File Copy

SERIAL NO. SSC-76

FINAL REPORT
(Project SR-120)

on

INVESTIGATION OF PERFORMANCE OF SEMIKILLED CARBON STEEL ABS CLASS B AND RIMMED STEEL ABS CLASS A UNDER DIRECT EXPLOSION TEST

by

G. S. MIKHALAPOV and W. A. SNELLING
Metallurgical Research and Development Company

Under Bureau of Ships Contract NObs-2386
(BuShips Project NS-011-067)

for

SHIP STRUCTURE COMMITTEE
Convened by
The Secretary of the Treasury

Member Agencies—Ship Structure Committee

Bureau of Ships, Dept. of Navy
Military Sea Transportation Service, Dept. of Navy
United States Coast Guard, Treasury Dept.
Maritime Administration, Dept. of Commerce
American Bureau of Shipping

Address Correspondence To:

Secretary
Ship Structure Committee
U. S. Coast Guard Headquarters
Washington 25, D. C.

SERIAL NO. SSC-76
BuShips Project NS-011-067

JULY 9, 1954

SHIP STRUCTURE COMMITTEE

MEMBER AGENCIES:

BUREAU OF SHIPS, DEPT. OF NAVY
MILITARY SEA TRANSPORTATION SERVICE, DEPT. OF NAVY
UNITED STATES COAST GUARD, TREASURY DEPT.
MARITIME ADMINISTRATION, DEPT. OF COMMERCE
AMERICAN BUREAU OF SHIPPING

ADDRESS CORRESPONDENCE TO:

SECRETARY
SHIP STRUCTURE COMMITTEE
U. S. COAST GUARD HEADQUARTERS
WASHINGTON 25, D. C.

July 9, 1954

Dear Sir:

As part of its research program related to the improvement of hull structures of ships, the Ship Structure Committee has sponsored an investigation of the performance of semikilled and rimmed ship plate steels and weldments when subjected to the direct explosion test. Herewith is a copy of the Final Report on this investigation entitled "Investigation of Performance of Semikilled Carbon Steel ABS Class B and Rimmed Steel ABS Class A under Direct Explosion Test" by G. S. Mikhalapov and W. A. Snelling.

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

This Report is being distributed to those individuals and agencies associated with and interested in the work of the Ship Structure Committee.

Yours sincerely,

K. K. Cowart

K. K. COWART
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

Final Report
(Project SR-120)

on

INVESTIGATION OF PERFORMANCE OF SEMIKILLED CARBON STEEL ABS CLASS B AND RIMMED STEEL ABS CLASS A UNDER DIRECT EXPLOSION TEST

by

G. S. Mikhalapov and W. A. Snelling

METALLURGICAL RESEARCH AND DEVELOPMENT COMPANY

under

Department of the Navy
BuShips Contract NObs 2386
BuShips Project No. NS-011-067

for

SHIP STRUCTURE COMMITTEE

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

REPORT ON INVESTIGATION OF PERFORMANCE OF SEMIKILLED CARBON STEEL ABS CLASS B AND RIMMED STEEL ABS CLASS A UNDER DIRECT EXPLOSION TEST

INTRODUCTION

A series of investigations[(1)] sponsored by the Bureau of Ships, Department of the Navy, revealed considerable difference in performance of welded alloy steel plate when subjected to the system of triaxial stresses believed to exist in the Direct Explosion Test. The Ship Structure Committee became interested in determining whether corresponding differences in performance would not be found in low carbon steel plate used for the construction of merchant marine vessels. The Committee was particularly interested in determining whether differences in welding procedure would not result in a marked difference in performance.

Accordingly, the Ship Structure Committee sponsored an investigation[(2)] wherein two heats, one of fully killed ABS Grade C and the other semikilled ABS Grade B, both 1-in. thick, were welded with different welding procedures and subjected to Direct Explosion Tests. The principal result of this investigation indicated a marked improvement in performance of fully killed steel when welded with low hydrogen electrodes over the performance of the same steel when welded with cellulose type electrodes. The difference in performance of semikilled steel when welded with the two respective grades of electrodes was less pronounced, the net effect being to approximate the performance of killed steel when welded with cellulose type electrodes. Although considerable scatter was observed to exist in the performance of semikilled steel plates welded with low hydrogen electrodes, even the specimens exhibiting the poorest performance still appeared to maintain a substantial, although not spectacular, superiority over the plates welded with cellulose type electrodes.

Accordingly, it was decided that an additional investigation should be conducted to determine the degree of magnitude of improvement of structural performance which the use of low hydrogen electrodes produced in semikilled steel and, if possible, to establish whether it was of real significance. In addition, a brief investigation of the performance of rimmed steels under the Direct Explosion Test was also undertaken.

However, part way through the investigation it became apparent that performance of a single heat of semikilled steel was not uniform but varied very considerably depending on the particular slab and even plate used. As a result, a secondary objective of the investigation developed, and an attempt was made to establish the degree of variation of performance which can exist within one heat of steel and to correlate, if possible, this variation with conventional notched sensitivity tests, such as Charpy impact and Navy tear tests.

An additional original objective of this investigation was a comparison of performance evaluation by Direct Explosion Test with performance evaluation by the Stand-off (Explosion Bulge) Test as developed by the Naval Research Laboratory. However, because of the difference in performance existing between different plates of the heat of steel purchased, the results of this comparison appear to be somewhat inconclusive.

METHOD OF TESTING

The Direct Explosion Test has been described in a number of previous reports[1,3]. It will be remembered that the test consists of subjecting a number of identical specimens to a blow produced by an explosion of a cylindrical charge of an explosive powder packed to a desired density. The magnitude of each charge is progressively increased until an energy value is reached which just fractures a specimen. The extent of deformation of the specimen subjected to the explosion of a charge just below the minimum charge to fracture is noted and provides an indication of the maximum deformation the plate tested can sustain under the test condition. Specimen failure is said to have occurred when the total length of all fractures exceeds 18 inches. (Actually, in the present investigation the overwhelming majority of plates which fractured at all fractured into several pieces).

As stated above, two grades of ship plate were procured, ABS Class B semikilled steel, and ABS Class A* rimmed steel. ABS Class B was procured in both 1-in. and 3/4-in. thickness, whereas Class A was procured in 3/4-in. thickness. The plate identification for these steels is given in Table I, and the mechanical properties and typical analyses are shown in Table II.

A complete performance record covering a temperature range of 70° to -90°F was obtained for unwelded or prime plate, whereas most of the comparisions between the performance of plates welded with different procedures were conducted at 10° and 32°F.

The majority of welds were made with Navy Grade 180 electrodes and with Class E6010 electrodes. Because one of the original objectives of the investigation was the determination of the optimum performance that could be expected from a semikilled or rimmed steel plate as a result of a specific welding procedure, several additional welding procedures were tried. These included use of Navy Grade 230 electrode, Unionmelt process with #36 and #40 rods, and Aircomatic welding process with two grades of welding wire. In addition, 400°F preheat and 1150°F thermal stress relief were used on both Grade 180 and Class E6010 electrode welded joints.

1. <u>Manual weld</u>: 60° double V, 5/32-in. root opening, 0 root face, root pass made with 5/32-in. diameter electrode, chipped out to sound metal and welded with three passes on

---

*Class A composition and strength specification rolled to 3/4-in. thickness.

Table I

LEGEND--PLATE CODE No.

Steel Designation	Code No.	Mill		Heat No.	Slab No.	Ingot No.	Cut No.	Plate
AR	1	Carnegie-Illinois		73U399	123519	2	2	A
"	2	"	"	"	"	2	2	B
"	3	"	"	"	123520	2	1	A
"	4	"	"	"	123522	3	1	B
"	5	"	"	"	123523	4	2	A
"	6	"	"	"	"	4	2	B
"	7	"	"	"	"	4	2	C
"	8	"	"	"	123524	4	1	A
"	9	"	"	"	"	4	1	B
ARX	10	"	"	"	123527	4	1	A
AT	11	Lukens		16445				A & B

TABLE II

CHEMICAL COMPOSITION AND MECHANICAL PROPERTIES OF SPECIMEN STEELS

Steel Designation	Mfgr.	Heat No.	Deoxidation	Thickness	LADLE ANALYSIS C	Mn	P	S	Cu	Ni	Cr	Si	Plate Code	CHECK ANALYSIS C	Mn	P	S	Cu	Ni	Cr	Si	MECHANICAL PROPERTIES Yield Point	Tens. Str.	Elong. 2"
AR	C. Ill	73U399	S.K.	1"	.17	.72	.018	.036					2	.19	.80	.014	.030	.04	.02	.02	.05	33500	57800	43%
													4	.21	.81	.017	.038	.04	.02	.02	.06	34600	62400	41%
													7	.20	.81	.017	.035	.03	.02	.02	.05	34300	59000	42%
													8	.19	.80	.017	.034	.04	.02	.02	.05	34200	61900	41%
													9	.21	.78	.017	.034	.04	.02	.02	.05	33500	61300	41%
ARX	C. Ill	73U399	S.K.	3/4"	.17	.72	.018	.036																
AT	Lukens	16445	Rim	3/4"	.27	.47	.017	.037	.30	.10	.074	--										*39400	68100	24%†
																						**38200	64300	26%†

NOTE: Check analyses and mechanical property data for plate codes 2, 4, 7, 8 and 9 are as reported in "Report of Investigation on the Notch-Sensitivity Characteristics and Other Properties of ABS, Class B, Steel Plate for Explosion Test Program under Ship Structure Committee - Lab. Project 4936-90, Parts 1 and 2, Final Report, NS 011-043 and NS 011-084" 3 August 1953, by the Material Laboratory, New York Naval Shipyard, Brooklyn 1, New York.

* Transverse

** Longitudinal

† Elongation in 8 inches

each side, using 1/4-in. diameter electrode. A total of seven passes.

2. Submerged arc weld: 90° double V, 1/4-in. root face, 0 root opening, submerged arc welded (using Unionmelt #20 Flux) with two passes of 1/8-in. electrode, one pass for each side.

Seventy degree (70°) F preheat and interpass temperature was used in all cases except in case of Grade 180 electrode where a number of specimens were prepared with 200° preheat and interpass temperature and, of course, in the case of specimens subjected to special weld treatments mentioned above.

Two sources of welding facilities were used, one the Baldwin-Lima-Hamilton Corporation and the other, the Philadelphia Naval Shipyard. When it became apparent that the performance of supposedly identical specimens made at the two facilities did not agree, an attempt was made to check the possibility of the variations in welding procedures between the two sources by having the Philadelphia Naval Shipyard make welds on specimens prepared from the steel plate used for some of the Baldwin specimens. The results of tests of these specimens showed similar performance, and since startling differences in performance of specimens made from two different unwelded plates were also observed, no further attempt to compare the quality of welding of the two sources was made.

As soon as the difference in performance of unwelded plate was established, a review of all available steel plate of the heat purchased was made. In general, it was found that each plate was identified as belonging to a certain slab, ingot, and cut. A slab number appeared to identify a specific cut of a specific ingot; thus slab #123520 is a first cut of ingot #2, whereas slab #123519 is the second cut of the same ingot. Similarly, slab #123524 was the first cut of ingot #4, whereas slab #123523 was the second cut of the same ingot. However, three plates, 73 in. by 220 in. in length, were rolled from each slab; and since these were not identified separately by the mill, they were given arbitrary designations of A, B and C.

