CASTABLE PLASTICS
IN PHOTOELASTIC STRESS ANALYSIS

Thesis by
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SUMMARY

An investigation was begun on the feasibility of utilizing castable, thermosetting plastics in experimental stress analysis by means of either photoelasticity or electrical strain gages imbedded in the plastic.

The first phase of the study was the development of a casting technique that would give a stress free casting suitable for photoelastic work. This was considerably complicated by the inherent shrinkage which occurs during the polymerization of the plastic. A good method was found for casting solid models, and a workable method was devised for casting hollow section models.

The second phase constituted the development and evaluation of the optimum physical properties of a resin known as Castolite. The results were encouraging with the exception that the strain creep was excessive. The rate of creep, however, is slow and it is possible to use the material for two dimensional photoelasticity with results comparable to those obtained from other photoelastic materials. The desirable features are a very low optical creep, stress-strain and stress-fringe number curves that are linear for constant loading time, no time-edge stress effects, chemical stability under high temperatures, modulus of elasticity of 600,000 psi, and a fringe value of 175 psi per in-fringe in tension

An additional feature is the ability to bond two or more cured plastic pieces together with the liquid plastic itself. The strength of the bonded area is equal to the rest of the structure.

Three dimensional frozen stress properties were not determined, but there is evidence that the resin would be suitable.

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NOTATIONS

E_0 = modulus of elasticity immediately after loading

E_{22} = modulus of elasticity 22 minutes after loading

f = fringe value in psi per inch per fringe in tension

$\sigma_{ult.}$ = maximum stress at failure of ultimate strength tensile specimens

$C = \frac{E_{22}\,\sigma_{ult.}}{f^2}$ = Suitability Factor

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I. INTRODUCTION

The ever increasing complexity of structural design problems in industry today makes the finding of practical solutions more difficult for the stress analyst. Theoretical solutions to many of these problems are either long and laborious or impossible. For this reason, more effort must be made in developing new and improving old methods of experimental stress analysis. Existing methods in the use of mechanical, electrical, and optical strain gages are limited to determining surface strains on bodies and, even then, are often unsatisfactory on sharp corners where stress concentration may occur. Photoelasticity offers an excellent means of experimentally determining stress within a body and stress concentrations on the surface but is seriously limited by the lack of materials with satisfactory photoelastic, mechanical, or fabrication properties.

The theories on strain gage and photoelastic stress analysis are well presented in various texts and papers on those subjects and will not be treated in this paper, although some standard works on the subject are listed in the references (1,2,3,4). Definitions of essential parameters and constants will be included in the body of the report.

a. Statement of the Problem

The aim of this study is to evaluate the possibility of utilizing thermosetting plastics in the casting of structural shapes of various complexities for the purpose of carrying out experimental stress analysis by either photoelastic methods or wire strain gages embedded in and on the cast structure. Work towards this enc was begun in July, 1949, and is still in progress at the time of this writing.

Such a procedure would result in a saving of time and expense and an increased versatility over the older method of machining structural shapes out of blocks of photoelastic material. Also, this procedure would remove the serious problem of size-limitation that has characterized photoelastic materials in the past. For example, Bakelite BT-61-893, one of the most common materials in use, can be obtained only in plates with a maximum thickness of the order of one inch.

A summary (5) of the desired requirements for an ideal photoelastic material for commercial engineering work is given as follows:

1. Low fringe constant, i.e. small increase in stress to give additional fringes,
2. Ease in machining into complicated shapes, or ability to cast into stress free and dimensionally accurate models,
3. Linear stress-strain relationship within the working range,
4. Linear stress-optical relationship within the working range,
5. High elastic limit and modulus,
6. Optical and physical homogeneity,
7. Absence of initial bi-refringence (fringe pattern) or possibility of removal by annealing,
8. Low optical and strain creep,

9. No permanent set or residual double refraction upon removal of the load,
10. Absence of edge stress on ageing,
11. High transparency and absence of color,
12. Possibility of making built-up models by bonding,
13. Low cost and availability.

b. Chemistry of Thermosetting Resins (6)

The thermosetting resins are solutions of unsaturated polyesters and monomers. The polyester and monomer are capable of co-reaction by addition polymerization, to yield strong, thermoset products without the evolution of any by-products.

Addition polymerization is that which occurs without the formation of water, ammonia, formaldehyde, or any other such low-molecular-weight by-product of the reaction.

In most cases of addition polymerization, many molecules of unsaturated monomer unite to form long-chain polymers in which the double bonds have disappeared and new single bonds are formed. The only by-product of this reaction is energy, which appears as heat.

The copolymerization of the monomer and polyester will occur after a relatively long period of time at room temperature. It can be accelerated by heating, and hastened still further by the use of peroxide catalysts. Auxiliary catalysts, such as mercaptans, amines, or heavy metal salts, have been found to permit a degree of curing even at ordinary room-temperatures.

There are at least six chemical factors which determine the properties of the resins before, during and after the copolymerization. These are:

(Features of the Polyester)

1. Molecular weight of the polyester
2. Ratio of unsaturated acid to saturated acid
3. Kind of saturated acid
4. Kind of glycol

(Features of the Monomer Solution)

5. Kind of monomer used
6. Ratio of polyester to monomer.

Any further detail of the chemistry of thermosetting resins is beyond the scope of this paper.

c. Polymerization Procedure

The complete polymerization, or curing, of a thermosetting plastic from the liquid state into the fully cured solid state for use as a structural model involves a maximum of five steps:

a. Addition of a certain percentage by weight of catalyst to the liquid plastic,

b. Use of moderate temperatures to generate or accelerate the gelation period,

c. Cooling of the plastic during the latter stages of the gelation period when the exothermic reaction of the polymerization releases large quantities of heat (This is a critical period because excessive temperatures in the plastic may cause cracks due to the vaporization of one or more of the components, or may induce thermal stresses in the finished casting that can not be annealed out),

d. Heating the firmly gelled plastic to a curing temperature that will complete the polymerization and produce the desired physical qualities and

e. Annealing the cured casting to remove casting stresses and, or improve the physical qualities.

Variations of the above steps can greatly influence the appearance, dimensions and physical properties of the final casting.

d. Evaluation Program

The greatest difficulty encountered in working with thermosetting plastics is the inherent volume shrinkage that occurs when the complete cure is effected from the gelled state to the hardened state. The average value of shrinkage is about 7½% in volume or 2½% in length. This presents two major problems in casting structures for stress analysis techniques. One is the difficulty of holding constant the desired relative dimensions of the casting. The other is the difficulty of obtaining a casting that is free of internal casting stresses and cracks. Unfortunately, a simple solution for either of the two problems usually aggravates the other condition.

In view of the preceding general information, a program for the evaluation of a castable plastic as a structural material for experimental stress analysis can be conducted in three phases after the preliminary investigations have been made. The preliminary investigations are to determine whether the physical properties and inherent characteristics are sufficient to warrant further extensive tests and development. Phase number one is the development of a satisfactory casting technique. Phase number two is the development and evaluation of the optimum physical properties for stress analysis applications. Phase number three is the practical application of the cast plastic structures to stress analysis methods of photoelasticity or strain gages.

e. Casting Techniques

A satisfactory casting technique must give a finished casting that is homogeneous throughout the body; that is, the interior should be free of striations, streaks, soft spots, cracks, bubbles, and other non-uniformities, the surfaces should be free of cracking and crazing and should maintain the smoothness and relative dimensions characteristic of the form or mold in which the plastic is cast. It should be highly transparent and colorless. The finished casting should ideally be free of internal stresses. In conjunction with the casting technique, may be included the ability to satisfactorily bond the fully cured plastic with itself by use of the liquid plastic or some other bonding agent.

f. Physical Properties

The physical properties may be divided into mechanical and optical properties of the plastic. The mechanical properties include mechanical creep, stress-strain relationships and edge stress-time effects. The optical properties include optical creep, optic-stress relationships and the mottle effect. In addition to the above, there is the "frozen" stress phenomena with the associated "freezing", or critical, temperature and the effective modulus and effective fringe values.

The variables which affect the casting and physical properties of castable plastics are the percentage of catalyst used, gelling temperature and time, intermediate cooling temperature and time, final curing temperature and time, annealing temperature and time, parting agents for the surfaces of the molds or forms, section thickness of castings, temperature of castings during test runs and observations, and the humidity and per cent vacuum of the atmosphere.

Fig. 1 is a schematic chart showing the relation between the casting and physical properties and the various variables.

II. EVALUATION OF CASTOLITE

a. General Comments on Castolite

Several commercial brands of thermosetting plastics were procured for preliminary evaluation as to possible use in this investigation. It appears that nearly all thermosetting plastics have potentialities as a photoelastic material. The plastic chosen for the further extensive tests and development which constitute the bulk of this report is supplied by the Castolite Company of Woodstock, Illinois under the trade name of Castolite. It is a member of the polyester class of resins. The basic resin forming components consist of a mechanical mixture of diethylene glycol maleate and monomeric styrene in the ratio 2 to 1 by weight. An inhibitor is used to prevent the liquid castolite from polymerizing. This mixture is stable for periods exceeding 12 months if stored at temperatures below 40^{O}F and kept free from light. Polymerization into the crystalline state can be accomplished by the addition of a suitable catalyst, such as cumene hydroperoxide, which was used in this series of tests. The rate and degree of polymerization can be increased by the use of heat. One very desirable feature of this material is that no by-products are formed or given off during polymerization, which eliminates the major cause for edge stress formation with ageing that has made other photoelastic materials undesirable.

The fully cured castolite is very stable at temperatures up to at least 250^{O}F and will not melt. In fact, high temperatures tend to harden it and improve its strength properties. It will not crack or craze due to sudden and frequent temperature changes.

Some of the more important physical properties of Castolite are listed in an appendix at the conclusion of this report. These data were supplied by the Castolite Company and one must bear in mind that they are average values calculated to cover a variety of curing procedures.

b. Casting of Castolite

One can not minimize the difficulty encountered in casting satisfactory specimens and models due to the inherent shrinkage that occurs when Castolite polymerizes. If the polymerization is allowed to proceed too fast, the heat released by the exothermic reaction can not be conducted away from the casting quickly enough and, hence, produces a high heat gradient in the plastic. Castolite in the liquid or solid state is a very poor conductor of heat. This causes the rate of polymerization to be much higher in the interior of the plastic than on the surfaces. The result will be that the interior is likely to begin shrinking while the surface is still in a liquid state. At worst, this will cause cracking in the interior of the specimen and almost certainly cause the surfaces of the specimen to be drawn away unevenly from the mold. The solution is to retard the rate of polymerization so that the liquid plastic will polymerize uniformly throughout the specimen. In this way, the specimen will be firmly gelled and tend to act as a solid body by the time appreciable shrinkage begins to occur.

