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PROGRESS SUMMARY

ON

INVESTIGATION OF FRACTURED STEEL PLATES REMOVED FROM WELDED SHIPS

BY

MORGAN L. WILLIAMS AND GEORGE A. ELLINGER
National Bureau of Standards

SHIP STRUCTURE COMMITTEE

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The Secretary of the Treasury

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SECRETARY,

SHIP STRUCTURE COMMITTEE

U. S. COAST GUARD HEADQUARTERS

WASHINGTON 25, D. C.

February 25, 1949

Dear Sir:

Herewith is a copy of the first Progress Report prepared by Morgan L. Williams and George A. Ellinger of the National Bureau of Standards on their investigation of "Fractured Steel Plates Removed from Welded Ships." The investigation is being conducted at the request of the Ship Structure Committee. This report covers the work done during the period from June 1942 to May 1948. Another report is presently being prepared covering the tests made through December 1948.

Any questions, comments, criticisms or other matters pertaining to the report should be addressed to the Secretary, Ship Structure Committee.

This report is being distributed to those individuals and agencies who were associated with the work reported. It is hoped that the information presented will prove useful.

Yours sincerely,

Ellis Reed-Hill

ELLIS REED-HILL
Rear Admiral, USCG
Chairman, Ship Structure Committee

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Preface

The Ship Structure Committee is distributing this report to those agencies and individuals who are actively associated with the research work on the brittle fracture of ship plate. The report represents a progress summary of the investigation conducted by the National Bureau of Standards on steel removed from ships that suffered fracture during the period January 1942 - June 1947. This report is issued in accordance with the Committee's mission - "to disseminate pertinent information to parties having an interest in building and operating ships, and to research investigators."

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REPORT

on

Investigation of Fractured Steel Plates Removed from Welded Ships

by

Morgan L. Williams and George A. Ellinger

ABSTRACT

This report covers the examination of fractured plates selected from 60 ships in which structural failures occurred. The chemical compositions and ordinary mechanical properties of most of the plates were satisfactory and met the specification requirements under which they were purchased. However, Charpy notched bar tests indicated that the plates in which fractures originated were notch sensitive at the temperature of fracture, and plates in which the fractures ended were generally less notch sensitive. Most of the fractures occurred at low operating temperatures, and the origin of each of the fractures examined could be traced to a notch such as a hatch corner, ladder opening, or a faulty weld. Such notches and defects create regions of stress concentration which may start failures in steels that are notch sensitive at the operating temperatures.

OUTLINE AND INDEX

INVESTIGATION OF FRACTURED STEEL PLATES REMOVED FROM WELDED SHIPS.

I. Introduction

During the winter of 1942-1943 a number of welded merchant vessels and tank ships experienced serious fractures of strength members. In January 1943, one tank vessel broke completely in two at its dock in Portland, Oregon, and in March another broke in two at sea just off New York. Two cargo vessels also broke in two at sea during heavy storms in the North Atlantic and were abandoned.

Examination of the two broken tank ships by representatives of the Navy Department, the Coast Guard, the Maritime Commission, the American Bureau of Shipping, and shipbuilders indicated that the sources of these fractures were in welded joints. The assistance of the Metallurgy Division of the National Bureau of Standards was requested and portions of the welded plates containing the sources of the fractures were submitted for examination.

The initiation and propagation of fractures in welded vessels were soon found to be a complex problem involving design, construction, and material. Studies of the factors involved were undertaken at various laboratories, the National Bureau of Standards being assigned the investigation of the plates removed from the fractured ships. In order to make certain that sufficient material would be made available, the Coast Guard in November 1943 issued instructions[1] to the effect that if steel is removed in repairing a fractured ship, samples of the fractured plates should be sent to the National Bureau of Standards for investigation.

Prior to July 1, 1947, samples of steel were received from 60 ships in which fractures had occurred. These samples ranged in size from a torch cut piece 2 inches in diameter to nearly a ton of steel. In some cases several plates were sent in from one ship. Information concerning the circumstances of the

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1. Numbers refer to references listed in the bibliography.

casualties, structural features of the ships, location and extent of the fractures and other pertinent details was obtained from the cooperating agencies.

When sufficient material was available, the tests included chemical analyses, tensile tests, microscopic examination, Charpy notched bar tests over a range of temperatures and measurement of the reduction of thickness at the fracture edge.

This report includes tests made on plates selected from 48 of the 60 ships. Samples from the other ships were not included for one or more of the following reasons:

1. They were not completely identified, contained insufficient material, were warped or battered, or contained welds or torch cuts which might influence the metallurgical properties of the steels.
2. They were not particularly pertinent to the problem of hull failures.
3. They were too thin for standard specimens, particularly Charpy notched bar specimens.

II Definitions.

Certain terms used throughout this report may not be familiar to all readers. These terms and the way in which they are used are defined or described as follows:

<u>Notched bar test specimens</u>: The standard Charpy V-notch specimen was used for the notch sensitivity tests. The dimensions of this specimen are shown as type A in Figure 3 of revised Tentative Standard E23-47T, 1947 Supplement to Book of ASTM Standards, Part I A, page 387. The orientation of the length of the specimen with reference to the direction of rolling of the plate is indicated by the letters L (longitudinal) or T (transverse). The orientation of the

notch with respect to the original plate surface is indicated by the symbols ⊥ (perpendicular or ‖ (parallel) following the letters L or T. Unless otherwise specified, the data refer to L⊥ specimens, that is, specimens cut so that the length of the specimen is parallel to the direction of rolling of the plate (longitudinal) and notched on a side perpendicular to the original plate surface. The specimens were taken from points at least an inch from the fractured edge of the plates or from welds, torch cuts, or battered areas, to avoid possible effects of heating or distortion on the notched bar properties of the material. Areas which had been bent as a result of the casualty were avoided, but tests were made on plates which had been bent during fabrication, to determine the properties of these plates as fabricated in the ship.

Notched bar test refers to the measurement of the energy absorbed in breaking a notched bar test specimen at a specified temperature, the specimen being supported as a simple beam and broken with a single blow by the impact of a pendulum striking at the center of the specimen on the side opposite the notch. A pendulum type Charpy impact testing machine of 224 foot pounds capacity, with a striking velocity of 16.85 feet per second, conforming to the requirements of ASTM specification E-23-47T was used for these tests. Usually 4 specimens were tested at each temperature, and the average of the 4 values was used as the energy absorption value under the particular test condition. The test specimens were immersed in a water bath maintained at the desired testing temperature for at least 20 minutes, and were removed and tested immediately. For temperatures below 40°F, the cooling bath was a mixture of water and ethylene glycol, cooled with dry ice. In the range of testing temperatures used in this investigation, the temperature change of the test specimens, from the time of removal from the temperature controlled bath until completion of the test, was negligible.

The transition temperature is that at which, for a given plate, the notched bar test curve (energy absorbed vs. temperature of test) for L ⊥ specimens crosses the line of 15 foot pounds energy absorption.

The failure temperature is that of the air or water at the time of the casualty involving the plate under consideration. In Figures 11-16 and in Table 3, the water temperature (W) is used for plates below or near the water-line and the air temperature (A) for plates definitely above the water line.

The reduction at fracture is the difference between the average thickness measured as near as possible to the fractured edge and the average plate thickness an inch or more away from the fracture, expressed as a percentage of the plate thickness.

Fracture in plates tested: The plates for which definite information regarding the fracture was available were classified in three groups, as follows:

(1) Source: Plates in which the ship fractures originated. This group includes some plates which contained both the source and the end of a short fracture, and also plates in which the fracture originated near a weld. However, if the fracture originated in a weld due to insufficient weld metal, poor fusion or slag inclusions, the adjoining plates were not included in this group.

(2) Thru: Plates which were fractured in the ship failures, but which contained neither a fracture source nor a fracture end.

(3) End: Plates in which the ship fractures ended, and which did not contain a fracture source.

A notch[2] may be defined as any discontinuity. As used in this report, a notch means a structural discontinuity, such as is occasioned by hatch openings, sheer strake cutouts, foundations, vent openings, bilge keels, the abrupt terminations of structural members, etc., and imperfections in the structure resulting from fabrication, such as peened-over cracks, undercut welds, porosity and inclusions in welds, and incomplete penetration which leaves voids at the center of the joint.

Notch sensitivity[2] may be defined as the property of a material which reflects its reluctance to absorb energy in the presence of notches and other strain inhibitors, such as low temperature and high rates of strain.

III Origin and Propagation of the Fractures

During the period (Jan. 1942 - June 1947) covered by this report at least 15 ships broke in two or were lost as a result of structural failures. From November 1942 thru March 1946 there were 132 major casualties and more than 1300 casualties of a less serious nature[2]. Figure 1 is a typical example of a completely fractured ship.

A list of the 48 vessels discussed in this report, and a brief summary of the available information regarding the casualties are given in Table I. The vessels were of several different types, and had been built at several yards. Some of the vessels had previous casualties as indicated in the table. The age of the ships (months afloat) at the time of the casualties ranged from one minute (after launching) to more than seventeen years. Most of the vessels were built during the war, and the majority were less than three years old when failure occurred.

Three of the casualties resulted from ice damage, one from a minor collision with a tug while docking, and one from an underwater explosion. The other casualties occurred under normal operating conditions or in a few cases during building or alterations. The weather and sea conditions at the time of the casualties ranged from calm, in port, to heavy storms, at sea.

Most of the casualties occurred at low temperatures. In some cases, the fractures were not found immediately and the temperatures reported were probably those existing at the time of their discovery. The highest temperature at which a fracture is definitely known to have started is 58°F, and the lowest, 20°F. Most of the fractures occurred between 30° and 40°F.

The locations of the starting points of the fractures in the ships represent a fairly complete sampling of the various starting points found in the much larger number of casualties analyzed in the Report of the Board of Investigation[2]. All of the fractures originated at points of stress concentration or structural notches. This, together with their occurrence at low temperatures, indicated that they were caused by stress concentration in steel which was notch sensitive at the operating temperatures. The most serious aspect, however, is not the fact that fractures start at structural notches, but that in a notch sensitive steel a crack, once started, is virtually self-propagating, since the crack itself forms a very severe notch. Five of the ships discussed in this report broke completely in two, and in five others complete fractures of the strength deck or of the bottom occurred, largely as the result of the propagation of a small initial crack from one plate to the next.

The importance of notch sensitivity and structural notches as factors contributing to the failures of welded ships was pointed out as early as May 1943, in the following paragraph of a report from this Bureau[3] to the Coast Guard:

"The notch sensitivities of these steels are not peculiarities of these particular materials since most hot rolled steels are notch sensitive at low temperatures. The obvious solution of the prevention of similar failures in other vessels of this type would be to provide as low stress concentration as possible by the use of proper welding techniques and sequences and by the elimination of structural notches. Proper techniques and sequences may be outlined in the original layout of procedure and then rigidly adhered to during the fabrication of the vessel. The structural notches may be eliminated by fairing the changes in structural sections into curves instead of angles."

The use of some form of crack arrestor to stop the progression of a fracture was suggested in August 1943 in another National Bureau of Standards Report[4]:

"The design of the vessel did not provide intervening structural members in a longitudinal direction to stop the progression of a fracture of this type. It is therefore quite probable that any fracture once started would progress uninterrupted until the vessel became a total casualty. Fractures start at points of high stress concentrations and must occur in areas where stress raisers are present. Defective welds provide excellent stress raisers and may generally be expected to cause stress concentrations of high order from which fractures may start and failures result. Since defective welds may be present in any vessel, it would be highly desirable to change the design so as to provide some means of preventing the progression of fractures into a complete failure."

One of the preventive measures taken subsequently (in vessels already built and in new construction) to stop the progression of fractures, was the installation of riveted straps covering a longitudinal slot in the deck or the sheer strake. These crack arrestors have been very effective in limiting the spread of fractures[2]. This shows quite conclusively that the propagation of the fractures was not a direct result of the loss of the strength and support of the structural members initially fractured, but was due primarily to notch sensitivity and to the fact that the fracture itself, as it propagates, carries its own notch along with it until the continuity is broken

? How about energy locked up in the system?

A third report from this Bureau[5] in June 1945, pointed out the fact that the ordinary static tension tests are wholly inadequate for the procurement inspection of steel, since these tests provide no indication of the notch sensitivity of the steel, nor of the temperatures at which it might become notch sensitive. This report also emphasized the importance of notch sensitivity and of low temperatures as contributing factors in the failures.

IV Examples of Typical Fractures.

It is probably unfortunate that ship construction requires large amounts of welding at points of geometrical discontinuity, since in many cases the welding is blamed for a failure which is really the result of stress concentration at a structural notch. While some fractures originated in defective welds, most of them started in structural notches in which welding was not the primary contributing factor. Typical examples of fracture sources, some starting as a result of welding operations and others in which welds were not involved, are shown in Figures 2 to 9 inclusive.

A small crack originating at a sharp corner in a cutout for a ladder opening in the sheer strake of a Liberty ship, type EC2-S-C1 is shown in Figure 2. Similar cracks were found in both the port and the starboard ladder openings of this vessel and although they had progressed only about one inch when discovered, they did form severe notches, which might have led to more serious failures. The openings had been made by hand torch cutting, and subsequently dressed by grinding. Several deep notches, however, still remained on the edges. The fracture, indicated by the arrow, was located at a sharp change in section, which was further aggravated by rough notches resulting from the flame cutting operation.

Another fracture also starting at a cutout in the sheer strake is illustrated in Figures 3 and 4. The source of this fracture (Figure 4) was at a sharp change in section at the toe of a fillet weld between the sheer strake (below) and the end of an insert plate (above). A small globule of weld metal (arrow) probably formed by the touching of the electrode to the plate was adjacent to the crack. The heat affected zone under this globule was quite shallow and was about the maximum hardness for this type of steel (Knoop number 400) indicating very rapid cooling and providing a metallurgical notch in addition to the geometrical notch at the change in section. The edge of the sheer strake plate at this point had been prepared by machine gas cutting. A notched bar test specimen taken from a point very close to this edge had an energy absorption only 60 per cent of the average energy absorption of three similar specimens taken from the interior of the plate and tested at the same temperature (70°F). This indicates that the notch sensitivity of the steel, which was already high, had been increased in the region of the flame cut edge by the heating during the cutting operation. The origin of this fracture was attributed to a combination of factors: (1) A notch sensitive steel, with the notch sensitivity at the edge of the plate further aggravated by heating incident to the flame cutting of the edge. (2) Stress concentration at a geometrical notch or sharp change in structural section. (3) A metallurgical notch near the geometrical notch. (4) Low temperature (45°F) and (5) rough seas and a strong wind(force 9) causing unusual stresses in the structure of the ship.

A typical example of a fracture originating at a hatch corner is shown in Figure 5. On this ship, similar fractures originated in the 1-1/4 inch deck insert plate at both the port and starboard after corners of No. 3 hatch. The starboard fracture ended at a bollard on the deck stringer which acted as a re-enforcement. The port crack progressed across the deck to the sheer strake and down the side into the H strake. The hatch end beams and coaming, and the deck in way of the hatch openings, did not fracture except for a few inches near the hatch corners.

A small fatigue fracture is shown in Figure 6. This is the only fatigue fracture which we have ever found in weld metal, and we have never found the characteristic markings of a fatigue failure in any of the fractured hull plates which we have examined.

A fracture in the shell plating of a tanker which broke in two at sea is shown in Figure 7. The herringbone markings on the fractured edge clearly indicated the source of the fracture in the shell plate, at the point marked by arrow A. This point, about 2-1/2 inches from a transverse bulkhead (punch-marked BHD in the photograph - top right), was 14 inches below the seam of D and E strakes, and was exactly at an end of a longitudinal. The end of the corresponding longitudinal on the other side of the bulkhead is indicated by arrow B in the photograph. The longitudinals here were interrupted for a space of about 6 inches to allow for insertion of the transverse bulkhead, and were connected through this bulkhead by gusset plates on the flanges of the longitudinals. The longitudinals were rigidly connected to the shell plating by fillet welds all around. The ends of these longitudinals were not rounded or tapered, but were cut square and perpendicular to the shell plating. This condition constituted a structural notch at the abrupt end of the longitudinal stiffener.

his ship was ilt in the very arly days of welding — TS

A sample of shell plating from a Coast Guard Cutter which was fractured while navigating through an ice pack is shown in Figure 8. There were two sources of fracture in the plate, indicated by arrows; No. 1 about 1/8 inch in from the toe of the weld and No. 2 about 1/2 inch from the weld. Both sources were at small weld globules in the plate where arcs had been struck. Several other examples of fractures starting in arcs struck on the plate metal adjacent to the weld have been observed. A number of fractures also have been found which had their origin in small welds on heavy plate, such as light tack welds or welds for the attachment of small clips.

An example of a faulty butt weld in a bulwark cap rail is shown in Figure 9. The edges of the plate were rough and not properly beveled and the weld metal did not penetrate to the center of the joint. The full strength of the joint was not attained, and the weak joint was at a highly stressed part of the vessel (the extreme fibers of a beam). The herringbone markings in the bulwark plate, at the right in the photograph, indicate clearly that the fracture originated in the faulty weld of the bulwark cap rail.

V Examination of Fractured Edges

The fractures in the plates which were examined were predominantly of the brittle or cleavage type, showing little or no evidence of ductility or reduction of thickness at the fracture edge. These cleavage fractures were approximately at a right angle to the plate surface and usually bore characteristic herring-bone markings. In a few instances parts of the fracture edges were of the shear type, having some reduction of thickness near the fracture, and usually showing some evidence of ductility by the cracking of the paint and scale for some distance from the fracture. The shear type fractures were usually associated with the presence of rivet holes or openings, bending of the plate, or the ending of a fracture and were generally found in thin plate. In the plates examined at this laboratory, shear type fractures were not found in plates more than 5/8 inch thick, except in one case, a deck plate (#46 C, Table 2) 13/16 inch thick, which had a shear type fracture intersecting a brittle fracture at nearly a right angle. Only one of the plates tested (#20B, Table 2) had a fracture which was entirely of the shear type in the sample received for examination.

The starting points of the fractures were found by means of the herringbone markings on the edges of the fractured plates, as illustrated in several of the photographs previously discussed.

The herringbone type of fracture was observed and reproduced in this laboratory many years ago in tests conducted to determine the source of a brittle failure in an aircraft part. The results of these tests were discussed in our first report on examination of steels from a fractured ship[3] from which the following paragraph is quoted:

"....This type of pattern is found only in tensile fractures which originate at notches. The source of the 'herringbone' type of fracture has been established at this Bureau by tensile tests of notched plate specimens. The apex of the herringbones has always been found to originate at the notch and to point directly to it. Failure is usually sudden and with little or no evidence of ductility. A brittle fracture of this type may be produced in a ductile metal by applying a tensile stress to a notched specimen. Consequently the origin of such fractures may be found by the examination of the fracture faces."

A typical end of a fracture in ship plate is shown in Figure 10. The original crack had rusted, and appears dark in the photograph. The lighter portion at the right was broken in tension in the laboratory. Herringbone markings, pointing to the left, can be seen in both the old and the new portions of the fracture. The original fracture had progressed somewhat farther at the center of the plate than at points nearer to the plate surfaces, resulting in a semicircular or oval shape at the end of the fracture. Similar oval shapes, of varying symmetry and convexity, were observed at every fracture end which was examined, and in every case the fracture was less advanced at points near the plate surfaces. The herringbone markings were approximately perpendicular to the oval shapes at the fracture ends, suggesting that these markings were probably the traces of irregularities in the advancing fracture front.

It was also noted that the apex angles of the herringbones were not the same in different plates or even in different parts of the same plates, but the cause of these variations is not known at present.

Semicircular or oval markings, similar to the shape of the end of a fracture, were observed in several of the fractured plates. Often these marks were accompanied by a difference in the degree of corrosion of the fracture edges, or by a slight change in direction of the fracture, indicating that the fracture had stopped temporarily at that point, and had progressed further at a later time or under different stress conditions.

VI Descriptions of Individual Plates.

Descriptions of the plates and a summary of the results of some of the tests are given in Table 2. The number (first column) assigned to each vessel is the same as that used in Table 1. (The names of the vessels are omitted, but the vessels are identified by type.) Since several plates from some of the vessels were tested, an identification letter is also assigned to each plate as listed in Table 2. In the charts and tables to follow, the plates will be identified by the "plate number" consisting of the ship number from Table 1 or Table 2, and the letter designating the plate as described in Table 2. In the second column of this table, the type of the vessel is given and the plates which were tested are described by name and number or by their location in the vessel. In column 3, the classification of the ship fracture in each plate is indicated as previously defined under "Fracture in Plates Tested" in Section II of this report. There are numerous blank spaces in this table, because many of the samples received were not suitable for all of the tests, or were too small to provide a sufficient number of test specimens.

VII Relation of Notch Sensitivity to the Failures of the Plates in Service.

Early in the investigation it became apparent that there were no obvious relationships between service fractures and the chemical compositions, static tensile properties, or the normal microstructures of the plates (at points some distance from the fractures). However, it was observed that the plates in which the ship fractures ended showed higher energy absorption in the notched bar impact test than those in which a fracture started. Therefore, the plates for which definite information was available were classified into three groups, those in which a fracture ended, those which contained a fracture source, and those which fractured completely through but which contained neither a source nor an end of a fracture. Later, a further subdivision was made on the basis of plate thickness, as a statistical check, and also because it had been observed that the plate thickness appeared to be a contributing factor in the notch sensitivity of the steels. The division on the basis of plate thickness was made, arbitrarily, at 3/4 inch, in order to obtain groups including approximately equal numbers of specimens.

The Charpy notched bar properties at various temperatures of plates which contained a fracture source are shown in Figure 11. The upper portion of the figure contains the curves for 9 plates 3/4 inch and over in thickness while the lower portion contains those for 10 plates less than 3/4 inch thick.

The two vertical bars superimposed on each group of curves show the ranges of the average energy absorption of the steels, at test temperatures of 30°F and

70°F, for each group of plates. The horizontal bars show the ranges of the transition temperatures for the steels in each group. The temperature at which the energy absorption was 15 foot pounds, (determined from the notched bar test curve for each steel) was taken as the transition temperature of the steel. This provides an index of the notch sensitivity which is relatively easy to determine from the numerical quantities derived from the tests, and which is free from the personal factors involved in determination of the transition from ductile to brittle fractures by examination of the fractured surfaces. Fifteen foot pounds appears to be a reasonable value based on experience in the field, and is the minimum acceptable value specified for Charpy notched bar tests under the ASME Boiler Code.

The reported temperatures at which the ship failures involving these plates occurred are indicated by the letter T above the corresponding curve, and the corresponding energy absorptions for each plate (determined from large-scale drawings of the curves) are shown in the second last column of the tables above each group of curves. The water temperatures reported at the time of the casualties were used for plates below or near the waterline, and air temperatures for plates definitely above the waterline, as indicated by the letters A (air) or W (water) in the third column of the tables. Other quantities, either measured or derived from the curves, are also shown, for each plate, in other columns. The average values of these quantities, and the range of values, for each group of plates are shown at the bottom of the tables.

