SSC-204

SIMULATED PERFORMANCE TESTING FOR SHIP STRUCTURE COMPONENTS

SHIP STRUCTURE COMMITTEE

1970

SHIP STRUCTURE COMMITTEE

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ADDRESS CORRESPONDENCE TO:
SECRETARY
SHIP STRUCTURE COMMITTEE
U.S. COAST GUARD HEADQUARTERS
WASHINGTON, D.C. 20591

1970

Dear Sir:

The need for obtaining full-scale ship design data, encouraged the Ship Structure Committee to undertake a project that would produce such data on a simulated basis. The project envisioned the design and construction of a large-scale test facility and validation of a test specimen under service conditions.

Herewith is a final project report entitled, "Simulated Performance Testing for Ship Structure Components".

Sincerely,

J. B. McCarty, Jr.
Capt., U.S. Coast Guard
Acting Chairman, Ship Structure
Committee

SSC-204

Final Report
to the
Ship Structure Committee

on

Project SR-169, "Simulated Performance Testing"

SIMULATED PERFORMANCE TESTING FOR SHIP STRUCTURE COMPONENTS

by

Robert Sherman

Southwest Research Institute
San Antonio, Texas

under

Department of the Navy
Contract NObs92294

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U.S. Coast Guard Headquarters
Washington, D.C.

1970

ABSTRACT

In this report, the results obtained from wide-plate tension tests undertaken for the purpose of simulating the full-scale performance of steel used in ships' hulls are presented. Information as to initiation and propagation of fast fracture in wide steel plates was first obtained through a series of nineteen tests performed on a newly developed wide-plate testing machine. The test material was the pressure vessel steel, ASTM A212 Grade B in 3/4-inch thickness. This information, and the techniques developed, were then applied to a total of eighteen tests using ABS Class C steel, having a thickness of 1-3/8-inch. All specimens were 10 feet wide and 3 were stiffened longitudinally. Test temperatures ranged from -100°F to a room temperature ambient of +75°F. A fatigue crack or a brittle bead was used as a crack initiator and large residual stresses were introduced.

In general, the tests indicated that, at sufficiently low temperatures, a fast fracture could be produced in ASTM A212 Grade B and ABS Class C steels if a sufficiently sharp initiation site was located within an area of relatively high applied and/or residual stress. Based on the results of the tests conducted, it is concluded that the ABS Class C material is not sensitive to fast fracture at temperatures well below service temperatures. Therefore, this material may be used to effect a fracture safe design for modern ship hulls.

CONTENTS

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I. INTRODUCTION

During the past two and a half decades, many investigations have been undertaken by both governmental and private laboratories in an attempt to explain the so-called brittle fracture phenomenon and to add information hopefully beneficial to the designer of modern, large size, heavily loaded structures. Though not unrecognized before this period, the severity of the problem was made graphically evident by the large number of catastrophic failures that occurred in welded steel merchant vessels during the early days of World War II(1) (2). Also, in ensuing years, added impetus has been provided by a host of technological advances, the success of which are often directly dependent upon the prevention of - or at least a knowledge of - this type of service failure. The effort discussed herein was directed toward providing the information needed to make it possible to design fracture safe ships.

To a large extent, the mechanism of brittle-like behavior has been qualitatively explained, first by Griffith(3) in his work concerning amorphous materials such as glass, then later by Irwin(4) and others on polycrystalline materials such as metals. For the former, the analytical treatment is quite simple and direct - and the results check reasonably well with experiment. For metals, however, the picture becomes considerably more complicated because of the inherent ability of a metal to plastically deform with a resultant redistribution of imposed strains. Analysis, therefore, becomes dependent on a knowledge of the behavior of the plastic zone. Factors such as size, shape and rate of growth of the plastic zone must be included and all are, in turn, dependent upon the particular material under consideration. Chemistry of the material, its metallurgical cleanliness and thermal treatment influences the toughness of the material which is the measure of a material's ability to withstand both initiation and propagation of fracture. For a given toughness, fracture will or will not occur depending on a host of other variables, such as the state of residual stress, type of load (static or dynamic), environmental conditions and design details. In short, the problem is extremely complex. A large number of parameters are involved and the interrelation between the parameters is not well established.

For the above reasons, much effort has gone into improving the metallurgical aspects of engineering materials and much progress has been made toward the improvement of toughness. Also, a great deal of work has been directed toward mathematically describing the conditions necessary for precipitation of fracture for both elastic and plastic conditions, see references 5 and 6*. In addition, many investigators have studied various means of determining material characteristics through the use of small scale tests such as the Navy Drop Weight Test(7), the explosion bulge test(8) and, perhaps the still most common, the Charpy-Vee notch impact test. Work has been accomplished on the correlation of small size specimen test results, Ref. 9, and additional effort, principally that of the University of Illinois, has been directed towards the performance of

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*For a comprehensive summary of other works, see the ASTM Special Technical Publications No. 381 and 410.

tests on large sized plate-type specimens. The University of Illinois work will be mentioned later in this report and will be discussed briefly in comparison with the results of the tests described herein.

In the present study, the objectives were to:

1) Develop a structural test that would simulate service behavior, particularly in regard to the levels of applied stress at which brittle fractures initiate.
2) Determine the requirements for brittle fracture propagation and for the arrest of a running brittle fracture.
3) Study the material structural behavior below the transition temperature to determine the stresses and crack length which the material will support before undergoing fast fracture.
4) Verify the reproducibility of the results within relatively narrow limits.
5) Attempt correlation of the test results with results obtained from smaller, well known, tests such as the Charpy-Vee notch and drop-weight tests.

The five objectives above were to be undertaken considering more than one type of test specimen and to include tests on more than one material thickness.

II. TEST MATERIALS

A. Exploratory Test Material

As stated in the Introduction, modern materials benefit greatly from improved techniques and quality control measures. Not only are modern materials made "stronger" from the standpoint of yield or ultimate strengths but, in general, they are less notch sensitive and, by virtue of a generally lower nil ductility temperature, are capable of greater energy absorption at service temperatures. These qualities imply an inherent non-susceptibility to rapid fracture. It was not known at the beginning of this program that fracture could even be initiated in the materials to be studied. Because of this situation and, to demonstrate the capability of the testing machine, it was decided to conduct some preliminary wide plate tests using a material generally considered to be fracture sensitive. Accordingly, the pressure vessel steel, ASTM A212 Grade B was chosen and commercially available mill stock, conforming to all applicable ASTM specifications, was selected and purchased. This material had a reported NDT of +40°F as measured by the Navy Drop Weight Test Procedure, and was in the standard normalized condition. Chemical analysis and mechanical properties are given in Table A-2 of Appendix A and a plot of the Charpy-Vee impact energy versus temperature is shown in Figure A-12, same Appendix.

Appendix A also contains a description of the nineteen tests performed on this material along with a summary and discussion of the ensuing results. Rapid fracture was effected, the capability of the testing machine was demonstrated and considerable insight was gained into the general requirements which could lead to fast fracture in the ABS Class C tests discussed in the following Section.

B. Material

At the conclusion of the exploratory tests on the pressure vessel steel ASTM A212 Grade B, a report was made to Advisory Group III, Ship Hull Research Committee, who recommended that testing be initiated on the ABS Class C ships' hull material. They also felt that information of most use would be generated by testing the 1-3/8" material which, by applicable specifications, would not require a normalizing treatment. Such plate, therefore, was purchased from stock-on-hand at the Avondale Shipyards, Inc. , New Orleans, Louisiana. The material chemistry and associated mechanical properties were determined and are as reported in Table 1 and Figure 1. The results of explosion bulge tests performed on the material are given in Appendix B, Figure B-9.

TABLE 1. CHEMICAL COMPOSITION AND MECHANICAL PROPERTIES OF THE ABS CLASS C TEST MATERIAL

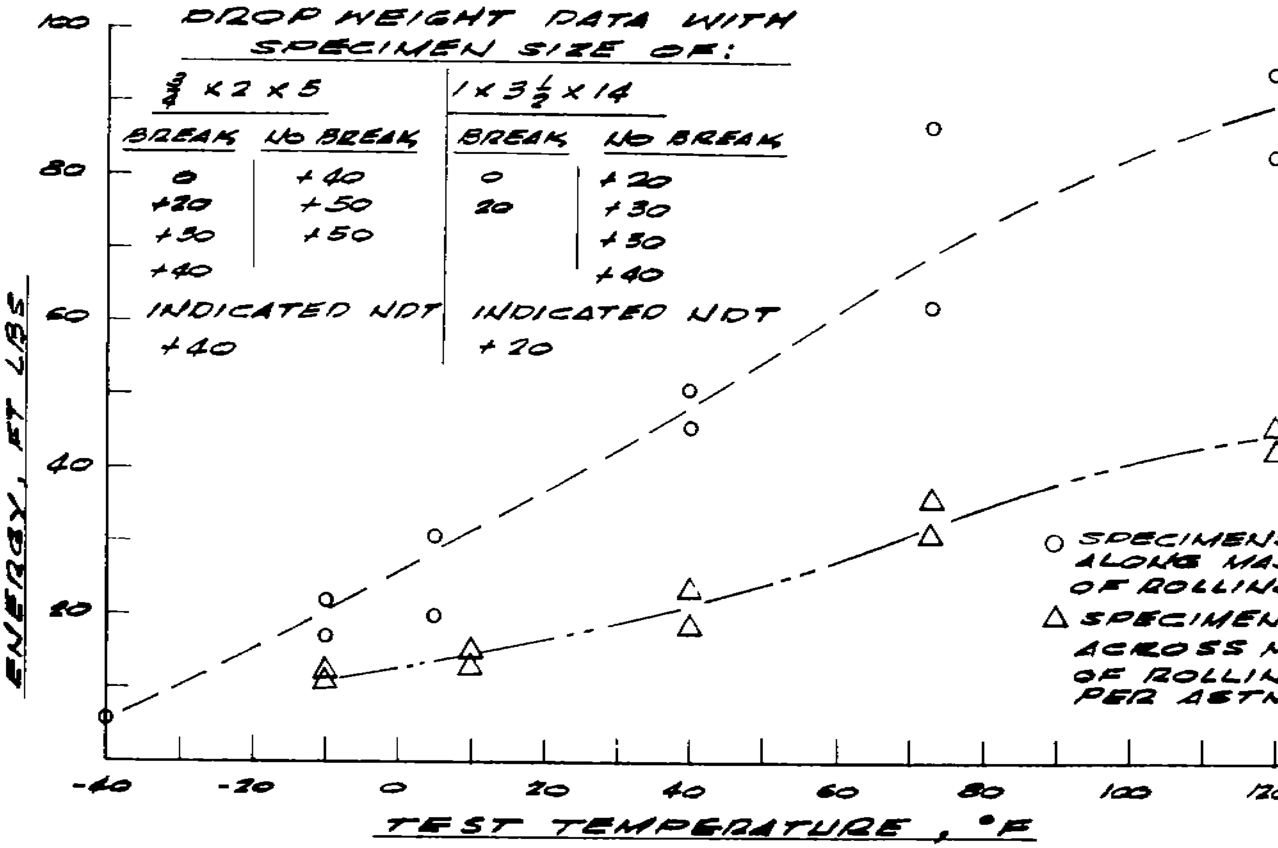
Material Form: 1-3/8-inch As Rolled

A. Chemistry

Carbon	0.19
Manganese	0.70
Phosphorus	0.011
Sulfur	0.009
Silicon	0.20
Aluminum	0.05

B. Mechanical Properties

	Longitudinal		Transverse
Ultimate Tensile Strength, psi	67,800		67,400
Yield Strength, psi, at 0.2% offset	35,300		35,000
Approximate Yield Strength, psi, apparent from large specimen tests		41,300	
Elongation, % in 8 inches	35.5		34.6
15 ft/lbs Charpy-Vee Transition Temperature, °F	-20		+10
Nil Ductility Temperature, °F, when estimated to be 60°F less than 50% FATT		+15	
Nil Ductility Temperature, °F, from Navy Drop Weight Tests		+20 to +40 depending on Specimen size	
Nil Ductility Temperature, °F, from Explosion Bulge Tests		+60	
ASTM Grain Size		5	



DROP WEIGHT DATA WITH SPECIMEN SIZE OF:

$\frac{3}{4}$ × 2 × 5		1 × $3\frac{1}{2}$ × 14	
BREAK	NO BREAK	BREAK	NO BREAK
0	+40	0	+20
+20	+50	20	+30
+30	+50		+30
+40			+40
INDICATED NDT +40		INDICATED NDT +20	

Fig. 1. Charpy Vee And Drop Weight Data For The ABS Class C Test Material

III. TEST PROCEDURE AND TEST RESULTS

A. Discussion of the ASTM A212 Grade B Exploratory Tests

As stated previously, one of the objectives of the program was to determine whether or not fast fracture could actually be initiated in full scale tests of plate material used in a modern day ship. The severity of defect required to trigger a fast fracture was unknown as was the influence of some of the obviously more important variables such as temperature, defect length and applied and/or residual stress. Material chemistry and fabrication history also play an important part, but the inclusion of all such facets was beyond the scope of this investigation. Therefore, it was decided to first establish the general requirements for fracture initiation by means of tests on an alloy felt to be more susceptible to rapid fracture, viz., the previously mentioned pressure vessel steel, ASTM A212 Grade B. The ensuing results would then be used as a guide for tests on the ships' hull material and emphasis therein could be directed towards repeatability and the effects of a variation in temperature and notch length. Appendix A contains a complete description of each test and the results of the tests.

The results may be summarized by noting that a very sharp ended defect was found to be a prime requirement for the occurrence of a brittle fracture. For instance, fracture did not result from a 12-inch central slot with ends sharpened by jeweler's saw nor from a test in which the specimen was subjected to arc strikes, gouges, slag, inclusions or porosity. Fatigue cracks, however, were a successful means of triggering fracture especially when a high residual tension stress was also present. Although the data showed a great deal of scatter, in most cases, an applied stress of 90 percent of yield or greater was required. This means, of course, that the material could not be classed as particularly notch sensitive. Also, a reduction in temperature had the expected effect of tending to lower fracture stress for a given defect length.

Crack arrest was a phenomena studied during the program, but in only a single case (Test A17) did a true arrest occur. In several other cases, distinct "pop-ins" (and, hence, momentary arrest) were noted but these were followed by complete fracture at a slightly higher load. Details of the test set-up and test procedures are given in Appendix A along with the overall test results. In all tests the specimen was welded to the attachment plates of the test facility after strain gages were installed. Cooling, if required by the test, was effected by placing narrow trays of dry ice over and below the plate surfaces until the desired temperature was reached. This could be easily varied by the simple expedient of raising or lowering of the trays, then waiting until the temperature was stable as indicated by thermocouples imbedded in upper and lower surfaces of the plate.

During the test, the load was slowly applied - the average test lasted about fifteen minutes - and strains were recorded on a continuous strip-type recorder. The temperature was checked periodically to insure that the specimen had not warmed during the test.

B. Discussion of the ABS Class C Fracture Tests

Based on the results of the exploratory tests performed on the ASTM A212 Grade B steel, a program for testing of the ABS Class C material was formulated. A fatigue crack was used as an initiation site and a determination of the effect of residual stresses was made. An attempt was also made to establish the repeatability of the test results. The effect of temperature on fracture was investigated and crack speed was measured. Test specimen variations included:

1) A weld along the longitudinal centerline of the specimen, parallel to the loading direction
2) A stiffener(s) parallel to the loading direction
3) Central and edge slots of various lengths.

Eighteen tests were performed on the ABS material, fifteen of which were of the plain plate configuration and three of a longitudinally stiffened version. These are discussed in detail in Appendix B. Eleven tests resulted in fracture completely across the 10-foot specimen width and, in addition, one test resulted in crack initiation followed by arrest within a distance of 18-inches. The latter test, however, was performed under rather extreme, but seemingly realistic service conditions, both as to residual stress and temperature. Residual stresses around the tip of the fatigue crack were deliberately maximized and the test was performed with the initiation site and material for a 2-foot distance immediately ahead of the fatigue crack at a temperature of -100°F. The balance of the specimen was kept at +70°F so that a crack, if initiated, would run into a warm area and, perhaps, arrest; this did occur as shown in Figure B-8.

In the stiffened plate tests, fracture initiated in two out of three cases and propagated across the plate and stiffeners alike. In both tests, the test temperature was below the lowest temperature determined (by drop weight tests) to be the material NDT*. In Test B15, no attempt was made to minimize residual stress and the gross section fracture stress was 21,500 psi. In the other, Test B16, a definite attempt was made to reduce residual stress and the fracture stress was higher (37,100 psi) although the test temperature was lower (-35°F) for B16 versus +10°F for B15.

In the tests in which a longitudinal weld was made along the specimen centerline, the principal difference in fracture was that the crack followed an irregular path across the specimen width rather than the usual, well defined, path normal to the loading direction. In addition, branch cracks at roughly 45 degrees to the main crack, were noted to the extent that in Test B10, a triangular section dropped from the side of the specimen opposite the initiation site. This may be seen in Figure B-5.

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*From the results of explosion bulge tests, the material NDT was +60°F.

The procedure for providing the fatigue crack initiation site for this series of tests was the same as used for the ASTM A212 Grade B exploratory tests. This consisted of welding into a cutout, made on one edge of the specimen, a slotted "patch" plate which contained a fatigue crack at the tip of the slot. The fatigue crack was generated by means of a hydraulically-supplied pull-release action which opened and closed the tip of the slot.

Residual stresses which, of course, accompanied the welding of patch into specimen, were varied by means of a change in patch geometry. For instance, when it was desired to minimize residual stress, extension members were welded to the patch before installation into the specimen and the resultant weld shrinkage (which gave rise to the residual stress) was then distributed over a greater length, hence with lesser unit strain and subsequent stress. The variations used in the individual tests and the resultant strains (converted to stresses) are discussed in the description of tests, Appendix B.

Temperature was varied by means of dry ice trays set above and below a section of the specimen in line with the direction of probable propagation of fracture. Temperature was sensed by thermocouples imbedded into the specimen and sufficient time for stabilization was allowed before loading. Generally, this was on the order of 1-1/2 to 3 hours depending on the desired decrease below room temperature conditions.

The measurement of crack speed was effected by means of crack wires which, when broken by the advancing fracture, would produce an unbalance of an electrical circuit, the output from which was recorded on a 14-channel Leach tape recorder. Fracture speeds, when measured, ranged from 4,000 - 5,000 ft/sec.

The data obtained from the tests on ABS Class C ships' hull material are summarized in Table 2 following and are discussed in greater detail in Section IV. In general, considerable scatter in the data exists. It is believed that this scatter can be attributed to the pronounced effect of residual stress (or strain) variations. Fractures, when they occurred, were at high levels of applied stress, considerably above those normally used in design. The fractures were basically flat with little evidence of shear lips and no indication of a thinning of the cross section.

Table 2. Tabulation Of The ABS Class C Test Results

Test No.	Date	Temp., °F	Length of the Patch Plate, In.	Load, Lb x 10^{-6}	Fracture ?	Avg. Stress, psi x 10^{-3} Gross Section	Net Section	% of Yield Strength Attained Across the: Gross Section	Net Section	K_I, psi $\sqrt{in}$ x 10^{-3}
B1	3-22-67	+40	12	6.65	Yes	40.3	42.4	97.5	102.6	196
B2	4-20-67	+40	8	5.28	Yes	32.0	33.7	77.5	81.7	156
B3	5-12-67	+40	8	3.90	Yes	23.6	24.9	57.2	57.2	115
B4	7-11-67	+35	12	5.73	No	34.7	34.7	84.0	84.0	--
B5	7-26-67	+40	24	6.18	No	37.5	39.4	90.8	95.4	--
B6	8-24-67	+40	120	6.80	No	41.2	43.3	99.7	104.9	--
B7	10-5-67	+10	120	7.55	No	45.8	48.1	111.0	116.7	--
B8	10-11-67	-35	120	6.90	Yes	41.8	44.0	101.2	106.5	203
B9	11-9-67	+10	120	7.10	Yes	43.0	45.3	104.1	110.0	209
B10	11-29-67	+10	120	6.50	Yes	39.4	41.5	95.4	100.4	191.5
B11	12-14-67	+5	12	4.10	Yes	24.8	29.2	60.0	70.7	209
B12	1-9-68	+10	--	3.78	Yes	22.9	25.4	55.5	61.6	101
B13	1-25-68	+15	--	5.27	Yes	31.9	45.7	77.2	110.8	250
B14	3-4-68	+40	120	6.95	No	38.3	40.1	92.8	97.1	--
B15	4-15-68	+10	120	3.72	Yes	20.5	21.5	49.6	52.0	99.5
B16	5-22-68	-35	120	6.73	Yes	37.1	38.9	89.8	94.3	180
B17	8-20-68	+10	120	6.80	No	41.2	43.5	100.0	105.0	--
B18	9-9-68	-100	12	3.10	No	18.8	19.8	45.3	47.9	--

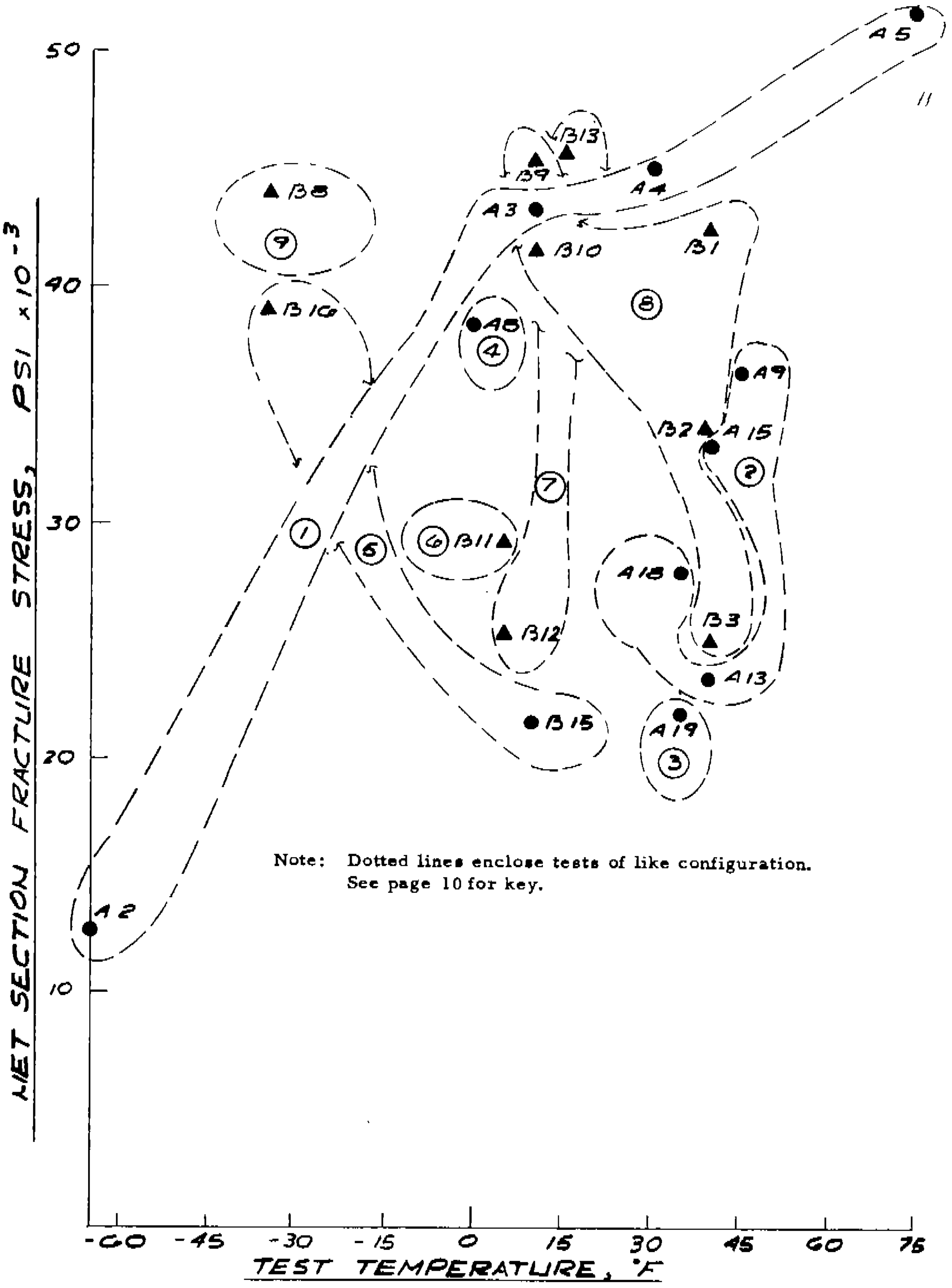
Note: All tests performed on specimens of 10 x 10 foot planform. Material thickness and form: 1-3/8-inch as-rolled plate.

