracture.

## CONCLUSIONS

1. All three steels, in the two heat treated conditions showed a definite increase in transition temperature with increasing plate thickness.
2. This increase in transition temperature was continuous, but tended to level off after 2 inches in the A537, after 1-1/2 inches in the ABS class C, and after 1 inch in the A517 grade F.
3. When the thickness parameter is expressed as a reciprocal power or a logarithmic function, straight line plots are obtained for both data from the literature and data obtained in this investigation.
4. If the thickness parameter is expressed as a reciprocal power, then it may be possible to extrapolate the curve to zero to get the transition temperature of an infinitely thick plate.
5. No conclusions can be drawn concerning the effect of strength level on transition temperature.
6. The NDT is not changed by varying the amount of crack starter material.
7. The loads required to cause failure in the slow bend drop weight specimens are not significantly changed by varying the amount of crack starter material.

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## TABLE 1

## CHEMICAL ANALYSIS OF STEELS USED IN TESTING

ABS Class C

| Thickness | C | Mn | P | S | Si |
|---|---|---|---|---|---|
| 1-1/2" | .17 | .78 | .012 | .027 | .21 |
| 3" | .17 | .82 | .010 | .022 | .23 |

A537

| Thickness | C | Mn | P | S | Si | Cu | Ni | Cr | Co | Al |
|---|---|---|---|---|---|---|---|---|---|---|
| 1" | .18 | 1.24 | .014 | .031 | .17 | .19 | .11 | .10 | .025 | .020 |
| 2" | .17 | 1.22 | .018 | .029 | .18 | .19 | .12 | .10 | .026 | .019 |
| 4" | .19 | 1.23 | .014 | .029 | .19 | .19 | .12 | .10 | .025 | .018 |

A517 Grade F

| C | Mn | P | S | Si | Cu | Ni | Cr | Mo | V | Ti | B |
|---|---|---|---|---|---|---|---|---|---|---|---|
| .17 | .79 | .009 | .016 | .21 | .31 | .88 | .47 | .51 | .04 | .006 | .004 |

## TABLE 2

## INFORMATION ON THE ANNEALING OF TEST SPECIMENS

| Steel | Thickness | Austenitizing Temperature | Time At Temperature | Half Temperature Time Cooling Rate |
|---|---|---|---|---|
| ABS Class C | 3/4" | 1675°F | 45 minutes | .080°F/sec. |
| | 1-1/2" | 1675°F | 90 minutes | .080°F/sec. |
| | 3" | 1675°F | 180 minutes | .080°F/sec. |
| A537 | 1" | 1700°F | 60 minutes | .080°F/sec. |
| | 2" | 1700°F | 120 minutes | .080°F/sec. |
| | 4" | 1700°F | 180 minutes | .080°F/sec. |
| A517 Grade F | 1/2" | 1700°F | 30 minutes | .080°F/sec. |
| | 1" | 1700°F | 60 minutes | .080°F/sec. |
| | 2" | 1700°F | 120 minutes | .080°F/sec. |

## TABLE 3

## INFORMATION ON QUENCHING PROCEDURES FOR THE VARIOUS PLATE THICKNESSES

| Steel Type | Plate Thickness | Orifice Diameter | Water Pressure | Delivery Rate | Mid-Thickness Cooling Rate To 1/2 Temp. |
|---|---|---|---|---|---|
| ABS-C | 3/4" | 1/16" | 15 psi. | 1.5 gal/min. | 7.7°F/sec. |
| | 1-1/2" | 3/16" | 18 psi. | 6.0 gal./min. | 7.3°F/sec. |
| | 3" | 15/32" | 36 psi. | 46 gal./min. | 7.6°F/sec. |
| A537 | 1" | 1/16" | 15 psi. | 1.5 gal./min. | 4.5°F/sec. |
| | 2" | 3/16" | 10 psi. | 4.5 gal./min. | 4.8°F/sec. |
| | 4" | 15/32" | 36 psi. | 46 gal./min. | 4.6°F/sec. |
| A517 | 1/2" | 1/8" | 10 psi. | 1.0 gal./min. | 10.8°F/sec. |
| | 1" | 3/16" | 22 psi. | 6.5 gal./min. | 10.7°F/sec. |
| | 2" | 15/32" | 36 psi. | 46 gal./min. | 11.0°F/sec. |

## TABLE 4

## MECHANICAL PROPERTIES OF STEELS USED IN VAN DER VEEN TESTS

| Steel Type* | Heat Treatment | Thick- ness | Yield Strength (psi) | Tensile Strength (psi) | % El. | %R.A. |
|---|---|---|---|---|---|---|
| ABS-Class C | Annealed | 3/4" | 34,200 | 58,800 | 45 | 62 |
| | " | 1-1/2" | 35,000 | 58,800 | 45 | 68 |
| | " | 3" | 33,900 | 59,300 | 45 | 67 |
| | Spray Quenched | 3/4" | 47,700 | 69,200 | 42 | 74 |
| | " " | 1-1/2" | 47,900 | 69,400 | 39 | 76 |
| | " " | 3" | 44,300 | 65,500 | 39 | 78 |
| A537 | Annealed | 1" | 43,600 | 71,800 | 39 | 63 |
| | " | 2" | 37,300 | 72,200 | 39 | 63 |
| | " | 4" | 42,800 | 72,000 | 39 | 64 |
| | Spray Quenched | 1" | 55,600 | 90,100 | 30 | 65 |
| | " " | 2" | 60,500 | 90,600 | 33 | 65 |
| | " " | 4" | 55,600 | 85,700 | 34 | 65 |
| A517-F | Annealed | 1/2" | 76,700 | 109,700 | 22 | 58 |
| | " | 1" | 78,500 | 114,400 | 19 | 48 |
| | " | 2" | 82,000 | 116,100 | 16 | 51 |

* Steels do not meet grade specifications with these laboratory heat treatments.

## TABLE 5

## RESULTS OF VAN DER VEEN AND CHARPY TESTS

| Steel Type* | Heat Treatment | Thickness | V-Notch Charpy 20 mil lat.exp. TT | V-Notch Charpy 50% Shear TT | Van der Veen 50% Shear TT | Van der Veen Adjusted TT |
|---|---|---|---|---|---|---|
| ABS Class C | Annealed | 3/4" | -20°F | +55°F | + 5°F | + 10°F |
|  | " | 1-1/2" | -15°F | +65°F | + 35°F | + 35°F |
|  | " | 3" | -20 to 0 | +60 to 80 | + 40°F | + 40°F |
|  | Spray Quenched | 3/4" | -90°F | -35°F | - 55°F | - 65°F |
|  | " " | 1-1/2" | -95°F | -25°F | - 55°F | - 65°F |
|  | " " | 3" | -100°F | -40 to -60 | - 35°F | - 35°F |
| A537 | Annealed | 1" | -55°F | +50°F | + 25°F | + 25°F |
|  | " | 2" | -25°F | +85°F | + 65°F | + 40°F |
|  | " | 4" | -50°F | +60°F | + 50°F | + 50°F |
|  | Spray Quenched | 1" | -10°F | +50°F | + 45°F | + 15°F |
|  | " " | 2" | -20°F | +60°F | + 70°F | + 45°F |
|  | " " | 4" | -50°F | +75°F | + 55°F | + 55°F |
| A517-F | Annealed | 1/2" | +170°F | +245°F | +220°F | +230°F |
|  | " | 1" | +180°F | +235°F | +250°F | +250°F |
|  | " | 2" | +170°F | +260°F | +270°F | +270°F |

*Steels do not meet grade specifications with these laboratory heat treatments.