Fortunately, the catalyzed liquid Castolite will gel at room temperature (75°F) within 24 hours so that the addition of heat, which is necessary to begin gelling in some plastics, can be eliminated with Castolite, thereby making possible a much slower rate of polymerization. This rate is further reduced by using the minimum amount of catalyst necessary to effect a complete gel. This amount decreases as the thickness of the casting increases. For ¼" thick specimens, this minimum has been found to be 3 drops of catalyst per 50 cubic centimeters of liquid Castolite, or about 0.3% by weight. The free surface of the liquid Castolite should be covered with a thin sheet of wax paper as air inhibits the polymerizing process. After the Castolite has firmly gelled, the polymerization is completed by curing at a temperature of not less than 180°F for 4 hours and slowly cooling at a rate not greater than 1°F per minute. Higher rates will introduce internal stresses due to the temperature gradient within the specimen. If the casting is to be annealed at a higher temperature, the time of this annealing may be subtracted from the 4 hours curing time listed above. In any event, the curing time should not be less than 60 minutes.

i. Casting of Rectangular Test Specimens

Specimens with constant thickness can easily be cast between two glass plates. The spacers between the glass plates can be carefully machined and polished so as to give the cast specimen the desired thickness and shape. The spacers can be made very easily out of metal, but it is more desirable to use plate glass, Plexiglass, or Lucite so that the heat conductivity will be nearly the same for all surfaces of the mold. Also, it was observed that the Castolite tends to bond itself to any metal surface not highly polished. A picture of the mold used to cast test specimens is shown in Fig. 2. The inside mold dimensions are $\frac{1}{4}$" x 1" x 10$\frac{1}{2}$".

Optically beautiful specimens can be cast in this mold. However, in order to be sure of stress free specimens, it is necessary to remove either the two flat plates, or the spacer from the mold assembly, before the final heat cure is applied. If the mold is left intact during the final cure, one side of the specimen is likely to adhere to one side of mold thereby restraining shrinkage in the plane of that surface and causing a residual casting stress when the fully cured specimen is removed. In any event, these residual casting stresses can always be removed by annealing for 1 hour at a temperature slightly in excess of the temperature used in the final heat cure.

Scotch tape or Molykote was very effective as a parting agent between the Castolite and the steel spacer surfaces. Lecithin or carnauba wax was used as a lubricating agent on the glass surfaces.

ii. Casting of Hollow Rectangular Models

The shrinkage problem becomes much more troublesome in the casting of hollow sectioned models requiring internal cores.

A rigid machined or fabricated metal mold can be used to obtain the outer surfaces of such a casting. However, a rigid, solid core prevents the necessary shrinkage from occurring, thereby causing severe tensile stresses which will crack the model walls during the final heat cure. Therefore, a suitable core must be spongy so that it will compress with the shrinking plastic, or it must become soft and pliable at the final curing temperature so that it can be "squeezed" out of the way, or it must melt at the final curing temperature and run away from the casting. If the hollow part of the model to be cast has no undercuts, a rigid core can be made in segments so that it may be removed after the plastic has firmly gelled but prior to the final heat cure. The removal operation must be made in such a manner that no sliding contact is made with the gelled plastic, as scuffing and tearing will result.

Although much time and effort was put forth on this problem no method has been found at the time of this writing that is entirely satisfactory.

Several synthetic rubber compounds were tried. The results obtained were not encouraging for the following reasons; either the core was not flexible enough, or the material would react with the Castolite and inhibit the polymerization, or the material would swell excessively when brought in contact with the liquid Castolite thereby causing the core surface to become warped and misshapen. This type of core inherently causes some residual casting stresses in the fully cured model, but they may be removed by annealing if they are not too severe.

Hollow rectangular section models were successfully cast by using a segmented rigid core made out of steel, which was removed before the final heat curing step when the greatest shrinkage occurs. The core was segmented so that it could be removed piece by piece from the gelled model without any sliding contact between the segments and the plastic surface. Extreme care must be taken to seal the assembled core so that the liquid Castolite will not seep into the cracks between the segments. Water pump grease and Lecithin were used as a sealant with moderate success. The disadvantage of this type of core is that it would be difficult, if not impractical, to use in casting models that have undercuts on the inner surfaces.

The most promising method of constructing cores is in the use of low-melting materials or alloys.* So far, only several varieties of waxes have been tried. The melting point of most waxes is well below the final curing temperature used for Castolite. The major difficulty encountered is that the liquid Castolite dissolves a small amount of the wax core before it has gelled. This amount is so small that no change in dimensions of the core can be discerned. The real difficulty is that the resulting solution of wax and liquid Castolite settles very slowly to the bottom of the casting as is evidenced by a thin, slightly cloudy layer at the surface which is almost imperceptible on the upper regions of the casting, but slowly thickens

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*During the editing of this thesis, a report was published on another castable plastic wherein a low melting metal alloy was used successfully to cast three dimensional models (7) toward the bottom of the casting. What effect this would have on the physical properties of the Castolite was not determined. Other waxes are being tried and, also, an attempt is being made to apply an impermeable coating or covering to the wax core. Scotch tape was found to be very effective.

The wax cores are made by essentially slush molding the melted wax in a metal mold. Two different methods can be used, depending on the complexity of the core. A detailed description follows because it is believed that the methods can be applied equally well to any other low melting point material.

One procedure is to pre-heat the metal mold to the melting temperature of the wax. This will prevent cracks on the surface of the finished core. The mold is then filled with the molten wax. As soon as a thin crust of hardened wax forms on the surface of the mold, the rest of the wax is poured off. The thin crust and mold is then allowed to cool to near room temperature. The cooled mold is again filled with molten wax and emptied after a small additional amount of crust has formed. This is repeated until the desired thickness is obtained. A thin walled core of this type is desirable because it will soften and melt faster than a solid core during the final heat cure of a plastic casting. Strips of screen wire may be embedded in the inner surface of the hollow core to give additional rigidity when the core is removed from the mold. If the wax is cast directly in the core mold without a parting material, heat must be applied through the mold surface to form a thin film of molten wax on the core so that it can slide free from the mold. Best results are obtained by using a fabricated mold which can be removed from the core in pieces. This procedure can be modified by the use of a parting agent such as thin metal sheeting which can be "peeled" away from the core after it has been removed from the mold. However, such a core must be built up very carefully to maintain the dimensions of the mold.

The above procedure produces a core that has the exact dimensions of the mold. The limitation is that it can be used only for cores with plane surfaces or constant cross sections.

The alternative procedure is to cast a solid core. Best results are obtained by pre-heating the mold to the melting temperature of the wax and then filling it with molten wax and allowing it to cool slowly. Small diameter metal rods should be inserted in the core to minimize the tendency of the solidifying wax to shrink unevenly away from the mold surfaces and cause a warped core. If the metal rods are further fixed securely to the mold, the core will tend to separate uniformly from the mold on all surfaces. The difficulty with this procedure is that the core may pull itself out of shape by adhering in places to the mold. The hardened core should have the metal rods removed and be further hollowed out to facilitate its melting away during the final heat cure of the plastic casting.

Fig. 3 shows several cast hollow rectangular section models and the necessary cores and molds used in the casting procedure. Dakes varnish may be applied to the surfaces of the castings to improve the transparency.

c. Bonding

A very desirable feature of Castolite is that two or more fully cured specimens can be bonded together by the catalyzed liquid Castolite itself. The procedure is to thoroughly polish the surfaces to be joined, using a very fine grain sand paper. The pieces are then placed in a retainer which serves to position and hold them during the bonding and, also, to contain the liquid Castolite within the joint. Scotch tape proved to be very effective for this purpose also. The liquid Castolite is catalyzed with about 2% catalyst by weight (35 drops of catalyst per 100cc of plastic) and applied to the surfaces to be bonded. This joint may then be heated at 120°F for thirty minutes or allowed to sit at room temperature for about ten hours. After either of these gelation processes, the joint is fully cured at 180°F for one hour and slowly cooled at a rate of about 1°F every two minutes. The final bond is as strong as the rest of the structure and introduces negligible internal stresses which, for all practical purposes, do not affect the fringe pattern.

d. Test Equipment and Procedure

All tests were conducted with the cast rectangular test specimens described above. The specimens were used in the "as cast" state, except for ultimate strength tests when 3/4" radius hollow grooves were filed 1/16" into opposite sides of the specimen. Fig. 4 shows an ultimate strength specimen with the steel jig used in filing the grooves to the desired dimensions. Fig. 4 also shows an "as cast" tensile specimen with the parallel knife edges and dial gages used to obtain strain readings. A Dillon dynamometer, with interchangeable 1000# and 10,000# heads, was used to apply tension loads. The ends of the test specimens were covered with medium grain emery cloth to prevent them from splintering in the serrated wedge grip jaws of the dynamometer (see Fig. 4). Fig. 5 shows the dynamometer set up for a test run. Fig. 6 shows a loading machine for applying pure bending to the test specimen. The polariscope consists of a 60 watt sodium vapor lamp, two spherical mirrors of 100cm. focal length, two polaroid lenses, two collecting lenses, and a screen or camera. The arrangement (8) of the polariscope and loading frame is shown schematically in Fig. 7 and in the laboratory in Fig. 8. A small electric, laboratory furnace, with a maximum range of 350°F and a variable temperature control, was used for the final curing and annealing operations. A circulating oil furnace with a means of controlling the rate of cooling would have been desirable for annealing operations as it was found that too high a rate of cooling from high temperatures produced surface cracks on the specimen.

e. Physical Properties at Room Temperature

Investigations were made to determine how the physical properties of Castolite were affected by the amounts of catalyst used, annealing temperatures, and duration of the curing and annealing temperatures. Records were taken of strain and fringe order against time for various loads for all specimens tested.

It was found that maximum repeatability was obtained when the specimen had been cured or annealed for 4 hours at the maximum temperature to which it had been subjected. There was no indication that the physical properties were affected by the length of time that the specimen was kept in the gelled state before the final cure was applied.

