WADC TECHNICAL REPORT 55-24

DETERMINATION OF THERMAL SHOCK CHARACTERISTICS OF GLASS

DAVID HORWITZ

ARMOUR RESEARCH FOUNDATION
OF ILLINOIS INSTITUTE OF TECHNOLOGY

JUNE 1955

MATERIALS LABORATORY
CONTRACT No. AF 33(616)-2240
PROJECT No. 7340

WRIGHT AIR DEVELOPMENT CENTER
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

Carpenter Litho & Prtg. Co., Springfield, O.
300 - 30 January 1956

FOREWORD

This report was prepared by the Armour Research Foundation under USAF Contract No. AF 33(616)-2240. The contract was initiated under Project No. 7340, "Rubber, Plastic, and Composite Materials", Task No. 73403, "Transparent Materials", formerly RDO No. 616-12, "Transparent Materials". The research and experimental investigations were conducted at the Armour Research Foundation (as a project designated by ARF as M045) for the Air Force, and entitled, "Determination of Thermal Shock Characteristics of Glass". It was administered under the direction of the Materials Laboratory, Directorate of Research, Wright Air Development Center, with Lt R. C. Smith and Capt F. J. Wilcox acting as project engineers.

In addition to D. Horwitz, author of the report, and G. Nagumo, author of Appendix A, the following ARF staff members made valuable contributions to the work covered in the project: E. Chez, E. Frank, J. Lang, and W. T. Savage.

This report covers work conducted from October 1953 to December 1954.

ABSTRACT

This is a study of the resistance to thermal shock of glass having different coefficients of linear thermal expansion and different tempers and subjected to shock applied to a single surface. The program was initiated in order to enable the selection of a suitable glass for windshields in supersonic aircraft.

Apparatus was designed to produce a timed sudden shock to a glass specimen at elevated temperatures, simulating skin temperatures which may develop in supersonic aircraft due to aerodynamic heating.

Instrumentation was developed to record "surface" temperature of the specimen independent of the conditions of the attacking fluid.

Time-temperature change curves were drawn, and the shock rates established for the various glasses were used as a means of comparison.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

M. R. WHITMORE
Technical Director
Materials Laboratory
Directorate of Research

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

DETERMINATION OF THERMAL SHOCK CHARACTERISTICS OF GLASS

INTRODUCTION

This program was initiated to establish the relative resistance to thermal shock of glass compositions having different coefficients of thermal expansion and different tempers. The primary objective was to permit the selection of a suitable glass for windshields in supersonic aircraft which may develop skin temperatures up to 600°F by aerodynamic heating. In accordance with USAF Contract No. AF 33(616)-2240, the tests were designed to subject the specimens to shock conditions on one surface only, rather than to employ the conventional type of thermal shock test in which a heated specimen is submerged in a cold medium and both surfaces chilled within a short period of time.

Investigations were conducted to determine an applicable shock medium, a representative test specimen, and an adequate thermocouple configuration for instrumentation of the specimens. Test apparatus obtained from Contract No. AF 33(038)-6429, "Research and Development of Laminated Glass Windshields", was modified to produce timed shocks of very short duration.

DETERMINATION OF THERMAL SHOCK CHARACTERISTICS OF GLASS

I. ANALYSIS OF THERMAL SHOCK

The objective of the program anticipated determination of the resistance to thermal shock of each of the various glasses with different coefficients of thermal expansion and different tempers by comparison of test results from the different glasses. To facilitate this comparison and to make the results generally applicable to other glasses, consideration was given to the stress condition generated by a true shock condition.

A. Thermal Stress and Shock Rate

The thermal stresses in a plate due to a non-linear temperature distribution through its thickness are given by the following equation:[1]

$$\sigma(c) = \frac{E \ \alpha \ T(c)}{1 - \nu} \qquad (1)$$

where $\sigma(c)$ = thermal stress due to temperature distribution $T(c)$, psi

E = Young's modulus of elasticity, 10×10^6 psi

α = coefficient of linear thermal expansion, in./in./°F

ν = Poisson's ratio, 0.25

$T(c)$ = any function representing a temperature distribution through the thickness, c, of the glass.

For a thermal shock condition applied to one surface of the glass the family of curves generated is dependent on time and initial temperature, but in each case the curves would fall in the general form shown in Fig. 1. The curve of surface temperature versus time is also a function of the initial temperature and physical characteristics of the test specimen. The straight line, $T(c)_o$, represents the temperature of the specimen previous to shock. The curves from $T(c)'$ to $T(c)_n$ represent a series of temperature distribution curves at successive intervals of time. Curve $T(c)$ represents a temperature distribution which will generate a large thermal stress, while each of the successive curves represents temperature distributions which generate lesser degrees of stress. $T(c)$ represents the linear temperature distribution which is equivalent to zero stress in an unrestrained pane.

---

1 WADC TR 53-99 "Engineering Design Factors for Laminated Aircraft Windshields." Armour Research Foundation, Project No. M011, April 1954.

Theoretically, the stress due to an "instantaneous" shock to one surface of a single glass pane is based on a stepwise temperature change as shown in Fig. 2 and is given by the equation:

$$\sigma = \frac{E \ \alpha \ (T_{max} - T_{min})}{1 - \nu} \qquad (2)$$

where,

σ = stress, psi

E = Young's modulus of elasticity, 10×10^6 psi

α = Coefficient of linear thermal expansion, in./in./^{o}F

ν = Poisson's ratio, 0.25

T_{max} = Maximum initial temperature of glass, ^{o}F

T_{min} = Minimum shock temperature of glass, ^{o}F

It is impossible to obtain this stepwise temperature distribution experimentally. Therefore, an arbitrary test condition was selected to approach this idealized step function as closely as practicable, while creating shock of sufficient severity to generate failure. The tests were conducted by shock-cooling one surface of the specimen from progressively higher temperatures, with a constant temperature shock fluid for a constant period of time.