## TABLE 6

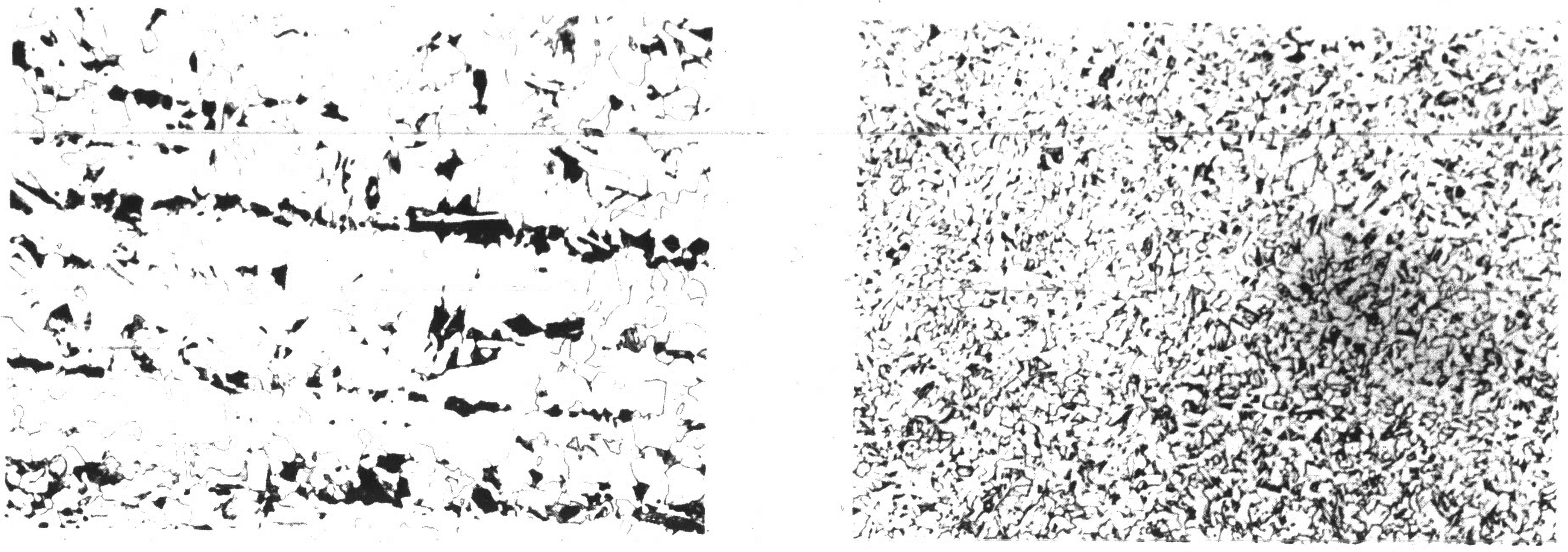
### Results of the Drop Weight Tests

| Configuration | NDT |
|---|---|
| Standard Test (15) | -40°F |
| Two Weld Beads (side by side) | -50°F |
| Two Weld Beads (one on top of the other) | -50°F |
| Four Weld Beads (two wide and two deep) | -50°F |

## TABLE 7

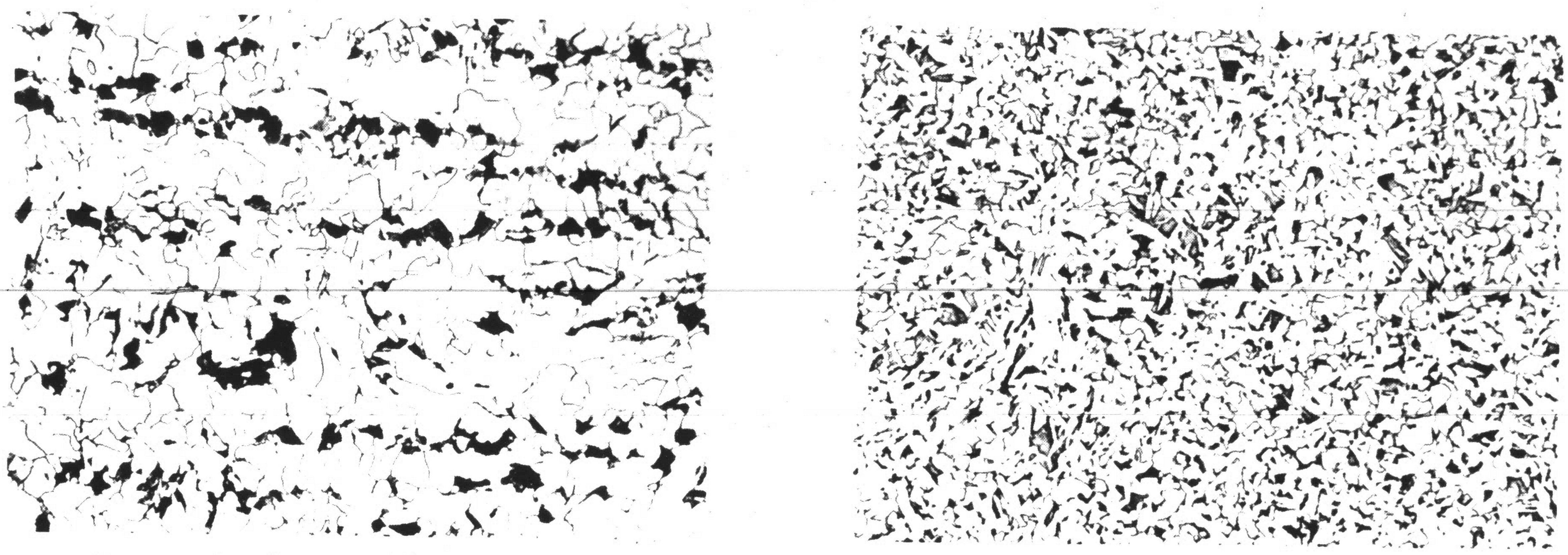
### Results of the Slow Bend Tests

| Configuration | Temp. (°F) | Load (Lbs.) |
|---|---|---|
| No Weld Beads | - 95°F | Yield at 26,400 |
| | - 95°F | 20,400 |
| One Weld Bead | -150°F | 21,900 |
| | - 95°F | 20,000 |
| Two Weld Beads (side by side) | -150°F | 20,000 |
| | - 95°F | 20,500 |
| Two Weld Beads (one on top of the other) | -150°F | -- |
| | - 95°F | 21,150 |
| Four Weld Beads (two wide and two deep) | -150°F | -- |
| | - 95°F | -- |
| Three Weld Beads (side by side) | -150°F | 22,800 |