The available identification of the steel plate used is given in Table I and is referred to herein after by the Code designation given in this table.

The steel mill was unable to provide any further identification of the plate shipped nor was it able to advance any theories as to why a difference in their performance could be expected.

Complete mechanical tests, including Charpy impact and Navy tear tests, were originally planned for the identification of the heat used. Unfortunately, these tests were planned and completed before the difference in individual plate performance was detected by the Direct Explosion Test; and accordingly, a complete test record of all of the plates tested is not available. However, it will be seen from Table III that Charpy

TABLE III

RESULTS OF CHARPY V-NOTCH AND NAVY TEAR TESTS ON STEEL AR

Plate Code No.	Location in Plate	Tear Test Transition Temperature, °F	Charpy V 15 ft-lb Transition Temperature, °F
2	End	90	24
4	End	80	17
	End*	--	30
	Center	90	19
	Opposite End	70	26
5	Middle	--	27
	End	--	28
7	(unknown)	--	25
	End	90	23
	Opposite End	100	22
8	End	90	18
	Center	100	16
	Center*	--	30
	Opposite End	90	22
9	End	90	20
	Center	120	20
	Center*	--	35
	Opposite End	110	22

NOTE: All results except those marked with (*) as reported in "Report of Investigation on the Notch-Sensitivity Characteristics and Other Properties of ABS, Class B, Steel Plate for Explosion Test Program under Ship Structure Committee - Lab. Project 4936-90, Parts 1 and 2, Final Report, NS 011-043 and NS 011-084" 3 August 1953; and Part 3 dated 30 November 1953, by the Material Laboratory, New York Naval Shipyard, Brooklyn 1, New York.

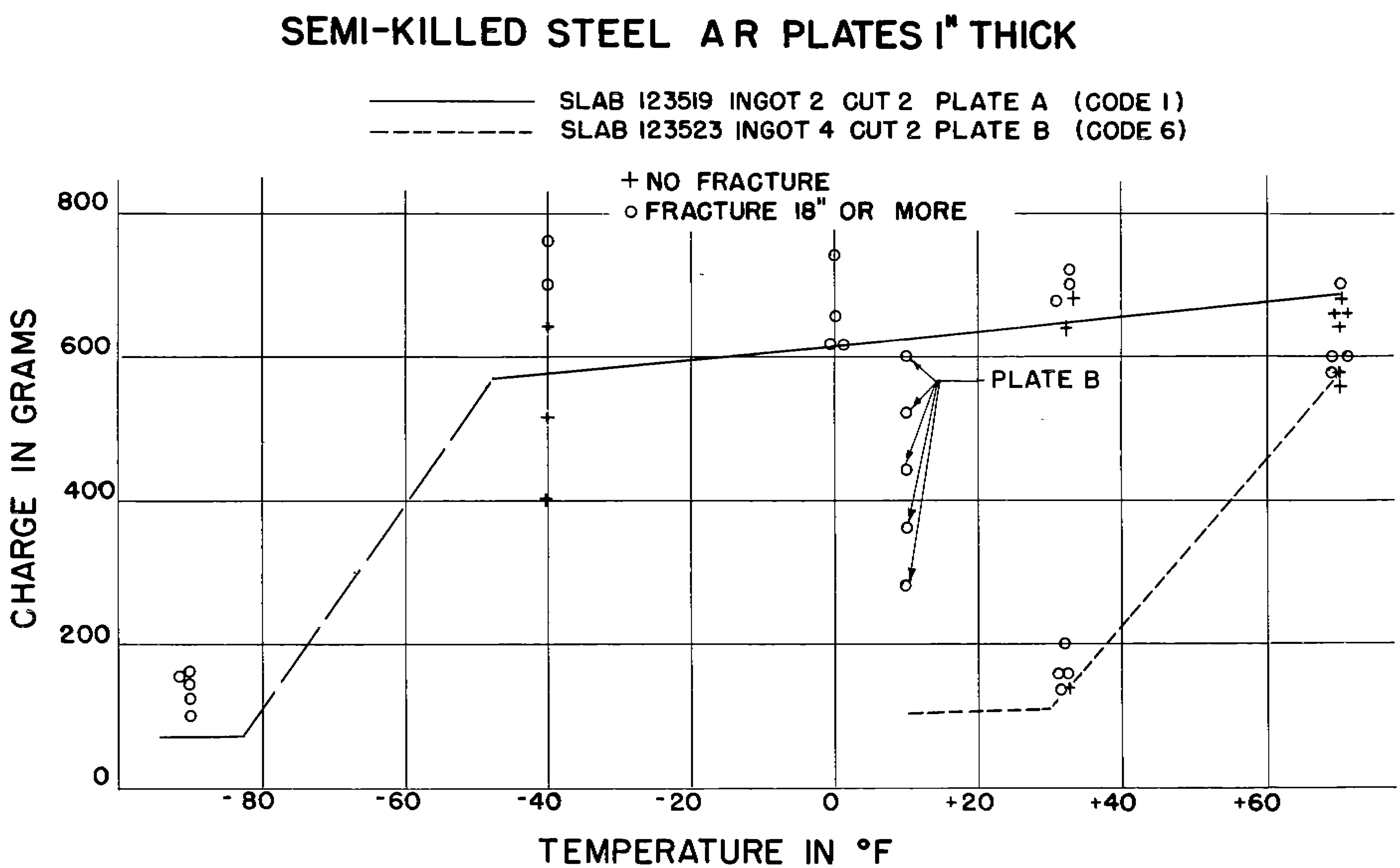
*Results marked with asterisk obtained by Naval Research Laboratory.

impact tests were made on four of the slabs used.

DISCUSSION OF RESULTS

Results of the tests are given in detail in Appendix A and are summarized graphically in Figures 1 through 8.

Figure 1 shows the performance of the two sets of specimens of unwelded plate made from two different slabs, namely, #123519 (Code 1) and #123523 (Code 6) of the same heat of 1-in. semikilled steel. Performance of each specimen is shown by a cross indicating a specimen which did not fail and by an O indicating those which did fail. It becomes immediately apparent that whereas performance of specimens made from slab #123519 (Code 1) remain virtually unchanged from room to below -40°F temperature, the performance at 32°F of specimens made from slab #123523 (Code 6) dropped drastically and nearly to the level of performance exhibited by slab #123519 (Code 1) at -90°. Since no tests were made at temperatures intermediate between -40° and -90° in case of slab #123519 (Code 1) steel and between 70° and 32° in case of slab #123523 (Code 6), the difference of transition temperature is somewhere between 72° and 160°. Referring to Table III, it will be seen that the difference in performance of these two slabs as determined by Navy tear tests is virtually nonexistent. However, it must be pointed out that the tear tests and Charpy specimens were not made from the same plate of their respective slabs as were the Direct Explosion specimens. In case of slab #123519 (Codes 1 and 2), the Direct Explosion Test failed to differentiate between


SEMI-KILLED STEEL A R PLATES 1" THICK
SLAB 123519 INGOT 2 CUT 2 PLATE A (CODE 1)
SLAB 123523 INGOT 4 CUT 2 PLATE B (CODE 6)
+ NO FRACTURE
o FRACTURE 18" OR MORE
PLATE B
800
600
400
200
0
-80
-60
-40
-20
0
+20
+40
+60
CHARGE IN GRAMS
TEMPERATURE IN °F
FIG. 1

plates A (Code 1) and B (Code 2), so that ostensibly the Charpy and tear tests made on plate B could be assumed to apply to plate A also. However, in case of slab #123523 (Codes 5, 6, and 7), some evidence exists that plate C (Code 7), from which the tear and Charpy test specimens were taken, is superior to plate B (Code 6), of the same slab from which the Explosion specimens were taken. This indication is based on the fact that the Aircomatic specimens prepared from plate C (Code 7) did not fracture at 32°F until after a charge of 250 grams was exceeded, whereas at the same temperature the unwelded specimens prepared from plate B (Code 6) fractured at as low a charge as 140 grams. Since it is hard to conjecture that a specimen welded with an Aircomatic process would have performance superior to that of an unwelded specimen of the same plate, it would appear that some difference in the performance of the three plates (Codes 5, 6, and 7) of this slab can be expected.

Figure 2 shows the relative performance of three welding procedures--Unionmelt, Manual Grade E6010, and Manual Grade 180--on plates A and B of slab #123519 (Codes 1 and 2, respectively). It will be observed that at 10°F the Unionmelt plate indicates a very appreciable superiority to plates welded with 180 electrodes, which in turn, is very much better than the plate welded with E6010 electrode. With the exception of plates welded with Grade 180 where some scatter was observed, the results are quite consistent.

SEMI-KILLED STEEL AR PLATES 1" THICK

SLAB 123519 INGOT 2 CUT 2 PLATES A & B (CODES 1 & 2)

