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Report Number 12 Metallurgical Observations of 21 Plate Steel Samples Taken From Seven Tank Cars Involved in the April 8, 1979 Railroad Accident at Crestview, Florida.

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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

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ABSTRACT

This is the second of two reports intended to give information on and metallurgical characterization for each of 21 plate samples taken from tank cars involved in an accident at Crestview Florida in April 8, 1979. The earlier report contains the results of a field investigation, which gives pertinent data on the thermal and deformation history of each of the 21 plate samples taken by the NBS for future studies. That report includes pictorial and other representations of the responses of the derailed tank cars observed at the accident site. This report includes results of chemical analyses, metallographic examinations (of microstructure and inclusion content) and hardness measurements conducted on each of these plate samples. This report also includes the results of standard Charpy V-notch impact tests conducted on seven of these plate samples. Thus, together these reports are intended as references for information needed to confirm or deny models proposed to explain the behavior of railroad tank cars in abusive service. In addition, the metallurgical characterization of each of the 21 plate samples will be useful in determinations of the suitability of each of these 21 samples for future laboratory studies.

1.0 INTRODUCTION

This is the second of two NBS reports on an accident that occurred 3.8 miles north of Crestview, Florida on April 8, 1979. These reports are intended to provide background information and a brief metallurgical characterization of each of 21 plate samples taken from that accident site, so that their suitablility for future experimental work can be established. In the first report, [1]*, observations made at the accident site, such as the measurements, photographs, etc., were documented for two reasons: (1) The first is to characterize the location and history of each plate sample taken from the cars, as the selection of materials for use in studies concerned with the suitability of plate materials for service in railroad tank cars requires that the deformation and thermal history be known. (2) The second reason relates to the establishment of a "context" for these studies of the behavior of plate steels in railroad tank cars subject to abusive service conditions. Some of these samples are taken from locally undamaged sections or parts of tank-car head and shell plates that had sustained considerable service abuse, e.g. they sustained deformation without rupture or the rupture had no highly undesired consequence.

For example, NBS Tank-Car samples 1 and 4 were taken from head plates that were very badly dented, but neither of these plates ruptured. Head plate NBS sample 1 is 0.76 inches thick and it was in pressurized service. The other head plate (NBS 4) is 0.46 inches thick and it was in "low-pressure" (acetone and methanol) service. In general, the steel plate materials of cars that were in "low-pressure" service seemed capable of sustaining greater amounts of damage, when compared with that observed for the pressurized cars. Thus, the second reason for the documentation is to furnish a "context" for future studies of these types of plates. This "context" is a set of actual observational experiences of tank cars that were used in pressurized service vis-a-vis those that were in abusive, "low-pressure" service. This "context" is considered to be useful in interpretation of models that might be developed to explain the behavior of the cars in abusive service.

The first of these two reports [1] presents observations made on the tank cars at or near the accident site, in the days immediately following the accident.

There were 23 "NBS Samples" selected at the accident site. Only 16 were used for the studies reported here. Six of the other seven are either valves (NBS 6, NBS 11, and NBS 16) that are not discussed here, or plate samples that were deleted for reasons related to safety (head plate NBS 5) or economy (shell plates of NBS 14, NBS 15). The seventh, NBS 20B was shipped to NBS and is available, but the plates contained in it are the same two shell courses contained in 20A. However, 20A contains a large puncture that caused chlorine to leak from the vessel. This second report gives laboratory observations and brief metallurgical characterizations of 16 plate samples taken from eight tank cars involved in the accident. Of the 16 "NBS Tank-Car Samples" taken from the accident site, five contained two plates (shell or head plate). Thus, there are 21 plate samples: Five head plates and 16 shell plates. These samples are identified in table 1 along with the "NBS Sample ID" and the railroad tank car from which the sample was taken. The lading of each tank car is also indicated.

*Brackets identify references listed in this report.

Substantial amounts of material are available for further study from among these 21 plate samples. The plate surface area available for each of the 21 samples varies over the range from 1 1/2 to 17 ft^2 with the average being about seven sq. ft.. The available plate surface area is indicated in Appendix A. In addition to the area data for the 21 plates listed in the Appendix, there are some other plates not otherwise mentioned in this report. These are plates that adjoin one or more of the plates involved in these studies.

The metallurgical examinations of the 21 plate samples includes chemical and metallographic analyses, as well as hardness surveys on all 21 samples. In addition, the standard longitudinal and transverse Charpy V-notch (CVN) impact tests were conducted on plate samples taken from the pressurized tank cars, i.e.,those from three tank cars with ladings of anhydrous ammonia or chlorine. The former were of two DOT Classes, 112S 400W and 105A 300W, and the later was of class 105A 300W [1]. Both classes are considered to be "high-pressure" service.

There were eight plate samples from the "high-pressure" service. Seven are shell plates, and one is a head plate. Although all seven shell plates were tested, the head plate was not tested, as completion of the plate orientation study could not be budgeted at this time. This sample is available as a candidate for future studies. Standard CVN samples have been machined for use in making a determination of the rolling direction of this plate, if needed. The other 13 plate samples are from five tank cars of DOT class 111A 100W, which is not intended for "high-pressure" service and impact studies of these were therefore not included in this study.

2. EXPERIMENTAL PROCEDURES

2.1 Chemical Analyses

Check chemical analyses were conducted on chemistry samples cut from each of the 21 plate samples. The analyses were conducted by a commercial testing laboratory by combustion-conductometric (for carbon content) and emission spectroscopic methods. Samples and target areas (diam. = 8.0 mm or 0.31 in) for these analyses were taken approximately at the quarter-thickness location of each plate sample. This was done by cutting away about 1/4 of the plate thickness from each chemistry check sample, using a cut-off wheel, and then grinding that cut surface of the sample using a tup grinder. The approximate quarterpoint actually used for this grinding operation can be determined as follows: Each plate was classified into one of three thickness (grinding) codes, as shown in table 2. Final thickness is one of three values: 0.30 inches for plates having initial thickness values of 0.40 to 0.46 inches; 0.41 inches for those initially at 0.54 to 0.57 inches; and 0.56 for those initially at 0.75 to 0.81. In table 2, these final thickness values are indicated respectively as grinding (or thickness) codes 1, 2, and 3. The initial thickness is the "as-received plate thickness".

Mill reports of chemical composition were available for only two of these plates, samples 20A-A and 20A-B, which are the two shell-plate samples cut from NBS Sample 20A from a tank car UTLX 2827 that had been in chlorine service and was punctured in the train derailment. The steels from all other tank cars were identified only by comparing the check chemical analyses with the specifications for chemical compositions of steels used in the manufacturing of railroad tank cars. The compositions of each of the steels was compared with the composition given in one of the following specifications: ASTM A515-Grade 65, ASTM A516-Grade 65, and AAR TC128-Grades A and -Grade B.

2.2 Metallography and Hardness Measurements

From each of the 21 plate samples, small pieces were machined for use as metallographic and hardness samples. These were mechanically polished flat and smooth before being used for metallographic observation and for hardness measurements. The plane of observation was taken normal to the plate surfaces. For the 16 shell plates, this plane contains the rolling direction of the plate and it is called a longitudinal plane, or a "C" plane [2, 3]. For the six head plates, an attempted metallographic determination of the rolling direction failed to give satisfactory results, so the plane of observation for each of these specimens is not a longitudinal plane, i.e. it does not necessarily contain the rolling direction. In the unetched condition, each of these 21 small pieces (or samples) was used to rate the inclusion content, using ASTM Method E45.

The metallographic evaluation included optical metallography of each sample in the nital-etched condition. Photomicrographs were taken at the quarter-thickness location of the plate, except as noted. Optical photomicrographs of areas that were considered to be representative of the microstructure were taken for each sample. Two photomicrographs were taken for each plate sample, using magnifications of X100 and X500. On one of the samples, the photomicrograph taken at X100 was not taken at this plate location. Rather, it is a view of the center of the plate thickness, which is intended to illustrate centerline segregation observed in three of the plate samples.

In addition, the ferrite grain size was rated from regions of the samples that clearly showed ferrite in a somewhat polygonal form. This rating was done acording to ASTM method E112. Average grain-size numbers are reported.

Hardness was determined on each of these same surfaces. Average hardness is reported, based on the results of five to seven Rockwell B hardness measurements. These were taken at various thickness levels between the two plate surfaces.

2.3 Impact Tests

Charpy V-notch (CVN) impact specimens were prepared from the seven samples of shell-plate steels taken from pressurized cars. Ladings for each of these cars was either anhydrous ammonia or chlorine (see table 2). Specimens were prepared and tested according to ASTM Specification E23-82, using the standard (10 mm) full-size specimens. These were cut from each plate according to one of two ASTM orientations described in in ASTM E616-82.

The orientations are commonly called transverse (or TL) and longitudinal (or LT). For the TL orientation, specimens are cut so that the long axis of the specimen contains the transverse direction of the plate, and the crack propagation direction is the longitudinal (or rolling) direction of the plate. For the LT orientation, the specimen's long axis is the longitudinal direction of the plate, and the crack propagation direction the transverse plate direction. The crack front is normal to the plate surfaces in both LT and TL specimens.

Due to the alignment and shape of inclusions that results from rolling of the steel into plate form, energy absorption in impact tests is a function of specimen orientation. For specimens with a crack front that is normal to the plate surfaces, energy absorption is at a minimum for the TL orientation and at a maximum for the LT orientation. For LS specimens (not tested here), which are oriented with the long axis of the specimen in the plane of the plate, but with the crack front parallel to the plate surfaces, the energy absorption has been observed to be still higher than that for the LT orientation [6].

For the transverse orientation, a full curve of impact energy vs. temperature was established by using the number of specimens normally considered adequate to fully describe the transition from ductile to brittle behavior. Whereas, for the longitudinal specimens, only tests for partial curves were conducted. These LT tests should have been conducted at temperatures that would permit the establishment of the upper-shelf behavior for longitudinal specimens. Actually, a disproportionate number of longitudinal specimens were tested in the transition region.

3.0 SPECIFICATIONS

The chemical composition requirements of the four grades of steel (for ladle analyses, as well as for two available product analyses) are given at the bottom of table 1. These requirements were taken from references 4 and 5, which contain the specifications for the following four grades of steel.

3.1 ASTM A515-Grade 65

This steel is intended to be used in pressure vessels, and is classified by the American Society for Testing and Materials (ASTM) as a carbon-silicon steel used for intermediate- and higher-temperature service in welded boilers and other pressure vessels. The designation "Grade 65" refers to the mimimum allowed tensile strength level, which is 448 MPa (65 ksi). Plates of thickness less than 50.8 mm (2 inches), would normally be supplied in the as-rolled condition.

3.2 ASTM A516-Grade 65

This steel is intended primarily for service in welded pressure vessels. It is classified by ASTM, as a carbon steel for moderate- and lower-temperature service. Plates 38mm (1.5 inch) and under in thickness are normally supplied to the car manufacturer in the as-rolled condition. This ASTM specification also permits the plates to be ordered in the normalized condition, the stress-relieved condition, or in the (combined) normalized and stress-relieved condition. The specification indicates that when notch-toughness tests are required on the steel, the plates shall be normalized. Cooling rates faster than still-air cooling are permissible for the improvement of toughness provided the plates are subsequently tempered in the temperature range of 590 to 700 C (1100 to 1300 F).

3.3 AAR TC128-Grade A Steel

This steel is produced according to an American Association of Railroads (AAR) specification M128.00 Specification for High Strength Carbon Manganese Steel Plates for Tank Cars, AAR TC128-70. This specification covers two grades of this steel, Grades A and B. Both are classified as flange quality. They are made to fine-grain practice. Grade A requires a minimum of 0.02 weight percent vanadium whereas Grade B has no minimum vanadium content requirement.

3.4 AAR TC128-Grade B Steel

This steel is produced according to AAR specifications and, as indicated above, the Grade B steel has no minimim required content for vanadium. It does have maximum limits for the contents of nickel, chromium, molybdenum, copper and vanadium, which are elements that may be commonly present in steel scrap used in production of these steels. These maximum limits are not specified for the Grade A steel.

Finally, it is noted that the maximum content permitted for manganese is greatest for the TC128 steels, it is intermediate for the A516 steel, and it is least for the A515 steel. In addition, the specification for A515 permits slightly higher carbon contents than do the other grades included here. See table 1.

4.0 RESULTS

4.1 Chemical Analyses

The results of check chemical analyses are given in table 1. When these results were compared with the specifications for chemical compositions of steels used in the manufacture of railroad tank cars, the chemical compositions of each of the steels examined closely matched the compositions given in one of the following specifications: ASTM A515-Grade 65, ASTM A516-Grade 65, and AAR TC128-Grades A and -Grade B. Accordingly, each has been classified in tables 1 and 2.

It is noted that, in accordance with the requirements of their grade, the A515 steels were silicon killed, and the other grades were made to fine-grained practice. For the two A516 steels, the aluminum contents (table 1) at 0.013% and 0.009% (percent by weight) reflect this. Note that the aluminum content for each of the silicon-killed A515 steels are indicated to be <0.005% Al.

Plate Sample 13B, an aluminum killed A516 steel, and Plate Sample 7, an A515 steel, both fail their respective requirements on carbon content. For Plate Sample 13B, the check analysis indicated that this steel contains 0.27 percent carbon, and the maximum specified product analysis for carbon in A516 steel is 0.26 percent. Thus, the check analysis indicates that plate 13B exceeds the carbon requirement for this grade by an amount equal to 0.01 percent. Likewise, at 0.29 percent carbon, Plate Sample 7 exceeds its specified product maximum (of 0.28 percent) by 0.01 percent carbon.

The manganese contents of the steels are noted to be lowest for the A515 steels (0.55 to 0.71 percent Mn), intermediate for the A516 steels (0.81 to 0.88 percent Mn), and highest for the TC128 steels (1.06 to 1.35 percent). This is in keeping with the maximum manganese content permitted under the specifications for these grades of steel.

Eleven of the samples have the TC128 composition, with its higher permitted manganese contents and its requirement for fine-grained practice. The minimum required vanadium content for Grade A was observed to be present in four of these 11, e.g. in Plate Sample Nos. 2, 3, 12, and 17. Thus, they are classified as Grade A.

The other notable anomalies in the chemical analyses (apart from the anomalous carbon content mentioned above) are in the values obtained for the molybdenum content shell courses 2 and 3 of UTLX 2827, for which the available mill report gives 0.18 and 0.13 weight percent, respectively. The check analyses indicate these values to be 0.02 and 0.01 weight percent, respectively. These differences (between values of the mill reports and the check analyses) are outside the bounds of measurement error. In fact, the maximum molybdenum content for the 21 analyses reported here is only 0.06 weight percent. Although no explanation is here offered for these anomalous differences, it is noted that the maximum molybdenum level permitted for ladle analyses is 0.08 weight percent for this grade of steel; the ladle analysis is considerably greater than both this specified maximum and the check chemical analyses. Thus, for each of two shell plates taken from UTLX28727, the molybdenum content satisfies the specification according to the check analysis, but does not satisfy the specification according to the ladle analysis. One would expect this discrepancy in the molybdenum content to have been discovered and reported or discussed, in connection with fabrication of this tank car.

The analyses of sulfur content indicate that the average sulfur content is 0.017 percent by weight, for the 21 plate samples. Seven plate samples have sulfur content greater than 0.020 percent. These are plate samples 2, 3, 10 A & B, 13 A & B, and 19A. Four have sulfur content less than 0.011 percent. These are plate samples 1, 7, 13/A, and 20A-B.

4.2 Hardness Measurements

The results of Rockwell B hardness measurements made on the 21 plate samples are given in table 2. These hardness measurements include an average value for each of the 21 plate samples as well as an average value for each of the four grades of steel. The average values for the grades of steel follow: 75.2 hardness Rockwell B (HRB) for ASTM A515-Grade 65, 75.4 HRB for ASTM A516-Grade 65, 91.1 HRB for AAR TC128-Grade A steels, and 82.9 for AAR TC128-Grade B steels. There are no requirements for hardness in any of these steels, but tensile strength correlates well with hardness. The minimum strength required for Grade 65 of the A515 and A516 steels is 448 MPa (65 ksi), which correlates with 73 HRB. The range of strength levels required of the Grades A and B of AAR TC128 steel is 558 to 696 MPa (81 to 101 ksi), and this correlates with 86 to 95 HRB.

These very limited surveys of hardness indicate that five of seven samples of TC128-B steel and one of the eight A515 steels appear to be at marginal strength levels for their grades. Almost all of the TC128 Grade B steels have hardness that is very marginal. As these results suggest that some of the steels may be below the strength level requirements of the grades to which they were produced, it is suggested that these steel be targeted for future study to determine whether or not strength level is at the expected level and to determine whether any strength level deficencies that are observed could have been the direct result of involvement in this accident.

4.3 Microstructures

The optical metallographic examinations for each of the 21 samples indicate that the steels contain ferrite and pearlite. Photomicrographs for all 21 samples are presented in figures 1 to 21. They are presented in the same sequence as that given for the same samples in table 2, which contains data pertinent to the discussion to follow. See the bottom of table 2 for the meaning of abbreviations A, B, H, M, S, and W, which are used in this table under the heading "metallographic code".

In the photomicrographs it is seen that, as nital-etched, the ferrite appears light (nearly white) and the pearlite appears dark. Pearlite is a mixture of ferrite (a solid solution of carbon in alpha iron) and cementite (Fe_3C), with a lamellar eutectoidal morphology. These microstructures indicate that most of these steels are in either the as-rolled or the normalized (or possibly hot-formed) condition. Some may have been overheated and/or possibly cooled more rapidly than normal air cooling. This conclusion arises in large measure from the appearance of the ferrite.

Normally, in steels of these grades, the ferrite is polygonal. It forms proeutectoidally and it is equiaxed both in the normalized and in the as-rolled conditions. In the cold-rolled condition, the polygons would be distorted and not equiaxed. In some of these steel samples, Widmanstätten ferrite and some acicular ferrite are present. These are indications of steels that have been either overheated and/or rapidly cooled.

The results of the measurements of ferrite grain size by ASTM specification E112, are given in table 2. The average G.S. is indicated to vary from plate to plate over a range of ferrite G.S. Nos. from 8.5 to 11.0. Thus, none is exceptionally coarse.

It is noted that the pearlite spacing, the apparent distance between alternate layers of cementite and ferrite, is much finer in some samples (on average). The carbides are not resolvable in the pearlite in some of the samples. Example are in figures 17 to 19 for samples 10A, 10B and 16A. At the higher magnification of X500, this pearlite does not appear at all lamellar.

Microstructural banding is present in many of these steels. Banding appears as alternate layers of ferrite and pearlite that are nearly parallel to the surfaces of the plate. Normally, the banding can not be removed by standard commercial heat treatments, which may even accentuate the microstructural banding. On the other hand, the pearlite spacing can be affected by either heat treatment or chemical composition. These two factors can also affect the ferrite grain size.

The metallographic examinations indicated that three of the shell-plate samples contained centerline segregation. This is a chemical enrichment, which is originally in the middle of a casting, i.e., in the part that is last to solidify. After ingot is rolled to plate form, this region becomes the center of the plate. These three samples are plate sample 20A-A (a

TC128-Gr B steel) and plate samples 3 and 17 (two TC128-Gr A steels). This centerline segregation is more readily apparent at lower magnifications than those used for the figures.

Metallographic observations of the 21 steel samples are discussed below, according to the grades to which the steels were produced.

4.3.1 ASTM A515-Grade 65

The results of metallographic observations of the eight samples of A515-Grade 65 steel are presented in figures 1 to 8. The first four are head-plate samples and the others are shell-plate samples.

These steels differ in the appearance of the ferrite and of the pearlite. A prominent feature among these microstructures is the wide variation in the amount, the size, and the distribution of the ferrite. In addition, the pearlite varies from large colonies containing Widmanstätten ferrite to lamellar structures that vary from coarse to fine. Some pearlites contain unresolvable carbides, the structures of which have not been determined here.

For an example of the amount of ferrite, note that in plate samples 13/A (Fig. 3), 18A (Fig. 6), and 19B (Fig. 8), there appears to be less pearlite than in the other five samples. These three steels contain less carbon than the others in this grade. In general, steels with less carbon contain less pearlite, and hence more ferrite.

The microstructures of the A515-Grade 65 samples (Figs. 1 to 8) consisted mainly of ferrite that is somewhat non-uniform in grain size. The ferrite grain size number, indicated under "ave G.S." in table 2, is an average for the sample.

This indicated average has wider variability for some samples. For example, plate sample 19A (Fig. 7), which has mixed ferrite of G.S. No. 6 to 7 to G.S. No. 9 to 10, and an indicated ave. G.S. No. of 8.0 to 8.5. This variability is not indicated in the table, but it can be deduced by inspection of the photomicrographs.

Typically, the microstructures of as-rolled steels are not very uniform. They have greater variability, in both the ferrite and the prior austenite grain sizes, when compared with that for the normalized condition. Further, normalizing produces a structure that is both finer and more uniform than the as-rolled structure.

The distribution of ferrite is more random in some samples. See the equiaxed ferrite of plate sample 7 (Fig. 2) for uniformly distributed ferrite. Compare this with the layered structures of the highly banded steels. Further compare the ferrite of the Widmanstätten structure where the ferrite is on orthogonal planes. See table 2 for the metallographic codes.

Varying degrees of banding are observed throughout the metallographic samples taken from plate samples 13/A, 18A, 19A, and 19B (Figs. 3a, 6a, 7a, and 8a respectively), and this is indicated by the metallographic codes SB, MB, and HB. The letter codes S, M, and H are abbreviations for "some", "more", and "heavy". The B represents "banding". Samples 18A, 19A and 19B were from shell plates and 13/A was from a head plate.

In table 2 it is noted that two head plates and one shell plate have been designated with metallographic codes for Widmanstätten ferrite, codes HW and SW. The Widmanstätten ferrite is particularly pronounced in plate samples 4 and 12, which are shown as figures 1 and 13, respectively. In the X100 photomicrograph it is seen that there are numerous very large colonies (or blown-up grains) of pearlite that contain the orthogonal ferrite, which characterizes the Widmanstätten structure. These blown-up grains reflect the size of the prior austenite grains from which this structure was formed upon cooling of the plate, either after rolling or after the heat treatment that accompanies a subsequent hot-forming operation. This structure indicates that the plate was overheated, either by finishing (the rolling) too hot or by forming at an excessively high temperature.

Due to the presence of the Widmanstätten structure, samples 8 (Fig 5a) and 18B (Fig. 4a) do not appear to be very equiaxed. They appear to be almost acicular. Numerous blown-up grains are also present in the X100 micrographs of these two samples. Further scans of the microstructure of these two plates would be warranted, if these plates are considered for use in further studies, and especially if the question of overheating is important to the study in question.

The most desirable microstructure of the lot examined is that shown as figure 3, which represents sample 13/A. Although this microstructure shows slight banding, it comes from a very fine prior austenite grain size. For improved toughness, it has fine ferrite, of ASTM G.S. No. 9.0 to 9.5, and it contains only 0.19 percent carbon. The low carbon level is reflected in the high percentage of ferrite observed in the microstructures shown in figures 3A and 3B.

4.3.2 ASTM A516-Grade 65

There are two plate samples of A516-Gr 65 steels: Plate samples numbered 13A and 13B. As seen in figures 9 and 10, these are both fine grained (G.S. No. 10.0) and moderately to heavily banded. The carbon content of the steel shown in figure 10 is 0.27 percent, whereas that of the steel shown in figure 9 is only 0.21 percent. This is reflected in the relatively greater amount of pearlite in the micrographs shown in figure 10 for plate sample 13B with its higher content (0.27 percent) of carbon, an amount that slightly exceeds the 0.26 percent carbon permitted for this grade.

4.3.3 AAR TC128-Grade A Steel and Grade B Steel

For the most part the microstructures of these TC128 Grade A and Grade B steels are rather similar to those of the A515 and 516 steels discussed above, except that these may contain a greater percent pearlite. This pearlite has a lower carbon content than that of the steels discussed above. This is due to the greater alloy content (Mn, Ni, Cr, Mo, V) in the TC128 steels. These alloying elements shift the eutectoid composition of pearlite to the hypoeutectoid (lower carbon) side of 0.80 percent, which is the equilibrium carbon content of pearlite in plain-carbon steels. As with all other steels examined for this report, the inclusions in these steels were found to be mainly manganese sulfide (MnS) inclusions.

Based upon specifications for all four grades, the most noticeable chemical factor (when compared with the ASTM Grades discussed above) is the ratio of manganese to carbon. The carbon content is lower and the manganese content is higher for both the Grade A and Grade B steels, so that these steels have a higher ratio of Mn/C, when compared with that allowed for Grades A515 and A516. The higher Mn/C ratio usually produces microstructures that tend to have lower impact transition temperatures. This is generally considered to be desirable in applications that may have requirements for improved impact energy absorption at ambient temperatures.

Centerline segregation was observed on two of the plate samples of TC128 Grade A steel (plate samples 3 and 17, shown in Figs. 12 and 14) and in one of the TC128-Grade B steels (plate sample 20A-A in Fig.20). The appearance of the centerline segregation is indicated in figure 14A, which is the X100 photomicrograph taken on plate sample 17. The richer centerline chemistry in this steel has increased the amount of pearlite near the center of the plate. The micrograph is much darker in this region of the photomicrograph. It is noted that the band of centerline segregation is not very broad.

4.3.3.1 TC128 Grade A Steel

Microstructures for the four plate samples of TC128-Gr A steels are shown in figures 11 through 14, which respectively represent plate samples numbered 2, 3, 12, and 17. Banding in the Grade A steels is rated (table 2) to be moderate to heavy in all samples except plate sample 12 (fig. 13), which contains heavy Widmanstätten ferrite.

4.3.3.2 TC128-Grade B Steel

Microsturctures for the seven plate samples of TC128-Grade B steel (plate samples 1, 9, 10A, 10B, 16A, 20A-A and 20A-B) are shown in figures 15 through 21. Samples 1 and 9 are taken from head plates, and they both have very fine ferrite as rated in table 2. For the five shell plates of TC128-Gr B, the ferrite is slightly more coarse (at 7.0 to 9.0) than that of the two head plates of this steel, which have ferrite G.S. Nos. of 9.5 to 10.0. Microstructural banding is observed in all of these TC128-Grade B steel samples (table 2), although only to a slight degree in sample 10A (Fig. 17).

The predominance of pearlite in these steels is particularly evident in figure 20, of plate sample 20A-A. The pearlite colonies are very large, indicating a large prior austenite grain size. In plate samples 10A, 10B, and 16A, the pearlite colonies are large, but not as large as in plate sample 20A-A. In plate sample 9, the pearlite colonies are much smaller; this reflects the size of the prior austenite grains from which they were formed. It is noted that the carbides of the pearlite are not resolvable in the photomicrographs of figures 17 and 19. It is suggested that these two samples be carefully rechecked to determine if the ferrite can be resolved usingpicral etchant to resolve the carbides and the appearance of the ferrite that seems to be present in the pearlite.

By far the most unusual microstructure of the lot examined here is that shown in figure 16 for sample 9. This structure is like an upper bainite. It is rather irregular, and very different from the other structures. If the treatment that produced this structure can not be resolved by further inspection of this sample, it could be resolved by simulated (laboratory) heat treatments. In any event, when compared with microstructures in the other figures, the microstructure shown in this figure is open to questions regarding its origin as well as the mechanical properties that one might expect.

4.4 Inclusion Ratings

The ratings of inclusion content are not presented in tabular form. The results indicated that the average inclusion content for these steels is 2.5 to 3.0 in the thin series for MnS. Five of the TC128 steel samples are rated to have more than the average inclusion content of the others. These include plate samples 2 and 3, which are TC128-Gr A steels, and samples 9, 10A and 10B, which are TC128-Gr B steels. In addition, plate sample number 1 was rated to have less than the average inclusion content. These findings do not agree with the finding on sulfur content. It is expected that steels with higer sulfur content (there were seven with S% > 0.020), would contain more MnS inclusions, and those with less (there were three with S < 0.011 percent) would contain fewer MnS inclusions. It turns out that four of the five steels that were rated to be heavier than average in content of thin series MnS are steels that contained more than 0.20 percent sulfur. The fifth steel rated high in MnS contained average sulfur content of 0.017 percent. That leaves three other steels with high sulfur that were rated average in MnS content, as well as the three steels with lower sulfur that were rated average in MnS content.

It is concluded that these discrepancies indicate that the rating for inclusions by ASTM Method E45 is either too qualitative to be a good indicator of the content of sulfide inclusions or that the examination of a single sample is not adequate for representation of the content of the plate sample. These results suggest that quantitative microscopy be used for the rating of inclusions (see Ref. 3) and that perhaps two to three samples per steel would be more representative as a sample of the steel plate.

4.5 Impact Test Results

Results for the standard CVN impact tests conducted on the seven plate samples of TC128 steels are summarized in table 3 and figures 22 through 29. The observed test results and the results of calculations used to construct these figures are presented in 28 tables given as Appendices B through H, which respectively represent plate samples 2, 3, 12, 16A, 17, 20A-A and 20A-B. Each of these Appendices has four pages: The first two pages give the results for specimens of the TL orientation and the last two pages give those for the LT orientation. For each orientation (each pair of tables), results for energy absorption are presented first, followed by those for shear fracture appearance (SFA). In the body of the report, seperate figures are given for eash steel and each figure contains the observed data as well as one regression line for each orientation. The results from data for energy absorption and for SFA are presented in seperate frames designated A (e.g. Fig.22a) for results of energy-absorption data and designated B for the SFA data. Figures 22 to 24 and 26 illustrate the results for the four plates of TC128-Grade A steels, and figures 25, 27, and 28 are given for the three plates of TC128-Grade B steels.

The summary of data presented in table 3 includes only selected values for all seven plates tested. These include upper-shelf energy-absorption values for longitudinal specimens, which are averages of two test results; as well as those for transverse specimens, as an average of 5 to 6 test results; and a cross-rolling index [6,7], which is the ratio of these two (TL/LT) energy-absorption values. The other data presented were taken from results of calculations for transverse specimens, which are given in the Appendix tables. These include several fracture criteria. For transverse specimens, the fracture criteria include computed values of energy absorbed at two ambient temperatures that span a range of temperatures very commonly encountered in tank-car service in many parts of this country: 21 C (70 F) and -1 C (30 F).

4.5.1 Upper-Shelf Energy Absorption

The upper-shelf energy-absorption values shown here follow a trend of decreasing energy with increasing strength of the steel, as shown in Figures 30 and 31, which represent the behavior observed for 13 longitudinal (LT) and 14 transverse (TL) sets of specimens taken from 14 different plate samples of railroad tank cars, some of which were reported on earlier [7-9]. It is noted that for these plots, strength was computed from available hardness data for the seven plates of table 2, as strength was not measured directly except for those data taken from previous reports. In Figure 30, the Ultimate Tensile Strength is the independent variable. In Figure 31, where the Yield Strength is the independent variable, there is also a reference curve (for LT specimens only) that was taken from the literature [10]. The results given here are consistent with results given in an earlier report [7]. Energy absorption in longitudinal specimens of the tank-car steels is significantly lower than that for the steels from which the reference line was derived. This is true for all strength levels and the difference becomes more pronounced as the strength level is increased.