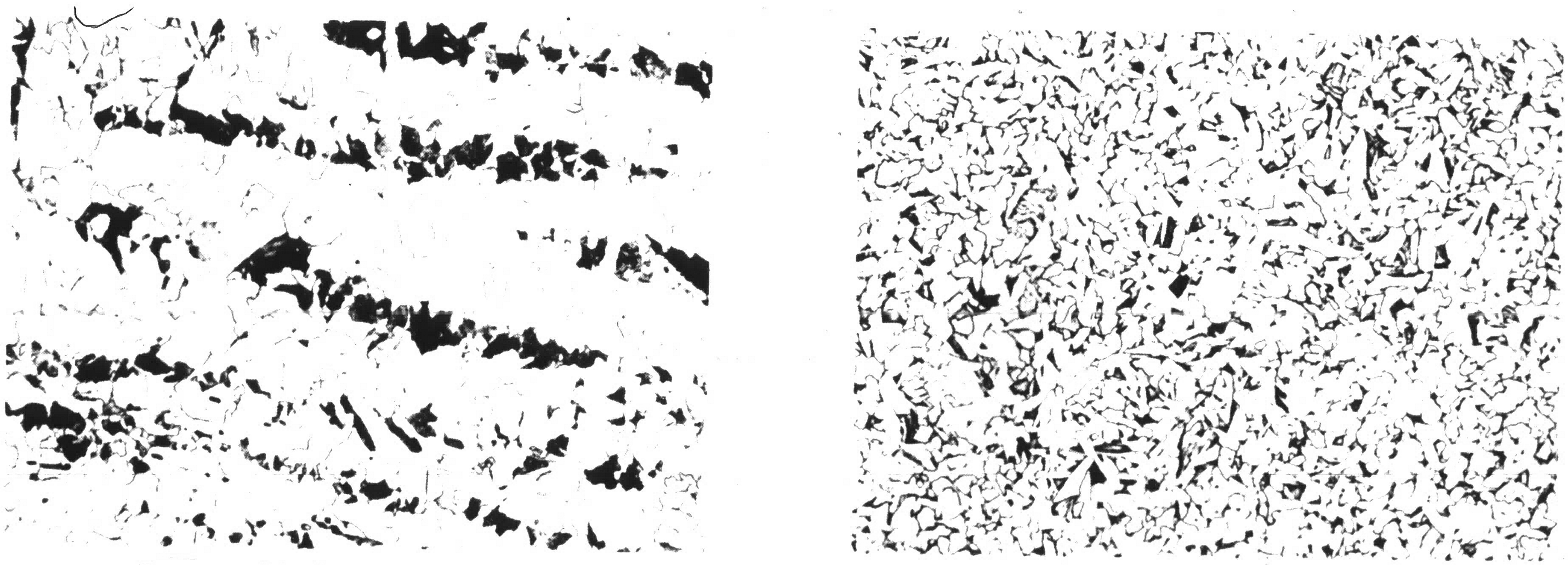
Annealed 3/4" Plate

Quenched 3/4" Plate



Annealed 1-1/2" Plate

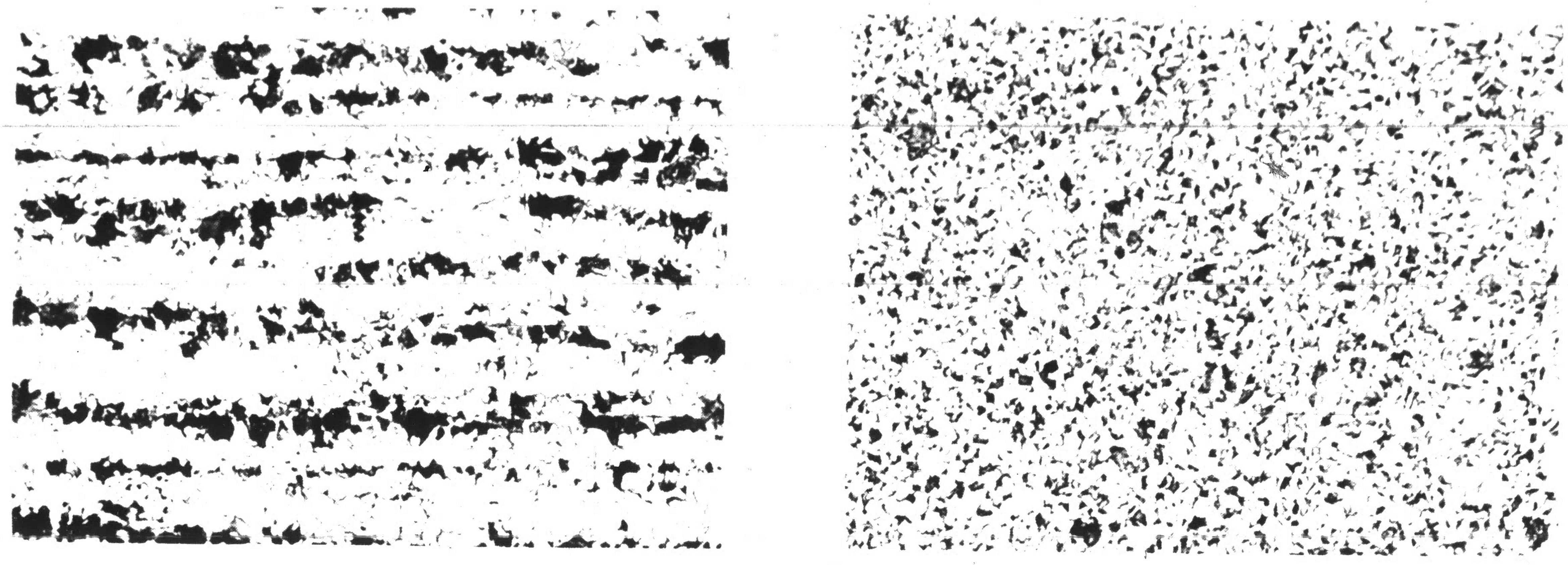
Quenched 1-1/2" Plate



Annealed 3" Plate

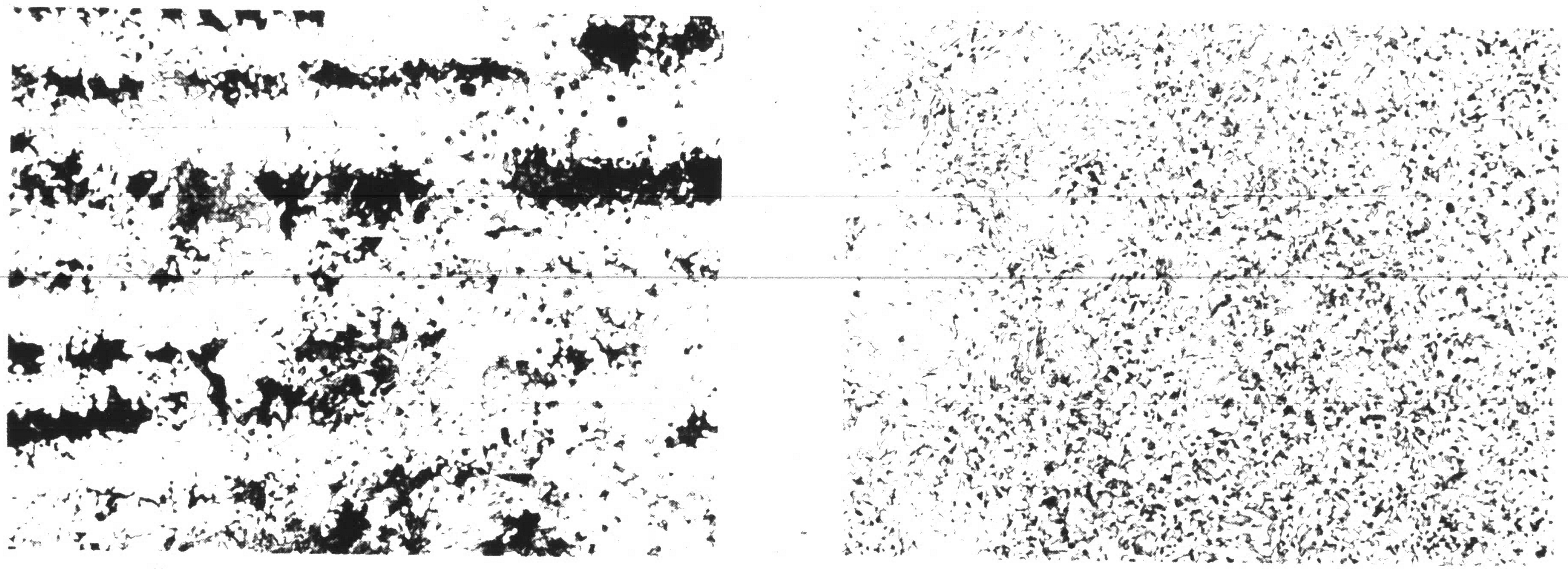
Quenched 3" Plate

Fig. 1. Microstructures of ABS Class C Plate. 100X, Nital Etch.



