A METHOD AND STUDY OF THE STRESSES AROUND AN OPENING UNDER CONCENTRATED STATIC LOADS USING STRESSCOAT

by

Garland S. Landrith, Jr.

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Signed: Garland S Landrith Jr
Garland S. Landrith, Jr.

Golden, Colorado
Date 23 May 1951

Approved: Clifton W. Livingston
Clifton W. Livingston

Golden, Colorado
Date 23 May 1951

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INTRODUCTION

The Corps of Engineers, U. S. Army, has been attempting to determine the effect of explosions upon underground openings in order to properly design and construct underground installations which will give protection against blasts of the size produced by the atomic bomb. Furthermore, any information obtained on the effects of explosions upon underground openings would increase the extremely sparse basic data about the manner, actual cause, and sequence of failure of rock. Field tests to determine the effect of explosions on surface openings in rock were conducted by the Colorado School of Mines in 1948. In these tests, blasts were set off at various distances from surface openings in rock, and the effects upon the openings were observed and recorded. The results of these experiments, known as Series I and Series II Experiments, are described in a report prepared by the Colorado School of Mines 1/.

1/ Series I and Series II Experiments, Report of the Colorado School of Mines, Dec. 1, 1948, 153 pp.

Laboratory tests to determine the stresses set up around an opening by impact forces were begun in order to complement the data from the field tests and from strictly theoretical analyses. Equipment and a method for determining stresses around an opening under impact loads were developed by Hesselbacher 2/, although sufficient time was available

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2/ Hesselbacher, George E., Jr., A method for the determination of stresses around an opening under impact loads: Master's Thesis t-656 submitted to the Faculty and Board of Trustees, Colorado School of Mines, Golden, Colo., May 1949, 67 pp.

to him only for preliminary experiments in which this method and equipment were used. However, the preliminary tests indicated that this method could be successfully used to solve problems relating to stresses around underground openings.

To compile specific, controlled laboratory data for comparison with field-test data, experiments are being continued at the Colorado School of Mines. The original purpose of the work reported in this paper was to determine the stresses around openings due to concentrated, unsymmetrical, static and dynamic loads, both separately and jointly. The results from the unsymmetrical and dynamic load tests could be compared with results observed on underground openings in rock from explosions at the surface and at various distances from the openings. The static-load tests would be required in order to correlate the data from the dynamic-load tests. However, it was soon discovered that the impact machine designed by Hesselbacher was inadequate for tests of concentrated static loads. A different method involving the adaptation of a hydraulic testing machine had to be devised for these tests. Thereupon, time limitations forced the curtailment of the project to tests involving concentrated static loads only, the results of which are reported in this paper.

A short discussion of Hesselbacher's work will serve as background for the better understanding of the present experiments. His procedure in general was to take a model cut out of a sheet of plastic material, coat the model with a strain-indicating lacquer (Stresscoat), and test the model in an impact machine which he designed. The plastic material he selected was Homalite CR-39 (formerly Allite CR-39), a clear, hard, thermosetting plastic developed by the Pittsburgh Plate Glass Company and manufactured by the Homalite Corporation of Wilmington, Delaware.

(A more complete description of Homalite is given in the section on Materials and Equipment of this paper, page 6 , and a list of its physical characteristics is given in Appendix I.) Sheets of this material, 1/4-in. thick, were purchased and were sent to a plastics fabricator in Denver to be cut to proper size, 6 x 6 in., and to have the openings cut in them. The openings he selected were of six different shapes, including circular, square, rectangular, and horseshoe shapes. He selected three types of load-contact surfaces, one flat, one semicircular with the circle of short radius, and one semicircular with the circle of long radius. After being cut and milled to the proper specifications, the models were sprayed with a coating of Stresscoat, a brittle lacquer coating for the indication of strains within the elastic range of the material being tested.

After coating, the models were tested in the impact testing machine which Hesselbacher designed and had constructed for this work. This machine operates on the principle of a striking hammer, or tup, attached to a beam which rotates about a fixed pivot to insure accurate registering of the impact upon the models. An adjustable holder for the models formed the base and was designed to use wedges to provide lateral confinement. Lateral confinement is necessary in order to simulate the condition that prevails in a large mass of rock that is subjected to an impact force. Hesselbacher states 3/: "If a unit cube in a large mass of rock is loaded by a compressive force, the great inertia of the rock mass will prevent the horizontal expansion of the cube just as the wedges

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3/ Op. cit., p. 28.

prevent the expansion of the model." Only a snug fit was used; an effort was made not to place the models in initial horizontal compression.

After the impact, the model was inspected for cracks in the coating and the isoentatics, or loci of the end points, of the cracks were lightly scribed with a pointed stylus. Then the process was repeated using an even higher drop until the breaking point of the model was approached. Photographs were taken of the models upon completion of the tests. In some tests, the models were dye-etched with a solution furnished with the Stresscoat equipment which is claimed to make the crack pattern easier to see and photograph.

Static loading tests were conducted by adding a beam extension to which was hung a large hooked rod and plate similar to the counterpoise stem and cup on a platform scales. On this rod were slipped slotted 20-lb weights up to a total of 750 lb. The remainder of the test was conducted like the impact test. Only a few static tests were conducted.

The main result of Hesselbacher's work was to indicate a laboratory method by which the direction of principal stresses around underground openings could be determined. This general method was used as a basis for the present study of concentrated static loads. Adaptations of the equipment and some changes in technique were necessary and will be described in the next section on Experimental Work.

A summary of procedure will be given here. Models of Homalite were cut out and milled in the Mining Laboratory. They were coated with Stresscoat one afternoon and tested the next morning. The models were inserted upside down in the new loading frame and placed under side confinement. The tup which gives concentration of the load was adjusted beneath the model, and the model lowered on to it. Then the loading frame was placed in the hydraulic testing machine for the test. Loading was done in increments of about 200 lb and was carried to approximately 1000 lb, about the maximum load for fully developed crack patterns when the models were properly side confined. The isoentatics of the tension cracks were marked after reaching each increment of load, and the model photographed. Pertinent remarks were recorded along with other essential data of the test. One model was tested to complete failure, and the sequence of failure recorded. Finally a model was tested in a polariscope, and the photoelastic results were compared with the Stresscoat results.

This paper will be divided into four parts: (1) Introduction, (2) Experimental Work, (3) Discussion, and (4) Conclusions.

EXPERIMENTAL WORK

The experimental work will be divided into two sections: (1) Materials and Equipment and (2) Test Procedure.

MATERIALS AND EQUIPMENT

Model Material

Perhaps this section might be best introduced by a comment on certain differences in plastics. Organic plastics may be divided according to their physical nature into two broad classes, which are known in plastic trade circles as thermoplastic materials and thermosetting materials. A truly thermoplastic material hardens upon cooling and softens as the temperature is raised until it reaches a stage where it can be stretched and molded into complex shapes without any appreciable change in the chemical structure; and this hardening and softening cycle can be repeated indefinitely without decomposition or deterioration of the plastic. On the other hand, thermosetting plastics become solids under the influence of temperature. If the temperature is increased sufficiently (usually above 300 F), they decompose without melting and without any substantial softening. Thus thermosetting plastics are often preferred where dimensional stability and heat resistance are important, and reforming requirements are negligible.

Although some thought was given to possible model materials other than Homalite CR-39, it was decided that the difficulties in machining it experienced by Hesselbacher could be overcome, and this material was selected for the tests.

Homalite CR-39 is a clear, almost colorless, thermosetting plastic possessing surfaces comparable in smoothness, lustre, and chemical resistance to polished plate glass. In resistance to abrasion, wear, and weathering, Homalite is intermediate between the better grades of thermoplastics and polished plate glass. It is quite hard and slightly more brittle than a thermoplastic. It does not craze (surface crack) under stress nor by contact with any chemical or solvent, being chemically inert. It has good resistance to plastic flow (continuing deformation under stress) at elevated temperatures. It has little time-edge effect (stresses at boundaries due to aging). As received, it has very little or no initial stresses; and with proper cutting and machining techniques, no stresses will be introduced. Although there has been a recent investigation of the mechanical and stress-optical properties of Homalite 4/, the results were inconclusive. Therefore the data herein reported was that given by the Homalite Corporation 5/. A complete list of the properties of Homalite as obtained from this source appears in Appendix I. Sheets 1/4-in. thick were purchased for the tests.

In addition to Homalite, Alclad, an alloy of aluminum, was selected as an additional material for the testing of models in the higher stress range. Being a much stronger material than Homalite and yet machining fairly easily, it would enable tests to be made using much larger impact

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4/ Coolidge, D. J., Jr., An investigation of the mechanical and stress-optical properties of Columbia Resin, CR-39: Proc. Soc. for Exper. Stress Anal., vol. 6, no. 1, pp. 74 to 82, June 1948.

5/ Homalite CR-39, transparent plastic sheet, The Homalite Corporation, Wilmington, Delaware, Oct. 1949, 10 pp.

forces than Homalite would permit. When preliminary static load tests were made with it, however, no cracks in the Stresscoat appeared even after the application of 10,000 pounds by the hydraulic testing machine. The test was stopped at this point because it was felt that further load might cause the loading frame to fail. If Alclad is used for controlled impact tests in later work and thus concentrated static-load tests are required to correlate the results, a much stronger loading frame must be designed to enable models of Alclad to be tested in the testing machine.

Cutting and Milling Machines

The cutting and milling of the Homalite models were done by a Delta jig saw, a Delta drill press, and an Atlas milling machine, in the Mining Department Laboratory (see Fig. 1, 2, and 3). All machines are small in size and have variable belt speeds. The jig saw is equipped with a set of coarse and fine files of various cross-sections for smoothing edges. In addition to a variable belt speed for the cutting tools, the milling machine has a variable feed that could be operated automatically or manually.

Stresscoat Materials and Application Equipment

The Stresscoat materials and application equipment are contained in the model ST-103 Stresscoat apparatus shown in Fig. 4. The materials include various brittle lacquer coatings for use under different conditions of temperature and humidity, aluminum-pigmented undercoating lacquer, dye-etchant for bringing out all patterns formed during testing, etchant emulsifier, and thinners for the undercoating lacquer and for the brittle coatings. Spraying equipment consists of an air compressor oper-

Fig. 1

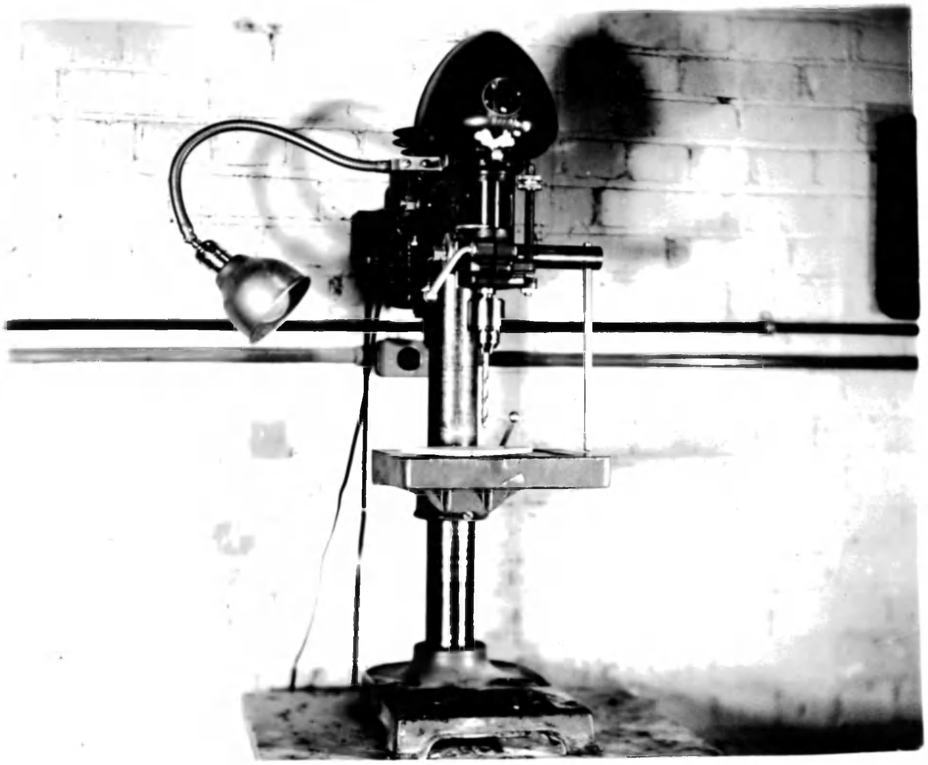

Fig. 2

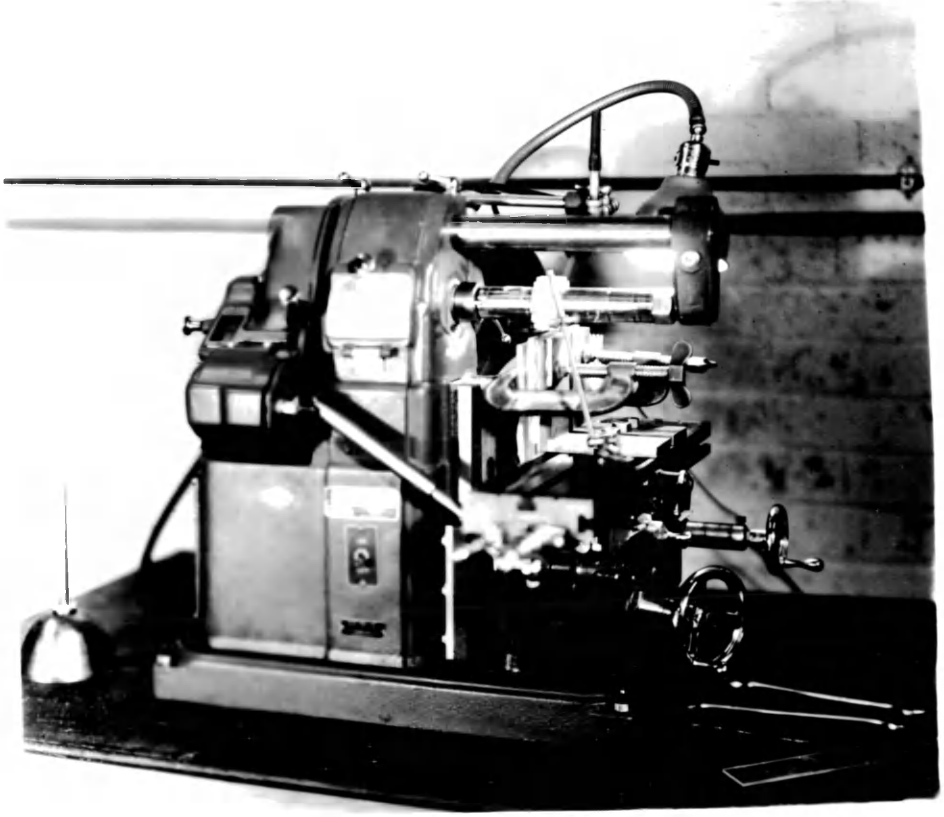

Fig. 3

Fig. 4

ated by a 1/4-hp electric motor, a small spray gun for the application of undercoating, a special spray gun for the application of Stresscoat, and the necessary hose and tools for assembly of the equipment. A sling psychrometer (a type of wet- and dry-bulb thermometer) is furnished in order to determine test conditions, and coating selection charts are given from which is selected the number of the proper coating to be used under the test conditions found by the psychrometer. A creep-correction chart is provided for finding the correction to be applied to quantitative results because of creep of the coating under load. The calibration equipment for quantitative work consists of a calibrator, a strain scale, and several aluminum-alloy calibration strips. A flashlight with a flexible cable extension for the bulb is furnished to inspect crack patterns, and styluses provided to mark positions of cracks in the coating. For a complete description of the use of brittle coatings in the stress analysis, see references 6/, 7/, 8/, and 9/.