IV. ANALYSIS OF THE RESULTS

Of the thirty-seven tests which have been described in the preceeding pages, ten performed on the pressure vessel steel ASTM A212 Grade B and eleven performed on the ABS Class C ships' hull material resulted in fracture. This is not a sufficient number to constitute a statistical sampling and, in addition, a large amount of scatter was present in the data. Certain consistencies, however, are apparent and it is felt that certain generalizations can be made. For instance, repeatability does exist to the extent that fracture at a temperature near the NDT may consistently be induced if an attempt is made to provide a sharp initiation site (such as a fatigue crack) located in the presence of a high residual strain field. Conversely, if either of the above requirements is purposely minimized, fracture at a temperature near the NDT consistently does not occur. Also, particularly for the ABS material, a stress significantly greater than normally used in design must be superimposed upon the residual stress (strain) field before fracture is likely to result. This, of course, is an ideal situation from the standpoint of the designer who, generally, is using design stresses considerably below the yield strength of the material.

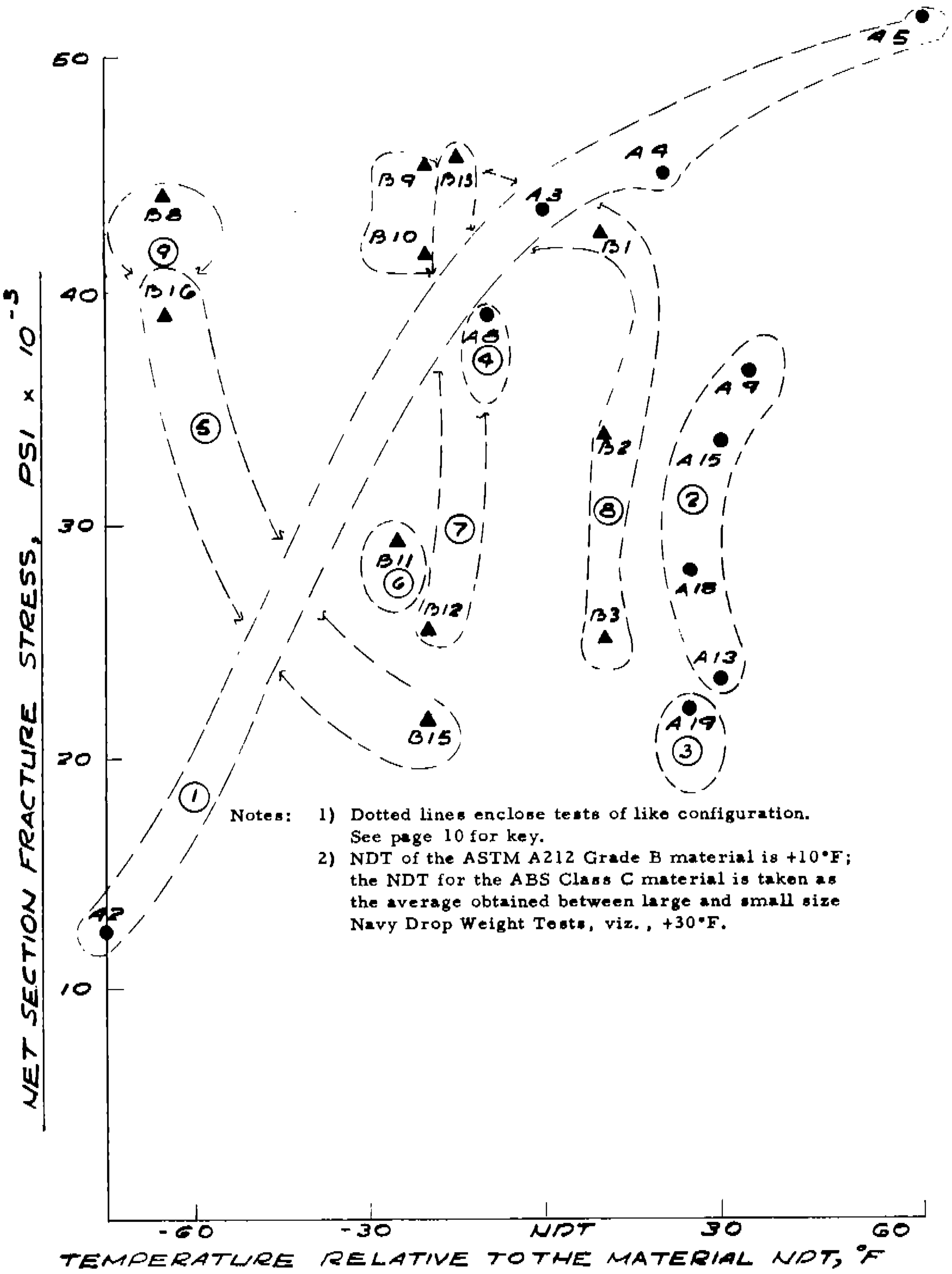
As mentioned, scatter is present in the results to the extent that specific correlation between individual tests does not appear to exist. This is also true with respect to correlation with the results of conventional small scale tests but, in either regard, it is to be remembered that the sampling is very small. Figures 2 through 12 present the data. As noted in these figures, the dotted lines encircle tests of like configuration within a given test material and are numbered according to the following key. ● is the A212 and ▲is the ABS materials, respectively.

1 Specimens with 40-inch central slot, brittle weld beads each end, Tests A2 - A5, inclusive.
2 Specimens with 5-1/2-inch edge slot plus 1/2-inch fatigue crack, Tests A9, A13, A15 and A18.
3 Single specimen, Test A19, with 12-inch central slot, fatigue crack each end.
4 Single specimen, Test A8, with wedge-induced crack 10-inches in length.
5 Stiffened specimens with 5-1/2-inch edge slot plus 1/2-inch fatigue crack, Tests B15 and 16.
6 Single specimen, Test B11, with 17-1/2-inch edge slot plus 1/2-inch fatigue crack.
7 Specimens with central slot of 2a = 12 inches, Test B12, and 2a = 36 inches, Test B13.
8 Specimens with 5-1/2-inch edge slot plus 1/2-inch fatigue crack, Tests B1, B2, B3, B9 and B10.
9 Single specimen, Test B8, with 6-inch edge slot plus 1-inch brittle bead.



Note: Dotted lines enclose tests of like configuration.
See page 10 for key.

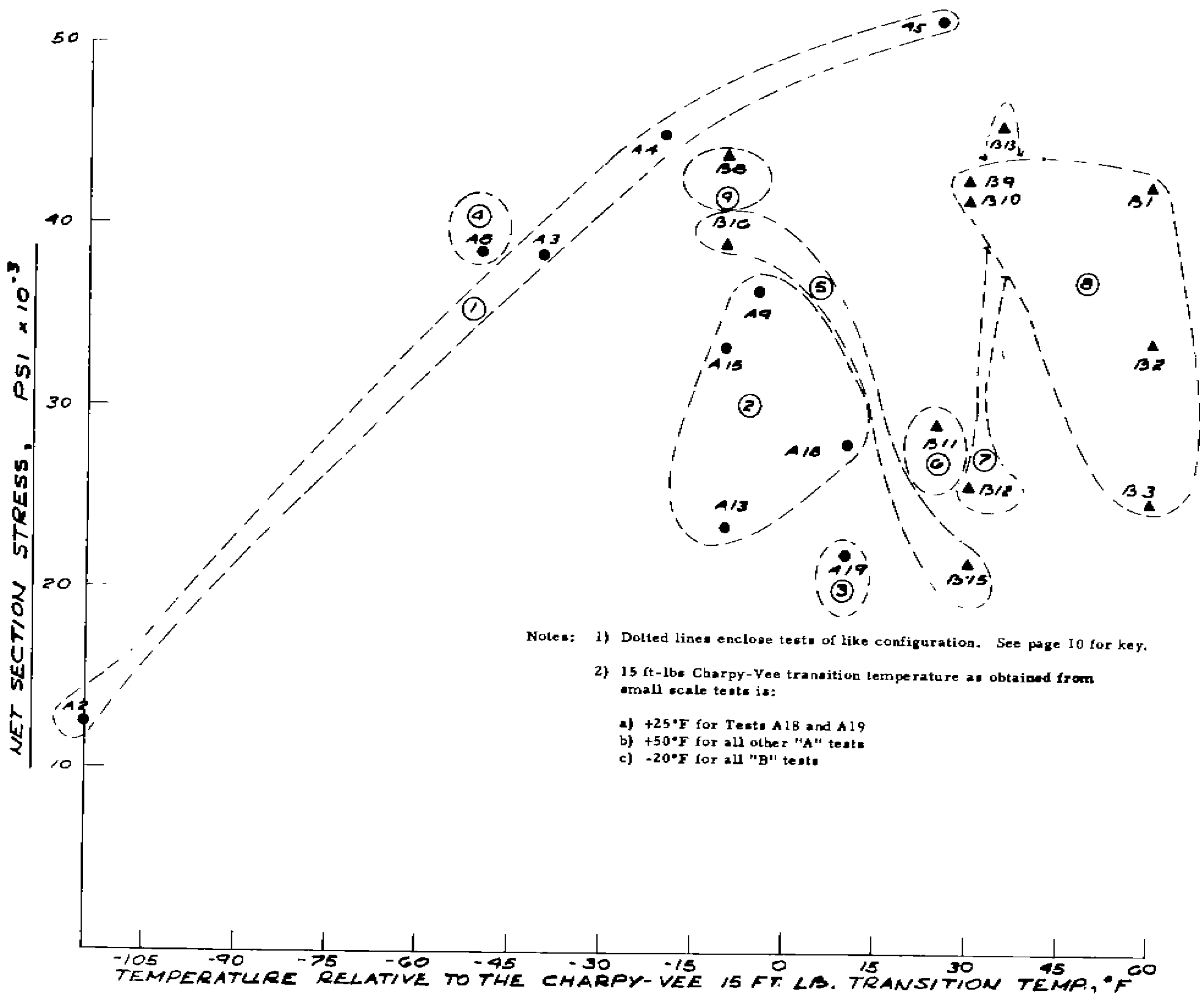
Fig. 2. Net Section Fracture Stress in Relation to Test Temperature.



Notes: 1) Dotted lines enclose tests of like configuration. See page 10 for key.

2) NDT of the ASTM A212 Grade B material is +10°F; the NDT for the ABS Class C material is taken as the average obtained between large and small size Navy Drop Weight Tests, viz., +30°F.

Fig. 3. Net Section Fracture Stress in Relation to the Material NDT.

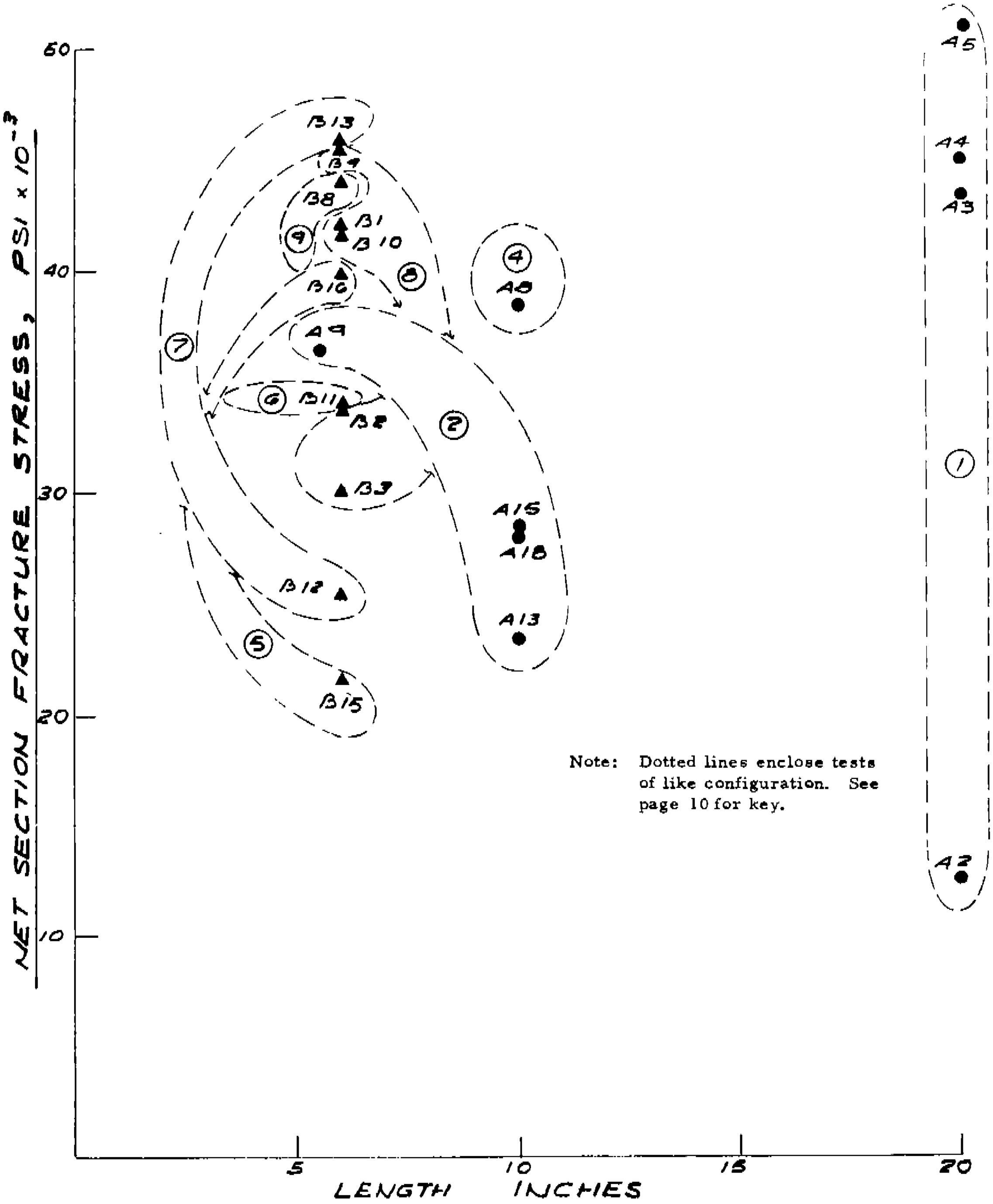


Notes: 1) Dotted lines enclose tests of like configuration. See page 10 for key.

2) 15 ft-lbs Charpy-Vee transition temperature as obtained from small scale tests is:

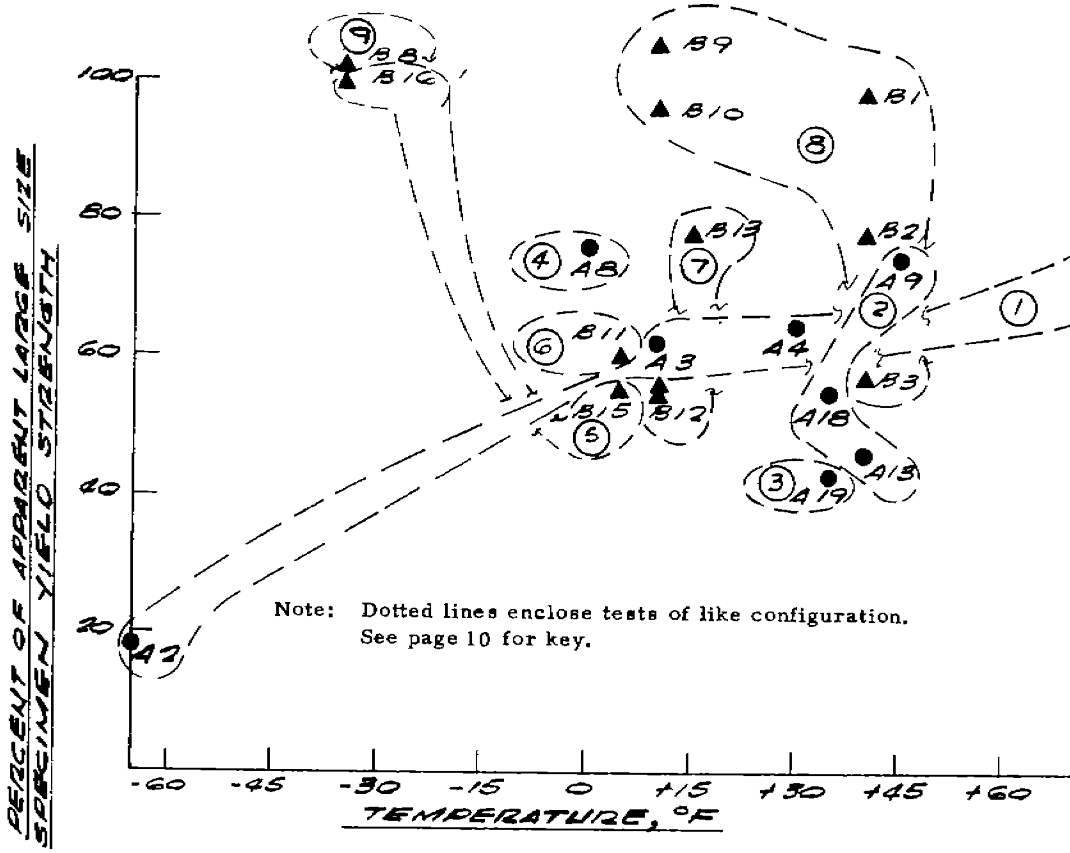
a) +25°F for Tests A18 and A19
b) +50°F for all other "A" tests
c) -20°F for all "B" tests

Fig. 4. Net Section Fracture Stress In Relation To The 15 Ft.-Lbs. Energy Charpy-Vee Transition Temperature.



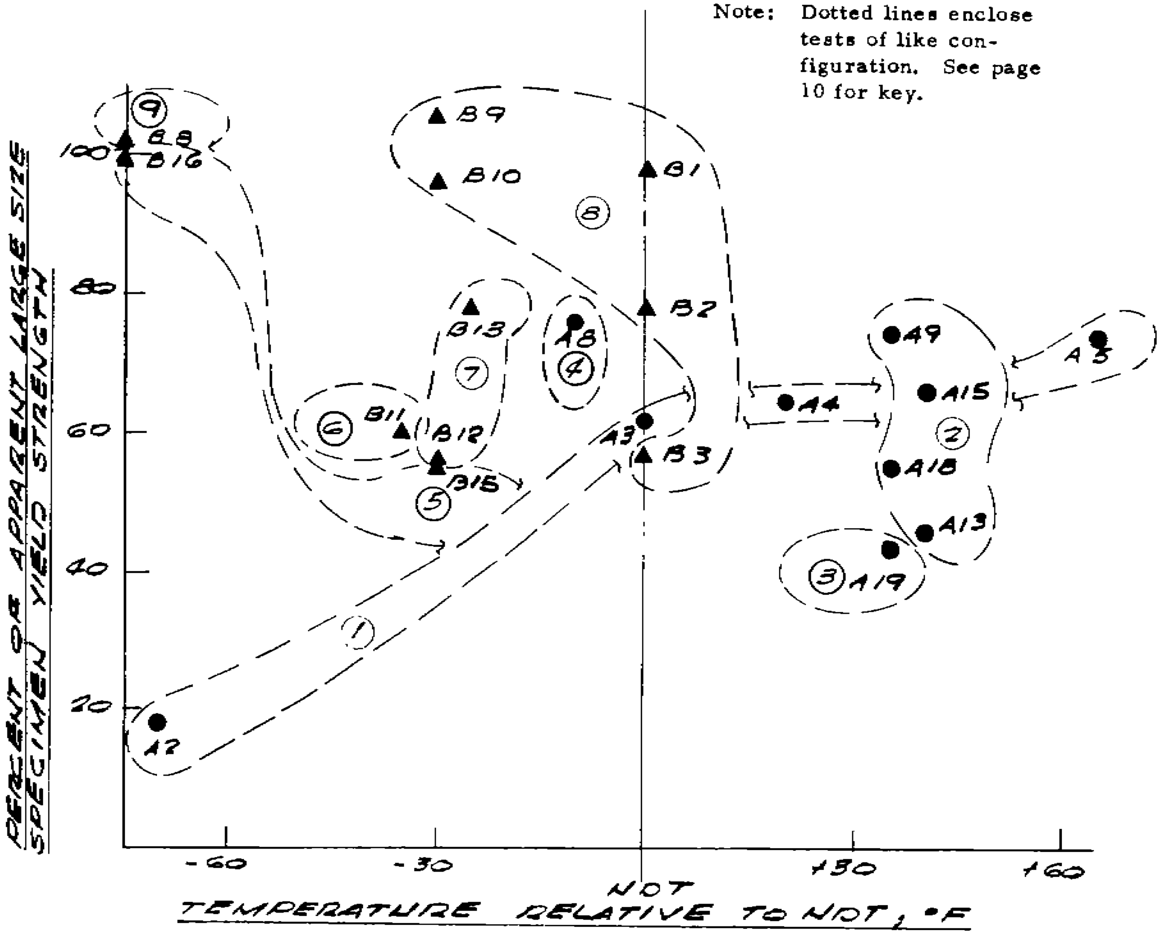
Note: Dotted lines enclose tests of like configuration. See page 10 for key.

Fig. 5. Net Section Fracture Stress in Relation to Defect Length.



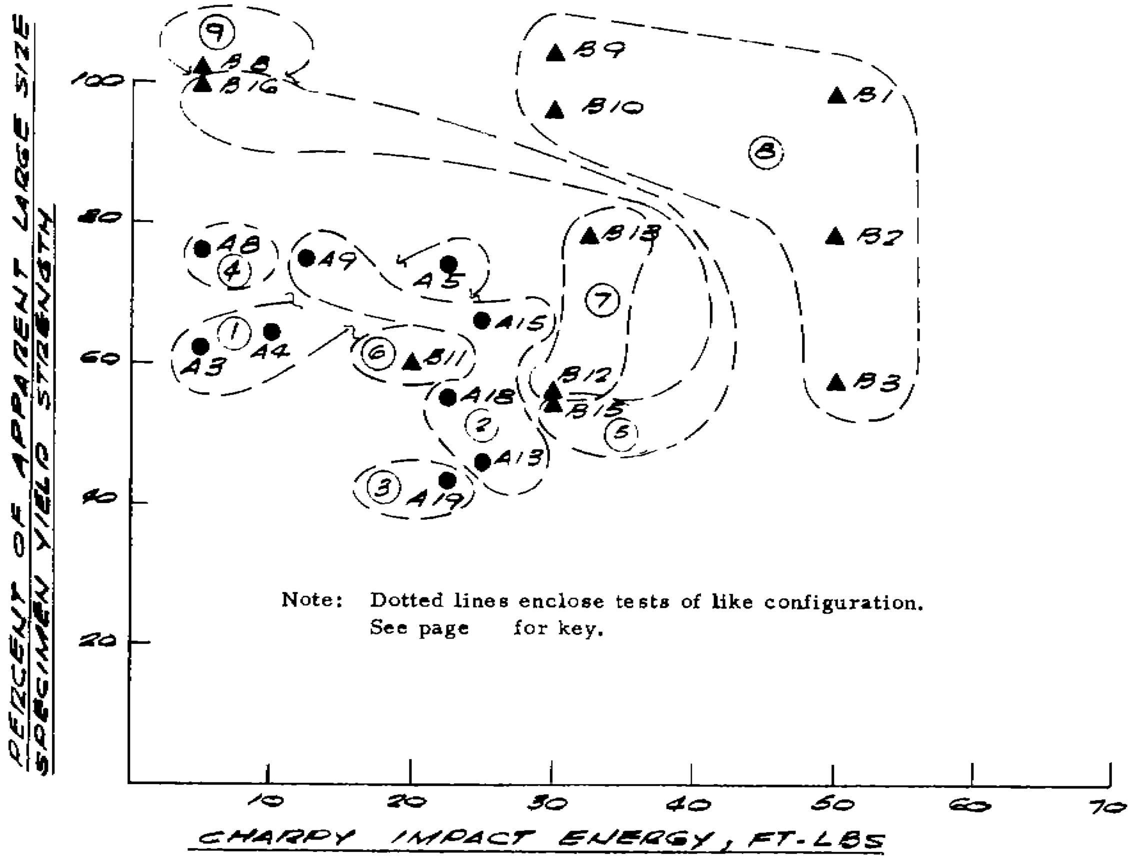
Note: Dotted lines enclose tests of like configuration. See page 10 for key.

