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REPORT

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Date: 28 APR 2016

Reviewer's name(s): A. THOMPSON,
P. HANNA

Declassification authority: NAVY DECLASS
MANUAL, 11 DEC 2012, O3 SERIES

29 January 1937

PHOTOELASTIC INVESTIGATION OF DECK STRUCTURE

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Report No. H-1342

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29 January 1937



NRL Report No. H-1342

NAVY DEPARTMENT

BUREAU OF ENGINEERING



Report

on

Photoelastic Investigation of Deck
Structure.

NAVAL RESEARCH LABORATORY
ANACOSTIA STATION
WASHINGTON, D.C.

Number of Pages: Text - 22 Tables - 3 Plates - 56

Authorizations: BuC&R ltr. NPL4(6)(RI) of 21 February 1936.

Date of Test: 1 March 1936 to 15 January 1937.

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BuEng. (2)
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ABSTRACT

The photoelastic method has been applied to the determination of stresses in celluloid models of a deck containing fifteen openings symmetrically arranged about the center line. The highest stresses are found in a narrow strip of deck plating lying along the center line of the ship between the lateral groups of openings. The strength of this deck strip is estimated to represent 2% of the entire deck strength, so that failure in it can not greatly affect the remainder of the deck. It is pointed out that this very weak strip of deck plating is constrained to follow any deformations which may occur in the surrounding deck and that only by reducing these deformations can the stresses along the center line be reduced. The addition of bulkheads and coaming plates effects such reductions in extension with resultant decreases in longitudinal tension along the center line of about 25%. The discontinuities in structure presented by the juncture of bulkheads with the base plate result in concentrations of stress not observed when no bulkheads were present. The maximum concentration factor so produced is 2.3. It has been found that: (1) doubling the plate thickness at these points of concentration, (2) breaking the union of bulkhead and base plate at points of concentration, and (3) addition of a special reinforcement designed to distribute load from the bulkheads over a more extended region of the deck, all fail to decrease the stress concentration. A modification of coaming plate structure in which longitudinal coaming plates of contiguous openings are extended beyond the transverse boundaries of the openings and joined together resulted in decreased stresses at the intersection of four such openings in the following amounts: shear 29%, longitudinal tension 41%, transverse compression 10%. Appended plates show the directions of principal stress, lines of equal stress difference, and results of stress integrations over the deck.

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CHAPTER 1.

INTRODUCTION

Authorization

1. The problem was authorized by Bureau of Construction and Repair letter NPL4(6)(RI) of 21 February 1936.

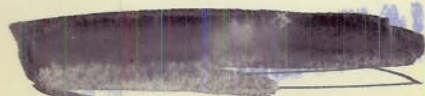
Statement of the Problem

2. Celluloid models of a deck with openings were made from drawings supplied by the Bureau of Construction and Repair (Specimen A of the letter of authorization, represented by Plate 1 of this report). These were loaded under tension as specified, and the stress distribution along specified sections was determined by the method of photoelastic analysis.

Scope of the Report

3. This report is supplementary to NRL Report No. H-1317. It includes the data contained in the earlier report and discusses in greater detail the methods by which these data were obtained.

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CHAPTER II.

MODELS AND METHODS OF LOADING

Description of Models

4. The proper choice of scale for a photoelastic model is important. The dimensions of minute sections of the model (say, the strip of deck along the center line between the hatch openings in Plate 1) must be large enough in comparison with the thickness to assure that the stresses approach the condition of planarity. Furthermore, in these small, segmented sections of the deck the space rate of change of stress in the plane of the model is most rapid, and dimensions should be large enough for easy visual location of the various isoclinic and isochromatic lines, upon the accuracy of which the excellence of the stress determination depends. Hence, a large model of Specimen A was required. The limit to the overall dimensions of the model was set by practical considerations of available sizes of sheet celluloid and the added difficulty of exploring an excessively large model in a beam of polarized light the maximum diameter of which is ten inches.

5. With these considerations in mind, four models of the test member were constructed of celluloid 0.125" thick and 19.60" wide, the scale being three times that of Plate 1. One model, a plain sheet with openings in it, designated "A", was tested under longitudinal loading as specified in paragraph 14. The results of the tests are shown in the "A" plates.

6. Celluloid bulkheads 1.50" high and coaming plates 0.45" high were cemented to the second model, designated "B". A thickness of 0.180" was used to represent 80-pound plate and .035" for 15-pound plate. Tests of this model are shown in the "B" plates.

7. The height of the bulkheads was arbitrarily set at 1.50", which is two thirds the width of the largest openings in the deck. The actual ship structure with bulkheads extending below and taking load from lower decks would have complicated the study, and it is thought that the height of the bulkheads in the present models is sufficient to introduce into the stress problem all first order effects depending upon them.

8. Hatch coaming was constructed around wooden forms of contours like those of the several openings and of such sizes that after forming the celluloid coaming strip to the shape of the block by means of softening in hot water the whole assembly could be slipped snugly inside the opening and the coaming cemented into place. After the cement hardened the wooden blocks were removed. The slight divergence from actual ship construction in attaching the coaming plates to the inside edge of the openings rather than to the deck flush with the edge of the opening cannot greatly affect the stress distribution in the deck, and

permits of better union of coaming and deck plates than would be possible if such thin material were cemented on edge to the surface of the deck. The fact that this method of attachment minimizes cement stains on the surface of the model is of greater practical importance than the small deviations from the true stress distribution which it may produce.

9. A model identical with B except for the omission of coaming plates, designated "C", and a model identical with B except for the addition of a special reinforcement, designated "D", were used for comparative purposes. The tests of these models are shown in Table 1 and Plate 11.

10. The four models described above utilize the full width of the largest sheet celluloid in stock. At the same time, the thickness of the models (0.125") is as small as is compatible with the condition that measurable amount of double refraction be produced by stresses within the elastic limit of the material. The ratio of width to thickness of the narrow deck strip along the center line of the ship is $0.375"/0.125" = 3$. This ratio is sufficiently large for satisfactory stress measurements in Model A, but is so small that difficulty in making the photoelastic measurements was encountered in Model B, where it is thought that coaming plates and bulkheads cause deviations from plane stress conditions so great as to make satisfactory measurements impossible.

11. Two large scale models of point 2, Plate 1, were built with such dimensions that the ratio of width to thickness was sixteen. One of these models, designated "S1", was identical with point 2. In the second, designated "S2", the coaming was made continuous from opening 8 to opening 10 and from opening 9 to opening 11. Each special model was loaded with a P stress (longitudinal tension) and a Q stress (transverse compression) proportional to the loads measured in the comparable plates of the complete Model B. Tests of Model S1 are shown in Plates 31S and 32S. Tests of Model S2 are shown in Plates 33S and 34S.

12. Model B is illustrated in Plate 2. Models A and C are not illustrated. Details of the special reinforcement of Model D are shown in Plate 11. Models S1 and S2 are illustrated in Plate 3.

Loading Frame

13. A special loading frame was constructed for the full Models A and B. This frame is shown in Plate 4. The model is held by the cross hatched steel grips, G, which distribute the load uniformly over its width. Total load was measured by means of the tension ring, T, of which two were available to cover the ranges 0-1000 pounds and 0-4000 pounds, respectively. Deflections of the rings were measured by the Ames dial gauge, D. The loading frame provided for vertical motion of the model in the beam of polarized light by means of the rollers R and the counter weights W. Horizontal motion was effected by rolling the entire frame along the floor.

Loading Conditions

14. Models A and B were subjected to an applied tension of 2290 pounds, giving rise to a mean applied stress of 930 pounds/inch². Models B were loaded to give the same amount of double refraction in the longitudinal and transverse plates as had been previously observed in Model B.

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CHAPTER III.

SUMMARY OF RESULTS

Description of Plates

15. The experimental results are given in Plates 5A to 35B. In all plates showing stress distribution, displacements are marked to show feet on the full scale deck and stresses are given in terms of the unit applied stress. Longitudinal tension is called a positive P stress and transverse compression a negative Q stress. The plates are described as follows:

Plates 5A and 6A show the isoclinic lines for Model A.

Plates 5B and 6B show the isoclinic lines for Model B.

Plates 7A and 8A show the stress lines over Model A.

Plates 7B and 8B show the stress lines over Model B.

Plates 9A and 10A show the isochromatic lines for Model A.

Plates 9B and 10B show the isochromatic lines for Model B.

Plate 11 is an index for Table 1, which gives a survey of P-Q, P, and Q values along the center line of the ship.

Plate 12 is an index for Table 2, which gives a survey of maximum concentration factors around the contours of openings.

Plates 13A and 13B give values of P, Q, and P-Q from opening 2 forward, and along the C axis.

Plates 14A and 14B give values of P-Q, P, and Q from opening 2 aft.

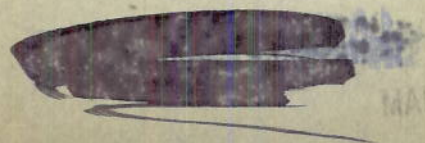
Plates 15A and 15B give values of P-Q, P, and Q along the longitudinal axis through point 1.

Plate 16B gives values of P-Q, P, and Q along the transverse axis through point 1.

Plates 17A and 17B give values of P-Q, P, and Q along axis D.

Plates 18A and 18B give values of P-Q, P, and Q along axis A.

Plates 19A and 19B give values of P-Q, P, and Q along axis B.



Plates 20A and 20B give values of P-Q, P, and Q along the center line aft of openings.

Plates 21A and 21B give values of P-Q, P, and Q along a longitudinal axis through point 3.

Plate 22B gives values of P-Q, P, and Q along a transverse axis through point 3.

Plate 23B gives values of P-Q, P, and Q along a longitudinal axis through point 2.

Plate 24B gives values of P-Q, P, and Q along a transverse axis through point 2.

Plates 25A and 25B give values of contour stresses around openings 1 and 2.

Plates 26A and 26B give values of contour stresses about opening 4.

Plates 27A and 27B give values of contour stresses about opening 6.

Plates 28A and 28B give values of contour stresses about opening 9.

Plates 29A and 29B give values of contour stresses about opening 12.

Plates 30A and 30B give values of contour stresses about opening 15.

Plates S refer to large scale models of point 2 which have been described in paragraph 11.

Plate 31S gives values of P-Q, P, and Q along a longitudinal axis through Model S1.

Plate 32S gives values of P-Q, P, and Q along a transverse axis through Model S1.

Plate 33S gives values of P-Q, P, and Q along a longitudinal axis through Model S2.

Plate 34S gives values of P-Q, P, and Q along a transverse axis through Model S2.

Plates 35A and 35B are color photographs of the isochromatic fringes in Models A and B.

Summary of Stress Concentration Factors - Model A

16. A summary of P-Q, P, and Q values along the center line and over adjacent transverse plates of Models A and B is given in Table 1, facing Plate 11. The regions of the deck corresponding to points "a,b,.....,k" of Table 1 are identified by Plate 11. Table 1 and Plate 11

also give P-Q values for Models C and D. The data presented in columns A and B are taken from Plates 9A to 34S.

17. The P stress remains constant and of value 2.3 at points a, d, and i of Model A. At points c and h maximum shear occurs, the P-Q values being about 3 at these points as compared with the value 2.6 at the symmetrical sections f. The P stresses are of the same order of magnitude at sections c, f, and h, having the values $P(c) = 1.75$, $P(f) = 1.63$, and $P(h) = 1.8$. By elimination between observed P-Q values and integrated P values, the Q values at these points are found to be $Q(c) = 1.35$, $Q(f) = -0.97$, and $Q(h) = -1.2$. Compressive Q stresses in the sections b, e, and g are in general equal to or less than unity.

Effects of Bulkheads and Coaming - Models B and C

18. Addition of bulkheads to form Model C and of bulkheads and coaming to form Model B results in a decrease in P-Q at all points along the center line except at points f and h. The section of deck, d, between the openings is very weak in comparison with the whole deck, the cross-sectional area of a section d being only 2% of that of the entire deck. This strip of deck will thus offer no significant resistance to extension of the deck as a whole, and stresses in it will be determined by the extension which is forced upon it by the outer deck. In other words, increasing the thickness all along the center line between the openings would not decrease the stresses there unless this narrow strip were made so heavy as to resist deformation of the ship as a whole. If the thickness were doubled all along this strip, making its strength about 4% of the total deck strength, the total extension for a given applied load would remain approximately the same because now the distribution of total load would be 90% to the outside deck, 10% to the central deck strip. The reduction in extension of the deck would thus be about 0.5% and the stress along the center line would remain approximately the same. The longitudinal bulkheads in Models B and C, however, strengthen the deck structure and bring about smaller extensions and hence smaller stresses along the center line. The observed stresses at sections d are 2.3 in Model A, 2.0 in Model C with bulkheads attached, and 1.7 in Model B with bulkheads and coaming, so that sections d carry 5% of the total load in A, 3.8% in C, and 3% in B. The further reduction in B over C is due to local reinforcement by the coaming plates, since if one part of the central deck strip is increased in thickness while the rest remains as before, the thicker section, being stiffer, shows less extension and lower stress per unit cross-sectional area, while the thinner section will show increased stress. This is the condition that produced reduced stress in section d of Model B when coaming plate was added to Model C. It might be expected then, that the ratio of P stress at f to P stress at d would be higher for Model B than for Model A. This is not the case, however, the ratio being -

$$\frac{1.63}{2.3} = .71 \text{ for A, and } \frac{1.2}{1.7} = .70$$

for B. This condition is brought about by encroachment of P stress into



sections e, which adjoin f, to a greater extent in Model B than in Model A, the coaming plate serving to transmit the stresses around the corner of the opening. A similar effect, but in the opposite sense, is observed in the effects of the coaming on Q stresses at f, which have the values -0.97 in Model A and -1.3 in Model B. The P stress at sections a and i of Model B is higher by 18% than the stress at sections d. Two contributing causes of this divergence from the behavior of Model A are possible: (1) the width of openings 4 and 5, and 14 and 15, may be too small to permit assumption of load by the coaming plate, and (2) warping of the transverse bulkheads under compressional load and of the longitudinal bulkheads under tension may result in clockwise bending of the deck plate b and counterclockwise bending of the corresponding plate between openings 5 and 7 so that the resultant longitudinal thrusts on section c are equal to the difference between the stress in a and the stress in d, thus keeping section c in equilibrium.

19. This "twist" at sections c and h is apparent in Plates 5B and 6B, and 7B and 8B, which show the isoclinic and stress lines for the section. It is also seen from Plates 5A, 6A, 7A and 8A, that this effect does not exist in Model A.

20. It is of interest also to note that at sections c and h of Model B, the integrated P stresses are higher than at the same points in Model A. P-Q values, however, are lower at these points in Model B than they are in Model A, so that the resulting Q values are much lower in B than in A, (29% at c, 41% at h). This is probably an effect of the transverse bulkhead, the range of influence of which easily extends to these sections.

21. At section f of Model B the P stress is lower by 27% and the Q stress is higher by 34% than at the same section of Model A. The magnitude of P-Q at f remains unchanged at the value 2.6 to 2.5 in the transition from Model A to Model B. A method for reducing the shear stress at sections f will be described in paragraph 54 of this report.

22. Concentrations of stress appeared at points j and k on Model B. These concentrations are caused by the discontinuity in structure presented by the bulkheads. The concentration factor is 2.3 at j and 1.8 at k. The higher value at j is presumed to be caused by the presence of openings 1, 2, and 3 which shield that part of the deck just forward of openings 4 and 5 and consequently cause higher stresses near the points j.

Special Reinforcements - Model D

23. Column D of Table 1 represent P-Q values for Model D, which is described in paragraph 9 and Plate 11. The special reinforcement which was fitted around openings 1, 2, 3 and joined to the bulkheads at points J gave rise to increased load in the bulkheads, generally increased P-Q values along the center line of the ship (as compared with Model B), and greatly increased shear at points c, f, and h. It was recognized before adding the special reinforcement that these results would follow, because increasing the load carried by the longitudinal bulkheads of

necessity increases the extension over the entire deck section bounded by the bulkheads. It was expected, however, that some decrease in concentration at points j might result. On the contrary, the concentration at j increased to the value 2.7. No attempt to relieve the concentration at points j and k has been successful. Apparently any device which is successful must avoid any short discontinuity in deck thickness such as introduced by the ordinary doublers. The following attempts have been made:

- (a) The corners of the bulkhead were cut free from the deck. The concentration was not at all decreased, but receded to the points at which the bulkhead was again rigidly attached to the base plate.
- (b) The corners were cut free from the deck and diagonal reinforcing members fitted across the inside of each corner joining the longitudinal and transverse bulkheads at the points of reattachment to the deck, with the same result as in (a).
- (c) Three-quarter circular doubling plates of radii $1/2''$ and $1''$ were cemented to the base plate at points k. The concentration factor did not decrease, but the region in the base plate over which maximum concentration occurred moved out in each case so that it fell just outside the boundary of the doubling plates.

Summary of Contour Stresses - Maximum Concentration Factors

24. Table 2 and Plate 12 summarize maximum values of P-Q observed on the boundaries of openings near corners, at which maximum concentration appears. The exact location of the points of maximum stress are not indicated in Plate 12 and Table 2. These are best determined by reference to Plates 25A and 25B to 30A and 30B which show the contour stresses in detail.

25. The P-Q values recorded in column A of Table 2 represent P or Q stresses as the boundary is longitudinal or transverse. The values recorded in column B, however, represent P-Q in the base plate at the boundary of the coaming plate. The true contour stress is that at the inner boundary of the coaming plate. It cannot be measured photoelastically, but it can be estimated by means of the relation -

$$dQ = (P-Q) ds/R$$

where R is the radius of curvature of the corner of the opening and ds is the thickness of the coaming plate. Assuming that P-Q does not change greatly in passing through the coaming plate, the change in Q in passing through the coaming plate is $dQ/(P-Q) = (ds/R) = 7.8\%$ for openings 6-13 of Model B. Thus, at point m, Plate 12, $P-Q = 1.7$. The increment in Q through the thickness of the coaming plate is about 8% of P-Q, or $dQ = 0.13$.

Then, approximately, $P = 1.57$ in the base plate at the boundary of the coaming. For the smaller openings, say opening 1, the effect is bigger. Here $d_s/R = 37\%$. Since the exact stress condition within the coaming plate cannot be measured, it has been considered safer to record measured values of $P-Q$ in the base plate without any correction for possible changes in stress through the thickness of the coaming plate. In the actual ship structure, while the ratio of coaming thickness to deck thickness remains equal to that ratio in the model, the ratio of thickness of coaming plate to width of openings is smaller by the factor $1/5.95$; therefore, the above calculations do not apply to the steel structure. More applicable results could be obtained from larger models, the size of the model being limited by the sizes of the laboratory room and available sheet celluloid. However, it is considered that the small increase in accuracy would not justify the large increase in cost of a larger model.

26. Survey of columns A and B of Table 2 shows that the addition of coaming plates and bulkheads effectively decreases the stress concentration factor at all corners except b, c, and d, where increases occur. These increases are about 20% at b, 100% at c, and 22% at d, and are ascribed to the stiffness of the bulkhead in Model B.

Contour Stresses - Detailed Examination

27. Plates 25A, 25B to 30A, 30B show the contour stresses around each type of opening individually. The measurements were taken from an optical image of four times magnification, and each opening is presented separately with the exception of 1 and 2.

28. The significance and reliability of the measured contour stresses are affected by the following considerations:

(a) Edge effects. After milling, small residual stresses develop along the edges of celluloid models. A suitable annealing furnace has not been available for specimens of the size used in this investigation, so that it has not been possible to eliminate the residuals entirely. It is possible to measure the amount of the edge stress, but corrections to measured values of applied stresses can hardly be made since the direction of the residual stress is in general indeterminate and may vary through the thickness of the plate. It will appear in Plate 27A, for example, that stresses are higher along the longitudinal boundary of opening 6 than along the center line between these openings, as shown in Plate 15A. The values of P are 2.58 at the edge of the opening (Plate 27A) and 2.3 along the center line (Plate 15A), the difference amounting to about 10%.

(b) Indeterminacy of isotropic points. In going around the corner of an opening from a longitudinal to a transverse boundary an isotropic point at which $P-Q = 0$ should be found. This is necessary since stresses along the longitudinal boundary must be entirely tension, and along the transverse boundary, entirely compression. These isotropic, or neutral,

points were located for certain openings of Model A, such points being designated "N" on the curves. P stresses (longitudinal tension) are represented by solid lines and Q stresses (transverse compression) by dotted lines in all cases in which the transition from P to Q stress is clearly delineated by an observable isotropic point. When the isotropic points were indeterminate all stresses are represented by solid lines, it being understood that along any boundary only stresses parallel to the boundary exist. In general, isotropic points could not be determined for openings in Model B, since in this model the points at which $P-Q = 0$ lie within the coaming plate.

29. The accuracy of contour stress measurements is estimated to be of the order of $\pm 15\%$, the probable error arising entirely from the physical condition of the celluloid model.

CHAPTER IV.

DETERMINATION OF P AND Q SEPARATELY BY GRAPHICAL INTEGRATION.

Isoclinic Lines.

30. The isoclinic lines, representing regions in the specimen of constant stress direction, are shown in Plates 5A, 6A and 5B, 6B for Models A and B, respectively. All parts of the model where changes in stress direction are unimportant near the sides and ends have been omitted and only one half of the model is shown in each plate in order that a sufficiently large scale might be used to show all necessary detail without making the plates inconveniently large.

31. The isoclinics for the two Models A and B are more informative if examined in comparison with each other than if examined separately. Forward of openings 1, 2 and 3 the stress pattern is dominated by the flexibility of those opening and the isoclinics are about the same for both models. The stiffness of the transverse bulkhead in Model B decreases the stress aft of these openings and also decreases the magnitude of the change in stress direction near the exposed corners of openings 6 and 7 outside of the bulkhead. At the boundaries of the different openings of Model A all stress lines must have the direction of the edge of the opening. However, as is shown by Plates 7B and 8B, stress lines may strike the bulkhead at a comparatively large angle even at places where the stress concentration is quite intense; for example, near the forward corners at points of greatest stress intensity the stress lines make an angle of 10 degrees with the bulkhead. Aft of openings 14 and 15 we see that the stiffness of the transverse bulkhead has spread the smaller isoclinics, for example, 5 degrees and 85 degrees, farther aft of the openings and much closer to the center line in Model B than in Model A.

Lines of Principal Stress.

32. Plates 7A, 8A and 7B, 8B show the lines of principal stress for Models A and B, respectively. These lines, which represent the directions of the P and Q stresses over the model, were derived graphically from the isoclinics. They do not in any way represent magnitudes of stress, but do represent the flow of stress from one part of the model to another.

33. Comparing Plates 7A and 7B, it is seen that the principal divergencies in stress behavior between the two models occur at points where the bulkheads or coaming plates are taking load from the deck. Both fore and aft of the transverse bulkheads quite a decided change in the direction of the stress lines is observed. Inside the corners of the bulkhead the deck plate is deformed by the deformation of the bulkhead under load and is almost independent of the stress in the plate outside of the bulkhead.

34. Near the corners of the different deck openings the directions of stress lines in Model B are affected by the fact that the coaming plate is taking a load from the deck. This gives stress concentrations along the longitudinal center line of B that are quite different from A. Directions of the stress lines of Plates 7B and 8B do not adequately represent this effect because of the small scale of the drawings. The effect of the coaming plates on the stress lines in the attached deck plating is more carefully represented under the discussion of two special models built on a larger scale and discussed under paragraphs 53 to 56. Curvature of the stress lines fore and aft of the transverse bulkheads at their intersections with the center line of the deck illustrates how the stress flows from the outer deck into the bulkhead and from the bulkhead into the inner sections.

35. The wide extent of stress lines representing small changes from the direction of the applied load in the lower part of 8B shows how the transverse compression load is developed and delivered to the transverse bulkhead.

36. Comparison of Plates 8A and 8B shows the principal difference that in the deck below the openings divergence of P stress directions from the direction of the longitudinal axis begins at about fourteen feet from openings 14 and 15 in A, and at about 25 feet from openings 14 and 15 in B.

37. Q stresses do not have significant values over most of the deck, but are of importance between the small openings 4 and 5, 14 and 15, and also between them and the adjacent larger openings for "A" and in and around the c, d and h region of Plate 11 where the corners of four deck openings come together. The greatest values are at c and h and just even with the upper edge of openings 4 and 5 for "A" and in the neighborhood of f for "B". These points of concentration are all well illustrated by the flow of the stress lines.

Isochromatic Lines - Models A and B

38. Plates 9A and 9B, and 10A and 10B represent the isochromatic lines, over each of which P-Q is constant, for Models A and B. The isochromatics were measured by introducing into the optical system a Soleil-Babinet quartz wedge compensator by means of which exact compensation for the double refraction existing at any point in the model could be brought about. Over any given isochromatic line the value of P-Q is given in terms of the unit applied stress by the number appearing on that line.

39. The isochromatic values may be taken as approximately equal to the P stress in regions of the deck outside the bulkheads. In the section of the deck enclosed by bulkheads, Q stresses reach important values, and stress concentration factors must be obtained from the curves showing separate values of P and Q calculated by stress integration.

40. Plates 35A and 35B show in color the isochromatic fringes produced in Models A and B under identical loads. The colors represent increasing P-Q values in the following order: grayish white, orange, red, purple, blue, and green. Increasing the stress above that producing green causes the "second order" colors to appear. They follow in the same sequence, but are much fainter than the first order colors. Stress concentrations at the corners of openings and regions of high shear over the plate can be very readily located on these plates.

Method of Graphical Integration

41. The isoclinic lines and isochromatic lines of Plates 5A to 10B were derived from an image of the specimen with two-fold magnification. Numerous sets of similar curves were obtained for restricted sections of the model with an image of eight-fold magnification in order that the details of their behavior might be clearer. These curves were used in integrations, but they were omitted from the report because their contribution to the solution of the stress problem is largely contained in the recorded results of the integrations, so that no detailed reference to them is necessary.