6/ de Forest, A. V., Ellis, Greer, and Stern, F. B., Jr., Brittle coatings for quantitative strain measurements: Jour. of Applied Mechanics, vol. 9, no. 4, pp. A-184 to A-188, Dec. 1942.

7/ Ellis, Greer, and Stern, F. B., Jr., Dynamic stress Analysis with brittle coatings: Proc. Soc. for Exper. Stress Anal., vol. 3, no. 1, pp. 102 to 111, June 1945.

8/ Ellis, Greer, Stress determination by brittle coatings: Mechanical Eng., vol. 69, no. 7, pp. 567 to 571, July 1947.

9/ Hetenyi, M., and Young, W. E., Application of the brittle lacquer method in the stress analysis of machine parts: Proc. Soc. for Exper. Stress Anal., vol. 1, no. 2, pp. 116 to 129, Dec. 1943.

Loading Equipment

As mentioned in the Introduction, the impact loading machine designed by Hesselbacher was tried first for concentrated static loading of models. The machine and the method of loading are shown in Fig. 5 and 6. For a more complete description of the machine, see Hesselbacher's work 10/.

After the model was adjusted in position, the beam was lowered until the tup rested in its receptacle. In lieu of using the beam extension and rod for suspending slotted weights, flat weights were placed on the steel beam directly above the model and bolted to prevent their falling off. The difficulties in using this machine for concentrated static loading were fourfold. First, the wedges used to obtain side confinement were difficult to adjust so that the tup exactly fitted its receptable in the model. Thus, either cracks appeared in the coating when the beam and tup were lowered into place or else slightly eccentric loading resulted in nonuniform crack patterns after loads were applied. Secondly, the placing of weights on the beam, however carefully done, caused small impact loads to form erroneous crack patterns, the combined result of the static load and the small impact load. Even the use of a hydraulic jack at the end of the beam to hold it steady while loading did not correct this difficulty. Thirdly, play in the beam pivot and slight eccentricities in loading caused similar erroneous crack patterns and so eliminated consistent results. Fourthly, use of all available weights (1200 lb) caused only a small crack pattern to form. Furthermore,

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10/ *Op. cit.*, pp. 22 to 33.

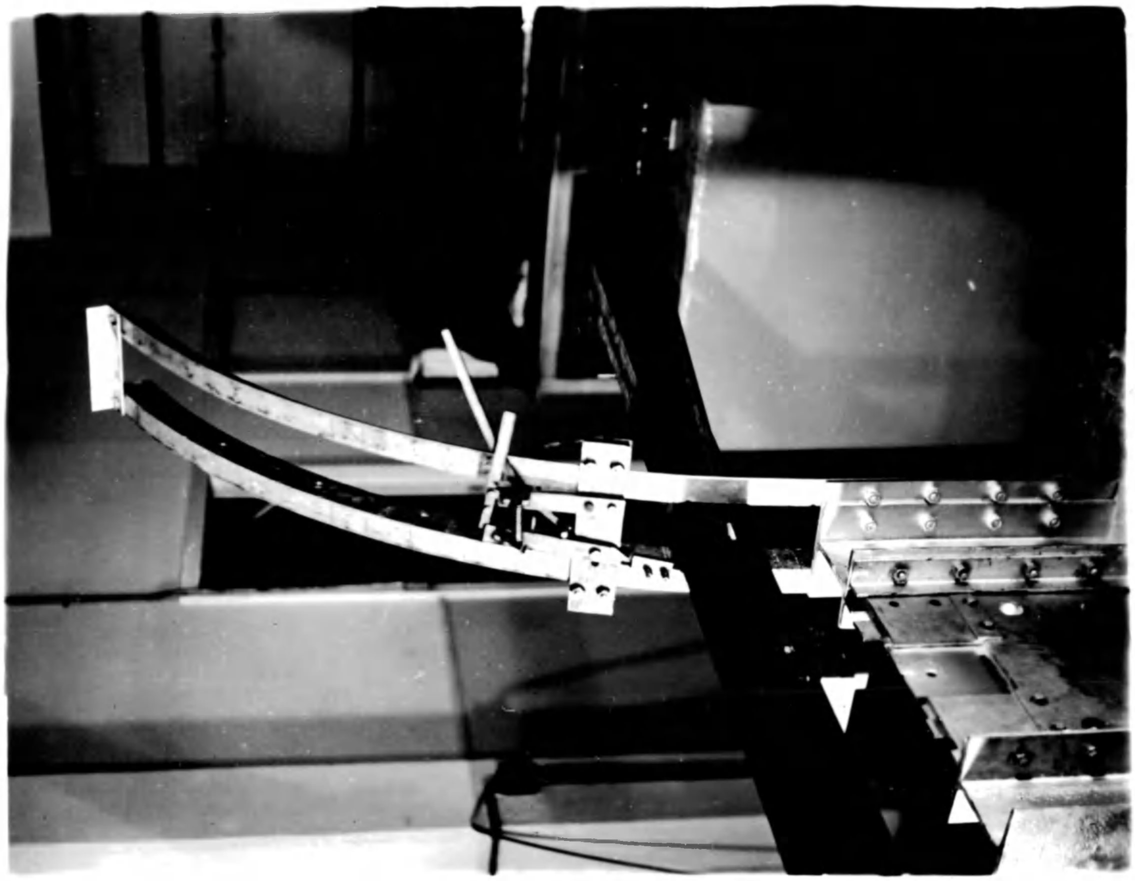

Fig. 5

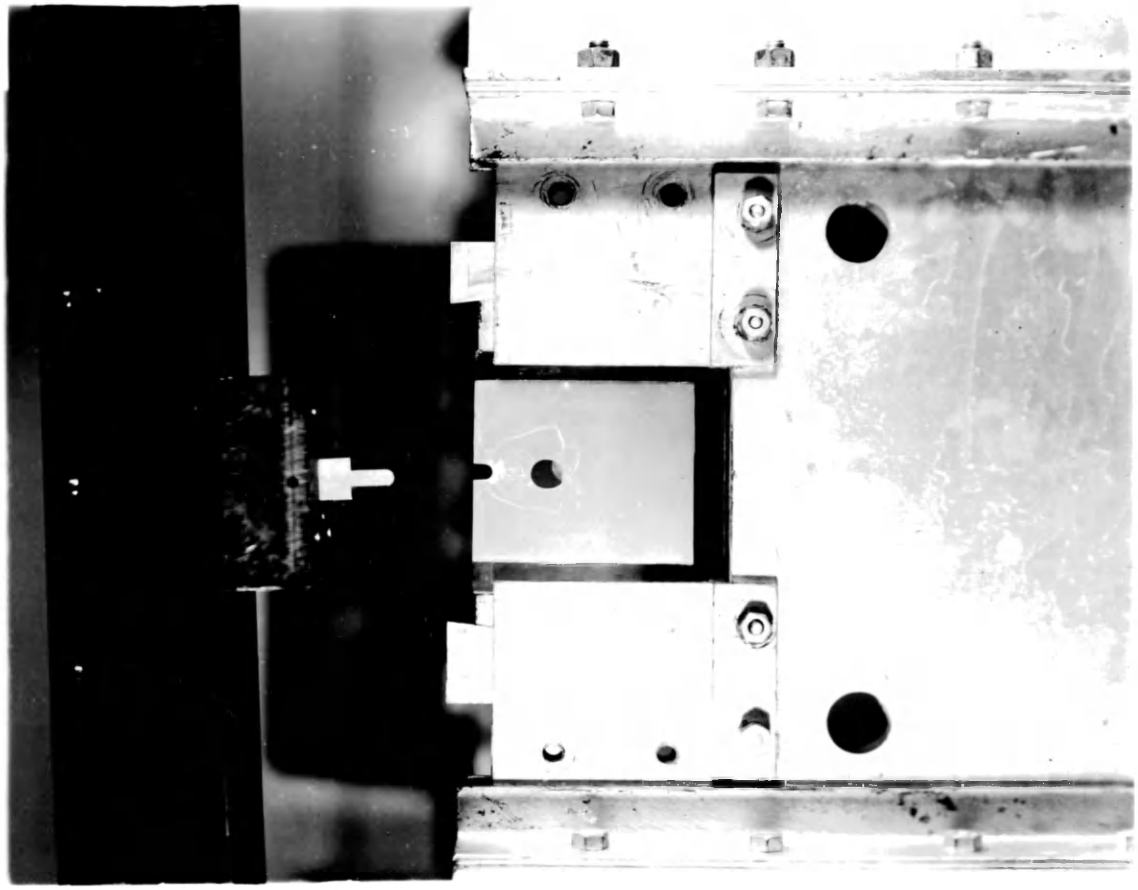

Fig. 6

with all these weights the beam was quite top-heavy, and the addition of more weights was deemed unsafe. It was decided to go to a universal hydraulic testing machine in which loading could be done evenly and slowly and to high enough values to produce fully-developed crack patterns.

A new loading frame was required in order to use the testing machine. A loading frame used for loading models in the polariscope was adapted for this work (see Fig. 7). The loading frame originally was made of four channel irons welded at the ends to form a rectangle. Steel holding plates were bolted to one side to overlap the edges of the models and prevent the models from falling out. A sliding-wedge arrangement of steel plates, similar to that used in the impact loading machine, was placed between the outer and inner holding plates to provide lateral confinement. In view of the difficulties encountered with wedge-type lateral confinement in the impact loading machine, a different arrangement was designed for this loading frame. A slotted steel plate was used on one side to get a general adjustment. On the other side, a plate with internal set screws was used for the final adjustment of lateral confinement. Spacer bars were used between the plate with set screws and the model to insure uniform confinement and to prevent the set screws from marring the model. A 1-in. square steel bar about 9 in. long was used to transfer compression from the loading head of the testing machine to the model. To prevent the bar from falling off, a slot 1/4 in. deep and slightly wider than the model thickness, 1/4 in., was cut lengthwise in the bar. Thus it could be slipped down on the model. To provide a secure base, the loading frame was bolted in the center of a flat 50-lb weight.

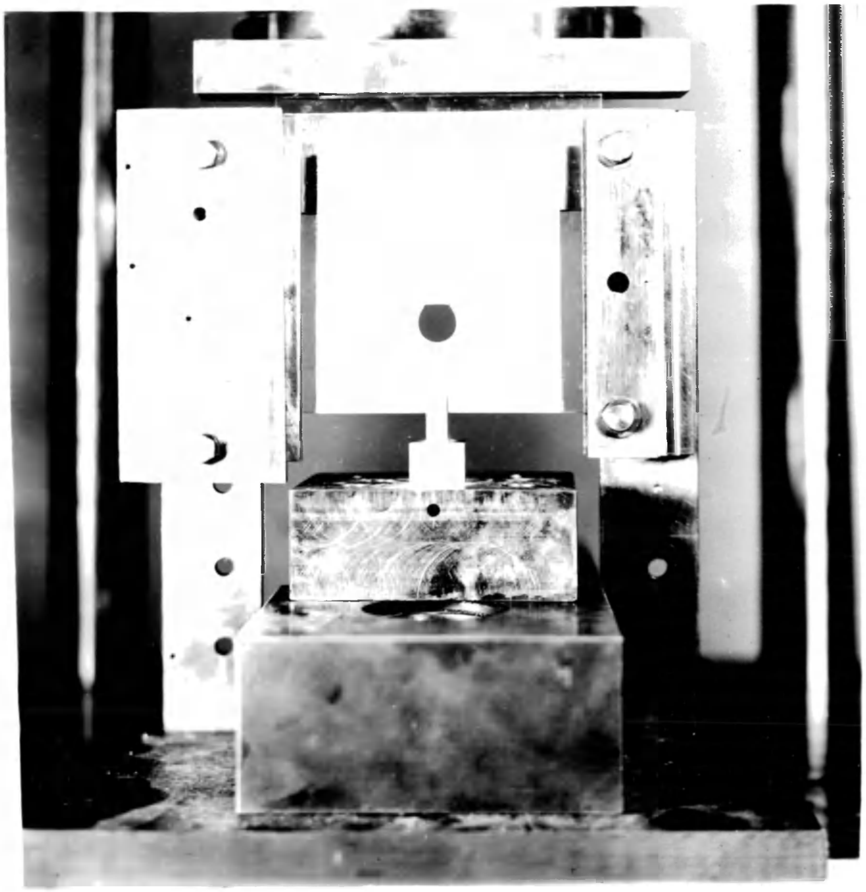

Fig. 7

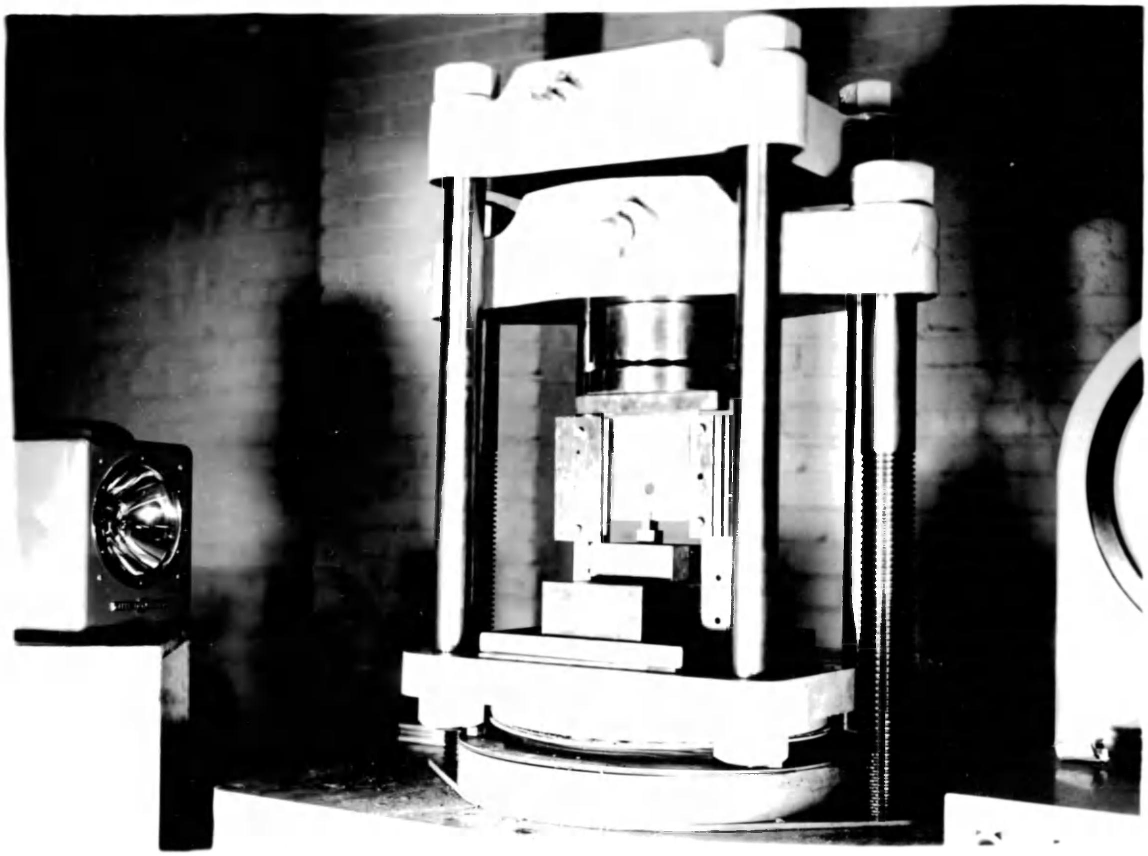

Fig. 8

To get concentration of the compressive load, tups of semicircular cross section of various diameters were designed and made from 1-in.-square stock by the Denver Machine Shop (see Fig. 5, 6, 7, and 8). The diameters used were 0.375, 0.625, and 1.0 in. because these were standard sizes and could be easily machined. The semicircular cross section for the load-contact surface was selected to simulate the theoretical shape of shock waves from an explosive charge and to prevent damage to the models that a sharp-pointed tup might cause. The tups were securely locked in a large steel block by means of set screws. Besides serving as a solid base for static tests (See Fig. 7), this block was designed to be bolted to the beam of the impact machine for later impact tests (See Fig. 5).

