Nature of Reported Results

Form of Data Presented. -- The test results reported hereinafter show primarily the strength and ductility of the plate specimens at various temperatures and the amounts of energy absorbed by these specimens up to maximum load. The principal results are presented in the form of tables, diagrams, and photographs, as follows:

General Summary of Flat Plate Test Results	Table 5, Figs. 12 through 21
Diagrams of Energy vs. Temperature	Figs. 12 through 14
Diagrams of Temperature Transition Range	Figs. 15 and 16
Maximum Nominal Stress vs. Width and Temperature	Figs. 17 through 21
Typical Strain Distribution Patterns at Various Loads	Figs. 22 through 29
Elongations Measured by Gages at Maximum Load	Fig. 30
Residual Elongations After Rupture	Figs. 31 through 35
Elongations over 2-in., 24-in. and 54-in. Gage Lengths at Various Loads	Figs. 36 and 37
Photo Diagrams of Micro-Hardness Surveys	Figs. 38 through 54
Results of Supplementary 3 in. Bar Tests	Figs. 55 through 68
Percent Elongations After Fracture	Appendix A

In the data summaries the symbols used to designate the individual test specimens have the following meaning:

First symbol designates lot or source of steel.

A -- Carnegie-Illinois steel obtained in 1944 for manufacture of large tubes on Project NRC-75.

B -- Bethlehem steel manufactured in December 1944 for use on Project NRC-92.

C -- Carnegie-Illinois steel manufactured in February 1945 for use on Project NRC-92.

D -- Lukens fully-killed steel used in University of Illinois investigation.

E -- Lukens rimmed steel used in University of Illinois investigation.

H -- Bethlehem fully-killed steel manufactured in December 1945 for use in this investigation.

N -- Lukens nickel alloy steel.

Q -- Republic quenched and drawn steel manufactured in October 1945 for use in this investigation.

Second symbol following the hyphen is the serial number (up to 10) that was assigned at the laboratory to the 6-ft. by 10-ft. plate of each lot of steel. For numbers above ten, the first digit, as in the preceding case, designates the number of the plate, and the second digit, together with the letter X, designates the number of the extra specimen cut from the plate. Normally only one specimen of each width tested was cut from any one 6-ft. by 10-ft. plate.

Third symbol designates the width of specimen cut from given plate.
A -- 72 in. wide
B -- 48 in. wide
C -- 24 in. wide
D -- 12 in. wide

Examples: 1.) Specimen B-1A is a 72-in. wide test plate of steel B, from a plate that has been assigned serial number 1.

2.) Specimen A-41XD is a 12-in. wide test specimen of steel A, from the plate which had been assigned serial No. 4 and is the first extra 12-in. plate tested.

Basis for Calculations of Strength, Ductility and Energy. -- In order to have a convenient basis for stating the load-carrying ability of the notched plates in various widths, reference is frequently made to the "nominal" stress or "nominal" strength of the plate. By this is meant the average stress on the net section through the notch, i.e. the load divided by the original net cross-sectional area. Due to the stress-concentrating effect of a notch, the actual localized stresses were higher at the base of the notch than at other points along a cross-section through the notch; an indication of this variation may be seen from the strain distributions plotted in Figs. 36 and 37.

In general, by "ductility" is meant the elongation of the plate up to maximum load or to rupture, within a specified gage length. Unless otherwise indicated, the elongation measurements were made at intervals across both faces of a plate specimen over a gage length equal to three-quarters of the gross-width of plate. By plate elongation is meant the average elongation thus determined.

The energy absorbed up to maximum load was computed by integrating graphically the load vs. elongation curves for each of the specimens.

Discussion of Results of Tension Tests of Wide Plates

The principal fracture data, -- strength, energy absorbed to maximum load, mode of fracture, and temperature of test--are summarized in Table 5. Because the program of testing is still in progress, the data are fragmentary for some of the conditions of test.

Not shown in the table are the results of a test on a piece of fully-killed steel (Steel D) on which complete tests are being made in a parallel phase of the investigation at the University of Illinois. This test was made on a 72-in. plate at 33°to 35°F. The plate fractured entirely in cleavage at a nominal stress of 39.0 ksi. and to the maximum load absorbed, 360 k-in. of energy in a 54-in. gage length.