Specimens were cast using 3, 5, 6, and 10 drops of catalyst per 50cc of liquid Castolite. Tests were then made of the specimens as cast (cured at 180°F), or after annealing at 210°F or 240°F. Figs. 9 and 10 are plots of various properties against amounts of catalyst used. The results indicate that the larger amount of catalyst used is beneficial in reducing the fringe value, but detrimental in reducing the modulus of elasticity and increasing the strain creep. The "Suitability Factor" (9), $C=\frac{E\sigma}{f^2}$, which is a useful measure of the practical application of a photoelastic material, can be modified for use here by replacing the modulus of elasticity, E, with a modulus calculated 22 minutes after the load is applied. In this way, the effect of strain creep is entered into the "Suitability Factor". 22 minutes was chosen because the creep rate had become very small after this length of time. The proportional limit, σ, may be replaced by the ultimate strength, σ_{ult} , and the fringe value, f, may be taken as the value obtained immediately after application of the load. This modified factor indicates that a minimum amount of catalyst gives the optimum physical properties.

Fig. 11 is a plot of the same properties against final heat treat temperatures of 180°F, 210°F, and 240°F. This plot is only for specimens cast using 3 drops of catalyst per 50cc of liquid Castolite. Except for the fringe value, all the properties are improved with higher annealing temperatures, at least within the range covered here. Also, the modified Suitability Factor, C, Suggests that annealing at 240°F or higher is desirable. However, Castolite becomes more brittle with increasing temperature heat treatment and, at 240°F, was found to be very sensitive to notches and surface discontinuities that produce stress concentrations and cause premature failure.

Strain creep is very pronounced in Castolite as is evidenced in Figs. 9, 10, 11 and 12. However, the creep is proportional to the strain as is shown by Fig. 13. This is very desirable in photoelasticity since it means that the relation between stresses in different parts of a strained body does not change with strain creep.

In view of the rather large strain creep, it is surprising that the optical fringe creep is so small. Figs. 9, 10, and 11 show this creep to be around 2½ per cent in 22 minutes, and Fig. 12 indicates that very little, if any, creep occurs after 22 minutes. Fig. 14 demonstrates that the fringe order is proportional to the stress. With these characteristics, it should be possible to obtain a fringe pattern that would be stable and true enough to give good two dimensional photoelastic results. Fig. 15 shows a specimen in pure bending immediately after loading, 22 minutes later, and 3 hours later.

f. Elevated Temperature Properties

There was not sufficient time to make an investigation of the physical properties at elevated temperatures or otherwise evaluate the frozen stress properties of Castolite for possible three dimensional photoelastic applications. The phenomenon of frozen stress in photoelasticity is adequately explained in several of the references listed (1, 2, 10). Pure bending stress patterns were successfully frozen into several test specimens. This indicates the probability that Castolite is suitable for three dimensional photoelastic stress analysis.

g. Edge Stress Effect

One of the big disadvantages of most photoelastic materials used today is the appearance of fringes on the edges of photoelastic models as they age. This is usually due to surface stresses set up by the oxidation of the surfaces, or evaporation of volatile materials from the surfaces. Castolite is very stable in this respect. Specimens 10 months old showed no visible signs of fringes appearing on the edges. Also, repeated annealing of the specimens does not introduce any edge stresses provided, of course, that the cooling rate does not exceed 1°F per minute.

III. CONCLUSIONS AND RECOMMENDATIONS

From work carried out thus far, it appears that Castolite has good photoelastic characteristics for stress analysis work. It has linear stress-strain and stress-fringe number relationships for a constant time of load application. It has a very small optical creep, although the large strain creep places a limitation on the length of load application and the general accuracy because of the distortion from the original shape and dimensions. The material is very stable and does not suffer any time-edge stress effects.

Castolite can be easily cast into stress free solid specimens and offers good capabilities of being cast, stress free, into intricate hollow sectioned models for use in three dimensional frozen stress analysis. Also, it has the desirable feature that two or more fully cured specimens can be bonded together into fairly arbitrary forms, thus presenting the possibility of fabricating models that can not be cast. The bonded surfaces are as strong as the rest of the structure and, for practical purposes, introduce no stresses that will affect a fringe pattern.

It is recommended that elevated temperature tests be completed and the "frozen stress" properties be determined. A model should be cast, loaded with a known stress pattern, and analyzed by the "frozen stress" method so that the authenticity and accuracy of Castolite as a three dimensional photoelastic material may be ascertained.

An attempt should be made to cast a model with electrical strain gages embedded in it, so that the feasibility of using this scheme as a stress analysis method may be determined.

A thermosetting plastic manufactured by the Rohm and Haas Company should also be evaluated for its casting and photoelastic properties. This product may prove to be a better material than Castolite, since its ultimate tensile strength is about 50% greater than that of Castolite and preliminary investigations have indicated that it has about the same fringe value as Castolite.

The Rohm and Haas Company has expressed an interest in this work and has furnished the necessary plastic to continue the research upon their product, Paraplex P-43. Preliminary results are satisfactory but no specific results can be reported at this time. It is recommended that the investigation of this plastic be continued.

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APPENDIX

a. General Comments on the Qualities of Finished Castolite (11)

The following are a few of the more important physical qualities of finished Castolite:

Color: It is water white, comparable to ordinary glass. The liquid Castolite is a syrup resembling honey and is tinted a light bluish-green. It has good color stability with practically no change under ordinary indoor lighting conditions. Under prolonged outdoor exposure to the sun and weathering conditions it turns slightly yellow.

Refractive Index:

a.	Liquid state	1.5378 at 77°F
b.	Solid state	1.5591 at 77°F

Viscosity

a.	Regular Castolite	525 centipoises
b.	Low Viscosity Castolite	50 centipoises

Shrinkage During Cure: The shrinkage is approximately 7.5% by volume.

Machining Properties: It is very easy to machine with a little practice. It will not "gum" on high speed tools. A lubricant, such as soap or paraffin oil, should be used in sawing and drilling operations. Machined pieces are readily buffed to produce a high surface gloss.

Effect of Chemicals: Castolite suffers no effects from the action of water, soaps, weak acids, vegetable oils, gasoline, kerosene, lubricating oils, and alcohol. It undergoes a slight softening under the action of acetone, carbon tetrachloride, alkalis and cleaning fluids.

No method is known for dissolving Castolite. However, it will slowly disintegrate under the action of acetone.

Average Physical Constants:

a.	Specific gravity	1.25 gm. per c.c.
b.	Tensile strength	4,000 psi.
c.	Flexural strength	10,000 psi.
d.	Flexural modulus	550,000 psi.
e.	Compressive modulus	500,000 psi.
f.	Impact strength	0.2 ft. lbs.
g.	Hardness	Barcol value 40-45 Rockwell M. value 115-125
h.	Heat distortion point	ASTM method 180°F