It may be noted that for these two groups of plates, in which ship fractures originated, the lowest transition temperature is 69°F, and that the highest energy absorption at 70°F is 15.2 foot pounds.

Two similar groups of curves, plotted on the same scale, for 9 plates 3/4 inch and over in thickness and for 16 plates less than 3/4 inch thick, which were completely fractured in the ship failures, but contained neither the source nor the end of a fracture (designated as the fracture thru groups) are shown in Figure 12. Note that the ranges of the transition temperatures for both of the plate thickness groups, indicated by the horizontal bars, are farther to the left, or toward lower temperatures, than those of the preceding figure, and that the ranges of energy absorption, both at 30° and at 70°F (vertical bars) are higher.

Similar groups of curves, for plates in which the ship fractures ended, are shown in Figure 13. The transition temperatures are still lower, and the ranges of energy absorption are higher, compared to the two preceding figures. This indicates that relative notch toughness of these steels was a contributing factor in halting the propagation of the fractures, just as notch sensitivity was a factor in the origin and propagation of the fractures.

Summaries of the data derived from the tables and curves of Figures 11, 12 and 13 are given in Table 3, and in Figures 14 and 15. These show a very definite relation between the nature of the fractures which occurred in the ship plates in service and the notch toughness of the same plates as measured by the notched bar test.

The 15 foot pound transition temperatures for the six groups of plates are compared in Figure 14. The horizontal bars, taken from the three preceding figures, represent the range of transition temperatures for each group, and the circles above the bars indicate the average transition temperatures for all plates in the group. The vertical lines in the bars, including the ends, represent the transition temperatures of individual plates. For plates 3/4 inch and over in thickness the average transition temperature for the fracture source group was higher, by 27°F, than the average for the group of plates in which the fractures ended, and the average for the fracture thru group was between the two. For the plates less than 3/4 inch thick, the difference is even more pronounced; the average transition temperature for plates in which the ship fractures originated was 112°F, and for plates in which the fractures ended the average was 53°F, a difference of 59 degrees.

In Figure 15, the horizontal bars represent the range of values of energy absorption at the temperatures of the ship failures, for each of the six groups of plates. The vertical lines in the bars indicate the energy absorption of individual plates, each at the temperature of the ship failure involving that plate. The circles above the bars show the average energy absorption for all plates in the respective groups. The ranges and averages of the failure temperatures for the different groups were nearly the same, as may be seen in Table 3 and in the tables above each group of curves in Figures 11, 12 and 13. For the plates 3/4" and over in thickness, the average energy absorption, at the failure temperatures, of 8 plates in which fractures originated was 7.0 foot pounds. The average energy absorption of eight plates in which the fractures ended was 57% higher or 11.0 foot pounds. For the plates less than 3/4" thick, the value of the average energy absorption of plates in which the ship fractures ended was more than twice that for plates in the fracture source group, the averages being 5.9 foot pounds for 8 plates in the fracture source group, and 12.2 foot pounds for 9 plates in the fracture end group. In spite of the rather large scatter of the values of energy absorption within each group, a very definite difference between the "fracture source" and "fracture end" groups is indicated also by the fact that both the upper and the lower limits of the ranges of energy absorption show the same trend as pointed out above for the average values. It should also be noted that (for both the thick and the thin plates) the higher limit of the range of energy absorption values for plates in the fracture source group was lower than the average for the fracture end group, and the lower limit of the range for the fracture end group was higher than the average for the fracture source group. The data obtained from notched bar tests therefore indicated that, in the range of temperatures at which the failures occurred, the plates in which the ship fractures ended were capable of absorbing considerably more energy than the plates in which ship fractures originated.

The ranges of the transition temperatures and of the energy absorptions for the various groups of plates, as shown in Figures 14 and 15, overlap somewhat, and indicate a rather large degree of scatter, but this is to be expected. The fractures in the ships were not controlled laboratory experiments, and many unknown factors contributed to the origin, propagation, and stopping of the fractures. The magnitude, direction, and duration of the forces acting on each plate at the time of failure were unknown; the reinforcing effect of nearby structural members or welds cannot be calculated in a structure as complex as a ship; and comparatively little is known about the effects of multiaxial and residual stresses, the interaction of elastic waves in the steel, temperature differences in different parts of the structure, sudden temperature changes and other factors.

The curves for several plates which were not included in the above analysis, either because the plates tested had not been fractured in the ship failures, or because of unusual circumstances of the failures involved are shown in Figure 16.

The upper curve, 38B, represents the plate which had the lowest transition temperature of any of the ship plates which were tested. This plate did not fracture, although fractures occurred in three adjoining plates. The dotted curve, 38A, shows for comparison the notched bar test data for one of these plates which fractured through. The fracture originated in a faulty butt weld between these two plates, near a seam weld. The weld bead, for a few inches, had been laid on the edge of plate 38B instead of in the joint, with resulting poor penetration in plate 38A. Near the point where the weld became more sound, as evidenced by a half inch jog of the weld bead, the fracture turned into plate 38A and progressed nearly parallel to the butt joint and one to three inches from the weld. The fact that the propagation of the fracture continued in plate 38A nearly parallel to the weld suggested that the fracture had followed the path of least resistance, since apparently the forces causing propagation of the fracture had not changed direction. The notched bar tests of these plates showed that although the notch toughness of plate 38A was comparatively high, that of adjoining plate 38B was much higher. At the failure temperature, 42°F, the energy absorption was 13.0 foot pounds for plate 38A, which fractured, and 25.4 foot pounds, for plate 38B, which did not fracture.

Curve 1A (Figure 16) represents a plate in which a fracture originated at the end of a bilge keel as a result of an underwater explosion which destroyed the propeller and the rudder and cracked a number of plates at the stern of the ship. The transition temperature for this plate was 41°F, much lower than for any of the plates tested in which fractures originated under normal operating conditions.

Plate 22A was not fractured, but was tested because it contained a slight indentation or buckle which appeared to have some relation to a small crack in a nearby plate. The transition temperature, 59°F, was in the range found for the fracture thru and fracture end groups, but was lower than that found for plates in which fractures originated.

Plate 27A contained the source and both ends of a semicircular fracture which resulted from a minor collision with a tug. The transition temperature, 80°F, was in the same range as that found for plates in which fractures originated, and indicated rather high notch sensitivity.

Plate 14B and 14A from a Coast Guard Cutter contained a semicircular fracture, similar to that in the preceding case. These plates were damaged by contact with ice, below the ice belt of the vessel. Two fracture sources were found in plate 14A, both at small arc craters (Figure 8). The transition temperature of this plate was 147°F, indicating a high degree of notch sensitivity. The transition temperature of plate 14B was also high, 111°F. These two plates were not included in the preceding statistical summary because the casualty resulted from a collision and also because the plates were thin and badly corroded, necessitating the use of notched bar test specimens which were slightly subsize in width.

A summary of the fracture data and the notched bar properties of each of the 72 plates for which the transition temperatures were determined is given in Table 4. These data were tabulated in the order of increasing transition temperatures. An inspection of the data indicated considerable scatter in the results, and plots using individual values were difficult to analyze. Consequently the data were assembled into successive groups of 9 and the averages of these groups were analyzed for definite trends.

It will be noted that there were no fracture sources in any plates with transition temperatures below 69°F, except for one resulting from an explosion. Also fractured plates which had a large reduction in thickness at the fracture generally had low transition temperatures. Both of these facts indicate that ductility is associated to some extent with low transition temperatures.

It is also observed that the thicker plates generally had higher transition temperatures.

The last 4 columns of this table give the energy absorption at 70°F for various specimen orientations. This will be discussed in section XII-D of this report.

VIII Tensile Properties of the Steels.

The specifications for steel for hull construction in effect at the time of purchase of most of these steels[6] were predicated on a heat sampling basis and included only a cold bend test and a tensile test. For plates not intended for cold flanging, the tensile requirements (using standard full plate thickness, longitudinal, 8" gage length coupons) were:

Tensile strength: between limits of 58,000 and 70,000 psi.

Yield point, minimum, psi: 0.5 tensile strength.

Elongation in 8", minimum, percent: 1,500,000./tensile strength.

Tensile tests were made on all plates from which sufficient and suitable material was available. Several different types of specimens were used, because of the wide variety of shapes and plate thicknesses of the samples received. Most of the samples were too small to obtain standard 8 inch gage length longitudinal specimens, and in many cases full plate thickness specimens could not be used because of corrosion of the plate surfaces. Consequently the majority of the tensile tests were made with smaller specimens. Only the results of tests of .505 inch diameter x 2 inch gage length machined specimens are shown in Table 5.

The tensile tests of samples from the fractured plates indicated that the plates which failed in service would probably have passed the acceptance tests required at the time of purchase. The few plates which failed by a narrow margin to meet the requirements for tensile properties showed no definite relation to the types of service failures. However, in analyzing these data, due consideration should be given to the following facts: (a) Because of size effects and the fact that plates, especially those of rimmed steel, are not homogeneous through the plate thickness, tensile tests made with specimens smaller than the 8" gage length full plate thickness specimen usually show a slightly higher yield strength and tensile strength, and a much higher percentage of elongation. (b) Hot rolled plates are not homogeneous through the width of the plate, or in different plates from the same heat. (c) In some cases the samples had been heated by welding or flame cutting, or had been deformed in fabrication, subsequent operation or incident to the casualty, and thus were not in the original hot-rolled condition.

The data for the 42 plates on which these tests were made are listed in Table 5 in the order of increasing transition temperatures of the plates, and averages were calculated for seven successive groups of six plates each. Since, for some of these plates, tensile test specimens for both the longitudinal and the transverse directions of the plate could not be obtained, the averages for each group were calculated separately for specimens taken from the plates in each direction. Thus, in the second and third columns of Table 5, two averages for the transition temperature and for the plate thickness are shown for each group. The "L" averages are for the plates from which longitudinal specimens were tested, and the "T" averages include only the plates in the group for which transverse tensile tests were made. In the group averages, equal weight was given to the value found for each plate, regardless of the number of specimens tested for that plate. The fourth column of the table shows the number of longitudinal (L) and transverse (T) specimens from each plate which were tested in the as-received condition at room temperature. The data shown in the following columns are the average values for all of these specimens for each plate. The ratio of yield point to tensile strength is shown as an index of the compliance with the specification requirement for the yield point, which states that the yield point shall not be less than 50% of tensile strength. The last numerical columns of the table show the product of the percent elongation in 2 inches and the tensile strength. The specification requirement for elongation may be restated "the product of the tensile strength and the percent elongation in 8 inches shall be not less than 1.5×10^6." The elongations shown in this table are for 2 inch gage length machined specimens, and therefore these elongations, and also the products of elongation and tensile strength, should be greater than the specification requirement, which was stated for 8 inch gage length, full plate thickness specimens. However, for all of these plates, the elongation in 2 inches, and also the reduction of area, were sufficiently high to indicate satisfactory ductility in the static tension test. Minor deviations from the specification requirements for tensile strength and yield point, for both longitudinal and transverse specimens, are indicated in the "remarks" column of Table 5.

The relations between transition temperatures of the plates and the tensile test data for standard .505 inch diameter test specimens, are shown in Figure 17. The relations between the average 15 foot pound transition temperatures and the average longitudinal tensile test properties are shown in the curves at the left of Figure 17, and similar curves for the transverse tensile test properties are on the right. The plotted points on the curves represent the average values of transition temperatures and of the various tensile test properties for groups of 6 plates, tabulated in the order of increasing transition temperatures of the plates (from Table 5). The only apparent relation between the transition temperatures and the properties determined from the tensile tests is in the ratio of yield point to tensile strength. The average curves for the yield/tensile ratio, for both the longitudinal and the transverse tensile tests, show a consistent decrease in this ratio with increasing transition temperatures of the plates. However, there is some scatter in individual values, as may be seen in Table 5, and there is no sharp demarcation between plates with high and low values of the yield/tensile ratio.

The cold bend tests were not generally made on the failed plates, because in most cases the samples received were badly corroded and a fair test could not be made on a full plate thickness specimen. Frequently the limited amount of material available could be used to better advantage for other tests.

IX Chemical Compositions of the Steels.

The chemical compositions of the fractured plates are given in Table 6. The analyses were made at three different laboratories, as indicated in the third column of the table by the abbreviations:

Phila. (Industrial Test Laboratory, Philadelphia Navy Yard)

N. Y. (Material Laboratory, New York Naval Shipyards)

NBS (Chemistry Division, National Bureau of Standards)

Spectroscopic determinations are indicated by an asterisk (*) following the numerical value for each element so determined.

The data were tabulated in the order of increasing transition temperatures of the plates, as in the preceding tables, and averages were calculated for eight successive groups of nine plates each. In calculating the averages, the symbols indicating "not more than" (<) were disregarded, so the figures indicating the averages may be considered as the upper limit of the average value for each group.

The ratio of manganese to carbon in a steel has been suggested as a factor in the notch toughness of the steel. This ratio was calculated for each plate and is shown in the last column of the table.

Determinations by the vacuum fusion method of the hydrogen, oxygen, and nitrogen content of samples from each of the plates were planned, but shortage of personnel has prevented completion of this work.

The average percentages of the various constituents for each of the eight groups of plates (from Table 6) were plotted against the average transition temperatures of the groups, and curves were drawn for each of these constituents as shown in Figure 18. In the range of the chemical compositions of these plates, the influence of any individual element is not uniquely significant. The transition temperatures appear to be higher with increasing contents of carbon, phosphorus, arsenic, and molybdenum, but in every case the scatter within individual groups (Table 6) was greater than the range of the averages for the eight groups. Similarly, the average curves for manganese and silicon show a general downward trend with increasing transition temperatures of the plates, but there was a large scatter within individual groups. For example, in the case of manganese, the highest group average is .450 for the second group, and the lowest is .380 for the last group. Within the first group, however, the range of scatter is from .33 to .54, and for the last group, .29 to .53. Thus the ranges of manganese content in the groups of plates with the highest and the lowest transition temperatures, respectively, are very nearly the same, and both of these ranges completely overlap the ranges of the group averages. It is evident from inspection of these curves and of the individual values in Table 6 that no single element had any marked effect on the transition temperatures.

The dotted curve in the left half of Figure 18 represents the relation between the averages of the Mn/C ratios for the eight groups of plates and the average transition temperatures. The scatter of the values of this ratio for individual plates is somewhat less than the scatter observed for the separate chemical elements, but is still too great to permit use of the Mn/C ratio alone as a criterion for the notch sensitivity of the steels. The number of plates which would be rejected from each group of 9 plates in Table 6, for various minimum values of the Mn/C ratio is given in Table 7.

Table 7. Effect of Various Minimum Requirements for the Mn/C Ratio, for the 72 Plates Tested.

Minimum Mn/C Ratio	Number of Plates Rejected (Groups of 9 Plates) Low - - - - - Transition Temperatures - - -High 1	2	3	4	5	6	7	8	Total Rejected	% Rejected
1.50	0	0	2	1	1	5	2	6	17	24
1.60	0	0	2	2	3	5	2	6	20	28
1.70	1	0	2	3	5	7	2	6	26	36
1.80	2	1	2	7	6	7	4	7	36	50
2.00	4	3	6	8	7	8	6	8	50	69
2.20	5	9	8	9	9	9	8	9	66	92

This tabulation shows that among the 72 plates under consideration, there was no sharp demarcation between plates with low or high transition temperatures, for any minimum requirement which might reasonably be selected for the Mn/C ratio. However, it may also be noted that for each of the minimum values of the ratio shown in Table 8, the number of plates which would be rejected was greater for the groups with high transition tempertures than for the groups with lower transition temperatures. For example, 36 of the 72 plates, or 50% of the total number of plates, would be rejected if a minimum Mn/C ratio of 1.80 were required, but only 12 of the rejections would be among the 36 plates with transition temperatures below 75°F (first four groups of Tables 6 and 7), and 24 of the 36 plates with transition temperatures above 75°F (groups 5-8) would be rejected. In other words, two thirds of the plates with high transition temperatures, and only one third of the plates with lower transition temperatures would be rejected under a requirement that the manganese content should be 1.80 times the carbon content of the steel.

This indicates that a low ratio of manganese to carbon might be one factor contributing to notch sensitivity, but not the sole controlling factor in the range of the chemical compositions of the steels under consideration (see Table 6).

X Microstructure

Specimens for microexamination were cut from each of the plates which contained a fracture. Generally several specimens were selected, one from the source of the fracture and others at various locations along its path. The metallographic features such as grain size, inclusions, banding and the like were noted and any unusual features are recorded in Table 2.

The microstructures were those of commercial quality hot rolled carbon steel plates. A few steels contained large numbers of non-metallic inclusions, while a few others were excessively banded, but in general the microstructures were satisfactory for this type of material. Several of the steels were of rimming origin as indicated by the carbon free rims on the surfaces of the plates. Most of the steels were judged to be semi-killed (later confirmed by chemical analysis).

Two unusual features were found in most of the specimens. These were Neumann bands, shown in Figures 19 and 20, and directional cracks, shown in Figures 20 to 24. Usually both features were present in a specimen containing a cleavage fracture, infrequently only one was found, and in one specimen neither was observed. In no case was either Neumann bands or directional cracks found in fractures of the ductile or shear type.

Neumann bands, or deformation twins, are formed at room temperature by impact or shock or at low temperatures by slow deformation. The method of formation or the reason for it is not exactly known but their presence is always associated with "brittle" metal. The more brittle the metal, the more readily the twins are formed. They are frequently observed in bismuth and certain silicon steels broken in tension at room temperature. To our knowledge they are not observed in metals which are ductile and non-notch sensitive at low temperatures.

They were found only near the original cleavage fracture in the ship plates, generally not more than 1/4 inch away, but occasionally as far as 1 inch. Neumann bands have not been observed in pearlite areas but only in the ferrite.

Numerous "secondary" directional cracks were found in most of the specimens containing cleavage fractures. These cracks are believed to have been formed at the same time and in the same manner as the original fracture. They usually are straight and in the same direction within a given grain, but change directions when going from one grain into another. This implies that these cracks are directional and that separation occurs on definite crystallographic planes. This separation is probably cleavage or parting, quite likely on the cleavage planes of the crystal.

Occasionally the cracks are so numerous and so close together as to form a zone of shatter (Figure 22). When this occurs, the metal between the cracks is very much distorted, showing distinct evidence of cold working. Another interesting phenomenon was the apparent displacement or slip of metal along the cracks indicating the adjustment of stresses in the immediate vicinity of the crack. Good evidence of this is shown in Figures 23 and 24.

XI Notch Sensitivity in Materials Other than Ship Plates.

The phenomenon of notch sensitivity is not peculiar to ship plate alone, and is not confined to metals. The scoring of glass in glass cutting, the perforation of postage stamps, the notching of cellophane wrappers, and the grooving of chewing gum and candy bars are familiar examples in which this phenomenon is utilized in non-metallic materials, to control the location or direction of a tear or fracture. In the foundry, notches are sometimes cast in the gates and risers of a casting so that they may be broken off easily, and in the shop and building trades metallic and non-metallic materials are often broken by first scoring or nicking at the desired location of the break.

A number of failures resulting from notch sensitivity have been observed at this laboratory in metallic materials other than ship plate. Brittle fractures in machined or forged parts such as gears, propellers, axles or crankshafts occur frequently. In several such parts it was found that fatigue cracks had formed very sharp notches, and that the remainder of the part had failed with a brittle herringbone type of fracture which originated at the notch formed by the fatigue crack. More frequently, however, there was no evidence of fatigue, but in every case examined the herringbone fractures could be traced to an origin at a notch resulting from design, machining, forging, welding, or internal defects. In the usual static tensile tests, material from the fractured parts generally showed apparently normal ductility in the absence of notches. However, notched bar impact tests, or tests of notched tensile specimens indicated that the material was notch sensitive, as illustrated by the following examples:

(1) An aircraft propeller hub had failed with a brittle herringbone type of fracture which originated at a sharp notch formed by a fatigue crack, which in turn had originated at a machined notch. The herringbone fracture was reproduced in this laboratory by breaking a notched specimen of the material in tension. The notched specimen showed practically no elongation or reduction of area, whereas an un-notched specimen of the same material showed evidence of good ductility.

(2) A cast steel hook from a 20 ton hoisting rig had failed with a cleavage type of fracture, showing practically no elongation or reduction of thickness. The average tensile strength of two specimens from the fractured hook was 139,000 psi. and the yield strength was 72,400 psi., both higher than the nominal properties of the steel. The elongation was 12.2% (measured on specimens .357 inch diameter x 1.4 inch gage length) and the reduction of area was 13.4%; both

lower than the nominal properties, but still high enough to indicate some ductility. A third tensile specimen had somewhat lower yield strength and tensile strength, and the elongation and reduction of area were considerably less (9.3% and 8.7% respectively). Examination of the fracture of this specimen revealed an internal flaw as the source of the premature fracture in the tensile test. The energy absorbed in notched bar tests of Charpy V-notch specimens was low, 6.6 foot pounds at 70°F, and the 15 foot pound transition was above 200°F, indicating that the steel was extremely notch sensitive at the operating temperatures. The casting contained a number of shrinkage cavities which could have acted as internal notches.

(3) A 100 pound kedge anchor failed with a brittle fracture at the junction of the shank and the crown when a 36 foot motor lifeboat was forced to anchor during a storm because of engine trouble. Tensile tests were made on standard .505 inch diameter specimens removed from the 2 inch diameter shank of the anchor, about 8 inches from the fracture. The average tensile properties were:

Yield point	29,300 psi.
Tensile strength	43,100 psi.
Elongation in 2 inch	50.5%
Reduction of area	79.6%

Notched bar tests were made on longitudinal V-notch Charpy specimens taken from the forged part of the shank adjacent to the fracture, and from the round shank just above the forged part. Results of the notched bar tests are shown in Table 8.

Table 8. Results of Notched Bar Tests of Specimens from Shank of Fractured Anchor.

Specimen	Test Temp °F	Energy Absorbed Ft. Lbs.	Remarks
Specimens from forged part adjacent to fracture (Notches at center of specimens about 1-1/2 inches from fracture)			
A1	70	3.9	Completely brittle fracture

Table 8 - continued.

Specimen	Test Temp. °F	Energy Absorbed Ft. Lbs.	Remarks
Specimens from forged part adjacent to fracture (Notches at center of specimens about 1 1/2 inches from fracture)			
A5	70	4.4	Completely brittle fracture
Ave.	70	4.2	
A3	160	10.7	Very slight necking
A6	160	9.6	" " "
Ave.	160	10.2	
A2	212	26.9	Partially ductile fracture
Specimens from round part of shank (notches about 4 inches from fracture)			
A9	70	4.8	Completely brittle fracture
A10	160	32.8	Partially ductile fracture
A7	212	79.7	Very ductile fracture
A8	212	45.7	Partially ductile fracture
Ave.	212	62.7	

Although the tensile strength of the steel was low, the elongation and reduction of area measured in the static tensile tests indicated excellent ductility. However, the notched bar tests indicated that the steel was extremely notch sensitive at 70°F and below.