Two criteria for defining the range of transition temperature have been used in this investigation, --energy absorbed to failure (maximum load), and the percentage of fracture in the shear mode, 100 percent shear being at the upper end of the range and 0 percent shear at the lower. The use of the two criteria place the transition temperature in slightly different ranges in some cases. However, it is believed that in the present state of knowledge of the problem, it is desirable to record the results of each method of defining the transition range. From the structural point of view, the energy criterion may be the more significant, but insofar as evidence of physical action (even though localized) is concerned, the type-of-fracture criterion is basic.

Steels A, B (as-rolled), and B (normalized) appear to have about the same notch sensitivity, with steel C, the chemical counterpart of steel A, being the more notch sensitive steel of the semi-killed group. Steel N is, as expected, the least notch sensitive of all, with steel Q having approximately the same transition range as steels A and B. No tests have yet been made on steel H.

Energy vs. Temperature. -- Diagrams showing the estimated variation of the energy absorbed to maximum load with the test temperature are shown in Figs. 12, 13 and 14. Curves for the 48-in. and 24-in. wide plates have not been plotted as insufficient number of plates were tested in these widths. For the 12-in. plates the transition temperature ranges have been fairly well defined for all the steels tested to date. With the exception of two test plates Q-1D and N-4D the results are reasonably consistent. For the 72-in. plates the transition ranges have been established for the semi-killed steels and the nickel alloy steel.

These data place the transition temperatures for both the A and B steels in about the same range, while those for steel C are some 50° to 60°F. higher. This was found to be the case with both the 12-in. and the 72-in. plates. A comparison of Figs. 12 and 13, shows that the transition ranges for 72-in. plates are from 10° to 30°F. higher than the transition ranges for corresponding 12-in. plates.

The transition range for the nickel alloy steel is about -40° to -50°F. for the 72-in. plates and -60° to -70°F. for the 12-in. plates. It is of interest to note that the drop in energy with decrease in temperature is relatively abrupt for this nickel alloy steel, and further, that the energy absorbed in the brittle range is remarkably high as compared with that absorbed in the brittle range by the semi-killed steels.

Attention is directed to the unusual behavior of one specimen of the Q steel (Fig. 14); the only explanation that can be offered at this time is that the sample represented one of the extremes that are encountered from time to time in random selection.

Percent Shear Fracture vs. Temperature. -- Figs. 15 and 16 show by diagram for the various temperatures of test the percentage of the cross-sectional area failing by shear for the several steels. The transition ranges have been blocked as shown, even though some points beyond the range show less than 100 percent shear, because the examination of the breaks for these plates definitely show that the small amount of cleavage resulted from a secondary tearing action that occurred only on one edge of the plate.

Strength vs. Plate Width. -- Figs. 17, 18, and 19 show the variation in the nominal strength at maximum load with the width of the plate for three different temperatures and for the two modes of fracture. The wider plates failed at lower nominal stresses than did the narrower plates, and this difference, with the exception of steel C, becomes more apparent for specimens broken at 32°F. than for specimens broken at higher temperatures. Figs. 20 and 21 show the variation in the nominal strength at maximum load with the test temperature for the 12-in. and 72-in. plates.

Plate Elongations. -- Typical distribution of longitudinal elongation of the plates at various loads are shown in Figs, 22 to 29. Diagrams are given for selected plate specimens in each width tested and for each type of fracture, shear or cleavage. The data represented by open circles were obtained from pairs of wire extensometers placed on opposite faces of the plates, and given the change in distance between two points at the ends of the longitudinal gage lines having, in all cases, lengths equal to three-quarters of the plate width. These elongations are shown for each of several loads (stated in terms of nominal stress), and include the separation of a plate across the notch and the crack, when and if cracking began before maximum load was reached, for example - in some cases the crack may have progressed several inches from the base of the notch before the maximum load was attained, and in case the crack has progressed farther on one side of the plate than on the other, a lack of symmetry of some of the diagrams would result.

In general, at the higher loads, the elongation was greater in the central portion of the plate than at the edges. Thus, since the longitudinal extension was not uniform across the width of the specimen, it was necessary to calculate from the elongation readings an **average elongation** which could be used to estimate the energy absorbed by the specimen. (See Fig. 2).

The data represented by the solid black circles were obtained from measurements on the specimens after failure occured. These values of residual elongation do not include the elastic elongation, nor do they include plate separation due to the opening of cracks; also the residual elongations were measured on one face of the specimens, so that the effect of distortion (if and when any existed) of the plate during rupture is included in the values shown.