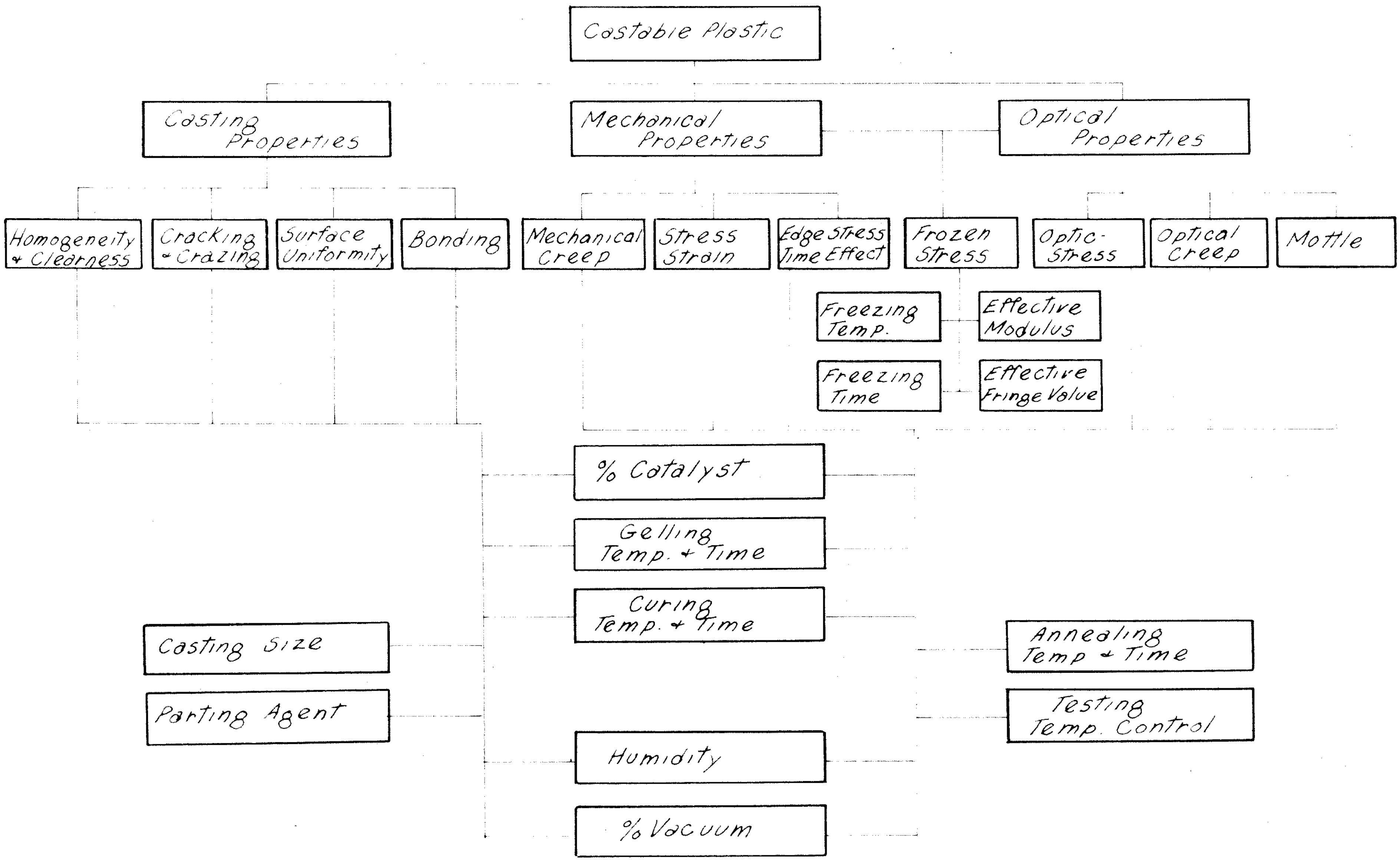


FIG. 1

SCHEMATIC CHART OF PROPERTIES AND VARIABLES OF PLASTIC CASTINGS

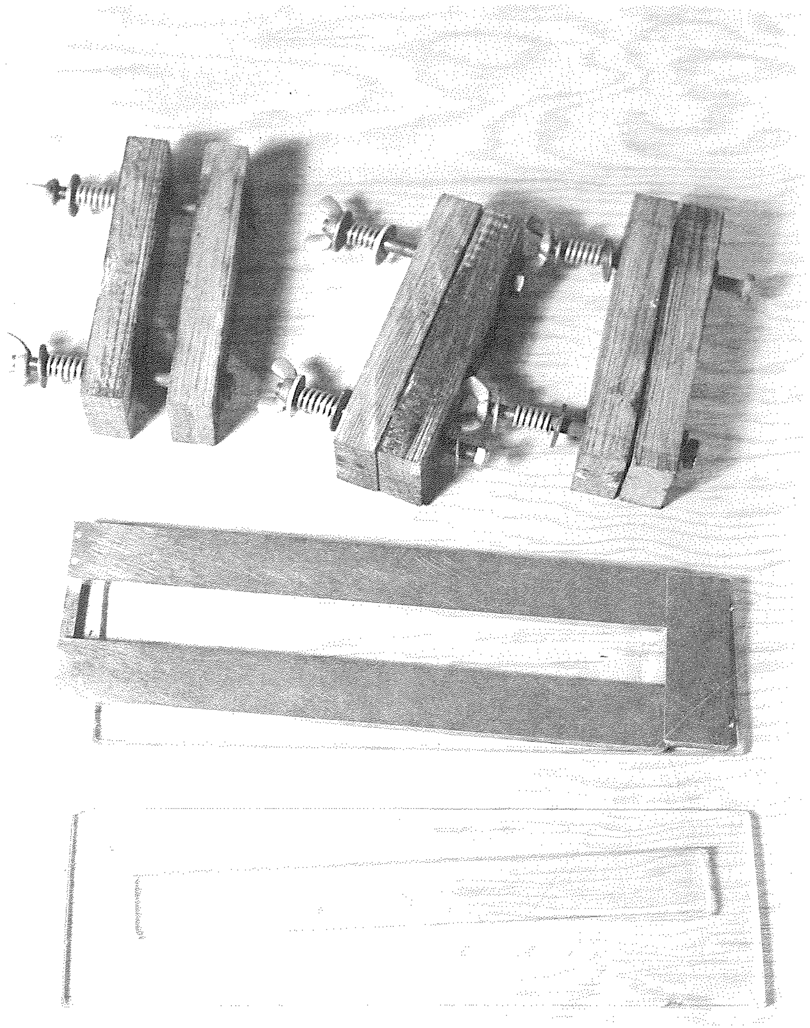


Fig. 2

Test specimen mold and test specimen.

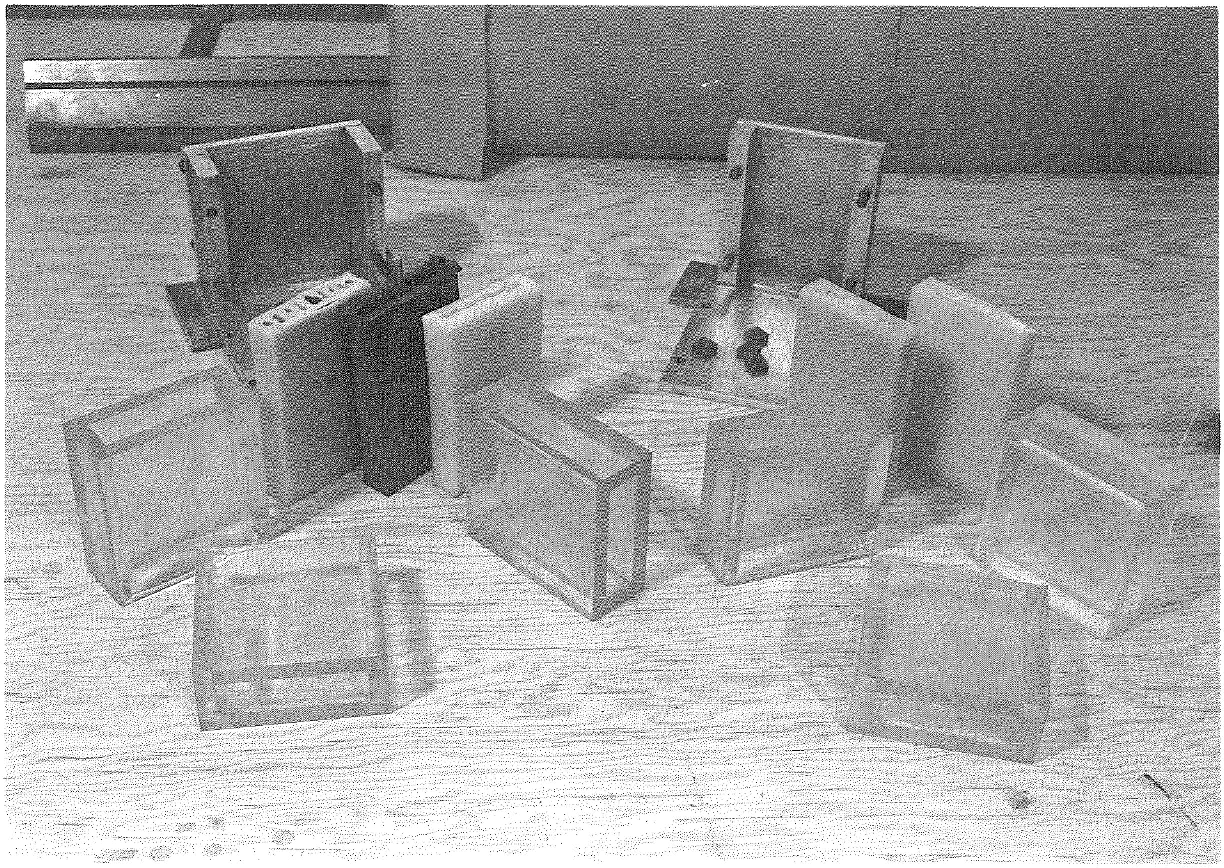


Fig. 3

Top left, metal mold for casting hollow rectangular models. Top right, metal mold for casting the cores that are used in casting the hollow models. Lower left grouping, castings and typical flexible cores used in their construction. Lower right grouping, castings and typical wax cores used in their construction.

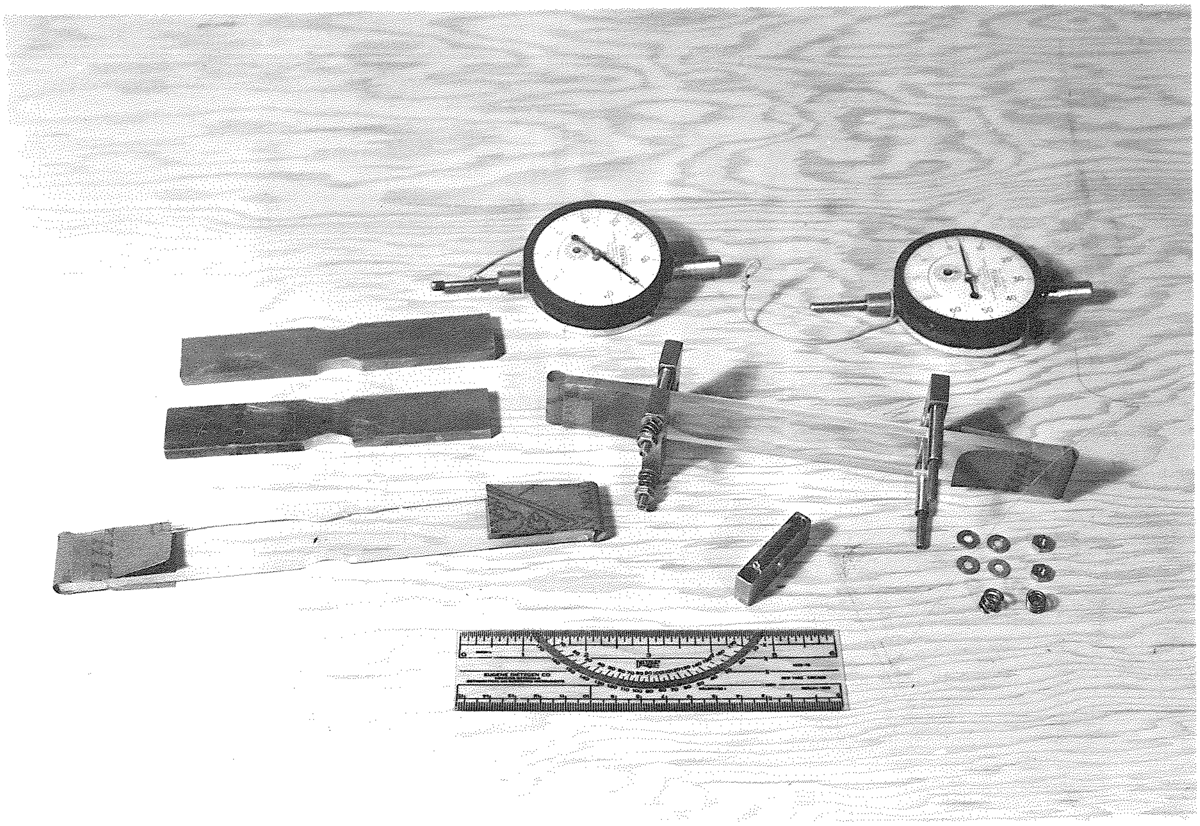


Fig. 4

Specimens ready for testing. Stress concentration factor for ultimate strength specimen is 1.2, i.e. $\sigma_{ult} = 1.2 \frac{F(max)}{A(min)}$.