42. Stress integrations were carried out by means of the following relations in one or another of their several equivalent forms:¹

$$dP = -(P-Q)ds_p/R_q$$

$$dQ = -(P-Q)ds_q/R_p$$

in which ds represents the increment in distance along the stress line over which the integration is progressing, and R represents the radius of curvature of the stress line orthogonal to the path of integration at the point at which dP or dQ is being evaluated. Subscripts (p) refer to P stress lines and subscripts (q) refer to Q stress lines. All integrations over the small deck sections along the center line were made from the greatly enlarged drawings of isoclinics and isochromatics described above.

43. In determining the P and Q stresses by integration through a symmetrical section such as point 2, Plate 1, the result was considered satisfactory if independent integrations from opposite sides of the section gave ultimate values for P or Q at the center which did not differ by more than 10%. Repeated determinations of isoclinic and isochromatic lines were made and independent integrations were based on them. The errors were large in some instances, particularly in Model B. These errors were largely due to the fact that the stresses measured were not entirely plane stresses and were not uniform through the thickness of the specimen, and are not characteristic of the photoelastic method. Model B, with coaming plates and bulkheads which contribute to the distribution of stress through the plate in indeterminate ways, represents a type of structure

1. References appended.

far from the ideal plate of Model A. In "A" errors are limited to those characteristic of the photoelastic method. In general, repeated integrations resulted in entirely acceptable values for P and Q. Attention will be called to discrepancies which do occur in the detailed discussion of results below.

Discussion of Errors

44. The probable error of any stress integration is about $\pm 10\%$. The expression for the increment in P along its own stress line can be written² -

$$dP = \Delta\phi(P-Q)ds_p/y$$

where $\Delta\phi$ is the change in stress direction between two neighboring isoclinics of parameters ϕ_1 and ϕ_2 , and between which the point under consideration lies, and y is the intercept between these two isoclinics measured normal to the P stress line. P-Q values can be determined to ± 0.5 compensator division, so that the percentage error in this measurement depends on the magnitude of the double refraction being measured. Unit stress in these experiments was represented by the compensator reading 10. For this reading, then, the probable error was $\pm 5\%$. $\Delta\phi$ is assumed to be known exactly; i.e., it is assumed that no sensible error in the setting of the Nicol prisms exists. The intercept between isoclinics y is subject to error in measurement, because it represents the measured distance between two lines which represent the centers of diffuse black fringes on the viewing screen. These fringes may vary in width from $1/4$ inch to an inch or more, and it is estimated the exact location of the center may be in error by $\pm 5\%$. It is assumed that measurement of ds, the increment in path length, is subject to no sensible error. The maximum probable error is then the sum of the percentage errors in P-Q and y, or $\pm 10\%$.

45. The stress P_i at any point i is obtained by adding to a known P_0 stress at some point¹⁰ the sum of all increments in stress dP from point 0 to point i; i.e. -

$$P_i = P_0 + \sum_0^i dP_i.$$

If each dP_i is accurate to $\pm 10\%$, then $\sum dP_i$ has a probable error of $\pm 10\%$. However, the final result of the integration may show a probable error smaller than 10%. In one particular integration taken from the records of this investigation, the numerical values of the terms of the foregoing equation are as follows:

$$P_0 = 34 \pm 0.5 \text{ compensator divisions.}$$

$$\sum dP_i = -9.28 \pm 10\% = -9.28 \pm 0.9 \text{ compensator divisions.}$$

$$P_i = 34 - 9.28 = 27.72 \pm 1.4 \text{ compensator divisions}$$

$$= 24.72 \pm 5\%.$$

Inconsistencies in integrations greater than $\pm 10\%$ are directly ascribable to inability to determine the exact positions of the isoclinic and isochromatic lines, which in turn is due to the limitations of thickness of model and divergence from planarity of stresses, and can be remedied if desired by the use of larger, thinner models.

Discussion of Results of Stress Integration

46. Plates 13A and 13B represent the stress distributions along the center line forward from opening 2, and along axis C. Along the center line where deck models A and B are subjected to a longitudinal tension of unit load, the P stress decreases fairly uniformly from a value of 1 near the end of the specimen to zero at opening 2. The rigidity of the steel gripping clamps which apply the load introduces a transverse tension (Q) which increases to maximum value of about 0.2 for A and 0.3 for B at three or four feet from opening 2. This effect is probably due to the experimental conditions and would not necessarily exist in an actual ship structure. Beyond the point at which Q reaches its maximum positive value there is a rapid drop in the value of Q introduced by deformation of the plate by the group of openings. Q reaches a maximum negative value of -0.7 in A, but the stiffness of the transverse bulkhead near openings 4 and 5 and the presence of the coaming about opening 2 reduces this value to -0.4 in B.

47. Along axis C (Plates 13A and 13B) P decreases toward the side of the ship, eventually falling to a constant value of about 1.2 near the sides. Q stresses remain small over this part of the deck.

48. Aft of opening 2, continuing along the center line as shown by Plates 14A and 14B, the Q stress builds up to a maximum compression at about three feet from the opening. This maximum is a little less than -0.3 for A and a little less than -0.7 for B. Beyond this point, Q values increase to a maximum tension almost in line with the forward edges of openings 4 and 5 where its value is 1.5 in Model A and 1.2 in Model B. Q values drop to zero near the center of the section between openings 4 and 5. P values increase from opening 2 to a maximum of 2.3 in Model A and 1.9 in Model B near the center of the section between openings 4 and 5. The shear, $(1/2(P-Q))$, shows an abrupt drop at the point where the Q stress reaches a maximum, as shown by Plates 13A and 13B. Beyond this point the shear increases to a maximum of 3.0 for Model A and 2.8 for Model B near the point marked #1 in the index Plate 1.

49. Plates 15A and 15B represent the stresses through point #1 of Plate 1. The P stress falls to a minimum value of 1.75 for A, and behaves anomalously for B, where P increases from the value 2.0 between openings 4 and 5 to a maximum of 2.05 from which it falls again to 1.7 between openings 6 and 7. Q stresses in Model B obtained by elimination between measured values of P-Q and the integrated value of P, reach a maximum compression (negative Q) of -0.8 at the center of the section, and a maximum tension (positive Q) of 0.7 just opposite the points of tangency of the corners of openings 6 and 7 with the longitudinal edges of these openings. The small negative Q appearing just aft of the

maximum positive value is probably not real. The peculiar behavior of P and Q stresses in this section is due to complication of the stress system by the presence of coaming plates near the unsymmetrical section #1. Plate 16B shows the results of integration of Q values along the transverse axis through point 1 of Model B. Q reaches a maximum compressive value of -0.4 at the center of the section which agrees none too well with the value -0.8 derived in Plate 15B. The discrepancy probably arises from the fact that the stresses are not entirely in the plane of integration. While the value of Q in 16B differs from 15B by 50%, the discrepancy between P values is only 27%.

50. Returning now to the transverse axis D, Plates 17A and 17B, it is seen that in Model A, P rises from 0.8 at the center line to the uniform value 1.5 at a distance of about 24 feet from the center line. The Q stress reaches a maximum value of -0.8 which is maintained over a distance of about 6 feet after which it falls to zero. Q stresses in Model B are small along this axis because of the proximity of the transverse bulkhead. Maximum Q is -0.4 at the center line. P reaches a maximum value of 2.2 at a point on D in line with the longitudinal boundary of opening 6. At the same point in "A" the P stress is only 1.25. The difference is due to load released to the deck by the bulkheads. Breaks in the P and Q curves represent a region in which integrations were extremely unreliable. The Q stresses are small so that measurements of the quantities entering into the stress equation were difficult. Determination of stress distributions along an axis such as D which is not itself a line of principal stress requires the separate integration of stress over a number of stress lines, beginning each integration near the end (or edge) of the model and proceeding inward until D is intersected. The time involved is prodigious and the value of the results for the region left undetermined in 17B is doubtful. It is certain that Q is small and that P approaches P-Q in value over this part of the deck.

51. Stresses along axis A are shown in Plates 18A and 18B, except that the stress distribution about point 2 of Model B is discussed below in connection with Plates 11, 20B, 24B, 31S, and 32S. Proceeding along axis A in Model A to the edge of the ship, P rises from zero at a point in line with the points of tangency of the corners of openings 10 and 11 to a maximum of 2.2 at a point on axis A distant from the transverse boundary of the openings by three feet. Q falls from its maximum value -0.8 between openings 10 and 11 to zero at the point of maximum P. From this point outwards P decreases uniformly to the edge of the ship where its value is 1.2. Along the same path in Model B (Plate 18B) Q rises from the value -0.2 between openings 8 and 10 to -0.35 at the bulkhead. P rises to a maximum value 1.2 at the bulkhead. The integration cannot be carried through the discontinuity presented by the bulkhead. A separate integration along axis A outside the bulkhead shows Q reaching a maximum negative value of about -0.5 at the bulkhead, falling to zero about 2 feet away. P rises from 1.6 at the bulkhead to 1.85 at a point 1.5 feet away from which it falls to the value 1.2 at the edge of the ship.

52. Returning now to point 2, Plates 17A, 20A, 23B, 24B, 31S, and 32S, show that near this point P-Q reaches a maximum value of 2.6 for both A and B and that at this point the Q compression -1.3 is equal to the P tension +1.3 for B. Q is equal to -0.9 for A, while P is equal to 1.7. The value of -0.75 for Q, shown by Plate 24B as obtained from transverse integration, compared with the value of -1.3, obtained from longitudinal integration, is probably a fair indication of the accuracy of integration based on the complete Model B in the small sections.

53. The most satisfactory investigations of point 2 of Plate 1 have been carried out on the large scale Models S1 and S2, illustrated in Plate 3. Tests of Model S1 are shown in Plates 31S and 32S. Tests of Model S2 are shown in Plates 33S and 34S. The results of longitudinal and transverse stress integrations in these two models are much more consistent with each other than corresponding longitudinal and transverse integrations in Model B, showing clearly that the greatly increased ratio of width to thickness of Models S1 and S2 has overcome the difficulties inherent to Model B. It should be said here that use of similar large models of points 1 and 3 of Plate 1 is not possible because of the asymmetric form of these intersections which give rise to the stress effects discussed in paragraph 18.

54. The effect of joining together the longitudinal coaming plates of contiguous hatch openings as shown in Model S2, Plate 3, is to reduce the stresses at the geometrical center of the section in the amounts shown in Table 3, the data of which are taken from Plates 31S and 33S.

Table 3

<u>Stress</u>	<u>Model S1</u>	<u>Model S2</u>	<u>Reduction in Stress S2 over S1</u>
P-Q	2.7	1.9	29%
P	1.7	1.0	41%
Q	-1.0	-0.9	10%

55. In an additional experiment, coaming plates were made continuous between both adjoining longitudinal and transverse sides of openings in one of the models with no further reduction in P-Q than had previously been observed in Model S2. The thickness of the coaming plates was the same in all experiments, namely, one-fourth the thickness of the base plate. The compressive stress probably would be reduced by this method of construction if the transverse members were made heavy enough to accept compressive load without buckling. However, the increase in strength of the deck plate would be small.

56. Plates 31S and 32S show an effect which does not appear in the whole Model B. Proceeding along the center line of the ship, Plate 31S, P rises from a value 1.7 to a value 2.0 opposite the point of tangency with the curvature of the corners of the openings. Q likewise has increased to a maximum at this point and the more rapid increase in Q gives a minimum



value for P-Q at this point. There, increases in both the P and Q stresses result from loading of the deck by the coaming plate plus spreading of the P stress from the section between openings 8 and 9 to the wider section about point 2. The P increase is entirely missing in Plate 33S, while the positive Q value is reduced by about 50%.

57. Plates 20A and 20B continue the stress distribution along the center line of the ship, showing maximum P-Q near point 3 of 2.9 for Model A and 3.0 for Model B. These values are comparable with the maxima of 3.0 and 2.8 found near point 1 (Plates 21A and 21B). The transverse integration of Plate 22B through point 3 shows Q equal to -0.5 near the center which should be considered satisfactory agreement with the value -0.8 obtained from longitudinal integration of Plate 21B.

58. Between openings 14 and 15 (Plates 20A and 21A) characteristic positive Q stresses are found for Model A opposite the corners of openings. The integrations for Model B through this section are shown in Plates 21B and 22B.

59. Stresses along axis B are given in Plates 19A and 19B. As is the case along axis A of Model A (Plate 13A), Q stresses are small and P falls rapidly away from a maximum of 2.7 near the opening to a value of 1.5 at a distance of 11 feet from the edge of the opening; in Model B, P increases slightly in going away from the opening, reaching a maximum of 2 and falling away to a constant value of 1.5 at 10 feet from the opening. The Q stresses appear as positive along this axis in Model B, while they were negative in Model A. The maximum Q stress is +0.3.

Criteria for Application of Results

60. The transference of the results presented in this report to full scale steel structure is dependent upon the following conditions:

- (1) The elastic limit must not be exceeded in either model or steel structure.
- (2) The applied loads must be strictly proportional for model and full scale structure.
- (3) The ratio of elastic constants must be same for both materials.

61. The first condition has been complied with in loading the experimental models used in this report. In regard to (2), experimental models have been loaded in such a way that force is applied uniformly across the ends. The metal tension grips which apply load to the model introduce transverse tension at points near the ends. These conditions may not exist in the actual steel structure. Concerning (3), it is known that in any elastic plate containing no discontinuities the stress distribution is independent of the elastic constants. This is true for

a plate with holes if the forces applied to the boundary of any opening produce a couple or form a system in equilibrium (a condition which is not true for a rivet in a plate). The celluloid model was welded together and unstrained with no applied load. The presence of coaming plates and bulkheads introduce discontinuities in the stress distribution over the base plate which will be similar to discontinuities introduced in steel, but will not be identical because of the increased thickness ratio for the celluloid.

62. On the whole, the results are considered to be safely applicable to full scale steel models, but discrepancies will probably be introduced by discontinuities such as riveted joints, and the effects of coaming plates and bulkheads will not be exactly duplicated.

CHAPTER V.

CONCLUSIONS

63. Openings in the deck structure reduce the cross-sectional deck plate area to 80% of the area of the uninterrupted deck, but if it is assumed that failure will occur from shear at point j, Plate 11, the strength of the deck is reduced to 43% of the strength of the uninterrupted deck. Bulkheads as specified for the study assume in the neighborhood of 30% of the total deck load, but the discontinuity in stress pattern introduced by the bulkhead just about compensates for this reduction in load, so that the maximum shear in the deck plating remains the same as for the deck without the bulkheads; in other words, the strength of the deck with openings and bulkheads is 43% of the strength of an uninterrupted deck. The cross-sectional area of the longitudinal bulkheads is 22% of the uninterrupted deck, or 29% of the deck with openings. When the deck is subjected to tension, the bulkheads are subjected to a tension greater than the average load in the deck plate. An arch introduced in Model D to smooth out some irregularities in the stress pattern increased the load in the already over-loaded bulkheads and this increased the stress for practically all points inside the rectangle of the bulkheads.

64. The principal effect of the coaming plates on the stress pattern is that they give an increase of about 34% in the transverse compression or Q stress, where four large deck openings form a corner, marked #2 in Plate 1.

65. The weakest points in the deck structure are the outer forward corners of openings 1 and 3. Failure would be expected there for a load equal to 29% of the maximum load for the uninterrupted deck or 67% of the maximum load for the deck with openings and bulkhead. This would be a local failure and might not affect the strength of the main deck structure. Points where the small openings corner on the large openings should be the next to fail and should fail at a load of 70% for the main deck. Complete failure of these sections would weaken the deck structure by less than 10%.

CHAPTER VI.

RECOMMENDATIONS.

66. The following recommendations are presented for consideration:

(a) The highly stressed corners of openings 1 and 3 should be reinforced.

(b) Either the longitudinal coaming plates should be made continuous between adjoining openings along the center line, or a flexible joint should be introduced to avoid overstressing the weak central deck strip. The weight of the deck plate along the center line should not be increased because this would not be effective in reducing stress concentrations in this section itself and increasing the stiffness of the central section would increase the stress at the already overstressed corners of openings 1 and 3.

(c) Further investigation of stress concentrations caused by joining bulkheads to deck plate might be of value.

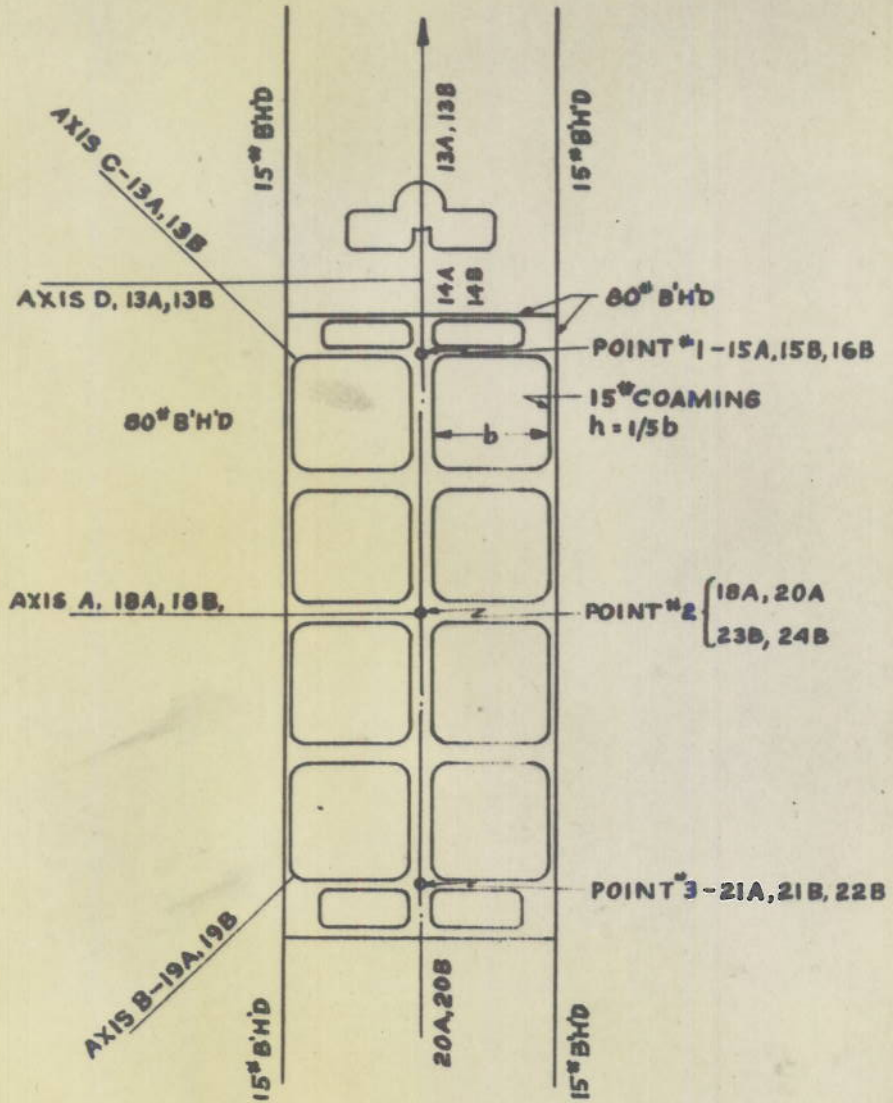


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1. Coker and Filon, Photoelasticity, p. 142. L.S.G. Filon, A Manual of Photoelasticity for Engineers, p. 66.
2. Coker and Filon, Photoelasticity, p. 146, L.S.G. Filon, A Manual of Photoelasticity for Engineers, p. 70.
3. Filon, A Manual of Photoelasticity for Engineers, p. 73.

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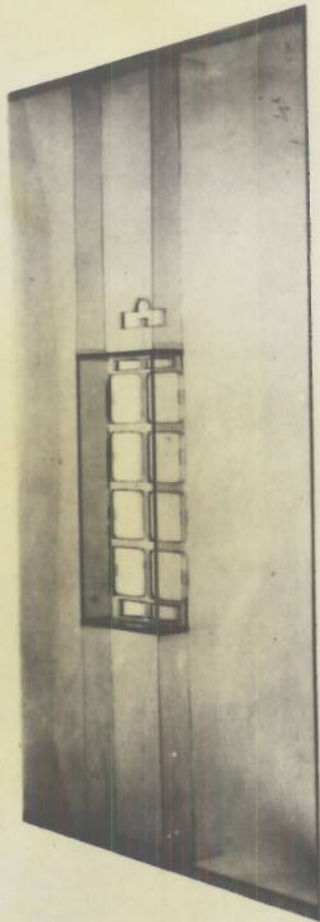


PLAN OF SPECIMEN
WITH PLATE INDEX

PLATE I

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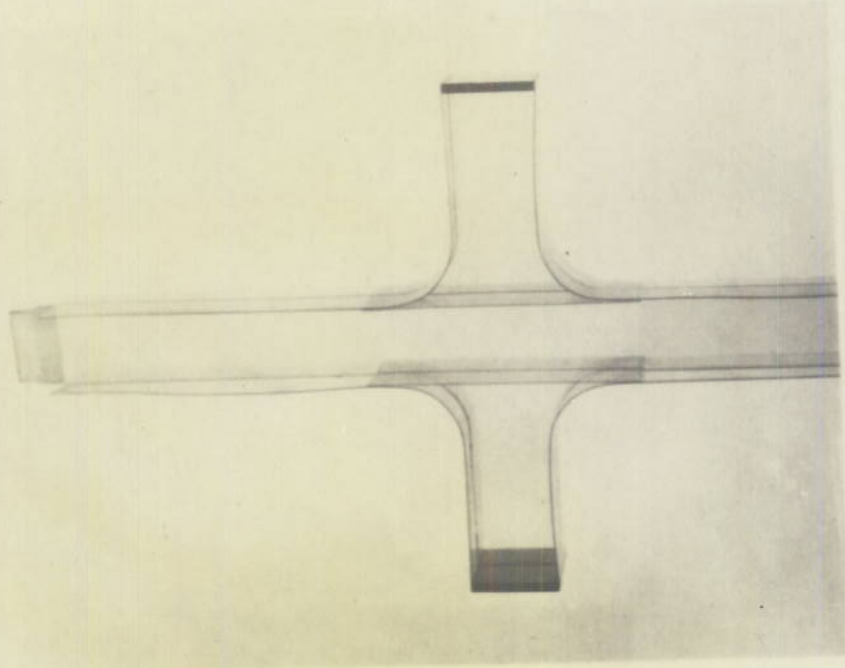


MODEL B

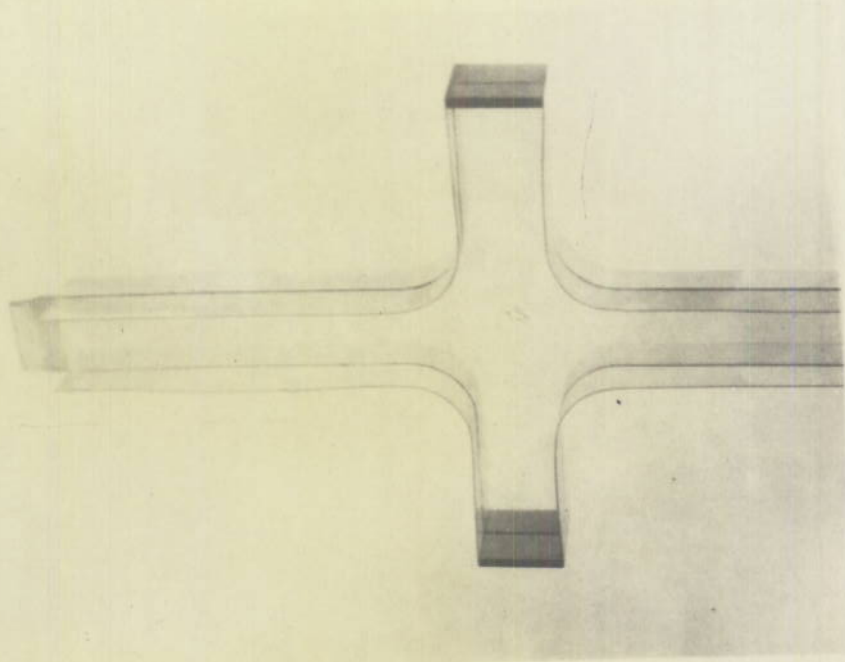
PLATE 2

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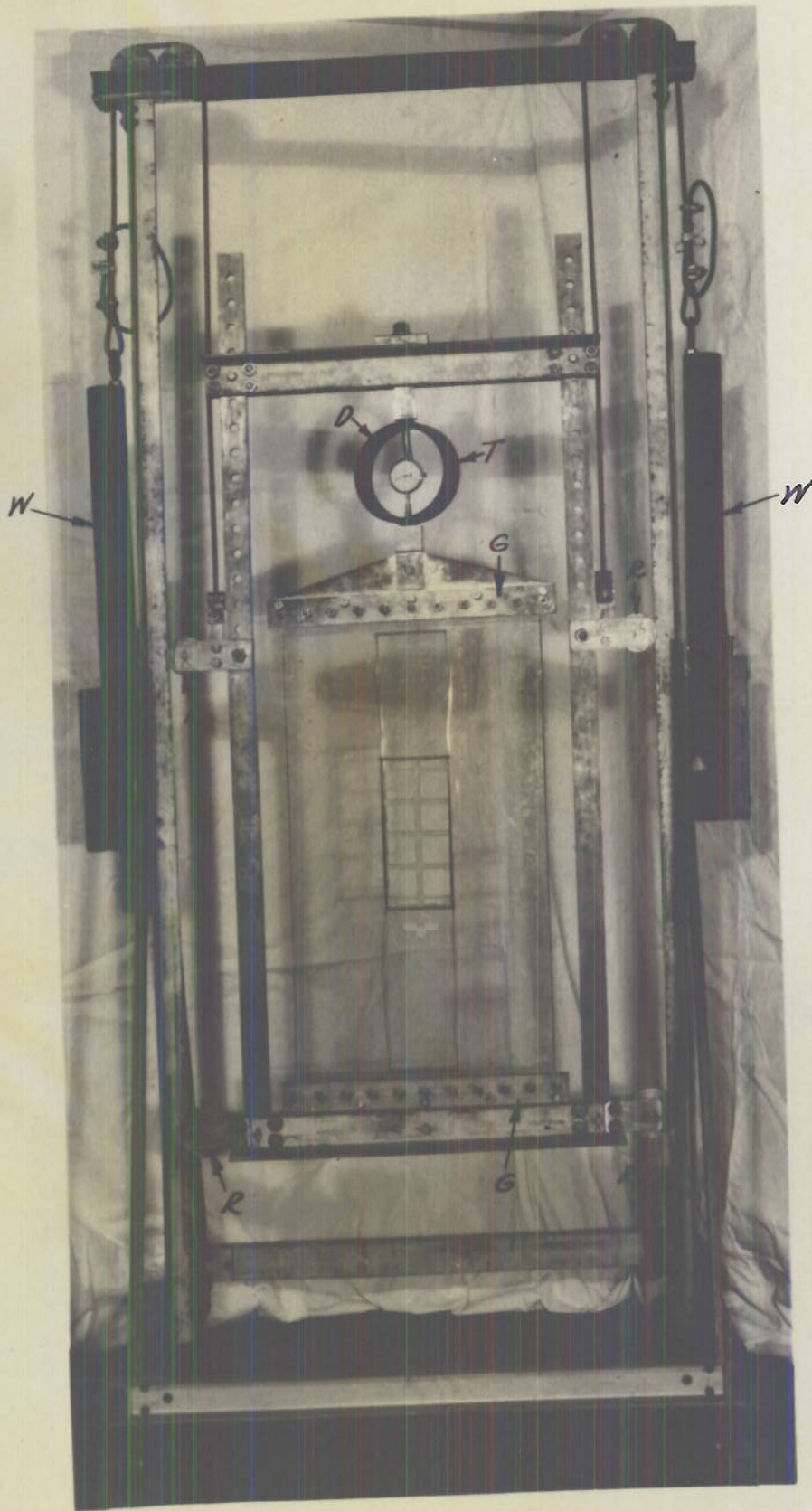