It may be noted from the diagrams that the residual elongations of elements traversing the base of the notch are less than the overall elongations determined from the wire gages. The reason was, that as the crack progressed outward from the notch, the stresses were reduced in the longitudinal elements which were severed by the crack, and plastic flow was lessened or completely stopped. In the specimens which failed by shear, during the progress of rupture those portions of the plate outboard from the advancing crack sustained the entire load and continued to yield, so that the residual elongations at the edges of the plate are relatively large. In cleavage type failures there was usually a small amount of shear type fracture near the base of the notch, so that here also, the residual elongations of the elemonts traversing the base of the notch are less than the elongation indicated by the wire extensometers. However, along elements across a cleavage type of fracture, the residual elongations were much closer to the over-all elongation. It is also to be noted that the magnitude of elongations are much smaller for the specimens that failed by cleavage than those that failed by shear.

A comparison of the residual elongation of specimens that behave in a ductile manner and a relatively brittle manner is given in Fig. 31. The elongations are shown in percent, and to compare specimens of different sizes the locations of the elements on which the measurements were made are plotted as fractions of the specimen width. The marked difference in magnitude and distribution of the residual elongations between ductile and brittle specimens are readily apparent from this figure. It is of interest to note that for the specimens failing by shear, the 12-in. specimens exhibited greater ductility than those of greater width; however, this was not true for the plates where cleavage fracture was predominant.

A comparison of the elongation at maximum load, as determined by the wire extensometers, of specimens which behaved in a ductile manner and in a relatively brittle manner is given in Fig. 30. Trends similar to those just discussed in connection with residual elongations are apparent here.

Figs. 36 and 37 show the elongation at various loads as measured over 2-in., 24-in., and 54-in. gage lengths on two 72-in. specimens. The local elongation near the fracture was very high and decreased as the gage length was increased. This is very pronounced for the ductile specimen B-5A, and less so for the brittle specimen C-1A.

Reduction in Thickness along Line of Fracture. -- As a further aid in judging tendency toward brittle behavior of the plate specimens broken at various temperatures, plate thicknesses were measured after rupture along the line of fracture. By comparison with a set of plate-thickness measurements made before application of load to a specimen, the percentage reductions in thickness were computed in each case. The thickness reductions are summarized in Table 6.

Although there are some exceptions, the general pattern of the data for the semi-killed steels is as follows. For the specimens which fractured entirely by shear the reductions in thickness were of the order of 5 percent at a point a small distance from the notch and increased to about 20 percent at the outside edge of the plate. The thickness reductions at the notch varied considerably, probably being greatly influenced by time of development of the initial crack in the base of the notch.

For the specimens of semi-killed steels which fractured entirely by cleavage, the thickness reduction was generally of the order of 3 to 5 percent at 1/2 in. from the notch and decreased to about 1 or 2 percent at the edge of the plate. The thickness reductions at the notch also varied considerably for plates having this mode of fracture, sometimes being much higher at the notch, and sometimes reaching a maximum for the whole plate at a point between the base of the notch and the 1/2-in. point. It is noteworthy that even for 100 percent cleavage fracture, the minimum reductions in thickness were usually at least 1 percent.

The Q steel appeared to follow a pattern of behavior somewhat similar to that of the semi-killed steels, except that the maximum reductions in thickness attained were appreciably greater.

The N steel did not follow the pattern of behavior described above; compared with the semi-killed steels it tended to exhibit greater thickness reductions where fracture occurred by cleavage, and sometimes showed less thickness reduction than the semi-killed steels where fracture occurred by shear.

Summary of Auxiliary Studies

Hardness Surveys of Fractured Plate Specimens

In attempt to obtain some indication of the localized stress distribution in the wide flat plates at fracture, it was considered desirable to conduct some experiments in which advantage would be taken of the strain-hardening property of steel to indicate maximum stress levels. Accordingly, some specimens were sectioned at intervals along the surface of fracture and hardness surveys were made so as to determine the variation in hardness throughout the metal near the fractured surfaces as described in a previous report (Cleavage Fracture of Ship Plate as Influenced by Design and Metallurgical Factors NS-336, Part II--Flat Plate Tests; OSRD No. 6452, Serial No. M-608, January 1946).

The true stress-natural strain curves for bars cut from specimens B-1A (which failed in a ductile manner), C-1A (which failed in a brittle manner), and C-2A (which failed in a brittle and partly in a ductile manner) are shown in Fig. 52. In Fig. 53 are shown the hardness vs. natural strain curves for the same specimens. From these curves was calculated the energy absorbed per cubic inch of strained material for various strains. The energy in inch pounds per cubic inch is plotted against the Knoop hardness number in Fig. 54.