The steel had a low carbon content, about 0.05 percent, and a large grain size. The fracture was of the cleavage type and numerous secondary cracks were found in the metal adjacent to the main crack. These cracks were directional within grains, and generally changed direction at grain boundaries, and were similar to the secondary cracks observed in fractured hull plates, always associated with cleavage (or brittle) type fractures and with steel of high notch sensitivity.

XII Effects of Extraneous Factors on Notch Sensitivity

During this investigation and in certain other tests it was noted that some of the fabrication processes used in ship construction apparently had an adverse effect on the notch sensitivity of the steels. It was also noted that the apparent notched bar test properties of a plate were dependent to a great extent on the selection and preparation of the test specimens.

Some of the factors to be considered in connection with notch sensitivity and notched bar testing will be discussed briefly in this section.

A. Flame Cutting, Welding, and Arc Craters.

Notched bar test specimens taken from near the flame cut edges of 10 plates were tested at various temperatures. In every case the energy absorption of these specimens was lower than the average for similar specimens taken from the interior of the plates; the decreases ranging up to 48 percent. Similar effects were observed in two cases where a welding arc had been dragged across the plates. Specimens which contained weld metal at the notch showed an increased energy absorption, but neighboring specimens which were notched in the heat affected zone near the weld bead or crater showed a decrease, compared to the unaffected part of the plate. The largest decrease observed was 55 percent, approximately the same as for the flame cut plates.

This evidence indicates that the notch sensitivity of steels of the type used in ship construction may be increased to a considerable extent by flame cutting or by small welds or arc craters. This confirms the observation that many of the ship failures originated as a result of such operations. The evidence also indicates that flame cutting should be avoided in the preparation of test specimens.

B. Heat Treatment.

Tests of samples of one steel indicated that the notched bar properties of this steel could be changed materially by heat treatment. Epstein[7] reported similar results for a duplex steel from a structural angle which failed during erection.

C. Deformation.

Several of the ship plates which were received for test had been bent or warped either during fabrication of the ship or incident to the casualty. Tests of specimens from the bent and the flat portions of two of these plates showed that the bending had increased the notch sensitivity of the steel, at both the tension and the compression sides of the bent area. Specimens from the eye of a cargo boom fitting which had been deformed by elongation and bending also had decreased energy absorption in the notched bar test, the notch sensitivity increasing as the amount of deformation increased. More extensive tests of the effect of previous strain were conducted in an investigation of cleavage fracture in rimmed steel[8]. Samples of this steel were strained in tension by various amounts, followed by aging for two hours at 212°F, and notched bar specimens were machined from the strained and unstrained blanks. The 15 foot pound transition temperature was 66°F for the unstrained specimens, 112°F for those strained 2 percent, and 134°F for those strained 4 percent. Further increases of the transition temperature were found for strains up to 10 percent, but the greatest effect was found in the first two percent of prestrain. Similar results were reported by Epstein[7] for open hearth, Bessemer, and duplex steels strained in compression or in tension.

The above evidence indicates that cold deformation by bending, extension or compression may increase the notch sensitivity of the steel and decrease the energy absorption at a given temperature to a considerable extent. This may explain some fractures which have occurred soon after a part such as a bilge keel had been straightened, and others which originated at such points as the turn of the bilge, where the plates had been formed by cold bending.

It was also noted that the "drop of needle" effect at the yield point was not found in the tensile tests of specimens which had previously been deformed by bending or by extension. In tests on a plate from one of the earlier ship casualties[4] it was observed that tensile test specimens taken adjacent and parallel to the fracture edge did not show the drop of the needle at the yield point, while such a drop did occur in specimens removed from the same plate an inch or two from the fracture. Specimens from several plates were tested by stressing to successively higher loads. The stress strain curves obtained from these tests showed that the "drop of needle" effect was no longer found after the specimens had been stressed beyond the yield point, that is, after permanent deformation had occurred. Similar results were obtained in tests of rimmed steel[8], and in specimens from bent or deformed plates. Gibbons[9] likewise reported similar results of tests on specimens from plates 3 1/2 inches thick which were bent to a radius of 20 1/4 inches. The tests on rimmed steel[8] and other tests at this laboratory showed that artificial aging at 212°F did not restore the "drop of needle" effect in previously strained tensile test specimens.

Evidence obtained from the examinations and tests of the fractured plates indicated that deformation due to tensile forces did not extend more than an inch or so from the fracture. The reduction of thickness at the fracture edge, and the cracking or peeling of the surface scale did not extend more than 1/2 inch from the fracture, and in the microscopic examinations Neumann bands or secondary cracks were not found at distances greater than an inch from the main fracture. In the tensile tests, the "drop of needle" effect at the yield point was observed for all specimens taken at points an inch or more from the fracture edge of plates which had not been deformed by bending, indicating that these plates had not been deformed by tensile strains.

D. Selection of the Test Specimens.

Since steels are generally not homogeneous throughout the plate thickness, and since the plates are non-isotropic due to the effect of the direction of rolling, the selection of the test specimens is an important factor in the determination of the notched bar properties. In specimens notched parallel to the plate surface, the depth of the rim in rimmed steel, and the relation of the notch to the rim and the core material, are variable factors which affect the values for energy absorption. Also, in laminated plates, the plane of the lamination would be perpendicular to the direction of propagation of the fracture in the notched bar tests and would greatly increase the apparent energy absorption. In a transverse specimen, notched either parallel or perpendicular to the plate surface, stringers or voids, elongated parallel to the direction of rolling, would also be parallel to the plane of fracture in the test specimen and would generally tend to decrease the energy absorption. In longitudinal specimens notched perpendicular to the plate surface, the effect of the variables mentioned above is much less, since the stringers are perpendicular to the direction of propagation of the fracture, and laminations are in a plane parallel to the direction of propagation. Notched bar specimens of the four different orientations from a number of the ship plates were tested, and it was found that the energy absorption at a given temperature was more uniform and reproducible for the $L\perp$ specimens. Specimens of this orientation were chosen as the standard for these tests for this reason and also because in these specimens the direction of propagation of the fracture is similar to that of the fractures which occurred in service.

The standard specimens used in the ship plate tests were taken from as near to the plate surface as possible, ao as to include both rim and core material in the test sample. In machining, only enough material was removed from the plate-surface side to clean up the specimen.

In a few cases, specimens taken from the center of the plate thickness were tested also. The energy absorption at several temperatures compared to that of the standard specimens from near the plate surface, averaged 9.2 percent less for specimens taken from the center of a plate 1.23 inches thick, which had an unusually deep rim (Plate #2A). For a semi-killed steel 0.72 inch thick (Plate #24B), the average energy absorption of the center of plate specimens was 25 percent higher than for the standard specimens.

E. Dimensional Tolerances of the Specimens.

It is well known that the transition temperature of a steel in notched bar tests is a function of the sharpness of the notch, but very little published data have been found regarding the effect of the external dimensions and the depth of the notch of V-notch Charpy specimens.

One set of ship plate specimens was accidentally machined .008 inch undersize in the dimension perpendicular to the notch. These specimens were notched so that the area under the notch was the same as for a standard specimen, but the depth of the notch was .008 inch less than the standard. At four different testing temperatures, the average energy absorption of these subsize specimens was higher than that of standard specimens from the same plate. In tests at 30°F, the average energy absorption of 4 standard specimens was 10.2 foot pounds, and for 4 of the subsize specimens the average was 15.9 foot pounds, a difference of 56 percent. The percentage increase was less at higher test temperatures: 43 percent at 70°F, 21 percent at 110°F, and 17 percent at 130°F. These tests showed that a difference of only .008 inch in the depth of the notch (about 10 percent of the notch depth) could cause an increase of over 50 percent in the energy absorption at certain temperatures, even though the area under the notch (the area fractured in the test) was standard. Further tests are in progress to verify this observation and to determine the effects of variations in other dimensions of the test specimens.

XIII Acknowledgments

The work on which this report is based was extended over a period of several years, starting early in 1943. Until July 1, 1946 it was sponsored by the Bureau of Ships, Navy Department, as a part of an extended research program supported by that Bureau. When that program was terminated, the work was continued on a part time basis by the National Bureau of Standards as the foundation of a research project on the nature of fracture and of fracture propagation. In July 1947, the Ship Structure Committee supplied additional funds to expedite the testing of the plates then on hand and the analyses of the accumulated data.

Much credit is due to Mr. E. M. MacCutcheon and to other members of the Merchant Marine Technical Division, U. S. Coast Guard Headquarters, who supplied the information regarding the ship failures and who assisted in identification of the samples and in many other ways, and to other members of the Coast Guard who were responsible for the selection and marking of the samples of the fractured plates.

The large number of test specimens required were prepared by the Shops Division of the National Bureau of Standards, in close cooperation with project personnel.

Valuable assistance in the preparation and testing of specimens and in the preparation of this report was rendered by Horace G. MacKerrow, Gordon L. Kluge, Leo R. Dale, Melvin R. Meyerson, and Mrs. Lura F. Roehl, all of the Metallurgy Division of the National Bureau of Standards.

XIV Summary and Conclusions

Samples of fractured plates from 60 ships were examined, and various laboratory tests were made on nearly a hundred plates selected from 48 of these ships. The failures were analyzed on the basis of information concerning the casualties supplied by the cooperating agencies and the data obtained from the laboratory tests.

The tests generally included visual examinations of the fractures, microscopic examination of the steels, chemical analyses, Charpy notched bar tests over a range of temperatures, measurement of the reduction of thickness at the fracture edge, and tensile tests. Some of these tests were omitted, for several of the plates, because of insufficient or unsuitable material, but reasonably complete data were obtained for 72 of the plates.

Typical examples of fractures originating at structural notches, and of faulty welding practices which were the causes of some of the failures are illustrated and discussed.

The tensile properties of samples from the fractured plates indicated that they would probably have passed the acceptance tests required at the time of purchase. No correlation was found between the service fractures and the tensile properties or the chemical compositions of the fractured plates.

Significant differences in the notch sensitivities of the different plates were observed in the data obtained from Charpy notched bar impact tests. Plates in which the ship fractures originated had very low energy absorptions in these tests, and the 15 foot pound transition temperatures of these plates were all above 69°F. The energy absorption was higher, and the transition temperatures were lower, for the plates which had fractured through but which contained neither a source nor an end of a fracture. Plates in which the fractures ended after progressing through one or more plates had considerably higher energy absorptions than the plates which fractured through; and the transition temperatures of these plates were lower.

The thick plates were generally more notch sensitive, on the basis of Charpy notched bar tests, than thin plates of approximately the same chemical composition and tensile properties.

The percentage reduction of plate thicknesses at the brittle fractures which occurred in service showed a definite relation to the notch sensitivity of the steels, but no such relation was found between the notch sensitivity and the reduction of area at the ductile fractures obtained in static tensile tests.

No definite relations were found between the notch sensitivity and the percentage of individual chemical elements. The ratio of manganese to carbon appeared to be more definitely related to the notch sensitivity than the concentration of any individual chemical element. The data indicated that the Mn/C ratio might be a factor contributing to the relative notch toughness of the steels, but not the sole factor.

The microstructures of the fractured plates were typical of commercial hot rolled carbon steel plates. Two unusual features were found in the microstructures near the cleavage fractures; Neumann bands, and secondary directional cracks within grains, both of which are associated with "brittle" metal.

Typical examples of failures due to notch sensitivity in steels other than ship plate were discussed.

Evidence presented in this report showed that the plates in which the ship fractures originated were definitely more notch sensitive than plates which did not contain fracture sources and that relative notch toughness of many of the plates in which fractures ended may have been a factor in halting the propagation of the fractures.

The convincing evidence that notch sensitivity was a major factor in the origin and propagation of the fractures in welded ships, as well as in other structures, indicates that some criterion of notch sensitivity should be included in the specification requirements for the procurement of steels for use where structural notches, restraint, low temperatures, or shock loading might be involved. The specifications in effect at the time of purchase did not provide criteria for the rejection of steels which might be notch sensitive in the range of operating temperatures.

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Table I. List of Ships Examined and Data Regarding The Casualties

No.	Type of Vessel Chronological order of multiple casualties	Months Afloat	Casualty Date Mo.	Casualty Date Yr.	Temperatures at Failure Air	Temperatures at Failure Water	Class of Casualty	Location and Extent of Failures	Probable Starting Point	Remarks
1	Tanker - Not M. C. Type Casualty #2	24	4	45	48°F	---	1	Shell plates B7, B8 C9 & D9, stbd. Fractured at time of under water explosion which demolished the propeller & rudder and damaged the stern.	End of Bilge Keel, plate D9 starboard	Explosion damage. Previous Class I fracture: Crack of similar shape occurred 19 days earlier in plates A & B, port, in way of no. 7 tank.
2	L6-S-B1	2	2	43	11°-29°	---	1	Sheer, stringer plates, and hopper sides, port & stbd. Frame 100 (no. 9 hatch)	Defective butt welds of hatch facing channels.	Complete fracture of strength deck. Fractures occurred at building dock.
3	EC2-S-C1	26	3	45	49°	56°F	3	Tank top, #1 double bottom tank. Crack 30" long following edge of doubler at base of stanchion	Intersection of welds at edge of doubler and base of tipping bracket	Faulty design and excessive accumulations of weld metal at heel of stanchion.
4	T2-SE-A1	50+	2	47	33°	40°	2	From 2' inboard of outer seam of B strake, port, along common butt weld B10-B11 and C9-C10, curving aft into D8, port; #5 Port Wing Tank	Junction of butt end seam welds between C9, C10 and D8 Port side Plating	Sample received does not include source or end. Opposite section taken by owners.
5	EC2-S-C1 Casualty #2	11	12	43	29°	42°	1	1 - Deck & sheer strake at fwd. stbd. & aft port corners of #3 hatch. 2 - stringer & 2 inboard strakes, sheer & strake below, Frames 85-86 port.	1 - Exactly at hatch corners 2 - Unknown	Complete fracture of strength deck. Previous failures by buckling - Port side.
6	EC2-S-C1 Casualty #2	10	1	44	8°	30°	2	Shell E9, Port, & Welded Butt -D strake. Frame 97, adjacent to blowdown valve	Latent defect in plate E9 or in welded butt-D strake.	Found after blowing boilers. Vibration possible cause. Previous class I failure: Sheer & stringer, March 1943
7	T2-SE-A1	11	4	44	Unknown		3	Keel Plate #7, Frame 73. Cracks 47" in plate and 29" in seam weld	Seam weld - Keel to 'A' plate	Discovered in drydock
8	T2-SE-A1	18	2	46	37°	41°-43°	1	Broke in two, no. 5 Tank at Frames 61-62. Vessel had additional strength girders installed.	Plate D7 Port, at end of 12th Longitudinal to Port of ₵, 14" below DE seam	Fifteen (15) lives lost on Bow section.
9	EC2-S-C1 Casualty #2	21	4	44	Unknown		2	Cracks about 1" long in Sheer Strakes J9 Port & Stbd., Frame 90, in lower forward corner of Cutaway for Ladder.	Change of section and rough torch cut.	Discovered in drydock
10	EC2-S-C1 Casualty #1	2	2	44	Unknown		3	Longitudinal crack - Aft End #1 Hatch, Frame 32, 'Tween-Deck, in coaming vertically, and Aft. 4' into Deck.	Unknown	Sample marked "start" was end of crack.

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			Mo.	Yr.	Air	Water				
11	T2-SE-A1 Casualty #1	7	3	43	30°-42°	—	1	Broke in two at sea, complete section of Hull at Frames 55-56 (no. 6 Tank)	Defective Butt weld of Centerline Strake, Main Deck.	Both halves salvaged, welded together and put back in service.
12	Tanker, not M. C. Type	27	5	45	43°	42°	1	Shell cracked around bottom from 2' below upper Deck (Port) to 4' below upper Deck (Stbd.) nos. 4 & 5 Cargo Tanks, Frames 28-32.	Defective butt weld, Port Bilge Strake. Second crack appears to start at fatigue crack in shell at end of longitudinal	Bottom completely fractured. Actual source not received at NBS. "Fatigue crack" not examined.
13	T2-SE-A1 Casualty #2	15	2	44	42°	56°	2	1. Shell plating E-F Strakes #2 Port Wing Tank. 2. Shell B to F Strakes #6 Starboard Tank. 3. Upper Deck from Gunwale to near Longitudinal Bulkhead, while at pier 5 days after cracks 1 & 2.	1. Butt Weld E Strake 2. Common Butt DE Strakes 3. Transverse welded Butt	Seven (7) casualties recorded for this ship from Feb. '43 to Feb. '45. This is casualty #2, Feb. 14 & 19, 1944
14	U. S. C. G. C.	55	2	47	34°	32°	2	Semicircular crack about 30" long between Frames 47-49, Strakes C1 & C2 Port Side, between Longitudinals L4 and L5.	Two (2) craters where Arcs were struck on plate near Lap Weld to B Strake.	Probably damaged by contact with ice
15	EC2-S-C1	16	12	44	39°-47°	48°-52°	1	Deck, Sheer, and Strake below, Frames 81-82 Port.	Defective Butt Weld of Stringer Plates.	Fractures in two directions in Deck Plate Aft of #3 Hatch.
16	EC2-S-C1	22	1	46	54°	62°	1	Upper Deck from Gunwale to Ventilator Fwd. of Deck Houses into Sheer Strake and to Bottom of H Strake, Port side, Frames 83-84	Butt Weld of triangular radius piece between top of Sheer and Heavy Bulwark Plate.	Bulwark Plating separate from Sheer Strake except heavy plates in way of mooring Pipes.
17	EC2-S-C1	10	3	45	76°	40°	2	Shell Plates C6, D8, E7, Port, Frame 79, and Tank Top 42" inboard from Shell.	D Strake or Inboard in Tank Top. (Fracture passed thru Scallop in Bilge Keel-Bilge Keel not fractured).	Occurred while dry docking, just as Dock was drying. Note air/water temperatures.
18	Z-ET1-S-C3	25	9	45	50°	52°	1	Deck thru Stringer and Sheer Strake J11 and 1" into H11. Inboard thru Deck Plate E11 & into D14. Total length 14'2".	After Starboard corner of Deckhouse, Frame 113.	Fracture opened as much as 3/4" while vessel was working in sea way.
19	Z-ET1-S-C3 Casualty #2	42	3	47	50° when discovered	45°	2	Fracture 25" long from Forward Stbd. corner #3 Hatch thru insert Plate & Deck Plate.	Insert Plate at Hatch corner.	Crack stopped at Welded Pad Eye on Deck.
20	EC2-S-C1	18	11	45	37°	42°	1	Upper Deck - Fr. 83 Stbd. Stringer Plate E8 Inboard to E7.	Aft edge of Doubler at Fwd. Stbd. corner of Deck House.	Stopped Outboard at Sheer Strake crack arrestor, inboard 2'4" within Line of Hatches, about 5' Aft. of #3 Hatch.

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			Mo.	Yr.	Air	Water				
21	Z-ET1-S-C3 Casualty #2	11	10	44	45°	50°	1	Sheer Strake J11 Starboard, ending at Rivet in H11. Deck Stringer and Strakes Inboard, ending at Ventilator Opening. Aft of Deck House. Frames 113-114 Stbd.	End of Slotted Freeing Port in Bulwark.	Vessel had 5 casualties. This is the second.
22	EC2-S-C1 Casualty #2	13	1	44	Unknown		2	Shell Plate D8 Port cracked 9". Plates A8 Port & Stbd. show indentation 1/4 to 3/4" between Frames 84 & 85. Plate A8 Port supposed to be laminated near indentation.	Near Bilge Keel	Found in drydock
23	EC2-S-C1 Casualty #3	49	3	47	—	32°-60°	Not Hull	Lower half of Rudder lost between port of London, England and Azores. Rudder Tube fractured above Shelf Plate. Shelf Plate broken off at weld.	Corrosion of welds at Shelf Plate or fatigue failure of Rudder Tube.	Rudder tube shows fatigue crack starting at Plug Weld to Side Plating. 2 previous casualties cracked welds in Shell Plating.
24	Tanker not M. C. Type	9	6	43	--	--	1	Bilge Strakes E7, D11 and Butt Weld C9 - C10 in way of #5 Port Tank. Frame 59. Bilge Keel and 5 Longitudinal Frames cr.cked.	Defective Butt Weld of Shell Plating.	Possibly damaged by depth charges dropped by convoy escort.
25	T2-SE-A1	23	11	45	50°	53°	1	Shell Strakes A to H, Port, Fr. 56 & 57, rupturing 20 Longitudinals, also Frame 60.	Plate E14 at Weld to Longitudinal.	Crack apparently stopped temporarily in H Strake 2 1/2" from Longitudinal, then later progressed to Longitudinal.
26	AP-3(V-24)	19	1	46	46°-78° During voyage	41°-78°	2	No. 3 double bottom tank top fractured across hold. Stbd. & Port Longitudinal Bulkheads fractured down 36" from Tank Top, Fr. 67.	Stbd. crack started in Brow Plate, in NBS. sample. Port & Stbd. cracks overlap, but are not joined.	Port crack ended in double bottom B Stbd. near Brow Plate, 4" from Stbd. crack, in NBS sample. End of Stbd. crack 1 1/4" from Port crack, in adjoining sample taken by American Bureau of Shipping.
27	AOG 55	--	3	46	—	—	3	Semicircular fracture 68" x 52" in first Strake above Sheer Strake,, Port Bow, Frames 15-16.	Near deck plate and seam weld to Sheer Strake.	Collision Damage: "Minor bump" from tug while docking.
28	U. S. C. G. C.	207	5	44	35°	32°	2	Shell E Strake, Port, Frame 17-18 cracked while scouting leads in ice.	'E' Strake Port	Riveted construction. One end of crack stopped in rivet hole, other end in same plate.
29	T2-SE-A1	18	5	44	72°	66°	2	Bilge Strakes D11 & E16, Stbd., at after end of Bilge Keel, Frame 55.	'E' Strake at end of Bilge Keel.	Bilge Keel previously straightened by application of heat & force.
30	Z-ET1-S-C3 Casualty #1	4	1	44	24°	34°	1	Deck from Ventilator to Gunwale, Sheer & Strakes below, & 18" into G11 at Frame 112	Probably at vent opening in Deck.	Oil in tanks heated for discharging. Average temperature 90°F

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			Mo.	Yr.	Air	Water				
31	EC2-S-C1 Casualty #1	10	1	44	38°	58°	1	Deck, Bulwark, Sheer and 2 Strakes below at Fwd. Stbd. corner #3 Hatch	Exactly at Hatch corner.	Samples poorly identified. Location in ship uncertain. Thickness of samples indicates shell plating.
32	C3-S-A2	17	1	44	55°	52°	1	After corners of #3 Hatch, across Deck to bollard on Starboard side; across Deck and down side into H Strake, Port side.	Hatch corners	Complete fracture of Strength Deck
33	C3-S-A2	21	6	46	84° When discovered	74°	2	Deck plate and Doubler at forward Outboard corner of Ventilator, Starboard side, Fr. 101. Fracture gradually extended to 36"	Weld of Doubler to Deck plate at sharp corner of Ventilator opening.	Progressive failure. Progress across doubler & Deck Plate observed for several months. Fracture shows no evidence of fatigue.
34	EC2-S-C1	5	4	44	50°-52°	57°	2	Deck, Fwd. Port corner #3 Hatch, extending 18" to edge of Insert plate. 4 other small cracks at both After corners #2 & 3 Hatches.	Hatch corners.	Insert plate. Rolling direction transverse to length of ship.
35	EC-2-S-C1	7	12	43	29°-36°	--	1	Broke in two at sea. Complete cross-section in way of Fwd. end #3 Hatch.	Exactly at Hatch corners.	Both parts salvaged.
36	T2-SE-A1	9	3	46	70° When discovered	70°	2	Fracture 5'6" long in Main Deck Plates, B & C Strakes Port, between Bulkhead 50 and Web Frame 49. One Deck Beam fractured.	Junction of Weld to Valve Stool and machine welded BC Seam.	--
37	C2-S-E1 Casualty #2	22	1	45	32°	47°	1	1. Deck & Side Shell, Port & Stbd. at middle of #3 Hatch. 2. Deck & Side Shell, Port, middle #4 Hatch. 3. Deck Fwd. of House for 7' Stbd.	1 & 2. Butt Welds of Bulwark cap rails. 3. Vicinity of Stringer. Deck Doubler.	Complete fracture of Strength Deck
38	EC2-S-C1 Casualty #3	25	1	46	50°	42°	1	Shell plates cracked vertically 11' from E6 to C5, Starboard, Frame 60-61. Seam at Frame 62 slugged.	Faulty Weld in Butt between D6 and D7.	Fractured while vessel was loading. Fracture end in E6 near Neutral Axis of ship.

