N. Eng. 70-C

REPORT NO. H-1401

FR-1401

DATE 28 September 1937

SUBJECT

Photoelastic Investigation of Stresses

Surrounding Reinforced Rectangular Deck Openings

BY

NAVAL RESEARCH LABORATORY

BELLEVUE, D. C.

28 September 1937
CONFIDENTIAL

NRL Problem No. H-56

NAVY DEPARTMENT

BUREAU OF ENGINEERING

Report

on

Photoelastic Investigation of Stresses Surrounding Reinforced Rectangular Deck Openings.

NAVAL RESEARCH LABORATORY
ANACOSTIA STATION
WASHINGTON, D. C.

Number of Pages: Text - 8 Tables - 1 Plates - 29

Authorization: BuC&R letter NP14-(6)(RI) of 21 February 1936.

Date of Test: 1 February 1937 to 1 July 1937.

Prepared by: H. B. Maris, Associate Physicist.

Reviewed by: E. O. Hulburt, Principal Physicist.

Approved by: H. M. Cooley, Captain, USN, Director.

Distribution:
BuEng. (2)
BuC&R (5)

mts

Table of Contents

Appendices

INTRODUCTION

Authorization

1. This problem was authorized by Bureau of Construction and Repair letter NP14-(6)(RI) of 21 February 1936.

Purpose

2. The report presents a detailed analysis of the stress pattern surrounding rectangular deck openings with nine types of reinforcement as specified in the letter of authorization. The different types of reinforcement are illustrated in Plates 1, 4, 7, 10, 13, 16, 19, 22 and 25.

Problem

3. The study was planned for a photoelastic analysis for which transparent models are required. Celluloid 1/8 inch thick was found to be most satisfactory material for fabricating the test members.

Test Specimens

4. Test specimens were made six inches wide, with openings two inches across. These dimensions gave a 1/4 inch radius for the fillet at the corners, and 0.4 inch width for the longitudinals and coaming plate. It was not possible to make a perfect union between the 1/8 inch thick coaming and the small radius curves of the fillet, but it was considered that the celluloid joints were no more imperfect than the riveted or welded steel joints of an actual ship structure would be. The stress pattern in the immediate vicinity of the corners of a reinforced opening was obscured by the presence of both the doubler plate and the longitudinals. For these reasons it was considered that the results from the specimens used were satisfactory, although it must be remembered that the celluloid models were relatively much thicker than steel structural members of the same lateral dimensions. This difference in the thickness ratio is not important in the main body of the structure, but it may be important at points of high stress concentration, for example near sharply curved edges, and at these points the concentration may be greater in the steel member because the stresses are more nearly plain stresses.

METHOD

Optical Arrangement

5. The stress analysis was made by the photoelastic method. The optical arrangement used was different from the standard photoelastic equipment and is shown in schematic outline in Plate 29; a is a source of light, b is a condenser which forms an image of a between c, a polarizer, and d, a compensator. Beyond d the cone of light spreads out to fill collimator e, which is a twelve-inch lens with a focal length of ten feet. The beam beyond e is plain polarized, and, because of the long focal length of the lens, very accurately parallel and moderately free from color fringes. The plain polarized parallel beam of light passes through the stressed test specimen f set

tion against polarizer c, and forms a sharp shadow image of f on the screen h.

6. This arrangement is very efficient. There is only one lens, e between the polarizer and the analyzer. The errors from internal strains in this lens are too small to be measured with the present equipment. Since there are no measurable strains in the lens, the entire field can be used with uniform accuracy.

Loading Frame

7. The transparent celluloid models 21 inches long were clamped in pivoted steel jaws as shown in Plate 28. They were loaded in tension through the circular spring scale as shown. The applied load could be read to the nearest pound on the dial in the center of the spring. Elastic hysteresis of the celluloid made use of the dial and absolute loading impractical. Each specimen was loaded to a uniform photoelastic reading at O, the central point of the section aa' (Plate 28) where the longitudinal or P stress is very nearly uniform across the specimen and the value of the transverse or Q stress which reaches a maximum at the center of the section is very small. The value of P-Q or photoelastic double refraction at the point O was taken as the unit load and all values of P, Q and P-Q for other parts of the specimen are expressed in terms of this unit load.

Measurements

8. A colored photograph (see Plates 1, 4, etc.) was made of each specimen showing what the observer saw as the image of the stressed specimen on the screen h. The photographs do not represent uniform loading since each specimen was given the load which presented the best contrast in the pictures. Regions of equal tint or color in these photographs represent regions of equal value of P-Q in the strained specimen. The left half of Plates 2, 5, etc. show maps of these regions or isochromatics. Each line represents a uniform value of P-Q, and the figure designating each line shows the value of P-Q represented by that line when the stress across section aa', Plate 28, is 10. The right halves of these plates are maps of the isoclinics or regions where the P and the Q stress lines have uniform slope as measured with reference to the central axis of the specimen. The system of mutually orthogonal lines built up over the isoclinic maps show the flow of P and Q stresses throughout the body of the specimens.

9. Plates 3, 6, etc. show values of P, Q and P-Q plotted as ordinates along the different axes for which stress analysis was requested. The unit load for these plots is 1 instead of 10 as shown on the isochromatic maps.

Results

10. Table 1 shows comparative data for the different specimens. Column 1 gives the number of the specimen for each line. Column 2 gives the maximum value of P-Q for each specimen in the free portion of the plate. This is the highest value shown by the deck plate beyond any doubler or

gitudinal. The highest stress probably often does occur back of a doubler or back of a longitudinal. No attempt was made to measure these stresses. Their magnitude could be estimated, but probably would be of little value as applied to the case of steel structures.

11. The largest numbers in column 2, namely, 2.8 and 2.24, show that the specimens to which they refer are the worst design. Likewise, the smallest numbers in column 2 indicate the best designs. Column 3 shows the minimum values of P-Q. Every specimen shows a minimum P-Q value along the A axis. These low values indicate distortion in the stress pattern introduced by the deck opening and small numbers indicate poor design, while large figures show good design. Column 4 gives the reciprocals of the greatest P value; this represents the strength of each plate as compared with the strength of a similar plate with no opening.

12. Columns 5 and 6, Table 1, show special stress values along the A axis. Maximum values of P-Q and P are omitted because in all cases they are 1. Minimum values of P-Q are in all cases those given in Column 3. The high Q compression of Column 6, lines 1 and 2, shows values very near the edge of the deck opening, while the tension Q values of the lower lines show values beyond the doubler. Measured at the same distance from the edge of the opening, the Q values for specimens 1 and 2 would be about the same as for the other specimens.

13. Columns 7 to 11, inclusive, show special stress values along the B axis with the exception of the last two lines which show special values along the D axis for specimens 8 and 9. These values may not be of greatest significance because the B axis may not pass through the regions of critical stress; for example, in Plates 1 and 2 the maximum stress is much greater than the maximum of the B axis.

14. Columns 12 to 15, inclusive, give special stress values along the C axis. **The figures of columns 12 and 14 are the significant figures,** where failure would be expected along the narrowed part of the plate, which is true of specimens 8 and 9, rather than at the corners of the openings, as would be expected for the other specimens.

TESTS

Specimens 1 and 2

15. Specimens 1 and 2 show the difference in stress patterns surrounding a square opening in a plane deck plate with and without the specified coaming plate and longitudinals but without any form of doubler. The white area within the blue immediately above and below the corners in specimen 2, Plate 4, show stresses introduced by the coaming plate. Since this plate is welded to the longitudinal, it carries near the centers of the sides of the openings approximately the same load per unit cross section as the deck plate at this point. All of the tension load must of course be delivered to the longitudinals and the deck plating at or near the corners. This introduces an area of very high tension fore and aft of the corners. A comparison

Table 1
Limiting Values of P, Q and P-Q along Special Axes of the Different Specimens.

Specimen No.	P-Q Max.	P-Q Min.	Predict Failure Load	Special Axes A: P Min.	A: Q Max.	B: P-Q Max.	B: P-Q Min.	B: P Max.	B: P Min.	B: Q Max.	C: P-Q Max.	C: P-Q Min.	C: P Max.	C: Q Max.
Column 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	2.8	.5	.36	0	-1.05	2.00	1.24	2.00	1.24	.46	2.20	1.21	2.20	.13
2	1.9	.55	.50	0	-0.89	1.89	1.11	1.78	1.09	.31	1.89	1.00	1.98	.09
3	1.60	.53	.63	.75	0.26	1.56	0.97	1.33	0.97	.40	1.35	0.97	1.39	.04
4	1.45	.66	.69	.80	0.22	1.45	0.97	1.16	0.97	.29	1.39	1.00	1.17	-.22
5	1.63	.62	.61	.77	0.20	1.60	1.00	1.33	0.99	.28	1.37	1.00	1.49	.12
6	1.42	.70	.70	.80	0.11	1.41	1.10	1.26	1.00	.15	1.33	1.07	1.43	.08
7	1.22	.70	.81	.74	0.07	1.20	1.00	1.07	1.00	.14	1.17	0.99	1.24	.08
8	2.24	.69	.44	.76	0.14	2.24	1.14	2.24	1.14	.05	2.25	1.15	2.29	.04
9	1.47	.77	.68	.80	0.10	1.44	0.88	1.33	1.12	.29	1.45	1.09	1.45	.04
D Axis														
8						1.25	1.06	1.13	1.02	.20				
9						1.28	1.00	1.11	1.00	.17				

of Plates 3 and 6 shows that this high P-Q value does not appear on the B axis but inspection of Plates 2 and 5 shows that where the B axis passes through maximum values of P-Q for Plate 2 it misses maximum in Plate 5. The very high maximum of 2.8 shown by Table 1 for specimen 1 is shown by Plates 1 and 2 to be confined to a very small edge effect outside of the four corners. This area, which marks the probable point of failure for specimen 1, is covered by the longitudinal in specimen 2. The stress distortion introduced by the coaming plate is further illustrated by the reversal of P-Q values in line with the cross members of the coaming plate as shown by Plate 4. The isoclinic pattern of Plate 5 shows that this low P-Q value results from comparatively high Q tensions introduced by distortion of the stress lines. Where specimen 1 shows in Plate 2 a reversal to 87° which extends a little over half way in from the edge of the specimen to the opening while specimen 2, Plate 5, shows a reversal to 80° which extends all the way in to the longitudinal. This distortion of the stress lines represents comparatively high Q tensions probably about .5 over a small area. These Q tensions probably have no bearing on the ultimate strength of the plate which would probably fail just above the B axis and above the corner at a load of about .50, the ultimate strength of the plate, whereas failure of specimen 1 would be expected just below the corner at a load of .36.

16. These stress patterns of specimens 1 and 2 have been discussed in detail because most of the differences in the two patterns are repeated in the comparisons of stress patterns for specimens 3 and 4, specimens 6 and 7, and specimens 8 and 9.

Specimens 3 and 4

17. Specimens 3 and 4 show openings similar to specimens 1 and 2, but reinforced as shown with a solid doubler plate which in the mid section has a cross sectional area equal to half the cross sectional area removed from the plate by the opening. The photographs of Plates 7 and 10 show differences very similar to those shown in 1 and 4. A comparison of the isoclinic patterns of Plates 8 and 11 shows differences very similar to the differences between 2 and 5.

18. A comparison of the photograph of specimen 3 in Plate 7 with similar photographs of specimens 5 and 6 in Plates 13 and 16 respectively shows that the open head doubler of specimen 5 or 6 are more efficient than the solid head of specimen 3. The open head doublers being flexible pick up load from the deck plate and deliver it to the side or longitudinal members with the least possible distortion. The unnecessary stiffness of the doubler with a solid head introduces unnecessary stress pattern distortions which make it less efficient than the more flexible doublers.

19. A comparison of the isoclinics at Plate 8 with those of Plate 17 or of the isoclinics of Plate 11 with those of Plate 20 shows very readily the importance of the unnecessary stiffness of the solid doubler. Above the B axis both solid doublers show the 15° isoclinic while but one open doubler shows the 10° isoclinic, the other shows only the 7°. Below the B axis, specimen 3 shows a reversal of 4° while specimen 6 shows only 2°. Specimen 4 shows a double reversal between the B and the C axis, whereas specimen 7 shows only a single reversal.

20. This difference in complexity of the isoclinic maps probably indicates the relative efficiency of the solid and open doubler better than a comparison of the stress distributions of the different specimens as shown by Plates 9, 12, 18, and 21.

Specimen 5

21. Plates 13, 14, and 15 show the stress data for Specimen 5. The photograph of Plate 13 shows at once that there is little distortion of the stress pattern introduced by the corners of the doubler plate. However, the whole stress pattern shows more distortion in specimen 5 than in 6. The stress maxima are greater and the stress lines are more strongly curved. Probably the load factors of 61 and 70 are good measures of the efficiency of the two doublers.

Specimens 6 and 7

22. Specimens 6 and 7 shown in Plates 17 and 19 respectively represent the best pattern of doublers. Their efficiency as measured against the other doublers is probably quite well expressed by the figures of lines 6 and 7 in column 4.

23. Stress patterns within the doublers are not discussed in other parts of the report but in Plates 16 and 19 they give a good demonstration of how the stress load is built up by the conditions found at the edge of the doubler. Just inside the corners on Plate 19 we find a region of high stress; this is induced by the pull of the coaming plate. Since the cross doubler member is in compression P-Q values reach a maximum. Outside of each corner there is a bright blue spot, a region of low value for P-Q. Beyond each corner is a bright red spot partially obscured by the longitudinal. This is a region of high values for P-Q which results from comparatively large values of -Q or compression. The value of P between these two spots probably changes very little.