The locations from which samples for the hardness tests were taken from the plates are indicated in Figs. 38, 39, 40 and 41. The samples used for determining the hardness were pieces about 1 in. long and 1/4 in. thick. The face that was polished and used for measurements was perpendicular to the face or plane of the specimen and parallel to the loading axis. A large number of readings was taken on the face of each sample so that hardness contours could be plotted. About six readings were taken at each point to give an average hardness value for each location. The normal scatter in the Knoop hardness number was ±5. (The Knoop hardness number is very nearly equal to the Brinell hardness number.)

The results of the hardness surveys for plate C-2A are shown in Figs. 42 to 48. These results are shown in the form of hardness "contours" on selected imaginary planes through the plates.

From the Knoop hardness numbers shown in Figs. 42 to 48 it is possible to determine the local distribution of energy at and near the fracture. An example of energy distribution is shown in Fig. 49 for plate B-1A, in Fig. 50 for plate C-1A, and in Fig. 51 for plate C-2A.

Specimen C-2A failed by cleavage for about 4 in. Then the fracture changed to the shear mode for 4 in., and then changed back to the cleavage mode. Large deformations occurred near the notch, then there was little deformation for several inches. In the next few inches extensive shear distortion occurred and then followed a region of cleavage failure with little deformation out to the edge of the plate. At the base of the notch, the microhardness survey indicated that much shear distortion had occurred. The region which failed by shear also showed evidence of great shear distortion, while the region adjacent to cleavage fracture showed much less evidence of plastic flow.

The conclusions that may be drawn from the results of the microhardness tests are:

(1) Extensive deformation occurs at the base of the notch for both shear and cleavage fractures. The strain hardening which occurs in this region is as great as that which occurs near the fracture of a standard tensile test bar.

(2) Some local plastic flow takes place near the fracture during the time that failure occurs. It should be noted that the volume of metal subject to large plastic strain was confined to a relatively localized region, when the fracture was predominently cleavage, while in cases where shear fracture occurred large plastic deformations took place over very extensive regions of the plate.

(3) It appears that more plastic flow occurs near the surfaces of the plate than at points remote from these surfaces.

(4) Cleavage failure may occur after varying amounts of plastic flow have taken place. Cleavage fracture is not necessarily an indication of lack of plastic flow.

Tests of Unnotched, Notched, and Sheared Edge Three-Inch Wide Specimens

An attempt was made to develop a simple, easily-prepared specimen that would behave in the same manner as internally notched wide plates used in the main part of this investigation. The 3-in. specimen flame cut from full thickness plate, does not require any machining and thus might be an inexpensive and fast method for determining the transition ranges of the various steels.

The principal phase of this part of the investigation involved tension tests on three types of flat 3-in. specimensof the various steels in order to determine their transition ranges.

The three different types of bars used in this investigation are shown in Fig. 58. The plain, unnotched bar was flame cut from the test plate to a 4-in. width and the central portion reduced by cutting away 1/2-in. from each edge on a Doall saw. The notched bar was made by flame cutting from a plate and by making a cut, 1/4-in. deep, on each edge of the bar with a hacksaw to produce a net width of 2 1/2 in. at the notch. The shear-edge bar was similar to the unnotched bar except that one edge was made to include the longitudinal sheared edge of the large test plate. The sheared edge bar was used in the tests in order to determine the effect of the sheared edge of plates on the transition range of the steel.

A special cooling unit and a jacket for the specimens were developed so that the temperature could be controlled within very narrow limits. Fig. 67 shows the cooling jacket in place about a specimen in the tensile machine, and Fig. 68 shows a general view of the apparatus used in the 3-in. wide bar tests.

Results of the 3-In. Bar Tests. -- Transition temperatures for the various steels used in this investigation as well as for steel D (fully killed) and steel E (rimmed) are shown in Fig. 55. Transition temperatures for the various thickness of steel C are given in Fig. 56. A comparison of the transition temperatures for the plain, sheared edge and notched edge bars of steels A and C are shown in Fig. 57. Fig. 59 through 66 show the fractures of the test bars for the various steels.

The results of the 3-in. bar tests indicate that the steels tested can be arranged in the same order as by the tension tests of the wider notched plates, although the transition temperatures may differ somewhat.