FINAL REPORT

ON

CAUSES OF CLEAVAGE FRACTURE IN SHIP PLATE, HIGH YIELD STRENGTH STRUCTURAL STEEL

BY

A. BOODBERG and E. R. PARKER

University of California
Under Bureau of Ships Contract NObs-31222

COMMITTEE ON SHIP CONSTRUCTION

DIVISION OF ENGINEERING AND INDUSTRIAL RESEARCH

NATIONAL RESEARCH COUNCIL

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UNDER

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September 21, 1949

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Dear Sir:

Attached is Report Serial No. SSC-28 entitled "Causes of Cleavage Fracture in Ship Plate, High Yield Strength Structural Steel." This report has been submitted by the contractor as a final report of the work done on Research Project SR-92 under Contract NObs-31222 between the Bureau of Ships, Navy Department and the University of California.

The report has been reviewed and acceptance recommended by representatives of the Committee on Ship Construction, Division of Engineering and Industrial Research, NRC, in accordance with the terms of the contract between the Bureau of Ships, Navy Department and the National Academy of Sciences.

Very truly yours,

C. Richard Soderberg

C. Richard Soderberg, Chairman
Division of Engineering and
Industrial Research

CRS:mh

PREFACE

The Navy Department through the Bureau of Ships is distributing this report to those agencies and individuals who were actively associated with the research work. This report represents a part of the research work contracted for under the section of the Navy's directive "to investigate the design and construction of welded steel merchant vessels."

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FINAL REPORT

U.S. Navy Research Project NObs-31222

CAUSES OF CLEAVAGE FRACTURE IN SHIP PLATE

HIGH YIELD STRENGTH STRUCTURAL STEEL

From: University of California, Berkeley, Calif.

Report Prepared by: Alexander Boodberg
Earl R. Parker

ABSTRACT

This report summarizes the work completed under the U.S. Navy Contract NObs-31222, from November 1946 to the termination date of the contract, 31 October 1948.

The primary objective of the investigation was to study the effect of variations in steel composition on the temperatures at which the mode of failure changed from ductile shear to brittle cleavage type. These transition temperatures were determined by means of tension tests on notched plates and welded structural assemblies.

Three types of specimens were used, two simple notched specimens and one that provided restraint to plastic flow at a corner produced by welding together steel plates set along three mutually perpendicular planes. The specimens were tested in tension at various temperatures and at a low rate of strain in order to determine the transition temperatures of four different heats of high yield strength structural steels. Auxiliary tests were conducted by using a simple bend test to determine the effect of welding on the behavior of the steels.

Results of the tests show that the four high yield strength structural steels used in this investigation, when tested in the form of restrained welded

specimens, have transition temperatures that vary from -65°F for one of the steels, to as high as +75°F for one of the others. The tests of notched specimens showed transition temperatures for a particular steel that were approximately 50°F lower than those indicated by tests of the large specimens. However, it was found that the steels are rated in the same order of transition temperatures by all three of the tests.

The nominal stress at the maximum load, during the tests of small notched specimens exceeded the ultimate strength (as determined by standard tensile bar tests) of the particular steel. However, the restrained welded specimens fractured at nominal stress values that were below the yield strength of the steel as measured in a standard tensile test.

The auxiliary bend tests of small welded specimens of high yield strength steel indicated that only two of the many types of mineral-coated electrodes tested would produce weldments that were not susceptible to cracking during the early stages of plastic deformation.

Relative hardenability of the four steels was also determined. Micro-hardness surveys of plate, weld and heat-affected zone materials are presented in Appendix A.

A description of the various types of auxiliary equipment used in these tests, methods used in the preparation of the specimens and other pertinent information are included in Appendix B of this report.

In order to compare the results of this investigation with results of similar tests of medium carbon steels, data from tests of medium carbon steels, "C" and "B" are included in this report.

FINAL REPORT

U. S. Navy Research Project NObs-31222

CAUSES OF CLEAVAGE FRACTURE IN SHIP PLATE

HIGH YIELD STRENGTH STRUCTURAL STEEL

From: University of California
Berkeley, Calif.

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Alexander Boodberg
Earl R. Parker

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INTRODUCTION

The results reported in this paper constitute a part of a large research program sponsored by the Bureau of Ships of the United States Navy and coordinated by the Committee on Ship Construction of the National Research Council. This investigation was primarily concerned with the behavior of various types of high yield strength structural steels that were tested in the form of welded structural assemblies at temperatures from $+100^{\circ}F$ to $-108^{\circ}F$. Previously conducted investigations,[1,2,3,4] which were a part of the same program, have been primarily concerned with the behavior of various types of mild steels under conditions similar to those of the present investigation.

Four alloy high strength structural steels were tested during the course of the program; the yield strengths of these ranged from 66,000 psi to 84,000 psi and the tensile strengths ranged from 89,000 psi to 105,000 psi. All steels were tested in the quenched and drawn condition, and one of the steels was also tested in the normalized condition. One heat of steel was re-heat treated to improve its notch toughness because some of the early tests showed poor results.

Results of the tests of relative hardness of the four steels and of the microhardness surveys of plate, weld and heat-affected zone materials are presented in Appendix A.

The primary objective of the investigation was to determine the effects of variations in steel composition on the temperature at which the type of fracture changed from the ductile shear type to the generally brittle cleavage type. The specimen used for these tests contained a discontinuity produced by welding together four plates on three mutually perpendicular planes to form a

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1,2,3,4 - See References

right angle corner.

The two minor objectives of the investigation were: (1) to determine the influence of temperature on the mode of fracture of notched flat tensile specimens of the various steels, and (2) to determine the effect of temperature on the brittle behavior of weldments that were made by welding the high yield strength structural steels with commercially available electrodes at various temperatures of preheat.

The physical properties and the chemical compositions of the steels used in the investigation are given in Table I and the electrode data are shown in Table II.

EXPERIMENTAL WORK

Test Program

The main feature of the investigation consisted of tension tests at various temperatures on specimens containing abrupt changes in section produced by welding together four pieces of plate as shown in Fig. 1a. These four pieces were cut from a large 3/4 in. x 72 in. x 120 in. plate according to the layout shown in Fig. 1b. These specimens, made of high yield strength structural steel, have been called "restrained welded specimens". They were similar in construction to, but considerably smaller in size than the previously tested "hatch corner specimens",[1] that were made of 3/4-inch thick mild steel. The high yield strength structural steels had to be tested in this reduced scale form in order that the capacity of the testing machine would not be exceeded, because the strength of the steels used in this investigation (see Table I) was almost twice as great as that of the mild steels previously used. The restrained welded specimen was selected for test because it incorporated restraint to plastic flow in a welded specimen having an extremely severe type of structural discontinuity.

In order to establish a basis for comparison between the results obtained on the behavior of the mild steels,[1,2,3] and those obtained in the present program on the behavior of the high yield strength structural steels, it was considered desirable to include data from tests of restrained welded specimens made from one of the mild steels previously used. The configuration and the loading axis for the restrained welded specimen used in this investigation were so chosen that the stress distribution in the main strength member would be similar to that found in the deck member of the "hatch corner" specimen.[1] Results obtained from the SR-4 strain gage installations at and near the corners of several of the restrained welded specimens, confirmed that the elastic stress distribution during the tension tests was almost identical to that found in "hatch corner" specimens, and was not affected by the type of steel used or by the change in the size of the specimen.

Tension tests were made on 12-inch wide centrally notched specimens and 3-inch wide edge notched specimens of the four high yield strength structural steels and of the one mild steel. For each steel and for each type of specimen the tensile strength, energy to maximum load and to failure, and the percent of the fracture surface which failed by shear, were determined at various test temperatures. From these data it was possible to determine the temperature at which the mode of fracture changed from shear to cleavage.

In order to obtain some idea of the weldability of the various steels, and to check the behavior of weldments, small specimens were welded with commercially available electrodes (enumerated in Table II), and then subjected to a bend test at different temperatures. These specimens were 3/4-inch thick, 6 inches wide and 9 inches long. They contained various types of longitudinal welds at the centerlines of the plates and the weld in most cases was ground flush with the surface of the plate prior to the test; no artificial notches were added. Various degrees of preheat temperature were tried in the welding of the different steels. These specimens were tested in a special jig, the specimens being loaded so that the direction of maximum stress was parallel to the weld. The low temperature tests were conducted by immersing the jig containing the specimen in a bath of alcohol which was maintained at the desired testing temperature to within $\pm$ 2°F during the test.

Test Procedure

The large restrained specimens, of the design shown in Fig. 1a, were tested in tension at several temperatures in order to establish the temperature vs. energy absorbed relationship for each steel. Manganin wire extensometers[2] were used on all specimens to measure the overall elongation of the specimens at various loads. From the load elongation curves thus obtained it was possible to determine the energy absorbed by the specimen during the test. Energy to maximum load and energy to fracture were determined. Specimens were loaded until fracture occurred in the main strength member as well as in the continuous longitudinal member. The specimens were maintained within $\pm$ 5°F of the testing temperature by circulating air, which had been cooled by dry ice, through an insulated plywood box which surrounded the specimen. The specimens that were tested at extremely low temperatures required additional cooling. This was provided by spraying liquid nitrogen into the box enclosing the specimen, with the nitrogen spray so adjusted that it was uniformly distributed throughout the box. After the temperature was brought down to below that desired, the nitrogen supply was shut off, allowing the specimen to warm up slowly to the desired test temperature. Thermocouples were used to check the distribution of temperature in the specimen, particularly in the critical region through which the fracture would pass. A maximum temperature of $\pm 5^{\circ}$F was observed at points approximately 20 inches below and above the corner. Except for the very low temperature tests, windows were provided in the box so that the formation and progress of cracks could be followed visually. High speed motion pictures were taken of the formation of cracks in two of the specimens. A specimen under test in the 3,000,000 lb. machine with the cooling box in place is shown in Fig. 2a. A view of a specimen under test at room temperature is shown in Fig. 2b.

Two types of notched tensile specimens were used. One of these was a 12-inch wide centrally notched specimen shown in Fig. 3a; the other was a 3-inch wide edge notched specimen shown in Fig. 3b. The 12-inch wide specimens were flame cut from large plates and had a 3/4-inch hole drilled in the center, from which 1-inch long hacksaw cuts were made, extending from the edges of the hole toward the edges of the specimen. This notch was further extended for an additional 1/8 inch toward each edge of the plate with a 0.010-inch thick jeweler's saw. The 3-inch wide specimens were flame cut from a large plate and 1/2-inch deep notches were made inward from each edge at midlength of the specimen with a 0.042-inch thick hacksaw blade. These two types of specimens were tested at various temperatures and the tensile strength, energy absorbed to maximum load and to failure, and the percent of fracture surface which failed by shear were recorded. From these data it was possible to determine a transition temperature for each type of specimen and each steel tested.

Specimens for the bend tests were made by butt welding two 3-inch wide by 9-inch long pieces of steel, as shown in Fig. 3c, with various types of commercially available electrodes and using various temperatures of preheat. Some specimens were made by depositing a weld bead on the surface of 6-inch by 9-inch by 3/4-inch plates. Since these specimens were small it was necessary to maintain careful control of the specimen temperature during welding. In a few cases it was found necessary to allow the specimen to cool to the proper preheat temperature before continuing with the welding. Most of the bent test specimens were tested at +70°F and at -40°F in the jig shown in Fig. 3d. Several of the specimens were tested at 0°F. The angle at which the first sign of cracking appeared was noted and the load and the deflection were recorded. The bend angle was measured by the relative movement of the jig members and checked after removal of the specimen from the fixture. The results of these tests were used as a preliminary criterion for estimating the performances of the large structural specimens and also for evaluating electrodes and determining desirable preheat temperatures.

Welding Procedure

All of the restrained specimens used in this investigation were welded according to the sequence and type of weld shown in Fig. 1a. For the first seven specimens of the high yield strength structural steels, Type 310 electrodes were used with 300°F preheat (± 25°F). Specimens subsequent to No. 7-S were made with Electrode "A" (See Table II) and 175°F preheat (± 25°F). Currents and voltages used were those recommended by the manufacturers of the electrodes, and are indicated in Table II. Each batch of electrodes was carefully heated for at least one hour at 600°F just prior to use to insure freedom from moisture. All specimens were welded by the same team of welders, and the critical areas around the corner were carefully examined by means of magnaflux; X-rays were taken of several of the specimens. With a few exceptions (Specimens 1-S, 3-S, 5-S and 7-S) a period of from 24 to 48 hours was allowed to elapse between the completion of the welding on the specimens and the actual test.

RESULTS

General

The primary objective of these tests was to determine the transition temperature of the several high yield strength structural steels by means of restrained welded specimens.

The transition temperature may be defined as a temperature at which the mode of fracture changes from the ductile shear type to the brittle cleavage type. If a sufficiently large number of specimens were tested (as in the case of the 3-inch wide edge notched specimen tests) this temperature may be established very closely. However, as the expense of testing a large number of specimens of the restrained welded type is prohibitive, in this investigation it was necessary to approximate the transition temperature of a particular steel by arbitrarily choosing a point halfway between the two test temperatures - one that resulted in a predominantly shear fracture of the test specimen and the other that gave a predominantly cleavage fracture. Thus the transition temperature for a steel as determined by the large restrained welded specimens may be in error by as much as $\pm$ 20°F because in some cases temperature differentials between the various tests were quite large.

The transition temperatures for the steels, when tested by means of 3-inch wide edge notched specimens, can be readily determined, as a large number of tests can be made rapidly and inexpensively.

The high yield strength structural steels could not be welded with cellulose-coated electrodes because of the occurrence of underbead cracking; consequently, it was necessary to conduct tests on several commercially available electrodes having mineral-type coatings. These electrodes included the 25 chromium - 20 nickel stainless steel, type 310. During the early part of the investigation the Type 310 electrodes produced bend test specimens which were much more ductile and thus less susceptible to cracking during the early stages of plastic deformation than any of the ferritic-type of mineral-coated electrodes which were available at that time. Consequently, two of the steels which were first investigated were welded with Type 310 electrodes, and a preheat temperature of 300°F was used because the preliminary bend tests indicated this to be the temperature resulting in the best performance.

Subsequently a low-hydrogen, ferritic-type electrode, Electrode "A", was obtained which compared favorably in ductility with Type 310 electrode, and in addition had considerably higher yield and tensile strengths than did the Type 310. For this reason the Electrodes "A", using a 175°F to 200°F preheat temperature, were employed for welding all remaining restrained welded specimens.

Restrained Welded Specimens

Five structural type specimens of Steel 1 were welded with the stainless steel electrode and 300°F preheat. These specimens were tested in tension at temperatures ranging from -35°F to +70°F in order to establish the transition temperature for the steel for this type of specimen. The results are shown in Figs. 4a and 4b, along with similar transition temperature curves for the other steels tested, and are tabulated in Table III.

The transition temperature for Steel 1, tested in the form of the restrained welded specimen, was about +40°F as compared with a transition temperature of about +5°F determined by tests of 12-inch wide plates, and -10°F as found by tests of 3-inch wide edge notched specimens. The shift in transition temperatures toward higher values for the larger, more complicated specimens is normal and is a tendency which was also exhibited by the mild steels that were tested previously.[2] However, the values of the maximum nominal stresses at failure for the welded specimens of Steel 1 decreased as the testing temperatures were lowered. This is contrary to the behavior of the other high yield strength structural steels and the mild steel B_r, the ultimate strengths of which remained approximately the same regardless of the testing temperatures. An additional specimen of Steel 1, welded with Electrode "A" and 200°F maximum preheat, was tested at the close of the program in order to obtain a comparison with the results of the tests of specimens of this steel welded with the Type 310 electrodes. There was no major difference in the behavior of the specimen welded with the Electrode "A" and that welded with the Type 310.

Two specimens of Steel 2 were welded with Type 310 electrodes at 300°F preheat. The one tested at +65°F failed with cleavage type fracture and had a relatively low energy absorption, 496,000 in.lbs. with a maximum nominal stress of 68,000 psi. The other specimen was tested at +100°F and failed by shear. The energy absorption for this specimen was 940,000 in. lbs. and the maximum nominal stress was 66,500 psi. An additional specimen of Steel 2 was subsequently welded with the ferritic Electrode "A", using a preheat temperature of 300°F. This specimen was tested at +73°F and failed by a mixed shear and cleavage fracture, having an energy absorption of 326,000 in. lbs., and a maximum nominal stress of 65,600 psi. Thus the apparent transition temperature for Steel 2, as approximated by means of tests of the three restrained welded specimens, is in the neighborhood of +75°F. As in the case of Steel 1, the use of a different welding electrode and preheat temperature did not seem to alter materially the behavior of the steel.

As the apparent transition temperature of Steel 2 was exceptionally high, additional heat treatment was performed on two of the plates in order to improve its notch toughness. Two restrained welded specimens were made from this re-heat treated steel and were tested at +37°F and +78°F; the result, however, indicated no significant improvement in performance. The energy absorption was low, the nominal stresses at maximum load were almost the same as for the specimens made of the steel that had no additional heat treatment. A very small apparent improvement in transition temperature might be credited to the second heat treatment, because the specimen that was tested at +37°F failed with 5 percent shear, as compared to the 0 percent shear fracture at +63°F of the specimen with no additional heat treatment. However, no definite statement can be made about the transition temperature on the strength of tests on only two specimens.

The transition temperatures determined by means of 3-inch wide and 12-inch wide notched specimens for Steel 2 in the original heat treated condition were about +20°F for both types of specimens. The additional heat treatment of Steel 2 resulted in no change in its transition temperature as determined by 3-inch wide edge notched specimens. These high transition temperatures were unexpected as it was believed that this steel would perform satisfactorily because of its chemical composition and good impact strength as determined by Charpy tests. The apparent 50°F difference in transition temperature between that determined by small notched specimens and the one obtained by tests of restrained welded specimens was similar to that of Steel 1 and the mild steel B_r.

Four specimens of Steel 3 were tested in the restrained welded form at temperatures ranging from -108°F to +70°F. The transition temperature for this steel in this type specimen was approximately -50°F. The 12-inch wide centrally notched plates and the 3-inch wide edge notched specimens were also tested over a wide range of temperatures and the transition temperature was found to be about -95°F for the 12-inch wide plate and -102°F for the 3-inch wide specimens. With this steel, as with Steels 1 and 2, the difference in transition temperature between the small notched specimens and the restrained welded specimens was approximately 50°F.

As some improvement was shown in the behavior of bend test specimens that were post-heated, one specimen of Steel 3 was made in a manner identical to all previous specimens, but all the welds and component parts, at and about the corner, were post-heated by means of oxy-acetylene torches to 650°F (± 50°F) for about 10 minutes. The specimen was then allowed to cool normally to 70°F. A very slight improvement in both the energy absorption to failure and maximum nominal stress values was shown by this specimen as indicated on Fig. 4a. However, energy absorption to maximum load was lower than that of the specimen that received no heat treatment. No explanation can be offered for this result.

Steel 4 was tested in the restrained welded specimen form at temperatures ranging from -83°F and +72°F. The transition temperature for the large welded specimen was in the neighborhood of -65°F, compared with the transition temperature of about -108°F for the 3-inch wide edge notched specimens and -102°F for the 12-inch wide centrally notched plates. The difference in transition temperature of about 40°F is not as great as that for the other high yield strength structural steels. This smaller difference in transition temperature may be significant in view of the fact that Steel 4 also exhibited an energy absorption ability that was by far greater than that shown by any of the other steels that were tested.

At the end of the test program one more specimen of Steel 4 was made in order to study the effect of the rolling direction on the behavior of restrained welded specimens. The various structural members of this additional specimen were laid out in such a manner that their longitudinal axes were perpendicular to the direction of the final roll of the steel plate from which they were cut, however, the welding technique, the electrodes, the preheat temperature and the sequence of assembly in the manufacture of this specimen were identical to the ones used on all other specimens. As shown in Figs. 4a and 4b, the results of a test at room temperature indicated that the energy to the maximum load and the nominal maximum stress were about the same as the corresponding values obtained on the specimen for which the direction of roll coincided with the loading axis. The energy absorption to failure as shown on Fig. 4a was approximately half of that of the standard-cut specimen. This lower value of the energy is due to the normally lower ductility of plates in a direction transverse to the roll, and is in general agreement with results obtained from Charpy tests.

As reported elsewhere[5], mild steel B in the as-rolled condition, was tested in the restrained welded specimen form at temperatures ranging from $+2^{\circ}F$ to $+72^{\circ}F$. These specimens were welded with E-6020 type electrodes using no preheat. The transition temperature for this steel was approximately $+58^{\circ}F$, compared with a transition temperature of $+15^{\circ}F$ and $+20^{\circ}F$ for the 12-inch wide centrally notched plates and the 3-inch wide edge notched specimens. The difference in transition temperatures, as determined by notched and restrained specimens, was approximately $40^{\circ}F$ for this mild steel, a value similar to that shown by the high yield strength structural steels tested. Thus it seems that geometry of the specimen is responsible for a shift of the transition temperature to a higher value as the size and restraint of the specimen are increased.

All of the restrained welded specimens failed in a manner similar to the fracture in the large "hatch corner" type of specimens of mild steel. All fractures originated at the square corner in the region of the intersecting welds, between the main stress member "MS", shown in Figs. 5a and 6a, the inboard transverse member "IT", and the continuous longitudinal member "CL". The fracture usually progressed outboard in the main strength member with the failure of the continuous longitudinal member beginning shortly after the origin of the fracture in the main strength member. Typical examples of the fractured surfaces of the high yield strength structural specimens are shown in Figs. 5b and 6b. Figs. 7 and 8 show a sequence of pictures taken during the fracture of Specimens 19-S and 21-S.

During the early tests a great deal of difficulty was encountered in fracturing the specimen because the corner formed by the pulling tabs, the continuous longitudinal and the main strength member acted as a more severe discontinuity than the corner of the specimen itself. This resulted in premature failure near the welded joint of the pulling tab and the specimen. Because of this difficulty, some of the earlier specimens had to be reloaded a number of times; for example, Specimen 3-S was tested four times before failure occurred in the welded corner. This retesting may have influenced the results of the energy absorption of this specimen. These premature failures were remedied by redesigning the pulling tabs and inserting a triangular plate near the joint of rhe end tab and the specimen, as indicated in Fig. 2b by "T".

<u>Notched Specimens</u>

Notched specimens were made from the four heats of high yield strength steel and from the mild steel B_r which was used in an earlier investigation[2]. The transition temperatures, at which the type of fracture changed from the ductile or shear type to that of the cleavage type, were determined for each steel by means of tension tests on 12-inch wide centrally notched specimens and 3-inch wide edge notched specimens. The results obtained for the various steels are shown in Figs. 9 and 10. These results show that there is very little difference in transition temperatures as determined by the 12-inch wide centrally notched plates and by the 3-inch wide edge notched specimens; the maximum difference was 15°F for Steel 1. This steel contained a considerable amount of inclusions and consequently the results were somewhat erratic.

Table IV shows the approximate transition temperatures for the various steels as determined by tests of the three different specimens. One of the most significant results of this investigation is that all steels are rated in the same order of relative brittleness by the three types of specimens. The transition temperatures determined by tests of large restrained specimens were approximately from 40°F to 55°F higher than the temperatures indicated by small notched specimens, for all of the steels tested. Thus, the approximately 50°F difference in transition temperatures may be attributed to the geometry and restraint of the larger specimens.

The relative energy absorption to maximum load and to failure of the notched specimens, as shown by Fig. 11, was similar to that of the large restrained specimens.

It is of interest to note that the high yield strength structural steels tested in the form of 3-inch wide edge notched specimens showed stresses at maximum loads which exceeded the nominal tensile strength, as determined by standard bar tests, by as much as 20 percent. The maximum tensile stress in the 12-inch wide centrally notched specimen was, however, either equal to or somewhat lower than the tensile strength obtained with standard tensile specimens. In the large restrained welded specimens the fracture invariably occurred at nominal stress values that were below the yield strength of the steel.

<u>Bend Tests</u>

Typical results of the bend tests carried out on the high yield strength structural steels are shown in Fig. 12. Most of the tests were made at two temperatures only, +70°F and -40°F. When tested at +70°F specimens failed by shear and the cracks were difficult to detect until they had progressed to a somewhat advanced stage. At -40°F, however, the formation of the first tiny crack was almost invariably followed by complete failure of the specimen. As shown by the preliminary tests, Steel 1, welded with the Type 310 electrodes using 300°F preheat, performed in the bend test in a commendable manner, and consequently these electrodes were chosen for the early tests on the restrained welded specimens. Subsequently, Electrode "A" was obtained, which also performed well and had much more desirable physical properties than did the Type 310 electrodes. In addition, Electrode "A" required lower preheat temperatures and was much easier to deposit than the Type 310, and therefore, it was used for all remaining large welded specimens.

It was found in the bend tests that there was an optimum preheat temperature for each steel. As shown in Fig. 13, specimens welded at this preheat temperature would invariably bend through larger bend angles before fracture would occur; both above and below this optimum preheat temperature the performance of the welded specimens was poorer.

Post heating the specimens by means of an oxy-acetylene torch to different temperatures from 650°F to 1100°F for various lengths of time appeared to have a certain amount of beneficial effect on the performance of the bend test specimens; typical results of post heat treatments are shown in Fig. 13. Practically all of the beneficial effect of post heating was obtained within the first five minutes of heating and there appears to be no difference in the performance of the specimens that were post heated by oxy-acetylene torches and those that were heated in furnaces.

A few tests were made using the T-bend test approved by the American

Welding Society in 1945 as a tentative standard. In this test the effect of preheating was found to be parallel to that obtained for the flat plate bend tests. Also a few of the T-Bend specimens welded with Type 310 electrodes were post heated in a furnace to 1100°F for periods ranging from a few minutes to as long as an hour. As in the case of flat plate bend test specimens, this post heat treatment also produced a certain amount of improvement in the ductility of the T-Bend test specimens, with practically all of the beneficial effect obtained within the first five minutes of heating.

Remarks

In order to present a complete picture, a few general remarks are in order with respect to the appearance, consistency of results, weldability, and general behavior of the steels used in this investigation.

Steel 1, which was tested in the normalized and in the quenched and drawn conditions, behaved somewhat erratically because of a relatively large amount of non-metallic inclusions. The results from tests of notched normalized specimens, shown in Figs. 9 and 10, indicate the difficulty that was encountered with this steel as a considerable number of specimens failed by what appeared to be cleavage fracture at temperatures well above the transition temperature for the steel. Upon a more complete and careful examination under a microscope it was found that the very thin laminations in the steel were responsible for the general cleavage appearance of the break, but that each thin layer of steel actually failed by shear. This same difficulty was encountered in estimating the fractures of Steel 3.

Although all of the steels tested had a certain amount of inclusions in them, the majority of the plates of Steels 1 and 3 appeared to have a larger quantity of inclusions, and several of these plates contained bad laminations.

The heavy mill scale, especially on Steel 3, made the cutting of these alloy steels difficult.

The welding of these steels presented several problems that were not normally encountered with the mild steels. Besides the necessity of preheating and employing special electrodes, extremely heavy stiffening was required due to excessive warpage that accompanied the cutting and welding operations. The warping was especially bad with Steels 1 and 3. These two steels have another bad feature - tearing of small chunks of steel from the surface of the plate at points where tack welds for flanging operations were made. This behavior can be attributed to the bad laminations present in these steels.

Of the four steels that were used in this investigation, Steel 4, aside from its better physical performance, seemed to be the best one with respect to its uniformity, weldability and lack of warpage.

In closing it should be pointed out that all the results obtained in this investigation are applicable only under the same conditions of loading as those prevailing in these tests and may be considerably different under conditions of dynamic loading such as the ones present in explosion tests.

Investigations of the high yield strength structural steels under conditions of dynamic loading should be carried out to supplement the findings of the static tests in order to rate properly the various steels; however, some of the steels, due to their erratic behavior, may well be eliminated from consideration for use as important structural members on the strength of only the static tests and of the physical observations of fractures and weldments.