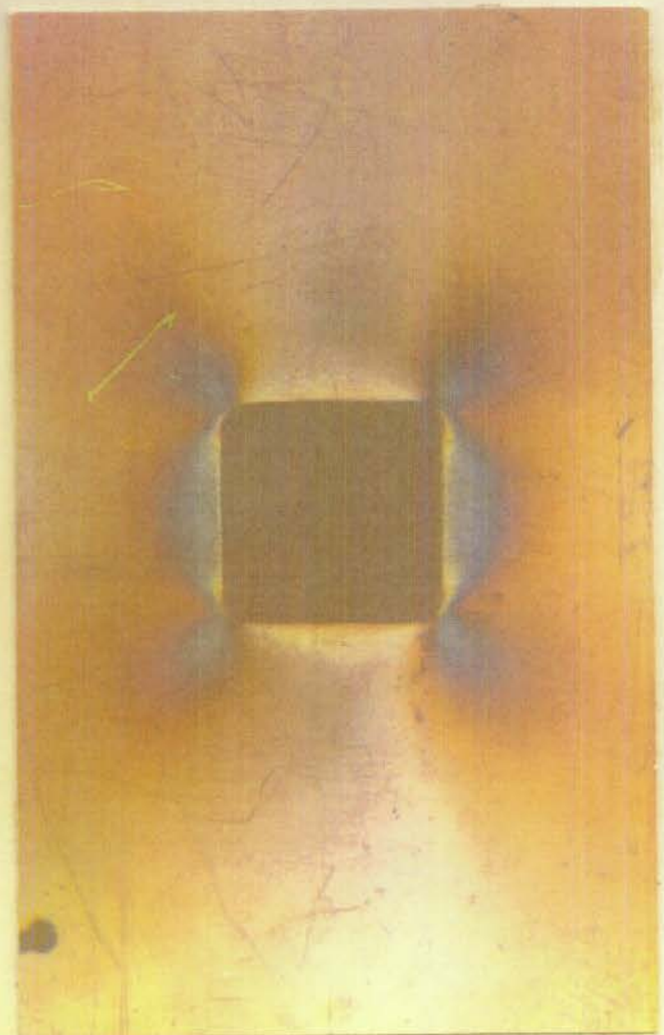
Specimens 8 and 9

24. Plates 22 and 25 show in specimens 8 and 9 doublers which cover only the fore and aft ends of the opening with no longitudinal member to carry the load from one end to the other; that is, the plate must carry the entire load past the C axis. The isochromatics of Plates 2 and 23 as plotted against the C axis in Plates 3 and 24 show the stresses across C to be almost identical for the two specimens. A comparison of the C axes on Plates 5 and 26 and the plotted values shown on Plates 6 and 27 show that the longitudinal and coaming plate in specimen 2 did not take the full load of the plate as it did in specimen 9, since the isochromatics of 5 are much higher than those of 26. If a doubler of the type of specimens 8 and 9 is to be used, some means must be provided to carry the load across between the two sections of the doubler.

SUMMARY

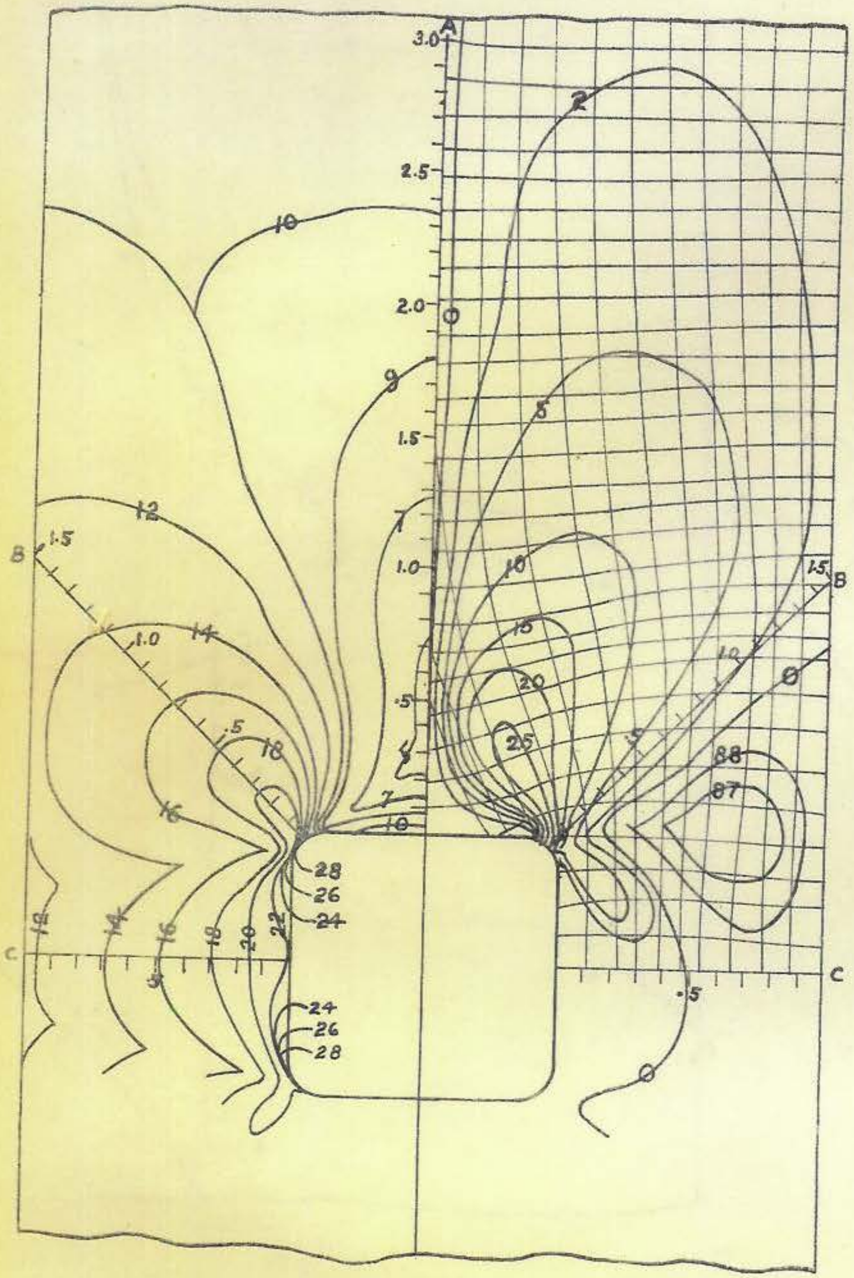
25. The study may be summed with the statement that a square opening in the center of a long plate removing one-third the cross sectional area of the sheet reduces the strength to one-third of the original value. If the opening is reinforced by longitudinals and coaming plate, each of which has a cross sectional area equal to 0.4 of the cross sectional area of the opening, the strength of the plate with the opening is equal to 0.5, the strength of a plane sheet with longitudinals. The same opening reinforced with a suspension type doubler as shown in specimens 7 and 6 reduces the strength of the sheet to 0.8 and 0.7 respectively with and without the coaming plate and longitudinal support. Doublers of the same form which support the ends but not the sides of the openings, as shown in specimens 9 and 8, show a reduction in strength to 0.7 and 0.4 respectively. Solid doublers of the same external outline, as shown by specimens 4 and 3, show reductions of strength to 0.7 and 0.6 respectively. A doubler of the same form as 6 but made of straight members, as shown in specimen 5, shows a reduction in strength to 0.6, the strength of the plane plate.

26. A doubler designed to support an opening in a deck must do three things: (1) It must take from the deck, fore and aft, the load which in the uninterrupted deck would be carried by the material removed from the opening. (2) It must carry that load past the deck opening. (3) Conditions 1 and 2 must be accomplished without distortion of the deck plating. All of the doublers shown meet condition 1 with about the same efficiency. The variations shown in the efficiency ratings of column 4, Table 1, therefore, come from variation in the meeting of conditions 2 and 3. A doubler could be completely effective in meeting requirement 2 if the cross section of **its longitudinal** members equalled the cross section of the deck material removed. The doublers tested had a cross section equal to half the material removed from the deck. Line 6, column 14, of Table 1, shows that this material under the best conditions carried a load of 1.43 per unit area, 1.43 x 0.5 = 0.72. The doubler in specimen 6 carried 72% of the opening load, leaving 28% to be carried by the deck. The efficiency of the doublers on specimens 6 and 7 is measured by their ability to meet condition 2. Condition 3 may be considered fully satisfied by these specimens. Specimens 8 and 9 fail completely to meet condition 2 and the figures of lines 8 and 9, column 4, Table 1, show that their doublers show a very low efficiency. A comparison of the efficiency figures for specimens 3, 5 and 6 show the importance of condition 3. Specimen 6 being most flexible and having curved members, is most efficient with a factor of 70%. Specimen 5 with angular members, is rated at 61%, while 3, because of the stiffness of its solid interior, is rated at 63%.