Energy absorption on the upper shelf can be compared for TL and LT specimens to obtain a cross-rolling index (see table 3), which is a measure of the anisotropy of the plates. Table 3 shows values of about 0.50 and 0.47, respectively for the indices for TC128-Grades A and B steels. These values represent seven shell-plate samples, and they are nearly identical to values reported earlier [7] for shell plate samples taken from three accident sites. This index is found to be somewhat higher for plates that have received more cross rolling, such as the head-plate steels taken from failed tank cars [7] in previous investigations, which averaged 0.68 for three plates tested.

For the TC128-Grade A steels, the maximum shelf energy is about 45 J (33 ft-lb) for transverse specimens. Longitudinal specimens have considerably greater values, with shelf-energy values that range from 60 to 90 Joules (44 to 70 ft-lbs).

The results for the TC128-Grade B steels are similar to those for -Grade A, except that the -Grade B are steels of lower strength levels. The shelf energy results for the TL specimens vary from 47 to 61 J (35 to 45 ft-lbs), which is higher than that observed for the Grade A steel. The observed differences between shelf-energy values of the -Grade A and the -Grade B steels reported here is interpreted to be a manifestation of the effect of strength level on the magnitude of the upper-shelf energy absorption, as reported in earlier works [7]. In general, The -Grade A steels are harder and thus, stronger than the -Grade B steels. This expected trend is shown in the plots of data given as figure 30. Data from various reports are presented here for both the yield strength (Fig. 30a), and the tensile strength (Fig. 30b). In the plots it is shown that, for either longitudinal or transverse data, upper-shelf energy absorpton decreases systematically with increasing levels of strength in of the steel. Further, it is indicated in figure 31 that the longitudinal shelf energy of tank-car steels is below the level given by a reference line taken from the literature.

All of the TC128-Grade B steels were observed to be microstructurally banded. The data for upper-shelf energy absorption indicates that this banding does not seem to affect the behavior for either the transverse or the longitudinal specimens, as shown by these trend lines (Figs. 30 and 31). It is noted that the sulfur contents of the Grade B steels are lower than those of the Grade A steels, but the data seem to indicate that the effect of sulfur on shelf energy is not the predominant effect; rather strength level predominates in determining the shelf energy. See figure 29a and tables 1 and 3.

4.5.2 Transition Temperatures

The upper-shelf occurs at roughly the same temperature for both the longitudinal and the transverse specimens. This is shown in figures 22b through 28b, which are given for SFA data. These figures indicate that the transition from ductile to brittle behavior is independent of orientation of the test specimen. From the SFA data, it is observed that: (1) The upper-shelf occurs at temperatures greater than about 43 C (100 F). See figure 29b for a summary plot for the seven shell-plate samples. (2) The 50% SFA, which is also referred to as the fracture appearance transition temperature (FATT), varies over the range of temperatures from -0.2 to 34.7 C (32 to 95 F), as indicated in Table 3.

The SFA data also indicate that the transition temperatures for the -Grade A steels are about the same as those for the -Grade B steels. Further, there is no consistent and obvious relationship between the FATT and any of the microstructural features discussed above, i.e. banding, grain size, and the type of ferrite.

Another transition temperature given in table 3 is the 15 ft-lb TT. This fracture criterion has values for transverse specimens that range from -4.4 to 9.0C (24 to 48F).

The transition temperatures of these transverse specimens are high enough, so that at common service temperatures, of 21C and -1C, the range of CVN energy-absorption values are shown (see table 3) to be only 12 to 27 ft-lbs. These values are only a fraction (usually half or less) of the value on the upper shelf. These observations of the transition temperatures are interpreted to indicate that these steels would not be expected to behave plastically in service, as might steels with lower transition temperatures.

5.0 SUMMARY AND CONCLUSIONS

Metallurgical observations were made on 21 plate samples taken from tank cars involved in an accident at Crestview, Florida. These observations include chemical analyses, metallographic examinations of microstructure and inclusion content, hardness measurements, and standard CVN impact tests. The metallographic analyses include ferrite grain size measurements by ASTM Method E112, and inclusion measurements by ASTM Method E45. In addition, on seven shell plates that were taken from tank cars used in pressurized service, CVN impact tests were conducted, using ASTM Method E23. Substantial amounts of these plate materials are available for further studies. The plate surface area available for each of the 21 samples varies over the range of from 1 1/2 to 17 ft^2, with the average being about 5 to 9 ft^2.

The results of the chemical analyses indicate that each of the 21 steel samples were produced to the requirements for the chemical composition of one or more of the following steels: ASTM A515-Grade 65, ASTM A515-Grade 65, AAR TC128-Grade A or -Grade B. Several anomalous result were observed, notably in the levels of carbon and molybdenum, which indicate that selected steels did not meet the compositional requirements for the steels in question.

The results indicate that the content of carbon for a steel judged to be made to A516-Gr 65 specifications and one made to A515-Gr 65 specifications each exceeds the product maximum for their grade by 0.01 percent carbon. Further, the ladle analysis of molybdenum, as given in the mill reports, exceeds that in the NBS check chemical analysis for each of two plates of TC128 steels taken from one tank car. These ladle analyses also exceed, by a considerable amount of 0.05 to 0.10 percent Mo, the specified maximum ladle analysis permitted for the TC128-B steel.

The sulfur content of the steels average 0.017 percent by weight. Five of the steels have sulfur exceeding 0.020 percent and four have sulfur at less than or equal to 0.010 percent.

The metallographic analyses show that the microstructures of these steels are mixtures of ferrite and pearlite, with the ferrite being one or more of the following types: polygonal, acicular, and Widmanstätten. Although these microstructures are typical for these steels, the acicular and Widmanstätten ferrites do indicate rapid cooling and/or overheating (coarse austenite grain size). Large austenite grain size is indicated by large pearlite colonies in some of the steel samples. In addition, for many samples varying degrees of microsturctural banding are observed, and this is not unusual for these grades of steel. All steels examined have ferrite grain sizes finer than ASTM 8.0, with some as fine as 11.0. Some unresolved carbides in three of the samples leave the question of their microstructures open to further study.

Inclusion analyses of 21 samples indicate that the vast majority of the steels contain inclusions that are predominantly 2.5 to 3.0 in the thin series for MnS, as rated by Method E45. Five of these samples were rated to have above average inclusion contents, two of which are TC128-Grade A samples and three are TC128-Grade B samples. In addition, one sample was rated to have fewer sulfides than the average .

The results of these inclusion analyses are not consistent with the results of chemical analyses for sulfur content. It is concluded that this indicates that the rating of inclusion analyses, using Method E45, is either too qualitative to be a good indicator of the content of sulfide inclusions or that the examination of a single sample is not adequate for representation of the content of the plate sample. These results suggest that quantitative microscopy be used for the rating of inclusions and that perhaps two to three samples per steel would be more representative as a sample of the steel plate.

Results of hardness measurements indicate that one of eight samples of A515-Gr 65 steel and five of seven samples of TC128-B steel may have marginal tensile strength in relation to the requirements for the grades to which they were apparently produced. These steels are suggested for further study.

Upper-shelf impact energy-absorption values could not be related directly to the sulfur level and the inclusion content. Shelf energy is shown to be related to the strength level of the steel; with the -Grade A steels, which in general are steels of higher strength levels, having the lower observed shelf energy-absorption values. These steels also contain more vanadium. Upper-shelf energy-absorption in the range of 34 to 45 J (25 to 33 ft-lbs) observed for the transverse specimens are considered to be somewhat low for the range of strength levels in question [10].

Further, several transition temperatures for these steels are given. The temperatures at which the upper shelf is obtained is generally above about 43 C (110 F), and this temperature is above the average daytime temperature for much of the U.S.A. The 15 ft-lb temperatures are in the range of temperatures from about -5C (about 25F) to almost 10C (about 50F). This fracture criterion would likewise not be met for much of the year in ambient conditions throughout the U.S.A. The 50% SFA (the FATT) temperatures are even higher: 0 C to 35 C (32 to 95F).

The energy absorption for CVN specimens at -1 C (30F), for these steels range from about 16.5 to 21.8 J (12.2 to 16.1 ft-lbs). Thus, fracture toughness could be considered to be marginal for these steels at temperatures just below the freezing point of water.

6.0 ACKNOWLEDGEMENT

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Table 1. Chemical Composition of 21 Plate Samples from 16 NBS Tank-Car Samples Cut from 8 Tank Cars

ID and Contents of Tank-Car	Shell Course ID	NBS Tank-Car Sample ID	ASTM Designation	Plate Sample NO.	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	Al	V
GATX 44019 CCl_4	4	NBS 8	A515-Gr65	8	0.28	0.71	0.005	0.15	0.17	0.01	0.07	0.01	0.01	<0.005	
ACFX 81395 (acetone)	2	NBS 13	A516-Gr65	13A	0.21	0.81	0.010	0.032	0.20	0.09	0.09	0.03	0.28	0.013	
	3	NBS 13	A516-Gr65	13B	0.27**	0.88	0.012	0.035	0.24	0.14	0.18	0.03	0.28	0.009	<0.005
	B-Head	NBS 13A	A515-Gr65	13/A	0.19	0.70	<0.005	0.010	0.22	0.07	0.05	0.01	0.08	<0.005	
GATX 5013 (methanol)	A-Head	NBS 7	A515-Gr65	7	0.29**	0.61	0.014	0.007	0.16	<0.01	0.04	<0.01	0.01	<0.005	
ACFX 82959 (acetone)	1	NBS 18	A515-Gr65	18A	0.22	0.67	<0.005	0.012	0.21	0.11	0.09	0.03	0.17	<0.005	
	A-Head	NBS 18	A515-Gr65	18B	0.27	0.57	<0.005	0.018	0.19	0.10	0.07	0.02	0.16	<0.005	
	5	NBS 19	A515-Gr65	19A	0.24	0.56	<0.005	0.021	0.18	0.10	0.07	0.02	0.15	<0.005	
	6	NBS 19	A515-Gr65	19B	0.22	0.66	<0.005	0.011	0.21	0.10	0.09	0.03	0.16	<0.005	
ACFX 89990 (methanol)	B-Head	NBS 4	A515-Gr65	4	0.22	0.56	<0.005	0.017	0.20	0.12	0.16	0.04	0.19	<0.005	
	3	NBS 9	TC128-GrB	9	0.23	1.06	0.005	0.017	0.20	0.16	0.12	0.04	0.21	0.026	not reported
	5	NBS 10	TC128-GrB	10A	0.24	1.26	0.021	0.025	0.24	0.03	0.23	0.06	0.03	0.045	" "
	4	NBS 10	TC128-GrB	10B	0.21	1.24	0.023	0.022	0.25	0.03	0.23	0.06	0.03	0.052	" "
UTLX 28727 (chlorine)	3	NBS 20A	TC128-GrB	20A-A	0.26	1.28	0.020	0.012	0.23	0.16	0.05	0.01	0.01	0.025	<0.005
		mill report	-	-	0.24	1.35	0.021	0.015	0.25	0.17	0.04	0.13**	0.01	-	-
	2	NBS 20A	TC128-GrB	20A-B	0.19	1.26	0.014	<0.005	0.23	0.14	0.05	0.02	0.01	0.024	<0.005
		mill report	-	-	0.23	1.35	0.022	0.012	0.25	0.16	0.04	0.18**	0.01	-	-
IMCX 2513 (anhydrous ammonia)	A-Head	NBS 1	TC128-GrB	1	0.19	1.26	0.010	0.008	0.22	0.19	0.19	0.02	0.25	0.034	0.007
	2	NBS 2	TC128-GrA	2	0.23	1.34	0.016	0.024	0.23	0.21	0.21	0.02	0.23	0.026	0.035
	5	NBS 3	TC128-GrA	3	0.24	1.13	0.011	0.021	0.22	0.21	0.19	0.01	0.28	0.017	0.032
	4	NBS 16A	TC128-GrB	16A	0.23	1.24	0.009	0.011	0.25	0.20	0.21	0.01	0.22	0.034	0.007
IMCX 2827 (anhydrous ammonia)	3	NBS 12	TC128-GrA	12	0.19	1.13	<0.005	0.017	0.22	0.20	0.20	0.06	0.06	0.030	0.024
	2	NBS 17	TC128-GrA	17	0.20	1.21	0.006	0.019	0.22	0.16	0.11	0.03	0.14	0.021	0.039
								$\bar{S}$=0.017							
Specifications (maximum wt. percent, except where range is indicated).															
ASTM A515-78-Grade 65				Ladle	0.28	0.90	0.035	0.04	.15/.30						
				Product	0.28	0.98	0.035	0.04	.13/.33						
ASTM A516-78-Grade 65 [1/2 in to 2 in (50mm)]				Ladle	0.26	.85/1.20	0.035	0.04	.15/.30					*	*
				Product	0.26	.79/1.30	0.035	0.04	.13/.33					*	*
AAR TC128-Grade A (1970)				Ladle	0.25	1.35	0.04	0.05	0.30	---	---	---	---	*	0.02 min
-Grade B (1970)				Ladle	0.25	1.35	0.04	0.05	0.30	0.25	0.25	0.08	0.35	*	0.08 max

* made to fine-grade practice   ** fails the chemical requirement for the grade.

Table 2 Test Sample Identity and Results of Metallographic Observations and Hardness Measurements Taken on 21 Plate Samples of Tank-Car Head and Shell Plates.

Specification	Content	Plate Sample ID.	Tank Car ID.	Shell or Head	Grinding Code***	As-Received Plate Thickness(in)	ASTM(E-112) ave. G.S.	Hardness HRB	Metallographic Code **
A515-Grade 65	Methanol	4	ACFX 89990	B-Head	1	0.46	8.5	75.3	HW
A515-Grade 65	Methanol	7	GATX 5013	A-Head	1	0.45	10.0	83.1	-
A515-Grade 65	Acetone	13/A	ACFX 81395	B-Head	1	0.41	9-9.5	69.8	SB
A515-Grade 65	Acetone	18B	ACFX 82959	A-Head	1	0.41	9.5-10.0	77.0	SW-MW
A515-Grade 65	CCl_4	8	GATX 44019	Shell 4	1	0.45	8-8.5	75.5	SW
A515-Grade 65	Acetone	18A	ACFX 82959	Shell 1	1	0.42	8.5	74.2	MB-HB
A515-Grade 65	Acetone	19A	ACFX 82959	Shell 5	1	0.40	8-8.5	73.1	HB
A515-Grade 65	Acetone	19B	ACFX 82959	Shell 6	1	0.41	9.5	74.1	HB
							ave	75.2	
A516-Grade 65	Acetone	13A	ACFX 81395	Shell 2	1	0.45	10	72.4	MB
A516-Grade 65	Acetone	13B	ACFX 81395	Shell 3	3	0.77	10	78.5	HB
							ave	75.4	
TC128-Grade A	An. Ammonia	*2	IMCX 2513	Shell 2	3	0.75	9.5	92.7	MB-HB
TC128-Grade A	An. Ammonia	*3	IMCX 2513	Shell 5	3	0.75	9-9.5	92.7	MB-HB
TC128-Grade A	An. Ammonia	12	IMCX 2827	Shell 3	2	0.57	8.5	87.0	HW
TC128-Grade A	An. Ammonia	17	IMCX 2827	Shell 2	2	0.57	9.5	91.8	SB, SW
							ave	91.1	
TC128-Grade B	An. Ammonia	1	IMCX 2513	A-Head	3	0.76	10.5-11	81.2	HB, SA
TC128-Grade B	Methanol	*9	ACFX 89990	B-Head	1	0.44	10-10.5	82.2	MB, MA
TC128-Grade B	Methanol	*10A	ACFX 89990	Shell 5	1	0.45	9	81.2	SB, SW
TC128-Grade B	Methanol	*10B	ACFX 89990	Shell 4	1	0.45	8.5-9	80.0	MB, SW
TC128-Grade B	An. Ammonia	16A	IMCX 2513	Shell 4	2	0.54	9.5-10	87.1	MB-HB
TC128-Grade B	Chlorine	20A-A	UTLX 28727	Shell 3	3	0.81	8.5	85.4	MB
TC128-Grade B	Chlorine	20A-B	UTLX 28727	Shell 2	3	0.79	8.5	83.0	HB, SW
							ave	82.9	

*Steels with higher inclusion contents than the average for all steels examined by the method of ASTM E-45.

** All are mixtures of ferrite and pearlite. Code for other observations follows:
A = accicular ferrite;
B = microstructural banding; W = Widmanstätten ferrite
S = Some, M = More, H = Heavy
e.g. SB means some microstructural banding

*** Grinding (or thickness) code 1= 10-12 mm (0.40-0.46in), 2= 13-15 mm (0.54-0.57in), 3= 19-20 mm (0.75-0.81in)

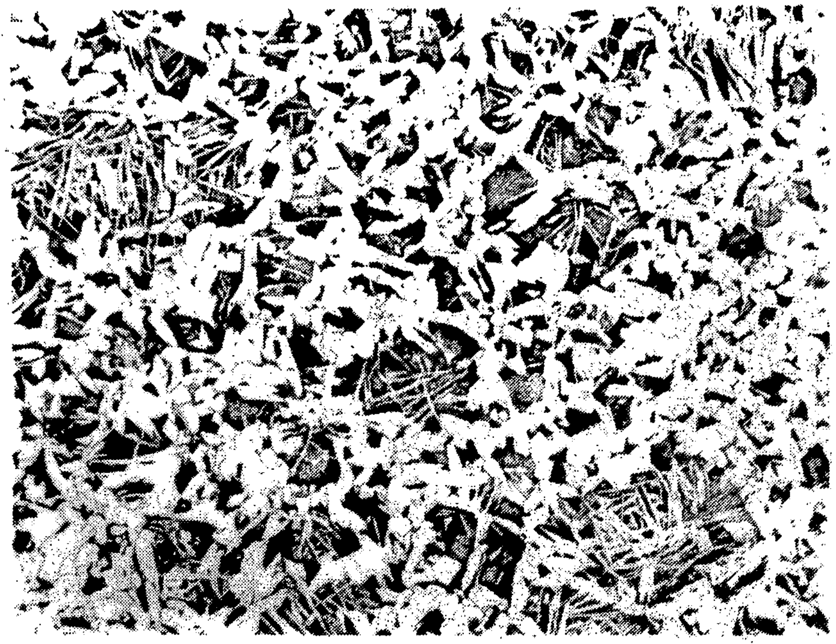
Table 3. Summary of Data for Standard Charpy V-Notch Specimens

Plate Sample ID	TC128 Grade	CVN ID	Cross-Rolling Index	Longitudinal Specimens** Upper Shelf Joules	(ft-lb)	Transverse Specimens Upper Shelf Joules	(ft-lb)	21 C, or 70 F Joules	(ft-lbs)	-1 C, or 30 F Joules	(ft-lbs)	15 ft-lb TT C	(F)	50% SFA FATT C	(F)
2	A	2	0.56	73	(54)	41	(30)	25.2	(18.6)	16.5	(12.2)	9.0	(48.2)	27.6	(81.6)
3	A	3	0.57	60	(44)	34	(25)	26.7	(21.9)	19.4	(14.3)	0.8	(33.5)	-0.2	(31.7)
12	A	4	0.36	95	(70)	34	(25)	27.1	(20.0)	18.7	(13.8)	3.1	(37.5)	8.6	(47.4)
17	A	6	*	-	(*)	45	(33)	26.7	(19.7)	18.2	(13.4)	4.9	(40.8)	34.7	(94.5)
16A	B	5	0.56	110	(81)	61	(45)	33.4	(24.6)	21.8	(16.1)	-4.4	(24.1)	27.1	(80.8)
20A-A	B	7	0.43	111	(82)	47	(35)	33.4	(24.6)	19.0	(14.0)	1.3	(34.3)	10.1	(50.1)
20A-B	B	8	0.42	140	(103)	58	(43)	36.6	(27.0)	21.3	(15.7)	-2.8	(27.0)	19.9	(67.9)

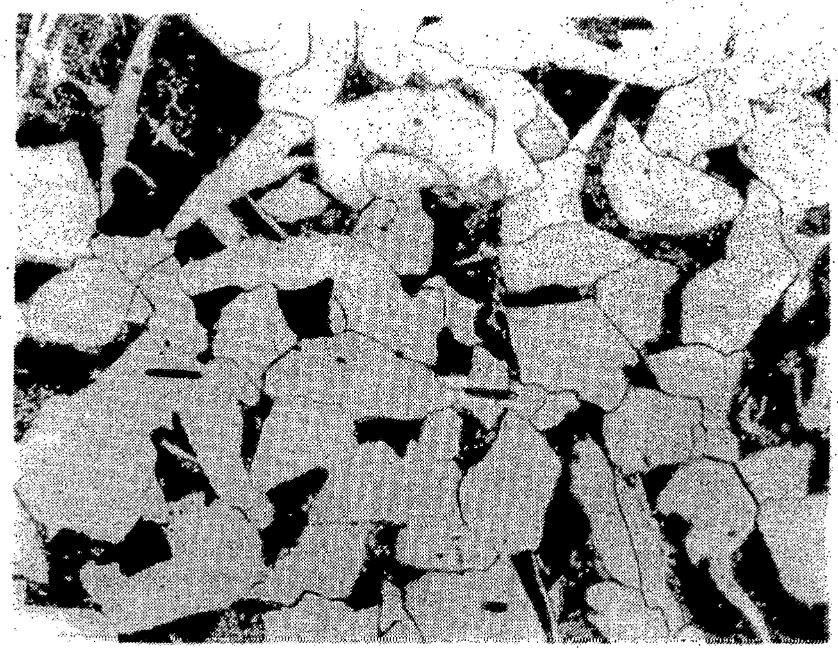
*Not estimated from the available data.

**Due to paucity of data, estimates for longitudinal specimens are tentative. See text.

TT - Transition Temperature
SFA - Shear Fracture Appearance
FATT - Fracture Appearance Transition Temperature

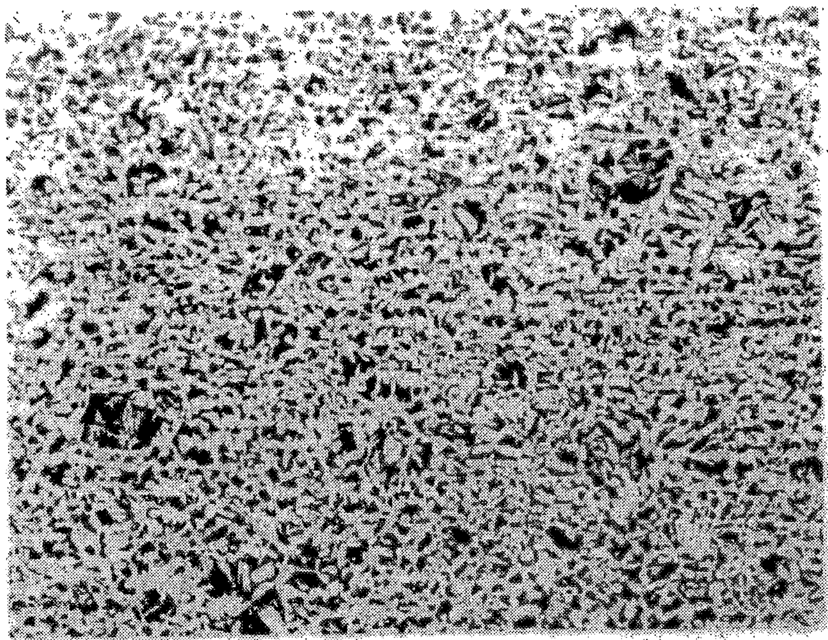


(a)

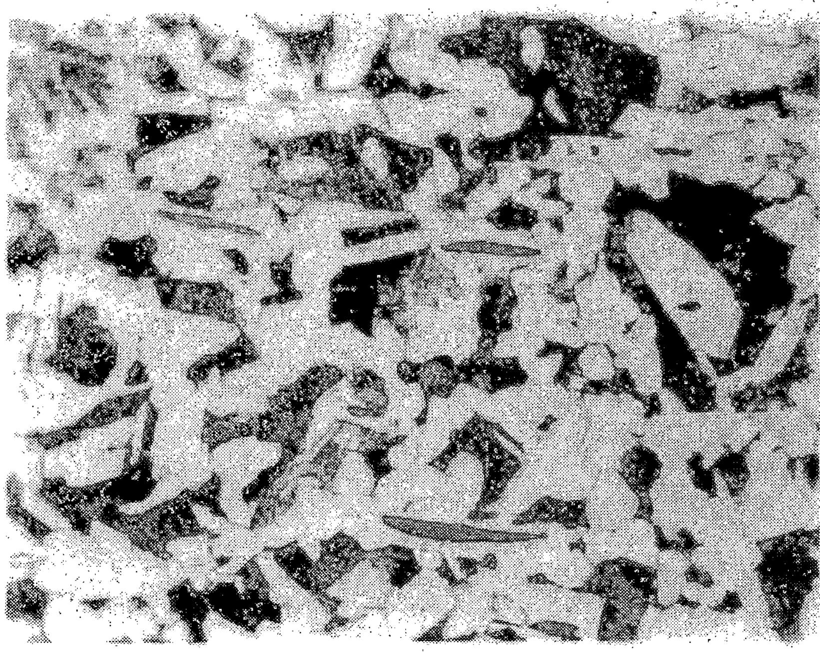


(b)

Figure 1. Photomicrographs of Plate Sample No. 4., Tank Car ACFX 89990, B-Head, ASTM A515-Grade 65. a) X100 b) X500 Etchant: Nital

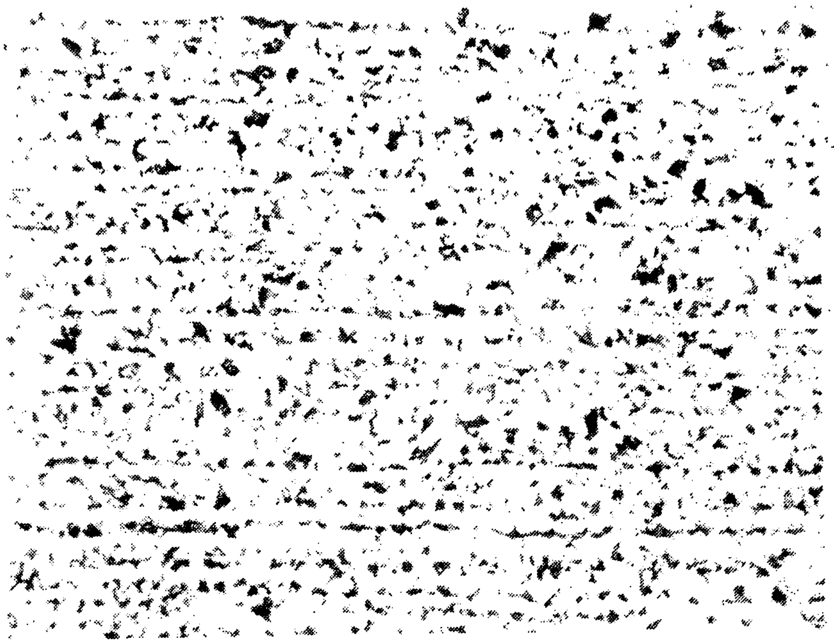


(a)

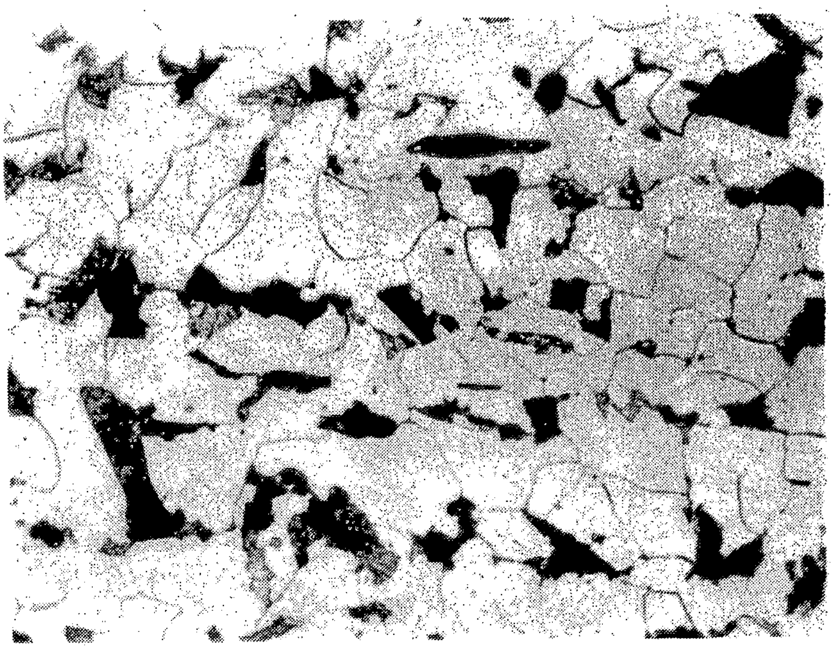


(b)

Figure 2. Photomicrographs of Plate Sample No. 7., Tank Car GATX 5013, A-Head, ASTM A515-Grade 65. a) X100 b) X500 Etchant: Nital