CONCLUSIONS

1. The restrained welded specimen has provided information on the behavior of high yield strength structural steels in combination with weld materials, heat affected zone, and a geometric design which restricted plastic flow.
2. Two types of electrodes, both mineral-coated, were found to give satisfactory performances in large welded structures subjected to plastic strain at low temperatures. These were stainless steel Type 310, and Electrode "A", which is a ferritic electrode having a high yield and tensile strength, good ductility, and a low hydrogen content.
3. The transition temperatures for the four types of high yield strength structural steels tested in the form of large restrained welded specimens ranged from about +75°F down to approximately -65°F.
4. The transition temperatures as determined by the 3-inch wide edge notched specimens and the 12-inch wide centrally notched specimens were almost the same for a particular steel and ranged from approximately +15°F to -108°F for the four steels tested.
5. The relatively constant difference of approximately 50°F in transition temperature which was observed in the tests of large restrained specimens, as compared to the transition temperature determined by tests of smaller notched specimens may be attributed to the geometry and welding of the large specimens.
6. The maximum nominal tensile stresses obtained during the tests of the 3-inch wide edge notched specimens of a particular steel were invariably greater than the nominal ultimate strength of the steel as determined by tests of standard tensile bars.
7. The maximum nominal tensile stresses for the 12-inch wide center-notched

specimens were either equal to or slightly below the nominal ultimate strength of the steel as determined by tests of standard tensile bars.

8. Fractures invariably started and failures occurred in the large restrained specimens at nominal stress values that were below the yield strengths of the steels as determined by the standard tensile tests.

9. Transition temperature is in itself not the only criterion in evaluating the performance of steel for low temperature service. The transition temperatures of Steels 3 and 4 were almost the same, but the energy absorbed by Steel 4 was much greater at any testing temperature than the energy absorbed by Steel 3.

10. It appears that the 3-inch wide edge notched specimens are a cheap and simple means for rating the various steels in their proper order of brittleness.

11. It should not be assumed that steels rated as to relative brittleness in static tests would perform in a similar relative manner when subjected to explosive or ballistic loading.

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TABLE I

PROPERTIES AND COMPOSITIONS OF HIGH YIELD STRENGTH STRUCTURAL STEELS USED IN THE INVESTIGATION

STEEL NO.	1	2	3	4	B**	C
TYPE HEAT TREATMENT	Alloy Quenched & Drawn	Alloy Quenched & Drawn	Alloy Quenched & Drawn	Alloy Quenched & Drawn	Mild Semi Killed as-rolled	Mild Semi Killed as-rolled
PHYSICAL PROPERTIES						
Yield Strength Psi. Average	66,000	80,000	80,000	84,000	36,000	39,000
Ultimate Strength Psi. Ave.	89,000	97,000	100,000	100,000	60,000	67,400
Elongation % in 2" Average	26	22	20	23	26	25.5±
Reduction in Area % Average	64	60	60	68	63	-
APPROXIMATE CHEMICAL COMPOSITION						
Carbon	.19	.14	.16	.16	.15	.24
Manganese	1.08	.75	1.45	.27	.77	.48
Silicon	.24	.77	.21	.17	.05	.05
Molybdenum	.42	.16	.48	.20	-	.005
Chromium	-	.60	-	1.13	-	.03
Zirconium	-	.09	-	-	-	-
Phosphorus	.014	.023	.017	.014	.010	.012
Sulphur	.023	.028	.038	.021	.029	.026
Vanadium	-	-	.08	-	-	-
Nickel	-	-	.53	2.32	-	.02

* Steel 1 was also used in a normalized condition for some of the tests

**Mild Steel B_r properties included for comparison

***

± Elongation in 8"

TABLE II
AVERAGE VALUES SHOWN FOR THE VARIOUS ELECTRODES USED IN THE INVESTIGATION

Manufacturer's data on Weld Deposits*

ELECTRODE CODE LETTER	A**	B	C**	D	E**	F**	G	310**
CLASSIFICATION	Low Alloy	Low Alloy	AWS E9020		Low Alloy	AWS E6015	Low Alloy	USN 46E4
PHYSICAL PROPERTIES				As Welded				
Tensil Strength psi.	95,000	110,000	98,000	78,000	96,000	72,000	112,000	80,000
Yield Strength psi.	77,000	95,000	85,000	59,000	85,000	60,000	92,000	
Elongation in 2" %	25	15	20	21	9	32	17	35
CHEMICAL ANALYSIS (%)								
Carbon	.08	.15	.12	.07	.15	.08	.16	-
Manganese	1.5	1.8	1.8	.53	1.7	.55	1.9	-
Silicon	.25	.25	.25	.06	.3	.25	-	-
Sulphur (Max %)	.03	.03	.04	.02	.01	.02	.03	-
Phosphorus	.03	.03	.04	.02	.01	.02	.03	-
Molybdenum	.35	.4	.35	.82	.35	-	.33	-
Chromium	-	-	-	-	-	-	-	25
Nickel	-	-	-	-	-	-	-	20
Arc Voltage 5/32" Electrode	21	22	23	23	22	22	21	23
Amperage " "	115	120	165	160	150	180	165	135
Arc Voltage 3/16" Electrode	22	22	23	26	22	23	22	24
Amperage " "	210	210	225	225	230	230	215	205

*Values for electrodes marked with **were checked at University of California

TABLE III

PRINCIPAL RESULTS OF RESTRAINED WELDED SPECIMENS TESTED

Maximum nominal stress computed by dividing maximum load by the original load carrying area

Load carrying area for specimens is 28.5 ± 5 sq. in.

Gage length for energy measurements is 54 inches.

Specimens 1-S through 7-S welded with Type 310 electrodes.

Specimens 8-S through 21-S welded with ferritic Electrode "A".

SPECIMEN NO.	STEEL	TEST TEMP. °F	NOMINAL MAX. STRESS PSI.	ENERGY TO MAX. LOAD	ENERGY TO FAILURE	TYPE FRACTURE IN % SHEAR	REMARKS
1-S	1	+70	72,456	811,000	1,426,000	100	
2-S	1	-35	43,860	117,200	117,200	0	
3-S	1	0	58,596	470,000	606,600	15	See Note 1
4-S	1	+11	65,614	427,000	568,000	0	
5-S	1	+30	66,210	524,000	725,000	20	
6-S	2	+63	68,070	496,000	496,000	0	
7-S	2	+100	66,500	530,000	940,000	100	
8-S	2	+73	65,600	326,000	326,000	73	
9-S	4	+72	68,400	462,000	2,256,000	100	
10-S	4	-18	62,100	490,000	2,040,000	100	
11-S	4	-48	70,200	598,000	2,040,000	97	
12-S	3	+70	61,400	240,000	426,000	100	
13-S	4	-83	61,000	390,000	830,000	8	
14-S	3	-108	32,000	90,000	90,000	0	
15-S	3	-44	65,000	338,000	540,000	88	
16-S	3	-62	57,000	126,000	126,000	0	
17-S	4	+73	73,500	460,000	1,120,000	100	See Note 2
18-S	3	+68	64,400	156,000	494,000	100	See Note 3
19-S	2*	+37	63,100	320,000	580,000	5	
20-S	2*	+78	65,300	374,000	756,000	100	
21-S	1**	+32	61,600	532,000	532,000	0	

Note 1. Reloaded 4 times due to end tab failure.

2. Component members of specimen cut in such a way that their longitudinal axes were in a direction perpendicular to the final roll of the plate.

3. All welds and areas adjacent to corner heated to 650°F for 10 minutes after all welding was completed.

* Made from plates of Steel 2 that were re-heat treated to improve notch toughness.

** Made from plates of the original heat of Steel 1, but that were rolled at a later date and were heat treated to approximately the same specifications as the original batch.

TABLE IV

APPROXIMATE TRANSITION TEMPERATURES OF HIGH YIELD STRENGTH STRUCTURAL STEELS DETERMINED BY MEANS OF DIFFERENT SPECIMENS

STEELS	1	2	3	4	B
TYPE OF SPECIMEN	APPROXIMATE TRANSITION TEMPERATURES				
3" Edge Notched	− 10°F	+18°F	−102°F	−108°F	+20°F
12" Centrally Notched	+50°F	+20°F	−95°F	−102°F	+18°F
Restrained Welded	+40°F	+75°F	−50°F	−65°F	+58°F

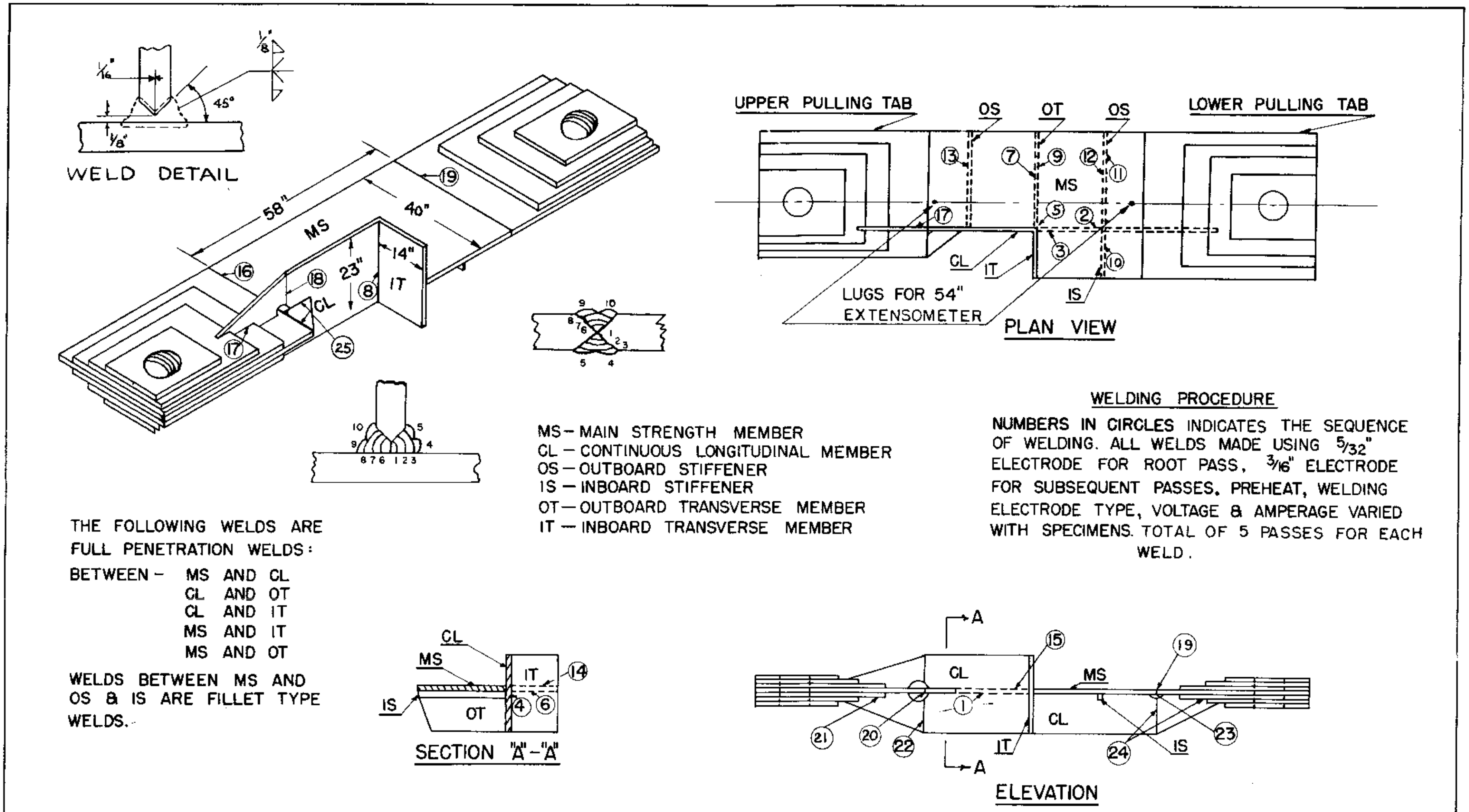


FIG. 1a RESTRAINED WELDED SPECIMEN USED FOR TESTS OF HIGH YIELD STRENGTH STRUCTURAL STEELS.

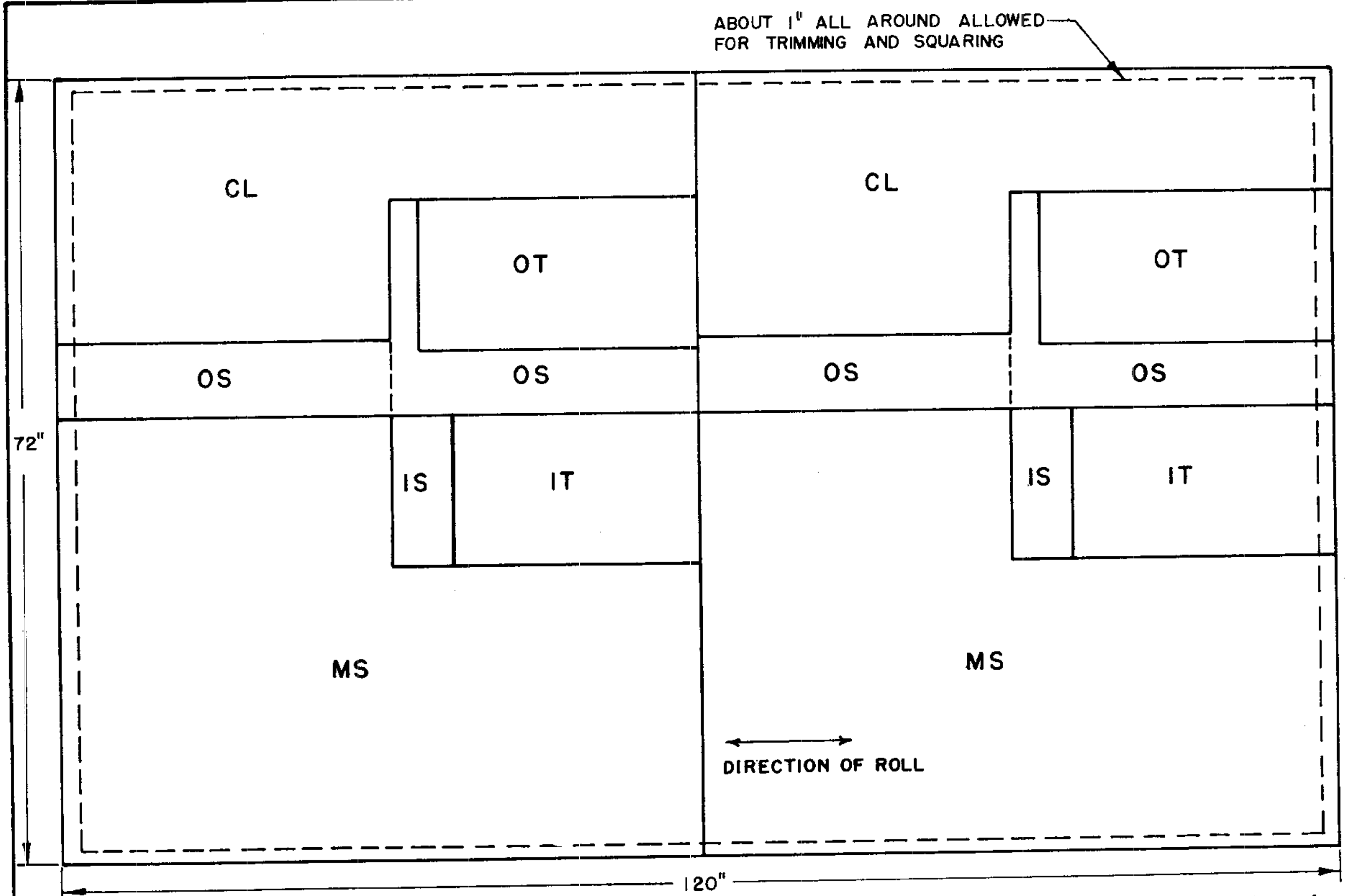


FIG. 1b LAYOUT FOR CUTTING PARTS FOR 2 RESTRAINED WELDED SPECIMENS FROM A 6' X 10' PLATE

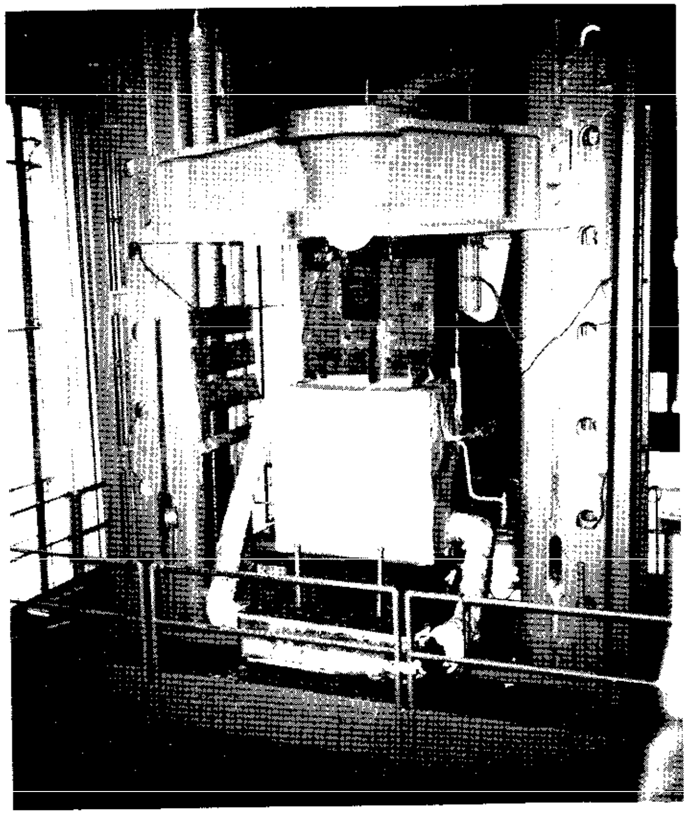


Fig 2a -- Restrained Welded Specimen Ready for Test, Showing Cooling Box, Dry Ice Heat Exchanger and Nitrogen Bottle.

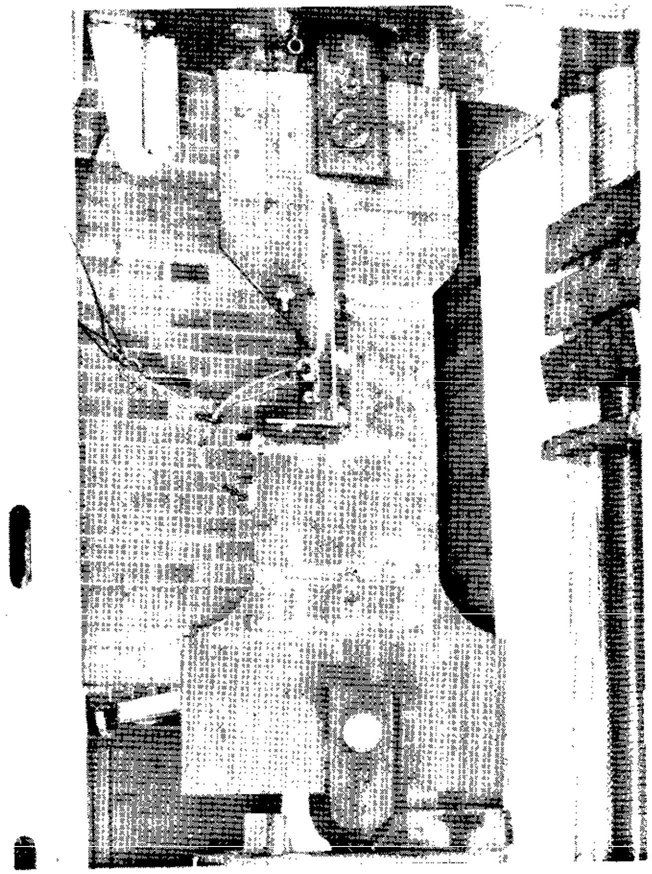


Fig. 2b -- Restrained Welded Specimen In Testing Machine, Showing Pulling Tabs and Manganin Wire Extensometer.

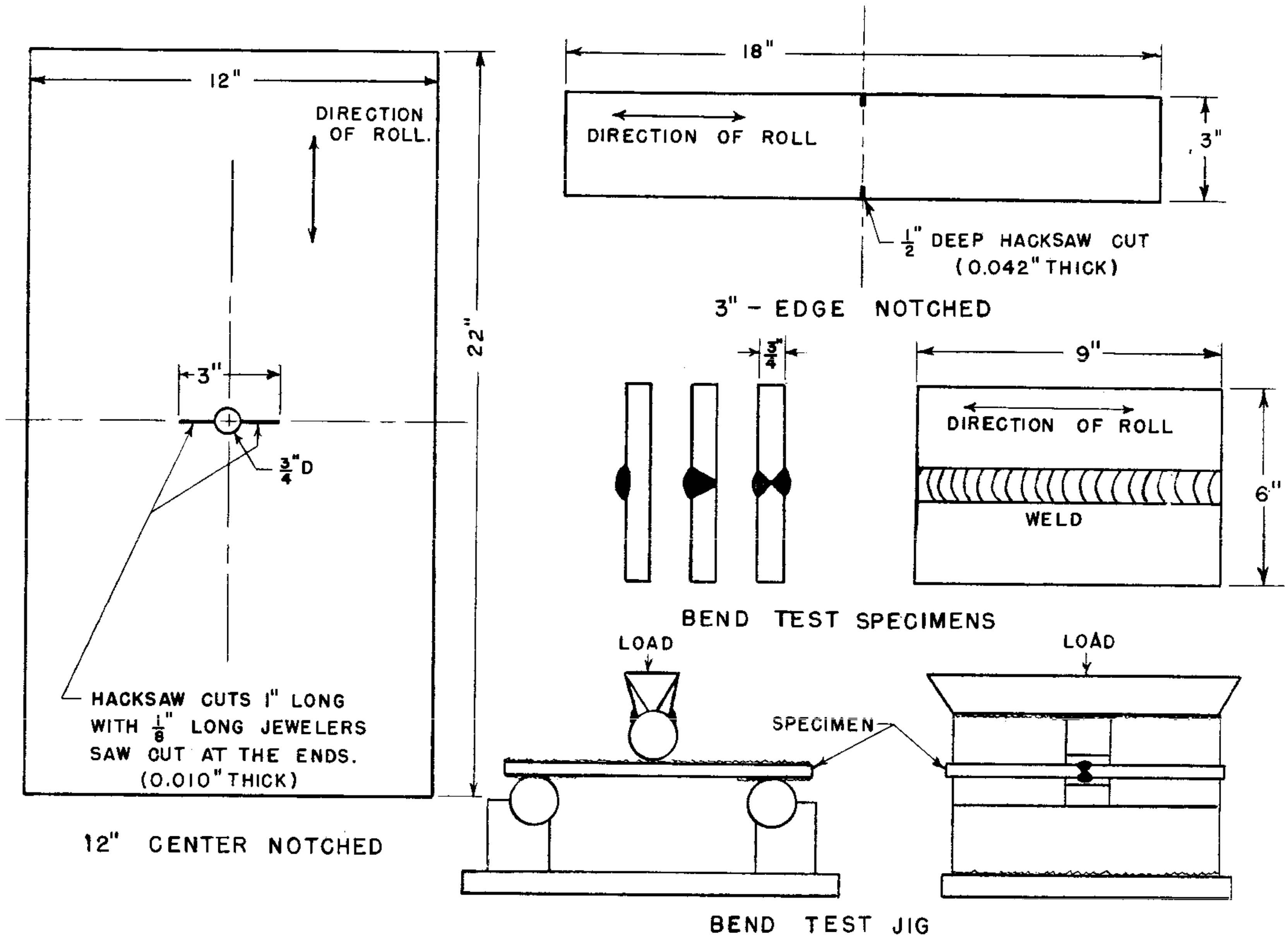


FIG. 3 VARIOUS TYPES OF AUXILIARY SPECIMENS

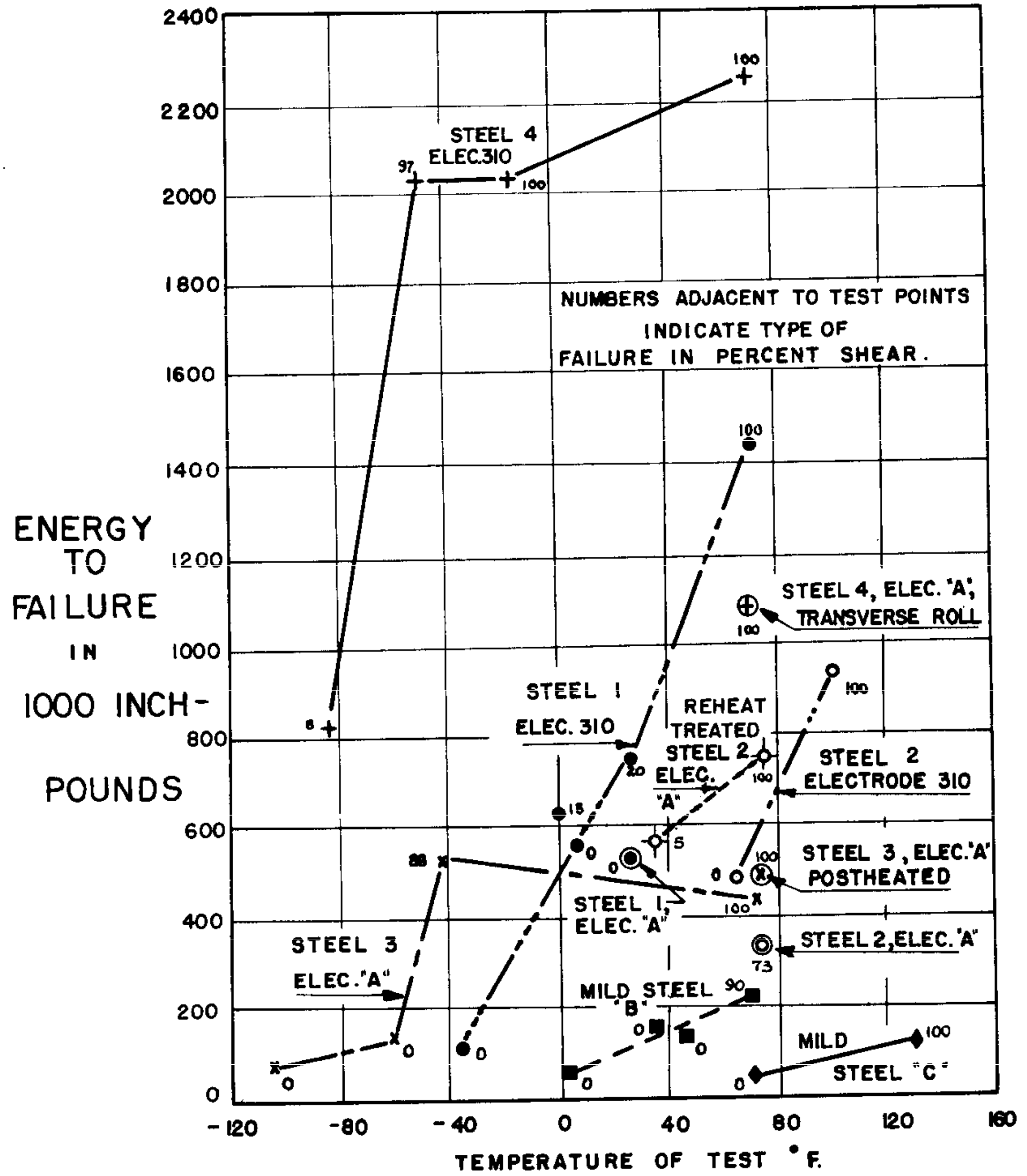


FIG. 4a ENERGY TO FAILURE VS. TEMPERATURE RELATION FOR RESTRAINED WELDED SPECIMENS OF HIGH YIELD STRENGTH STRUCTURAL STEELS.

RESULTS OF TESTS OF SPECIMENS MADE FROM MILD STEEL WITH E-6020 ELECTRODE ARE SHOWN FOR COMPARISON.

