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PHOTO-ELASTIC INVESTIGATION OF DESTROYER DECK STRUCTURE

By

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A B S T R A C T

Studies of the stress distribution in the deck of the 1850 ton type destroyer have been carried to partial completion by means of photo-elastic observation on celluloid models of the deck under uniform tension. These studies indicate that the framing has little effect on the distribution of stresses in the deck and that the present type of doubler produces high concentrations of stress in the deck plate at the points at which the load is delivered by the doubler to the deck plate.

A new type of deck fitting in the form of a parabolic arch for use around openings is suggested, its principal feature being that it redistributes the stress over an extended region in the deck, thus preventing concentrations of stress in the deck plate.

Color photographs and black and white drawings are presented to illustrate the various observations which have been made.

I. INTRODUCTION

AUTHORIZATION

1. This study was authorized by Engineering letter NP14(5-6-W8) of 12 July 1935.

SCOPE OF THE PROBLEM

2. The object of the investigation was to determine the distribution of stresses in existing types of deck structure when the ship is in hogging condition. In particular, the effect of the framing and doublers on the stress distribution near deck openings was required. Subsequently, remedial modifications of the deck structure were sought.

II. GENERAL CONCLUSIONS

3. The data obtained have pointed to several important facts which are discussed below.

EFFECT OF FRAMING ON THE STRESS DISTRIBUTION

4. The framing has little effect on the general distribution of stresses in the deck, hence studies carried out on a model without framing apply to a model with framing attached.

EFFECT OF PRESENT TYPE OF DOUBLER ON THE STRESS DISTRIBUTION

5. High concentrations of stress occur in the deck plate near the ends of the type of doubler presented for study and will be introduced by any doubler which presents sharp angles in the change of stiffness of the deck. Plate 12 illustrates the concentration of stress produced by the doubler.

NEW TYPE OF DECK FITTING

6. A parabolic arch type of fitting has been devised which, in the manner of the cables of a suspension bridge, receives the load from an extended region of the deck without producing concentrations of stress greater than 6%.

III. DETAILS OF EXPERIMENTAL METHODS AND RESULTS

TYPES OF MODELS STUDIED

7. Observations of the stress distributions in five types of models were made. These models are identified here for reference purposes.

(a) Model A. Deck without framing or doublers, Plate 10.
(b) Model B. Deck with framing attached, Plate 11.

(c) Model C. Deck with framing and doublers, Plate 6.
(d) Model D. Deck without framing, but with doubler attached, Plate 12.
(e) Model E. Deck with parabolic arch type of fitting, Plates 7, 13 and 14.

STRESS DISTRIBUTION IN MODEL WITHOUT FRAMING OR DOUBLERS (MODEL A)

8. A numerical determination of the stress distribution by the photo-elastic method proceeds in four steps:

(1) The determination of the isoclinic lines or lines of equal slope for the principal stresses, P and Q.

(2) The determination of the isochromatic lines for the different values of P - Q.

(3) The graphical construction of the lines of principal stress from the isoclinic lines.

(4) The evaluation of P and Q along chosen stress lines.

9. All physical observations and measurements leading up to step (4) were made on celluloid models of half the deck, the side of the ship being one longitudinal boundary and the middle line of the deck the other. Careful preliminary investigations showed that no asymmetry in loading occurs when only half the deck is used in place of the full width deck. This was to be expected, since the middle line of the deck is an axis of symmetry, and no distortion of the stress pattern was produced when the deck was cut along this line, the applied load being maintained at a uniform tension across the deck. The economy of material and shop labor justified the procedure.

10. Plate 1 shows the isoclinic lines observed in such a model without framing or doublers attached, the applied load being a uniform tension at the ends. Of particular interest on this figure are the several neutral or null points "N" through which all isoclinics pass. The two principal stresses will be designated by the symbols P and Q, P representing the principal stress along the longitudinal axis of the deck, and Q the stress orthogonal to P at every point. At a neutral point, $P - Q = 0$. It is evident that the neutral points represent the points along the contour of the opening at which the stress in the deck changes from tension to compression.

11. Plate 1 shows clearly the effects of openings 3 and 4 upon the isoclinic patterns due to openings 1 and 2, slightly more marked changes in direction of the principal stresses occurring between openings 1 and 3, 2 and 4, than would be found in the deck if openings 3 and 4 were not present. It is also to be noted that no isoclinics appear between openings 3 and 4 except those which represent directions of principal stress along or perpendicular to the longitudinal axis of the deck. Consequently, no concentration of stress occurs between these openings.

ISOCHROMATIC LINES

12. Values of P - Q, the difference in principal stresses, are determined from the so-called isochromatic lines which are shown in Plate 3. Over

any given isochromatic line P – Q remains constant in value, and all isochromatic lines bearing the same identification number in Plate 3 represent the same value of P – Q. The relative values of the stress difference for the various isochromatics were determined by means of a Babinet-Soleil quartz wedge compensator, individual compensator readings being reproducible to within 2%.

13. It is seen from Plate 3 that the isochromatic numbered 6 represents the difference in principal stresses near the ends of the model and along the sides. In these regions of the model the Q stress is zero, and isochromatic number 6 represents the applied tensile stress. The values of P – Q over the other isochromatics have been taken relative to the value represented by number 6. They are tabulated below and on Plate 3.

TABLE I

Isochromatic	P – Q (Relative)
1	1.40
2	1.35
3	1.23
4	1.14
5	1.07
6	1.00
7	0.79
8	0.75
9	0.67
10	0.59

It is only necessary to multiply each of these numbers by the value of the applied stress in order to determine the actual values of P – Q in the steel deck.

LINES OF PRINCIPAL STRESS

14. Plate 2 shows the lines of principal stress which were constructed graphically from the isoclinic lines. These lines represent the directions of the principal stresses P and Q over the model. They must not be considered as representative of the value of these two stresses, but their changes in direction show that changes in the values of P and Q are taking place. For example, the curvature of the P stress lines near openings represents concentration of P stresses and indicates the development of Q stresses.

INTEGRATION OF STRESSES

15. Knowledge of the values of P – Q and the curvatures of the lines of principal stress permits evaluation of P and Q separately along any chosen stress lines. The results of such a calculation are shown in Plate 4. The summations of P in the several cases are along the lines AA', BB', CC', the unit of distance along these lines in each case being the width of the opening. Values of P – Q, P, and Q are plotted as ordinates.