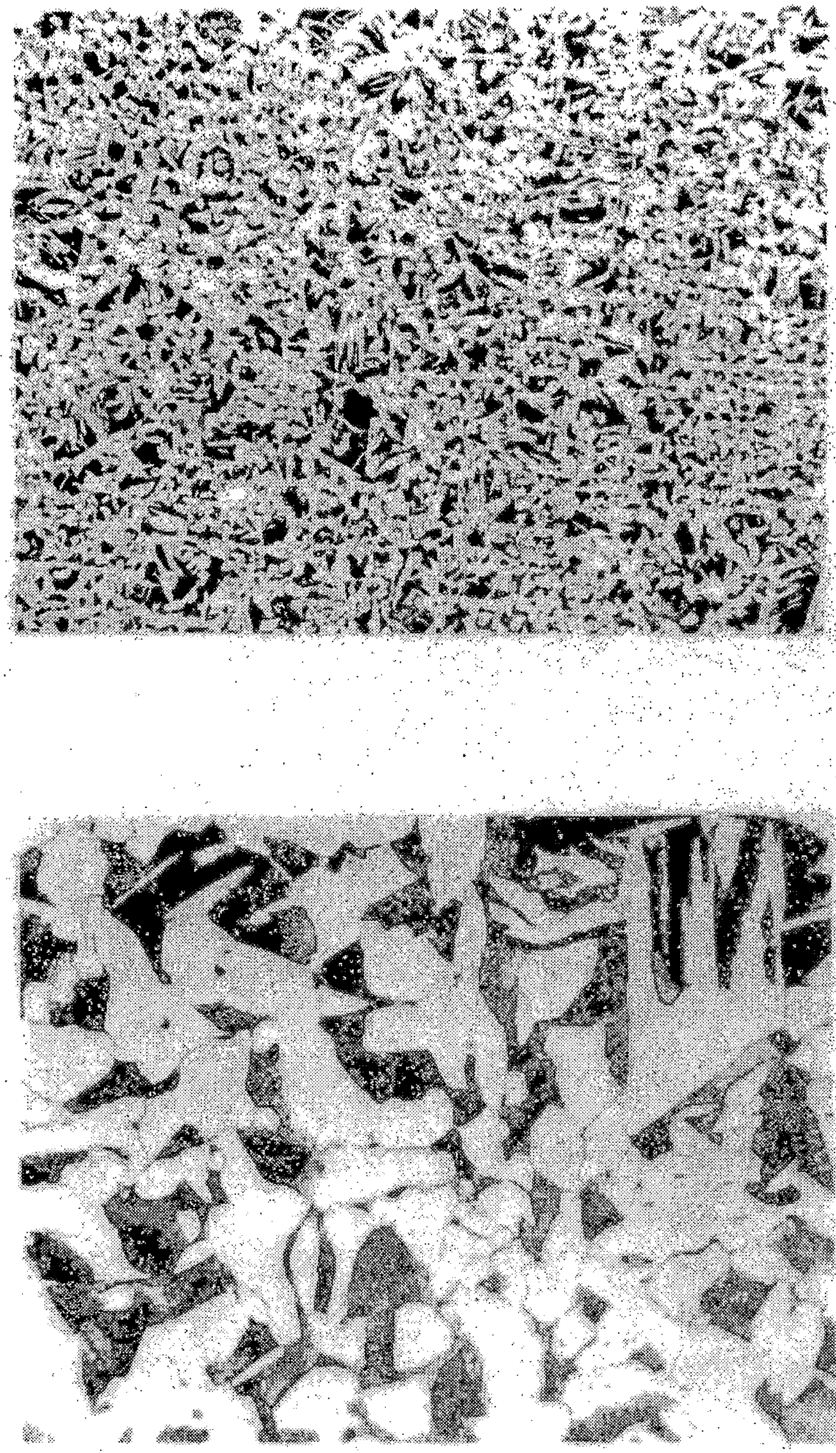


(a)



(b)

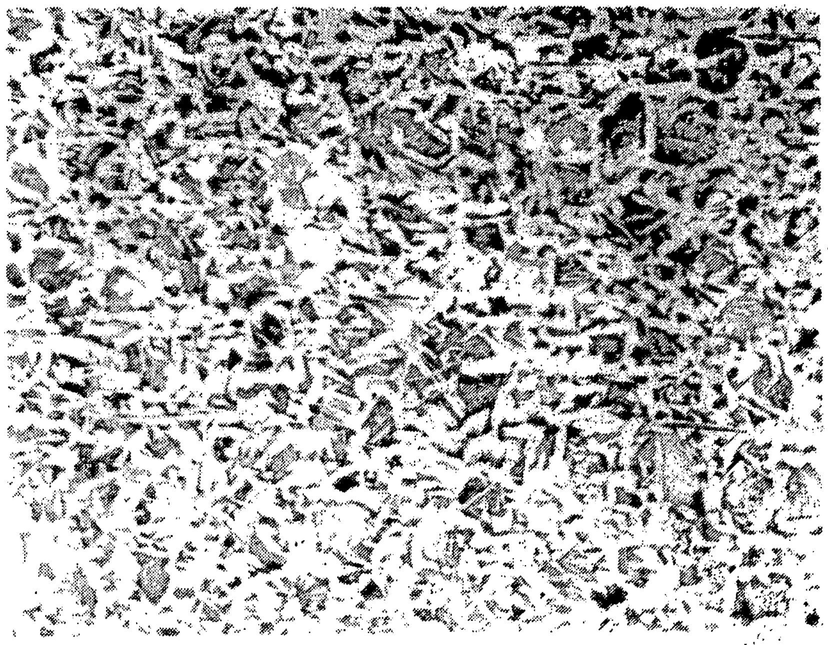
Figure 3. Photomicrographs of Plate Sample No. 13/A Tank Car ACFX 81395, B-Head, ASTM A515-Grade 65
a) X100 b) X500 Etchant: Nital



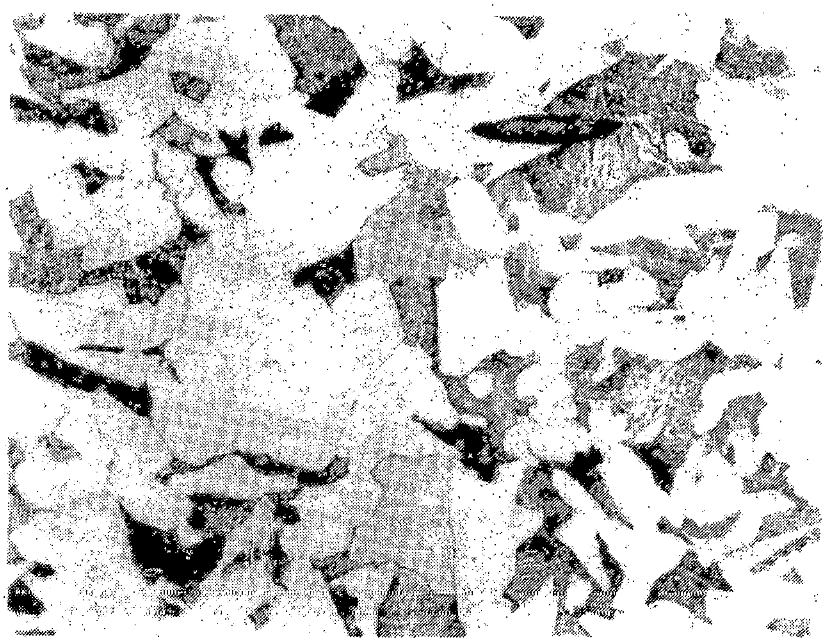
(a)

(b)

Figure 4. Photomicrographs of Plate Sample No. 18B, Tank Car ACFX 82959, A-Head, ASTM A515-Grade 65. a) X100 b) X500 Etchant: Nital

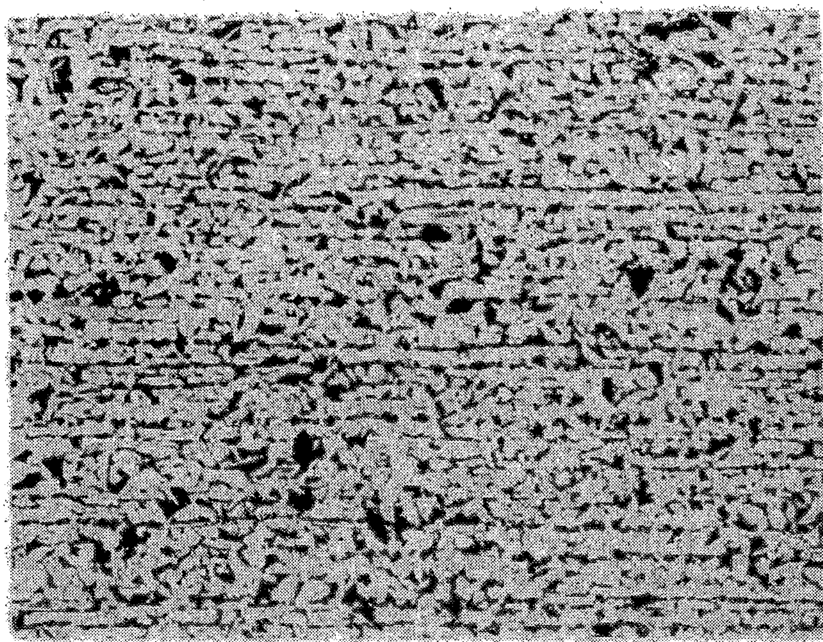


(a)



(b)

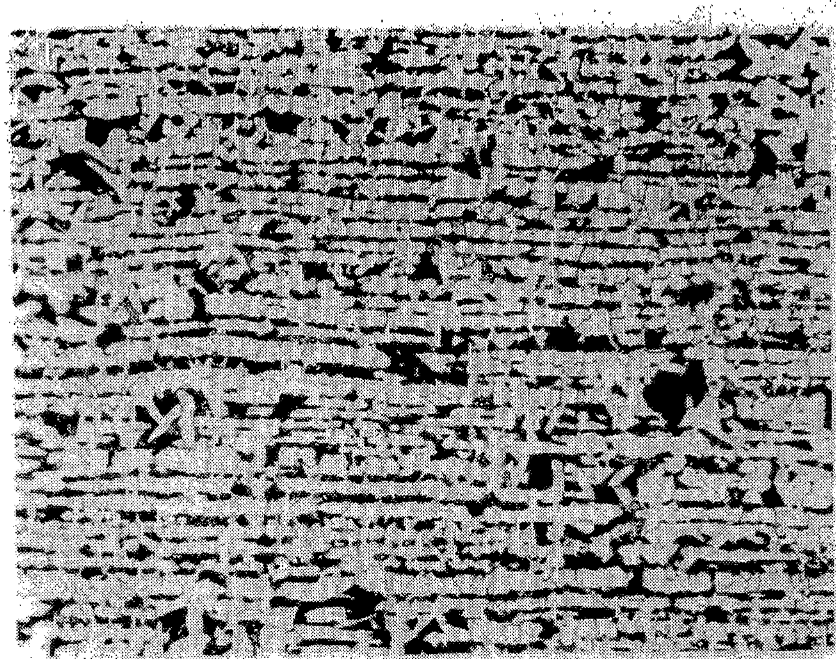
Figure 5. Photomicrographs of Plate Sample No. 8, Tank Car GATX 44019, Shell Course 4, ASTM A515-Grade 65. a) X100 b) X500 Etchant: Nital



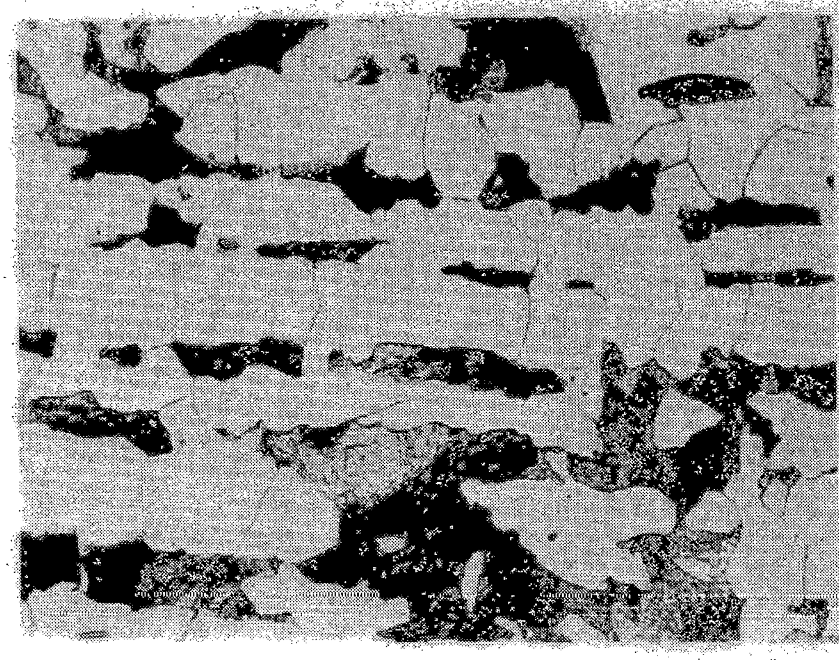
(a)

(b)

Figure 6. Photomicrographs of Plate Sample No. 18A, Tank Car ACFX 82959, Shell Course 1, ASTM A515-Grade 65 a) X100 b) X500 Etchant: Nital

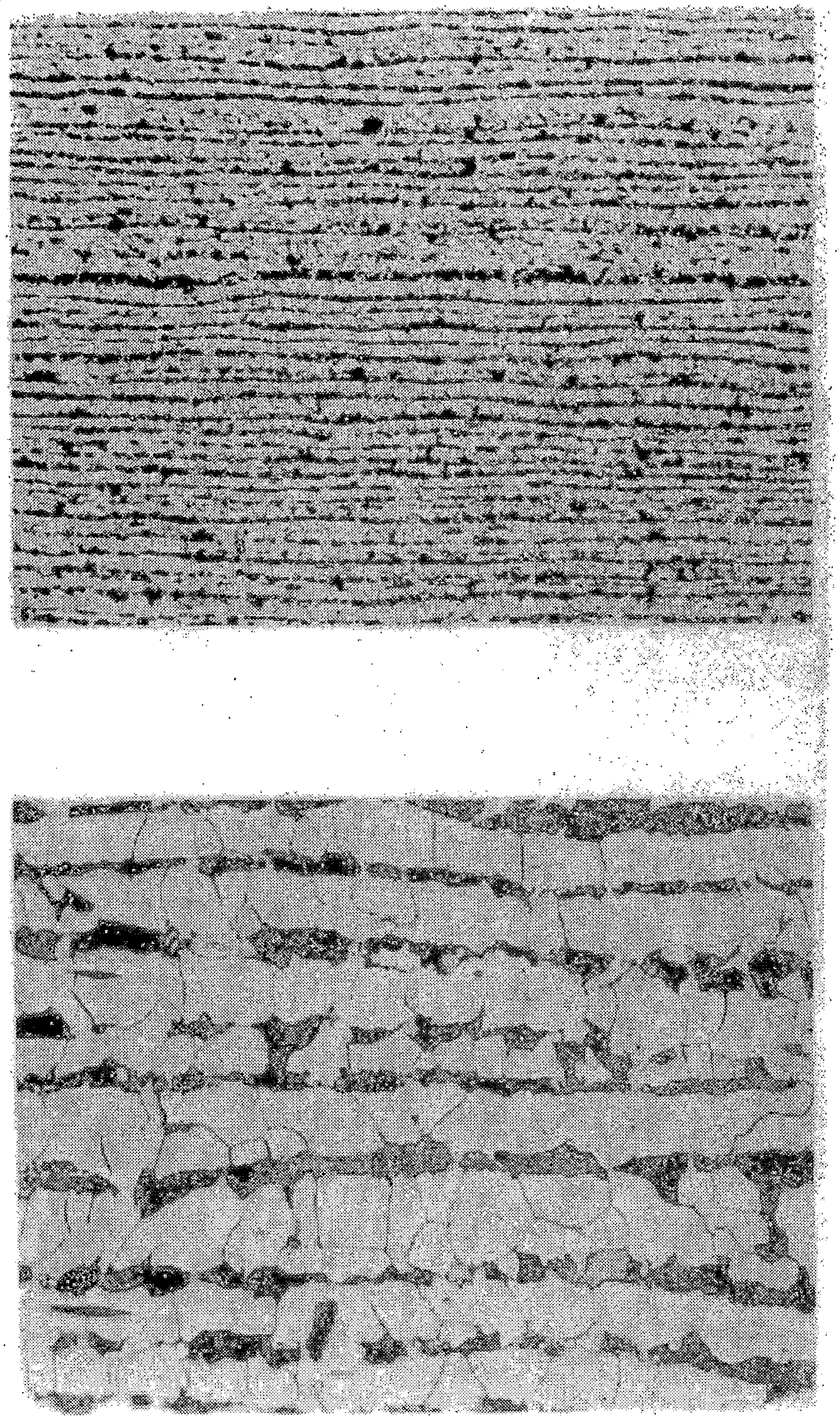


(a)



(b)

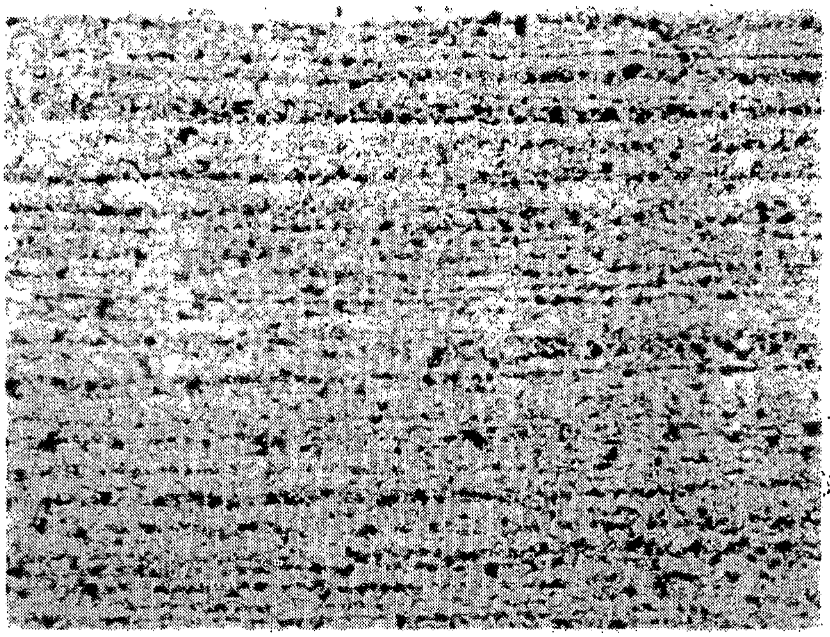
Figure 7. Photomicrograph of Plate Sample No. 19A, Tank Car ACFX 82959, Shell Course 5, ASTM A515-Grade 65. a) X100 b) X500 Etchant: Nital



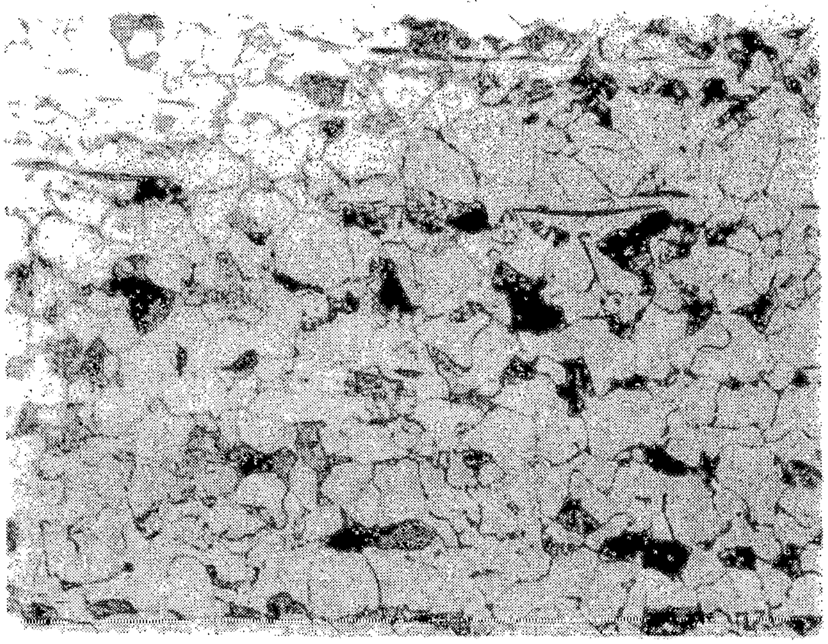
(a)

(b)

Figure 8. Photomicrograph of Plate Sample No. 19B, Tank Car ACFX 82959, Shell Course 6, ASTM A515-Grade 65. a) X100 b) X500 Etchant: Nital

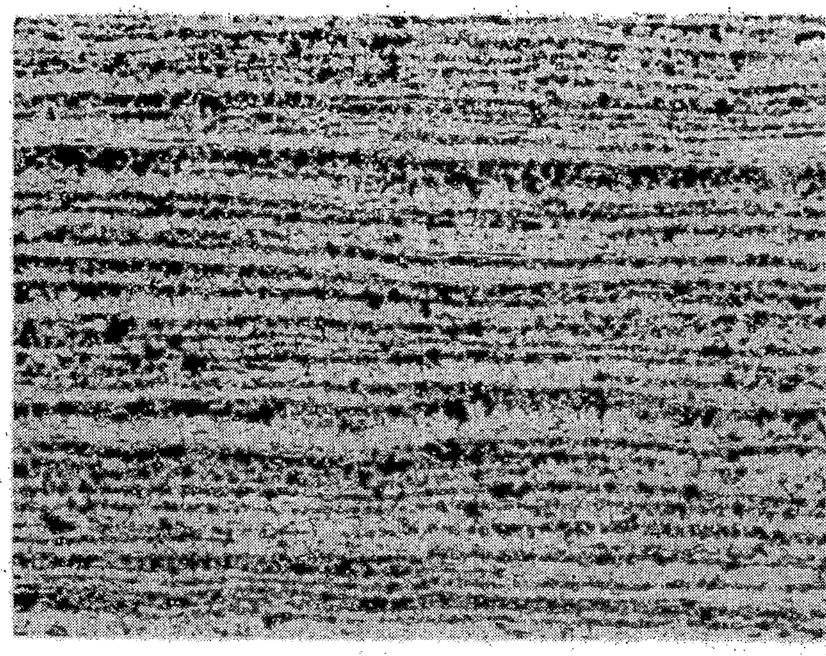


(a)

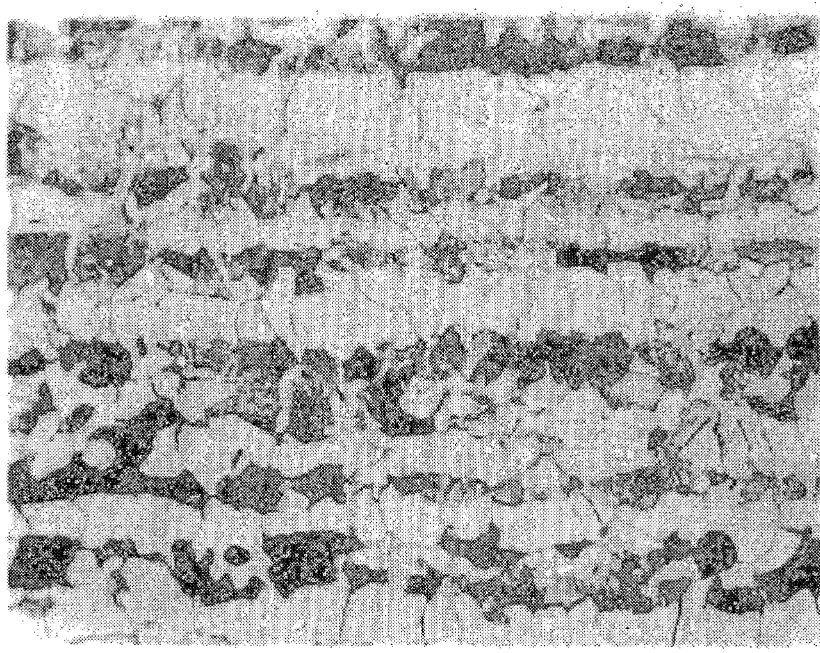


(b)

Figure 9. Photomicrograph of Plate Sample No. 13A, Tank Car ACFX 81395, Shell Course 2, ASTM A516-Grade 65 a) X100 b) X500 Etchant: Nital

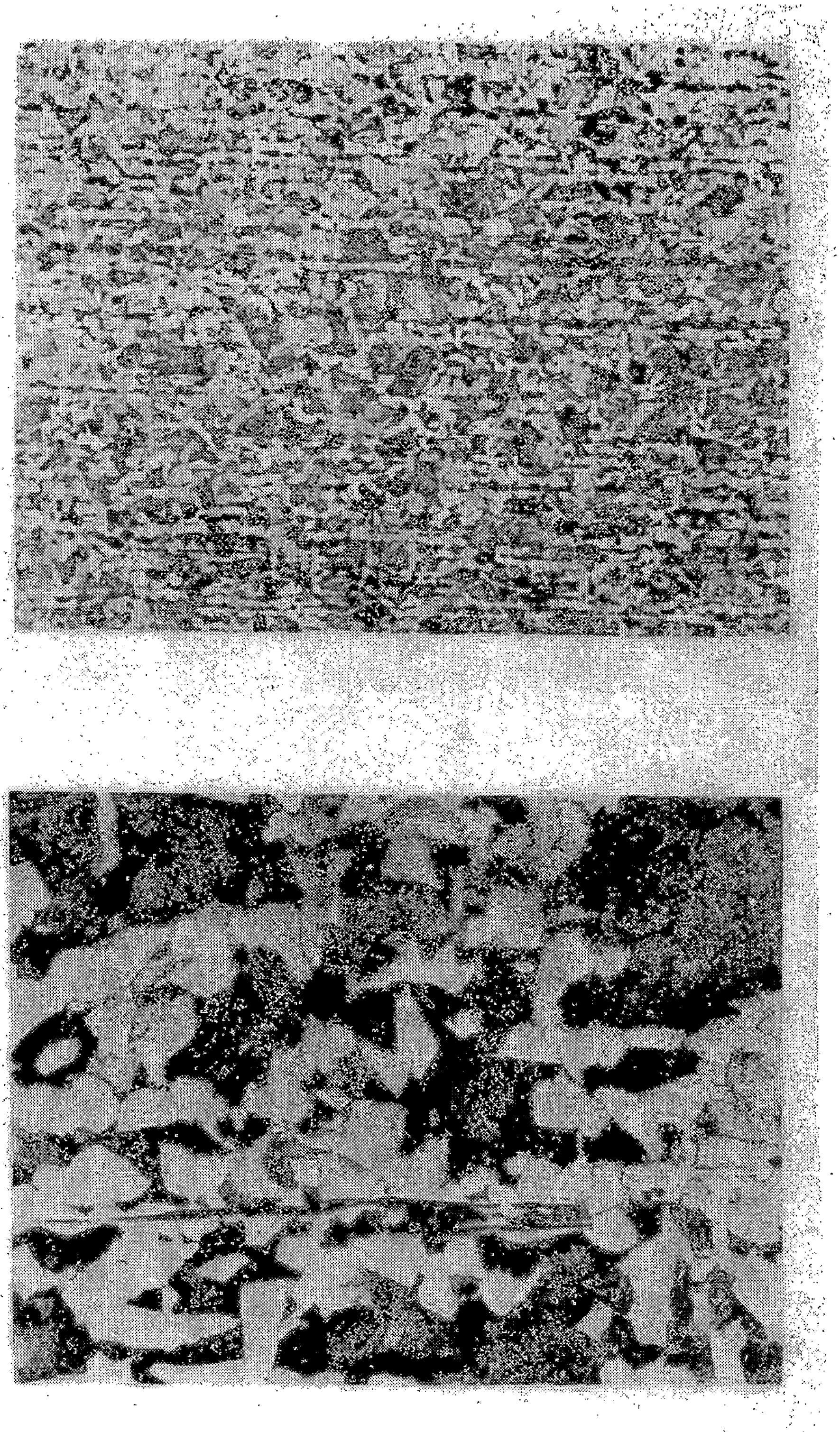


(a)



(b)

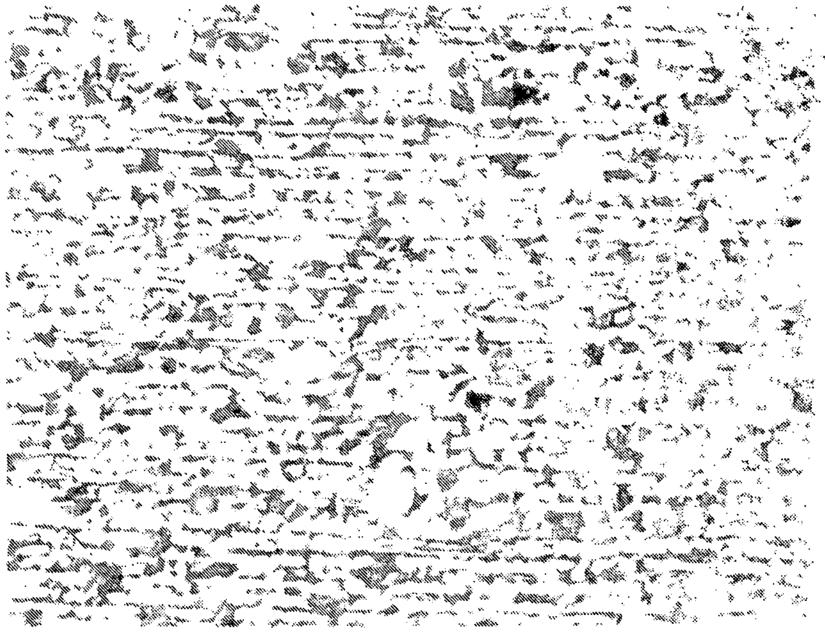
Figure 10. Photomicrograph of Plate Sample No. 13B, Tank Car ACFX 81395, Shell Course 3, ASTM A516-Grade 65. a) X100 b) X500 Etchant: Nital



(a)

(b)

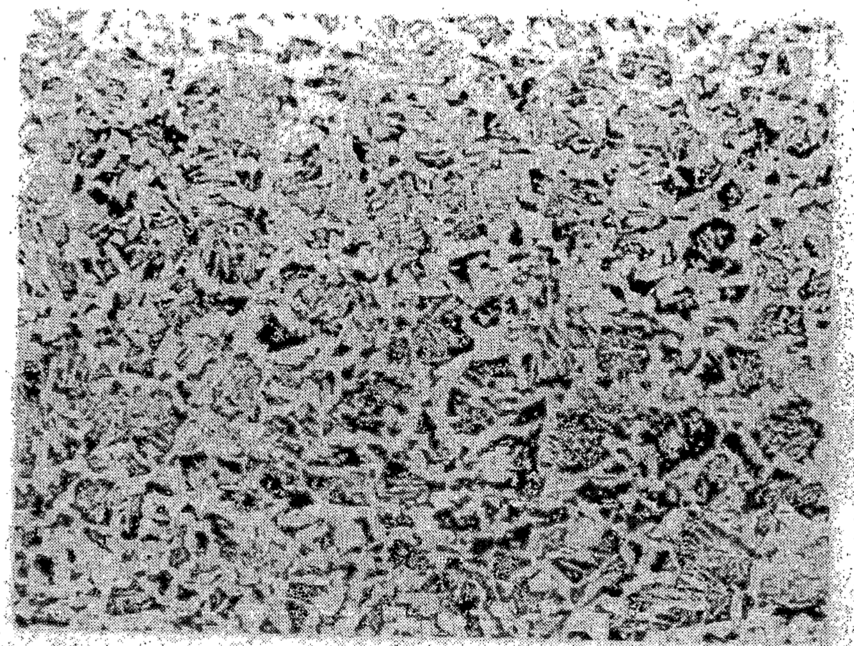
Figure 11. Photomicrographs of Plate Sample No. 2, Tank Car IMCX 2513, Shell Course 2, AAR TC128-Grade A. a) X100 b) X500 Etchant: Nital



(a)

(b)

