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Effects of welding conditions fna microstructure on the notch toughness of multiple-pass welds

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EFFECTS OF WELDING CONDITIONS AND MICROSTRUCTURE ON THE NOTCH TOUGHNESS OF MULTIPLE-PASS WELDS

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ABSTRACT

The beneficial and harmful effects on the notch toughness of weld metal resulting from reheating during multiple-pass welding have been investigated. Grooved one inch thick plates of A517 Grade F steel, a quenched and tempered low-carbon, low-alloy steel, were welded with a Mn-Ni-Mo electrode by the inert-gas-metal arc process.

A comparison of Charpy V-notch energy impact tests of multiple-pass welds made with current levels of 250, 325 and 400 amperes, travel speeds of 5, 10, 15, 20 and 25 inches per minute and preheats of ambient temperature and 250 degrees Farenheit, has indicated that controlled welding conditions are needed to obtain a satisfactory level of notch toughness. The data showed a critical value of heat input of approximately 80,000 joules per inch, below which absorbed energy transition temperatures were in the neighborhood of -90°F, while above the critical heat input value transition temperatures were in the neighborhood of -45°F. There was a difference in critical values depending on the preheat temperature; the 250°F preheated specimens showed a slightly lower critical value of heat input.

A change in the current level or the travel speed alone was found not to be a reliable means of improving the notch toughness. These welding parameters affected the notch toughness only to the extent that they affected the

heat input.

Lineal analysis tests used to measure the percent of recrystallized weld metal have shown the microstructure to be directly related to the notch toughness. Above a critical value of percent of recrystallized weld metal of approximately 50%, good notch toughness was maintained. Specimens with percentages of recrystallization below the critical value were those welded with values of heat input above the critical value of 80,000 joules per inch. The critical value of percent of recrystallized weld metal for the 250°F preheated specimens appears to be higher than that for the room temperature preheated specimens.

Weld bead width varied linearly with the heat input at both levels of preheat with specimens preheated to 250°F being wider in all cases. Specimens with a weld bead width above 0.76 inches showed high transition temperatures, heat inputs above 80,000 joules per inch and recrystallization percentages below 50.

The notch toughness found for any welding condition is believed to be controlled by the heat input and the effect the heat input has on the microstructure. Heat input appears to be the parameter which controls the percent of recrystallized weld metal. Careful control of heat input during multiple-pass welding with low-alloy filler wires is needed to improve notch toughness of the weld metal.

INTRODUCTION

In the past decade, high strength quenched and tempered steels have been used in a large number of applications including pressure vessels, bridges and ships. Good weldability is a major factor in the selection of these steels. However, welded constructions have been called upon to meet ever increasing service requirements over a wide range of operating temperatures. These applications have demanded strong, defect-free joints which exhibit high yield strength and good low temperature notch toughness.

One of these materials is A517 Grade F steel, a low-carbon, low-alloy steel used in the quenched and tempered condition. This steel offers 100,000 psi minimum yield strength, together with the desirable characteristics of good notch toughness, good weldability, and sufficient ductility to undergo bending to reasonable radii. Although A517 steels have been used successfully in the above applications, certain weldability problems have arisen, particularly in multiple-pass welds.

The increasing use of multiple-pass arc welds at various service temperatures in these quenched and tempered steels has necessitated a better understanding of the beneficial or harmful effects of the reheating that accompanies the later passes. The metallography of multiple-pass arc welds has been shown by Stout[1] and others[2] to reflect the thermal history of the point in question. In arc welding, characterized by rapid heating and cooling rates, accicular grain structures are observed in the weld metal. Irvine and Pickering[3] have shown that subsequent welding passes cause partial recrystallization of the weld metal previously deposited in much the same manner as the base metal heat-affected-zone is altered during single-pass welding. The time-temperature distribution will determine the type and degree of refinement experienced by any particular point in the weld metal. In the unmelted metal adjacent to the fused weld metal of any weld pass, there are essentially four regions that undergo structural change. The region immediately adjacent to the fusion line which experiences a maximum temperature for the heat-affected-zone undergoes grain coarsening. This region has been shown by Grossman[4] to exhibit low impact properties. This enlarged grain size diminishes rapidly from the fusion line into a region of complete grain refinement. This region exhibits an equi-axed grain structure with a minimum in ferrite grain size. The ferrite phase has been shown by Kottcamp and Stout[5] to be the controlling microconstituent in influencing the notch toughness. With its small ferrite grain size, this refined region exhibits maximum toughness. Bordering the region of total refinement and extending outward is a region of partial refinement. The width of this region depends on the carbon produced by the partial austenitization experienced. The notch toughness controlling microconstituent of ferrite is less affected by the maximum temperature in this region and tends to approach the original grain size. The fourth region is a narrow region of spheroidization within which lamellar carbides tend to dissolve on heating and re-form as spheroidal particles on cooling. These carbides appear as colonies within the areas originally pearlitic. The matrix of ferrite remains completely unaffected by the relatively low maximum temperature reached in this region. The ferrite grain size and the notch toughness remain essentially that of the base metal.

The problem becomes more complex with multiple-pass welds since previously deposited weld metal will experience a series of thermal cycles depending on the number of subsequent weld passes. Therefore, the weld metal becomes, in reality, an agglomeration of metallurgical structures brought about by the thermal histories of particular regions.

When arc welding A517 steel, careful consideration must be given to the metallurgical changes which occur in the heat-affected-zone. For multiple-pass welds, there will be a series of heat-affected-zones throughout previous-pass weld metal, depending on the number of passes. For steels with low carbon and low alloy contents which have been quenched and tempered to obtain optimum properties, such as A517, good notch toughness has been accounted for according to Nippes[6] by the presence of low-carbon martensite which has excellent properties in the quenched condition.

Therefore, to obtain low-carbon martensite and small ferrite grain size in multiple-pass welds careful control of the weld metal composition and thermal history must be maintained. The various time-temperature cycles, which make up the thermal history of a multiple-pass weld, are controlled by the common welding parameters of arc current, arc voltage, travel speed and preheat temperature.

In an effort to obtain maximum notch toughness in inert-gas-metal arc multiple-pass welds, a series of tests was undertaken on grooved one-inch thick plates of A517 Grade F steel using M1-88 electric weld wire in an atmosphere of argon - 1% oxygen. To vary the thermal histories over a wide range, the welding conditions included: three current levels, five travel speeds and two preheat temperatures. Current levels were 250, 325 and 400 amperes. Travel speeds were 5, 10, 15, 20 and 25 inches per minute, and the preheat temperatures were ambient temperature and 250 degrees Farenheit.

To determine notch toughness, conventional Charpy Vee-notch tests were conducted on all welds over a temperature range from room temperature to minus 200 degrees Farenheit. To determine whether adequate tensile properties were being maintained, 0.2% yield strength, ultimate tensile strength and percent reduction in area tests were performed.

To correlate the weld metal microstructure to the weld metal notch toughness, lineal analysis tests were run at 100 diameters to determine the percent of refined weld metal.

Weld bead width studies using the maximum width of the last weld pass measured parallel to the plate surface were conducted to determine any relationship between weld bead width and weld metal notch toughness.

This investigation is a systematic study of the reheating effects of multiple-pass welds. It was possible to determine the welding conditions that maximized the percent of recrystallized weld metal and improved the weld metal notch toughness.

EXPERIMENTAL DETAILS

Materials

The base metal used for this investigation is one inch thick plate stock of USS "T-1" steel. T-1, or ASTM designation A517F, constructional steel is a quenched and tempered low-alloy, low-carbon steel exhibiting a combination of high yield strength, excellent notch toughness, high resistance to impact abrasion and good weldability. Linde Type M1-88 electric weld wire was used as the filler metal. The compositions of the base metal and weld metal appear in Table I.

The shielding gas was Linde argon--1% oxygen. Use of 1% oxygen allowed a stable arc to be more easily produced. The gas flow rate was forty cubic feet per hour, which was measured while thoroughly purging the system immediately prior to the welding of each specimen.

Welding

All welding was performed on automatic, inert-gas-metal-arc welding apparatus using direct current and reverse polarity. The exact equipment identification is listed below:

Linde Power Supply Type SVI-500
Linde Sigma Welding Control Type SEC-6
Linde Wire Feeder Type SEH-3
Linde MIG Welding Torch Type ST-12
Linde Electronic Governor Type EC-103
Oxweld Regulator and Flowmeter Type R-502

The three phase rectifier current unit allowed current and voltage controls to be preset. Immediately before welding the setting was standardized to allow for line voltage variations. The travel carriage to which the torch is attached could be preset to give the desired speed levels. The torch was tilted two degrees toward the direction of carriage movement.

A multiple grounding system was used for all welds in an effort to eliminate magnetic arc blow. Grounds were attached to copper studs on each end of the plate directly beneath the groove. A third ground was similarly attached to the bottom center of each plate.

Heat input values in joules per inch were calculated using the following relationship:

$$\frac{\text{Heat Input}}{\text{inch of weld deposited}} = \frac{E \times I \times 60}{T}$$

E = voltage across the arc in volts
I = current through the arc in amperes
T = travel speed in inches per minute

A complete set of welding conditions and preheat temperatures used in this investigation are given in Table II.

Specimen Preparation

Plates six inches by eighteen inches were cut from one inch T-1 and grooved according to the specifications shown in Figure 1. A 0.1 inch hole was drilled in each plate at a distance of nine inches in and 3/4 inches down from the top corner of the specimen. The hole was three inches deep and allowed a thermocouple to be placed

$\frac{1}{4}$ inch directly beneath the center of the groove. The chromel-alumel thermocouple was connected to a Leeds and Northrup Speedomax Strip Chart Recorder Type G and was used as one of the means to accurately determine interpass temperatures. The positioning of the thermocouple is shown in Figure 1. The grooved and adjacent base metal areas were cleaned with a wire brush and acetone to remove any traces of machine oil and dirt. Between subsequent weld passes, the weld and adjacent areas were wire brushed to remove any surface deposits.

Preheat Conditions

Two preheat temperatures were used for this investigation. The first series of eight welds were conducted using ambient preheat and interpass temperature. Room temperature was determined by thermocouple readings.

The second series of welds received a preheat of 250°F. The specimens were cleaned and then heated for eight hours in a still air furnace at 260°F. The specimens were then mounted on the welding table and allowed to cool to 250°F before welding. Interpass temperature for this series was 250°F. A subsequent pass was laid when the weld had cooled to 250°F as checked by the thermocouple reading and by a series of Tempil sticks above and at the interpass temperature. All welds were allowed to air cool.

Radiography

Radiograms were made of the first three welds to determine whether any porosity or lack of fusion had occurred. The radiograms were taken using a Westinghouse 150 kilovolt Industrial Unit and a Westinghouse Thermax 150 Type 979284 Unit. The X-ray exposures showed no porosity and no lack of fusion. Using these results it was decided that further X-raying would be unnecessary.

Tensile Tests

Two tensile specimens were taken from each plate transverse to the weld direction. These specimens were of the conventional 0.505 inch diameter type with the exception of the weld metal area which was tapered to insure that the failure occurred in the weld metal. Testing was performed on an Instron Tensile Testing Machine.

Charpy V-Notch Tests

Approximately twenty Charpy V-notch specimens were machined from each welded plate depending on the length of the weld. Nearly two inches at each end of the plate were discarded to insure that regions tested would have similar heat treatments. Specimens were cut transverse to the weld and notched on the thickness direction.

Charpy V-notch tests were conducted over a temperature range from room temperature to minus 200 degrees Farenheit. Test temperature intervals were 20°F except in the transition region where intervals of 5°F and 10°F were used. Each specimen was held at the test temperature for a minimum of five minutes before testing to insure a uniform temperature throughout.

The experimental data from the Charpy V-notch tests fluctuated from a smooth transition curve. This did not allow the transition temperature to be determined precisely. However, the scatter in energy and transition temperature data was minimized by accurate control of the notch contours and the specimen dimensions. The dimensions were continuously checked during machining, and metallographic examination of random specimens was used to determine if proper notch conditions were being maintained. The remaining scatter is inherent in the test.

Linear expansion tests were performed on all Charpy V-notch specimens with a mounted knife-edge dial indicator calibrated in thousandths of an inch.

Percent fibrous fracture was determined by visual approximations of the fractured surface of all Charpy V-notch specimens.

Metallography

Specimen Preparation and Observation

One section of each specimen was sectioned with a band saw under coolant. Thereafter, the specimens were surface ground on a fine wheel and wet ground on 120, 240, 320 and 400 grit emeries. Polishing was begun on wheels with 6, 3, and 1 micron diamond paste followed by finish polishing on Linde A and Linde B alumina wheels. Metallographic observation was done on a Bausch and Lomb

Balphot II Metallograph.

Etching

Several etchants including ammonium persulfate, picral and nital were tried using various etching times. It was determined that a fresh two percent nital solution was best for clearly distinguishing recrystallized and columnar regions of the multiple-pass welds. Swabbing for fifteen to twenty seconds proved to be most satisfactory and all specimens were etched in this manner.

Weld Bead Width Studies

Weld bead width measurements were made on polished and etched specimens using a table microscope. The weld bead width used in this investigation was taken as the maximum width of the last pass parallel to the plate surface. All readings were taken at a magnification of three diameters using a scale calibrated to the nearest hundredth of an inch.

Lineal Analysis

Lineal analysis techniques were used to determine the percent of recrystallized weld metal in a given cross section of a polished and etched specimen. A small motor was connected to the stage of the Bausch and Lomb Balphot II Metallograph. The gear combination used gave a scanning speed of 0.1 inches per minute. Two timers were used, one giving total time for the complete scan of the weld area and the other being separately engaged when recrystallized regions appeared during scanning. Five scans were performed on each specimen at a magnification of 100X.

RESULTS AND DISCUSSION

Charpy V-Notch Tests

Charpy V-notch test results on weld metal specimens cut transverse to the weld and notched on the thickness direction appear as absorbed energy versus test temperature curves in Figures 2, 3, 4 and 5. The forty ft.-lb. energy absorbed transition temperature for each weld in degrees Farenheit is taken from these plots and appears in Table III.

It is clear from Figures 2 thru 5 that there were essentially two groupings of values. Specimens 3-5, 4-5, 2T-5, 3T-5 and 4T-5 had gradual increases in absorbed energy with increases in test temperature. Distinct upper shelf energy values were not found in the temperature range investigated. The 40 ft.-lb. transition temperatures for these specimens were high and ranged from -35 to -55°F. Specimens 2-5, 2-10, 3-10, 4-10, 4-15, 4-25, 2T-10, 3T-10, 4T-10, 4T-15 and 4T-20 showed definite transition regions with transition temperatures ranging from -80 to -115°F with a grouping of values at -90°F. These specimens had clearly defined upper shelf energy values.

Table IV shows increasing heat input and the 40 ft.-lb. absorbed energy transition temperatures. There was evidence of a marked decrease in notch toughness when the heat input increased from 79,200 to 82,500 joules per inch. There was a critical heat input below which the specimen had a definite transition region and a marked improvement in notch toughness.

Separating this analysis into the two groupings of preheating temperatures, room temperature and 250°F, it can be seen by referring to Tables III and IV that the critical value of heat input for the 250°F preheated specimens was between 76,800 and 82,500 joules per inch. However, for the room temperature preheat conditions a critical value of heat input can not be as precisely determined, since there were no welding conditions used in this investigation that yielded heat inputs in the range from 79,200 to 120,900 joules per inch. Regardless, it is very likely that the critical value occurs at a higher heat input than that for the 250°F preheated specimens. This conclusion is based on the fact that a 250°F preheat would slow down the cooling rate and decrease the martensite and bainite while increasing the amount of free ferrite. It has been shown by Irvine and Pickering[3] that the microstructure of the as-deposited weld metal made on top of other weld passes has a columnar structure. With preheat the columnarity decreases and the amount of ferrite increases. The increased amounts of ferrite present has been shown by Gross and Stout[7] to be the main cause of decreased notch toughness in low-carbon, low-alloy steels. It must also be remembered that preheating decreases the enthalpy needed to melt and superheat the base metal and the previous-pass weld metal. Thus preheating would inherently decrease the maximum heat input that would allow a satisfactory level of notch toughness to be maintained.