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			Mo.	Yr.	Air	Water				
39	EC2-S-C1 Casualty #1	3	12	43	34°	35°	1	Stringer, Sheer Strake & Bulwark, Frames 101-102 Port.	Herringbones on samples indicate source Inboard on Deck.	Ended just above seam in Sheer Plate.
40	EC2-S-C1	0	11	44	Unknown		3	Crack arrestor at Sheer Strake Fr. 40-41, Port, thru rivet hole.	Rivet hole near edge of Plate.	Found during installation. Probably developed while punching rivet hole.
41	EC2-S-C1 Casualty #1	26	10	45	58°	61°	1	Sheer Strake Plate J9 Port, between Frames 89-90, fractured down to Seam, Stringer Plate fractured inboard 1 foot.	Top edge of Sheer Strake Plate	--
42	EC2-S-C1	7	5	43	--	--	1	Bilge Keel and B, C, & D Strakes Starboard, Frames 64-65.	Defective Butt Weld of Bilge Keel Plates.	Small fatigue fracture found in defective weld of Bilge Keel Plate.
43	N3-S-A2 Casualty #1	0	12	43	0°	33°	3	Tank Top. Semicircular crack near center, Frame 92. Cracks in vertical Keel & Floor Plate.	Tank Top.	Fractured one minute after launching. Note air/water temperatures. Temperature 11° below during previous night.
44	EC2-S-C1	0	6	43	Range 25°F	--	3	From Longitudinal Seam G15-F13, down thru F13 to rivet hole, Frame 152.	Longitudinal Seam.	Fractured during construction. Welding done on this Plate during previous night.
45	U. S. C. G. C.	--	2	45	-	Ice	3	Hull plating ruptured in ice collision.	Unknown	Collided with large growler.
46	T2-SE-A1	33	3	46	37°	38°	1	Broke in two at No. 5 Tank, Aft of Deck House. Snapped in a matter of seconds.	Unknown	Bow Section capsized & sunk by gunfire. Stern part salvaged.
47	T2-SE-A1	2	1	43	23°-[illegible]°	40°	1	Deck, side Shell and longitudinal Bulkheads in Way of #5 Tank.	Defective weld connecting Starboard Fashion Plate and Sheet Strake.	Broke in two in Port. Repaired.
48	EC2-S-C1	20	3	44	52°	54°	3	Boat Deck, Stbd., Frame 97. Frames or Beams did not break.	Lifeboat Fall Reel foundation.	Fracture apparently old when discovered.

Totals

24 Class 1 casualties, including
5 ships which broke completely in two
4 cases of complete fracture of Strength Deck, and
1 case of complete fracture of the bottom.

14 Class 2 casualties
9 Class 3 casualties
1 Rudder failure, not classified.

Total 48 casualties involving 48 different ships.

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Table 2. Descriptions of Plates Tested

Ship and Plate No.	Type of Vessel Plates Tested	Fracture in This Plate	Plate Thickness Inches	Reduction at Fracture %	15 Ft.lb. Trans. Temp. °F	Features Observed in Microscopic Examination	Remarks
1 A	Tanker, Not N. C. Type Shell D9 Starboard	Source-Explosion	0.69	—	41	Many pits or inclusions in ferritic areas.	Explosion damage. Fracture source at end of bilge keel.
2 A	L6-S-B1 Deck Plate - Port	Thru	1.23	0.4	83		
B	Deck Plate - Starboard	Thru	1.23	1.0	102	Rimmed. Directional cracks. Many Neumann bands. Dirty.	
3 A	EC2-S-C1 Tank Top	2 Ends	0.44	—	36		Source in weld at edge of doubler. 2 ends of fracture in this plate.
4 A	T2-SE-A1 Shell, D8 Port	End	0.78	—	63	Slight secondary cracking.	
5 A	EC2-S-C1 Shell H9 Port, Frame 85	Thru	0.59	—	53		Fracture welded. Suspected longitudinal crack not found.
6 A	EC2-S-C1 Shell, H9 Port, Frame 96	End-at rivet	0.63	—	65	Steel very dirty.	Fracture end at rivet hole - riveted frame.
7 A	T2-SE-A1 Keel Plate #7, Frame 82	End	0.81	—	66	Rimmed. Secondary cracks showing slip. Neumann bands.	Insufficient material for tensile tests.
8 A	T2-SE-A1 Shell D7 Port, Frame 62	Source	0.75	—	79		Fracture source at end of longitudinal.
9 A	EC2-S-C1 Sheer Strake J9 Port, Fr. 90	Source & End	0.71	—	83	No directional cracks or Neumann bands.	Plate laminated.
B	Sheer Strake J9 Stbd, Fr. 90	Source & End	0.72	—	91		
10 A	EC2-S-C1 Face Plate - Aft #1 Hatch	End	0.62	3.9	27	Probably semi-killed. Flow. Non-directional cracks.	Insufficient material for tensile tests.
11 A	T2-SE-A1 Deck, center, fwd. of weld	Thru	0.82	1.6	92		Incomplete tests on several other plates reported previously.
12 A	Tanker, Not N. C. Type Shell D6 Starboard	Source	0.85	2.7	76	Numerous directional cracks.	Source reported as fatigue crack. See Table 1.
B	Shell C6 Port	Thru	0.84	—	64		End of Port crack.
C	Shell F8 Port	End	0.81	—	75		End of Aft branch of forward crack - Starboard.
D	Shell H9 Starboard	End	0.81	—	81		
13 A	T2-SE-A1 Deck Plate - Starboard	End	0.90	2.2	41	Semi-killed. Shallow rim. Neumann bands. Distortion.	Insufficient material for tensile test.
B	Shell E Strake, #6 Tank	Thru	0.78	—	53	Rimmed. Banding. Secondary cracks. Distortion.	Insufficient material for tensile test.
14 A	USCGC Shell, G1 Port	Source & End	0.38	1.1	147	Banding of pearlite and ferrite.	Ice damage. Fracture sources at weld craters. Fracture end at pad weld. High notch toughness at weld bead.
B	Shell, G2 Port	End-at weld	0.38	0.8	111		
15 A	EC2-S-C1 Sheer Strake, Port, Frame 82	Thru	0.69	—	75	Neumann bands. No directional cracks.	
B	Deck Plate, aft of #3 Hatch	Source	0.39	1.6	117		Several secondary fractures.
16 A	EC2-S-C1 Deck, Port of House	Thru	0.69	2.1	79	Rimmed. Ferrite banding.	Possible source of secondary cracks.
B	Deck, Forward of House	Thru	0.69	2.5	78	Slight intergranular cracking near fracture.	
17 A	EC2-S-C1 Shell, C6 Port	End	0.65	3.0	55	Many directional cracks.	
B	Shell, D8 Port	Source	0.63	2.2	82	Directional cracks. Dirty.	
C	Shell, E7 Port	End	0.64	3.2	45	Numerous cracks. Very dirty.	

Table 2. Descriptions of Plates Tested - (continued) - page 2

Ship and Plate No.	Type of Vessel Plates Tested	Fracture in This Plate	Plate Thickness Inches	Reduction at Fracture %	15 Ft.lb. Trans. Temp. °F	Features Observed in Microscopic Examination	Remarks
18	Z-ET1-S-C3						
A	Deck, Aft corner of House	Source	0.71	1.3	151	Directional cracks. Some intergranular cracks.	Insufficient material for tensile tests.
19	Z-ET1-S-C3						
A	Deck Plate Stbd of #3 Hatch	End-at weld	0.69	—	62		
B	Insert Plate #3 Hatch	Source	0.69	—	122		
20	EC2-S-C1						
A	Deck Stringer, Stbd. Frame 83	Source	0.71	0.5	153	Directional cracks. Dirty. Shear type fracture.	Highest transition temperature of plates tested.
B	Deck - Near ℄ Frame 84	End-near Hatch	0.41	—	86		End of fracture 2'4" within line of Hatches.
C	Deck - Inboard Plate, Fr. 84	Thru	0.75	—	72		Fracture stopped at crack arrestor slot.
D	Sheer Strake Stbd. Fr. 83	Thru	0.69	—	65		
21	Z-ET1-S-C3						
A	Sheer Strake, Stbd. Fr. 113	Source	0.72	0.5	69	Rimmed. Directional cracks. Dirty.	Source at arc crater and structural notch. Very hard at weld.
22	EC2-S-C1						
A	Shell A8 Port, Frame 85	No fracture	0.62	—	59		Plate shows indentation or buckle - no fracture.
23	EC2-S-C1						
A	Rudder tube	Source	1.00	1.4	144		Source - fatigue crack starting at plug weld.
24	Tanker, Not M. C. Type						
A	Shell - C Strake	End	0.78	—	75		Insufficient material for tensile tests.
B	Shell - D Strake	Thru	0.72	1.0	67		Insufficient material for tensile tests.
25	T2-SE-A1						
A	Shell - K14 Port	Source	0.82	1.9	78	Directional cracks. Dirty.	Fracture source at welded flange.
B	Shell - H11 Port	End	0.62	—	40	Directional cracks. Very dirty.	Fracture end near longitudinal.
26	AP3-(V24)						
A	Double Bottom B Starboard	Ends of 2 cracks	0.50	3.4	30		Starboard crack started in brow plate.
27	AOG						
A	Strake above Sheer, Port Bow	Source & End*	0.44	3.6	80	Some secondary cracking.	*Collision damage.
28	USCGC						
A	Shell E2 Port, Frame 18	Source & End*	1.00	—	106	Directional cracks 1/8" to 1/2" from fracture.	*Ice damage. Fracture source at rivet hole.
29	T2-SE-A1						
A	Shell, D11 Starboard	End	0.83	2.2	62	Directional cracks. Dirty.	
B	Shell, E16 Starboard	Source & End	0.83	1.5	102	Directional cracks. Cracks in heat affected zone of weld.	Fracture source at end of bilge keel.
30	Z-ET1-S-C3						
A	Shell, H Strake, Frame 114	Thru	0.59	—	50		Oil in tanks 90°F, air temperature 24°F.
B	Sheer (J) Strake Frame 113	Thru	0.75	—	41		
31	EC2-S-C1						
A	Shell - Unknown - Mark F	End - Probable	0.72	2.8	50	Neumann bands. No directional cracks.	Samples poorly identified. Locations in ship assumed from photograph of fracture.
B	Shell - Unknown - Mark G	Thru - Probable	0.70	0.3	89	Numerous directional cracks.	Insufficient material for tensile tests.
32	C3-S-A2						
A	Deck, Port, Aft #3 Hatch	Source	1.25	0.8	128	Rimmed. Neumann Bands 1/4" from fracture.	Fracture source at Hatch corner opening.
B	Deck, Stbd. Aft #3 Hatch	Thru or Source	1.27	1.7	97	Rimmed. Neumann Bands. Directional and intergranular cracks.	Fracture source in weld at Hatch Corner.
33	C3-S-A2						
A	Deck Plate	End - progressive	0.81	—	88		Gradual progress of fracture observed for several months.
B	Doubler Plate	Thru	0.69	2.3	86		Fracture source in weld.

Table 2. Descriptions of Plates Tested - (continued) - page 3

Ship and Plate No.	Type of Vessel Plates Tested	Fracture in This Plate	Plate Thickness Inches	Reduction at Fracture %	15 Ft.lb. Trans. Temp. °F	Features Observed in Microscopic Examination	Remarks
34 A	EC2-S-C1 Deck, Insert Plate #3 Hatch	Source & End	0.71	0.7	140	Semi-killed. Neumann bands. Directional cracks in grains.	
35 A	EC2-S-C1 Deck, Port, #3 Hatch	Thru	0.72	—	49	Numerous directional cracks.	Insufficient material for tensile tests.
36 A	T2-SE-A1 Deck, B Strake	End	0.80	1.1	82		Fracture ended near longitudinal bulkhead.
B	Deck, C Strake	End	0.80	0.5	73		Fracture source in weld.
37 A	C2-S-E1 Deck Plate at #3 Hatch-Port	Thru	0.72	3.6	33		Probably one of last plates to fracture.
B	Long. Hatch Girder #3 Hatch	Thru	1.00	1.6	112		
C	Deck Stringer-Port, Fr. 83	Thru	0.69	—	59		
D	Deck Stringer-Port, Fr. 129	Thru	0.71	1.6	69	Cracks, may or may not be directional.	
E	Sheer Strake K9 Port, Fr. 83	Thru	0.62	3.5	48		
F	Sheer Strake K9 Stbd. Fr. 83	Thru	0.62	3.5	47		
38 A	EC2-S-C1 Shell D6 Starboard, Fr. 60	Thru	0.62	—	44		Fracture turned into plate from butt weld.
B	Shell D7 Starboard, Fr. 61	No fracture	0.62	—	24		Lowest transition temperature of plates tested.
C	Shell E6 Stbd. Fr. 60 1/2	End	0.59	—	90		Fracture ended at neutral axis of ship.
39 A	EC2-S-C1 Deck Stringer, Port, Fr. 101	Source	0.75	1.4	72	Neumann bands. No directional cracks.	Probable source of fracture in this plate.
B	Sheer Strake, Port, Fr. 101	End	0.75	1.8	62	Directional cracks. Neumann bands. Dirty.	Fracture end just above seam weld.
40 A	EC2-S-C1 Crack Arrestor at Sheer Strake	Source & End	0.77	0.9	88	Directional cracks. Few Neumann bands. Non-homogeneous.	Fracture source at rivet hole.
41 A	EC2-S-C1 Sheer Strake J9 Port.	Source & End	0.69	1.4	83		
42 A	EC2-S-C1 Bilge Keel Aft Frame 74	At weld	0.46	—	—	Semi-killed.	(Fracture source in defective butt weld.
B	Bilge Keel Fwd. Frame 74	At weld	0.46	—	—	Semi-killed.	(Small fatigue fracture found in weld.
43 A	N3-S-A2 Tank Top	Thru	0.37	2.3	—	Secondary cracks. Shatter. Directional cracks.	Insufficient material for notched bar or tensile tests.
44 A	EC2-S-C1 Shell F13 Port, Frame 152	Source & End	0.52	1.1	—	Directional cracks. Shatter. Displacement along crack.	Insufficient material for notched bar or tensile tests.
45 A	USCGC Shell Plating	End	0.40	—	—	Probably semi-killed. No cracks or Neumann bands.	Notched bar specimens subsize.
46 A	T2-SE-A1 Sheer Strake, Port, Fr. 60	Thru	1.25	—	101		Additional tests in progress.
B	Sheer Strake, Stbd. Fr. 60	Thru	1.25	—	65		
C	Deck Plate	Source-Possible	0.81	—	60		Fracture partly of shear type.
47 A	T2-SE-A1 Deck Stringer	Thru	1.09	—	—	Normal.	(Notched bar tests made on specimens notched
B	Sheer Strake	Source-Weld	1.22	—	—	Normal. Many Al_2O_3 inclusions.	(parallel to plate surface, and on smaller (testing machine.
48 A	EC2-S-C1 Boat Deck, Stbd., Fr. 97	Source	0.33	0.7	—	Neumann bands. Directional cracks. Oxide inclusions.	Fracture source at hard weld bead. Insufficient material.

Table 3. Relation of Notched Bar Test Data and Nature of Ship Fracture

Charpy Notched Bar Test Data (V notch, longitudinal specimens, notched perpendicular to plate surface)		Nature of Ship Fracture In Plates Tested					
		Plate Thickness 0.75" and Over			Plate Thickness Under 0.75"		
		Source	Thru	End	Source	Thru	End
Number of Plates Tested		9	9	11	10	16	11
Plate Thickness - Inches	Ave	0.89	0.96	0.81	0.67	0.67	0.59
	Range	0.75-1.25	0.75-1.27	0.75-0.90	0.39-0.72	0.59-0.72	0.41-0.72
Temperature (air or water) at Time of Ship Failure-°F	Ave	46	34	51	46	36	42
	Range	32-66	20-55	34-70	37-58	24-54	30-50
Number of Plates, Known Failure Temperatures		8	9	8	8	14	9
15 ft lb. Transition Temperature - °F	Ave	97	80	70	112	62	53
	Range	72-144	41-112	41-88	69-153	33-89	27-90
Energy Absorbed at 70°F Ft. lb	Ave	10.0	13.5	14.7	8.6	19.2	23.1
	Range	4.9-13.8	7.4-26.2	9.8-23.1	3.8-15.2	10.5-32.9	8.8-48.8
Energy Absorbed at 30°F Ft. lb	Ave	5.2	6.8	6.9	5.0	8.0	9.8
	Range	3.5-7.0	4.0-13.4	4.4-12.0	2.5-9.0	5.0-14.1	5.5-16.4
Energy Absorbed at Temperature of Ship Failure, Ft. lb.	Ave	7.0	7.3	11.0	5.9	9.4	12.2
	Range	4.0-10.6	3.8-12.4	7.1-16.0	3.2-11.4	6.0-14.7	6.0-21.4

Table 4. Notched Bar Test Data

Plate No.	15 ft lb Transition Temp. °F	Fracture in This Plate	Plate Thickness Inches	Reduction at Fracture %	Energy Absorbed at 70°F - Ft lb Charpy Notched Bar Test Specimen Orientation			
					L ⊥	L ∥	T ⊥	T ∥
38B	24	No Fracture	0.62	--	32.8	45.1	23.2	--
10A	27	End	0.62	3.9	48.8	99.2	22.6	--
26A	30	Ends - 2 cracks	0.50	3.4	30.3	55.0	19.8	--
37A	33	Thru	0.72	3.6	26.5	--	--	--
3A	36	2 Ends	0.44	--	27.4	--	16.9	--
25B	40	End	0.62	--	25.0	--	--	--
1A	41	Source - Expl.	0.69	--	29.6	35.4	18.4	--
30B	41	Thru	0.75	--	26.2	43.1	23.3	33.1
13A	41	End	0.90	2.2	23.1	--	--	--
Ave	34.8		0.65	3.3	30.0	55.6	20.7	33.1
38A	44	Thru	0.62	--	29.3	--	21.5	--
17C	45	End	0.64	3.2	23.3	38.4	16.6	22.6
37F	47	Thru	0.62	3.5	23.6	--	--	--
37E	48	Thru	0.62	3.5	21.6	--	--	--
35A	49	Thru	0.72	--	32.9	--	--	--
31A	50	End - probable	0.72	2.8	25.6	--	--	--
30A	50	Thru	0.59	--	23.5	39.0	17.6	22.8
5A	53	Thru	0.59	--	23.0	--	--	--
13B	53	Thru	0.78	--	19.2	--	--	--
Ave	48.8		0.66	3.2	24.7	38.7	18.6	22.7
17A	55	End	0.65	3.0	21.2	21.1	17.4	--
22A	59	No Fracture	0.62	--	21.3	26.5	15.8	17.3
37C	59	Thru	0.69	--	18.6	--	--	--
39B	62	End-- at Seam	0.75	1.8	18.0	18.3	16.7	15.5
29A	62	End	0.83	2.2	17.3	18.1	16.0	20.8
19A	62	End - at Weld	0.69	--	16.3	--	--	--
4A	63	End	0.78	--	16.5	24.9	19.0	--
12B	64	Thru	0.84	--	16.4	16.8	--	--
20D	65	Thru	0.69	--	16.5	--	--	--
Ave	61.2		0.73	2.3	18.0	21.0	17.0	17.9
6A	65	End - at Rivet	0.63	--	16.2	21.0	13.1	18.1
7A	66	End	0.81	--	15.6	--	14.9	--
24B	67	Thru	0.72	1.0	16.2	--	14.8	17.1
37D	69	Thru	0.71	1.6	15.2	12.5	15.7	17.7
21A	69	Source	0.72	0.5	15.2	--	--	--
20C	72	Thru	0.75	--	14.2	15.5	12.7	--
39A	72	Source	0.75	1.4	13.8	11.8	10.3	12.0
36B	73	End	0.80	0.5	13.5	--	9.0	--
15A	75	Thru	0.69	--	13.3	22.6	14.7	---
Ave	69.8		0.73	1.0	14.8	16.7	13.2	16.2

Table 4. - continued

Plate No.	15 ft lb Transition Temp. °F	Fracture in This Plate	Plate Thickness Inches	Reduction at Fracture %	Energy Absorbed at 70°F - Ft lb, Charpy Notched Bar Test, Specimen Orientation			
					L ⊥	L ∥	T ⊥	T ∥
24A	75	End	0.78	--	13.0	--	--	--
12C	75	End	0.81	--	12.2	14.7	--	--
12A	76	Source	0.85	2.7	12.0	17.1	11.0	10.4
16B	78	Thru	0.69	2.5	12.8	--	12.6	--
25A	78	Source	0.82	1.9	12.2	16.6	11.8	11.2
16A	79	Thru	0.69	2.1	12.9	--	11.3	--
8A	79	Source	0.75	--	12.0	15.6	12.0	--
27A	80	Source & End*	0.44	3.6*	12.8	17.2	11.5	--
12D	81	End	0.81	--	11.7	12.9	--	--
Ave	77.9		0.74	2.3*	12.4	15.7	11.7	10.8
17B	82	Source	0.63	2.2	11.1	11.5	12.5	15.8
36A	82	End - near bhd.	0.80	1.1	10.8	11.4	10.3	--
9A	83	Source & End	0.71	--	12.8	14.5	15.0	14.0
2A	83	Thru	1.23	0.4	12.5	13.8	12.0	12.5
41A	83	Source & End	0.69	1.4	12.0	--	11.8	--
33B	86	Thru	0.69	2.3	10.8	--	9.2	--
20B	86	End - near hatch	0.41	--	10.7	--	13.2	--
40A	88	Source & End	0.77	0.9	11.6	12.4	9.6	13.3
33A	88	End - progressive	0.81	--	9.8	11.4	10.3	--
Ave	84.6		0.75	1.4	11.3	12.5	11.5	13.9
31B	89	Thru - probable	0.70	0.3	10.5	--	--	--
38C	90	End - neutral axis	0.59	--	8.8	9.4	10.7	--
9B	91	Source & End	0.72	--	10.9	13.1	11.8	12.4
11A	92	Thru	0.82	1.6	9.4	15.9	--	9.7
32B	97	Thru or Source	1.27	1.7	8.2	--	8.0	7.8
29B	102	Source & End	0.83	1.5	8.3	11.6	11.8	12.8
2B	102	Thru	1.23	1.0	7.6	--	12.0	--
28A	106	Source & End	1.00	--	7.7	--	--	--
14B	111	End - at Weld	0.38	0.8	5.3	--	6.0	--
Ave	97.8		0.84	1.2	8.5	12.5	10.0	10.7
37B	112	Thru	1.00	1.6	7.4	--	8.0	--
19B	122	Source	0.69	--	5.2	--	5.6	--
32A	128	Source	1.25	0.8	7.2	6.5	6.3	6.0
34A	140	Source & End	0.71	0.7	3.8	--	3.5	4.1
23A	144	Source - Fatigue	1.00	1.4	4.9	5.7	--	--
15B	147	Source	0.39	1.6	5.8	--	3.6	--
14A	147	Source & End	0.38	1.1	3.8	--	4.8	--
18A	151	Source	0.71	1.3	5.3	--	--	--
20A	153	Source	0.71	0.5	4.4	5.7	5.0	4.8
Ave	138.2		0.76	1.1	5.3	6.0	5.3	5.0

* Collision Damage, omitted in average

Table 5. Tensile Test Data - Type 1, .505" diameter Machined Specimens.