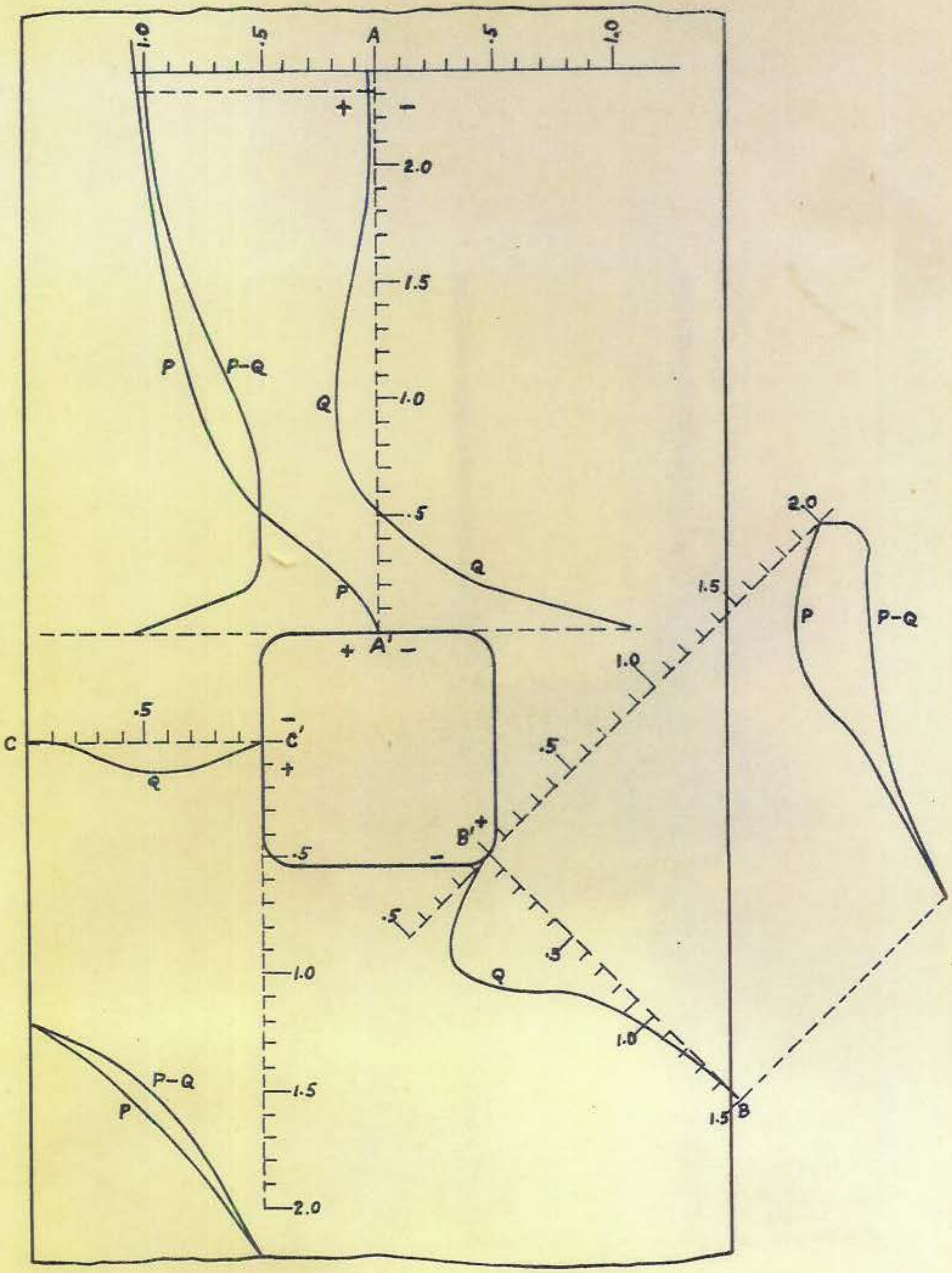
SPECIMEN I

PLATE I

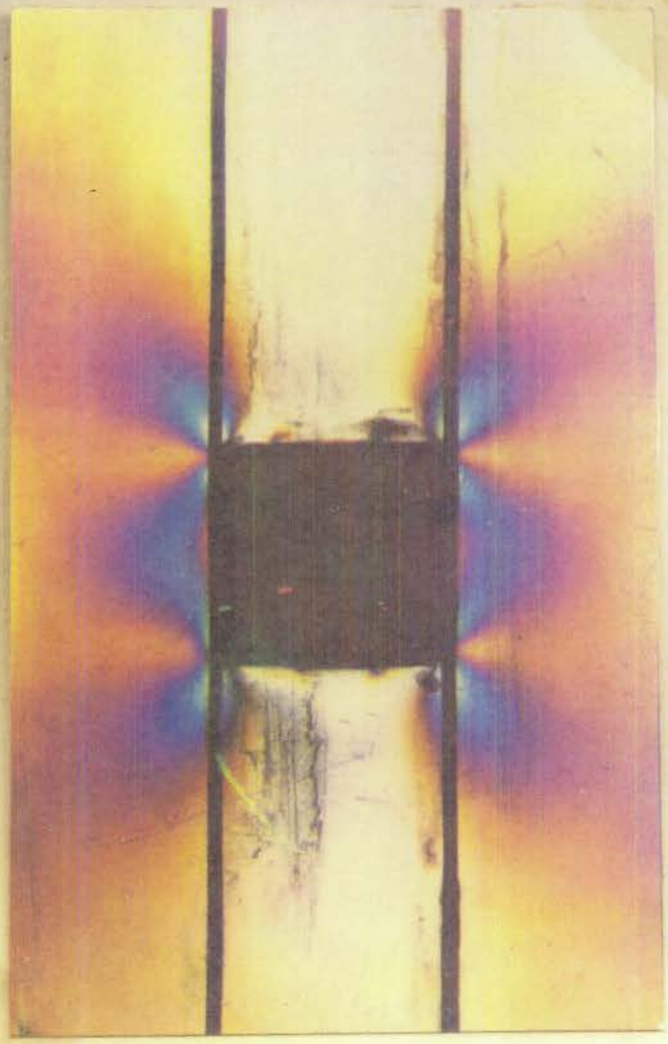


Isochromatics Isoclinics

Plate 2

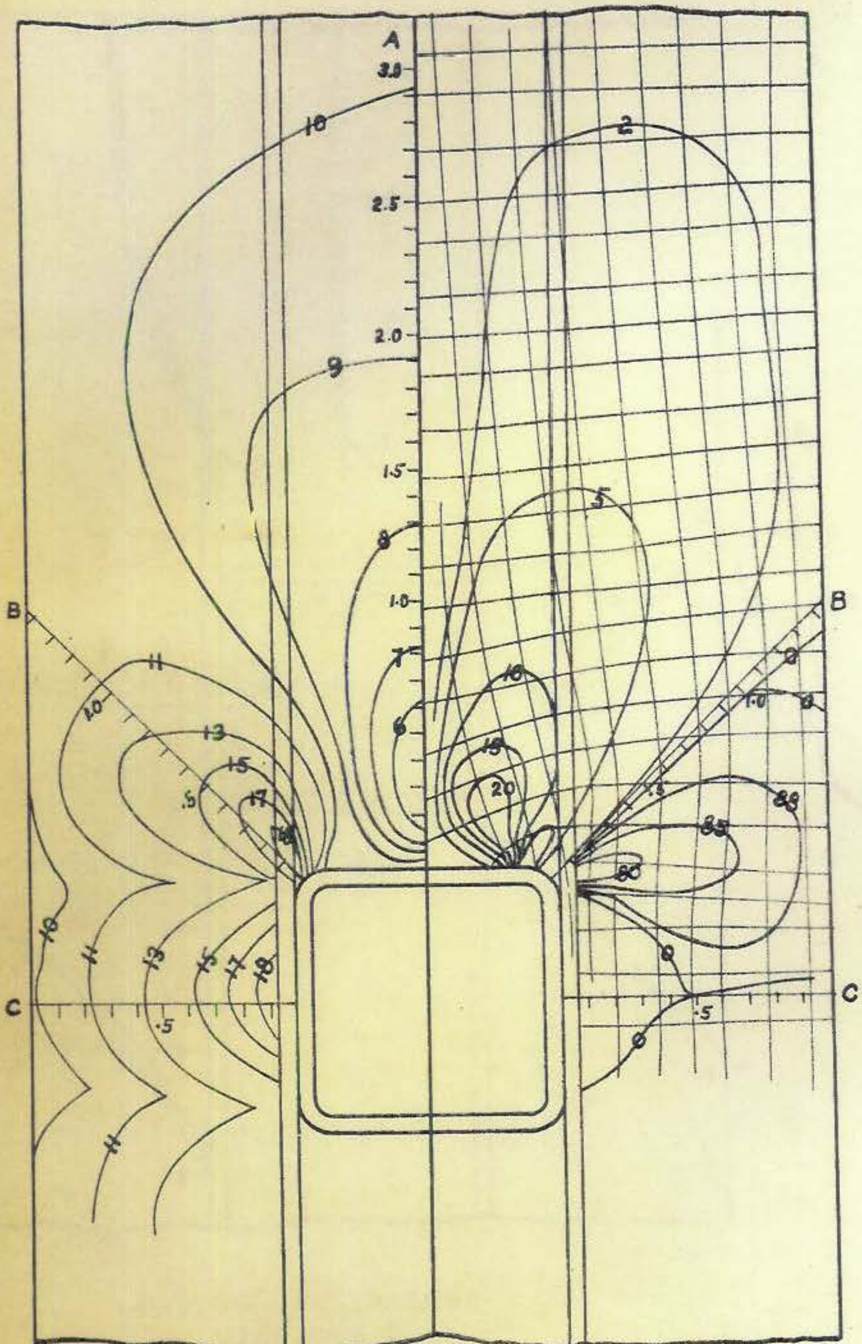


P,Q and P-Q values
Specimen 1



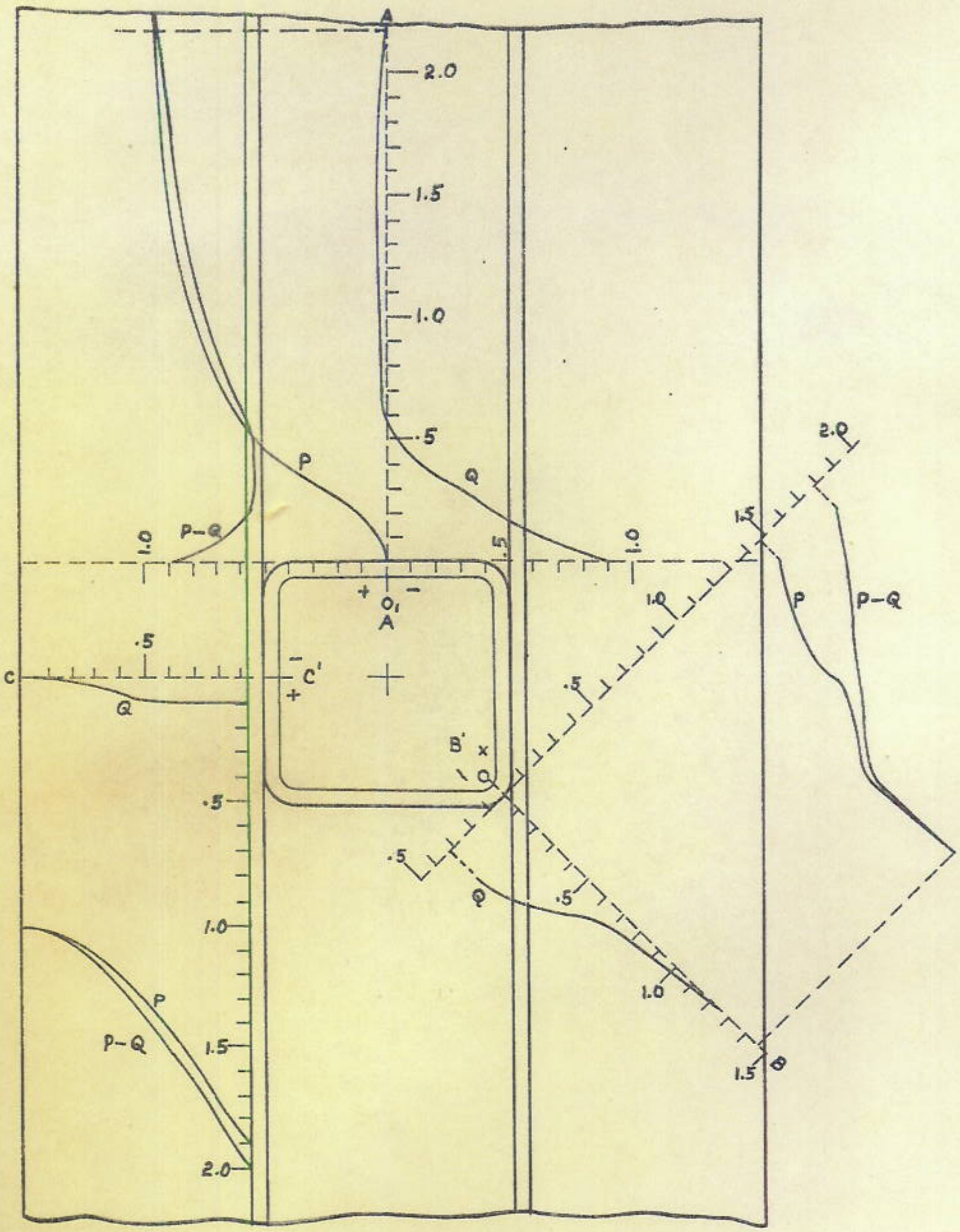
SPECIMEN 2

PLATE 4



Isochromatics Isoclinics