Fig. 6. Percent Of Material Yield Stress Attained Before Fracture In Relat
To Specimen Test Temperature.



Note: Dotted lines enclose tests of like configuration. See page 10 for key.

Fig. 7. Percent Of Material Yield Stress Attained Before Fracture In Relation To The Material NDT.



Note: Dotted lines enclose tests of like configuration.
See page for key.

Fig. 8. Percent Of Material Yield Stress Attained Before Fracture In Relation To The Charpy-Vee Impact Energy Measured At The Specimen Test Temperature.

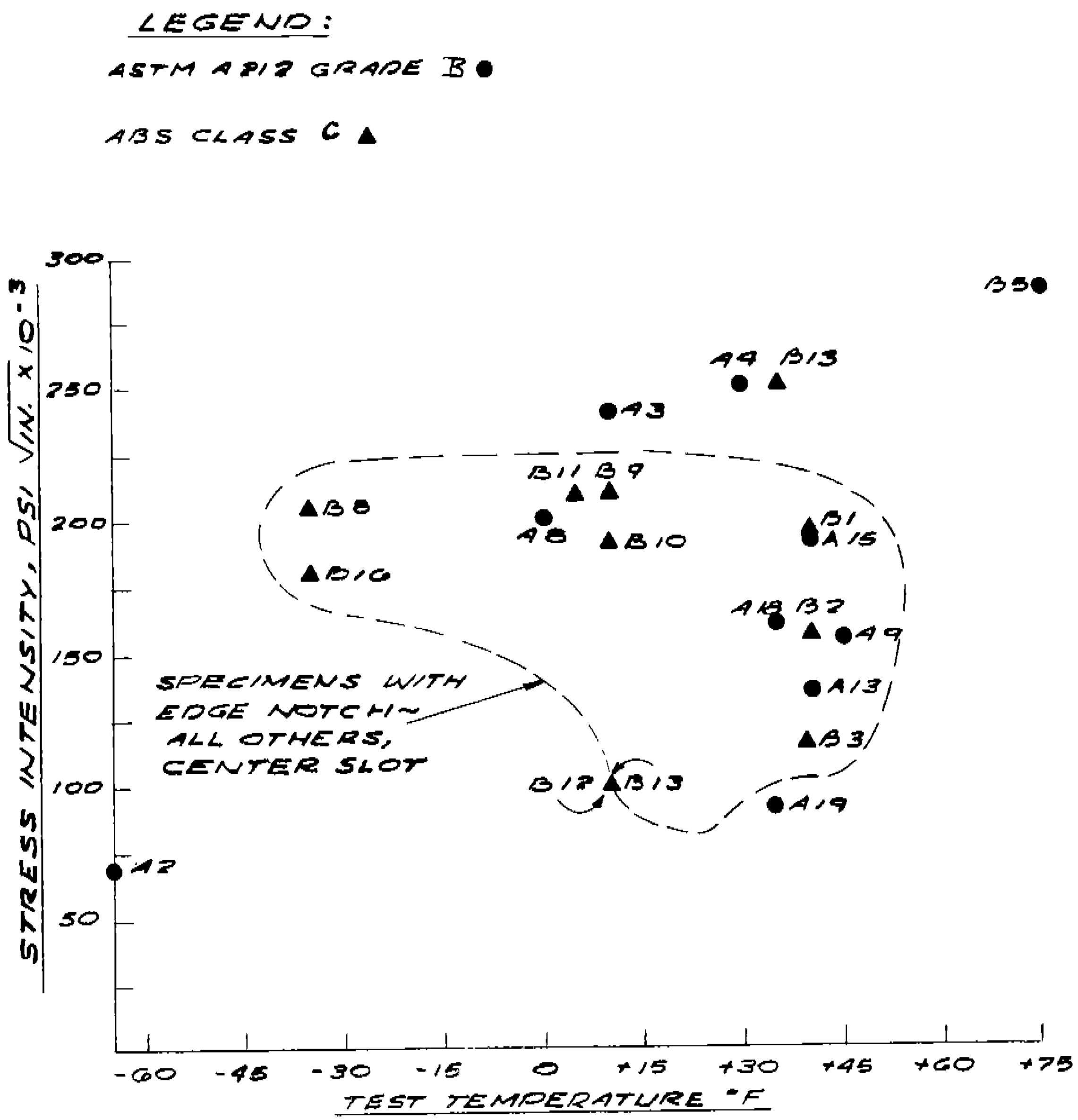


Fig. 9. Stress Intensity at Fracture in Relation to Temperature.

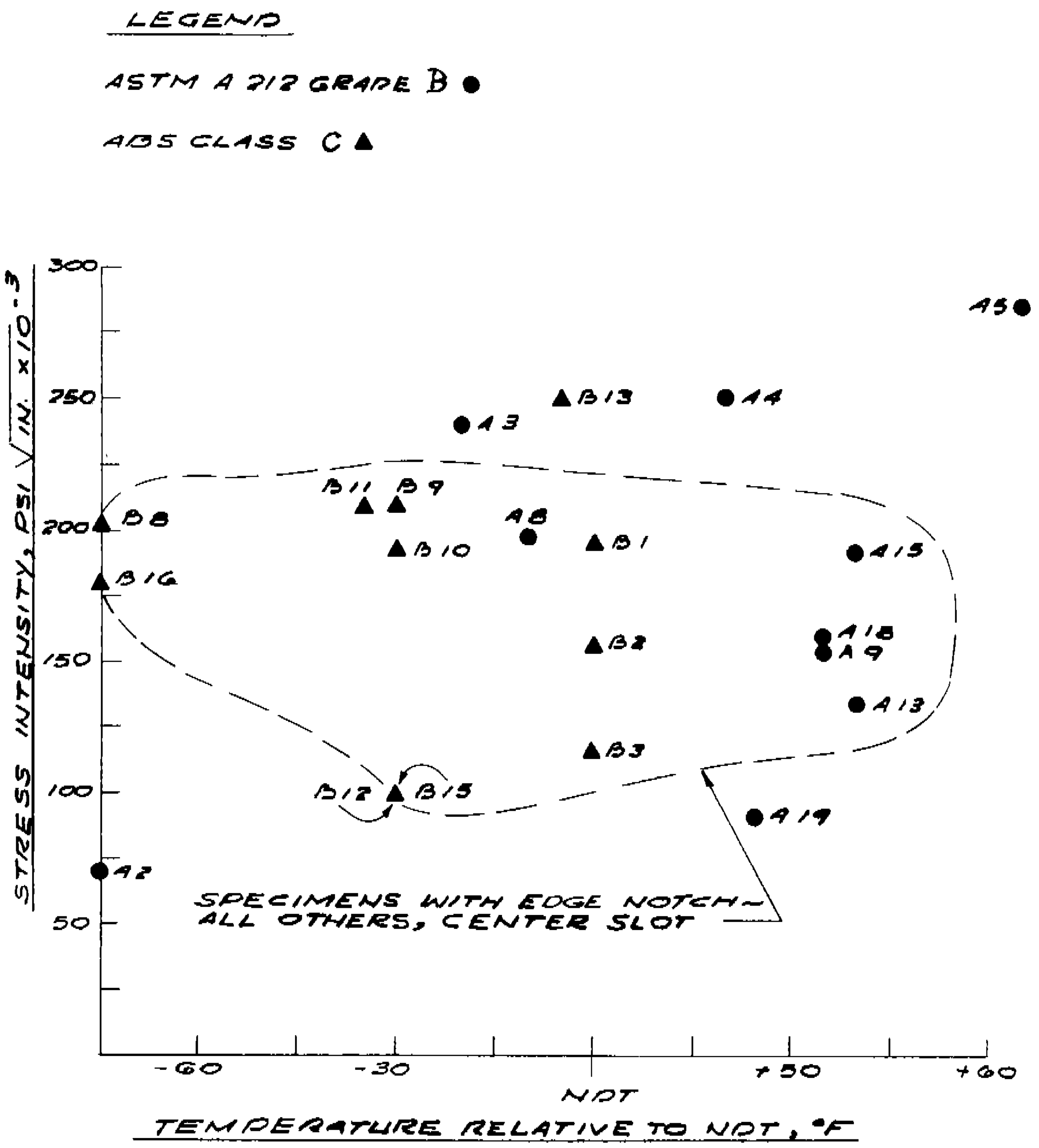


Fig. 10. Stress Intensity at Fracture in Relation to Material NDT (NDT Measured by D. W. T.).

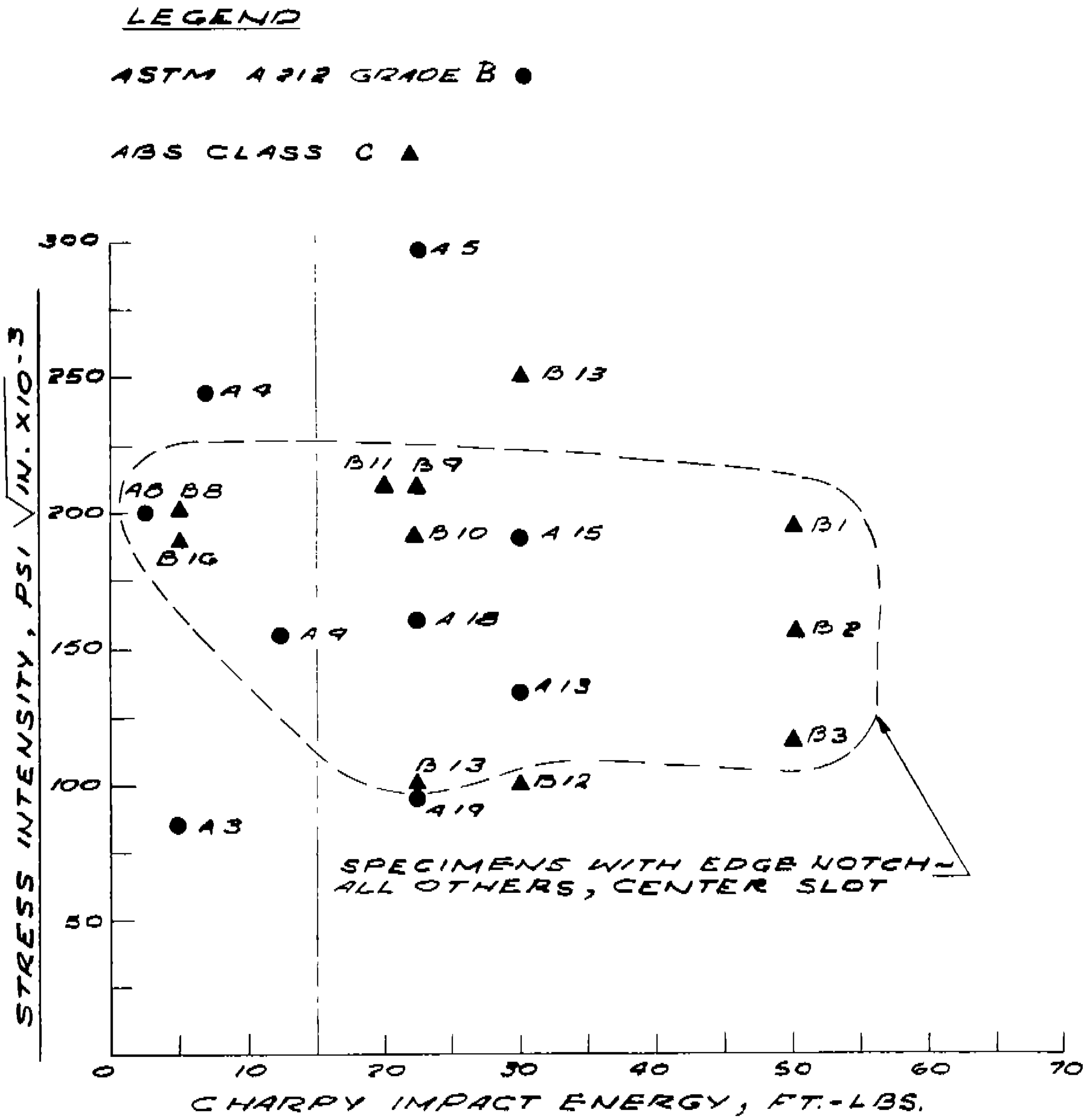
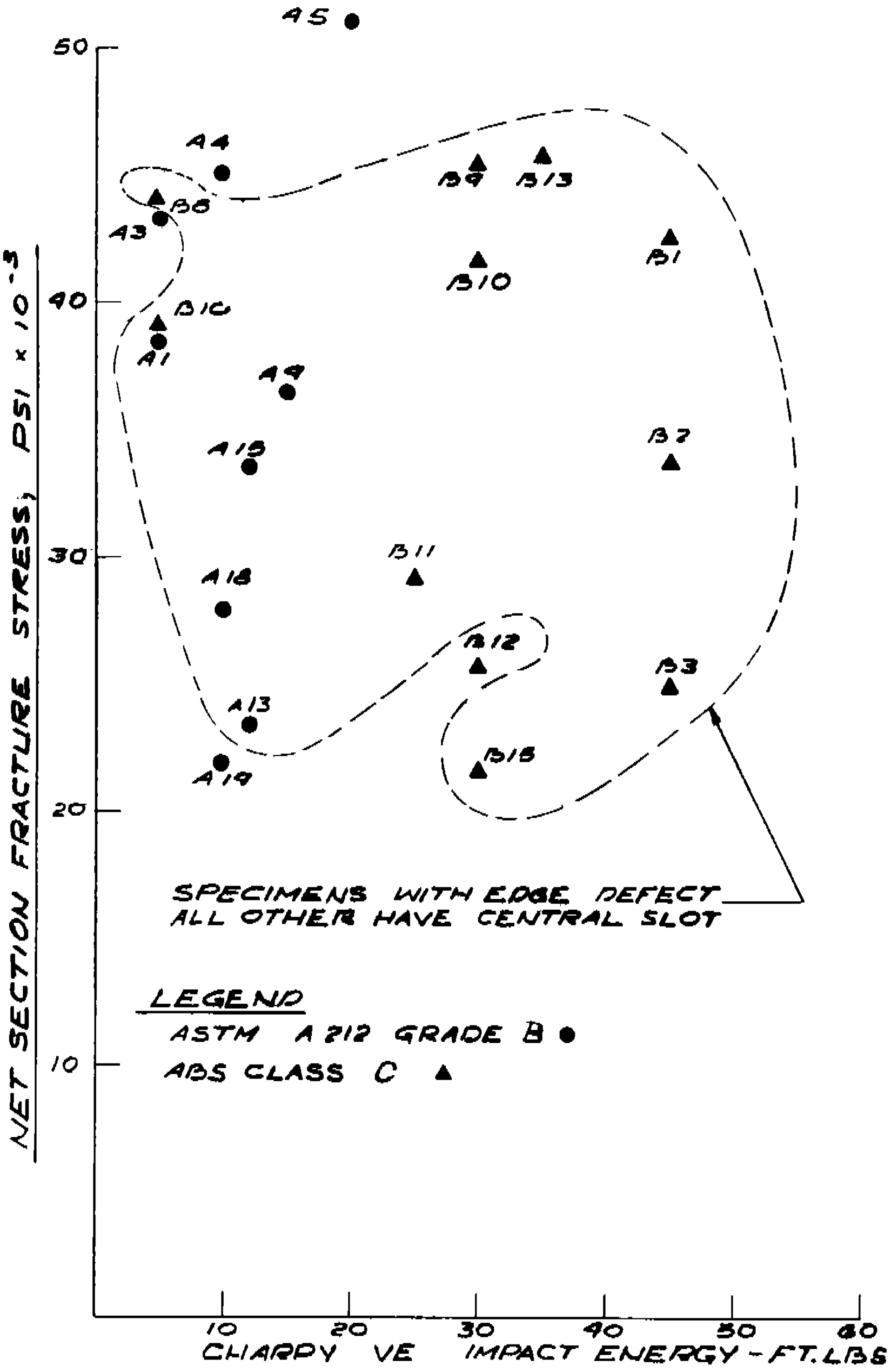


Fig. 11. Stress Intensity in Relation to Charpy Impact Energy Measured at Specimen Test Temperature.



SPECIMENS WITH EDGE DEFECT
ALL OTHER HAVE CENTRAL SLOT

Fig. 12. Net Section Fracture Stress in Relation to Charpy-Vee Impact Energy Measured at Specimen Test Temperature.

V. COMPARISON WITH OTHER WIDE PLATE TEST RESULTS

The effort discussed herein is but one of many concerning the brittle-like behavior of wide plates subjected to tension and it is therefore of interest to compare the results obtained with those as determined by others. Of particular interest, and perhaps the most direct in relation, is the work performed at the University of Illinois and reported, Ref. 10 thru 13*. These tests, though of narrower width, i. e. , 72" versus the 120" width used for this study, afford some basic common generalizations, the most important of which is that a residual tensile stress was found to be an aid to fracture initiation. The corollary, i. e. , that residual compression retards initiation and then slows fracture once fracture is effected, was not demonstrated in the present investigation because the weld induced residual stresses were always tension. Another similarity was the fracture appearance. In the present investigation, the fractured surface was always rough normal to the surface of the specimen and characterized by the familiar chevron pattern. Shear lips, when they occurred, were invariably short in length and thinning of the cross section was not visible. These features, in general, seem to correspond quite well with the University of Illinois fracture work. Fractures produced in this investigation propagated at about the same speed and, as in the University of Illinois tests, dropped off towards the unnotched side of the plate.

Another similarity between the two groups of tests concerns the departure of the fracture path from a straight line upon the introduction of a weld transverse to the probable path. For instance, in two unstiffened cases which also incorporated a centerline weld, near fragmentation resulted. In one case a large triangular area dropped completely from the specimen. In contrast, however, it is interesting to note that in two tests involving stiffened plates, such was not the case; instead, the fracture propagated straight across the specimen and did not deviate upon approaching a stiffener.

Because of material differences and differences in crack initiator geometry, no common basis for comparison of the data generated in the course of this investigation with that of the University of Illinois work exists. In the latter work, initiation was by means of a saw cut extended at the ends by further sawing with a jeweler's saw; in this investigation, the much sharper, and therefore more severe, fatigue crack was used. Also, as mentioned before, the specimen was wider and the investigation was confined to two specific materials, viz. , ASTM A212 Grade B and ABS Class C hull material; these were not tested at the University of Illinois.

In regard to the Japanese tests described in Ref. 15, these are of considerable interest but are not directly comparable to those of this investigation because of the smaller specimen size of about 18 x 20 inches by 0. 8-inch in thickness. They are mentioned mainly to call attention to the fact that the pressed-notch technique was successfully used and that crack speed was found to increase with decreasing temperature and/or level of applied average stress.

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*This work is summarized, Ref. 4 and again, with additional work by the University of California, Esso Research, DTMB and others including some Japanese tests in Ref. 15.

VI. CONCLUSIONS

A. Exploratory Tests on the ASTM A212 Grade B Material

It is apparent from the test results that fast fracture of the ASTM A212 Grade B material can occur at temperatures above the material NDT provided a fatigue crack resides within an area subjected to a relatively high stress field made up us residual and/or applied stress. Given these requirements, the fractures which resulted during the test program occurred under applied gross section stresses ranging from, approximately, 40 to 75 percent of material yield strength. This is a rather wide variation which, it is felt, can be accounted for only in part by changes in notch length or test temperature. It is believed that the principal source of scatter results from differences in the intensity of residual stress produced by the welding. Such reasoning, though somewhat speculative, results from a consideration of the following:

1) Although the central slot lengths for Tests A4 and A19 were 40 and 12-inches, respectively, fracture occurred at a gross section stress of 30,000 psi for Test A4 and but 19,800 psi for Test A19. There was, however, a five degree difference in test temperature, but it is not felt that the five degree difference in temperature accounts for the approximately 10,000 psi difference at which fracture took place.
2) Two tests, of identical configuration, A13 and A15, were performed at +40°F; both resulted in fracture, but at quite different gross section stresses, namely, 21,300 and 30,600 psi, respectively. In addition, Test A12, though identical in all outward respects to A13 and A15, did <u>not</u> result in fracture. Obviously, a portion of this variation could be attributed to material differences, but it is felt that such differences, in themselves, are insufficient to explain the entire range of fracture stress variation.
3) In Tests A16, A17 and A18, only one fracture resulted although all specimens were ostensibly identical. In the test in which fracture did result (Test A18), the gross section fracture stress was low, particularly so when it is noted that the specimen load direction was parallel to the major direction of loading. Presumably then, if all things are equal except for a 5°F lower test temperature, the fracture stress of A18 would exceed that for Tests A13 and A15; it did, by a small amount (25,500 vs. 21,300 psi) for A13 but not for A15.

It is also apparent from the test results that the effect of a change in test temperature is, as would be expected, to lower fracture stress if the temperature is lowered and to raise fracture stress if the temperature is raised. This is clearly shown by the trend established during Tests A2 - A5, inclusive and by the fact that Tests A10, A11 and A14 did not result in fracture at a test temperature of +75°F while the similar tests, A13 and A15 did at a temperature of +40°F.

As mentioned earlier, one of the program objectives was to establish the correlation between small scale tests and the results of the wide plate tests of this investigation. However, correlation does not appear to exist, see Figures 2 through 12 which plot the test results versus various pertinent parameters. It will be noted that the results are scattered and random to the extent that no clear-cut trends are discernible.

Also, as a program objective, was a study of the requirements for crack arrest. True arrest occurred only in Test A17, but this was as a gross section stress of 46,500 psi which is the material yield stress. Meaningful conclusions as to arrest, therefore, cannot be drawn.

The fractures that occurred during tests of the ASTM A212 Grade B material were, in general, flat faced with very little or no evidence of thinning of the cross section. Shear lips were virtually non-existent except in the tests performed at +75°F where, when fracture did result, a lip 1/2 to 1-inch in length occurred in the area adjacent to the initiation site.

B. Tests on the ABS Class C Material

It is apparent from the results of tests on the ABS Class C ships' hull material that, like the ASTM A212 Grade B steel, fast fracture may result if a sharp initiation site exists (fatigue crack or sharper) in the presence of a high residual stress field. The required applied stress, however, is a larger portion of the yield, in fact full yield stress or above in some cases. This is evident from a consideration of the results of Tests B1 - B3, inclusive, and Tests B5 and B6. All were performed at a test temperature of +40°F and were of identical configuration except for length of patch plate. The patch length was increased for B5 and B6 in order to minimize residual welding strains and determine whether or not lesser strains would result in higher fracture stresses. The attempt was successful because Tests B1, 2 and 3 resulted in fracture at percentages of 98, 78 and 57, respectively, of the material yield. Tests B5 and B6, however, did not result in fracture.

As for the A212 Grade B steel, temperature seems to play a part in the fracture behavior of the ABS material. For instance, in no case did a fracture occur at a room temperature ambient of 75°F but in all other tests, except one, which were performed near NDT or below, fracture did result. Fracture stresses, however, were high regardless of test temperature; the minimum stress occurred in Test B15, a stiffened plate configuration tested at +10°F. In the two tests at the coldest temperature (-35°F) fracture stress was at or near yield stress.

Again, as for the ASTM A212 material, no correlation with small scale test results seems possible. In this regard, it is felt that correlation may well be obscured by the role played by residual stress (or strain) - and residual stress (or strain) seems to be the dominant variable.

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APPENDIX A

RESULTS AND DISCUSSION OF THE EXPLORATORY TESTS PERFORMED ON THE PRESSURE VESSEL ALLOY ASTM A212 GRADE B

In the following pages, nineteen wide plate tests performed on the alloy, ASTM A212 Grade B are described and the results obtained therefrom are presented. All tests were made on specimens 10 x 10 feet in planform that had a thickness of 3/4-inch. All specimens were of the plain plate type.