16. The determination of P values is as follows. First, values of P – Q obtained from Table I and the isochromatic curves are plotted against distance from the edge of the opening. Then, beginning at the edge of the opening, say at the point A where P = 0, the summation proceeds away from the opening by means of the equation

$$dP = - \frac{P - Q}{\rho 2} ds_1$$

ds_1 is measured along the stress line over which the integration is being made, in this case AA'. $\rho 2$ takes the values of the radii of curvature of the Q stress lines at their points of intersection with the path of integration. P – Q is obtained at each point from the previously plotted curve.

Values of Q are readily found from the values of P – Q and P.

SUMMARY OF STRESSES IN MODEL A

17. It is seen from Plate 4 that Q reaches its greatest negative value, representing compression, at the points A, B, and C where its value is 1.25 x the applied stress in tension.

18. The negative value of Q decreases in each case as the distance from the opening is increased, becoming zero at a distance of about half the width of the opening for openings number 2 and 3, and at a distance of about 0.75 for opening number 4. Q then becomes a tension, the maximum value occurring at distances from the opening of about 0.8 for openings 2 and 3 and about 1.25 for opening 4. The maximum value of the tensile stress is 1/4 the applied tensile stress for opening 2, but only about 1/8 the applied tension for openings 3 and 4.

19. The maximum value of P at the point L_2 (Plate 4) is 2.1, and the maximum value of P – Q at the corner M where maximum concentration occurs is 2.7.

20. Differences in P occur between the two sides of openings 3 and 4. These are shown in the following Table:

TABLE II

Point	P
p	1.87
q	1.75
r	2.10
s	1.75

Over the region marked t the value of Q is -0.37.

STRESSES IN OTHER MODELS

21. The foregoing method of investigating the distribution of stresses is the simplest and most expedient of any, no extensometer measurements being required. However, such an integration can only be carried out in a model bearing no framing, since it is not possible to integrate over the boundaries introduced by framing members.

22. That the results of the study are directly applicable to deck plate with framing attached is clearly shown by Plate 5 which represents the isoclinic lines in such a model (Model B). Comparison of Plate 5 with Plate 1 shows no important differences in the patterns of isoclinics. Furthermore, Plates 10 and 11, which represent the color patterns produced in the two models, are not essentially different.

23. Plate 6, showing the isoclinics in a model with both framing and doublers (Model C) is also quite similar to Plate 1.

24. Plate 12 shows the effect of the doublers on the distribution of stresses in a model without framing (Model D). It is seen that high concentrations of stress occur in the deck plate at the ends of the doubler. The doubler is effective in relieving the deck of the load in the region over which it extends, but it creates high concentration of stress at the points where it takes the load from the deck because of the narrow ends.

25. It should also be pointed out that concentrations of stress occur on the unprotected side of opening 2 and near the openings 5 and 6.

26. While in general the distribution of stresses in the model with framing is identical with the distribution in the model without framing, differences in the maximum values of P and Q are quite radically changed, because the areas involved are small as compared with the dimensions of the girders. In Table III, values of Q at the point A (plate 4) and values of P at the point L are shown for the various models.

27. The data for Model A without framing or doublers are repeated in this Table:

TABLE III

	Q (at A)	P (at L)	P - Q (at corners)
Model A	1.25	2.10	2.7
Model B	1.00	1.30	
Model C	1.00	1.70	2.3
Model E	Maximum value of P - Q = 1.06		

It is seen from this Table that in Model B the transverse frames near the ends of opening 2 reduce the maximum value of Q and the longitudinal members of the framing structure reduce the value of P at the boundary of the opening.

28. The effects of the transverse member of the framing on Q and of the longitudinal member on P are real improvements in the strength of the

structure, but they do not indicate a change in the general stress pattern since in each case the region of maximum stress is directly attached to the frame member.

IV. PARABOLIC ARCH TYPE OF DECK FITTING

DESCRIPTION

29. The ideal type of doubler would cause the deck to behave like a uniform plate with no openings. The best approximation to the ideal form is found in the suspension bridge type of structure illustrated in Plates 8 and 14. The parabolic arches at the ends of the doubler receive the load from the deck uniformly and transfer it around the opening through the longitudinal members AB and CD. Re-delivery of the stress to the deck is also uniform. The action of the arches is exactly that of the cables of a suspension bridge, the road bed of which is of constant weight per unit length. The uniform tension in the deck plate at the ends of the doubler corresponds to the road bed of the suspension bridge.

30. The cables in such a bridge hang in parabolic form represented by the equation

$$x^2 = ay, \text{ where "a"} = 2\ T_x/w,$$

T_x being the horizontal component of the tension in the cable and w being the weight per unit length of the road bed. The angle θ which the tangent to the curve at the point P makes with the x axis is determined by Tx/Ty, where Tx is the horizontal component and Ty is the vertical component of the tension at the point P in Plate 8. In adapting this type of structure to the deck fitting illustrated in Plate 8 the determination of the correct eccentricity of the parabola is influenced by the ratio of tensile to compressive strength and by the fact that the deck itself is capable of carrying part of the load. If the arch were required to carry the complete load, tangent θ would be equal to the ratio of tensile strength of the tension member to compressive strength of the compression member AC. When tangent θ is determined the course of the curve is completely specified, the constant "a" being determined from the relationship

$$\tan\theta = dy/dx = 2x/a = \frac{2y}{x}$$

The fitting shown in Plate 8 was designed with tan θ = 2.5 which results in the ratio (depth of arch)/(width of opening) = 0.6. It so happens that this fitting almost completely removes the load from the regions of the deck enclosed by the ends of the arches. This is in part due to the presence of the cross members AC and BD, which have been provided in the model because of the high compressive stress developed along the fore and aft edges of the openings, (see Plate 4). It is possible that the deck plate can take this stress without damage, thus dispensing with the cross members or permitting a decrease in their weight. This is a question the answer to which depends upon knowledge of the relative importance of the tensile and compressive strengths in the ship structure.

31. It should be noted that in the fittings around the oval openings 5 and 6 no compression member has been provided. This omission was based on the assumption that the compressive stress developed at the forward and after edges of these openings could be taken by the deck plating which lies outside the boundary of the fitting. Here, the effect on the deck plating will be that produced by a transverse tension. However, it must always be remembered that compressive stresses are present and must be carried by a compression member unless the deck and framing can carry the load. The cross section of each fitting is equal to the product of one-half the width of the opening and the thickness of the deck plate. The doublers are thus about three times as heavy as the material removed from the opening, which is about equal to the weight of the older type.