Plate No.	15 Ft lb Transition Temp	Plate Thickness	Number of Specimens		Yield Point		Tensile Strength		Elongation in 2"		Reduction of Area		Ratio Yield/Tensile		Elongation x Tensile Strength		Remarks
			L	T	L	T	L	T	L	T	L	T	L	T	L	T	
	°F	Inches			PSI	PSI	PSI	PSI	%	%	%	%	%	%	X10^-6	X10^-6	
38B	24	0.62	2	2	37,300	36,500	63,500	64,300	38.2	40.8	64.2	58.8	59	57	2.42	2.62	
37A	33	0.72	2	3	40,800	39,000	68,700	68,500	37.0	32.8	56.9	48.5	59	57	2.54	2.24	
1A	41	0.69	2	2	34,600	32,800	60,000	59,100	37.8	33.8	62.7	54.1	58	56	2.27	2.09	
38A	44	0.62	2	2	39,300	37,200	61,800	61,100	37.8	38.8	62.4	60.7	64	61	2.34	2.37	
17C	45	0.64	2	2	36,800	36,900	60,700	59,800	39.2	37.0	60.5	48.9	61	62	2.38	2.21	
37F	47	0.62	2	2	37,000	37,200	62,200	62,100	38.5	35.?	59.4	49.8	60	60	2.39	2.18	
Ave.L	39	0.65			37,633		62,817		38.1		61.0		60		2.39		
T	39	0.65				36,600		62,483		36.4		53.5		59		2.27	
37E	48	0.62	2	2	35,400	36,000	61,400	61,700	43.5	33.5	61.6	52.2	58	58	2.67	2.06	
17A	55	0.65	2	2	37,900	35,900	62,400	62,700	40.8	36.8	62.2	57.9	61	57	2.54	2.30	
37C	59	0.69	2	3	36,500	37,800	60,400	60,300	40.5	36.5	58.0	56.7	60	63	2.44	2.20	
39B	62	0.75	2	1	34,000	36,100	62,500	62,500	39.5	36.0	61.0	55.7	54	58	2.47	2.25	
29A	62	0.83	2	-	35,100	—	59,900	—	34.8	—	62.3	—	59	—	2.08	--	
19A	62	0.69	2	2	37,100	37,000	69,600	69,600	35.8	36.0	58.4	53.6	53	53	2.49	2.50	
Ave.L	58	0.71			36,000		62,700		39.2		60.6		58		2.45		
T	57	0.68				36,560		63,360		35.8		55.2		58		2.26	
4A	63	0.78	2	2	35,000	35,400	63,200	63,000	38.5	36.8	59.4	55.0	55	56	2.43	2.32	
12B	64	0.84	2	2	35,100	34,600	60,800	61,500	38.5	32.8	60.8	56.8	58	56	2.34	2.02	
20D	65	0.69	1	-	36,400	—	61,100	--	39.5	—	61.4	--	60	—	2.41	—	
37D	69	0.71	2	2	36,400	37,100	62,600	62,400	35.3	36.5	61.0	58.0	58	59	2.21	2.28	
20C	72	0.75	2	3	37,300	37,900	64,500	63,700	38.2	39.5	60.0	54.9	58	59	2.46	2.51	
39A	72	0.75	2	1	34,200	29,900	61,600	61,600	36.5	33.0	58.5	56.4	56	49	2.24	2.03	Transverse Yield Low
Ave.L	68	0.75			35,733		62,300		37.8		60.2		58		2.35		
T	68	0.77				34,980		62,440		35.7		56.2		56		2.23	
36B	73	0.80	2	2	29,200	31,000	60,900	60,200	40.5	39.8	61.2	56.2	48	51	2.46	2.39	Longitudinal Yield Low.
12C	75	0.81	2	1	40,500	42,700	64,500	62,700	31.3	32.0	58.8	54.0	63	68	2.02	2.01	Longitudinal Specimens 8" g.l.
12A	76	0.85	-	2	--	31,800	—	58,900	—	36.3	—	60.3	—	54	—	2.14	
16B	78	0.69	2	2	36,200	34,900	65,700	66,600	34.8	31.3	54.1	50.1	55	52	2.28	2.08	
25A	78	0.82	2	-	33,600	—	66,600	—	34.3	—	56.5	—	50	--	2.28	—	
16A	79	0.69	2	3	37,600	35,400	66,900	67,000	37.2	32.8	60.2	54.2	56	53	2.49	2.20	
Ave.L	77	0.76			35,420		64,920		35.6		58.2		54		2.31		
T	76	0.77				35,160		63,080		34.4		55.0		56		2.16	

Table 5 - continued

Plate No.	15 Ft lb Transi-tion Temp °F	Plate Thick-ness. Inches	Number of Specimens L	Number of Specimens T	Yield Point L PSI	Yield Point T PSI	Tensile Strength L PSI	Tensile Strength T PSI	Elongation in 2" L %	Elongation in 2" T %	Reduction of Area L %	Reduction of Area T %	Ratio Yield/Tensile L %	Ratio Yield/Tensile T %	Elongation x Tensile Strength L X10^{-6}	Elongation x Tensile Strength T X10^{-6}	Remarks
8A	79	0.75	2	2	34,300	34,400	64,200	62,400	32.2	34.5	59.8	56.8	53	55	2.06	2.16	
12D	81	0.81	2	2	34,400	40,200	68,200	67,800	35.0	36.8	52.5	56.3	50	59	2.38	2.49	
36A	82	0.80	2	2	36,300	31,700	67,100	65,200	35.0	37.3	60.8	58.7	54	48	2.34	2.43	Transverse Yield Low
2A	83	1.23	2	2	34,500	31,700	65,700	65,700	33.5	32.0	54.5	52.3	53	48	2.20	2.10	Transverse Yield Low
41A	83	0.69	2	2	33,800	34,700	64,800	65,000	37.8	38.3	58.8	57.9	52	53	2.44	2.49	
33B	86	0.69	2	2	33,000	38,500	69,600	69,000	34.5	32.8	57.3	48.6	47	56	2.40	2.26	Longitudinal Yield Low
Ave. L	82	0.83			34,383		66,600		34.7		57.3		52		2.30		
T	82	0.83				35,200		65,850		35.3		55.1		53	2.32	2.32	
40A	88	0.77	2	2	33,600	32,000	63,300	63,700	35.0	37.0	59.1	52.5	53	50	2.22	2.36	
33A	88	0.81	2	2	32,200	33,900	61,100	62,800	38.2	34.8	60.6	53.9	53	54	2.33	2.18	
38C	90	0.59	2	2	32,700	30,800	60,500	60,500	39.8	41.8	62.1	58.7	54	51	2.41	2.53	
11A	92	0.82	6	5	29,300	34,300	62,200	62,500	38.3	35.0	59.9	54.3	47	55	2.38	2.25	Longitudinal Yield Low
29B	102	0.83	2	2	34,800	30,100	64,100	62,200	34.8	34.8	59.3	53.6	54	48	2.23	2.16	Transverse Yield Low
2B	102	1.23	1	-	33,700	—	59,200	—	39.0	—	60.5	—	57	—	2.31	—	
Ave. L	94	0.84			32,717		61,733		37.5		60.3		53		2.31		
T	92	0.76				32,200		62,340		36.9		54.6		52		2.30	
28A	106	1.00	2	-	31,100	—	56,700	—	36.0	—	64.5	—	55	—	2.04	—	Longitudinal Tensile Strength Low
37B	112	1.00	2	2	35,800	36,200	70,900	73,000	35.2	26.8	51.4	47.6	51	50	2.50	1.96	Tensile Strength High
19B	122	0.69	2	2	31,800	32,600	64,100	64,200	41.5	37.5	55.3	52.0	50	51	2.68	2.40	
34A	140	0.71	2	2	32,000	30,000	58,200	57,800	37.5	33.0	55.9	51.7	55	52	2.18	1.91	Transverse Tensile Strength Low
23A	144	1.00	2	-	40,100	—	68,300	—	34.0	—	53.8	—	59	—	2.32	—	
20A	153	0.71	2	2	32,300	31,500	60,900	61,000	35.5	34.5	57.2	54.8	53	52	2.16	2.10	
Ave. L	130	0.85			33,850		63,183		36.6		56.4		54		2.31		
T	132	0.78				32,575		64,000		33.0		51.5		51		2.09	

Table 6 Chemical Analyses of the Steels

Plate No.	15 Ft lb Transition Temp	Lab	Chemical Analyses, Percent * = Spectrographic Determinations														Ratio % Mn/% C
			C	Mn	P	S	Si	Cu	Ni	Cr	V	Mo	Al	Ti	As	Sn	
38B	24	N.B.S.	.22	.44	.017	.028	.12*	<.03*	.05*	.05*	<.003*	.02*	.007*	<.005*	<.03*	<.01*	2.00
10A	27	Phila.	.18	.34	.010	.025	.05	.11	.06	.05	<.001	.02			.008		1.89
26A	30	N.B.S.	.22	.41	.016	.034	.07*	.03*	.04*	.04*	<.003*	.01*	<.002*	<.005*	<.03*	<.01*	1.86
37A	33	N.B.S.	.28	.47	.026	.036	.09*	.12*	.03*	.05*	<.010*	.01*	.008*	<.01*	.008		1.68
3A	36	N.B.S.	.24	.53	.009	.034	.07*	<.03*	.02*	<.03*	<.003*	.01*	.007*	<.005*	<.03*	<.01*	2.21
25B	40	N.Y.	.23	.40	.010	.035	.05	.01*	.04*	.02*	.003*	.004*	.041*	.002*			1.74
1A	41	N.B.S.	.19	.45	.006	.043	.09*	.13*	.06*	.03*	<.003*	.02*	.004*	<.005*	<.03*	.03*	2.37
30B	41	Phila.	.20	.44	.019	.034	.03	.01	.02	.05	<.001	.006			.008		2.20
13A	41	N.B.S.	.20	.48	.005	.027	.06*	.05*	.05*	.04*	<.010*	<.01*	.018*		.012		2.40
Ave	35		.218	.440	.013	.033	.070	.058	.041	.040	.004	.012	.012	.005	.019	--	2.04
38A	44	N.B.S.	.20	.41	.010	.030	.04*	.05*	.04*	.03*	<.003*	.01*	.006*	<.005*	<.03*	<.01*	2.05
17C	45	Phila.	.24	.42	.006	.043	.03	.02	.02	.02	<.001	.000			.005		1.75
37F	47	N.B.S.	.23	.47	.009	.041	.02*	.06*	.03*	.03*	<.010*	.01*	.007*	<.01*	.008		2.04
37E	48	N.B.S.	.22	.42	.008	.040	.03*	.05*	.03*	.03*	<.010*	.01*	.009*	<.01*	.003		1.83
35A	49	N.Y.	.19	.39	.011	.036	.09	.04*	.11*	.03*	.003*	.025*	.013*	.004*	.009		2.05
31A	50	N.Y.	.20	.40	.010	.042	.02	.01*	.02*	.02*	.003*	.002*	.022*	.003*			2.00
30A	50	Phila.	.24	.48	.014	.035	.05	.02	.02	.03	<.001	.006			.008		2.00
5A	53	N.B.S.	.24	.47	.009	.030	.06*	.04*	.16*	.07*	<.010*	.01*	.009*	<.01*	<.02*		1.96
13B	53	Phila.	.27	.59	.025	.031	.01	.21	.07	.10	<.001	.006			.010		2.18
Ave	49		.227	.450	.011	.037	.039	.056	.056	.040	.005	.009	.011	.007	.012	—	1.98
17A	55	N.Y.	.37	.39	.011	.035	.00	.05*	.03*	.03*	.003*	.007*	.017*	.004*			1.05
22A	59	Phila.	.26	.36	.007	.036	.02	.05	.03	.02	<.001	.006			.006		1.38
37C	59	N.B.S.	.17	.31	.014	.060	<.02*	.12*	.04*	.05*	<.010*	.01*	<.002*	<.01*	.053		1.82
39B	62	N.Y.	.24	.51	.017	.035	.00	.01*	.01*	.02*	.003*	.002*	.013*	.002*			2.13
29A	62	N.B.S.	.21	.41	.006	.028	.05*	.25*	.02*	.02*	<.010*	<.01*	.005*		.017		1.95
19A	62	N.B.S.	.27	.51	.032	.034	.08*	.06*	.09*	.04*	<.003*	.02*	.002*	<.005*	<.03*	<.01*	1.89
4A	63	N.B.S.	.24	.49	.012	.034	.04*	.04*	.02*	.04*	<.003*	.01*	.007*	<.005*	<.03*	.06*	2.04
12B	64	N.B.S.	.21	.38	.009	.016	<.02*	.16*	.20*	.06*	<.005*	.01*	<.002*	<.005*	<.03*		1.81
20D	65	N.B.S.	.19	.42	.017	.035	.03*	.17*	.03*	.04*	<.010*	<.01*	.014*	<.01*	.044		2.21
Ave	61		.240	.420	.014	.035	.029	.101	.052	.036	.005	.009	.008	.006	.030	--	1.81
6A	65	Phila.	.27	.42	.008	.031	.04	.03	.01	.03	<.001	.002			.009		1.55
7A	66	Phila.	.23	.41	.007	.039	.02	.04	.04	.03	<.001	.006			.011		1.78
24B	67	Phila.	.24	.43	.013	.035	.05	.02	.05	.03	<.001	.002			.006		1.79
37D	69	N.Y.	.22	.39	.015	.030	.00	.05	.03*	.04*	.003*	.023*	.006*	.002*			1.77
21A	69	Phila.	.21	.46	.022	.019	.04	.01	.02	.01	<.001	.004			.008		2.19
20C	72	N.B.S.	.26	.47	.008	.033	.04*	.04*	.02*	.03*	<.010*	<.01*	.014*	<.01*	.013		1.81
39A	72	N.Y.	.25	.37	.008	.030	.01	.05*	.07*	.03*	.003*	.030*	.015*	.003*			1.48
36B	73	N.B.S.	.23	.41	.021	.026	.04*	.08*	.01*	<.02*	<.003*	.01*	.009*	<.005*	.06*	<.01*	1.78
15A	75	N.Y.	.25	.42	.010	.030	.03	.02*	.05*	.03*	.003*	.019*	.042*	.002*			1.68
Ave	70		.240	.420	.012	.030	.030	.036	.033	.028	.003	.012	.017	.004	.018	—	1.76

Table 6 Chemical Analyses of the Steels - continued

Plate No.	15 Ft lb Transition Temp	Lab	Chemical Analyses, Percent * = Spectrographic Determinations														Ratio % Mn/% C
			C	Mn	P	S	Si	Cu	Ni	Cr	V	Mo	Al	Ti	As	Sn	
24A	75	N.B.S.	.24	.43	.011	.028	.05*	.05*	.02*	.05*	<.010*	<.01*	.015*				1.79
12C	75	N.B.S.	.21	.43	.014	.037	.05*	.22*	.03*	.04*	<.005*	<.003*	.05*	<.005*	<.03*		2.05
12A	76	N.Y.	.23	.42	.016	.025	.00	.17*	.15*	.06*	.003*	.030*	.005*	.003*			1.83
16B	78	N.B.S.	.28	.34	.010	.028	.03*	.07*	.04*	.03*	<.003*	.01*	<.006*	<.005*	<.03*	<.01*	1.21
25A	78	N.Y.	.30	.46	.007	.035	.01	.03*	.02*	.02*	.003*	.008*	.008*	.002*			1.53
16A	79	N.B.S.	.27	.45	.026	.024	<.01*	.08*	.07*	.06*	<.003*	.01*	.009*	<.005*	<.03*	.01*	1.67
8A	79	N.B.S.	.22	.44	.015	.016	.05*	.15*	.01*	.01*	<.005*	<.003*	.009*	<.005*	<.03*		2.00
27A	80	N.B.S.	.26	.39	.010	.026	.05*	.03*	.01*	<.02*	<.010*	<.01*	.013*	<.010*	<.02*		1.50
12D	81	N.B.S.	.25	.42	.014	.025	<.02*	.21*	.13*	.07*	<.005*	.01*	<.002*	<.005*	<.03*		1.68
Ave	78		.251	.420	.014	.027	.030	.112	.053	.040	.005	.010	.013	.005	.028	—	1.70
17B	82	N.Y.	.28	.40	.008	.030	.00	.05*	.03*	.03*	.003*	.006*	.022*	.002*			1.43
36A	82	N.B.S.	.24	.50	.016	.015	.05*	.03*	.01*	<.02*	<.003*	.01*	.01*	<.005*	.08*	<.01*	2.08
9A	83	Phila.	.29	.47	.014	.042	.01	.24	.10	.05	<.001	.008			.013		1.62
2A	83	Phila.	.30	.42	.014	.039	.04	.03	.02	.06	<.001	.004			.008		1.40
41A	83	N.B.S.	.29	.43	.018	.028	.05*	<.03*	.01*	<.03*	<.003*	.02*	<.006*	<.005*	<.03*	<.01*	1.48
33B	86	N.B.S.	.27	.49	.030	.038	.04*	.06*	.04*	<.03*	<.003*	<.003*	.008*	<.005*	<.03*	<.01*	1.81
20B	86	N.B.S.	.28	.37	.010	.026	<.02*	.05*	.03*	.04*	<.010*	.04*	<.002*	<.010*	.011		1.32
40A	88	Phila.	.23	.37	.014	.034	.03	.02	.04	.02	<.001	.004			.008		1.61
33A	88	N.B.S.	.23	.34	.009	.035	.05*	<.03*	.02*	<.03*	<.003*	.003*	.009*	<.005*	<.03*	<.01*	1.48
Ave	85		.268	.421	.015	.032	.032	.060	.033	.034	.003	.011	.010	.005	.026	—	1.58
31B	89	N.Y.	.29	.32	.015	.035	.02	.03*	.05*	.03*	.003*	.006*	.052*	.003*			1.10
38C	90	N.B.S.	.23	.40	.006	.029	<.01*	<.03*	.06*	<.03*	<.003*	.01*	.020*	<.005*	<.03*	<.01*	1.74
9B	91	Phila.	.27	.54	.053	.028	.01	.28	.12	.11	<.001	.012			.010		2.00
11A	92	N.B.S.	.24	.45	.007	.027	.02	.03	<.10	.02	<.050	<.01					1.87
32B	97	N.B.S.	.24	.43	.040	.055	<.02*	.16*	.05*	.03*	<.010*	.06*	<.002*	<.010*	.13		1.79
29B	102	Phila.	.22	.42	.036	.038	.04	.03	.03	.06	<.001	.002			.009		1.91
2B	102	N.Y.	.23	.32	.013	.035	.04	.03*	.02*	.03*	.003*	.002*	.017*	.002*			1.39
28A	106	N.B.S.	.23	.50	.013	.041	.01		Trace								2.17
14B	111	N.B.S.	.20	.45	.007	.029	.05*	.04*	.04*	<.02*	<.010*	<.01*	.006*	<.010*	<.02*		2.25
Ave	98		.239	.426	.021	.035	.024	.079	.052	.041	.010	.014	.019	.006	.040	—	1.80
37B	112	N.B.S.	.32	.37	.035	.031	<.02*	.11*	.03*	.04*	<.010*	.01*	<.002*	<.010*	.060		1.15
19B	122	N.B.S.	.31	.34	.009	.038	.06*	.06*	.02*	<.02*	<.003*	.02*	.01*	<.005*	<.03*	<.01*	1.10
32A	128	Phila.	.26	.46	.041	.060	.01	.17	.06	.03	<.001	.05			.130		1.77
34A	140	Phila.	.30	.29	.014	.029	.02	.03	.02	.02	<.001	.004			.007		0.97
[illegible]3A	144	N.B.S.	.29	.53	.008	.024	<.02*	.03*	<.01*	<.02*	<.010*	.01*	.005*	<.010*	<.02*		1.83
15B	147	N.B.S.	.38	.39	.008	.031	<.02*	.06*	.05*	.06*	<.010*	.05*	<.002*	<.010*	<.02*		1.03
14A	147	N.B.S.	.23	.46	.007	.031	.05*	.03*	.04*	<.02*	<.010*	<.01*	<.002*	<.010*	<.02*		2.00
18A	151	N.Y.	.37	.38	.011	.042	.02	.04*	.06*	.03*	.003*	.030*	.009*	.003*			1.03
20A	153	N.Y.	.30	.20	.010	.020	.00	.01*	.02*	.03*	.003*	.004*	.053*	.002*			0.67
Ave	138		.307	.380	.016	.034	.024	.060	.034	.030	.006	.021	.012	.007	.041	—	1.28
Average All plates	76.8		.249	.422	.015	.033	.035	.070	.044	.036	.005	.012	.013	.006	.027	—	1.74