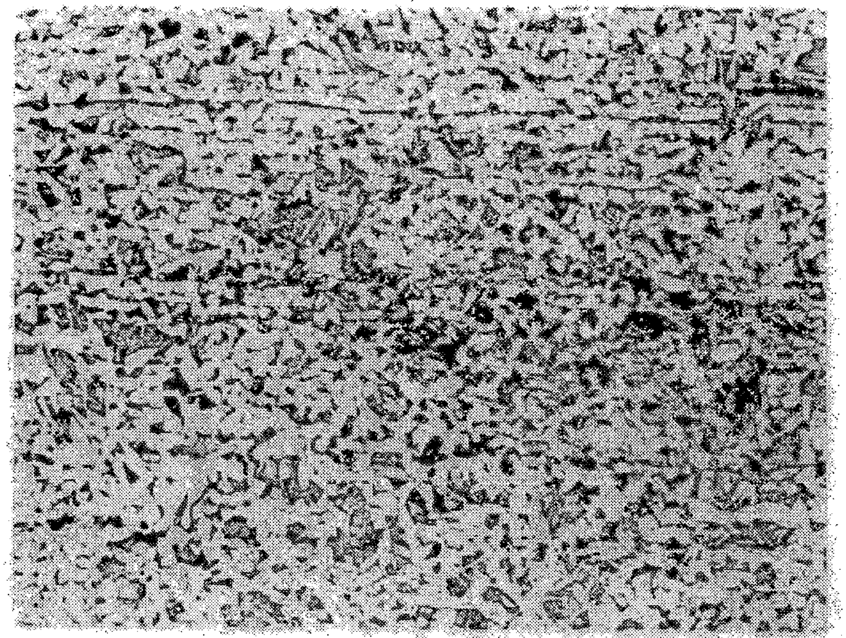
Figure 12. Photomicrographs of Plate Sample No. 3, Tank Car IMCX 2513, Shell Course 5, AAR TC128-Grade A. a) X100 b) X500 Etchant: Nital



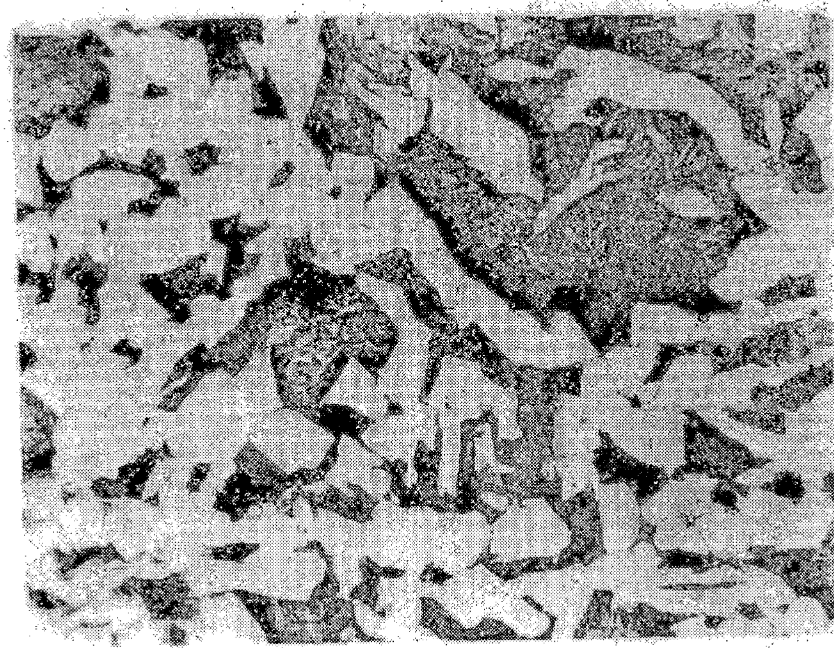
(a)

(b)

Figure 13. Photomicrographs of Plate Sample No. 12, Tank Car IMCX 2827, Shell Course 3, AAR TC128-Grade A. a) X100 b) X500 Etchant: Nital

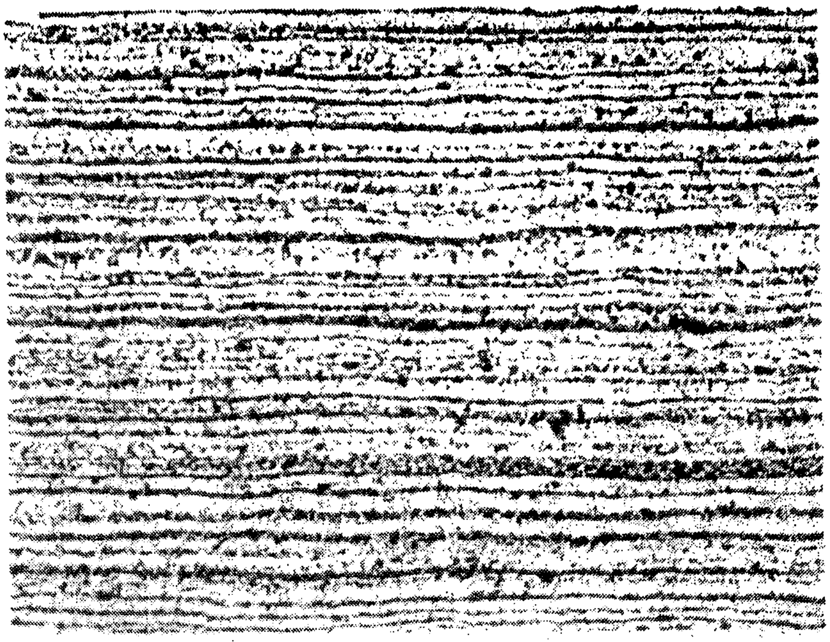


(a)

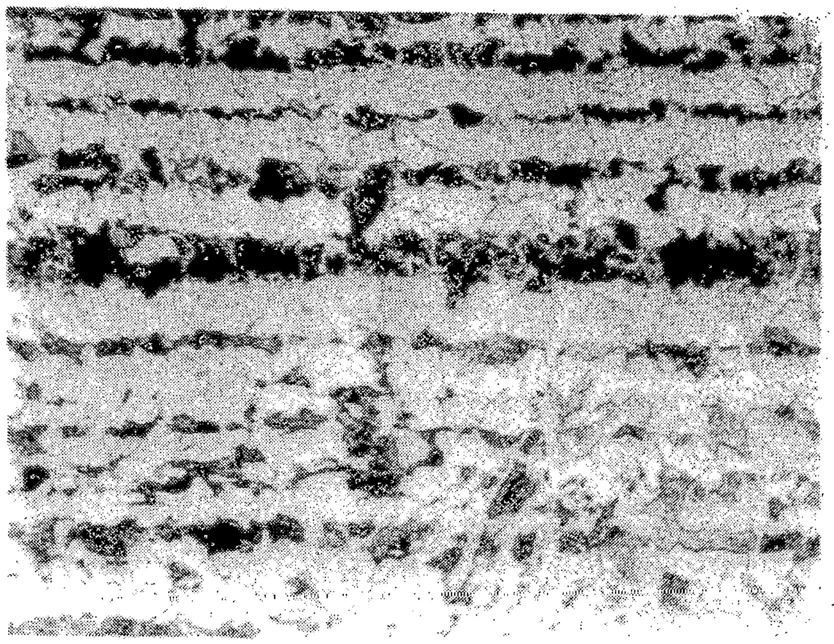


(b)

Figure 14. Photomicrographs of Plate Sample No. 17, Tank Car IMCX 2827, Shell Course 2, AAR TC128-Grade A. a) X100 b) X500 Etchant: Nital

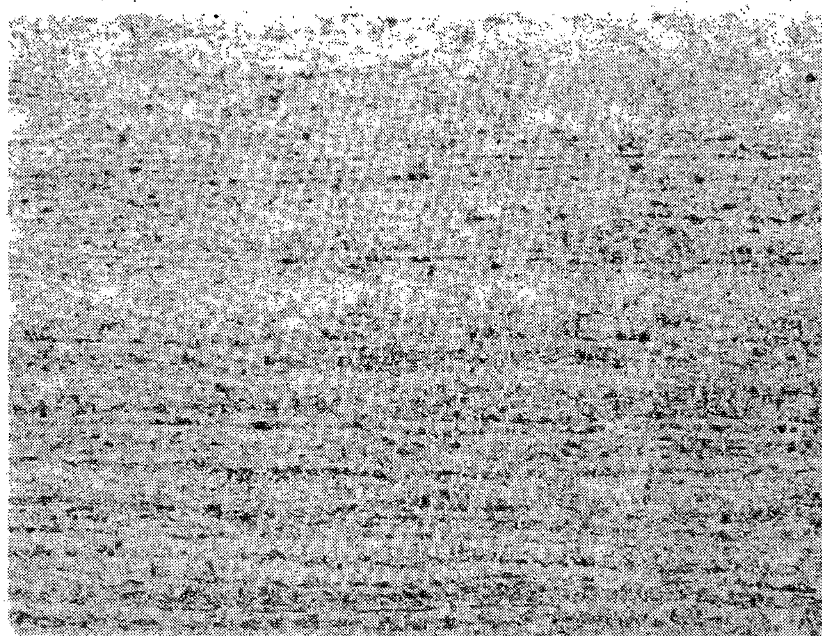


(a)

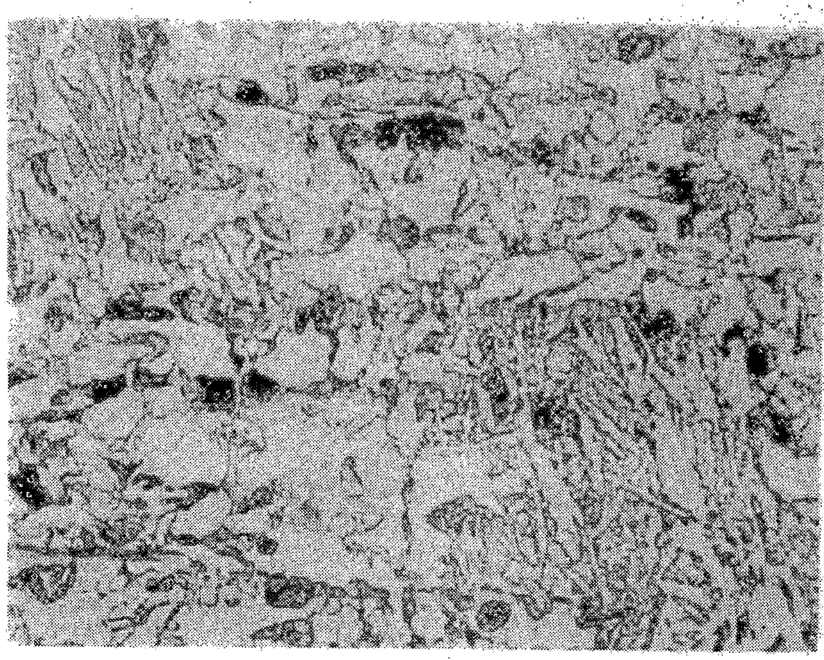


(b)

Figure 15. Photomicrographs of Plate Sample No. 1, Tank Car IMCX 2513, A-Head, AAR TC128-Grade B. a) X100 b) X500 Etchant: Nital

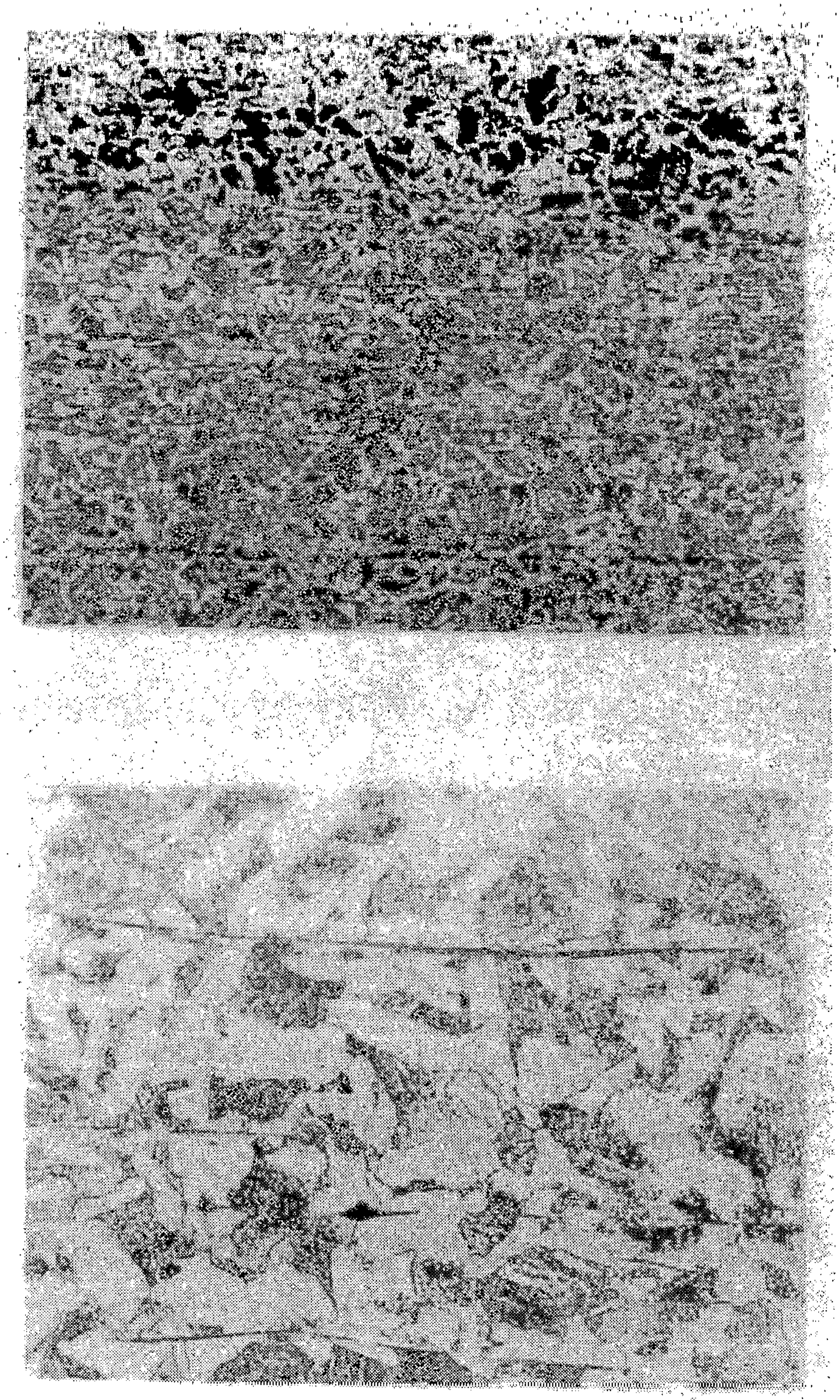


(a)



(b)

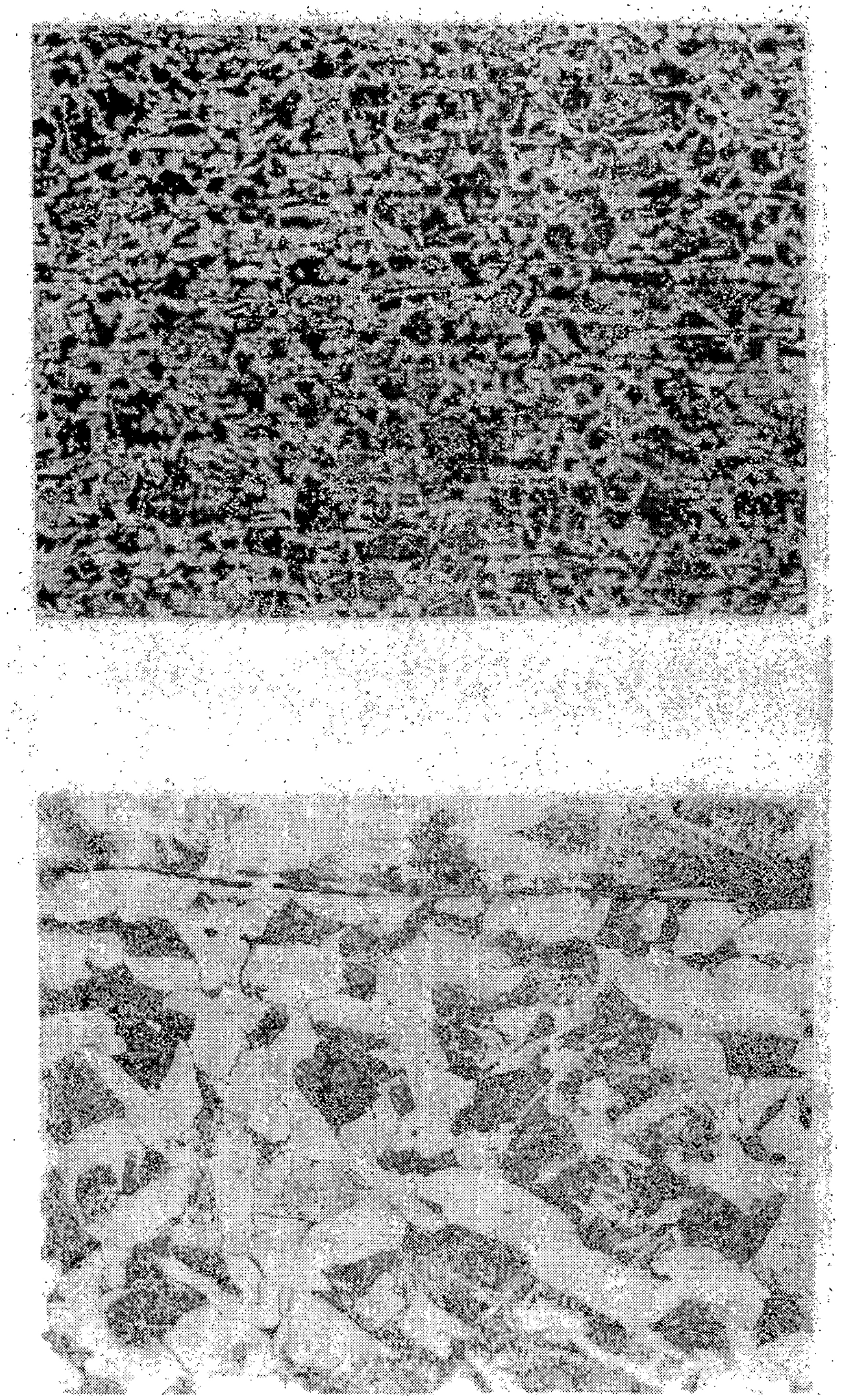
Figure 16. Photomicrographs of Plate Sample No. 9, Tank Car ACFX 89990, B-Head, AAR TC128-Grade B. a) X100 b) X500 Etchant: Nital



(a)

(b)

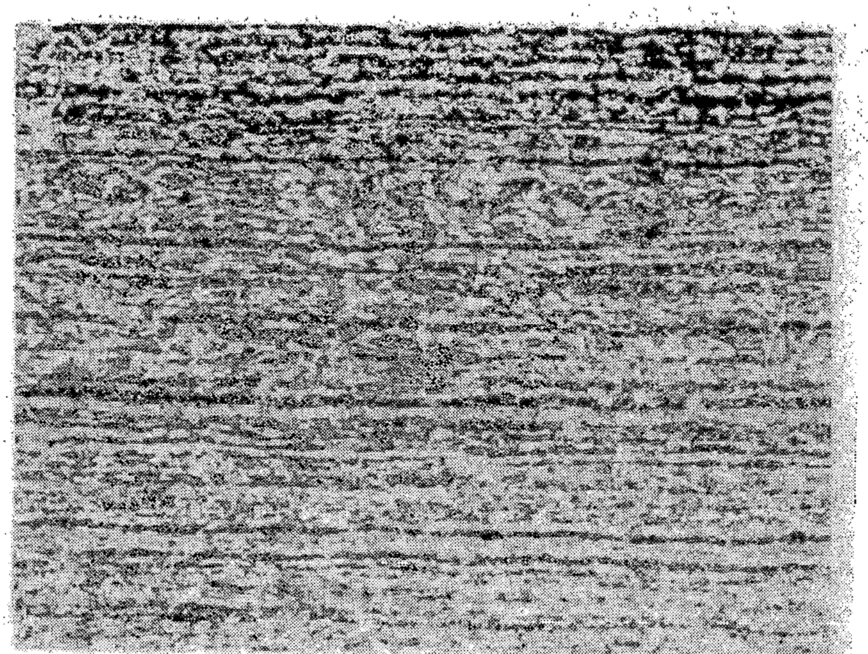
Figure 17. Photomicrographs of Plate Sample No. 10A, Tank Car ACFX 89990, Shell Course 5, AAR TC128-Grade B. a) X100 b) X500 Etchant: Nital



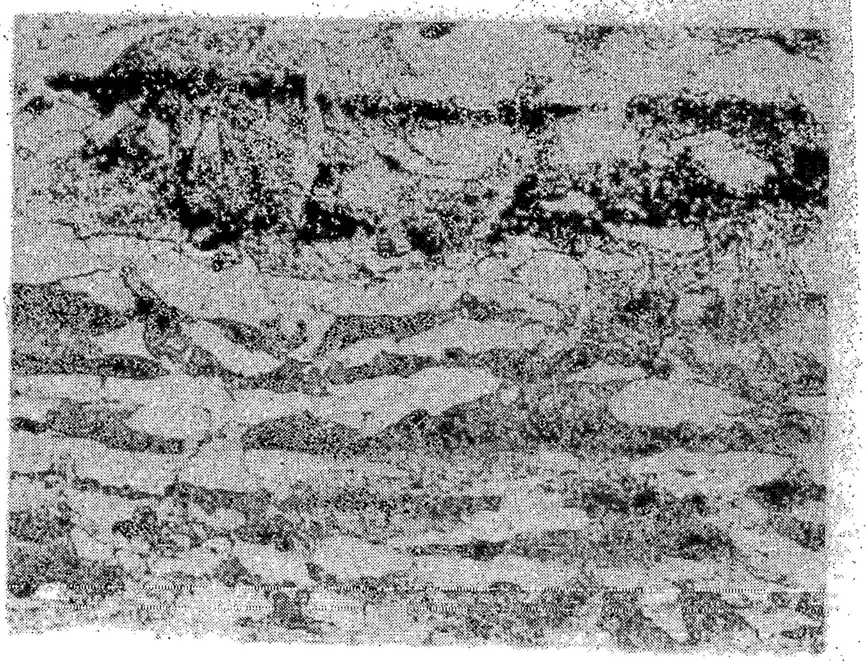
(a)

(b)

Figure 18. Photomicrographs of Plate Sample No. 10B, Tank Car ACFX 89990, Shell Course 4, AAR TC128-Grade B. a) X100 b) X500 Etchant: Nital

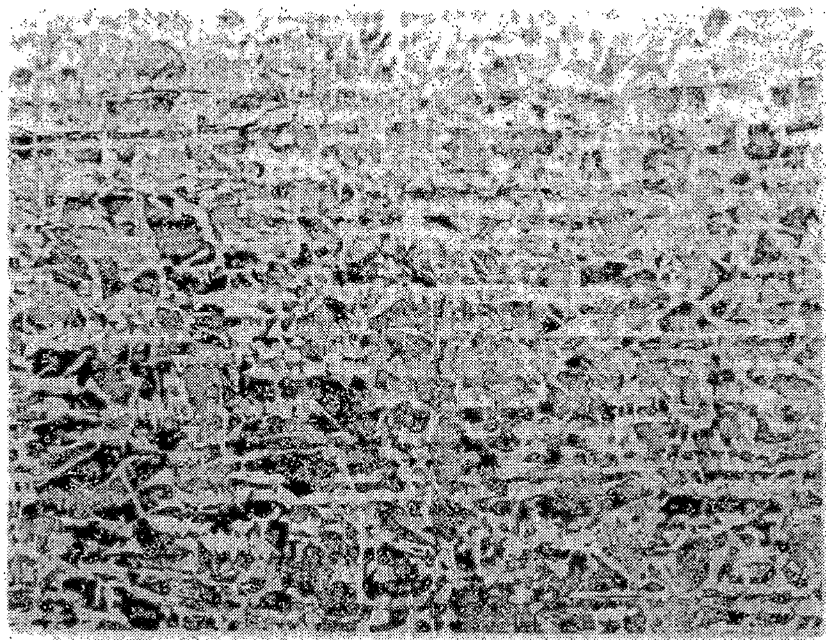


(a)



(b)

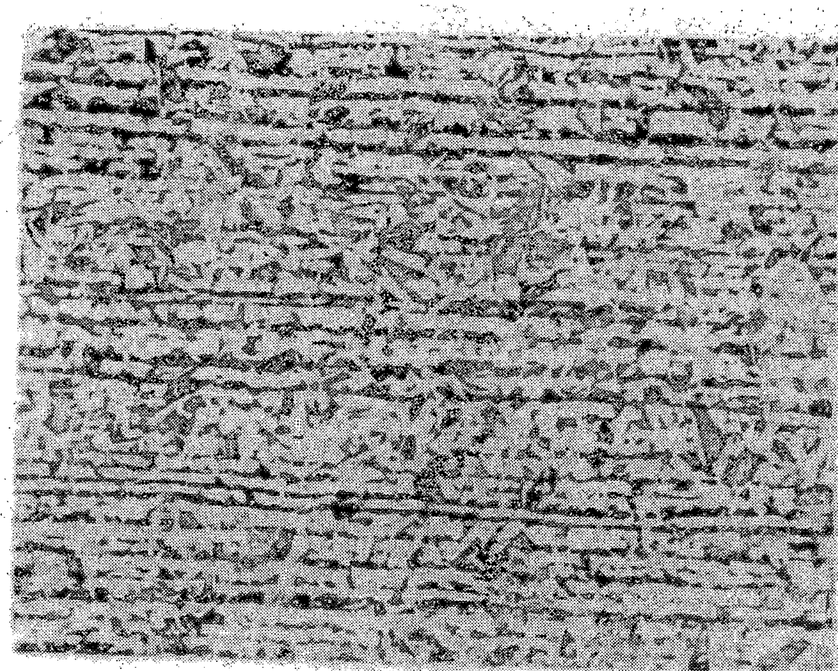
Figure 19. Photomicrographs of Plate Sample No. 16A, Tank Car IMCX 2513, Shell Course 4, AAR TC128-Grade B. a) X100 b) X500 Etchant: Nital



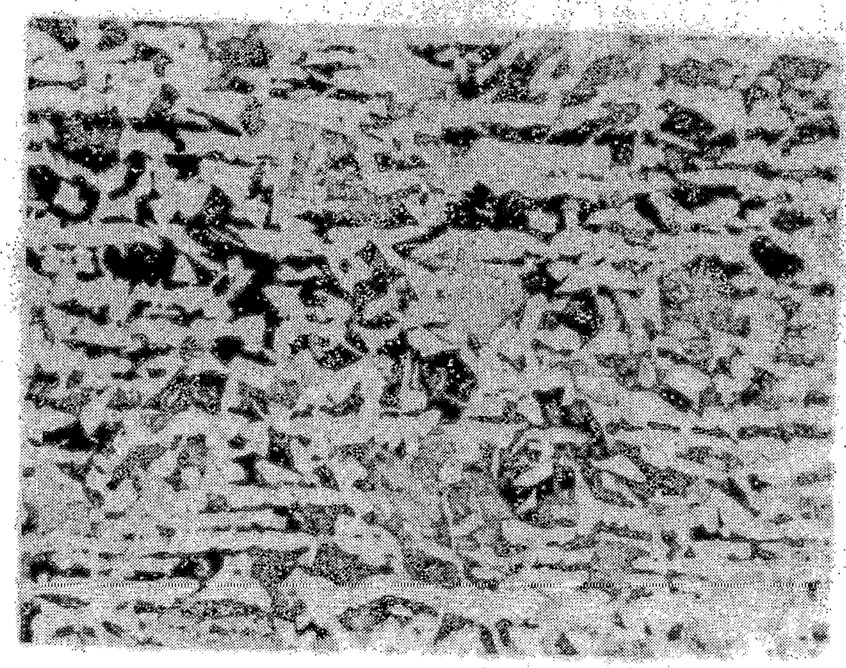
(a)

(b)

Figure 20. Photomicrographs of Plate Sample No. 20A-A, Tank Car UTLX 28727, Shell Course 3, AAR TC128-Grade B. a) X100 b) X500 Etchant: Nital



(a)



(b)

Figure 21. Photomicrographs of Plate Sample No. 20A-B, Tank Car UTLX 28727, Shell Course 2, AAR TC128-Grade B. a) X100 b) X500 Etchant: Nital

Figure 22A. Charpy V-Notch Test Results for CVN ID 2, Plate Sample 2, AAR TC128-Grade A, Shell Course 2.

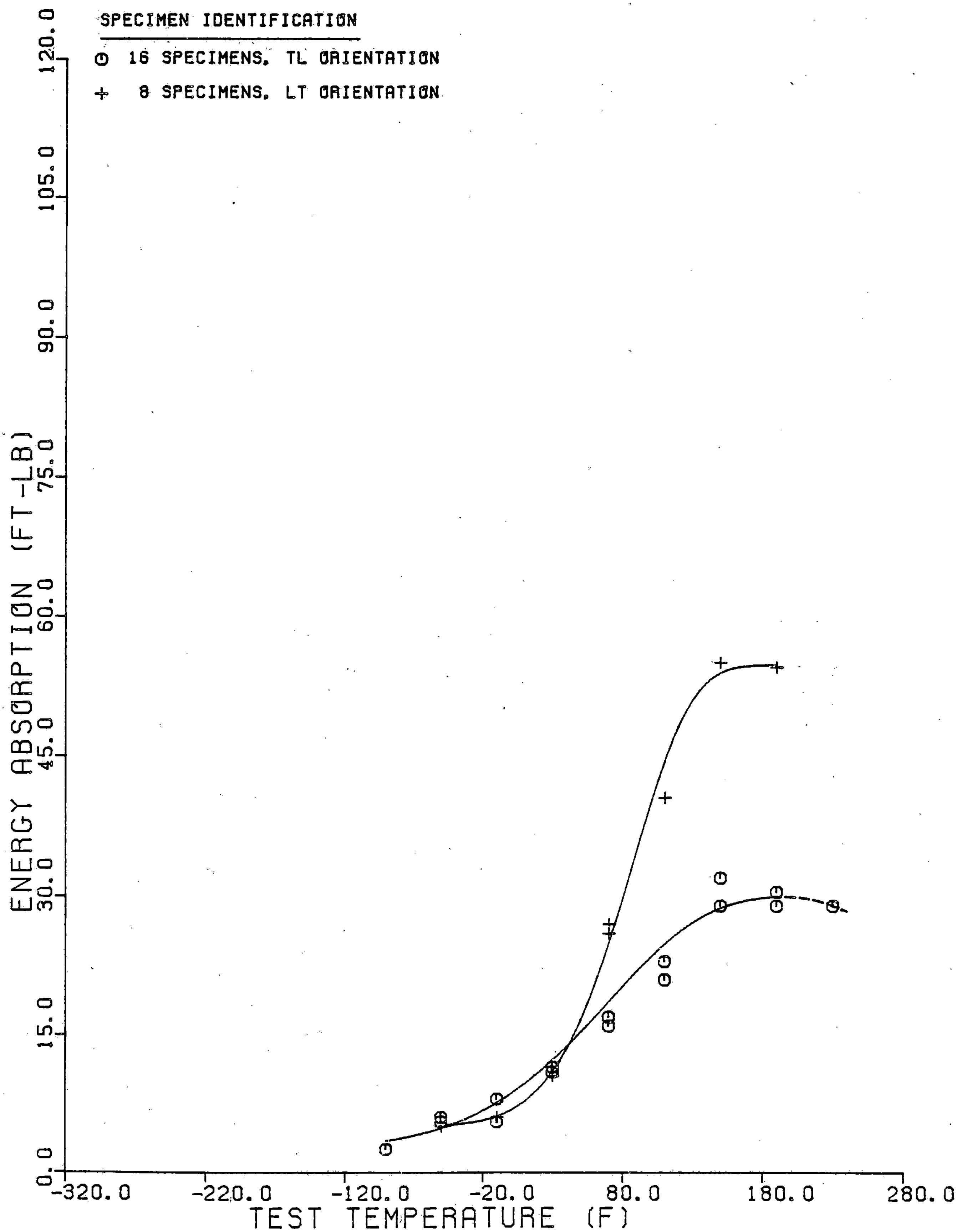


Figure 22B. Charpy V-Notch Test Results for CVN ID 2, Plate Sample 2, AAR TC128-Grade A, Shell Course 2.