32. Since the form of the arch should be as conservative of weight as possible, the following calculation has been made showing the least depth of arch "d" required to support a uniform load across a fixed span. The length of a parabolic arch from the vertex to the point P(x,y)(Plate 8) is given by the expression

$$s = x + 2y^2/3x$$

The tension along the cable at any point is given by

$$R = wx \ (1 + x^2/4y^2)^{1/2}$$

where w is the uniform load supported by the cable. Let x = 1 = half the width of the opening in the deck. Then the total weight of the cable may be represented by

$$W = Kw \ (1 \times 2y^2/3) \ \ (1 + 1/4y^2)^{1/2}$$

where K is a proportionality factor giving the relationship between the tension in the cable and the weight of unit length of cable required to withstand this tension.

For a minimum,

$$dW/dy = 16y^4 + 2y^2 - 3 = 0$$

y = 0.61 is the only one of the four solutions of this equation which has physical significance.

This result means that the ratio

$\frac{\text{depth of arch}}{\text{width of opening}} = 0.3$ satisfies the condition of least weight.

Twice this ratio was used in the model to reduce compressional stresses.

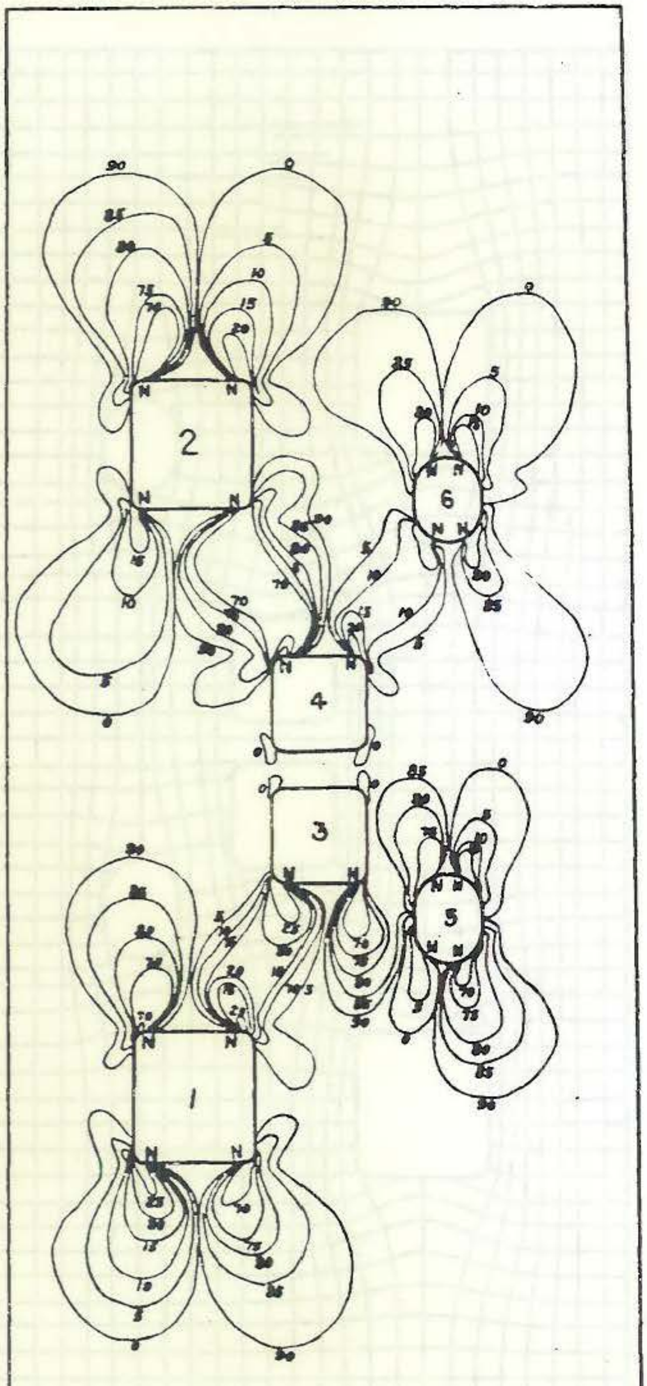
EFFECT ON STRESS DISTRIBUTION

33. The effect which this fitting has on the distribution of stress in the deck is illustrated in Plate 7 which shows the isoclinic lines in a model of the deck without framing, and in Plate 13 which is a color photograph of the stress pattern.

34. Plate 13, in marked contrast to Plates 10, 11, and 12 shows no points of high concentration. It was found that with this type of fitting the maximum concentration of stress is only 6% higher in value than the average applied stress P_o. This represents a remarkable improvement over the other models which is easily seen by comparing the maximum values of P and Q and P - Q for the various models. These data are recorded in Table II.