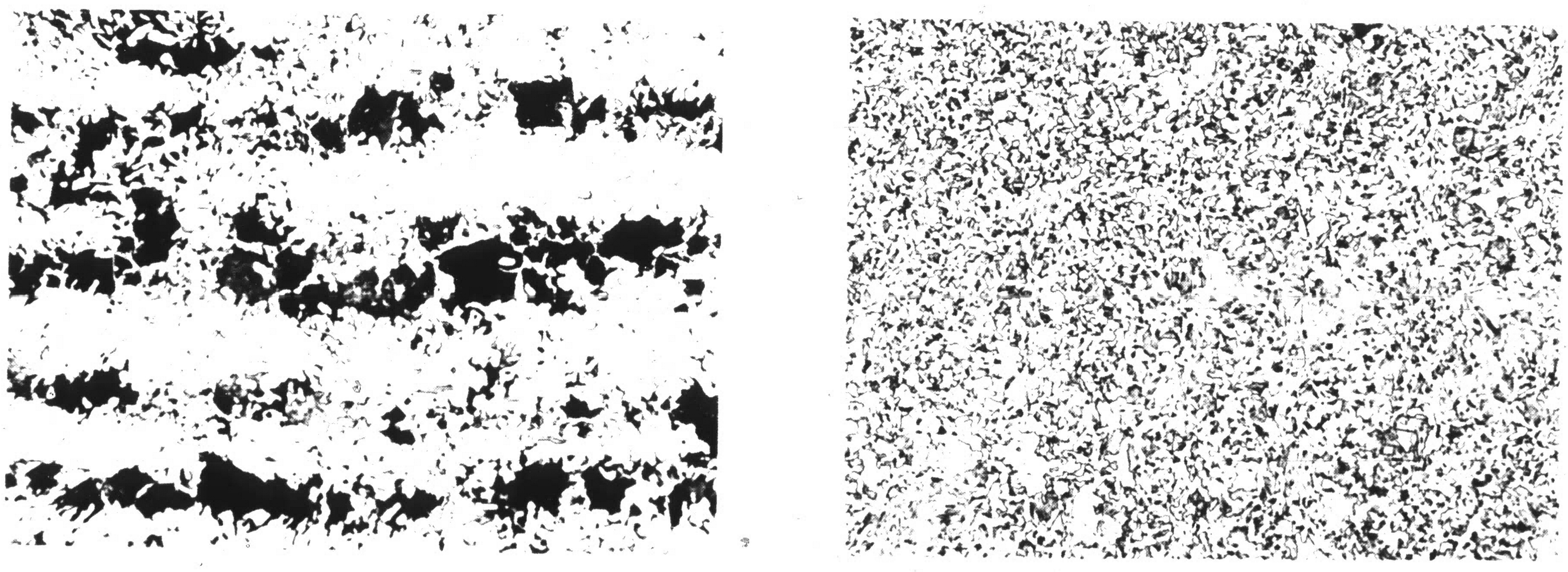
Annealed 1" Plate

Quenched 1" Plate



Annealed 2" Plate

Quenched 2" Plate

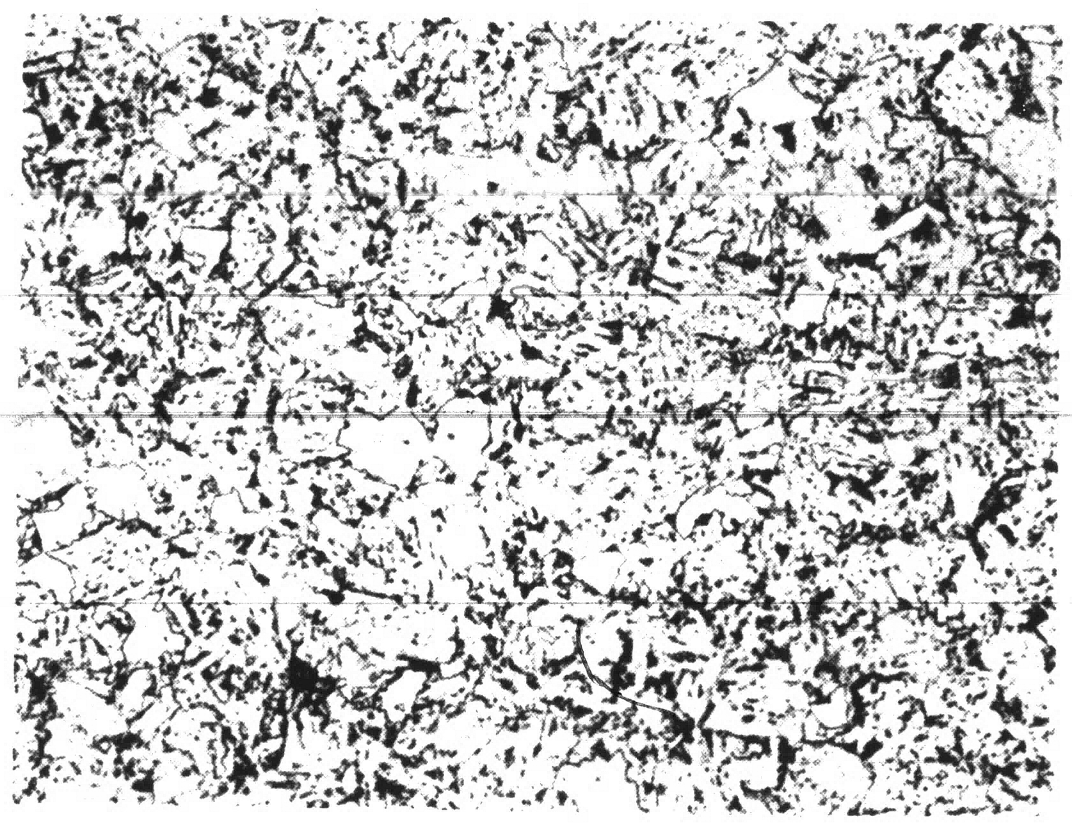


Annealed 4" Plate

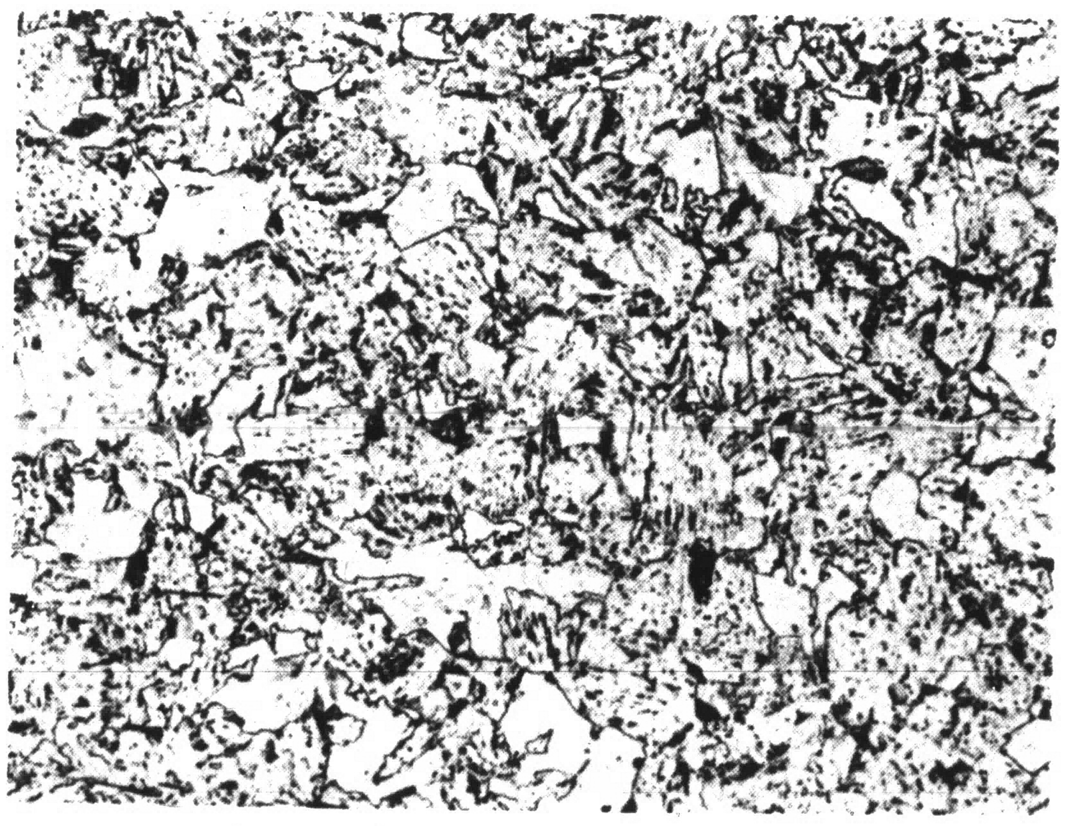
Quenched 4" Plate

Fig. 2. Microstructures of A537 Plate. 100X, Nital Etch.

Annealed 1/2" Plate



Annealed 1" Plate



Annealed 2" Plate

Fig. 3. Microstructures of A517 Grade F Plate. 100X, Nital Etch.