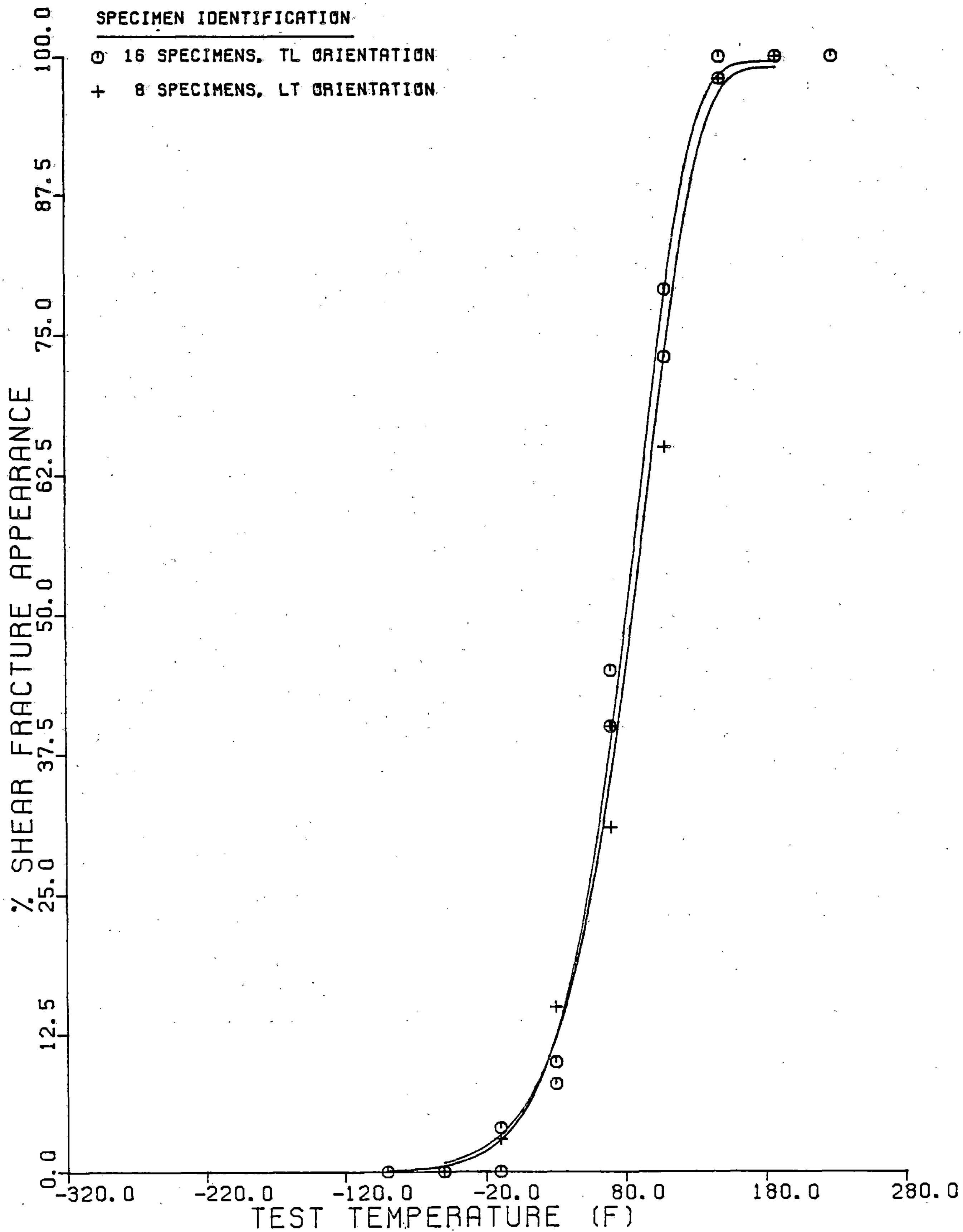


Figure 23A. Charpy V-Notch Test Results for CVN ID 3, Plate Sample 3, AAR TC128-Grade A, Shell Course 5.

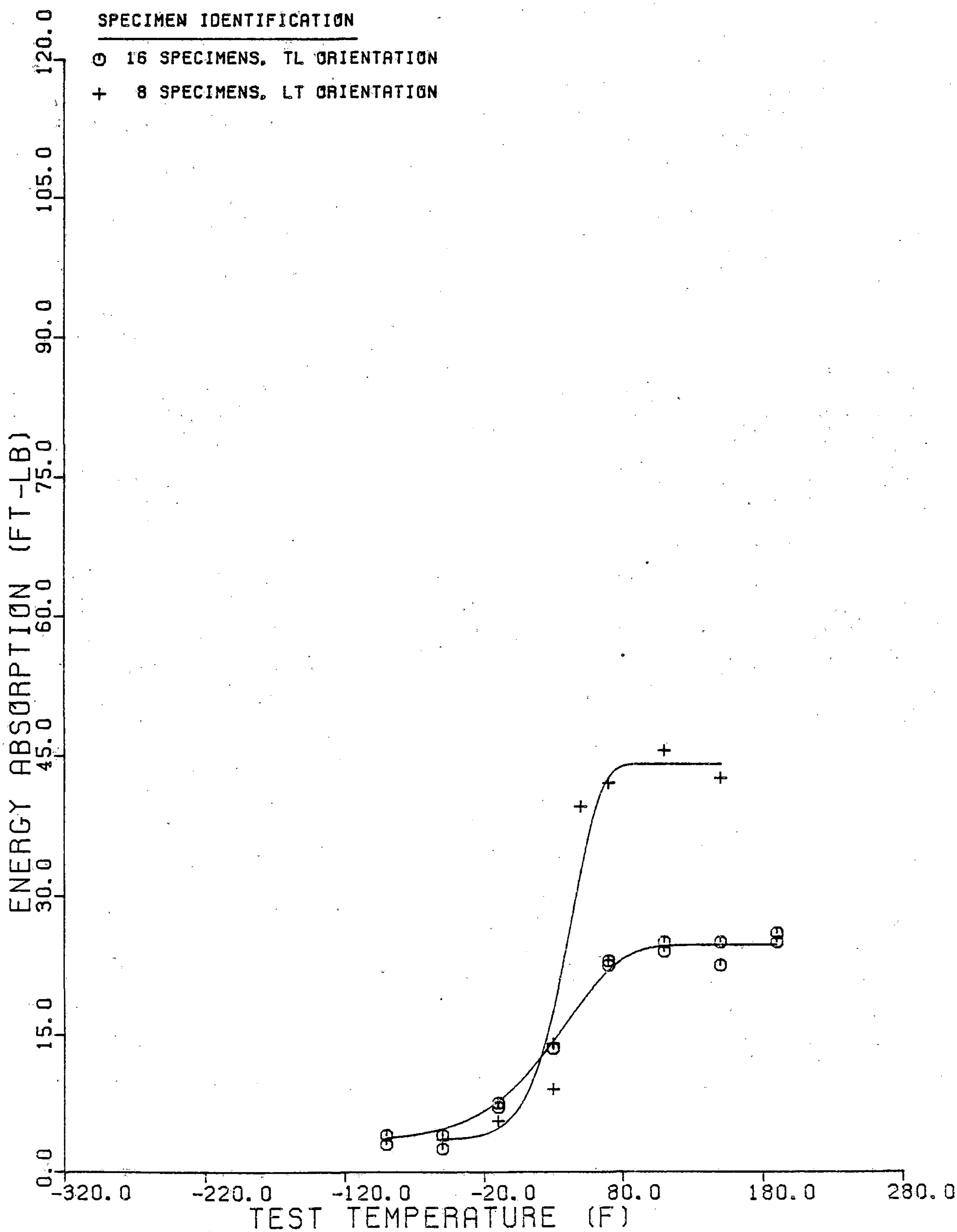


Figure 23B. Charpy V-Notch Test Results for CVN ID 3, Plate Sample 3, AAR TC128-Grade A, Shell Course 5.

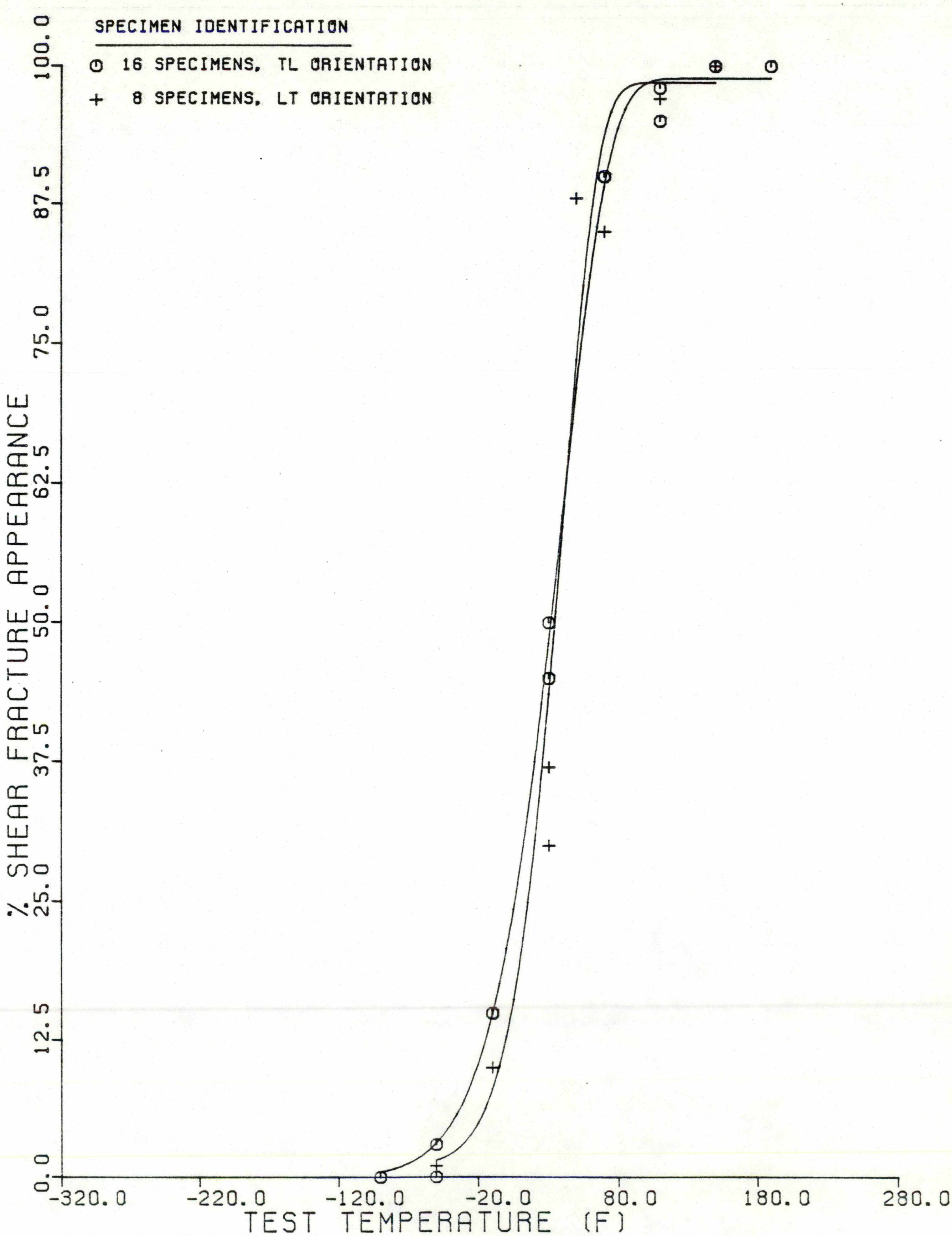


Figure 24A. Charpy V-Notch Test Results for CVN ID 4, Plate Sample 12, AAR TC128-Grade A, Shell Course 3.

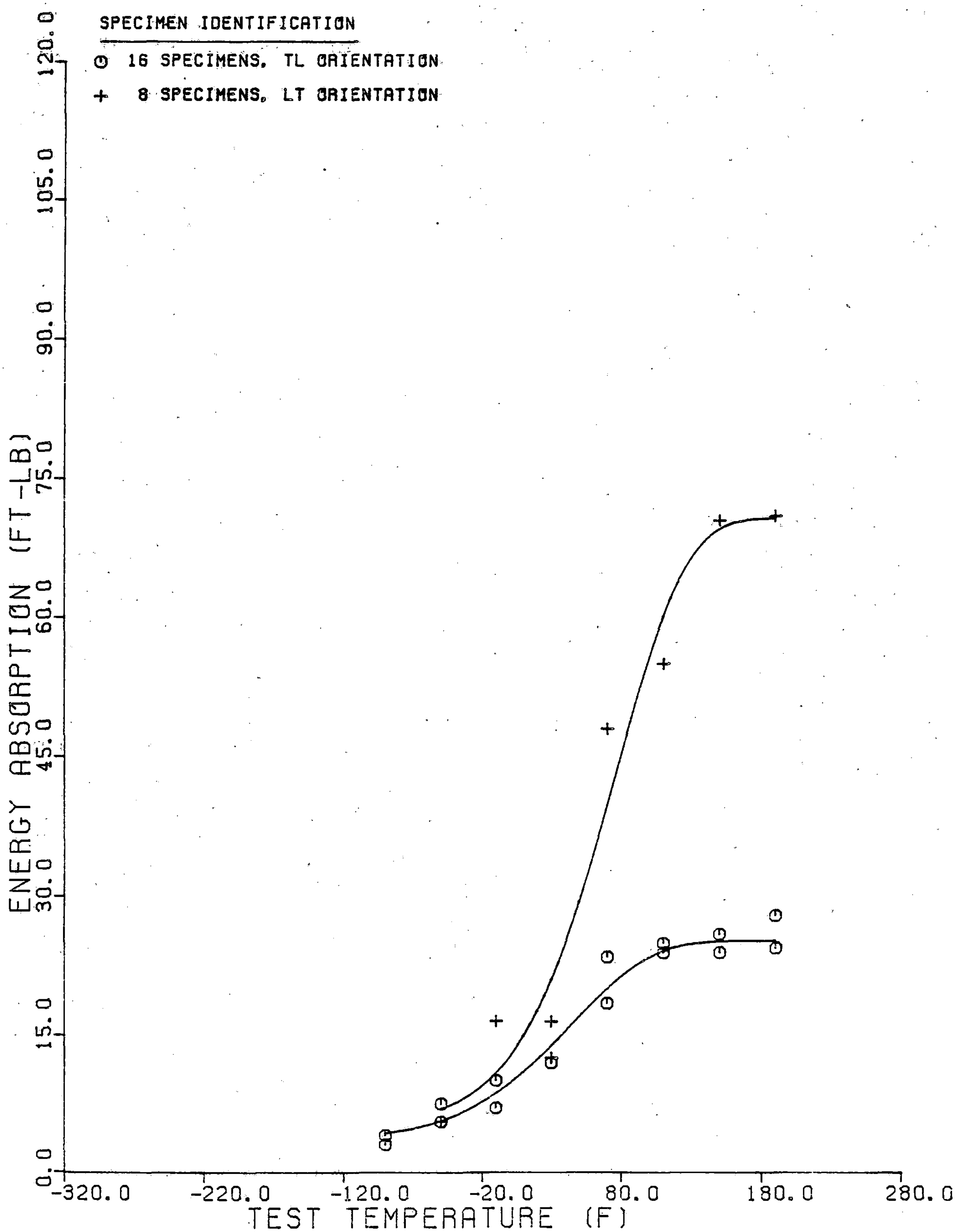


Figure 24B. Charpy V-Notch Test Results for CVN ID 4, Plate Sample 12, AAR TC128-Grade A, Shell Course 3.

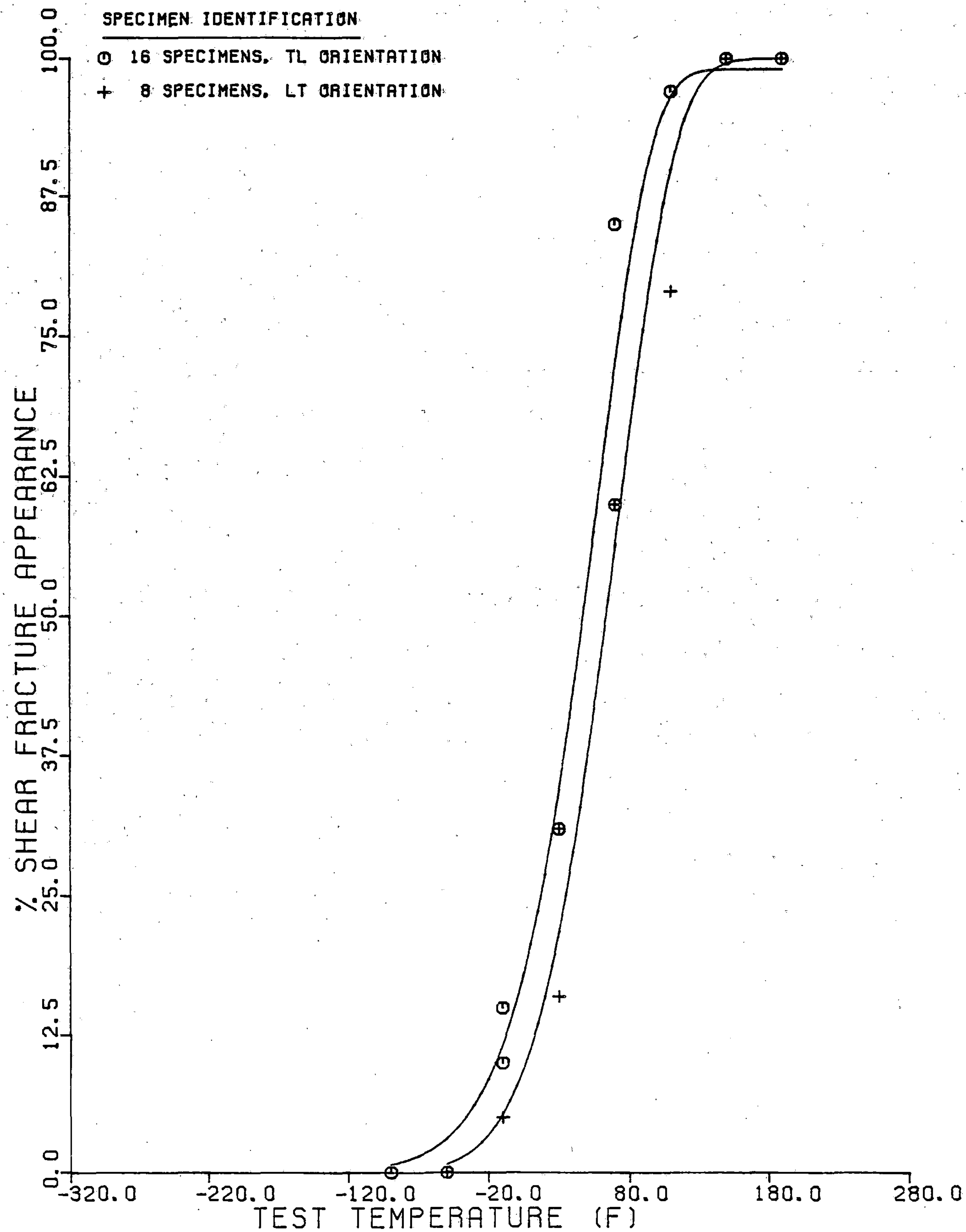


Figure 25A. Charpy V-Notch Test Results for CVN ID 5, Plate Sample 16A, AAR TC128-Grade B, Shell Course 4.

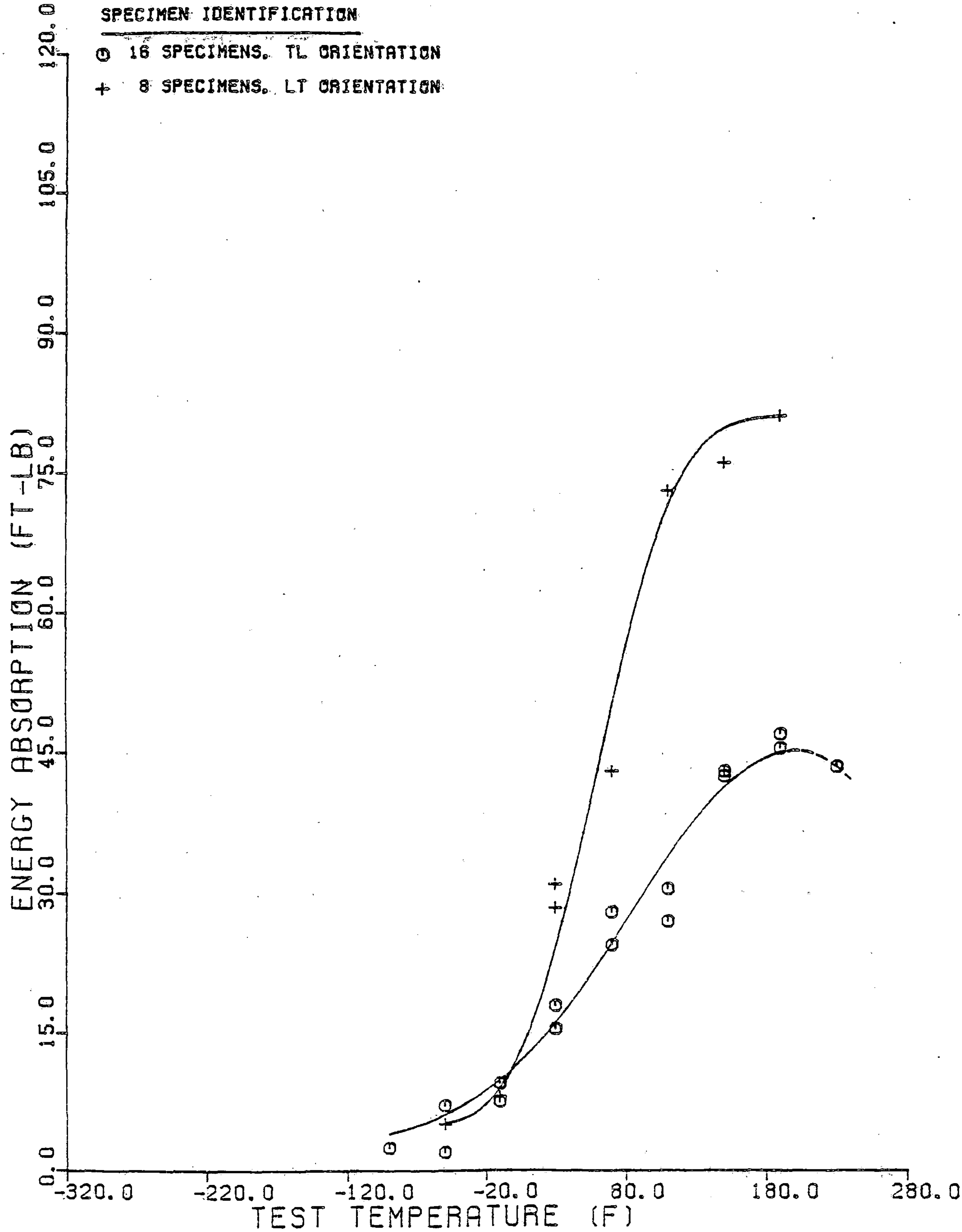


Figure 25B. Charpy V-Notch Test Resutls for CVN ID 5, Plate Sample 16A, AAR TC128-Grade B, Shell Course 4.

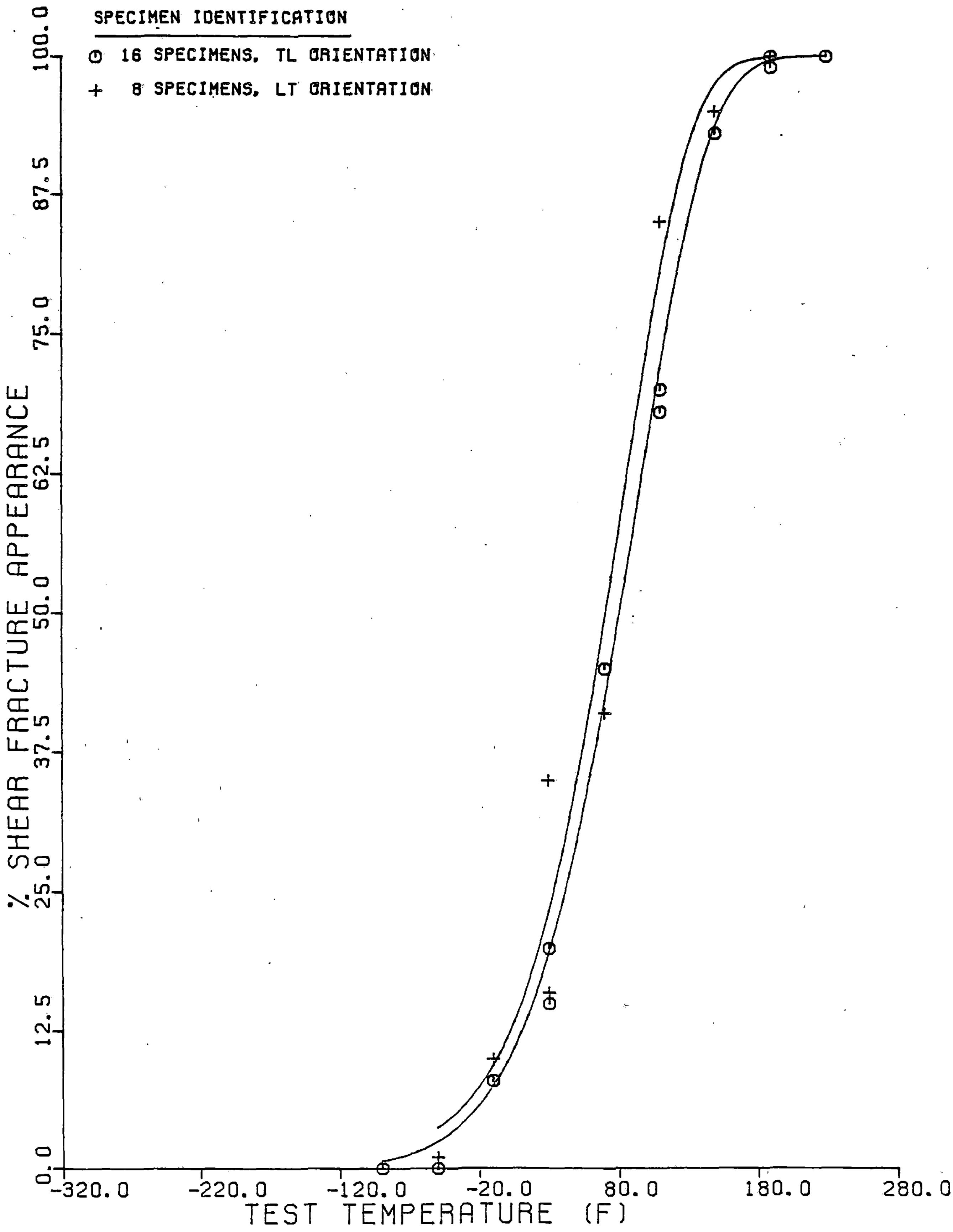


Figure 26A. Charpy V-Notch Test Results for CVN ID 6, Plate Sample 17, AAR TC128-Grade A, Shell Course 2.