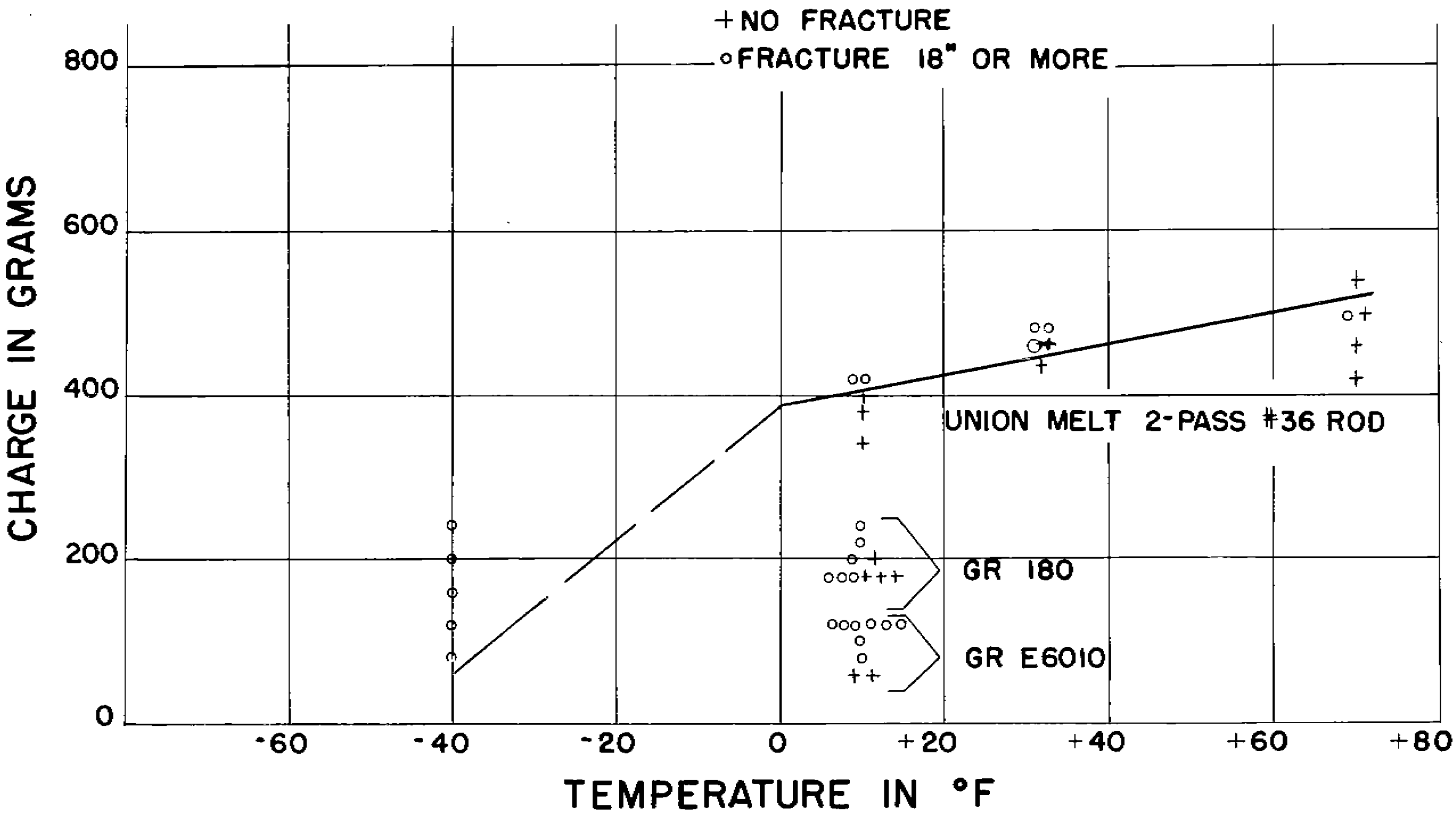


FIG. 2

Figure 3 attempts to indicate the effect of the slab and plate on the performance of specimens welded with Unionmelt, Grade 180, and Class E6010 electrodes. Only the critical points, that is, the points at which fracture occurred, are plotted. It will be seen that performance of specimens made from slab #123523 (Codes 5 and 6) is virtually the same regardless of the welding procedure used and is virtually identical to the performance of all slabs (Codes 1, 2, 5 and 8) when welded with Grade E6010 electrode. By comparison, slab #123524 (Codes 8 and 9) and #123519 (Codes 1 and 2) performed considerably better when welded with Grade 180 and Unionmelt. From the data on pages A-4 and A-5 of Appendix A, it can be seen that, when welded with Grade 180 electrode, Plate A of slab #123519 (Code 1) performed better than Plate B of the same slab (Code 2) and both performed better than Plate B of the slab #123524 (Code 9).

Figure 4 shows the performance of a plate of 3/4-in. thick ABS Class A steel (Code 11). The performance of the prime plate is considerably inferior to the performance of the best of the two semikilled steel plates (Code 1) but surprisingly enough is superior to the performance of the second semikilled steel plate (Code 6) despite the fact that the latter is 1/4 in. thicker. It will be noted that at 10°F little difference in the performance of welded plate is

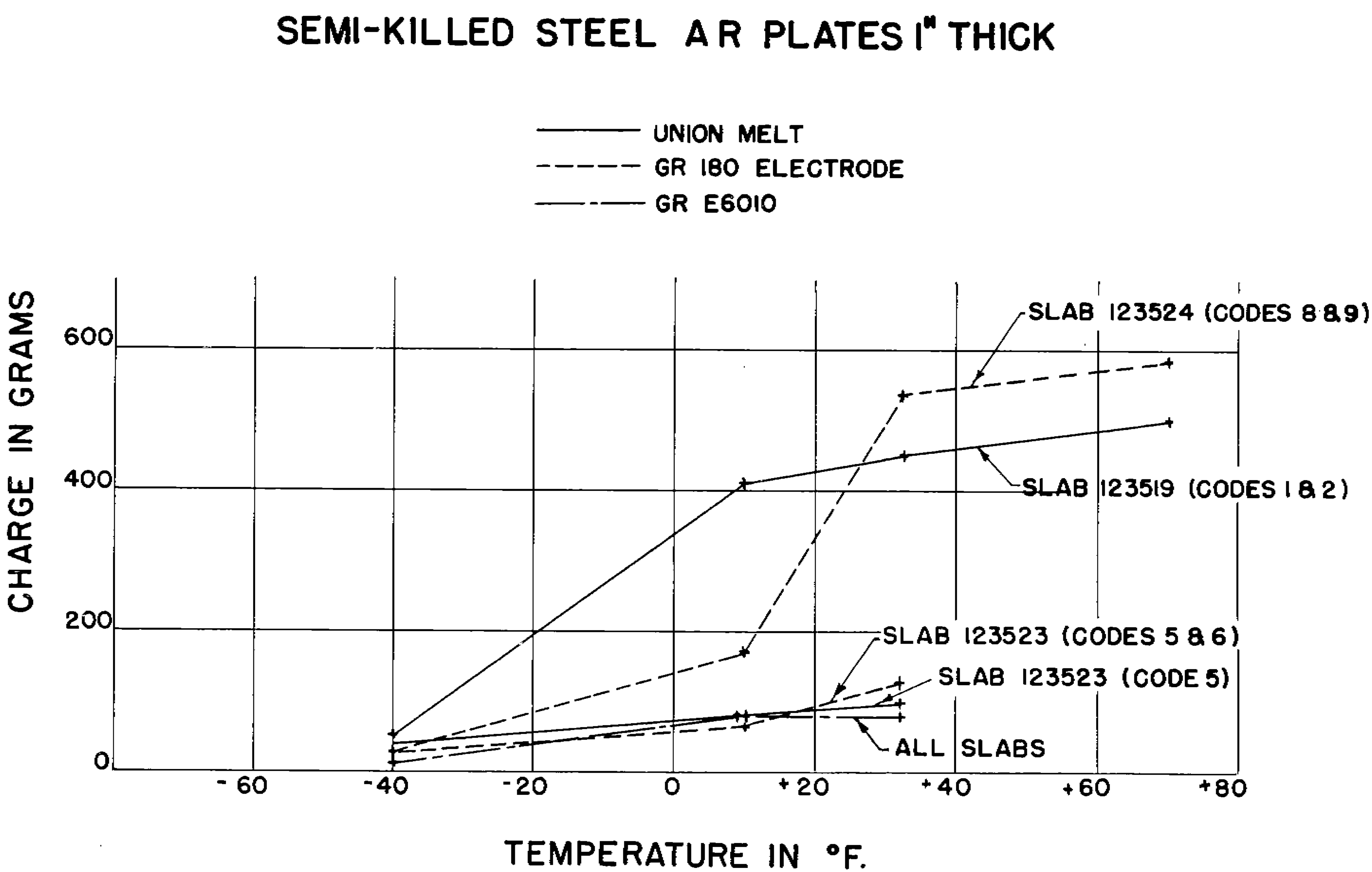

SEMI-KILLED STEEL AR PLATES 1" THICK
UNION MELT
GR 180 ELECTRODE
GR E6010
CHARGE IN GRAMS
600
400
200
0
- 60
-40
-20
0
+20
+40
+60
+80
SLAB 123524 (CODES 8 & 9)
SLAB 123519 (CODES 1 & 2)
SLAB 123523 (CODES 5 & 6)
SLAB 123523 (CODE 5)
ALL SLABS
TEMPERATURE IN °F.

FIG. 3

RIMMED STEEL AT PLATE 3/4" THICK

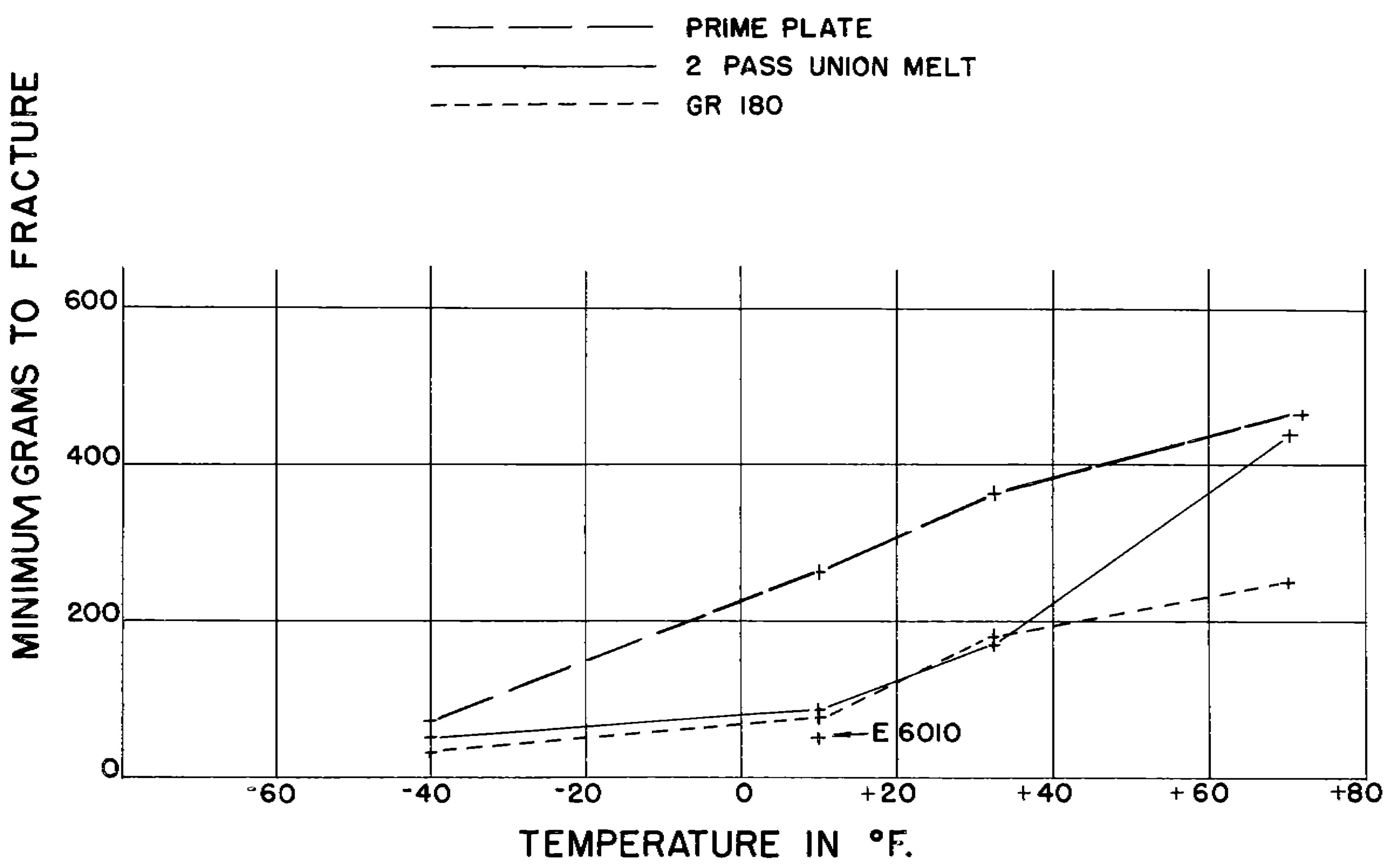


FIG. 4

encountered regardless of whether the welding is made by Unionmelt, Grade 180 electrode, or Class E6010 electrode. Surprisingly enough, at 70°F the performance of Unionmelt weld is again superior to that of one made with Grade 180 electrode and is very similar to the performance of the prime plate.