Photographic Equipment

A Kodal press-type camera with tripod was used with 5 x 7-in. cut film for photographing the models. The film used was Kodak Super XX and Ansco Triple S Pan. With Super XX film, a diaphragm opening of f.11 was used. With Triple S Pan film, a diaphragm opening of f.16 was used. Prints were made on Kodak Velox F-5 paper, a high-contrast paper which brought out the crack patterns clearly. The light source was a General Electric Photolight, shown in Fig. 8 and described by Hesselbacher 11/.

11/ *Op. cit.*, p. 35.

TEST PROCEDURE

Preparation of Models

The tunnel shape selected was a horseshoe type as shown in Fig. 9.

The dimensions were selected to fit a 6 x 6-in. model in accordance with the principle of Duval 12/ that "if the width of the plate is equal to four times the width of the opening, the error produced in computing the maximum stress has been shown to be less than 7 percent." The shape of the load-contact surface was determined by that of the tup used, 0.375-in. diameter.

The 6 x 6-in. models are cut from a sheet of Homalite with the jig saw, leaving a margin of about 0.1 in. on all sides for later milling. Sawing should be done with a slow feed using a medium-thin blade, both of which will reduce chipping of the brittle Homalite. Sheets cut to this size can be obtained from the manufacturer, but they are usually slightly smaller than 6 x 6 in., and the sides are not exactly square. The squaring of the sides reduces the dimensions still further. In order to exclude all possible sources of eccentric loading later in the tests, it is essential that the sides be parallel to each other and perpendicular to adjacent sides. In fact, special care must be taken at all stages of preparation of the models to insure accuracy to the greatest degree possible and thus to eliminate causes of error.

Thin dimension lines are scratched with a sharp scribe to outline the final edges of the model. Adjacent lines must be perpendicular. Scales with 100 divisions to the inch are preferred for this work. The model is then cut to exact size in the milling machine. In clamping the model to the feeding plate, tape or scrap Homalite plates should be used

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12/ Duval, W. I., Stress analysis applied to underground mining problems: U. S. Bur. Mines Rept. Inv. 4192, p. 4, March 1948.

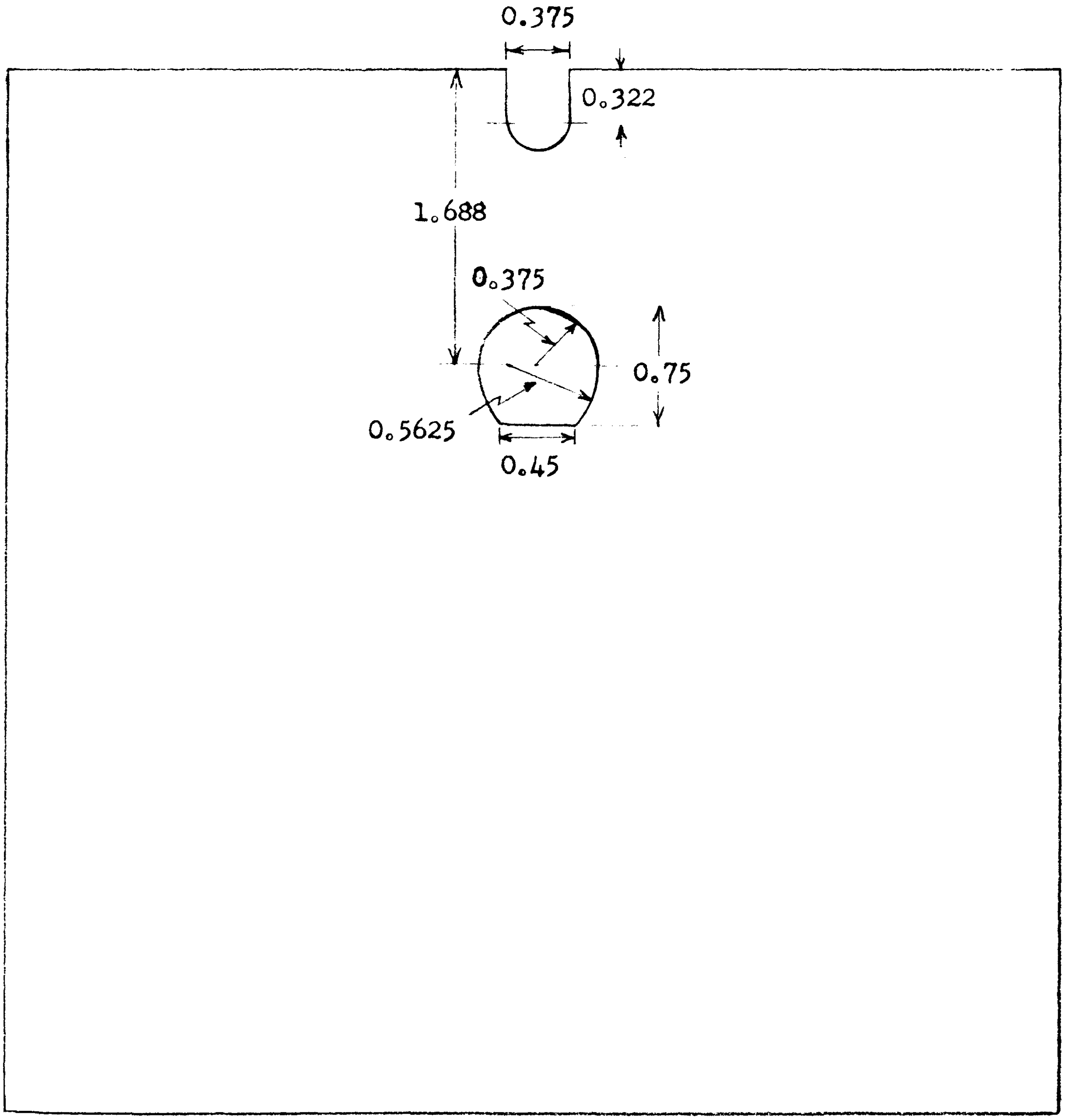

Fig. 9 (Full Scale)

on both sides of the model to protect the surfaces from being scratched or marred, because these imperfections will interfere later with the interpretations of crack patterns in the Stresscoat. The model is carefully levelled by means of a surface gage before clamping tightly. Vibration between model and cutting tool should be minimized for good results. The milling method used is inward side-milling -- the work proceeds in the same direction as would a tangent from the leading edge of the cutter flute at the point of cutting. Shallow cuts of not more than 0.010 in. should be taken until the scribed line is reached. The depth of cut is progressively reduced until the last 3 or 4 cuts are only 0.001 in., the smallest cut possible with this machine. The cutter speed should be fast, but the feed should be slow (about 2.7 in. per min) and even. Because of the brittleness and extreme hardness of Homalite, cutting tools should be harder than woodworking tools to eliminate frequent sharpening and replacement. Carboloy- or Stellite-tipped tools are the most satisfactory. Tools must be kept sharp for good results and should not be used to cut other materials. Generally speaking, deep cuts, improper feeding, and dull tools produce machining stresses, heat, and chipping.

After the sides of the model have been milled, the shape of the desired opening is carefully laid out, and the outline marked with the scribe. Next, a hole of suitable size is drilled through the model well inside the outline of the opening. Here again, a slow feed and sharp drills are necessary to prevent chipping and concentration of stresses. In addition, holes should be drilled halfway through from one side of the model and completed from the other side. This technique relieves the tendency of the drill to grab and crack the plastic as it breaks through. A suitable jig saw blade is then passed through the hole, and a rough cut is made about 1/16 in. inside the outline of the opening. Care must be taken to see that any chipping by the saw does not extend beyond the outline. The remaining material is removed by coarse files, and the final shape smoothed with fine files, both of which are operated in the jig. If necessary, the inner edge may be further smoothed with very fine sandpaper.

Coating the Models

A detailed explanation of the application of Stresscoat is given in the Stresscoat Operating Instruction, a booklet included with the apparatus 13/. A further explanation of the technique best applicable for the type of tests herein reported upon was given by Hesselbacher 14/. Only slight additional comment will be made in this report to emphasize or explain obscure or troublesome parts.

The steps in coating the models are (1) cleaning the surfaces, (2) masking the edges, (3) warming the models, (4) applying the undercoating, (5) determining the wet- and dry-bulb temperatures at place of test, (6) selecting the proper brittle coating, (7) applying the coating, and (8) drying. One or more calibration strips are coated in like manner

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13/ Stresscoat Operating Instructions, Form No. 200-2, Magnaflux Corp., Chicago, Ill., 38 pp.

14/ Op. cit., pp 12 to 15.

at the same time the models are coated.

In cleaning the models, previous coatings must be completely removed. Warming of the models enables the coatings to be applied easier. It is done with a 100- or 150-watt electric lamp. Slotted wood holders, each holding 5 models, are used to facilitate the warming phase and the later drying phase.

Difficulty was experienced in predicting the temperature and humidity conditions of the test room. This prediction is necessary in order to select the proper Stresscoat to be used for the tests. Since temperature and humidity in the test room varied from one day to the next, and control over them was lacking, one coating was selected and used throughout the tests. Coating number 1204 was the one selected since it fulfilled most of the test conditions. This technique should not influence interpretation of results, however, since a calibration strip is coated and tested at the same time as the models.

The application of Stresscoat is the most difficult step in the coating of models. Thick or uneven coatings cause formation of drying cracks which obscure the crack patterns. The formation of heavy, yellowish dust on the surface can be eliminated by diluting Stresscoat with thinner, which does not change the characteristics of the coating. The spraying is done as shown in Fig. 10. Both sides of the model are coated. The model is propped against two nails, one at each side of a wooden backstop, which touch the masked edges of the model and keep the freshly sprayed reverse surface from being marred. In Fig. 10, the spray gun being held by the operator is used for Stresscoat; the other spray gun is used for undercoating. (Under normal operating conditions the

Fig. 10

compressor was placed on the floor.) These spray guns were cleaned carefully with thinner after each use to prevent clogging. The use of a galvanized iron hood and exhaust fan eliminated the need for using a gas mask as formerly required.

The spraying of the models was done one afternoon, and the testing, the next morning. During this drying period, the models and calibration strips were kept warm in a closed cabinet by means of a 100-watt lamp until an hour before testing. Such warming prevents the formation of craze and drying cracks. One hour is required for the models to come down to test-room temperature.

Loading

The masking tape is first removed from the edges of the model. Then the edges are greased so that the model will slip down on the tup even though its sides are confined. Then the model is inserted in the loading frame, and the side confinement plates adjusted and tightened until snug. About 1/2-in. of the model extends above the loading frame so that the slotted steel bar can be placed on the model and still leave sufficient room for compression of the model. The model is inserted with the tup hole down so that the tup can be adjusted easily without danger of cracking the coating in the process (see Fig. 7 and 8). The clear space around the edge of the model shows where the masking tape was removed. Then the entire loading frame is centered in the testing machine, and the loading head lowered until it is just about to exert load on the model. The dial of the testing machine is zeroed and the test begun. The loading is done in increments. The steps in testing are (1) loading to desired value, (2) marking isoentatics of the crack pattern, (3) photographing model, and then (4) loading further to next value. After the desired maximum load is reached, marked, and photographed, the load is released. A calibration strip is tested in the calibrator to get a standard value of strain. The amount of each load, the photograph number, the total time to reach maximum load, and remarks is recorded along with such basic data as coating number, wet- and dry-bulb temperatures, camera opening, and calibration value. Although all but one model cracked at or about the maximum load, loading of one model was continued until it fractured in many pieces, and the manner of failure was recorded. Although both sides of the models were coated, only one side could be photographed because of the construction of the loading frame; therefore, the side coated the best was placed facing the camera.

Photographing

The camera was placed as close to the model as the tripod would permit and focused before the beginning of tests. The cut film holders were then inserted before taking each photograph. The Photolight was placed to the side as shown in Fig. 8 at an angle. Its position was limited to that where the columns of the testing machine would not mask its light. The photographing procedure was to open the shutter, load the camera, shut off all lights, pull the film protecting sheet, activate the Photolight, insert the film protecting sheet, and turn on the lights. Dye-etchant was not used on the models before photographing because it softens the coating and renders it useless for further testing.

DISCUSSION

The discussion will be divided into three sections: (1) Failure of Stresscoat, (2) Test Data, and (3) Deficiencies and Errors. Since the use of brittle coatings for the analysis of stress is a recent development, it is believed that some discussion of the failure of Stresscoat should be included. Included in the section on Test Data is a complete description of the sequence of growth of the crack patterns; the topic is treated in the section "Results of Tests to Obtain Statistical Average," which is concerned with an interpretation of the best pattern produced.

FAILURE OF STRESSCOAT

The use of brittle coatings such as Stresscoat is one of the most convenient methods of indicating strains. On complicated engineering structures, such coatings will indicate areas of highest strain in a visual manner, show directions of principal tensile stress, and if properly controlled, yield quantitative values of sufficient accuracy for design purposes 15/.

The coatings have the property of fracturing at low values of strain (about 0.0007 in. per in.), and the cracks apparently fracture in a direction that is perpendicular to the direction of the principal tensile stress in the area of the cracks. Stresscoat will also show larger values of strain by flaking off the surface of a coated structure in much the same way as the flaking of mill scale. According to de Forest

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15/ *Op. cit.*, de Forest, et al, p. A-184.

Ellis, and Stern 16/ "the flaking occurs in the initial yield region of most metals and correlates directly with the amount of compression strain present." Information supplied by the Magnaflux Corporation 17/, manufacturers of Stresscoat, states that the most sensitive type of Stresscoat will start to flake at a compression strain of 0.01 in. per in. Using this value, Hesselbacher 18/ has shown that flaking occurs within the elastic range of plastics. Although it has been assumed that Stresscoat will crack when the maximum tensile strain reaches some critical value, Durelli and De Wolf 19/ have shown that there are some cases where this maximum tensile strain law does not apply. It was further found in the present investigation that compression spalling later filled certain of the same areas covered by the tension cracks (the area between tup hole and tunnel opening), with no change in the nature of the load applied (compression) but with only an increase in the intensity thereof. This would tend to discount the maximum tensile strain law and the explanation of compression spalling thereby. Possibly

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16/ *Idem*.