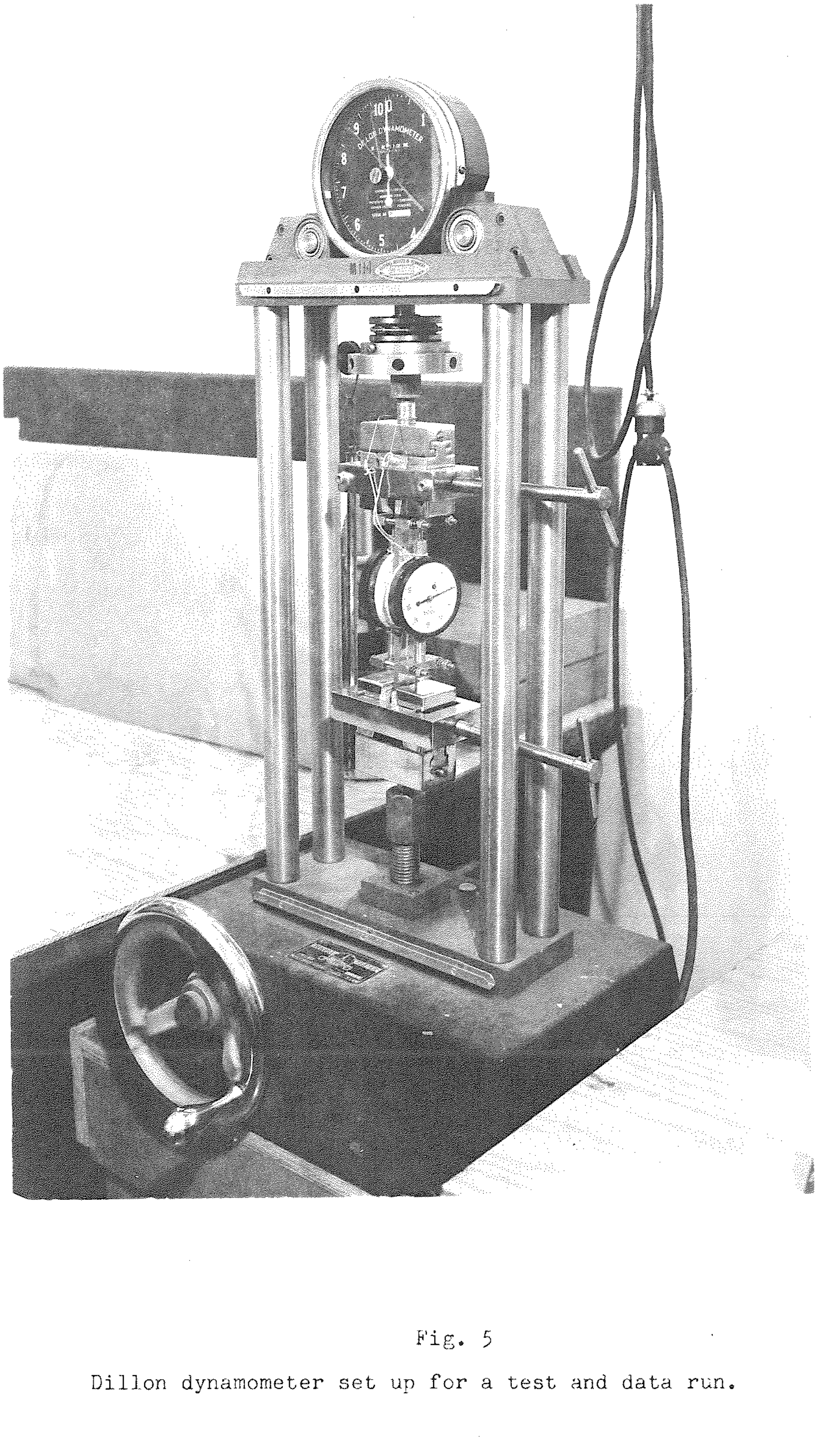


Fig. 5

Dillon dynamometer set up for a test and data run.

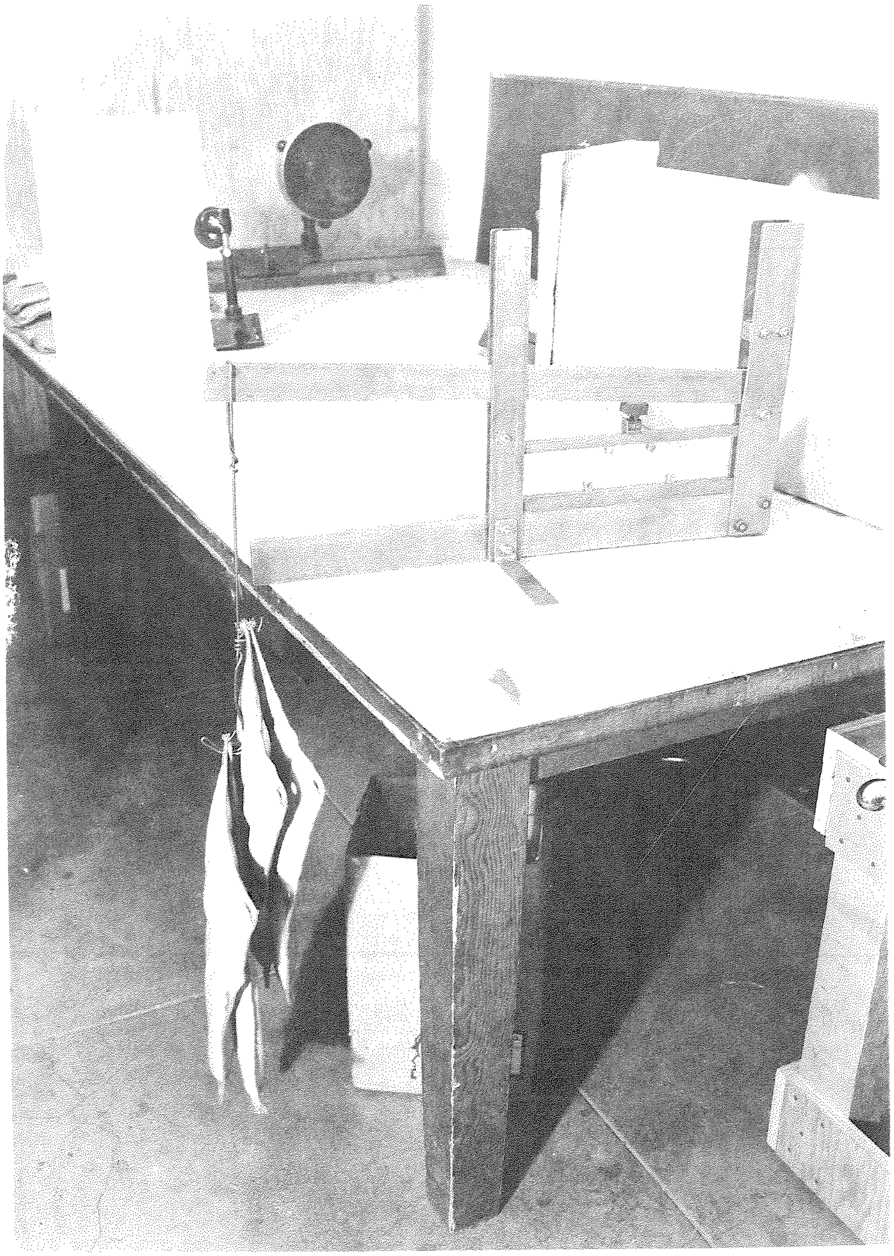


Fig. 6

Loading machine applying pure bending
to a test specimen.

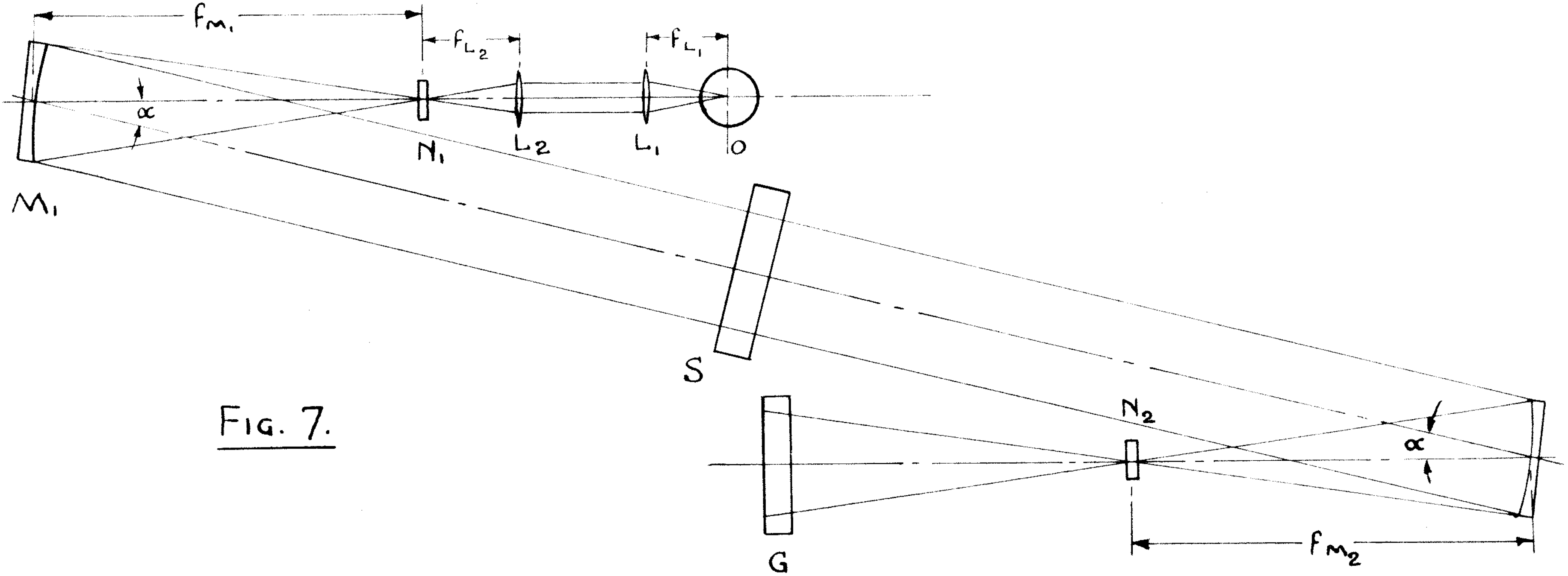


FIG. 7.

SCHEMATIC PLAN VIEW OF PHOTOELASTICITY EQUIPMENT.

O = LIGHT-SOURCE. (60-WATT SODIUM VAPOR LAMP).
L_1 AND L_2 = CONDENSING LENSES.
f_{L_1} AND f_{L_2} = FOCAL LENGTHS OF LENSES L_1 AND L_2 RESPECTIVELY.
N_1 = POLARIZER (LOCATED AT FOCAL POINT OF LENS L_2 AND MIRROR M_1)
N_2 = ANALYZER (LOCATED AT FOCAL POINT OF MIRROR M_2).
M_1 AND M_2 = SPHERICALLY GROUND MIRRORS (RADIUS = .1 METERS).
f_{M_1} AND f_{M_2} = FOCAL LENGTHS OF MIRRORS ($f_{M_1} = f_{M_2} = 1$ METER).
S = SPECIMEN OR MODEL IN LOADING FRAME.
G = GROUND-GLASS SCREEN OR FILM PLATE.