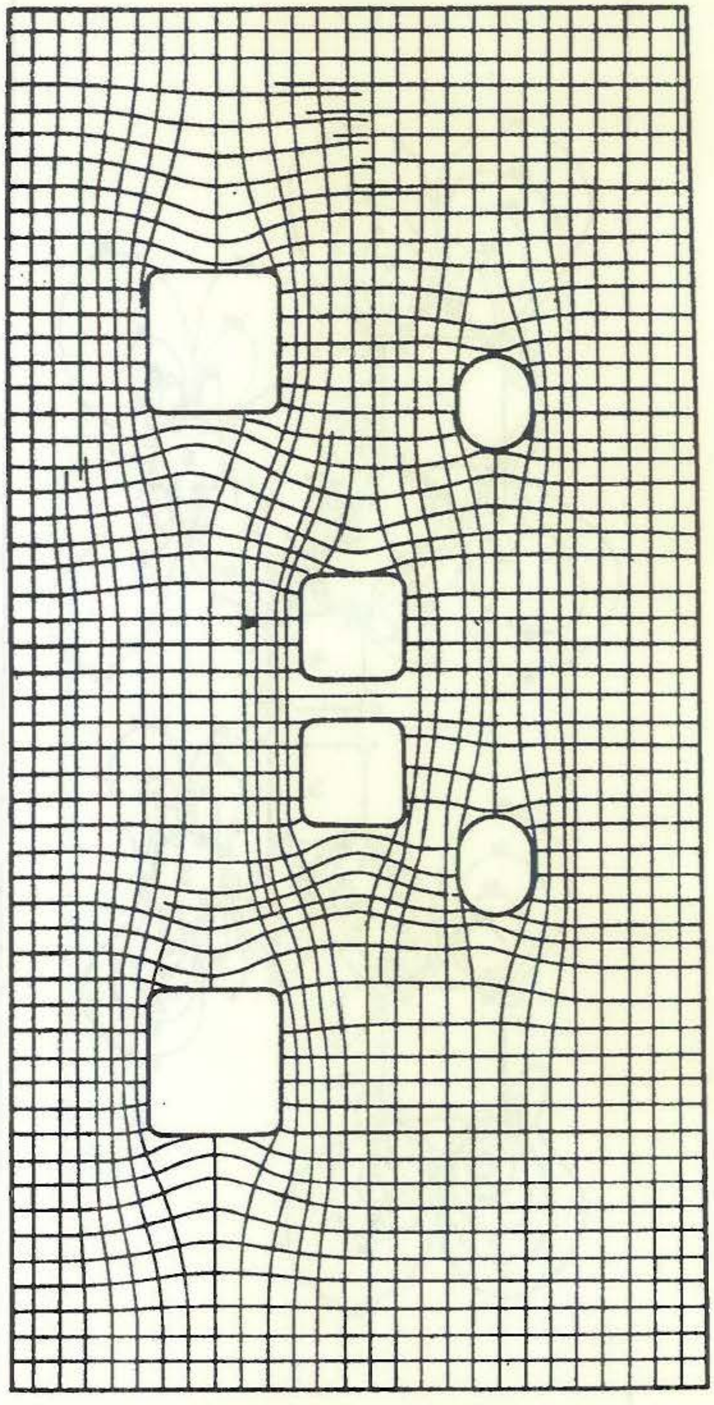
35. It is possible that the design of the doubler could be altered to the form shown in Plate 9 without changing its characteristics to a great degree. Here, the parabolic arches are replaced by straight members which may make any desired angle with the longitudinal axis of the deck, and the vertex of parabola is replaced by one of the transverse members of the framing. Such an arrangement has not been subjected to photoelastic investigation. It is mentioned as a possible modification of greater structural simplicity.

36. It is not expected that a simple "V" shaped end for the doublers would suffice. It seems probable that a concentration of stress would occur at the vertex of the V. For given weight it would not be possible to design a plate doubler as efficient as the beam design of Model E.