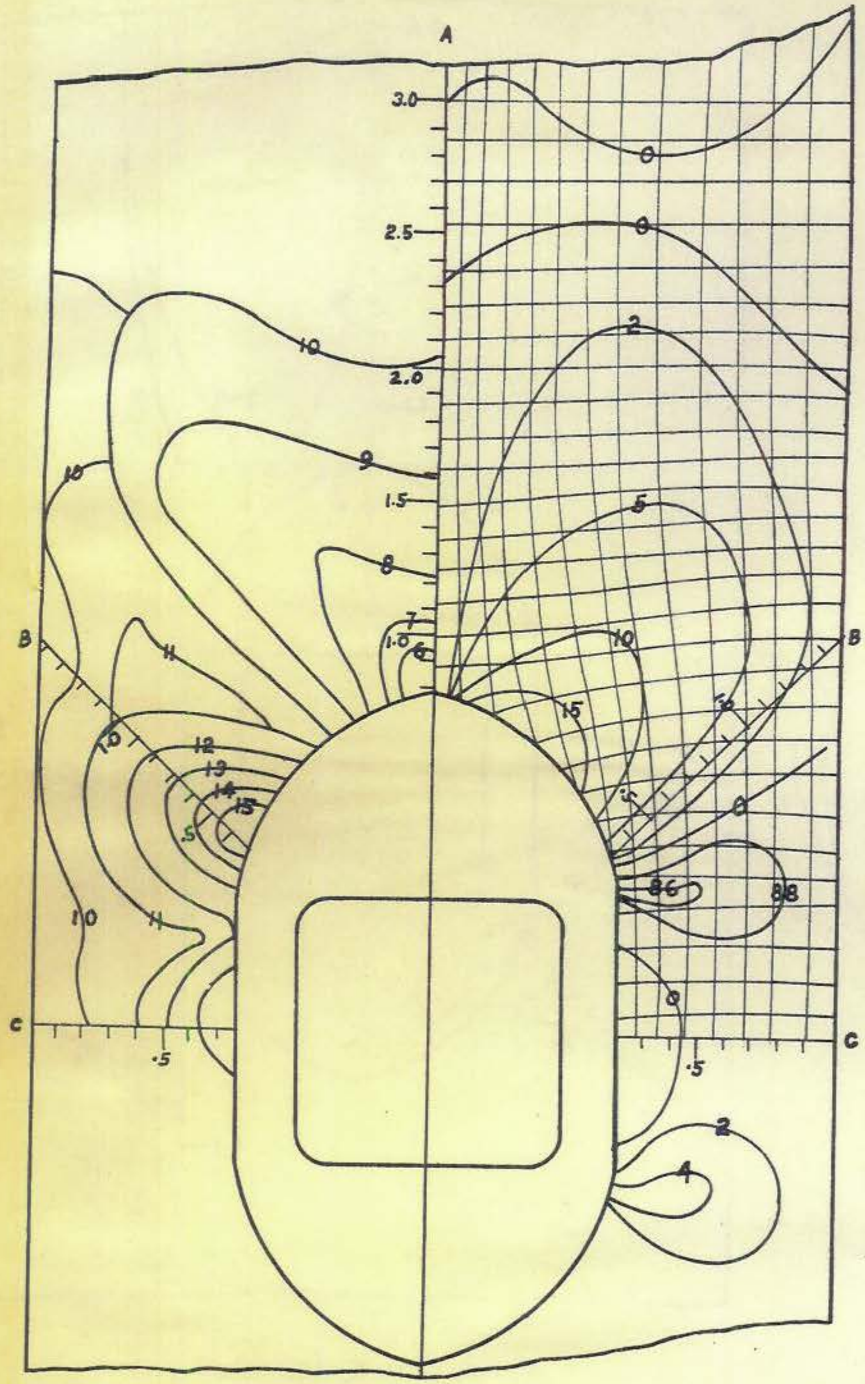
Plate 5



P,Q and P-Q values
Specimen 2

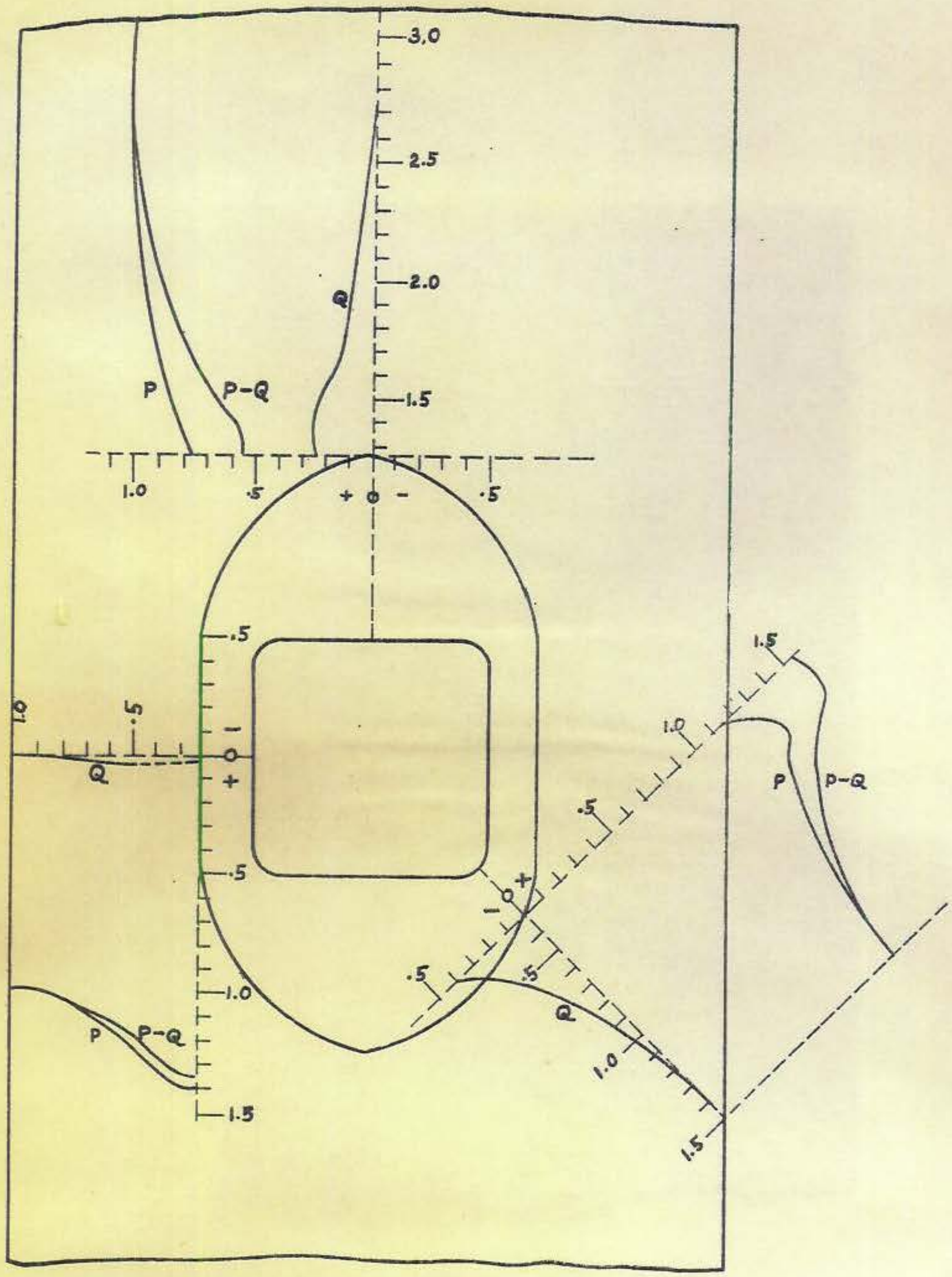
SPECIMEN 3

PLATE 7

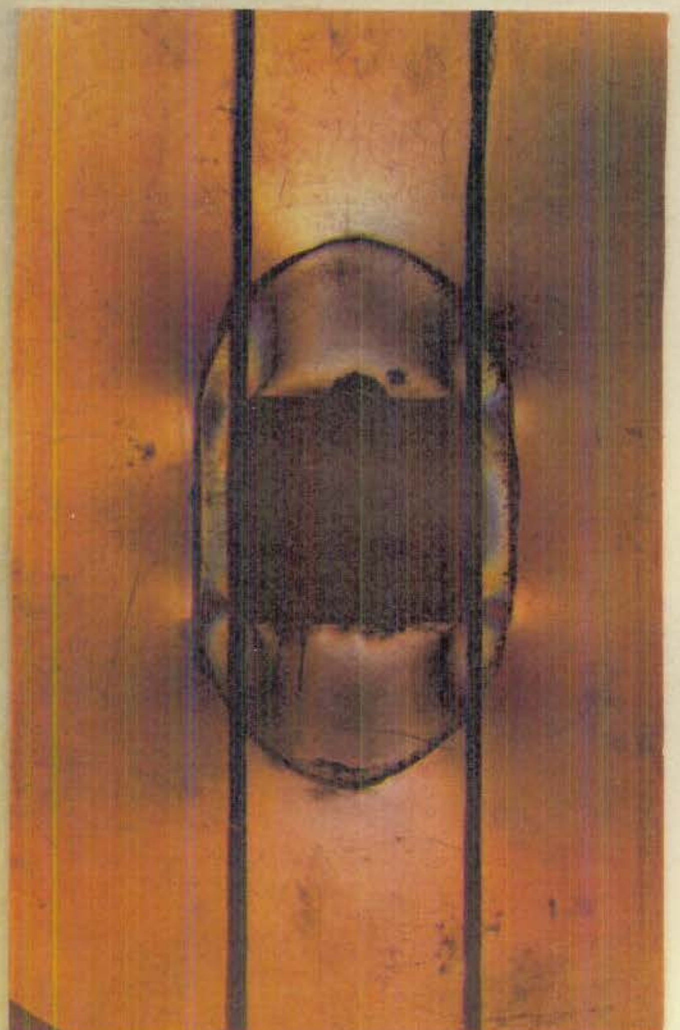


Isochromatics Isoclinics

Plate 8

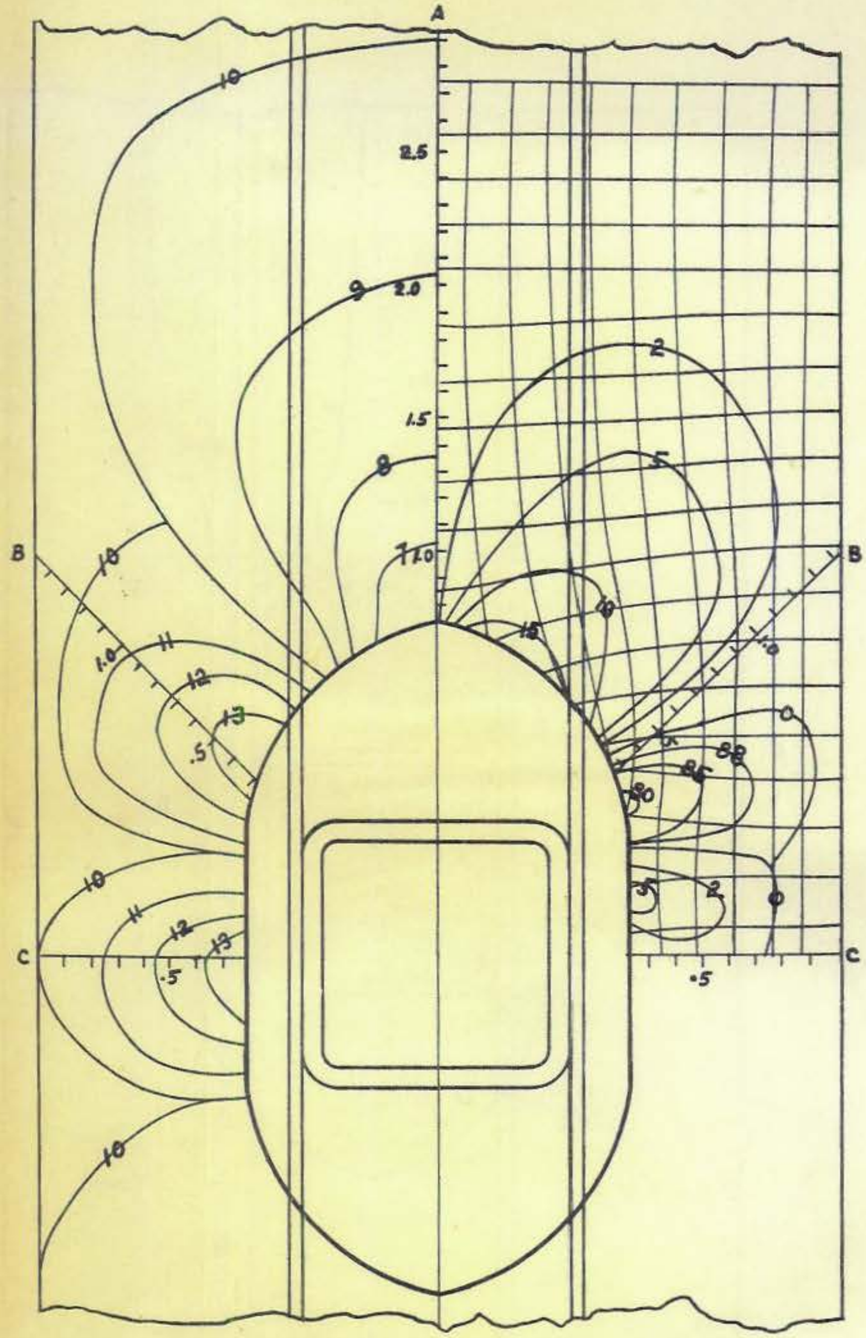


P,Q and P-Q values
Specimen 3



SPECIMEN 4

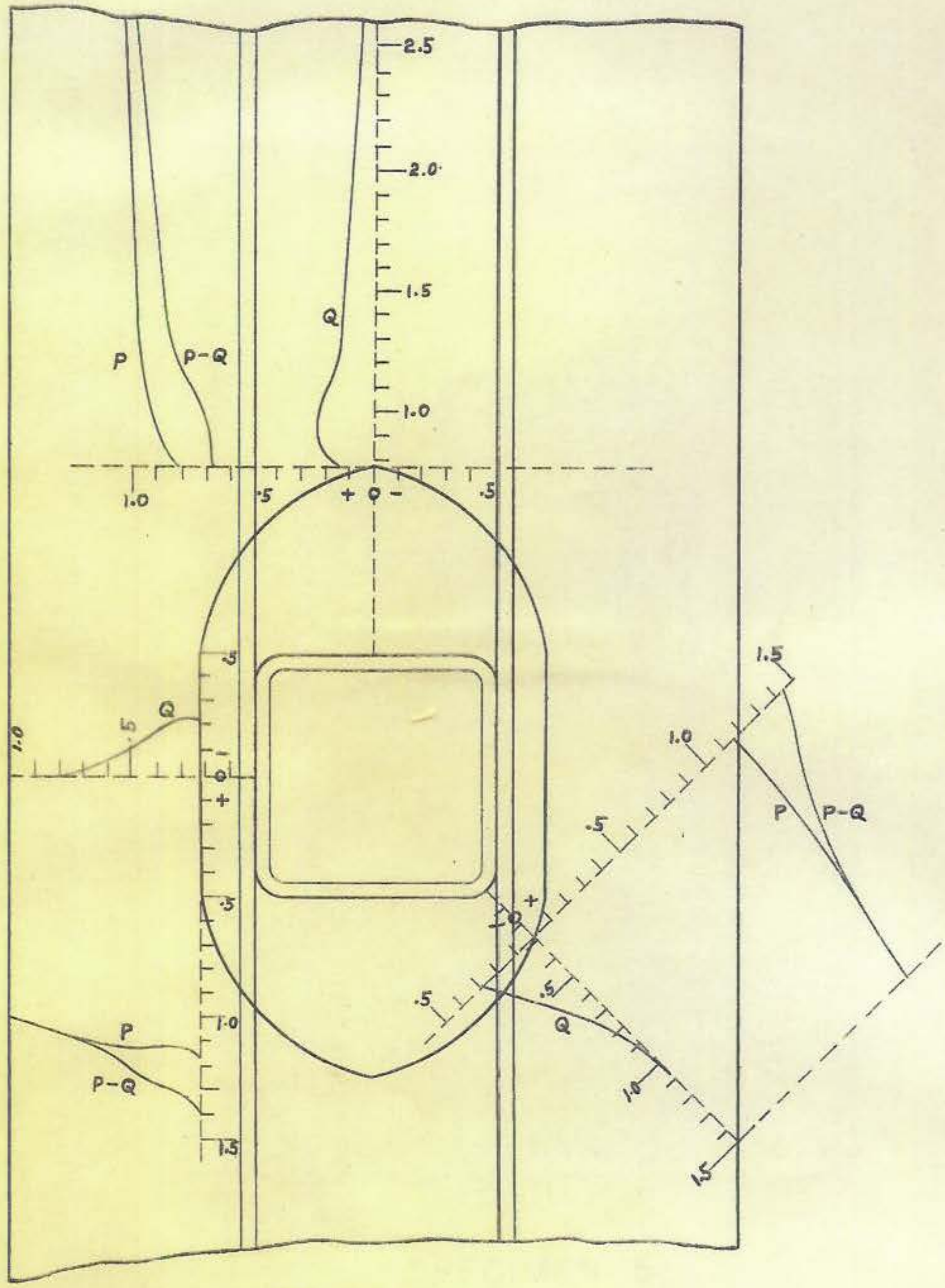