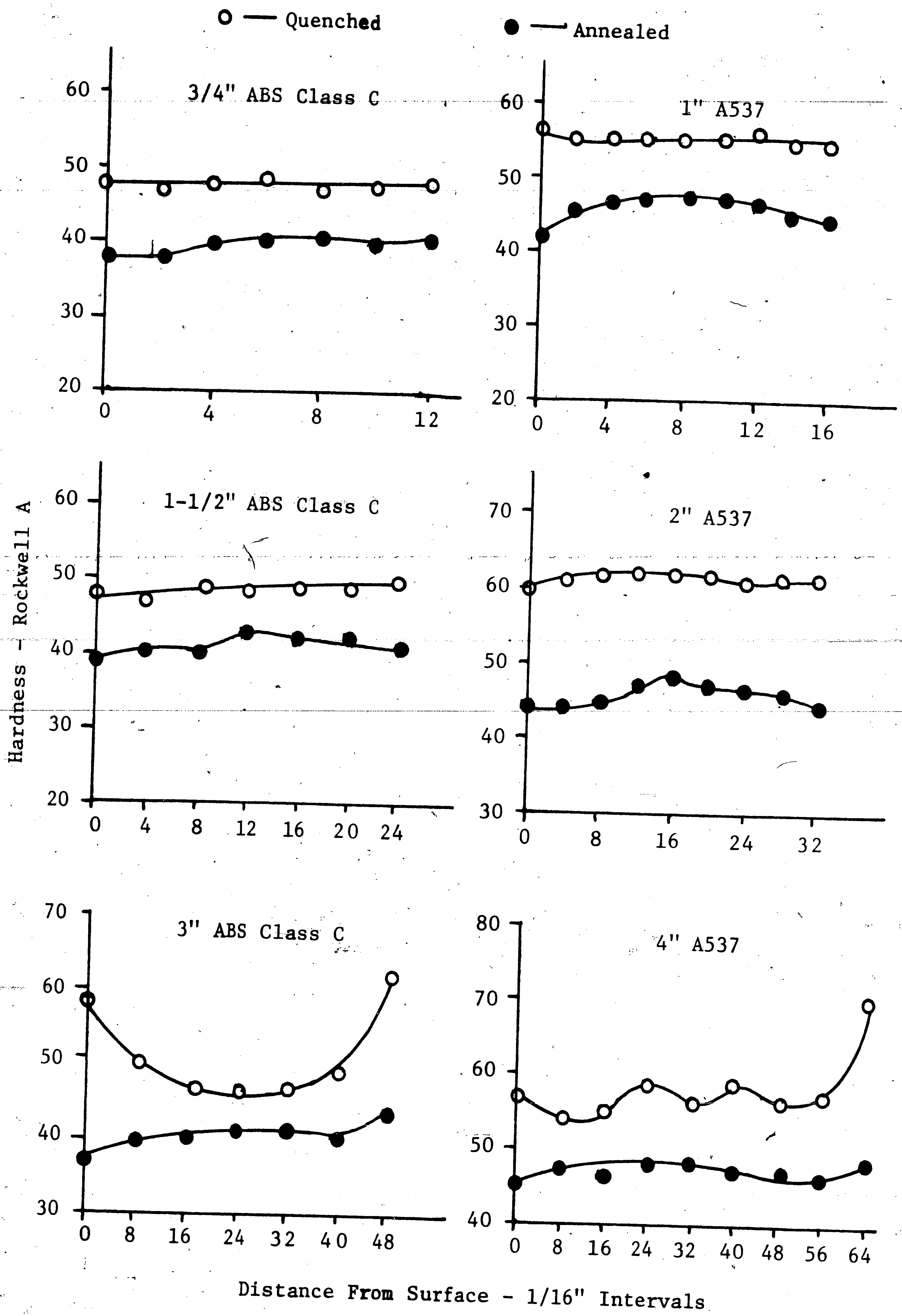


Fig. 4 Hardness Profiles of Plates Used in Testing

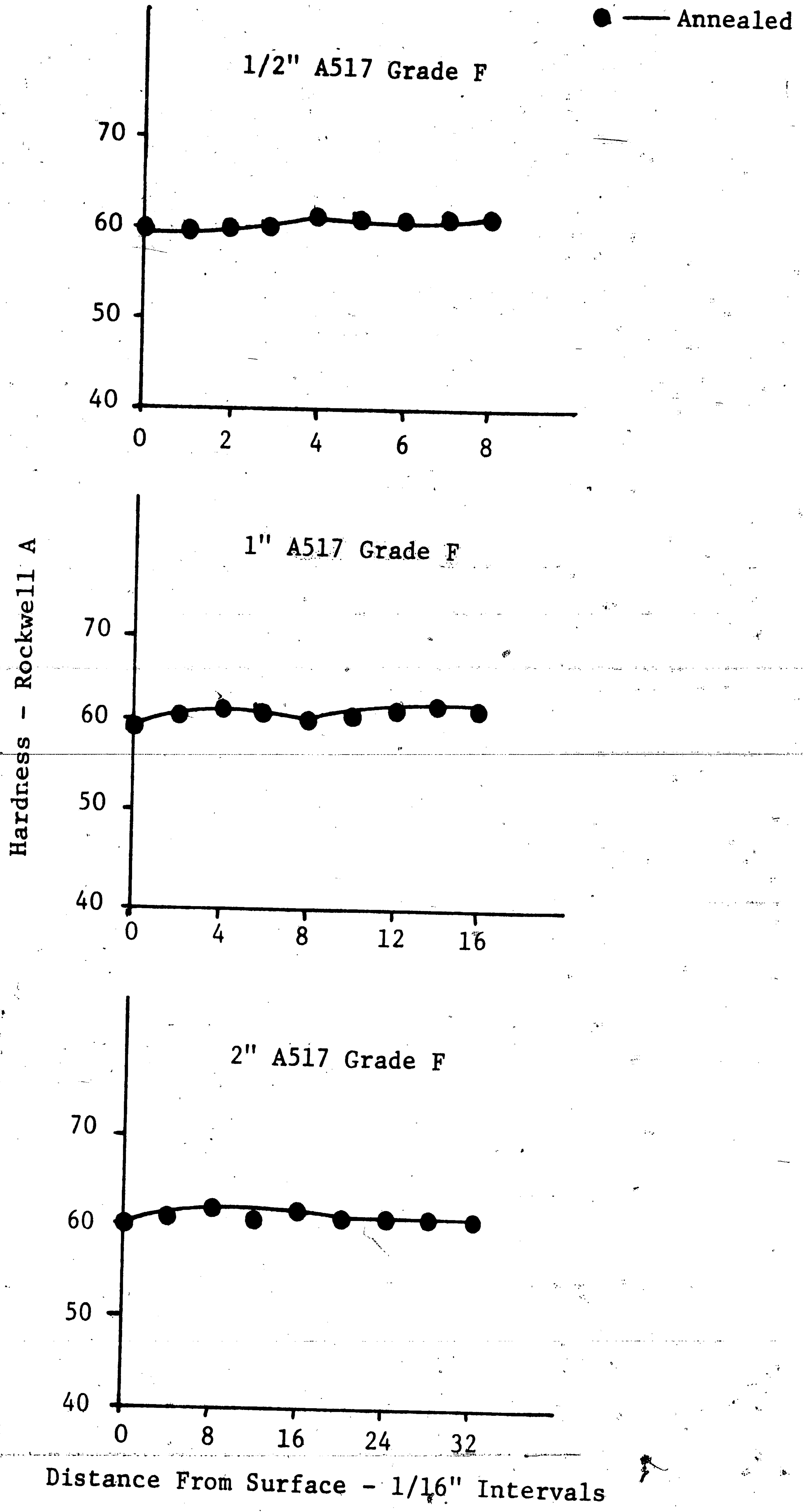


Fig. 4 (Continued) Hardness Profiles of Plates Used in Testing

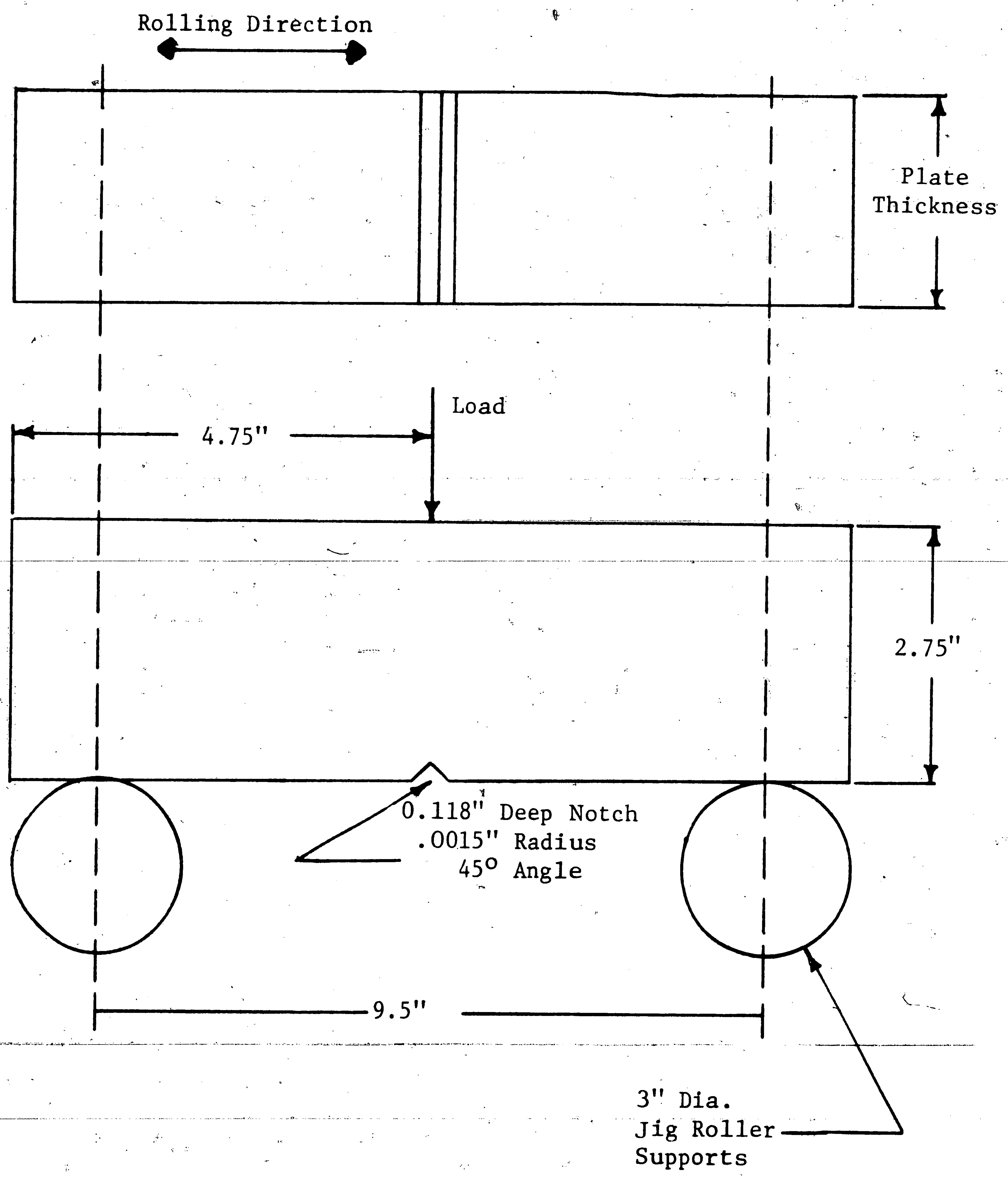