17/ *Op. cit.*, Stresscoat operating instructions, p. 22.

18/ *Op. cit.*, p. 8.

19/ Durelli, A. J., and De Wolf, T. N., Law of failure of Stresscoat; Proc. Soc. for Exper. Stress Anal., vol. 6, no. 2, pp. 68 to 83, Dec. 1948.

a better explanation could be given by a stress-difference theory: the coating fails because of differences in the maximum principal stresses at a given point.

TEST DATA

Preliminary Observations and Modified Techniques

The preliminary tests of concentrated static loading using the impact machine resulted (1) in the findings reported previously in the section on Loading and (2) in the change to the use of a hydraulic testing machine. The first tests in the hydraulic testing machine showed that the steel holding plates of the new loading frame interfered with the free formation of crack patterns in the Stresscoat due to the load (see the peculiar patterns along the sides of the model in Fig. 11). The tightening of the holding plates initiated confining stresses on the flat surface of the model which increased when the load was applied. To eliminate this effect, two layers of masking tape were placed between the spacer bars and the holding plates; and the sides of the model in contact with the holding plates were greased. In a similar manner, the ends of the model were greased so that friction would be reduced between the model and the plates producing lateral confinement. The model thus would be free to move down under load and yet would remain under the required confinement.

In one test, when the side confinement plates were inadvertently adjusted so as to leave the model unconfined, the model compressed almost 1/4 in. under load without breaking. At that point, 2900 lb, the top spacer bar rested on the loading frame, and loading was discon-

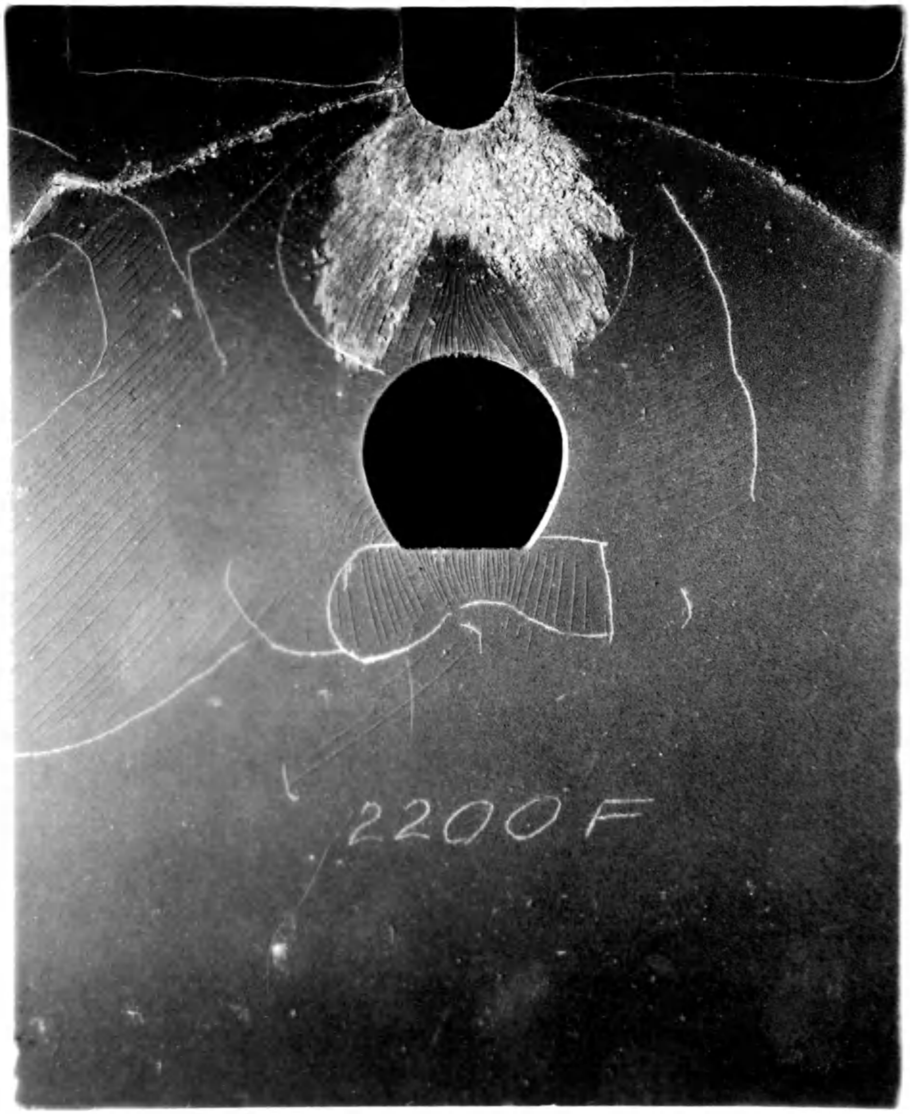

Fig. 11

tinued.

These preliminary tests showed that the adjustment of the holding plates and the placement of the model in lateral confinement are critical phases of the tests and should be done carefully. With the technique modified as described above, no further difficulty was experienced.

Results of Initial Tests Using Modified Technique

The next tests were conducted using the modified technique of adjusting the holding plates and placing the models in lateral confinement. The first observation was that the crack pattern as it developed under increasing load was non-symmetrical. This non-symmetry in the development of the crack pattern was observed at the top of the tunnel opening, at the bottom of the tunnel opening, and at both sides of the tup opening (see Fig. 12). As the load approached the maximum, the crack pattern usually tended to become symmetrical (see Fig. 13). Furthermore, the crack patterns developed non-uniformly; that is, the increase in area of the pattern was neither the same for equal increments of load nor consistent in becoming progressively larger or smaller. Moreover, if this non-symmetry and non-uniformity in the development of the patterns continued in later tests, they would interfere with any attempt to get a correlation of load to pattern by such means as areas or dimensions of crack patterns.

Another observation was that the crack patterns on the front and back of the same model differed in the load at which they appeared initially and in the speed with which they developed. However, the general shape of the patterns was similar. Since the loading frame

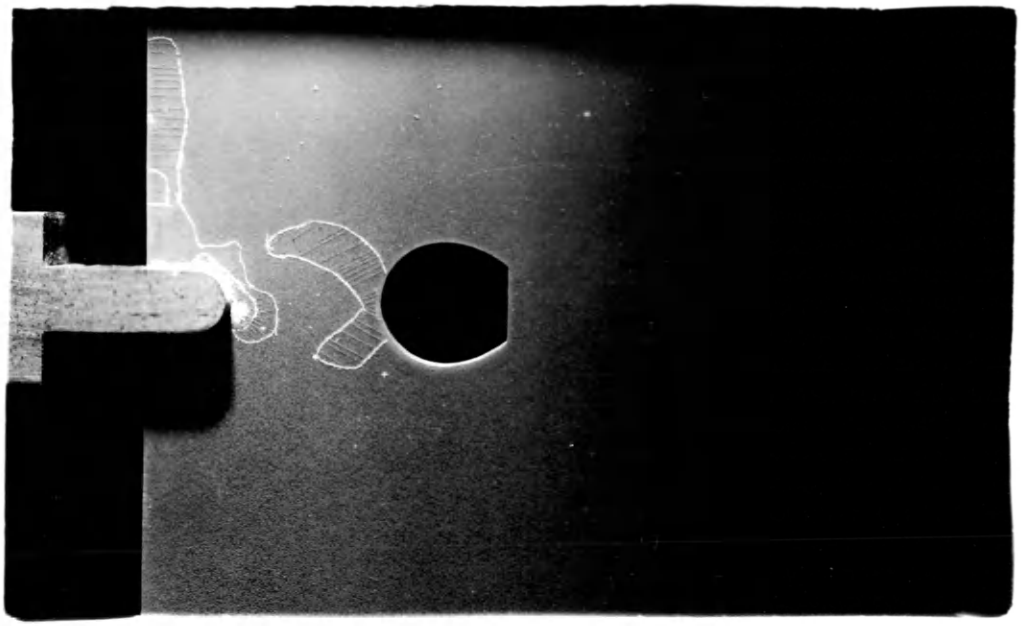

Fig. 12

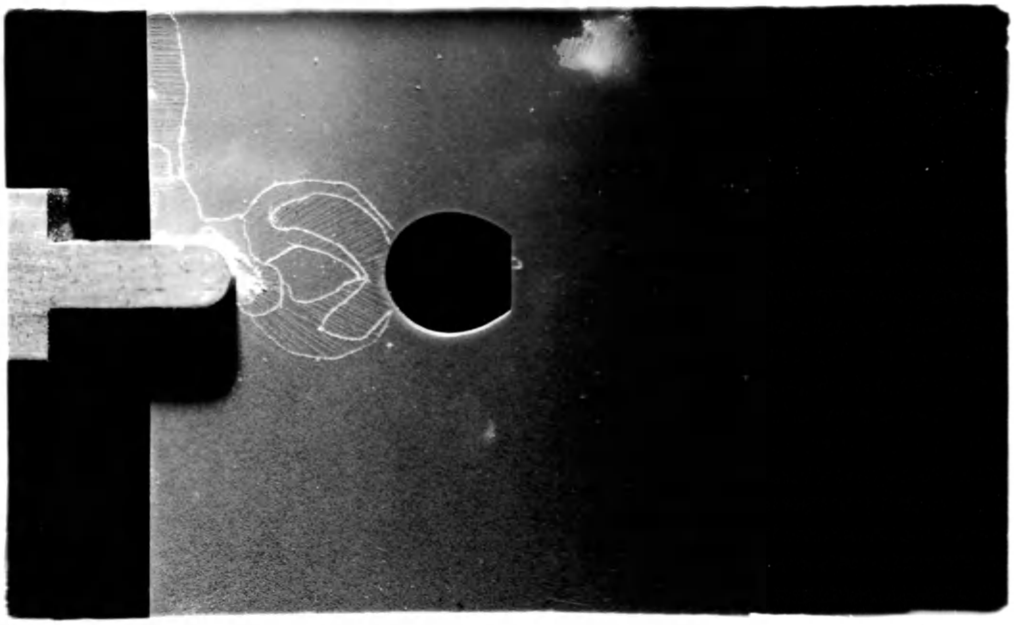

Fig. 13

obstructed the view of the patterns on the back, photographs of the back side could be taken only at the completion of the tests. Figure 14 shows the front of a model and Fig. 15, the back of the same model, both taken after loading was completed. The vertical patterns at the top and bottom of the tunnel opening and at the top of the model itself are the result of loading, whereas the horizontal patterns at each side of the tunnel opening are the result of the slow release of the load. A careful examination of the figures will show the similarity of the patterns on the front and back as well as the unsymmetrical and nonuniform development of such patterns. Cracks around the top of the tunnel opening began on the front at 200 lb, but did not appear on the back until after 400 lb. In the test preceding the one photographed, the difference in load between front and back at which initial cracks appeared was 700 lb, and the cracks appeared first on the back. The difference in areas of crack patterns between the front and the back as well as the nonuniform development of patterns on the same side can easily be seen in these figures.

The release patterns at each side of the tunnel opening shown in Fig. 14 and 15 are typical for slow release of the load. Rapid release of the load results in the fractures covering the model much more completely (see Fig. 26). These release patterns apparently indicate a compression zone in which the maximum tensile strain has not reached the threshold value of the coating as indicated by the calibration strip based on the maximum tensile strain theory) or, what is more plausible, they indicate that the stress difference in maximum principal stress has not reached the threshold value of the coating (based on the stress