PLATE 10



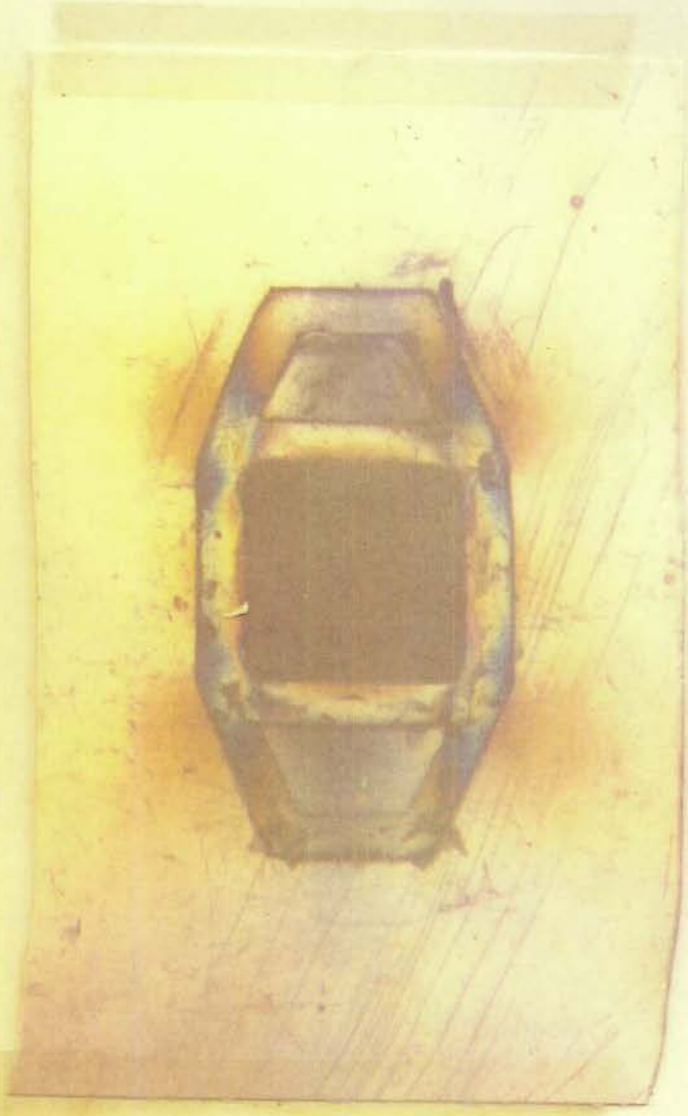
Isochromatics

Isoclinics

Plate 11

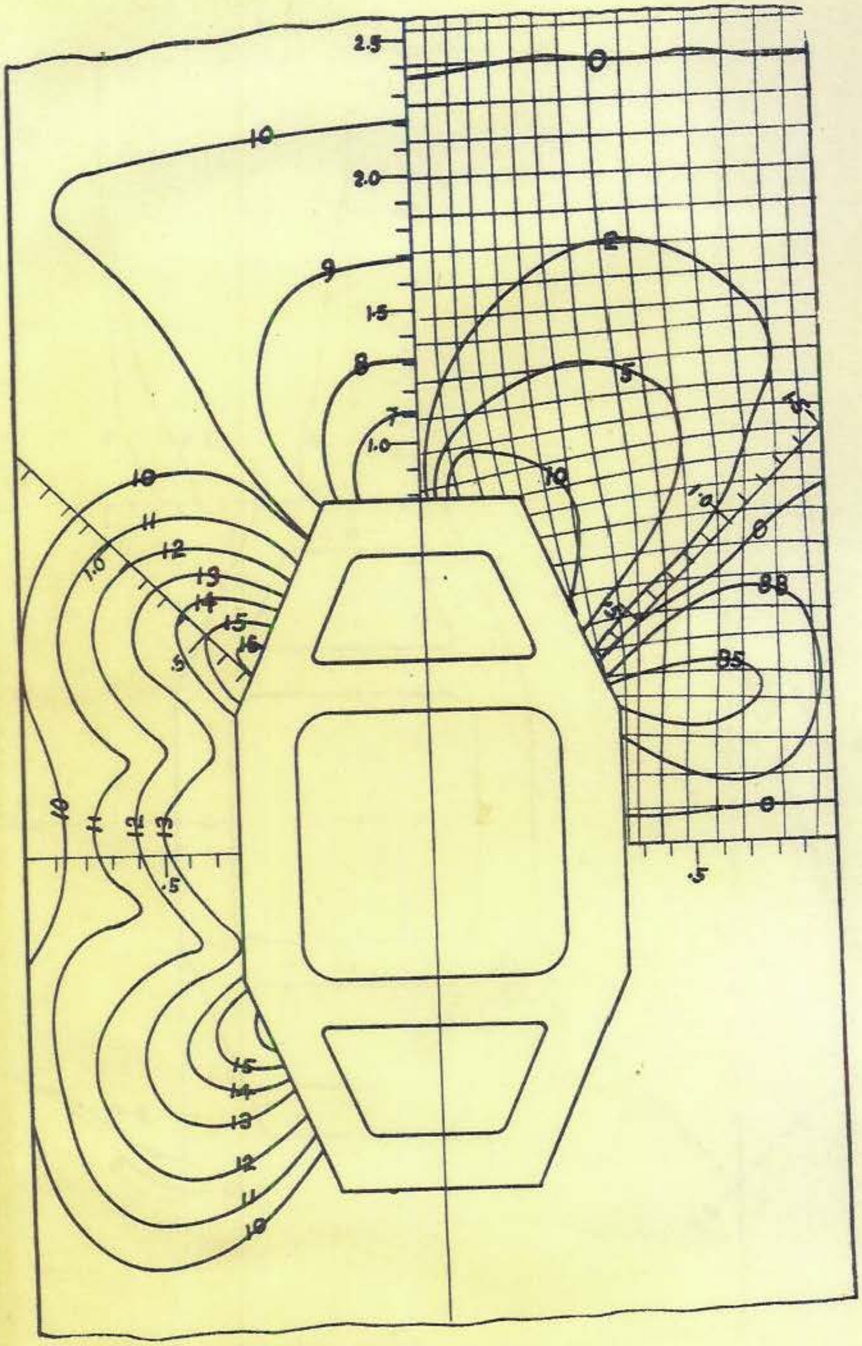


P,Q and P-Q values
Specimen 4



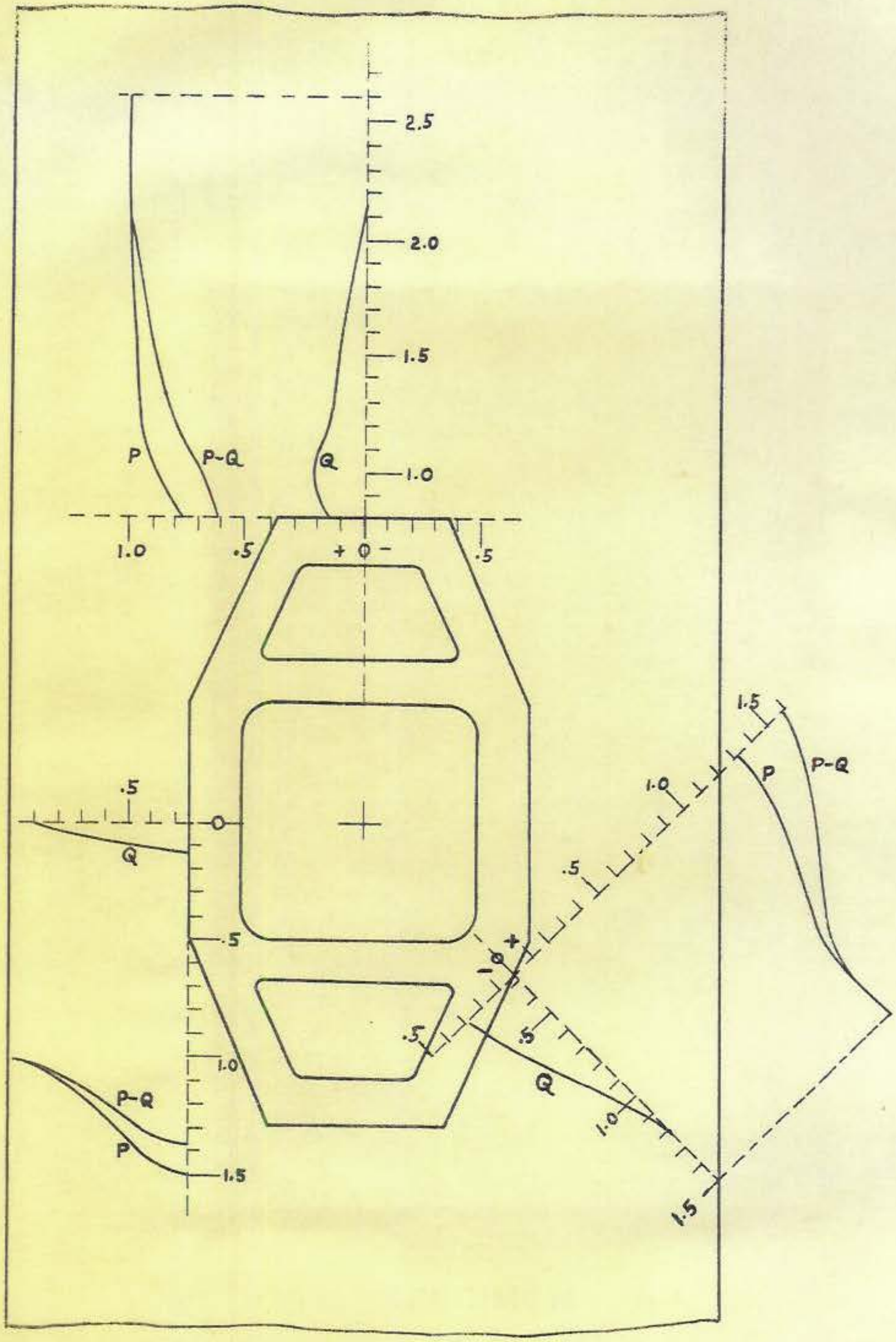
SPECIMEN 5

PLATE 13



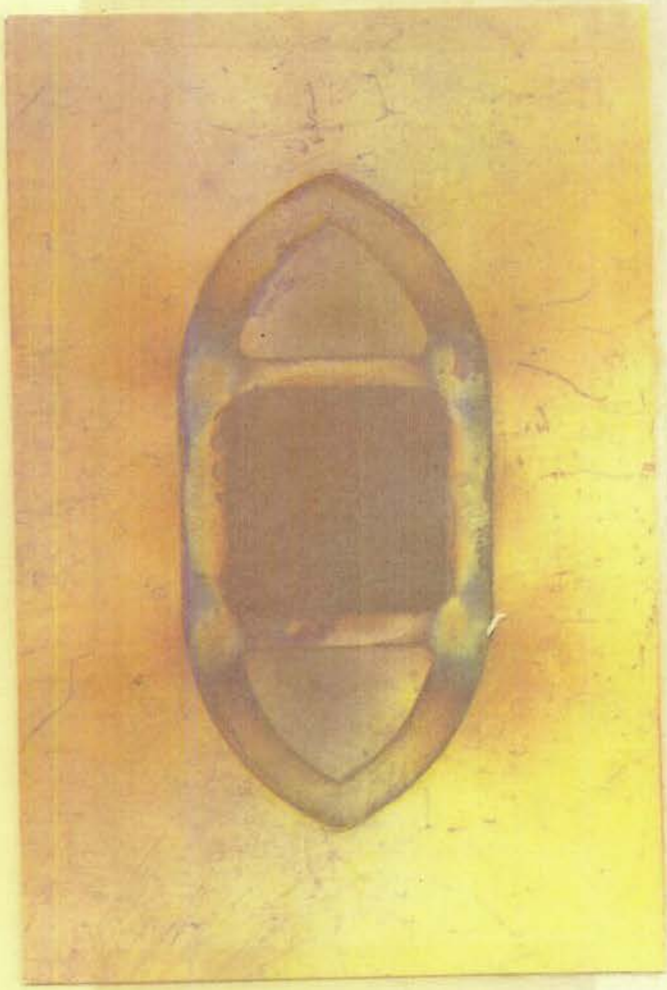
Isochromatics Isoclinics

Plate 14