A family of curves depicting surface temperature as a function of time for each of the successive shocks could then be drawn as in Fig. 3. Each curve in Fig. 3 is associated with a particular family of curves similar to those shown in Fig. 1, but successive curves from T_{ia} to T_{ii} represent successively larger maximum stresses.

In an effort to evaluate each type of glass on an equivalent basis, it is necessary to find the T curve from the family shown in Fig. 3 which produces a temperature distribution of T(c) in Fig. 1, representing a large enough stress to cause failure. A line representing the temperature drop equivalent to minimum failure stress (based on Equation 2 and called minimum glass strength), is then drawn, on the family of time-temperature curves for successive shocks, to represent the temperature drop above which no failure should occur. The failure probably will occur at some temperature drop greater than that indicated for the minimum strength of the glass. The exact strength of the test specimen cannot be known; therefore, the temperature at which failure occurred cannot be established. However, failure undoubtedly does occur at a temperature drop in the vicinity of this minimum, and, since the portion of the curve between the initial shock and the failure stress is essentially a straight line, the surface-temperature-versus-time rate of change is constant. The intersection of the stress line for failure with the failure curve gives the time at which the minimum stress necessary to fail glass has been reached in the failure test.

For example, in the hypothetical curve this point is at 0.16 seconds and a temperature drop of 125°F. A shock rate is then established by dividing the temperature drop ΔT by the time. This shock rate represents a temperature distribution $T(c)_1$ which generates a failure stress from a minimum initial shock temperature. With the use of the above method, the shock rates associated with failure of the various glasses can be compared on an equivalent basis.

B. Theoretical Considerations and Assumptions

Since the theoretical analysis of a thermal shock is based on the assumption that surface temperature change is "instantaneous" and that significant tensile stress is developed uniformly over the shocked surface without bending of the test pane, this condition was simulated as closely as possible in the laboratory. It was necessary to use the most effective heat transfer medium available and limit the period during which the shock takes place. An ice-water shock fluid achieved the necessary heat removal within a short interval of time during which the glass remained essentially plane, generating: (1) stress distributions across the pane's thickness which closely approximates the theoretical shock, and (2) tensile stress sufficiently large in magnitude to fail glass.

No forseeable service condition could impose heat removal and shock conditions of sufficient magnitude to fail the types of glass which were under consideration by thermal differential through the glass thickness alone. Non-uniform temperature distribution induced in the plane of the glass by sudden cooling, however, is expected to be a more important factor in service than theoretical uniform surface shock. Hence, an evaluation of glass under each type of stress, i.e., uniform surface shock and non-uniform planar distribution would be desirable, but it was found to be impractical to generate non-uniform temperature distributions with any consistency in the laboratory. Furthermore, realistic magnitudes and distribution patterns of the planar stresses have not been established for any one aircraft and probably would vary considerably for different aircraft designs.

The two cases have common factors involved in the calculation of theoretical stress: Young's modulus, the thermal coefficient of expansion, and Poisson's ratio. The only essential difference between the two cases is in the distribution pattern of temperature differential in relation to the geometry of the glass. Therefore, for all practical purposes, the results of the tests enable the selection from available compositions of that glass which offers the greatest resistance to thermal shock - whether the shock generates uniform surface stresses or non-uniform planar stresses. For the reasons cited above, the tests for this program were planned to measure the resistance of the glass to uniform planar thermal shock, creating a temperature differential only across the thickness.

By designing a test fixture in which the fresh shocking fluid is constantly attacking the glass and being removed, rapid changes in the surface temperature of the glass were obtained. Failures of glass, accomplished by imposing sufficient severity of shock, are comparable on the basis of total temperature drops or the rates of drop for the period required to develop failure stresses.

The following assumptions were made to simplify the analysis of test results:

1. The period of shock selected is short enough to prevent the glass from assuming any curvature, and the specimen remains in a plane.

2. The glass is homogeneous, and therefore the temperature distribution which takes place through the thickness is uniform throughout the specimen.

3. The period of shock begins coincident with discernible temperature drop on the surface of the glass.

4. Glasses with different coefficients of linear thermal expansion have approximately equal strength: from 5500 to 6500 psi for annealed and from 25,000 to 27,000 psi for tempered; Poisson's ratio and modulus of elasticity are approximately the same for all types of glasses.

C. Hot-to-Cold Versus Cold-to-Hot Shock

The hot-to-cold shock procedure selected was based on previous theoretical analysis[1] which indicates that the stress in a glass pane is a function of the temperature distribution across its thickness. For sudden chilling, the coldest surface would be stressed in tension, and, for sudden heating, the warmest surface would be under compressive stress. Assuming that the same temperature differential would be created with either of the shock procedures, the magnitude of maximum stress would be identical - only the type of stress would be different. Since glass is several times stronger in compression than it is in tension, it is inconceivable that failures can be produced in service by the magnitude of compressive stresses that will be generated. Therefore, for evaluation purposes, only the case of hot-to-cold shock is significant.

1 WADC TR 53-99 "Engineering Design Factors for Laminated Aircraft Windshields." Armour Research Foundation, Project No. M011, April 1954.