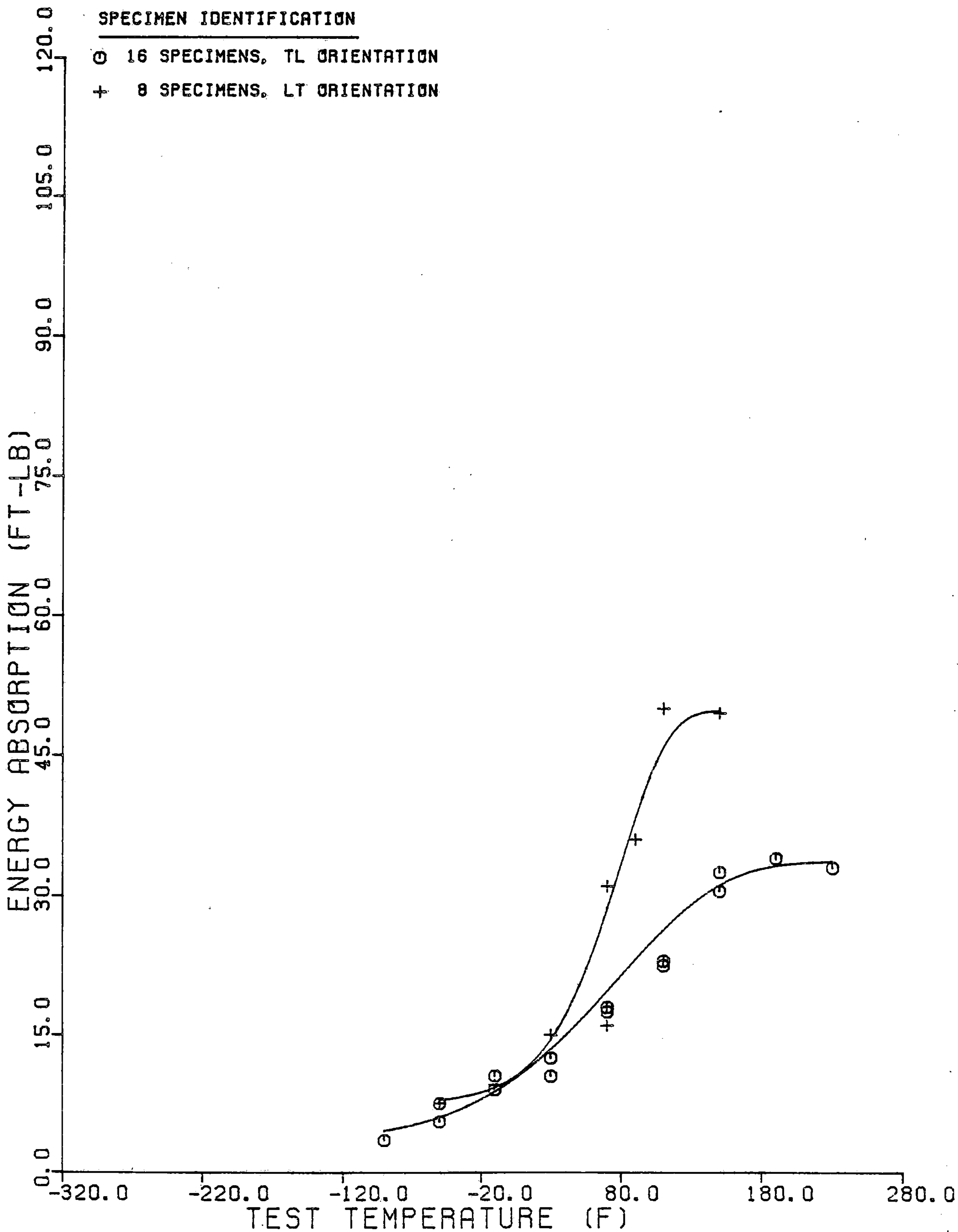


Figure 26B. Charpy V-Notch Test Results for CVN ID 6, Plate Sample 17, AAR TC128-Grade A, Shell Course 2.

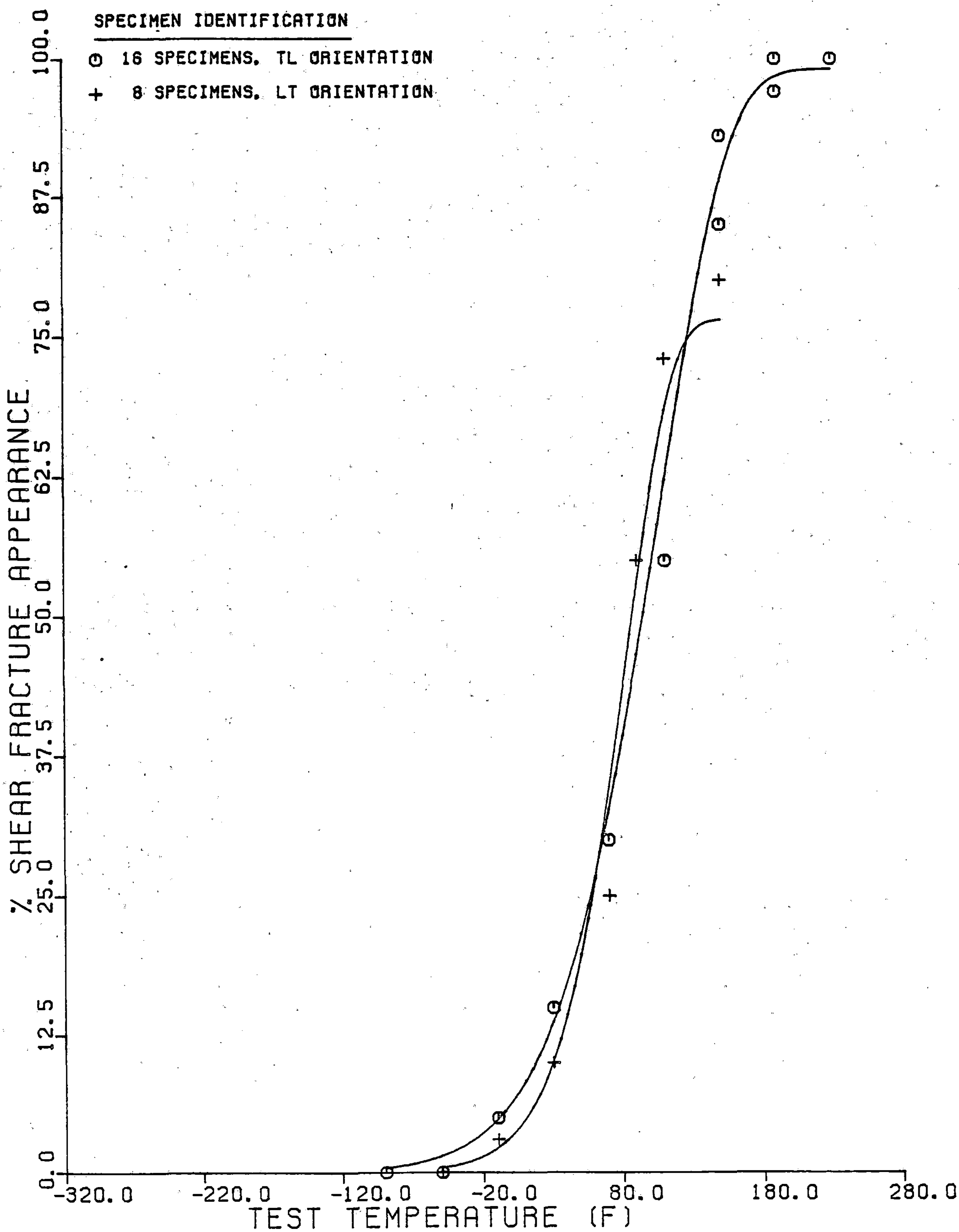


Figure 27A. Charpy V-Notch Test Results for CVN ID 7, Plate Sample 20A-A, AAR TC128-Grade B, Shell Course 3.

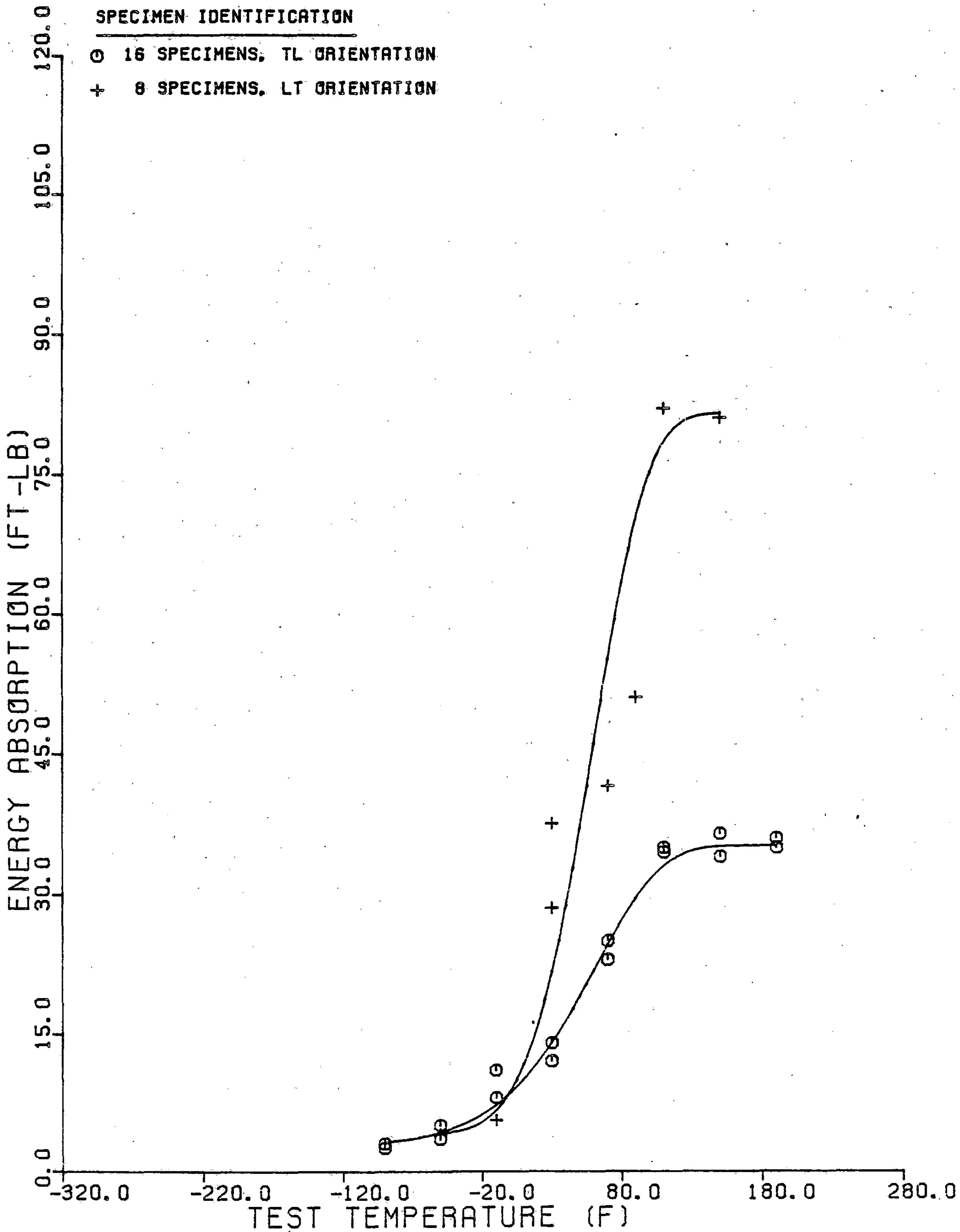


Figure 27B. Charpy V-Notch Test Results for CVN ID 7, Plate Sample 20A-A, AAR TC128-Grade B, Shell Course 3.

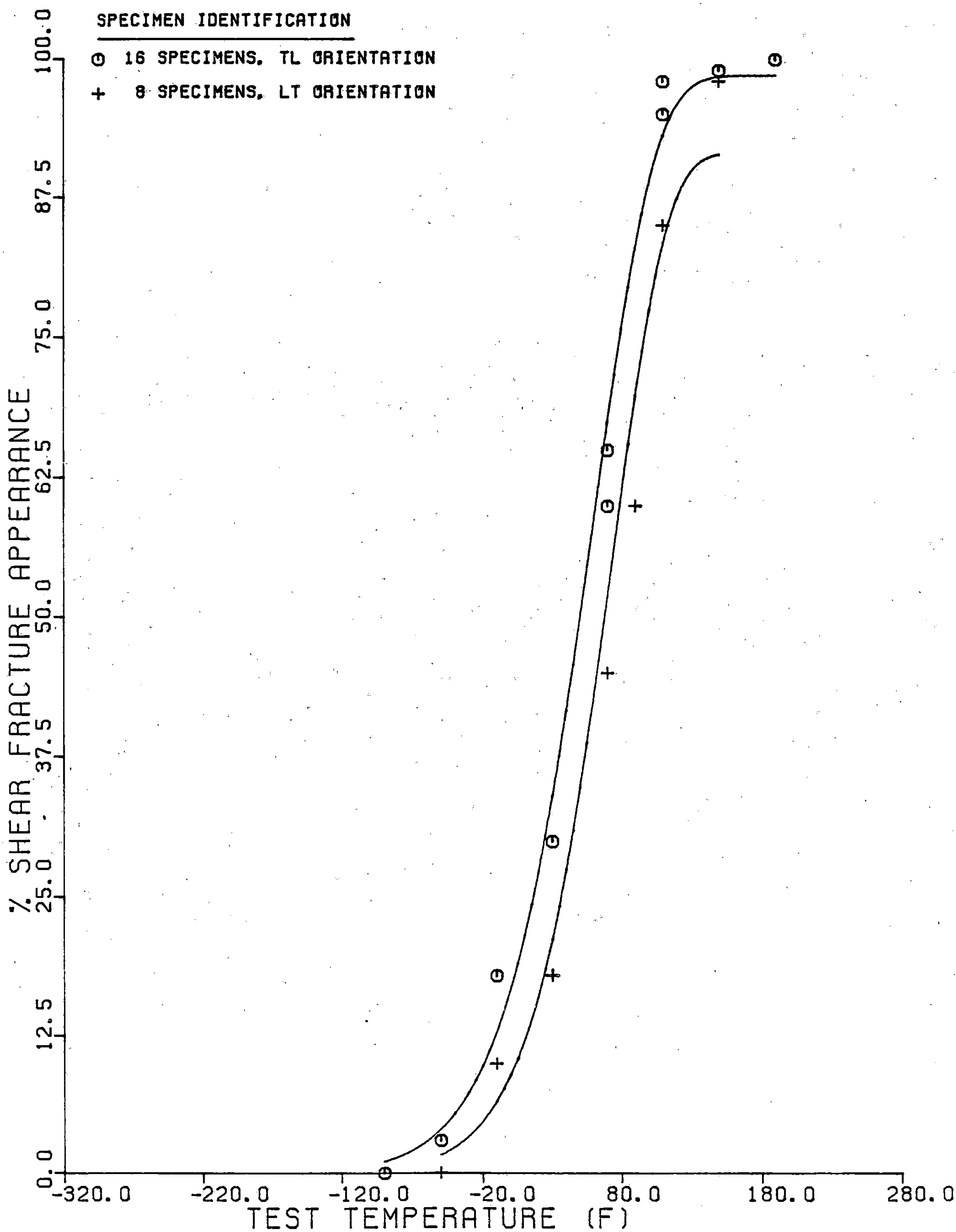


Figure 28A. Charpy V-Notch Test Results for CVN ID 8, Plate Sample 20A-B, AAR TC128-Grade B, Shell Course 2.

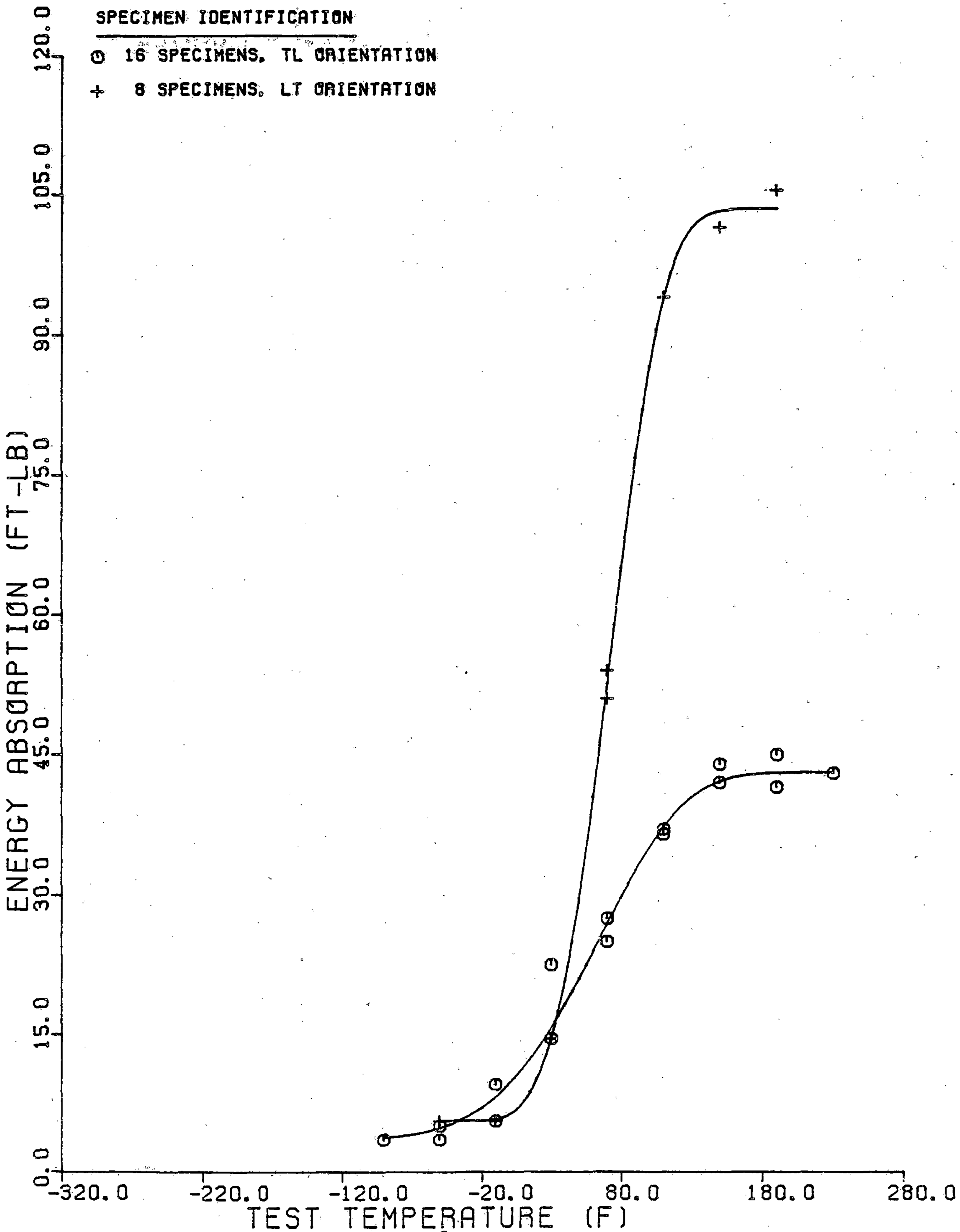


Figure 28B. Charpy V-Notch Test Results for CVN ID 8, Plate Sample 20A-B, AAR TC128-Grade B, Shell Course 2.

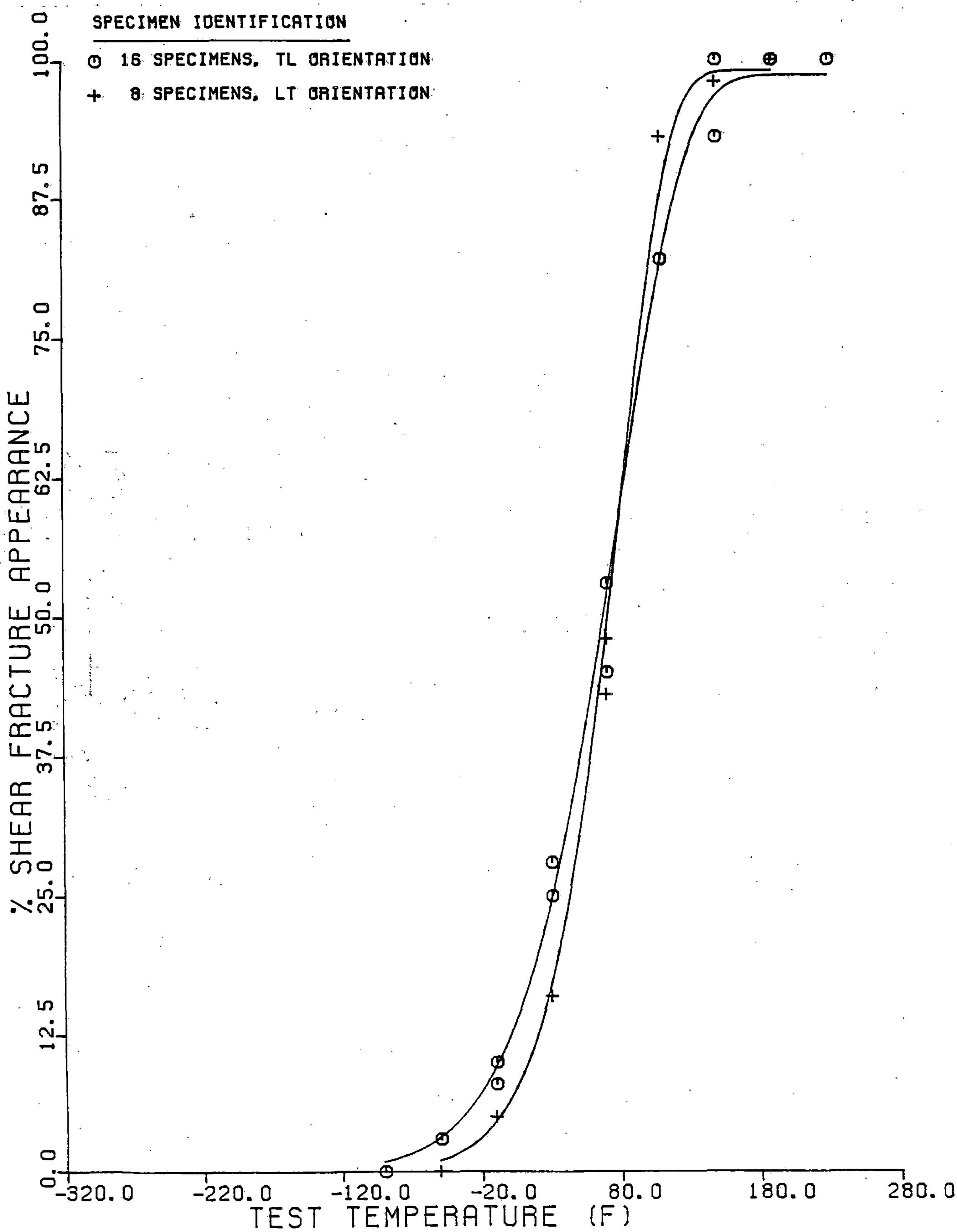


Figure 29A. Charpy V-Notch Results of Transverse Specimens Taken from Seven Shell-Plate Samples of AAR TC128 Steels.

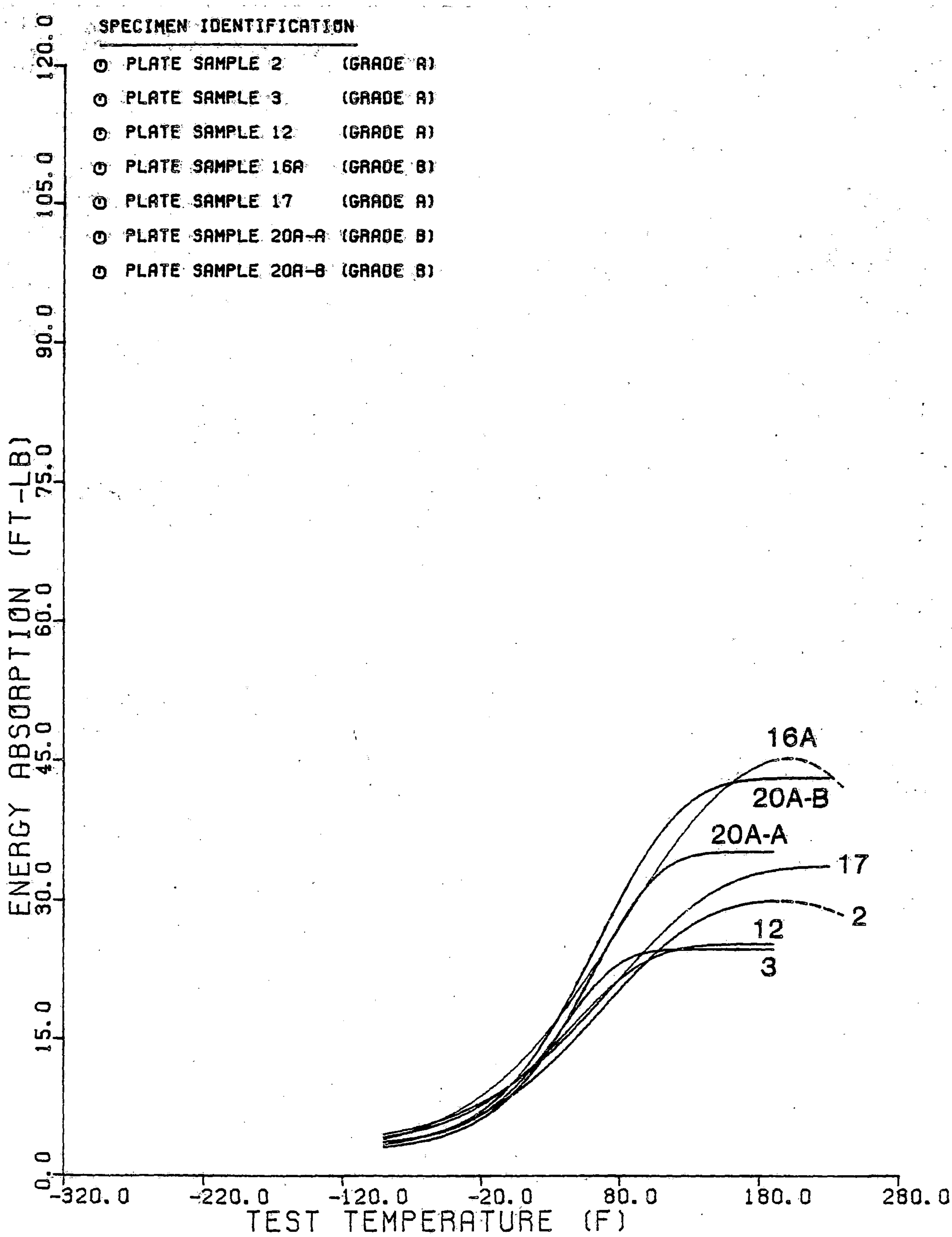
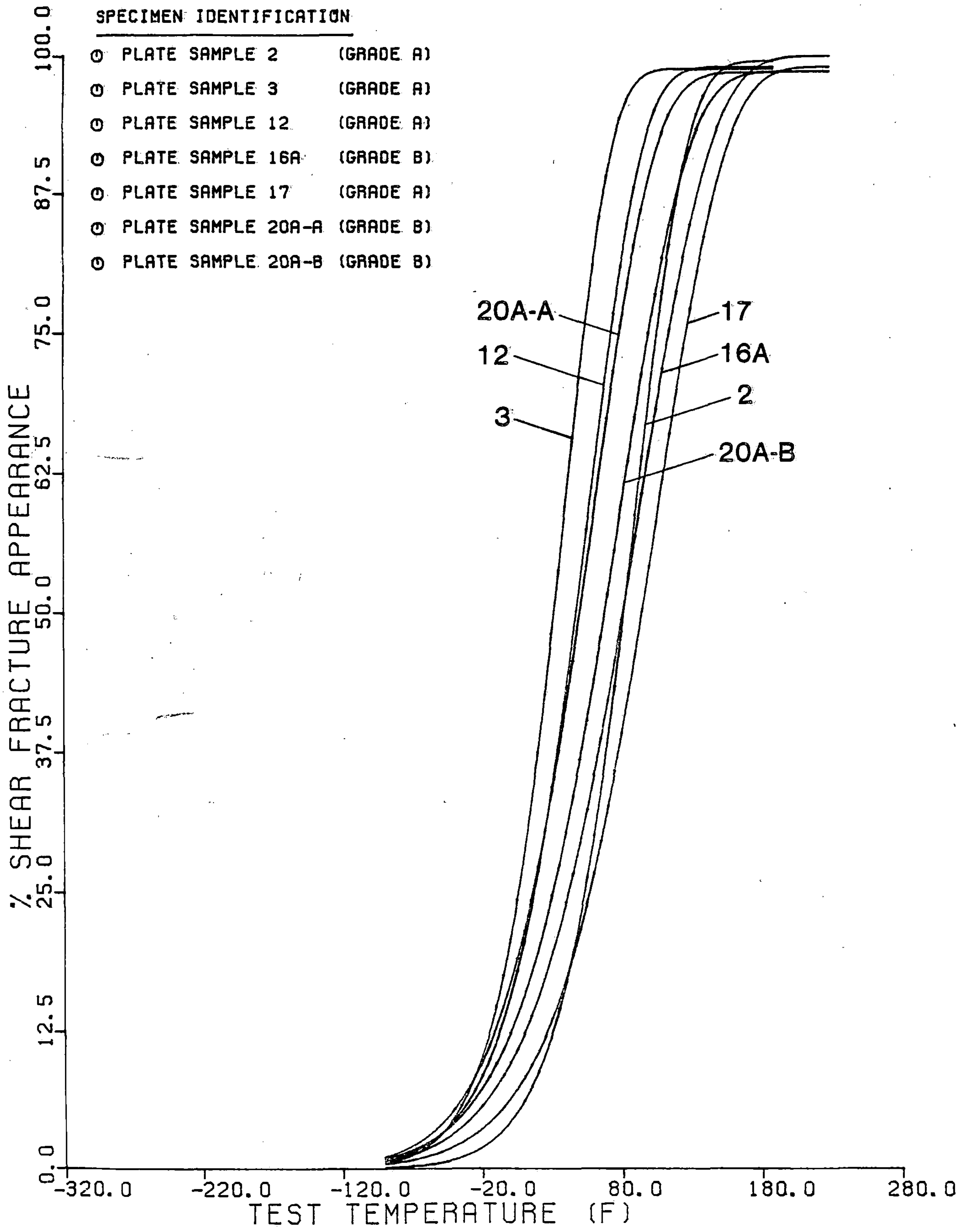


Figure 29B. Charpy V-Notch Results of Transverse Specimens Taken from Seven Shell-Plate Samples of AAR TC128 Steels.