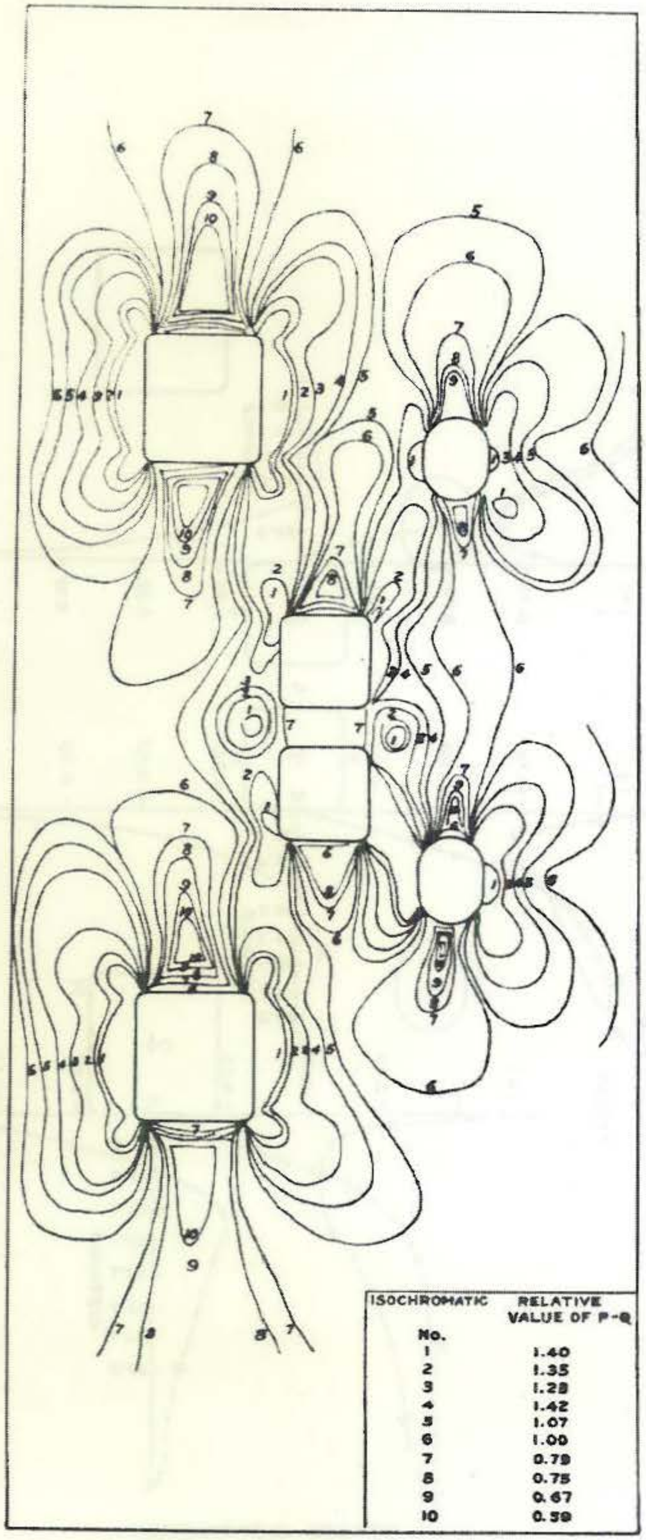
ISOCLINIC LINES IN DECK MODEL
WITHOUT FRAMING OR DOUBLERS

PLATE I



LINES OF PRINCIPAL STRESS IN MODEL
WITHOUT FRAMING OR DOUBLERS

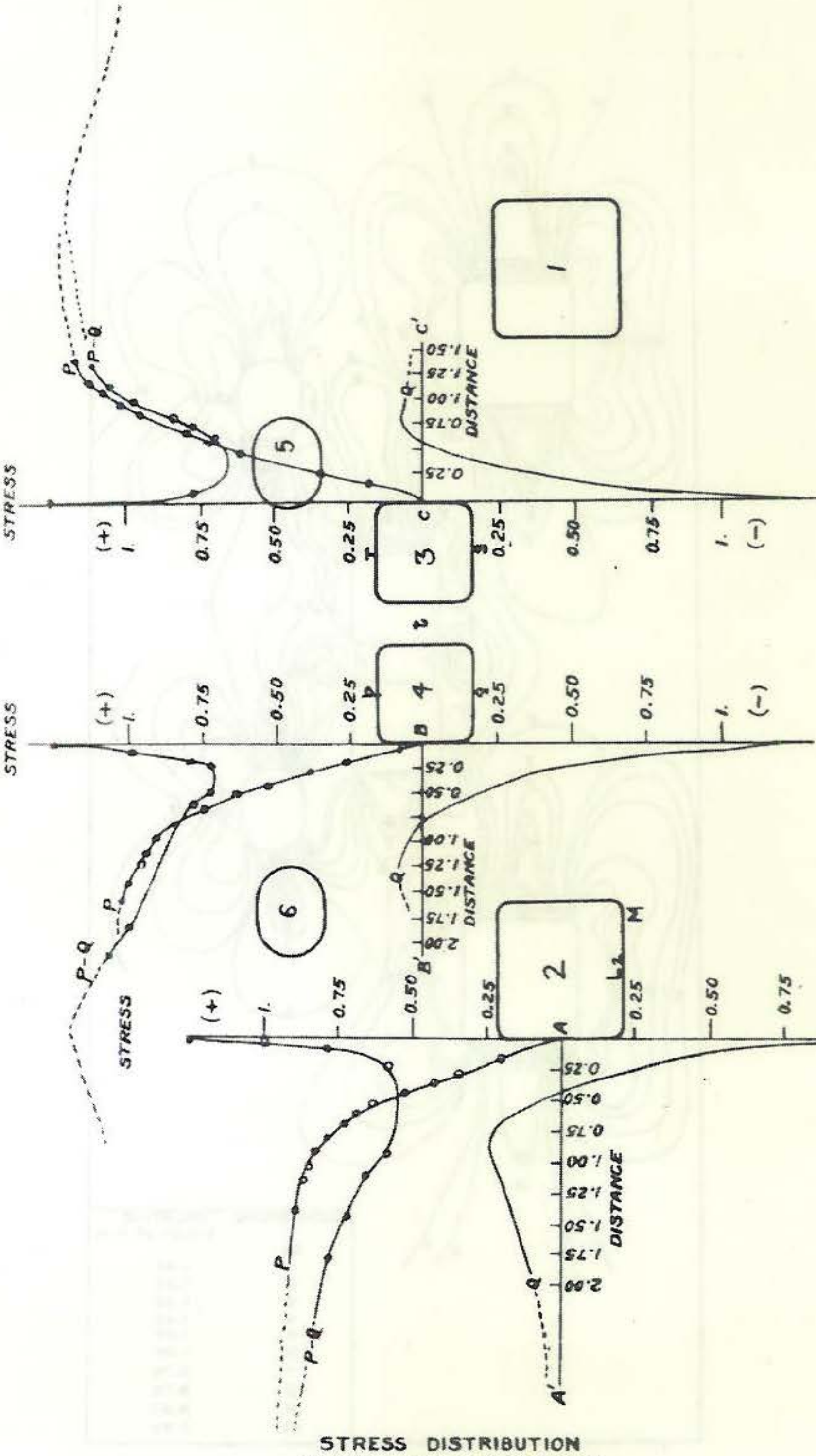
PLATE 2



ISOCHROMATIC No.	RELATIVE VALUE OF P-Q
1	1.40
2	1.35
3	1.28
4	1.42
5	1.07
6	1.00
7	0.79
8	0.75