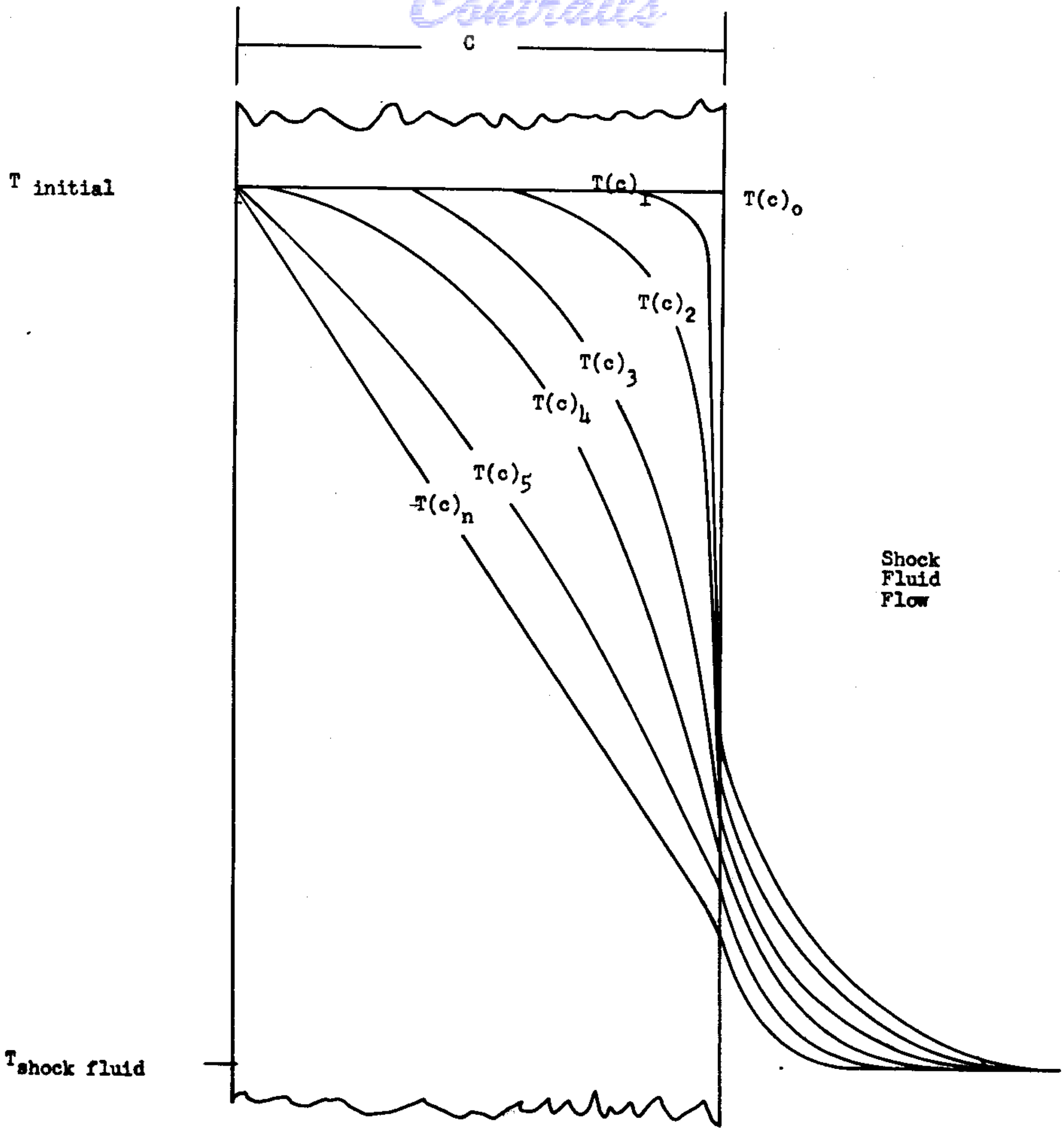


Fig. 1 Family of Time-Temperature Distributions for Suddenly Applied Shock

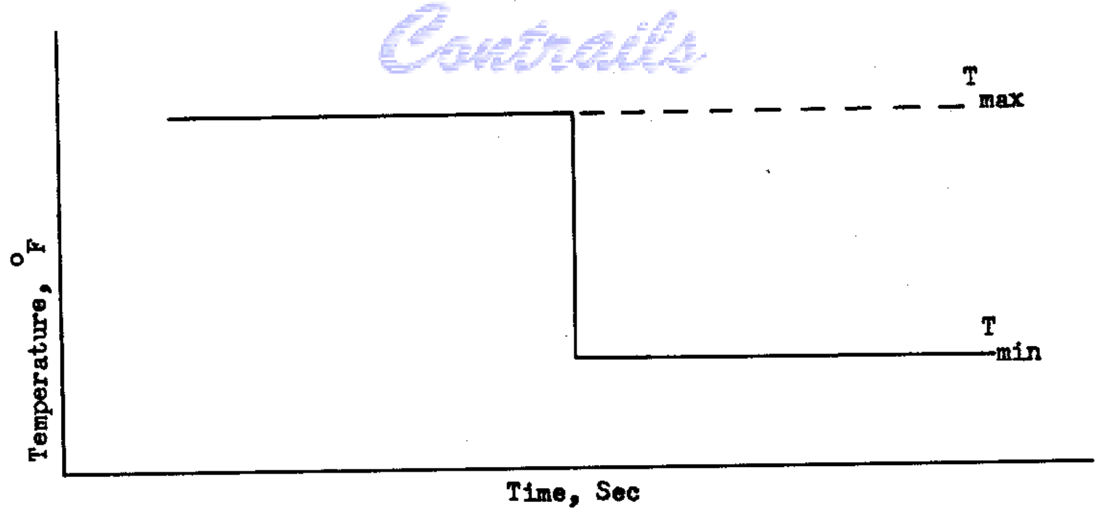


Fig. 2 Stepwise Temperature Distribution

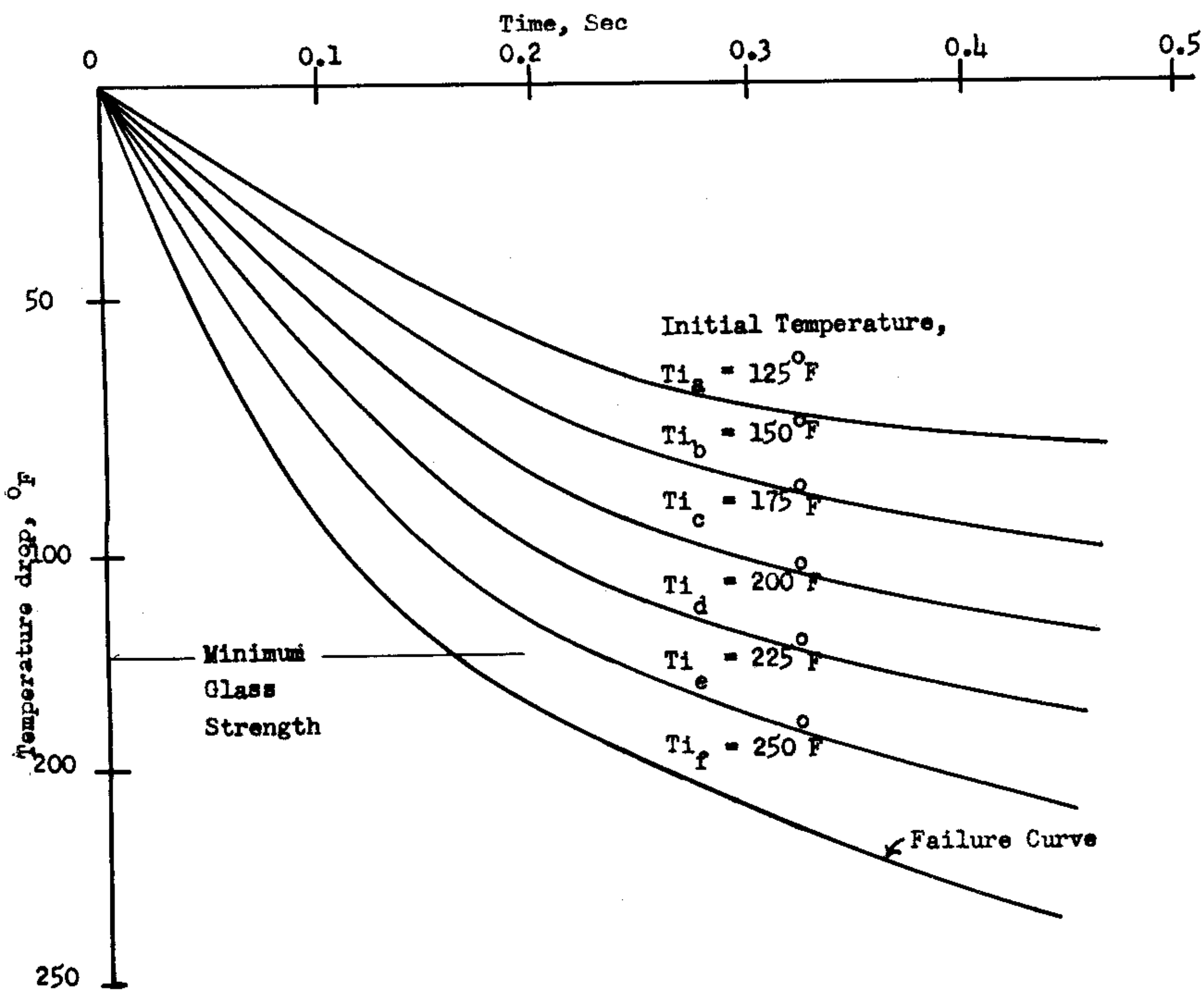


Fig. 3 Family of Hypothetical Time-Temperature Curves for Successive Shocks

II. SELECTION OF SHOCK FLUID MEDIA

Investigations were made of quantity, velocity, and temperature of shock media necessary to satisfy the heat transfer conditions for shocking the specimen.

Early in the program a study was made of the available experimental results and theoretical analysis for gas as a shock fluid. Calculations from both analytical and numerical methods were presented to show the relationship of the heat transfer coefficient and the attacking fluid temperature. From this investigation and preliminary experiments with compressed air released through various sized nozzles, it became apparent that the use of gas was not economically feasible. Since the temperature of any economical attacking fluid could not be reduced significantly, it was necessary to find an attacking fluid with a high heat transfer coefficient.

A comparison of heat transfer coefficients for[1] different attacking fluids can be made by examining the ratio, $h_1 : h_2$,[1]

$$\frac{h_1}{h_2} = \frac{k_1 \, (N_{Pr})^n}{k_2 \, (N_{Pr})^n} \qquad (3)$$

where

h = heat transfer coefficient at surface of glass, BTU/hr/ft^2/^{o}F
k = thermal conductivity of attacking fluid, BTU/hr/ft/^{o}F
$(N_{Pr})^n$ = Prandtl Number $\frac{C_p \mu}{k}$

1,2 = subscripts denoting different attacking fluids

Assuming equivalent Reynolds numbers, this ratio showed fluids to be much more efficient than gases, i.e., the ratio of ethelene-glycol-to air was about 70, water-to air about 45. Ice-water was selected as a shock fluid, since it is easily kept constant at a practical low temperature (near 32^{o}F) by the addition of ice and provides a high transfer coefficient.