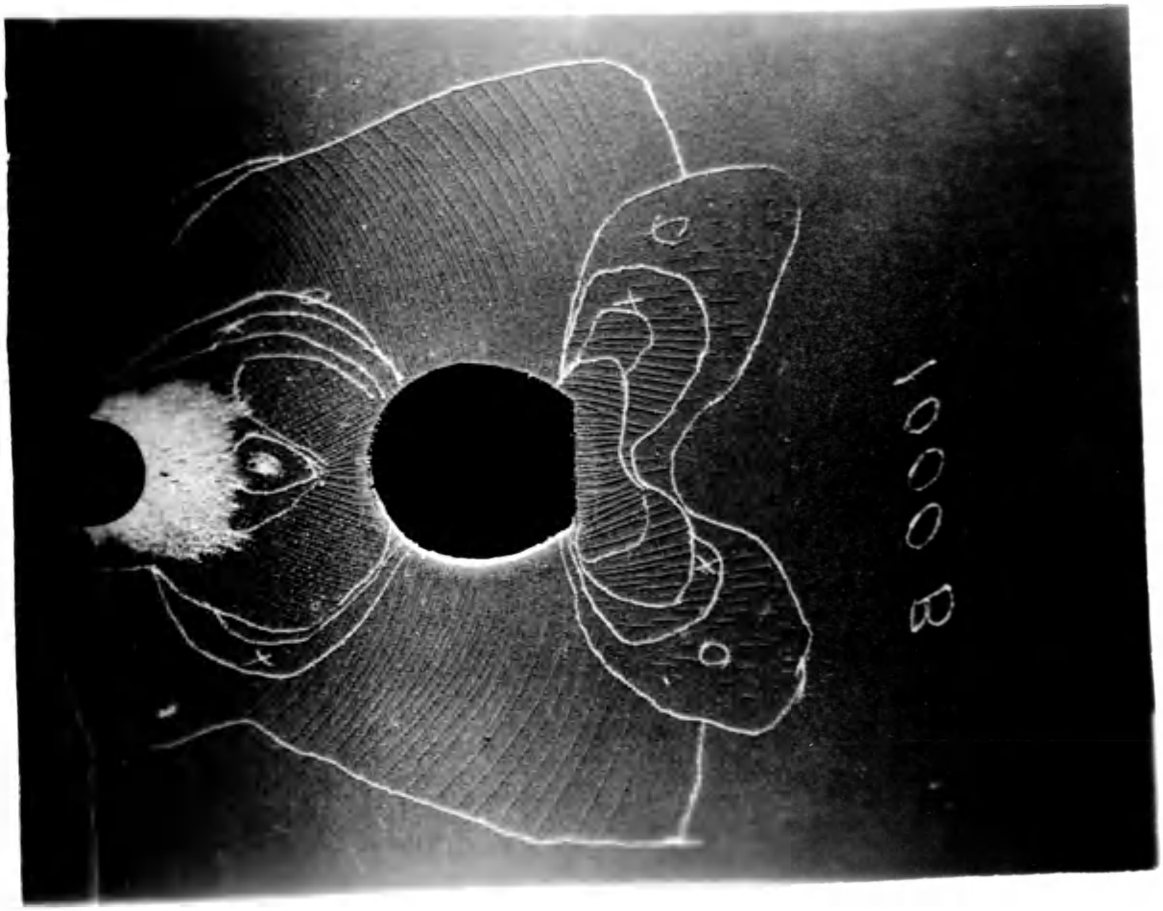

Fig. 14

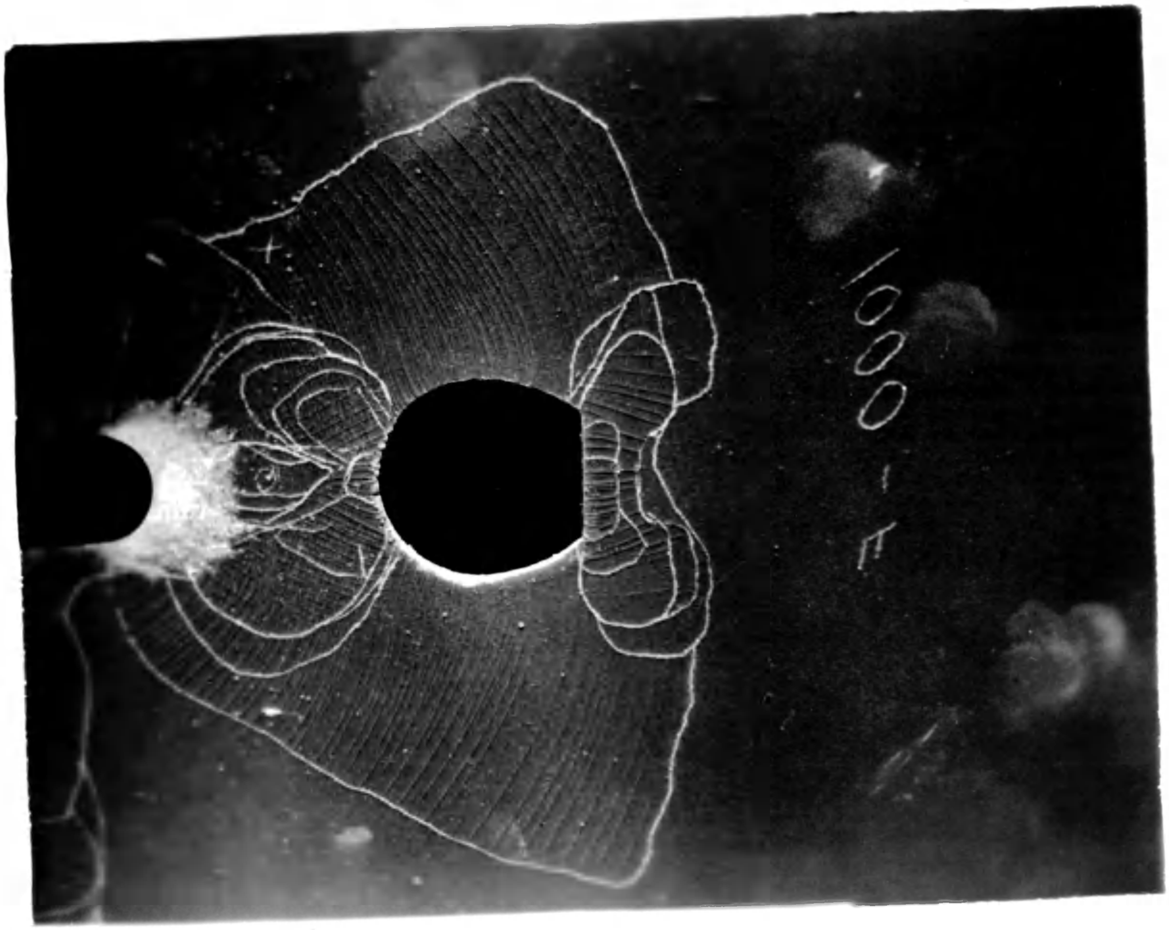

Fig. 15

difference theory). As load was released, many of the vertical tension cracks would shorten; and some would disappear completely.

A small area was noted in which no vertical cracks appeared during loading. This area was located on a vertical line through the center of the tup and tunnel openings. As observed originally, it was a small, arc-shaped area with the arc cupped upward and was located about halfway between the bottom of the tup hole and the top of the tunnel (see Fig. 16). This area might indicate that point at which vertical and horizontal principal stresses are equal -- an hydrostatic area.

The final observation was made on the manner of failure of the Homalite model. Models failed usually as load approached the maximum. The failure occurred as a crack radiating out and downward from one or both sides of the tup hole beginning at the juncture of the semicircular bottom and the vertical sides which are tangent thereto; this was the first contact point between tup and tup hole (see Fig. 11). This crack appeared quite suddenly and was completely developed in its initial appearance. The sharp downward extension of the crack shown in Fig. 11 which resulted from the release of the holding plates, demonstrates their interference in the conduct of the tests which was later corrected.

Results of Tests to Investigate Initial Findings

Further tests showed that unsymmetrical crack patterns and nonuniform growth of such patterns continued even though every effort was made to find and eliminate all possible causes thereof. Likewise, the differences in the crack patterns on the front and back continued in these later tests. Release patterns appeared as before.

Of special interest was the confirmation of the hydrostatic area or

Fig. 16

area of no vertical cracks. In these later tests, this area was much larger than originally observed and tended to become elliptical in shape with the long axis vertical (see Fig. 17 and 18). It should be noted that the delineation of this area is difficult because of the tendency of very small fine cracks to form which can be seen only by careful inspection in strong light coming at an angle. In addition, as the load increases, the area of compression spalling moves slowly downward from the tup hole to the tunnel opening. As the load approaches the maximum, this spalling increases in speed and eventually moves into the upper part of the hydrostatic area, and thus obscures possible tensional crack patterns (see Fig. 24 and 25).

The failure of the models themselves duplicated previous failures. In these later tests, careful fitting of the tup to the tup hole eliminated the possibility that stresses sufficient to cause failure might concentrate at some irregularity in the tup hole. Therefore, this type of failure is apparently typical for these tests. This failure can be seen to coincide with the direction of principal stresses as indicated by the long radial tension cracks emanating from the circumference of the tup hole. As the load increased, the stress along the cracks closest to the top point of contact between tup and tup hole approached the yield point of Homalite, and thus, the failure occurred. This deduction is further strengthened by the position of the release cracks in the Stresscoat along the failure crack which cross the failure crack at right angles thereto. This is in accord with the theory of the formation of such release cracks in Stresscoat.

Results of Tests to Obtain Statistical Average

A final test was made in an attempt to arrive at an average pattern

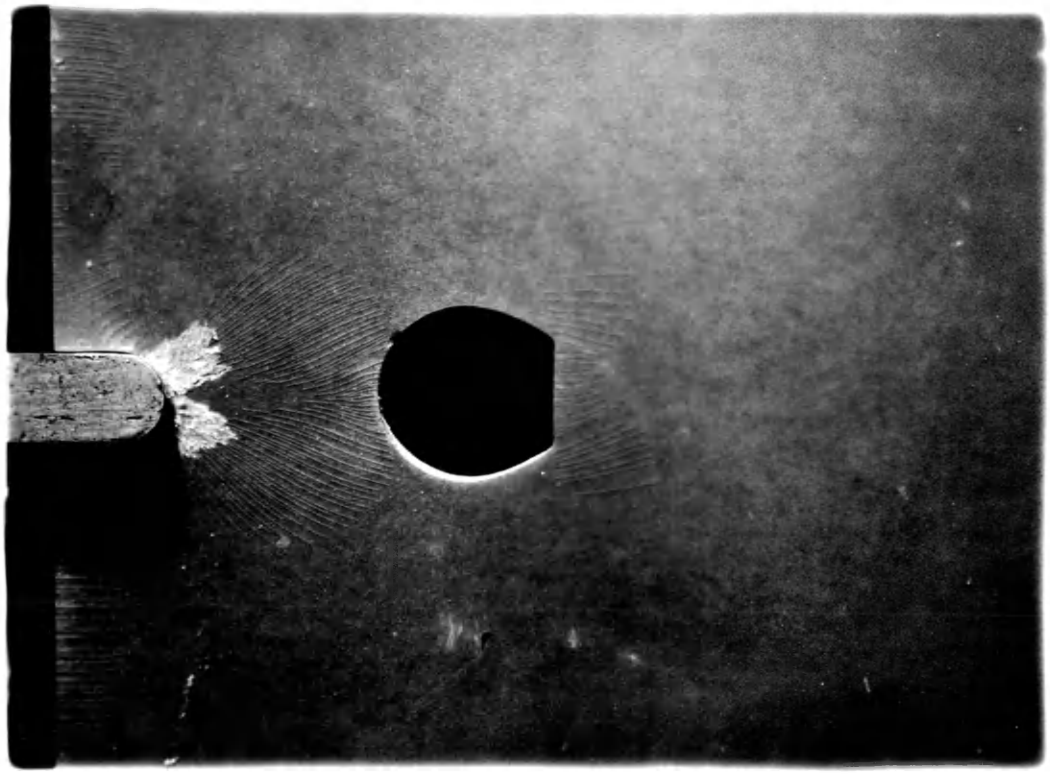

Fig. 17

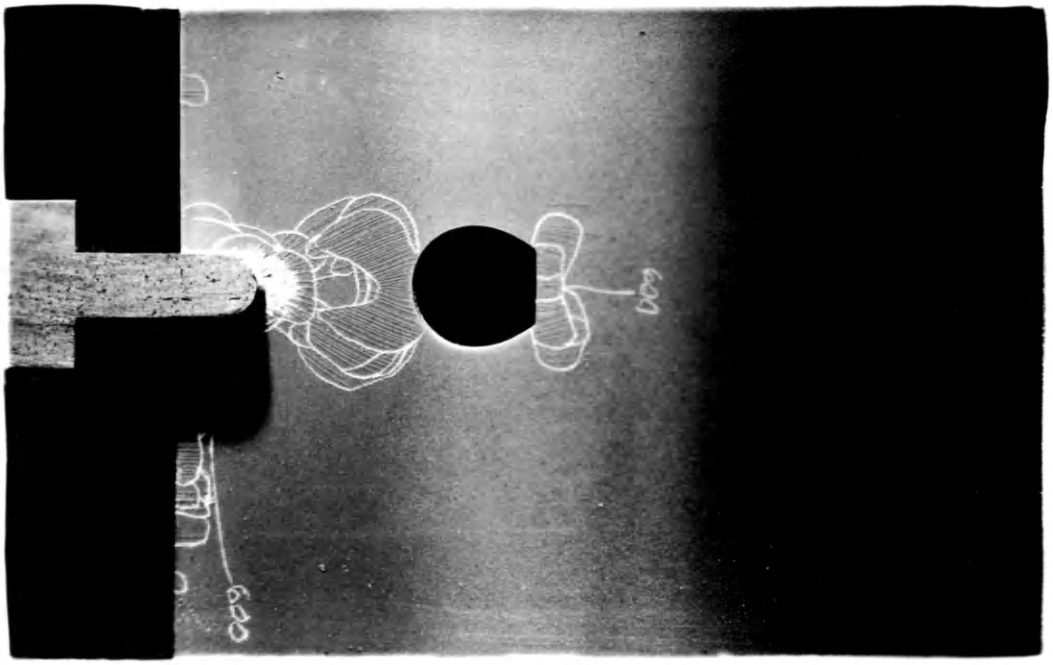

Fig. 18

of development which would correlate the variations previously described. It was thought that if a group of models were cut, coated, and tested together the uncontrollable factors influencing the results might average out. Thus, three models were prepared together for this test and were tested one after the other. The results were no different than those of previous tests. Difficulties were experienced in the variation in the value of the load at which the initial cracks appeared, the non-symmetry of crack patterns, the nonuniform development of crack patterns, the difference in crack patterns on the front and back sides of the model, and the variation in size and shape of the hydrostatic area. Although the similarity of the results from each test was strong, the crack patterns were not sufficiently alike in area or dimensions to permit a reliable, statistical correlation of pattern and load.

The results of the best test in this group, that of model 2, are shown in Fig. 19 to 26. The first five pictures were taken at 200-lb increments from 200 to 1000 lb, at which load the slotted side-confinement plate slipped. The next picture was taken at 1400 lb and the next at 3050 lb. The pictures of these last two increments are obviously unreliable for correlation of pattern to load but are certainly acceptable for showing the general pattern. Figure 26 was taken after the load was released rapidly.

Tension cracks appeared around the bottom of the tup hole between 50- and 75-lb load. The first tension cracks appeared at the top of the tunnel opening at 175 lb and developed to the pattern shown in Fig. 19 at 200 lb. Note that there are no cracks along the top of the model or at the floor of the tunnel.

Between 200 and 400 lb, the crack pattern at the top of the tunnel increased symmetrically; and patterns appeared symmetrically along the top of the model on both sides of the tup hole (see Fig. 20). Note that the direction of the tension cracks around the top of the tunnel indicates quite clearly the direction of principal stresses as modified by the tunnel. Note, also, that there has been no extension of the cracks around the bottom of the tup hole nor have any cracks appeared at the floor of the tunnel.

Cracks appeared in the tunnel floor at 450 lb and developed to the pattern shown in Fig. 21 at 600 lb. In this picture, non-symmetry appears for the first time in the development of the crack pattern around the top of the tunnel. The increase in the area is greater on the right side than on the left. Nonuniform growth of the pattern in this area can be observed from a comparison of the patterns in Fig. 19, 20, and 21. Furthermore, comparison will show an increase in the density of the cracks, which are much more numerous in areas of Fig. 21 than in identical areas of Fig. 20.

Two interesting developments are shown in Fig. 22. First, the pattern at the top of the tunnel has now become symmetrical. Second, compression spalling around the tup hold, which was just beginning in the previous pictures, has now completely filled and extended outside the area of tension cracks that had been previously marked. This increase in the area of compression spalling occurred with no visible increase in the tension cracks in the same area.