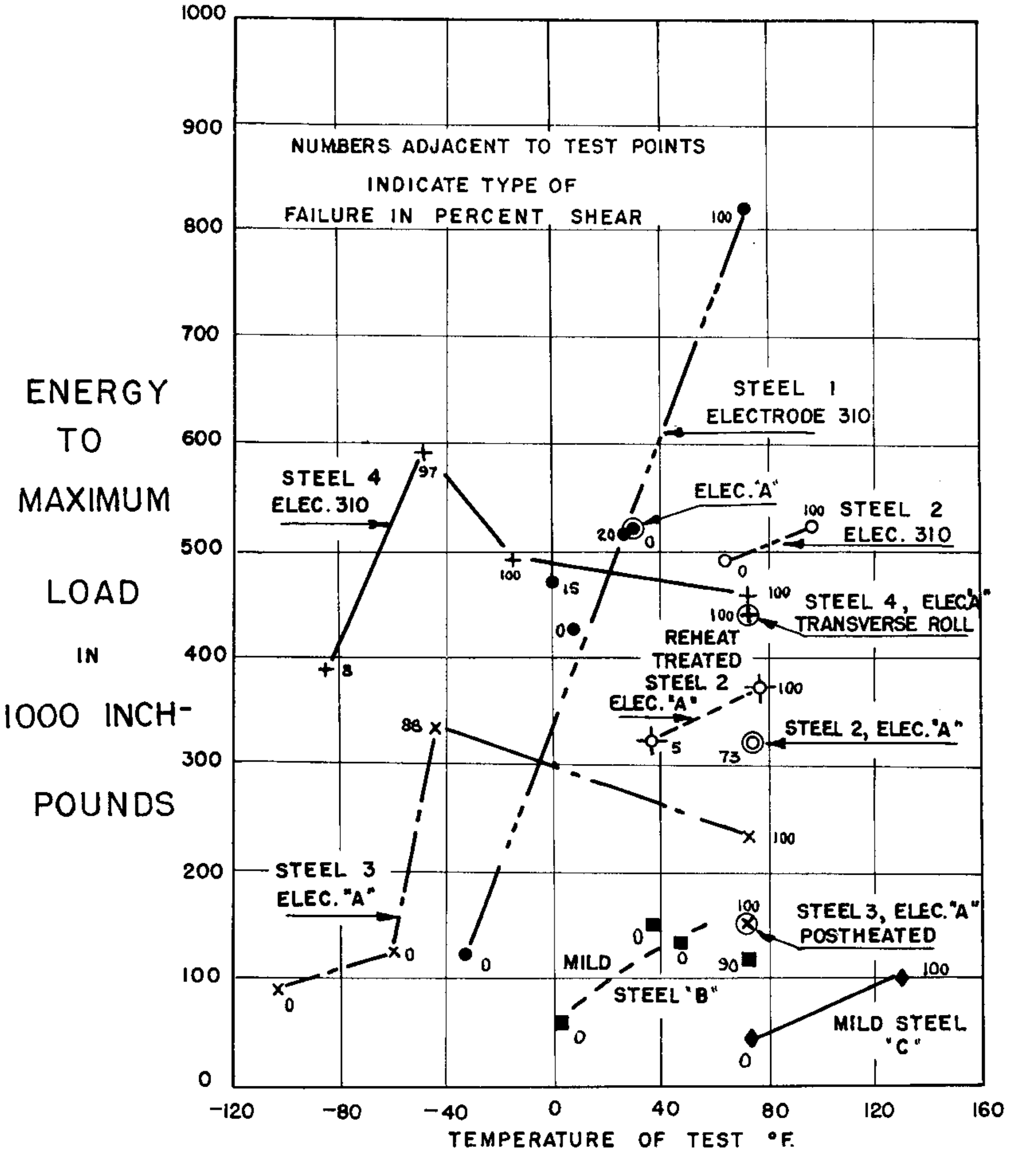
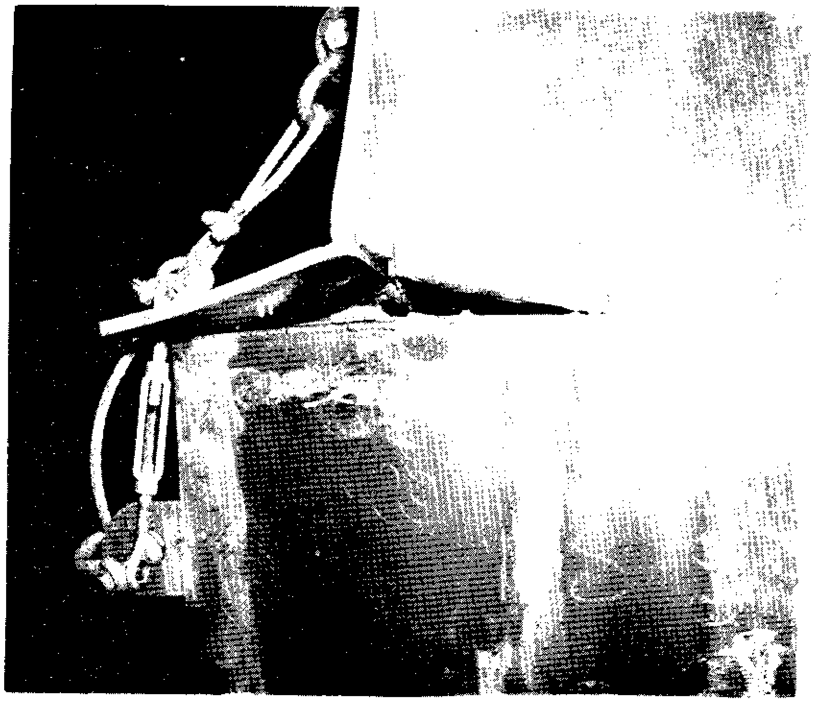
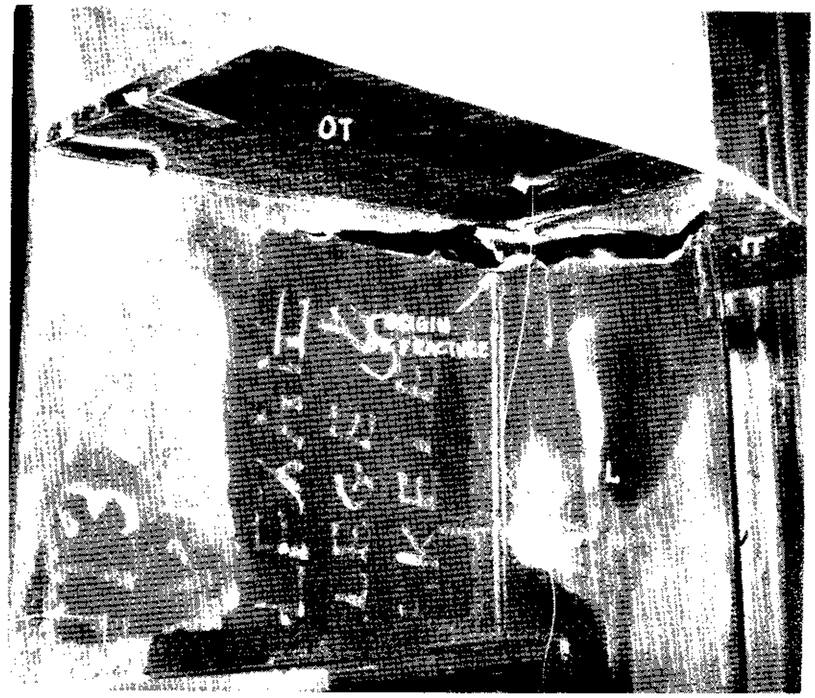


FIG.4b ENERGY TO MAXIMUM LOAD VS. TEMPERATURE RELATION FOR RESTRAINED WELDED SPECIMENS OF HIGH YIELD STRENGTH STRUCTURAL STEELS.

RESULTS OF TESTS OF SPECIMENS MADE FROM MILD STEEL WITH E-6020 ELECTRODE ARE SHOWN FOR COMPARISON.



Front View



Back View

Fig. 5a -- Specimen 11-S Shear Type Failure

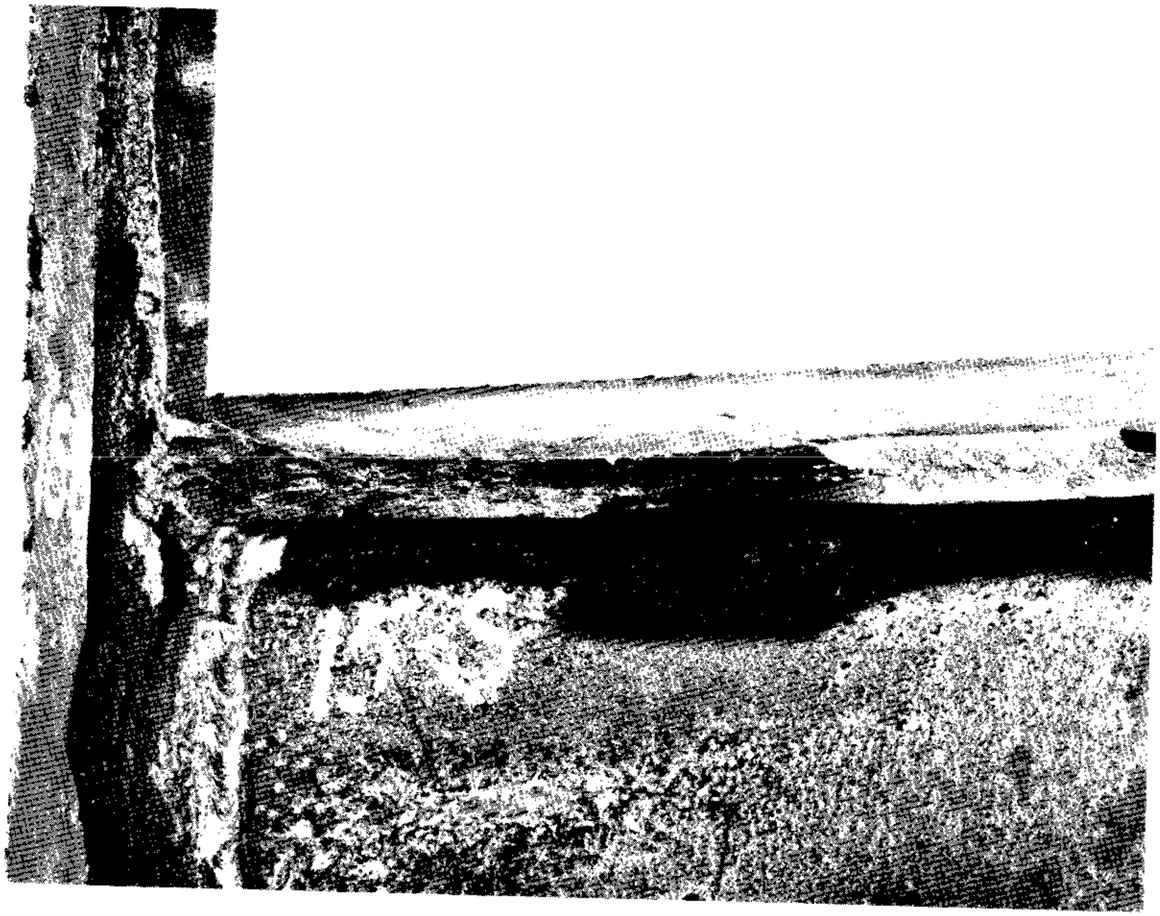
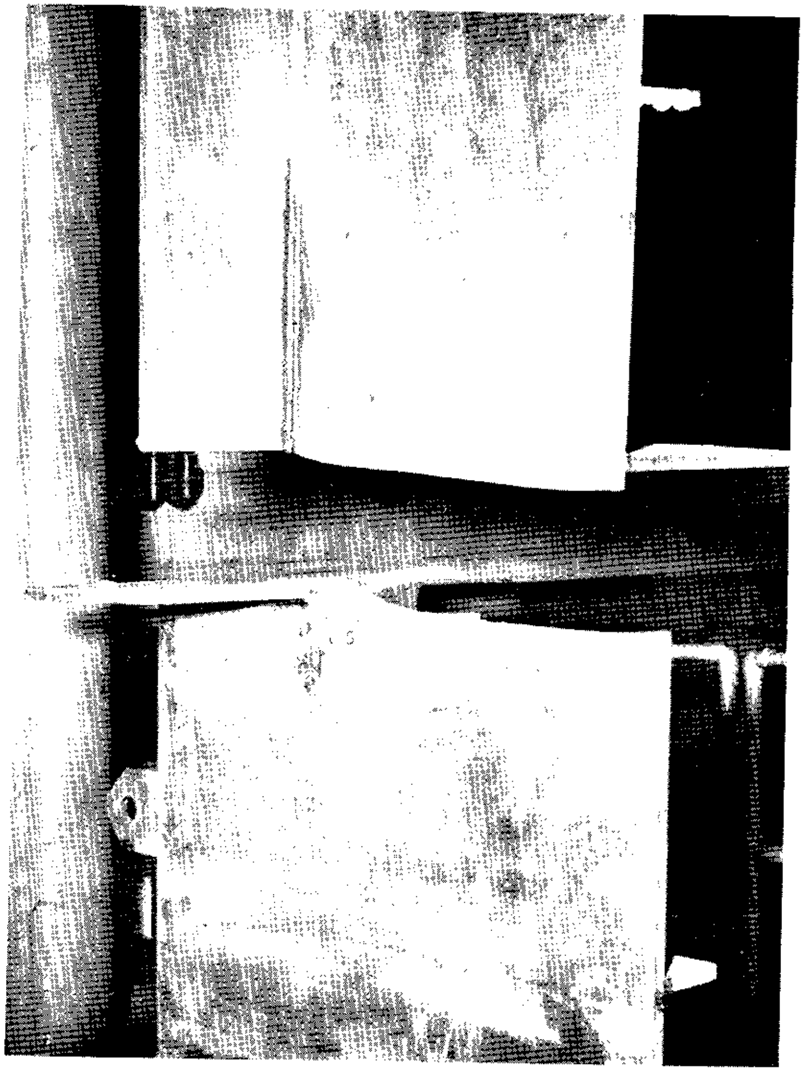
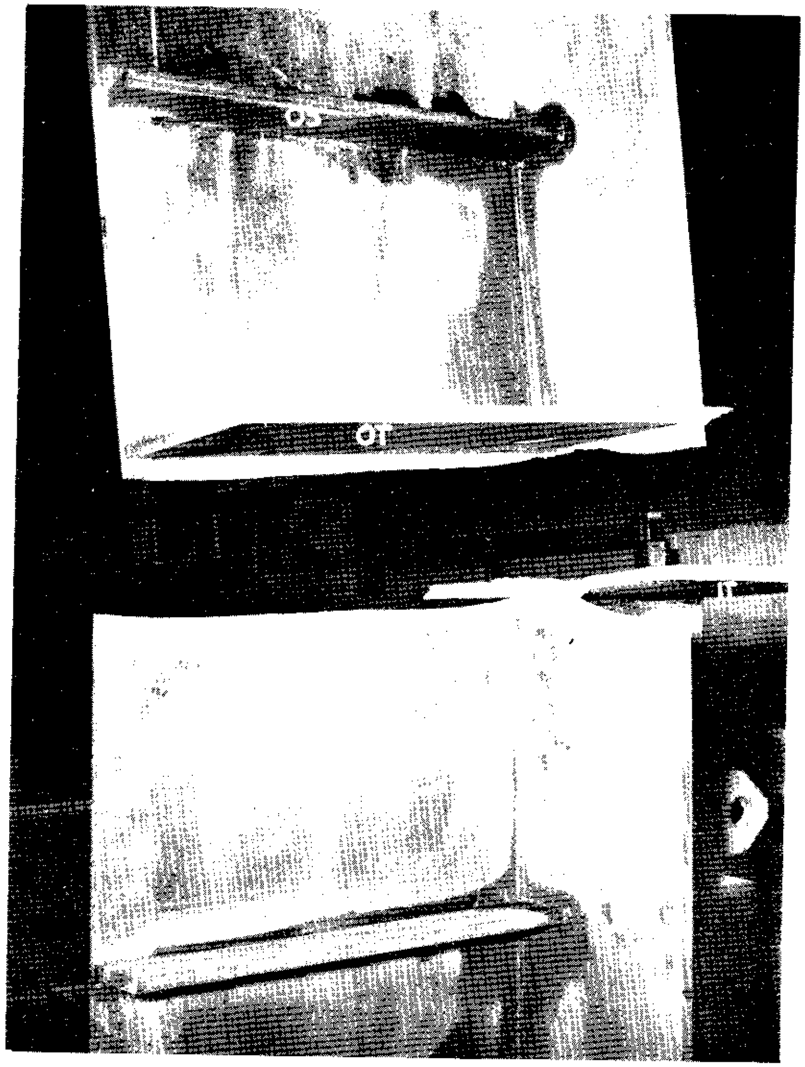


Fig. 5b -- Close-up Shear Type Failure



Front View



Back View

Fig. 6a -- Specimen 16- S Cleavage Type Failure

Fig. 6b -- Close-up Cleavage Type Failure

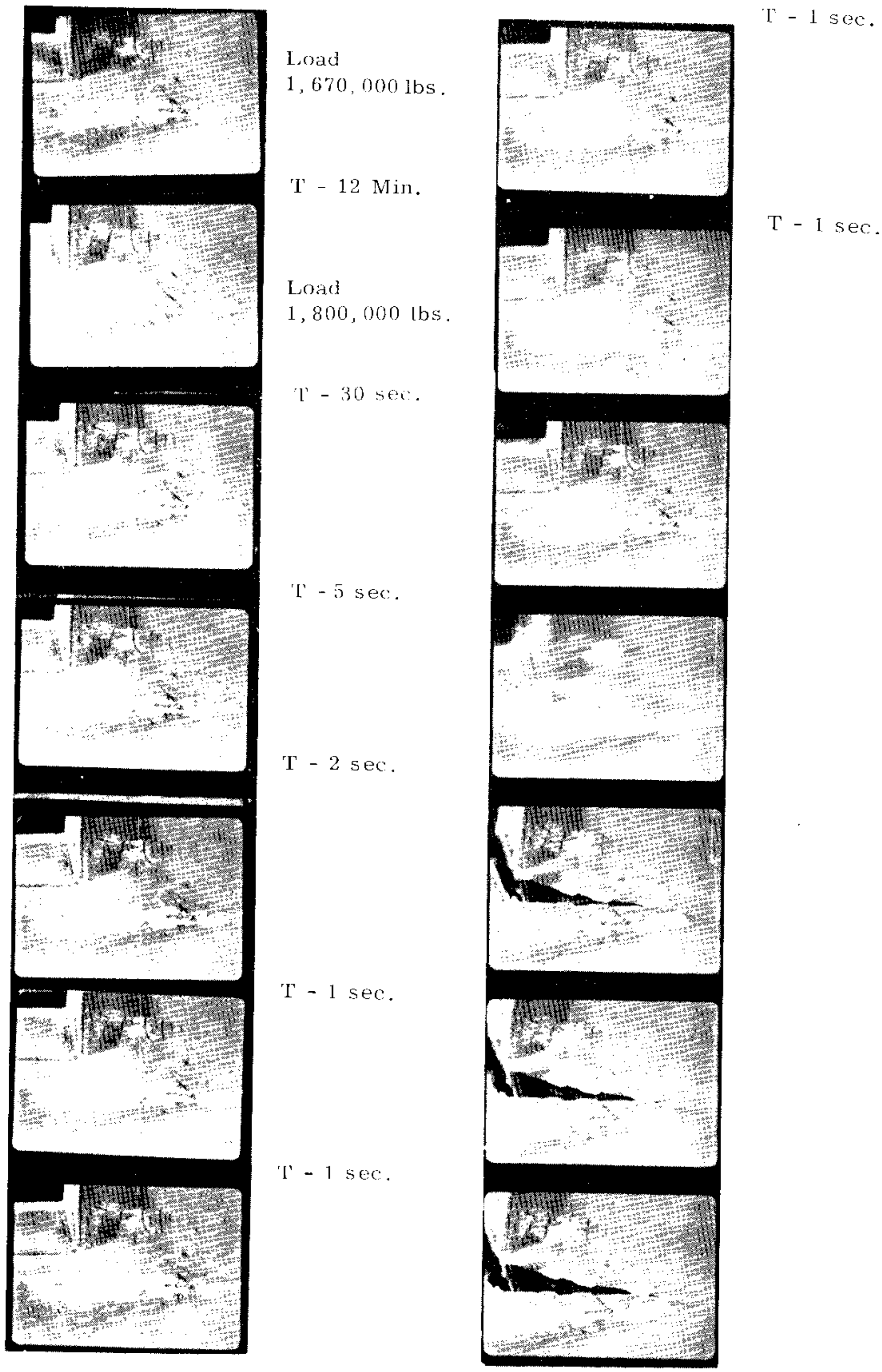


Fig. 7 -- Fracture Sequence in Specimen 19-S
Exposure time 1/500 sec.; time interval between frames 1/50 sec. unles otherwise noted

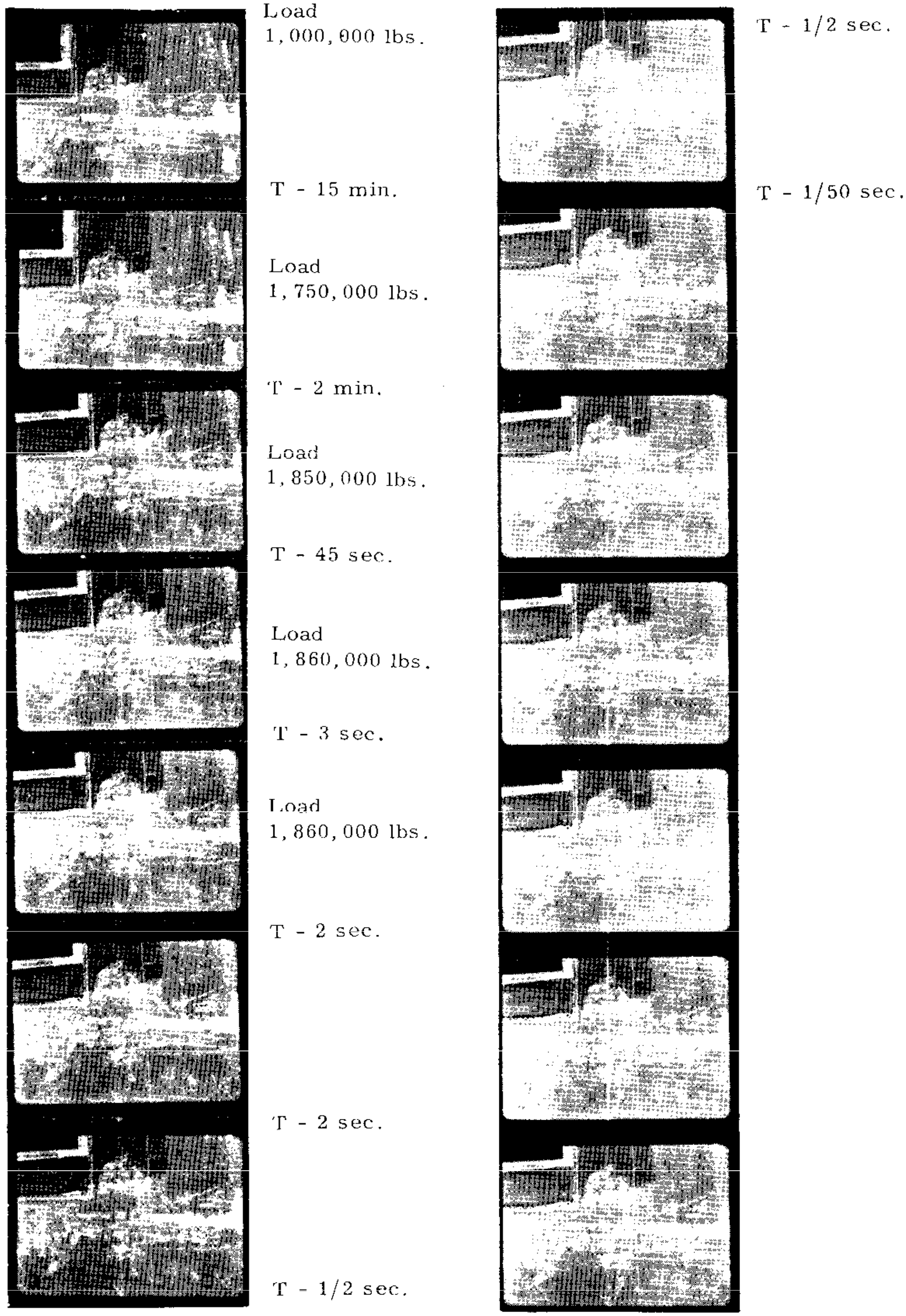


Fig 8a -- Fracture Sequence in Specimen 20-S
Exposure time 1/500 sec.; time interval between frames 1/50 sec. unless otherwise noted.

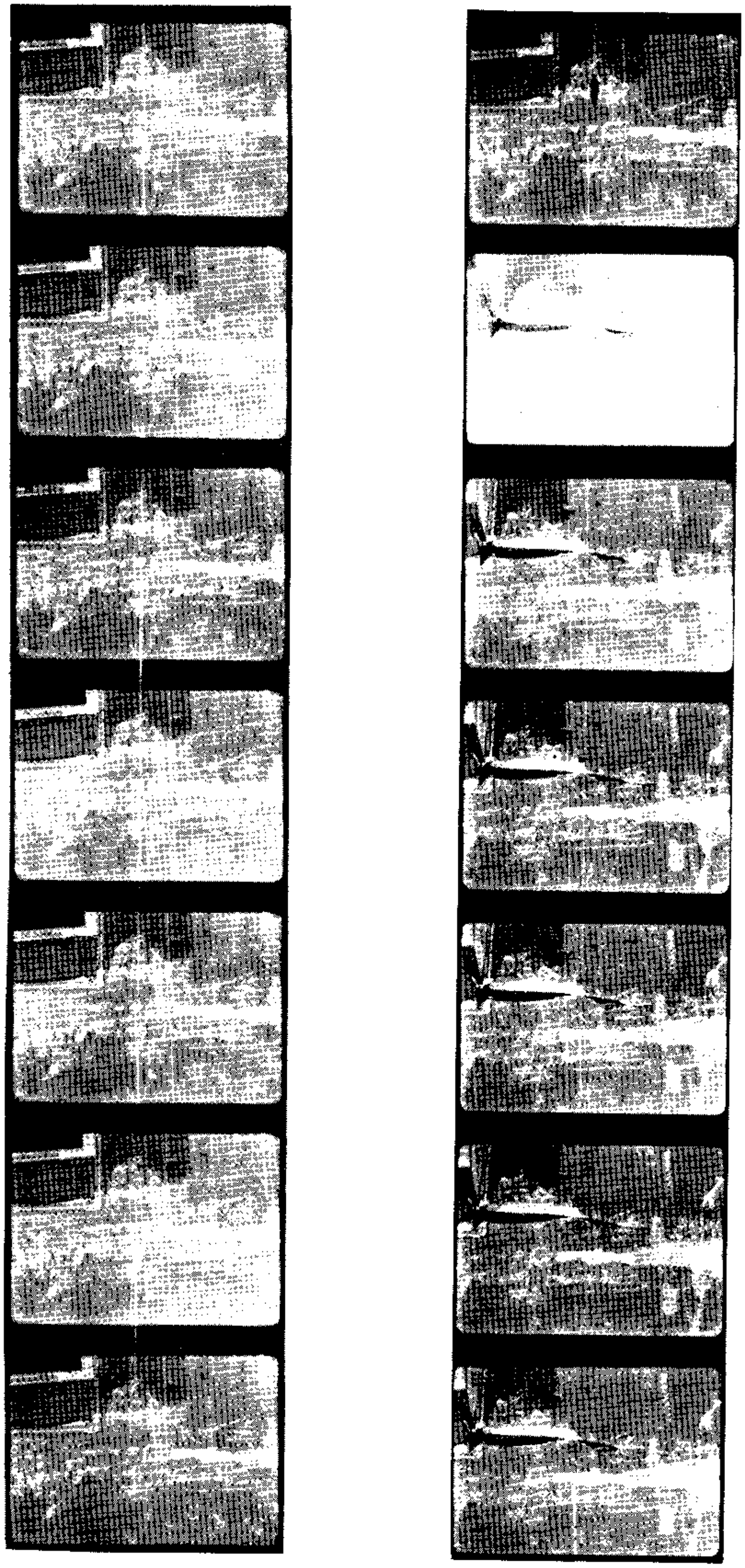


Fig. 8b -- Fracture Sequence in Specimen 20-S
Exposure Time 1/500 sec.;
Time interval between frames 1/50 sec.