MODEL S2



MODEL S1

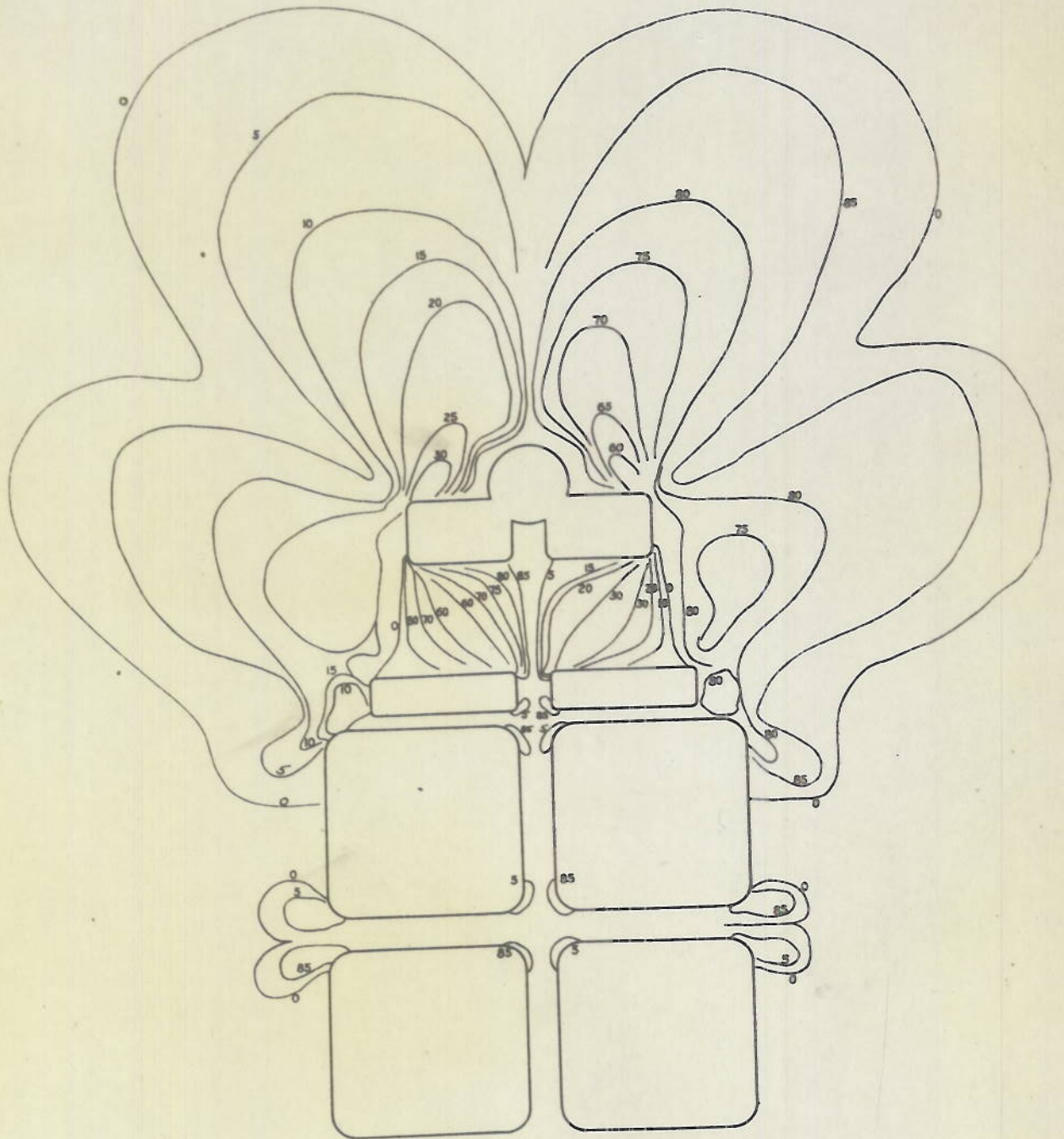




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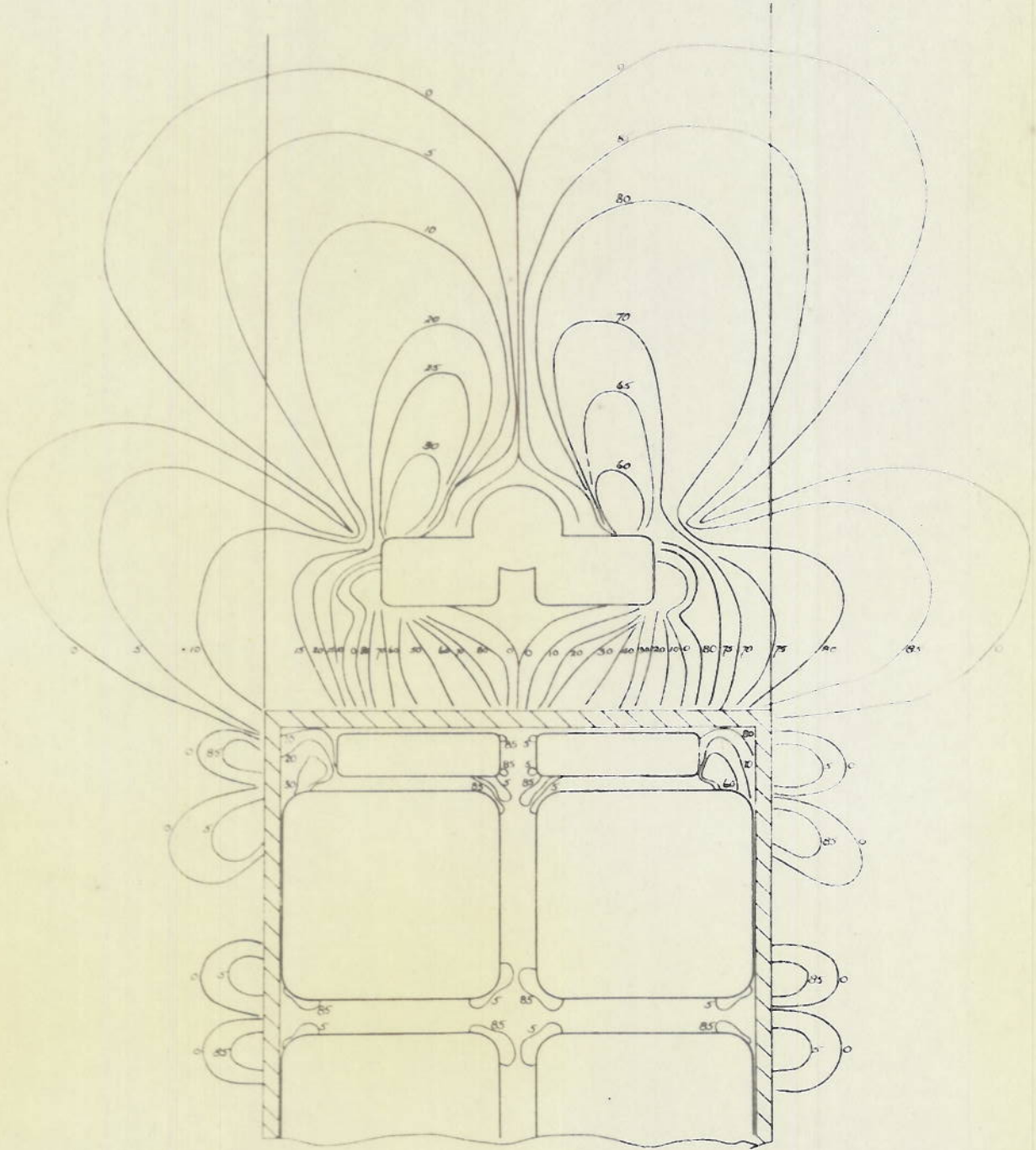
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PLATE 4



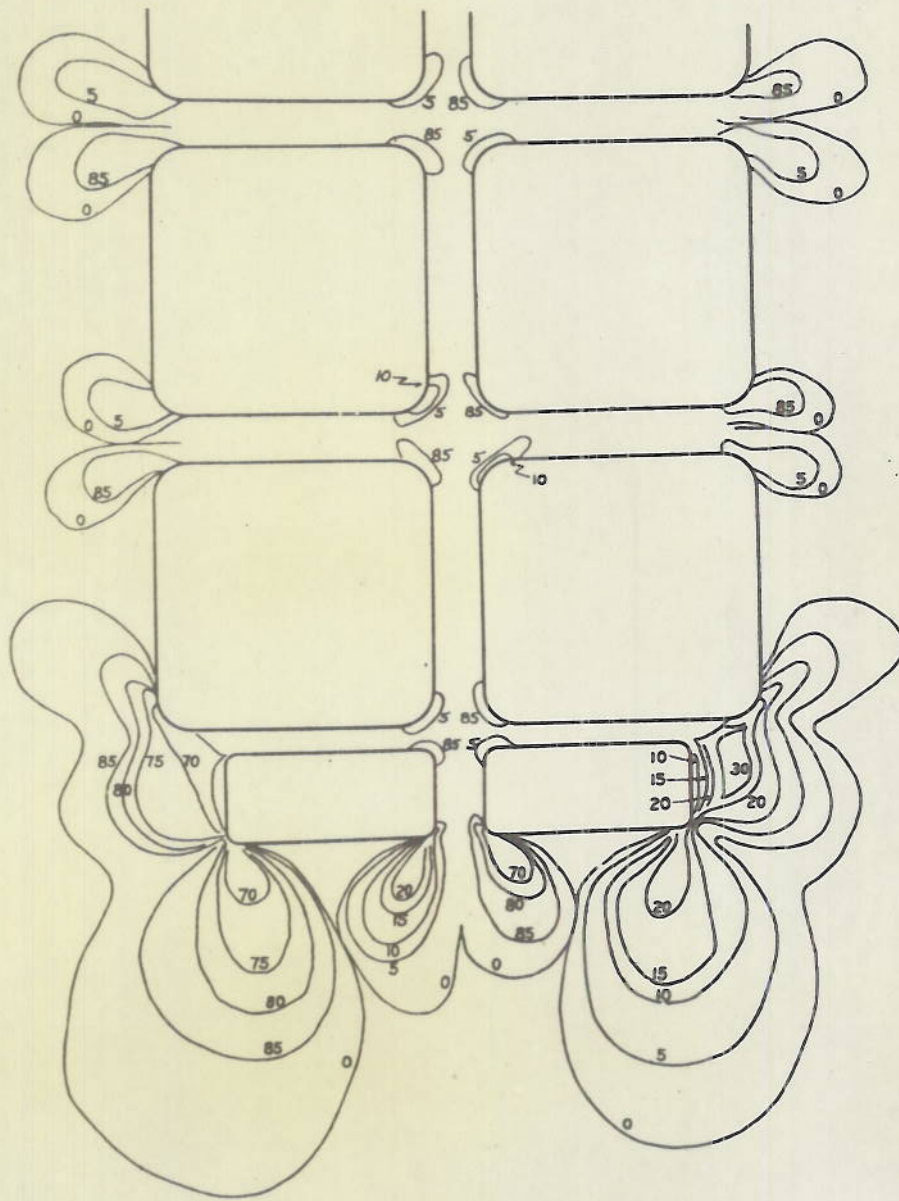
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~~_____~~ Plate 5A



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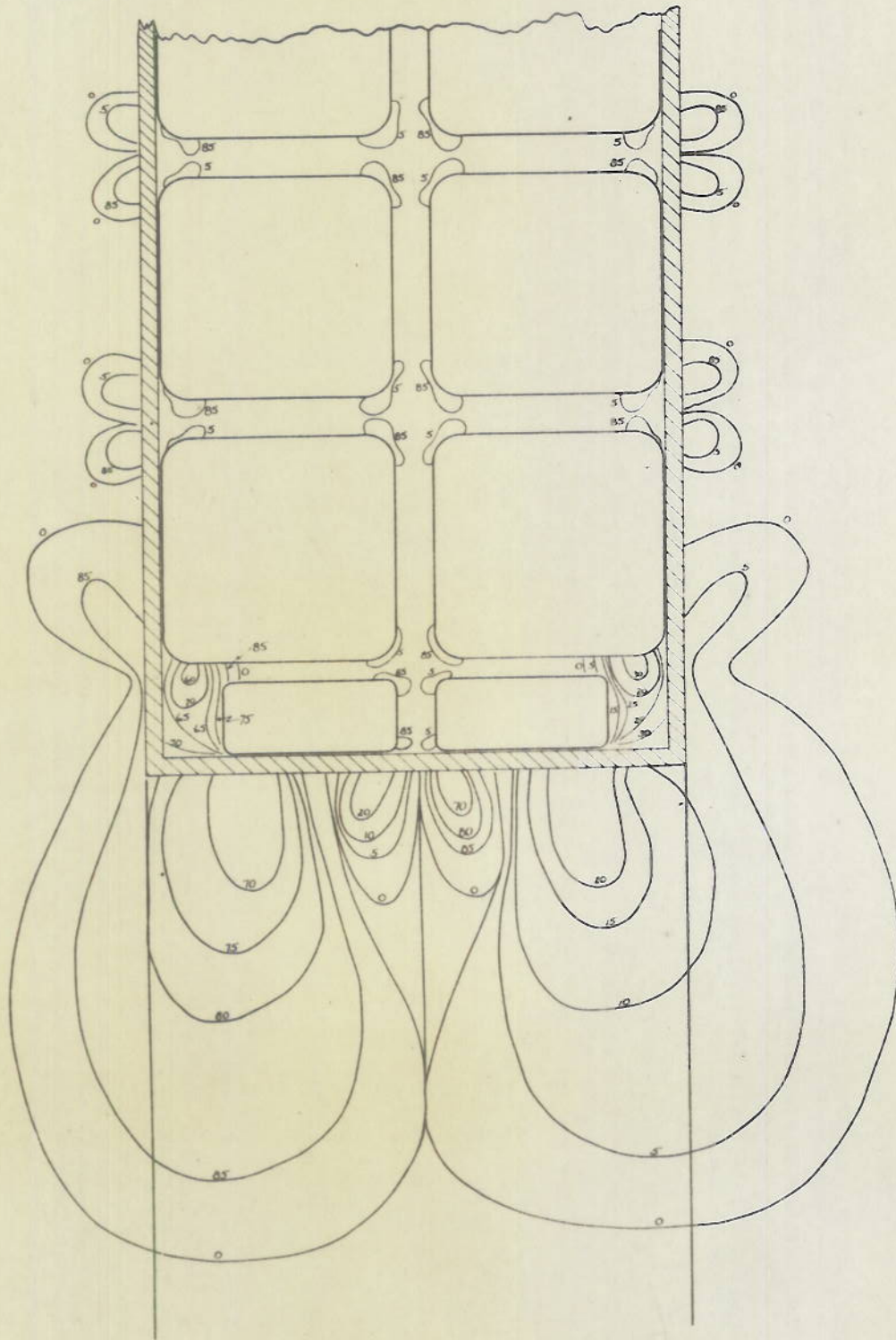


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Plate 6A

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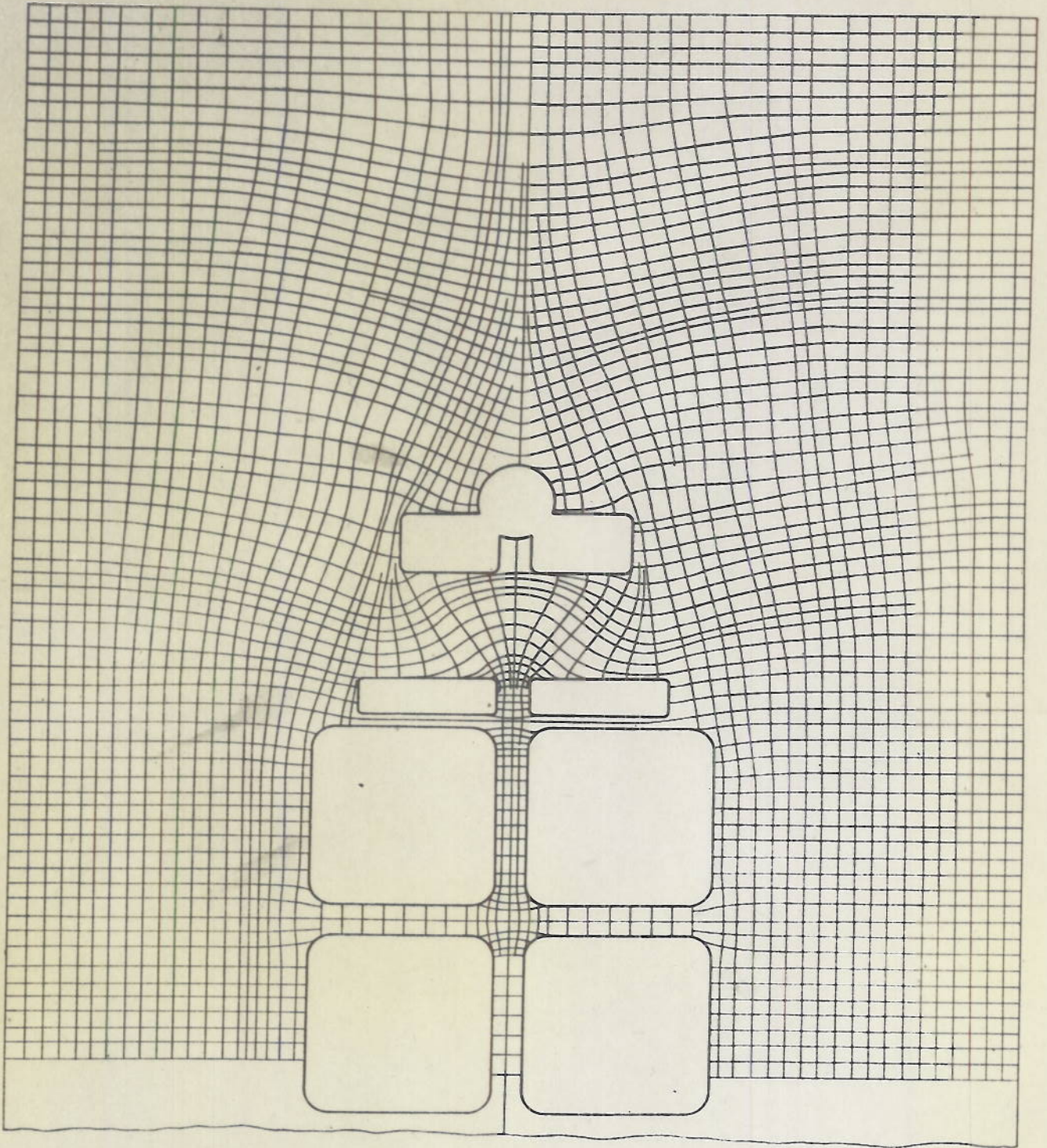


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Plate 6B

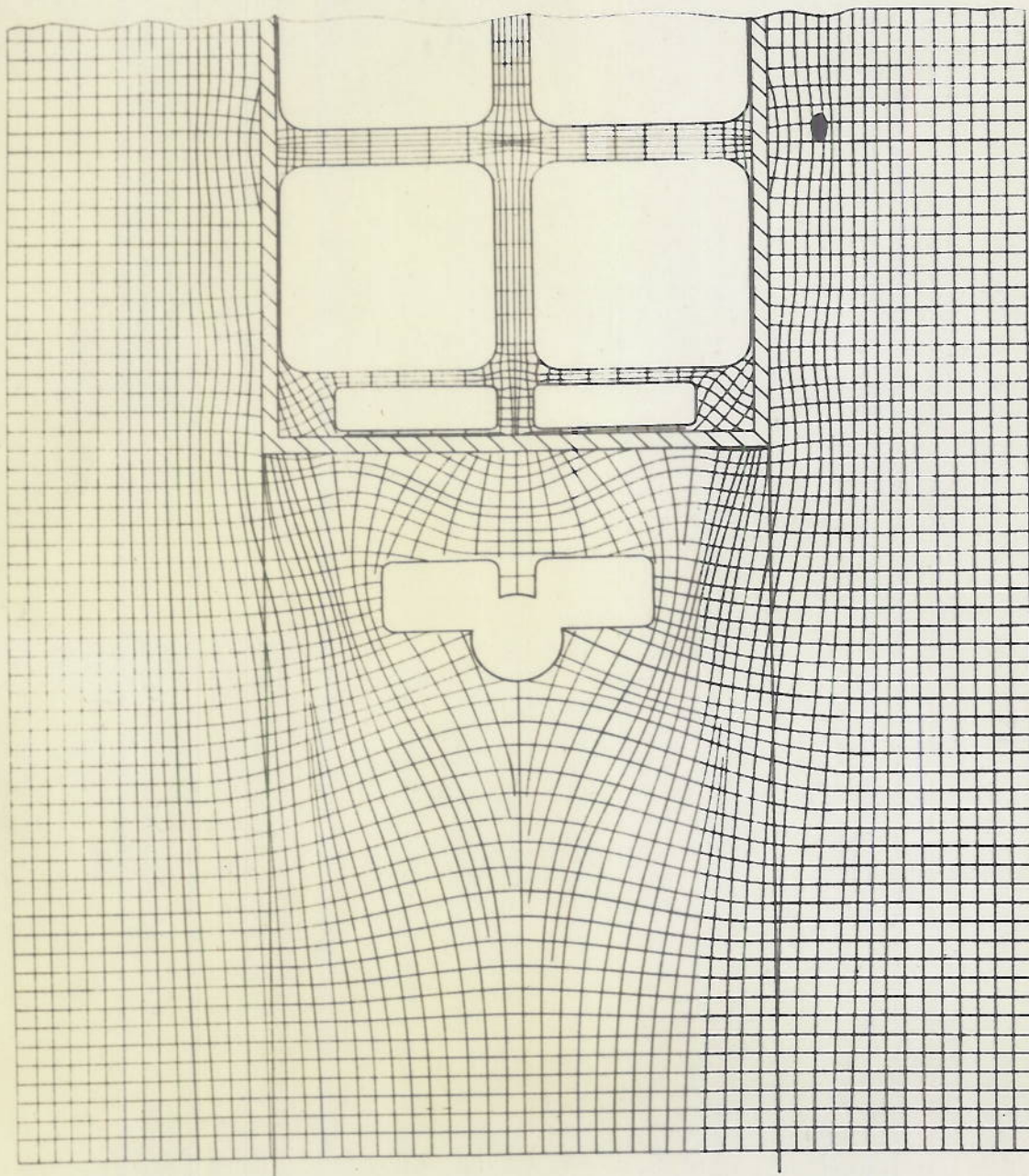
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OCPlate 7A