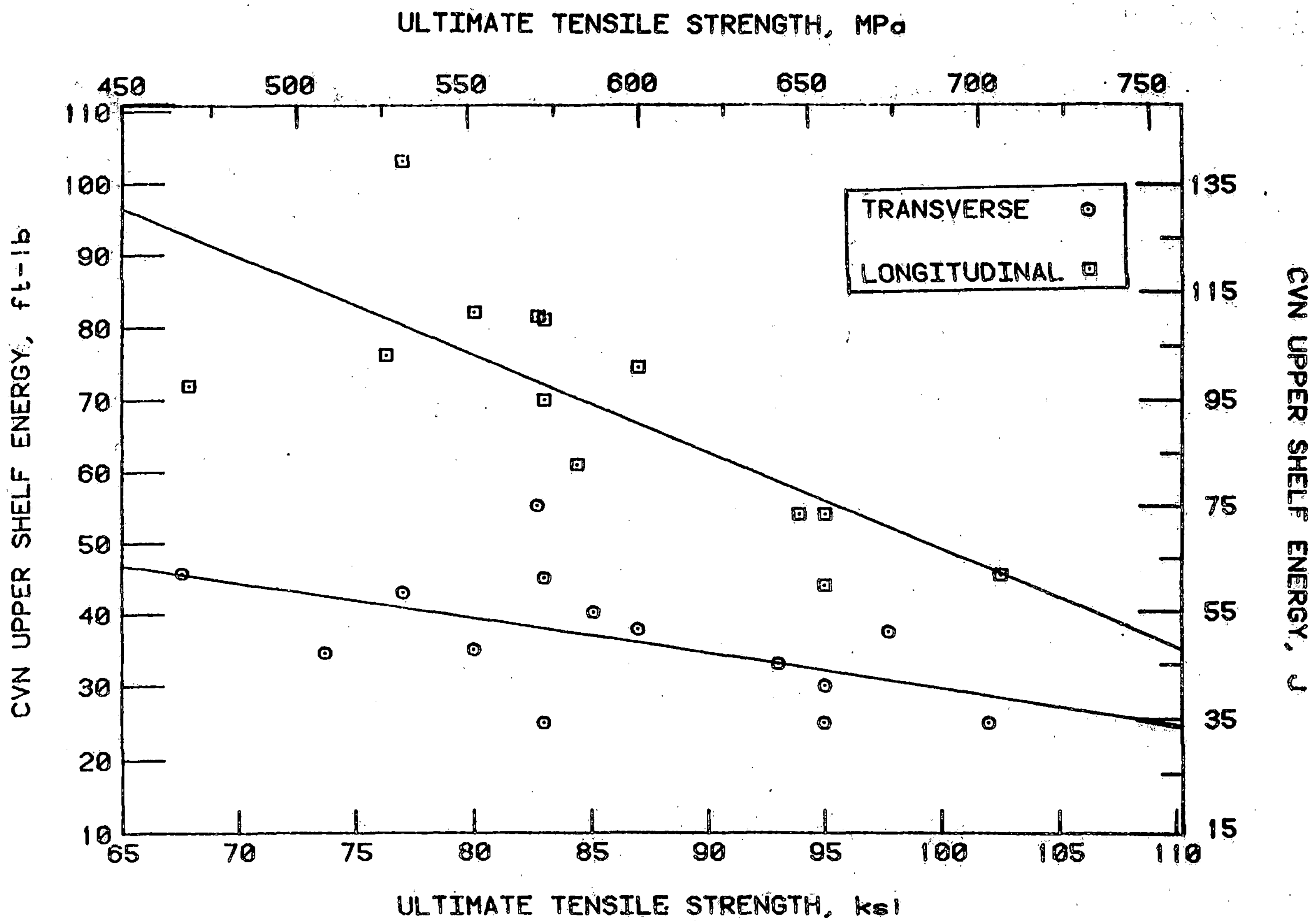


Figure 30. Charpy V-Notch Upper-Shelf Energy-Absorption for Longitudinal (LT) and Transverse (TL) Specimens Plotted as Functions of Ultimate Tensile Strength for Steel Plate Samples Taken from Railroad Tank Cars.

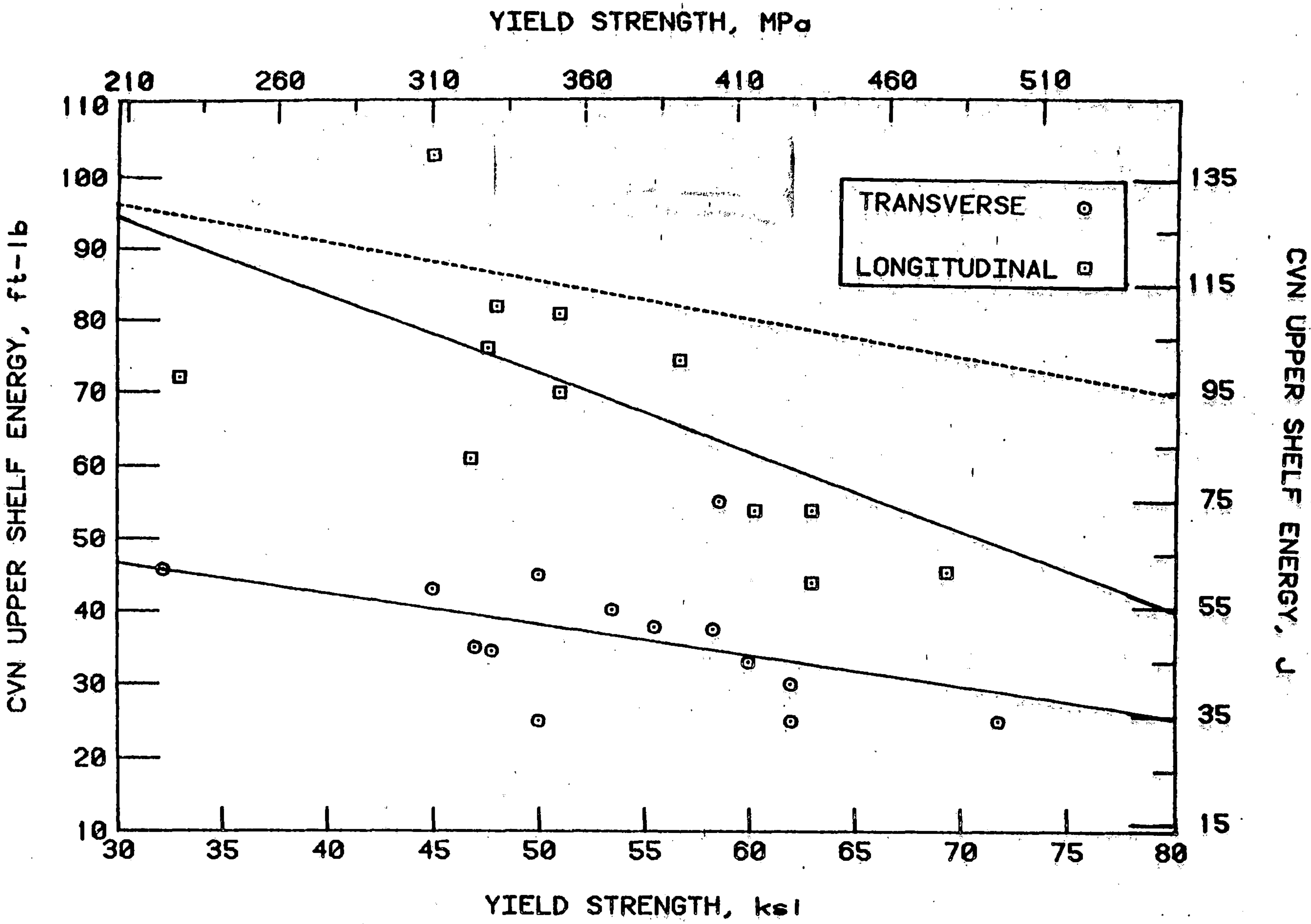


Figure 31. Charpy V-Notch Upper-Shelf Energy-Absorption for Longitudinal (LT) and Transverse (TL) Specimens Plotted as Functions of Yield Strength for Samples Taken from Railroad Tank Cars are Compared with a Reference Curve Taken from the Literature [10]. The dotted line represents the literature [10] trend line, which is based upon results for longitudinal (LT) specimens.

Appendix A

Available Plate Material from NBS Tank-Car Samples

Plate Sample ID	Approximate area (ft^2)	Comments
1	9	
2	14	
3	9	
4	9"	
7	6	
8	9	
9	4	
10A	2	plus adjoining double plate
10B	5	
12	9	plus small amount of course No. 6
13A	3 to 5	
13B	6 to 8	
13/A	5	plus small piece of adjoining shell plate
16A	10	
17	7	plus small piece of adjoining plate
18A	8	
18B	6	
19A	1-1/2	
19B	3	
20A-A	9	plus 8 ft^2 of same course on 20B
20A-B	5	plus 6 ft^2 of same course on 20B

Appendix B

Observed and Calculated Values of Energy Absorption and Shear Fracture Appearance in CVN Tests: Results for CVN ID 2, Plate Sample 2.

CHARPY V-NOTCH TEST RESULTS FOR PLATE SAMPLE 2, A SHELL PLATE OF AAR TC128-GRADE A STEEL TAKEN FROM TANK-CAR IMCX 2513
CALCULATIONS FOR ENERGY ABSORPTION DATA OF
16 SPECIMENS, TL ORIENTATION

SPECIMEN	TEMPERATURE(F)	OBSERVED ENERGY ABSORPTION(FT-LB)	CALCULATED ENERGY ABSORPTION(FT-LB)
2T8	-90.0	2.50	3.4
2T3	-50.0	5.50	4.8
2T2	-50.0	6.00	4.8
2T14	-10.0	5.50	7.6
2T9	-10.0	8.00	7.6
2T12	30.0	11.00	12.2
2T7	30.0	11.50	12.2
2T13	70.0	16.00	18.6
2T4	70.0	17.00	18.6
2T10	110.0	21.00	24.8
2T1	110.0	23.00	24.8
2T15	150.0	29.00	28.7
2T6	150.0	32.00	28.7
2T11	190.0	29.00	30.0
2T5	190.0	30.50	30.0
2T16	230.0	29.00	29.0

TRANSITION REGION, CALCULATED VALUES

ENERGY ABSORPTION	CALCULATED TEMPERATURE(F)	/	TEMPERATURE (F)	CALCULATED ENERGY ABSORPTION(FT-LB)
5.0	-45.7	/	-40.0	5.3
10.0	12.9	/	-35.0	5.6
15.0	48.2	/	-30.0	6.0
20.0	78.5	/	-25.0	6.3
25.0	111.3	/	-20.0	6.7
		/	-15.0	7.1
		/	-10.0	7.6
		/	-5.0	8.0
		/	.0	8.5
		/	5.0	9.1
		/	10.0	9.6
		/	15.0	10.3
		/	20.0	10.9
		/	25.0	11.6
		/	30.0	12.2
		/	35.0	13.0
		/	40.0	13.7
		/	45.0	14.5
		/	50.0	15.3
		/	55.0	16.1

CHARPY V-NOTCH TEST RESULTS FOR PLATE SAMPLE 2, A SHELL PLATE
OF AAR TC128-GRADE A STEEL TAKEN FROM TANK-CAR IMCX 2513
CALCULATIONS FOR SHEAR FRACTURE APPEARANCE DATA OF
16 SPECIMENS, TL ORIENTATION

SPECIMEN	TEMPERATURE(F)	OBSERVED SHEAR FRACTURE (%)	CALCULATED SHEAR FRACTURE (%)
2T8	-90.0	.00	.1
2T3	-50.0	.00	.5
2T2	-50.0	.00	.5
2T14	-10.0	.00	2.9
2T9	-10.0	4.00	2.9
2T12	30.0	10.00	12.4
2T7	30.0	8.00	12.4
2T13	70.0	45.00	38.7
2T4	70.0	40.00	38.7
2T10	110.0	73.00	78.7
2T1	110.0	79.00	78.7
2T15	150.0	100.00	98.3
2T6	150.0	98.00	98.3
2T11	190.0	100.00	99.5
2T5	190.0	100.00	99.5
2T16	230.0	100.00	100.0

TRANSITION REGION, CALCULATED VALUES

% SHEAR FRACTURE	CALCULATED TEMPERATURE(F)	/	TEMPERATURE (F)	CALCULATED SHEAR FRACTURE(%)
2.0	-19.0	/	-10.0	2.9
5.0	4.2	/	-5.0	3.5
10.0	23.6	/	.0	4.3
15.0	35.9	/	5.0	5.2
50.0	81.6	/	10.0	6.2
85.0	117.6	/	15.0	7.4
90.0	125.1	/	20.0	8.9
95.0	135.8	/	25.0	10.5
98.0	147.9	/	30.0	12.4
		/	35.0	14.6
		/	40.0	17.0
		/	45.0	19.8
		/	50.0	22.9
		/	55.0	26.3
		/	60.0	30.1
		/	65.0	34.3
		/	70.0	38.7
		/	75.0	43.4
		/	80.0	48.4
		/	85.0	53.5

CHARPY V-NOTCH TEST RESULTS FOR PLATE SAMPLE 2, A SHELL PLATE OF AAR TC128-GRADE A STEEL TAKEN FROM TANK-CAR IMCX 2513
CALCULATIONS FOR ENERGY ABSORPTION DATA OF 8 SPECIMENS, LT ORIENTATION

SPECIMEN	TEMPERATURE(F)	OBSERVED ENERGY ABSORPTION(FT-LB)	CALCULATED ENERGY ABSORPTION(FT-LB)
2L6	-50.0	5.00	5.1
2L5	-10.0	6.00	6.1
2L7	30.0	10.50	11.0
2L3	70.0	26.00	24.9
2L4	70.0	27.00	24.9
2L2	110.0	40.50	44.4
2L8	150.0	55.00	53.9
2L1	190.0	54.50	54.7

TRANSITION REGION, CALCULATED VALUES

ENERGY ABSORPTION	CALCULATED TEMPERATURE(F)	/	TEMPERATURE (F)	CALCULATED ENERGY ABSORPTION(FT-LB)
10.0	25.1	/	30.0	11.0
15.0	45.1	/	35.0	12.2
20.0	59.0	/	40.0	13.5
25.0	70.3	/	45.0	15.0
30.0	80.5	/	50.0	16.6
35.0	90.3	/	55.0	18.4
40.0	100.3	/	60.0	20.4
45.0	111.5	/	65.0	22.6
50.0	126.2	/	70.0	24.9
		/	75.0	27.3
		/	80.0	29.8
		/	85.0	32.3
		/	90.0	34.9
		/	95.0	37.4
		/	100.0	39.9
		/	105.0	42.2
		/	110.0	44.4
		/	115.0	46.4
		/	120.0	48.1
		/	125.0	49.7

CHARPY V-NOTCH TEST RESULTS FOR PLATE SAMPLE 2, A SHELL PLATE OF AAR TC128-GRADE A STEEL TAKEN FROM TANK-CAR IMCX 2513
CALCULATIONS FOR SHEAR FRACTURE APPEARANCE DATA OF 8 SPECIMENS, LT ORIENTATION

SPECIMEN	TEMPERATURE(F)	OBSERVED SHEAR FRACTURE (%)	CALCULATED SHEAR FRACTURE (%)
2L6	-50.0	.00	.8
2L5	-10.0	3.00	3.4
2L7	30.0	15.00	12.2
2L3	70.0	31.00	35.5
2L4	70.0	40.00	35.5
2L2	110.0	65.00	73.3
2L8	150.0	98.00	96.7
2L1	190.0	100.00	99.0

TRANSITION REGION, CALCULATED VALUES

% SHEAR FRACTURE	CALCULATED TEMPERATURE(F)	/	TEMPERATURE (F)	CALCULATED SHEAR FRACTURE(%)
2.0	-24.6	/	-20.0	2.4
5.0	1.7	/	-15.0	2.8
10.0	23.4	/	-10.0	3.4
15.0	37.0	/	-5.0	4.0
50.0	86.1	/	.0	4.7
85.0	124.1	/	5.0	5.6
90.0	132.0	/	10.0	6.6
95.0	143.5	/	15.0	7.7
98.0	158.1	/	20.0	9.0
		/	25.0	10.5
		/	30.0	12.2
		/	35.0	14.1
		/	40.0	16.3
		/	45.0	18.8
		/	50.0	21.5
		/	55.0	24.5
		/	60.0	27.9
		/	65.0	31.5
		/	70.0	35.5
		/	75.0	39.7

Appendix C

Observed and Calculated Values of Energy Absorption and Shear Fracture Appearance in CVN Tests: Results for CVN ID 3, Plate Sample 3.

CHARPY V-NOTCH TEST RESULTS FOR PLATE SAMPLE 3, A SHELL PLATE OF AAR TC128-GRADE A STEEL TAKEN FROM TANK-CAR IMCX 2513
CALCULATIONS FOR ENERGY ABSORPTION DATA OF
16 SPECIMENS, TL ORIENTATION

SPECIMEN	TEMPERATURE(F)	OBSERVED ENERGY ABSORPTION(FT-LB)	CALCULATED ENERGY ABSORPTION(FT-LB)
3T10	-90.0	3.00	3.7
3T3	-90.0	4.00	3.7
3T14	-50.0	2.50	4.7
3T2	-50.0	4.00	4.7
3T1	-10.0	7.00	7.7
3T13	-10.0	7.50	7.7
3T9	30.0	13.50	14.3
3T4	30.0	13.50	14.3
3T7	70.0	22.50	21.9
3T12	70.0	23.00	21.9
3T6	110.0	24.00	24.6
3T16	110.0	25.00	24.6
3T15	150.0	22.50	24.7
3T5	150.0	25.00	24.7
3T11	190.0	25.00	24.7
3T8	190.0	26.00	24.7

TRANSITION REGION, CALCULATED VALUES

ENERGY ABSORPTION	CALCULATED TEMPERATURE(F)	/	TEMPERATURE (F)	CALCULATED ENERGY ABSORPTION(FT-LB)
5.0	-42.9	/	-40.0	5.2
10.0	6.8	/	-35.0	5.5
15.0	33.5	/	-30.0	5.8
20.0	58.2	/	-25.0	6.2
		/	-20.0	6.6
		/	-15.0	7.1
		/	-10.0	7.7
		/	-5.0	8.3
		/	.0	9.0
		/	5.0	9.7
		/	10.0	10.5
		/	15.0	11.4
		/	20.0	12.3
		/	25.0	13.3
		/	30.0	14.3
		/	35.0	15.3
		/	40.0	16.4
		/	45.0	17.4
		/	50.0	18.4
		/	55.0	19.4

CHARPY V-NOTCH TEST RESULTS FOR PLATE SAMPLE 3, A SHELL PLATE OF AAR TC128-GRADE A STEEL TAKEN FROM TANK-CAR IMCX 2513
CALCULATIONS FOR SHEAR FRACTURE APPEARANCE DATA OF 16 SPECIMENS, TL ORIENTATION

SPECIMEN	TEMPERATURE(F)	OBSERVED SHEAR FRACTURE (%)	CALCULATED SHEAR FRACTURE (%)
3T10	-90.0	.00	.4
3T3	-90.0	.00	.4
3T14	-50.0	3.00	3.1
3T2	-50.0	.00	3.1
3T1	-10.0	15.00	14.8
3T13	-10.0	15.00	14.8
3T9	30.0	45.00	48.1
3T4	30.0	50.00	48.1
3T7	70.0	90.00	89.0
3T12	70.0	90.00	89.0
3T6	110.0	95.00	98.7
3T16	110.0	98.00	98.7
3T15	150.0	100.00	98.8
3T5	150.0	100.00	98.8
3T11	190.0	100.00	98.8
3T8	190.0	100.00	98.8

TRANSITION REGION, CALCULATED VALUES

% SHEAR FRACTURE	CALCULATED TEMPERATURE(F)	/	TEMPERATURE (F)	CALCULATED SHEAR FRACTURE(%)
2.0	-59.5	/	-50.0	3.1
5.0	-38.5	/	-45.0	3.8
10.0	-20.9	/	-40.0	4.7
15.0	-9.6	/	-35.0	5.8
50.0	31.7	/	-30.0	7.0
85.0	64.5	/	-25.0	8.5
90.0	71.5	/	-20.0	10.3
95.0	81.8	/	-15.0	12.4
98.0	95.7	/	-10.0	14.8
		/	-5.0	17.6
		/	.0	20.7
		/	5.0	24.3
		/	10.0	28.3
		/	15.0	32.7
		/	20.0	37.5
		/	25.0	42.7
		/	30.0	48.1
		/	35.0	53.8
		/	40.0	59.6
		/	45.0	65.4

CHARPY V-NOTCH TEST RESULTS FOR PLATE SAMPLE 3, A SHELL PLATE OF AAR TC128-GRADE A STEEL TAKEN FROM TANK-CAR IMCX 2513
CALCULATIONS FOR ENERGY ABSORPTION DATA OF 8 SPECIMENS, LT ORIENTATION

SPECIMEN	TEMPERATURE(F)	OBSERVED ENERGY ABSORPTION(FT-LB)	CALCULATED ENERGY ABSORPTION(FT-LB)
3L8	-50.0	3.50	3.5
3L5	-10.0	5.50	4.7
3L2	30.0	9.00	17.5
3L6	30.0	14.00	17.5
3L7	50.0	39.50	32.5
3L3	70.0	42.00	42.6
3L1	110.0	45.50	44.0
3L4	150.0	42.50	44.0

TRANSITION REGION, CALCULATED VALUES

ENERGY ABSORPTION	CALCULATED TEMPERATURE(F)	/	TEMPERATURE (F)	CALCULATED ENERGY ABSORPTION(FT-LB)
5.0	-7.0	/	.0	6.0
10.0	15.4	/	5.0	6.9
15.0	26.0	/	10.0	8.2
20.0	33.7	/	15.0	9.9
25.0	40.4	/	20.0	11.9
30.0	46.7	/	25.0	14.5
35.0	53.5	/	30.0	17.5
40.0	62.2	/	35.0	20.9
		/	40.0	24.7
		/	45.0	28.6
		/	50.0	32.5
		/	55.0	36.0
		/	60.0	38.9
		/	65.0	41.1
		/	70.0	42.6

CHARPY V-NOTCH TEST RESULTS FOR PLATE SAMPLE 3, A SHELL PLATE OF AAR TC128-GRADE A STEEL TAKEN FROM TANK-CAR IMCX 2513
CALCULATIONS FOR SHEAR FRACTURE APPEARANCE DATA OF 8 SPECIMENS, LT ORIENTATION

SPECIMEN	TEMPERATURE(F)	OBSERVED SHEAR FRACTURE (%)	CALCULATED SHEAR FRACTURE (%)
3L8	-50.0	1.00	1.5
3L5	-10.0	10.00	8.0
3L2	30.0	30.00	43.6
3L6	30.0	37.00	43.6
3L7	50.0	88.00	73.5
3L3	70.0	85.00	93.6
3L1	110.0	97.00	98.5
3L4	150.0	100.00	98.5

TRANSITION REGION, CALCULATED VALUES

% SHEAR FRACTURE	CALCULATED TEMPERATURE(F)	/	TEMPERATURE (F)	CALCULATED SHEAR FRACTURE(%)
2.0	-40.7	/	-40.0	2.0
5.0	-19.6	/	-35.0	2.5
10.0	-5.3	/	-30.0	3.1
15.0	3.3	/	-25.0	3.9
50.0	34.4	/	-20.0	4.9
85.0	59.2	/	-15.0	6.3
90.0	64.6	/	-10.0	8.0
95.0	72.8	/	-5.0	10.2
98.0	85.6	/	.0	12.9
		/	5.0	16.2
		/	10.0	20.2
		/	15.0	24.9
		/	20.0	30.4
		/	25.0	36.7
		/	30.0	43.6
		/	35.0	51.0
		/	40.0	58.6
		/	45.0	66.3
		/	50.0	73.5
		/	55.0	80.1

Appendix D

Observed and Calculated Values of Energy Absorption and Shear Fracture Appearance in CVN Tests: Results for CVN ID 4, Plate Sample 12.

CHARPY V-NOTCH TEST RESULTS FOR PLATE SAMPLE 12, A SHELL PLATE OF AAR TC128-GRADE A STEEL TAKEN FROM TANK-CAR IMCX 2827
CALCULATIONS FOR ENERGY ABSORPTION DATA OF
16 SPECIMENS, TL ORIENTATION

SPECIMEN	TEMPERATURE(F)	OBSERVED ENERGY ABSORPTION(FT-LB)	CALCULATED ENERGY ABSORPTION(FT-LB)
4T4	-90.0	3.00	4.2
4T6	-90.0	4.00	4.2
4T16	-50.0	5.50	5.6
4T1	-50.0	7.50	5.6
4T12	-10.0	7.00	8.6
4T3	-10.0	10.00	8.6
4T7	30.0	12.00	13.8
4T9	30.0	12.00	13.8
4T14	70.0	18.50	20.0
4T13	70.0	23.50	20.0
4T11	110.0	24.00	24.1
4T15	110.0	25.00	24.1
4T5	150.0	24.00	25.2
4T2	150.0	26.00	25.2
4T8	190.0	24.50	25.2
4T10	190.0	28.00	25.2

TRANSITION REGION, CALCULATED VALUES

ENERGY ABSORPTION	CALCULATED TEMPERATURE(F)	/	TEMPERATURE (F)	CALCULATED ENERGY ABSORPTION(FT-LB)
5.0	-62.9	/	-60.0	5.1
10.0	2.5	/	-55.0	5.3
15.0	37.5	/	-50.0	5.6
20.0	69.7	/	-45.0	5.8
25.0	133.9	/	-40.0	6.1
		/	-35.0	6.5
		/	-30.0	6.8
		/	-25.0	7.2
		/	-20.0	7.6
		/	-15.0	8.1
		/	-10.0	8.6
		/	-5.0	9.1
		/	.0	9.7
		/	5.0	10.3
		/	10.0	10.9
		/	15.0	11.6
		/	20.0	12.3
		/	25.0	13.1
		/	30.0	13.8
		/	35.0	14.6

CHARPY V-NOTCH TEST RESULTS FOR PLATE SAMPLE 12, A SHELL PLATE
OF AAR TC128-GRADE A STEEL TAKEN FROM TANK-CAR IMCX 2827
CALCULATIONS FOR SHEAR FRACTURE APPEARANCE DATA OF
16 SPECIMENS, TL ORIENTATION

SPECIMEN	TEMPERATURE(F)	OBSERVED SHEAR FRACTURE (%)	CALCULATED SHEAR FRACTURE (%)
4T4	-90.0	.00	.7
4T6	-90.0	.00	.7
4T16	-50.0	.00	3.1
4T1	-50.0	.00	3.1
4T12	-10.0	10.00	11.6
4T3	-10.0	15.00	11.6
4T7	30.0	31.00	34.4
4T9	30.0	31.00	34.4
4T14	70.0	60.00	72.2
4T13	70.0	85.00	72.2
4T11	110.0	97.00	96.4
4T15	110.0	97.00	96.4
4T5	150.0	100.00	99.0
4T2	150.0	100.00	99.0
4T8	190.0	100.00	99.0
4T10	190.0	100.00	99.0

TRANSITION REGION, CALCULATED VALUES

% SHEAR FRACTURE	CALCULATED TEMPERATURE(F)	/	TEMPERATURE (F)	CALCULATED SHEAR FRACTURE(%)
2.0	-61.8	/	-60.0	2.1
5.0	-36.1	/	-55.0	2.6
10.0	-14.8	/	-50.0	3.1
15.0	-1.3	/	-45.0	3.7
50.0	47.4	/	-40.0	4.4
85.0	85.4	/	-35.0	5.2
90.0	93.3	/	-30.0	6.1
95.0	104.9	/	-25.0	7.2
98.0	119.6	/	-20.0	8.5
		/	-15.0	9.9
		/	-10.0	11.6
		/	-5.0	13.5
		/	.0	15.6
		/	5.0	18.0
		/	10.0	20.7
		/	15.0	23.6
		/	20.0	26.9
		/	25.0	30.5
		/	30.0	34.4
		/	35.0	38.6

CHARPY V-NOTCH TEST RESULTS FOR PLATE SAMPLE 12, A SHELL PLATE OF AAR TC128-GRADE A STEEL FROM TANK-CAR IMCX 2827
CALCULATIONS FOR ENERGY ABSORPTION DATA OF 8 SPECIMENS, LT ORIENTATION

SPECIMEN	TEMPERATURE(F)	OBSERVED ENERGY ABSORPTION(FT-LB)	CALCULATED ENERGY ABSORPTION(FT-LB)
4L7	-50.0	5.50	6.9
4L6	-10.0	16.50	10.8
4L2	30.0	12.50	21.0
4L5	30.0	16.50	21.0
4L4	70.0	48.00	39.7
4L3	110.0	55.00	60.2
4L1	150.0	70.50	69.6
4L8	190.0	71.00	70.7

TRANSITION REGION, CALCULATED VALUES

ENERGY ABSORPTION	CALCULATED TEMPERATURE(F)	/	TEMPERATURE (F)	CALCULATED ENERGY ABSORPTION(FT-LB)
10.0	-15.3	/	-10.0	10.8
15.0	10.6	/	-5.0	11.6
20.0	27.3	/	.0	12.6
25.0	40.2	/	5.0	13.7
30.0	51.3	/	10.0	14.8
35.0	61.2	/	15.0	16.2
40.0	70.5	/	20.0	17.6
45.0	79.6	/	25.0	19.2
50.0	88.8	/	30.0	21.0
55.0	98.5	/	35.0	22.9
60.0	109.6	/	40.0	24.9
65.0	124.0	/	45.0	27.1
70.0	155.2	/	50.0	29.4
		/	55.0	31.8
		/	60.0	34.4
		/	65.0	37.0
		/	70.0	39.7
		/	75.0	42.5
		/	80.0	45.2
		/	85.0	48.0

CHARPY V-NOTCH TEST RESULTS FOR PLATE SAMPLE 12, A SHELL PLATE OF AAR TC128-GRADE A STEEL FROM TANK-CAR IMCX 2827
CALCULATIONS FOR SHEAR FRACTURE APPEARANCE DATA OF 8 SPECIMENS, LT ORIENTATION

SPECIMEN	TEMPERATURE(F)	OBSERVED SHEAR FRACTURE (%)	CALCULATED SHEAR FRACTURE (%)
4L7	-50.0	.00	.7
4L6	-10.0	5.00	5.3
4L2	30.0	16.00	21.8
4L5	30.0	31.00	21.8
4L4	70.0	60.00	56.4
4L3	110.0	79.00	89.9
4L1	150.0	100.00	99.6
4L8	190.0	100.00	100.0

TRANSITION REGION, CALCULATED VALUES

% SHEAR FRACTURE	CALCULATED TEMPERATURE(F)	/	TEMPERATURE (F)	CALCULATED SHEAR FRACTURE(%)
2.0	-31.3	/	-30.0	2.1
5.0	-11.3	/	-25.0	2.7
10.0	6.4	/	-20.0	3.4
15.0	18.1	/	-15.0	4.3
50.0	63.6	/	-10.0	5.3
85.0	102.1	/	-5.0	6.5
90.0	110.2	/	.0	7.9
95.0	121.7	/	5.0	9.5
98.0	133.8	/	10.0	11.4
		/	15.0	13.5
		/	20.0	16.0
		/	25.0	18.7
		/	30.0	21.8
		/	35.0	25.2
		/	40.0	28.9
		/	45.0	32.9
		/	50.0	37.2
		/	55.0	41.7
		/	60.0	46.5
		/	65.0	51.4

Appendix E

Observed and Calculated Values of Energy Absorption and Shear Fracture Appearance in CVN Tests: Results for CVN ID 5, Plate Sample 16A.