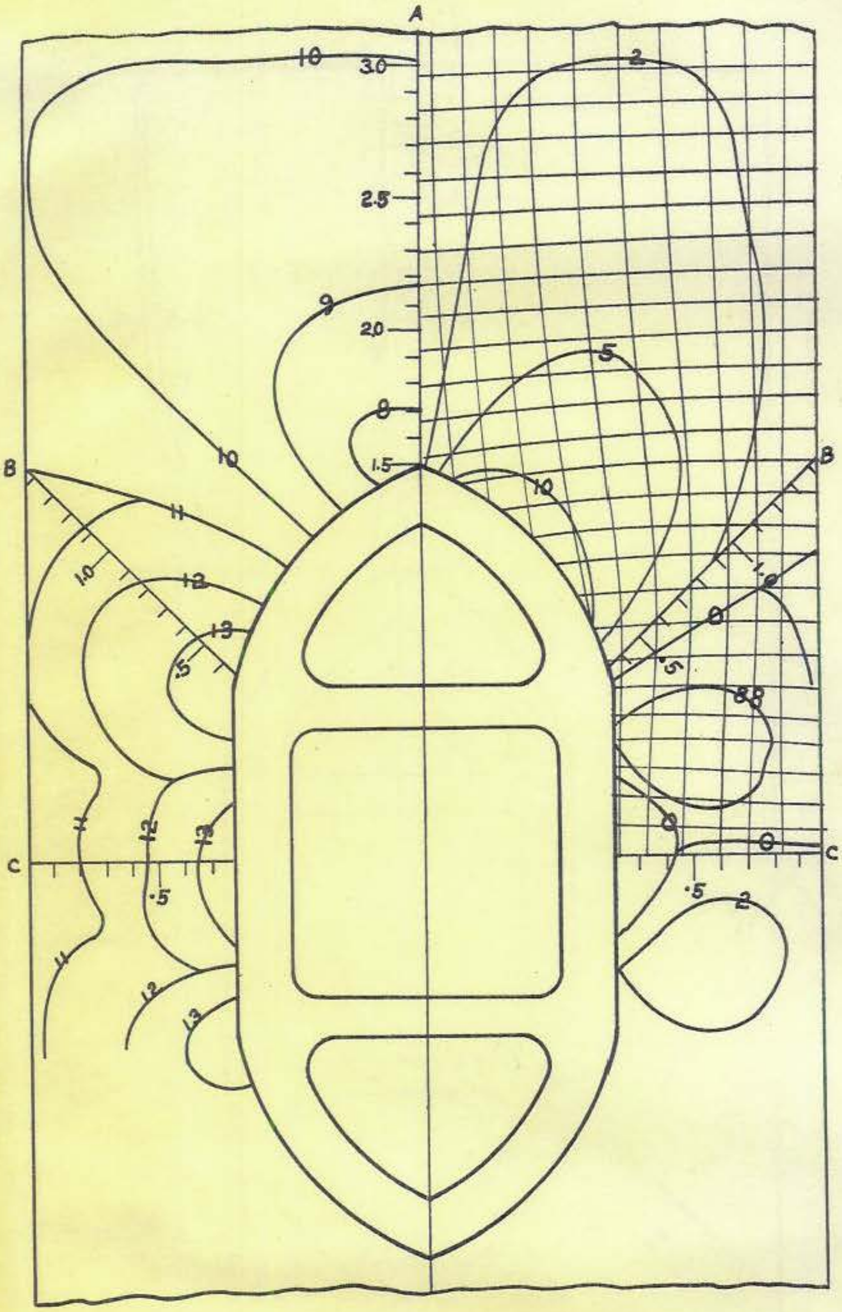
P,Q and P-Q values
Specimen 5

Plate 15



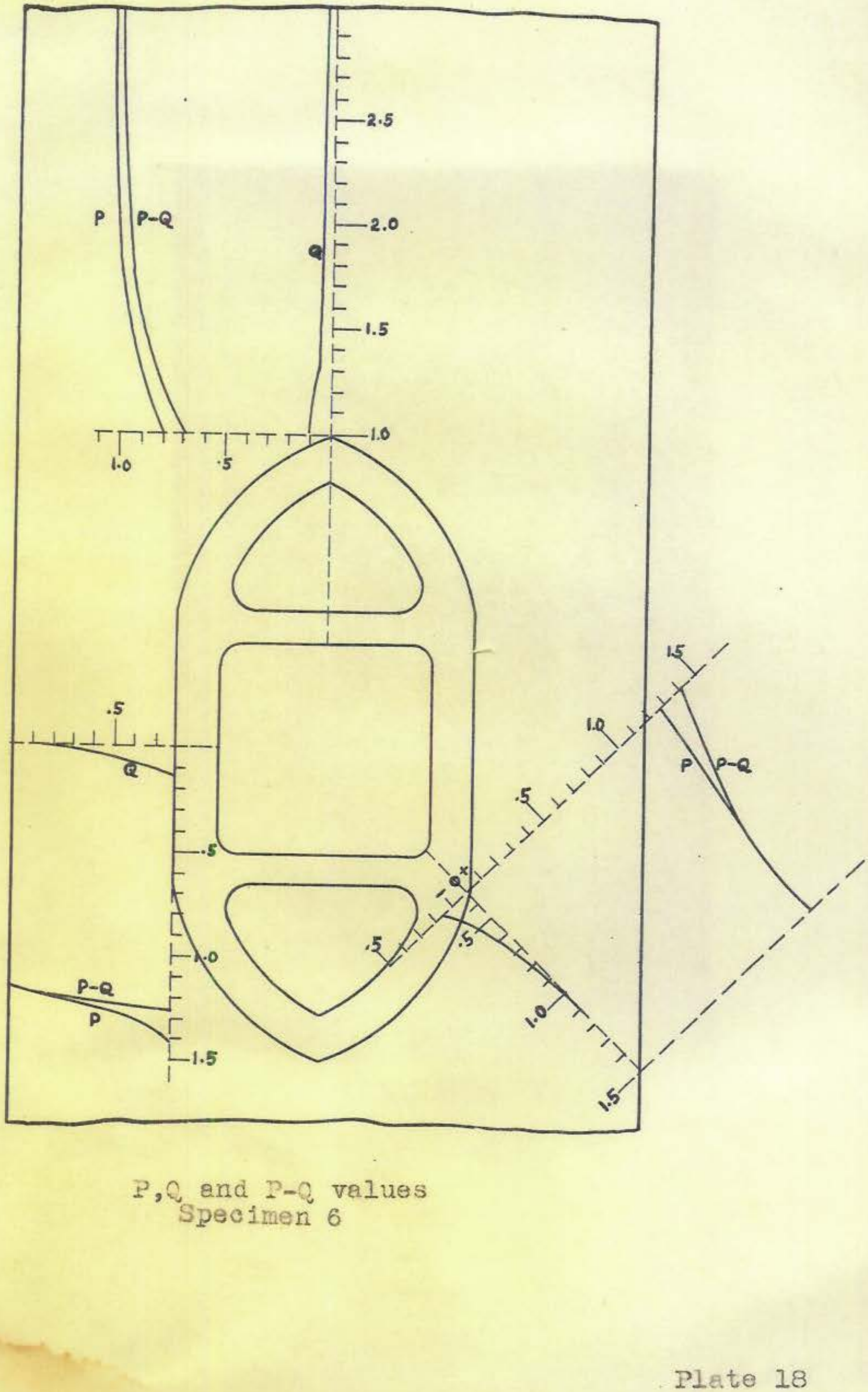
SPECIMEN 6

PLATE 16

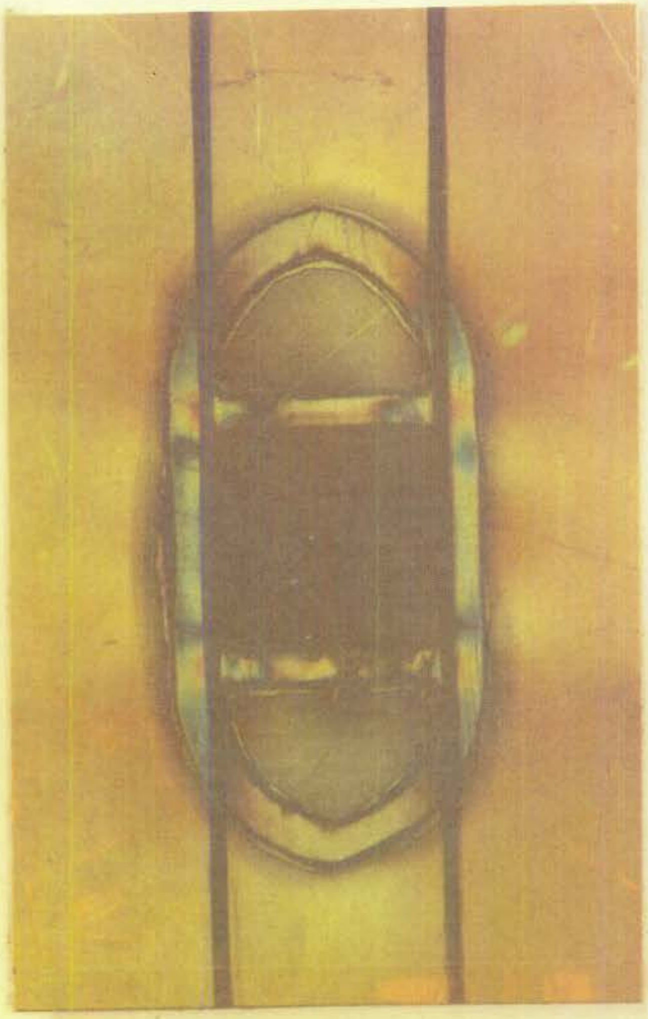


Isochromatics Isoclinics

Plate 17

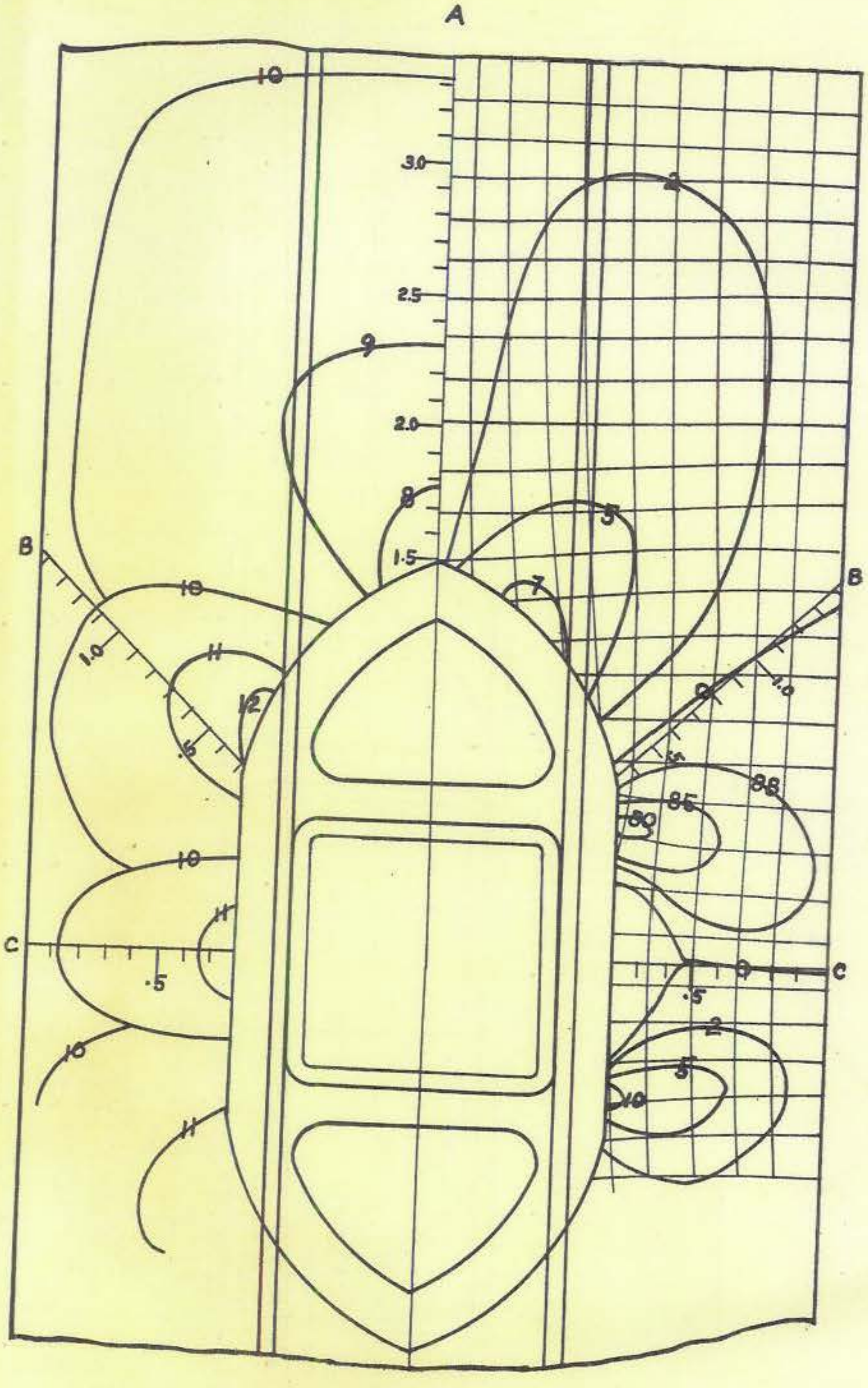


P,Q and P-Q values
Specimen 6