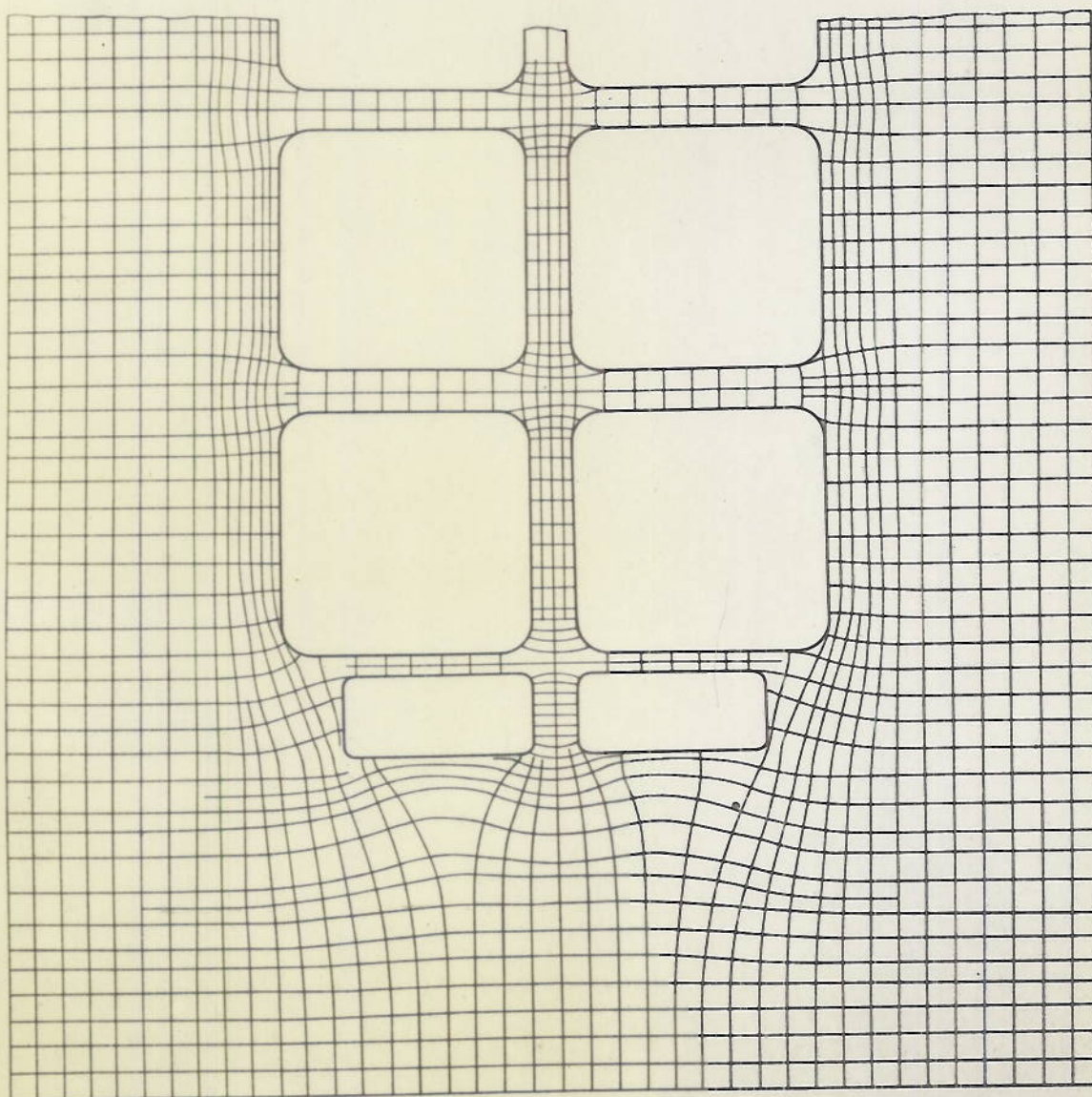


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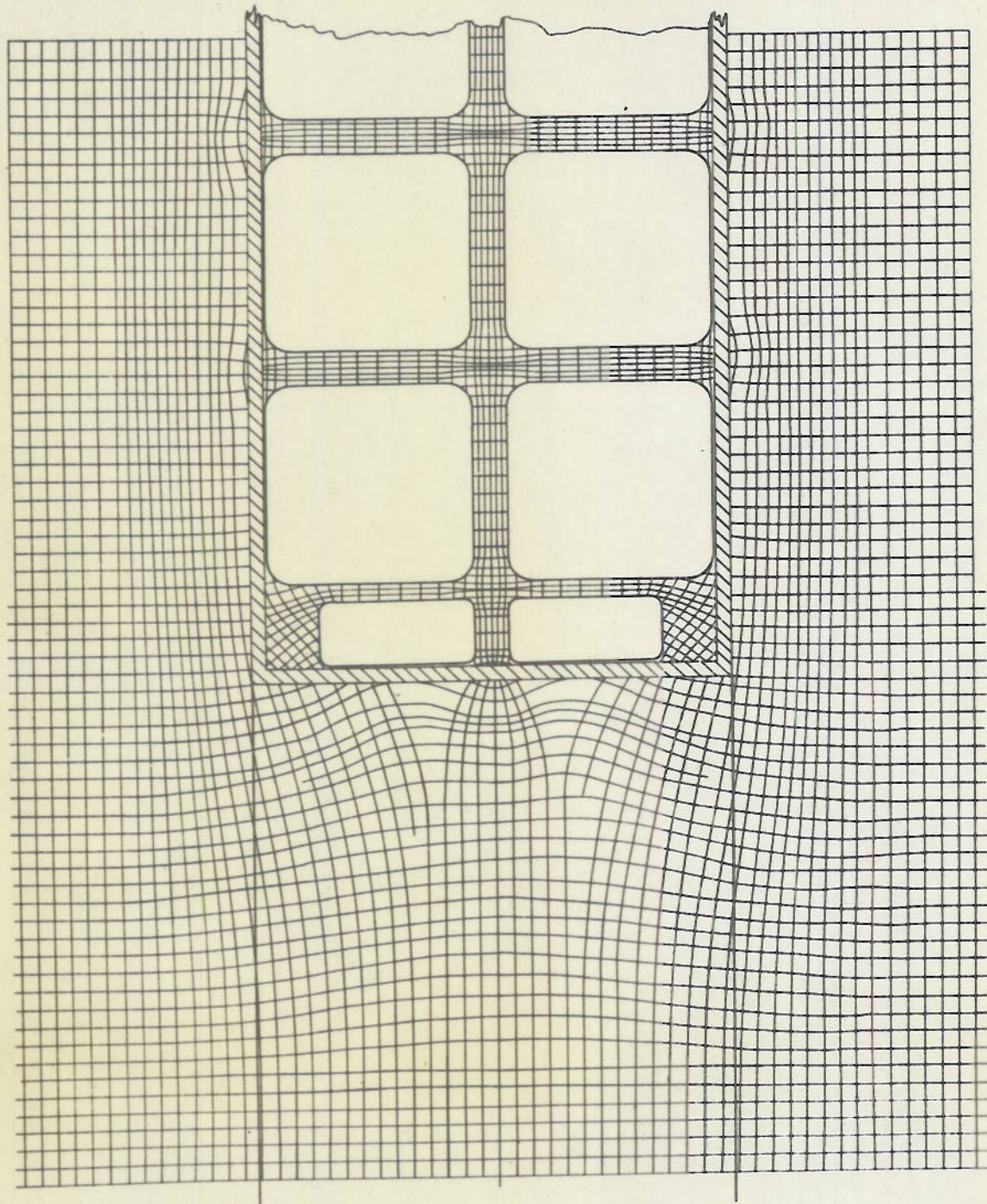
Plate 7B



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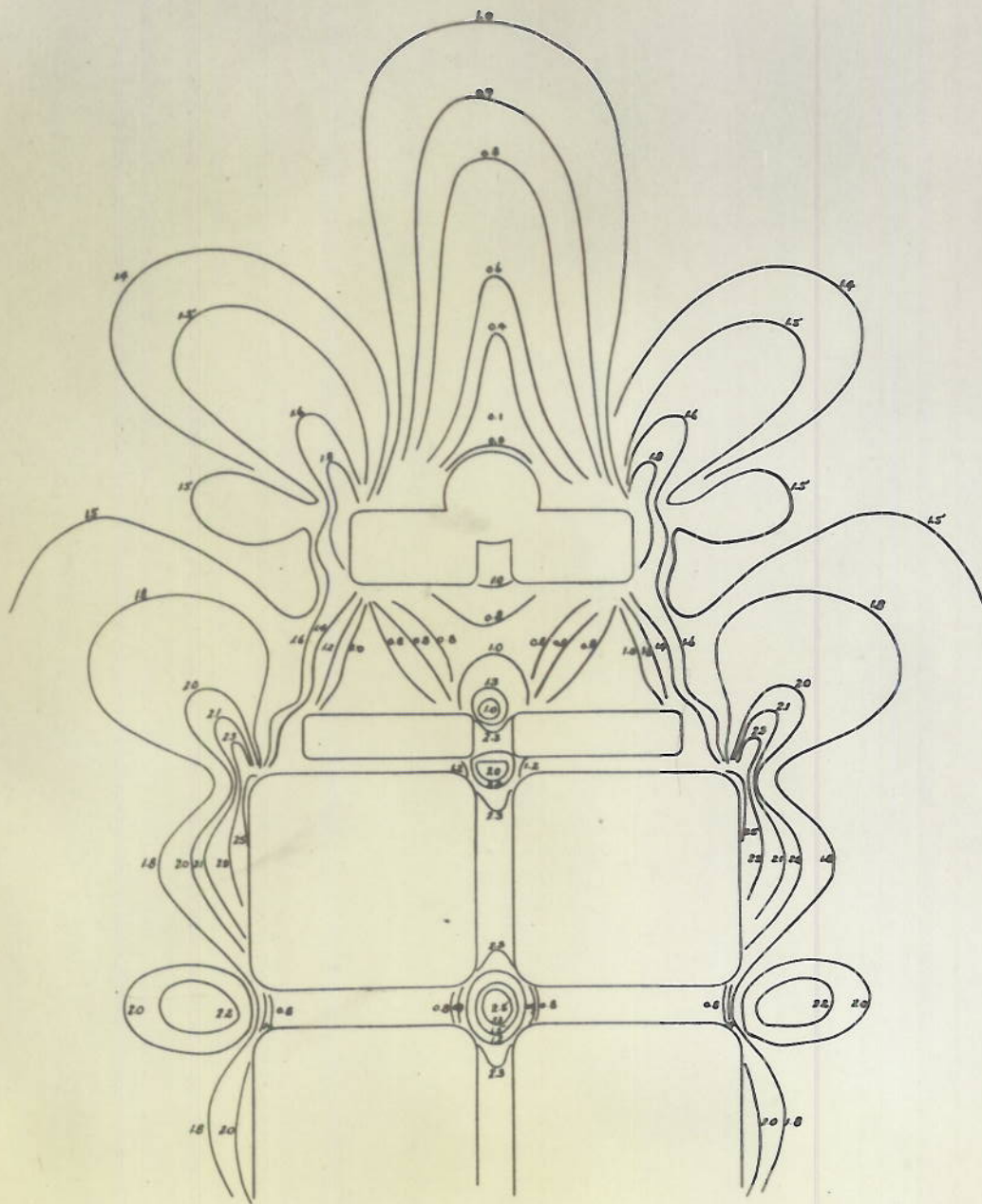


Plate 8A

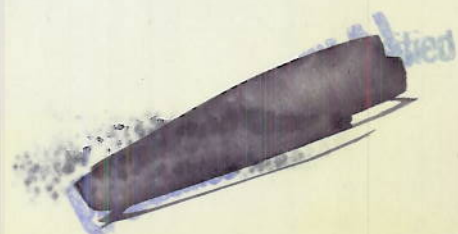


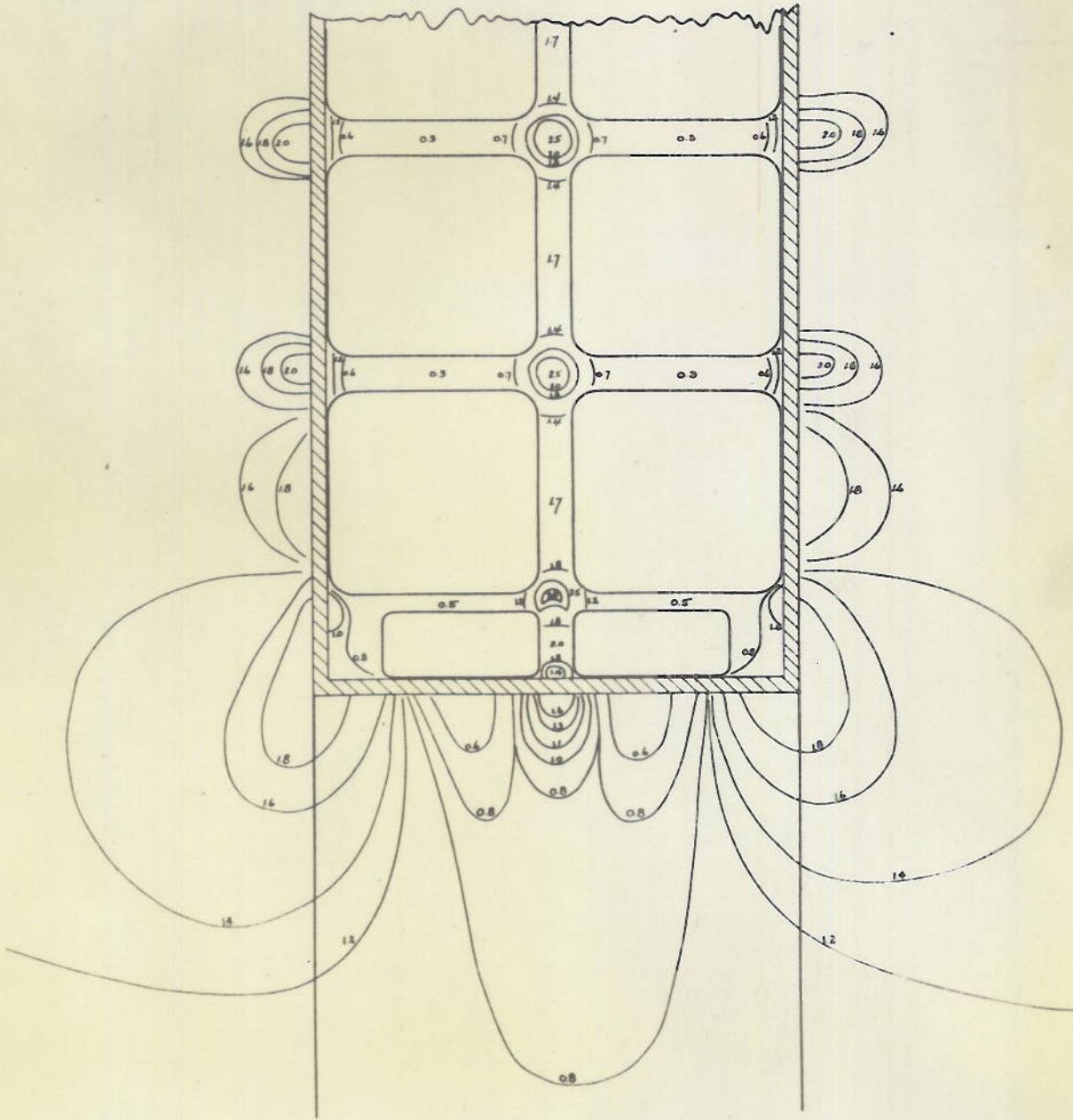
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Plate 8B



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Plate 10B

Table 1
SUMMARY OF STRESS CONCENTRATION FACTORS

Point		Model			
		A	B	C	D
a	P-Q	2.3	2.0	2.0	2.2
	P	2.3	2.0	2	2.2
	Q	0	0	0	0
b	P-Q	1.2	0.2	0.8	0.8
	P	0	0	0	0
	Q	-1.2	-0.2	-0.8	-0.8
c	P-Q	3.1	2.8	2.4	3.8
	P	1.75	2.0		
	Q	-1.35	-0.8		
d	P-Q	2.3	1.7	2.0	2.2
	P	2.3	1.7	2.0	2.2
	Q	0	0	0	0
e	P-Q	0.8	0.4	0.6	0.8
	P	0	0	0	0
	Q	-0.8	-0.4	-0.6	-0.8
f	P-Q	2.60	2.5	2.5	3.2
	P	1.63	1.2		
	Q	-0.97	1.3		
g	P-Q	1.0	0.4	1.0	0.6
	P	0	0	0	0
	Q	-1.0	-1.0	-1.0	-0.6
h	P-Q	3.0	3.0	2.9	4.0
	P	1.8	2.2		
	Q	-1.2	-0.8		
i	P-Q	2.3	2.0	2.1	2.7
	P	2.3	2.0	2.1	2.7
	Q	0	0	0	0
j	P-Q		2.3		2.7
k	P-Q		1.8		1.8

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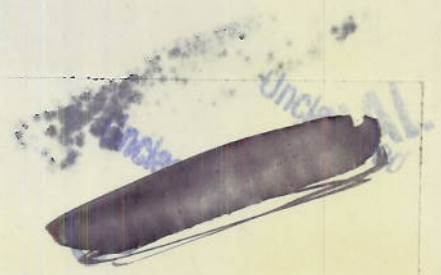
Table 2

MAXIMUM VALUES - CONTOUR STRESSES

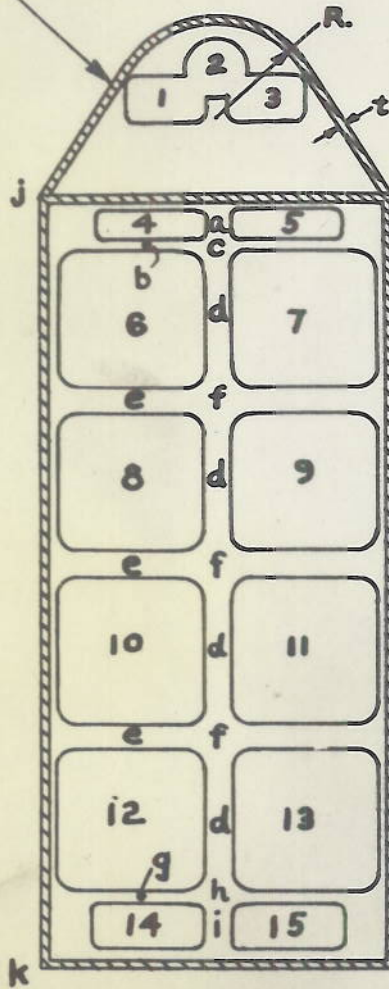
<u>Point</u>	<u>Model</u>	
	<u>A</u>	<u>B</u>
a	3.5	3.2
b	2.3	2.8
c		1.35
d	.7	.9
e	1.73	.9
f	3.2	1.7
g	3.2	3.1
h	4	2.7
i	2.95	1.7
j	2	2
k	3	2.3
l	2.7	1.55
m	2.95	1.7
n	2.7	1.55
o	2.95	1.7
p	2.7	1.7
q	3.35	1.8
r	4	2.3
s	3.35	2.2
t	.9	1.0
u	3.1	2.75
v	3.4	2.3
w	2.58	2.2

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SPECIAL REINFORCEMENT MODEL D
 ACTUAL SIZE - $R=1\frac{1}{2}''$, $t=\frac{1}{4}''$
 HEIGHT ABOVE DECK = $\frac{5}{8}''$

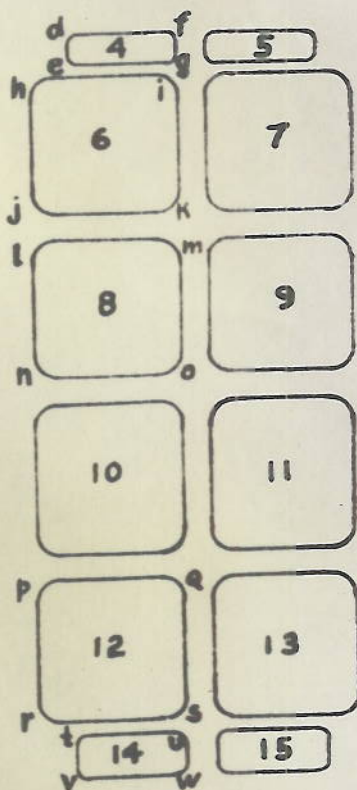
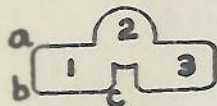


INDEX FOR TABLE I

PLATE II

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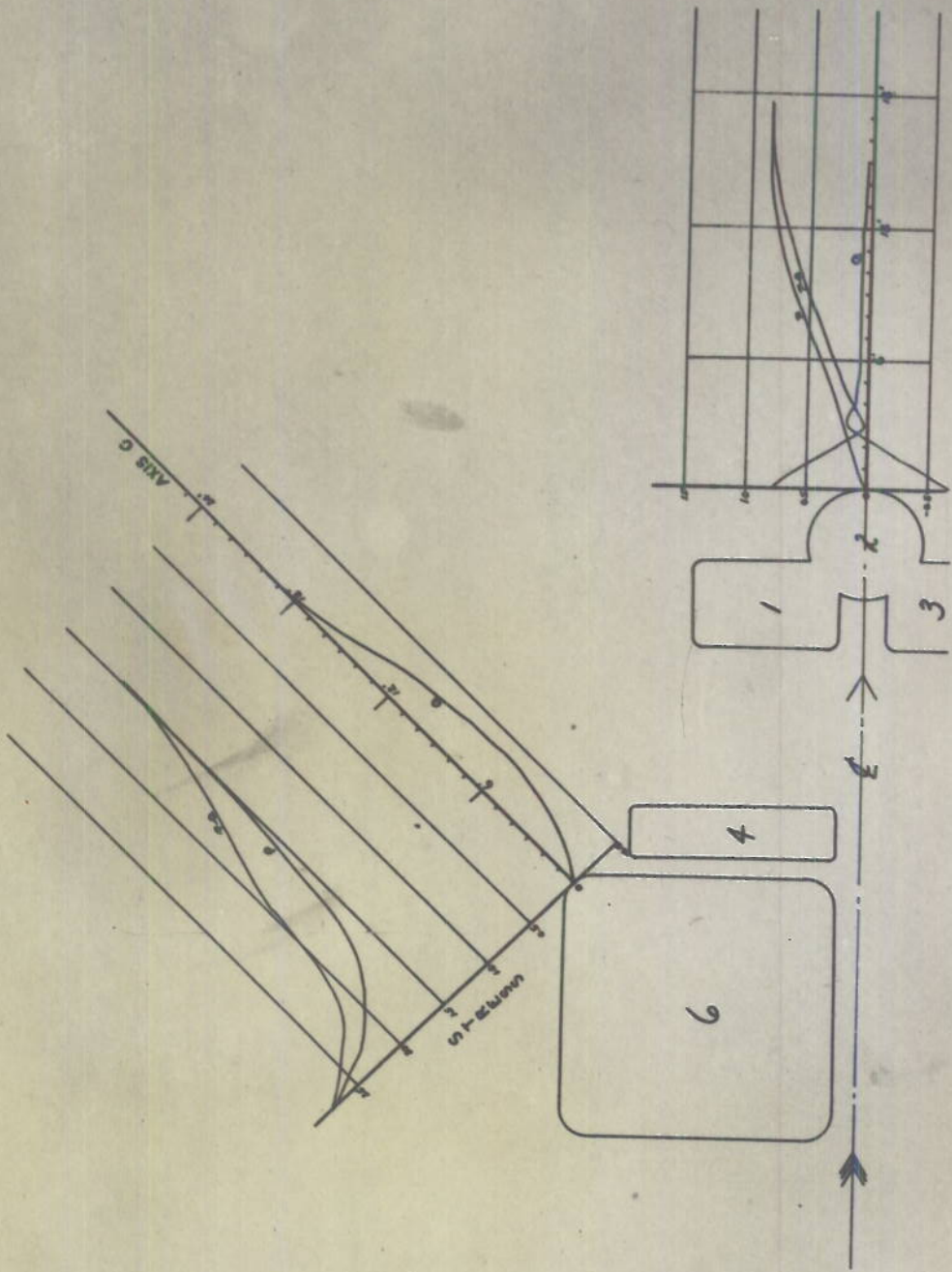


INDEX FOR TABLE 2

PLATE 12

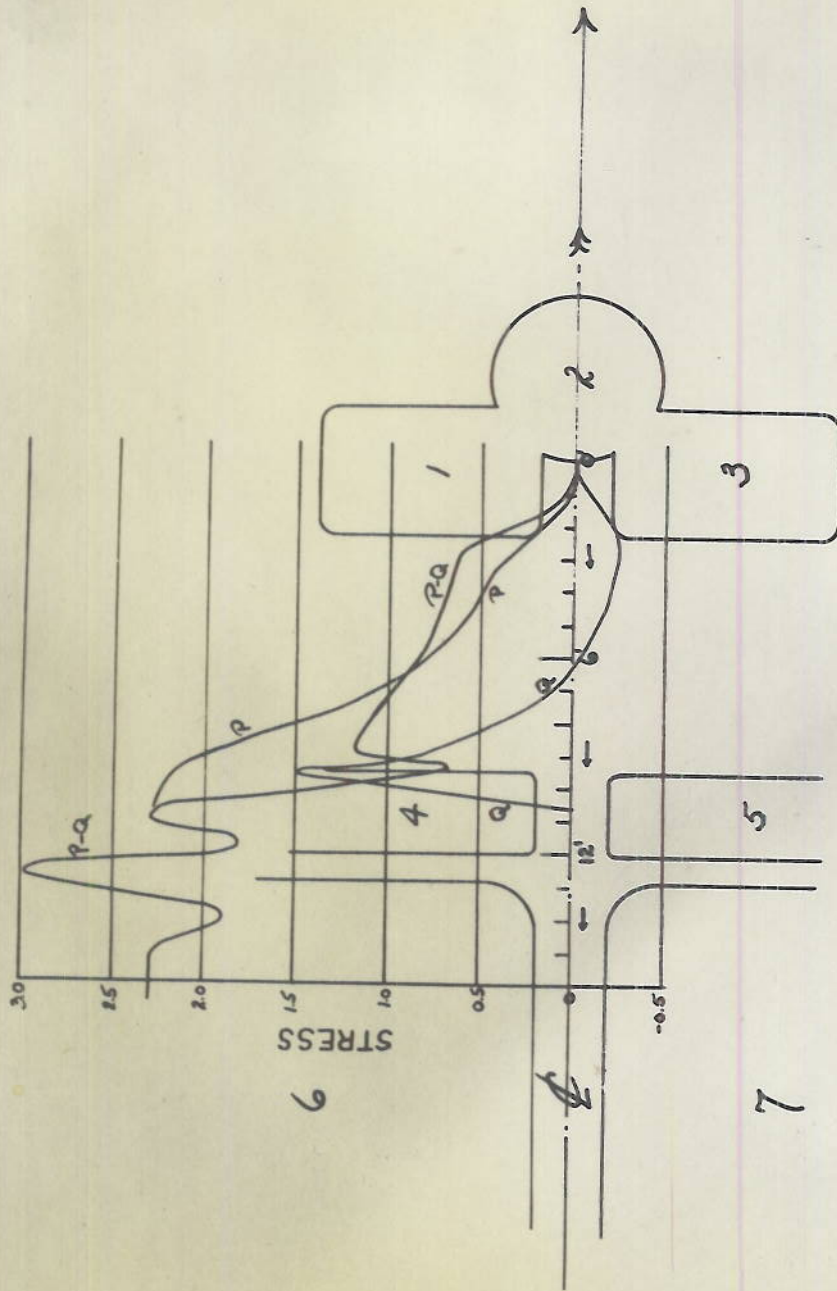
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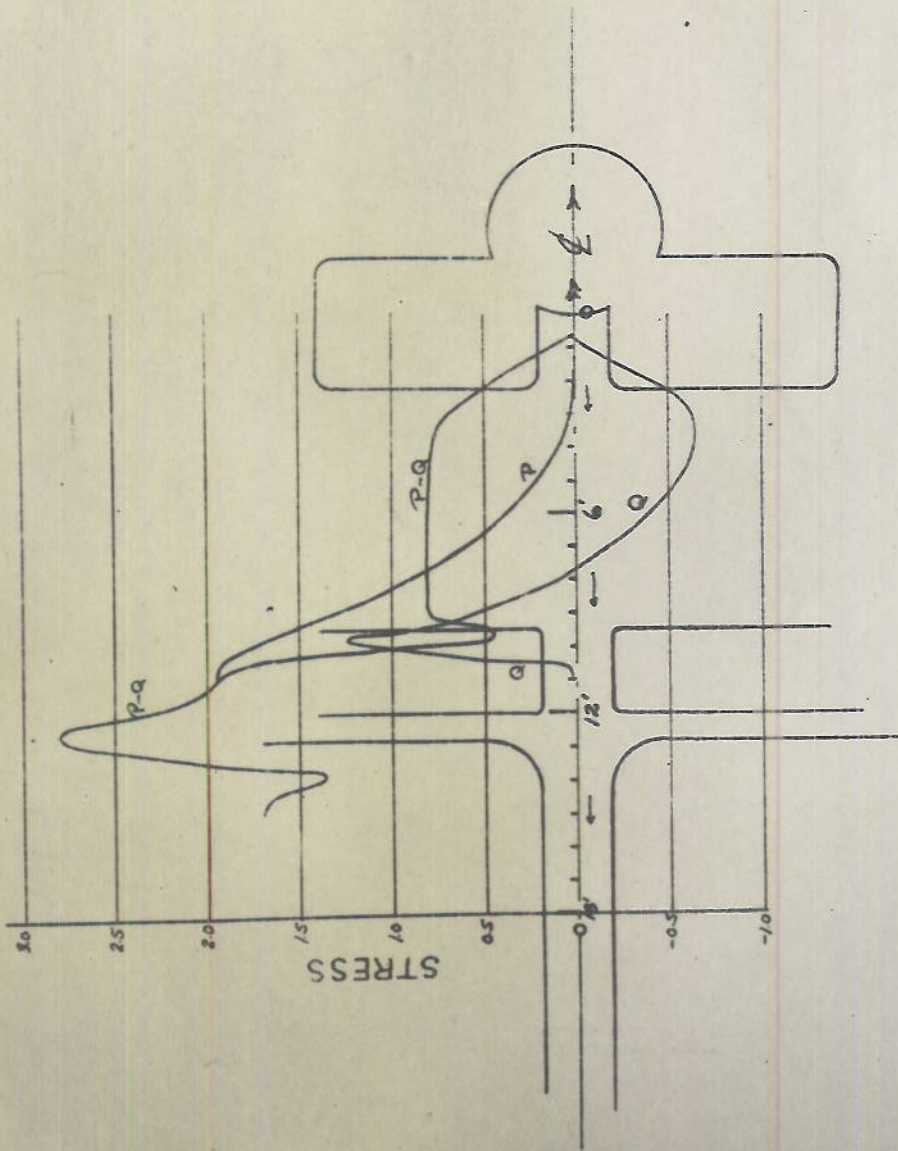
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[Redacted stamp]
 [Redacted stamp]
 [Redacted stamp]