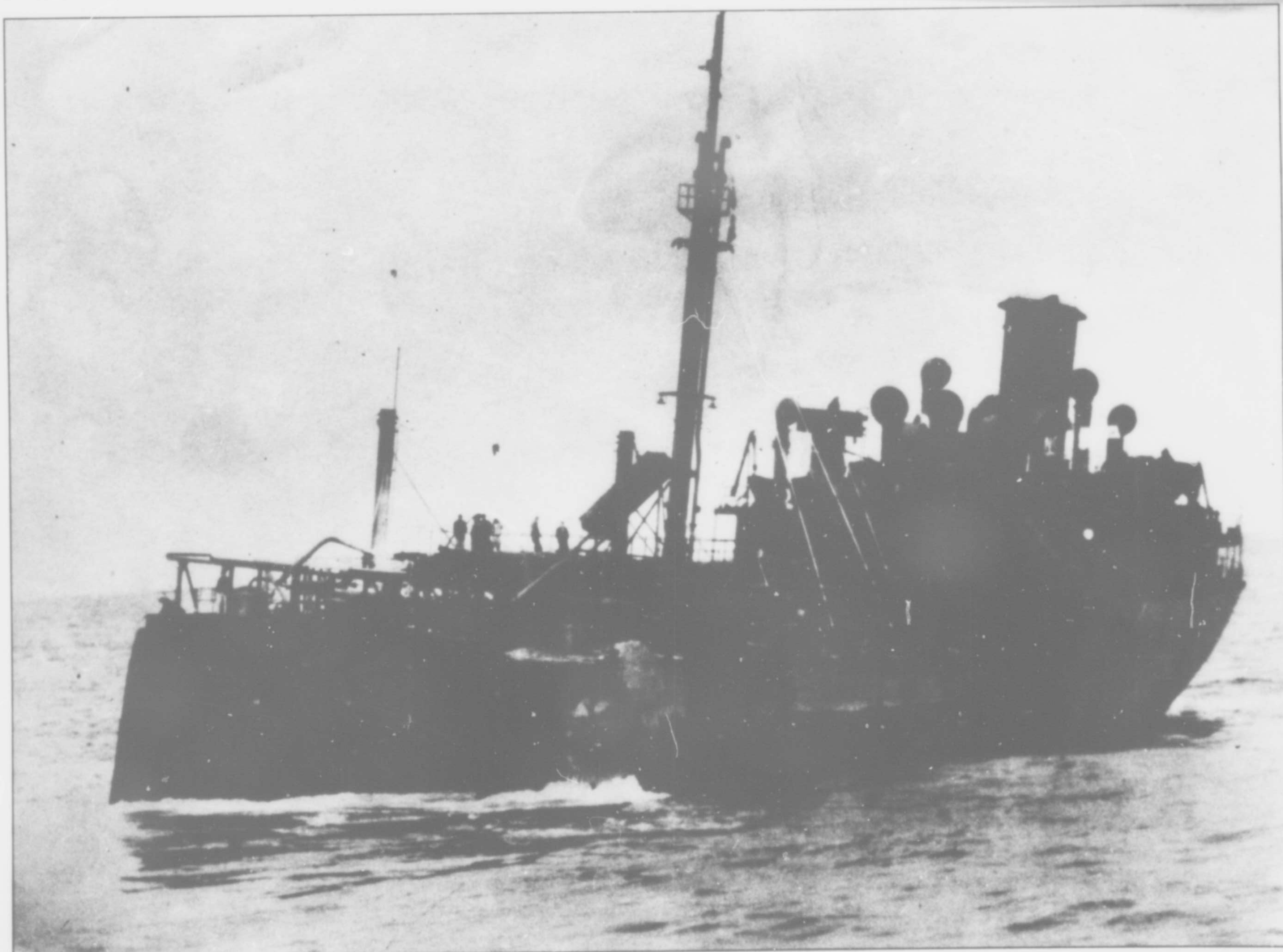


Fig. 1. Stern section of a T2 Tanker which broke in two at sea. (U. S. Navy Photograph).

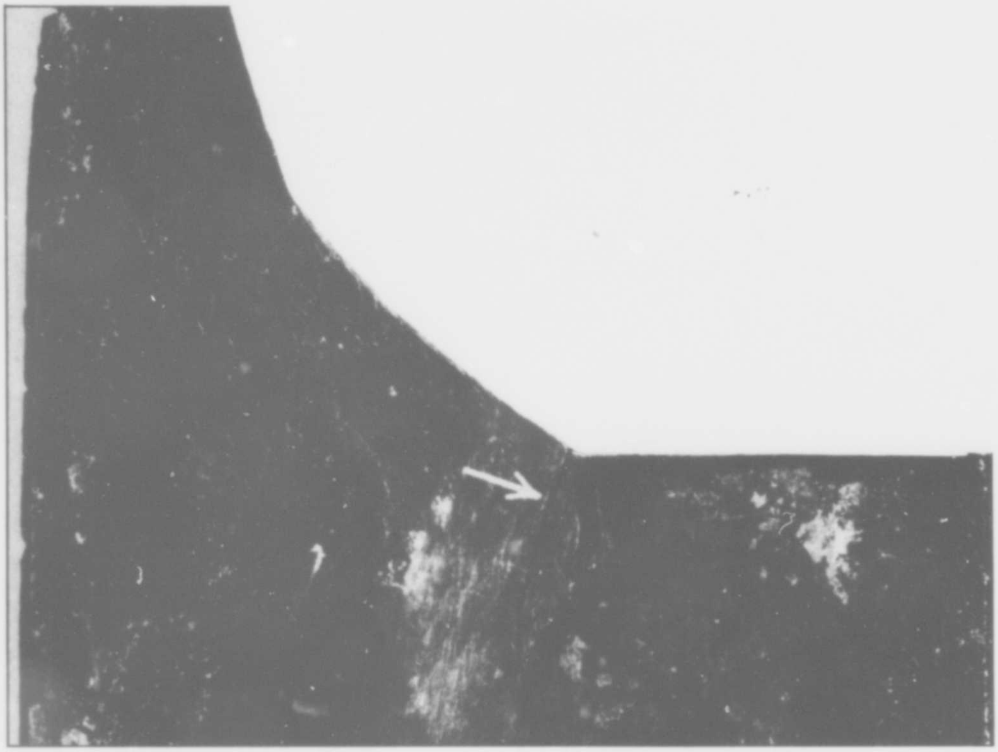


Fig. 2. Fracture source at cutout in sheer strake. x 1.

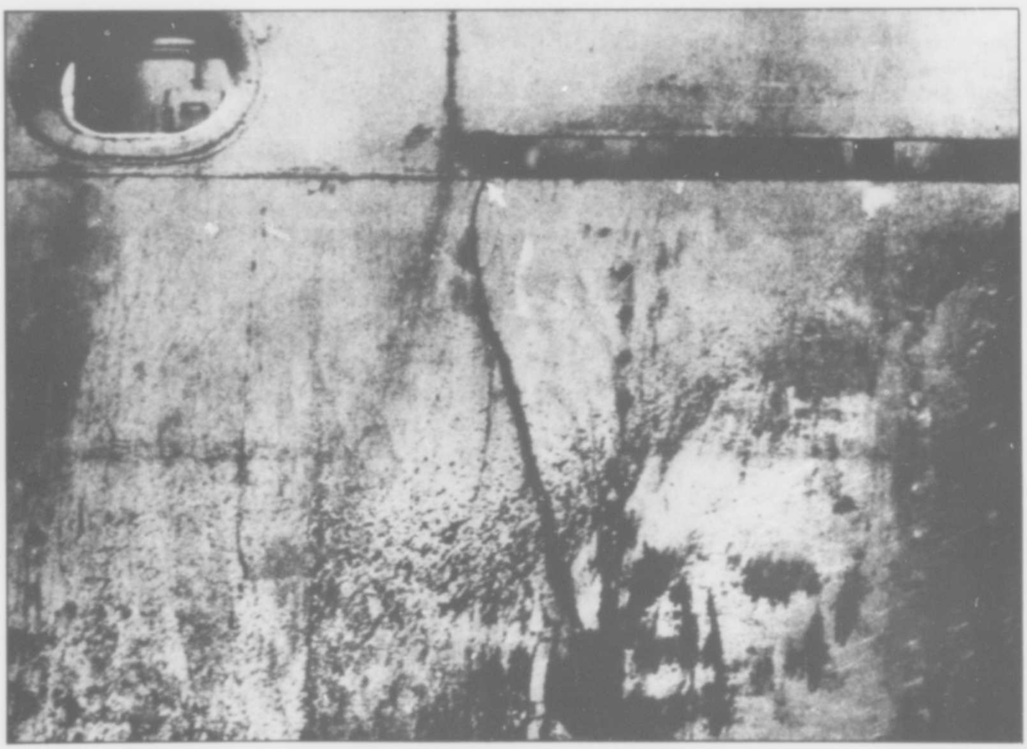


Fig. 3. Fracture originating at change of section at end of slotted freeing port. (U. S. Navy Photograph).

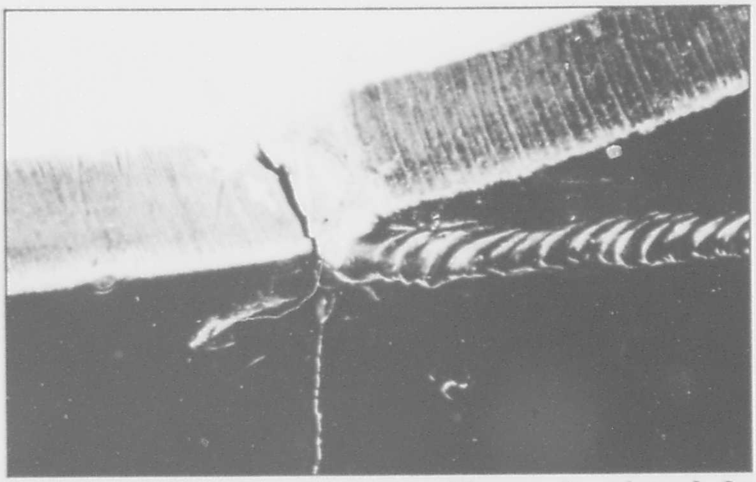


Fig. 4. Source of fracture shown in Figure 3, viewed from inboard and above. Arrow shows globule of weld metal on edge of sheer strake plate. x 1.

Fig. 5. Fracture originating at hatch corner of cargo vessel. (U. S. Coast Guard Photograph).

Fig. 6. Small internal fatigue fracture in weld metal. Note also the slag inclusions, poor penetration of weld metal, and rough weld beads. x 3.

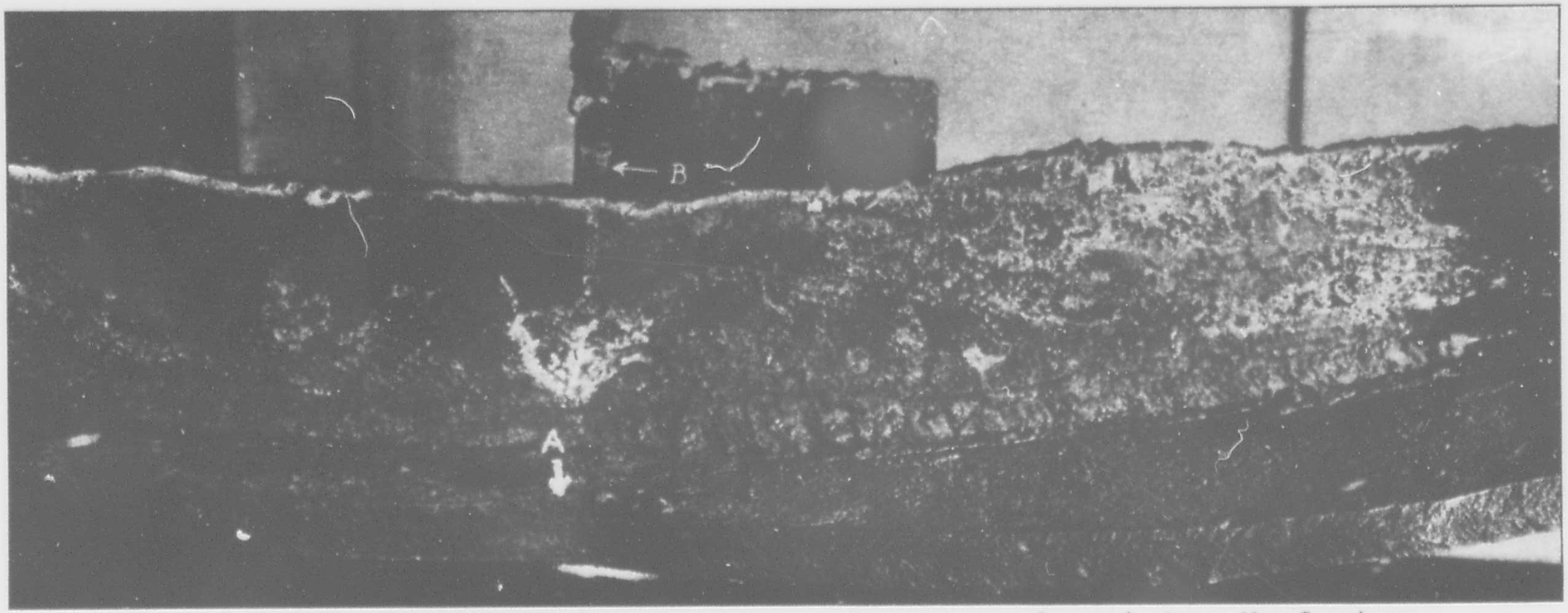


Fig. 7. Fracture edge in shell plating of a tanker. Arrow A shows the fracture source, at the point where the longitudinal ended near a bulkhead. Arrow B indicates a similar longitudinal on the other side of the bulkhead.

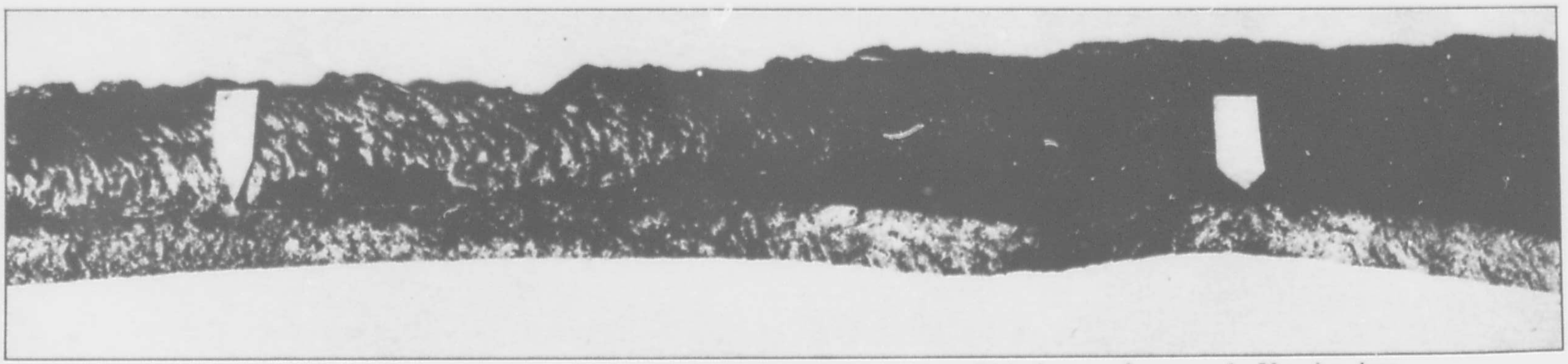


Fig. 8. Shell plating of vessel damaged by ice collision. Arrows indicate two fracture sources at craters where arc was struck on plate. x 1.

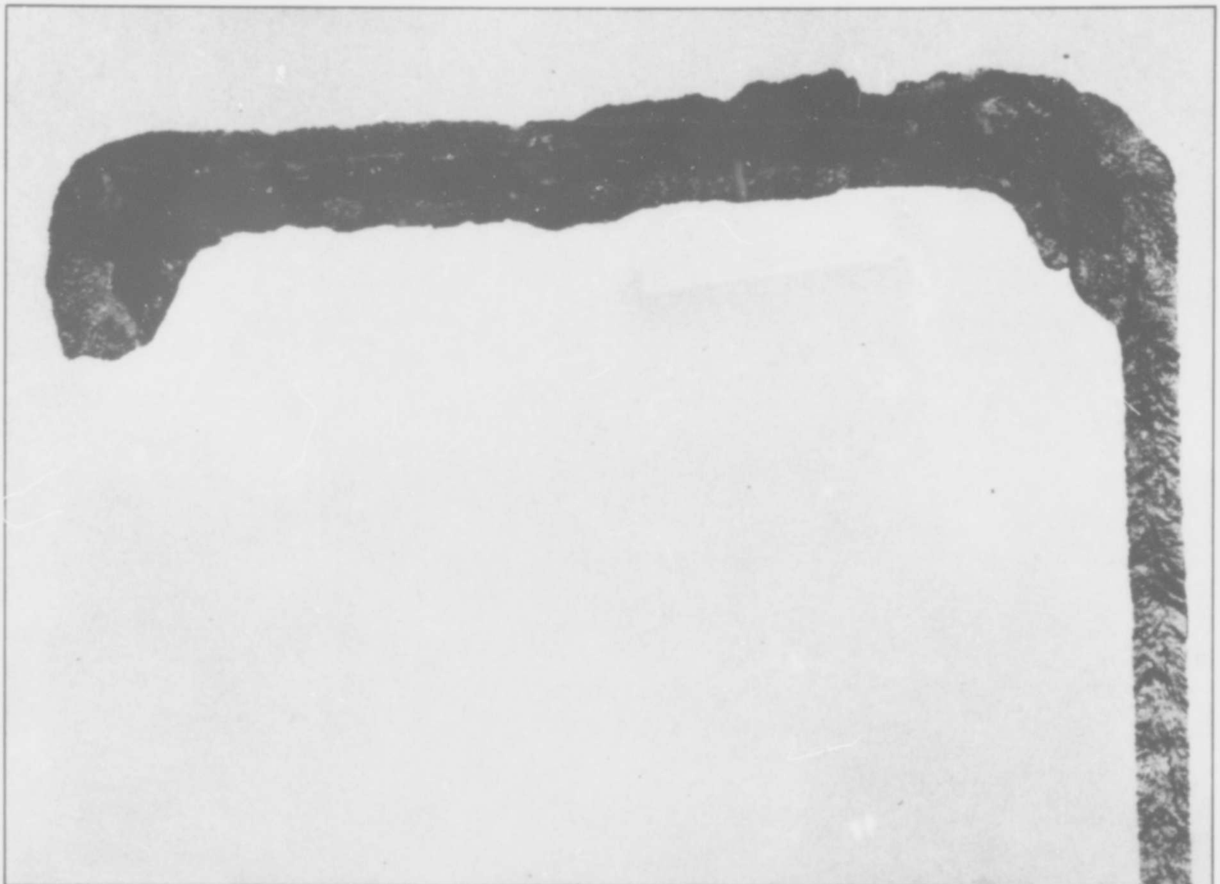


Fig. 9. Saddle weld in bulwark cap rail. Note the herringbone markings in bulwark plate (right) pointing to source of fracture in defective weld of cap rail (top). x 1.

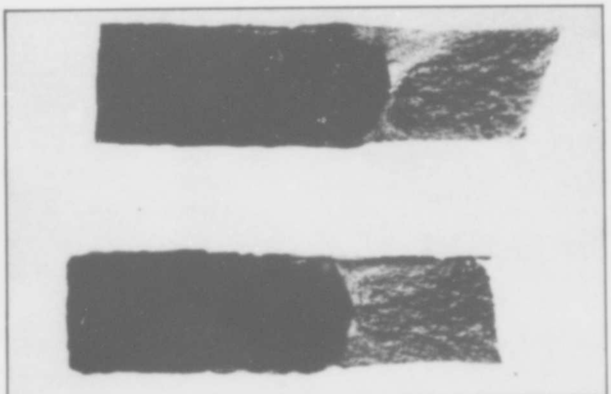


Fig. 10. Typical end of crack. The dark part at the left is the original crack; the light portion was broken in tension in the laboratory. x 1.