At 850 lb, the tension cracks coming from the top of the tunnel joined with the compression spalling coming from the tup hole. At 950

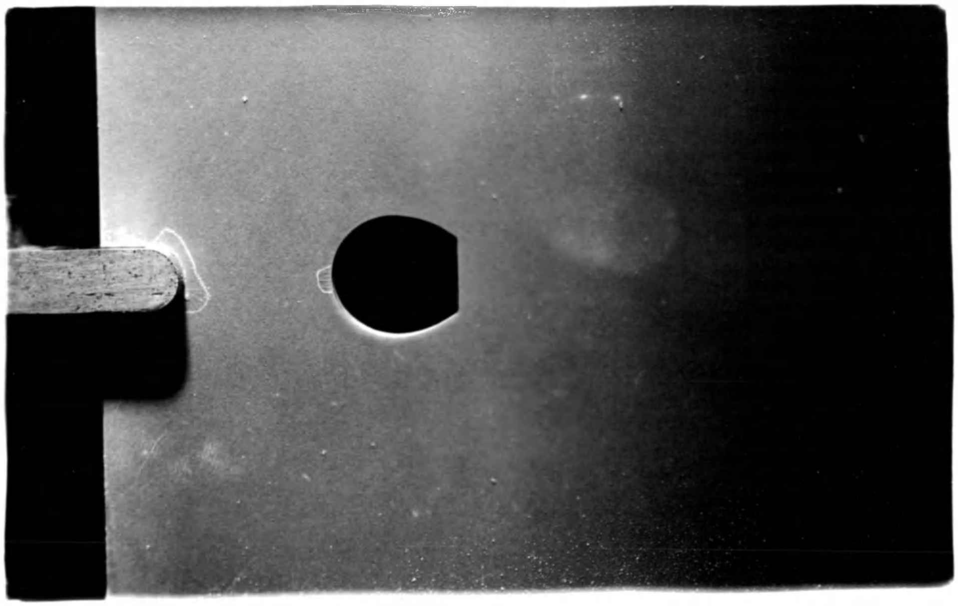

Fig. 19

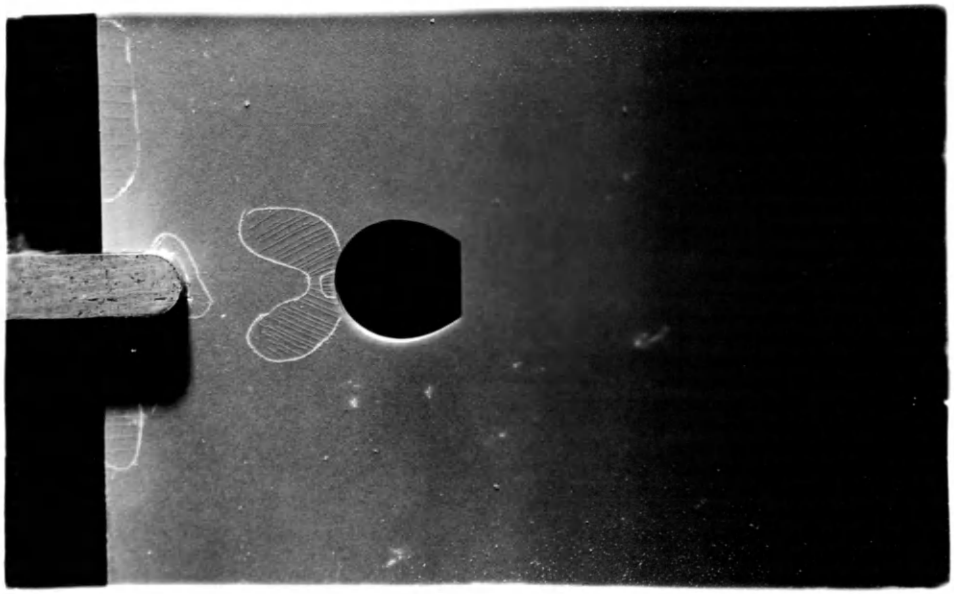

Fig. 20

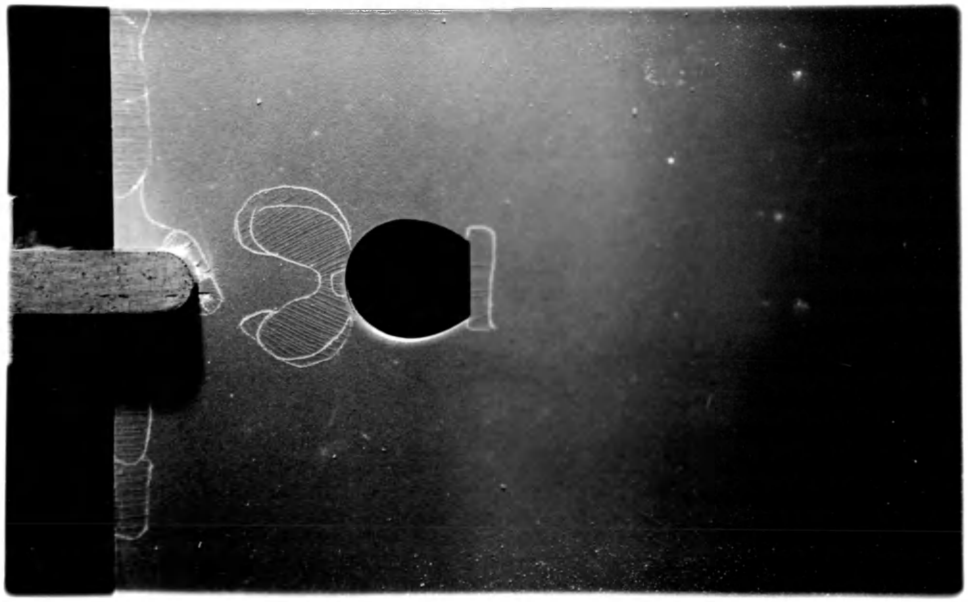

Fig. 21

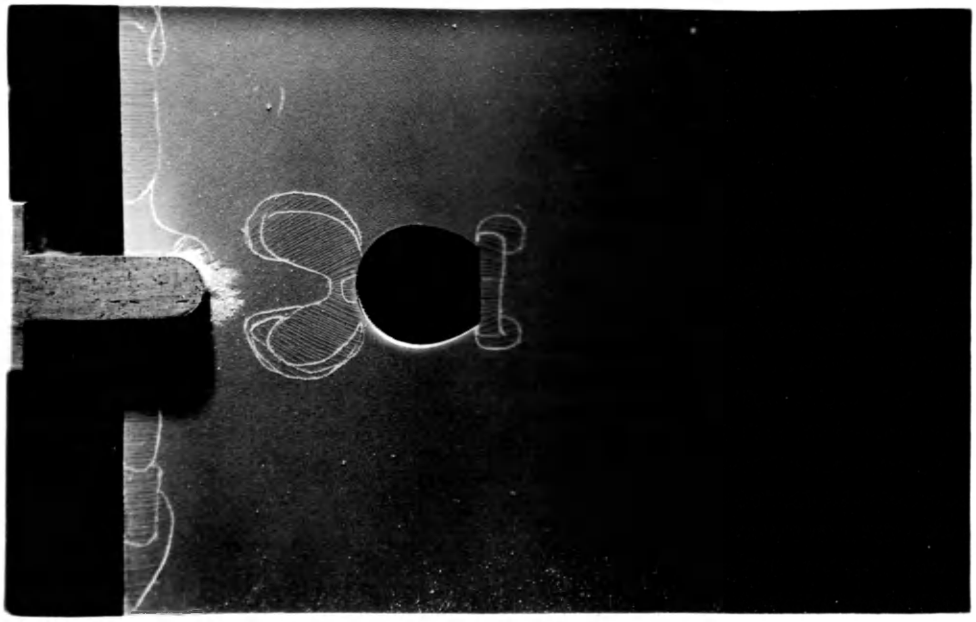

Fig. 22

lb, a failure crack appeared at the right side of the tup hole. At 1000 lb, after the patterns had been marked but before the picture had been taken, a failure crack appeared at the left side also (See Fig. 23). This figure shows quite clearly the similarity in directions of the tension cracks and the failure cracks as well as the short curved release cracks crossing the failure cracks at right angles thereto. The area of tension cracks in the tunnel floor has increased greatly. However, the tension crack pattern in the tunnel floor is now unsymmetrical. The hydrostatic area is clearly defined about halfway between the bottom of the tup hole and the top of the tunnel although after it was marked a few tension cracks extended into the left side of the area due to creep of the coating.

Figures 24 and 25 serve only to show the increase in area of the tension cracks in the tunnel floor and the progress of the compression spalling. The hydrostatic area, although difficult to determine accurately, has diminished to a top-shaped area. Of particular interest is the manner in which the compression spalling has extended downward on each side in long, inward-curving fingers, almost reaching the top of the tunnel. In the final test, which was carried to complete fracture of the model, the progress of the spalling was quite similar.

Figure 26 shows the extent of the release cracks with a rapid release of load.

The complete series of pictures recording the results of the other two tests will not be included here, but the first and last pictures of each routine series will be included to show the variations and deviations. Figures 27 and 28 are the first and last pictures of the test on model one, taken at loads of 325 and 1000 lb, respectively. No cracks

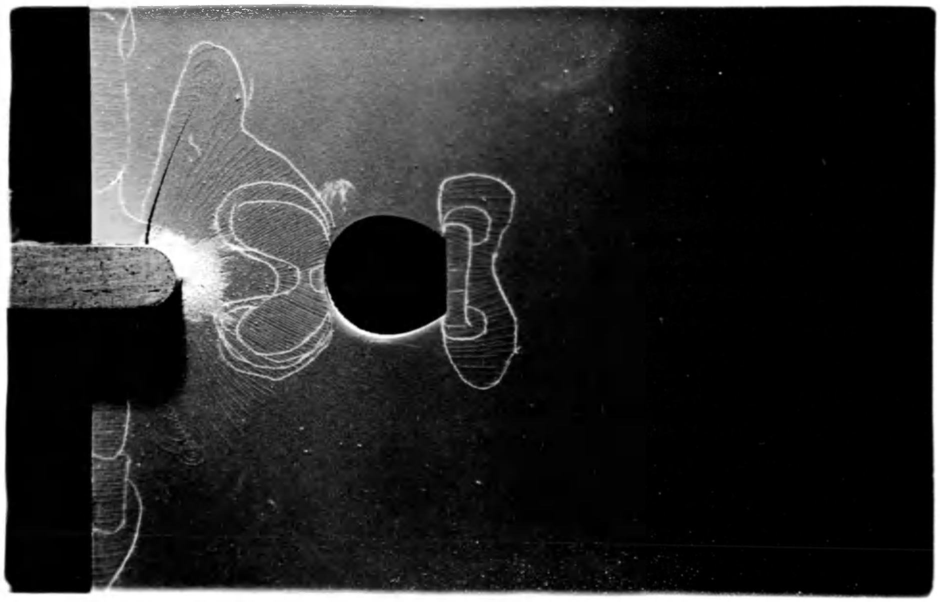

Fig. 23

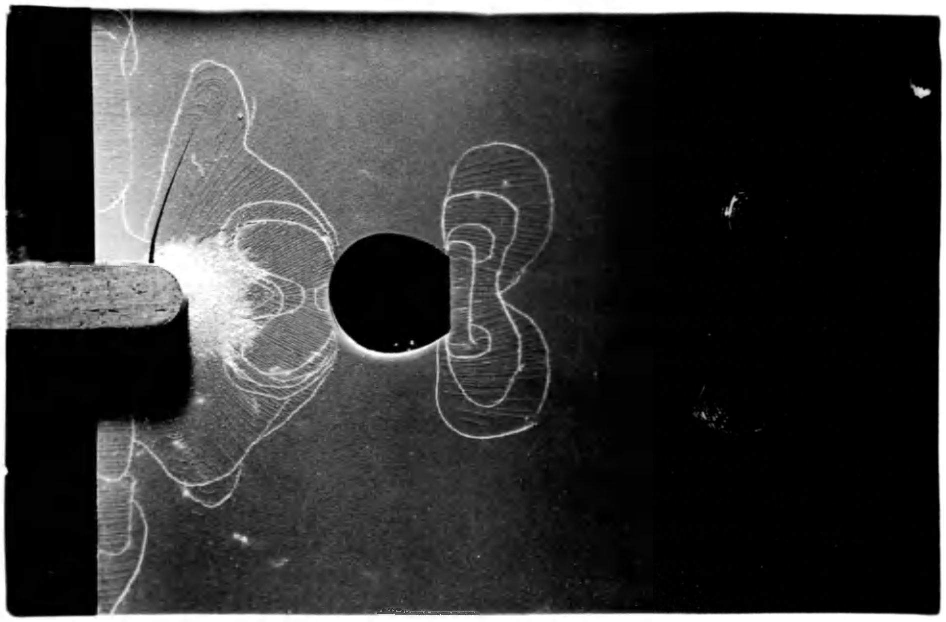

Fig. 24

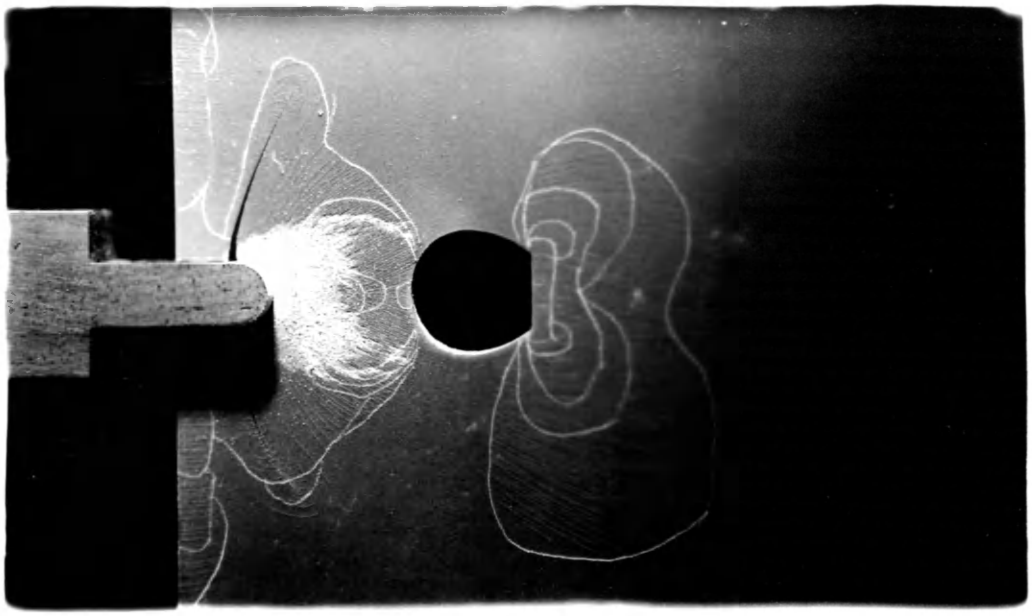

Fig. 25

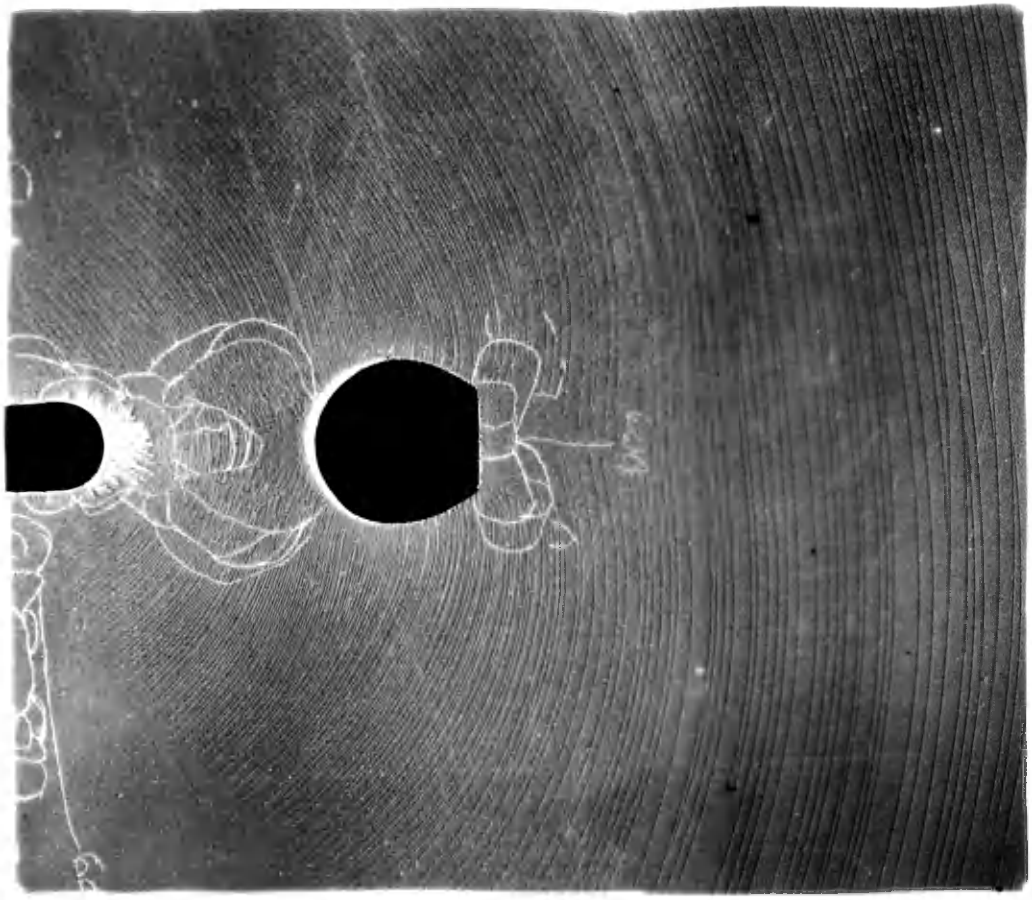

Fig. 26

were visible at the initial load of 200 lb. Figures 29 and 30 are the first and the next to last pictures of the test on model 3, taken at loads of 200 and 1000 lb, respectively. All the variations mentioned previously in this paper can be seen by a comparison of the pictures of models 1, 2, and 3 at similar loads.