Figure 5 shows the summary of all tests conducted at 10° and 32°F of specimens made from slab #123523 (Codes 5, 6, and 7) with various welding procedures. At 10°F the performance is uniformly poor with the possible exception of Aircomatic (on Code 7 steel) and E6010 electrodes furnace stress relief annealed at 1150°F. At 32°F Aircomatic (on Code 5 steel) is again the best performer, although improvement over performance of 10°F is not very great, and virtually no improvement is manifested by the other welding procedures tried. It is tempting to make a conclusion that the quality of the plate is so poor that it completely overrides the effect of welding. The superiority of Aircomatic must be tempered by the remembrance that the Aircomatic specimens were prepared from plate C (Code 7) whereas the rest of the specimens which compare unfavorably to the Aircomatic specimens were made from plates A and B (Codes 5 and 6) of the same slab. Furthermore, it must be again remembered that the performance of specimens welded with Aircomatic on plate C (Code 7) is superior to the performance of plate B (Code 6) in prime condition, a fact which is hard to explain except by the presence of inherent differences in plates B (Code 6) and C (Code 7).

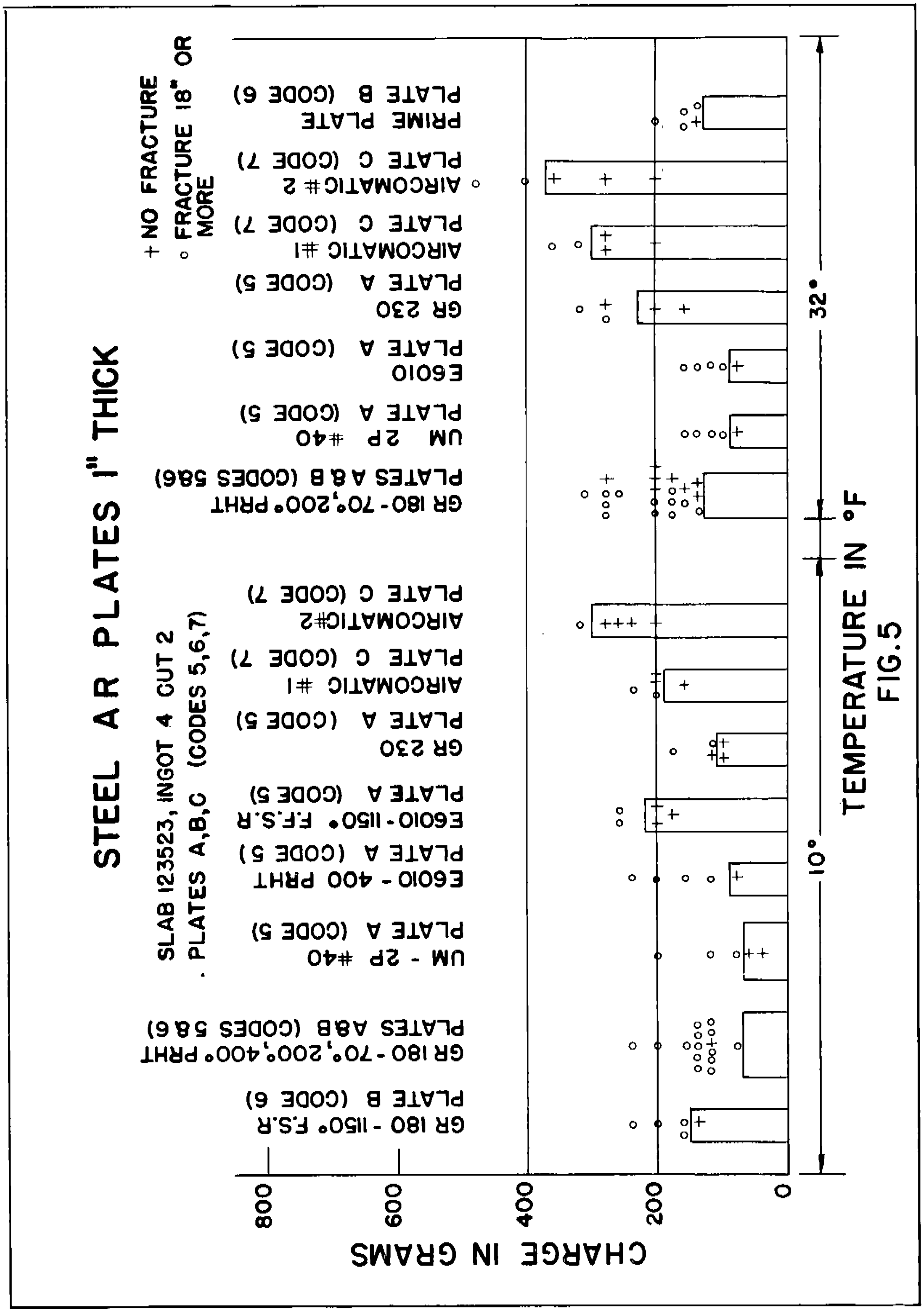

STEEL AR PLATES 1" THICK
SLAB 123523, INGOT 4 CUT 2
PLATES A,B,C (CODES 5,6,7)
+ NO FRACTURE
○ FRACTURE 18" OR MORE
GR 180 - 1150° F.S.R
PLATE B (CODE 6)
GR 180 - 70°, 200°, 400° PRHT
PLATES A&B (CODES 5&6)
UM - 2P #40
PLATE A (CODE 5)
E6010 - 400 PRHT
PLATE A (CODE 5)
E6010 - 1150° F.F.S.R
PLATE A (CODE 5)
GR 230
PLATE A (CODE 5)
AIRCOMATIC #1
PLATE C (CODE 7)
AIRCOMATIC#2
PLATE C (CODE 7)
GR 180 - 70°, 200° PRHT
PLATES A&B (CODES 5&6)
UM 2P #40
PLATE A (CODE 5)
E6010
PLATE A (CODE 5)
GR 230
PLATE A (CODE 5)
AIRCOMATIC #1
PLATE C (CODE 7)
AIRCOMATIC # 2
PLATE C (CODE 7)
PRIME PLATE
PLATE B (CODE 6)
0
200
400
600
800
CHARGE IN GRAMS
10°
32°
TEMPERATURE IN °F

FIG.5

Figure 6 summarizes data obtained at all temperatures on slab #123524 (Codes 8 and 9) when welded with Grade 180 and E6010 electrodes. On this slab a marked improvement in performance of Grade 180 is apparent at all temperatures above -40°. Unfortunately, incomplete data preclude determination of the exact degree of superiority of Grade 180 over E6010.

Figure 7 presents all data obtained with Unionmelt on slabs #123523 (Code 5) and #123519 (Code 1). These data have already been presented in condensed form in Figure 3, and the main purpose of Figure 7 is to show the lack of scatter of these data.

Figure 8 presents all data taken on rimmed steel and summarized in Figure 4. There appears to be considerable scatter in performance of plates welded with Grade 180 electrodes and tested at 10°F.

It is interesting to note that the Stand-off Explosion Test reveals essentially equivalent performance (except possibly at 40°F) between specimens made from slab #123524 (Codes 8 and 9) and welded with E6010 and Grade 180 electrodes(6). Although as pointed out above, the exact degree of difference between the performance of specimens made with those two electrodes on the same slab has not been clearly determined, a definite superiority of the low hydrogen electrode appears to be indicated by the Direct Explosion Test, at least at 32°F, as shown in Figure 6. It can be concluded, therefore, that at least insofar as performance of those two electrodes is concerned, the Direct