There was a twofold overall purpose in the testing of this material. First, it was desired to determine the type of defect required to initiate fast fracture and, second, to investigate the effect on fracture load and fracture characteristics of the more important variables such as residual stress, temperature and initial flaw length. With these things in mind, four distinct series, involving the nineteen individual tests were then conducted. These are outlined below as to purpose of the test, specimen geometry and preparation, type of instrumentation used, specific test conditions and test results.

A. 1 Series 1 - A Central Slot Configuration - Tests A1 - A5

Series 1, the initial test series, consisted of five tests performed primarily for the purpose of determining the nature of defect required to trigger a fast fracture. Also, as mentioned in the text of this Report, a secondary purpose was involved, viz., to determine the behavior of the test machine itself.

A. 1. 1 Preparation and Installation of the Specimen

For the first test, a transverse central slot 12" in length was introduced into the specimen. Eleven inches of this length, 5-1/2" each way from the specimen center line, was cut by torch and an extension through the resultant flame hardened area was then made with an ordinary hack saw. Next, each end was further lengthened 1/16" by jeweler's saw; this produced an initiation site with tip radius of about 0. 003".

The specimen was next welded into the test machine taking care to make certain that the midplane passed through the axis of pins which attach the fore and aft connecting beams to the machine proper. This insured that the bending moment, introduced by subsequent application of the test load, would be minimized.

The specimen was now ready for instrumentation and this is described in A. 1. 2 following. However, as will also be discussed shortly, fracture did not occur during the first test and the slot, therefore, was simply welded shut and about 8" away a parallel slot was cut for use in the second test. This slot had an overall length of 42", 1" of each end of which was, after cutting, re-welded with Hardex N hard facing weld rod. Upon cooling, a brittle area with an accompanying severe residual stress field was thereby produced; this formed the initiation site.

Subsequent specimens, A3, A4 and A5 were of like configuration and were all performed on the same basic test plate. In each case, from Test A2 on, fracture did result and the specimen was simply re-welded and a new slot cut in an unaffected area. This served to conserve material and, in addition, did not necessitate the cutting out of an old specimen and re-welding in of a new.

A. 1. 2 Instrumentation

Because the prime objective of tests on the ASTM A212 Grade B material was to study factors involved in fracture initiation rather than a resultant stress distribution, elaborate instrumentation of the specimen was not deemed necessary. Always, however, seven resistance strain gages were installed across a section remote from the slot and, in addition, near the ends of the slot, midway to each edge and 1" away from each edge. No instrumentation was placed on the underside of the specimen because, as previously stated, it was felt that the applied bending moments would be small.

A. 1. 3 Test Conditions

The first and last test of Series 1 was performed at room temperature and Tests A2, A3 and A4 at temperatures of -65, +10 and +30, respectively. For the below-room temperature tests, cooling was effected by means of dry ice placed in trays positioned near both upper and lower surfaces of the specimen. These trays were about 2 feet in width and could be raised or lowered at will to obtain a particular temperature as indicated by thermocouples imbedded in both surfaces of the specimen at the quarter, half, and three-quarter points across the width. Though relatively simple, this means of temperature regulation proved quite effective; when necessary, it was sometimes complemented by means of an insulating blanket laid over one or both trays.

A. 1. 4 Test Results

Fracture from the first configuration did not result although the load applied was 4. 18 x 10^6 lbs. This is the apparent yield load of the specimen as indicated by the seven strain gages located across an unnotched section remote from the 12" flaw, and is equivalent to a gross section stress of 46,500 psi. Though somewhat greater than the yield strength of about 44,500 psi obtained by small specimen tests, a stress of 46,500 psi reflects, no doubt, an averaging of tensile properties along the strain gaged cross section. It is to be noted, incidentally, that the load as indicated by an observed hydraulic cylinder pressure of 1425 psi was 4. 28 x 10^6 lbs. This is in good agreement with the strain gage results and confirms the assumption that bending moments are small if care is taken to properly position the specimen during installation.

Tests A2 through A5, inclusive, all resulted in fracture at loads as given in the tabulation of Figure A-1 of this Appendix. Except for the magnitude of failure loads, no differences were noted. In this regard, it is to be noted that one test of this series, Test A2, resulted in fracture at a very low value of applied stress, viz., 27% of yield based on the gross section area. As evidenced by the complete absence of shear lips or thinning of the cross section, this was the only truly brittle-like test of the entire program. All other fractures were basically flat and shear lips, where evidenced, were very short and immediately adjacent to the tip of the initial flaw.

A. 2 Series 2 - An Unnotched Configuration with Lateral Stiffener - Tests A6 - A8

This series, which involved three individual tests, was undertaken as a means of further studying fracture initiation. It was planned to introduce weld defects by means of poor welding techniques and, also to determine qualitatively the effect of weld induced residual stresses.

A. 2. 1 Preparation and Installation of the Specimen

In order to insure that previous loadings of the Series 1 tests in no way affect the results of this series, the old material was removed from the test machine and a new plate installed. A 3 x 3 x 1/4" angle was then welded across the midsection, in a direction normal to the load axis, using the poorest possible weld procedure by a totally inexperienced welder. This resulted in undercutting, numerous random arc strikes and gouges, and liberal amounts of slag and inclusions; also, an improper rod was used in order to insure high residual stress because of excessive and uneven heat. In short, a deliberate attempt was made to provide a multiplicity of initiation sites, particularly at the specimen edges. Fracture, however, did not occur at either of two test temperatures (mentioned later) and a 10" torched slot was cut parallel to, and about 8" away from, the angle for the third test of the series. The tip of this slot was then extended by hack saw and cooled with liquid nitrogen. Next, a wedge was driven inward to initiate a starter crack. Though it was intended to produce a crack only about an inch in length, the result was one nearly 8" long with tip headed towards the welded-on angle.

A. 2. 2 Instrumentation

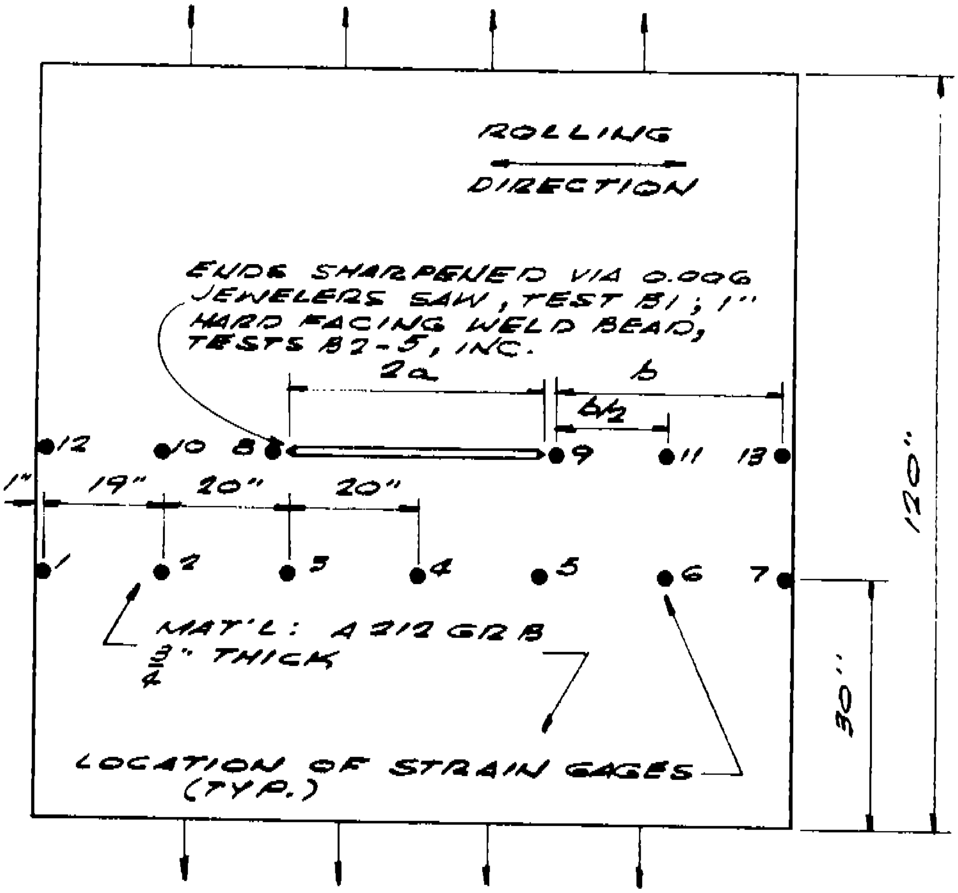
Instrumentation for this series of tests was the same as that used for the previous series.

A. 2. 3 Test Procedure

A test was first run at +75°F, then again, using the same specimen, at +10°. The final test, i. e. , the one with the wedge induced crack discussed above, was performed at 0°F. Cooling procedures were as outlined in the Series 1 tests, see Section A. 1.

As indicated above, fracture did not result from Test A6, the first of the series, nor did it result from Test A7. On Test A8, however, initiation was effected with a resultant fracture very much like those of Series 1. In this regard, however, it was of interest to note that the crack did not parallel the stiffener but veered away along a path that, at least ostensibly, was in a region of lower residual stress. No explanation to this happening is offered except the obvious, viz. , that this was the path of least resistance.

A. 2. 4 Test Results



Test	2a, Ins.	Temp., °F	Fracture ?	Load Lbs x 10^{-6}	% of Yield Strength(*) Attained Across the: Gross Section	Net Section
A 1	12	+75	No	4.18	100.0	111.0
A 2	40	-65	Yes	0.75	17.9	26.9
A 3	40	+10	Yes	2.60	62.1	93.4
A 4	40	+30	Yes	2.70	64.5	96.8
A 5	40	+75	Yes	3.10	74.1	111.0

(*)Based on an apparent full size specimen yield strength of 46,500 psi.

Fig. A-1. Specimen Configuration and Summary of Results - Series 1 Tests on the ASTM A212 Grade B Material.

A summary of the fracture loads and test conditions is included in Figure A-2.

A. 3 Series 3 - Edge Notched Specimens with a Fatigue Crack Initiator - Tests A9 - A18

In this series of tests, it was desired, first, to determine whether or not fracture could be initiated by means of a fatigue crack and, second, if so, to find if the results were at all repeatable. Temperature was to be varied so that some tests would, and others would not, result in fracture and it was felt useful to determine differences which might result from a change in applied load from "across" to "with" the major direction of rolling.

A. 3. 1 Preparation and Installation of the Specimen

Because it was not practical to attempt to generate a fatigue crack in the full sized 10 x 10 foot specimen, it was decided to torch cut a slot lengthwise in a 1 x 2 foot patch, then induce the fatigue crack at the bottom of the slot by means of a pull-release action supplied by a hydraulic cylinder suitably mounted in an external frame. Such a frame was devised and, for the first specimen, a slot 5" in length was cut. The actual generation of the fatigue crack turned out to be a fairly simple task; a crack 1/2" in length could be grown in about four hours and, later, this time was shortened by use of blocks of dry ice strapped to the sides of the patch. Next, the patch was spliced into a cut-out made at the edge of the specimen and the assembly was then ready for installation.

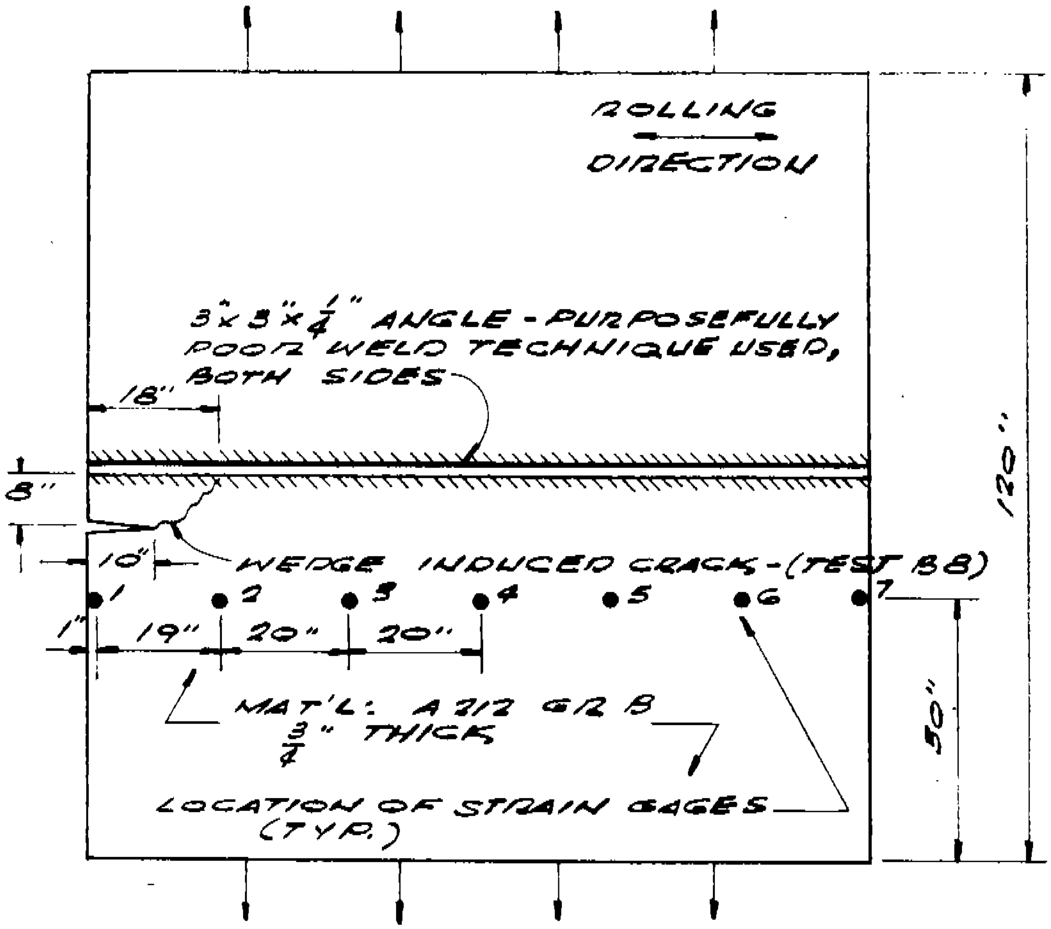
All specimens in this series were made in like manner except that the subsequent nine had torch cut slots 10", instead of 5", in depth. Installation was in the identical manner as discussed in Section A. 1. 1. The series was started using new material and this was re-used for Tests A9 through A15, all of which were loaded normal to the major direction of rolling. New material was then used for Tests A16, 17 and 18 with load, for these cases, applied along the direction of rolling.

A. 3. 2 Instrumentation

With one exception, instrumentation for all tests of this series consisted of the previously described pattern of seven strain gages located remotely from the notched section. The exception was for Test A15 where, in order to check the assumption that little bending resulted from the applied tensile load, strain gages were mounted on the underside of the specimen. Location of these gages is as shown in Figure A-3.

A. 3. 3 Test Conditions

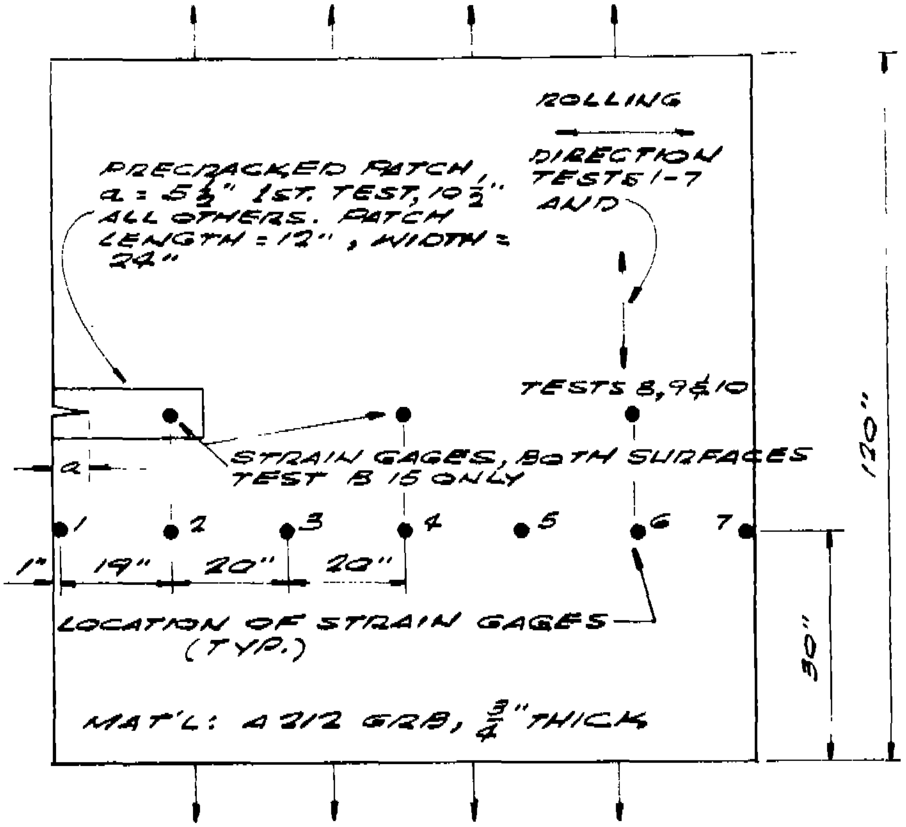
Three temperatures were used during this series of tests, viz., a room ambient of 75°F, a temperature of +40° and, for tests conducted with the load parallel to the direction of rolling, +35°F.



Test	a, Ins.	Temp., °F	Fracture ?	Load Lbs x 10^{-6}	% of Yield Strength(*) Attained Across the: Gross Section	Net Section
A 6	-	+75	No	4.18	100.0	-
A 7	-	+10	No	4.18	100.0	-
A 8	10	0	Yes	3.18	76.1	82.8

(*) Based on an apparent full size specimen yield strength of 46,500 psi.

Fig. A-2. Specimen Configuration and Summary of Results - Series 2 Tests on the ASTM A212 Grade B Material.



Test	Ins.	Temp., °F	Fracture ?	Load Lbs x 10^{-6}	% of Yield Strength(*) Attained Across the: Gross Section	Net Section
A 9	5.5	+45	Yes	3.12	74.5	78.1
A 10	10.5	+75	No	4.18	100.0	109.5
A 11	10.5	+75	No	4.18	100.0	109.5
A 12	10.5	+40	No	4.18	100.0	109.5
A 13	10.5	+40	Yes	1.92	45.9	50.2
A 14	10.5	+75	No	4.18	100.0	109.5
A 15	10.5	+40	Yes	2.75	65.7	72.0
A 16	10.5	+40	No	4.18	100.0	109.5
A 17	10.5	+35	No	4.18	100.0	109.5
A 18	10.5	+35	Yes	2.29	54.8	60.0

(*)Based on an apparent full size specimen yield strength of 46,500 psi.

Fig. A-3. Specimen Configuration and Summary of Results - Series 3 Tests on the ASTM A212 Grade B Material.

A. 3. 4 Test Results

The previously mentioned Figure A-3 not only shows the specimen configuration and a tabulation of test temperatures, but also summarizes results obtained for this series. Therein, definite trends will be evident. For instance, fracture did not result in either of three tests conducted at +75°F but was achieved three out of four times at temperatures near 40°. In all seven tests, the load direction was across the major direction of rolling and fracture, therefore, was propagated in the "weak" direction. For the following three tests, however, the rolling direction was changed so that a crack had to propagate across the "strong" direction. Changing direction resulted in one test involving fracture and two tests with no-fractures; this is what might be expected if 40°, or thereabouts, was close to or within a rather sensitive temperature range. Actually, this appears to be the case because, as shown by the results of small sized specimens, see Figure A-12, though the indicated NDT for the particular heat involved was 20°F, there was a large amount of scatter in the data. From the standpoint of repeatability, then, it would seem the odds are slightly in favor of fracture for the case of a fatigue crack initiation and a test temperature near NDT. If the temperature is +75° or above, however, there appears little likelihood of such occurrence, regardless of load direction with respect to rolling direction.

One other point of particular interest is that a distinct "pop-in" was noted during the first test of the series (Specimen A9) using an edge slot with fatigue crack. This occurred at about one third load, i. e., 1 x 10^6 lbs which is a gross section stress of 11,600 psi. The "pop-in" extended the slot about two feet. No change in the load required to hold the specimen in its cracked condition was noted during an inspection of the crack and, when loading was resumed, no further extension was evident before fracture. Then, on Test A17, a "pop-in" occurred but further load application failed to trigger fracture. The crack, however, did extend about 12-inches before blunting, thus resulting in true arrest.

Concerning the Test A15 which was instrumented on both surfaces, the strain gage data indicate that little bending resulted from application of the load. The strain data are given in Figure A. 3. 1 which shows, also, a typical stress distribution across the specimen width.

A. 4 Series 4 - A Center Slotted Specimen with Fatigue Crack Initiators - Test A19

This series of tests was performed to compare with earlier Series 1 Tests in which brittle weld beads had served as crack initiators.

A. 4. 1 Preparation and Installation of the Specimen

For this test, two 1 x 1 foot patches with 5-1/2" torch cut slots were fabricated and a fatigue crack 1/2" in length was generated in each patch. Except for the shorter overall length, these were identical to the patches of the previous series. A cut-out was next made in a new 10 x 10 foot specimen and the patches were welded in. This produced a slot of 12" total length as shown in Figure A-4. Rolling direction for both patch and specimen proper was oriented to be parallel to the direction of loading.

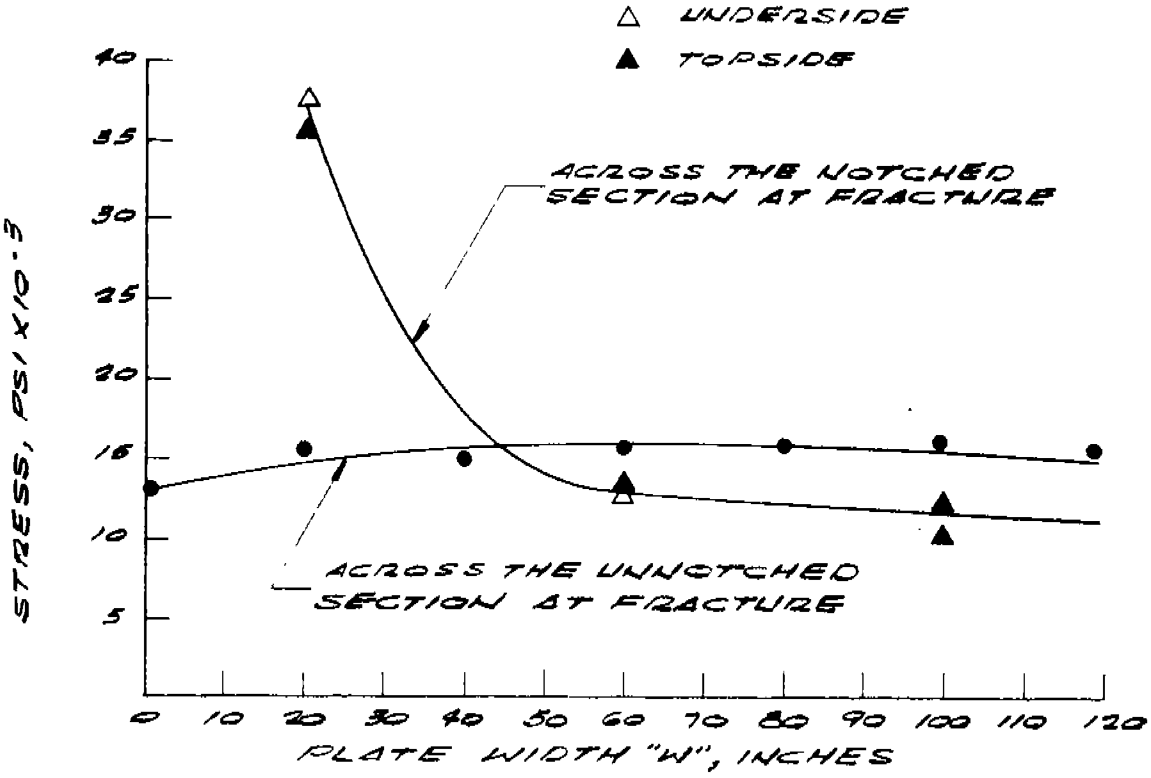
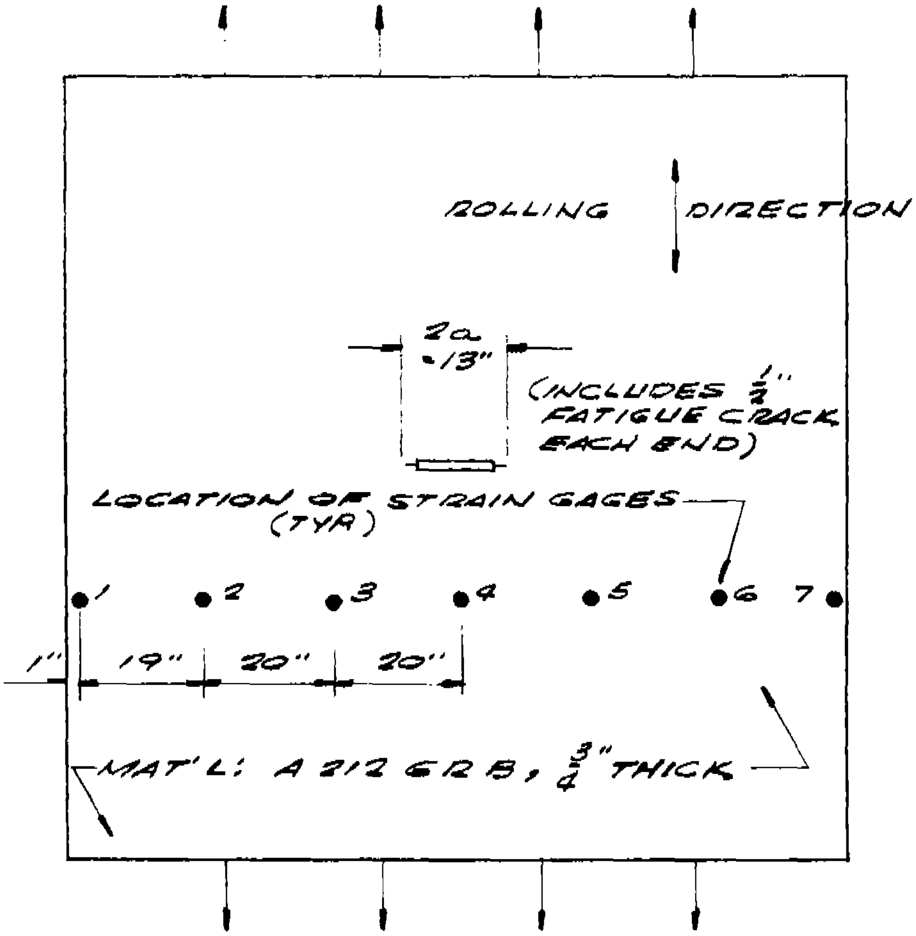


Fig. A-3.1. Typical Stress Distribution Just Prior to Fracture as Measured During Test A15.