Results of Test Carried to Complete Failure of Model

The third model of the last group tested was loaded to complete failure. Because all but one film holder had been used in the first part of the test, only one photograph of this part of the test could be made. However, it is believed that an account of the ultimate failure of this model will be of interest. Since development of the crack patterns was similar to that of previous tests, some reference will be made to pictures of previous tests.

Progress of the crack patterns followed that described in the preceding section. The last picture made of this model was taken at 1200 lb (see Fig. 31). The compression spalling reached the top of the tunnel in two long inward-curving fingers (see Fig. 25) which then broadened out similarly to the wide fingers shown in Fig. 32. The spalling then moved down to fill in the central area above the tunnel and broadened to the outside extremities of the tension cracks above the tunnel. After filling this area, the spalling began to move down along each rib of the tunnel in a series of steps. It would move about 1/4 in. down each side in a thin finger about 1/32 in. wide. Without further downward movement, the spalling would broaden to about 1/4 in. at the top half of this finger. Then the step would be repeated. The spalling progressed in this manner to the point at which the ribs joined the

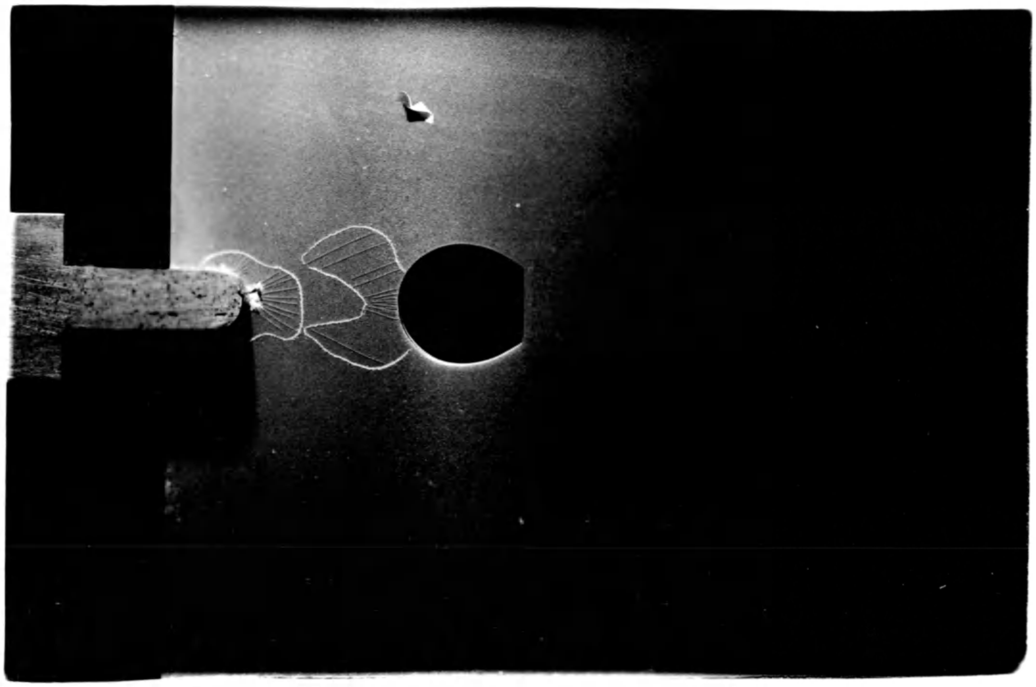

Fig. 27

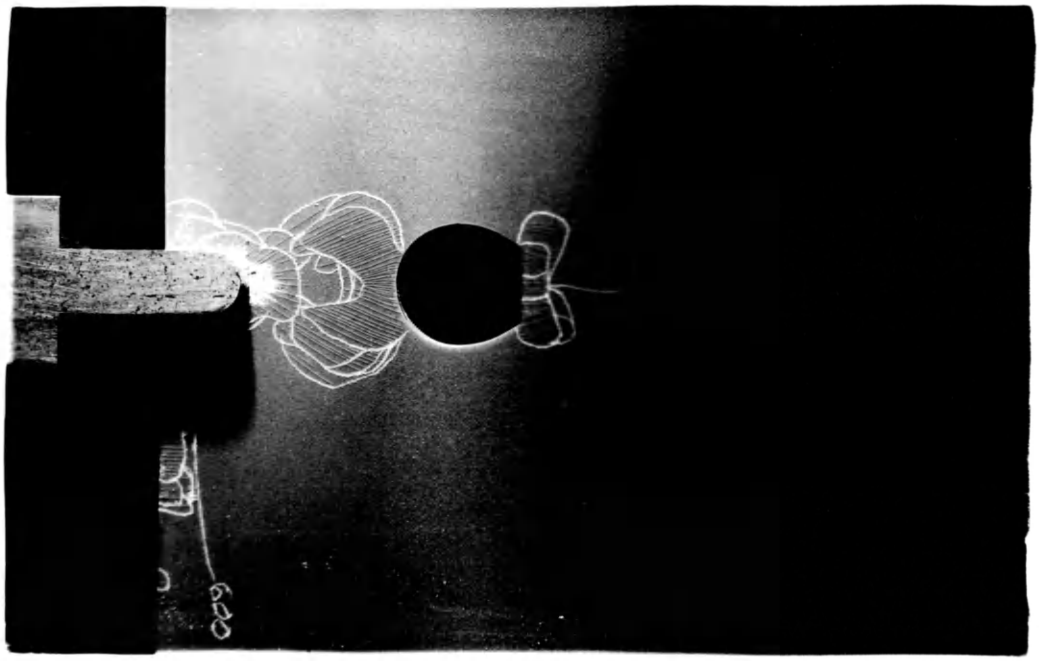

Fig. 28

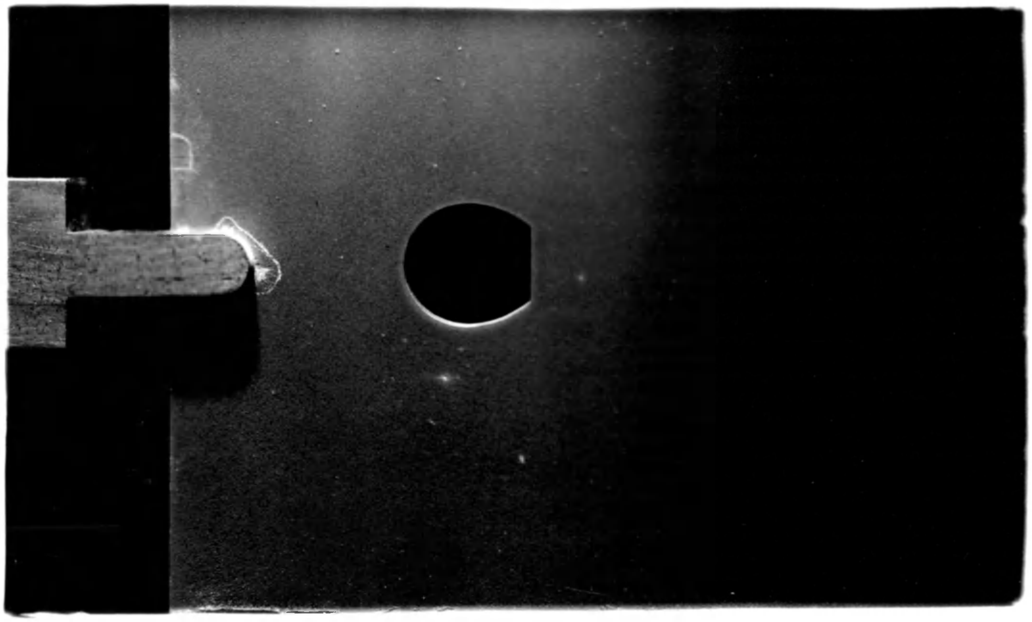

Fig. 29

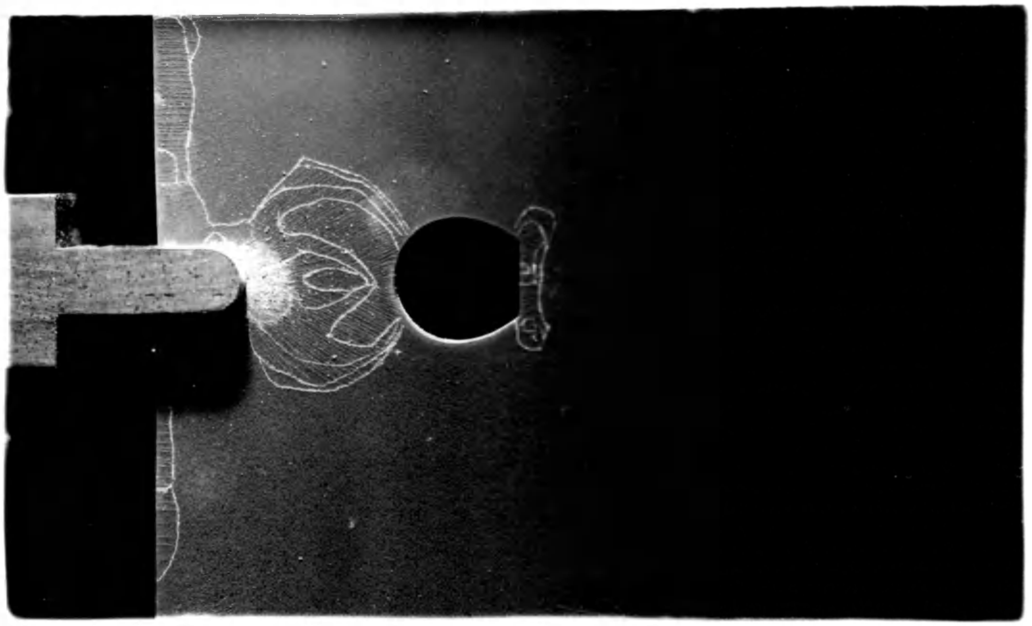

Fig. 30

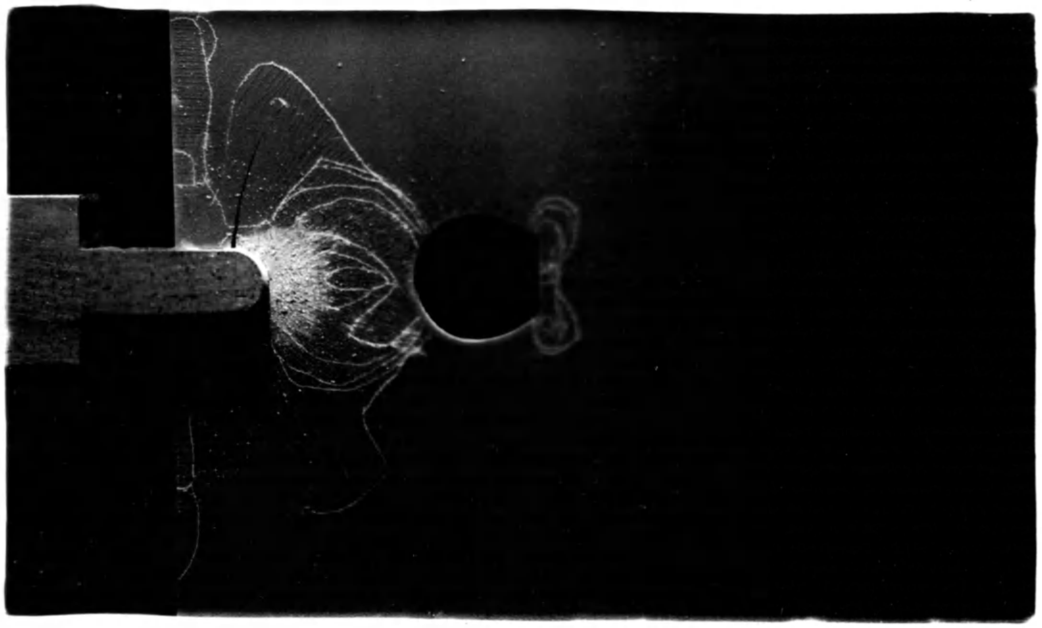

Fig. 31

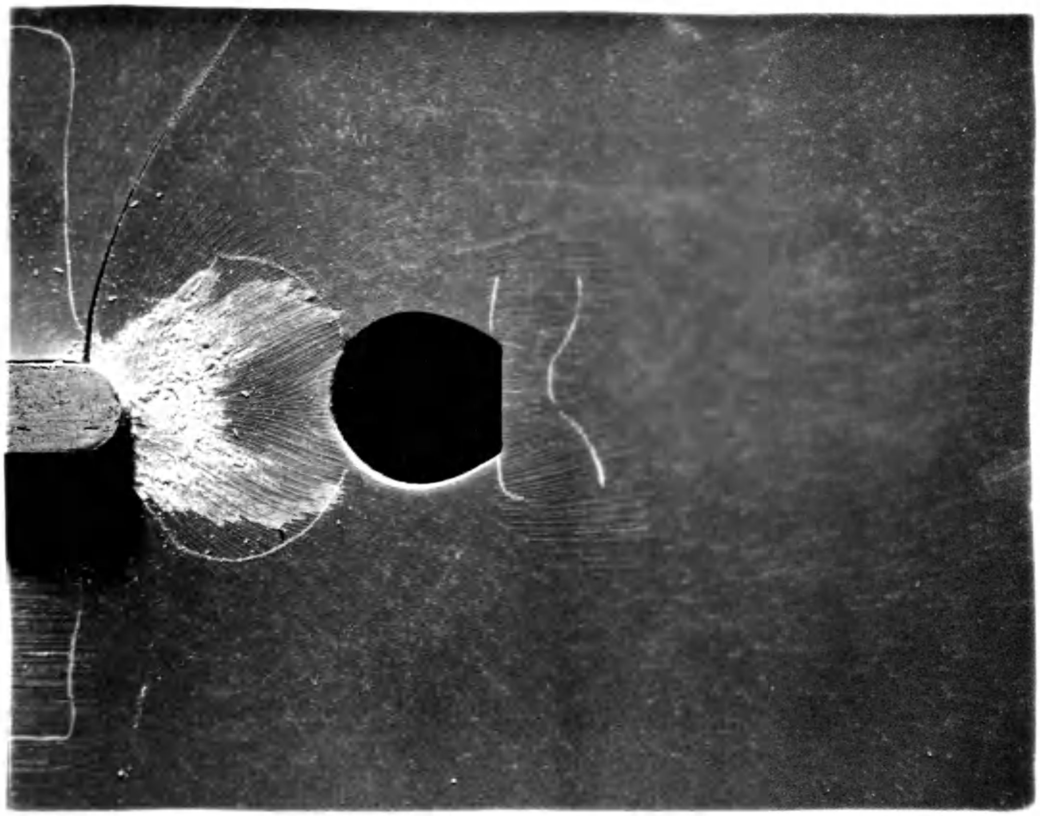

Fig. 32

floor. There was no spalling along the floor. At almost the same instant that the fingers of spalling reached the level of the floor, the model bulged in the spalled area between the tup hole and the tunnel, and broke into many pieces with a loud noise. Although this last phase proceeded quite rapidly, the bulge was confined to the spalled area above the tunnel so far as could be observed. The load at the time of complete failure was 1525 lb, which would indicate that lateral confinement was operating.