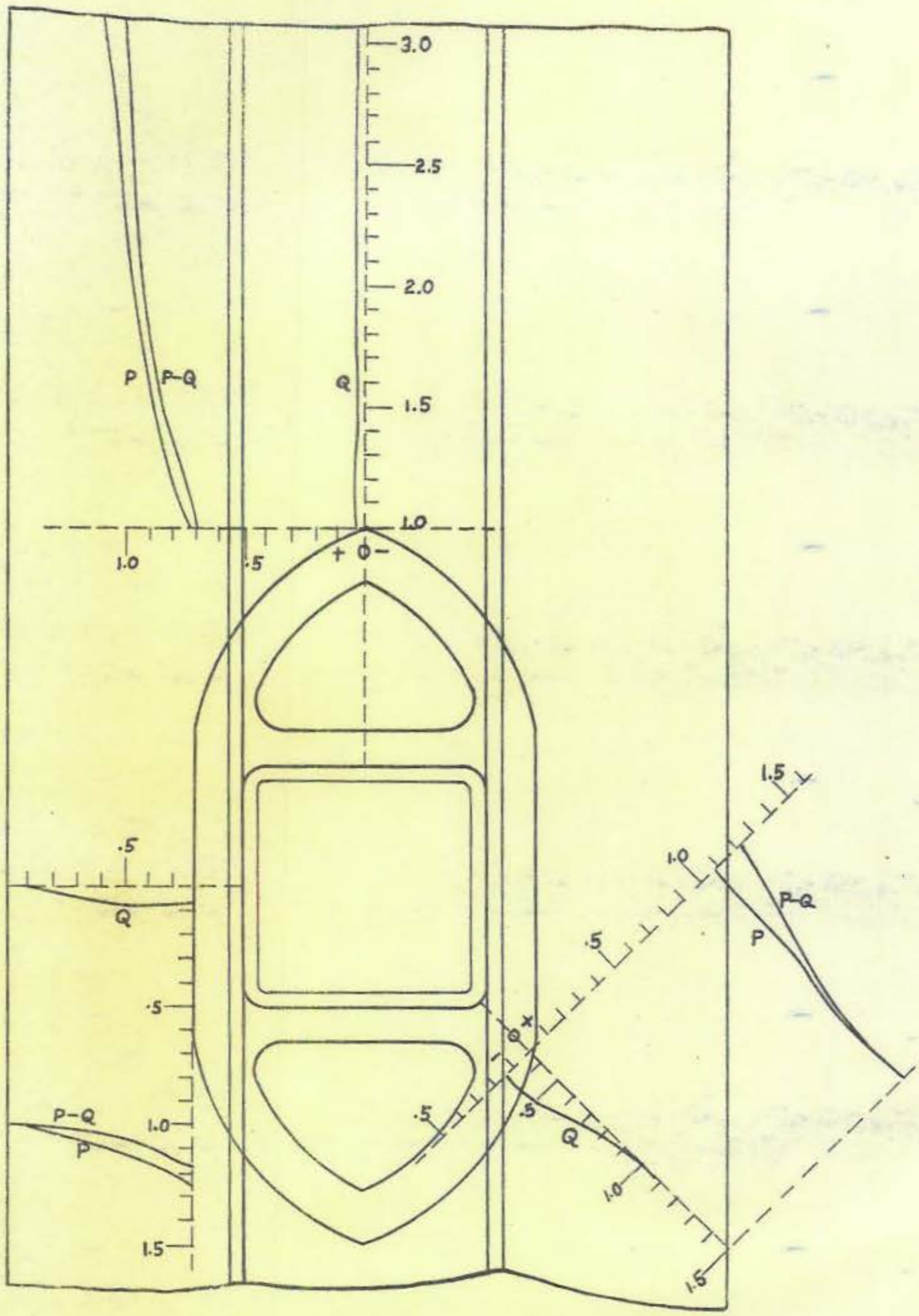


SPECIMEN 7

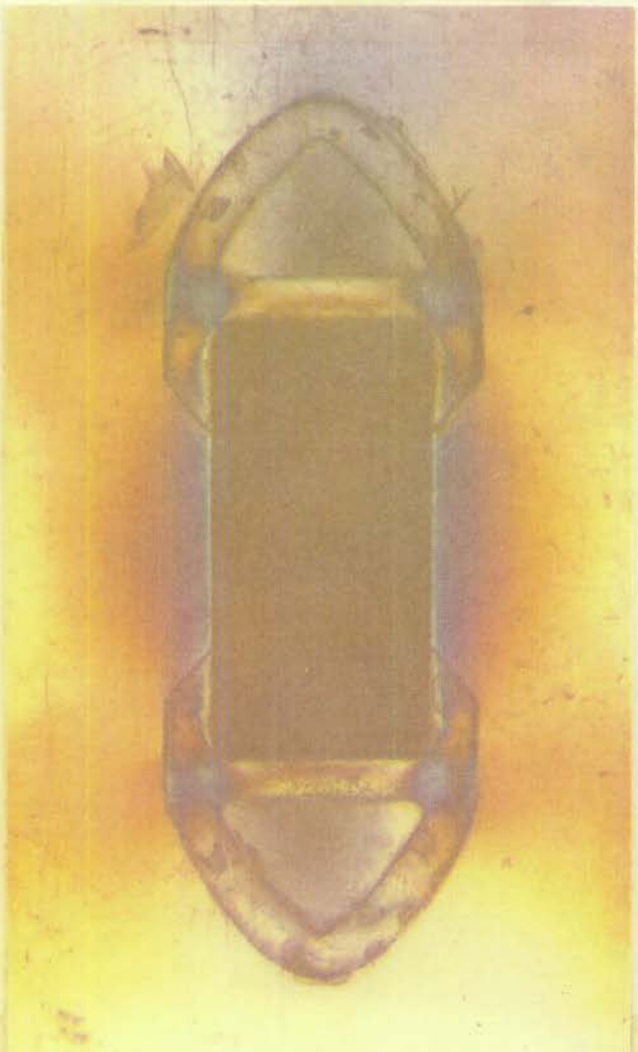
PLATE 19



Isochromatics Isoclinic

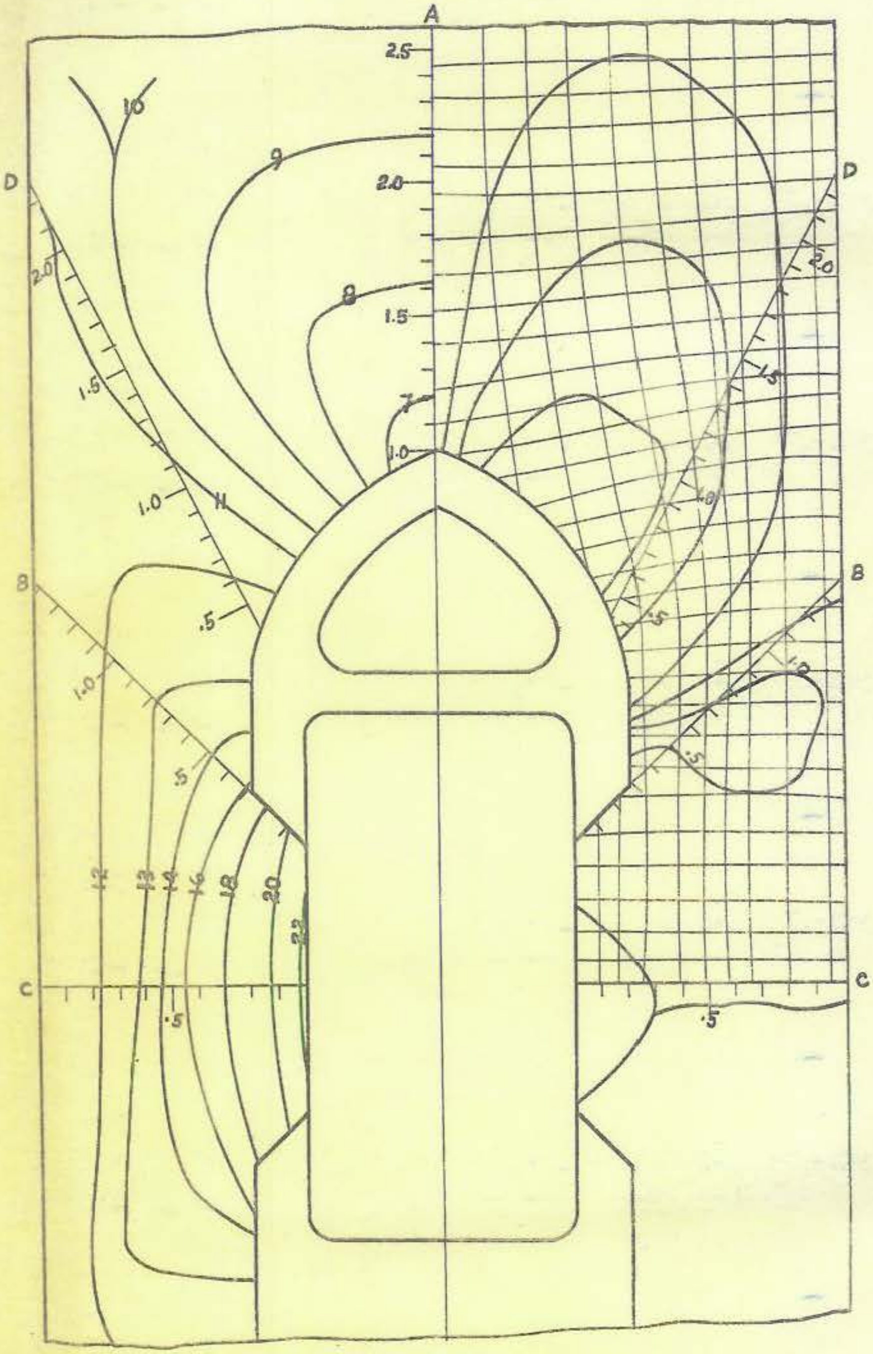


P,Q and P-Q values
Specimen 7



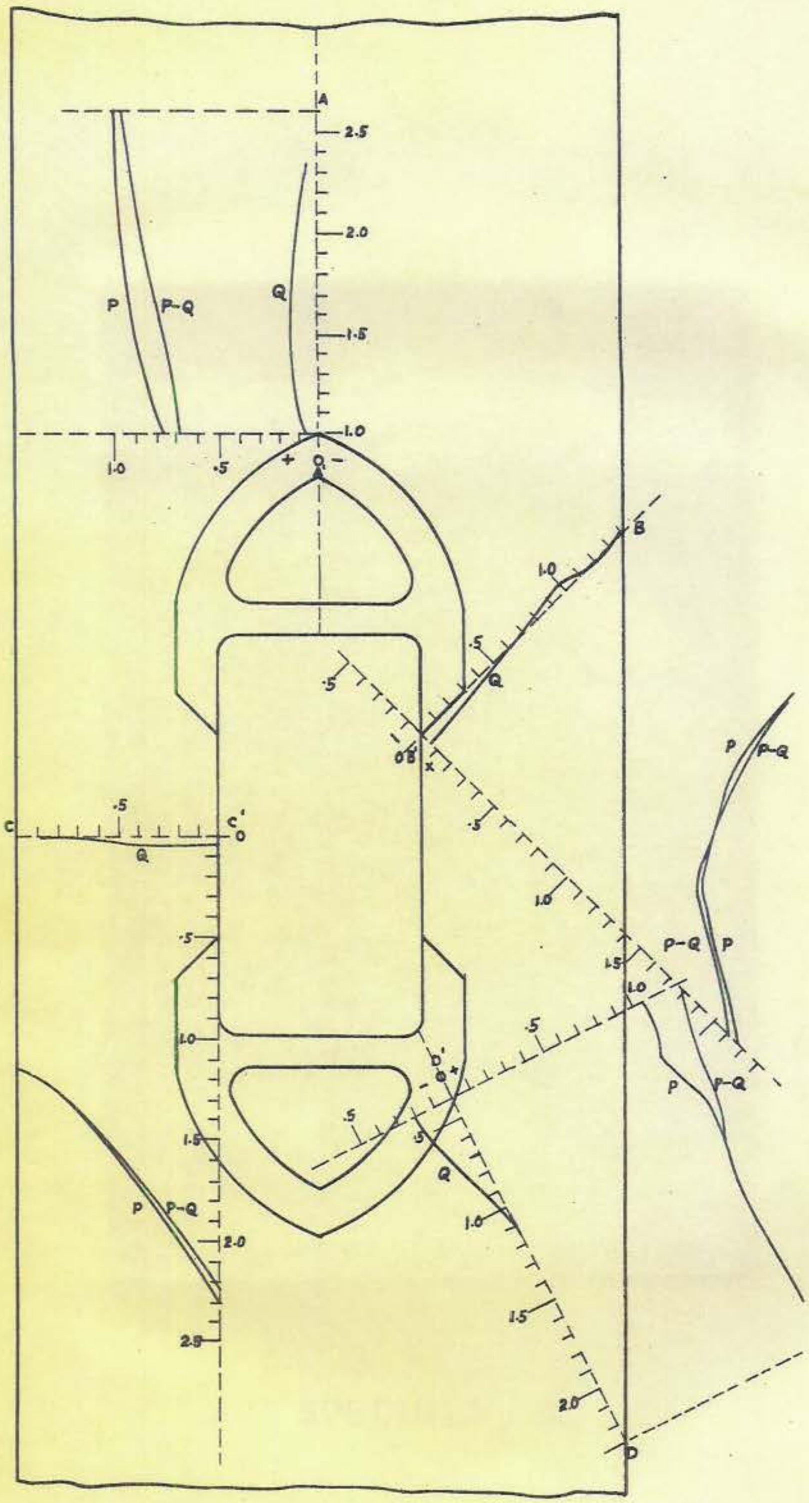
SPECIMEN 8

PLATE 22

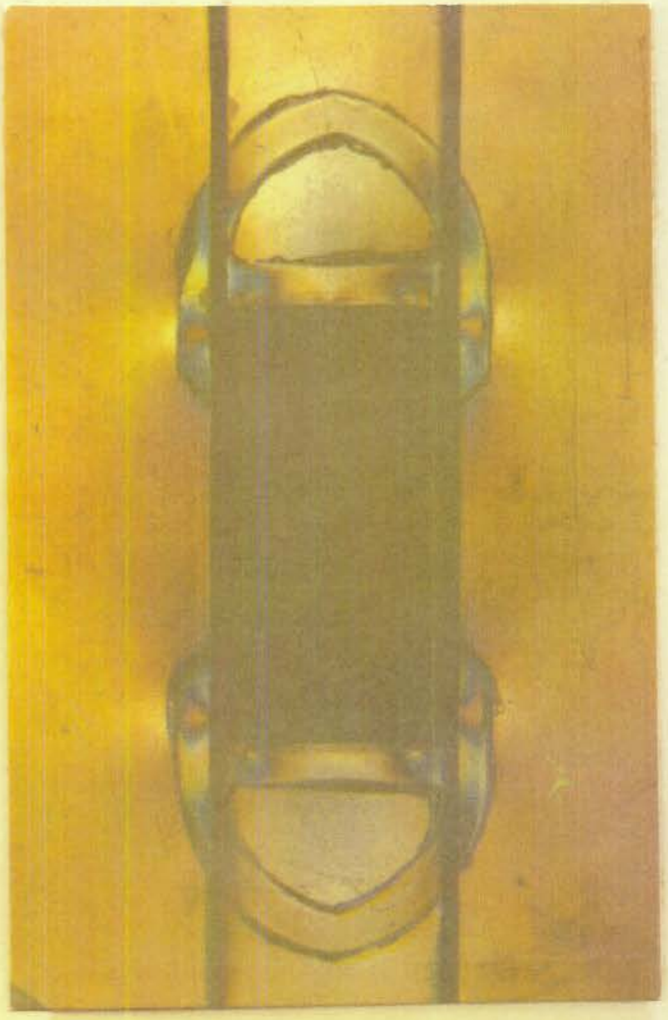


Isochromatics Isoclinics