---
[1] Appendix B

III. SPECIMEN SELECTION

The two prime considerations in the selection of the test specimen were: the ultimate usage of the glass being tested and the adaptability of the available equipment. Since the 600°F skin temperatures are due to aerodynamic heating at high speeds, it was assumed this glass would be used in missile-shaped aircraft. Consideration was given to the mechanical stresses to be expected from cabin pressure loadings of practical windshield sizes. Stress calculations were made for various glass sizes and thicknesses, to provide a rational basis for selection of realistic dimensions.

A test specimen with a 2:1 ratio (length-to-width) was selected, since this general shape is most frequently used in high-speed aircraft. A maximum specimen length of 20 inches was chosen to simplify fabrication of inserts in the thermal evaluation equipment. A minimum thickness of 1/4 inch was selected on the basis of theoretical mechanical stress calculations and accepted aircraft-manufacturering practices.

The specimens ordered were 1/4 by 10 by 20 inches polished plate, allowing for the customary manufacturers' tolerances. Table I lists the suppliers of the glass specimens together with their specified coefficient of thermal expansion:

TABLE I

TYPES OF GLASS SPECIMENS

Glass Company	Type	Coefficient of Expansion, in/in°Cx10^{-7}
Corning	Pyrex	32
Pittsburgh	3235	65
Blue Ridge	Aklo	74
Blue Ridge	Lime	90

IV. TEST APPARATUS

The test apparatus was comprised of three basic units: (1) the thermal units, consisting of heater and spray unit, (2) the specimen bed, consisting of the mounting plate and supporting members, and (3) the operation panel, consisting of timer, by-pass system, and switches for heater and pump.

The thermal units were tandem-mounted on a single movable rack with cam followers, which permitted the interchange of the heater and the spray unit with a minimum of time and mechanical operation. The heater consisted of a side panel from a 12 A Model KH Huppert oven covered with a 1/4-inch copper sheet to provide uniform distribution of heat. The amount of heat input was controlled by a 20-amp, 7-kv-amp variac. The heater was mounted with elevating bolts to allow the heater surface to be adjusted to any desirable height with reference to the test specimen. The spray unit consisted of a grid of 3/8-inch copper tubing with holes drilled 1 inch on centers, to provide a uniform spray distribution of shocking fluid over an area exceeding that of the specimen. A photograph of the thermal units is shown in Fig. 4.

The specimen was supported from a steel plate, equipped with rails for the thermal units cam followers, and provided with a 10-by-20-inch window opening for mounting the test specimen. Insulation was provided between the test specimen and the steel bed by a Transite frame to minimize heat loss from the specimen edges. Test specimens were suspended below the Transite insulation frame on three Transite swivel blocks. The swivel blocks facilitate ease of insertion and removal of the test specimen and permit free expansion and contraction due to temperature changes.

The operation panel had two manual switch controls for the heater unit and a Vickers' model VC-109-CD-3DD 2 pump, a solenoid switch, an air valve, two air pistons, two quick-acting fluid valves, and an electronic photo-timer, model TM-5. The photo-timer controlled the solenoid switch which actuated an air valve. The air valve operated two air pistons which moved quick-opening valves, one normally open and one normally closed, for by-passing the shock fluid in the spray system.

A photograph of the control panel is shown in Fig. 5.