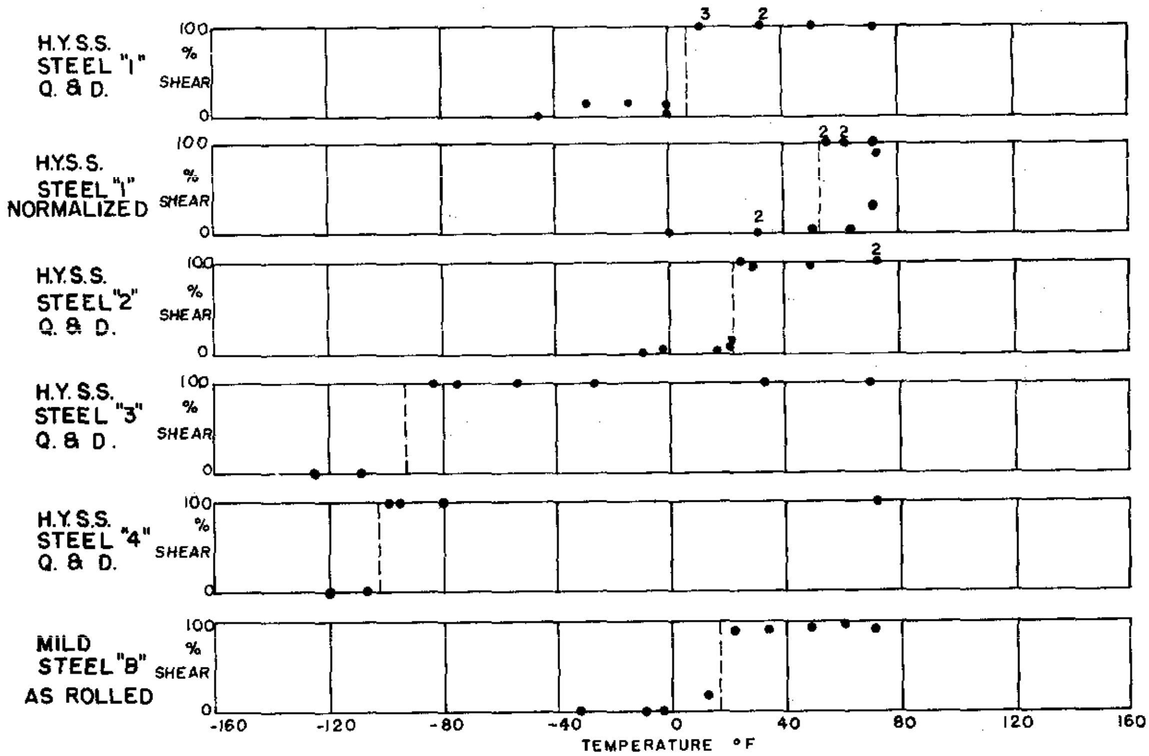


FIG. 9 TRANSITION TEMPERATURES FOR H.Y.S.S. STEELS & MILD STEEL B AS DETERMINED BY 12" CENTRALLY NOTCHED SPECIMENS

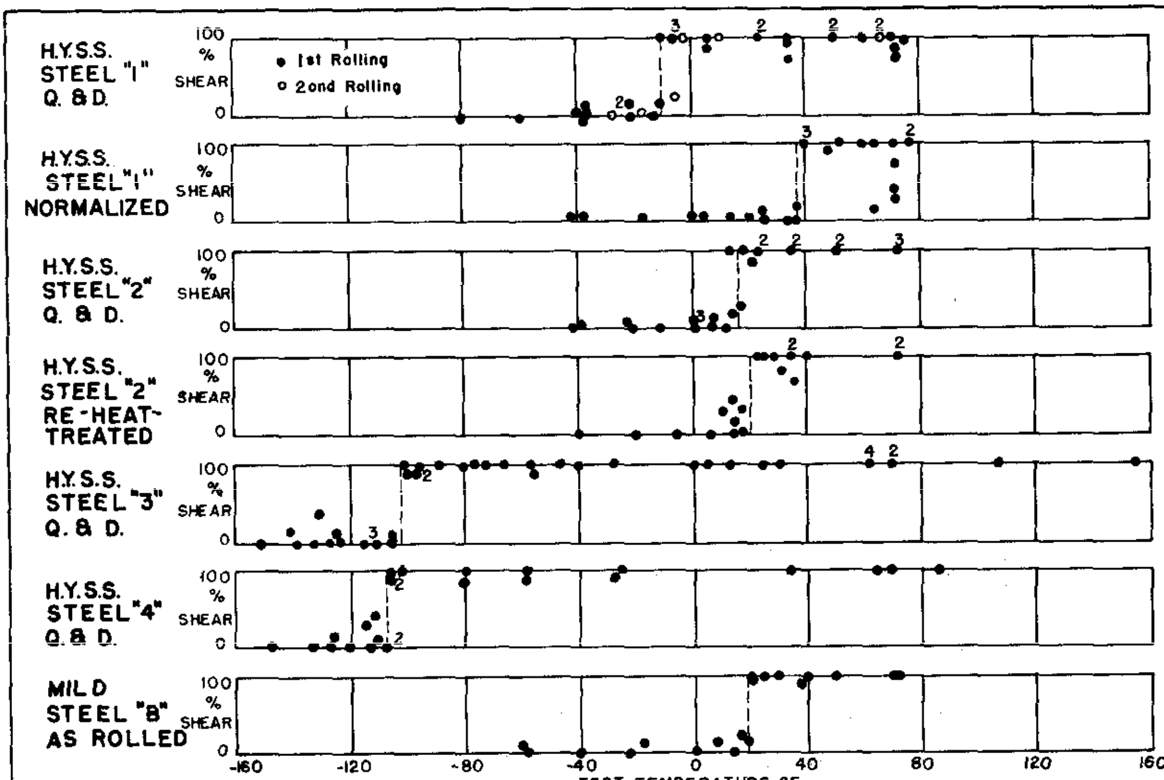


FIG. 10 TRANSITION TEMPERATURES FOR H.Y.S.S STEELS & MILD STEEL "B" AS DETERMINED BY TESTS OF 3 INCH EDGE NOTCHED SPECIMENS

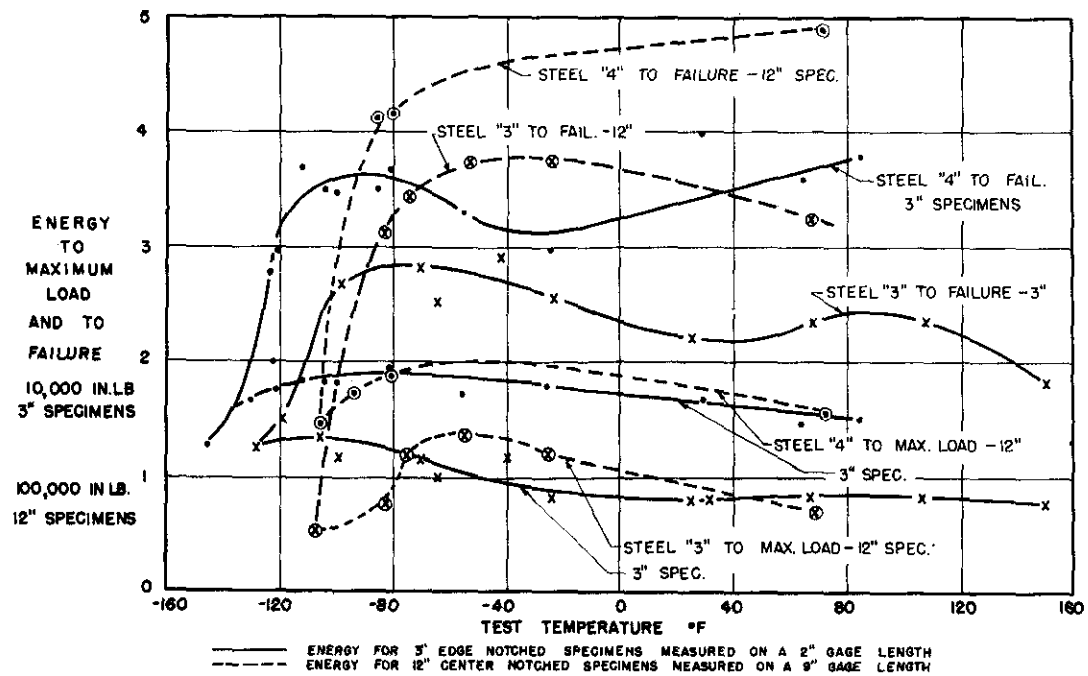


FIG. 11 ENERGY ABSORPTION TO MAXIMUM LOAD AND TO FAILURE FOR NOTCHED SPECIMENS OF H.Y.S.S. STEELS "3" AND "4".

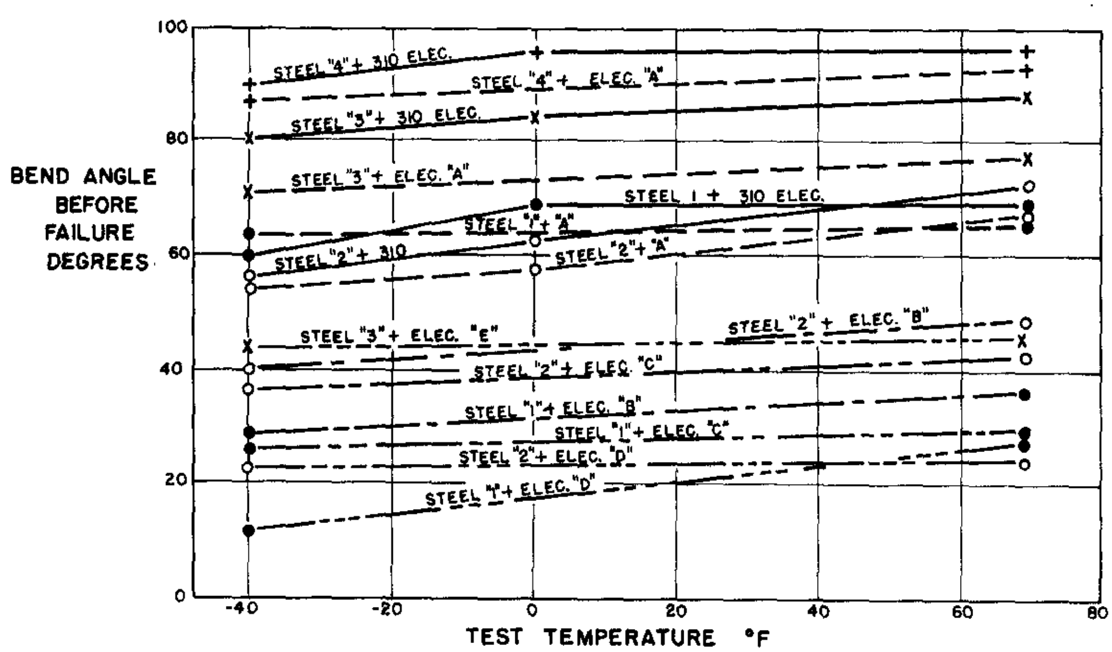


FIG. 12 TYPICAL BEND TEST RESULTS — H.Y.S.S. STEELS WELDED WITH VARIOUS MINERAL COATED ELECTRODES

NO PREHEAT, DOUBLE VEE BUTT WELDS, WELDS GROUND OFF FLUSH WITH SURFACE OF PLATE

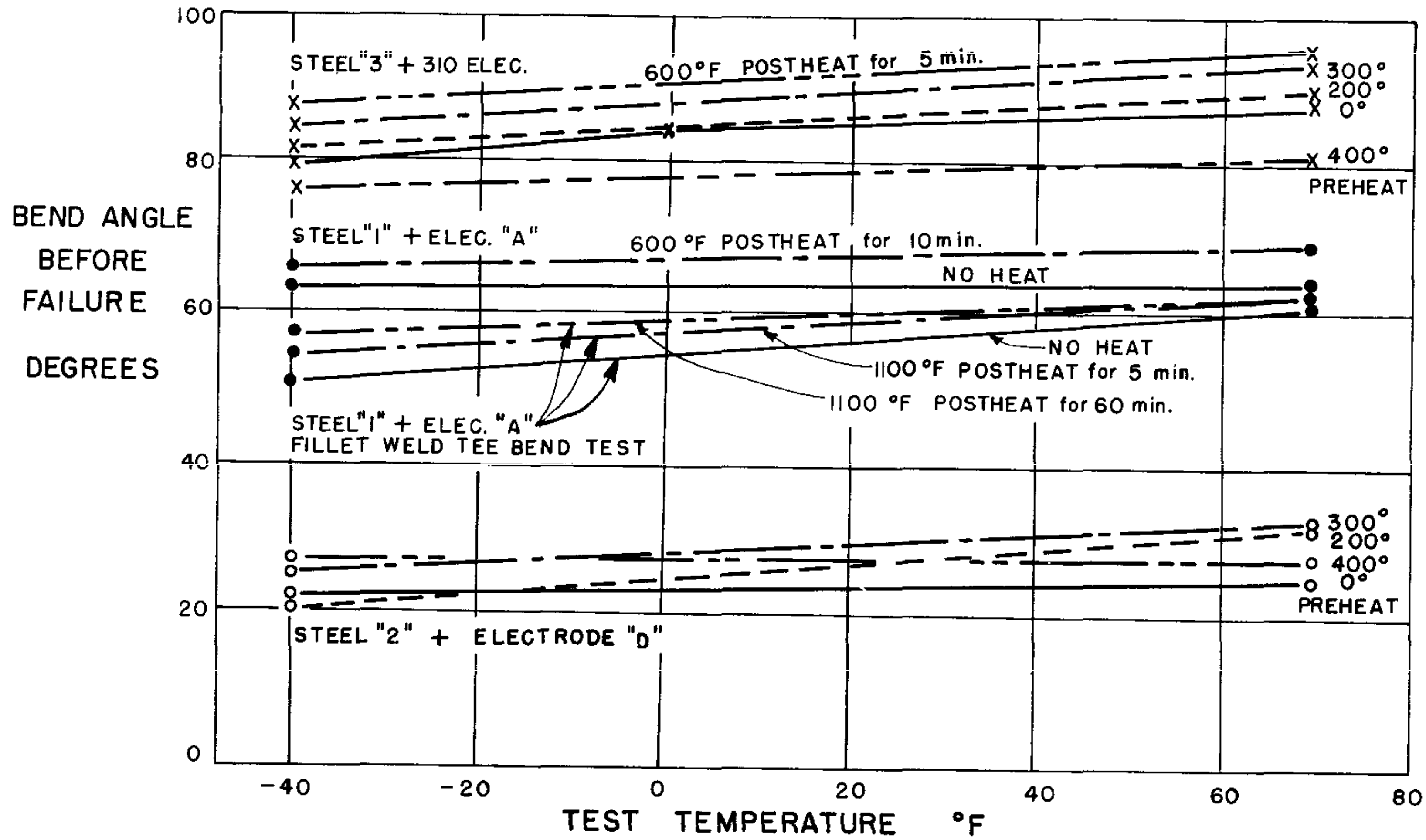


FIG. 13 TYPICAL BEND TEST RESULTS — H.Y.S.S. STEELS WELDED USING VARIOUS PREHEAT & POSTHEAT TREATMENTS.

DOUBLE VEE BUTT WELDS, WELDS GROUND OFF FLUSH WITH SURFACE OF SPECIMEN, UNLESS OTHERWISE NOTED.

APPENDIX A

CAUSES OF CLEAVAGE FRACTURE IN SHIP PLATE;
HARDNESS, HARDENABILITY AND METALLOGRAPHIC TESTS
OF HIGH YIELD STRENGTH STEELS AND COOLING RATES OF WELDS

LIST OF FIGURES - APPENDIX A

APPENDIX A

The main program of tests was concerned with the determination of transition temperatures of various types of high yield strength steel specimens. A number of auxiliary studies were made during the investigation which were not directly concerned with the transition temperature determinations but which were nevertheless pertinent to the general subject of low temperature brittle failures of steels. These data are presented in this appendix to the Final Report and consist of: (1) Jomminy curves for the four alloy steels, (2) typical cooling curves for the heat affected zone of the plate metal in the restrained welded type specimens, (3) photomicrographs of each steel showing the structure of the plate metal, the heat affected zone and the weld metal, (4) microhardness surveys across the heat affected zones of the four steels, and (5) microhardness surveys of sections cut from the main strength members of fractured specimens of each of the steels.

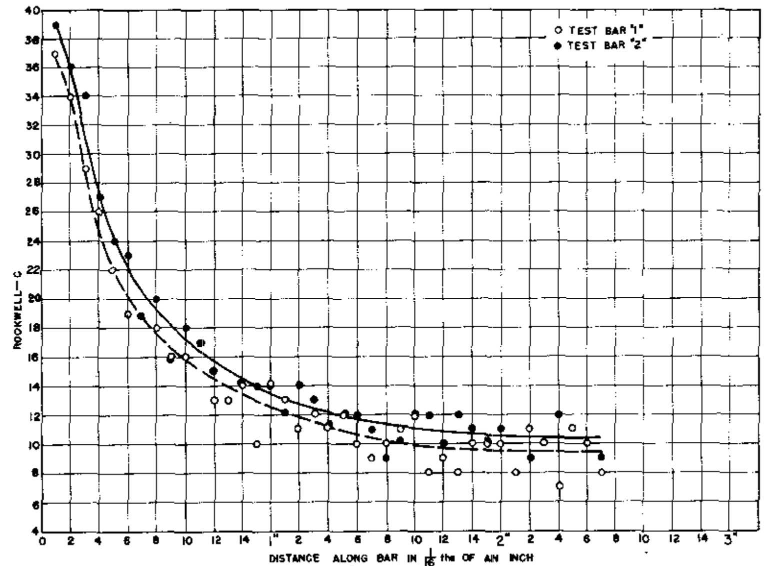
The object of including this additional information was to provide a more complete picture of the characteristics of the steels than was given in the main body of the report.

The Jomminy hardenability curves, Fig. A 1a, clearly show the relative hardenability of the four steels. The cooling curves for the critical part of the heat affected zone in the restrained welded specimen have been included as Fig. A 1b to show the thermal history of this portion of the plate metal during welding.

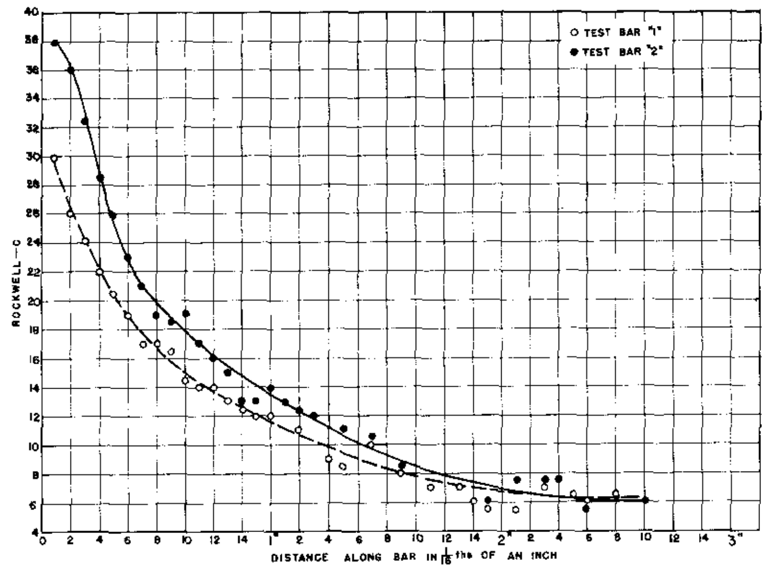
The photomicrographs, shown in Figs. A2, A3, A4 and A5, have been included to show the variation in microstructures in the plate metal, the heat affected zone and the weld metal of each of the high strength structural steels. The photomicrographs of the heat affected zones were taken approximately half-way through the heat affected region.

The widths of the heat affected zones for the various steels are shown in Fig. A6. In this figure the hardness is indicated at various positions in the weld metal, the heat affected zone and the base plate.

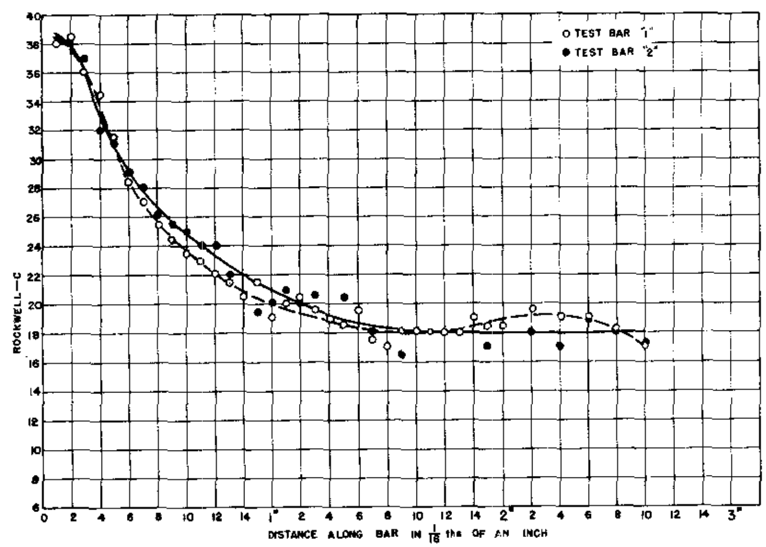
Figs. A7, A8, A9, and A10 are microhardness surveys on longitudinal sections cut from the main strength member of the restrained welded specimens. These pieces were cut from the plate as near to the origin of fracture as possible. In a few cases the specimens actually contained a small amount of the material that had been affected by the heat of welding. Two pieces were cut from each steel: one from a specimen which had failed by cleavage, the other from a specimen which had failed by shear. These surveys were made to show the local variations in work hardening which occur in fractured specimens. They are similar to the curves previously published for mild steels.[2]



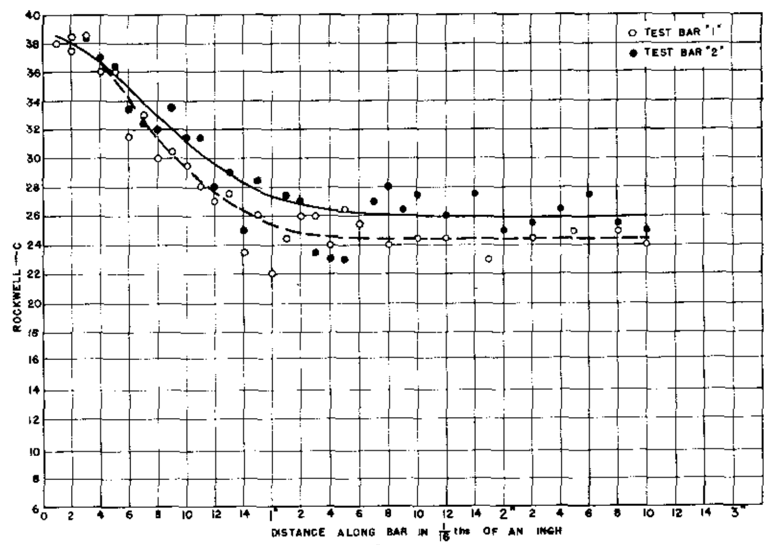
STEEL "1" RC — HARDNESS
JOMMINY .205D INSERT SPECIMEN



STEEL "2" RC — HARDNESS
JOMMINY .205D INSERT SPECIMEN



STEEL "3" RC — HARDNESS
JOMMINY .205D INSERT SPECIMEN



STEEL "4" RC — HARDNESS
JOMMINY .205D INSERT SPECIMEN

FIG. A1a

JOMMINY HARDENABILITY CURVES
FOR H.Y.S.S STEELS

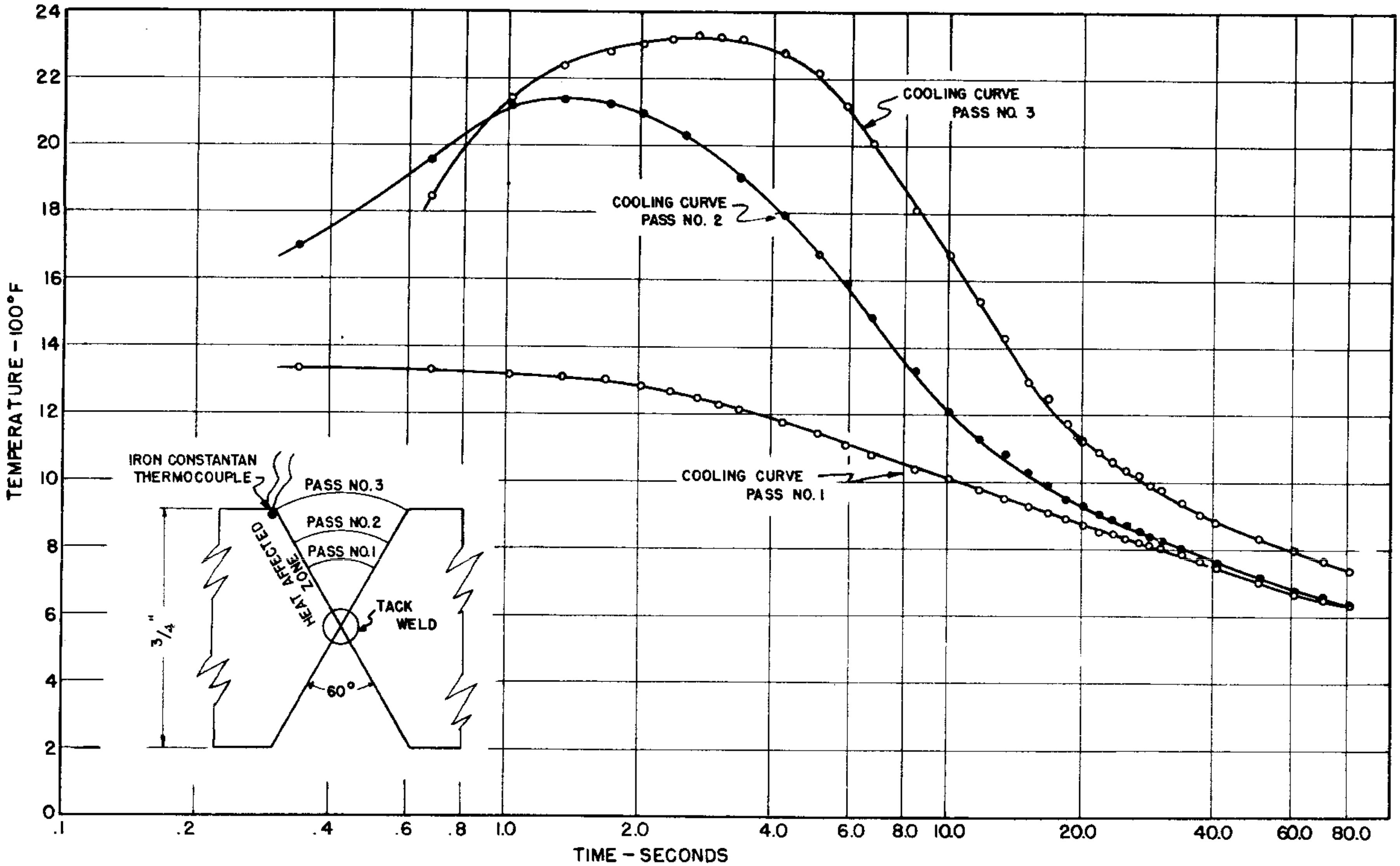


Fig. A1b. COOLING CURVES FOR WELD IN 3/4" PLATE
PLATE PREHEATED TO 300° F.