Figure 6 shows a plot of 40 ft.-lb. transition temperatures versus heat inputs for room temperature and 250°F preheated specimens. The dashed curve represents an estimate of the critical heat input region for the specimens receiving a room temperature preheat. It appears that preheating at a temperature of 250°F for A517 steel, in order to lessen the danger of cracking in stressed areas, would produce tough weld metal only if a maximum of 76,800 joules per inch heat input is not exceeded.

Current Variations

The absorbed energy values obtained for the welding conditions used indicated that the notch toughness of the alloy weld metal was not directly dependent on the current level. In Tables II, III and IV current is shown not to be the controlling parameter, since high and low transition temperatures were obtained at all three current levels. This was particularly noted in the case of specimens 2-5 and 2T-5, which differed only in preheat temperature. However, specimen 2-5 with a heat input of 78,000 joules per inch had an absorbed energy transition temperature of -95°F, while specimen 2T-5 with a heat input of 82,500 joules per inch had an absorbed energy transition temperature of -45°F.

Travel Speed Variations

Weld travel speed was varied from 5 to 25 inches per minute. Specimens welded with faster travel speeds were found to have better notch toughness, as shown in Table V. However, this is believed to be true only in so far as the weld travel speed affects the heat input. Since travel speed bears an inverse relation to the heat input, faster travel speeds will lower the heat input, thereby improving the notch toughness. Table V shows specimen 2-5, with a travel speed of 5 inches per minute, having an absorbed energy transition temperature of -95°F, while specimen 3-5, also having a travel speed of 5 inches per minute, has an absorbed energy transition temperature of -35°F. Travel speed combines with arc current, arc voltage and preheat temperature in determining the heat input which has been shown to be directly related to the notch toughness.

Number of Weld Passes

The total number of weld passes needed to fill the grooved A517 specimens varied from three to thirteen passes. The number of weld passes required influences the microstructure of the weld metal. Each subsequent weld pass affects the previous passes by subjecting each area to a different heating and cooling cycle. All sections of the grooves will be subjected to a number of different time-temperature cycles depending on the number of weld passes. This repeated heating and subsequent cooling determines the microstructure. The specific effect on any particular weld area will depend on the metal composition, rate of heating, temperature reached, time at temperature and cooling rate. The metal composition of each weld pass will vary slightly, with the passes at the bottom and sides of the groove having more mixing with the base metal than the centerline passes. For each pass there will be a heat-affected-zone within which a refined zone will be found. The extent of this metallurgically refined zone will depend on the metal composition and the welding conditions. For multiple-pass welds there will be a number of these refined regions depending on the number of weld passes. Figure 7 shows the cross section of specimen 4-5 at 2.5 diameters. A total of three weld passes and the same number of refined regions are shown for each side of a weld bead. The columnar region of the last weld metal pass is also clearly evident.

Table VI shows the number of passes and the absorbed energy transition temperatures. It can be seen that, as might be expected, the number of weld passes correlates with the notch toughness in much the same manner as heat input.

Tensile Tests

Tensile tests were conducted to determine the relative strengths of the welds as compared to the base metal. A complete listing of the average tensile properties of two specimens for each welding condition is found in Table VII.

Base metal yield strength was in the vicinity of 100,000 psi, while the weld metal yield strengths varied from 75,000 to 116,000 psi. On the average yield strength values of the weld metal were slightly below that of the base metal. Tensile strengths likewise varied from 89,000 to 130,000 psi, being on the average below the 125,000 psi level of the base metal. These tests showed that the weld metal did not have adequate strength to match the base metal.

The weld metal percent reduction in area varied from a low of 41.3% to a high of 73.3%. On the average the weld metal percent reduction in area was greater than the 50% level of the base metal.

There was no significant repeatable difference in the yield strengths, tensile strengths or percent reductions in area for specimens having high or low absorbed energy transition temperatures.

Lateral Expansion Measurements

Lateral expansion is a measure of the plastic- deformation work done on the Charpy V-notch specimens during fracture. Lateral expansion in thousandths of an inch is plotted against test temperature in Figures 8, 9, 10 and 11. The 20 mil lateral expansion transition temperature values are taken from these curves and appear in Table III. These values showed considerable scatter but fell essentially into the same two groupings as the absorbed energy transition temperatures. The high transition temperature group showed a gradual increase in expansion with increasing test temperature, while the other group showed a definite transition region on the lateral expansion versus test temperature plots. These data can be directly related to the heat input. Specimens with a definite transition region and upper shelf value on the plots of lateral expansion versus test temperature had heat inputs equal to or less than 79,200 joules per inch.

Fracture Appearance Measurements

All Charpy V-notch specimens were examined to determine the level of fibrosity of the fracture. Approximate percent fibrous fracture is plotted against test temperature in Figures 12, 13, 14 and 15. The fifty percent fibrous fracture transition temperature values were taken from these curves and appear in Table III. Once again there were essentially two groupings of values with the exceptions of specimens 2-10 and 4-25. These values showed a direct relation to the heat input but were not as pronounced as either the lateral expansion or the absorbed energy measurements.

Lineal Analysis

In an attempt to correlate the microstructure found in the weld metal to the notch toughness, lineal analysis tests were conducted on the polished and etched weld specimens. A series of five scans were run on each specimen, three longitudinal and two transverse, to determine the average percent of recrystallized weld metal. The recrystallized weld metal is distinguished from the as cast weld metal by a fine essentially equiaxed grain structure.

Figures 16, 17 and 18 show a sample of the technique used. Figure 18 is a photomacrograph of specimen 2-10 at a magnification of 3.5 diameters. The overlay of Figure 17 shows the location of the five scans. The three vertical scans were located at the weld centerline and one tenth of an inch to either side, labeled R and L. Measurements started at a point parallel to the base metal and ended at the fusion line between the weld metal and the base metal. The two transverse scans were located at a distance of one tenth of an inch and two tenths of an inch, labeled T_1 and T_2 respectively, below and parallel to the plate surface. The transverse scans started and ended at the fusion lines between the base metal and the weld metal at opposite sides of the groove. The solid lines in Figure 17 indicate scanned regions. The values shown at the end of each line indicate the percent of refined weld metal for that particular scan. Figure 16 shows the location of the Charpy V-notch specimen in relation to the lineal analysis measurements made on specimen 2-10. Lineal analysis measurements were taken from the same relative weld area of all specimens. These five scans were found to give a representative average value of the percent of recrystallized weld metal. Accurate values of percent of recrystallized weld metal in and around the v-notch of the Charpy specimen were thus obtained.

Table VIII gives the results of the lineal analysis measurements on all specimens including average values and absorbed energy transition temperatures. Values of T_1 scans were nearly all lower than the average percent of recrystallized weld metal and can be justified from the fact that this scan passes through the top weld passes which have not had the benefit of the heat treatment from subsequent weld passes.

Since microstructure is a critical factor in determining the notch toughness, Table VIII is particularly useful in describing its correlation to Charpy V-notch impact data. Figure 19 shows a plot of the absorbed energy transition temperatures versus the average percents of recrystallized weld metal. Linear curves were used to approximate the two separate groupings of data points. Both show gradual increases in absorbed energy transition temperature with increased percent recrystallization with the slopes being nearly parallel. There was a critical transition region of recrystallization between 46 and 51%, above which absorbed energy transition temperatures were in the range from -80 to -115°F. This indicates that the notch toughness depended on some aspect of microstructure. The results of this investigation did not show whether the microstructural aspect resulted from recrystallization or from various cooling rates. In any case, a critical percent of refined weld metal was needed to obtain a satisfactory level of notch toughness.

By analyzing separately the two preheat temperatures used, it was seen that the critical recrystallization range for the room temperature preheated specimens was between 43 and 51 percent, while the specimens preheated at 250°F had a transition range between 46 and 65 percent. Realizing that the higher preheat temperature would produce a slower cooling rate and change the morphology of the microstructure present; it would be expected that a slightly higher percentage of recrystallization is needed before satisfactory notch toughness is attained in the 250°F preheated specimens.

Table IX is a comparison of the welding parameter of heat input and the microstructure parameter of percent of recrystallized weld metal. There was a direct relationship between these two parameters. For heat inputs of 79,200 joules per inch and below, a minimum of 51.3% refinement was attained. Specimens 3-5, 4-5, 2T-5, 3T-5 and 4T-5 with heat inputs of 82,500 joules per inch and above showed recrystallization percentages of less than 46. These were the same specimens which had high absorbed energy transition temperatures. Both heat input calculations and percent recrystallization measurements illustrate the concept of a critical value which is needed to produce adequate notch toughness.

It can clearly be seen from Tables IV and IX and from Figures 6 and 19 that the transition in toughness occurs for the parameters of heat input and percent of recrystallized weld metal. This further indicated that the notch toughness of the weld metal is directly controlled by the welding conditions, manifested in the heat input, which in turn controls point-to-point variations in chemistry, thermal histories and microstructures.

By referring to Table VI it can be seen that when the number of weld passes was increased there was an increase in the percent of recrystallized weld metal. However, this increase was not uniform, which indicated that increasing the number of weld passes did not directly increase the percent of refined weld metal.

Weld Bead Width Measurements

Weld bead width studies were undertaken to determine if these widths could be correlated with the notch toughness.

The weld bead width directly decreased with increasing weld travel speeds; the extremes of this can be seen in Figure 20. Specimen 4-5 with a weld travel speed of five inches per minute had a weld bead width of 0.98 inches, while specimen 4-25 with a travel speed of twenty-five inches per minute had a weld bead width of 0.40 inches. Both specimens were welded with an arc current of 400 amperes.

Weld width measurements, defined as the maximum width of the last pass parallel to the base-metal plate surface, are given in Table X. It can be seen that in every case the weld bead width was larger for the 250°F preheated specimens than for the room temperature preheated specimens at corresponding current levels. This is also indicated in Figure 21 where weld bead width is plotted against heat input. Both preheat temperature levels showed linear plots of increasing weld bead width with increasing heat input, with the 250°F preheated specimen values being displaced above and approximately parallel to the room temperature preheated specimen values.

As shown in Table X, a specimen having a weld bead width equal to or greater than 0.76 inches had a high heat input and a high absorbed energy transition temperature, while specimens with a weld bead width below 0.68 inches had heat inputs below the critical value and absorbed energy transition temperatures ranging from -80 to -115°F.

It can be seen by comparing specimens in Tables IX and X that the weld bead width correlated with the notch toughness in much the same manner as heat input and percent of recrystallized weld metal. Specimens 3-5, 4-5, 2T-5, 3T-5 and 4T-5 had large weld bead widths, high heat inputs, low percentages of recrystallized weld metal and high absorbed energy transition temperatures. These same specimens were the ones that had high 20 mil lateral expansion transition temperatures and high 50% fibrous fracture transition temperatures.

Summary

The notch toughness of a low-alloy weld metal was controlled by the welding conditions, manifested in the heat input, which in turn controlled the microstructure of the weld metal.

The parameters of heat input, percent of recrystallized weld metal and weld bead width displayed critical values as related to the notch toughness. Specimens with a combination of low heat input, high percent of recrystallized weld metal and small weld bead width had good notch toughness with transition temperatures in the range from -80 to -115°F.

Arc current, travel speed and preheat temperature did not uniquely determine the notch toughness. The effect of these parameters on notch toughness was best expressed by their effect on the main variable of heat input.

CONCLUSIONS

The conclusions reached and the observations made during this investigation may be summarized in the following statements:

1. The heat input was the most significant parameter to the notch toughness of a Mn-Ni-Mo alloy steel weld metal.

2. Charpy V-notch tests showed that specimens with a heat input at or below 79,200 joules per inch regardless of the preheat condition had energy transition temperatures ranging from -80 to -115°F.

3. The critical value of heat input needed to obtain adequate notch toughness was lower for the 250°F preheated specimens than for the specimens receiving room temperature preheat.

4. Arc current and travel speed are interlocked variables in their control of notch toughness of weld metal.

5. Tensile tests showed that the weld metal did not have adequate strength to match the base metal.

6. Lineal analysis measurements showed that a rather sudden gain in notch toughness was obtained as the percent of recrystallized weld metal rose from 46% to 51%. Specimens with heat inputs at or below 79,200 joules per inch had recrystallization percentages above 51%.

7. A higher percentage of recrystallized weld metal was needed for improved notch toughness in the specimens preheated to 250°F than in those welded at room temperature.

8. Weld bead width decreased with increasing travel speeds and increased linearly with increasing heat input.

9. Weld bead widths were larger for the 250°F preheated specimens than for those receiving room temperature preheat.

10. Weld bead widths of 0.68 inches corresponded to the critical levels of heat input and percent of recrystallized weld metal, at which a marked change in the notch toughness occurred.

APPENDIX

During the course of this investigation, two relationships were verified that have been previously reported in the literature.

Lateral expansion measurements of the Charpy V-notch specimens showed that a linear relationship existed between absorbed energy and lateral expansion with lateral expansion increasing with increasing amounts of absorbed energy. Figure 22 shows a representative example of this relationship. A linear relationship is expected since increased absorbed energy during the test should produce a corresponding increase in plastic-deformation work.

The impact energy in the temperature range within which fracture undergoes transition from brittle to ductile fracture has been shown by Newhouse[8] to be linearly related to the proportion of fibrosity with percent fibrosity increasing with increasing absorbed energy. Figure 23 shows examples of this relationship. All specimens which exhibited transition regions in the absorbed energy versus test temperature plots were found to have this linear relationship. However, it is noteworthy that each specimen showed a somewhat different slope to the curve. Low percent fibrosity and low absorbed energy at any test temperature would be considered unsatisfactory since they would offer little resistance to fracture propagation.

BIBLIOGRAPHY

[1] Stout, R. D. and McGeady, L. J. "The Meaning and Measurement of Transition Temperature," Welding Journal, Vol. 27, 1948, p. 209-s.

[2] Tremlett, H. F., Baker, R. G., and Wheatley, J. M. "Mechanical Properties and Metallurgical Features of Mild Steel Weld Metals," British Welding Journal, Vol. 8, 1961, p. 437.

[3] Irvine, W. P., Jr. and Pickering, F. B. "Relationship Between Microstructure and Mechanical Properties of Mild Steel Weld Deposits," British Welding Journal, Vol. 7, 1960, p. 354.

[4] Grossman, N. and MacGregor, C. W. "The Brittle Transition Temperature of Various Low Carbon Steels Welded by the Same Method," Welding Journal, Vol. 27, 1948, p. 267-s.

[5] Kottcamp, E. H., Jr. and Stout, R. D. "Effect of Microstructure on Notch Toughness--Part IV," Welding Journal, Vol. 38, 1959, p. 435-s.

[6] American Welding Society. The Weld Heat-Affected Zone. The 1958 Adams Lecture by Ernest F. Nippes, American Welding Society, 1958.

[7] Gross, J. H. and Stout, R. D. "Effect of Microstructure on Notch Toughness," Welding Journal, Vol. 35, 1956, p. 72-s.

[8] Newhouse, D. L. "Relationships Between Charpy Impact Energy, Fracture Appearance, and Test Temperature in Alloy Steels," Welding Journal, Vol. 42, 1963, p. 105-s.

Gurev, H. S. and Stout, R. D. "Solidification Phenomena in Inert Gas Metal--Arc Welds," Welding Journal, Vol. 42, 1963, p. 298-s.

Hatch W. P., Jr. and Hartbower, C. E. "Toughness of Welds Evaluated Separately and in Composite," Welding Journal, Vol. 37, p. 455-s.