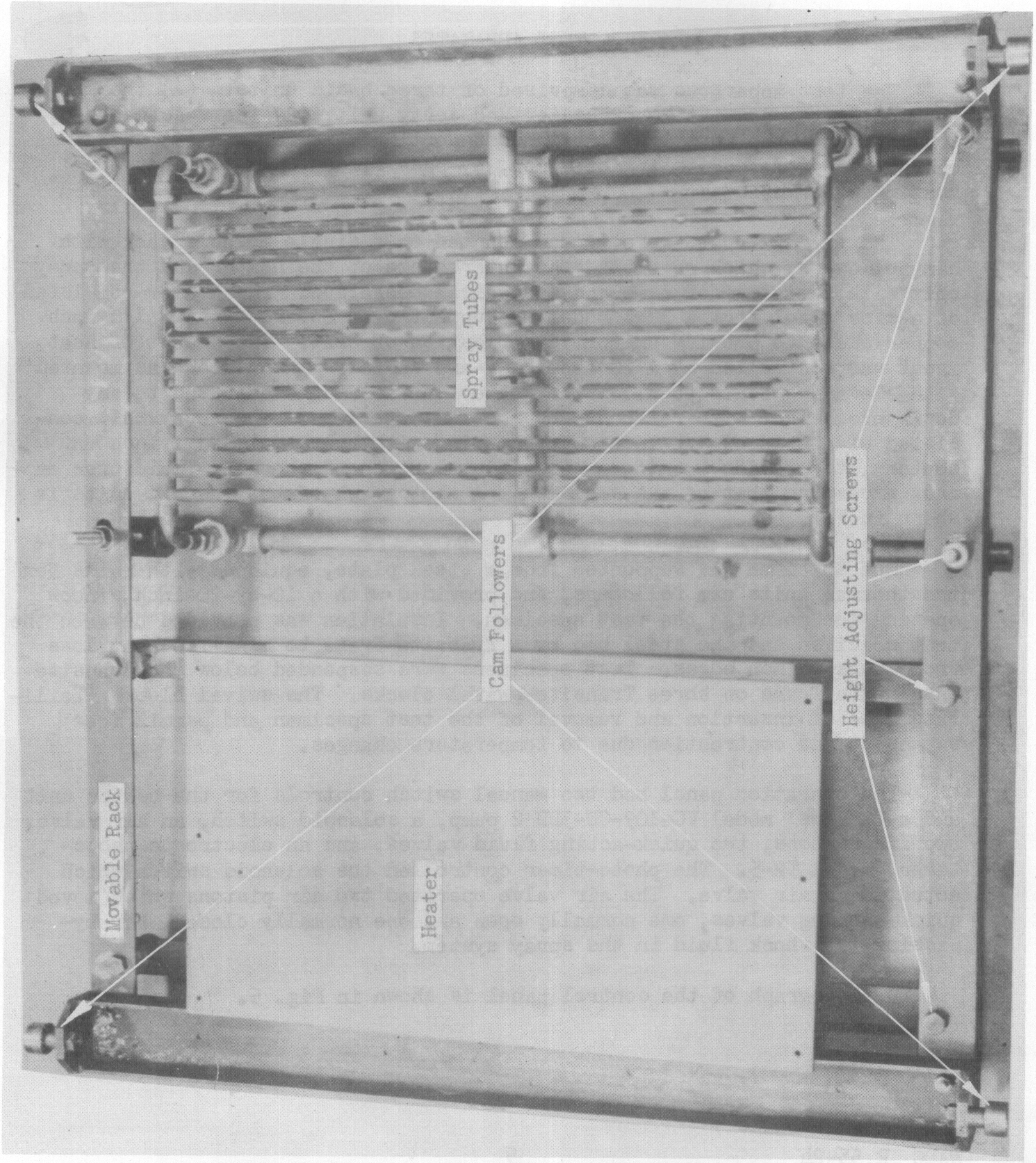


Fig. 4 Heater and Spray Unit on Moveable Rack

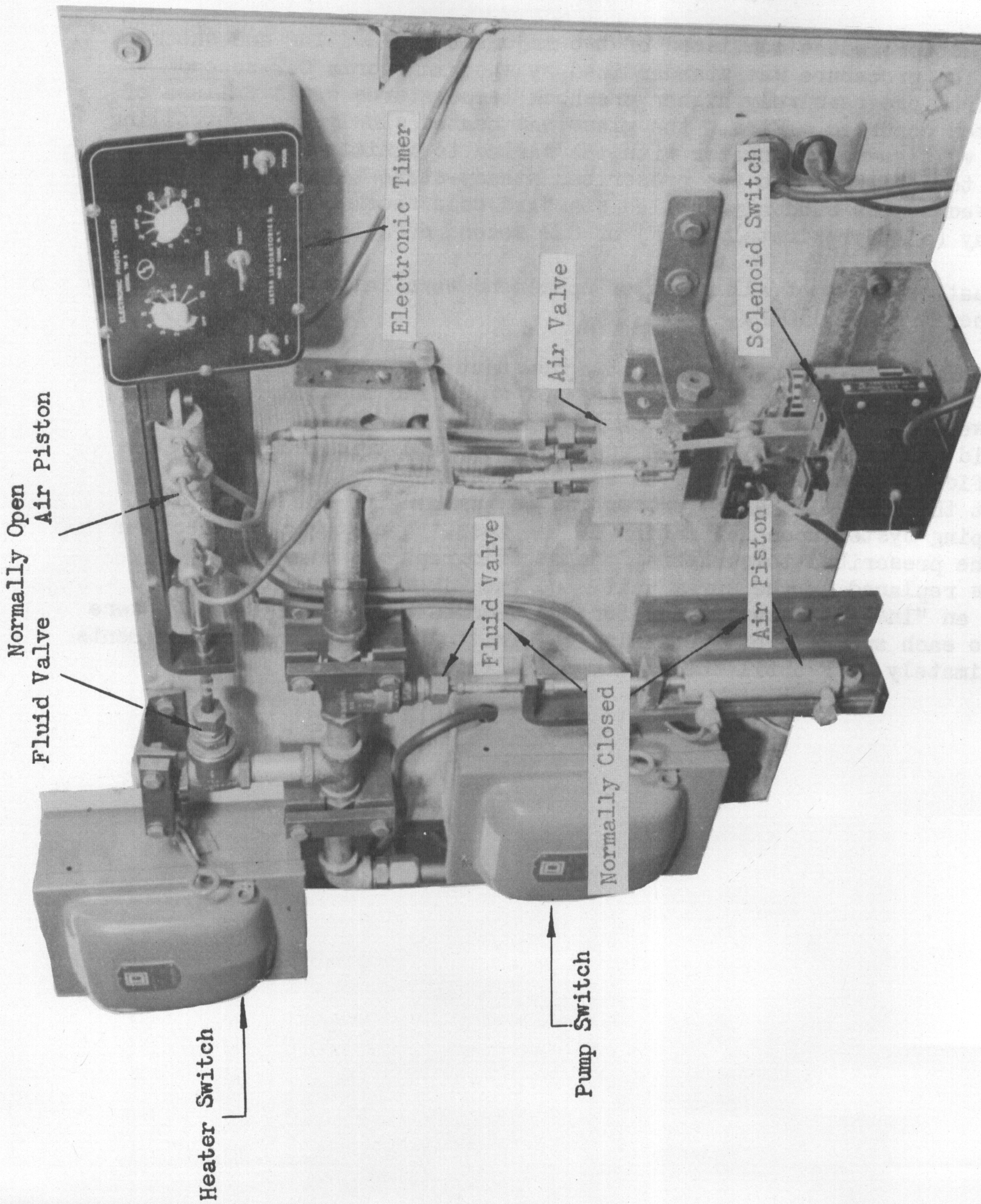


Fig. 5 Control Panel

V. TEST PROCEDURE

The test procedure consisted of two major steps, heating and shock-cooling. The procedure was standardized by shocking for a 0.2-second interval from progressively higher preshock temperatures until failure of the specimen occurred. First, the glass was heated slowly, by controlling the input voltage to the heater with the variac to minimize stresses caused by uneven temperatures, to the prescribed steady-state temperature. This was followed by the suddenly applied standard cold shock consisting of a water spray (at approximately 32°F) of 0.2 second duration.