Plate Metal

Heat-Affected Zone

Weld Metal
Type 310

Fig. A2 - Steel I 1000X

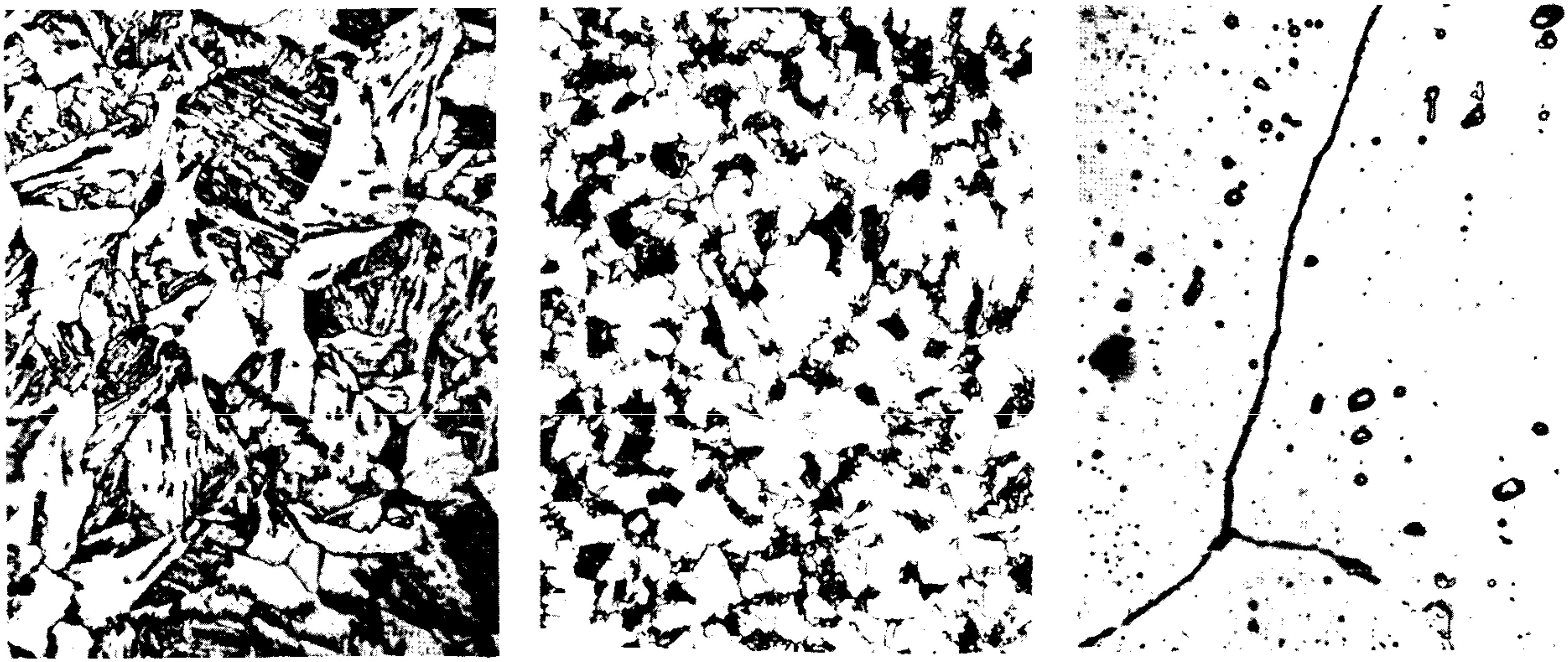


Plate Metal

Heat-Affected Zone

Weld Metal
Type 310

Fig. A3 - Steel 2 1000X

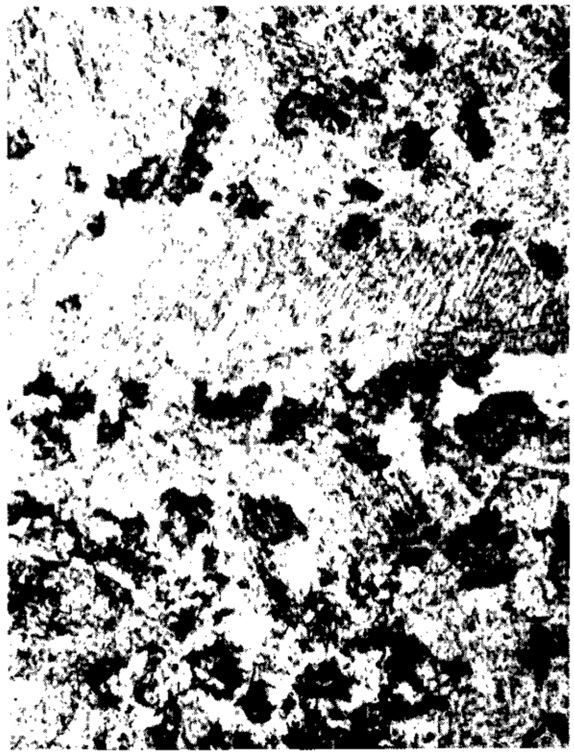
Plate Metal

Heat-Affected Zone

Weld Metal
(Electrode A)

Fig. A4 - Steel 3 1000 X

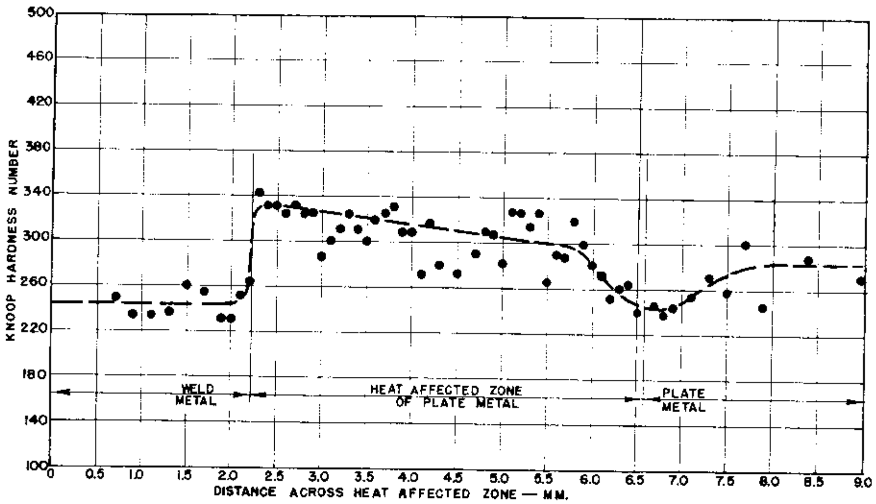
Plate Metal



Heat-Affected Zone

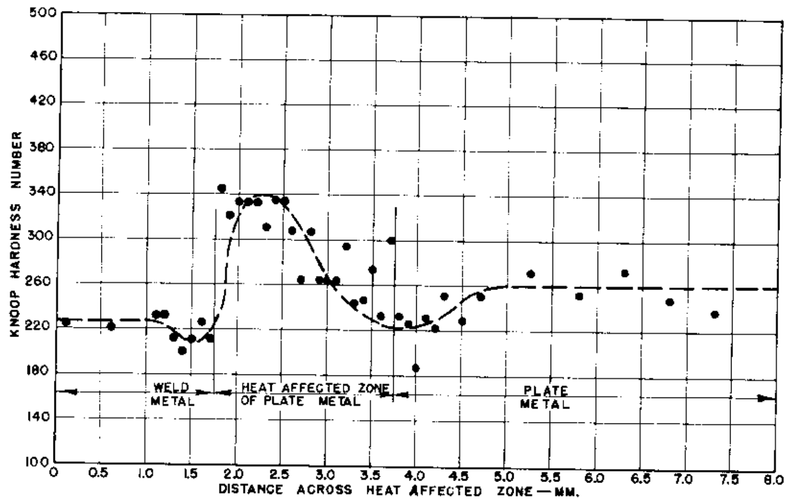
Weld Metal
(Electrode A)

Fig. A5 - Steel 4 1000 X



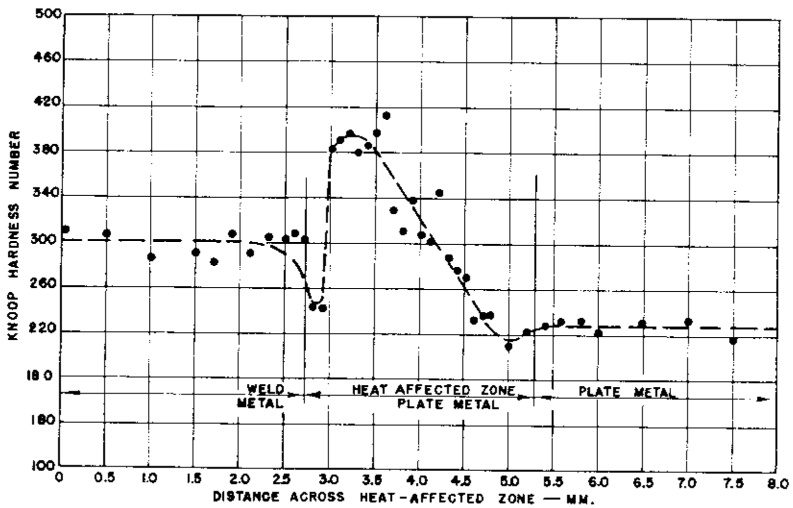
KNOOP HARDNESS NUMBER ACROSS HEAT AFFECTED ZONE

STEEL 1 SPEC. 3-S



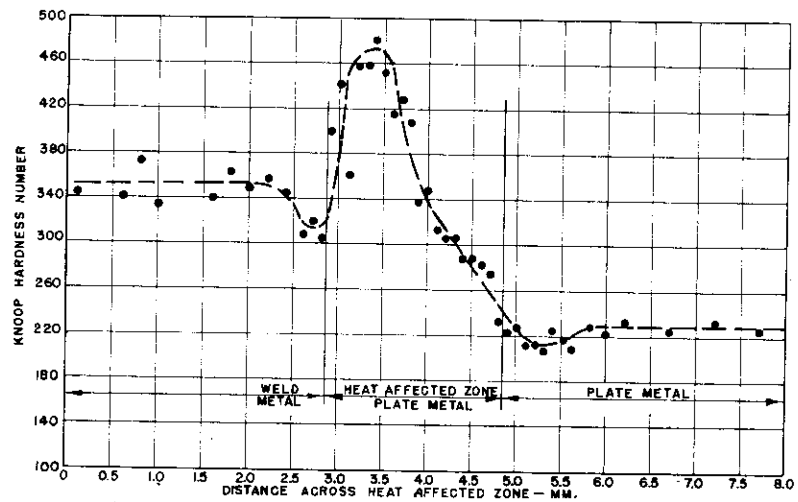
KNOOP HARDNESS NUMBER ACROSS HEAT AFFECTED ZONE

STEEL 2 SPEC. 6-S



KNOOP HARDNESS NUMBER ACROSS THE HEAT AFFECTED ZONE

STEEL 3 SPEC. 14-S

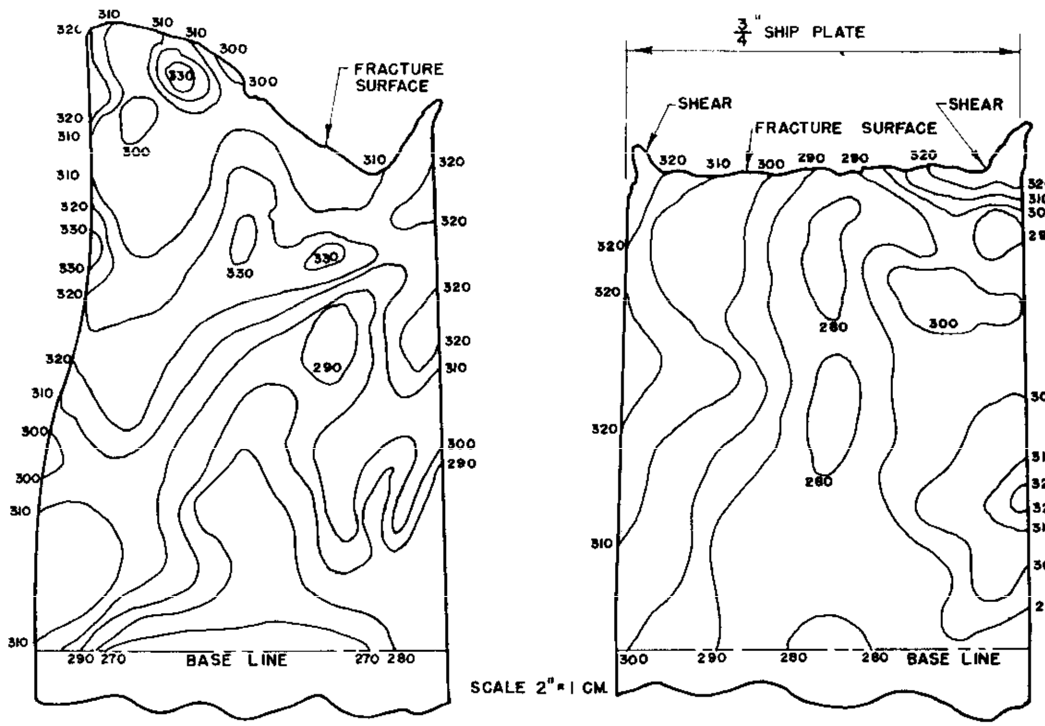


KNOOP HARDNESS NUMBER ACROSS THE HEAT AFFECTED ZONE

STEEL 4 SPEC. 11-S

FIG. A6

MICROHARDNESS SURVEYS ACROSS HEAT AFFECTED ZONE OF HIGH YIELD STRENGTH STEELS

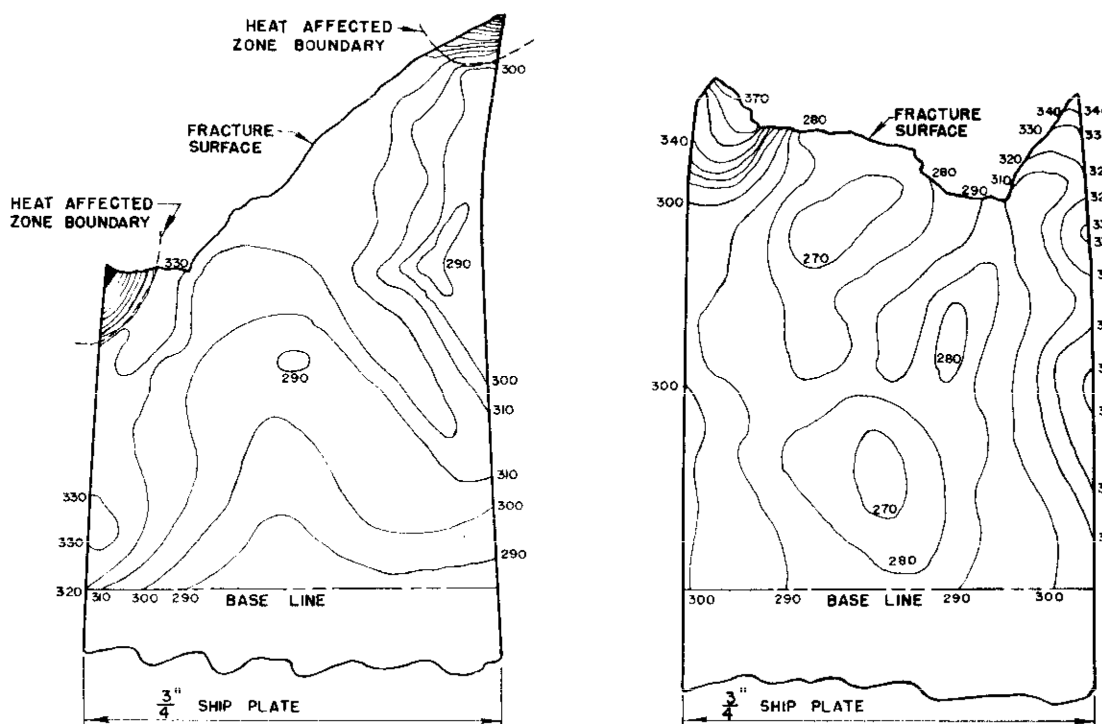


SPECIMEN 4-S
SHEAR FRACTURE

SPECIMEN 3-S
CLEAVAGE FRACTURE

MICROHARDNESS SURVEY OF SHIP PLATE FRACTURE SPECIMENS, STEEL 1
PLANE OF SURVEY PERPENDICULAR TO PLATE SURFACE & FRACTURE FACE

FIG. A7



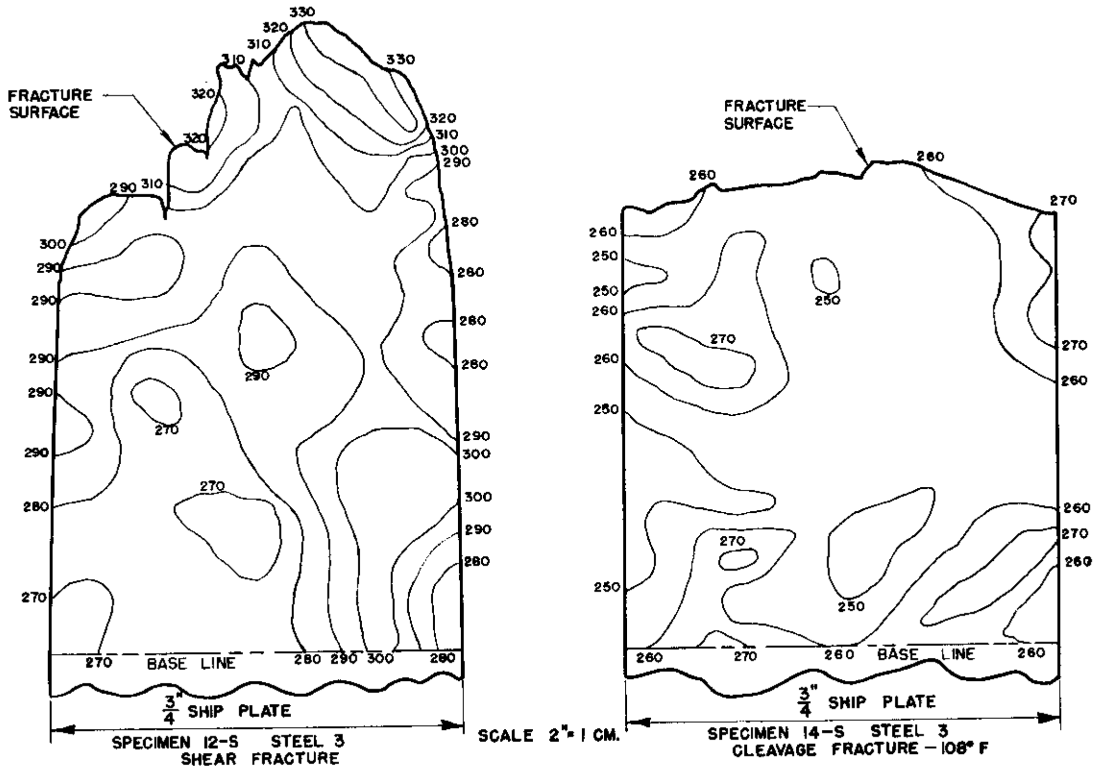
SPECIMEN 7-S STEEL 2 + 100° F
SHEAR FRACTURE

SCALE 2" = 1 CM.

SPECIMEN 6-S STEEL 2 + 63° F
CLEAVAGE FRACTURE

MICROHARDNESS SURVEY OF SHIP PLATE FRACTURE SPECIMENS, STEEL 2
PLANE OF SURVEY PERPENDICULAR TO PLATE SURFACE & FRACTURE FACE

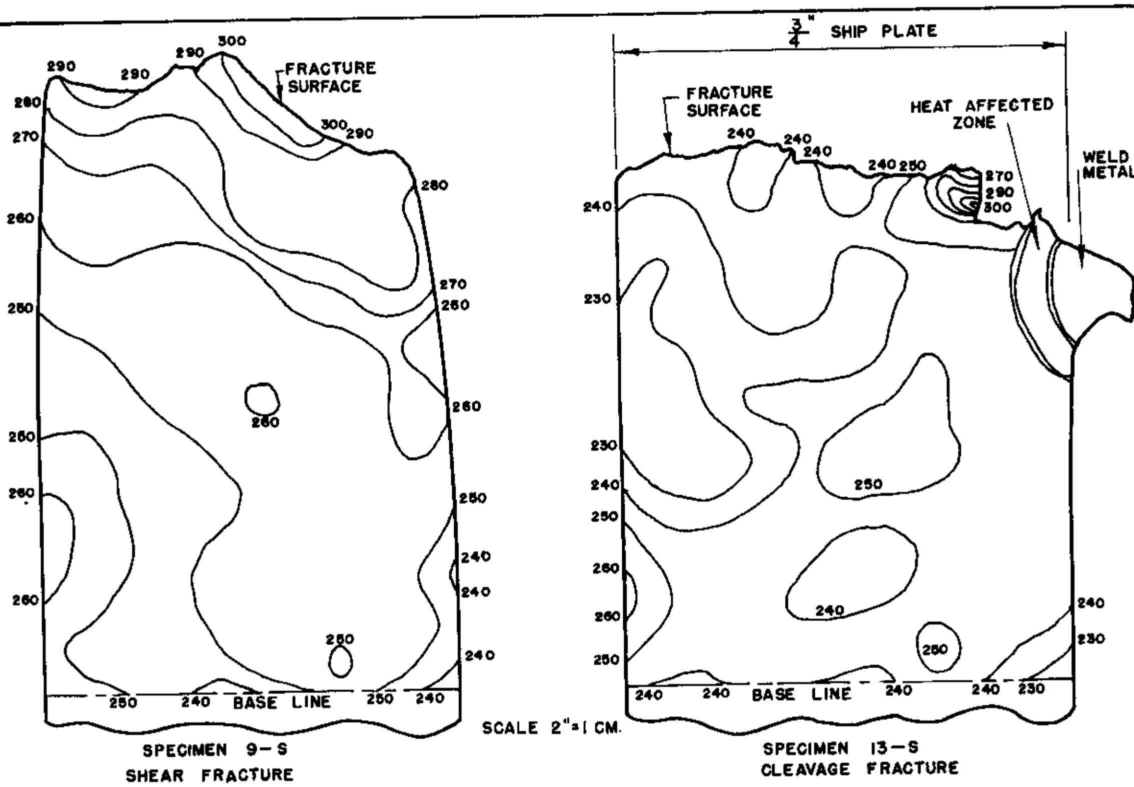
FIG. A8



MICROHARDNESS SURVEY OF SHIP PLATE FRACTURE SPECIMENS, STEEL 3

PLANE OF SURVEY PERPENDICULAR TO PLATE SURFACE & FRACTURE FACE

FIG. A9



MICROHARDNESS SURVEY OF SHIP PLATE FRACTURE SPECIMENS, STEEL 4

PLANE OF SURVEY PERPENDICULAR TO PLATE SURFACE & FRACTURE FACE

FIG. A10

APPENDIX B

CAUSES OF CLEAVAGE FAILURE IN SHIP PLATE

REPORT ON TESTING TECHNIQUES USED IN THE INVESTIGATION

CONTENTS

LIST OF ILLUSTRATIONS

Introduction

In order to conserve time for some investigators that may undertake tests similar to the ones described in the reports on high yield strength structural steel tests[1], and the hatch corner tests[2] it seems advisable to collect all the material that pertains to the manufacture of specimens, welding sequences and procedures used, testing techniques and temperature control devices employed, and the different methods of strain measurements used in these tests into a single short report.

MANUFACTURE OF SPECIMENS AND PULLING TABS

The component parts of the large type specimens were flame cut from 3/4-inch x 72-inch x 120-inch steel plates as shown in Fig. B 1 and were assembled together according to the sequence outlined in Figs. B 2 and B 3. The hatch corner specimens due to their size and weight were assembled in a special jig shown in Fig. B 4, but it was found that restrained welded specimens were sufficiently small and light to be assembled easily without the use of a jig as shown in Fig. B 5. The sequence of assembly of a restrained welded specimen are shown in Figs. B 6, B 7, and B 8. The specimens after having been assembled were welded between two heavy pulling heads so that they could be mounted into the testing machine for the performance of the tension tests. The double V butt welds between the specimen and the pulling heads were made with high tensile strength type electrodes using 200°F preheat and the welds at the edges of the plate were very carefully filled in, in order not to create any notches that could result in failure of the specimen at this point. In the early part of this program it has been found that the joint at the upper pulling tab and the parts MS and CL of the specimen invariably created a more severe condition of

[1,2] See References

restraint than the corner of the specimen itself and failure between the pulling tab and the specimen were common. In order to eliminate this condition snipe holes were provided in the extension of the continuous longitudinal member and a 10-inch x 10-inch x 10-inch triangular plate was welded, as shown in Fig. B8, between the pulling head and the CL member of the specimen.

The pulling tabs were made by welding together 9 plates of high tensile strength steel as shown in Fig. B 9 and the hole for the pulling clevis pin was then machined in the completed assembly. The average life of a pulling tab was from 5 to 6 tension tests of specimens of high yield strength structural steel when these specimens failed by cleavage. Pulling tabs had considerably longer life if they were used in tests where specimens failed by shear as a much lesser shock load at the failure of specimen was placed on the plates of the pulling tab to which the ends of the continuous longitudinal member of the specimen were attached.

TENSION TESTS OF LARGE SPECIMENS

The specimens were placed in the large testing machine with both the upper and lower pulling tabs securely blocked against the heads of the machine by means of timbers to prevent the sideward motion of the parts of the specimen when fracture occurred, Cables fastened around the columns of the testing machine and on to the specimen were added as additional safety measures.

At the start of the program the cooling or heating of the specimen was accomplished by circulating air through a "zippered" canvas bag that totally enclosed the specimen. Later as the temperature requirement became more severe a double walled plywood box was used in place of the canvas bag. Fig. B 10 shows the construction of this plywood box. Fig. B 11 shows the construction of the special heat exchanger used to heat or cool the air that was circulated around the specimen. Cooling of the circulating air was accomplished by 1-1/4 inch thick blocks of dry ice placed in special wire containers inside of the heat exchanger. When tenperatures over 70°F were desired radiant heaters were used in the same heat exchanger with a special switch provided that turned the heaters off if the air circulating motor stopped for any reason.

For some of the extremely low temperature tests additional cooling was required. This was provided by supplying liquid nitrogen, which was forced by air pressure from the nitrogen container through a syphon shown in Fig. B 12, to sprinkler pipes (Fig. B 11) that were located at various strategic points about the specimen.

The liquid nitrogen impinging on the specimen would cool it to temperatures of as low as -150°F in a matter of a few minutes. Temperatures were measured by thermocouples and a uniform temperature distribution was obtained by controlling the nitrogen spray at the various points of the specimen. When a uniform temperature of about 10 to 15°F below that desired was reached, the nitrogen supply was completely shut off and the specimen was allowed to warm up slowly to the desired test temperature. Even at test temperatures of as low as -108°F the heat gain through the pulling tabs and the cooling box was extremely slow so that the specimen temperature remained constant (± 5°F) throughout the test period of about 45 minutes. For most of the cold temperature tests additional insulation about the cooling box was required; this was provided by covering the entire cooling box with heavy wrapping paper and carefully sealing off all joints with 2-inch wide painter's tape.

The test temperature of the specimen was checked by means of 12 thermocouples located at various places on the specimen. These were connected to a switch so that the temperatures at the different points could be obtained quickly. Tension tests were started when the thermocouples in the region of the specimen corner were within ±2°F of each other. In some instances, when specimens failed by shear, it was impossible to maintain the temperature within the region of fracture closer than ±5°F of the desired test temperature, due to heat generated by the fracture.

The specimens were loaded in the large tensile testing machine at an approximate rate of 50,000 lbs. per minute until failure occurred in the main strength member, "MS", as well as in the continuous longitudinal, "CL". The energy absorption was measured by means of a manganin wire extensometer, shown in Fig. B 13, that was connected to an SR-4 Strain Recorder. A fast drive was provided for the recorder chart (one complete chart revolution in 2 minutes) and while a load increment was applied to the specimen the chart motor was shut off. At certain intervals, usually 50,000 lb. increments, the load was maintained a short time, the reading on the load dial was called off by the testing machine operator and the chart motor on the SR-4 recorder was started and run for about 10 seconds. This resulted in a series of "steps" being recorded on the chart for the different loads. (An example of a recorder chart for a test of a hatch corner specimen of B_r steel is shown in Fig. B 20). After the maximum load was reached, the recorder was kept running continuously and the strain readings on the chart vs. the loads were "called off" by the operator and were recorded by an observer. From this record it was possible to plot the strain-load curve, the integration of which would give the energy absorption by the specimen. The method just described provided a reliable, simple way of recording the data necessary for energy determinations. After the failure of the specimen, the overall elongation was checked by actual measurements of the distances between the extensometer lugs and the fractured edges of the specimen.

Stress distribution studies on several of the specimens were made by means of SR-4 electric strain gages. It was found that time and effort could be saved by using many manually operated SR-4 indicating instruments rather than a single multiple point recorder, since the automatic unit requires rather extensive and careful initial balancing to get the many gages within the range of the instrument. In this investigation six different circuits with manually operated indicators were used, thus each operator had only 12 readings to take for any one load condition; a complete set of reading was usually obtained in less than 2 minutes. Several "key" gages were connected to continuously operated SR-4 strain recorders to give a check on the overall elongation at certain points of the specimen. The strains at various points of the specimens were computed from the averages of the readings of the two gages directly opposite each other on the two surfaces of the steel plates.