STEEL A.R - PLATES 1" THICK

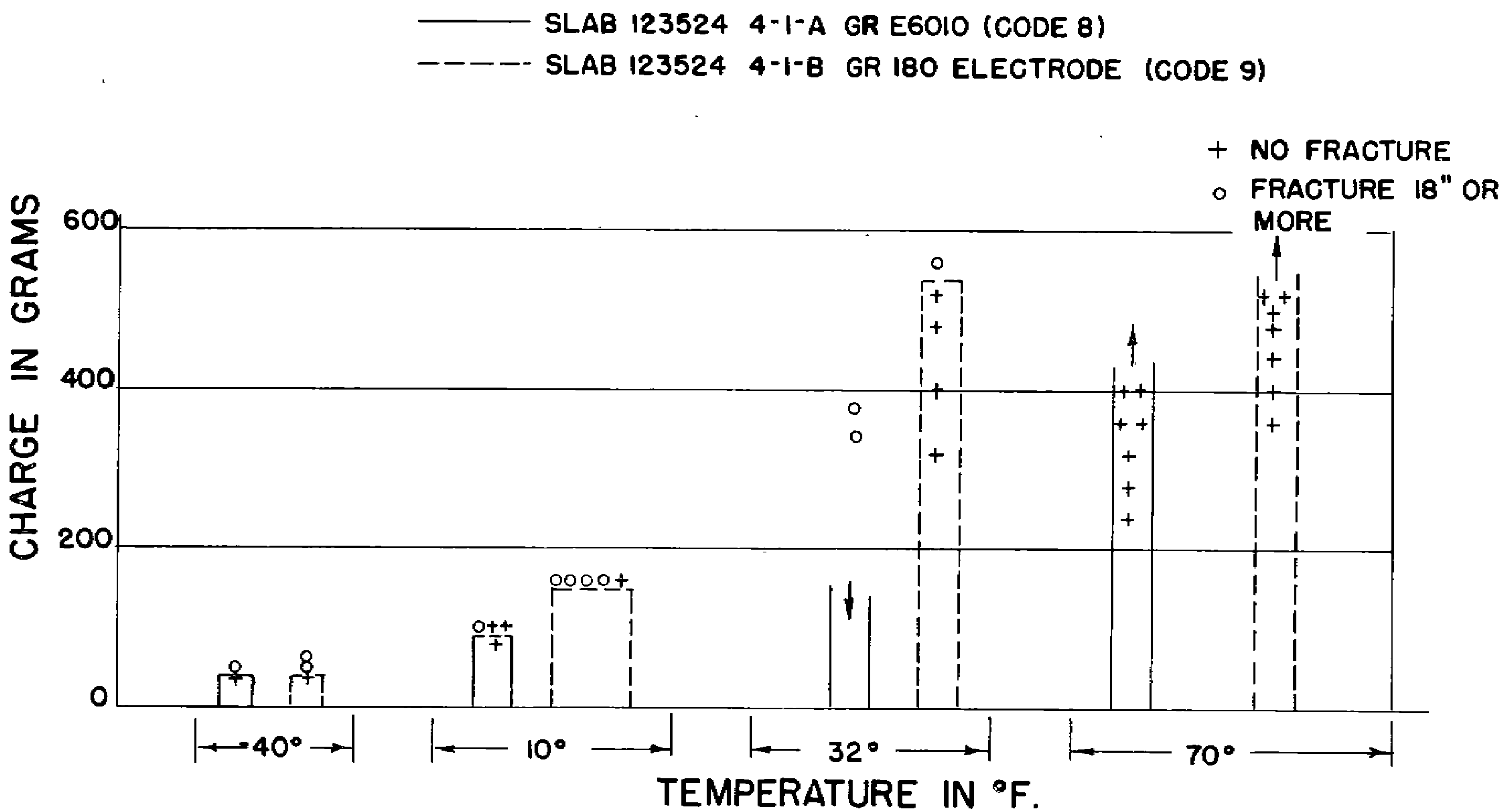


FIG. 6

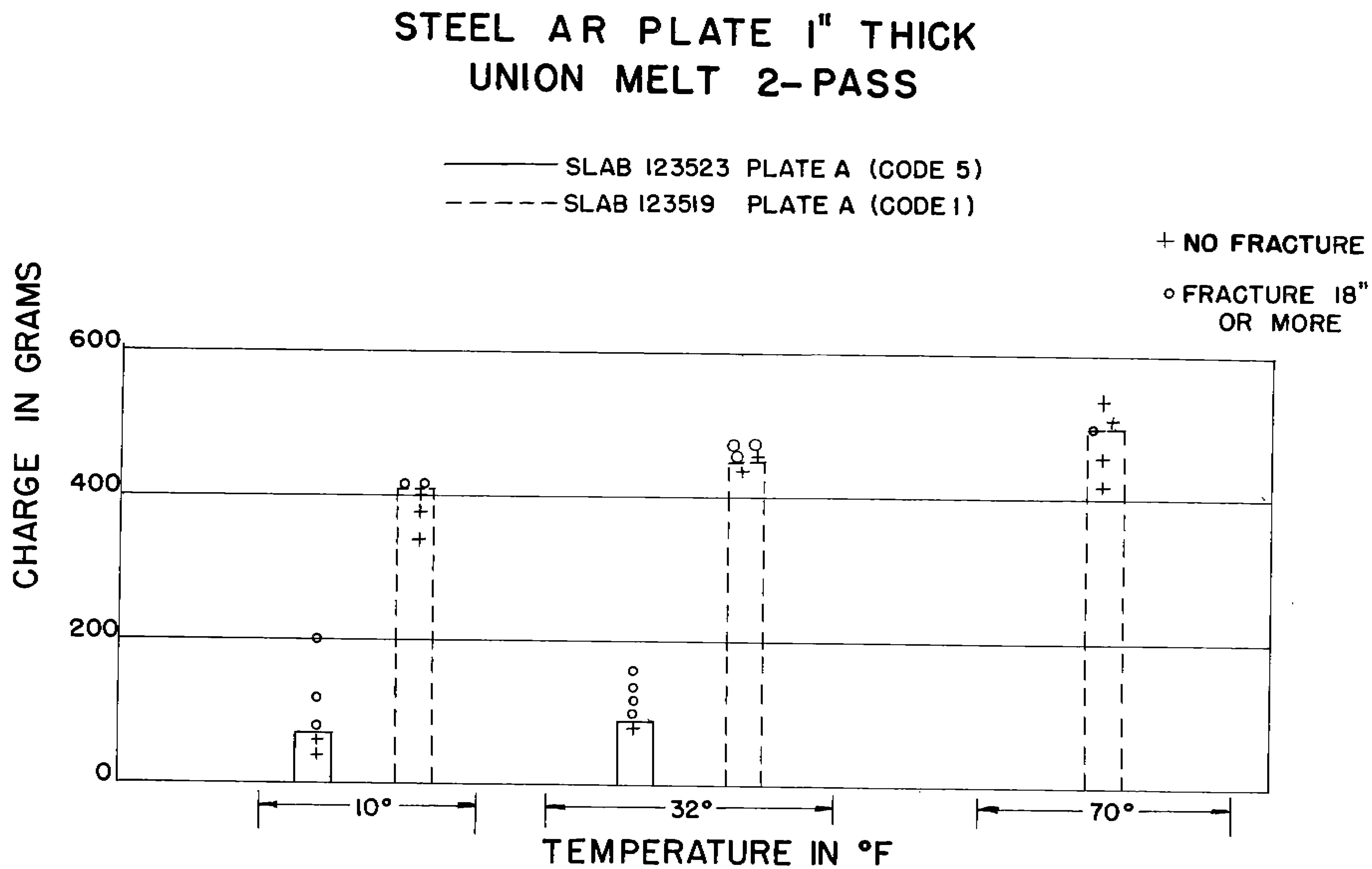

STEEL AR PLATE 1" THICK
UNION MELT 2-PASS
SLAB 123523 PLATE A (CODE 5)
SLAB 123519 PLATE A (CODE 1)
+ NO FRACTURE
o FRACTURE 18" OR MORE
CHARGE IN GRAMS
600
400
200
0
10°
32°
70°
TEMPERATURE IN °F

FIG. 7

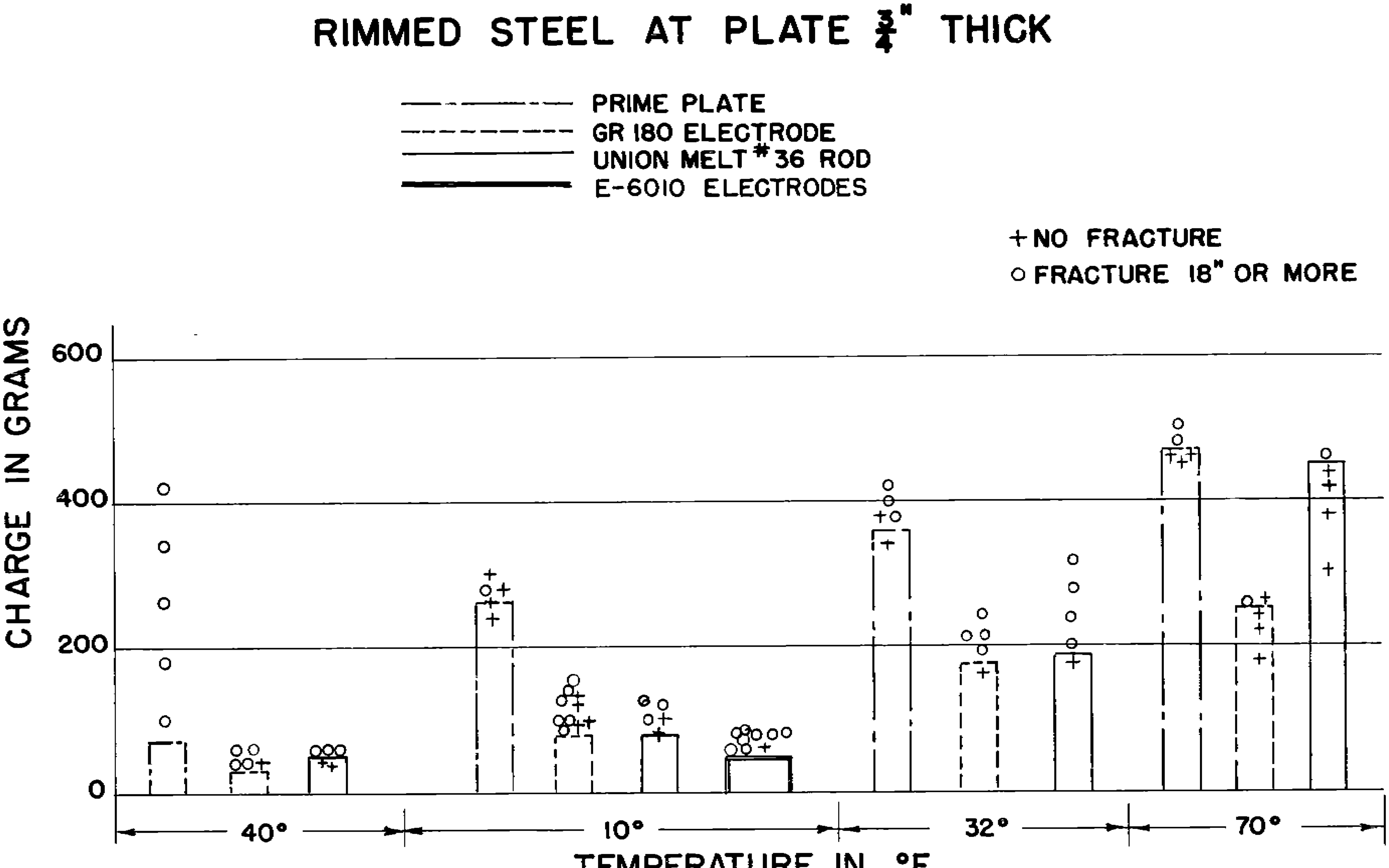

RIMMED STEEL AT PLATE 3/4" THICK
PRIME PLATE
GR 180 ELECTRODE
UNION MELT #36 ROD
E-6010 ELECTRODES
+ NO FRACTURE
○ FRACTURE 18" OR MORE
CHARGE IN GRAMS
600
400
200
0
40°
10°
32°
70°
TEMPERATURE IN °F.

FIG. 8

Explosion Test might be somewhat more discriminatory than the Stand-off (Explosion Bulge) Test.

A collateral investigation conducted with the aid of the Naval Research Laboratory determined the extent of surface strain and reduction in thickness of specimens subjected to the Direct Explosion Test. Table IV shows the comparison of depth of dish produced by the Direct Explosion Tests with the maximum surface strain on the back of the specimen as measured by the Naval Research Laboratory. It will be observed that there is a reasonably good correlation between the two sets of measurements and that the maximum dish observed in Direct Explosion testing does not exceed 20% surface strain on the back side of the plate. It is also interesting to note that in case of overmatching electrodes the surface strain of the heat-affected zone is nearly double that of the weld.

In comparing the deformation produced by the Direct Explosion and Stand-off (Explosion Bulge) Tests, Pellini and Eschbacher[4] (See Appendix B) point out that whereas the Stand-off or Bulge Test produces a reasonably uniform biaxial strain over nearly the entire specimen, the strain is localized in case of the Direct Explosion Test to a comparatively small circular area 2 in. in radius directly under the charge. It is interesting to note that in the Direct Explosion Test the maximum reduction in thickness in this concentrated area of strain is greater (18%) than

Table IV

COMPARISON OF DEPTH OF DISH
AND SURFACE STRAIN* AND REDUCTION OF THICKNESS

Sp. No.	Welding Condition	Temp.	Charge	Depth of Dish, in.	Max. Surface Strain	Surface Strain at Weld	Thickness Reduction
AR-0-26(M-6)	Prime Plate	70	600	3.68	19.3%	--	--
-27(M-19)	" "		560	3.54	18.8		18.8
AR-21-20(M31)	Gr. 180 Electrode		500	3.36	15.0	8.0	--
-27(M38)	Gr. 180 Electrode		520	3.35	15.9	6.0	--
AR-16-20(M51)	Gr. E6010 Electrode		400	3.27	16.0	16.0	
-14(M57)	Gr. E6010 Electrode		360	2.86	12.0	12.0	

* As reported in NRL Memorandum Report 190, "Investigation of the Performance of Ship Steel Weldments and Prime Plate Material", by the Metallurgy Division, Naval Research Laboratory, Washington, D. C. Dated July 1953.

the maximum reduction in thickness of the Stand-off Explosion specimens (around 10%). However, the total area under the curve in the reduction of thickness vs. distance from the center of the plate graph is reasonably the same for both tests. Thus, the stress gradient in the direction of thickness is much more severe in the case of the Direct Explosion Test, producing a condition of triaxial tension not unlike that present in the root of a notch. This might explain the reason why the Direct Explosion Test appears to be more discriminating than the Stand-off Test.