Evaluation tests of all types of specimens were initiated from a preshock temperature of 150°F.

The cold shock water was held at a constant temperature near 32°F by a supply of ice cubes in the reservoir tank which fed the pump. The tank and pump were connected to the by-pass system and the timing device. Shock fluid was circulated through the apparatus and trickled through the spray orifices prior to shocking to establish steady-state temperature throughout the system, thereby preventing any warming of the shock fluid by the piping system upon initiation of the test. When the test specimen reached the prescribed temperature, the oscillograph was started, the heater was replaced by the spray unit, and the timer was tripped thus providing an "instantaneous" shock for 0.2 second. Progressive shocks were applied to each specimen by increasing the initial temperature in increments of approximately 25°F until the specimen failed.

VI. INSTRUMENTATION

Temperature measurement was accomplished with two instruments: (1) a Wheelco potentiometer to read steady-state temperatures during the heating cycle, and (2) a Consolidated 14-channel photographic oscillograph unit to record the time-temperature change relationship during the shock.

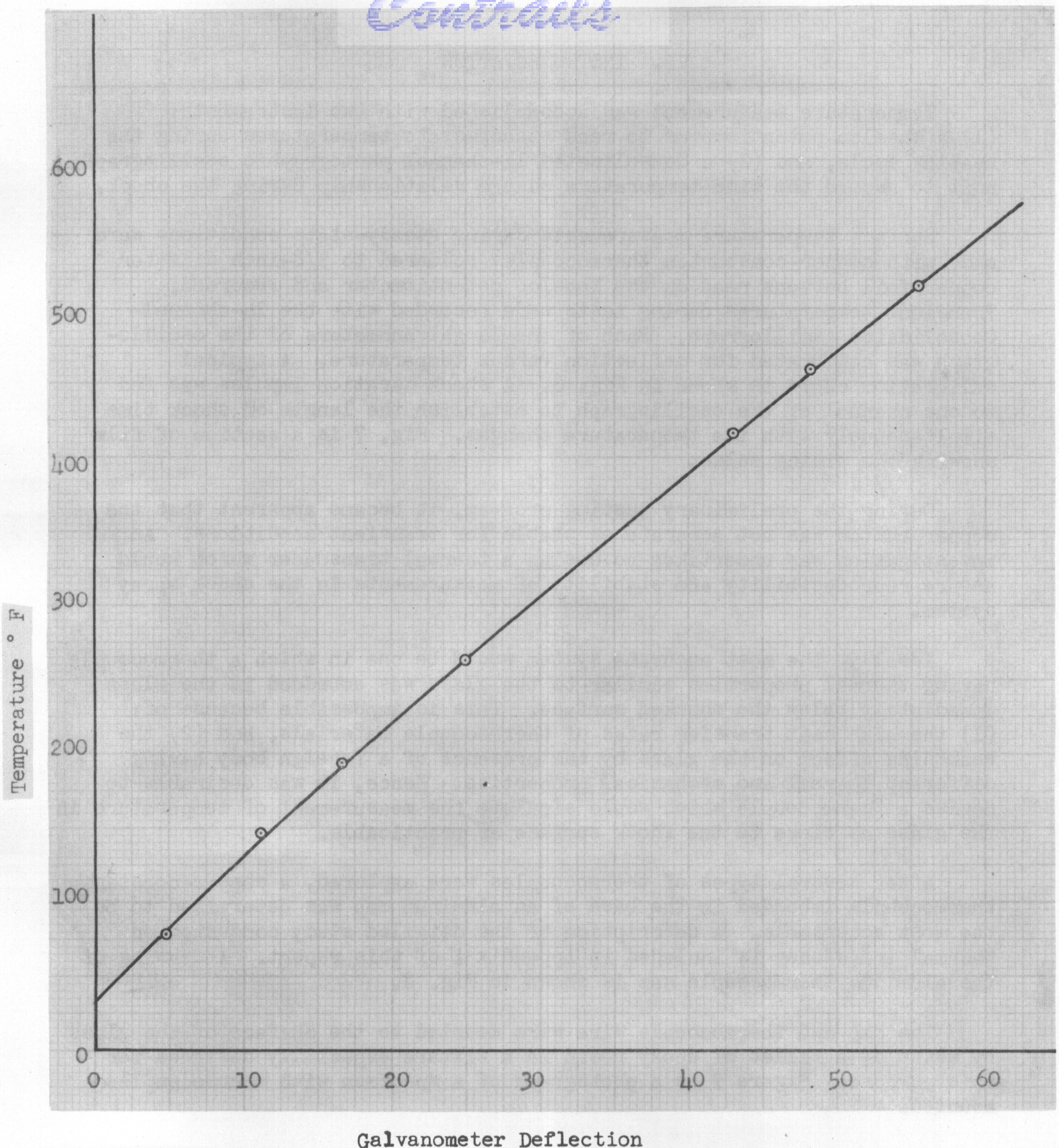
Surface temperature measurements during steady-state conditions were made with copper-constantan thermocouples soldered to 3/8-inch diameter copper foil buttons read on the Wheelco potentiometer and recorded. Transient temperatures during tests were recorded with the 14-channel Consolidated oscillograph. Each of the 14 galvanometers of the oscillograph was calibrated for deflection versus temperature. A typical calibration curve is shown in Fig. 6. A shock duration impulse was fed to one channel of the oscillograph to establish the length of shock time simultaneously with the temperature changes. Fig. 7 is a section of film showing the timing pulse.