12-inch Wide Notched Specimen

The 12-inch wide notched specimens were prepared by flame cutting 3/4-inch x 12-inch x 22-inch pieces from the large steel plates (with the 22-inch dimension parallel with the direction of roll), and by drilling a 3/4-inch hole in the center of each specimen. From this hole, in a direction perpendicular to the longitudinal axis of the specimen, hacksaw cuts were made for 1 inch toward the edges of the specimen, and the notches thus created were made more severe by extending each hacksaw cut for an additional eighth of an inch with a 0.010-inch thick jeweler's saw. The specimens were then welded by the Unionmelt process between pulling heads shown in Fig. B 14. The run-off tabs were cut off and the edges of the welds were carefully hand welded and ground to prevent cracks at the edges of the butt welds.

The specimens were tested in tension in the 3,000,000 lbs. machine at various temperatures. The cooling of the specimens was accomplished by using dry ice in the same heat exchanger that was employed for cooling the large restrained welded specimens. The cooling box for these specimens is shown in Fig. B 15, and for the extremely low temperature tests the single nitrogen spray, also shown in that figure, was used near the top of the specimen. Five thermocouples were used to check the temperature of the specimen and three 9-inch long manganin wire extensometers were used on each face of the specimen -- two near the edges and one at the centerline. These were connected in series and thus the average strain was recorded on the chart of the SR-4 continuous recorder to which they were connected. Strain readings at various loads were recorded by an observer and the load-deformation curve plotted for the specimen. The energy absorption was obtained by integration of the area under this curve.

The 3/4-inch x 6 5/8-inch unnotched specimens were flame cut from a large plate by using a special 1/4-inch thick steel template which was used as a guide for the tip of the cutting machine. These specimens were welded to pulling head in a manner similar to the 12-inch centrally notched specimens. The welds on the 3/4-inch x 6 5/8-inch wide "welded" specimens were deposited into 3/8-inch deep flame gouged grooves with a Unionmelt machine using 1/4-inch rod at approximately 9 inches per minute speed and 825 amps. at 29 volts.

These unnotched specimens were tested in a manner similar to the 12-inch center notched specimens, but four 6-inch span clip gages (similar to the 2-inch clip gage shown in Fig. B 13) were used to measure the overall elongation of the specimen -- one at the centerline on each face of the specimen and one at each edge. The centerline gages were connected in series to one recorder and the two edge gages, also in series, were connected to another SR-4 continuous recorder. The results of the two records were averaged for plotting the load-elongation curve from which the energy absorption was determined.

3-Inch Wide Notched Specimens

The 3/4" x 3" x 18" specimens were flame cut from a large plate with the 18" dimension in the direction of the roll of the plate. The specimens were then notched for 1/2" at each edge with a 0.042-inch thick Doall saw. No attempt was made to check the sharpness of the notch except for an occasional check on the width of the saw blade and the sharpness of its teeth. The depth of the notch and thus the net width of the specimen was kept to 2" $\pm$ .010". As the consistency of the results for most of the steels indicate, there was no apparent effect produced by the minor variations in the sharpness of the notches made with saws of different tooth sharpness.

The 3-inch wide edge notched specimens were clamped directly into the flat jaws of the testing machine and energy measurements were made by means of two 2-inch long clip gages, shown in Fig. B 13, which straddled the notch at each edge of the specimen, as shown in Fig. B 16. The desired test temperatures were obtained by circulation of alcohol through two copper cooling jackets, shown in Fig. B 17, that were clamped to both of the specimen faces, thus forming a "sandwich" as shown in Fig. B 18. The temperature was checked by means of two thermocouples soldered near the notch to each edge of the specimen. The alcohol that was circulated through the jackets was cooled and pumped by means of the special heat exchanger unit shown in Fig. B 19. Dry ice was used to cool the alcohol and by proper manipulation of the by-pass valve good temperature control of the specimen could easily be obtained. For extremely low temperature tests, liquid nitrogen was expanded and circulated through the jackets with the aid of the siphon shown in Fig. B 12, and thus test temperatures of as low as -160°F were easily maintained.

For test temperatures of over + 70°F water was used as the circulating medium and thermostatically controlled electric heaters were used in the exchanger unit to heat and maintain the circulating water at the proper temperature.

Energy absorption was measured by two 2-inch clip gages (Fig. B13) connected in series to a Foxboro SR-4 recorder equipped with a fast chart drive. The recorder was operated in a manner similar to the one used for recording strains on the large test specimens. From zero to the maximum load, the various load increments were marked off on the recorder chart by operating the driving motor for a few seconds at the desired loads; the rest of the time the chart remained stationary. Beyond the maximum load the recorder motor was kept running continuously and the marks for the various loads above the maximum were made on the chart by momentarily closing a special shorting switch so arranged that either the compensating or the active gage could be shorted at will. The shorting of the active gage, used for marking 2,000 lbs. load increments, resulted in a pen displacement in one direction, while the shorting of the compensating gage, used to mark 5,000 lbs. increments, would displace the pen in the opposite direction. In this manner the conduction of the test and recording of the data could be accomplished, if necessary, by a single operator. The lower part of Fig. B 20 shows an SR-4 recorder chart with the data from a test of a 3-inch wide edge-notched specimen.

Bend Test Specimens

For the bend test specimens 3-inch wide strips about 38 inches long were cut from a large plate of steel and one of the edges was flame beveled for welding. Two of these 3-inch strips were securely fastened to a large heavy plate to prevent excessive warping and heating, and were welded together with due precaution exercised to keep the temperature at the desired level during the welding procedure. The 6-inch x 38-inch strips thus formed were then cut into four 3/4-inch x 6-inch x 9-inch bend test specimens. Weld overbuilds were ground off at the center of the specimen with care being exercised to have the grind marks in the direction of the weld. The specimens were precooled in a dry ice and alcohol bath and the test was performed in a special jig[1] that was totally immersed in another alcohol bath placed on the lower table of the testing machine. This bath was kept at the desired temperature by means of a 60-foot long coil of 5/8-inch diameter copper tubing through which alcohol from the heat exchanger, shown in Fig. B 19, was circulated. The bend angle of the specimen was measured by a calibrated 6-inch span clip gage (similar to the one shown in Fig. B 13) that actually measured the vertical downward movement of the load application member of the bend test jig. The clip gage indications were recorded on a chart of a continuous SR-4 strain recorder and the various loads applied to the specimen were indicated on the recorder chart by means of the small deflections of the recording pen which were caused by momentarily short circuiting the gage circuit, as already described in connection with the 3-inch wide specimen tests. Bend angles after failure were measured by means of a protractor and served as a check on the ones obtained from the measurement of the vertical movement of the loading member of the jig.

Recommendation

It is strongly recommended that tests of large restrained specimens be performed only as final checks on the behavior of steels that have been thoroughly tested by other means (including dynamic tests). From all indications to date, the tests performed on smaller less expensive specimens (12-inch wide or 3-inch wide notched specimens or U. S. Navy tear test specimens) rate the steels in the same order as the tests of the large restrained welded specimens, so additional tests of the large specimens at present are not justifiable. Even with the extremely favorable labor situation that prevailed at the University of California, such as using the same crew of four technicians as welders, chippers, cutters, riggers etc., the cost of each restrained welded specimen was about $1600.00 for labor and overhead, with an additional $175.00 for the material used in each specimen.

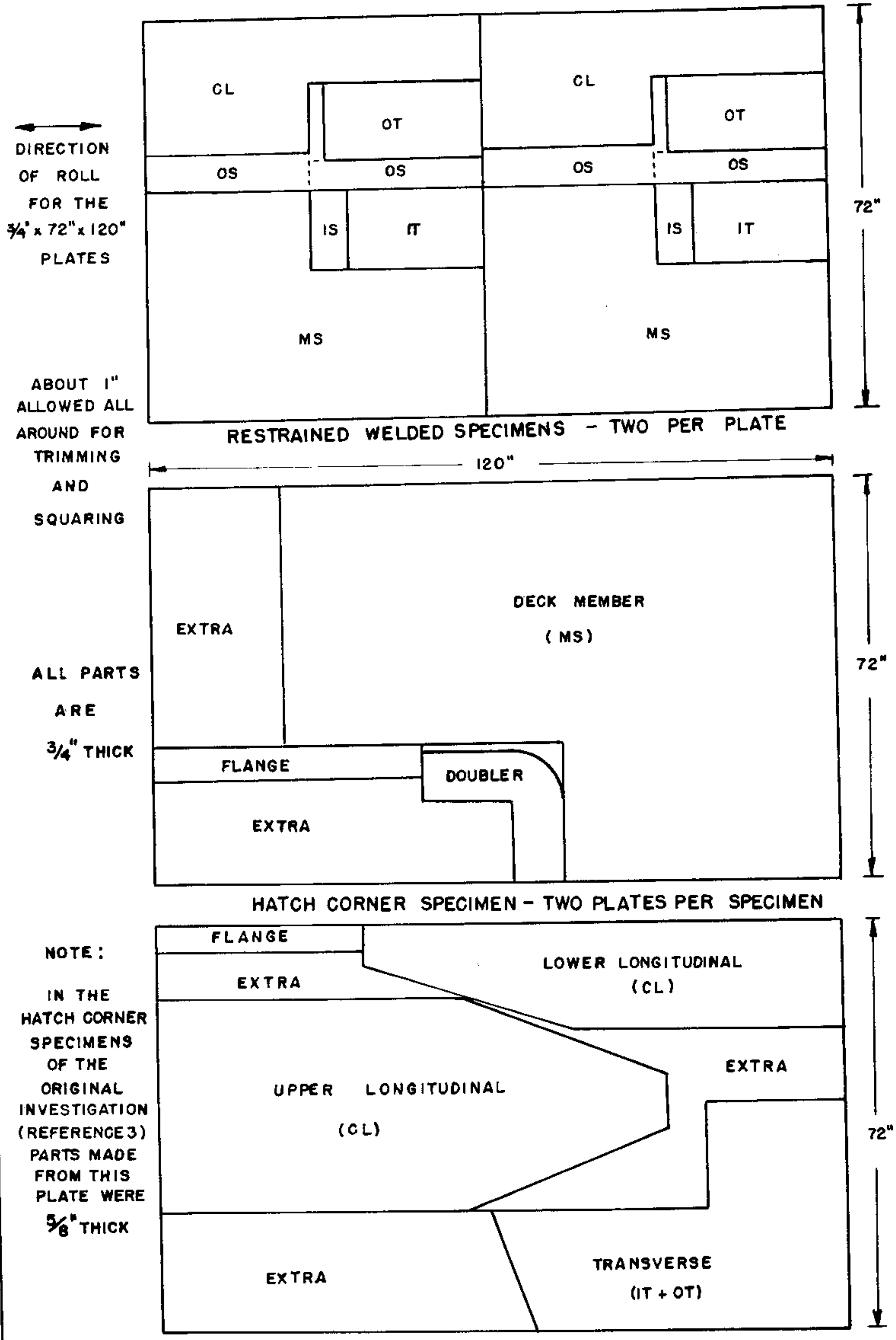


FIG. B1 PLATE LAYOUT FOR CUTTING PARTS OF LARGE SPECIMENS.

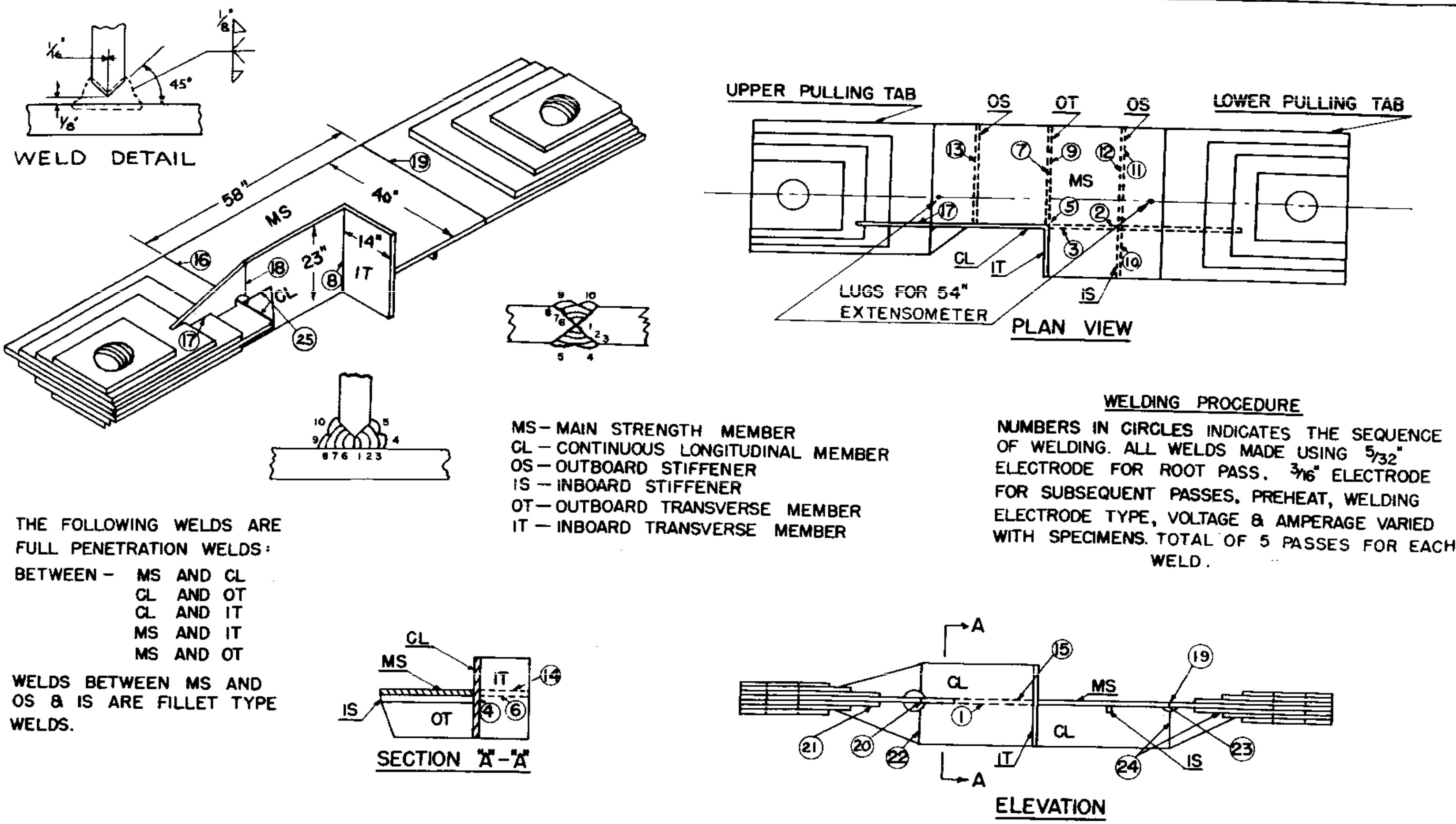


FIG. B2 RESTRAINED WELDED SPECIMEN USED FOR TESTS OF HIGH YIELD STRENGTH STRUCTURAL STEELS.

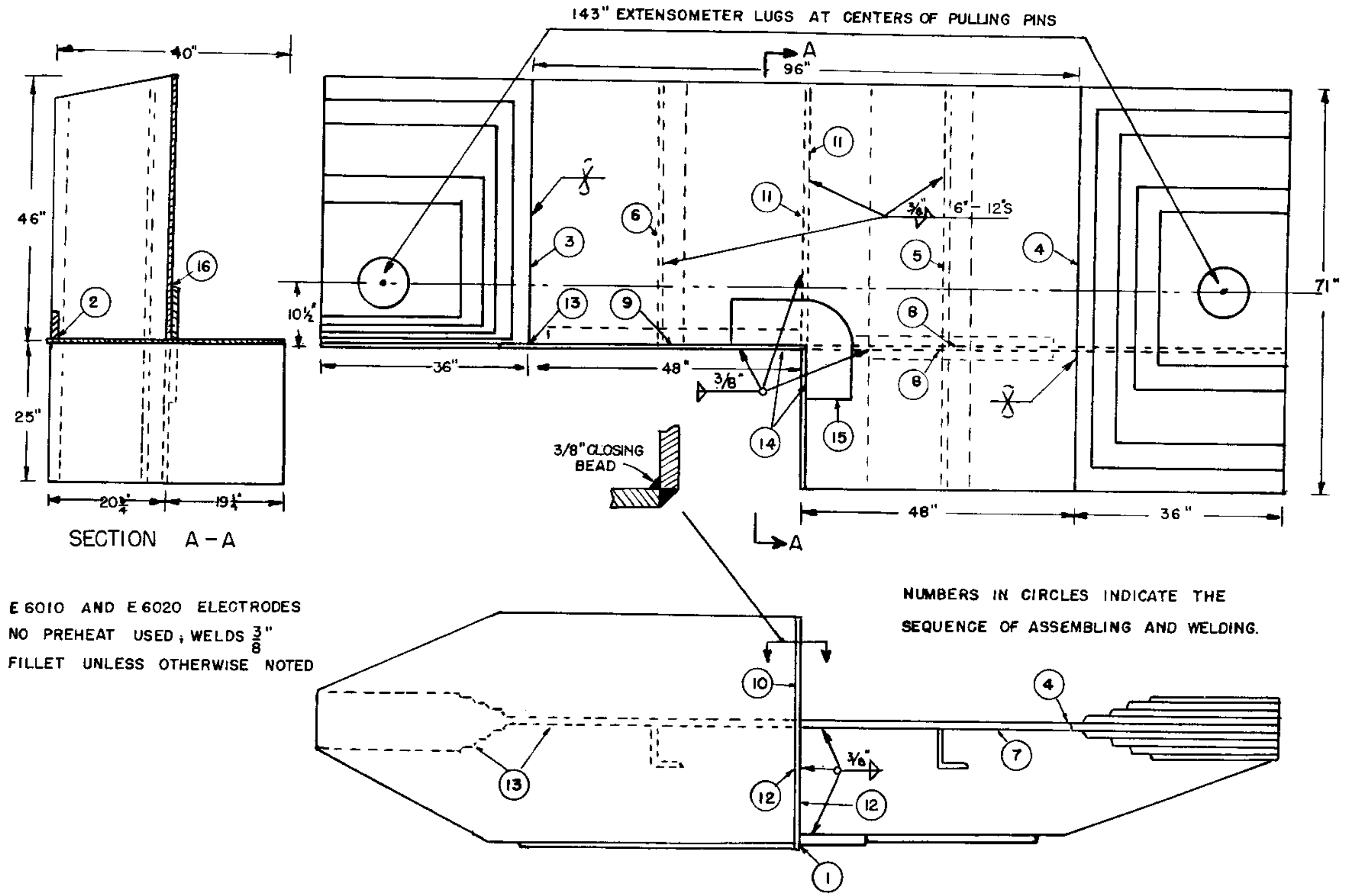


FIG. B3 HATCH CORNER TYPE SPECIMEN USED IN THE INVESTIGATION

Fig. B4 - Jig used for Welding Hatch Corner Specimens

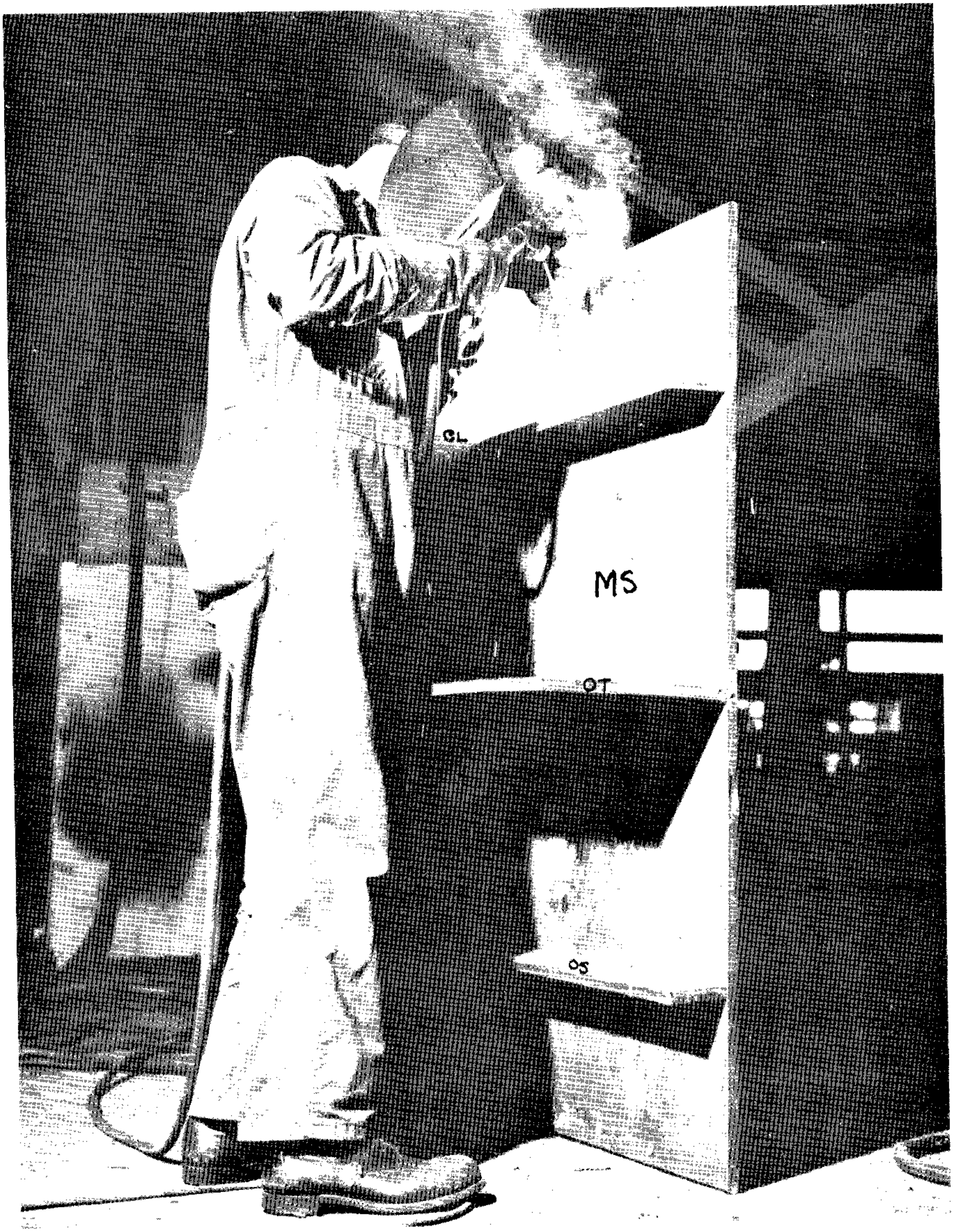
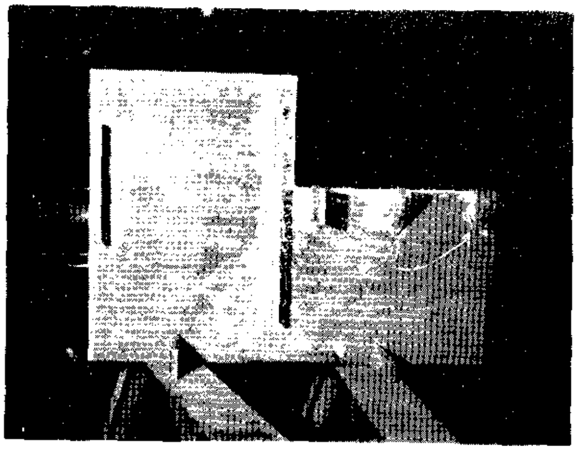
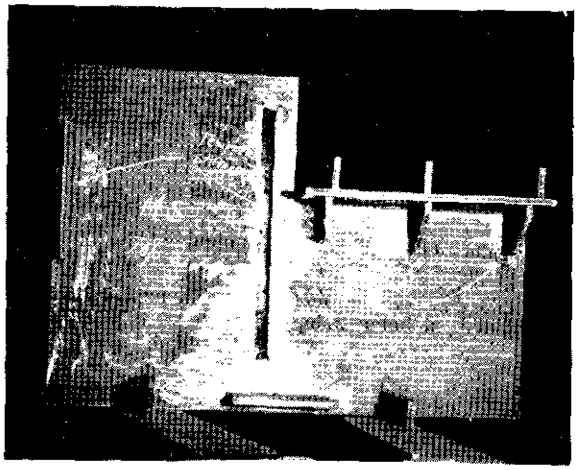


FIG. 85 WELDING AN OUTBOARD STIFFENER ON THE RESTRAINED WELDED SPECIMEN



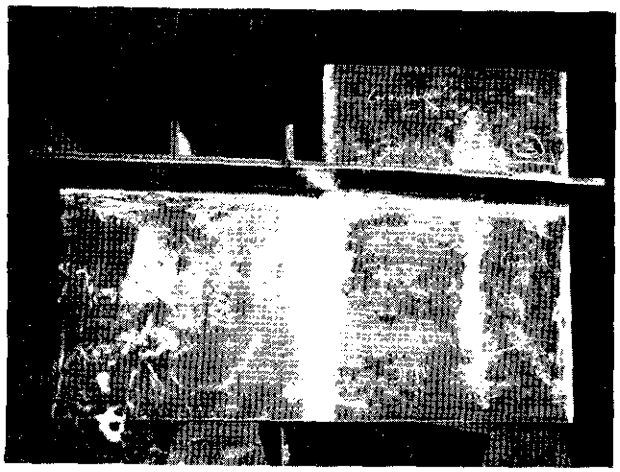
TOP VIEW

MAIN STRENGTH MEMBER "MS" WITH TEMPORARY STIFFENERS AND BRACKETS



TOP VIEW

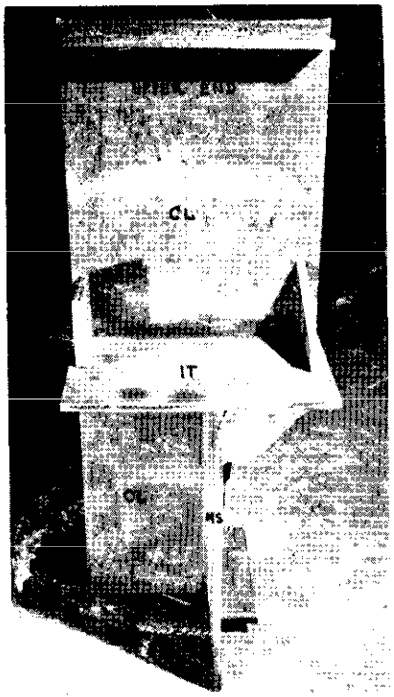
MAIN STRENGTH MEMBER "MS" WITH THE CONTINUOUS LONGITUDINAL MEMBER "CL" AND ITS TEMPORARY BRACKETS IN PLACE.