CONCLUSIONS

The following tentative conclusions appear to be justified as a result of this investigation:

1. Performance of unwelded semikilled steel plate, 1-in. thick, rolled from the same heat of steel appears to vary widely, depending on the portion of the heat from which the plate was rolled.
2. Based on the limited investigations conducted, the reasons for the wide variations found within the same heat of steel are not certain, although they appear to be associated with a particular cut and ingot.
3. The difference in performance of specimens welded with different welding procedures appears to be very appreciable in case of the better performing plate of a specific heat of

semikilled steel tested and virtually disappears in case of the poorest performing plate of that heat.

4. Performance of welded joints made with Unionmelt, Grade 180, and Class E6010 electrodes appears to line up in this order of performance in case of the better performing plate with Unionmelt being superior to E6010 by a factor of 4 at 10°F.

5. The effect of thermal stress relief at 1150°F is beneficial to welds made with E6010 electrodes on the poor performing portion of the heat of semikilled steel tested.

6. The performance of prime rimmed steel 3/4-in. thick is very much inferior to that of the 3/4-in. thick semikilled steel at all temperatures from 32°F down. However, it is comparable to that of the poorly performing portion (Code 6) of the 1-in. thick semikilled steel of the same heat.

7. Performance of all welded specimens of rimmed steel, 3/4-in. thick regardless of welding procedure used, is about the same and is similar to that of welded specimens made of the worst portion of the 1-in. thick semikilled steel (Code 6) tested.

8. The Direct Explosion Test appears to be more discriminatory than the Stand-off (Explosion Bulge) Test when applied to specimens welded with Grade 180 and Class E6010 electrodes and prepared from the better portion of the heat of the semikilled steel used, though the evidence is not too conclusive since the data on which it is based are limited.

9. The stress gradient, particularly in direction of thickness produced by the Direct Explosion, appears to be much steeper than that produced by the Stand-off Explosion.

10. The difference in performance of different portions of the heat of the semikilled steel tested, detected by Direct Explosion Test, is not generally apparent on the basis of either the Charpy impact or the Navy tear test conducted.

REFERENCES

1. Mikhalapov, G. S. "Direct Explosion Tests of Welded Joints," THE WELDING JOURNAL, Res. Suppl., March 1950, pp. 109-s--122-s.

2. Mikhalapov, G. S. "Evaluation of Welded Ship Plate by Direct Explosion Testing," THE WELDING JOURNAL, Res. Suppl., April 1951, pp. 195-s--201-s.

   Mikhalapov, G. S. "Evaluation of Notch Sensitivity of Mild Steel Ship Plate by Direct Explosion Test," Ship Structure Committee Report Serial Number SSC-43, March 15, 1951.

3. Mikhalapov, G. S. "Direct Explosion Test to Evaluate Load-Carrying Capacity of Welded Steel Structures," A. S. T. M. Bulletin, No. 172, February 1951.

4. Pellini, W. S., and Eschbacher, E. W. "Investigation of the Performance of Ship Steel Weldments and Prime Plate Material," NRL Memorandum Report 190, Naval Research Laboratory, Washington, D. C., July 1953.

5. Mikhalapov, G. S. "Evaluation of Ship Welding Procedures by Direct Explosion Testing," Final Report, Ship Structure Committee Report, Serial Number SSC-46, August 31, 1951.

6. Pellini, W. S., and Eschbacher, E. W. "Investigation of the Performance of Weldments and Prime Plate of ABS-B Steel," Final Report, Part II, Ship Structure Committee Report, Serial Number SSC-78, June 18, 1954.

APPENDIX A

APPENDIX

Test Results

Semi-Killed Steel AR - 1" Thick

No.	Plate Code No.	Welding Procedure	Test Temp °F	Charge Grams	Depth of Dish,ins.	Extent of Fracture
AR-0-18	1	None - Prime Plate	70	640	3.54"	None
-11				660	3.54	2" Back only
-7				660	3.60	1" Front-3" Back
-8				680	3.64	5"
-14				700	---	18"
-5			32	640	3.41	None
-9				680	3.45	None
-2				680	---	4 Pieces
-3				700	---	2 Pieces
-1				720	---	2 Pieces
-16			0	600	3.12	None
-12				620	---	24"
-10				620	---	9 Pieces
-6				660	---	8 Pieces
-4				740	---	8 Pieces
-15			-40	400	2.19	None
-13				520	2.62	None
-19				640	2.94	None
-20				700	---	16 Pieces
-17				760	---	14 Pieces
-22			-90	100	---	5 Pieces
-25				120	---	7 Pieces
-21				140	---	8 Pieces
-23				160	---	6 Pieces
-24				160	---	6" Front-30" Back
AR-0-26 (M-6,grid)	4		70	600	3.68	2" Crack Back
AR-0-27 (M-19,grid)				560	3.54	None
AR-0-28 (M-20,grid)			-40	600	---	15 Pieces
AR-0-29 (M-17,grid)				480	---	12 Pieces

Semi-Killed Steel AR - 1" Thick

No.	Plate Code No.	Welding Procedure	Test Temp °F	Charge Grams	Depth of Dish, ins.	Extent of Fracture
AR-0-35	6	Prime Plate	70	560	3.25"	None
-32				580	3.26	None
-41				580	--	40"
-42				600	--	28" Front-35" Back
-39				600	--	42" Front-45" Back
AR-0-36	6	Prime Plate	32	140	1.17	None
-43				140	--	26"
-37				160	--	34"
-44				160	--	36" - 2 Pieces
-45				200	--	34"
AR-0-34	6	Prime Plate	10	280	--	4 Pieces
-38				360	--	6 Pieces
-40				440	--	8 Pieces
-33				520	--	8 Pieces
-46				600	--	10 Pieces
AR-2A-8	5	Gr.230-70°Prht.& Intp.T.	32	160	1.17	None
-4				200	1.44	None
-9				280	1.79	None
-3				280	--	38" - 3 Pieces
-1				320	--	29" - 2 Pieces
AR-2A-7	5	Gr.230-70°Prht.& Intp.T.	10	100	--	20"
-5				100	.62	4" Back only
-10				120	--	12" Front-19" Back
-6				120	--	30"
-2				180	--	5 Pieces
AR-7-6	2	U.M.#36 Rod-2Pass-70°Prht.& Intp.T.	70	420	2.35	None
-5				460	2.48	None
-19				500	2.73	None
-3 *				500	--	2 Pieces
-2				540	2.88	None
AR-7-1	2		32	440	2.43	None
-20				460	2.49	None
-7				460	--	7 Pieces
-12				480	--	5 Pieces
-8				480	--	6 Pieces

* Fracture appearance revealed incomplete penetration welds.

No.	Plate Code No.	Welding Procedure	Test Temp °F	Charge Grams	Depth of Dish, ins.	Extent of Fracture
AR-7-10	2	U.M.-2 pass - #36 Rod-70°Prht.& Intp.T.	10	340	1.90	None
-13				380	2.08	None
-4				400	2.11	None
-9				420	—	5 Pieces
-17				420	—	5 Pieces
-16	2	U.M.-2Pass-#36Rod-70°Prht. & Intp.T.	-40	80	—	4 Pieces
-11				120	—	6 Pieces
-15				160	—	5 Pieces
-14				200	—	9 Pieces
-18				240	—	5 Pieces
AR-15-5	5	U.M.-2Pass-#40Rod-70°Prht. &Intp.T.	32	80	.48	None
-6				100	—	12" Front-20" Back
-8				120	—	28" Front-37" Back
-9				140	—	27" Front-32" Back
-7				160	—	25" Front-26" Back
AR-15-14	5		10	40	.05	17" Back only
-10				60	—	22" Back only
-11				80	—	12" Front-21" Back
-12				120	—	3 Pieces - 36"
-13				200	—	3 Pieces - 63"
AR-16-21	8	E6010-70°Prht. & Intp.T.	70	240	1.69	None
-12				280	1.82	None
-11				320	2.04	1"Crack weld only.Transv.
-15				360	2.26	None
-13				400	2.34	None
-14(Grid)*				360	2.86	None
-20(Grid)*				400	3.27	None
AR-16-25	8		32	340	—	4 Pieces
-24				380	—	4 Pieces
AR-16-54	5		32	80	—	9" Back only
-50				100	—	7" Front-17" Back
-51				120	—	22" Front-26" Back
-53				140	—	26" Front-29" Back
-52				160	—	36" Front and Back
AR-16-7	2		10	120	—	49" Crack
-8				120	—	45" Crack
-9				120	—	42" Crack
-10				120	—	48" Crack
-6				120	—	2 Pieces

* Reinforcement removed from weld both sides.

No.	Plate Code No.	Welding Procedure	Test Temp °F	Charge Grams	Depth of Dish, ins.	Extent of Fracture
AR-16-17	8	E6010-70°Prht.& Intp.T.	10	80	.31	None
-16				100	.54	None
-19				100	.50	None
-18				100	--	4 Pieces
-5	1		10	60	.09	None
-1				60	--	10" Back only
-2				80	--	3-1/2"Front-17" Back
-4				100	--	22" Front-32" Back
-3				120	--	5 Pieces
-22	8		-40	40	.05	None
-23				50	--	18" Front-39" Back
AR-21-20* (grid)	9	Gr.180-70°Prht.& Intp.T.	70	500	3.36	None
-27* (grid)				520	3.35	None

* Weld reinforcement removed from both sides.

No.	Plate Code No.	Welding Procedure	Test Temp °F	Charge Grams	Depth of Dish, ins.	Extent of Fracture
AR-21-21	9	Gr.180-70°Prht.& Intp.T.	70	360	2.22	None
-19				400	2.44	None
-18				440	2.63	None
-16				480	2.70	None
-17				520	2.86	None
AR-21-14	9		32	320	1.96	None
-15				400	2.30	None
-11				480	2.51	None
-13				520	2.74	None
-12				560	--	5 Pieces
AR-21-69	6		32	140	.95	None
-68				200	1.39	None
-65				200	1.38	None
-66				200	--	3 Pieces
-67				280	--	4 Pieces
AR-21-64	5		32	140	--	22" Front-25" Back
-63				160	1.10	None
-59				160	--	35" - 2 Pieces
-60				200	--	37" Front-39" Back
-57				280	--	51" - 4 Pieces
AR-21-3	1		10	180	1.14	None
-2				200	1.31	None
-4				200	--	3 Pieces
-1				220	--	5 Pieces
-5				240	--	4 Pieces

No.	Plate Code No.	Welding Procedure	Test Temp °F	Charge Grams	Depth of Dish, ins.	Extent of Fracture
AR-21-8	2	Gr.180-70°Prht.& Intp.T.	10	180	1.18	None
-10				180	1.17	None
-9				180	--	3 Pieces
-7				180	--	3 Pieces
-6				180	--	4 Pieces
AR-21-24	8		10	160	1.01	None
-25	9			160	--	6 Pieces
-23	9			160	--	5 Pieces
-22	9			160	--	5 Pieces
-26	9			160	--	5 Pieces
AR-21-71	3		10	140	.95	None
-70				140	.90	None
-72				140	.91	None
-74				140	1.00	None
-73				140	--	12" Back only
AR-21-62	5		10	140	--	39" Front-45" Back
-61				140	--	3 Pieces
-55				140	--	4 Pieces
-58				140	--	2 Pieces
-56				140	--	3 Pieces
AR-21-29	9		-40	40	.01	None
-28				50	--	4 Pieces
-30				60	--	4 Pieces
AR-22-14	6	Gr.180-200°Prht.& Intp.T.	32	140	.92	None
-12				200	1.35	None
-17				260	--	2 Pieces
-11				280	1.77	None
-13				280	--	3 Pieces
-15				320	--	2 Pieces
-19	6		32	180	1.22	None
-20				180	--	17"(in plate 2-3" fm weld)
-18				180	--	39"
-16				180	--	39"
AR-22-5	3		10	80	.35	None
-3				120	--	3 Pieces
-2				140	--	3 Pieces
-1				160	--	4 Pieces
-4				200	--	6 Pieces
AR-22-23	6		10	120	.73	None
-22				120	--	30"
-24				120	--	27" Front-33" Back
-21				120	--	43" - 4 Pieces