9	0.67
10	0.58

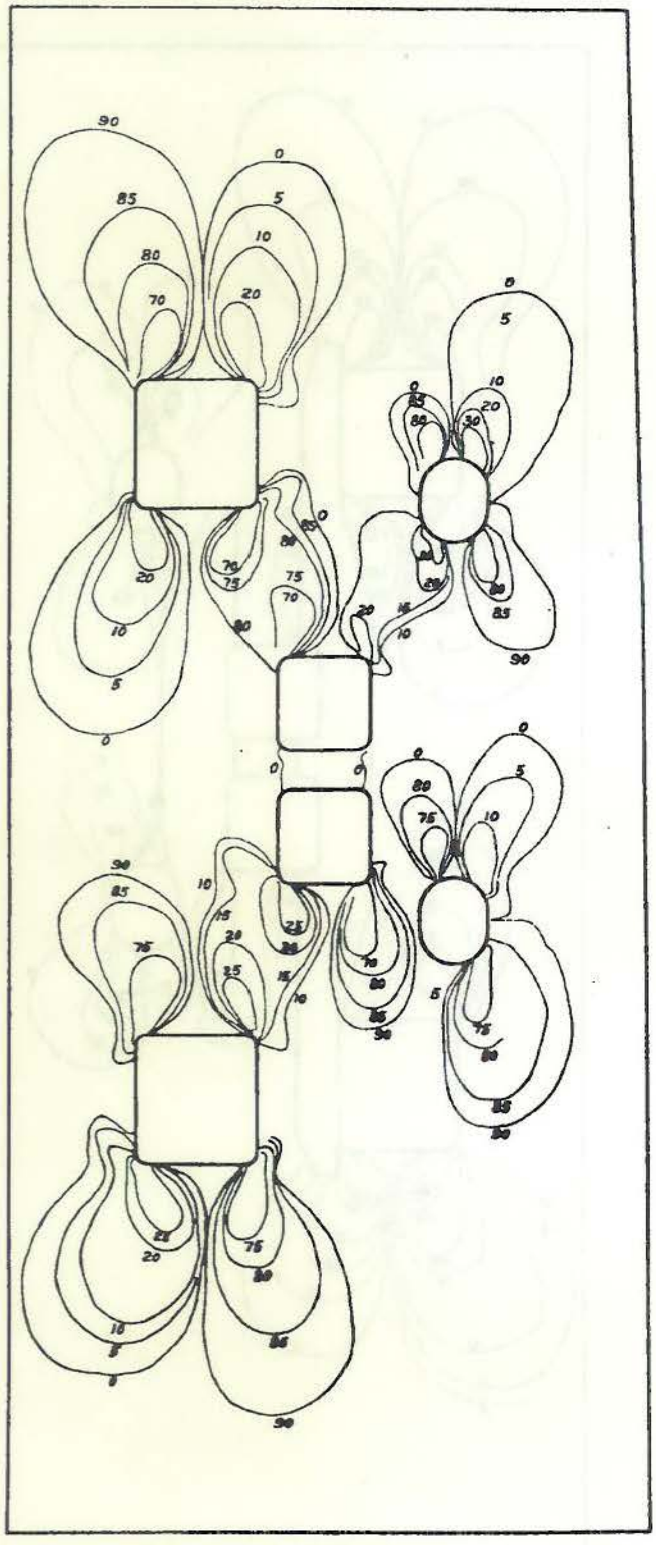
ISOCHROMATIC LINES IN MODEL
WITHOUT FRAMING OR DOUBLERS

PLATE 3



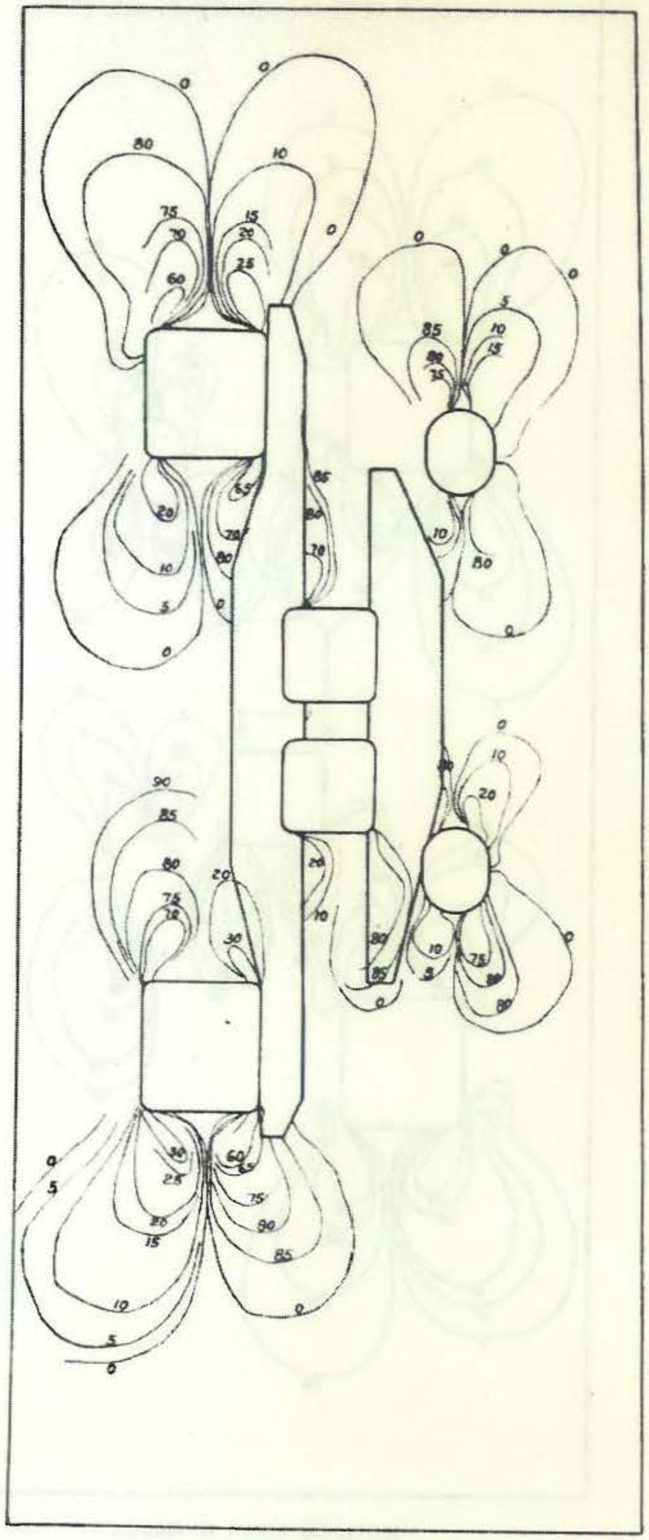
STRESS DISTRIBUTION
ALONG LINES A-A', B-B', C-C'

PLATE 4



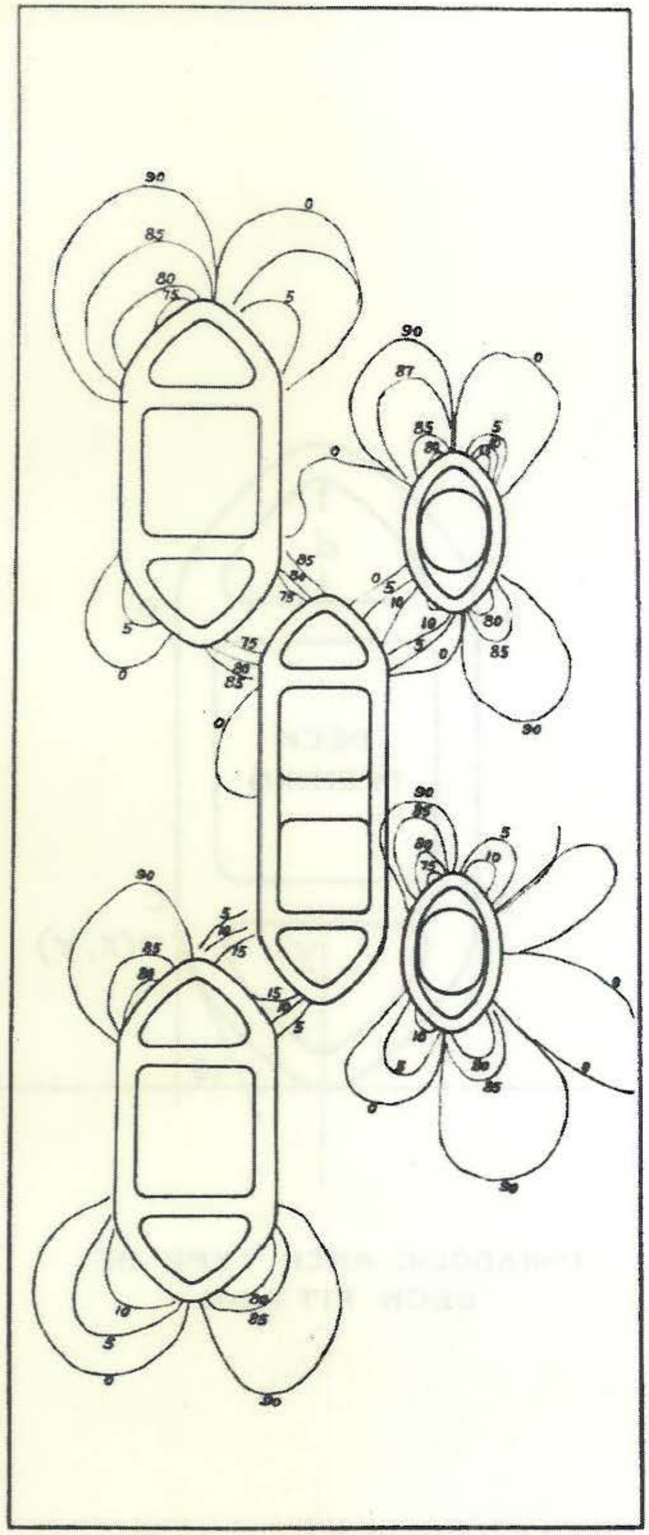
ISOCLINIC LINES IN MODEL
WITH FRAMING ATTACHED