BOTTOM VIEW

MAIN STRENGTH MEMBER "MS" AND CONTINUOUS LONGITUDINAL "CL" TACK WELDED IN PLACE

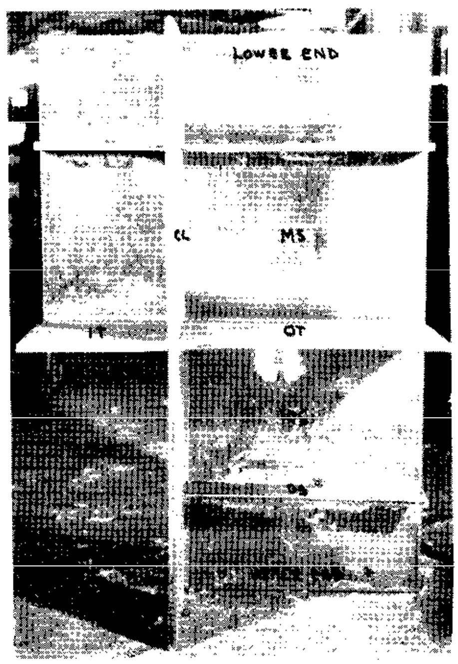
FIG. 86 SEQUENCE OF ASSEMBLING PARTS OF THE RESTRAINED WELDED SPECIMEN



SIDE VIEW
INBOARD TRANSVERSE MEMBER "IT"
IN POSITION SHOWING THE TEMPORARY
BRACKETS

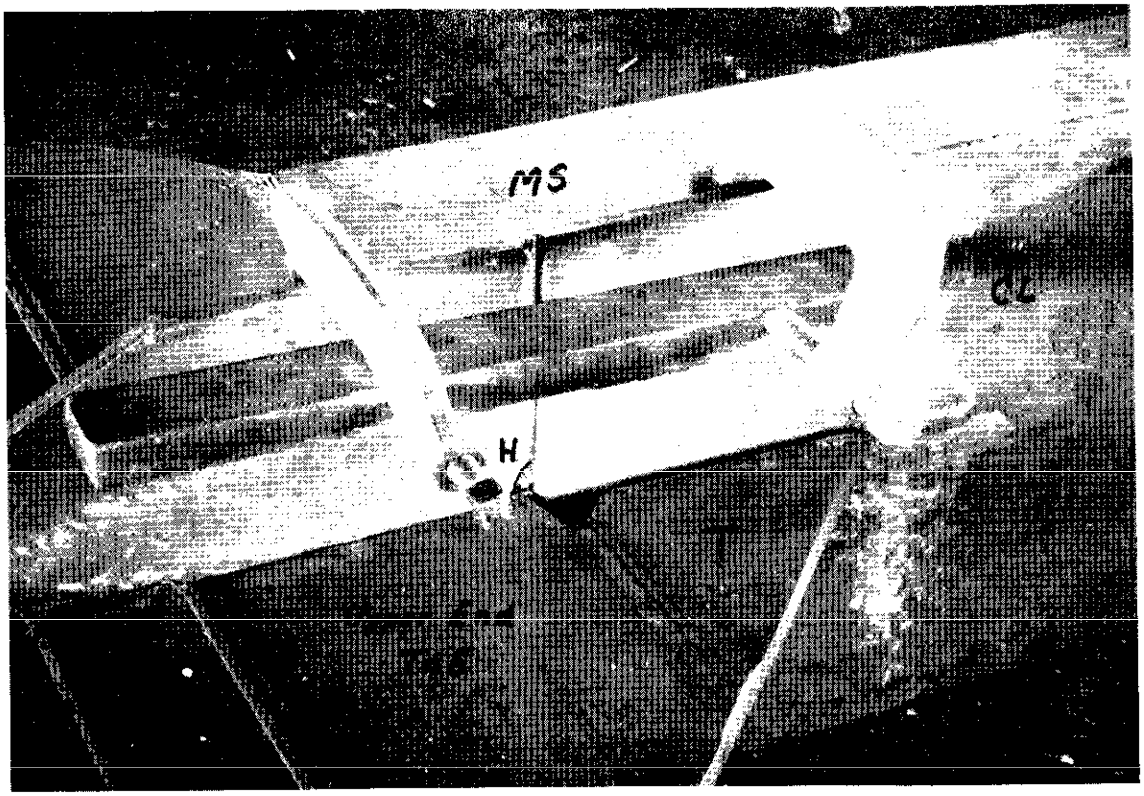
BOTTOM VIEW
OUTBOARD TRANSVERSE MEMBER "OT"
IN POSITION SHOWING THE TEMPORARY
BRACKETS

TOP VIEW
SPECIMEN ALMOST COMPLETED
TEMPORARY BRACKETS STILL IN PLACE

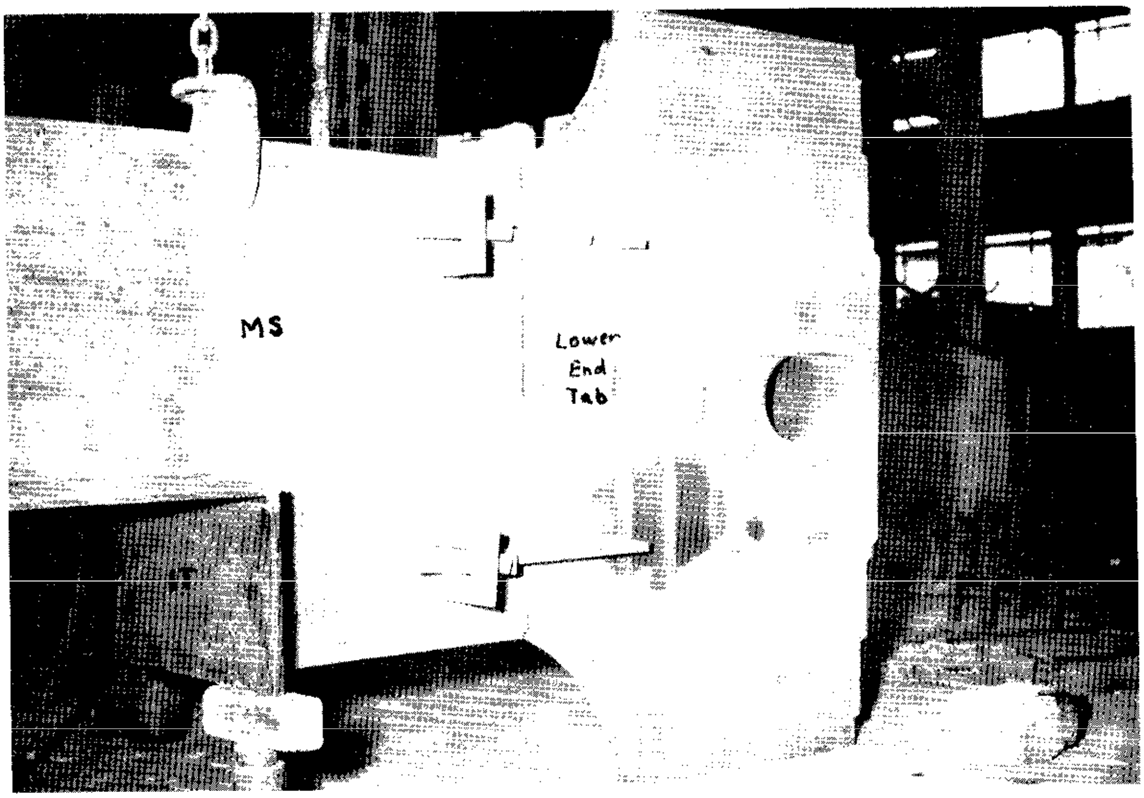


BOTTOM VIEW
SHOWING THE COMPLETED SPECIMEN

FIG. B7 RESTRAINED WELDED SPECIMEN UNDER CONSTRUCTION

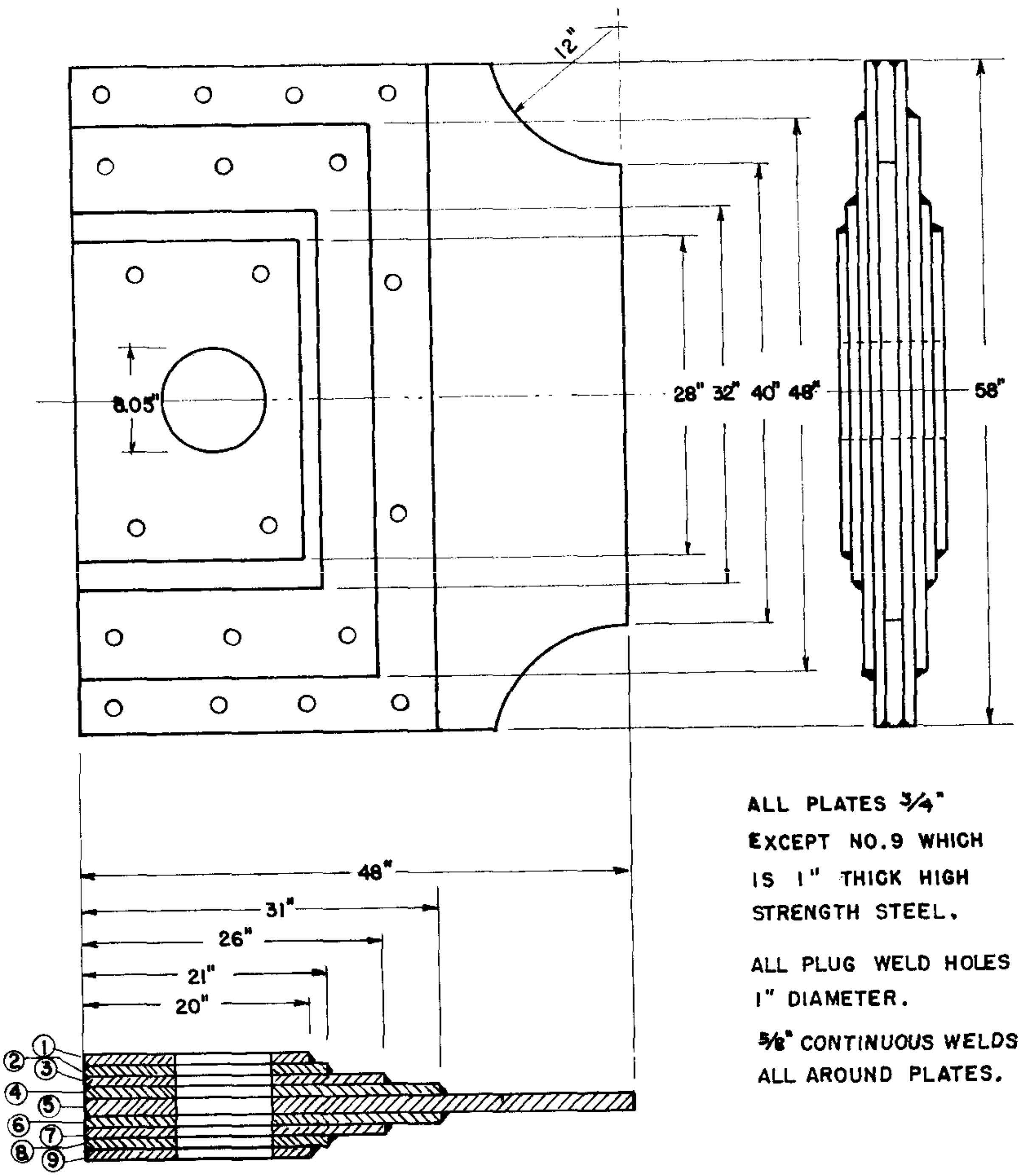


UPPER PULLING TAB, READY FOR TACK WELDING, SHOWING TRIANGULAR INSERT "T" AND SNIPE "H" IN THE EXTENSION OF CONTINUOUS LONGITUDINAL "CL"



LOWER PULLING TAB IN POSITION

FIG. B8 RESTRAINED WELDED SPECIMEN — UPPER & LOWER PULLING TABS.



1. PLATES 4 & 6 PLUG WELDED TO 5, WELDS GROUND OFF FLUSH.
2. PLATES 3 & 7 ARE THEN PLUG WELDED TO THE ASSEMBLY, WELDS GROUND OFF FLUSH.
3. PLATES 2 & 8 WELDED TO ASSEMBLY AND THE PLUG WELD HEADS GROUND OFF FLUSH.
4. PLATES 1 & 9 PLUG WELDED TO ASSEMBLY. CONTINUOUS FILLET WELDS MADE ALONG ALL EDGES. HOLE BORED IN COMPLETED ASSEMBLY.

FIG: B9 PULLING TABS FOR LARGE WELDED SPECIMENS.

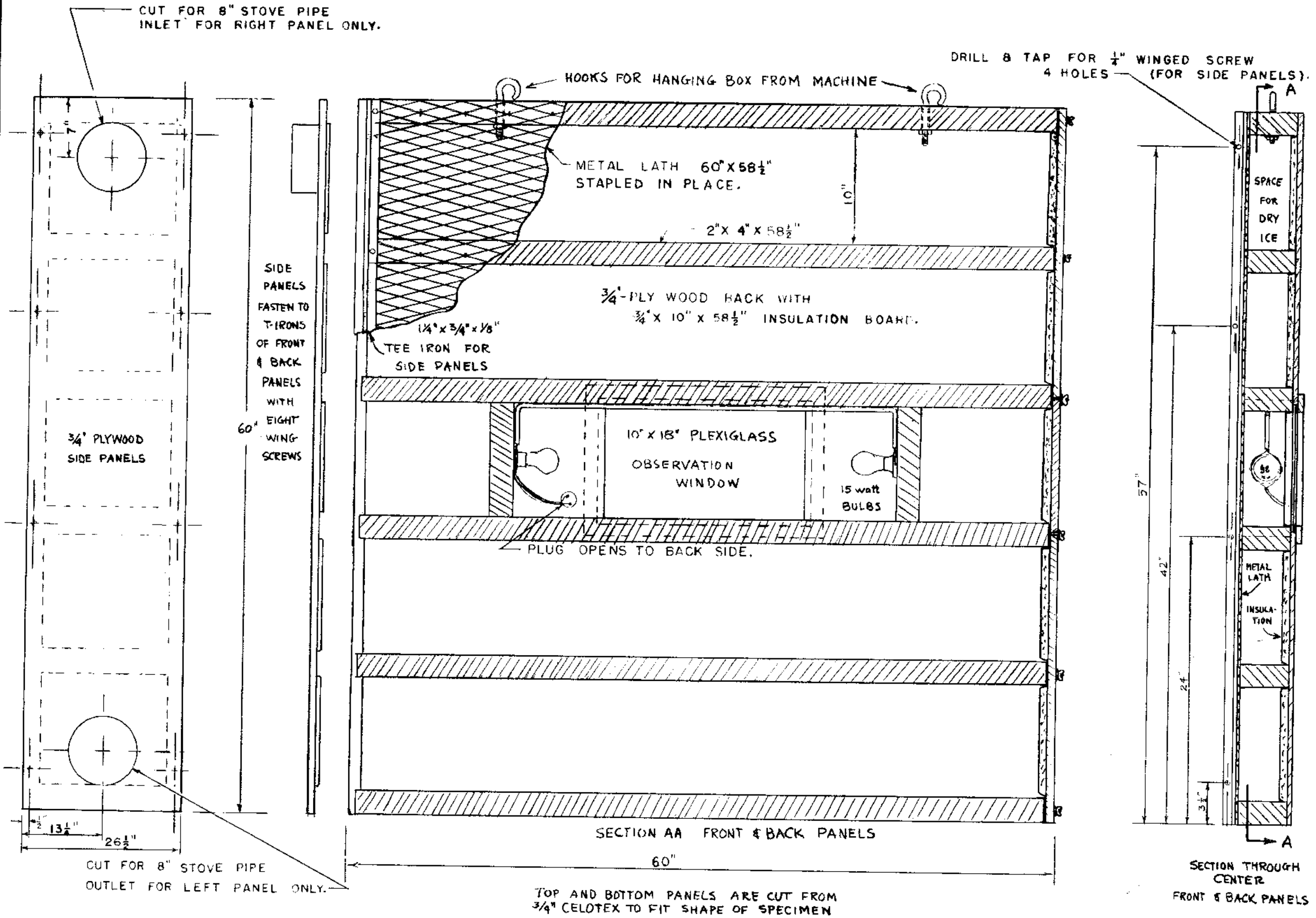
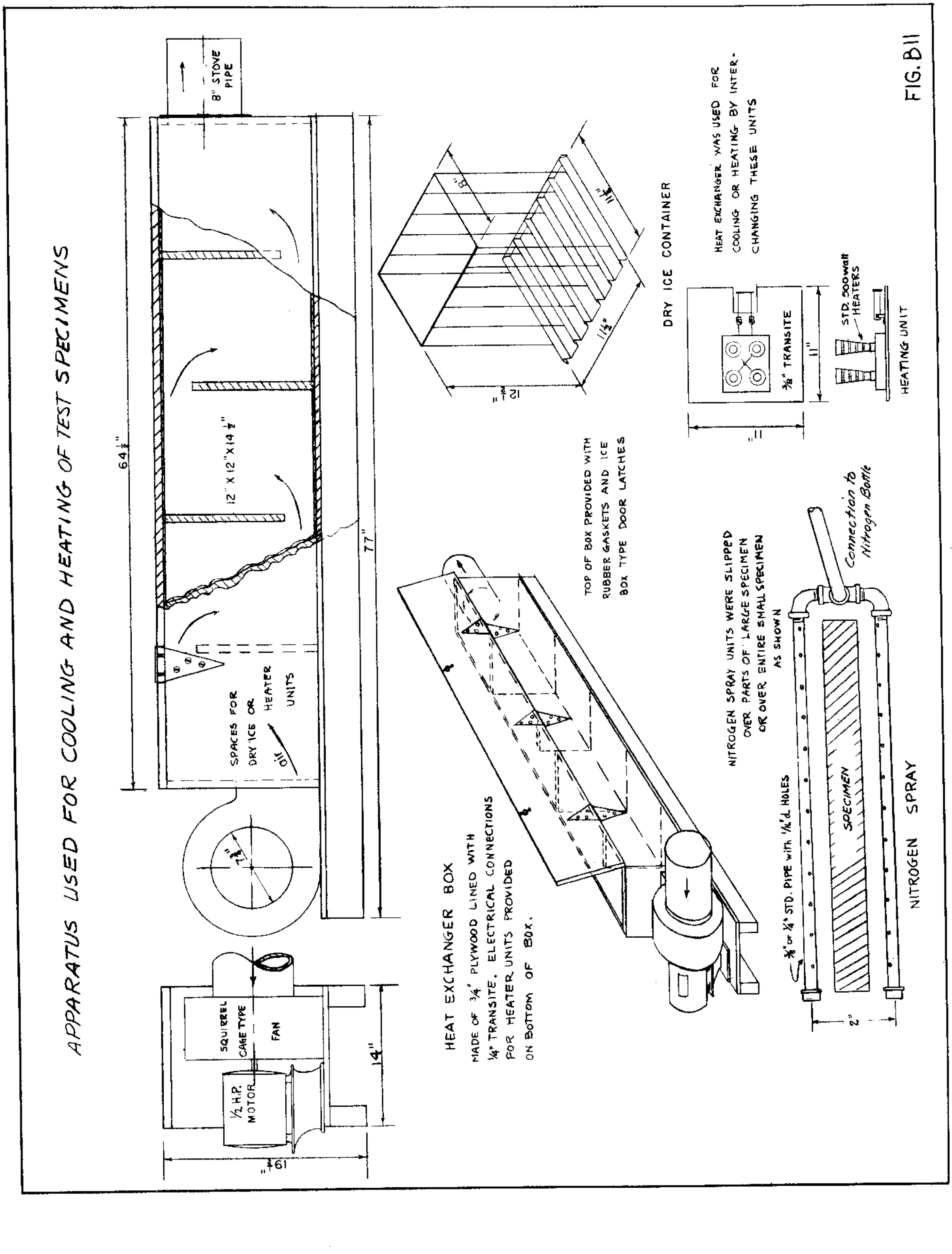


FIG. B-10 COOLING BOX FOR RESTRAINED WELDED SPECIMEN



APPARATUS USED FOR COOLING AND HEATING OF TEST SPECIMENS

FIG. B11

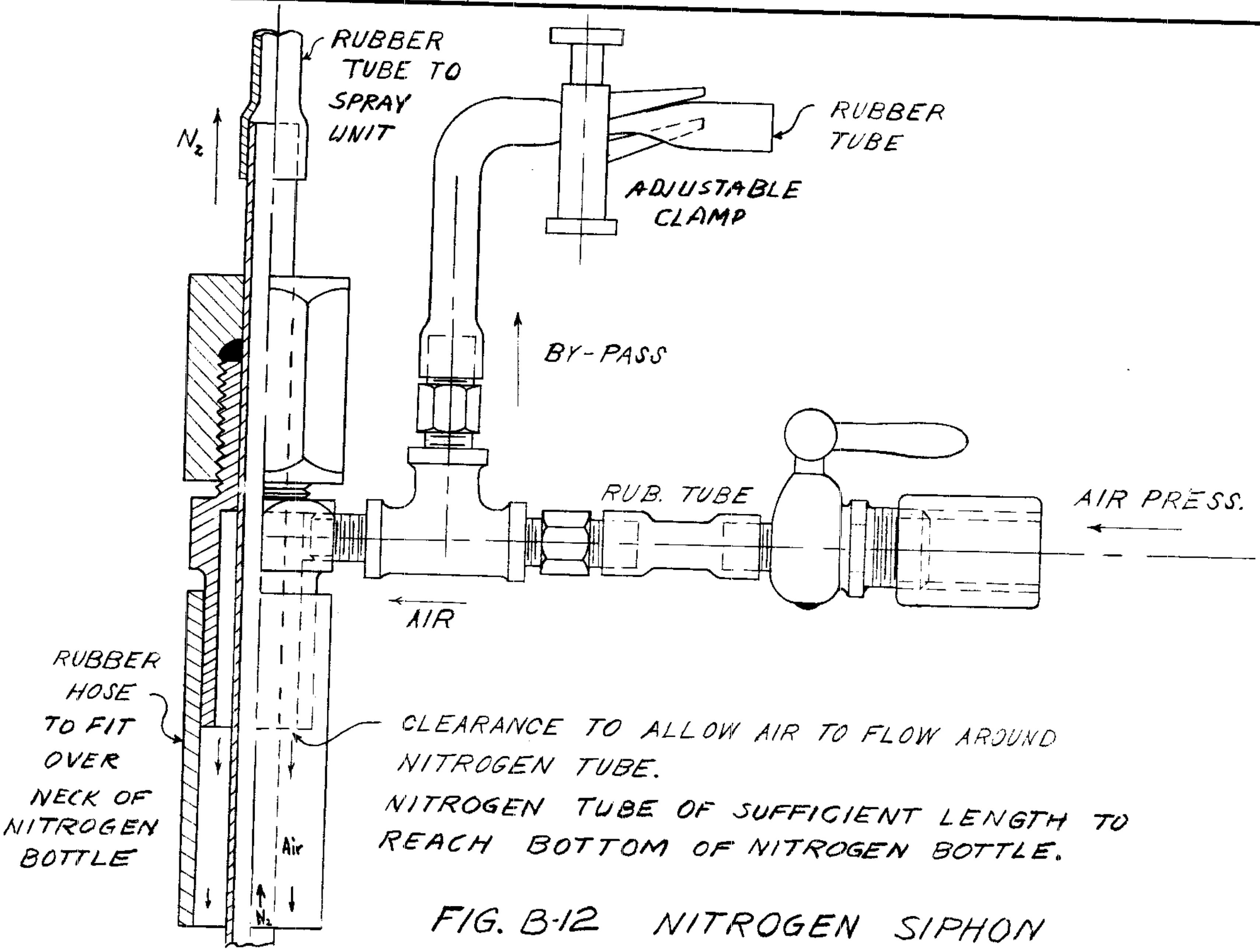
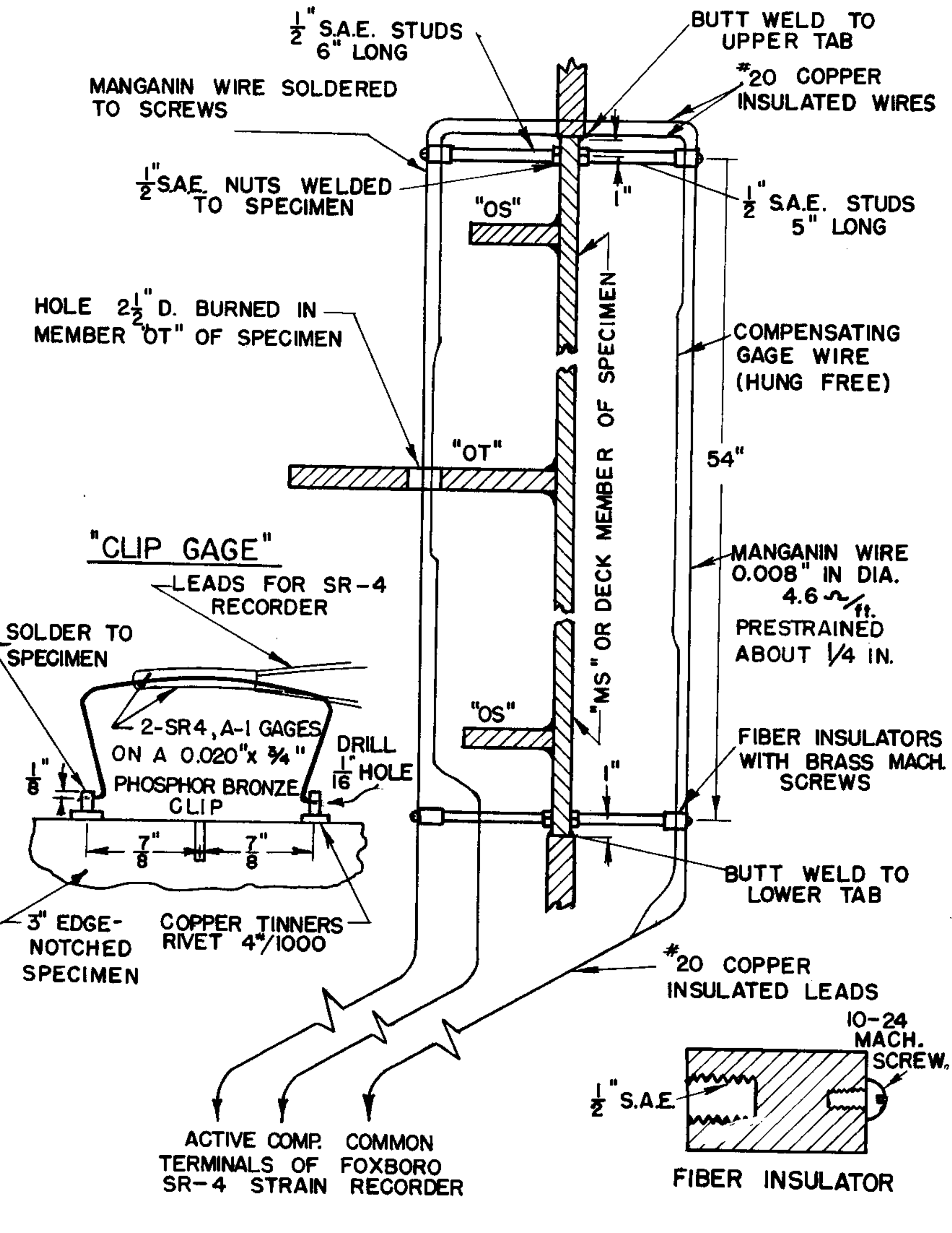
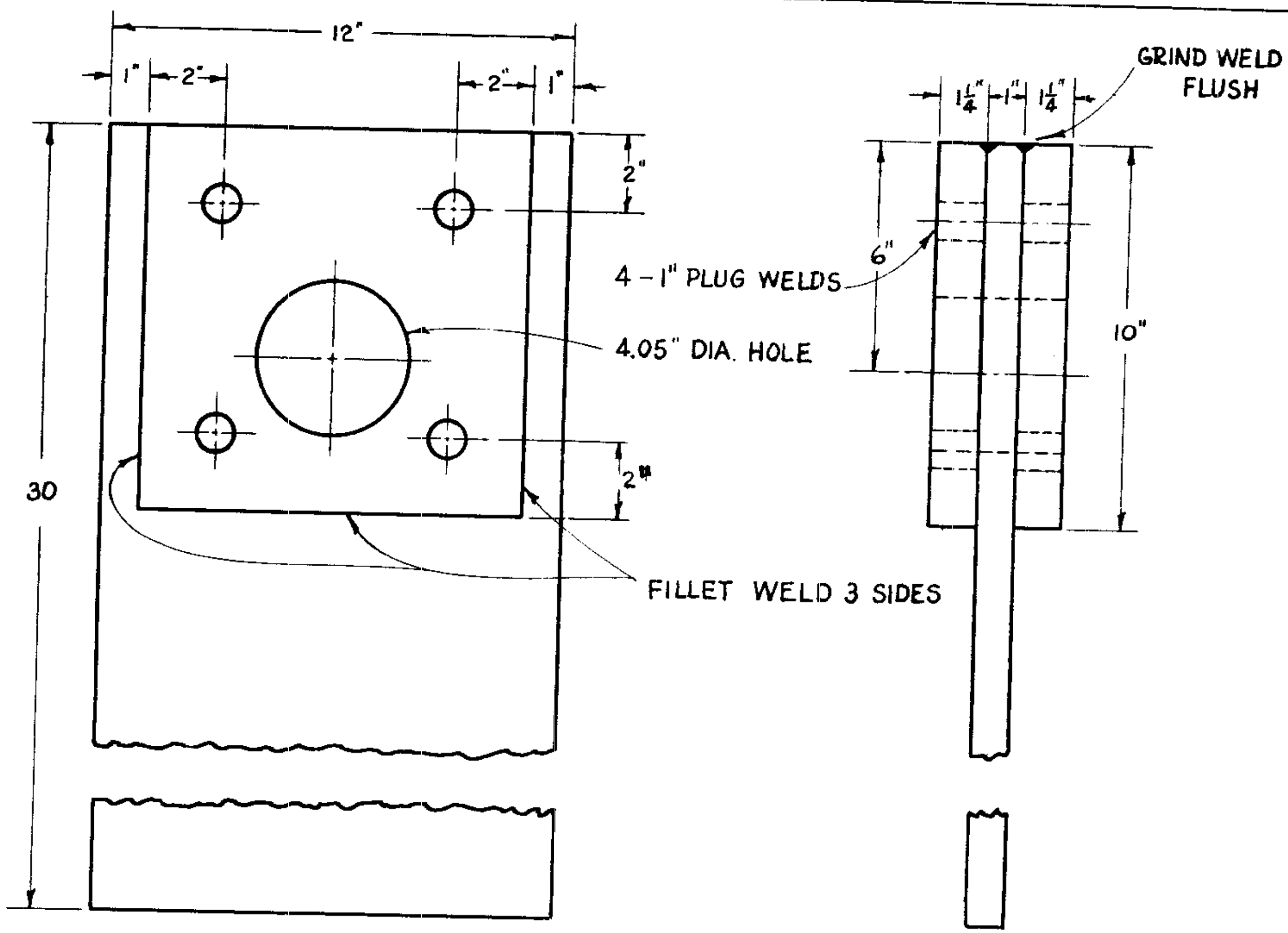