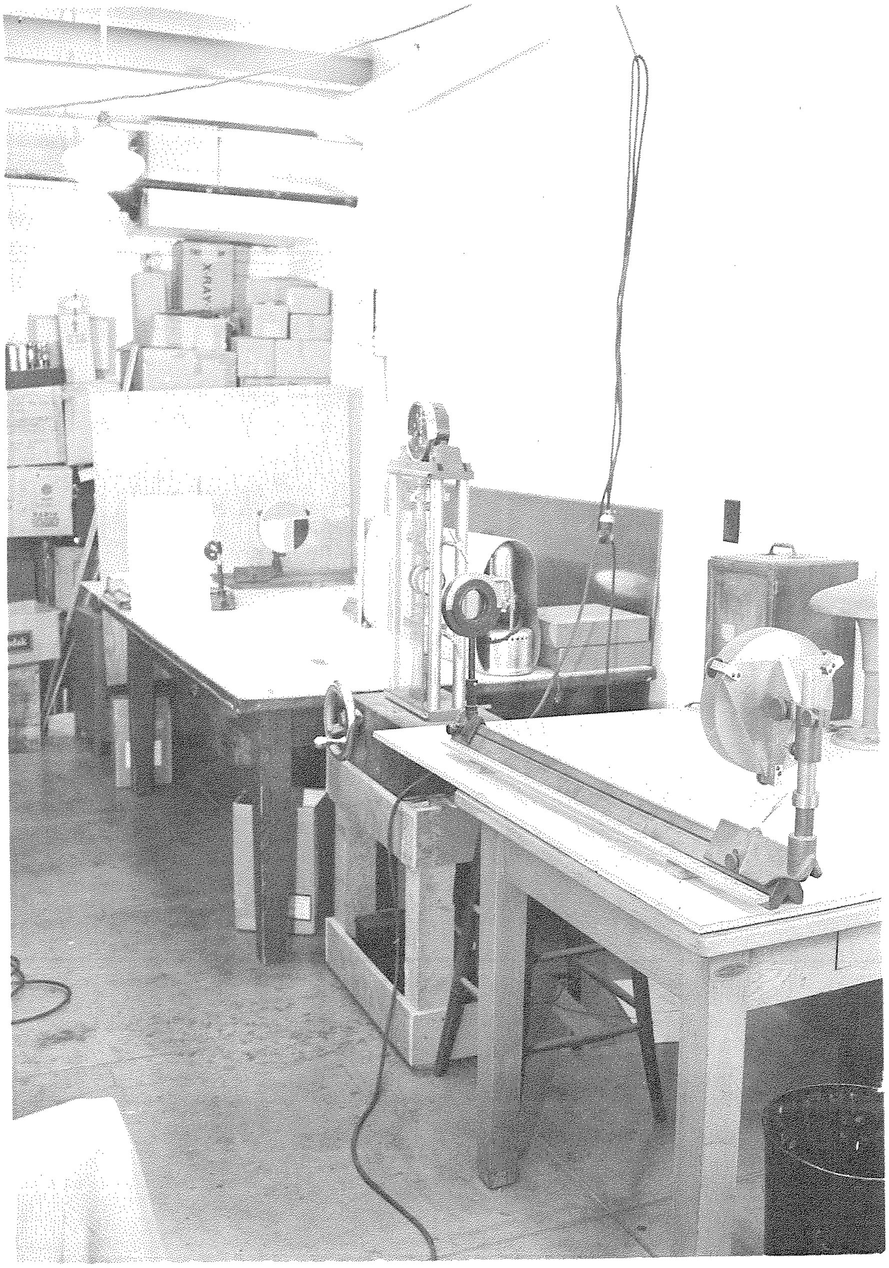
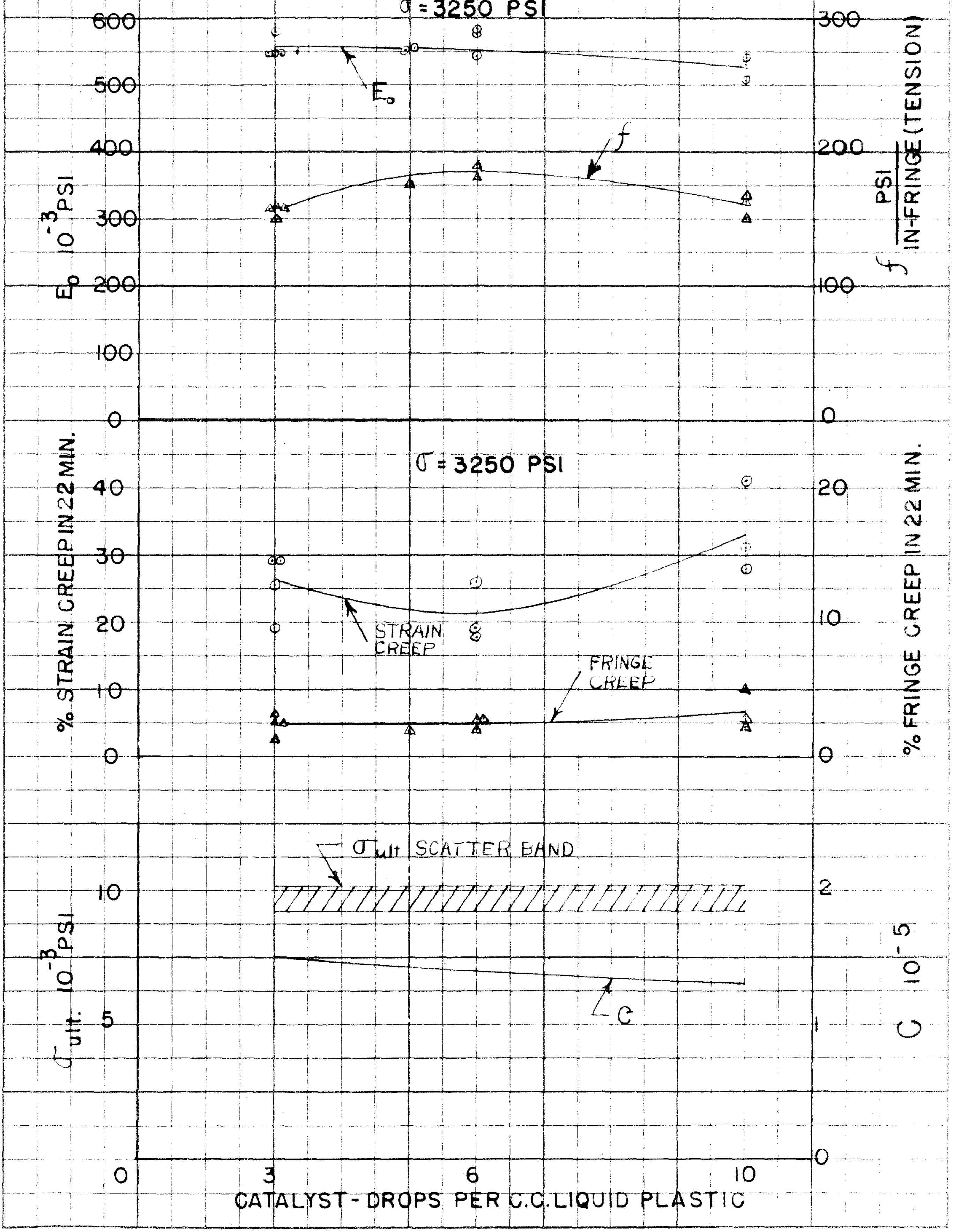


Fig. 8

Laboratory polariscope.