Nippes, E. F. and Savage, W. F. "Tests of Specimens Simulating Weld Heat-Affected Zones," Welding Journal, Vol. 28, 1949, p. 599-s.

Orner, G. R. and Hartbower, C. E. "Effect of Specimen Geometry on Charpy Low-Blow Transition Temperature," Welding Journal, Vol. 36, 1957, p. 521-s.

Orner, G. R. "Charpy Brittle-Fracture Transitions by the Lateral Expansion Energy Relationship," Welding Journal, Vol. 36, 1958, p. 201-s.

Owen, W. S., Cohen, M., and Averbach, B. L. "The Influence Of Ferrite Banding on the Impact Properties of Mild Steel," Welding Journal, Vol. 37, 1957, p. 368-s.

Owen, W. S., Whitman, D. H., Cohen, M., and Averbach, B. L. "Relation of Charpy Impact Properties to Microstructure of Three Ship Steels," Welding Journal, Vol. 36, 1957, p. 503-s.

Pellini, W. S. "Notch Ductility of Weld Metal," Welding Journal, Vol. 35, 1956, p. 217-s.

Rhinebolt, J. A. and Harris, W. J., Jr. "Statistical Analysis of Tests of Charpy V-Notch and Keyhole Bars," Welding Journal, Vol. 30, 1951, p. 202-s.

Tempil Corporation. Preheating for Welding. a pamphlet prepared by Tempil Corporation, New York, 1966.

Tremlett, H. F. and Baker, R. G. "Part II--Metallographic Examination of Double-Run Specimens," British Welding Journal, Vol. 8, 1961, p. 448.

United States Steel Corporation. Design and Engineering Seminar--1964. Collection of papers presented at the Design and Engineering Seminar, Chicago: United States Steel Corporation, 1964.

Wayman, C. M. and Stout, R. D. "Factors Affecting the Tensile Properties of Steel Weld Metal," Welding Journal, Vol. 36, 1957, p. 252-s.

Wheatley, J. M. and Baker, R. G. "Mechanical Properties of a Mild Steel Weld Metal Deposited by the Metal-Arc Process," British Welding Journal, Vol. 9, 1962.

Wundt, B. M. and Newhouse, D. L. "Slow Bend and Impact of Nitrided Charpy V-Notched Specimens," Welding Journal, Vol. 42, 1963, p. 326-s.

TABLE I

Chemical Composition of T-1 Base Metal and M1-88 Weld Wire

T-1 Base Metal*

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V
0.18	0.82	0.010	0.015	0.22	0.30	0.87	0.58	0.44	0.04

M1-88 Weld Wire

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V
0.04	1.60	0.010	0.010	0.30	0.30	1.65	0.10	0.25	0.01

* Heat Number 73P365

TABLE II

Complete Set of Welding Conditions Used in This Investigation

Specimen	Current Amperes	Voltage Volts	Travel Speed ipm	Preheat Deg. F	Heat Input ji	Number of Passes
2-5	250	29.0	5	R.T.	78,000	6
2-10	250	27.0	10	R.T.	40,500	12
3-5	325	31.0	5	R.T.	120,900	5
3-10	325	31.0	10	R.T.	60,450	11
4-5	400	30.0	5	R.T.	144,000	3
4-10	400	33.0	10	R.T.	79,200	7
4-15	400	29.0	15	R.T.	46,400	9
4-25	400	27.0	25	R.T.	25,900	13
2T-5	250	27.5	5	250	82,500	5
2T-10	250	27.5	10	250	40,250	10
3T-5	325	29.5	5	250	115,050	4
3T-10	325	29.0	10	250	56,500	7
4T-5	400	32.0	5	250	153,600	4
4T-10	400	32.0	10	250	76,800	5
4T-15	400	33.0	15	250	52,800	10
4T-20	400	31.0	20	250	37,200	13

TABLE III

Forty Foot Pound Absorbed Energy, Twenty Mil Lateral Expansion and Fifty Percent Fibrous Fracture Transition Temperatures

Specimen	Transition Temperature Degrees F		
	40 ft. lb.	20 mil lat expan	50% Fibrous Fracture
2-5	-95	-95	-75
2-10	-80	-50	-40
3-5	-35	0	-10
3-10	-115	-105	-90
4-5	-40	-10	-15
4-10	-85	-85	-80
4-15	-95	-85	-60
4-25	-80	-60	-55
2T-5	-45	-60	-50
2T-10	-90	-90	-85
3T-5	-35	-30	-50
3T-10	-85	-80	-95
4T-5	-55	-65	-55
4T-10	-80	-75	-80
4T-15	-90	-85	-85
4T-20	-95	-95	-85

TABLE IV

Increasing Heat Inputs and Forty Foot Pound Absorbed Energy Transition Temperatures

Specimen	Heat Input	Absorbed Energy Transition Temp.
4-25	25,900 ji	-80 Deg. F
4T-20	37,200	-95
2T-10	40,250	-90
2-10	40,500	-80
4-15	46,400	-95
4T-15	52,800	-90
3T-10	56,550	-85
3-10	60,450	-115
4T-10	76,800	-80
2-5	78,000	-95
4-10	79,200	-85
2T-5	82,500	-45
3T-5	115,050	-35
3-5	120,900	-35
4-5	144,000	-40
4T-5	153,600	-55

TABLE V

Weld Travel Speed and Forty Foot Pound Absorbed Energy Transition Temperatures

Specimen	Travel Speed	Absorbed Energy Transition Temp.
3T-5	5 ipm	-35 Deg. F
3-5	5	-35
4-5	5	-40
2T-5	5	-45
4T-5	5	-55
2-5	5	-95
2-10	10	-80
4T-10	10	-80
4-10	10	-85
3T-10	10	-85
2T-10	10	-90
3-10	10	-115
4-15	15	-90
4T-15	15	-95
4T-20	20	-95
4-25	25	-80

TABLE VI

Increasing Number of Weld Passes, Percent of Recrystallized Weld Metal and Forty Foot Pound Absorbed Energy Transition Temperatures

Specimen	Number of Passes	% Recrystallized Weld Metal	Absorbed Energy Transition Temperatures
4-5	3	43.4	-40 Deg. F
3T-5	4	26.1	-35
4T-5	4	42.6	-55
3-5	5	34.0	-35
2T-5	5	45.6	-45
4T-10	5	66.8	-80
2-5	6	52.5	-95
4-10	7	67.0	-85
3T-10	7	66.8	-85
4-15	9	69.2	-95
2T-10	10	65.4	-90
4T-15	10	69.7	-95
3-10	11	62.4	-115
2-10	12	51.3	-80
4-25	13	53.7	-80
4T-20	13	70.4	-95

TABLE VII

Average Yield Strengths, Tensile Strengths and Percent Reductions in Area

Specimen	0.2% Yield Strength	Tensile Strength	% Red. Area
2-5	79,300 psi	89,400 psi	55.4
2-10	89,000	95,000	64.5
3-5	105,200	109,100	69.4
3-10	108,000	112,000	66.0
4-5	116,300	129,400	41.3
4-10	84,450	95,000	72.4
4-15	100,100	108,700	65.1
4-25	105,000	113,700	68.5
2T-5	75,200	92,500	71.2
2T-10	90,400	102,300	73.3
3T-5	76,900	95,250	71.8
3T-10	90,900	104,800	47.7
4T-5	75,750	95,400	71.1
4T-10	83,200	101,000	70.5
4T-15	85,050	99,100	71.2
4T-20	100,200	110,050	62.2

TABLE VIII

Lineal Analysis Measurements

Specimen	C-L	R	L	T_1	T_2	Avg.	Abs. Energy Trans. Temp.
2-5	56.4%	46.4%	57.5%	46.6%	55.5%	52.5%	-95 Deg. F
2-10	52.9	50.9	56.8	44.2	51.5	51.3	-80
3-5	37.7	26.5	35.7	28.1	42.6	34.0	-35
3-10	47.9	54.5	69.6	60.5	79.7	62.4	-115
4-5	40.3	42.0	61.3	34.3	39.3	43.4	-40
4-10	69.9	72.3	67.0	55.3	70.7	67.0	-85
4-15	69.4	75.5	69.4	63.7	67.9	69.2	-95
4-25	55.3	44.9	61.8	51.7	54.9	53.7	-80
2T-5	43.7	43.7	43.5	35.8	61.5	45.6	-45
2T-10	67.4	64.4	71.6	50.7	72.8	65.4	-90
3T-5	20.3	21.0	31.4	22.1	35.9	26.1	-35
3T-10	64.5	73.1	68.5	53.3	74.5	66.8	-85
4T-5	47.9	38.4	39.0	35.5	52.2	42.6	-55
4T-10	66.6	58.5	63.8	68.7	76.6	66.8	-80
4T-15	73.6	64.2	80.4	61.1	69.4	69.7	-90
4T-20	51.3	82.0	76.8	67.1	74.9	70.4	-95

TABLE IX

Increasing Heat Inputs and Percent of Recrystallized Weld Metal

Specimen	Heat Input	% Recrystallized Weld Metal
4-25	25,900 ji	53.7
4T-20	37,200	70.4
2T-10	40,250	65.4
2-10	40,500	51.3
4-15	46,400	69.2
4T-15	52,800	69.7
3T-10	56,550	66.8
3-10	60,450	62.4
4T-10	76,800	66.8
2-5	78,000	52.5
4-10	79,200	67.0
2T-5	82,500	45.6
3T-5	115,050	26.1
3-5	120,900	34.0
4-5	144,000	43.4
4T-5	153,600	42.6

TABLE X

Increasing Heat Inputs, Weld Bead Width Measurements and Forty Foot Pound Absorbed Energy Transition Temperatures

Specimen	Heat Input	Weld Bead Width	Absorbed Energy Transition Temperature
4-25	25,900 ji	0.40 in.	-80 Deg. F
4T-20	37,200	0.50	-95
2T-10	40,250	0.62	-90
2-10	40,500	0.43	-80
4-15	46,400	0.49	-95
3T-10	56,550	0.67	-85
3-10	60,450	0.41	-115
4T-10	76,800	0.68	-80
2-5	78,000	0.67	-95
4-10	79,200	0.66	-85
2T-5	82,500	0.78	-45
3T-5	115,050	0.97	-35
3-5	120,900	0.76	-35
4-5	144,000	0.98	-40
4T-5	153,600	1.06	-55

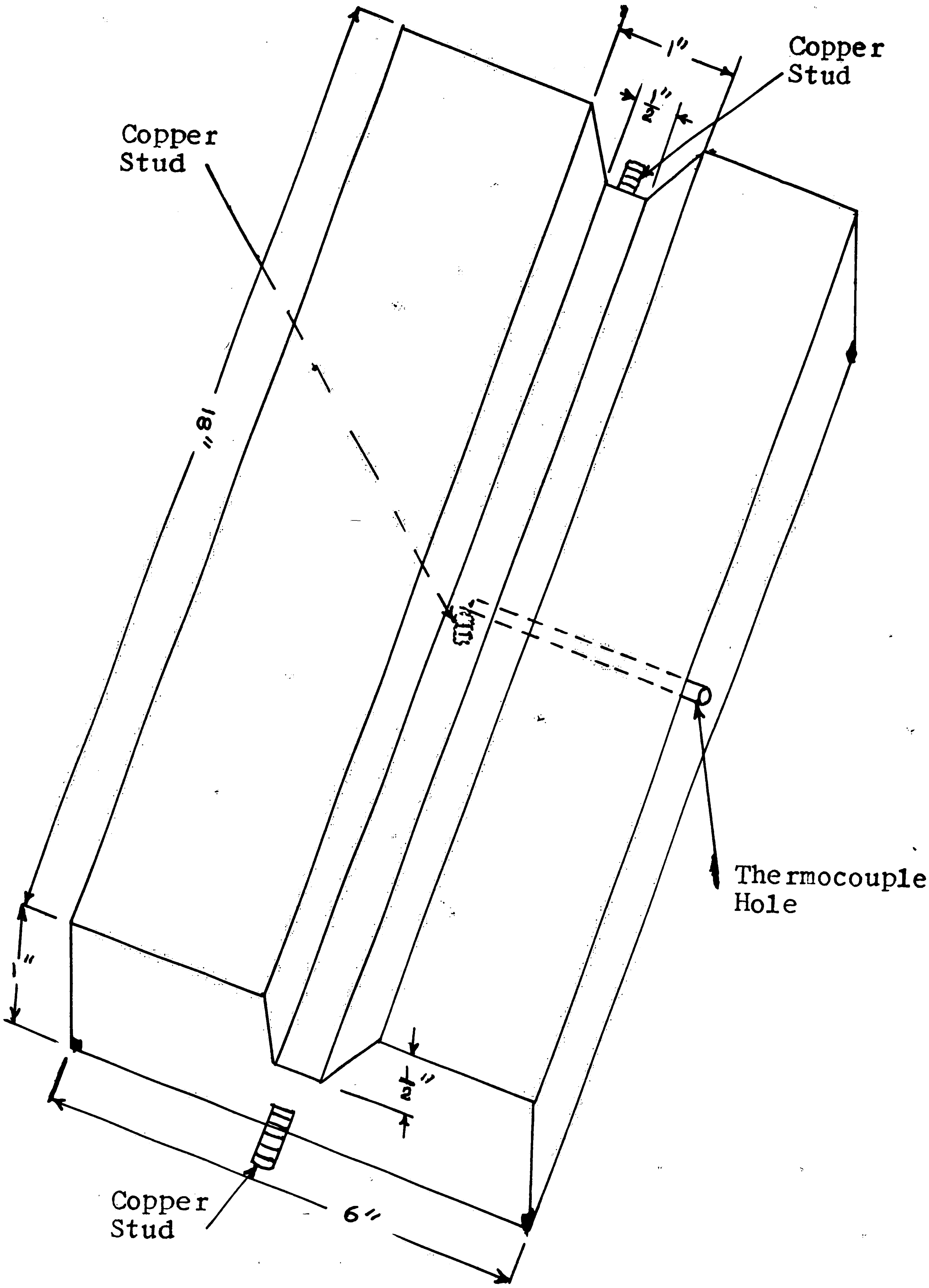

Figure 1 Schematic of Specimen Design and Thermocouple Positioning

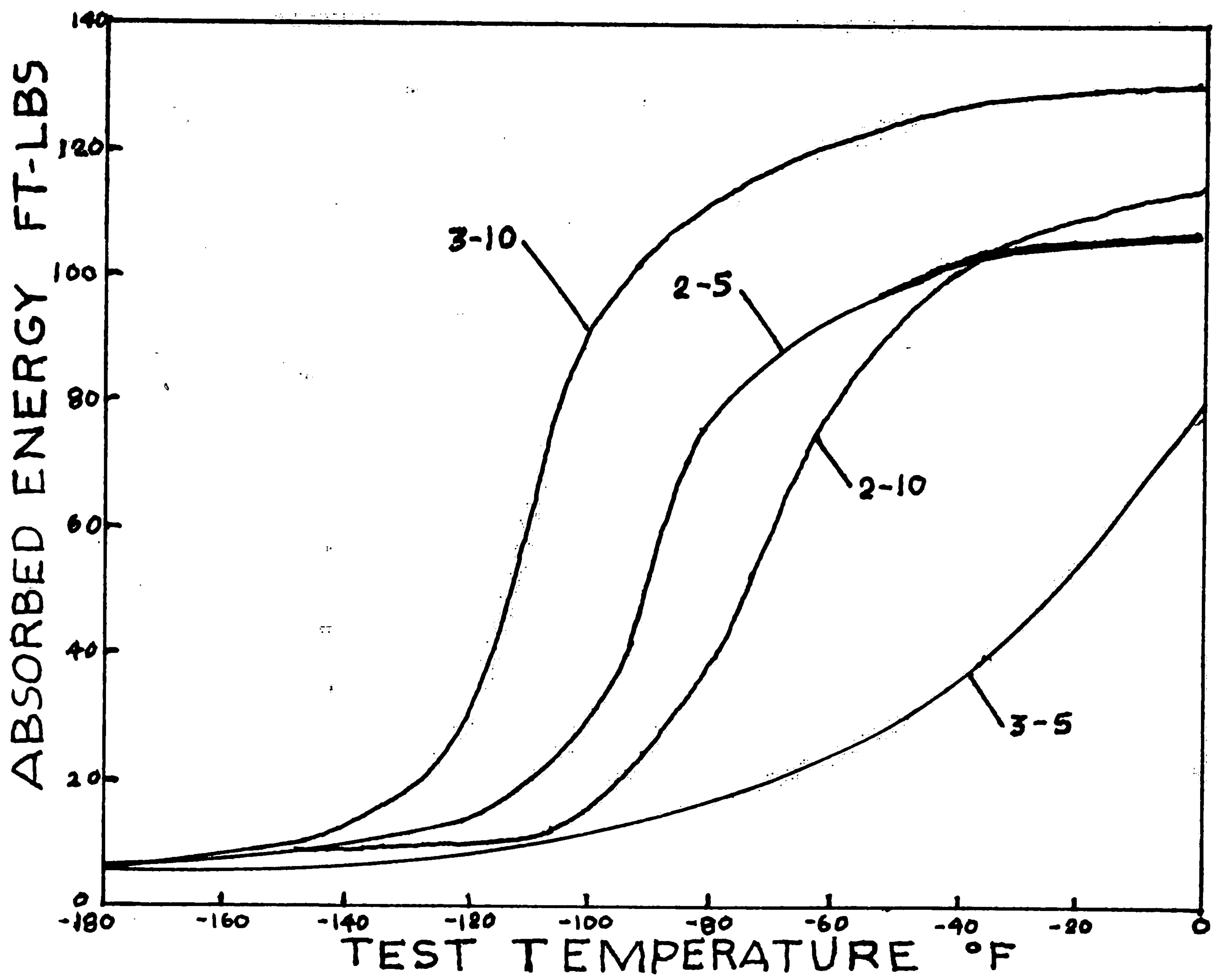

Figure 2 Absorbed Energy versus Test Temperature for Specimens 2-5, 2-10, 3-5 and 3-10