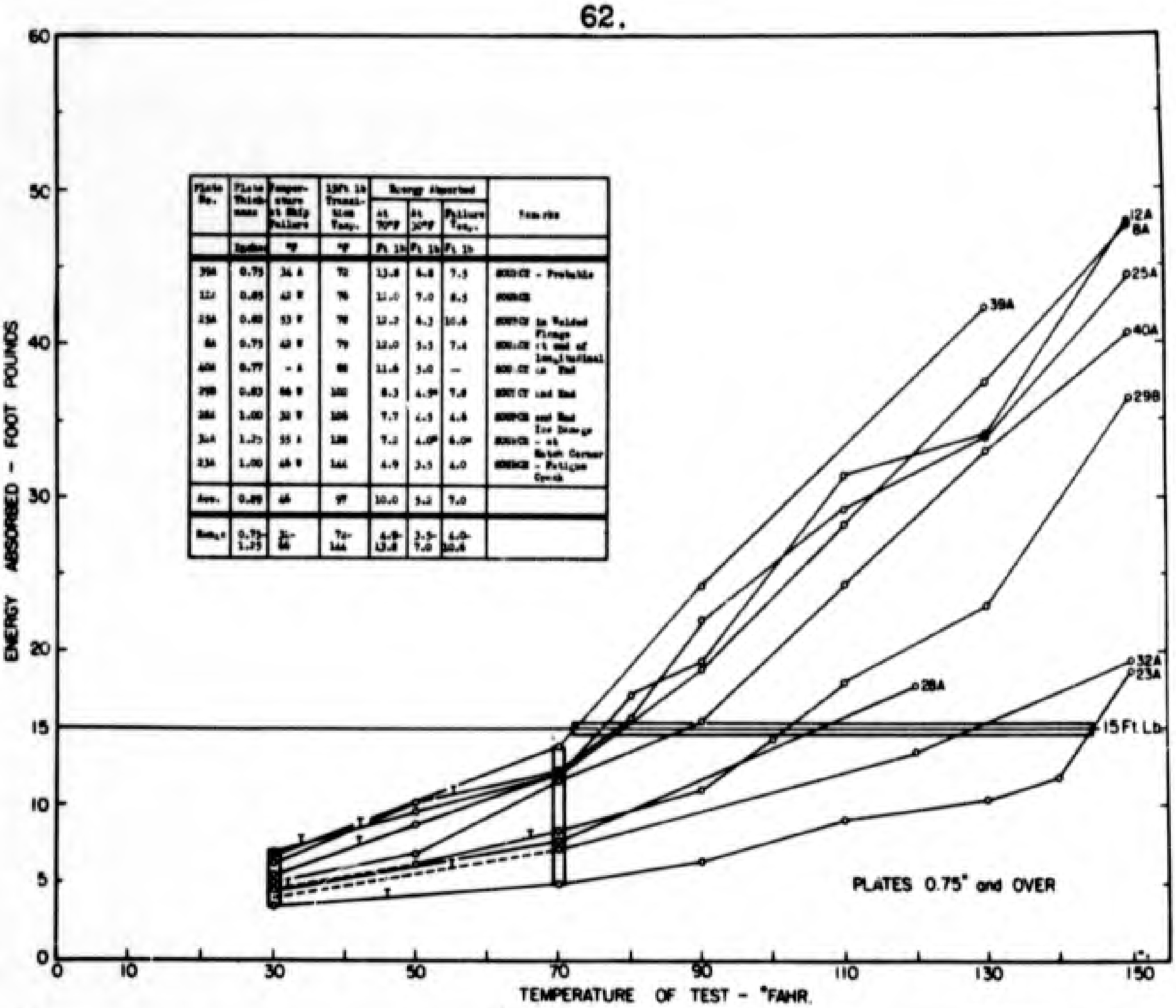


Plate No.	Plate Thickness	Temperature at Ship Failure	15Ft lb Transition Temp.	Energy Absorbed At 70°F	At 30°F	Failure Temp.	Remarks
	Inches	°F	°F	Ft lb	Ft lb	Ft lb	
39A	0.75	34 A	72	13.8	6.8	7.5	SOURCE - Probable
12A	0.85	42 W	76	11.0	7.0	8.5	SOURCE
25A	0.80	53 W	78	12.3	6.3	10.6	SOURCE in Welded Flange
8A	0.75	42 W	79	12.0	5.5	7.4	SOURCE at end of longitudinal
40A	0.77	- A	80	11.6	5.0	—	SOURCE in Pad
29B	0.83	66 W	102	8.3	4.9*	7.8	SOURCE and Pad
28A	1.00	32 W	106	7.7	4.5	4.6	SOURCE and Pad Ice Damage
32A	1.25	55 A	138	7.2	4.0*	6.0*	SOURCE - at Hatch Corner
23A	1.00	48 W	144	4.9	3.5	4.0	SOURCE - Fatigue Crack
Ave.	0.89	46	97	10.0	5.2	7.0	
Range	0.75-1.25	32-66	72-144	4.9-13.8	3.5-7.0	4.0-10.6	

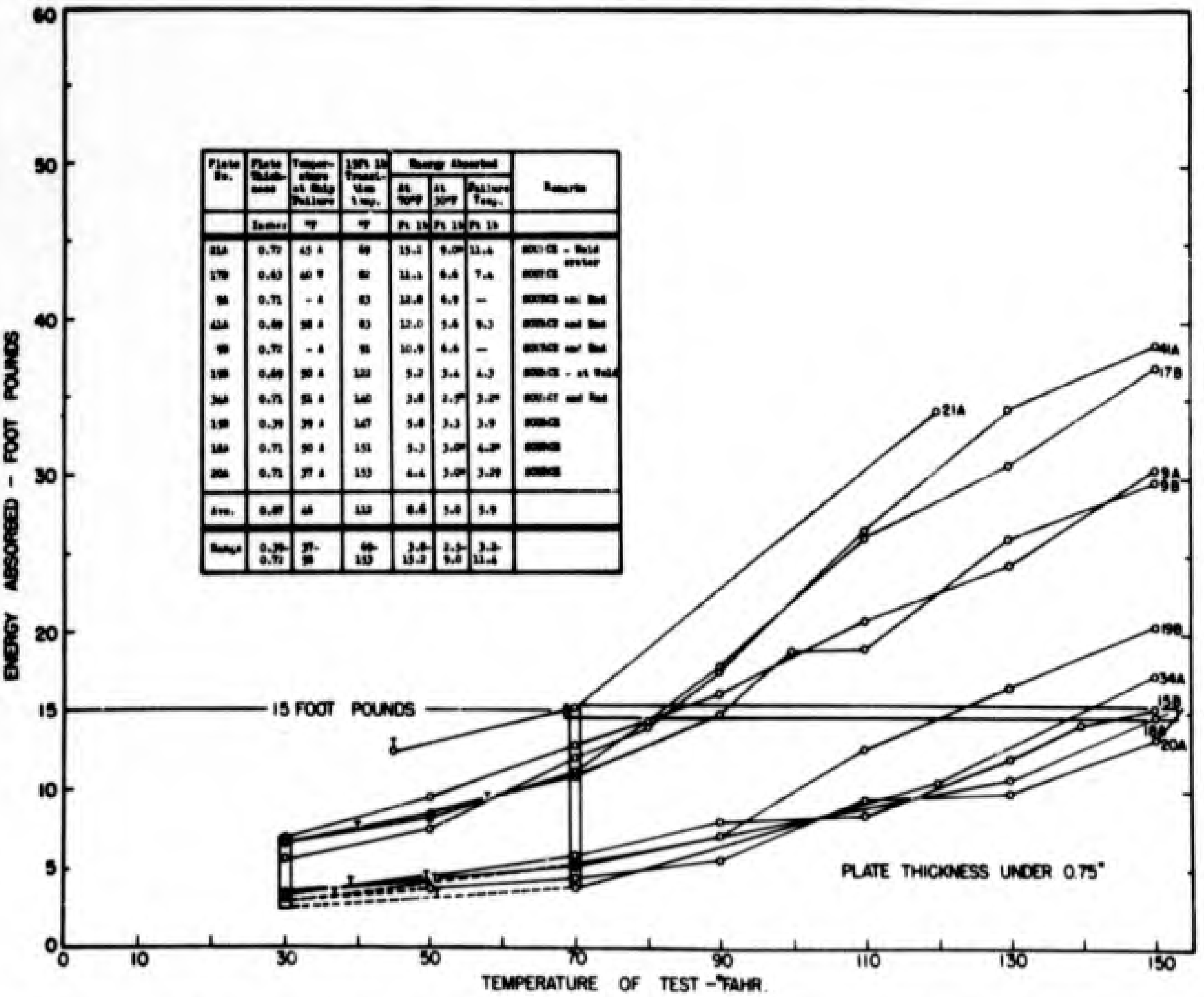
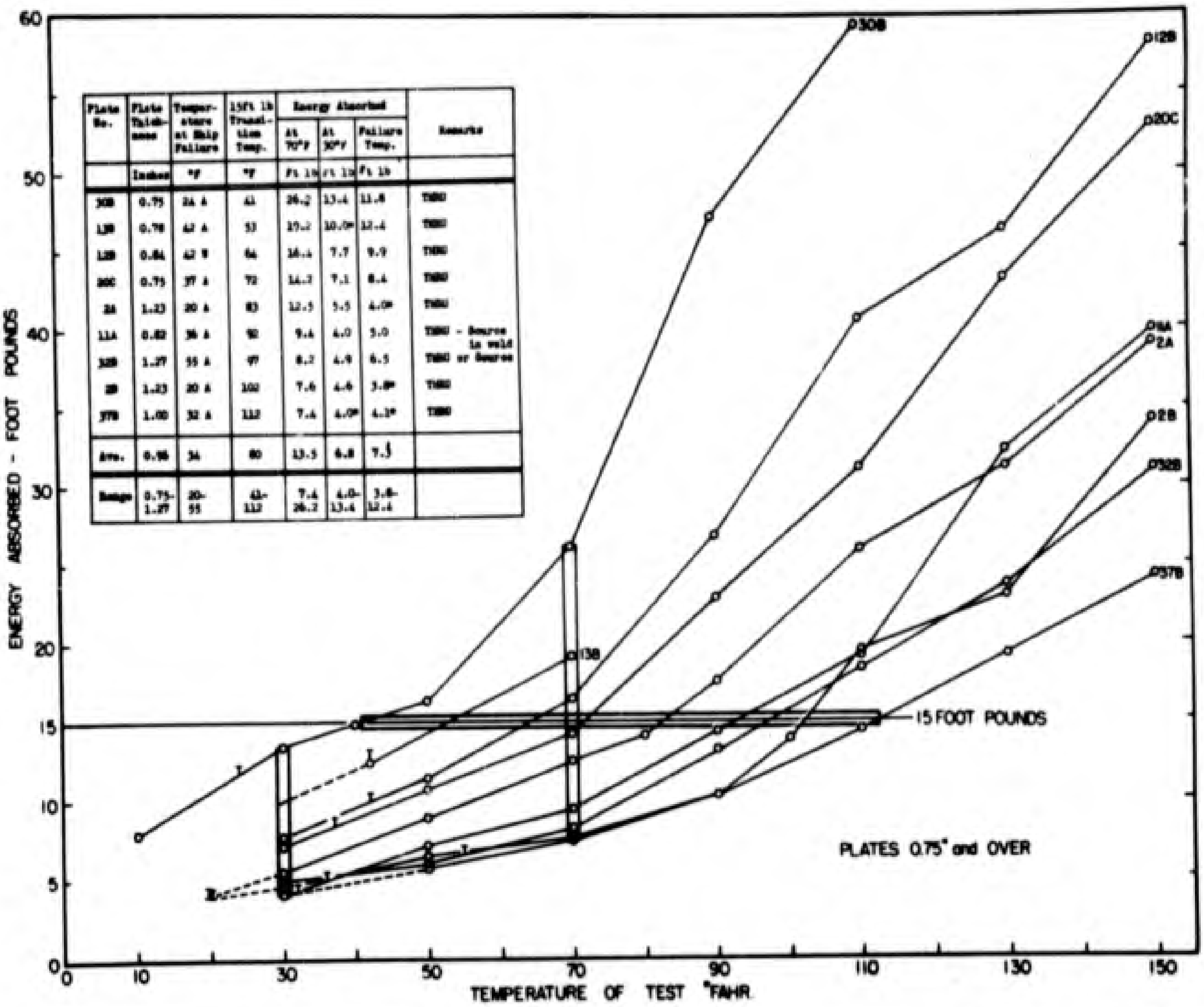


Plate No.	Plate Thickness	Temperature at Ship Failure	15Ft lb Transition Temp.	Energy Absorbed At 70°F	At 30°F	Failure Temp.	Remarks
	Inches	°F	°F	Ft lb	Ft lb	Ft lb	
21A	0.72	45 A	69	15.2	9.0*	11.4	SOURCE - Weld crater
17B	0.63	40 W	82	11.1	6.6	7.4	SOURCE
9A	0.71	- A	83	12.8	6.9	—	SOURCE and Pad
41A	0.69	58 A	83	12.0	5.6	9.3	SOURCE and Pad
9B	0.72	- A	91	10.9	6.6	—	SOURCE and Pad
19B	0.69	50 A	122	5.2	3.4	4.3	SOURCE - at Weld
34A	0.71	51 A	140	3.8	2.9*	3.2*	SOURCE and Pad
15B	0.39	39 A	147	5.8	3.3	3.9	SOURCE
18A	0.71	50 A	151	5.3	3.0*	4.2*	SOURCE
20A	0.71	37 A	153	4.4	3.0*	3.3*	SOURCE
Ave.	0.67	46	112	8.6	5.0	5.9	
Range	0.39-0.72	37-58	69-153	3.8-15.2	2.9-9.0	3.2-11.4	

Fig. 11. Notched bar properties of plates in which the ship fractures originated. Temperatures at time of ships failure are indicated by the letter "T" on the curves. In the tables, "A" indicates air temperature, and "W", water temperature (for plates below water line). Compare to Figures 12 and 13.



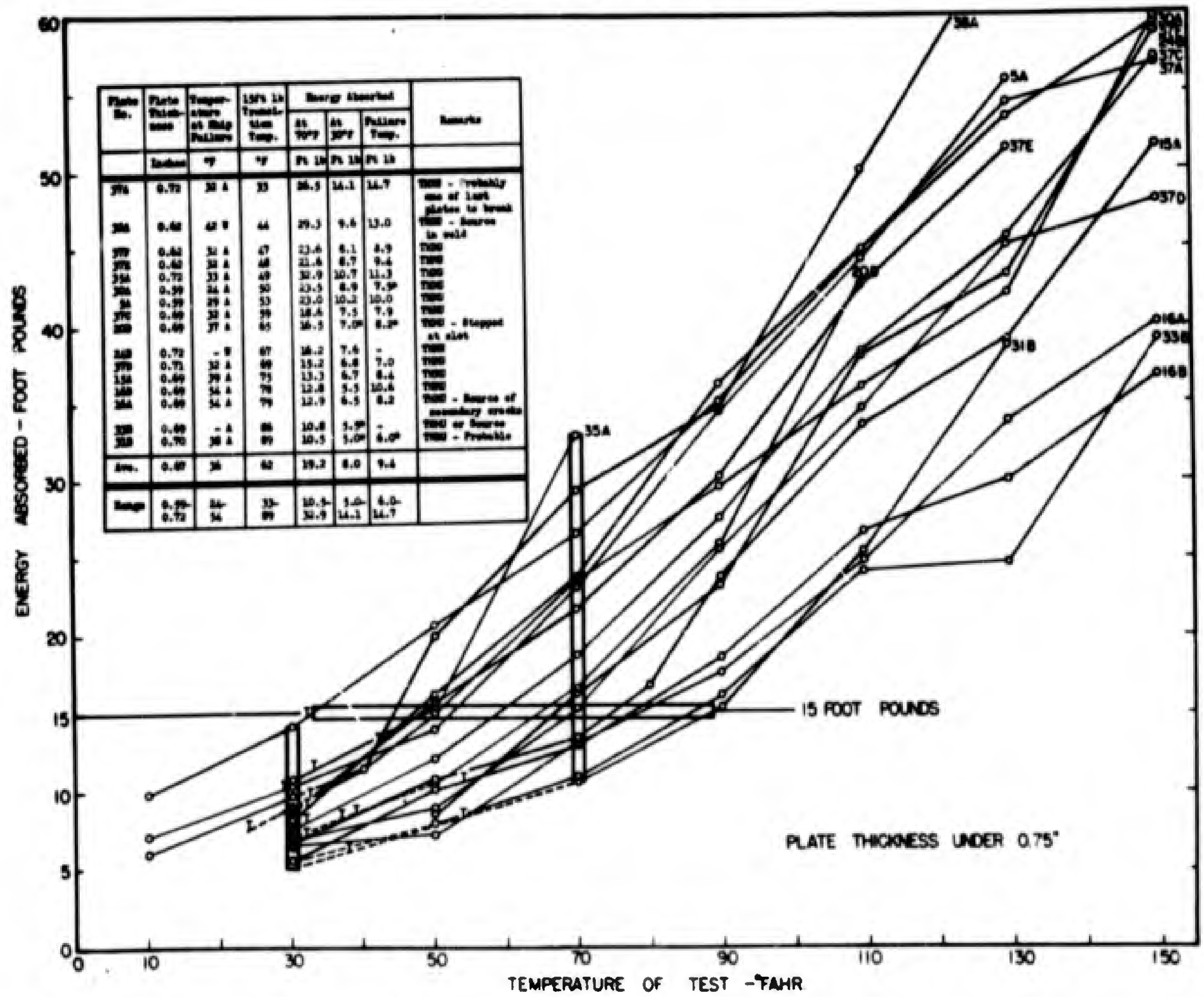
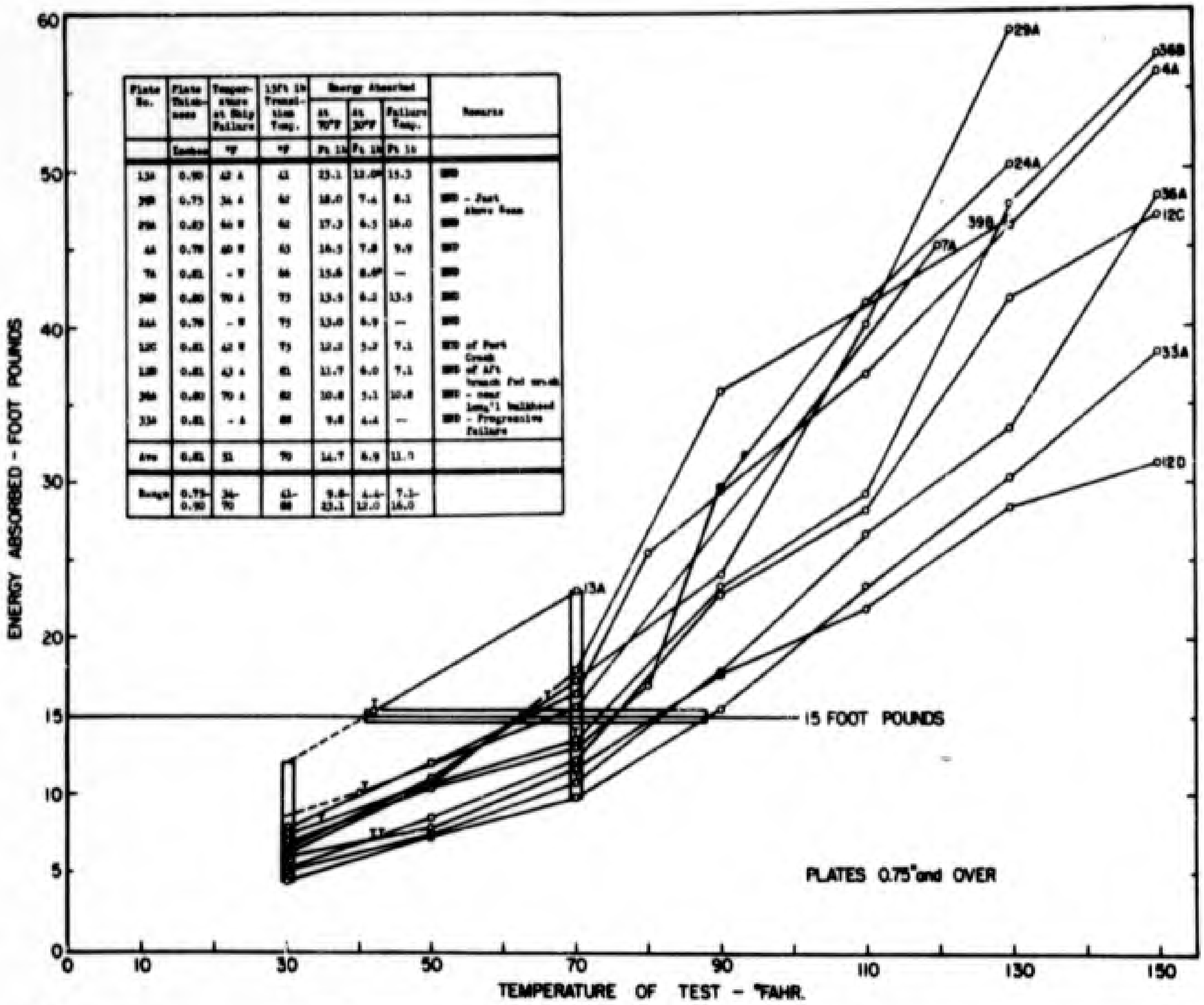


Fig. 12. Notched bar properties of plates which were fractured in the ship failures, but which contained neither source nor end of the fractures. Horizontal bars indicate range of transition temperatures. Vertical bars indicate range of energy absorbed in tests at 30°F and at 70°F.



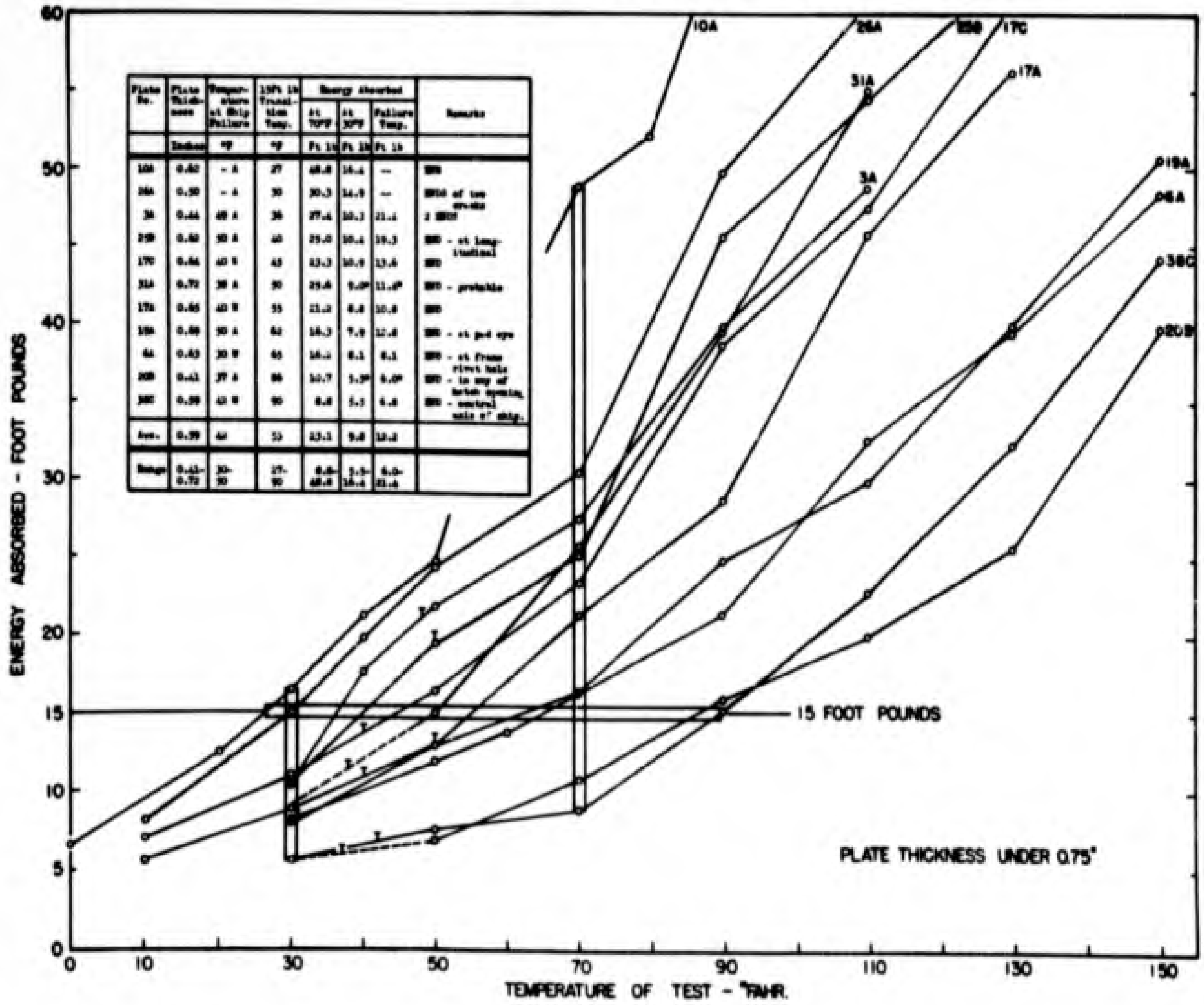


Fig. 13. Notched bar properties of plates in which ship fractures ended. Note lower transition temperatures and higher energy absorption, compared to Figures 11 and 12.