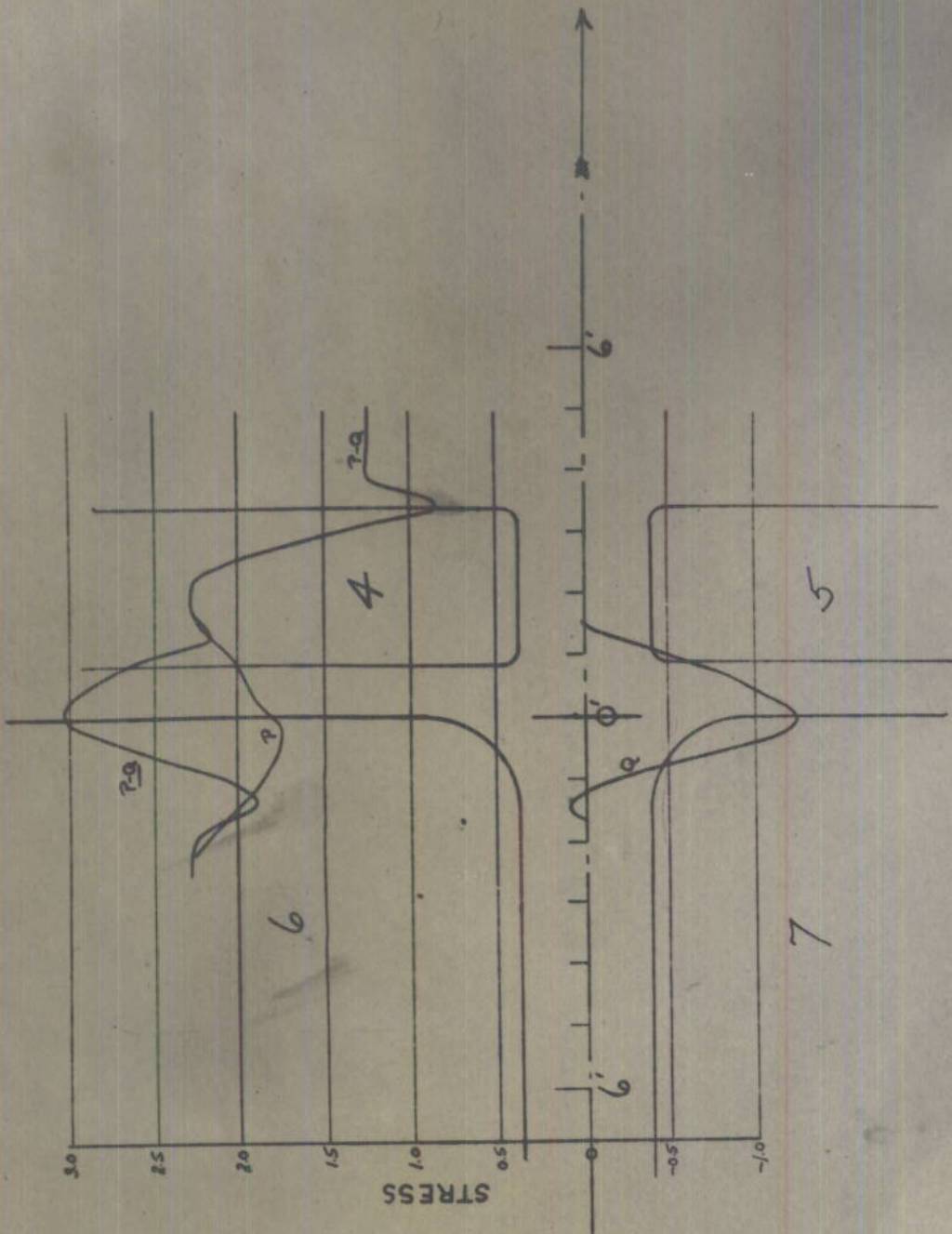
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Classified
 Plate 14A



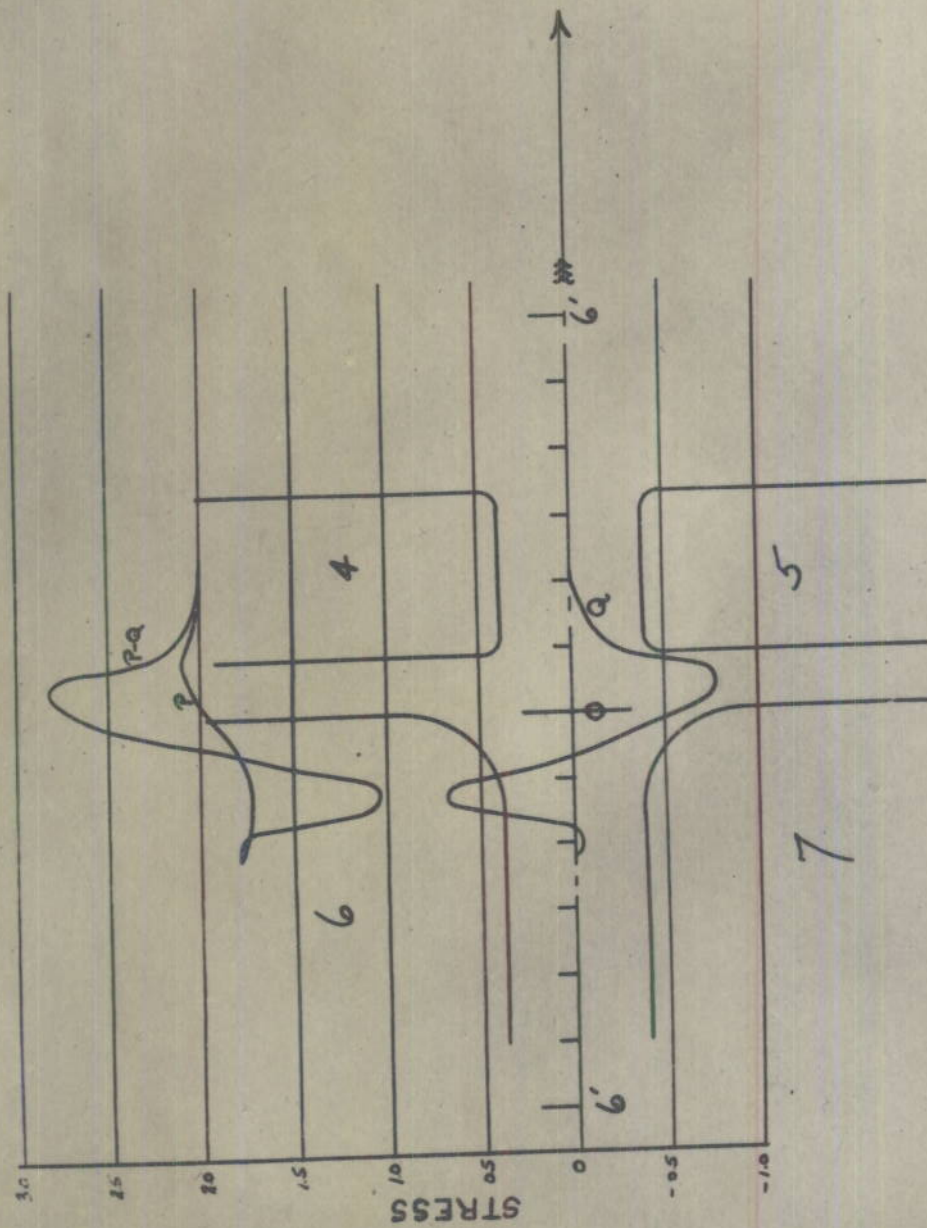
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Plate 14B



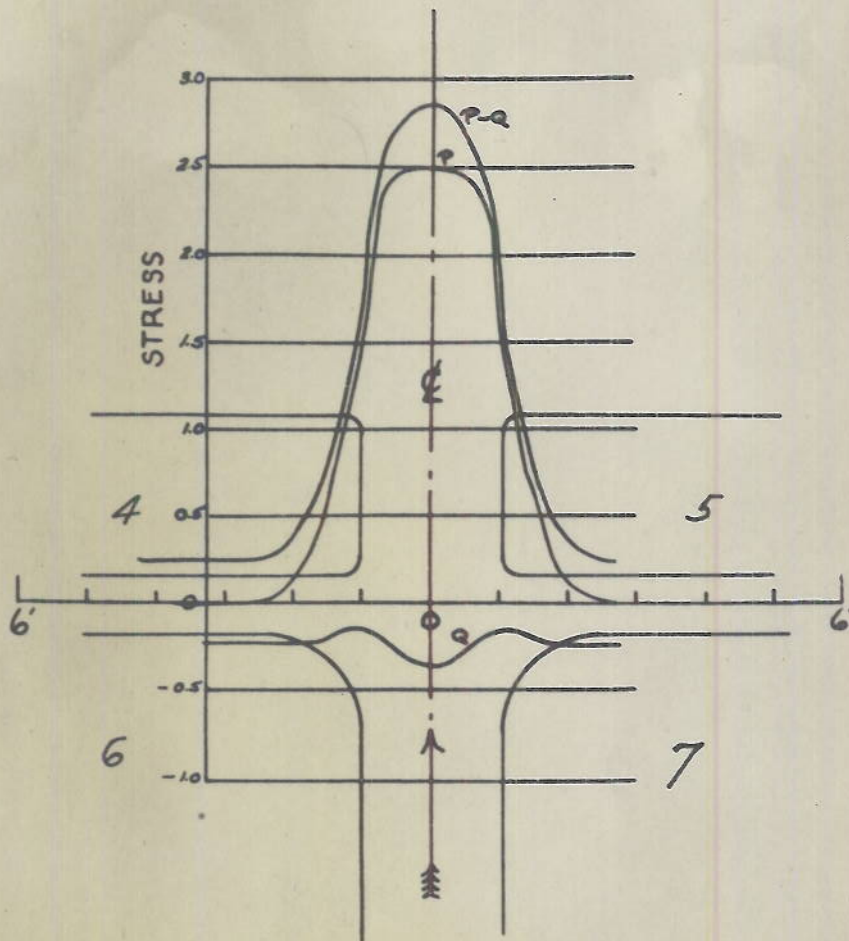
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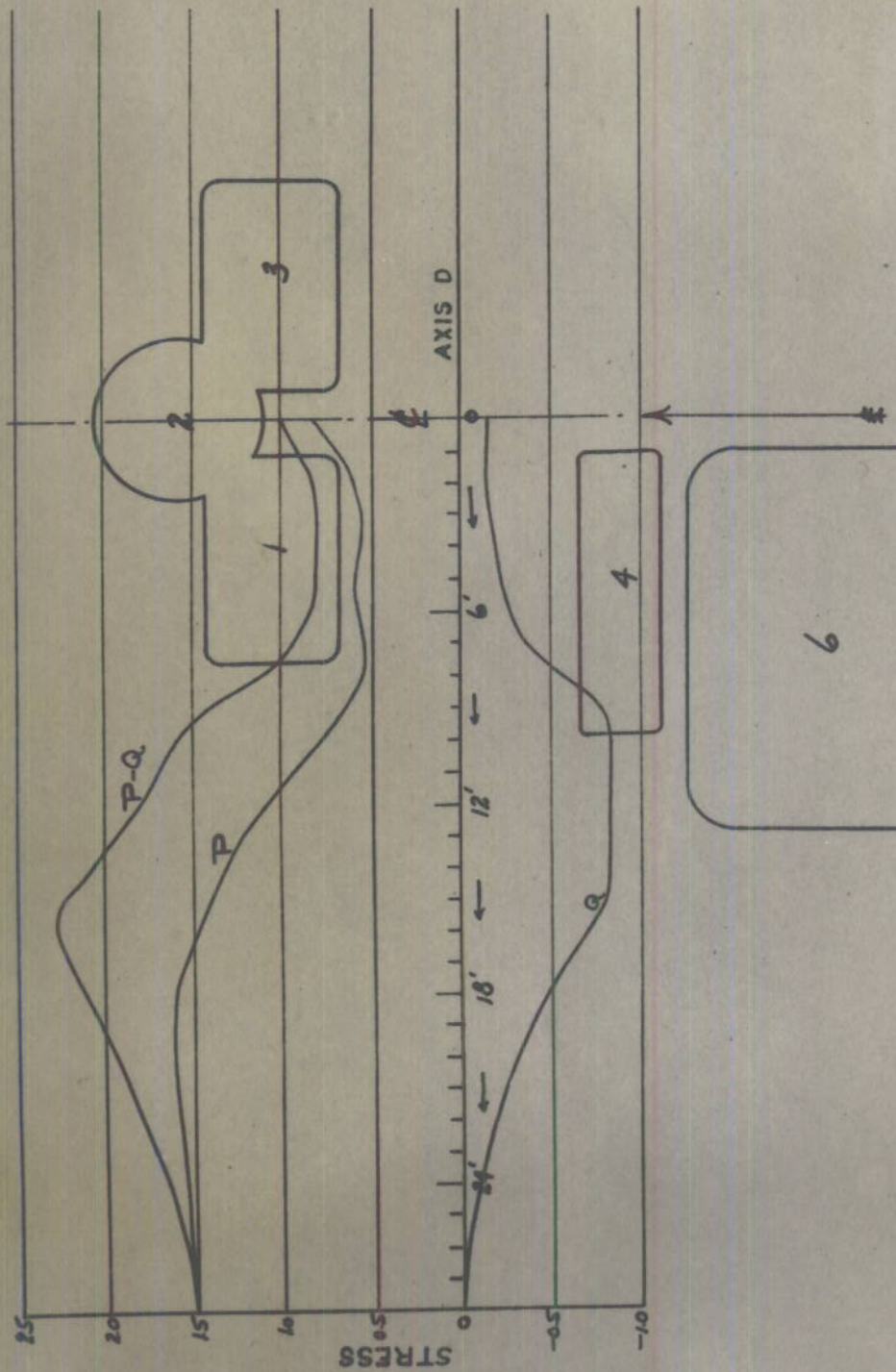


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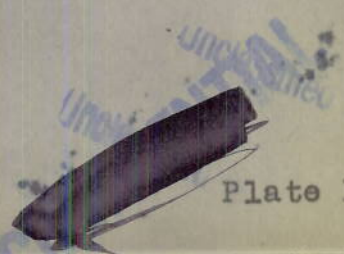
UNCLASSIFIED
 Plate 15B

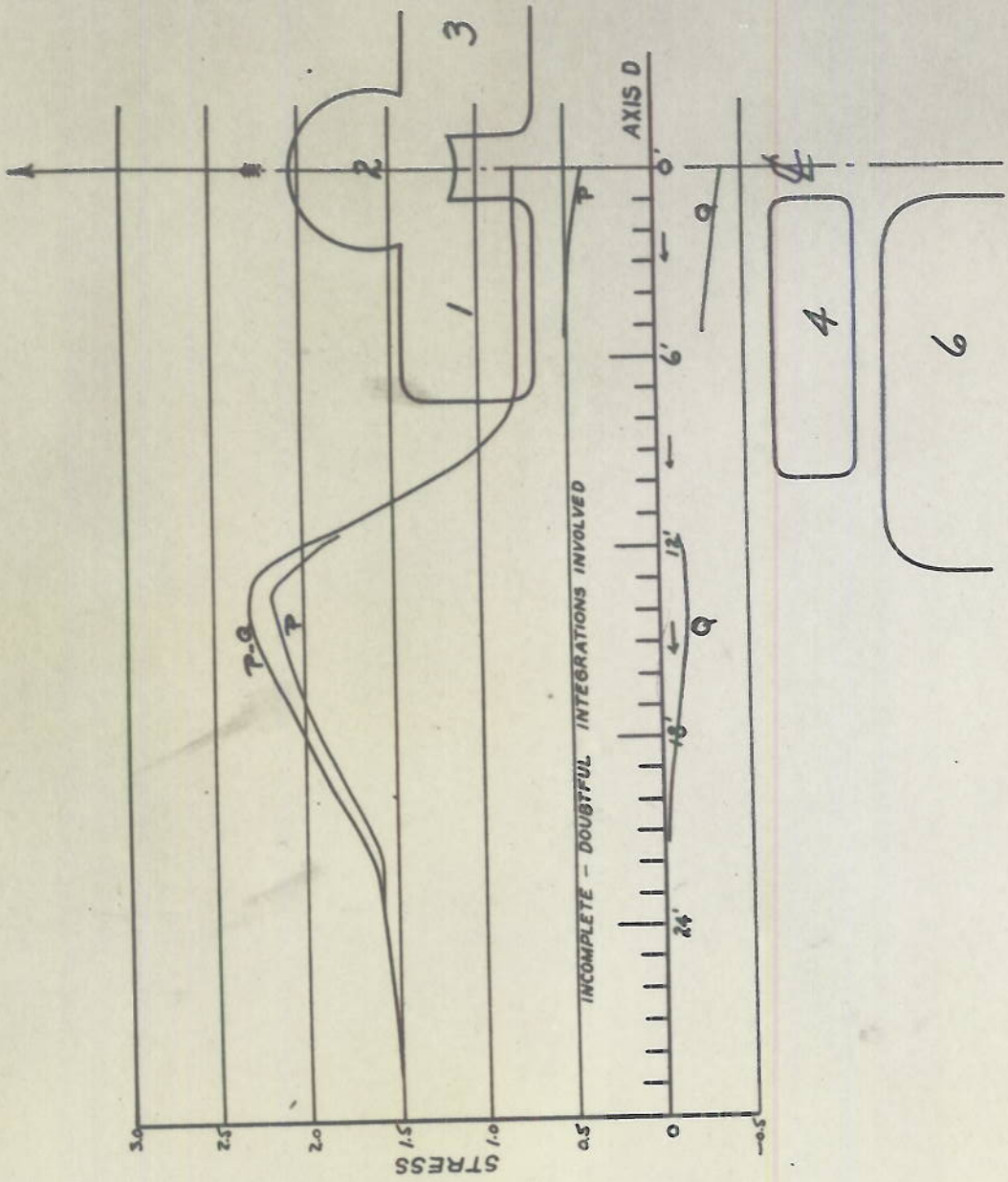


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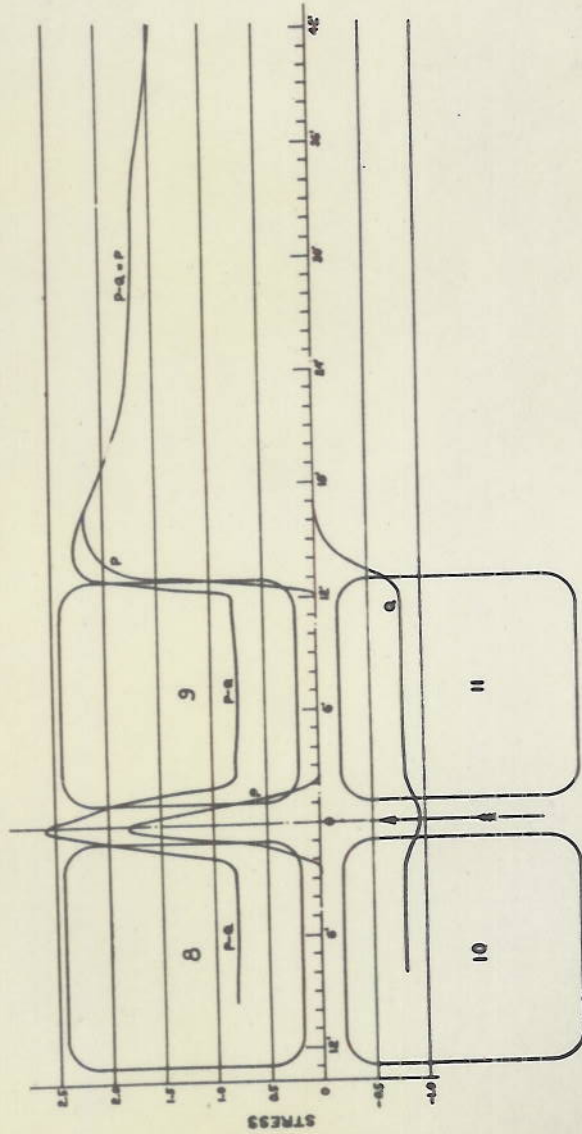
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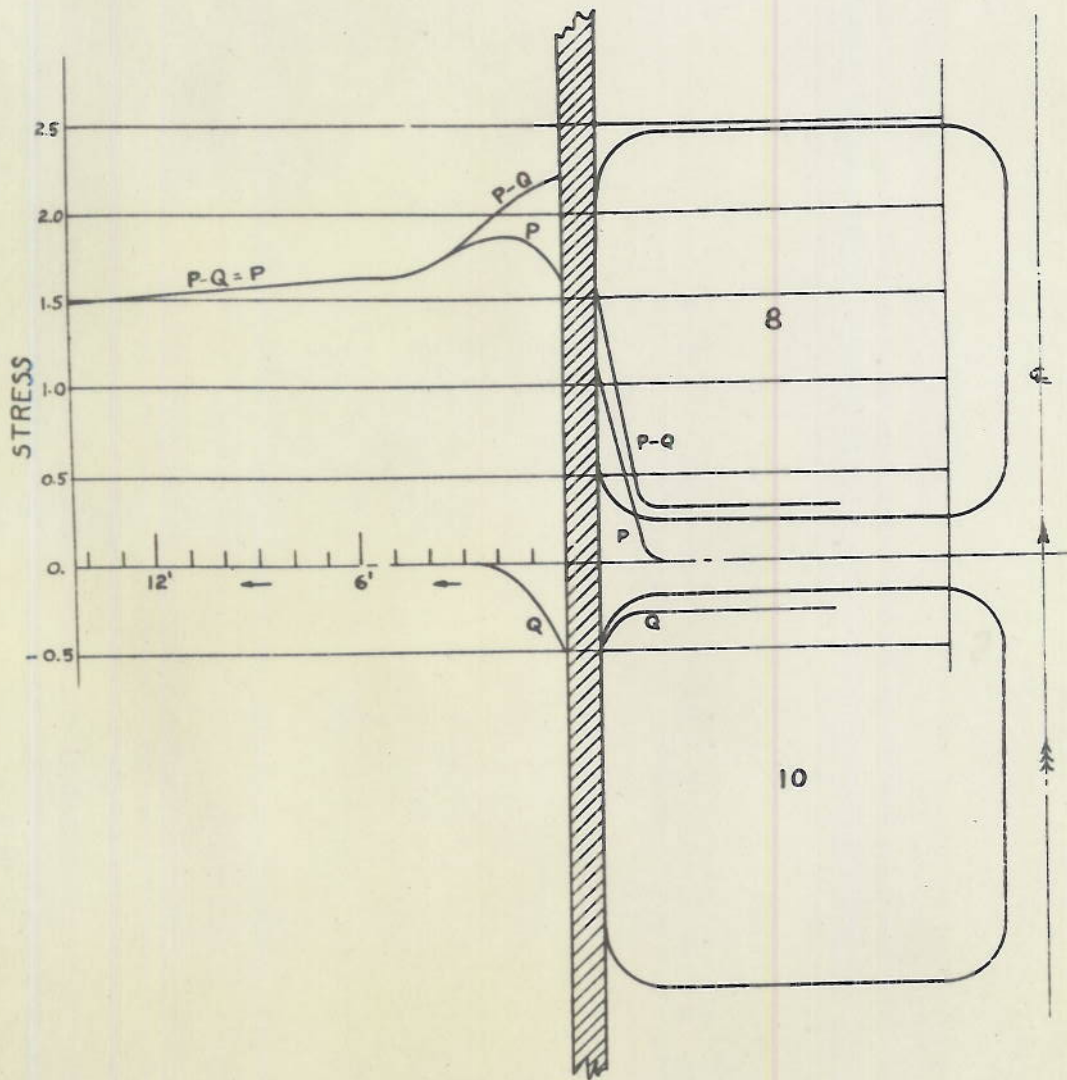
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 Plate 17B