Test	2a, Ins.	Temp., °F	Fracture ?	Load Lbs x 10^{-6}	% of Yield Strength(*) Attained Across the: Gross Section	Net Section
B 19	12	+35	Yes	1.78	42.7	47.7

(*) Based on an apparent full size specimen yield strength of 46,500 psi.

Fig. A-4. Specimen Configuration and Summary of Results - Single Test of Series 4 on the ASTM A212 Grade B Material.

A. 4. 2 Instrumentation

The instrumentation for this test was identical to that for the Series 1 tests.

A. 4. 3 Test Conditions

Although the primary purpose of this test was for comparison with those of the Series 1, it seemed also desirable that the test be conducted at the same temperature as edge-notch Test A18. Both were installed with loading parallel to the major direction of rolling and, if a test temperature of +35°F was used, a comparison of edge notched versus center notched results would then be afforded. Hence, +35°F was used.

A. 4. 4 Test Results

Upon loading, fracture occurred on specimen A19 at 1.78×10^6 lbs, a value lower than for either Test A4 or Test A18. The specimens used in Tests A4, A18 and A19 all had center slots. Specimen A19, however, had fatigue cracks at each end of the slot and A4 and A18 did not. Though it might appear that the lower fracture load for A19 resulted from solely for reason of a sharper initiator, such is not felt to be the case. As will be pointed out later, residual stresses are shown to play too great a part for sharpness of initiator to be the sole governing variable.

A. 5 Recapitulation of Results of Tests on the A212 Grade B Material

In summary, nineteen tests in all were performed on the above material, ten of which terminated in rapid fracture at loads well below the unflawed section yield load. As will be noted later, no precise pattern is readily apparent. Always though, if fracture did occur, the resultant surface was basically flat with shear lips evident only for an inch or two near the tip of the original flaw. There was no visual evidence of thinning of the cross section though the specimens did not meet the ASTM STP 410 requirements for the plane strain case. Definitely, the need for a very sharp ended crack initiator is indicated and, as would be expected, it seems apparent that, in general, the fracture stress is greater at the higher test temperatures.

Table A-1 summarizes the test series and Figures A-5 through A-10 are photographs of some of the resultant fractures. Figure A-11 is a photograph showing the central slot configuration used for Test A19. As was mentioned previously (Section III), Figure A-12 is a plot of the Charpy-Vee and Navy Drop Weight data.

Table A-1. Tabulation Of Results Of Tests Performed On The 3/4-Inch Thickness ASTM A212 Grade B Material.

Test No.	Date	Material Heat Number[a]		Load Direction[b]	Defect	Initiator	Test Temp, °F	Test Load, Lb x 10^{-6}	Fracture ?	Avg. Stress, psi x 10^{-3}	
		Main Test Plate	Patch Plate		Type and Length, In.	Type and Length, In.				Gross Section	Net Section
A 1	11-22-66	A-0260	NOT USED	Normal	Central Slot, 12	Saw Cut, 1/2	+75	4.18	No	46.5	51.6
A 2	11-22-66				, 40	Brittle Bead, 1	-65	.75	Yes	8.3	12.5
A 3	11-30-66				, 40		+10	2.60	Yes	28.9	43.4
A 4	12-5-66				, 40		+30	2.70	Yes	30.0	45.0
A 5	12-7-66				Central Slot, 40	Brittle Bead, 1	+75	3.10	Yes	34.5	51.7
A 6	1-6-67				Angle Welded 120 Across Spec.	Poor Weld, 120	+75	4.18	No	46.5	--
A 7	1-9-67				Angle Welded 120 Across Spec.	Poor Weld, 120	+10	4.18	No	46.5	--
A 8	1-13-67		NOT USED		Angle as Above, 10 & Edge Slot	Impact Gen- 10 erated Crack	0	3.18	Yes	35.3	38.5
A 9	1-17-67		A-0260		Edge Slot, 5.5	Fatigue Crack, 1/2	+45	3.12	Yes	34.7	36.5
A 10	1-20-67	A-0260	P-4023		10.5		+75	4.18	No	46.5	50.8
A 11	1-23-67	P-4023					+75	4.18	No	46.5	50.8
A 12	1-24-67						+40	4.18	No	46.5	50.8
A 13	1-26-67						+40	1.92	Yes	21.3	23.4
A 14	1-27-67						+75	4.18	No	46.5	50.8
A 15	2-1-67			Normal			+40	2.75	Yes	30.6	33.5
A 16	2-17-67			Parallel			+40	4.18	No	46.5	50.8
A 17	2 21-67						+35	4.18	No	46.5	50.8
A 18	3-3-67				Edge Slot, 10.5		+35	2.29	Yes	25.5	27.9
A 19	3-9-67	P-4023	P-4023	Parallel	Central Slot, 12	Fatigue Crack, 1/2	+35	1.78	Yes	19.8	22.0

Notes:
(a) See Table A-1 for mechanical property data
(b) With respect to the direction of principal rolling
(c) Based on an apparent full size specimen yield strength of 46,500 psi
(d) For single edge notch: $K_I = 1.12\,\sigma\,(\pi a)^{1/2}$
For central notch: $K = 1.05\,\sigma\,(\pi a)^{1/2}$

TABLE A-2. CHEMICAL COMPOSITION AND MECHANICAL PROPERTIES OF THE 3/4-INCH IN THICKNESS ASTM A212 GRADE B MATERIAL

A. Chemistry

	Heat Number	
	A-0260	P-4023
Carbon	0.22	0.26
Manganese	0.86	0.80
Phosphorus	0.008	0.009
Sulfur	0.025	0.022
Silicon	0.30	0.25
Aluminum	0.02	0.02

B. Mechanical Properties

	Heat A-0260		Heat P-4023	
	Longitudinal	Transverse	Longitudinal	Transverse
Ultimate Tensile Strength, psi	72,100	72,100	78,200	77,900
Yld. Strength, psi, at 0.2% offset	40,100	40,500	44,300	44,800
Approx. Yld. Strength, psi, apparent from large specimen tests	46,500		46,500	
Elongation, % in 8 inches	34.0	32.5	33.0	32.0
15 ft/lb Charpy-Vee Transition Temp., °F (See Fig. A-12)	+50		+25	
Nil Ductility Temperature, °F, when estimated to be 60°F less than 50% FATT	+15		+10	
Nil Ductility Temp., °F, from Drop Weight Tests	+10		+20	
ASTM Grain Size	5		6	

Fig. A-5. Overall View Of A Typical Fracture - Test A2; Configuration: Central Slot With Brittle Weld Bead, Each End; Test Temperature: -65°F; Fracture Stress: 8,300 Psi On The Gross Section, 12,500 Psi Avg. On The Net.

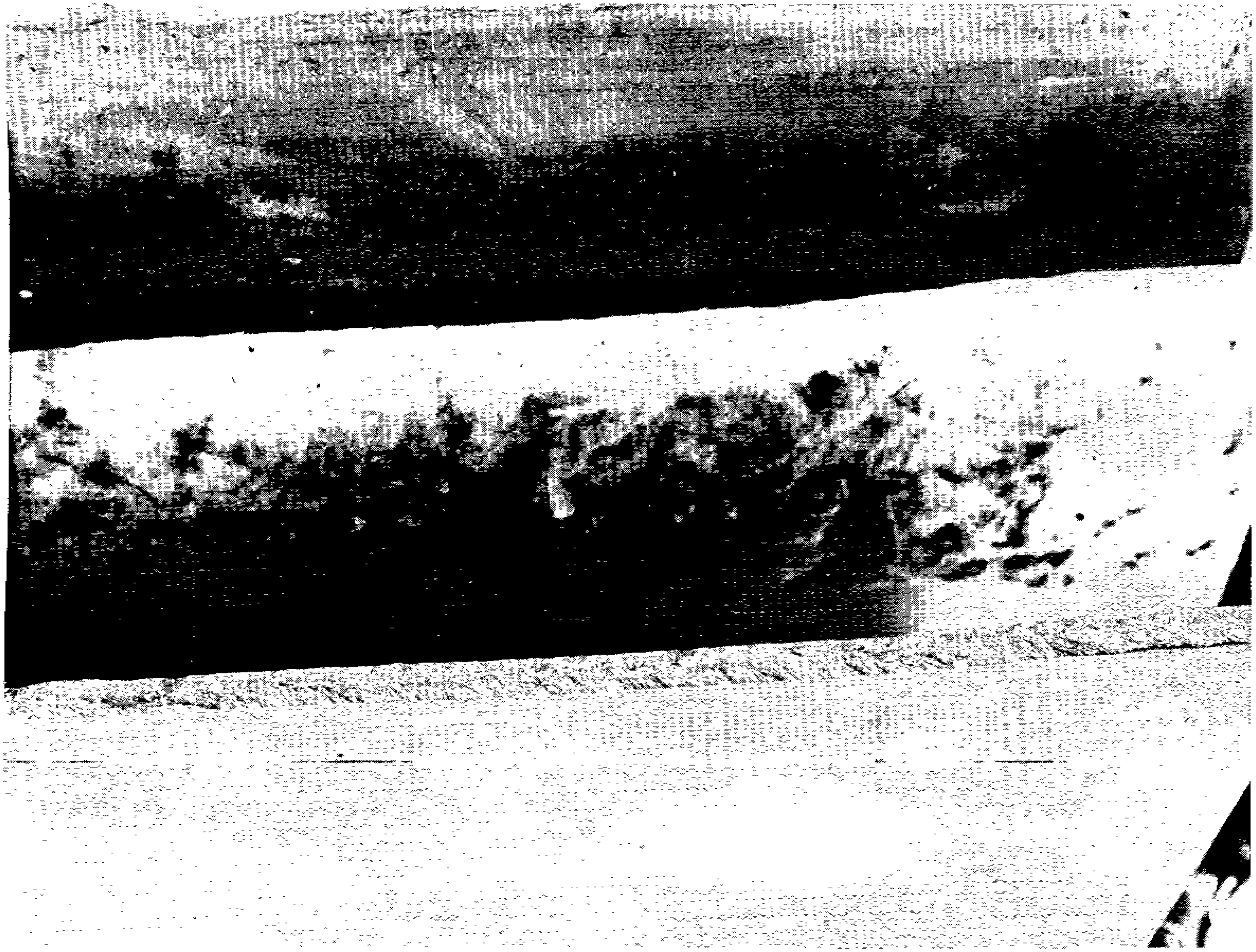


Fig. A-6. Appearance Of A Typical Fracture Surface - Test A3; Configuration: Central Slot With Brittle Weld Bead, Each End; Test Temperature: +10°F; Fracture Stress: 28,900 Psi On The Gross Section, 43,400 Avg. On The Net.

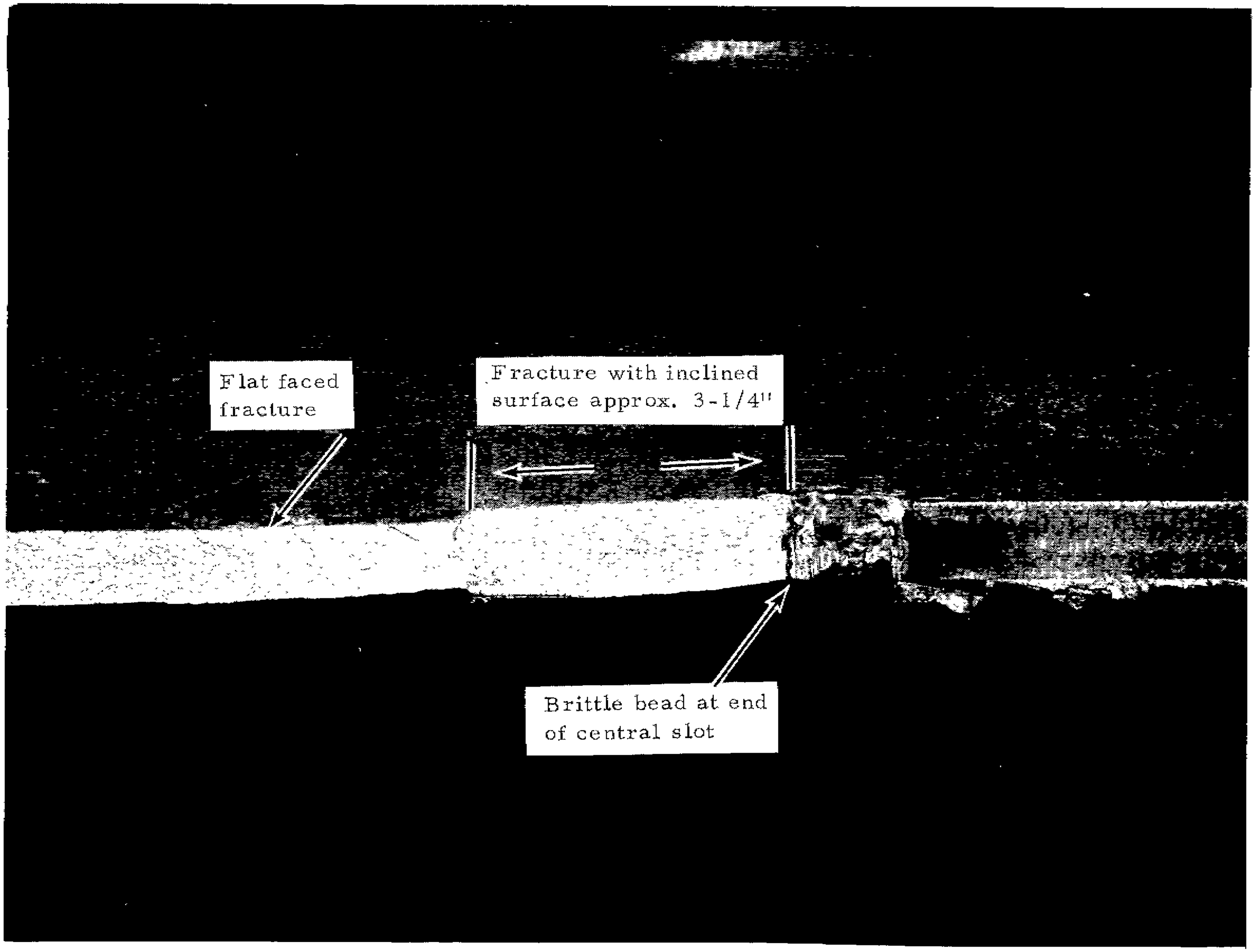


Fig. A-7. Appearance Of The Fracture Surface - Test A5; Configuration: Central Slot With Brittle Weld Bead, Each End; Test Temperature: +75°F; Fracture Stress: 34,500 Psi On The Gross Section; 51,700 Psi Avg. On The Net.

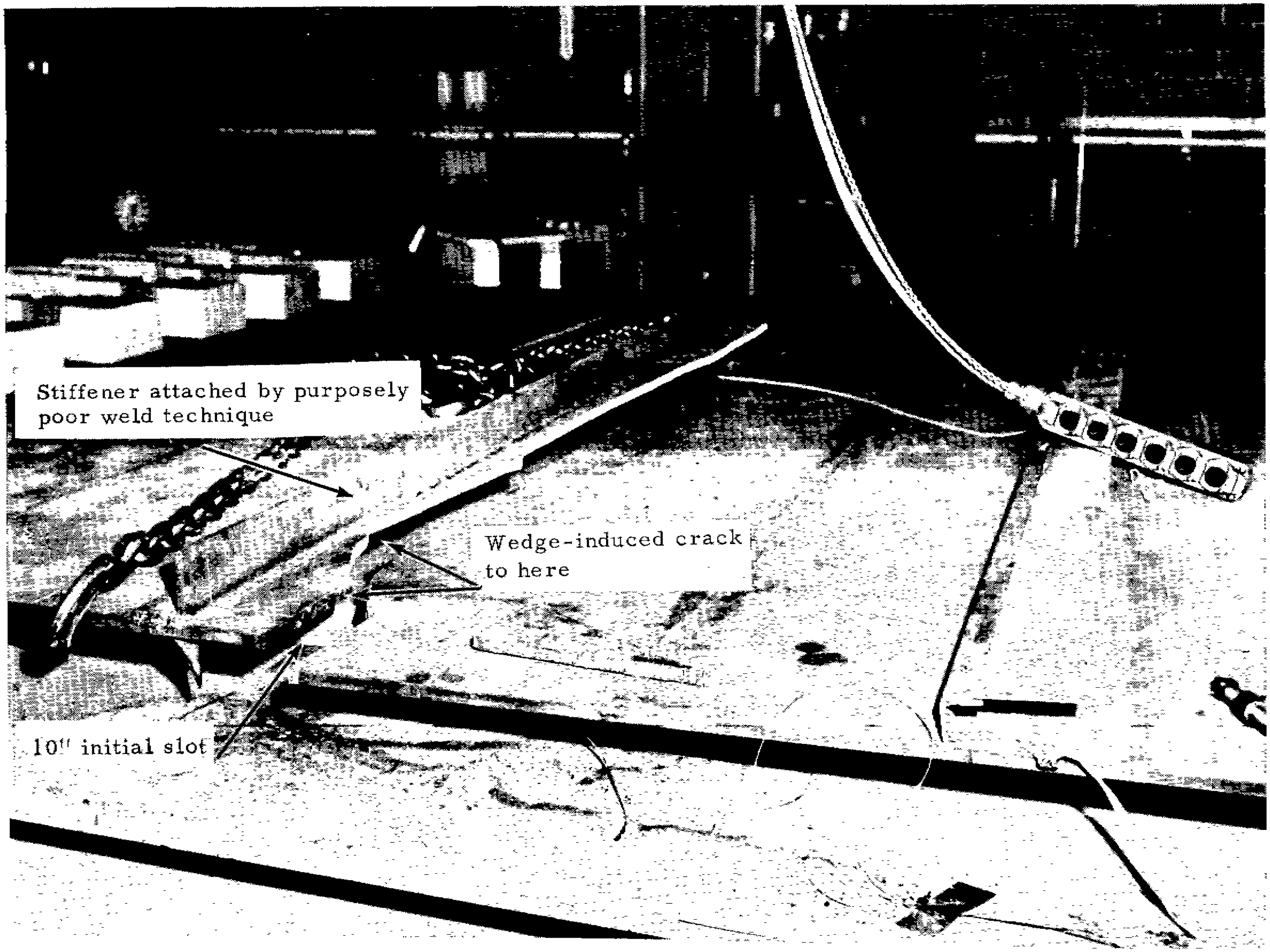


Fig. A-8. Overall View Of The Fracture - Test A8; Configuration: Edge Slot With Wedge Induced Starter Crack; Test Temperature: 0°F; Fracture Stress: 35,300 Psi On The Gross Section; 38,500 Psi Avg. On The Net.

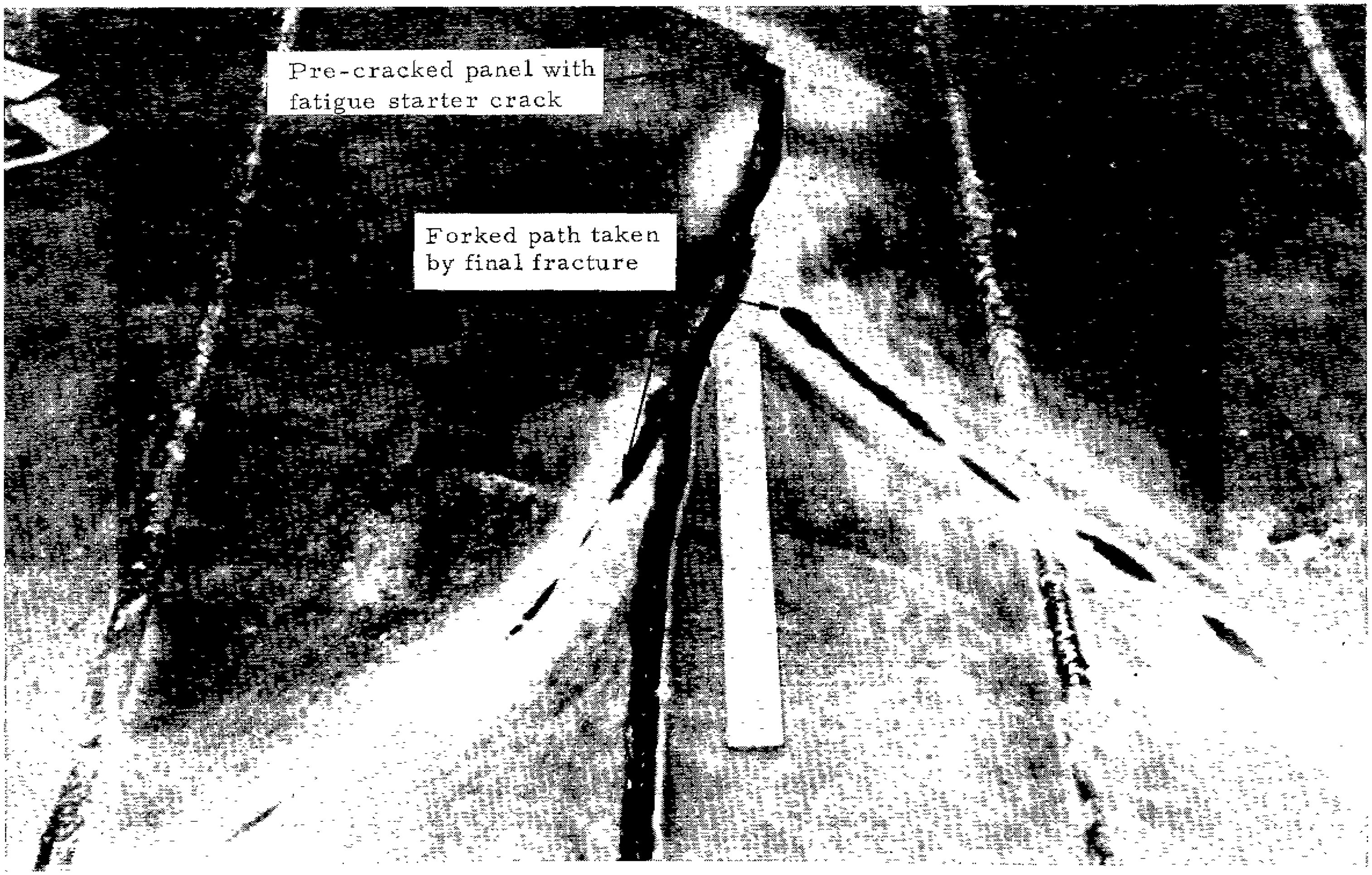


Fig. A-9. General View Of The Fracture - Test A9; Configuration: Fatigue Crack Initiator Generated At The End Of A 5" Edge Slot; Test Temperature: +45°F; Fracture Stress: 34,700 Psi On The Gross Section; 36,500 Psi Avg. On The Net.