FIG. 9

EFFECT OF CATALYST ON PROPERTIES OF CASTOLITE CURED AT 180°F



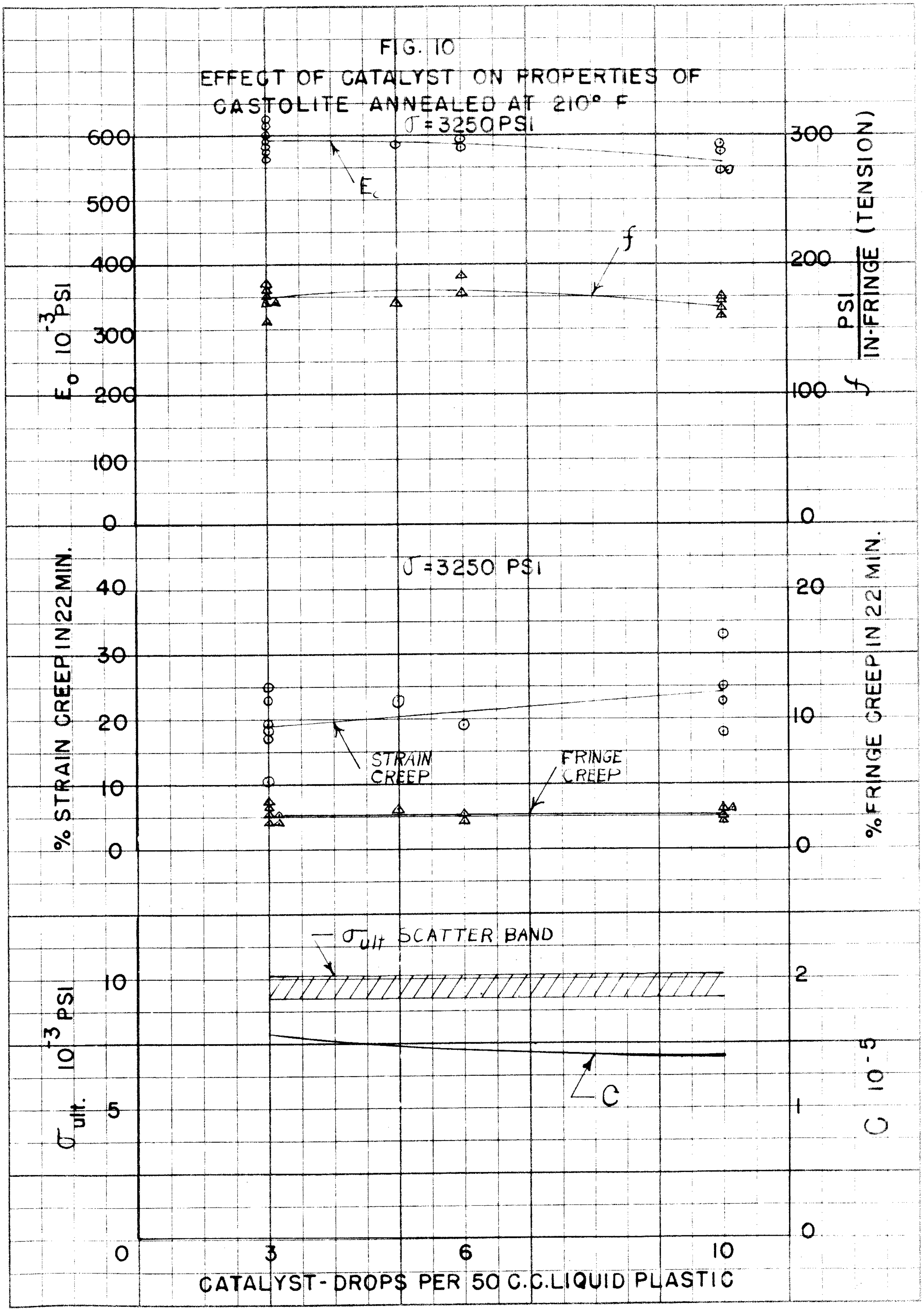


FIG. 10

EFFECT OF CATALYST ON PROPERTIES OF CASTOLITE ANNEALED AT 210° F

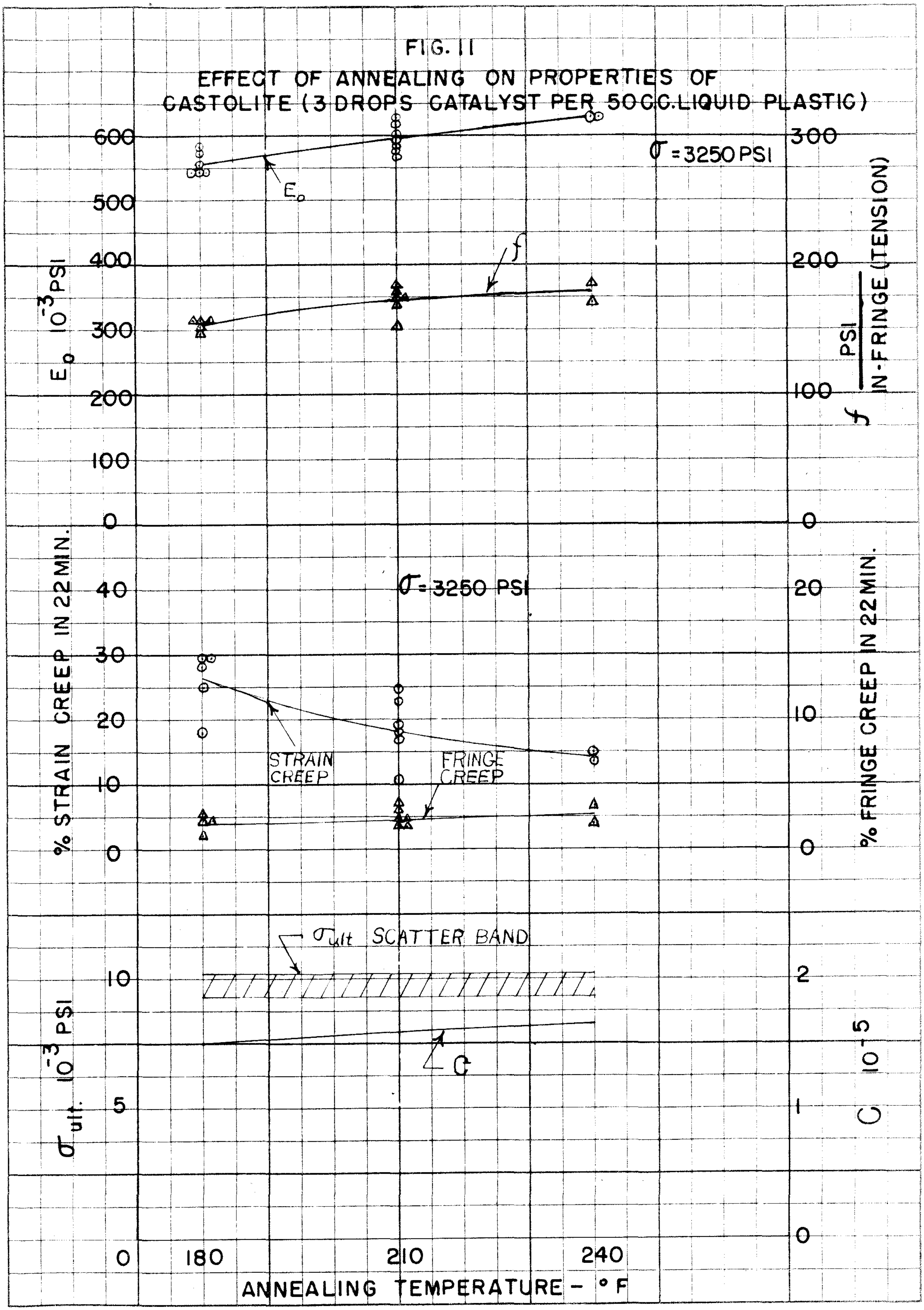


FIG. 11

EFFECT OF ANNEALING ON PROPERTIES OF CASTOLITE (3 DROPS CATALYST PER 50 CC. LIQUID PLASTIC)

FIG. 12

CREEP CURVES FOR CASTOLITE (3 DROPS CATALYST PER 50 C.C. LIQUID PLASTIC)

σ = 3250 PSI, SPECIMEN NO.59, LOADING TIME=10 SEC.

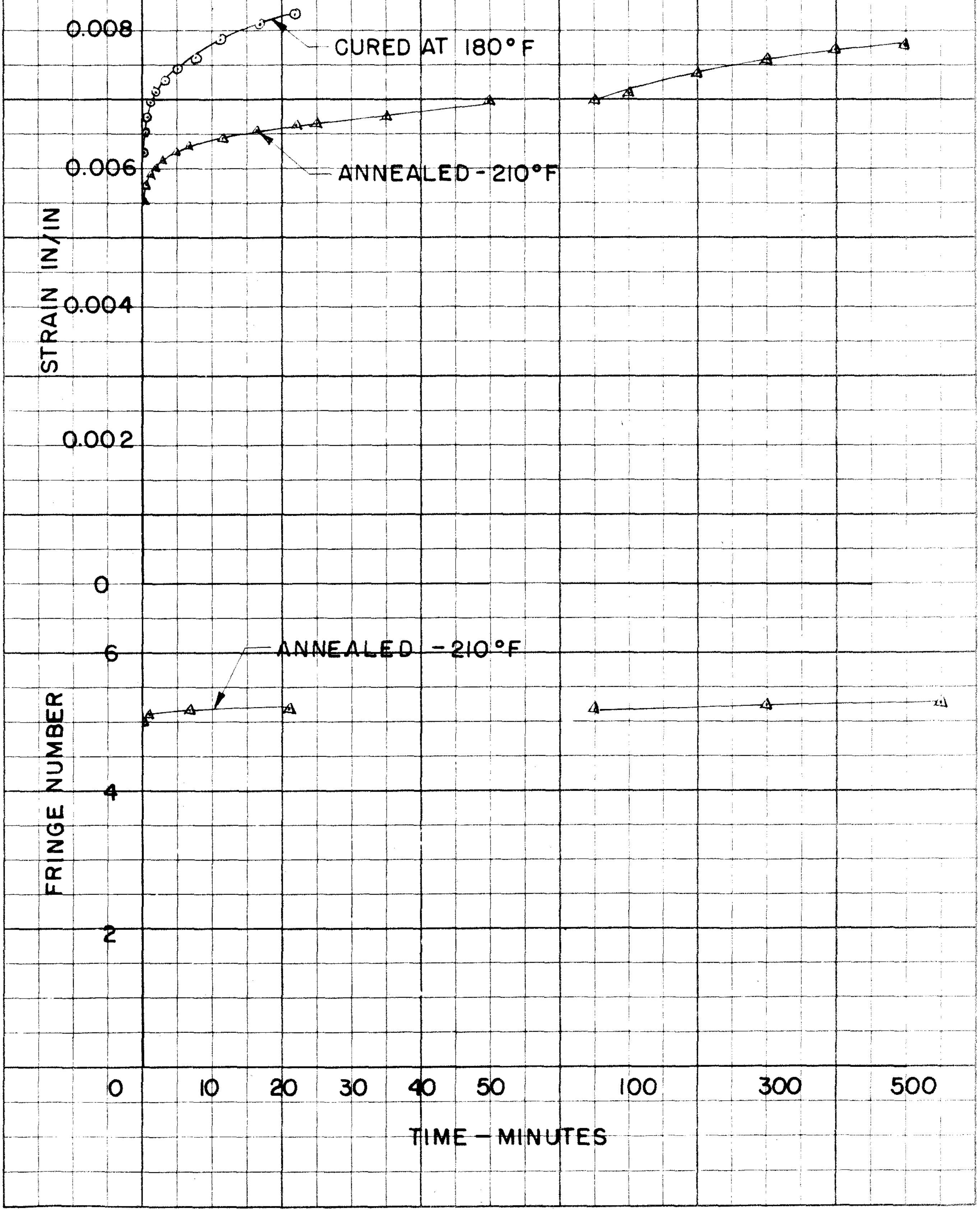


FIG. 13

STRESS-STRAIN CURVES FOR VARIOUS LOAD DURATIONS
(3 DROPS CATALYST PER 500 C.C. LIQUID PLASTIC-ANNEALED 210°F)