Fig. 5 Dimensions of the Van der Veen Specimen

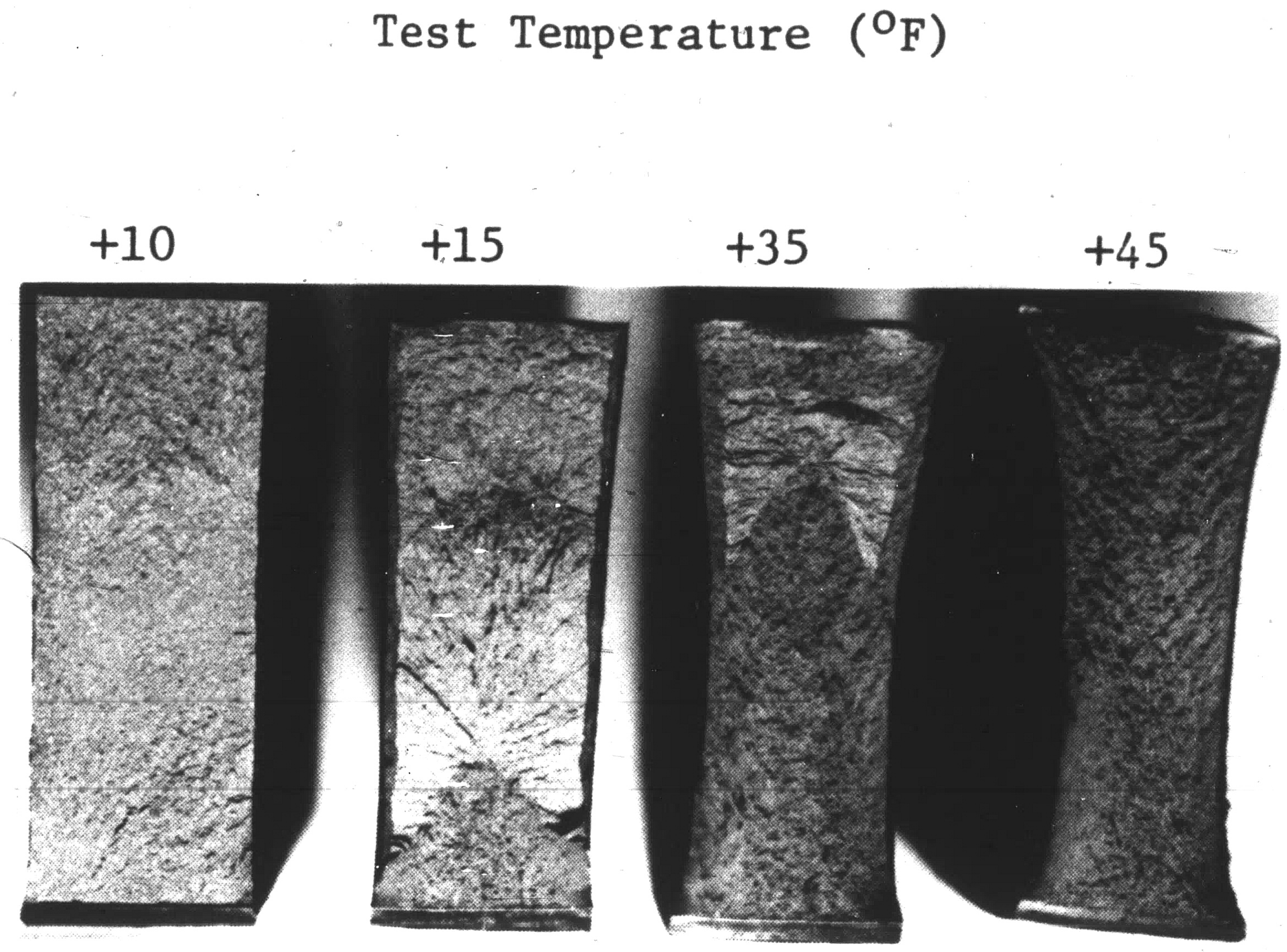


Fig. 6 Typical Fracture Surfaces From the Van der Veen Test

Fig. 7 Van der Veen Specimen Ready to be Tested

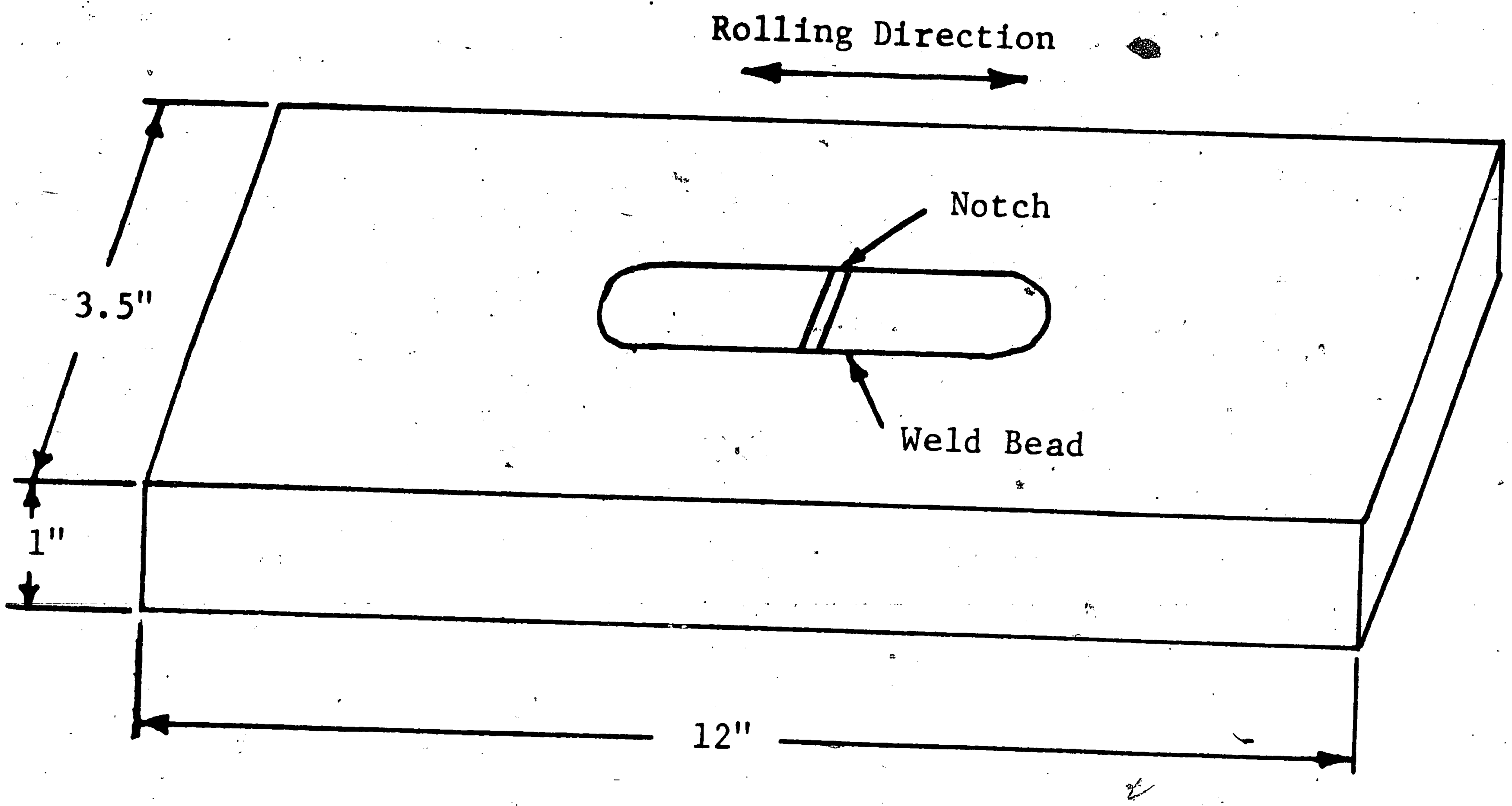
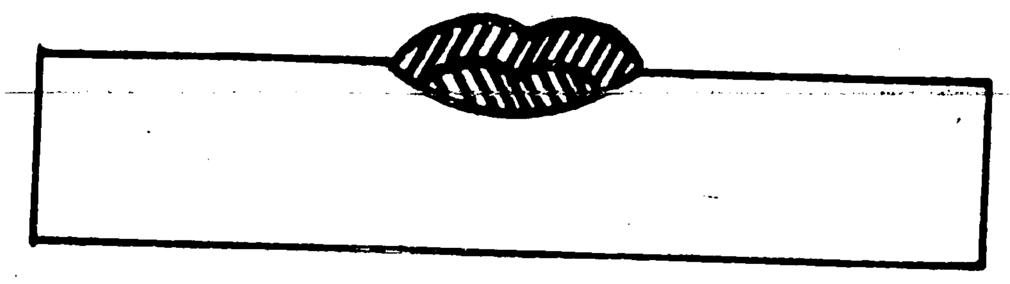