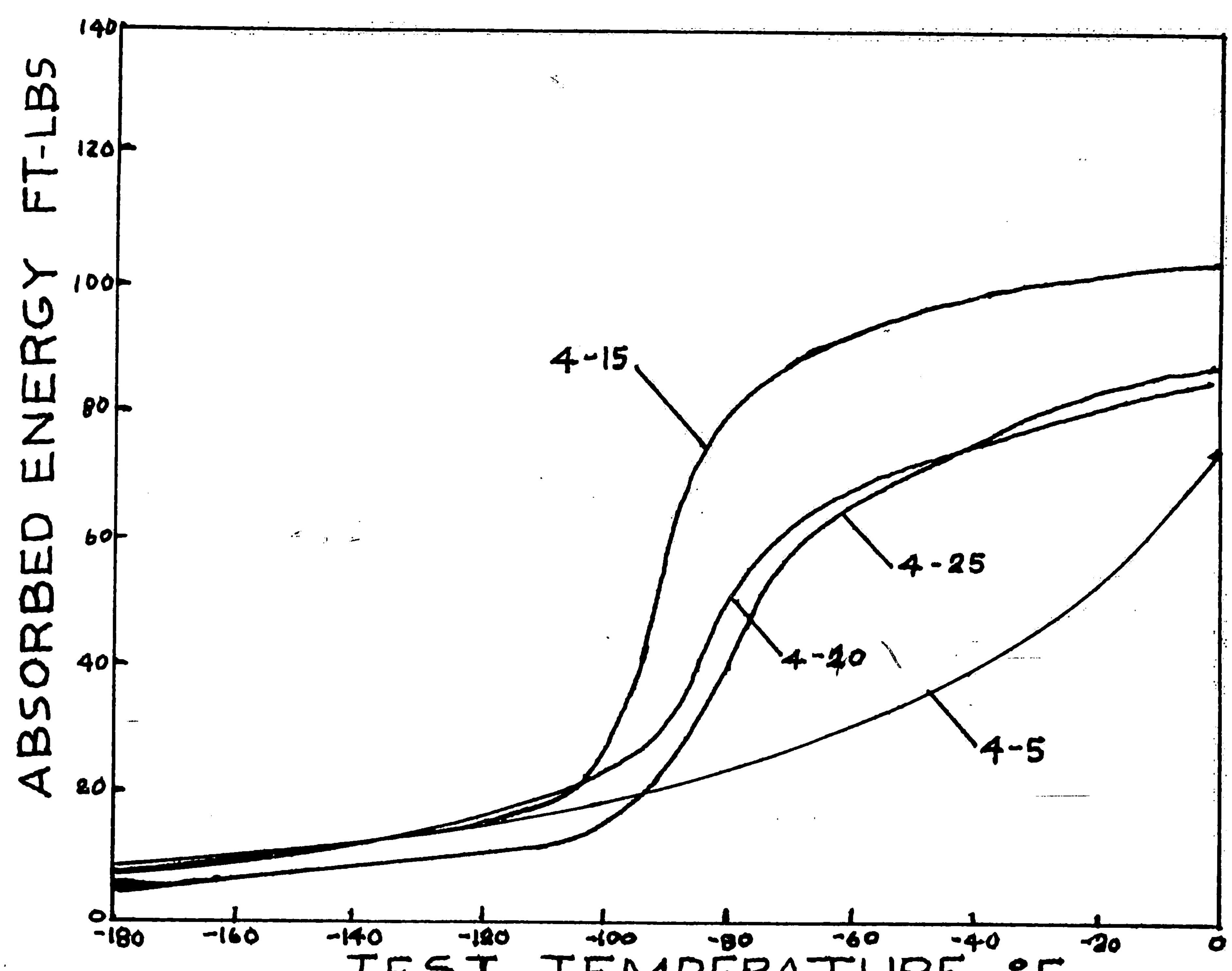

Figure 3 Absorbed Energy versus Test Temperature for Specimens 4-5, 4-10, 4-15 and 4-25

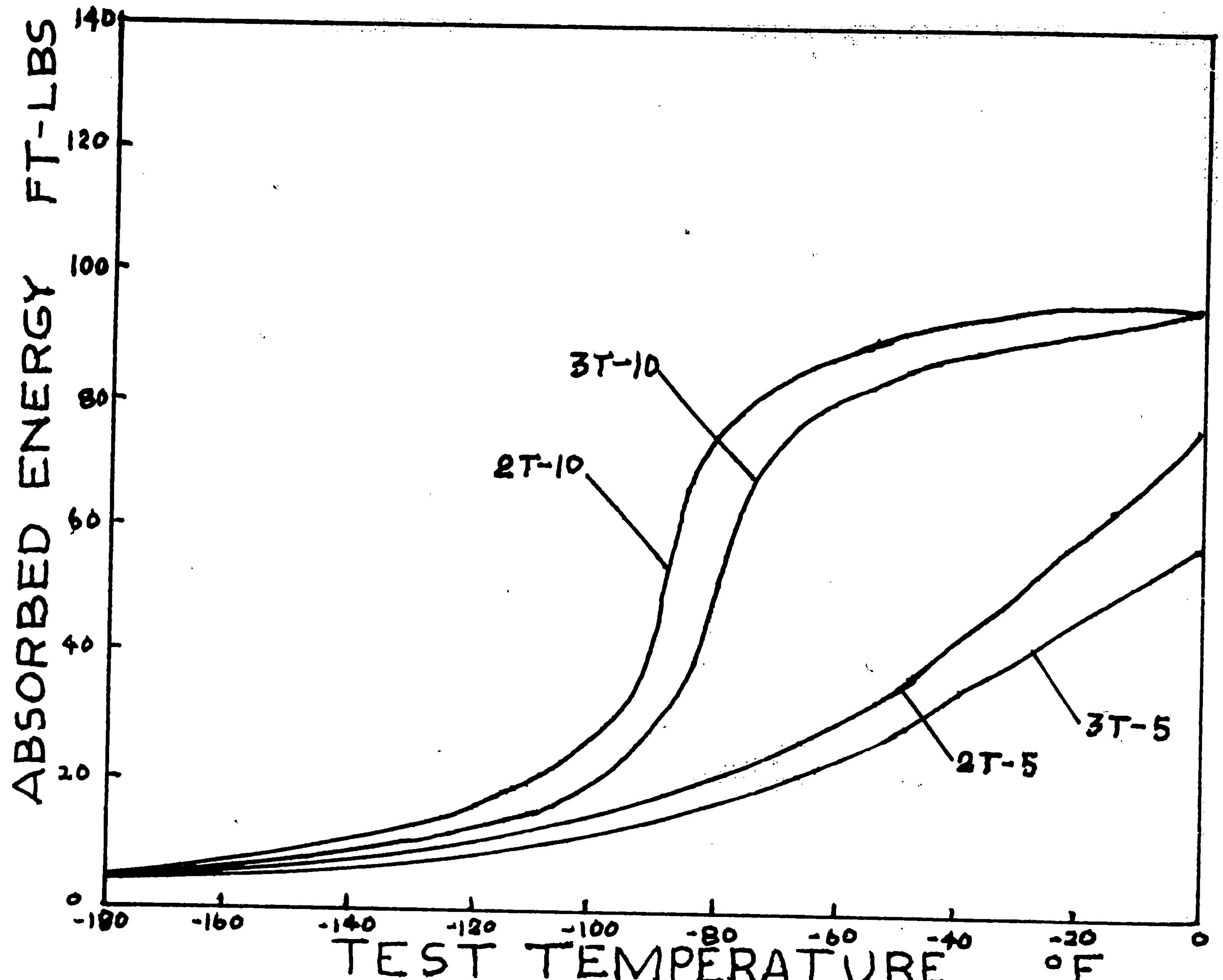

Figure 4 Absorbed Energy versus Test Temperature for Specimens 2T-5, 2T-10, 3T-5 and 3T-10

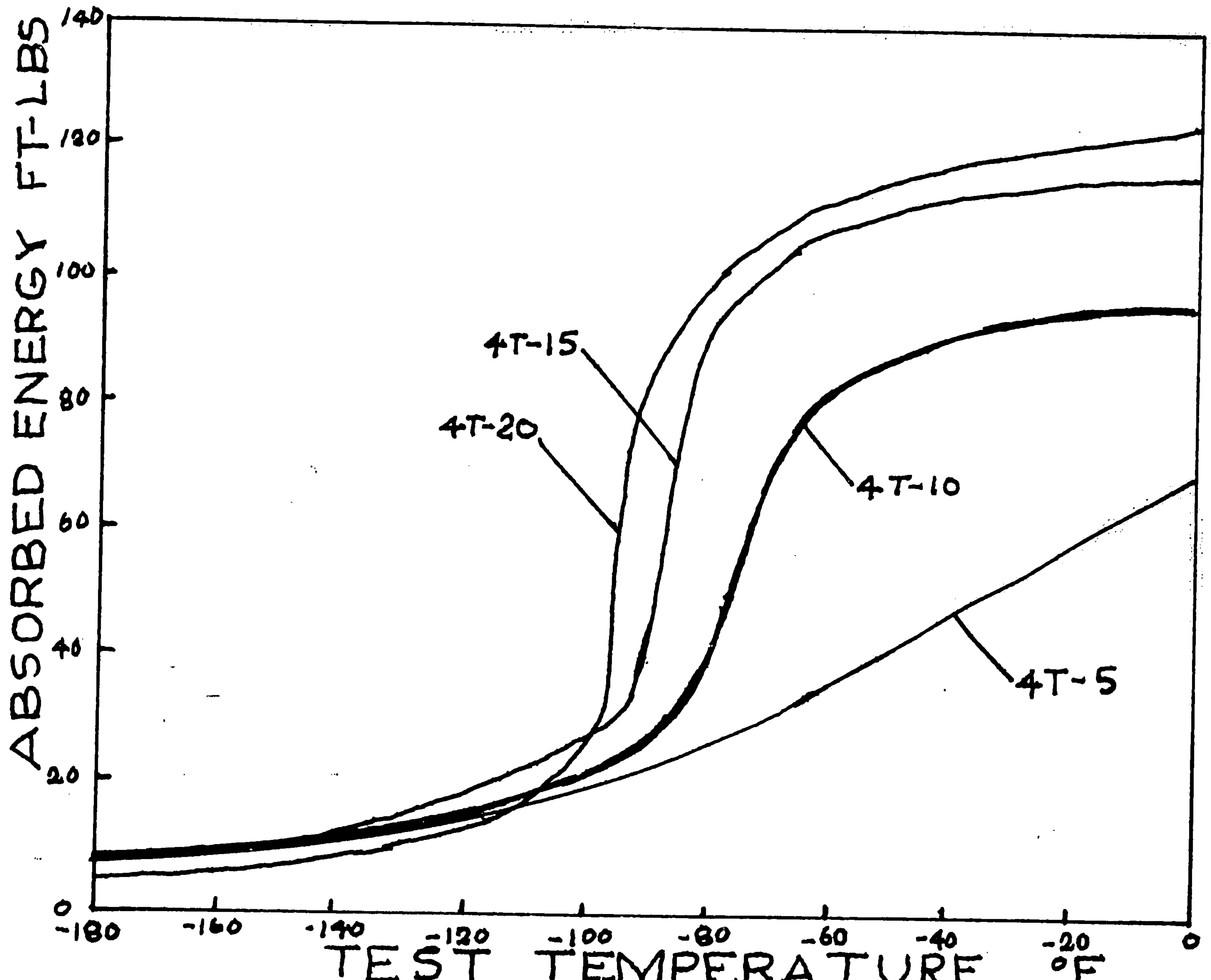

Figure 5 Absorbed Energy versus Test Temperature for Specimens 4T-5, 4T-10, 4T-15 and 4T-20