No.	Plate Code No.	Welding Procedure	Test Temp °F	Charge Grams	Depth of Dish, ins.	Extent of Fracture
AR-22-9	3	Gr.180-200°Prht.& Intp.T.	10	60	.06	None
-10	4			60	.04	None
-6	3			60	—	3" Back only
-8	3			60	—	5" Back only
-7	3			60	—	3" Back only
AR-27-1	5	E6010-400°Prht.& Intp.T.	10	80	—	18" Back only
-3				120	—	3 Pieces
-4				160	—	3 Pieces
-2				200	—	5 Pieces
-5				240	—	5 Pieces
AR-28-4	5	E6010-70°Prht.& Intp.T.	10	180	1.23	None
-1				220	1.63	None
-2				220	1.50	None
-5				260	—	4 Pieces
-3				260	—	4 Pieces
	Specimen furnace stress relieved at 1150°F					
AR-32-5	3	Gr.180-10°Prht.& Intp.T.	10	120	.67	None
-2	8			120	—	4 Pieces
-4	3			140	.84	None
-3	8			160	—	5 Pieces
-1	8			180	—	4 Pieces
-10	3		10	100	—	4 Pieces
-8				80	—	5" Back only
-7				80	—	3" Back only
-9				80	—	5" Back only
-6				80	—	4" Back only
AR-39-2	7	Aircomatic-#1 Rod-70°Prht. & Intp.T.	32	200	1.40	None
-1				280	1.75	None
-6				280	1.77	None
-10				320	—	55" - 3 Pieces
-5				360	—	50" - 4 Pieces
AR-39-8	7		10	160	1.16	None
-4				200	1.33	None
-7				200	1.36	None
-9				200	—	5 Pieces
-3				240	—	3 Pieces

No.	Plate Code No.	Welding Procedure	Test Temp °F	Charge Grams	Depth of Dish, ins.	Extent of Fracture
AR-40-10	7	Aircomatic-#2 Rod-70°Prht. & Intp.T.	32	200	1.34	None
-4				280	1.79	None
-5				360	2.12	None
-7				400	—	28"Front-32"Back-2 pcs.
-6				480	—	52" - 3 Pieces
-8	7		10	200	1.33	None
-3				240	1.51	None
-1				260	1.67	None
-2				280	1.79	None
-9				320	—	4 Pieces
AR-44-3	5	Gr.180-400°Prht.& Intp.T.	10	80	—	9" Front-18" Back
-2	5			120	—	4 Pieces
-5	6			160	—	4 Pieces
-1	5			200	—	5 Pieces
-4	6			240	—	5 Pieces
AR-45-5	6	Gr.180-1150°Furnace Stress Relief	10	140	1.00	None
-2				160	—	2 Pieces
-3				160	—	4 Pieces
-4				200	—	5 Pieces
-1				240	—	7 Pieces

Semi-Killed Steel ARX- 3/4" Thick

No.	Plate Code No.	Welding Procedure	Test Temp °F	Charge Grams	Depth of Dish, ins.	Extent of Fracture
ARX-0-4	10	None - Prime Plate	70	560	4.55	None
-5				560	4.60	2"
-2				580	4.63	3"
-3				580	—	43"
-1				600	—	42" - 2 Pieces
-8			32	580	4.52	None
-6				580	4.59	2"
-10				580	—	2 Pieces
-9				600	—	60"
-7				600	—	4 Pieces
-12			0	520	4.11	None
-13				560	4.30	None
-17				560	4.23	None
-14				580	—	6 Pieces
-11				600	—	12 Pieces
-15			-40	300	2.72	None
-16				420	3.37	None
-18				540	3.96	None
-20				580	—	17 Pieces
-19				620	—	17 Pieces

Rimmed Steel AT - 3/4" Thick - Code No. 11

No.	Plate Code No.	Welding Procedure	Test Temp °F	Charge Grams	Depth of Dish, ins.	Extent of Fracture
AT-0-11	11	None - Prime Plate	68	440	--	1-1/2" Back only
-5				460	4.40	None
-8				460	4.30	None
-15				480	--	5 Pieces
-7				500	--	3 Pieces
-3			32	340	3.49	None
-9				380	3.71	None
-16				380	--	9 Pieces
-14				400	--	12 Pieces
-13				420	--	6 Pieces
-18			10	240	2.62	None
-10				260	2.84	None
-19				280	--	10 Pieces
-17				280	2.99	None
-12				300	3.05	None
-2			-40	340	--	11 Pieces +
-4				420	--	17 Pieces +
-1				100	--	2 Pieces
-6				180	--	10 Pieces
-20				260	--	16 Pieces
AT-7-11	11	U.M.-#36 Rod-2 Pass - 70°Prht.& Intp.T.	70	300	3.53	None
-8				380	3.68	None
-19				420	3.90	None
-17				440	3.90	None
-7				460	--	7 Pieces
-20			32	180	2.20	None
-1				200	--	5 Pieces
-16				240	--	6 Pieces
-4				280	--	8 Pieces
-5				320	--	9 Pieces
-9			10	80	.76	None
-2				100	1.09	None
-15				100	--	6 Pieces
-10				120	--	4 Pieces
-3				120	--	4 Pieces
-18			-40	40	.04	None
-14				50	.07	None
-13				60	--	3 Pieces
-6				60	--	2 Pieces
-12				60	--	2 Pieces

Rimmed Steel AT - 3/4" Thick - Code No. 11

No.	Plate Code No.	Welding Procedure	Test Temp °F	Charge Grams	Depth of Dish, ins.	Extent of Fracture
AT-16-4	11	E6010-7Pass-70°Prht.& Intp.T.	10	80	—	3 Pieces
-5				80	—	4 Pieces
-3				80	—	4 Pieces
-2				80	—	4 Pieces
-6				60	.63	None
-9				60	—	4" Front-9" Back
-7				70	—	2 Pieces
-10				70	—	2 Pieces
-8				80	—	3 Pieces
-1				80	—	5 Pieces
AT-21-15	11	Gr.180-7Pass-70°Prht.& Intp.T.	68	180	2.23	None
-1				220	2.54	None
-8				240	2.56	None
-6				260	2.70	None
-2				260	—	4 Pieces
-4			32	180	—	None
-14				200	—	6 Pieces
-5				220	—	16" Crack
-20				220	—	5 Pieces
-16				240	—	6 Pieces
-9			10	120	1.50	None
-22				120	—	4 Pieces
-17				130	1.54	None
-10				130	—	4 Pieces
-19				140	—	5 Pieces
-3				100	1.21	None
-24				100	—	4 Pieces
-21				100	—	4 Pieces
-25				90	1.08	None
-23				90	—	4 Pieces
-13			-40	40	.45	None
-12				40	—	5" Front-18" Back
-11				40	—	5" Front-18" Back
-18				60	—	3 Pieces
-7				60	—	4 Pieces

APPENDIX B

APPENDIX B

STRAIN STUDIES OF DIRECT EXPLOSION TEST SPECIMENS*

The nature of the strain conditions developed in the Explosion Bulge Tests has been described in a previous report(3). Briefly, a circular area of 1 1/2" to 2" radius at the center of the bulge shows essentially uniform strain for a prime plate bulge of 10% or less thickness reduction (approximately a 4" deep bulge). This signifies that bending is minimized and a condition approaching simple biaxial straining is developed in this region; also that the strain developed in a weld located at the center of the bulge is not greatly in excess of that of the adjacent plate material. Unless this condition is approached the weld would be tested at the disadvantage of being located in a position of naturally higher strain level than the adjacent plate material.

The Direct Explosion Test method utilizes a 6" diameter charge placed in contact with the test plate and therefore produces a condition of concentrated loading. Strain grid studies were conducted to determine the nature of strain conditions developed in Direct Explosion Tests. The plates were surface ground to provide a flat, smooth surface required for photo-gridding. Fig. B-1

---

*This discussion and associated figures are verbatim reproductions of Part II in the report "Investigation of the Performance of Ship Steel Weldments and Prime Plate Material," NRL Memorandum Report 190, by William S. Pellini and Earl W. Eschbacher, July 1953. The permission of the authors for use of this material is appreciated.