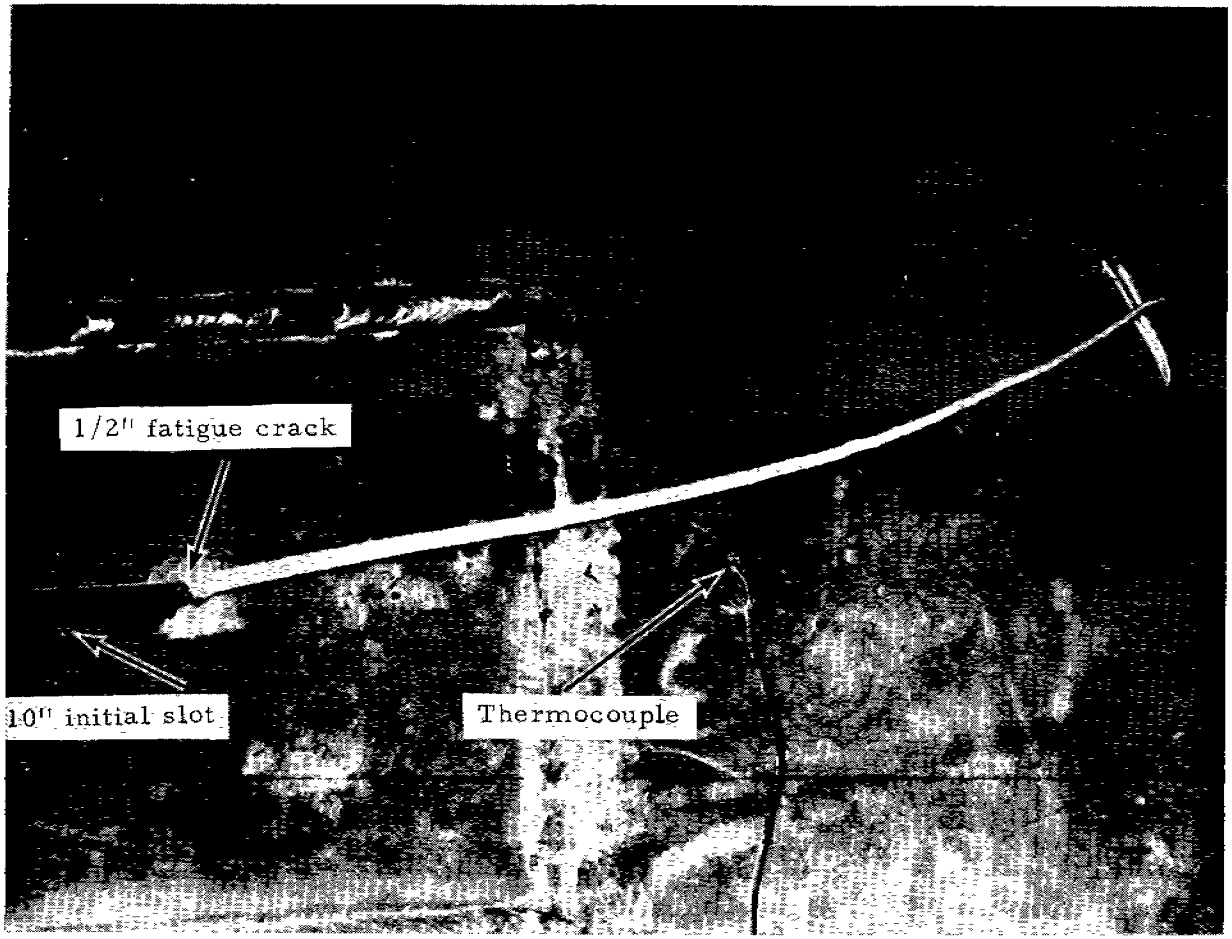


Fig. A-10. View Of An Arrested Crack - Test A17; Configuration: Fatigue Crack At End Of A 10" Edge Slot; Test Temperature: +35°F: Stress At Arrest: 46,500 Psi On The Gross Section (46,500 Psi Is The Specimen Yield Stress).

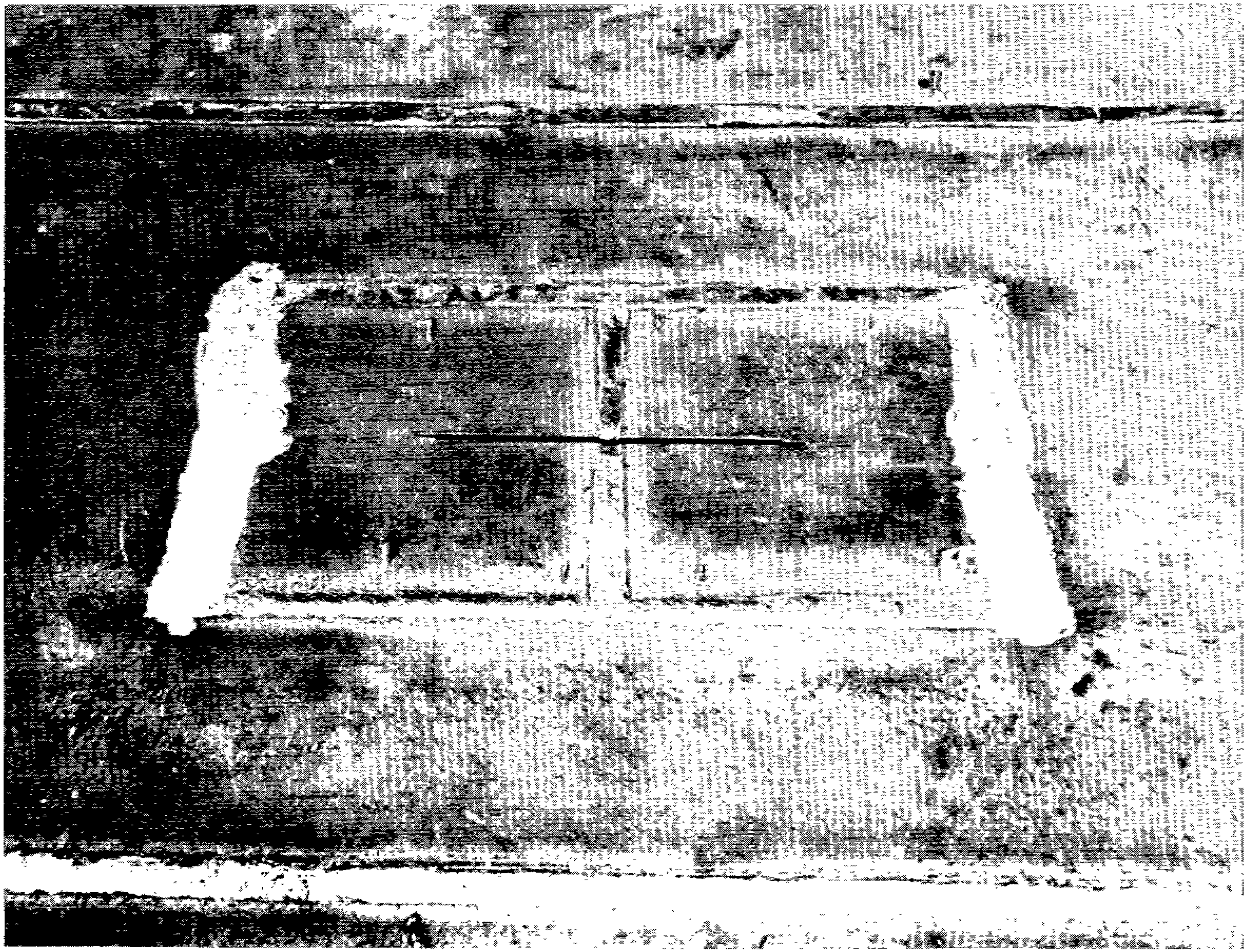


Fig. A-11. View Of The Central Slot With Fatigue Cracks, Each End, Used To Initiate Fracture For Test A19.

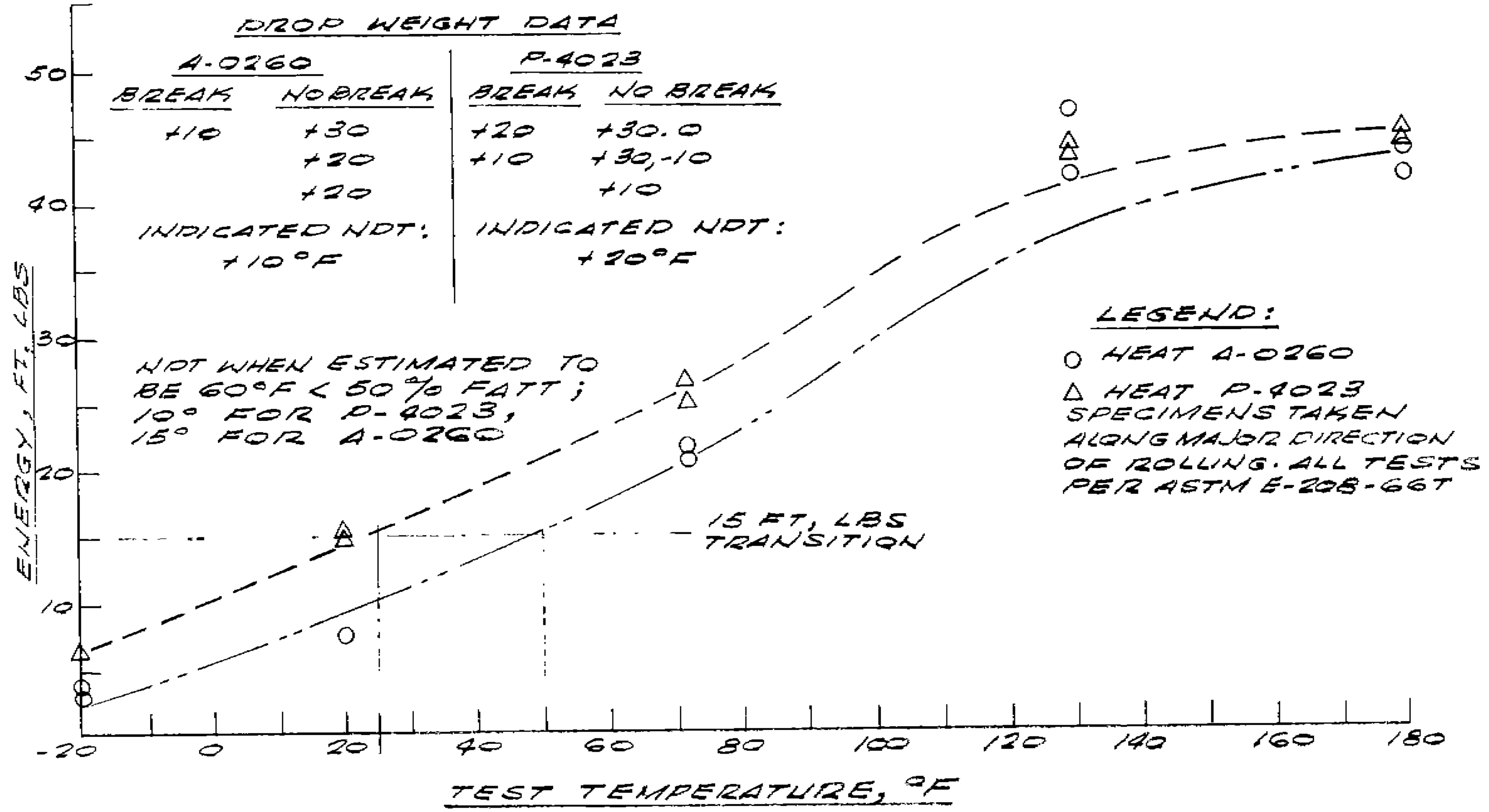


Fig. A-12. Charpy-Vee And Drop Weight Data For The 3/4-Inch ASTM A212 Grade B Material Used For The Exploratory Tests.

APPENDIX B

RESULTS AND DISCUSSION OF THE TESTS PERFORMED ON THE ABS CLASS C SHIPS' HULL MATERIAL

In the following pages eighteen wide plate tests performed on the ships' hull material, ABS Class C, are described and the results obtained therefrom are presented. All tests were conducted on specimens 10 x 10 foot in planform by 1-3/8-inch in thickness; three were stiffened by means of two bars 6-inches in height x 1-3/8-inch in thickness welded to the upper surface of the plate in a direction parallel to the load line. The other fifteen specimens were of the plain plate type.

In the pages following, each test is outlined in brief as to specific purpose, specimen preparation, test conditions and more significant results. The results have been previously summarized, see Section IV.

B. 1 Test B1

Test B1, the first of the series using 1-3/8-inch ABS Class C plate material, was performed for the purpose of determining whether or not fast fracture could be initiated as in the ASTM A212 Grade B material. Accordingly, a 10 x 10 foot specimen was welded into the test facility and a 12 x 12 inch patch, with fatigue crack generated at the tip of a 5-1/2-inch torch cut slot, was spliced into the specimen. Strain gages were affixed at several locations across a section remote from the fatigue crack and in three places directly ahead of the probable path of fracture. The specimen was cooled to the NDT of +40°F, the load slowly applied and, at 6. 65 x 10^6 lbs, fracture did result. This is shown in the photograph of Figure B-1, this Appendix.

During installation of the specimen bowing resulted from welding to the test facility and there was an inadvertent preload introduced when, as the welds cooled, the specimen shortened, and the hydraulic loading cylinders bottomed out. In magnitude, this preload was about 1. 51 x 10^6 lbs as evidenced from the fact that no strain gage output was apparent until the loading cylinder pressure during test reached 500 psi. (By virtue of the test machine geometry, 100 psi hydraulic pressure is equivalent to 302,000 lb load on the specimen).

As to information derived from the test, that of most significance is the fact that fast fracture can occur at a temperature near NDT in an ABS Class C material. For Test B1, however, the unnotched section stress field was 6. 65 x 10^6 lbs ÷ an area of 165 sq. in.; this is an average of 40,000 psi stress, somewhat above the 35,300 psi yield at 0. 2% offset determined by tests on small scale specimens.

B. 2 Test B2

Test B2 was performed for the purpose of determining whether a decrease

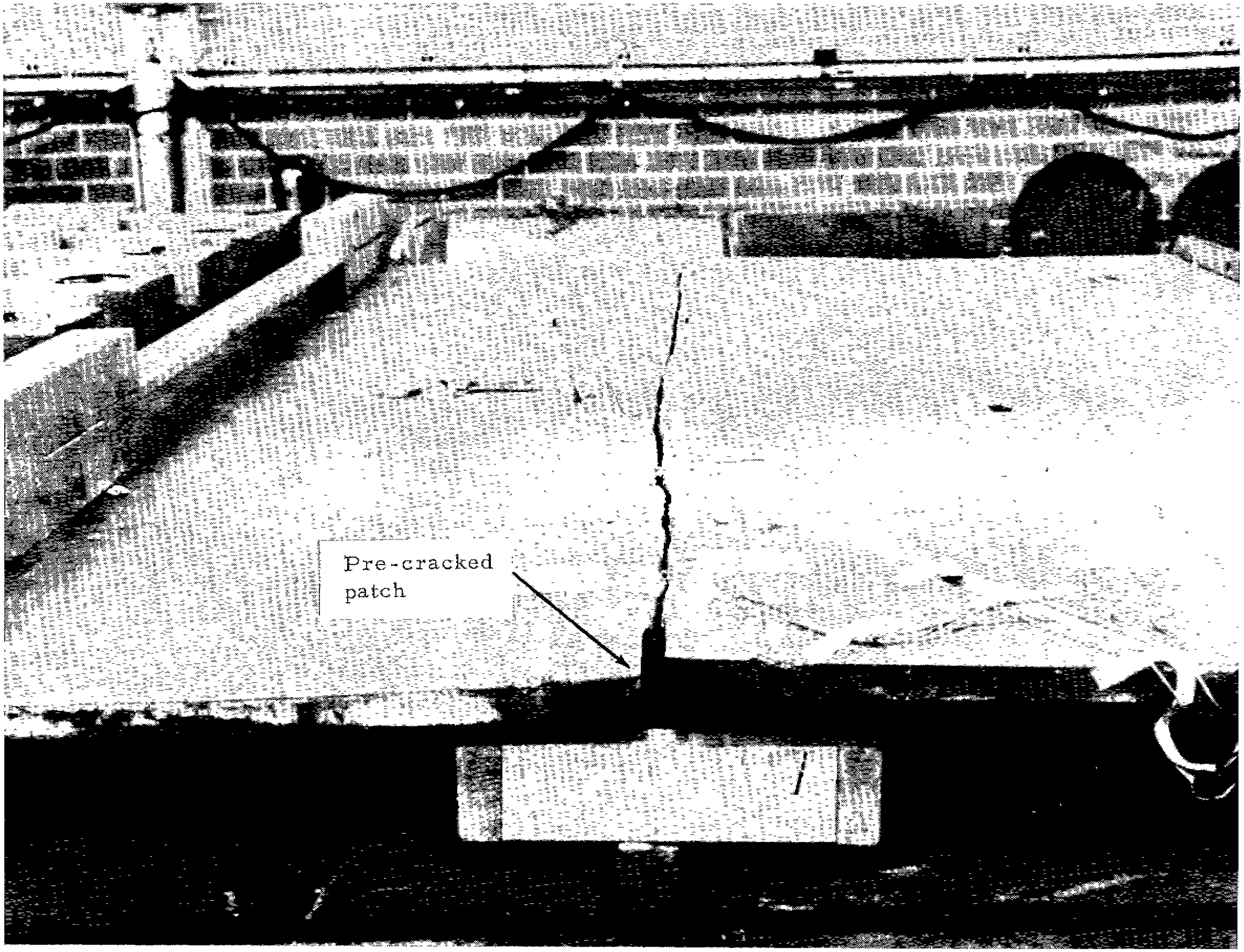


Fig. B-1. Overall View Of The Fracture - Test B1; Specimen Configuration: Fatigue Crack Generated At The Tip Of A 6" Edge Slot; Test Temperature: +40°F; Fracture Stress: 40,300 Psi On The Gross Section; 42,400 Psi Avg. On The Net.

in length[*] of the patch plate would materially affect the value of the fracture load when the temperature remained at +40°F as before. Also, it was desirable to eliminate the inadvertent preload of Test B1, to minimize the tendency of the specimen to bow during the welding process and to measure the magnitude of stress induced near the crack tip when the patch was spliced into position. Therefore, a new 30-inch wide test panel with gages pre-installed on both top and bottom surfaces, was welded into the basic 10 x 10 foot test section. As low a heat as possible was used in making the welds and peening was employed after each pass. An 8 x 12 inch patch, with fatigue crack generated at the tip of a 5-1/2 inch torch cut slot, was instrumented with weldable type strain gages applied near the tip and the patch was then spliced into the specimen.

The test terminated in fracture at 5.28×10^6 lbs, (see Figure B-2), a value somewhat less than for Test B1. However, this is not surprising because residual stresses surrounding the fatigue crack tip were, if anything, somewhat higher than in the previous test because of the decreased patch width. The magnitude of these stresses, however, was not determined due to loss of the strain gages during welding; also, bowing was not eliminated in spite of the care used in welding. The bowing was obvious visually and was likewise apparent in the derived strain data which showed that the area under the curve of stress across the unnotched section at fracture indicated an applied load of 3.78×10^6 rather than 5.28×10^6 lbs. However, the strain gages on the underside of the specimen measured yield stress or greater, thus giving an average gross section stress of about 31,000 psi. This value, multiplied by the specimen area, gives a load of 5.2×10^6 lbs which is in good agreement with the value indicated by the loading cylinder pressure.

Noteworthy of Test B2 is that a "pop-in" occurred at 4.53×10^6 lbs which is a nominal stress of 27,500 psi. The crack extended two feet, thus producing a new notch length of 30 inches. No decrease in load on the specimen accompanied the extension of the crack.

B. 3 Test B3

As in Test B2, Test B3 was performed for the purpose of investigating a variation in patch geometry, in this case an increased width. The previously used 8-inch length patch was removed and a new and slightly longer full-width panel was installed in the same manner and with essentially the same instrumentation as before. Warpage from welding of the panel to the basic specimen did not appear excessive, but, after making the patch cut-out and splicing in an 8 x 24 inch patch, a large amount of distortion was evident. As in previous tests, this had a decided effect on the test results which, unfortunately, indicate little except that the failure stress (at a test temperature of +40°F) of 23,600 psi was lower than in the two previous tests. Once more, because of the heat from welding, no meaningful data were obtained from the gages that were intended to measure the weld-induced

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[*] Length "1" is measured along the load axis, therefore it is sometimes the shorter dimension.

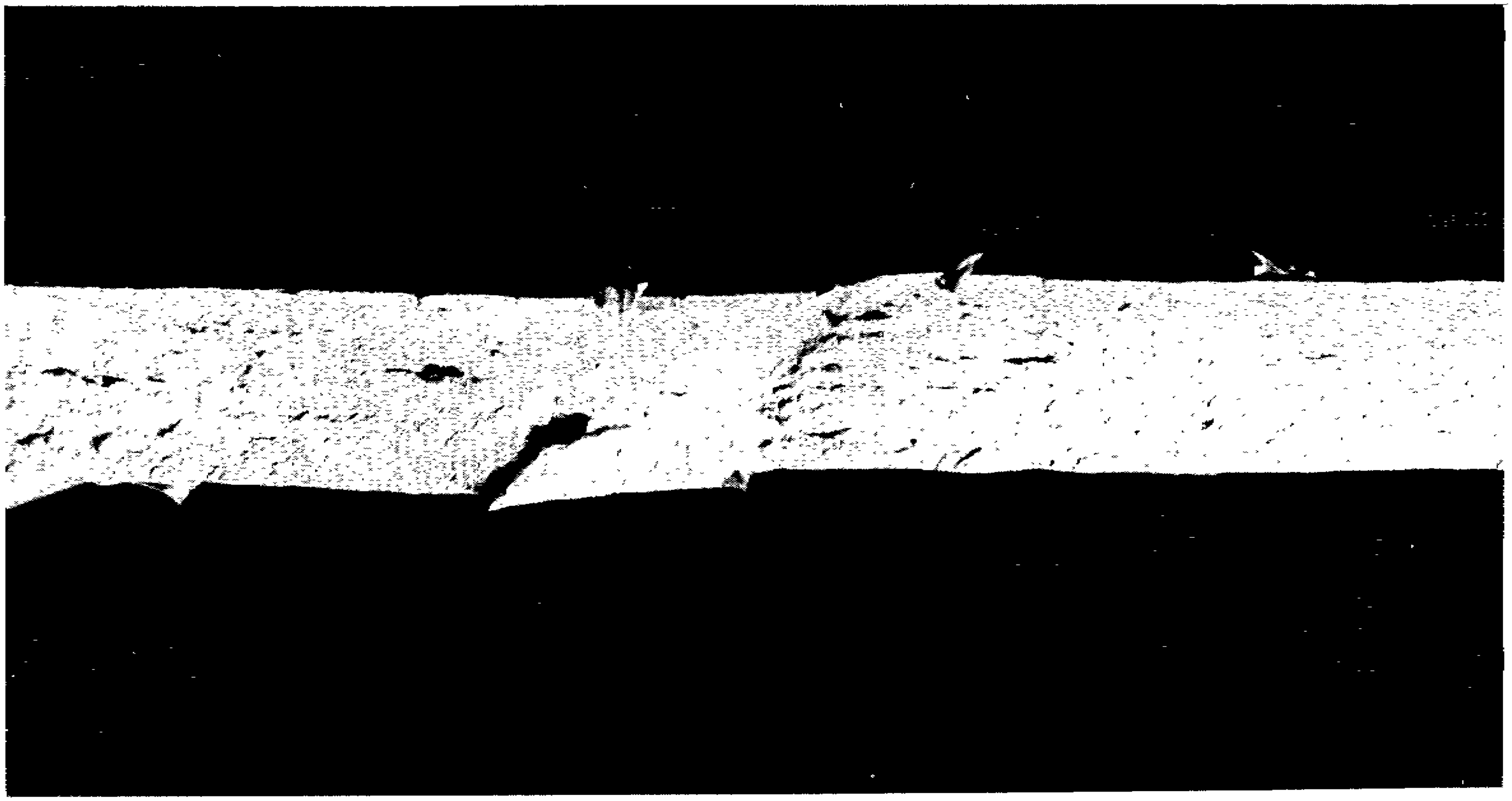


Fig. B-2. Appearance Of The Fracture Surface - Test B2; Specimen Configuration: Fatigue Crack Generated At The Tip Of A 6" Edge Slot; Test Temperature: +40°F; Fracture Stress: 32,000 Psi On The Gross Section; 33,700 Psi Avg. On The Net.

residual stresses at the fatigue crack tip. It may be postulated that the residual stress field around the tip of the fatigue crack encompassed more material because of the wider (24 versus 12 inches) patch; therefore, a fracture load lower than for Test B2 resulted.