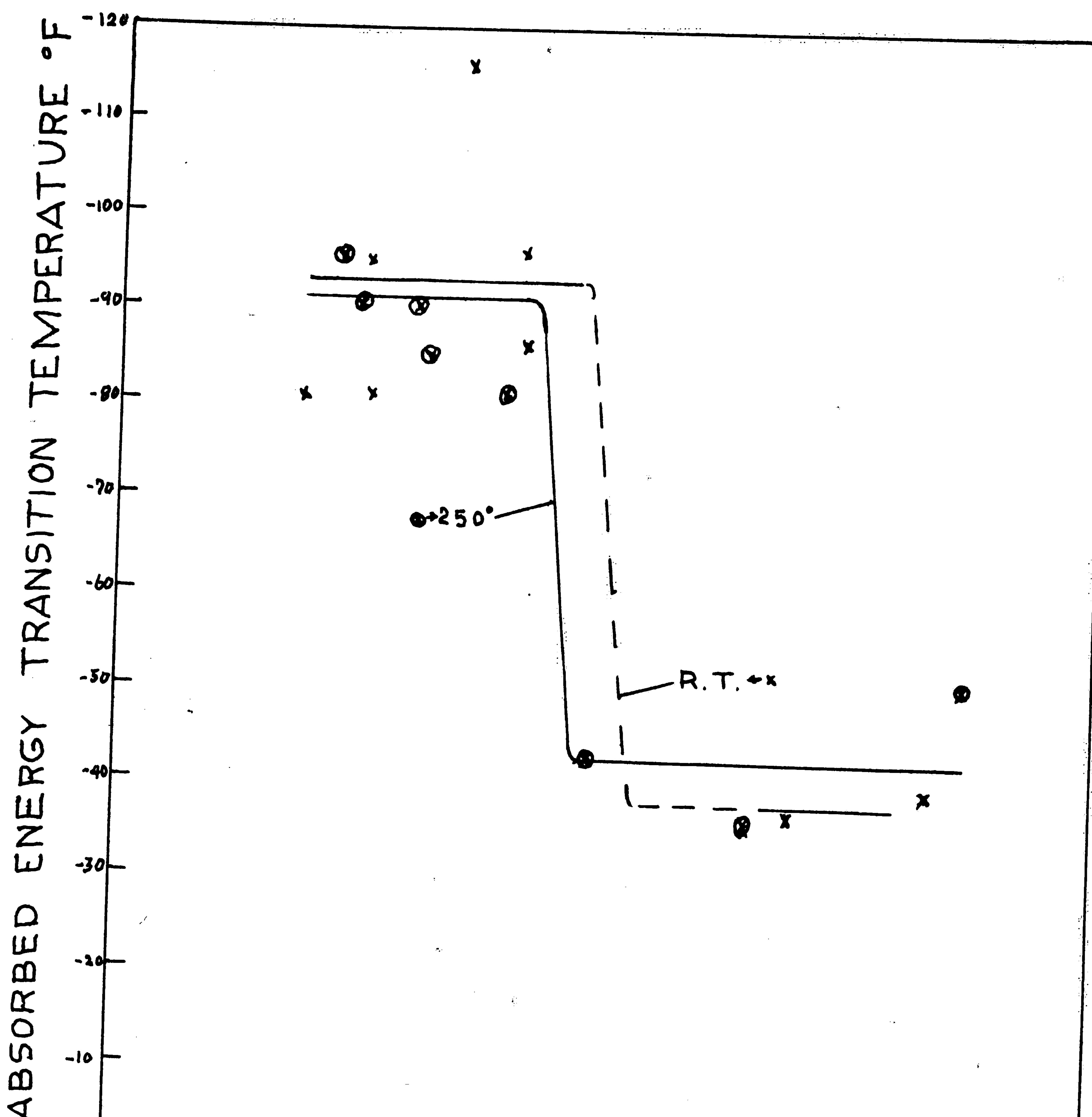

Figure 6 Forty Foot Pound Absorbed Energy Transition Temperatures versus Heat Input

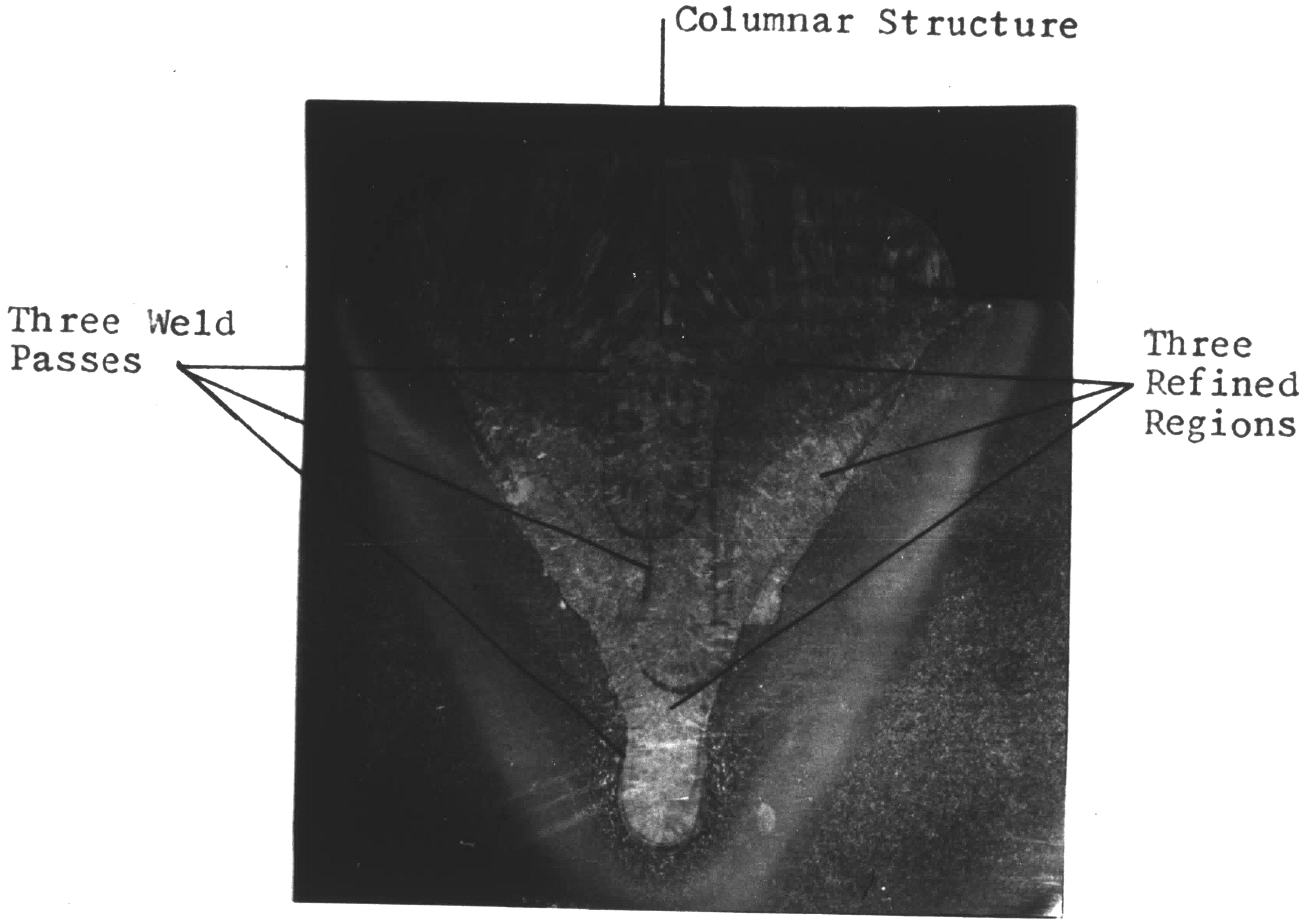

Figure 7 Photomacrograph of Specimen 4-5 showing Weld Passes and Refined Weld Metal Regions 2.5X

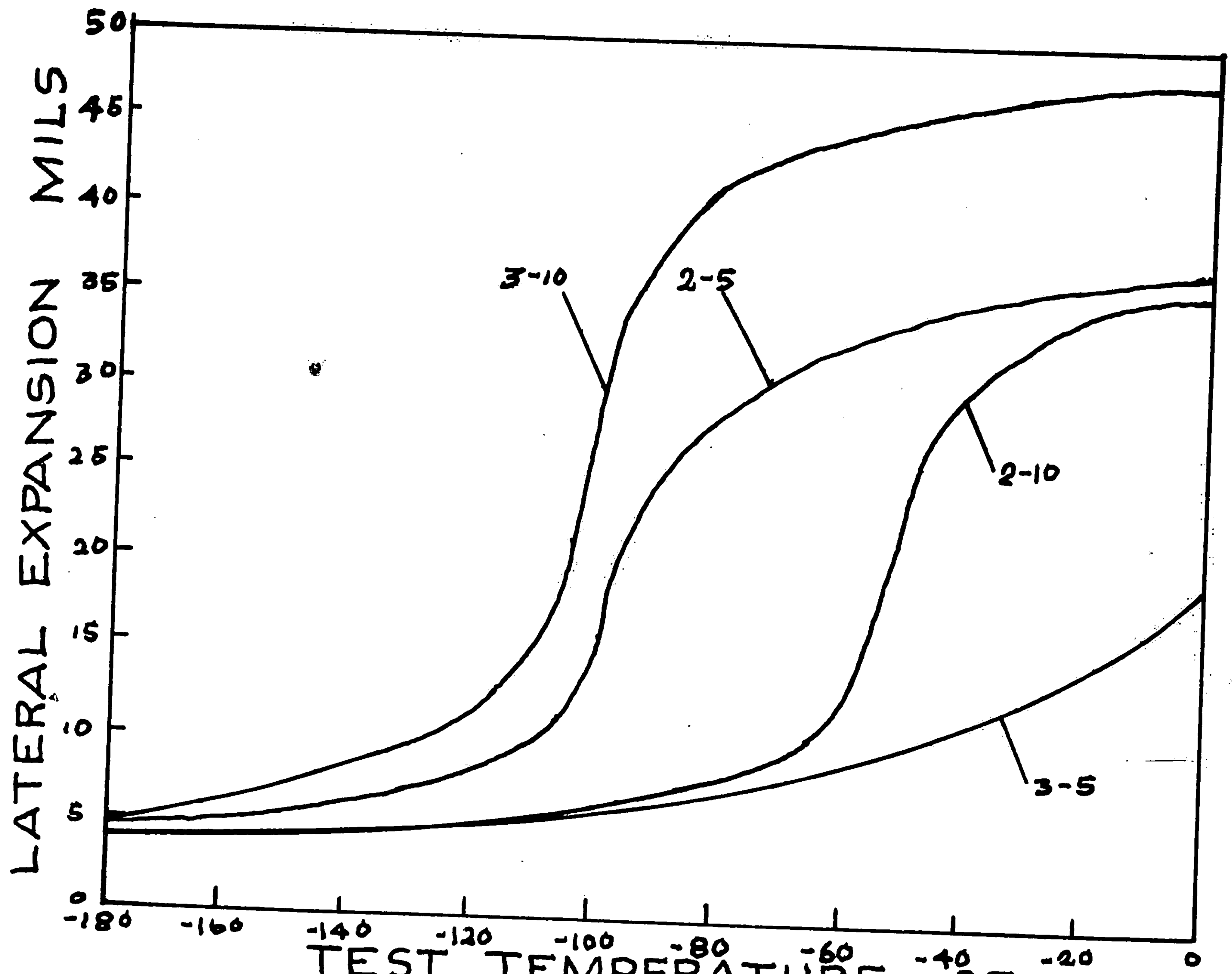

Figure 8 Lateral Expansion versus Test Temperature for Specimens 2-5, 2-10, 3-5 and 3-10

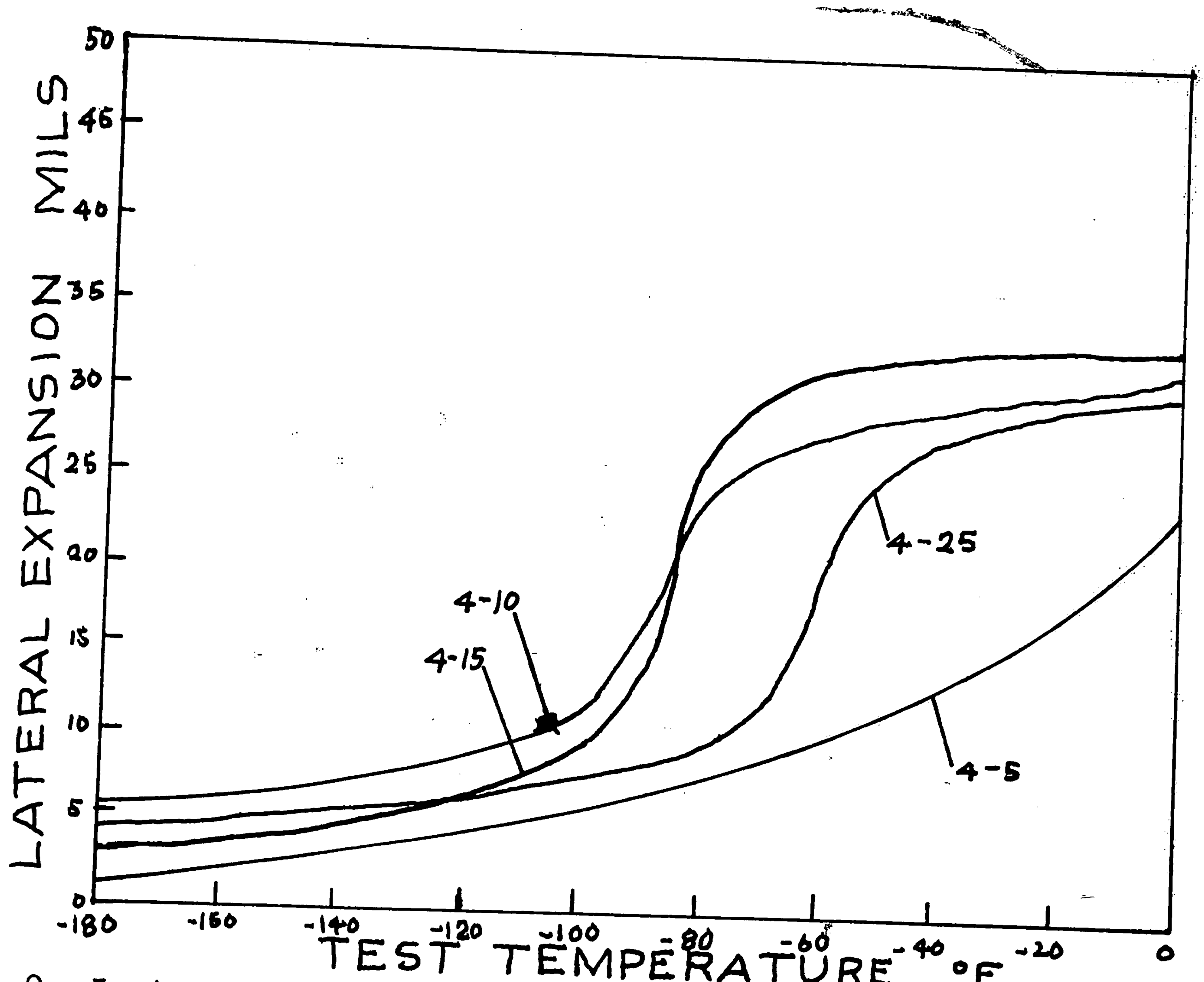

Figure 9 Lateral Expansion versus Test Temperature for Specimens 4-5, 4-10, 4-15 and 4-25

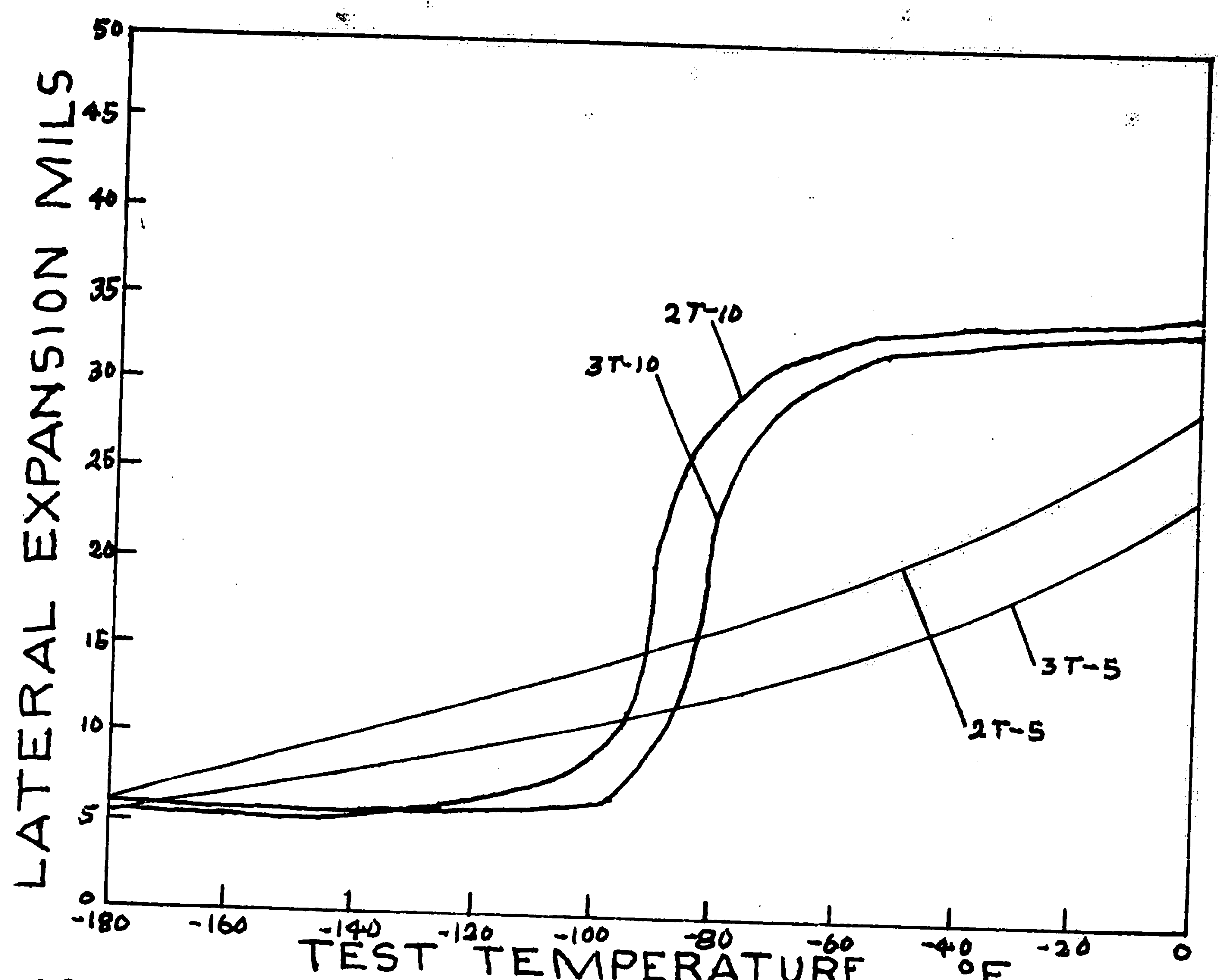

Figure 10 Lateral Expansion versus Test Temperature for Specimens 2T-5, 2T-10, 3T-5 and 3T-10