Fig. 8 Standard Drop Weight Specimen

Two Weld Beads, Side by Side

Two Weld Beads, Two Deep



Four Weld Beads, Two Wide and Two Deep

Fig. 9 Cross Section of Drop Weight Specimens Used

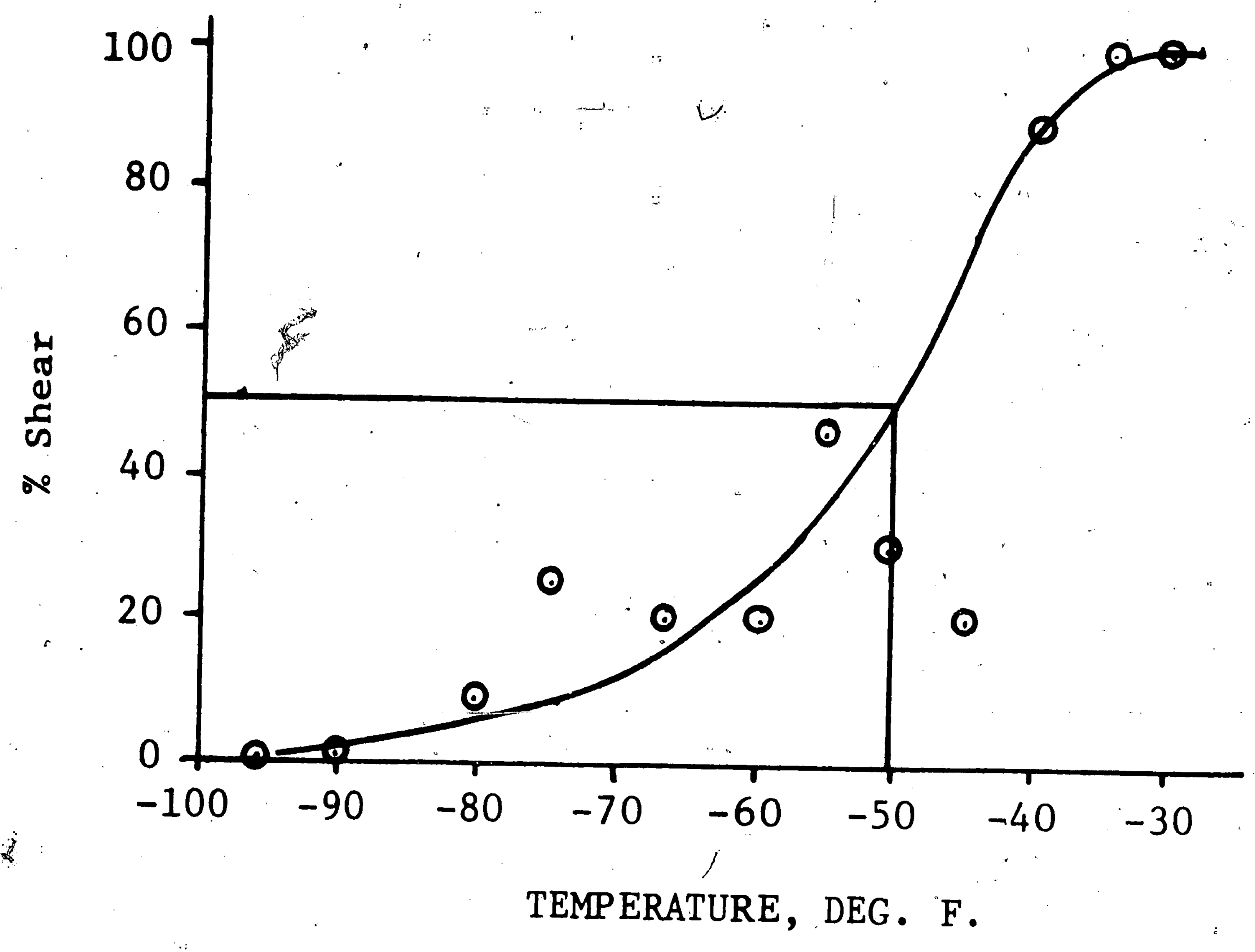


Fig. 10 Typical Van der Veen Transition Curve

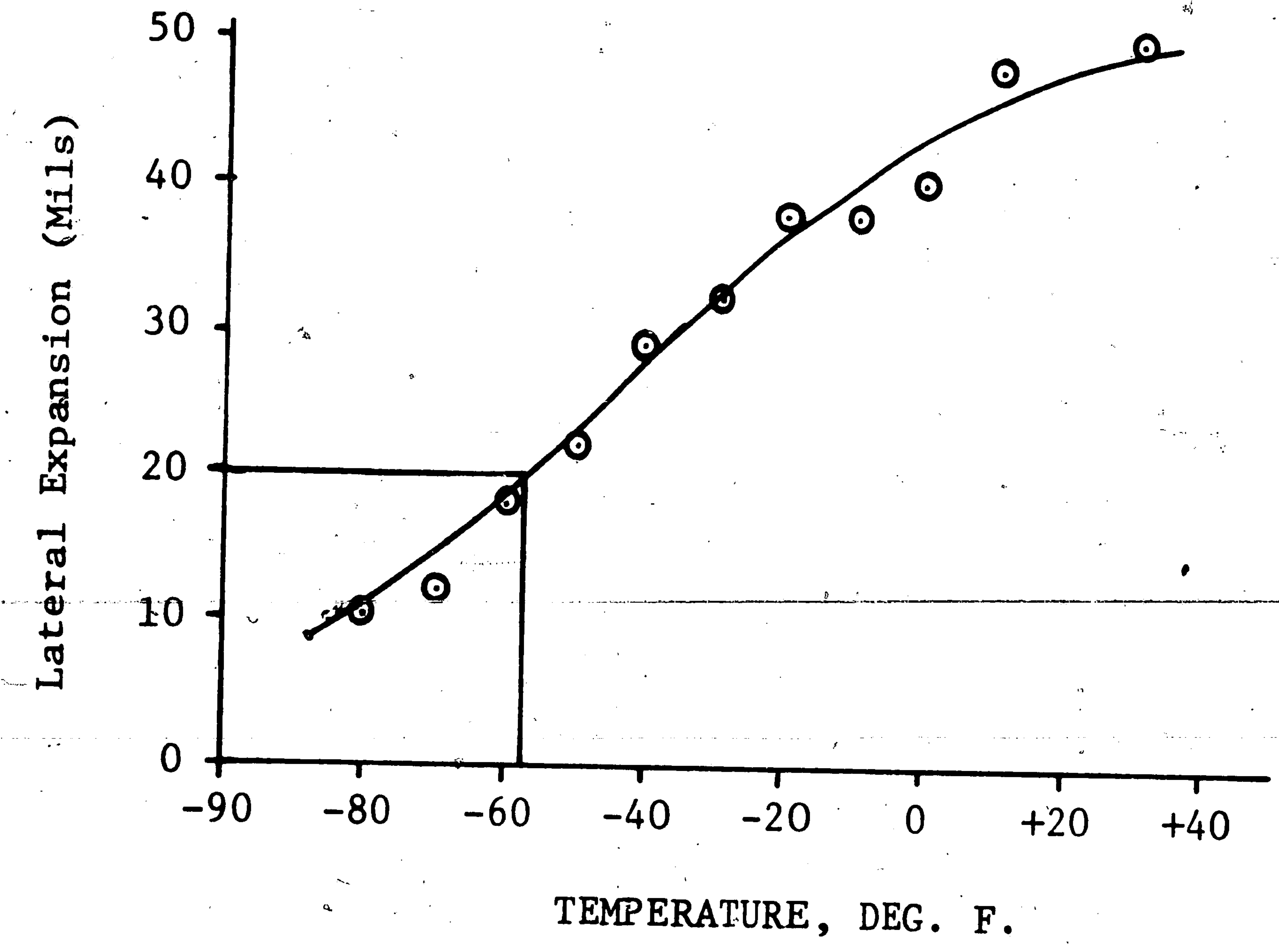


Fig. 11 Typical Charpy Transition Curve

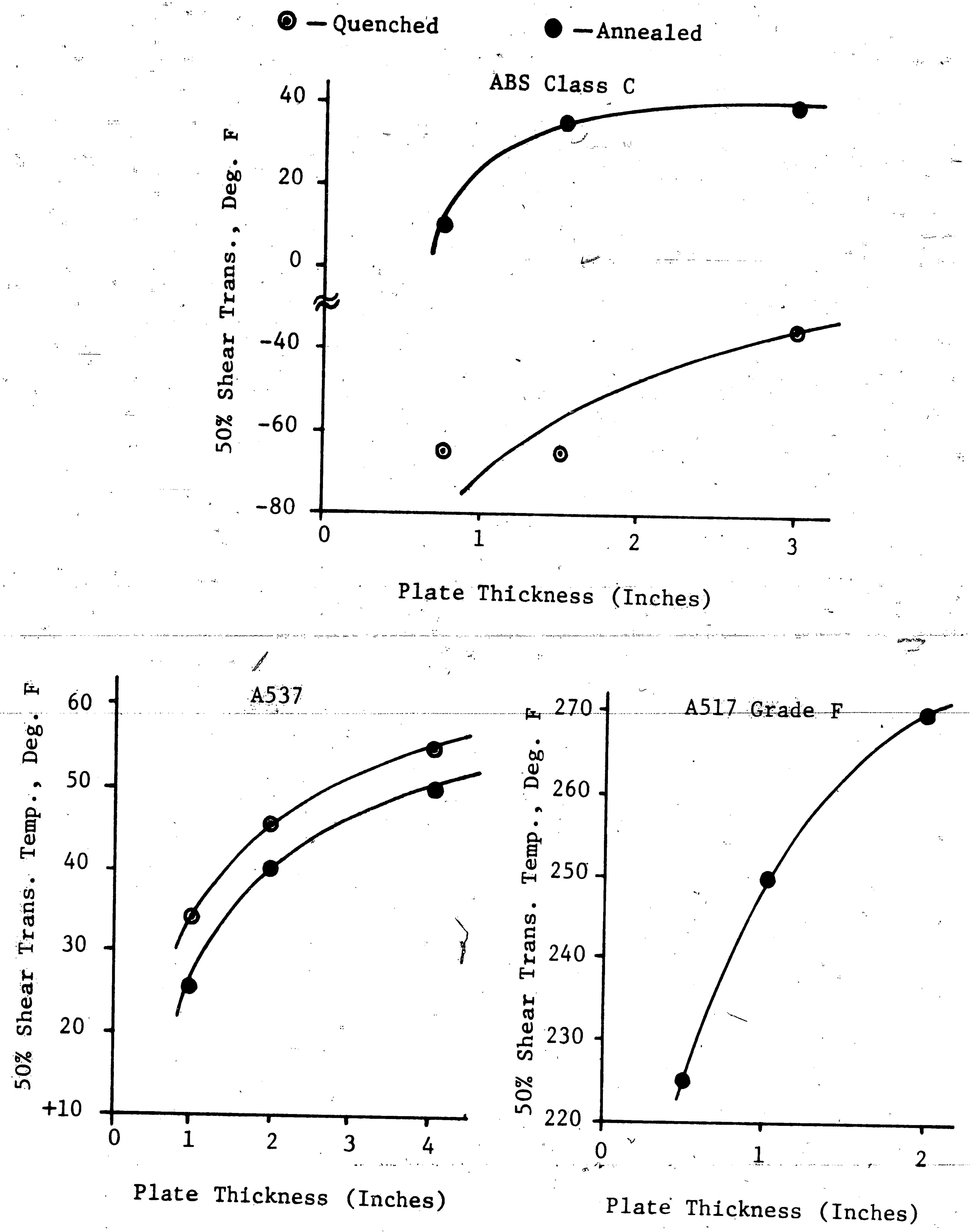


Fig. 12 Effect of Plate Thickness on the Transition Temperature in the Van der Veen Test