B.4 Test B4

Test B4 was performed for the purpose of determining if fracture could be initiated from a Charpy-Vee notch pressed into the side of the specimen. If so, it was felt that much of the weld induced distortion could be eliminated, thereby making the strain gage data more accurate, meaningful, and easier to interpret. Accordingly, a new unnotched patch and panel was spliced into the specimen used for Test B3 and a hydraulic cylinder was attached to an outrigger which, in turn, was welded to the test facility. A Charpy-Vee notching die was pressed to a depth of 0.080 inch into the patch with a 50,000 lb load; the panel was then cooled to +35°F and the load slowly applied to a value of 5.75×10^6 lbs. Though this was close to yield in the unnotched section (34,700 psi), fracture did not initiate.

B.5 Test B5

This test was performed for the purpose of determining whether or not an increase in patch length to, say 24-inches - and, hence, an accompanying decrease in the welding induced residual stress field about the fatigue crack tip - would retard or perhaps preclude the initiation of fracture. Another panel was therefore prepared with fatigue crack, as before, generated at the end of a 5-1/2-inch slot. Again, weldable gages were installed near the tip of the fatigue crack and the patch was spliced into a new test section to which strain gages had been affixed both top and bottom surfaces. No fracture resulted even though a 6.18×10^6 load, which corresponds to an average gross section stress of 37,500 psi, was applied. Deformation from welding was considerably less than in the previous tests and this was also apparent in the strain data because the underside strain gages affixed to the unnotched section read very nearly the same as their top surface counterparts. The measurement of residual stress at the crack tip this time was successful. The strain gage readings indicated a stress of about 28,000 psi tension on the upper surface and 10,000 psi compression, lower surface. Though not uniform as would be hoped, the values were at least below yield, thus indicating that the attempt to minimize the weld strains was successful.

B.6 Test B6

This test was essentially a re-run of Test B5 and was performed for the purpose of confirming the fact that lowering the residual stresses induced by welding seemed to inhibit the initiation of fracture. Also, it was planned that, if fracture did result, measurement of the speed of propagation would be useful information. Past experience, however, indicated that to simply replace the patch would lead to excessive distortion as well as high residuals. For this reason, a 12-inch strip was removed from the specimen width, and patch plus extensions (which ran

B.7 Test B7

Test B7 was performed for the purpose of determining if fracture would result using the Test B6 configuration at a lower temperature, say NDT minus 30°, which is +10°F. A new patch with full length extensions was therefore prepared and spliced into the old B6 specimen. Residual stresses near the fatigue crack tip were again successfully measured and this time, were fairly low, viz., 2500 psi on the upper surface, 16,500 psi on the lower surface; both were compression. After cooling, a load of 7.55 x 10^6 lbs (i.e., a gross section stress of 45,800 psi) was applied but fracture did not occur.

B.8 Test B8

As mentioned previously, instrumentation for the measurement of crack speed had been installed on the B6 specimen and it was desirable that this be used. Test B8, therefore, was conducted primarily for the purpose of generating a fracture without regard to the control or measurement of residual stresses. Therefore, a 6-inch torch cut slot was made on the side of the specimen opposite the Test B7 patch. The last inch of the slot was then filled with Hardex N weld rod as had been done for the Series 1 ASTM A212 Grade B specimens. Temperature was reduced to -35°F and load applied. As would be expected, fracture did result, but the load at fracture was 6.9 x 10^6 lbs, a value surprisingly high. On a reduced net section area of about 109" x 1-3/8" or 150 sq. in., this is an average stress of 46,000 psi. Fracture speed was found to be approximately 4000 ft/sec and, as indicated by the chevron pattern of the fracture, initiation occurred at the brittle weld bead. An overall view of the fractured specimen is shown in the photograph, Figure B-3.

B.9 Test B9

In general, Tests B5 through B8, inclusive, had at least loosely established the fact that failure at the NDT of +40°F was not likely to occur if an effort was made to reduce residual stresses at the tip of the fatigue crack. For these tests, residual stresses had been minimized by adding an extension to the patch, then splicing the assembly of patch plus extension pieces into the specimen proper. Test B9 therefore, was performed for the purpose of determining the effect of a lowered temperature, viz., to +10°F, keeping the same configuration except that, in this case, a longitudinal weld was made along the specimen center line. In regard to this weld, it was felt that the possibility of initiation would not be affected by the weld because of the physical distance from the fatigue crack. If fracture did initiate, however, it would be of interest to determine the effect on both path and speed as the crack crossed the weld. Accordingly, the specimen was fabricated, then welded into the test machine. Upon loading to 7.1 x 10^6 lbs, fracture did initiate, see Figure B-4. Fracture speed as determined from measurements on the first half of the plate was about 5500 ft/sec; therefore, no data was obtained because the crack progressed outside the break wires which were used to determine speed. An average stress of 44,000 psi was measured across the gross section.

B.10 Test B10

Test B10 was performed as a means of determining if the results of Test B9

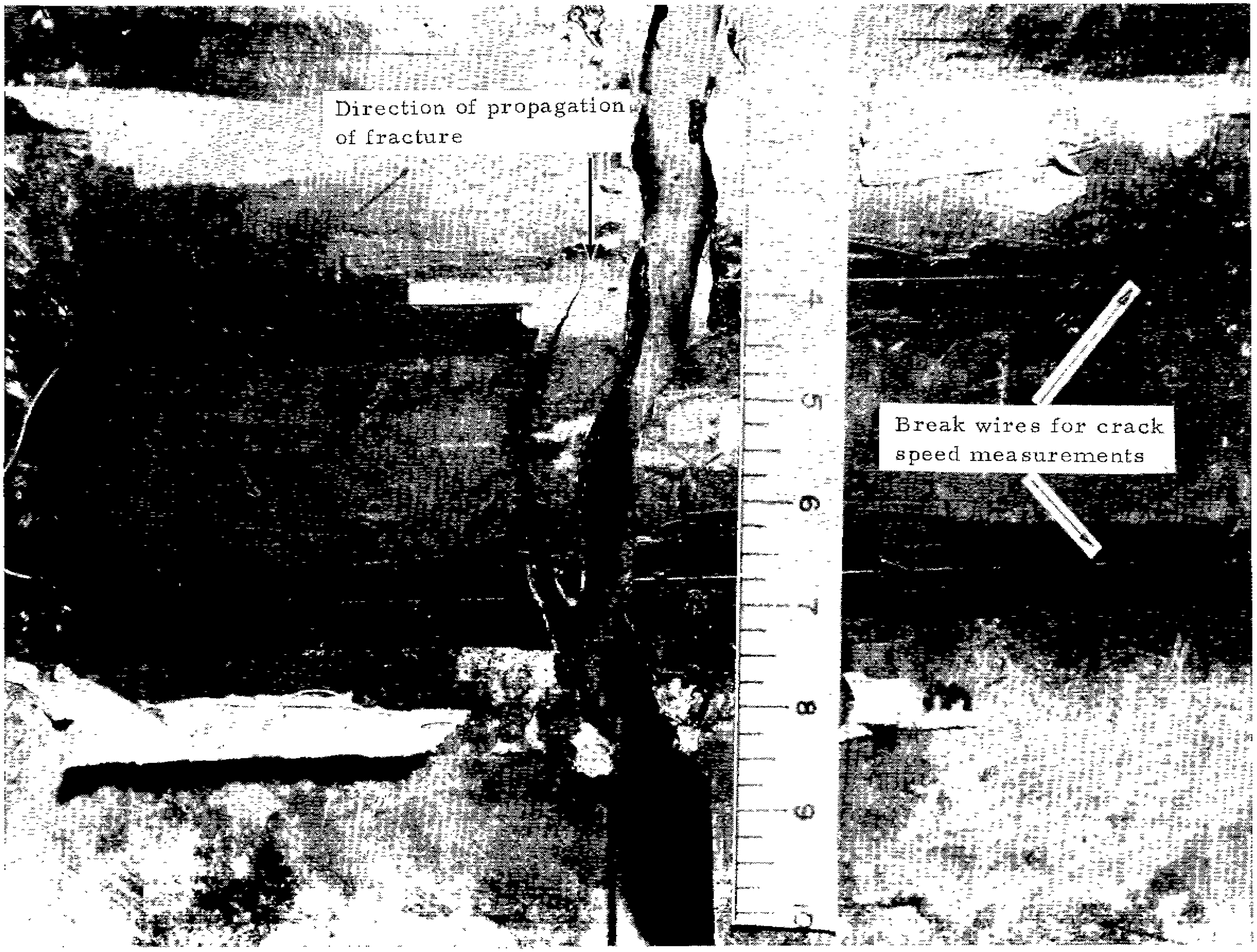


Fig. B-3. General View Of The Fracture - Test B8; Specimen Configuration: Initiation By Means of Brittle Bead At The End Of A 6" Edge Slot, Other Side Of Specimen; Test Temperature: -35°F; Fracture Stress: 41,800 Psi On The Gross Section; 44,000 Psi Avg. On The Net.

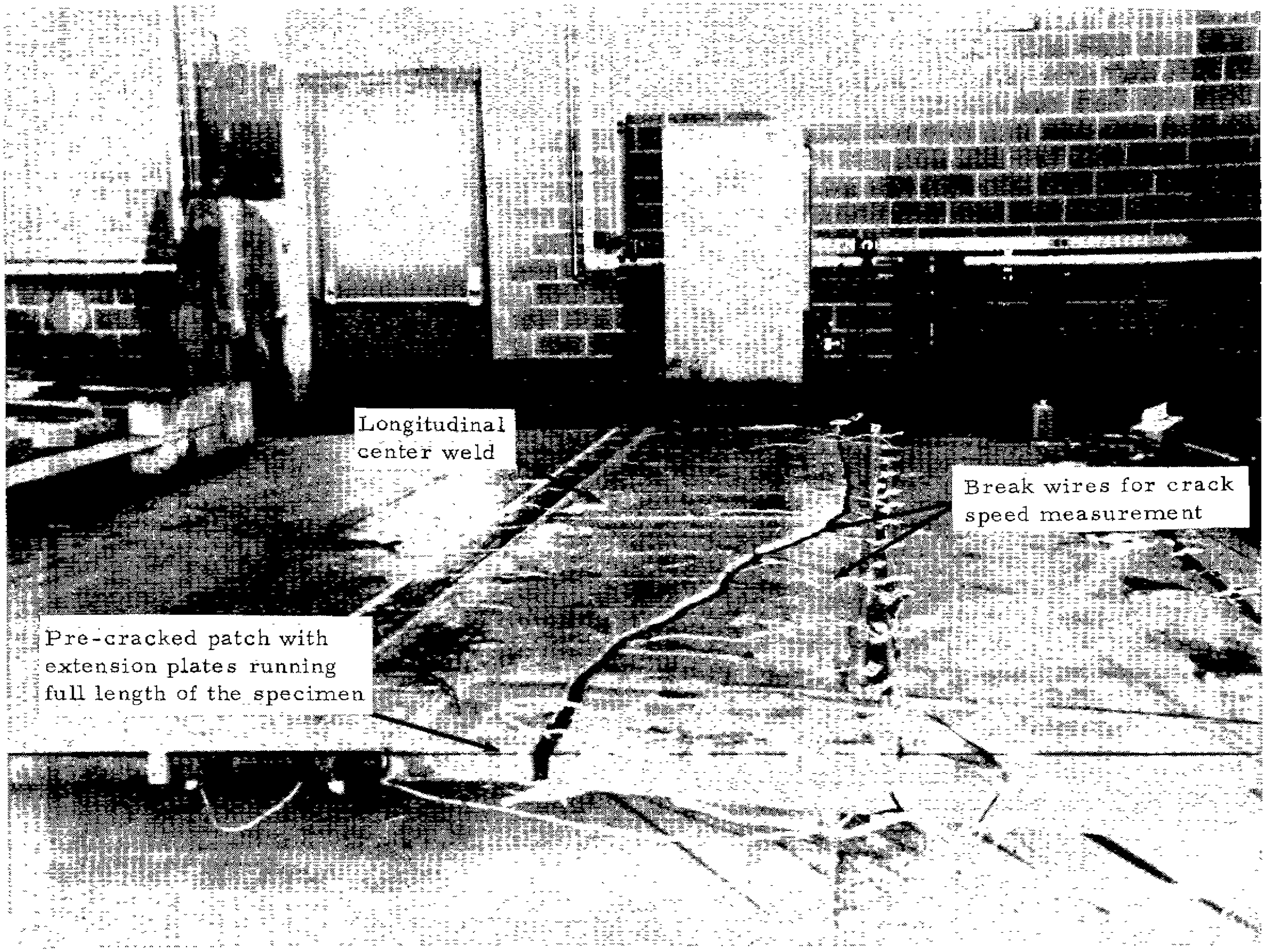


Fig. B-4. Overall View Of The Fracture - Test B9; Specimen Configuration: 5-1/2" Edge Slot Plus 1/2" Fatigue Crack In A 120 x 12" Patch. Specimen Has Weld Along The Longitudinal Centerline; Test Temperature: +10°F; Fracture Stress: 43,000 Psi On The Gross Section; 45,300 Psi Avg. On The Net.

could again be achieved; therefore, a pre-gaged panel of 35-inch length and full specimen width was spliced into the B9 fracture area. Again, temperature was +10 °F and a fracture nearly identical to the one obtained in Test B9 occurred. The fracture load was 6.5 x 10^6, somewhat lower than for Test B9. The indicated fracture speed was 5000 ft/sec; the average unnotched section stress, 34,000 psi. An overall view of the fracture is shown in the photograph, Figure B-5.

B.11 Test B11

With the exception of Test B4, all tests on the ABS Class C material thus far had been performed using an edge notch of 6 inch total length measured into the specimen width. It was therefore of interest to increase the length of the notch, thus the purpose of Test B11 in which the length of the torched slot plus fatigue crack was 18 inches. After preparation of the specimen and attachment to the test machine, temperature of the specimen was lowered to +5 °F and the load applied. Fracture resulted at an applied load of 4.1 x 10^6 lbs, a value considerably less than for the similar test, B1. Also, Test B8 resulted in a "pop-in" at an applied load of 3.77 x 10^6 lbs with crack extension to a value of slot plus "popped-in crack" to about 30 inches. As reported for Test B2, in which a "pop-in" was also noted, no drop in load was apparent and fracture followed at an applied gross section stress of 24,800 psi.

B.12 Test B12

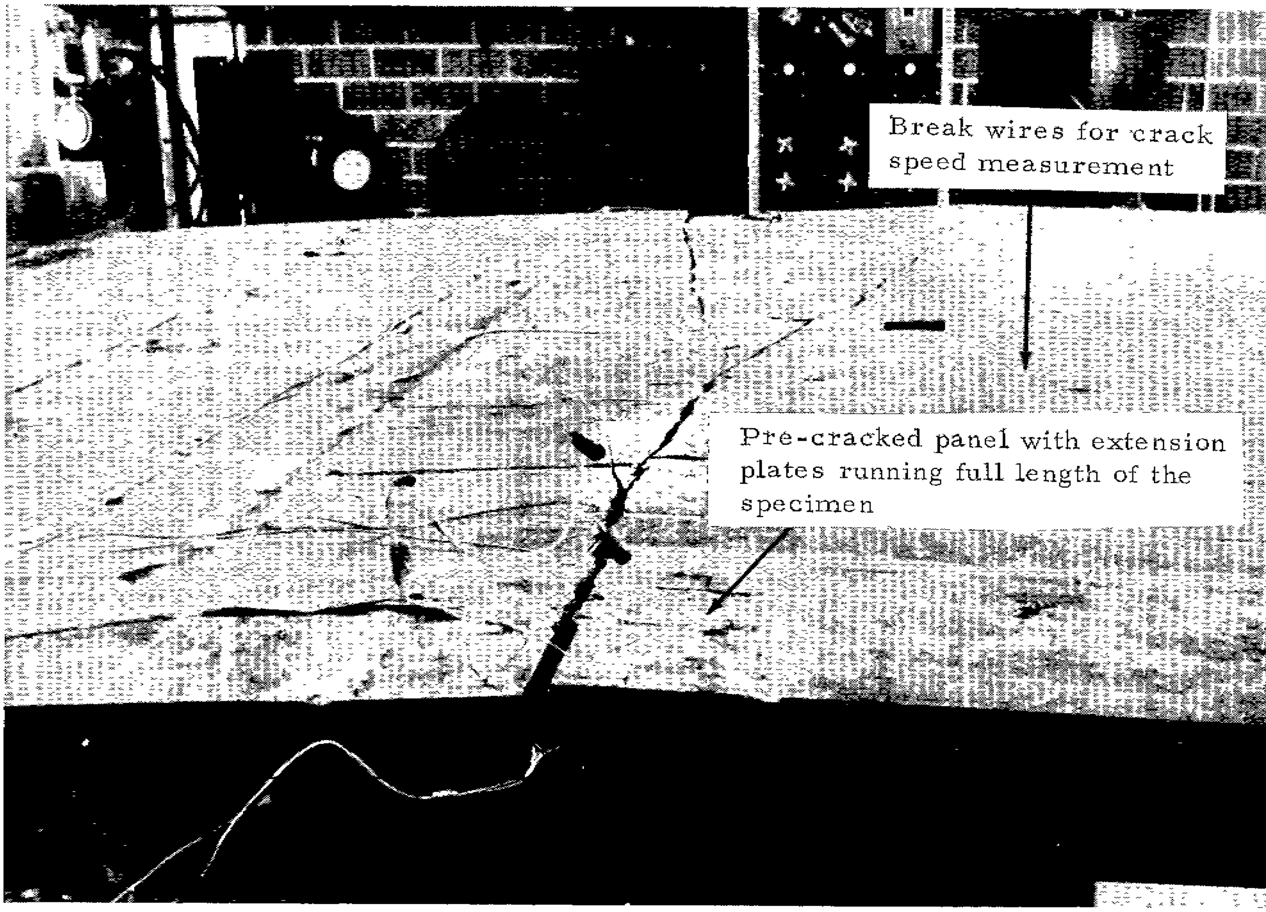
Test B12, and later B13, were performed for the purpose of comparison with the ASTM A212 Grade B test series. It will be remembered that the ASTM A212 Grade B specimens had a center slot and fracture was triggered by means of a brittle weld bead. For Test B12, a similar specimen geometry was used but initiation was accomplished by means of fatigue cracks generated in a pair of patch plates which were butted together and spliced into a cut-out at the specimen center; the total crack length "2a" was 13-inches. A temperature of +10 °F was chosen as the test temperature, the load applied and fracture at an applied load of 3.78 x 10^6 lbs resulted. Crack speed was measured and found to again be about 5000 ft/sec.; the gross section stress was 22,900 psi.

B.13 Test B13

Test B13 was performed for the purpose of investigating the effect of an increase in crack length "2a" of the center notched panel of Test B12. The configuration was fabricated using a new 45-inch center section to replace that of the previous test. Total crack length "2a" was 36 inches, three times that used in Test B12. The test temperature was +15 °F and fracture resulted at a load of 5.27 x 10^6 lbs. It is believed that this value, which is 40% above that of Test B12, resulted from the influence of excessively high residual stresses which tended to blunt the crack tips an amount sufficient to retard initiation of the fracture.

B.14 Test B14

Test B14, the first of a series of three stiffened plate tests, was performed for the purpose of determining the effect of stiffeners welded parallel to the load



Break wires for crack speed measurement

Pre-cracked panel with extension plates running full length of the specimen

Fig. B-5. Overall View Of The Fracture - Test B10; Specimen Configuration: 5-1/2" Edge Fatigue Crack In A 120 x 12" Patch. Specimen Has Weld Along The Longitudinal Temperature: +10°F; Fracture Stress: 39,400 Psi On The Gross Section; 41,50 Net.

axis of the specimen. The selected configuration consisted of the 1-3/8" ABS Class C plate material plus two 1-3/8 x 6" bars welded 18 inches each side of the specimen center line. As for the test previously described, the initiation site was a fatigue crack generated at the end of a 5-1/2" torch cut slot which was made in a 12 x 12" patch plate. New material was used for Test B14. As before, strain gages were applied, the patch spliced into the basic plate and, in this case, stiffeners attached before welding the assembly into the test machine. The assembly was lowered 1/4 inch with respect to the loading plane of the test facility in order to insure that the load was applied on the centroidal plane of the specimen. Basically, the instrumentation affixed to this specimen was similar to that of the previous tests but additional gages were added to the stiffeners at points in line with the fatigue crack. As stated before, all gages were laid prior to welding in order to measure the welding-induced residual stresses. In magnitude, these stresses were in all cases considerably less than the material yield. However, it was again impossible to prevent overall bowing of the specimen. After installation, the selected test temperature of +40°F was attained and a load of 6.95 x 10^6 lbs was applied to the specimen. Fracture did not occur but the fatigue crack did extend a distance of about 1/2-inch during the test.

B.15 Test B15

This test, the second of the stiffened plate series, was performed for the purpose of determining the effect of lowering the test temperature to +10°F. The crack starter patch was replaced by one of slightly larger size, viz., 14 x 12 inches, the temperature reduced and the load applied. All instrumentation from Test B14 remained. This time, at a load of 3.0 x 10^6 lbs, (20,500 psi on the gross section) fracture did occur. The fracture path was straight and in line with the fatigue crack, and there was no indication that the stiffeners had any influence on the fracture load. An overall view and a closeup of the fracture surface is shown, see Figures B-6 and 7.

B.16 Test B16

Because of the nature of the fracture resulting from Test B15, it was desired to repeat the test as to configuration but at a lower temperature and without benefit of the high residual stresses induced by welding-in of the small patch plate. Specimen B16 was therefore welded together, the specimen installed in the test machine and the temperature lowered to -35°F. Fracture occurred, but at the surprisingly high load of 6.73 x 10^6 lbs. This is an average unnotched section stress of 37,100 psi based on a plate plus stiffener area of 182 in^2. The fracture appeared identical to that for Test B15.