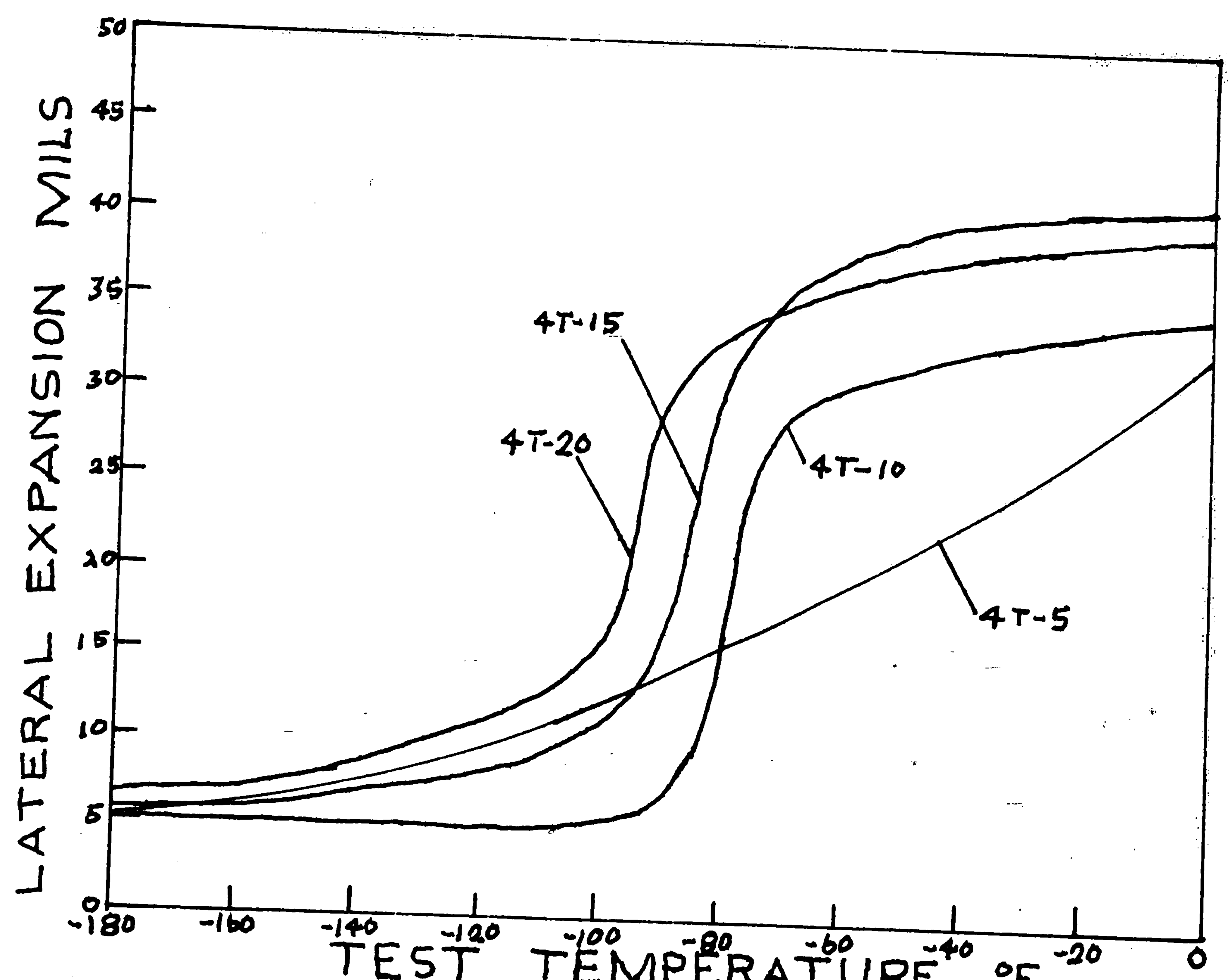

Figure 11 Lateral Expansion versus Test Temperature for Specimens 4T-5, 4T-10, 4T-15 and 4T-20

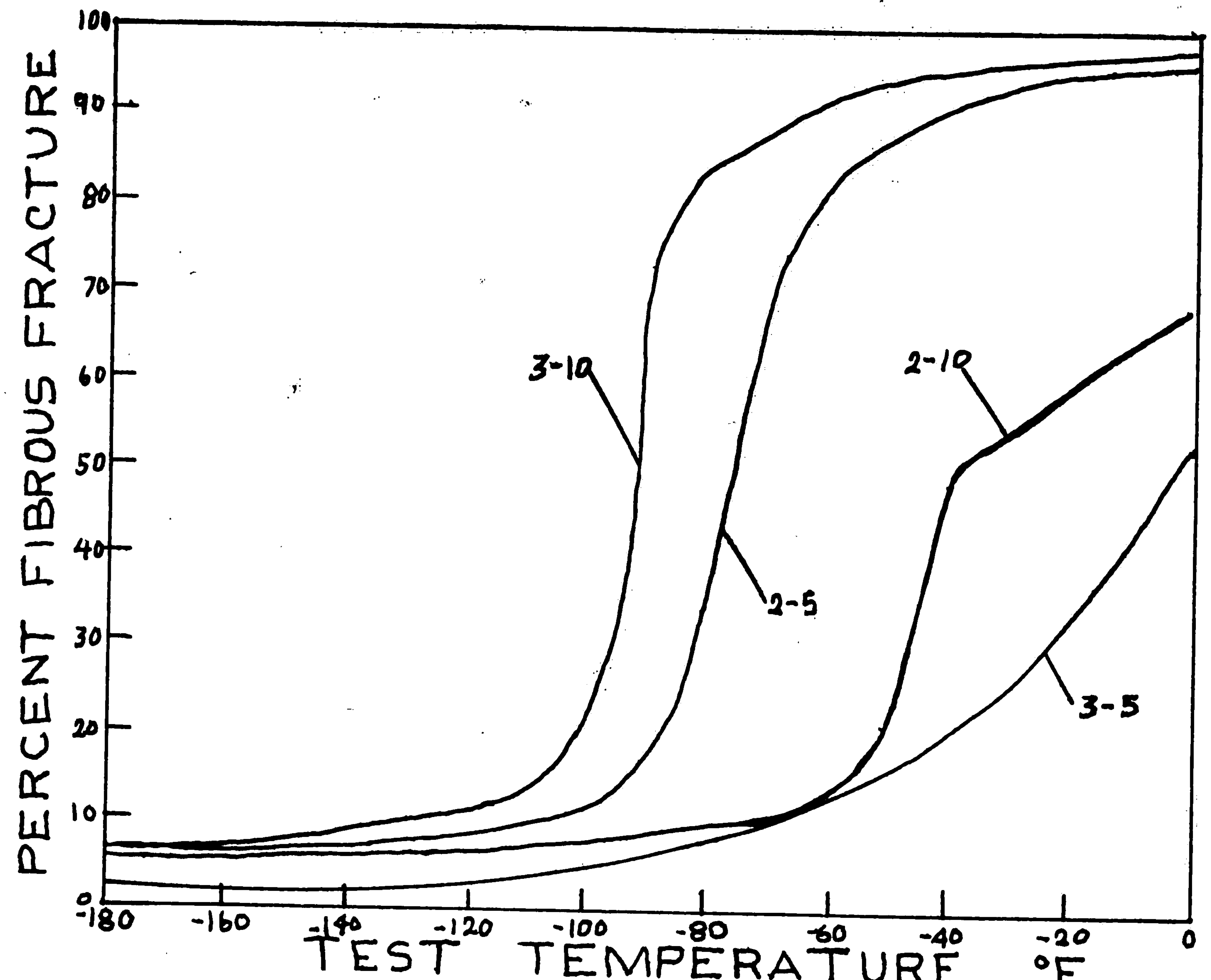

Figure 12 Percent Fibrous Fracture versus Test Temperature for Specimens 2-5, 2-10, 3-5 and 3-10

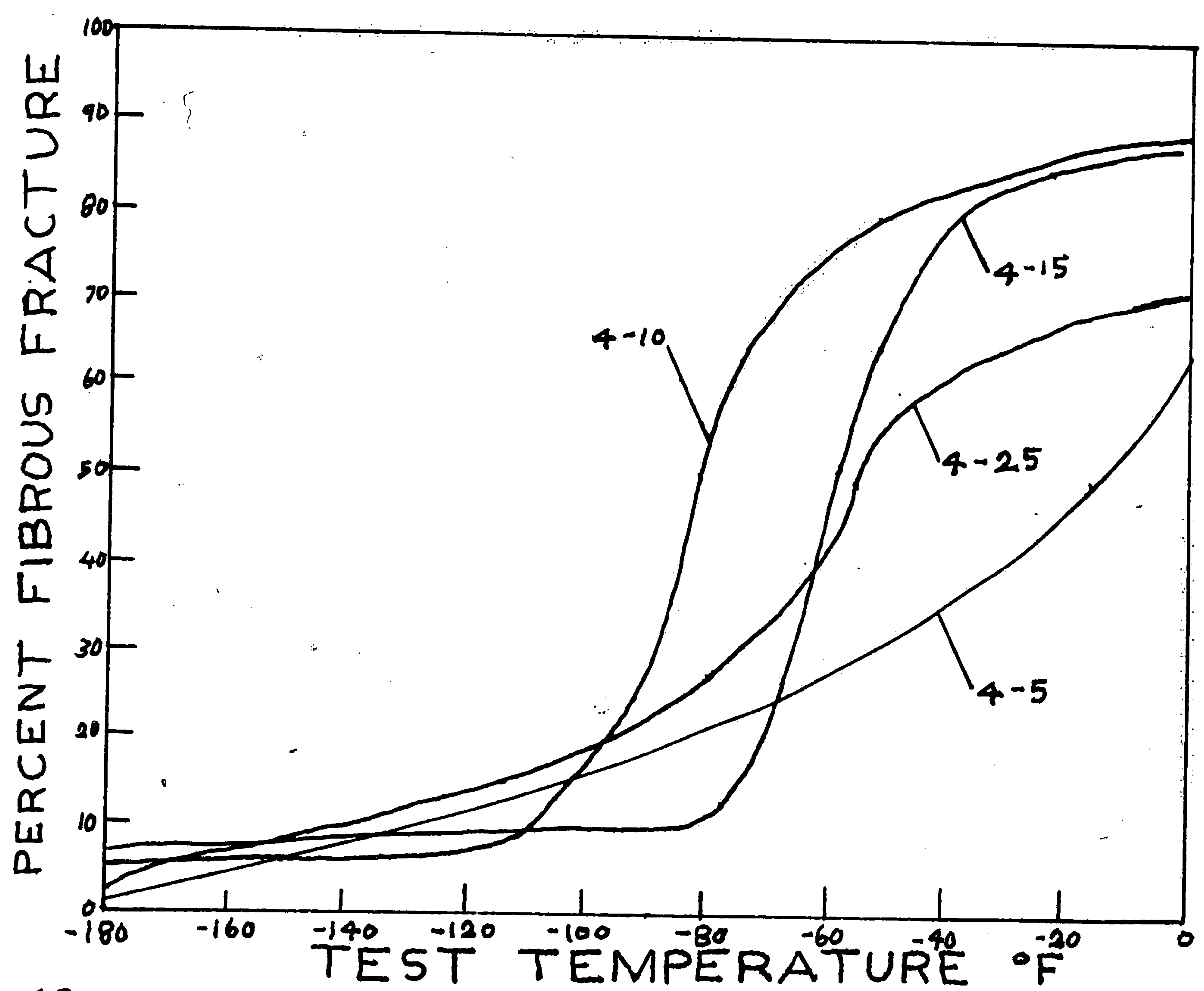

Figure 13 Percent Fibrous Fracture versus Test Temperature for Specimens 4-5, 4-10, 4-15 and 4-25

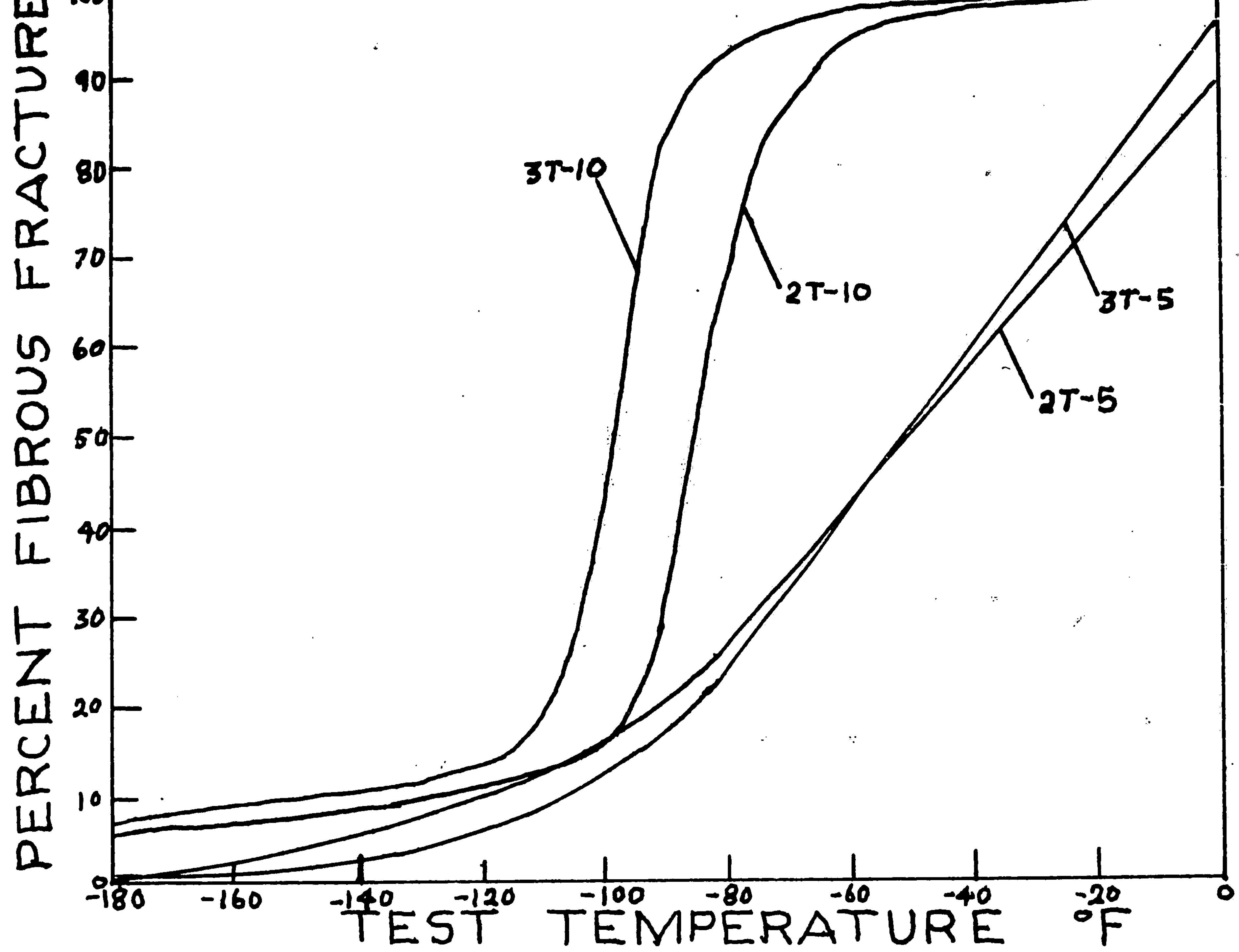

Figure 14 Percent Fibrous Fracture versus Test Temperature for Specimens 2T-5, 2T-10, 3T-5 and 3T-10