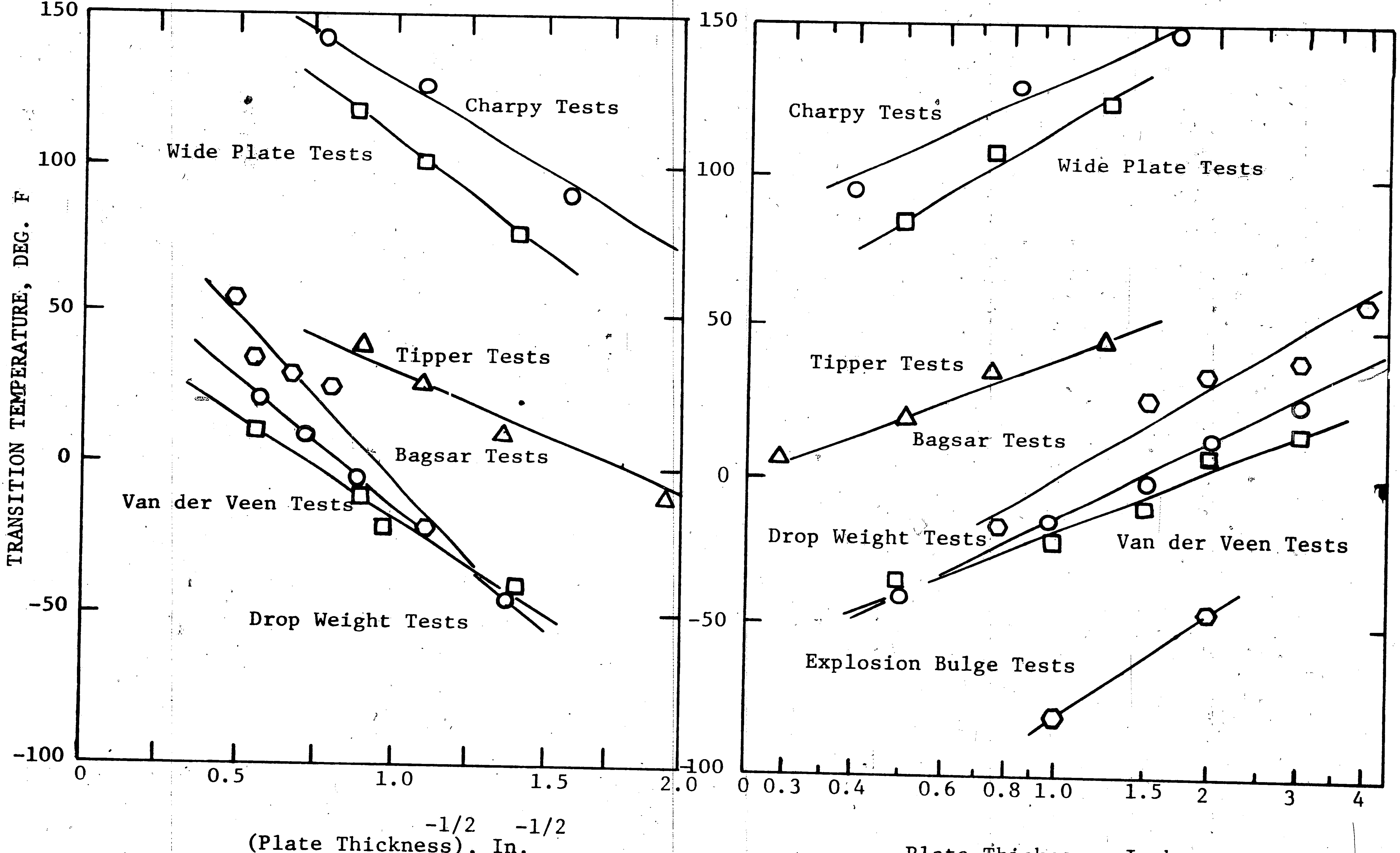


Fig. 13 Variation of Transition Temperature With Two Empirical Parameters of Thickness For Data Found in the Literature

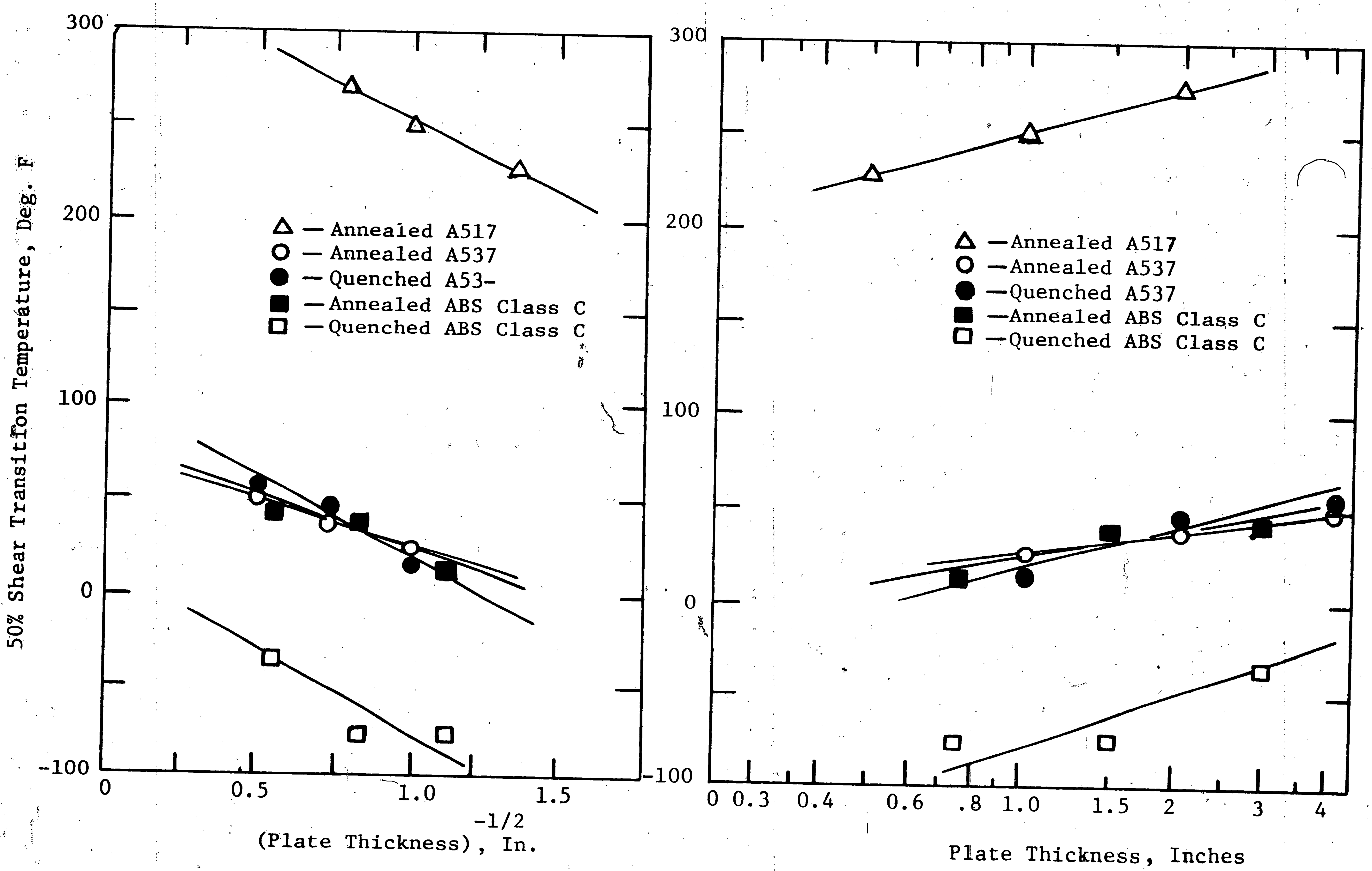


Fig. 14 Variation of Transition Temperature With Two Emperical Parameters Of Thickness For the Van der Veen Test

## VITA

Karl August Koschnitzke was born on March 26, 1943, in Chicago, Illinois, the son of Mr. and Mrs. August Koschnitzke. He attended St. Priscilla Grade School and Lane Technical High School, graduating in June, 1961. In September, 1961, he entered Michigan Technological University and graduated in June, 1965, with a Bachelor of Science degree in metallurgical engineering. He entered Lehigh University in July, 1965, as a graduate research assistant in metallurgical engineering.