Results of Photoelastic Test

A photoelastic test was made of one model to determine whether or not the results would confirm the results from the tests with Stresscoat. A model was prepared identical to the models used in previous tests but was not coated. It was tested in a polariscope using a loading frame which permitted lateral confinement similar to that used in previous tests. Since the procedure of testing in the polariscope was standard, its description here would be superfluous. The important points to consider are that the model was laterally confined, using oil to reduce friction, and that concentrated stress was applied at the tup hole. Loads were applied in seven increments to a point at which a full stress pattern was developed. Each increment was photographed (see Fig. 33 to 36).

In Fig. 36, the most fully developed stress pattern, maximum shear contours can be seen hanging from the tup hole in two lobes and in three long fringes on each side, beginning at the tup hole and ending at the lower boundary of the tunnel. One fringe begins at the tup hole and goes completely around the tunnel opening without touching it. Other

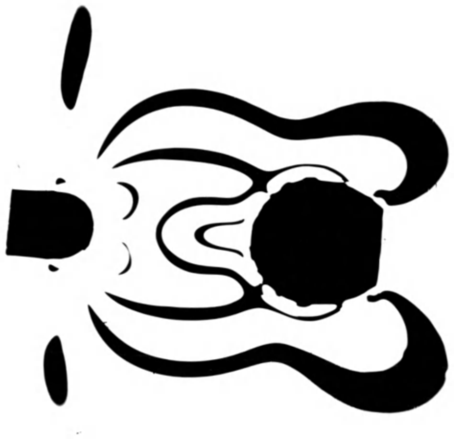

Fig. 33

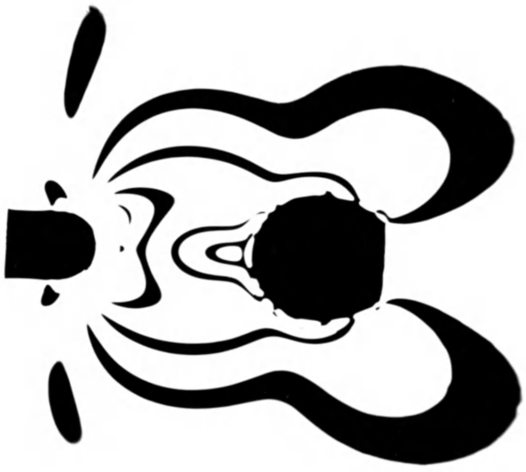

Fig. 34

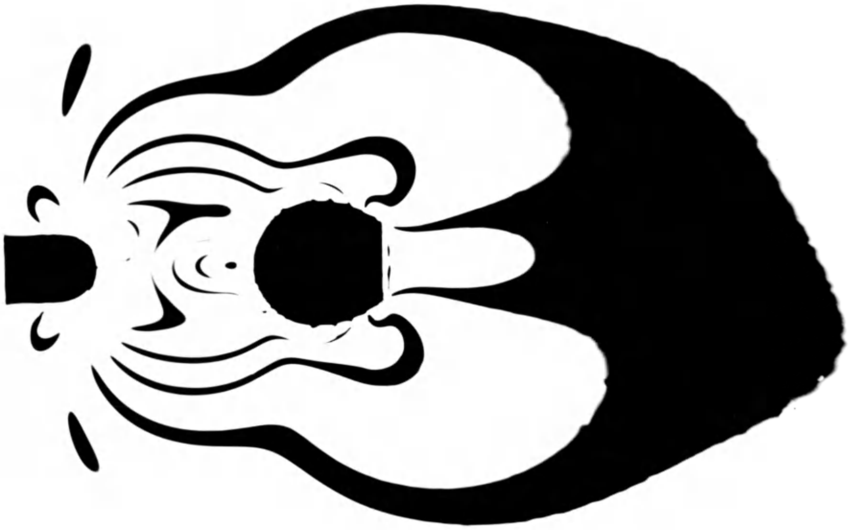

Fig. 35

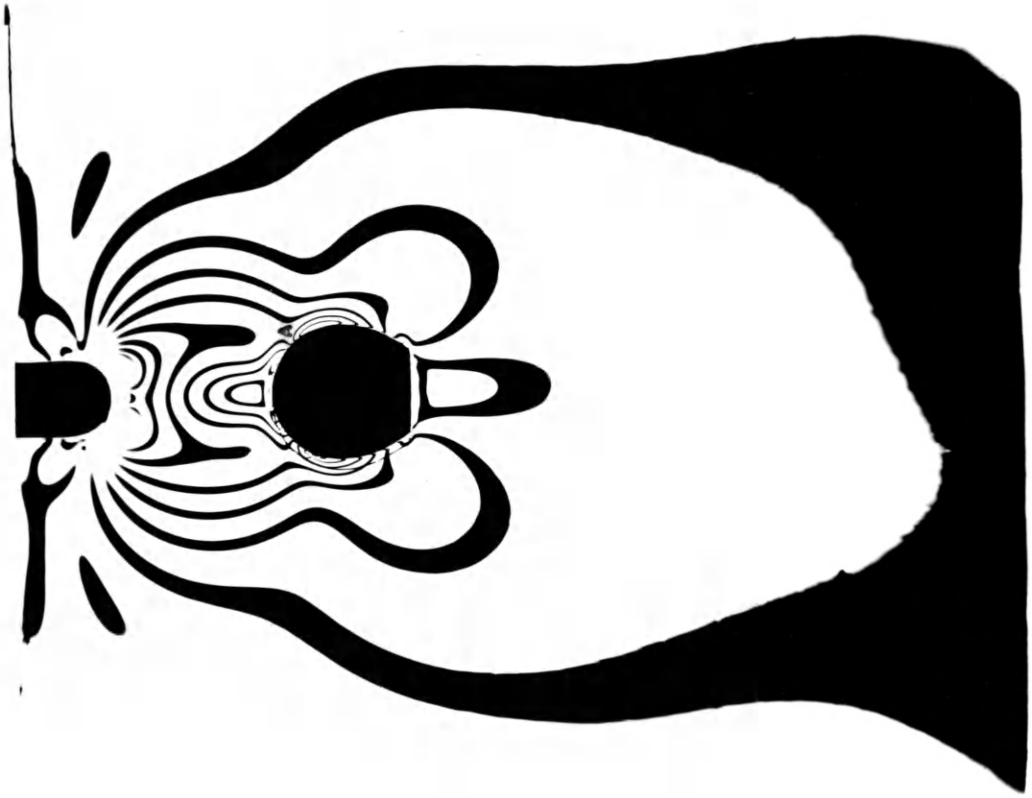

Fig. 36

maximum shear contours in the form of small bumps, two on each side, can be seen about 2/3 of the way up on each rib. These are thought to indicate compression at the points in which they touch the boundary of the tunnel. However, an exact analysis cannot be made since Poisson's ratio for Homalite has never been determined. Shear contours of different shapes can be seen at the top and bottom of the tunnel. These are thought to indicate tension at the points at which they touch the boundary of the tunnel, but lacking Poisson's ratio, an exact analysis cannot be made. For purposes of this discussion, those fringes which are thought to indicate compression along the boundary will be referred to as "compression fringes," and those which are thought to indicate tension will be referred to as "tension fringes." It is believed that the point of no stress along the top boundary of the tunnel lies in the zone on each side of the tunnel boundary between the last tension fringe and the first compression fringe (Zone A on Fig. 36). These points lie approximately 0.65 in. above the tunnel floor. This corroborates the findings from the Stresscoat tests. In these tests, the point at the top of the tunnel boundary below which tension cracks did not move appeared at approximately the same spot: in the last nine tests, the low was 0.605 in.; the high, 0.70 in.; and the average, 0.65 in. (All heights were taken from the photographs and were correlated with the known floor width to compensate for photographic distortion.) In the last three tests, the heights taken from Fig. 25, 27, and 29 and corrected for distortion were 0.65, 0.66, and 0.66 respectively.

The extent of the tension fringes in the floor of the tunnel corresponds generally with that of the tension cracks in the Stresscoat tests. Although not too clearly defined, the tension fringes apparently begin at the point of contact between ribs and floor. The last compression fringe reached the boundary a short distance up on each rib; therefore the change from compression to tension is thought to take place in the zone between this point and the point at which the first tension fringe touches the boundary. In the Stresscoat tests, the tension cracks closest to the tunnel boundary begin at the juncture of rib and floor or slightly up on each rib (see Fig. 32).

The area of compression spalling at certain stages corresponds generally with the two lobes of compression fringes hanging from the tup hole of Fig. 32).

Without knowledge of Poisson's ratio for Homalite, a further and more exact analysis is impossible. However, it can be seen that preliminary analysis shows a great deal of similarity between the results of the Stresscoat tests and the photoelastic test.

DEFICIENCIES AND ERRORS

A few overall observations should be made about deficiencies in facilities and possible experimental errors. Some of these have been discussed previously in the relevant sections and will not be discussed again here. Others, as reported earlier in this paper, were eliminated as they became known.

There were also certain other deficiencies in equipment. The tolerances in the milling machine were so large as to make difficult the attainment of the required degree of accuracy. Likewise, the mechanisms for holding and aligning the model in the machine were awkward to use and caused some slight errors in making the sides exactly parallel and perpendicular to one another. To keep cutting tools and files sharp was always a problem; the machines and tools were being used much of the time for non-research projects which required their use on metals. The results of this use were dull, broken, and lost tools and abuse of the machines. In the spraying and testing of the models, a room with controlled temperature and humidity would be of great aid. The deficiencies in loading mechanisms were fully discussed in the section on Loading Equipment. A general recommendation for loading equipment would be to redesign the loading frame to provide lateral confinement plates with set screws for both sides (in lieu of the one slotted plate which tended to slip), to make it stronger, to eliminate the necessity of extending the model 1/2 in. above the top, and to remove obstructions in viewing the rear of the model. The new photographic equipment to facilitate picture taking mentioned by Hesselbacher 20/ has not yet been received. A deficiency in the photographs lay in the shadow of the tup on the upper part of the model. A light source at each side would probably correct this deficiency.

The effect of possible errors in the cutting and machining of the models was mentioned in the section on Preparation of Models. There are errors also in the behavior of the Stresscoat due to the lack of control over the temperature and humidity of the spray room and test room. Other possible errors in the use of the coating include improper thickness, creep, and improper drying.

There may be errors in the application of lateral confinement even

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20/ *Op. cit.*, pp. 33 to 38.

when the confinement is thought to be proper; it is certainly true that confinement was improperly applied in some tests and confinement plates slipped in others, as already reported. Furthermore, since confinement is static and cannot be varied, there is a possible error in the basic assumption of its application; it may be that lateral confinement should be increased with increase in load. Since any assumption on lateral confinement depends on Poisson's ratio and the value of this ratio for Homalite is unknown, there is room for error. In addition, this ratio is even known to vary with load and should not be considered a constant for the material being used.

The loading of the model itself is believed to be free from errors. Because of the time required to reach the desired load, to inspect for and mark crack patterns both front and back, to photograph under awkward conditions, and to record data, creep of the coating undoubtedly occurred. Other than loading the calibration strip for the same total time as it took to completely load the model, no attempt was made to correct the results for this error in creep. It is also highly possible that there was some slight bending of the model due to unknown eccentricities in loading or inaccurate machining of the model. However, no obvious bending cracks appeared in the coating such as those experienced in the work of Hesselbacher 21/. The use of model material 1/2 in. thick might tend to reduce possible bending.

21/ *Op. cit.*, pp. 43 to 49.

CONCLUSIONS

As a result of this investigation, the main conclusion to be drawn is that a study and a final determination of the laws of failure of Stresscoat should be carried out. Unexplained by any previous investigation or by the commonly accepted maximum tensile strain law is the paradoxical development of compression spalling over the same area as that occupied by tension cracks. (The area between tup hole and tunnel opening.) If the tension cracks form as a result of the action of the maximum principal tensile strain in that area, how can so-called "compression" spalling later cover the same area when there has been absolutely no change in the nature of the load applied (compression) but only an increase in intensity? Perhaps failure of Stresscoat is due to a stress difference between the maximum principal stresses, but this point will have to be left to future investigators to determine.

After the laws of failure of Stresscoat have been determined and some of the deficiencies previously described have been eliminated, it is concluded that the method described here can be used to obtain reliable statistical results for correlating static and impact loads on an opening. However, as the writer has found in this work, the results will be valid only if the following precautions are taken:

1. Models must be carefully laid out, cut, and machined to the highest degree of accuracy possible.
2. Stresscoat must be carefully applied and properly dried, under controlled temperature and humidity if possible.
3. Models must be carefully adjusted in the loading frame under lateral confinement so as to prevent absolutely any eccentricity or variation in loading.
4. Loading must be smoothly and evenly applied.

5. Crack patterns must be located and immediately marked when the desired load is reached.
6. Photographs must be taken quickly, preferably by using a mechanism by which light and shutter operate simultaneously.

To make the test run smoothly and to prevent excessive creep of the coating, two persons are required: one to operate the hydraulic testing machine and one to locate and mark crack patterns, photograph the model, and record the data.

An interesting result of this investigation was the apparent discovery of the area of hydrostatic pressure. Although this area was difficult to delineate and varied in different tests, its presence was certainly observed. Only after the laws of failure of Stresscoat have been determined can this area be more fully investigated.

One final conclusion is that an early determination of Poisson's ratio for Homalite is required if this material is to be used in future studies.

The possible future investigations suggested by the present work are:

1. The effect of size and shape of the opening upon the stress distribution around the opening.
2. The effect of tup size and shape upon the stress distribution around an opening.
3. The effect of the depth of tup hole and of its lateral position upon the stress distribution around an opening.
4. The effect of impact loads upon all the above items.
5. The correlation of impact and concentrated static loads.

APPENDIX I (Cont'd)

Modulus of Elasticity in Flexure, psi x 10^5 (g) (h)

50 C (122 F)	1.6-2.0
25 C (77 F)	2.5-3.3
-10 C (14 F)	3.7-4.0
-57 C (-70 F)	3.4

Compressive strength

Ultimate, psi (i)	22,800
Modulus, psi x 10^5	2.3

Impact strength, 25 C, ft - lb per in.

Izod, notched	0.3-0.4
Charpy, notched	0.3-0.4
Izod, unnotched	2-3
Charpy, unnotched	3-4

Thermal expansion (l) linear coef, per deg C x 10^{-5}

-40 C to -10 C	7.0
-10 C to +25 C	8.7
25 C to 50 C	10.7
95 C to 120 C	15.3

NOTE: Letters (a), (b), (c), etc., refer to methods of test which are reported in Pittsburgh Plate Glass Company Plastics Bulletin No. 2.