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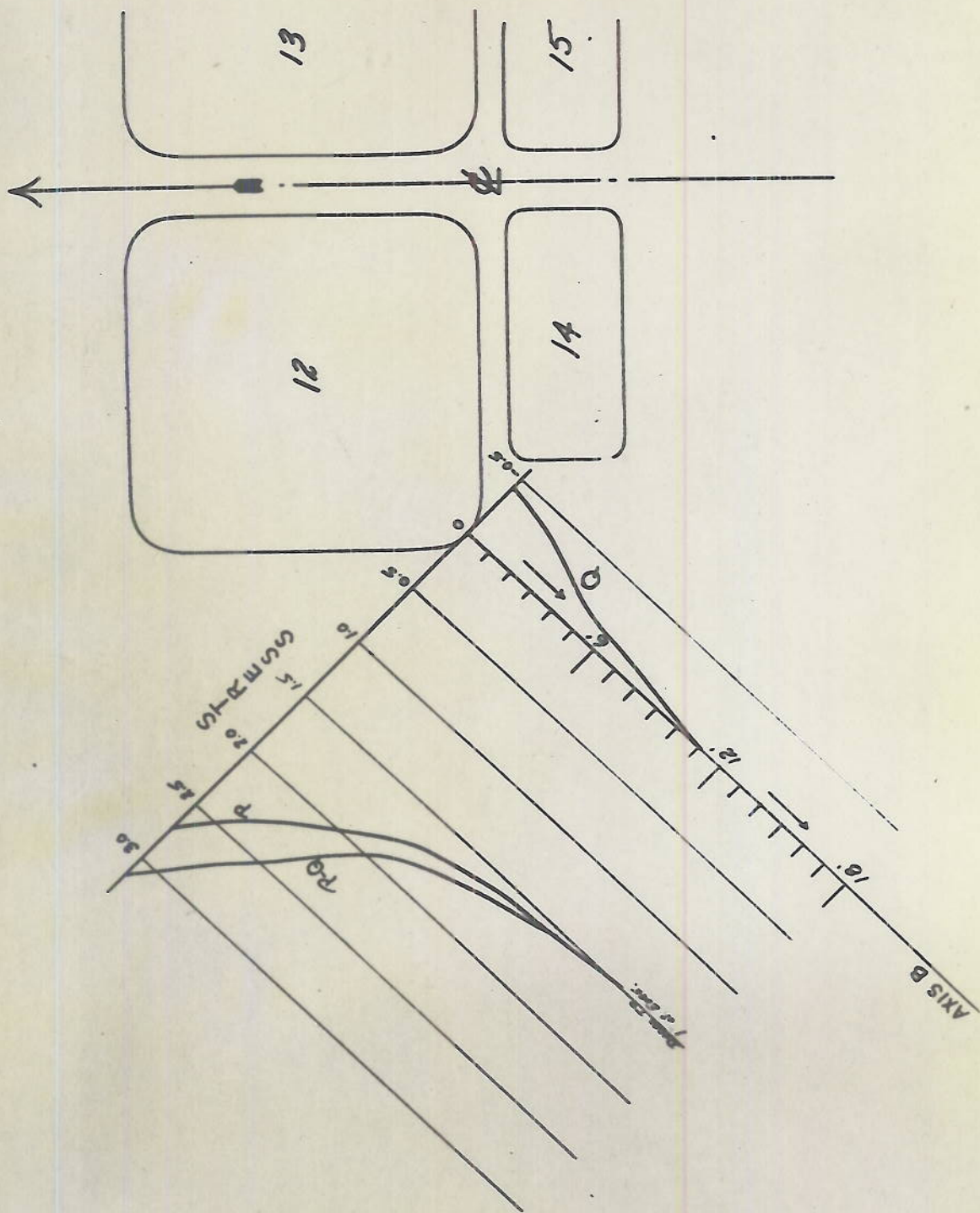
CONFIDENTIAL

Plate 18A



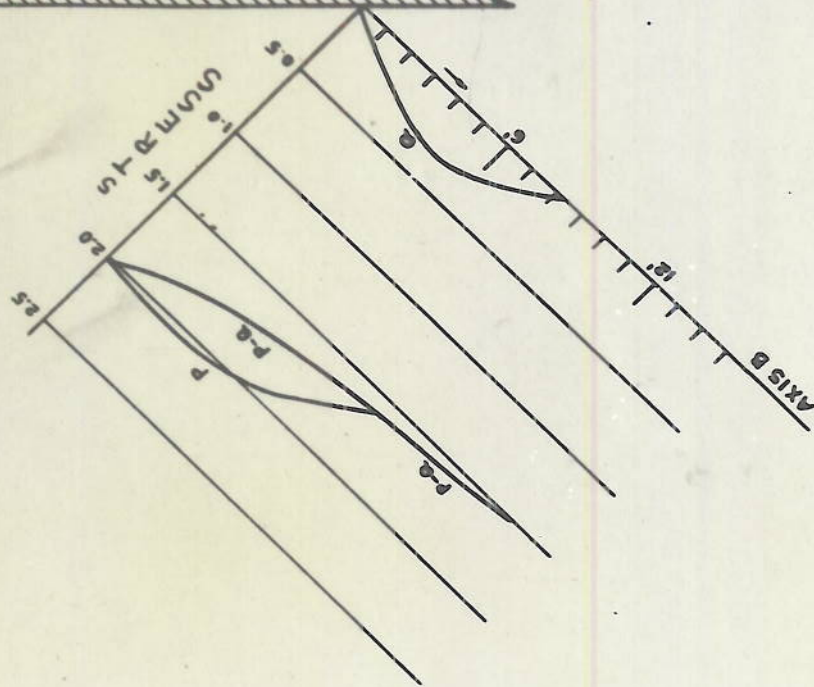
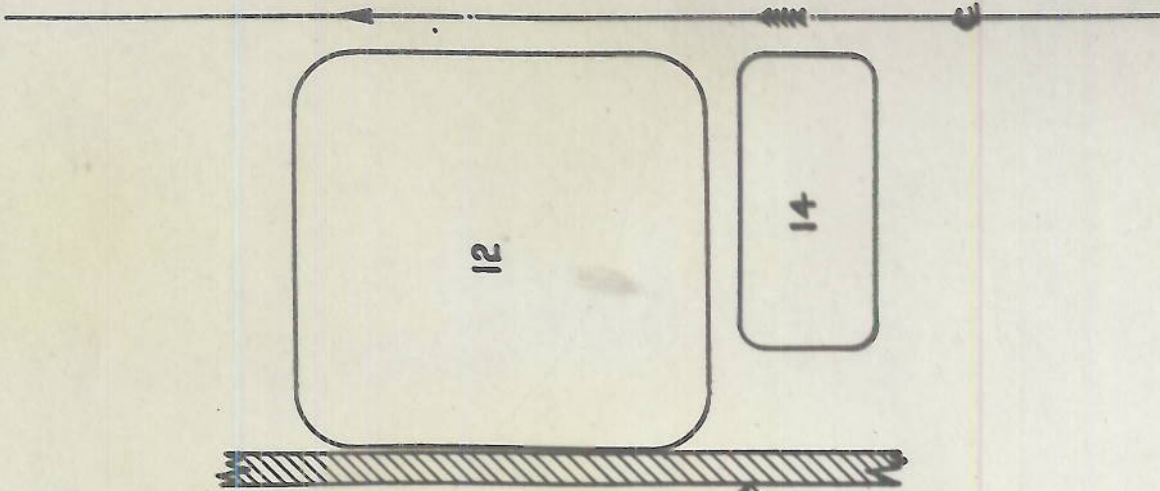
DECLASSIFIED

UNCLASSIFIED
 Plate 18B



DECLASSIFIED

Unclassified



DECLASSIFIED

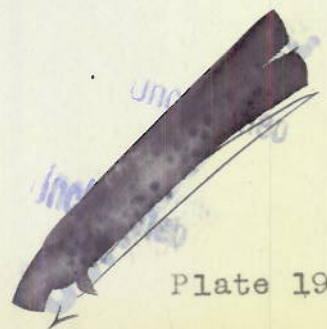
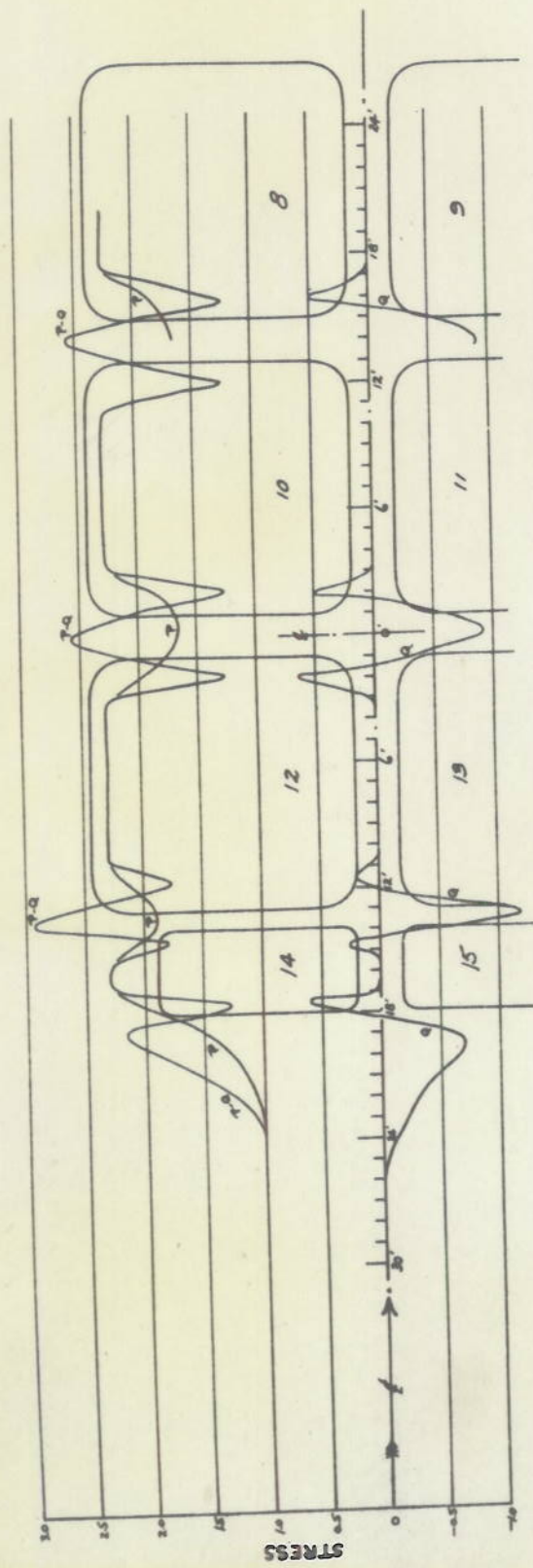
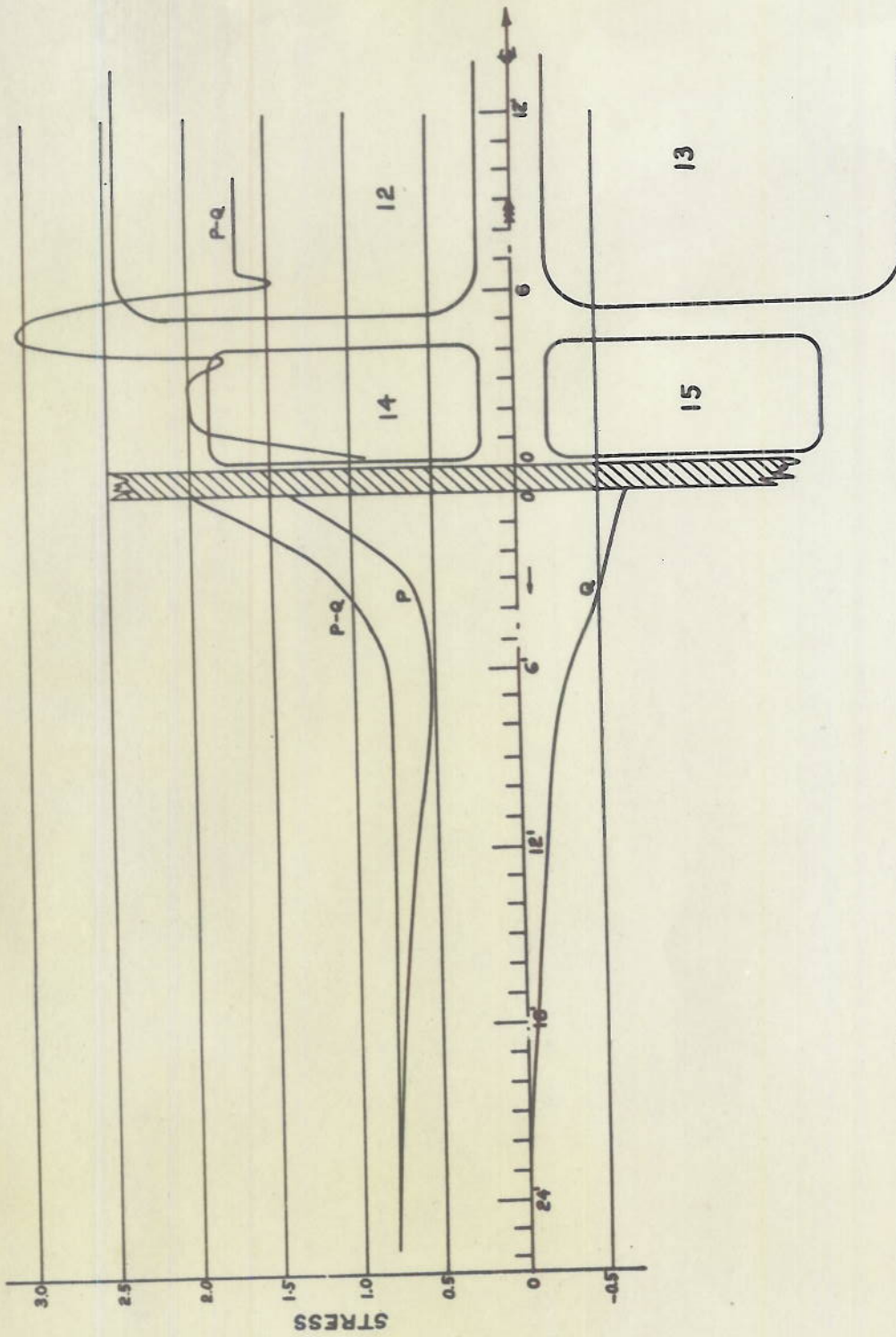


Plate 19B



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UNCLASSIFIED
 DATE 11/10/00
 BY [redacted]
 Plate 20A

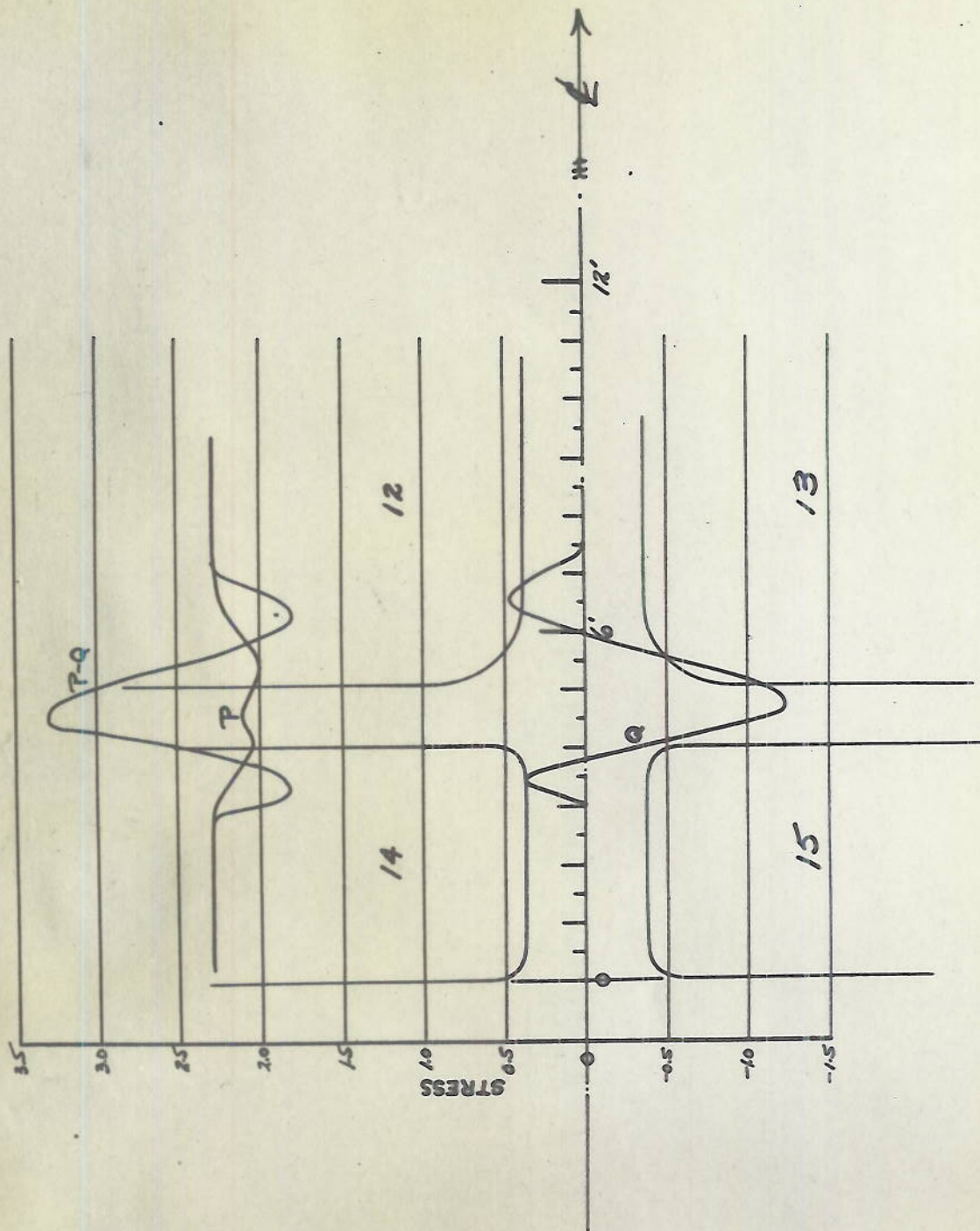


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Unclassified

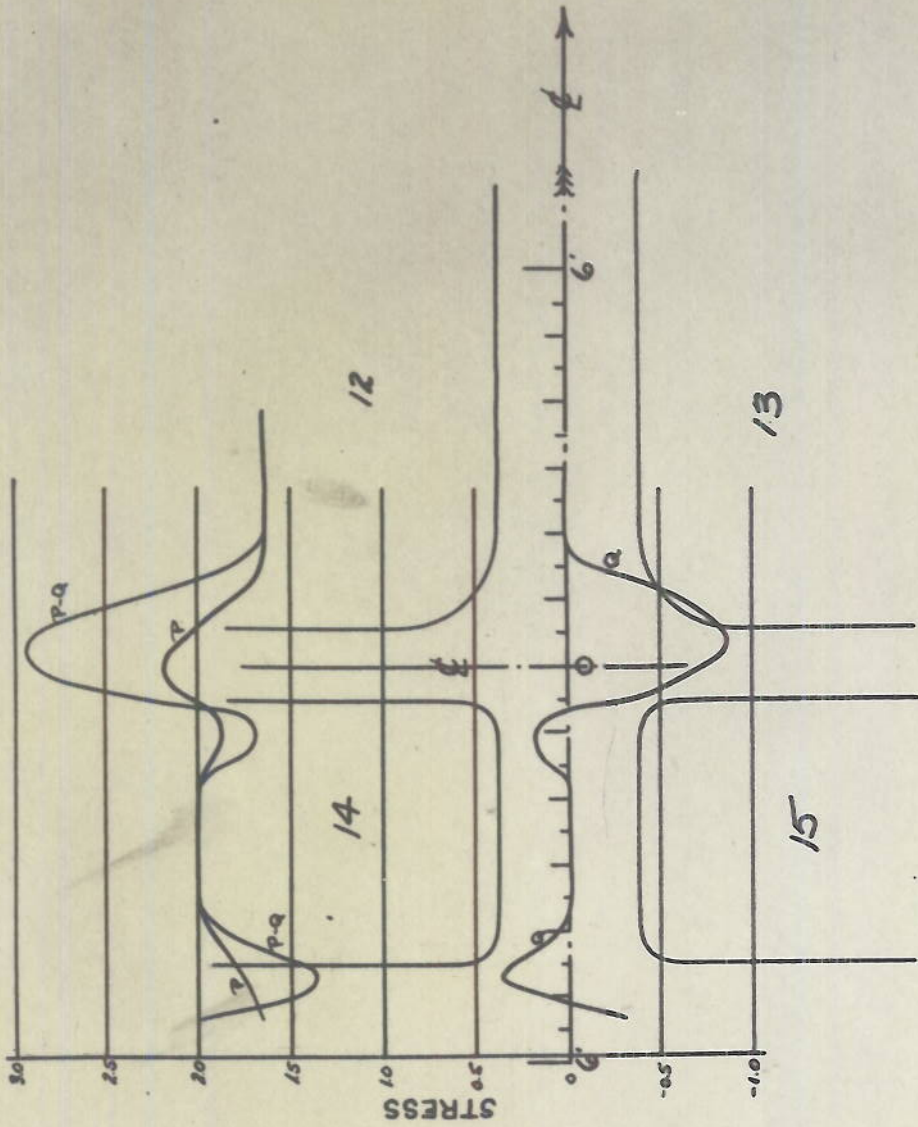
MAR 4 1937



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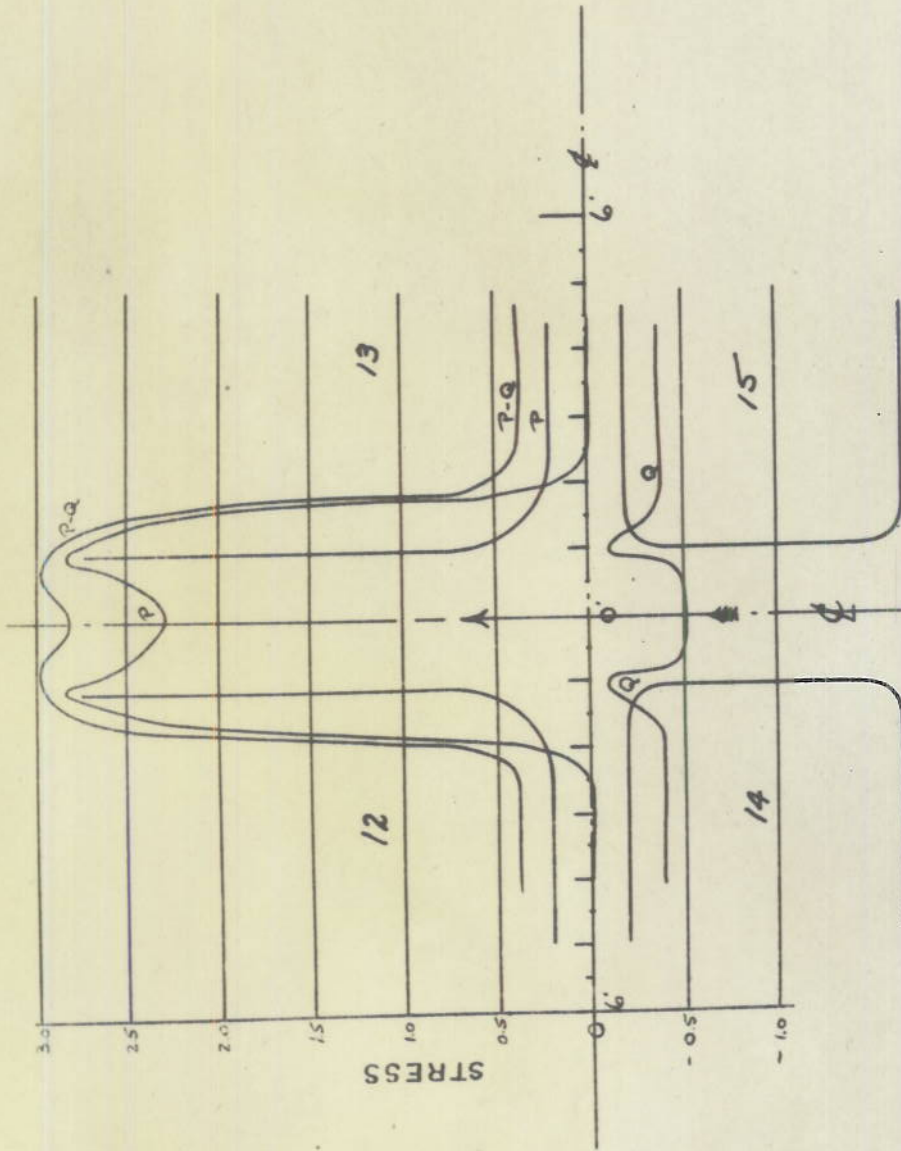
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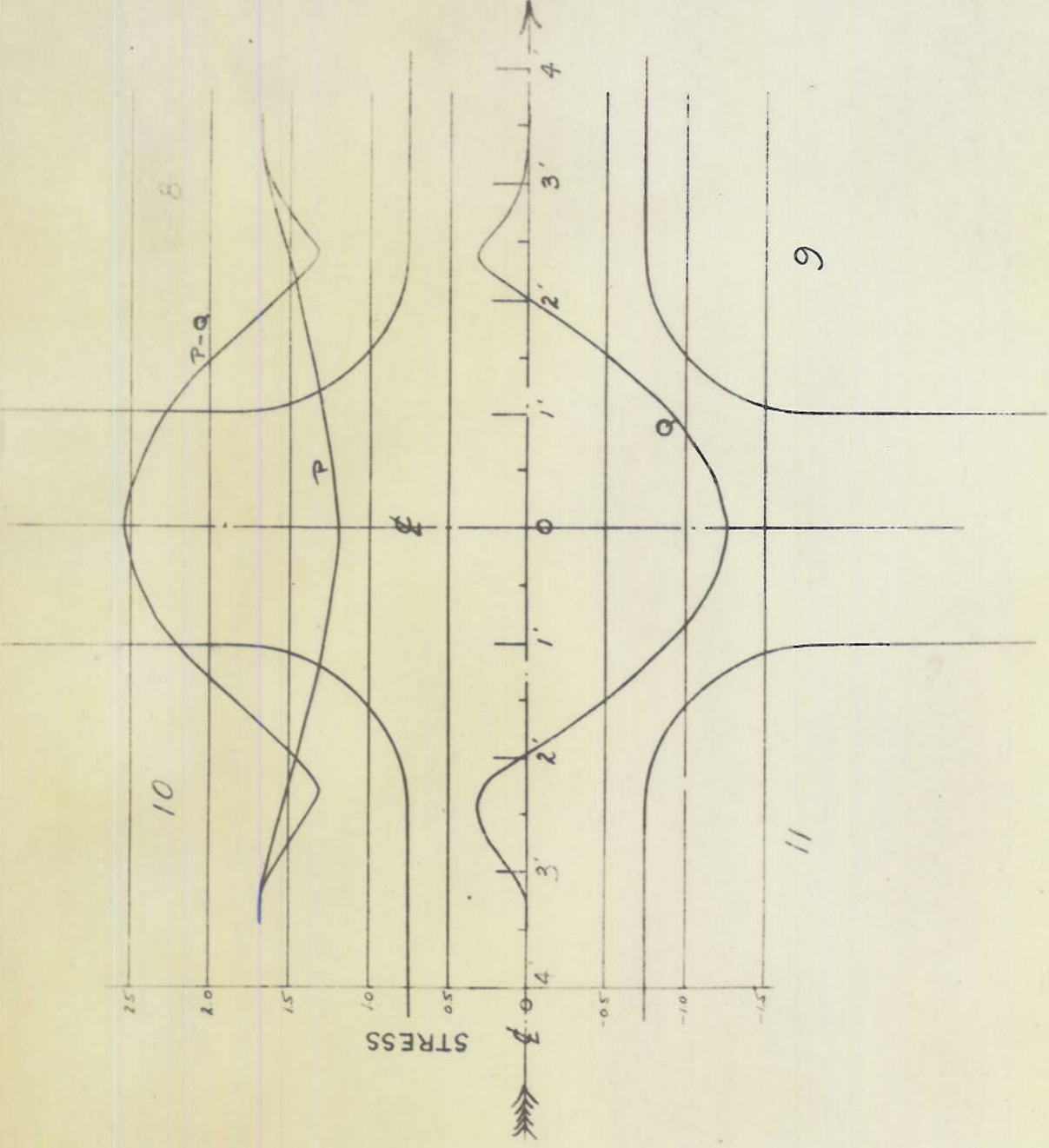
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 Plate 21B