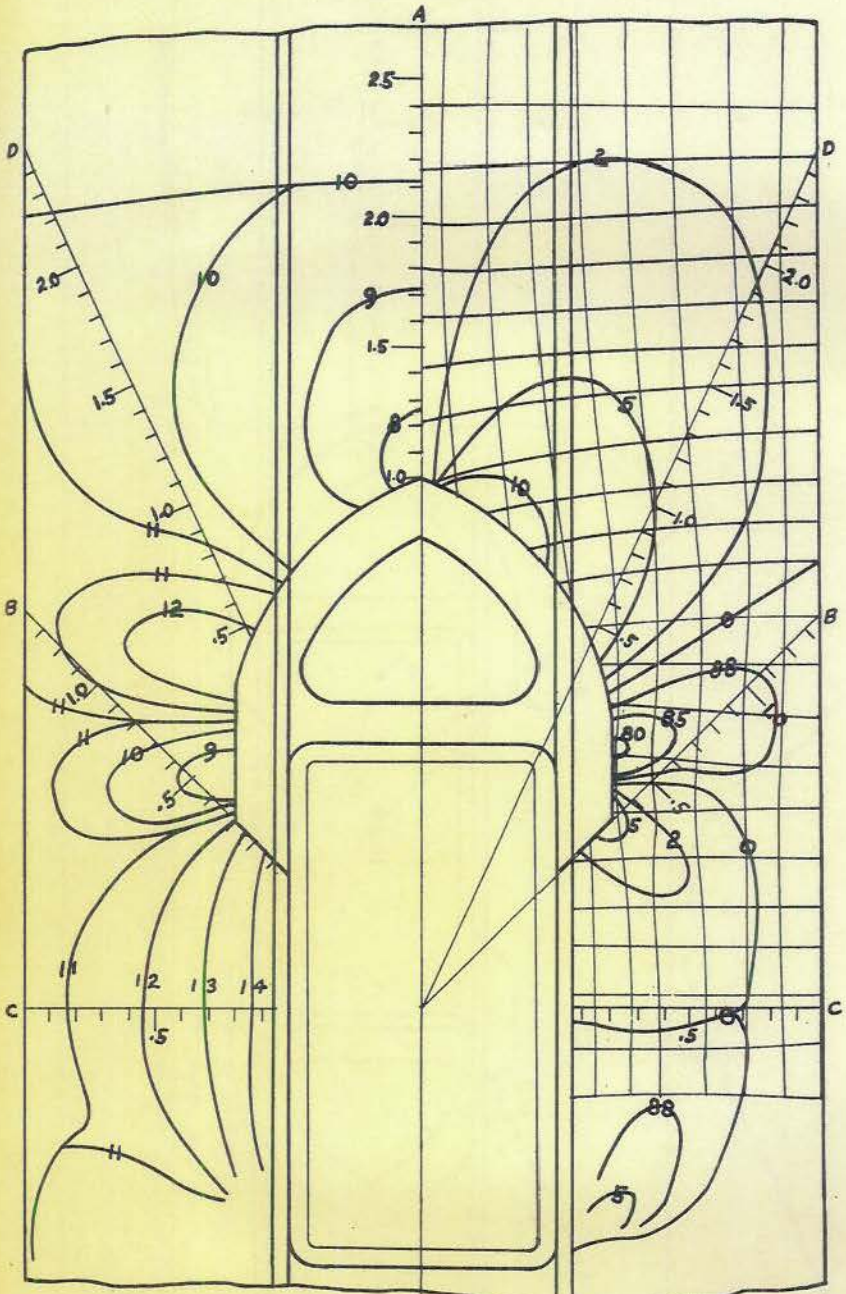
Plate 23



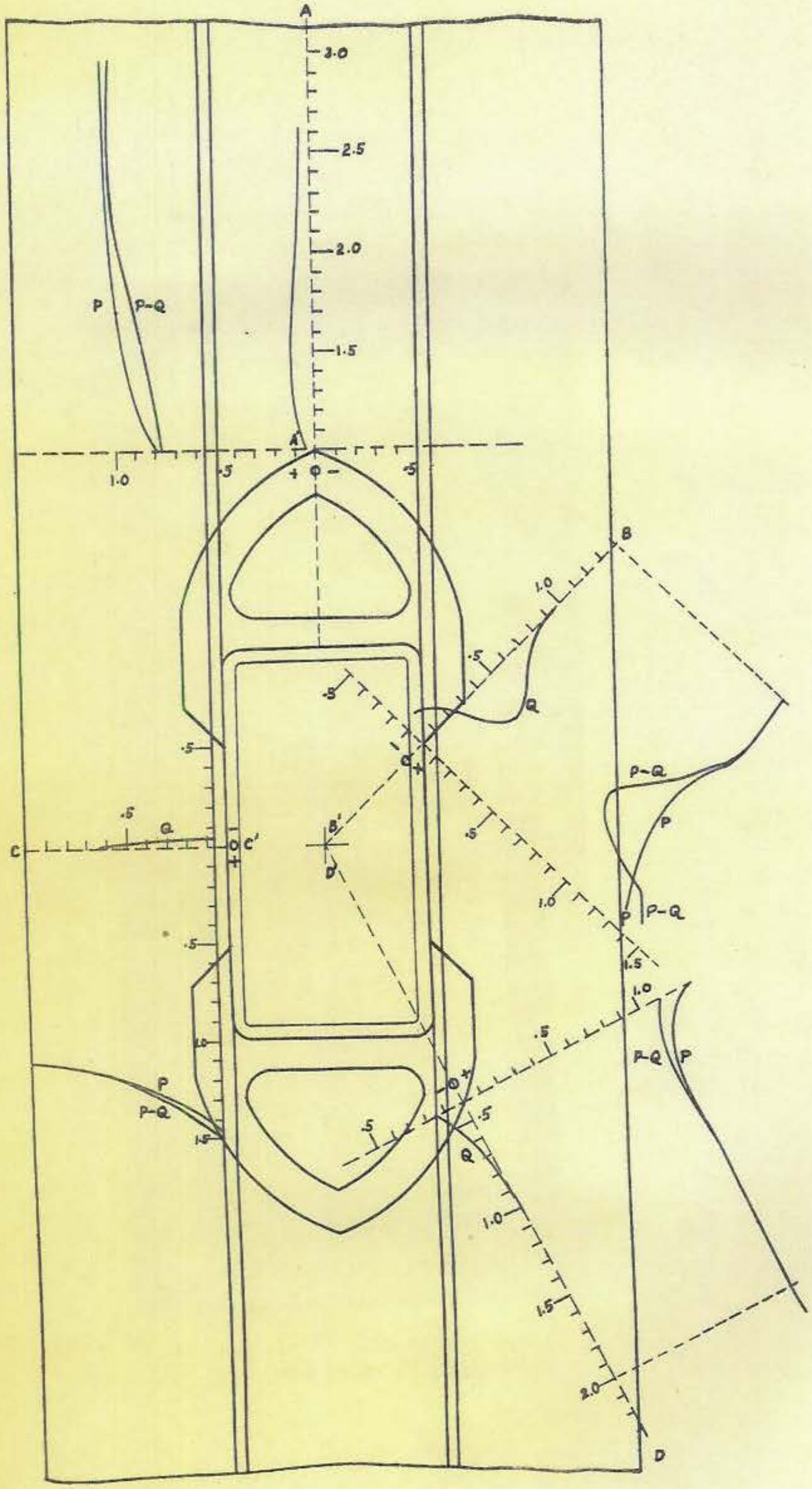
P,Q and P-Q values
Specimen 8



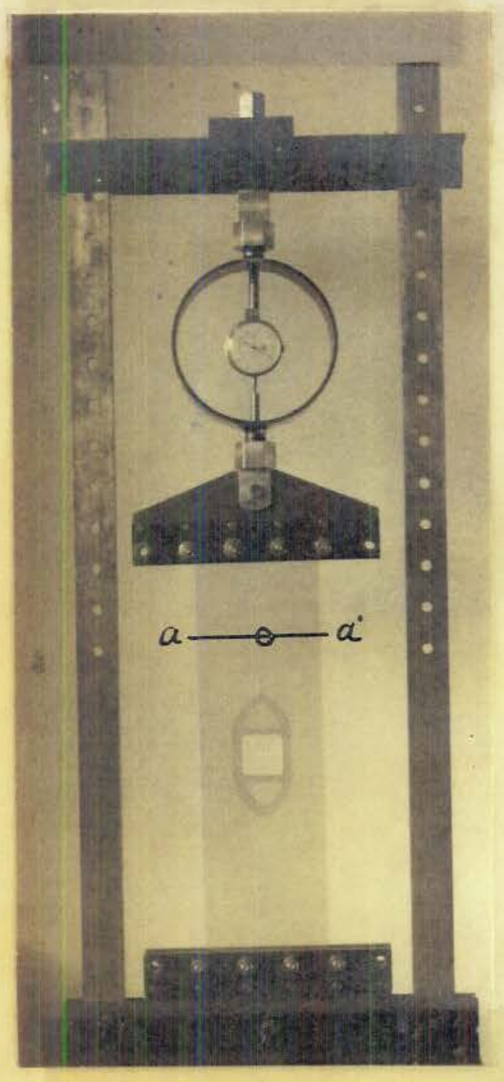
SPECIMEN 9



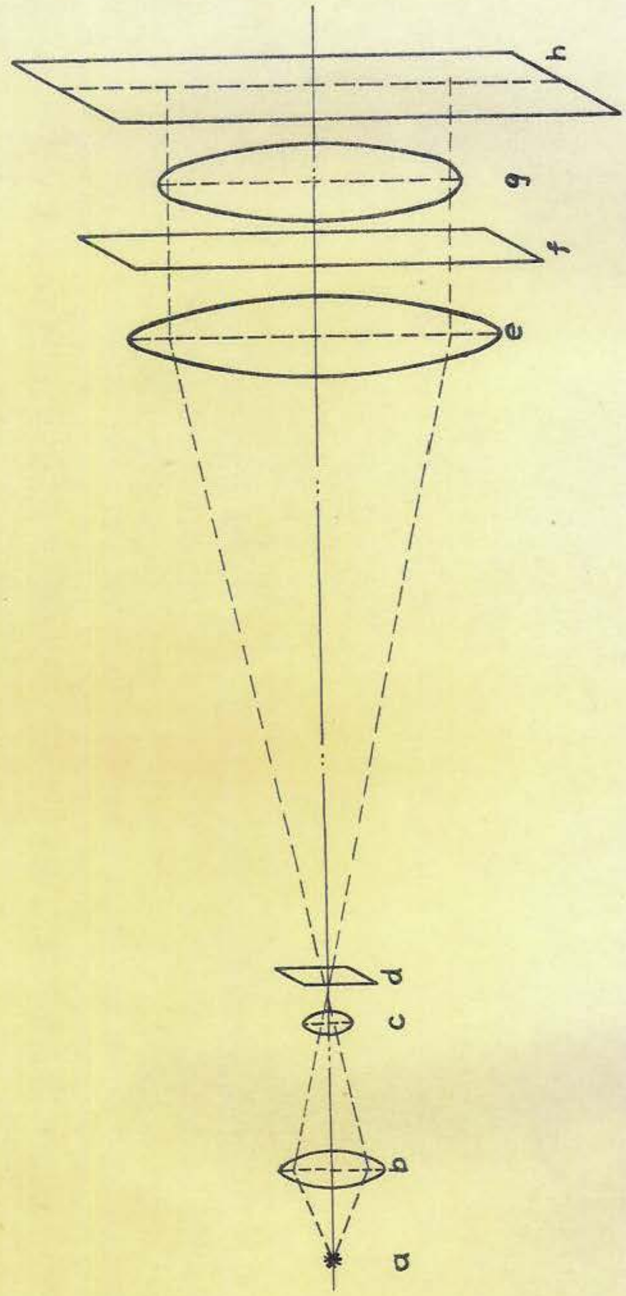
Isochromatics   Isoclinics



P,Q and P-Q values
Specimen 9



Loading Frame



Optical Arrangement