SPECIMEN NO. 59

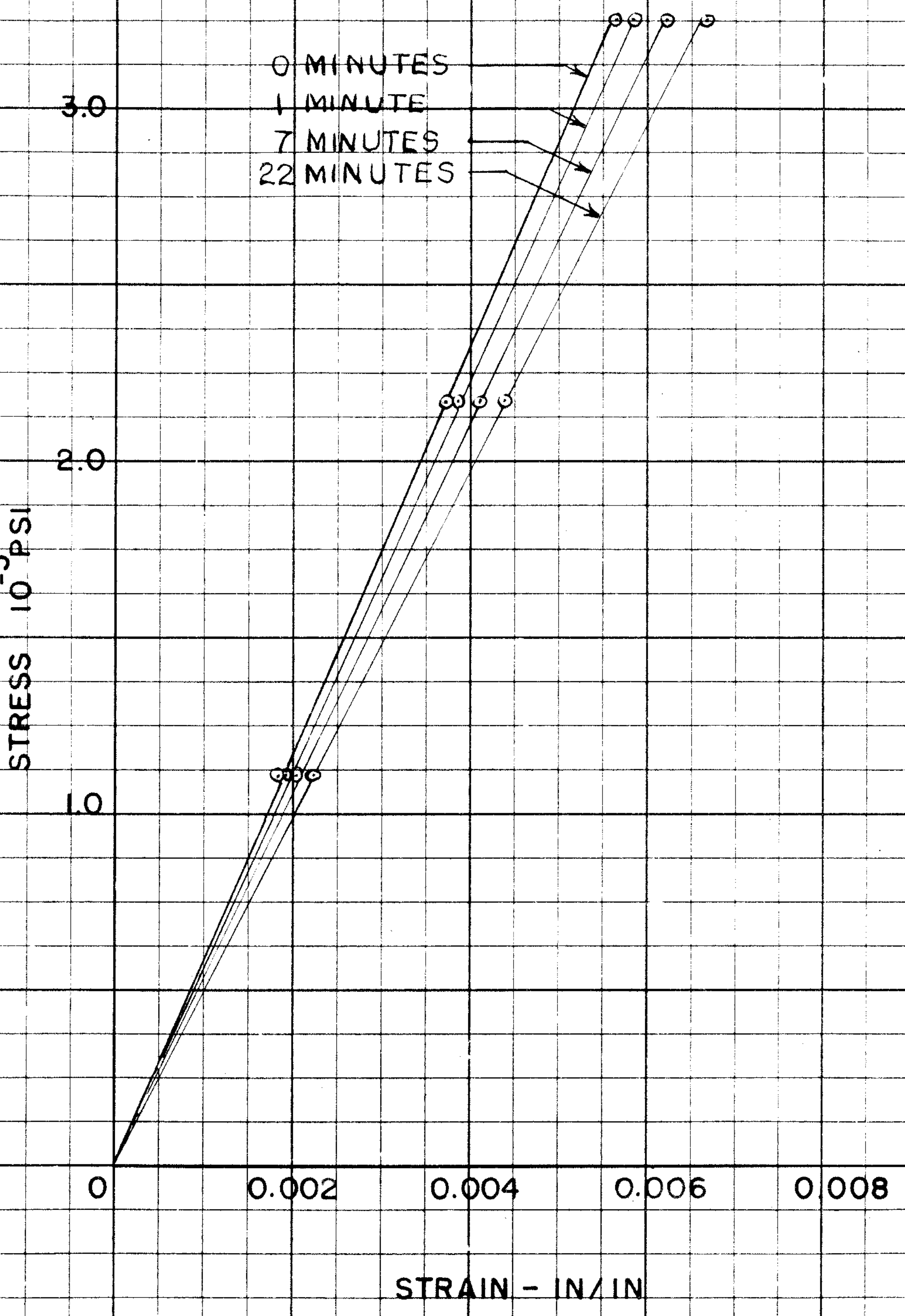
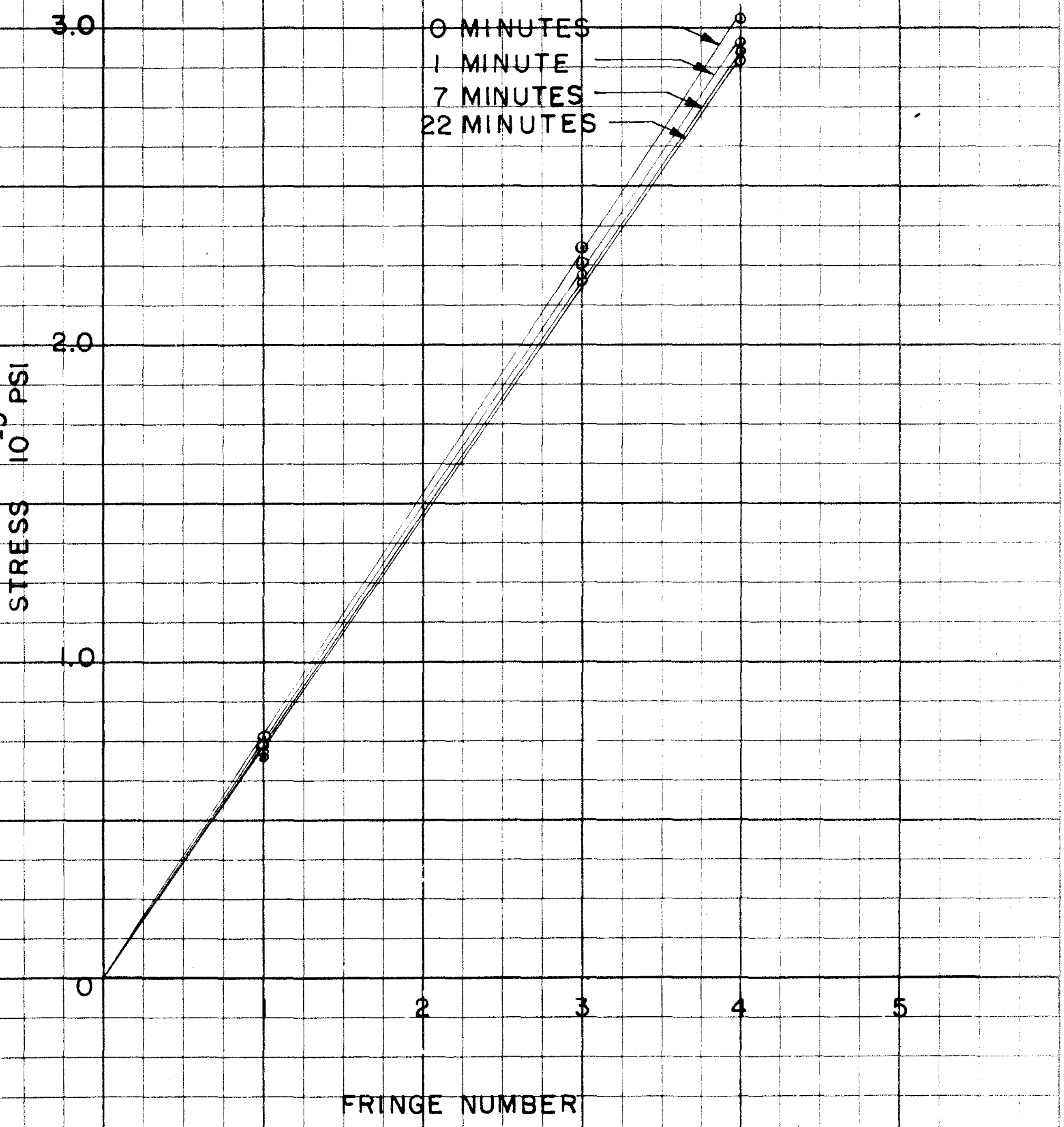


FIG. 14

STRESS-FRINGE CURVES FOR VARIOUS LOAD DURATIONS
(3 DROPS CATALYST PER 50 C.C. LIQUID PLASTIC-ANNEALED 210°F)
SPECIMEN NO. 59



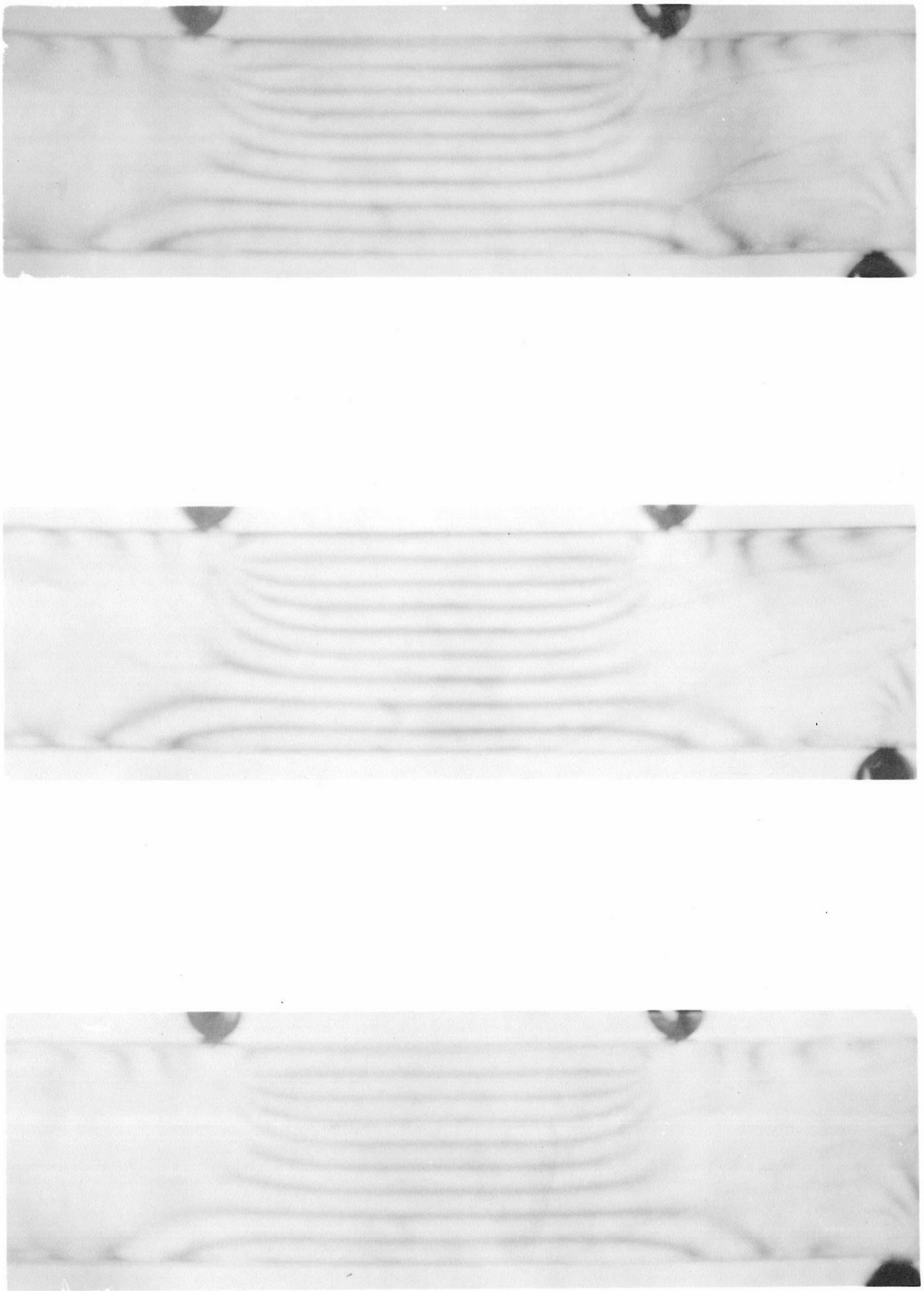


Fig. 15

Pure bending fringes. Upper picture taken immediately after loading. Center picture taken 22 minutes later. Lower picture taken 3 hours after loading. Specimen thickness is 0.235 inch. Maximum tensile stress is 3800 psi.