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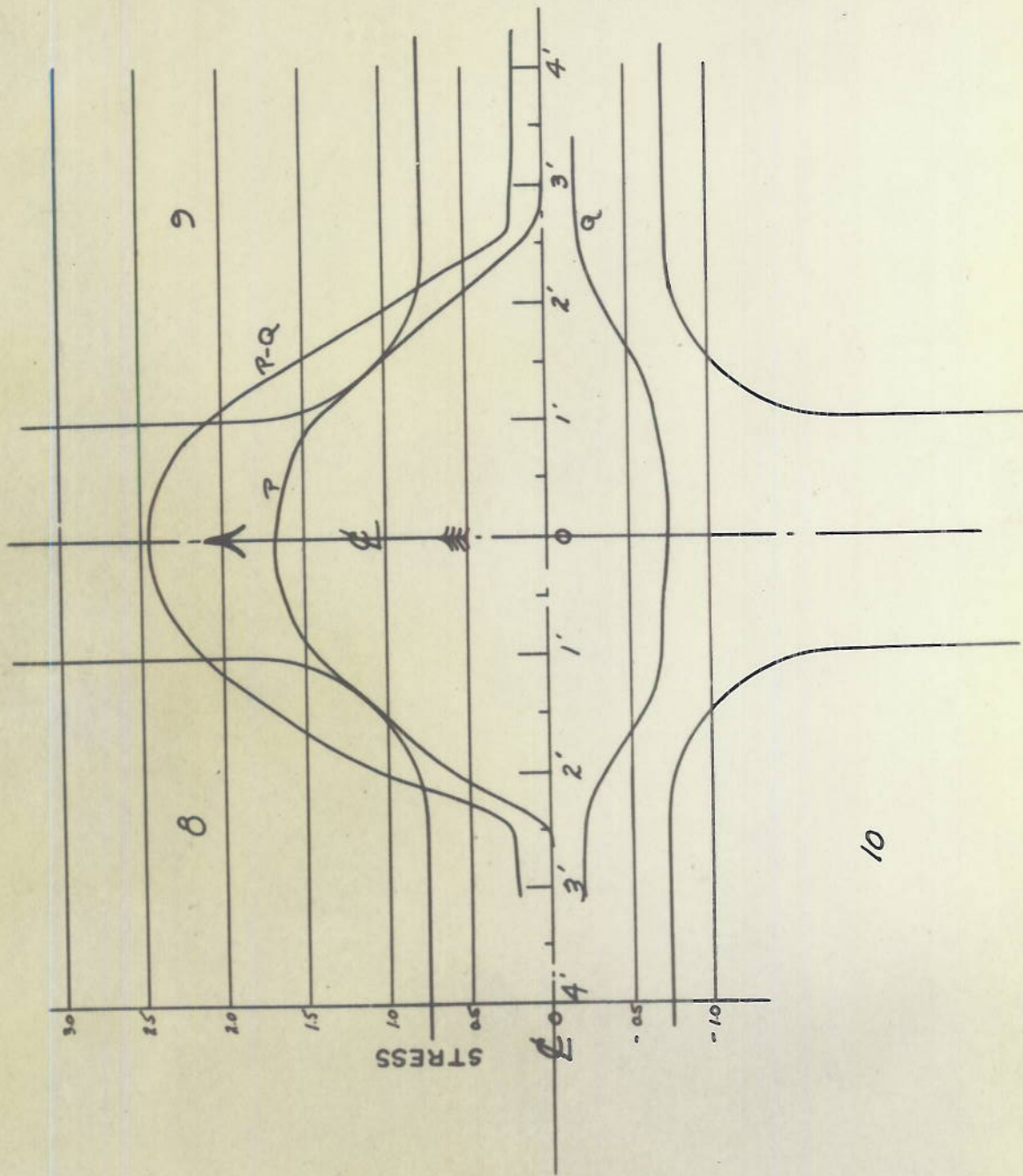


Plate 22B



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Unclassified
 Unclassified

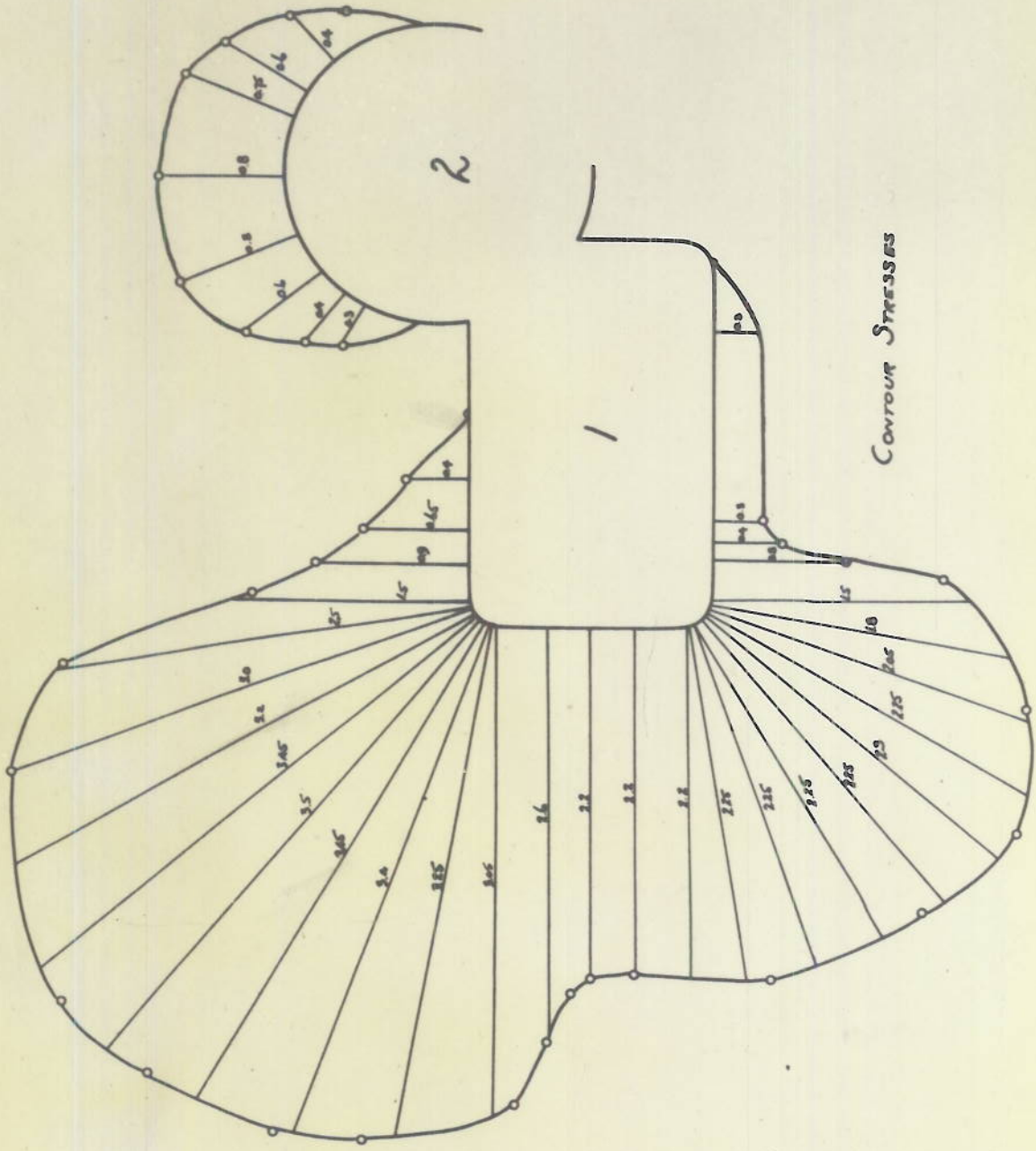


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Unclassified

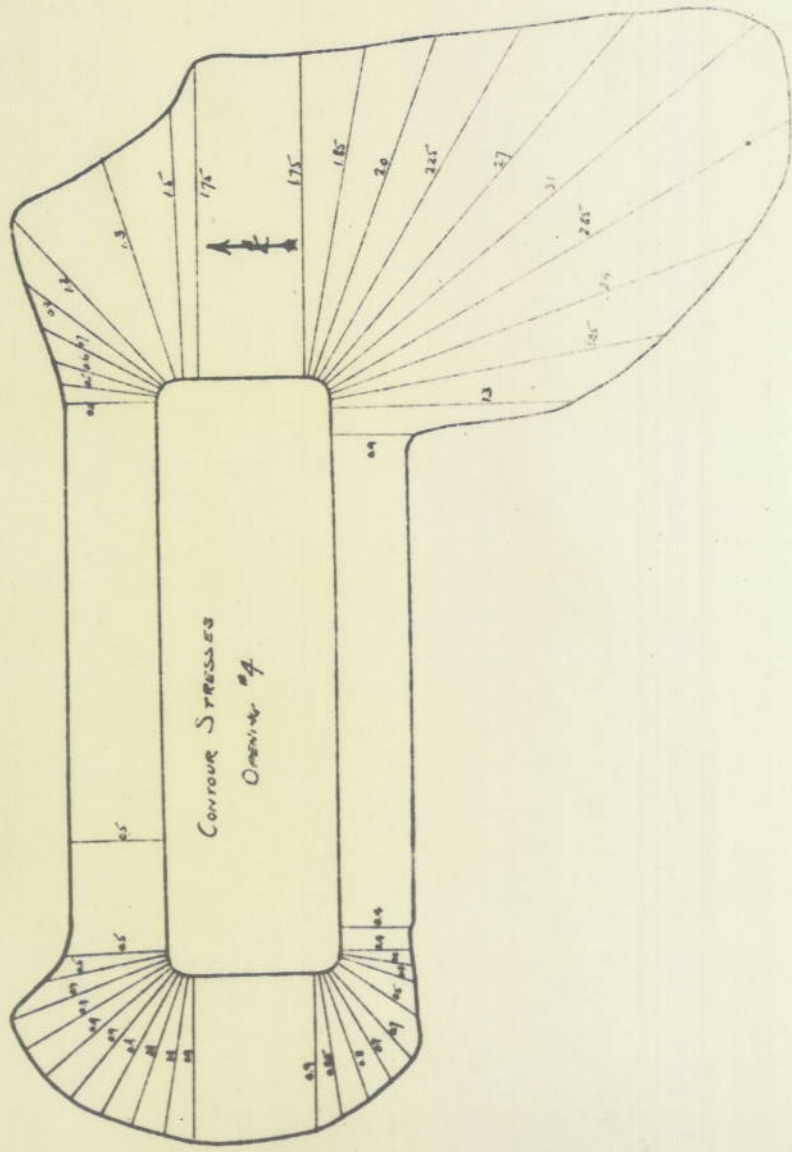
Plate 24B



CONTOUR STRESSES

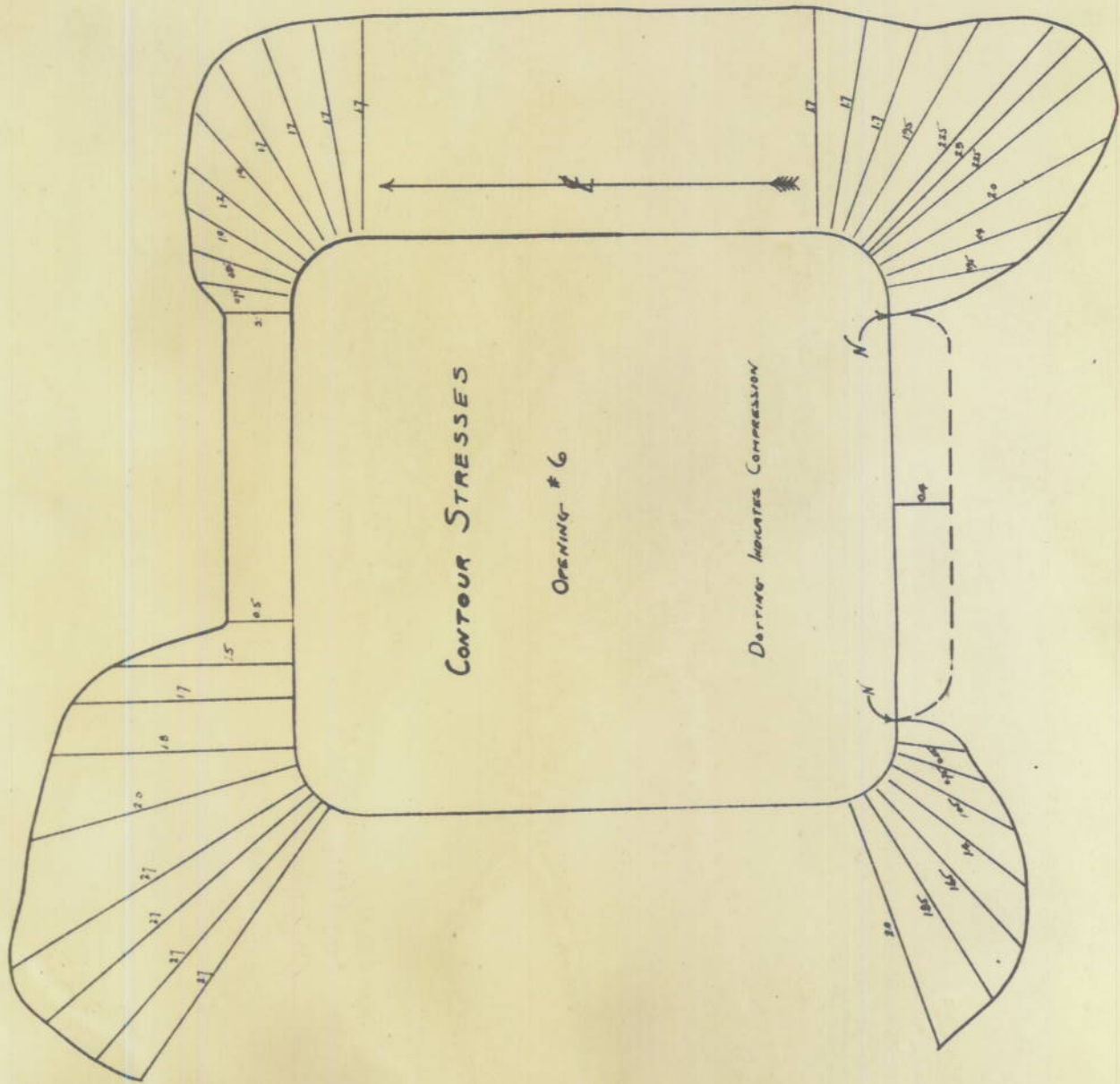
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~~SECRET~~