PLATE 5



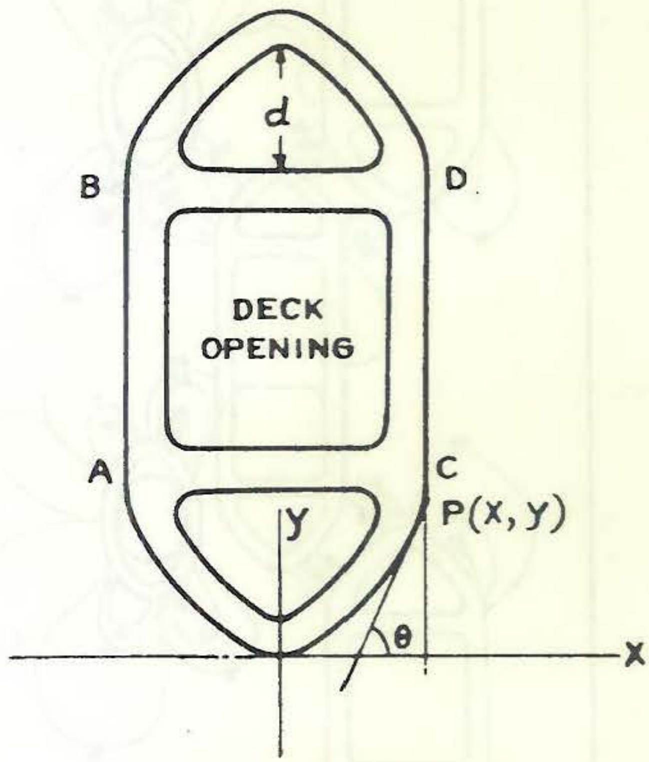
ISOCLINIC LINES IN DECK MODEL
WITH FRAMING AND DOUBLERS ATTACHED

PLATE 6



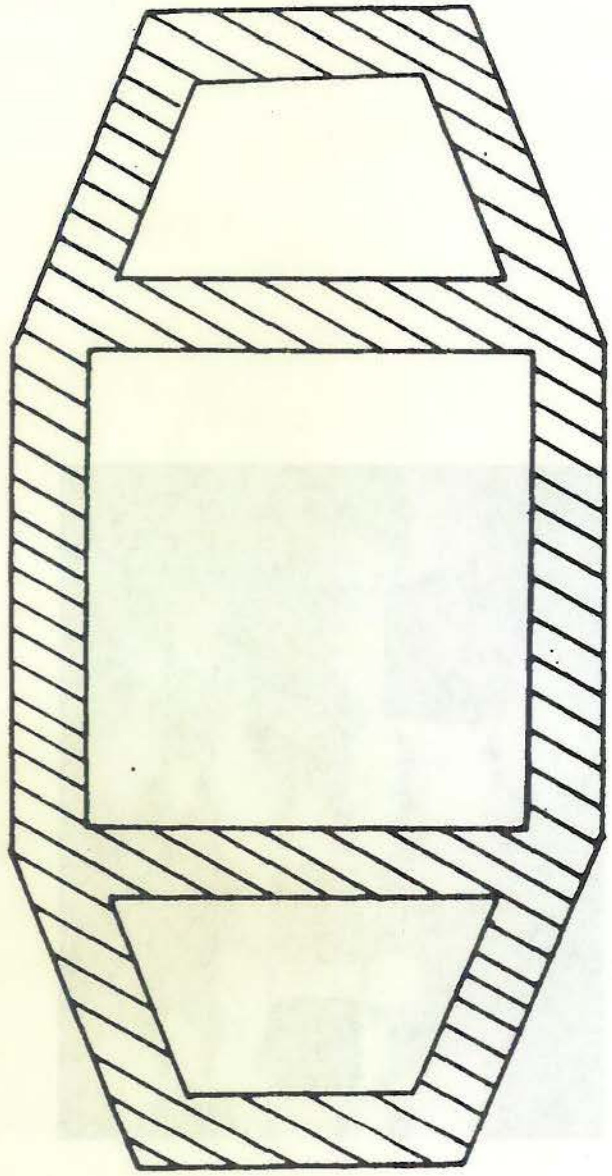
ISOCLINIC LINES IN DECK MODEL
WITH PARABOLIC TYPE FITTINGS

PLATE 7



PARABOLIC ARCH TYPE OF
DECK FITTING

PLATE 8



DECK FITTING
WITH STRAIGHT MEMBERS