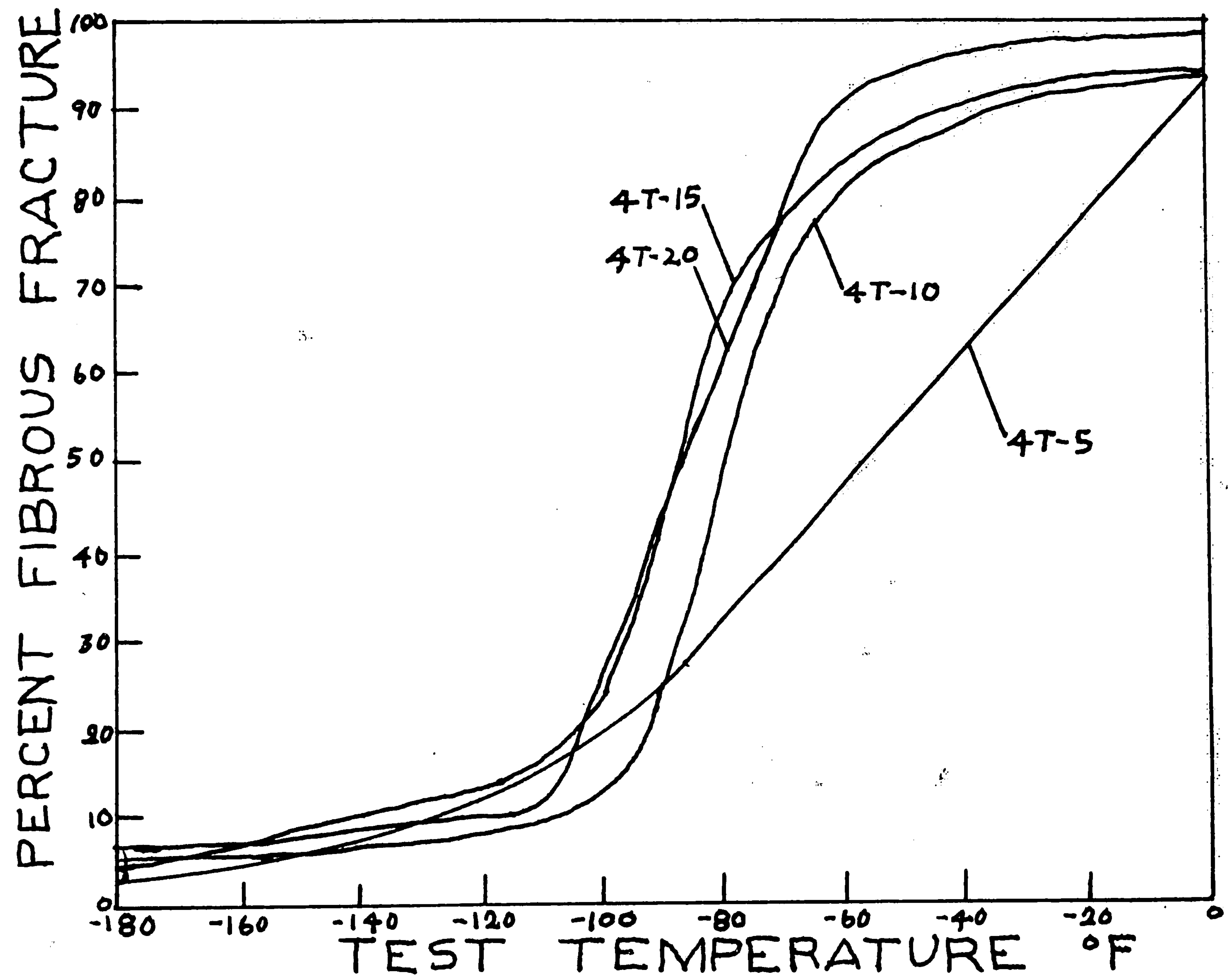

Figure 15 Percent Fibrous Fracture versus Test Temperature for Specimens 4T-5, 4T-10, 4T-15 and 4T-20