FIG. B-12 NITROGEN SIPHON



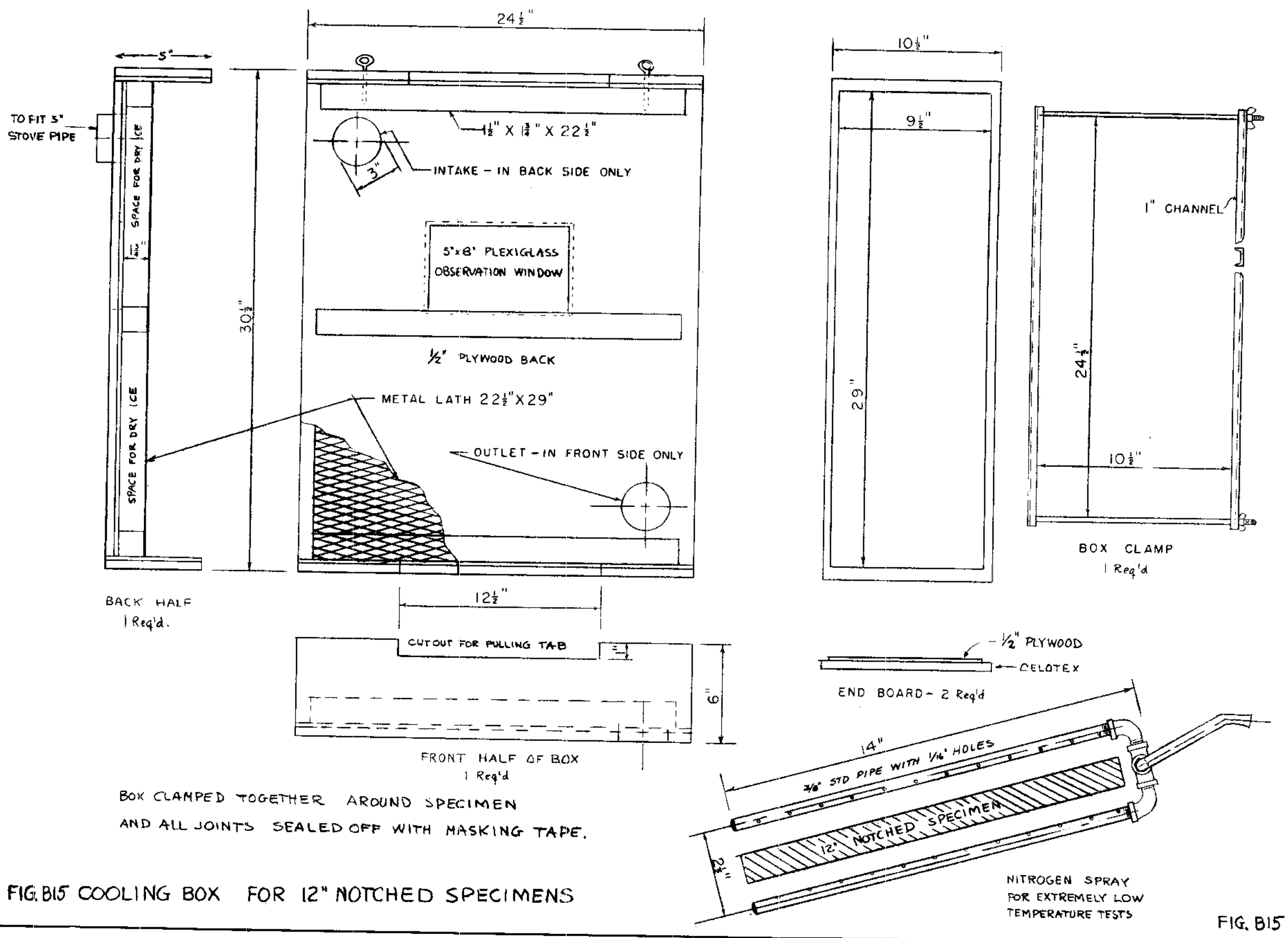
TWO TYPES OF EXTENSOMETERS USED FOR STRAIN MEASUREMENTS.

FIG. B-13



PLUG WELD 10"x10"x1¼" PLATES TO 12"x30"x1" PLATE.
FILLET WELD AROUND 3 SIDES, WELD ACROSS TOP SIDE & GRIND FLUSH.
DRILL 4.05" HOLE THRU 3 PLATES.

COLLEGE OF ENGINEERING UNIVERSITY OF CALIFORNIA BERKELEY, CALIFORINIA	PULLING HEADS FOR 12" NOTCHED SPECIMEN	SCALE	QUARTER	DATE	FIG-B14
		DR. BY	RFR	4/30/46	
		CK. BY	AB	5/2/46	



BOX CLAMPED TOGETHER AROUND SPECIMEN AND ALL JOINTS SEALED OFF WITH MASKING TAPE.

FIG. B15 COOLING BOX FOR 12" NOTCHED SPECIMENS

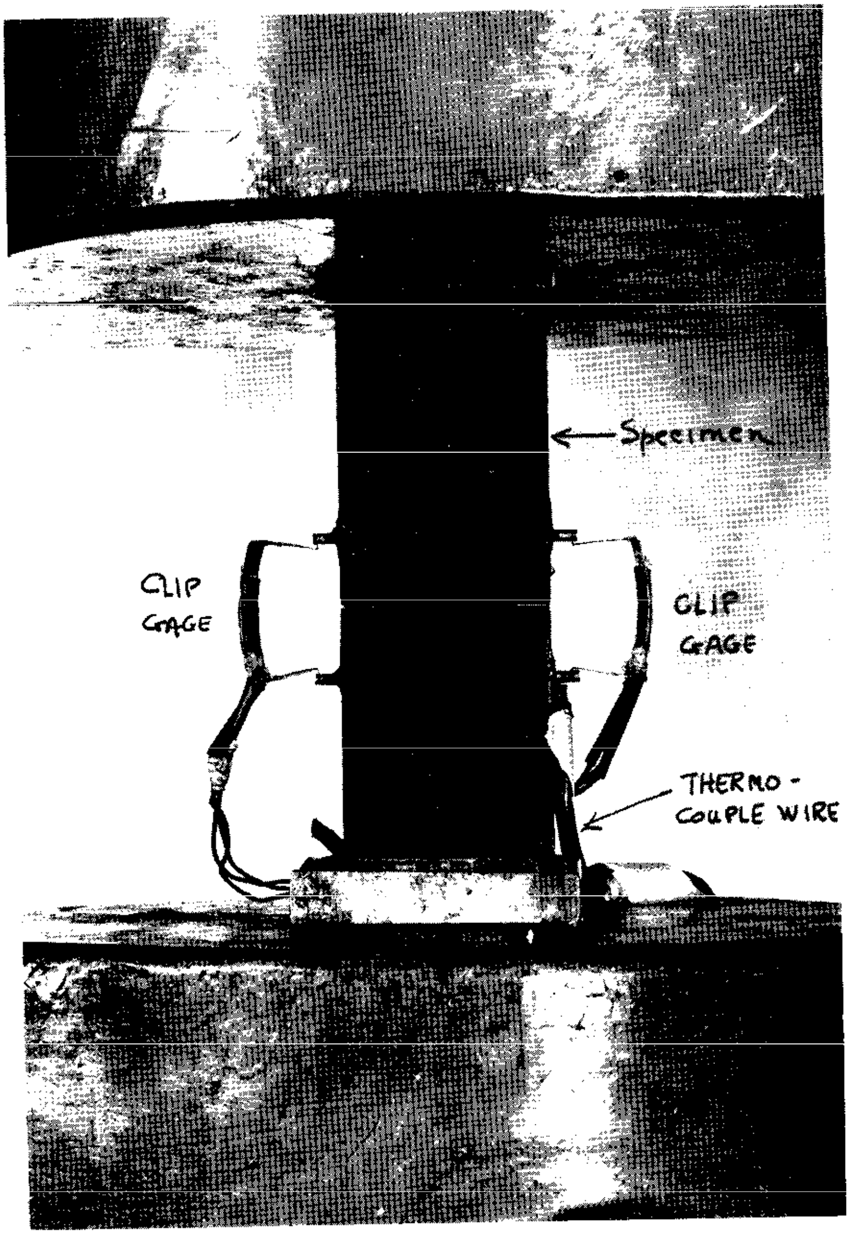


Fig. B16 - 3"Edge Notched Specimen in Testing Machine Showing Extensometer

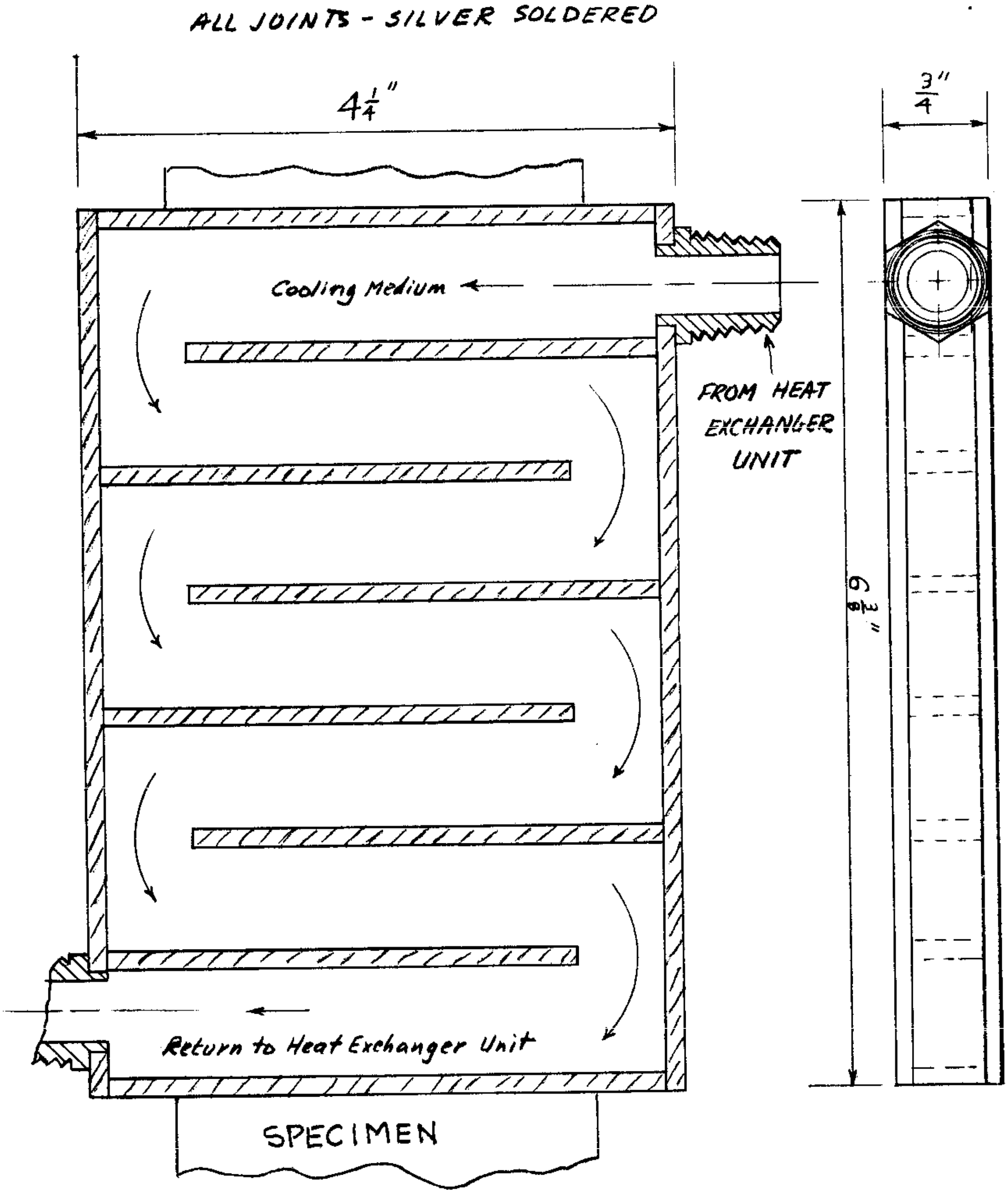


FIG. B17 - INTERNAL CONSTRUCTION OF THE COOLING UNIT FOR 3" EDGE NOTCHED SPECIMENS.

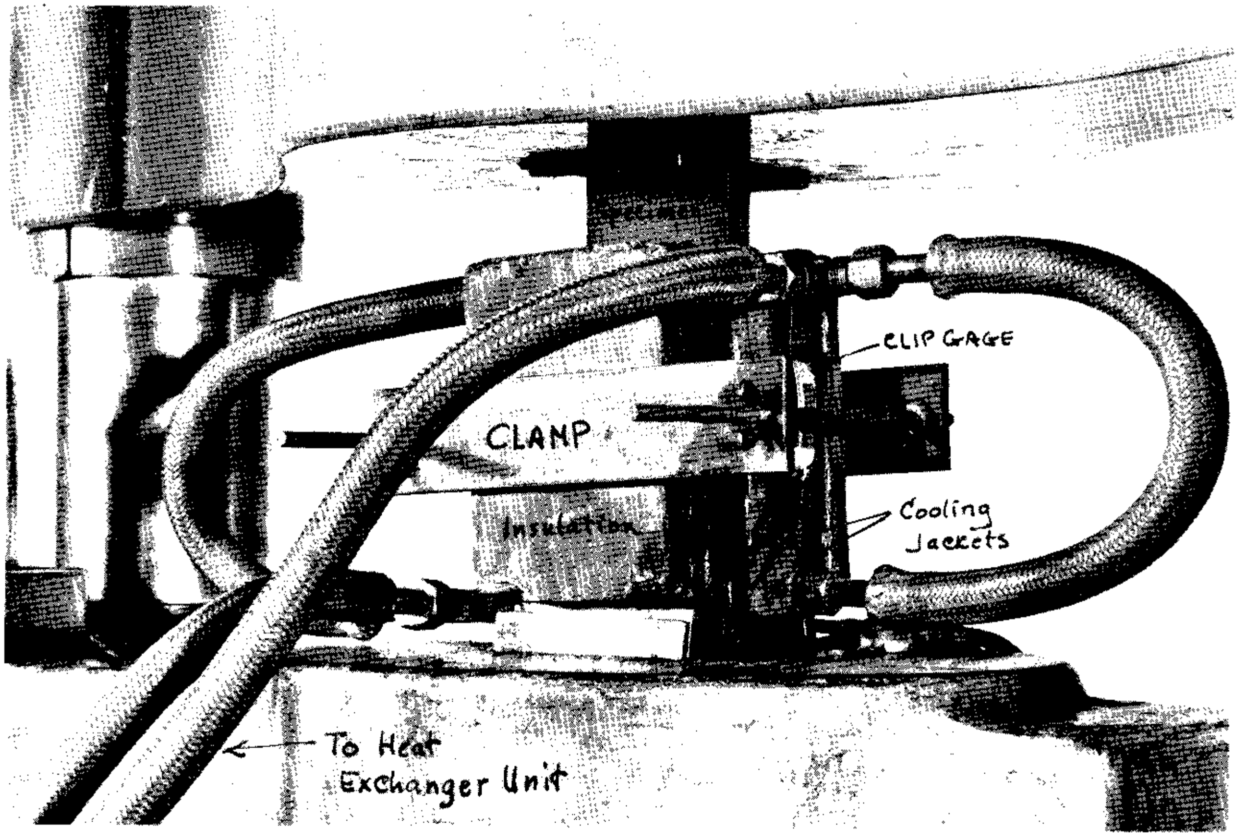
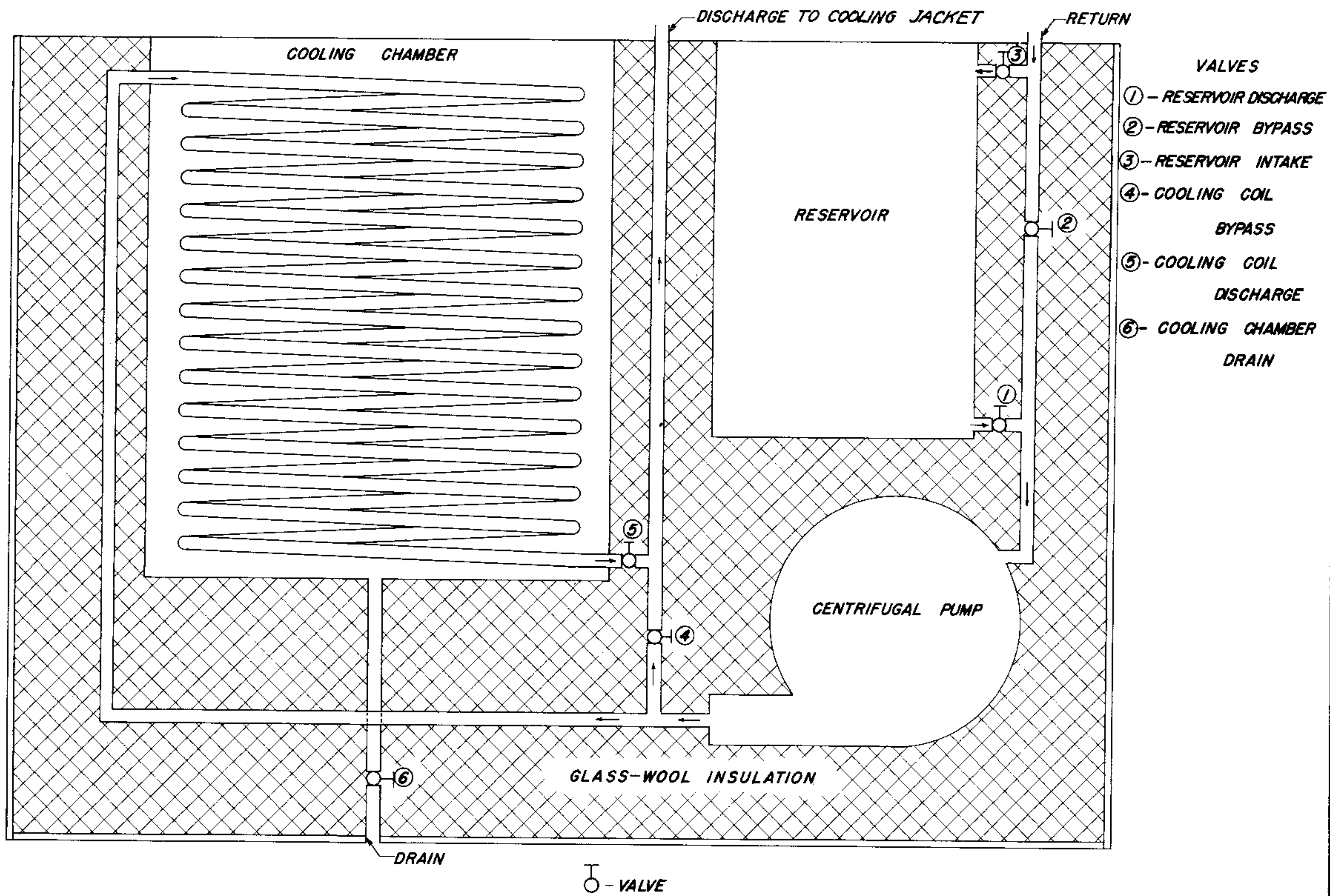


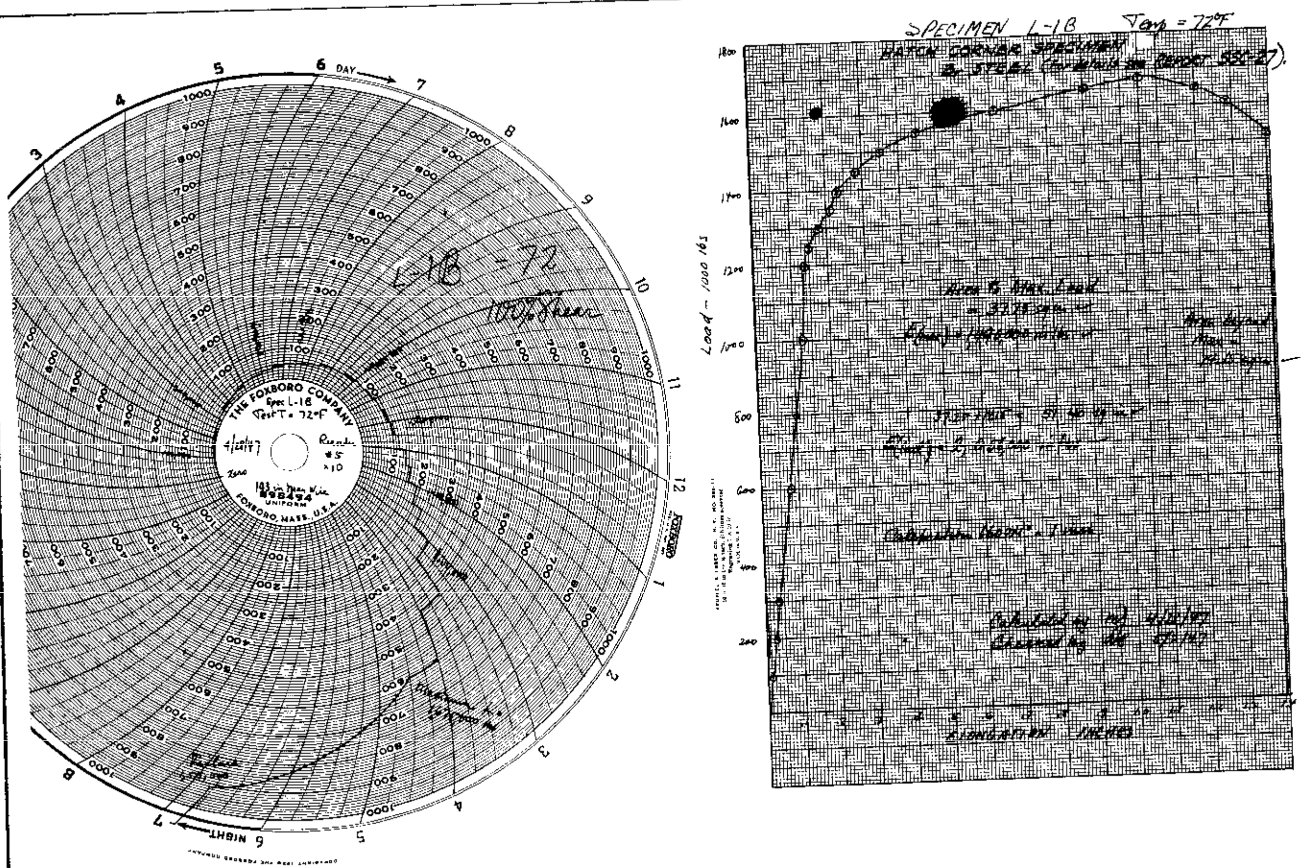
Fig. B18 - Cooling Unit Used for 3" Edge Notched Specimens



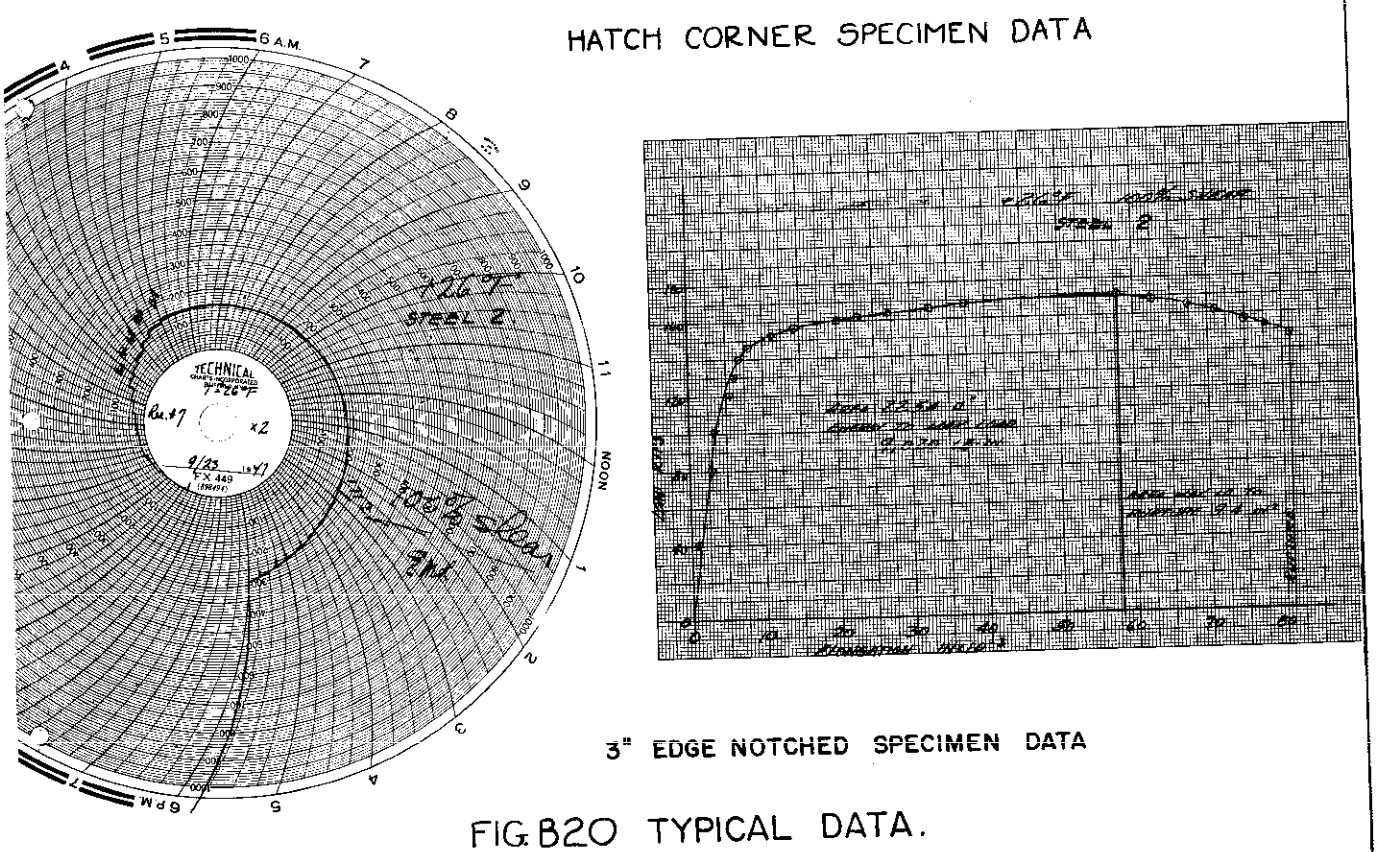
NOTE 1. FOR INTERNAL PRIMING USE RESERVOIR. IN USING RESERVOIR, OPEN ① AND EITHER ② OR ③ OR BOTH.

NOTE 2. FOR EXTERNAL PRIMING THE RESERVOIR IS NOT USED. IN THIS CASE CLOSE BOTH ① AND ③ AND OPEN ②.

PORTABLE HEAT-EXCHANGE UNIT (USED TO MAINTAIN CONSTANT TEMPERATURE ON TEST SPECIMENS.) FIG. B19



HATCH CORNER SPECIMEN DATA



3" EDGE NOTCHED SPECIMEN DATA

FIG. B20 TYPICAL DATA.