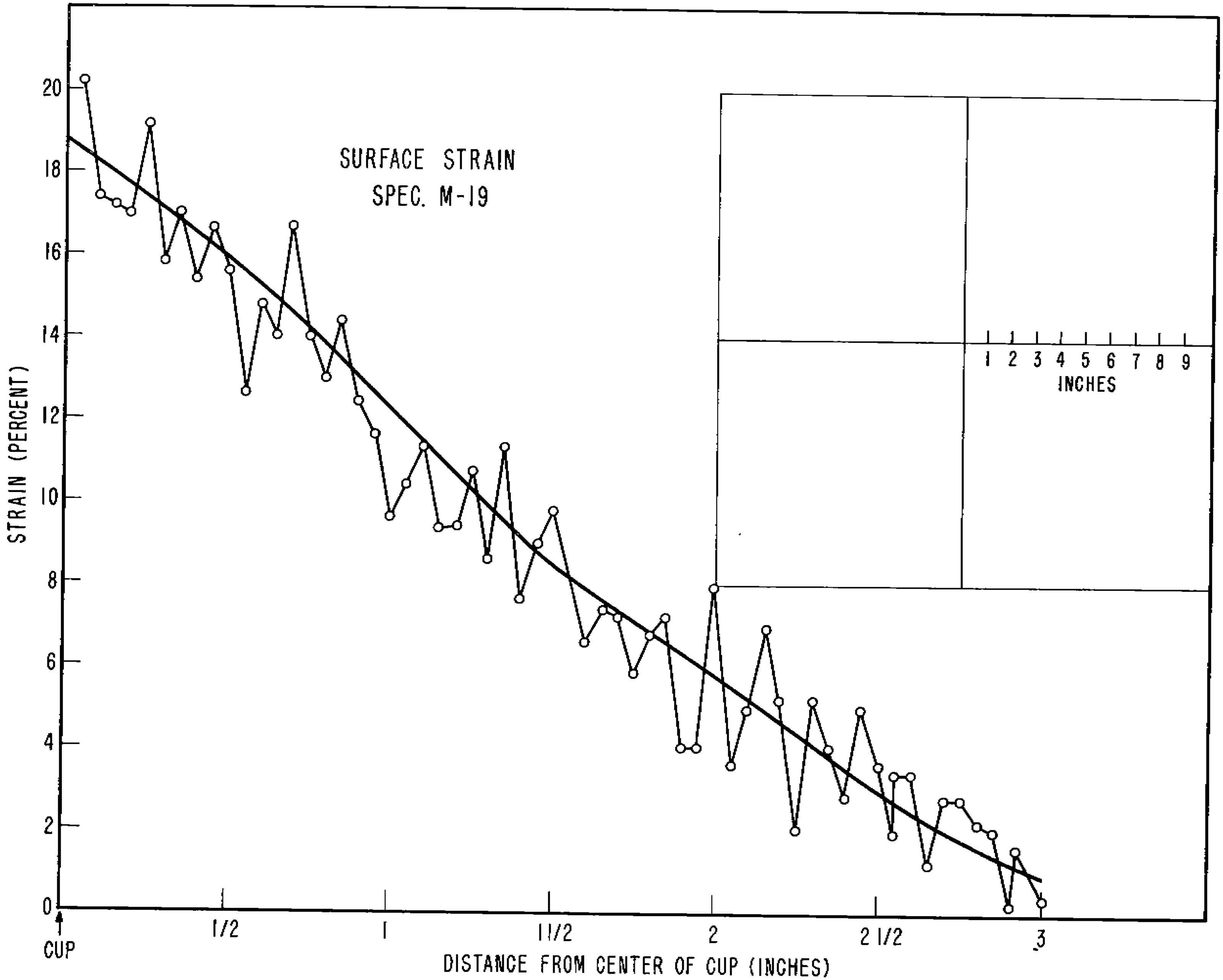


Figure B-1 - Photogrid strain data for prime plate direct explosion test specimen M19. Test conditions - 560 gms of explosive at 70° F presents a typical strain grid record obtained by measuring the stretch of individual .050 inch grid squares. Readings were obtained in one radial direction only, as indicated on the figure. Figure B-2 illustrates the results of the various strain determinations for 3 prime plates and four weldments (welds ground flush); a typical surface strain plot for the Explosion Bulge method is presented also. Thickness reduction measurements for specimen M19 (Direct Explosion) and P2 (Explosion Bulge) are shown at the top of Fig. B-2. Fig B-3 shows cross sections of M19 and P2. It is evident from these various figures and plots that the Direct Explosion tests results in pronounced deformation gradients and bending conditions. Within a 3" distance from the center of the Direct Explosion cup the surface strain falls from approximately 20% to essentially nil values and the thickness reduction from approximately 18% to nil values.

Since $E_1 + E_2 = E_3$ (sum of biaxial surface strains (positive) is equal to thickness strain (negative)) as dictated by constancy of volume considerations, it should be expected that simple biaxial straining should be characterized by a thickness reduction equal to the sum of the surface strains. Specimen M19 shows that the thickness reduction is only half the biaxial surface strain total and accordingly that the inner surface must have strained considerably less than the outer surface. In simple terms, pronounced bending conditions must have been developed so as to produce high strains on the outer surfaces and low strains on the inner surface. It is

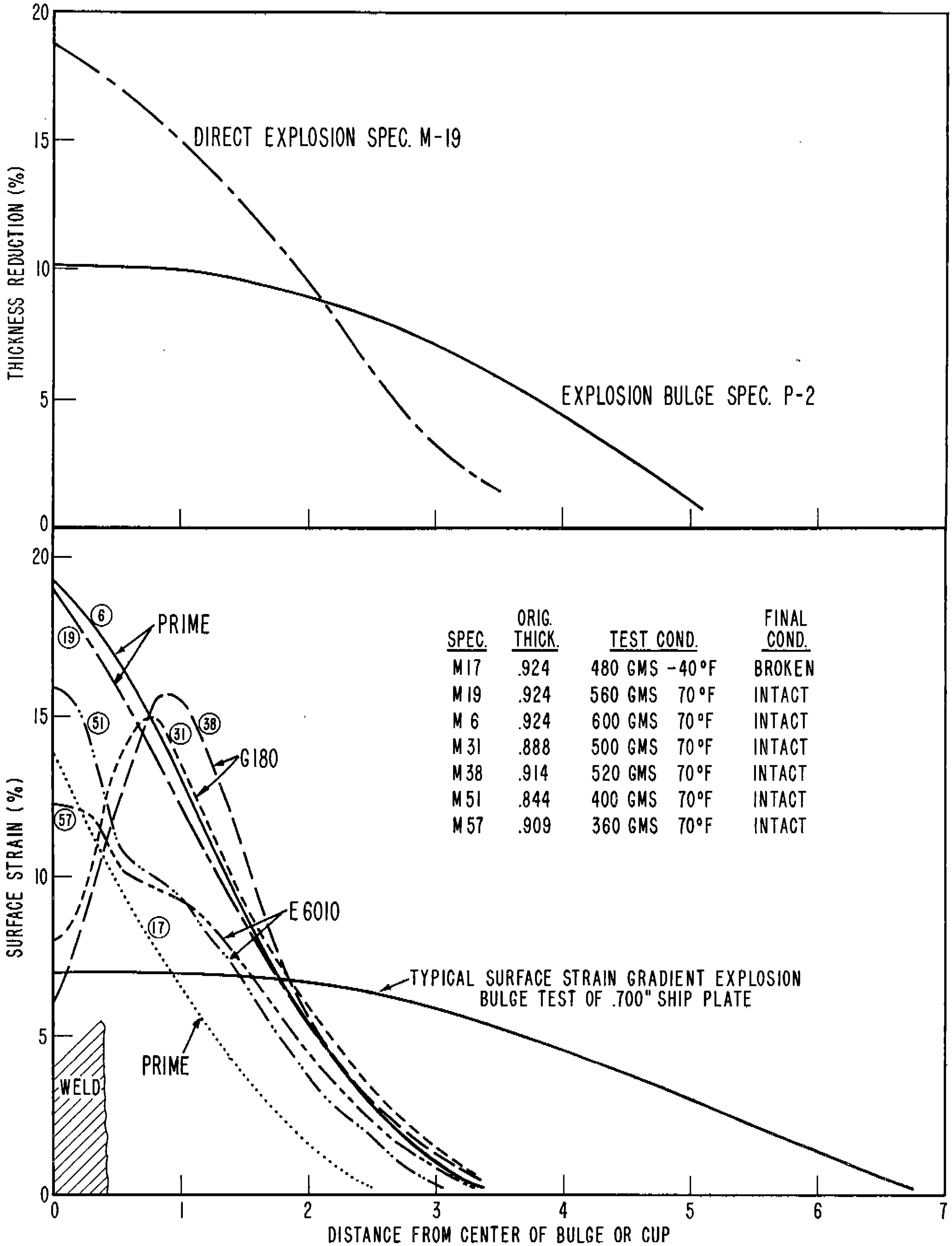


Figure B-2 - **Comparison of deformation conditions developed in direct explosion and explosion bulge tests**

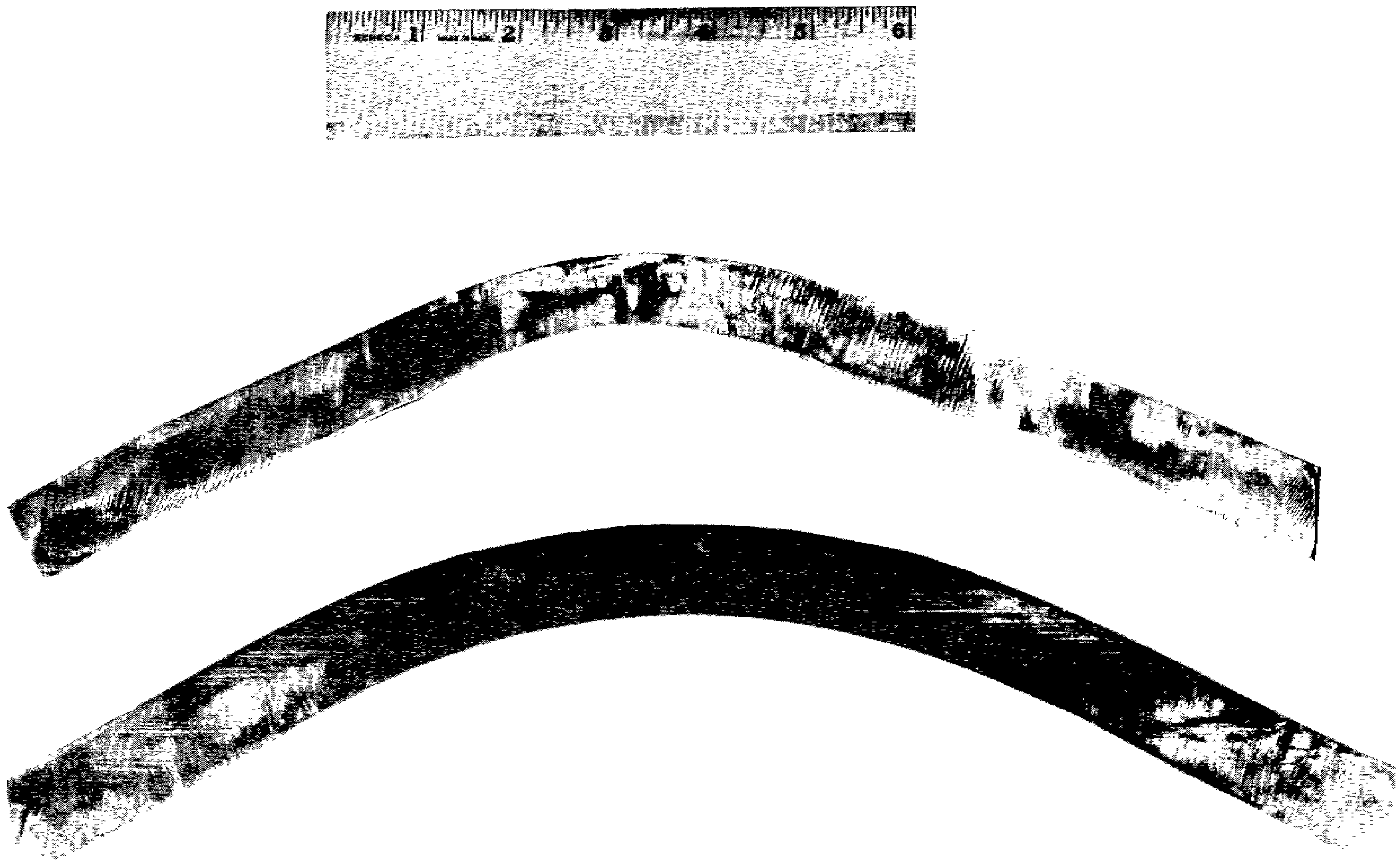


Figure B-3 - Cross sections of specimens direct explosion specimen M19 (top) explosion bulge specimen P2 (bottom) concluded that the stress mechanics resulting from Direct Explosion loading entail highly localized biaxial bending conditions.

The strain plots for the Direct Explosion Test weldments show a strain deconcentration for the high flow strength (overmatching) G180 welds and a strain concentration for the lower flow strength (undermatching) E6010 weld. It should be noted that this effect is obtained only in a transweld direction and that strains (but not stresses) are equivalent in the weld longitudinal direction. Such strain and stress conditions should be expected in biaxial tension irrespective of the degree of bending involved. This subject has been discussed in detail in a previous report[3].