CHARPY V-NOTCH TEST RESULTS FOR PLATE SAMPLE 16A, A SHELL PLATE OF AAR TC128-GRADE B STEEL FROM TANK-CAR IMCX 2513
CALCULATIONS FOR ENERGY ABSORPTION DATA OF 16 SPECIMENS, TL ORIENTATION

SPECIMEN	TEMPERATURE(F)	OBSERVED ENERGY ABSORPTION(FT-LB)	CALCULATED ENERGY ABSORPTION(FT-LB)
5T12	-90.0	2.50	4.0
5T13	-50.0	2.00	6.0
5T15	-50.0	7.00	6.0
5T2	-10.0	7.50	9.8
5T4	-10.0	9.50	9.8
5T7	30.0	15.50	16.1
5T14	30.0	18.00	16.1
5T10	70.0	24.50	24.6
5T11	70.0	28.00	24.6
5T9	110.0	27.00	33.9
5T5	110.0	30.50	33.9
5T8	150.0	42.50	41.3
5T3	150.0	43.00	41.3
5T1	190.0	45.50	45.1
5T16	190.0	47.00	45.1
5T6	230.0	43.50	43.5

TRANSITION REGION, CALCULATED VALUES

ENERGY ABSORPTION	CALCULATED TEMPERATURE(F)	/	TEMPERATURE (F)	CALCULATED ENERGY ABSORPTION(FT-LB)
5.0	-66.5	/	-60.0	5.4
10.0	-8.7	/	-50.0	6.0
15.0	24.1	/	-40.0	6.8
20.0	49.4	/	-30.0	7.7
25.0	71.6	/	-20.0	8.7
30.0	92.8	/	-10.0	9.8
35.0	114.9	/	.0	11.2
40.0	141.4	/	10.0	12.6
45.0	189.0	/	20.0	14.3
		/	30.0	16.1
		/	40.0	18.0
		/	50.0	20.1
		/	60.0	22.3
		/	70.0	24.6
		/	80.0	27.0
		/	90.0	29.4
		/	100.0	31.7
		/	110.0	33.9
		/	120.0	36.1
		/	130.0	38.0

CHARPY V-NOTCH TEST RESULTS FOR PLATE SAMPLE 16A, A SHELL PLATE
OF AAR TC128-GRADE B STEEL FROM TANK-CAR IMCX 2513
CALCULATIONS FOR SHEAR FRACTURE APPEARANCE DATA OF
16 SPECIMENS, TL ORIENTATION

SPECIMEN	TEMPERATURE(F)	OBSERVED SHEAR FRACTURE (%)	CALCULATED SHEAR FRACTURE (%)
5T12	-90.0	.00	.6
5T13	-50.0	.00	2.4
5T15	-50.0	.00	2.4
5T2	-10.0	8.00	7.5
5T4	-10.0	8.00	7.5
5T7	30.0	20.00	19.5
5T14	30.0	15.00	19.5
5T10	70.0	45.00	42.2
5T11	70.0	45.00	42.2
5T9	110.0	68.00	71.9
5T5	110.0	70.00	71.9
5T8	150.0	93.00	93.5
5T3	150.0	93.00	93.5
5T1	190.0	99.00	99.6
5T16	190.0	100.00	99.6
5T6	230.0	100.00	100.0

[redacted]

TRANSITION REGION, CALCULATED VALUES

% SHEAR FRACTURE	CALCULATED TEMPERATURE(F)	/	TEMPERATURE (F)	CALCULATED SHEAR FRACTURE(%)
2.0	-55.9	/	-50.0	2.4
5.0	-24.8	/	-40.0	3.2
10.0	1.4	/	-30.0	4.3
15.0	18.3	/	-20.0	5.7
50.0	80.8	/	-10.0	7.5
85.0	130.5	/	.0	9.6
90.0	140.7	/	10.0	12.3
95.0	154.9	/	20.0	15.6
98.0	169.7	/	30.0	19.5
		/	40.0	24.1
		/	50.0	29.5
		/	60.0	35.5
		/	70.0	42.2
		/	80.0	49.4
		/	90.0	56.9
		/	100.0	64.5
		/	110.0	71.9
		/	120.0	78.7
		/	130.0	84.7
		/	140.0	89.7

CHARPY V-NOTCH TEST RESULTS FOR PLATE SAMPLE 16A, A SHELL PLATE OF AAR TC128-GRADE B STEEL FROM TANK-CAR IMCX 2513

CALCULATIONS FOR ENERGY ABSORPTION DATA OF 8 SPECIMENS, LT ORIENTATION

SPECIMEN	TEMPERATURE(F)	OBSERVED ENERGY ABSORPTION(FT-LB)	CALCULATED ENERGY ABSORPTION(FT-LB)
5L8	-50.0	5.00	5.1
5L7	-10.0	8.00	8.9
5L5	30.0	28.50	24.1
5L2	30.0	31.00	24.1
5L3	70.0	43.00	49.9
5L4	110.0	73.00	71.5
5L6	150.0	76.00	79.7
5L1	190.0	81.00	80.9

TRANSITION REGION, CALCULATED VALUES

ENERGY ABSORPTION	CALCULATED TEMPERATURE(F)	/	TEMPERATURE (F)	CALCULATED ENERGY ABSORPTION(FT-LB)
10.0	-5.2	/	.0	11.4
15.0	10.6	/	5.0	13.0
20.0	22.1	/	10.0	14.8
25.0	31.5	/	15.0	16.8
30.0	40.0	/	20.0	19.0
35.0	47.8	/	25.0	21.5
40.0	55.3	/	30.0	24.1
45.0	62.7	/	35.0	27.0
50.0	70.1	/	40.0	30.0
55.0	77.8	/	45.0	33.2
60.0	86.0	/	50.0	36.4
65.0	95.2	/	55.0	39.8
70.0	106.2	/	60.0	43.2
75.0	121.2	/	65.0	46.6
80.0	154.2	/	70.0	49.9
		/	75.0	53.2
		/	80.0	56.4
		/	85.0	59.4
		/	90.0	62.2
		/	95.0	64.9

CHARPY V-NOTCH TEST RESULTS FOR PLATE SAMPLE 16A, A SHELL PLATE OF AAR TC128-GRADE B STEEL FROM TANK-CAR IMCX 2513
CALCULATIONS FOR SHEAR FRACTURE APPEARANCE DATA OF 8 SPECIMENS, LT ORIENTATION

SPECIMEN	TEMPERATURE(F)	OBSERVED SHEAR FRACTURE (%)	CALCULATED SHEAR FRACTURE (%)
5L8	-50.0	1.00	3.6
5L7	-10.0	10.00	9.4
5L5	30.0	16.00	23.3
5L2	30.0	35.00	23.3
5L3	70.0	41.00	49.3
5L4	110.0	85.00	80.4
5L6	150.0	95.00	97.4
5L1	190.0	100.00	100.0

TRANSITION REGION, CALCULATED VALUES

% SHEAR FRACTURE	CALCULATED TEMPERATURE(F)	/	TEMPERATURE (F)	CALCULATED SHEAR FRACTURE(%)
5.0	-36.3	/	-30.0	5.8
10.0	-7.3	/	-25.0	6.5
15.0	10.1	/	-20.0	7.4
50.0	70.9	/	-15.0	8.3
85.0	117.3	/	-10.0	9.4
90.0	126.8	/	-5.0	10.6
95.0	139.8	/	.0	11.9
98.0	153.4	/	5.0	13.3
		/	10.0	15.0
		/	15.0	16.8
		/	20.0	18.8
		/	25.0	20.9
		/	30.0	23.3
		/	35.0	25.9
		/	40.0	28.7
		/	45.0	31.6
		/	50.0	34.8
		/	55.0	38.2
		/	60.0	41.7
		/	65.0	45.5

Appendix F

Observed and Calculated Values of Energy Absorption and Shear Fracture Appearance in CVN Tests: Results for CVN ID 6, Plate Sample 17.

CHARPY V-NOTCH TEST RESULTS FOR PLATE SAMPLE 17, A SHELL PLATE
OF AAR TC128-GRADE A STEEL FROM TANK-CAR IMCX 2827
CALCULATIONS FOR ENERGY ABSORPTION DATA OF
16 SPECIMENS, TL ORIENTATION

SPECIMEN	TEMPERATURE(F)	OBSERVED ENERGY ABSORPTION(FT-LB)	CALCULATED ENERGY ABSORPTION(FT-LB)
6T4	-90.0	3.50	4.5
6T2	-50.0	5.50	6.0
6T13	-50.0	7.50	6.0
6T10	-10.0	9.00	8.8
6T9	-10.0	10.50	8.8
6T12	30.0	10.50	13.4
6T6	30.0	12.50	13.4
6T8	70.0	17.50	19.7
6T15	70.0	18.00	19.7
6T3	110.0	22.50	26.3
6T5	110.0	23.00	26.3
6T7	150.0	30.50	31.1
6T14	150.0	32.50	31.1
6T11	190.0	34.00	33.2
6T1	190.0	34.00	33.2
6T16	230.0	33.00	33.6

TRANSITION REGION, CALCULATED VALUES

ENERGY ABSORPTION	CALCULATED TEMPERATURE(F)	/	TEMPERATURE (F)	CALCULATED ENERGY ABSORPTION(FT-LB)
5.0	-73.3	/	-70.0	5.1
10.0	2.3	/	-60.0	5.5
15.0	40.8	/	-50.0	6.0
20.0	71.6	/	-40.0	6.5
25.0	101.4	/	-30.0	7.2
30.0	138.2	/	-20.0	7.9
		/	-10.0	8.8
		/	.0	9.8
		/	10.0	10.9
		/	20.0	12.1
		/	30.0	13.4
		/	40.0	14.9
		/	50.0	16.4
		/	60.0	18.1
		/	70.0	19.7
		/	80.0	21.4
		/	90.0	23.1
		/	100.0	24.8
		/	110.0	26.3
		/	120.0	27.8

CHARPY V-NOTCH TEST RESULTS FOR PLATE SAMPLE 17, A SHELL PLATE
OF AAR TC128-GRADE A STEEL FROM TANK-CAR IMCX 2827
CALCULATIONS FOR SHEAR FRACTURE APPEARANCE DATA OF
16 SPECIMENS, TL ORIENTATION

SPECIMEN	TEMPERATURE(F)	OBSERVED SHEAR FRACTURE (%)	CALCULATED SHEAR FRACTURE (%)
6T4	-90.0	.00	.4
6T2	-50.0	.00	1.5
6T13	-50.0	.00	1.5
6T10	-10.0	5.00	4.8
6T9	-10.0	5.00	4.8
6T12	30.0	15.00	13.7
6T6	30.0	15.00	13.7
6T8	70.0	30.00	32.6
6T15	70.0	30.00	32.6
6T3	110.0	55.00	62.2
6T5	110.0	55.00	62.2
6T7	150.0	85.00	88.9
6T14	150.0	93.00	88.9
6T11	190.0	97.00	98.3
6T1	190.0	100.00	98.3
6T16	230.0	100.00	99.0

TRANSITION REGION, CALCULATED VALUES

% SHEAR FRACTURE	CALCULATED TEMPERATURE(F)	/	TEMPERATURE (F)	CALCULATED SHEAR FRACTURE(%)
2.0	-40.0	/	-30.0	2.7
5.0	-8.7	/	-20.0	3.6
10.0	17.3	/	-10.0	4.8
15.0	33.9	/	.0	6.4
50.0	94.5	/	10.0	8.3
85.0	142.4	/	20.0	10.7
90.0	152.5	/	30.0	13.7
95.0	167.2	/	40.0	17.3
98.0	186.0	/	50.0	21.6
		/	60.0	26.7
		/	70.0	32.6
		/	80.0	39.3
		/	90.0	46.5
		/	100.0	54.3
		/	110.0	62.2
		/	120.0	70.0
		/	130.0	77.2
		/	140.0	83.6
		/	150.0	88.9
		/	160.0	92.9

CHARPY V-NOTCH TEST RESULTS FOR PLATE SAMPLE 17, A SHELL PLATE
OF AAR TC128-GRADE A STEEL FROM TANK-CAR IMCX 2827
CALCULATIONS FOR ENERGY ABSORPTION DATA OF
8 SPECIMENS, LT ORIENTATION

SPECIMEN	TEMPERATURE(F)	OBSERVED ENERGY ABSORPTION(FT-LB)	CALCULATED ENERGY ABSORPTION(FT-LB)
6L8	-50.0	7.50	7.8
6L4	-10.0	9.50	9.2
6L5	30.0	15.00	14.5
6L3	70.0	16.00	28.7
6L1	70.0	31.00	28.7
6L2	90.0	36.00	38.3
6L6	110.0	50.00	45.9
6L7	150.0	49.50	49.7

TRANSITION REGION, CALCULATED VALUES

ENERGY ABSORPTION	CALCULATED TEMPERATURE(F)	/	TEMPERATURE (F)	CALCULATED ENERGY ABSORPTION(FT-LB)
10.0	.3	/	10.0	11.1
15.0	32.2	/	15.0	11.7
20.0	49.2	/	20.0	12.5
25.0	61.9	/	25.0	13.4
30.0	72.8	/	30.0	14.5
35.0	83.1	/	35.0	15.7
40.0	93.8	/	40.0	17.1
45.0	107.1	/	45.0	18.6
		/	50.0	20.3
		/	55.0	22.2
		/	60.0	24.2
		/	65.0	26.4
		/	70.0	28.7
		/	75.0	31.1
		/	80.0	33.5
		/	85.0	35.9
		/	90.0	38.3
		/	95.0	40.5
		/	100.0	42.5
		/	105.0	44.3

CHARPY V-NOTCH TEST RESULTS FOR PLATE SAMPLE 17, A SHELL PLATE
OF AAR TC128-GRADE A STEEL FROM TANK-CAR IMCX 2827
CALCULATIONS FOR SHEAR FRACTURE APPEARANCE DATA OF
8 SPECIMENS, LT ORIENTATION

SPECIMEN	TEMPERATURE(F)	OBSERVED SHEAR FRACTURE (%)	CALCULATED SHEAR FRACTURE (%)
6L8	-50.0	.00	.4
6L4	-10.0	3.00	2.2
6L5	30.0	10.00	10.2
6L3	70.0	25.00	34.6
6L1	70.0	25.00	34.6
6L2	90.0	55.00	53.0
6L6	110.0	73.00	68.4
6L7	150.0	80.00	76.5

TRANSITION REGION, CALCULATED VALUES

% SHEAR FRACTURE	CALCULATED TEMPERATURE(F)	/	TEMPERATURE (F)	CALCULATED SHEAR FRACTURE(%)
2.0	-12.5	/	-10.0	2.2
5.0	10.5	/	-5.0	2.7
10.0	29.4	/	.0	3.3
15.0	41.3	/	5.0	4.0
50.0	86.8	/	10.0	4.9
85.0	150.0	/	15.0	5.9
90.0	150.0	/	20.0	7.1
95.0	150.0	/	25.0	8.6
98.0	150.0	/	30.0	10.2
		/	35.0	12.1
		/	40.0	14.4
		/	45.0	16.9
		/	50.0	19.8
		/	55.0	23.0
		/	60.0	26.5
		/	65.0	30.4
		/	70.0	34.6
		/	75.0	39.1
		/	80.0	43.7
		/	85.0	48.4

Appendix G

Observed and Calculated Values of Energy Absorption and Shear Fracture Appearance in CVN Tests: Results for CVN ID 7, Plate Sample 20A-A.

ENERGY ABSORPTION	CALCULATED TEMPERATURE(F)
5.0	-34.7
10.0	10.0
15.0	34.3
20.0	53.6
25.0	71.6
30.0	92.1
35.0	142.5

TEMPERATURE (F)	CALCULATED ENERGY ABSORPTION(FT-LB)
-30.0	5.3
-25.0	5.7
-20.0	6.1
-15.0	6.6
-10.0	7.2
-5.0	7.8
.0	8.5
5.0	9.2
10.0	10.0
15.0	10.9
20.0	11.8
25.0	12.9
30.0	14.0
35.0	15.2
40.0	16.4
45.0	17.7
50.0	19.0
55.0	20.4
60.0	21.8
65.0	23.2

CHARPY-V-NOTCH TEST RESULTS FOR PLATE SAMPLE 20A-A, A SHELL PLATE
OF AAR TC128-GRADE B STEEL FROM TANK-CAR UTLX 28727

CALCULATIONS FOR ENERGY ABSORPTION DATA OF
16 SPECIMENS, TL ORIENTATION

SPECIMEN	TEMPERATURE(F)	OBSERVED ENERGY ABSORPTION(FT-LB)	CALCULATED ENERGY ABSORPTION(FT-LB)
7T9	-90.0	2.50	3.1
7T8	-90.0	3.00	3.1
7T7	-50.0	3.50	4.2
7T14	-50.0	5.00	4.2
7T5	-10.0	8.00	7.2
7T6	-10.0	11.00	7.2
7T2	30.0	12.00	14.0
7T1	30.0	14.00	14.0
7T16	70.0	23.00	24.6
7T15	70.0	25.00	24.6
7T12	110.0	34.50	33.0
7T13	110.0	35.00	33.0
7T10	150.0	34.00	35.1
7T11	150.0	36.50	35.1
7T4	190.0	35.00	35.2
7T3	190.0	36.00	35.2

TRANSITION REGION, CALCULATED VALUES

CHARPY V-NOTCH TEST RESULTS FOR PLATE SAMPLE 20A-A, A SHELL PLATE
OF AAR TC128-GRADE B STEEL FROM TANK-CAR UTLX 28727
CALCULATIONS FOR SHEAR FRACTURE APPEARANCE DATA OF
16 SPECIMENS, TL ORIENTATION

SPECIMEN	TEMPERATURE(F)	OBSERVED SHEAR FRACTURE (%)	CALCULATED SHEAR FRACTURE (%)
7T9	-90.0	.00	1.0
7T8	-90.0	.00	1.0
7T7	-50.0	3.00	4.0
7T14	-50.0	3.00	4.0
7T5	-10.0	18.00	12.9
7T6	-10.0	18.00	12.9
7T2	30.0	30.00	34.0
7T1	30.0	30.00	34.0
7T16	70.0	60.00	67.4
7T15	70.0	65.00	67.4
7T12	110.0	98.00	93.0
7T13	110.0	95.00	93.0
7T10	150.0	99.00	98.4
7T11	150.0	99.00	98.4
7T4	190.0	100.00	98.5
7T3	190.0	100.00	98.5

TRANSITION REGION, CALCULATED VALUES

% SHEAR FRACTURE	CALCULATED TEMPERATURE(F)	/	TEMPERATURE (F)	CALCULATED SHEAR FRACTURE(%)
2.0	-70.6	/	-70.0	2.0
5.0	-42.6	/	-60.0	2.9
10.0	-19.2	/	-50.0	4.0
15.0	-4.3	/	-40.0	5.4
50.0	50.1	/	-30.0	7.3
85.0	93.3	/	-20.0	9.8
90.0	102.5	/	-10.0	12.9
95.0	116.6	/	.0	16.8
98.0	138.1	/	10.0	21.6
		/	20.0	27.3
		/	30.0	34.0
		/	40.0	41.6
		/	50.0	49.9
		/	60.0	58.7
		/	70.0	67.4
		/	80.0	75.7
		/	90.0	82.9
		/	100.0	88.8
		/	110.0	93.0
		/	120.0	95.8

CHARPY-V-NOTCH TEST RESULTS FOR PLATE SAMPLE 20A-A, A SHELL PLATE OF AAR TC128-GRADE B STEEL FROM TANK-CAR UTLX 28727
CALCULATIONS FOR ENERGY ABSORPTION DATA OF
8 SPECIMENS, LT ORIENTATION

SPECIMEN	TEMPERATURE(F)	OBSERVED ENERGY ABSORPTION(FT-LB)	CALCULATED ENERGY ABSORPTION(FT-LB)
7L3	-50.0	4.00	4.1
7L7	-10.0	5.50	6.5
7L5	30.0	28.50	21.6
7L6	30.0	37.50	21.6
7L2	70.0	41.50	55.1
7L8	90.0	51.00	70.2
7L1	110.0	82.00	78.4
7L4	150.0	81.00	81.5

TRANSITION REGION, CALCULATED VALUES

ENERGY ABSORPTION	CALCULATED TEMPERATURE(F)	/	TEMPERATURE (F)	CALCULATED ENERGY ABSORPTION(FT-LB)
5.0	-23.4	/	-20.0	5.3
10.0	5.2	/	-15.0	5.8
15.0	18.1	/	-10.0	6.5
20.0	27.4	/	-5.0	7.4
25.0	35.0	/	.0	8.6
30.0	41.6	/	5.0	10.0
35.0	47.6	/	10.0	11.6
40.0	53.3	/	15.0	13.6
45.0	58.8	/	20.0	15.9
50.0	64.3	/	25.0	18.6
55.0	69.9	/	30.0	21.6
60.0	75.8	/	35.0	25.0
65.0	82.2	/	40.0	28.7
70.0	89.7	/	45.0	32.8
75.0	99.5	/	50.0	37.0
80.0	118.4	/	55.0	41.5
		/	60.0	46.1
		/	65.0	50.6
		/	70.0	55.1
		/	75.0	59.4

CHARPY V-NOTCH TEST RESULTS FOR PLATE SAMPLE 20A-A, A SHELL PLATE OF AAR TC128-GRADE B STEEL FROM TANK-CAR UTLX 28727
CALCULATIONS FOR SHEAR FRACTURE APPEARANCE DATA OF 8 SPECIMENS, LT ORIENTATION

SPECIMEN	TEMPERATURE(F)	OBSERVED SHEAR FRACTURE (%)	CALCULATED SHEAR FRACTURE (%)
7L3	-50.0	.00	1.6
7L7	-10.0	10.00	6.5
7L5	30.0	18.00	21.2
7L6	30.0	18.00	21.2
7L2	70.0	45.00	52.0
7L8	90.0	60.00	69.8
7L1	110.0	85.00	83.3
7L4	150.0	98.00	91.3

TRANSITION REGION, CALCULATED VALUES

% SHEAR FRACTURE	CALCULATED TEMPERATURE(F)	/	TEMPERATURE (F)	CALCULATED SHEAR FRACTURE(%)
2.0	-44.4	/	-40.0	2.3
5.0	-18.1	/	-35.0	2.8
10.0	3.6	/	-30.0	3.3
15.0	17.3	/	-25.0	4.0
50.0	67.9	/	-20.0	4.7
85.0	113.6	/	-15.0	5.5
90.0	131.4	/	-10.0	6.5
95.0	150.0	/	-5.0	7.7
98.0	150.0	/	.0	9.0
		/	5.0	10.4
		/	10.0	12.1
		/	15.0	14.0
		/	20.0	16.2
		/	25.0	18.6
		/	30.0	21.2
		/	35.0	24.2
		/	40.0	27.4
		/	45.0	30.9
		/	50.0	34.7
		/	55.0	38.7

Appendix H

Observed and CalculatedValues of Energy Absorption and Shear Fracture Appearance in CVN Tests: Results for CVN ID 8, Plate Sample 20A-B.

CHARPY V-NOTCH TEST RESULTS FOR PLATE SAMPLE 20A-B, A SHELL PLATE OF AAR 1C128-GRADE B STEEL FROM TANK-CAR UTLX 28727
CALCULATIONS FOR ENERGY ABSORPTION DATA OF
16 SPECIMENS, TL ORIENTATION

SPECIMEN	TEMPERATURE(F)	OBSERVED ENERGY ABSORPTION(FT-LB)	CALCULATED ENERGY ABSORPTION(FT-LB)
8T15	-90.0	3.50	3.7
8T16	-50.0	3.50	4.7
8T9	-50.0	5.00	4.7
8T11	-10.0	5.50	8.2
8T5	-10.0	9.50	8.2
8T1	30.0	14.50	15.7
8T4	30.0	22.50	15.7
8T8	70.0	25.00	27.0
8T7	70.0	27.50	27.0
8T2	110.0	36.50	37.3
8T3	110.0	37.00	37.3
8T12	150.0	42.00	42.1
8T14	150.0	44.00	42.1
8T13	190.0	41.50	43.0
8T10	190.0	45.00	43.0
8T6	230.0	43.00	43.1

TRANSITION REGION, CALCULATED VALUES

ENERGY ABSORPTION	CALCULATED TEMPERATURE(F)	/	TEMPERATURE (F)	CALCULATED ENERGY ABSORPTION(FT-LB)
5.0	-45.1	/	-40.0	5.3
10.0	2.3	/	-35.0	5.6
15.0	27.0	/	-30.0	6.0
20.0	46.2	/	-25.0	6.5
25.0	63.4	/	-20.0	7.0
30.0	80.5	/	-15.0	7.5
35.0	99.5	/	-10.0	8.2
40.0	126.7	/	-5.0	8.9
		/	.0	9.6
		/	5.0	10.5
		/	10.0	11.4
		/	15.0	12.3
		/	20.0	13.4
		/	25.0	14.5
		/	30.0	15.7
		/	35.0	17.0
		/	40.0	18.3
		/	45.0	19.7
		/	50.0	21.1
		/	55.0	22.5

CHARPY V-NOTCH TEST RESULTS FOR PLATE SAMPLE 20A-B, A SHELL PLATE OF AAR TC128-GRADE B STEEL FROM TANK-CAR UTLX 28727
CALCULATIONS FOR SHEAR FRACTURE APPEARANCE DATA OF 16 SPECIMENS, TL ORIENTATION

SPECIMEN	TEMPERATURE(F)	OBSERVED SHEAR FRACTURE (%)	CALCULATED SHEAR FRACTURE (%)
8T15	-90.0	.00	.9
8T16	-50.0	3.00	3.1
8T9	-50.0	3.00	3.1
8T11	-10.0	8.00	9.6
8T5	-10.0	10.00	9.6
8T1	30.0	28.00	24.7
8T4	30.0	25.00	24.7
8T8	70.0	45.00	51.7
8T7	70.0	53.00	51.7
8T2	110.0	82.00	81.7
8T3	110.0	82.00	81.7
8T12	150.0	93.00	96.6
8T14	150.0	100.00	96.6
8T13	190.0	100.00	98.6
8T10	190.0	100.00	98.6
8T6	230.0	100.00	98.6

TRANSITION REGION, CALCULATED VALUES

% SHEAR FRACTURE	CALCULATED TEMPERATURE(F)	/	TEMPERATURE (F)	CALCULATED SHEAR FRACTURE(%)
2.0	-64.2	/	-60.0	2.3
5.0	-33.7	/	-50.0	3.1
10.0	-8.2	/	-40.0	4.2
15.0	8.0	/	-30.0	5.6
50.0	67.9	/	-20.0	7.3
85.0	115.6	/	-10.0	9.6
90.0	125.9	/	.0	12.3
95.0	141.3	/	10.0	15.7
98.0	163.9	/	20.0	19.8
		/	30.0	24.7
		/	40.0	30.4
		/	50.0	36.8
		/	60.0	44.0
		/	70.0	51.7
		/	80.0	59.6
		/	90.0	67.5
		/	100.0	75.0
		/	110.0	81.7
		/	120.0	87.3
		/	130.0	91.6

CHARPY V-NOTCH TEST RESULTS FOR PLATE SAMPLE 20A-B, A SHELL PLATE OF AAR TC128-GRADE B STEEL FROM TANK-CAR UTLX 28727

CALCULATIONS FOR ENERGY ABSORPTION DATA OF 8 SPECIMENS, LT ORIENTATION

SPECIMEN	TEMPERATURE(F)	OBSERVED ENERGY ABSORPTION(FT-LB)	CALCULATED ENERGY ABSORPTION(FT-LB)
8L7	-50.0	5.50	5.5
8L8	-10.0	5.50	5.7
8L2	30.0	14.50	14.5
8L4	70.0	51.00	52.6
8L1	70.0	54.00	52.6
8L5	110.0	94.00	93.9
8L3	150.0	101.50	103.3
8L6	190.0	105.50	103.5

TRANSITION REGION, CALCULATED VALUES

ENERGY ABSORPTION	CALCULATED TEMPERATURE(F)	/	TEMPERATURE (F)	CALCULATED ENERGY ABSORPTION(FT-LB)
10.0	19.6	/	20.0	10.1
15.0	31.0	/	25.0	12.1
20.0	38.7	/	30.0	14.5
25.0	45.0	/	35.0	17.4
30.0	50.3	/	40.0	20.9
35.0	55.1	/	45.0	25.0
40.0	59.6	/	50.0	29.7
45.0	63.8	/	55.0	34.8
50.0	67.9	/	60.0	40.5
55.0	71.9	/	65.0	46.4
60.0	75.9	/	70.0	52.6
65.0	79.9	/	75.0	58.9
70.0	84.0	/	80.0	65.1
75.0	88.3	/	85.0	71.2
80.0	93.0	/	90.0	76.8
85.0	98.2	/	95.0	82.0
90.0	104.2	/	100.0	86.6
95.0	111.9	/	105.0	90.6
100.0	124.1	/	110.0	93.9
		/	115.0	96.6

CHARPY V-NOTCH TEST RESULTS FOR PLATE SAMPLE 20A-B, A SHELL PLATE
OF AAR TC128-GRADE B STEEL FROM TANK-CAR UTLX 28727
CALCULATIONS FOR SHEAR FRACTURE APPEARANCE DATA OF
8 SPECIMENS, LT ORIENTATION

SPECIMEN	TEMPERATURE(F)	OBSERVED SHEAR FRACTURE (%)	CALCULATED SHEAR FRACTURE (%)
8L7	-50.0	.00	1.0
8L8	-10.0	5.00	4.6
8L2	30.0	16.00	17.2
8L4	70.0	43.00	48.8
8L1	70.0	48.00	48.8
8L5	110.0	93.00	87.7
8L3	150.0	98.00	98.8
8L6	190.0	100.00	99.0

TRANSITION REGION, CALCULATED VALUES

% SHEAR FRACTURE	CALCULATED TEMPERATURE(F)	/	TEMPERATURE (F)	CALCULATED SHEAR FRACTURE(%)
2.0	-32.1	/	-30.0	2.2
5.0	-7.4	/	-25.0	2.6
10.0	12.8	/	-20.0	3.2
15.0	25.6	/	-15.0	3.8
50.0	71.2	/	-10.0	4.6
85.0	106.3	/	-5.0	5.4
90.0	113.6	/	.0	6.5
95.0	124.2	/	5.0	7.7
98.0	137.7	/	10.0	9.1
		/	15.0	10.7
		/	20.0	12.6
		/	25.0	14.7
		/	30.0	17.2
		/	35.0	19.9
		/	40.0	23.0
		/	45.0	26.5
		/	50.0	30.3
		/	55.0	34.4
		/	60.0	38.9
		/	65.0	43.7

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C.G. Interrante, S.R. Low, C.H. Brady. and G.E. Hicho

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

This is the second of two reports intended to give information on and metallurgical characterization for each of 21 plate samples taken from tank cars involved in an accident at Crestview, Florida in April 8, 1979. The earlier report contains the results of a field investigation, which gives pertinent data on the thermal and deformation history of each of the 21 plate samples taken by the NBS for future studies. That report includes pictorial and other representations of the responses of the derailed tank cars observed at the accident site. This reporte includes results of chemical analyses, metallographic examinations (of microstructure and inclusion content) and hardness measurements conducted on each of these plate samples. This report also includes the results of standard Charpy V-notch impact tests conducted on seven of these plate samples. Thus, together these reports are intended as useful references for information needed to confirm or deny models proposed to explain the behavior of railroad tank cars in abusive service. In addition, the metallurgical characterization of each of the 21 plate samples will be useful in determinations of the suitability of each of these 21 samples for future laboratory studies.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

acicular ferrite; chemical composition; fracture toughness; hardness; impact properties; inclusion content; metallography; pressure vessels; Railroad tank cars; steels; Widmanstatten ferrite

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