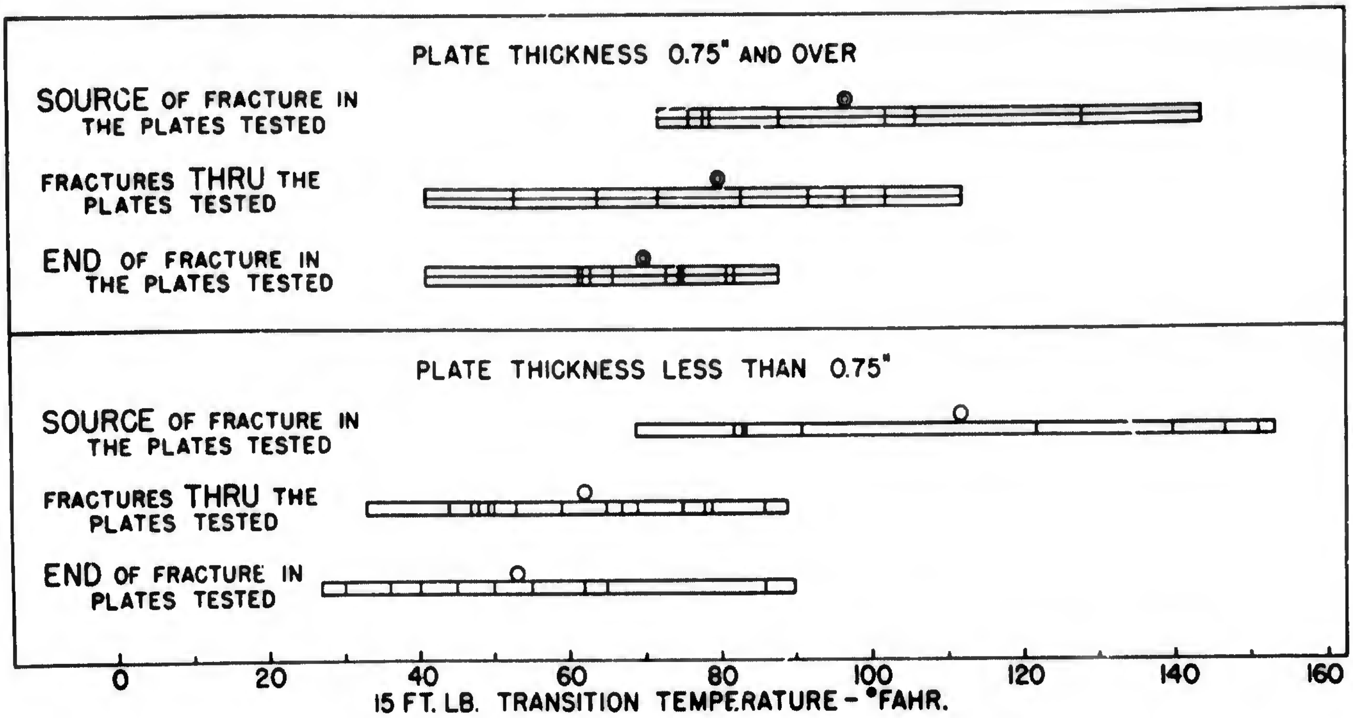


Fig. 14. Relation of 15 foot pound transition temperature to the nature of fracture in ship plates.

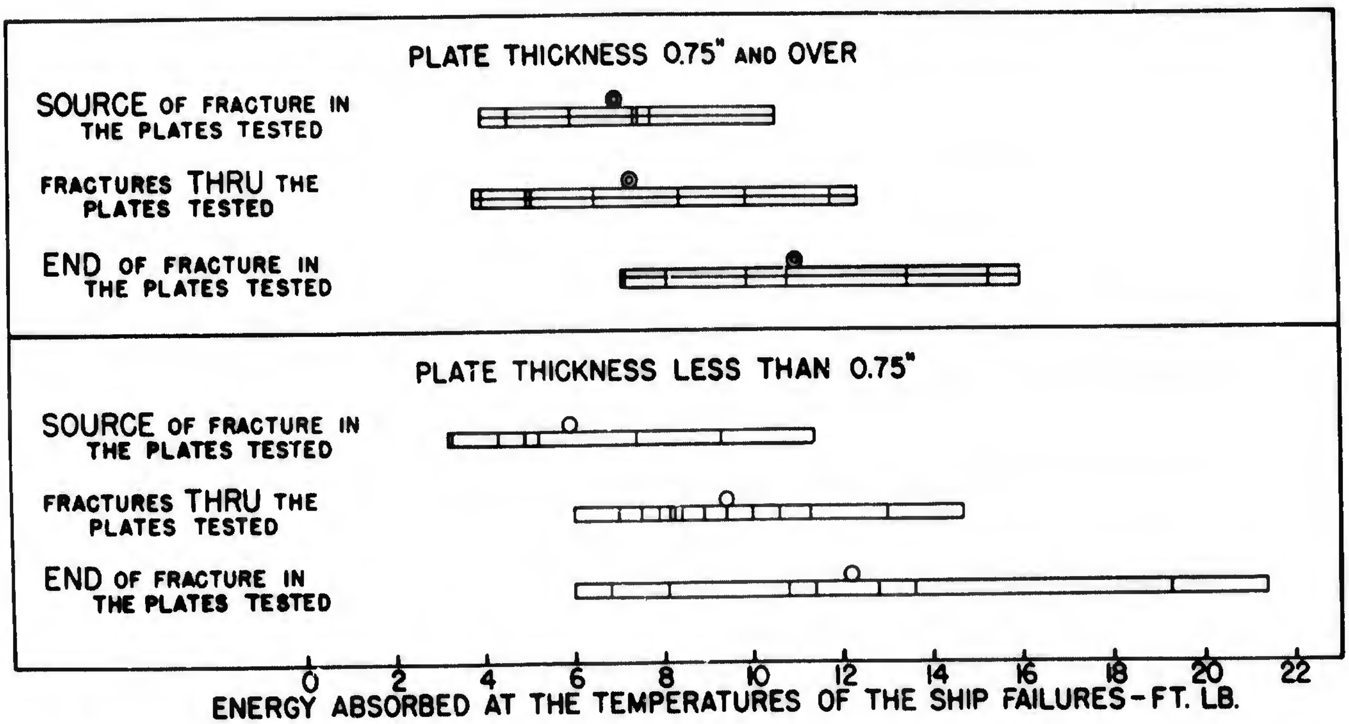
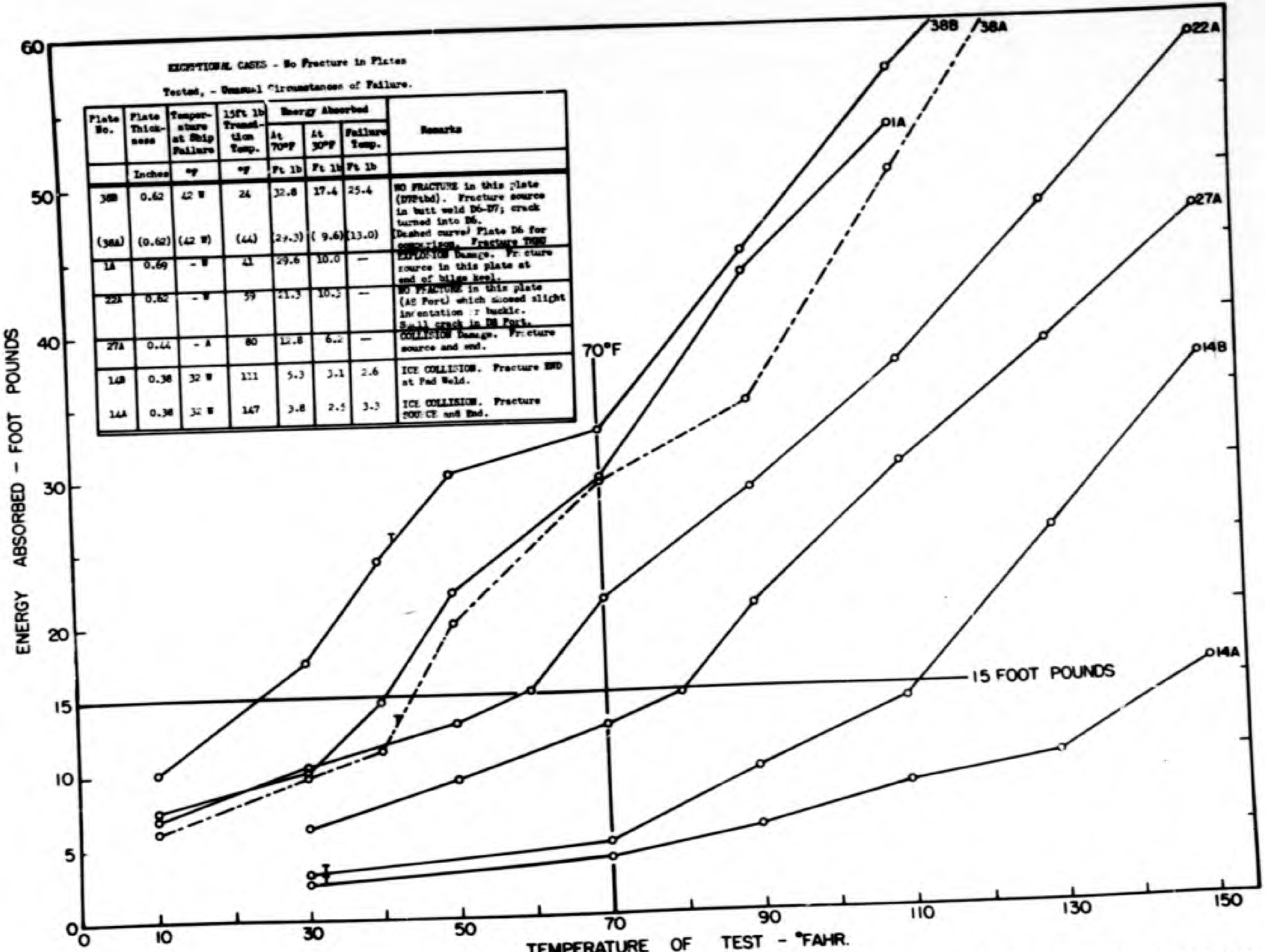


Fig. 15. Relation of energy absorbed in notched bar tests at the temperatures of the ship failures to the nature of fracture in ship plates.



EXCEPTIONAL CASES - No Fracture in Plates

Tested, - Unusual Circumstances of Failure.

Plate No.	Plate Thickness	Temperature at Ship Failure	15ft lb Transition Temp.	Energy Absorbed At 70°F	Energy Absorbed At 30°F	Energy Absorbed Failure Temp.	Remarks
	Inches	°F	°F	Ft lb	Ft lb	Ft lb	
38B	0.62	42 W	24	32.8	17.4	25.4	NO FRACTURE in this plate (DTPtbd). Fracture source in butt weld D6-D7; crack turned into D6.
(38A)	(0.62)	(42 W)	(44)	(29.3)	(9.6)	(13.0)	(Dashed curve) Plate D6 for comparison. Fracture THRU
1A	0.69	- W	41	29.6	10.0	—	EXPLOSION Damage. Fracture source in this plate at end of bilge keel.
22A	0.62	- W	59	21.3	10.3	—	NO FRACTURE in this plate (AE Port) which showed slight indentation or buckle. Small crack in DB Port.
27A	0.44	- A	80	12.8	6.2	—	COLLISION Damage. Fracture source and end.
14B	0.38	32 W	111	5.3	3.1	2.6	ICE COLLISION. Fracture END at Pad Weld.
14A	0.38	32 W	147	3.8	2.5	3.3	ICE COLLISION. Fracture SOURCE and End.

Fig. 16. Notched bar properties of plates with no fracture, or unusual circumstances of failure.

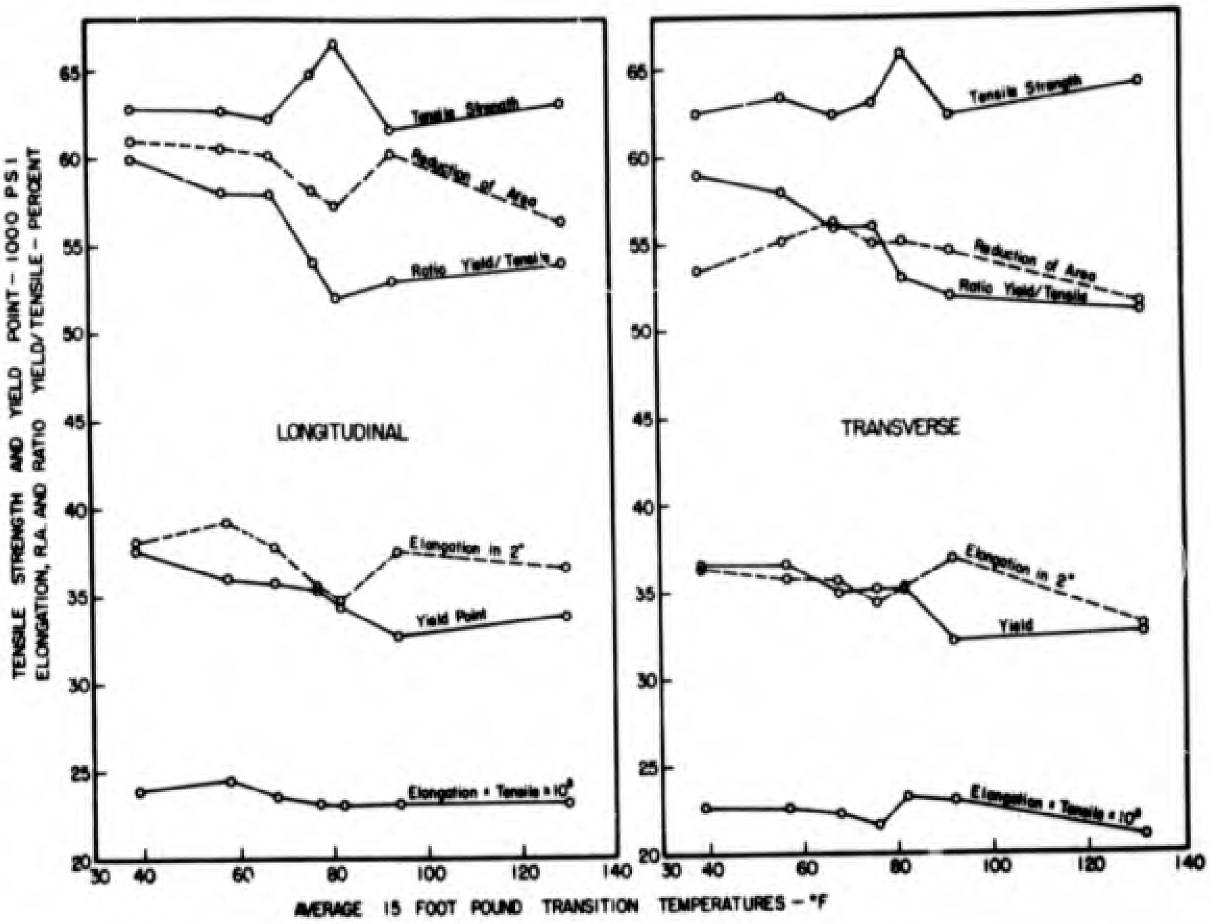


Fig. 17. Relation of average tensile properties of longitudinal and transverse .505" diameter specimens to the average 15 foot pound transition temperatures of successive groups of plates.

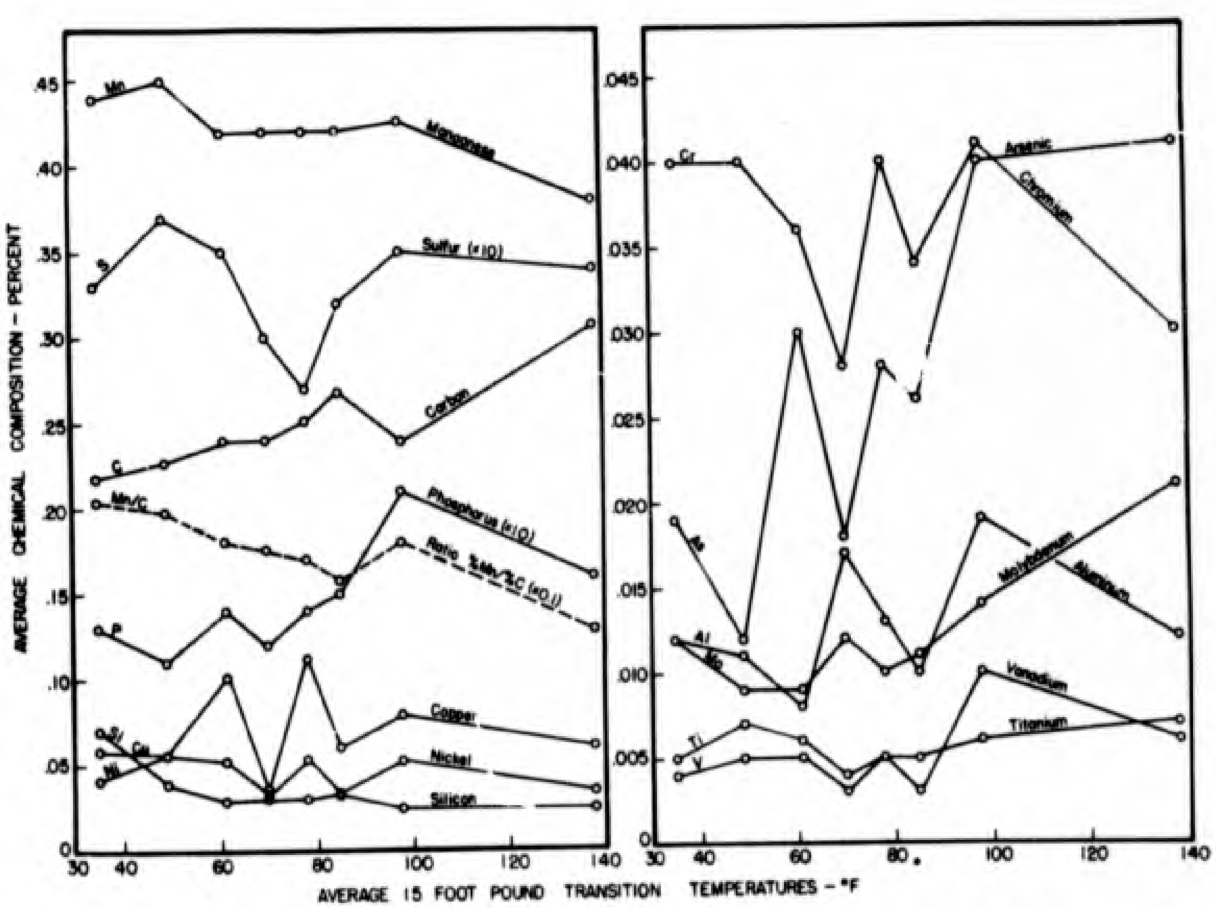


Fig. 18. Relation of average chemical compositions to the average 15 foot pound transition temperatures of successive groups of plates.

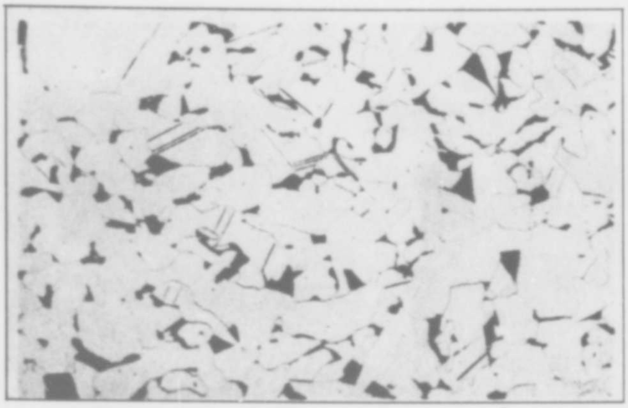


Fig. 19. Neumann bands 1/4 inch from fracture. x 100

Fig. 20. Neumann bands and cracks. x 500

Fig. 21. Directional cracks adjacent to main fracture. x 500

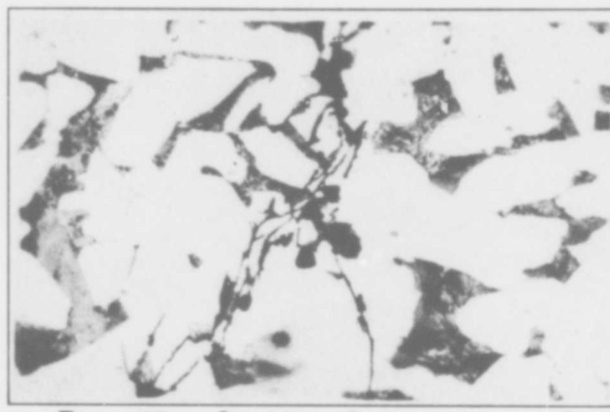


Fig. 22. Shattered zone near main fracture. x 500

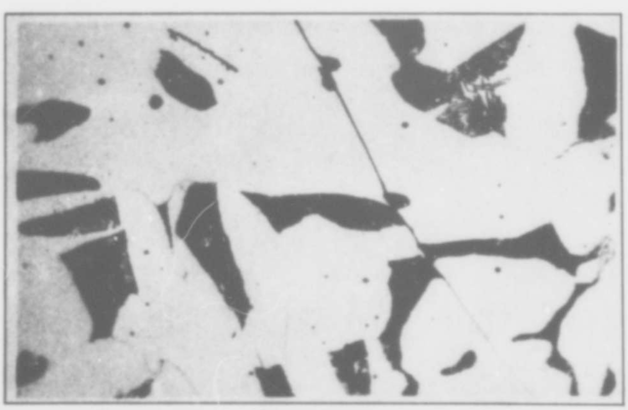


Fig. 23. Displacement of fractured pearlite grains along crack. x 500

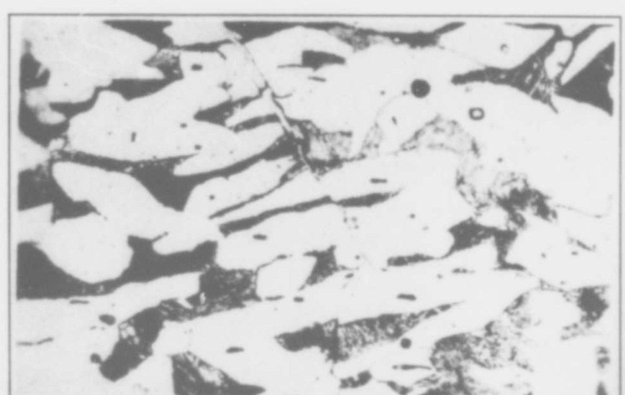


Fig. 24. Displacement of fractured grains along crack. x 500

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13. ABSTRACT

This report covers the examination of fractured plates selected from 60 ships in which structural failures occurred. The chemical compositions and ordinary mechanical properties of most of the plates were satisfactory and met the specification requirements under which they were purchased. However, Charpy notched bar tests indicated that the plates in which fractures originated were notch sensitive at the temperature of fracture, and plates in which the fractures ended were generally less notch sensitive. Most of the fracutres occurred at low operating temperatures, and the origin of each of the fractures examined could be traced to a notch such as a hatch corner, ladder opening, or a faulty weld. Such notches and defects create regions of stress concentration which may start failures in steels that are notch sensitive at the operating temperatures.

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NONE
Security Classification