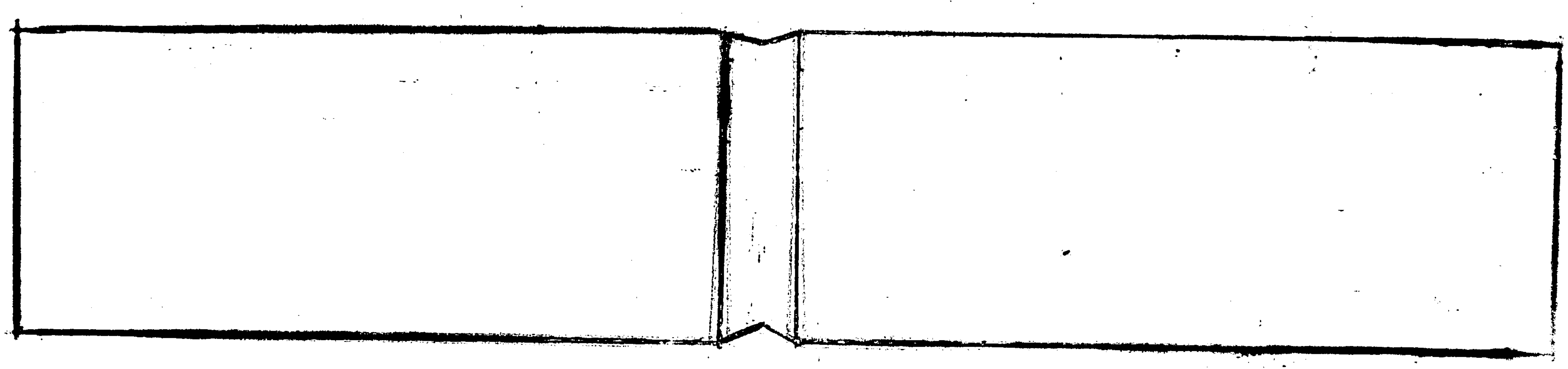

Figure 16 Schematic Overlay of Charpy V-Notch Specimen

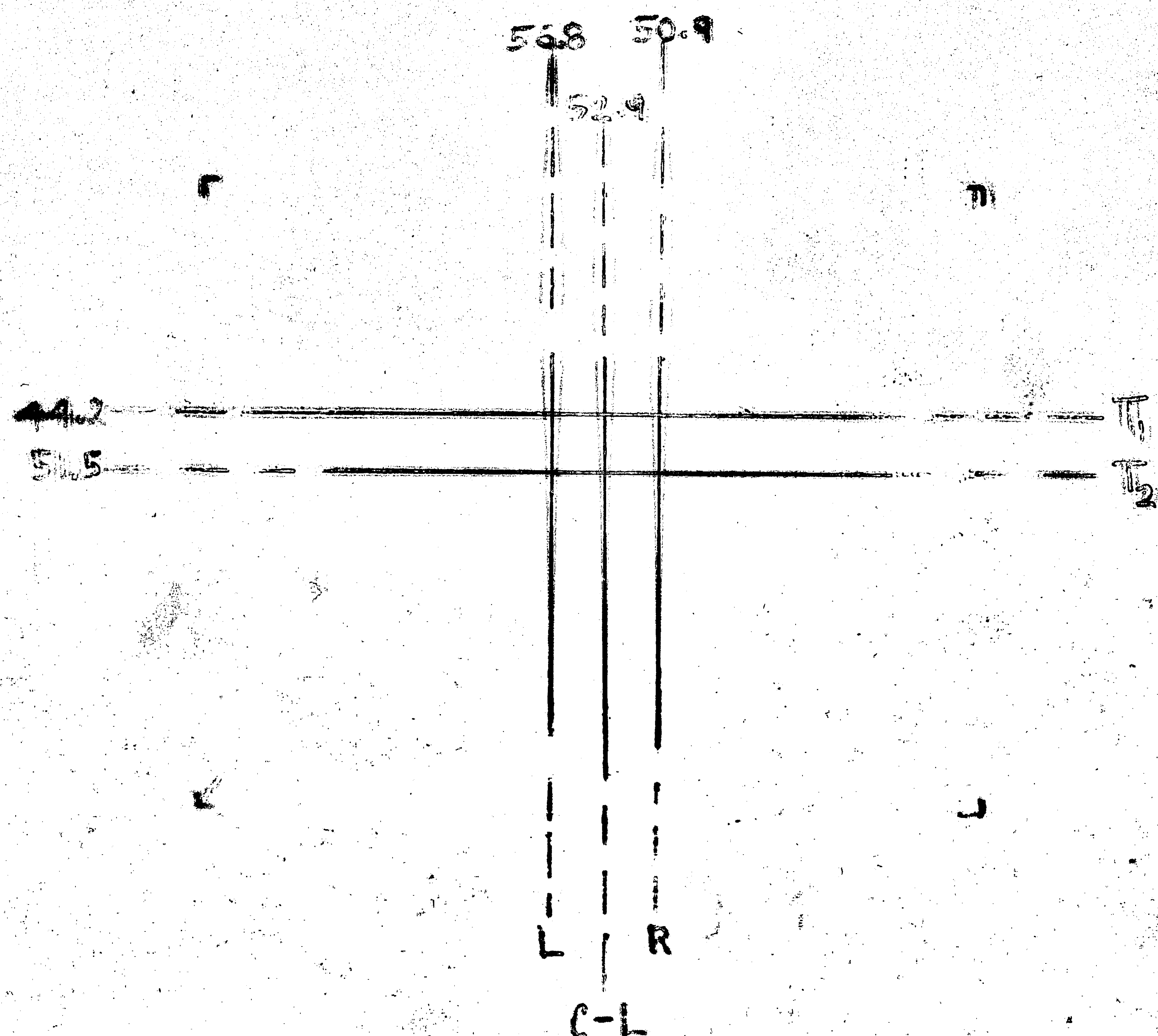

Figure 17 Schematic Overlay Illustrating the Technique of Lineal Analysis

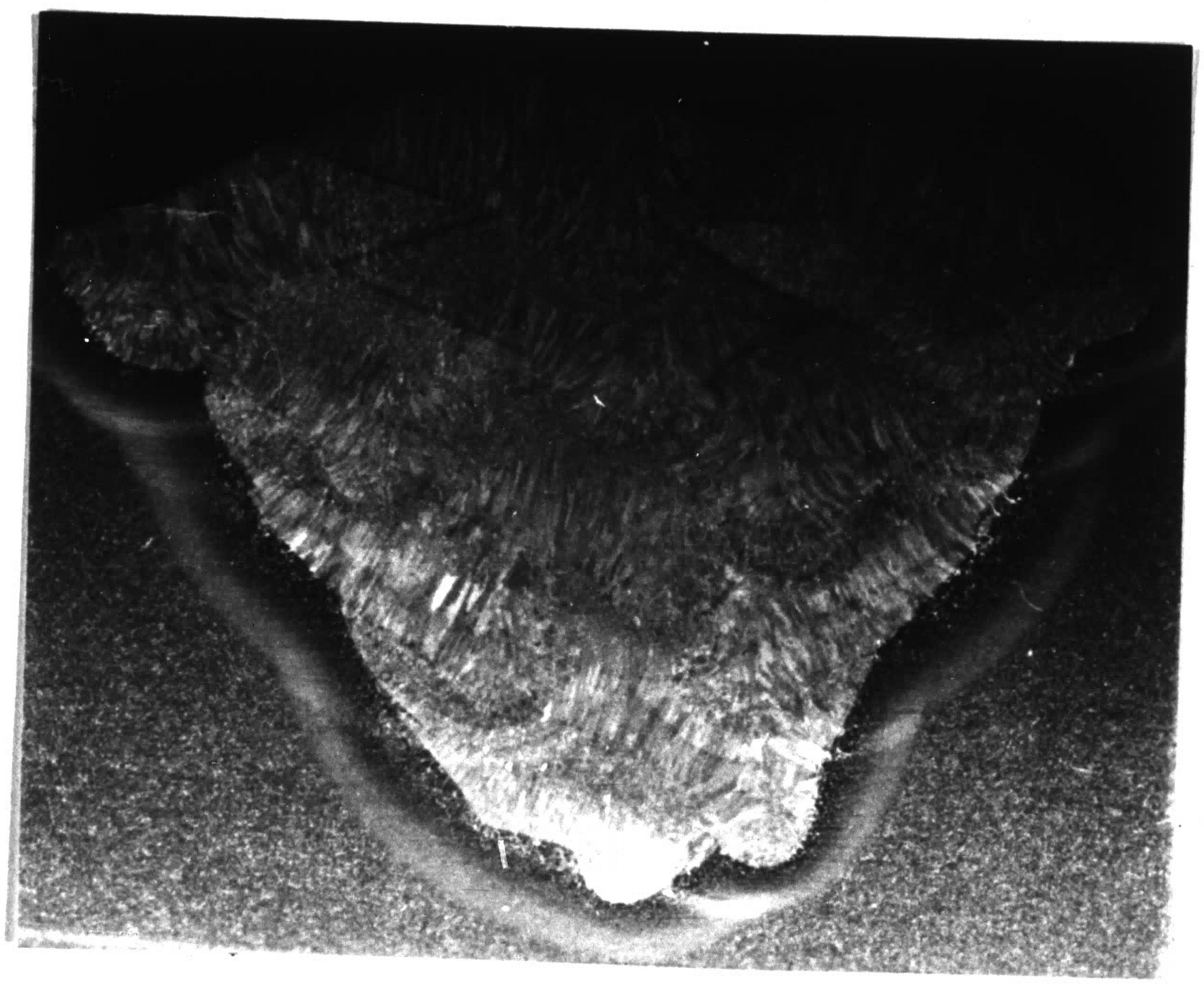

Figure 18 Photomacrograph of Specimen 2-10 3.0X

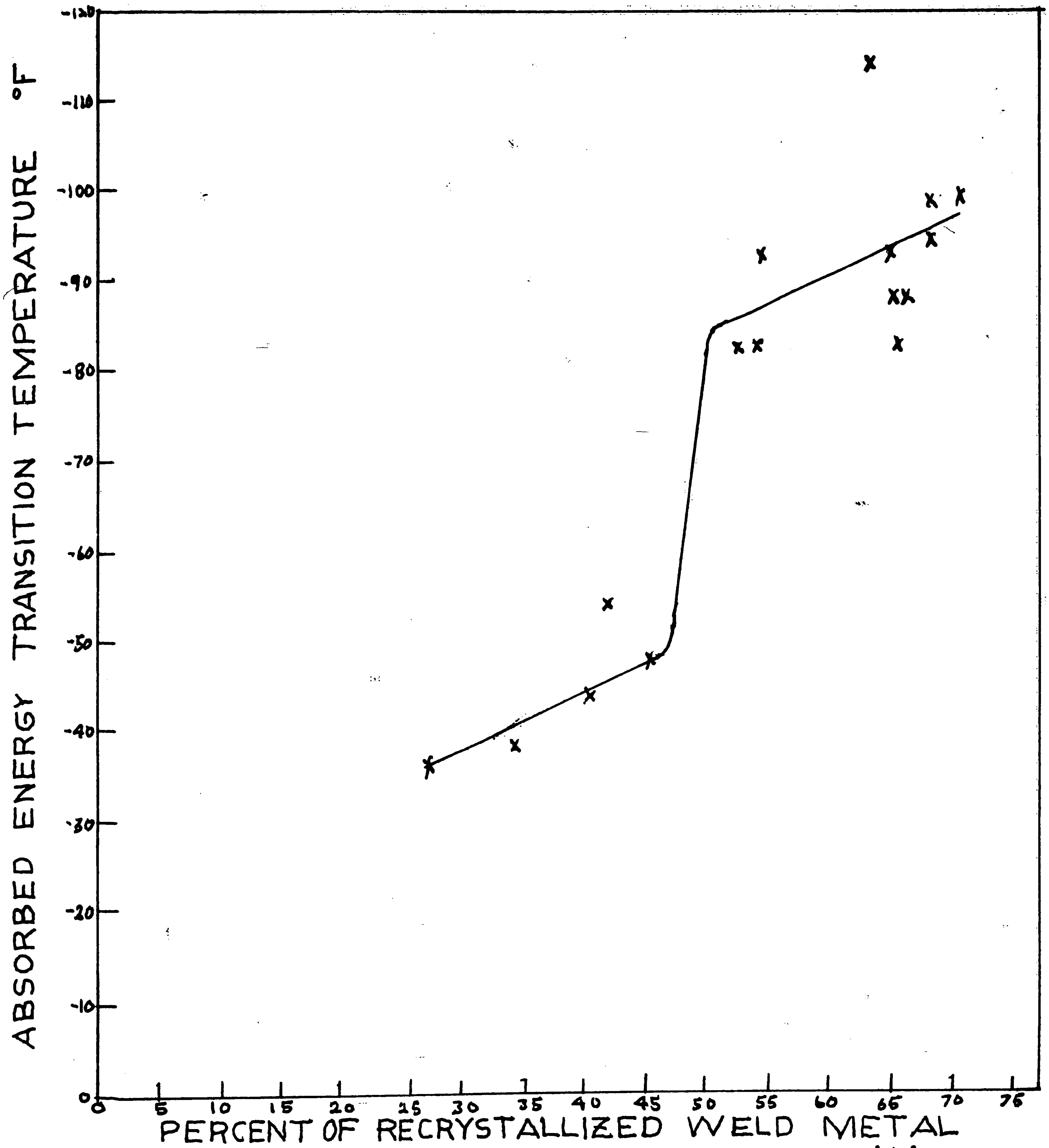

Figure 19 Forty Foot Pound Absorbed Energy Transition Temperatures versus Percent of Recrystallized Weld Metal

4-5 2.5X

4-25 3.5X

Figure 20 Photomacrographs of Specimens 4-5 and 4-25 showing the Affect of Weld Travel Speed on Weld Bead Width

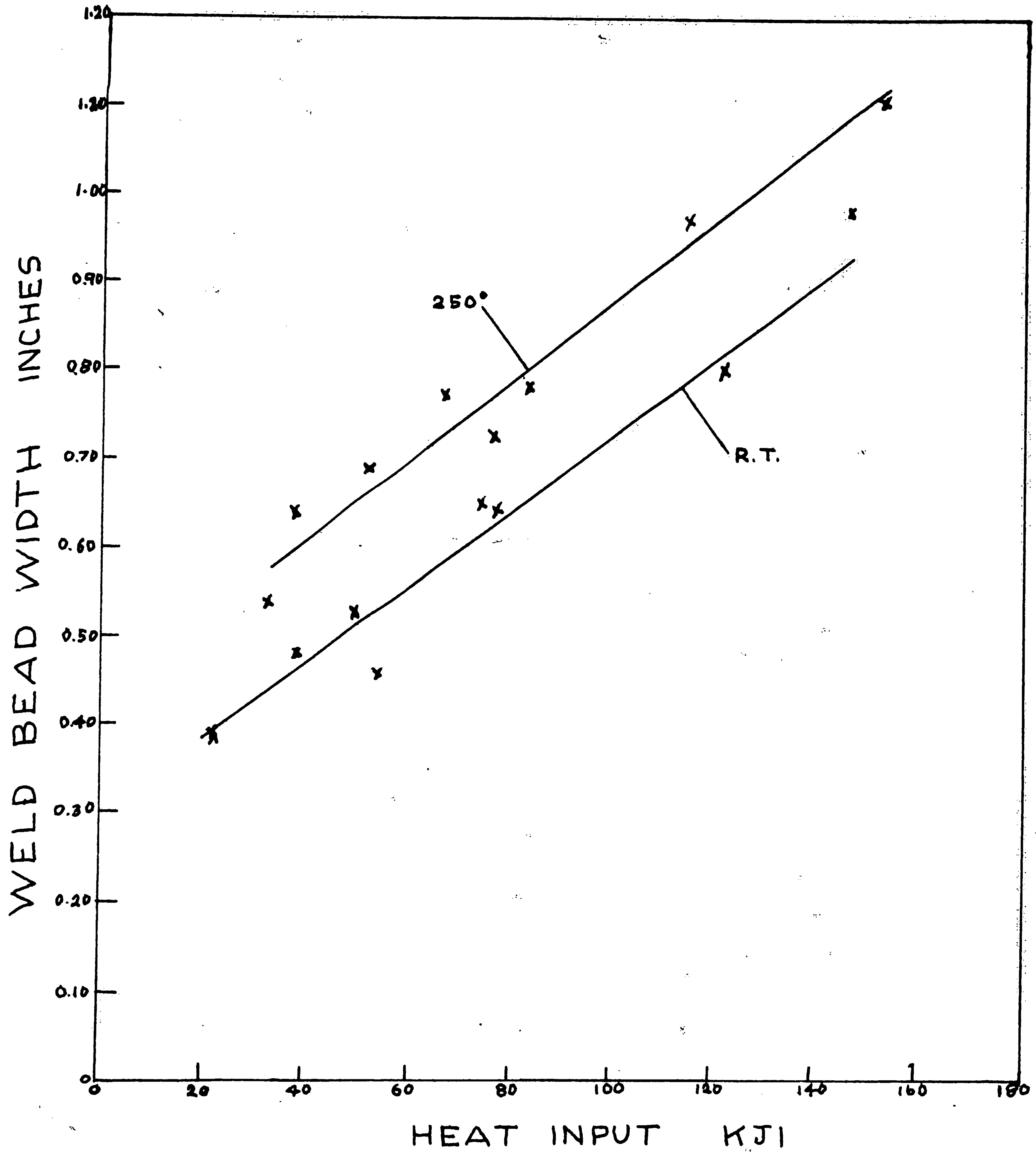

Figure 21 Weld Bead Widths versus Heat Input

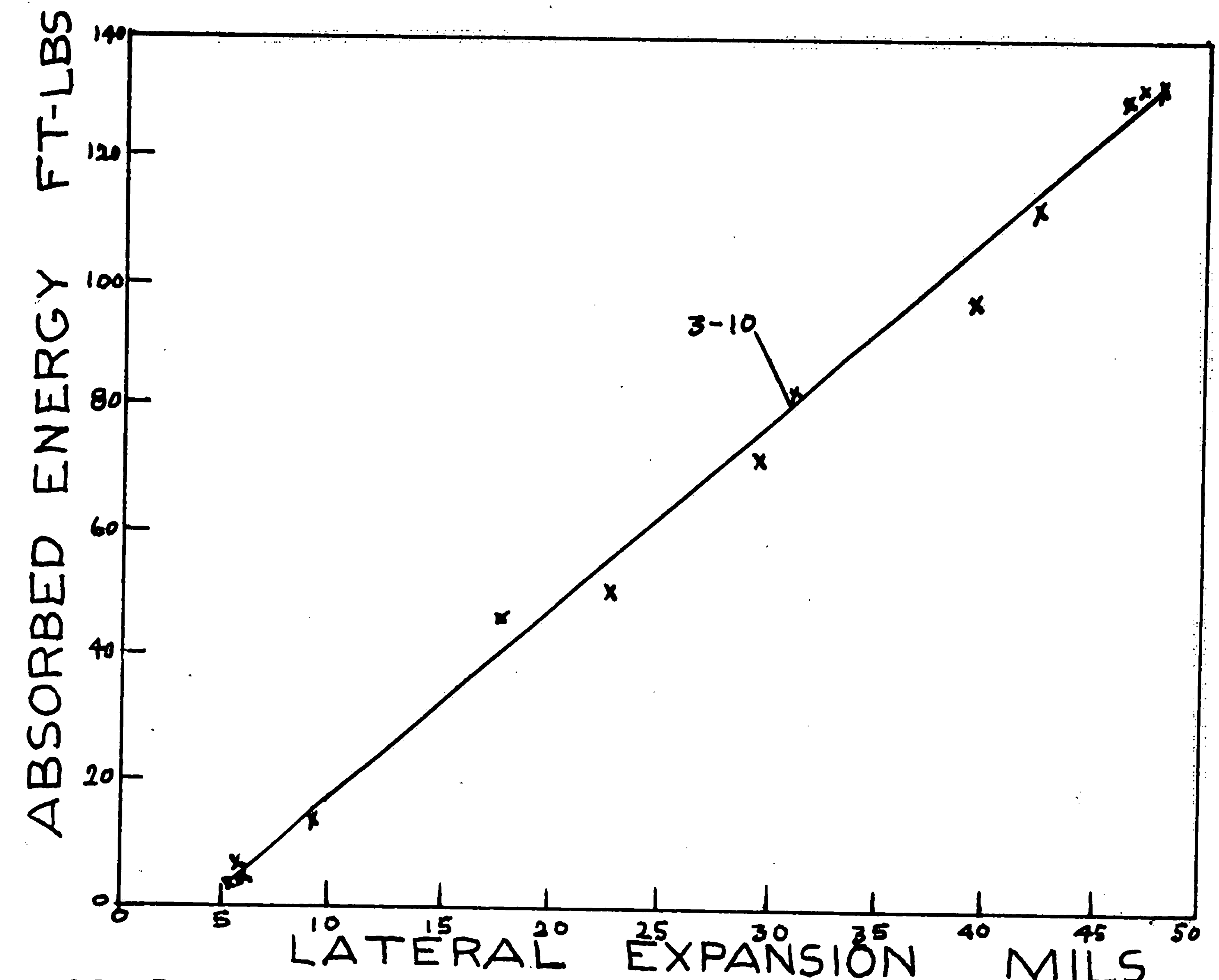

Figure 22 Representative Example of the Linear Relationship between Absorbed Energy and Lateral Expansion

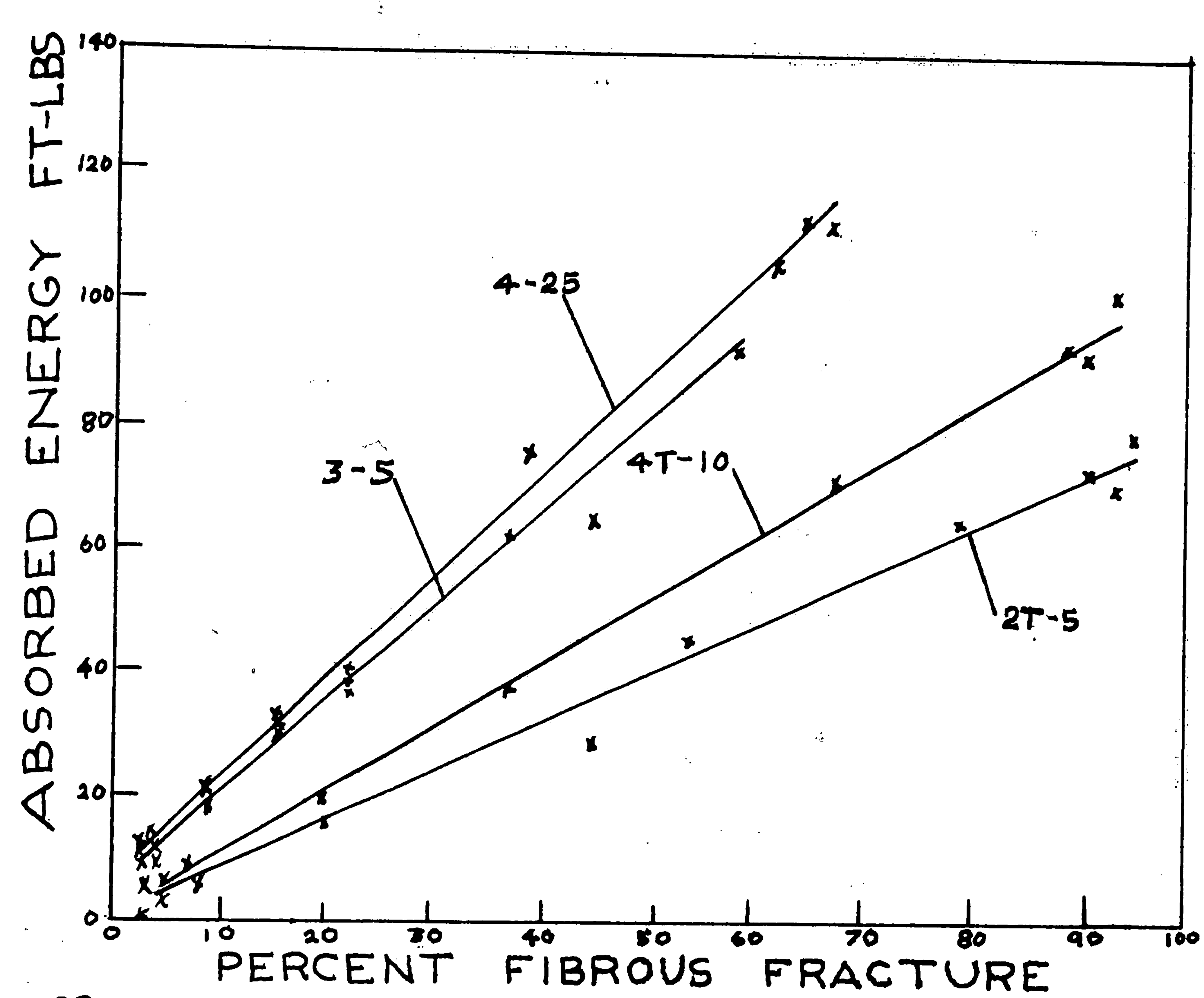

Figure 23 Representative Example of the Linear Relationship between Absorbed Energy and Percent Fibrous Fracture

VITA

Paul Francis McLaughlin was born in Quincy, Massachusetts, on December 4, 1945, to Francis C. and Enid D. McLaughlin. He attended public school in Quincy and Weymouth, Massachusetts. After graduation from Weymouth High School in June, 1963, the author entered Rensselaer Polytechnic Institute under a Rensselaer scholarship. In June, 1967, he was graduated with a Bachelor of Metallurgical Engineering degree. In the fall of that year Paul entered the Graduate School of Lehigh University on a National Defense Fellowship.