B.17 Test B17

Test B17 was devised in an attempt to obtain a complete crack arrest, a phenomena which thus far had not been obtained on the ABS Class C material. This was considered important and a plain plate with the usual patch with slot plus fatigue crack was therefore fabricated and installed in the test machine. For this test, however, the cooled portion was an area 1 foot wide by a two foot length extending across the specimen width. A fracture, if effected, would then run into a warm (70°F) area and perhaps arrest. Temperature near the fatigue crack was

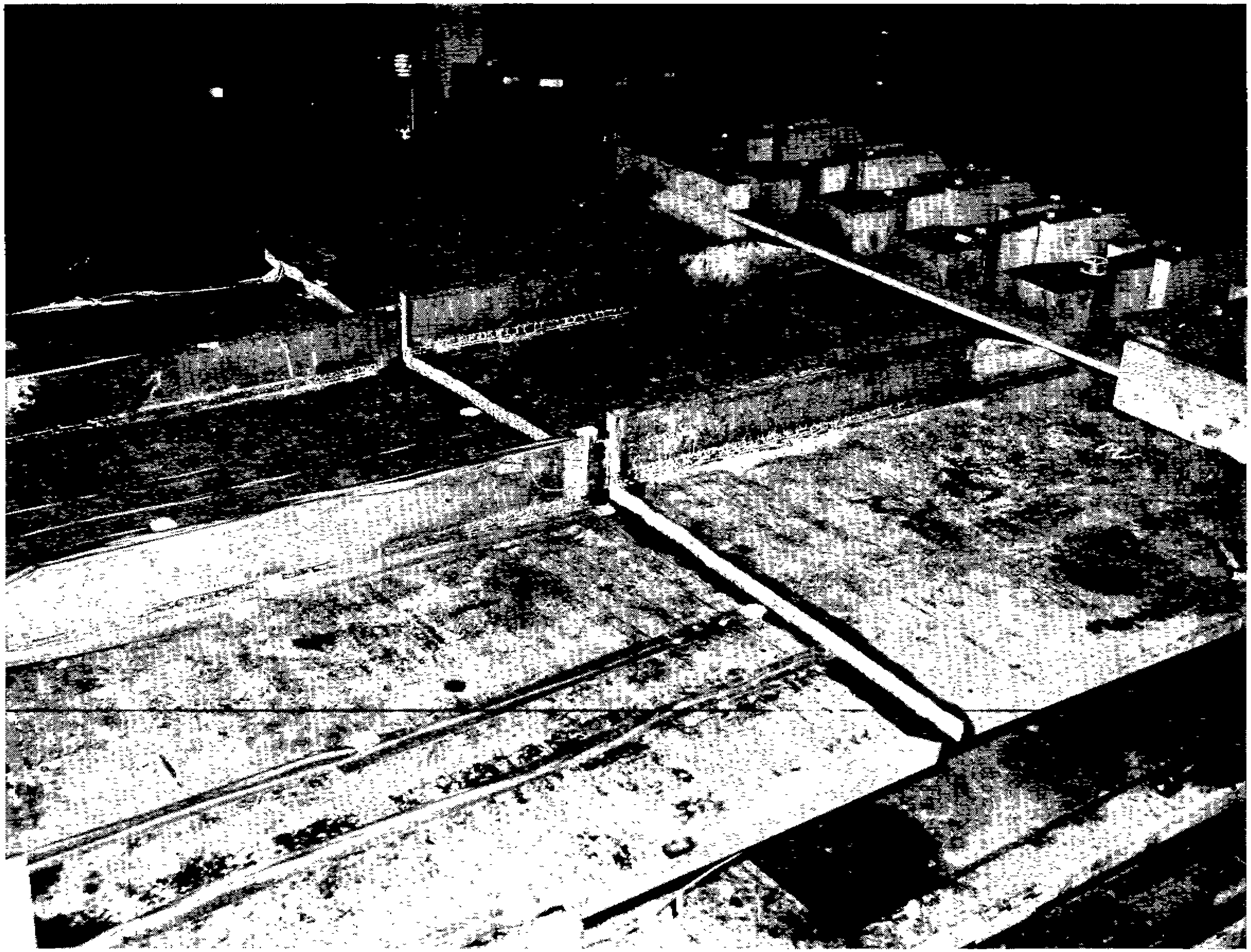
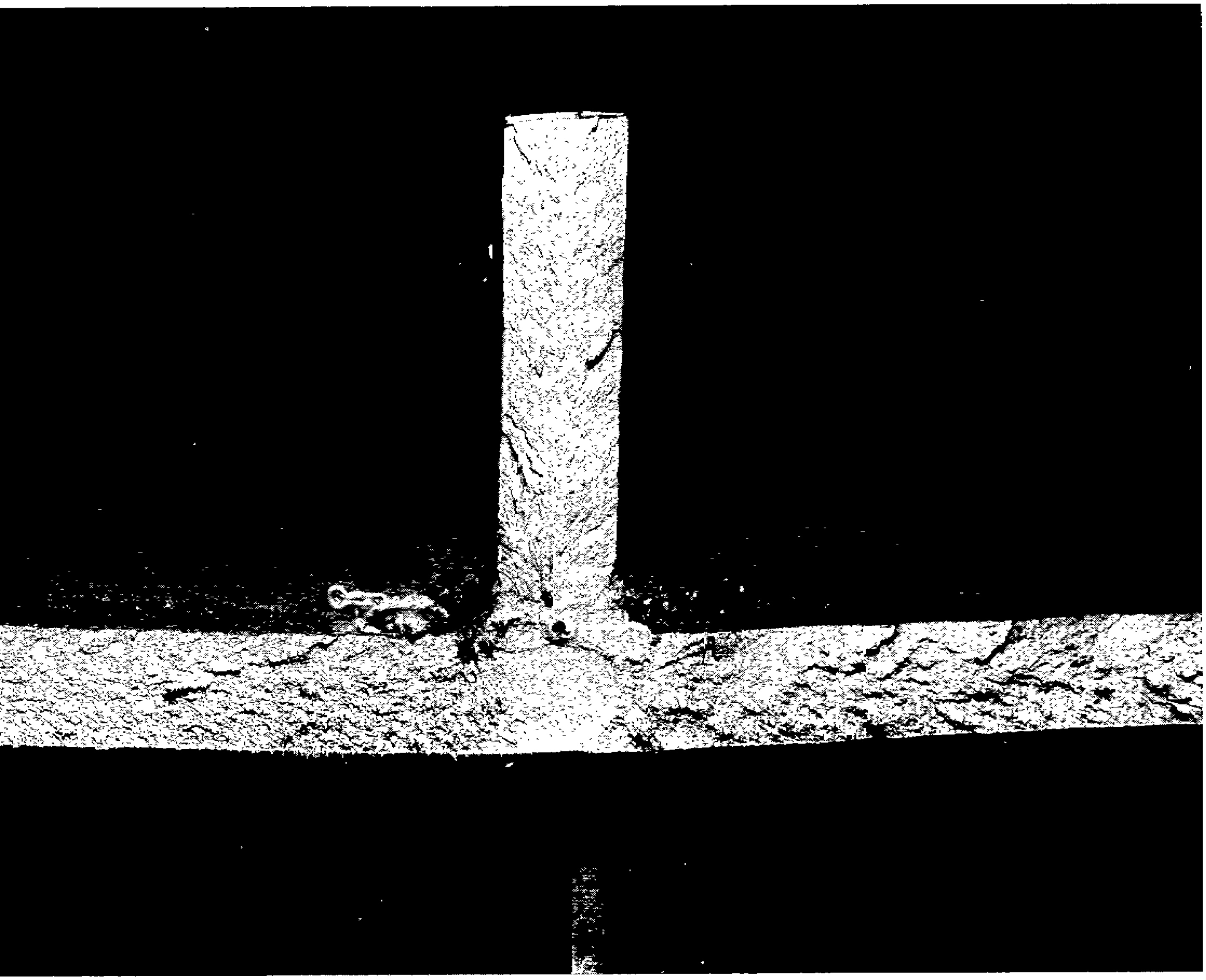


Fig. B-6. Overall View Of The Fracture - Test B15; Specimen Configuration: 5-1/2" Edge Slot Plus 1/2" Fatigue Crack In A 120 x 12" Panel - Stiffened Plate; Test Temperature: +10°F; Fracture Stress: 20,500 Psi On The Gross Section; 21,500 Psi Avg. On The Net.



3-7. Fractured Surface Thru A Stiffener And Adjacent Plate - Test B15.

next lowered to +10°F and load applied to the specimen; fracture did not occur even at an applied load of 6.8 x 10^6 lbs, i.e., 41,200 psi.

B. 18 Test B18

Because fracture did not initiate in the case of Test B17, a new pre-cracked patch was installed and Test B18 performed with the fatigue cracked area at a temperature of -100°F. Though not measured it was known from previous measurements that yield point residual stresses would be induced near the crack tip; this fact, coupled with the very low temperature, should induce fracture at a low load, hence low energy. This, it was felt, might very well result in the attempted arrest. Such was indeed the case; fracture occurred at a load of 3.1 x 10^6 lbs, (i.e., 18,000 psi) and, as shown in photograph, Figure B-8, fracture stopped after traveling a distance of 18 inches.

B. 19 Explosion Bulge Tests of the ABS Class C Test Material

The results of explosion tests performed on the material are presented in Figure B-9.

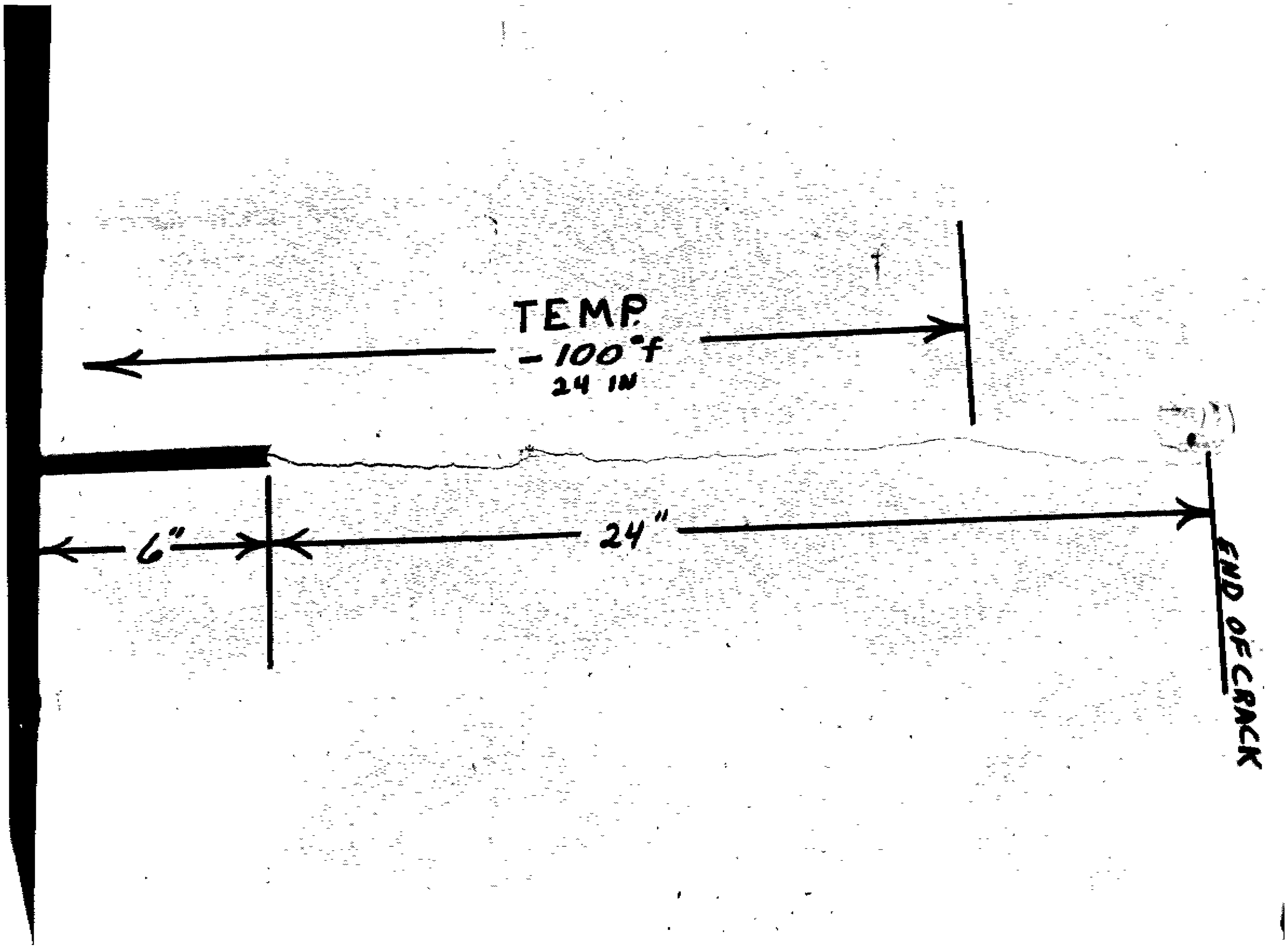


Fig. B-8. Crack Arrest - Test B18; Specimen Configuration: 5-1/2" Edge Slot Plus 1/2" Fatigue Crack In A 12 x 12" Patch; Cooling Effected Only Around The Fatigue Crack And For A Distance Of 24" Across The Specimen Width; Test Temperature: -100°F; Fracture Stress: 18,800 Psi On The Gross Section; 19,800 Psi Avg. On The Net.

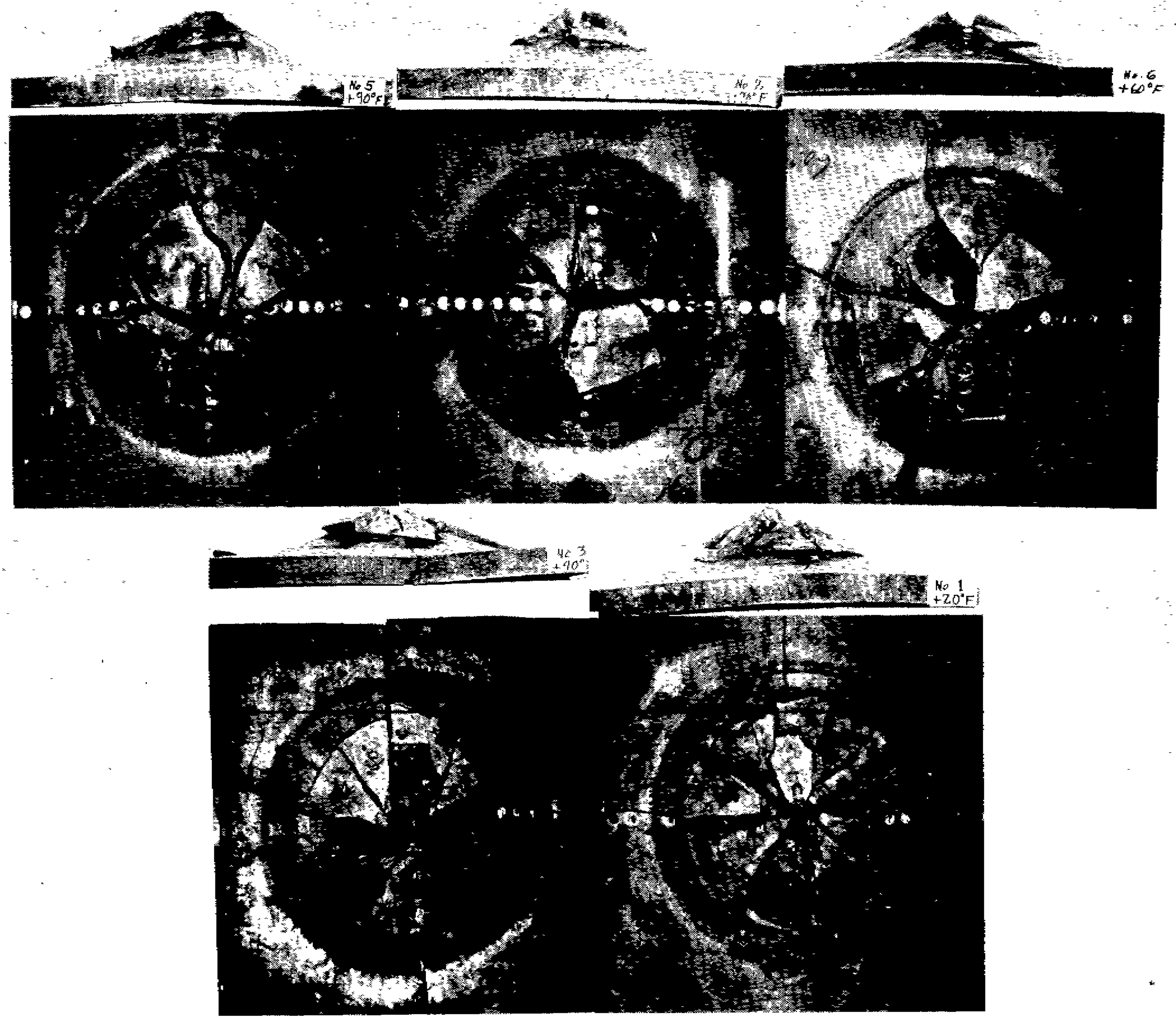


Fig. B-9. Photographs Of The Explosion Bulge Tests Of The ABS Class C Test Material.

APPENDIX C

DESCRIPTION OF THE TEST FACILITY

It was decided in the preliminary planning for this investigation that the smallest sized test article that would realistically simulate a full scale ship structure was a panel type specimen about 10' x 10' in planform. Further, if not for the immediate program, then for future study, a material such as HY 80 plate in thickness as great as 1-1/2", might merit testing. To produce yield stress across the entire width, a load of about 15,000,000 lbs would thus be required. These considerations established the test facility requirements, a photograph of which is shown in Figure C-1.

The test machine was designed and built by personnel of Southwest Research Institute, at Institute expense. Basically, it is a simple mechanical lever made to rather large proportions. The machine is attached to a reinforced concrete base weighing, roughly, 300,000 lbs; the levers, of which there are eight connected in parallel, are reinforced 14 x 14-1/2" standard wide flange beams weighing 264 lbs/ft. The levers have a mechanical advantage of 7.5:1 and the driving force is supplied by hydraulic cylinders which lie within the cantilevered portion of the platform; these may be seen towards the top of the photograph. All cylinders receive pressure from a 63:1 ratio air-hydraulic reciprocating booster which operates on 80 psi air. The release of energy resulting from specimen fracture is absorbed by the mass of the testing machine and by plastic deformation which occurrs in the large lead blocks when they are impacted by the lever beams. The edge of one of these blocks can be seen in Figure C-1. The machine has the following characteristics:

1) Load capability: 15,000,000 lbs, tension or compression, applied along a plane 7-1/2" above the machine base.
2) Loading rate: approximately 0.2 inch per minute maximum with the present hydraulic system. The minimum rate can be as slow as desired.
3) Special loading: normal load to ± 1,500,000 lbs; cyclic load capability to ± 5,000,000 lbs, axial, and ± 1,500,000 lbs, normal.
4) Travel: 1.0" minimum along a plane 7-1/2" above the base.
5) Specimen size: 10' in length by 15' in width.
6) Temperature: specimens at temperatures between -100 and +250°F can be tested.

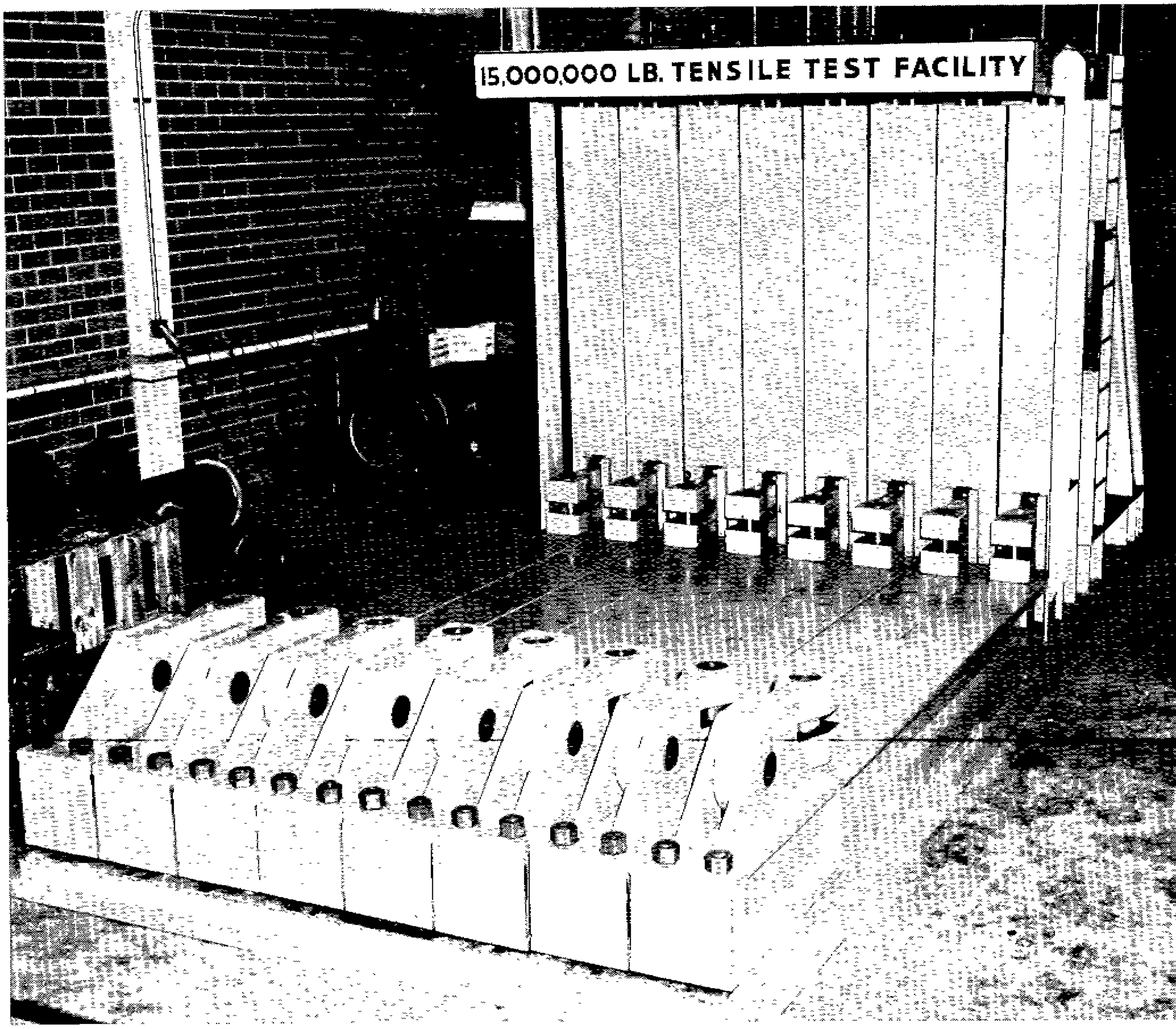


Fig. C-1. The 15,000,000 Lb. Capacity Tensile Test Facility - Department Of Structural

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1. ORIGINATING ACTIVITY *(Corporate author)* Southwest Research Institute	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b GROUP

3. REPORT TITLE

SIMULATED PERFORMANCE TESTING FOR SHIP STRUCTURE COMPONENTS

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Final Report

5. AUTHOR(S) *(Last name, first name, initial)*

Robert Sherman

6. REPORT DATE 1970	7a. TOTAL NO. OF PAGES 64	7b. NO. OF REFS 12

8a. CONTRACT OR GRANT NO. NObs92294	9a. ORIGINATOR'S REPORT NUMBER(S) SwRI Project No. 03-1695
b. PROJECT NO.	
c.	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)* SSC-204
d.	

10. AVAILABILITY/LIMITATION NOTICES

Distribution of this document is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Naval Ship Systems Command

13. ABSTRACT

In this report, the results obtained from wide-plate tension tests undertaken for the purpose of simulating the full-scale performance of steel used in ships' hulls are presented. Information as to initiation and propagation of fast fracture in wide steel plates was first obtained through a series of nineteen tests performed on a newly developed wide-plate testing machine. The test material was the pressure vessel steel, ASTM A212 Grade B in 3/4-inch thickness. This information, and the techniques developed, were then applied to a total of eighteen tests using ABS Class C steel, having a thickness of 1-3/8-inch. All specimens were 10 feet wide and 3 were stiffened longitudinally. Test temperatures ranged from -100°F to a room temperature ambient of +75°F. A fatigue crack or a brittle bead was used as a crack initiator and large residual stresses were introduced.

In general, the tests indicated that, at sufficiently low temperatures, a fast fracture could be produced in ASTM A212 Grade B and ABS Class C steels if a sufficiently sharp initiation site was located within an area of relatively high applied and/or residual stress. Based on the results of the tests conducted, it is concluded that the ABS Class C material is not sensitive to fast fracture at temperatures well below service temperatures. Therefore, this material may be used to effect a fracture safe design for modern ship hulls.

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