SUGGESTED AS PRACTICAL

PLATE 9

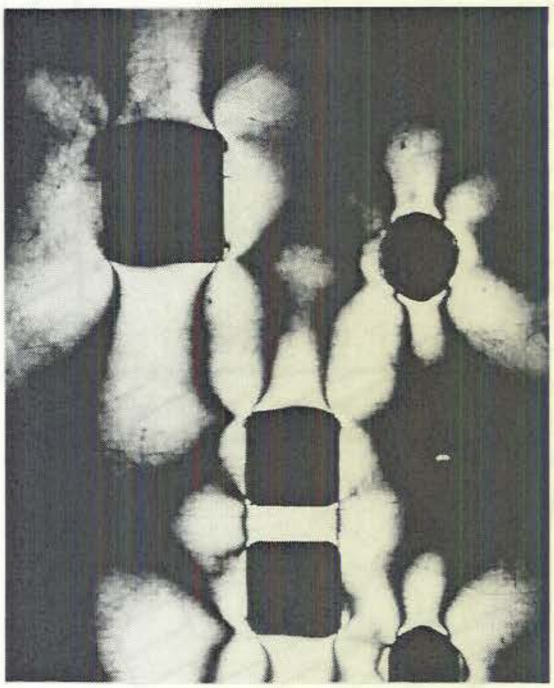


Plate 10

Plate 11

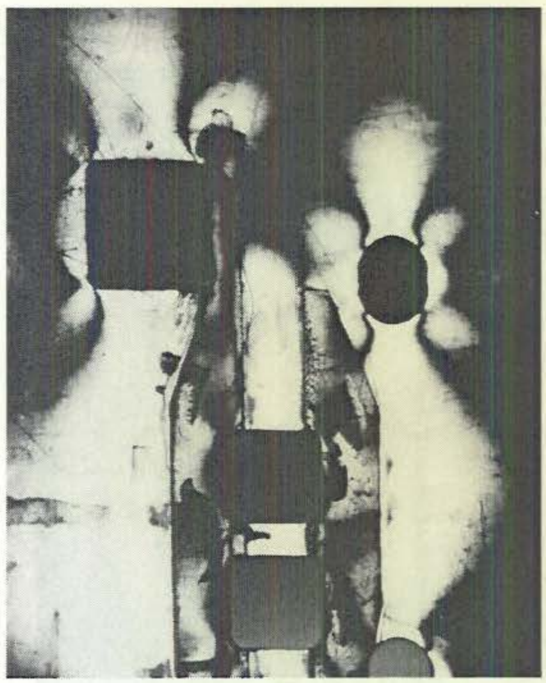


Plate 12

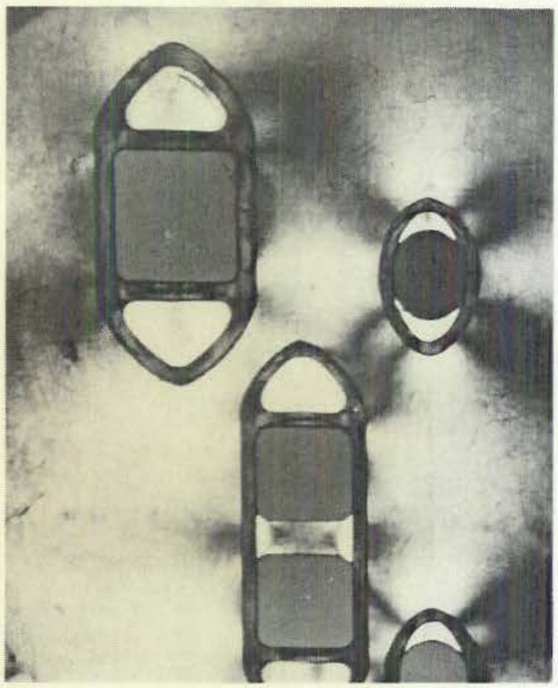


Plate 13

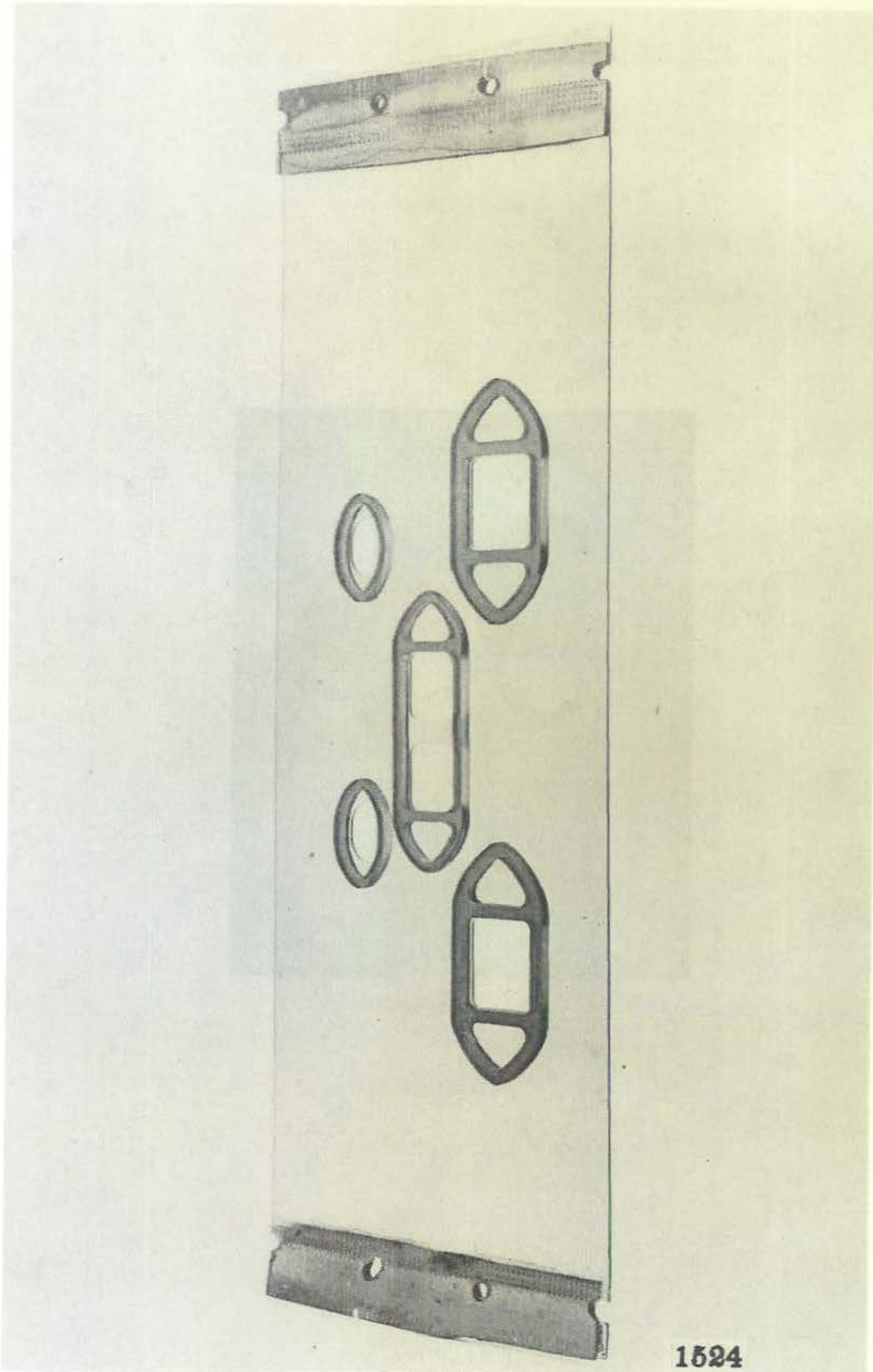


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Plate 14