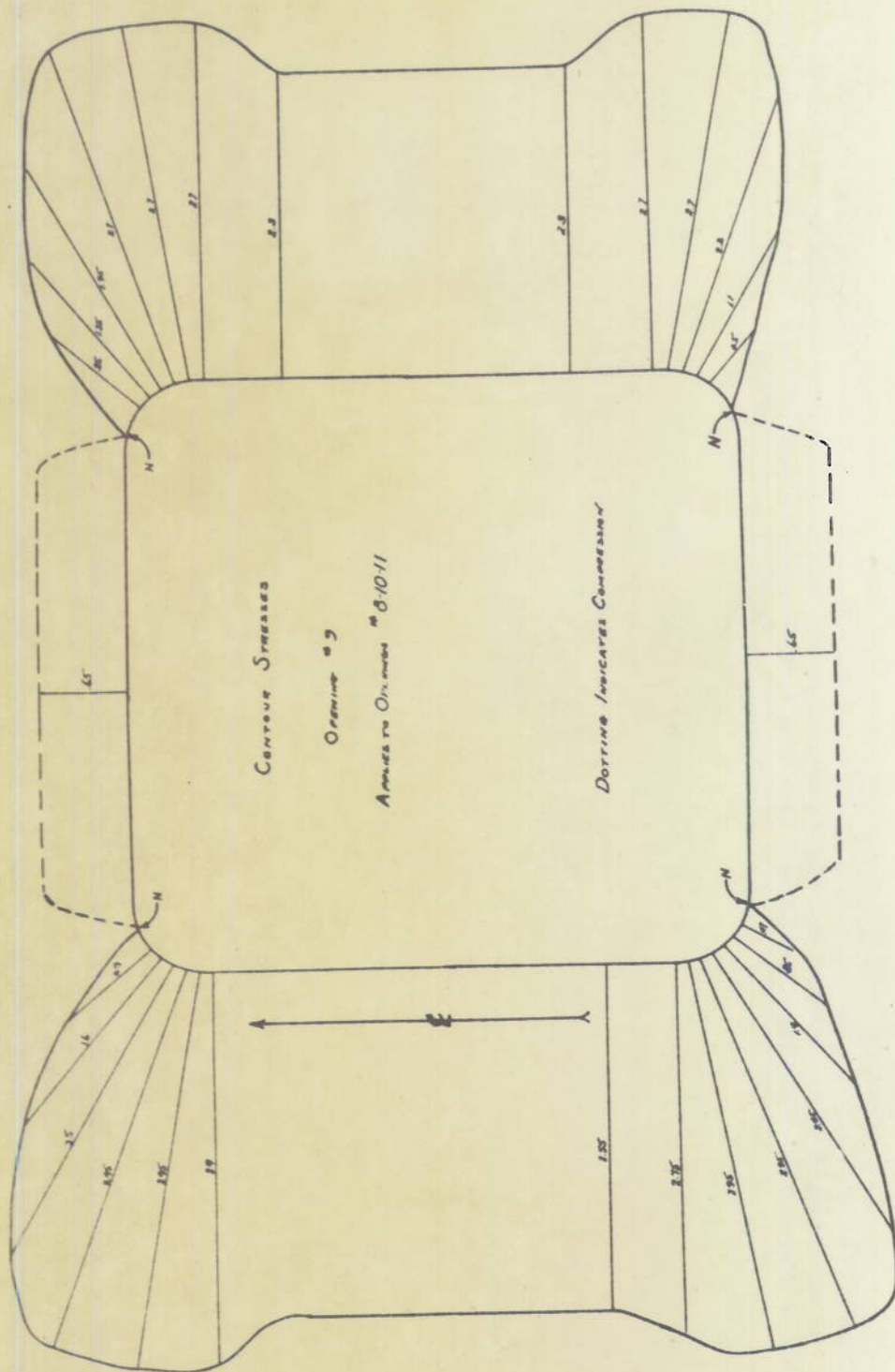
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INCLAS 20
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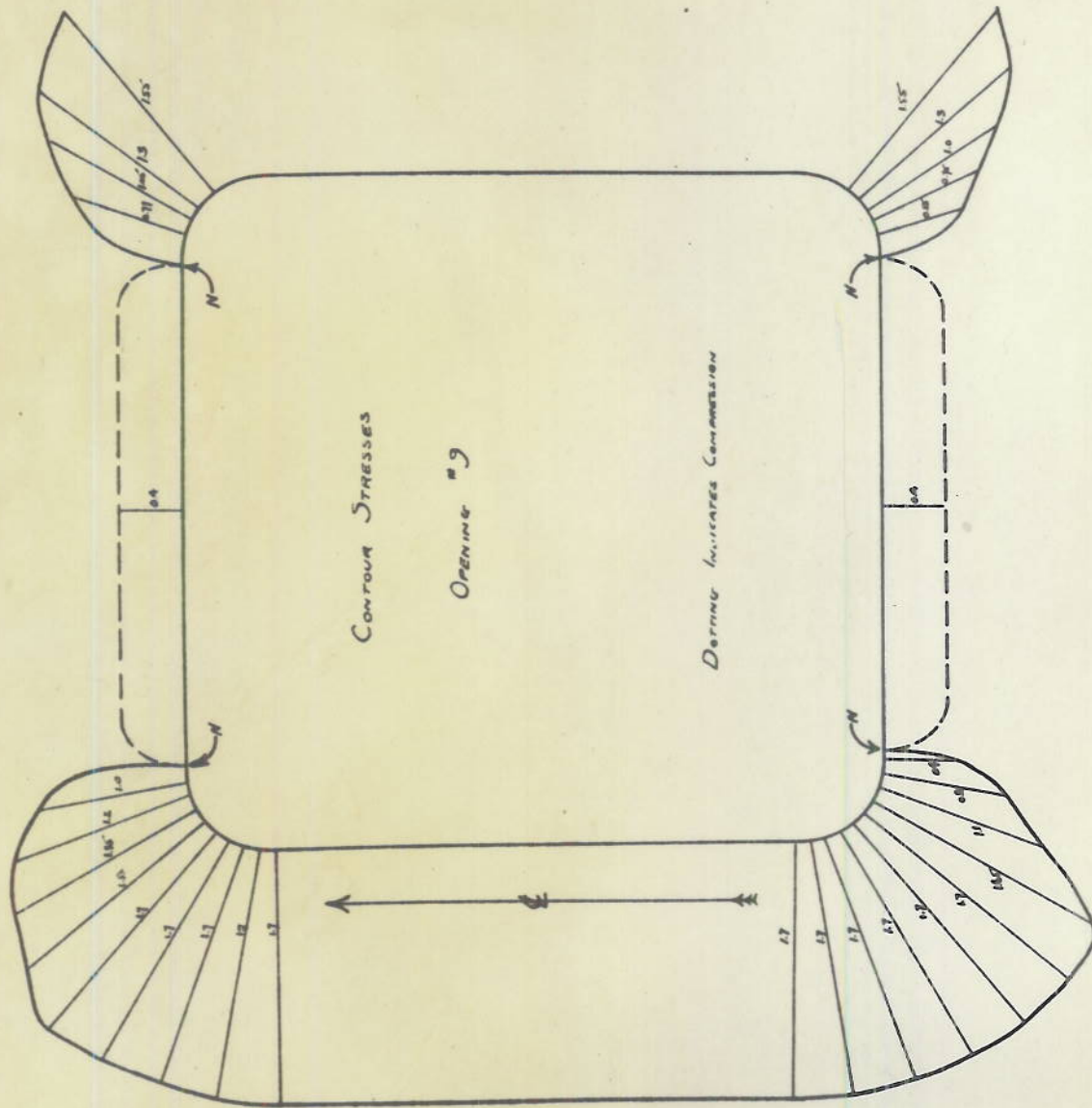
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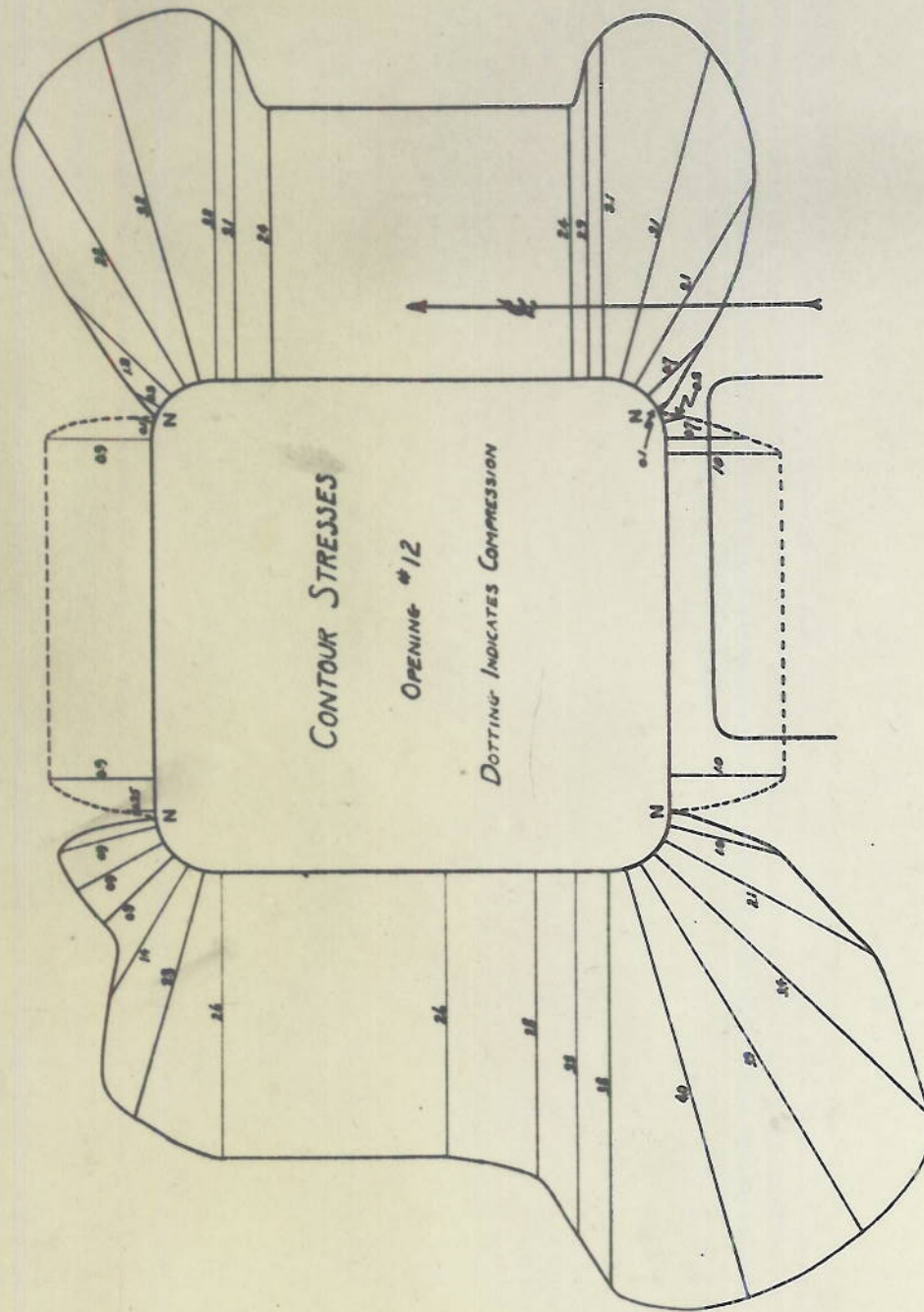
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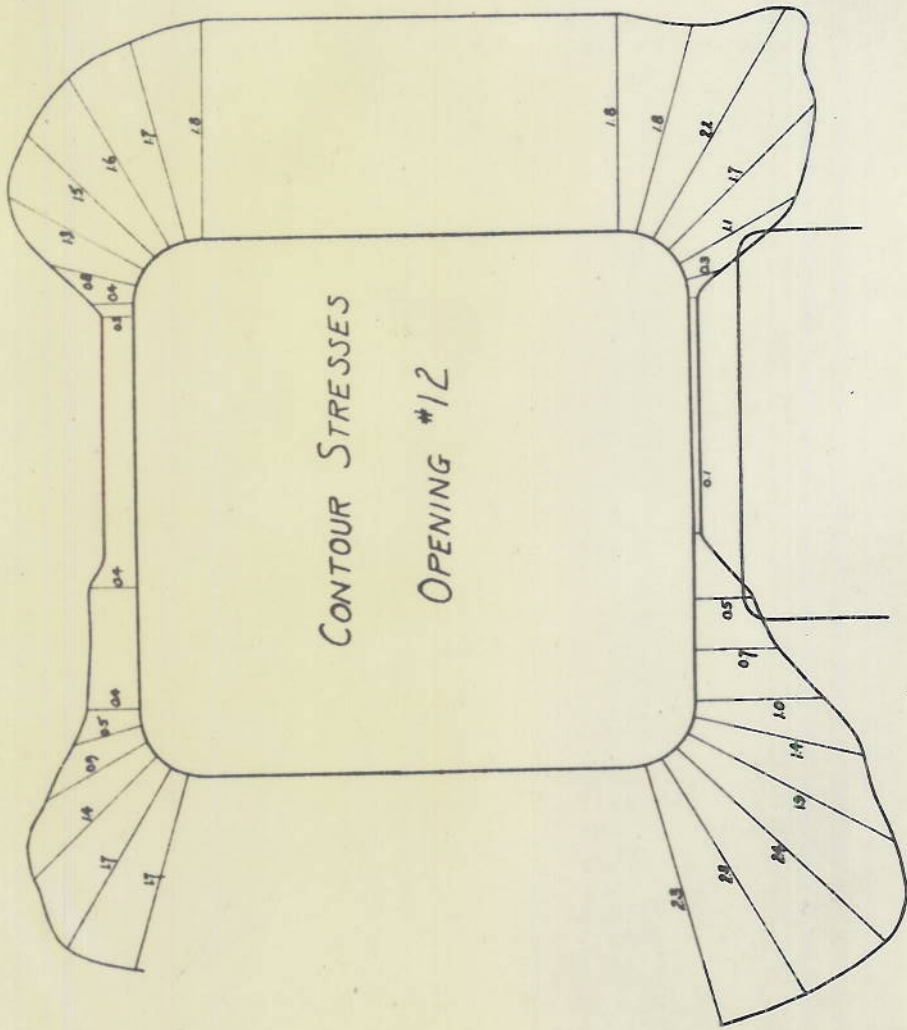
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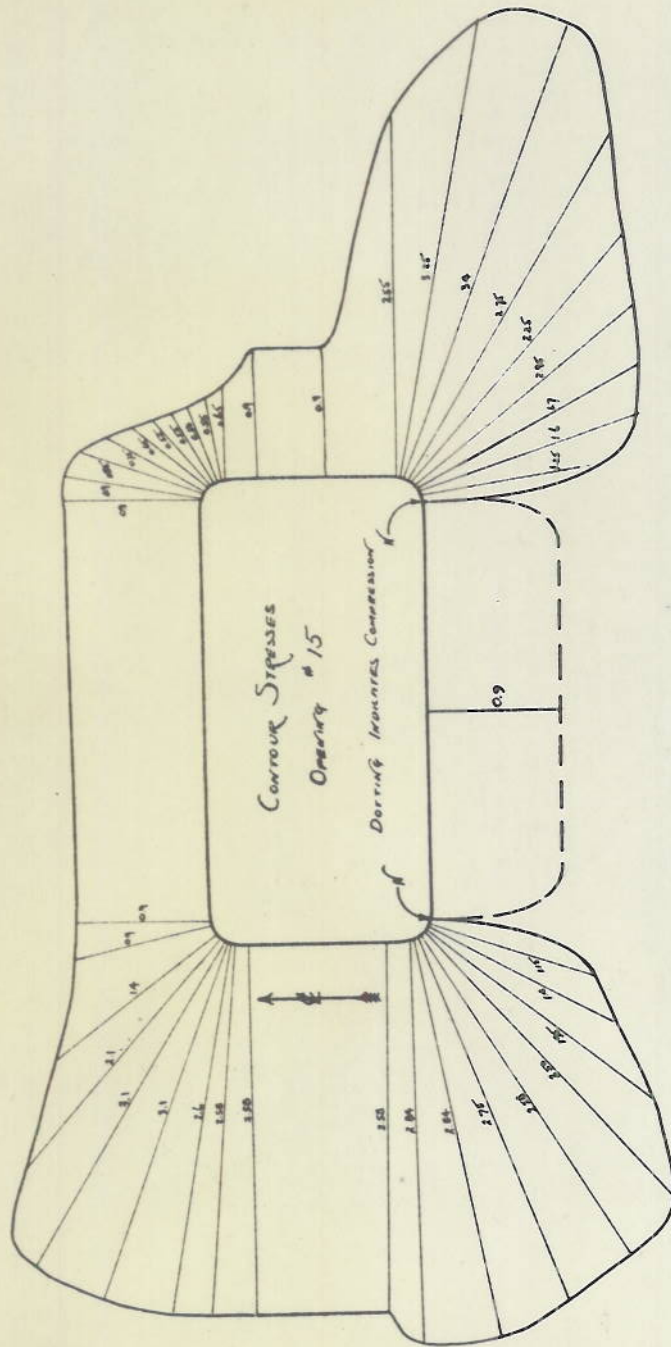
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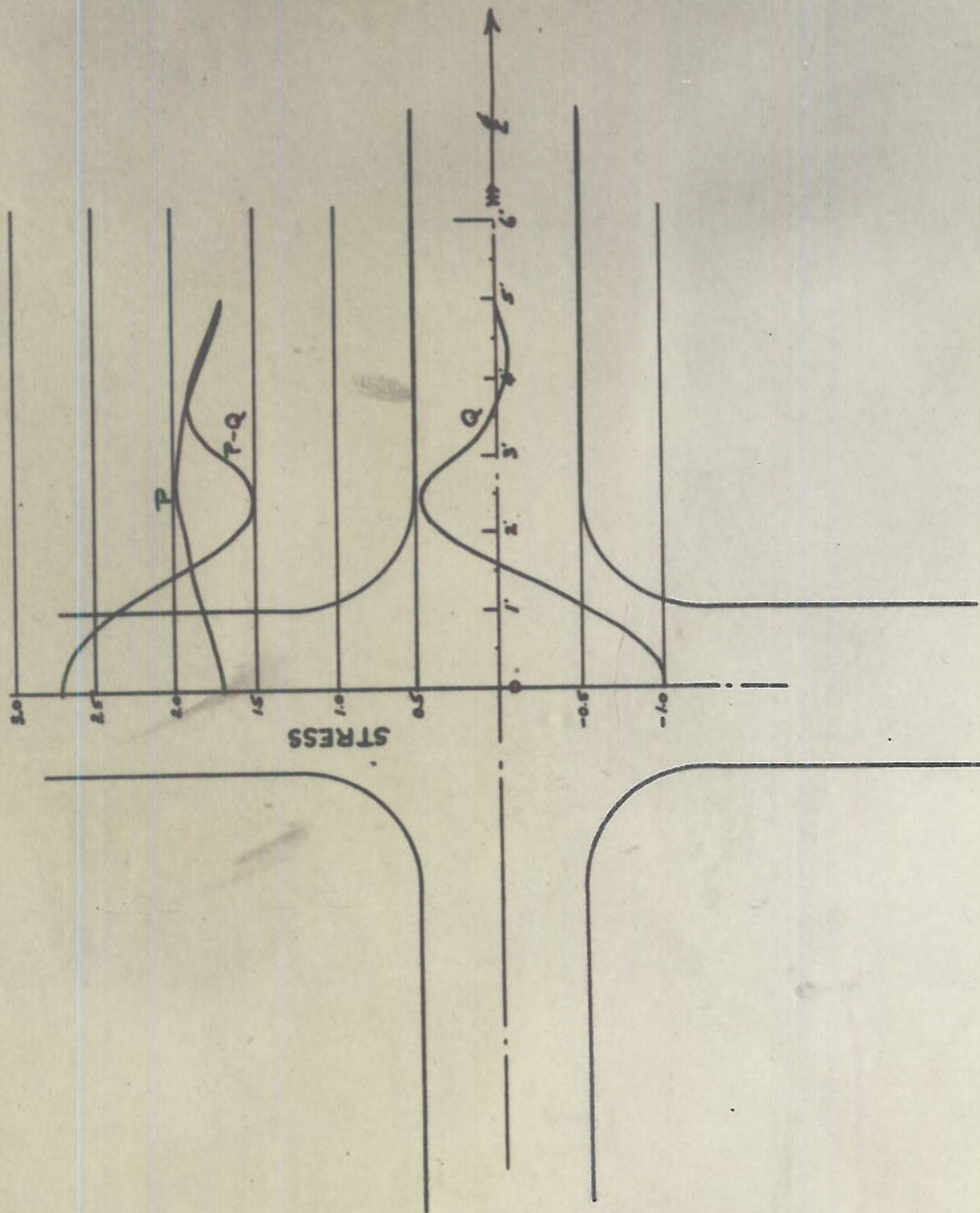
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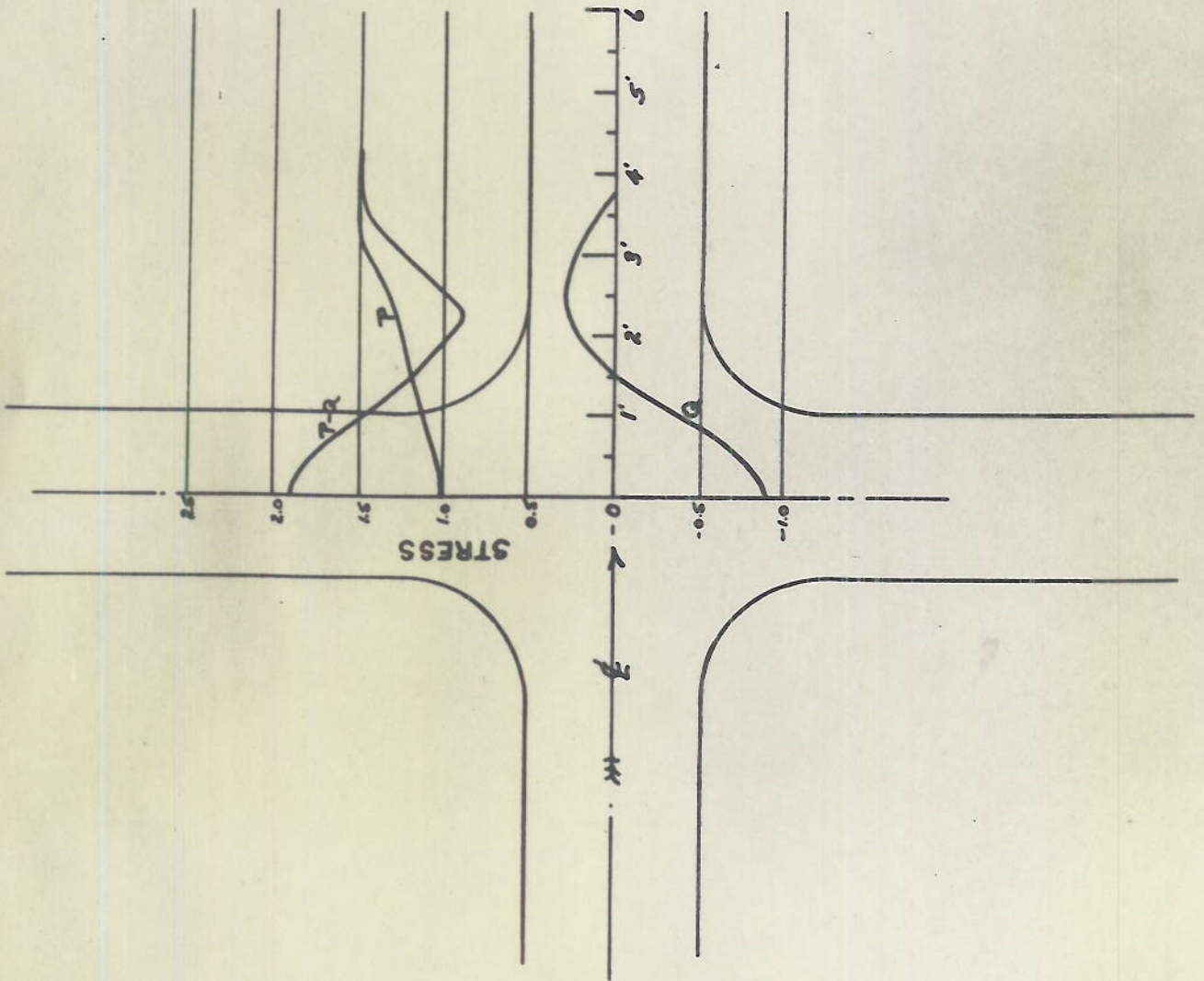


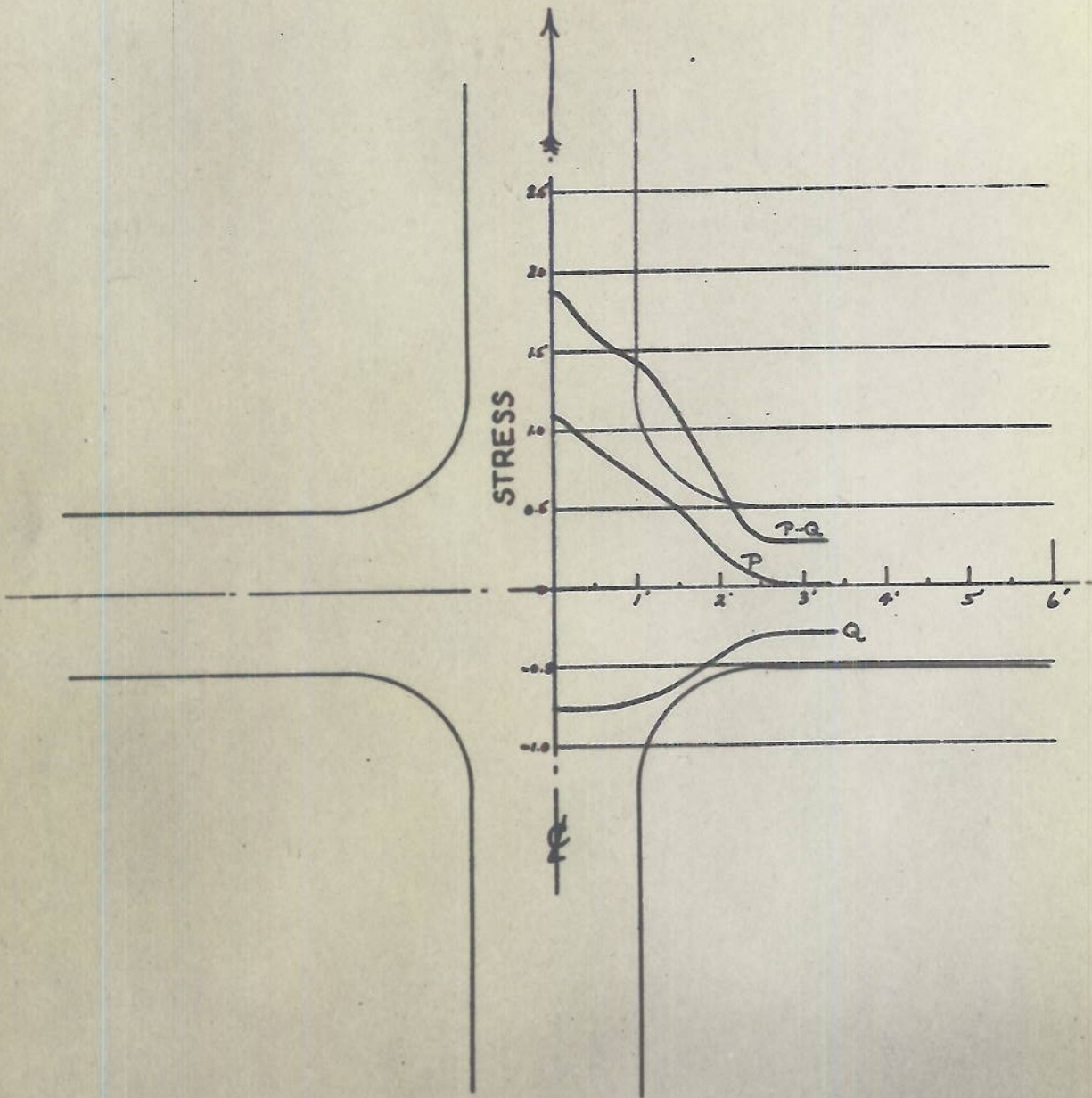
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DECLASSIFIED





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Plate 34S

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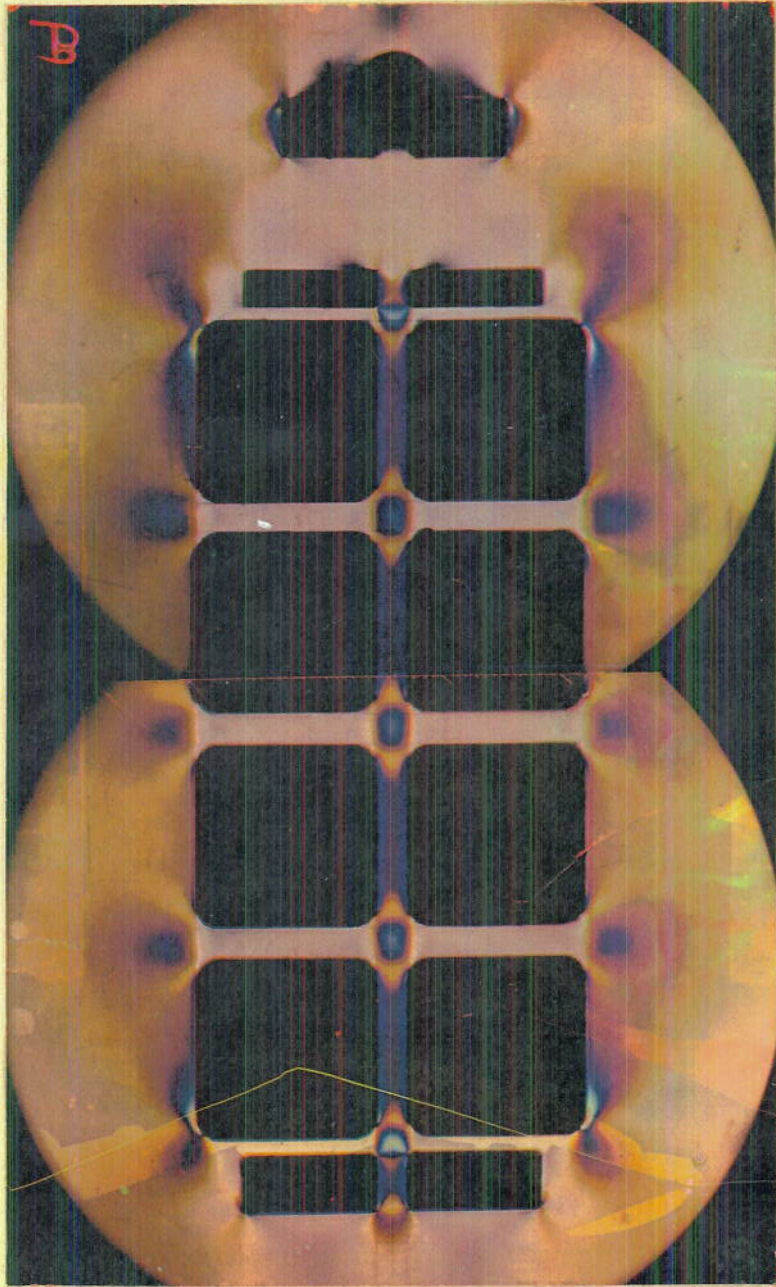
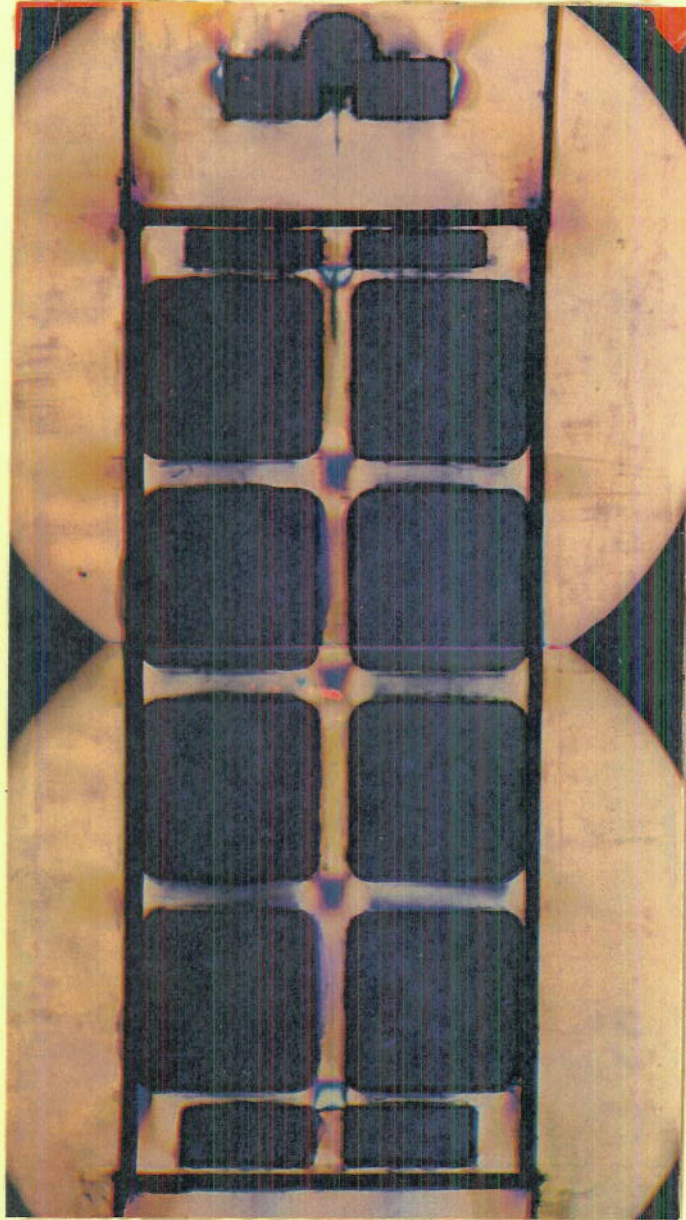


Plate 35 A

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PLATE 35B