During the preliminary testing program, it became apparent that the copper button was not accurate or stable for transient conditions. An investigation was undertaken to design a thermal transducer which would assure reproducibility and stability of measurements in the shock spray system.

Ideally, the most accurate system would be one in which a thermocouple having thermal properties similar to the glass was embedded in the glass immediately below the shocked surface. This is impossible because of: (1) the high heat transfer rates of thermocouple materials, and (2) the weakening effect on the glass by the presence of a foreign body having different thermal and mechanical properties. Hence, it was desirable to devise a thermocouple which would simulate the measurement of temperature in the glass as close to the shock surface as practicable.

After several types of thermocouples were explored, a copper-constantan thermocouple imbedded in the base of an aluminum cap was determined to be the most acceptable. A description of the detailed study conducted on thermal transducer is included in Appendix A of this report. A drawing of the aluminum thermocouple cap is shown in Fig. 8.

The cap and thermocouple wire were mounted to the surface of the glass by means of a fillet of epoxy resin in a fixture especially designed for this purpose. Figure 9 is a photograph of a specimen with thermocouples mounted.



(All measurements made with optical gage, l = 0.025 inch)

Fig. 6 Typical Calibration Curve of Galvanometer No. 2

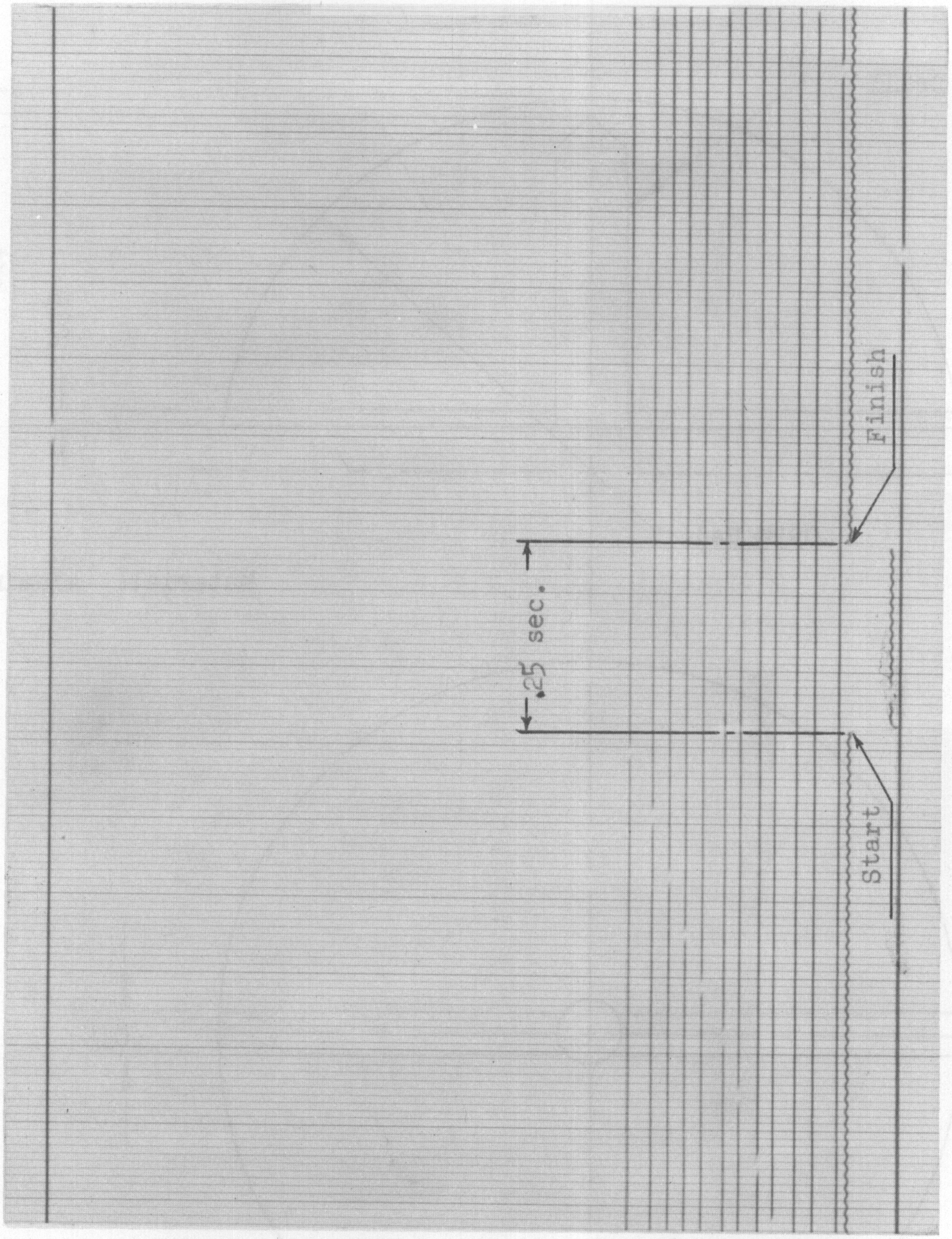


Fig. 7 Shock Duration Time Pulse

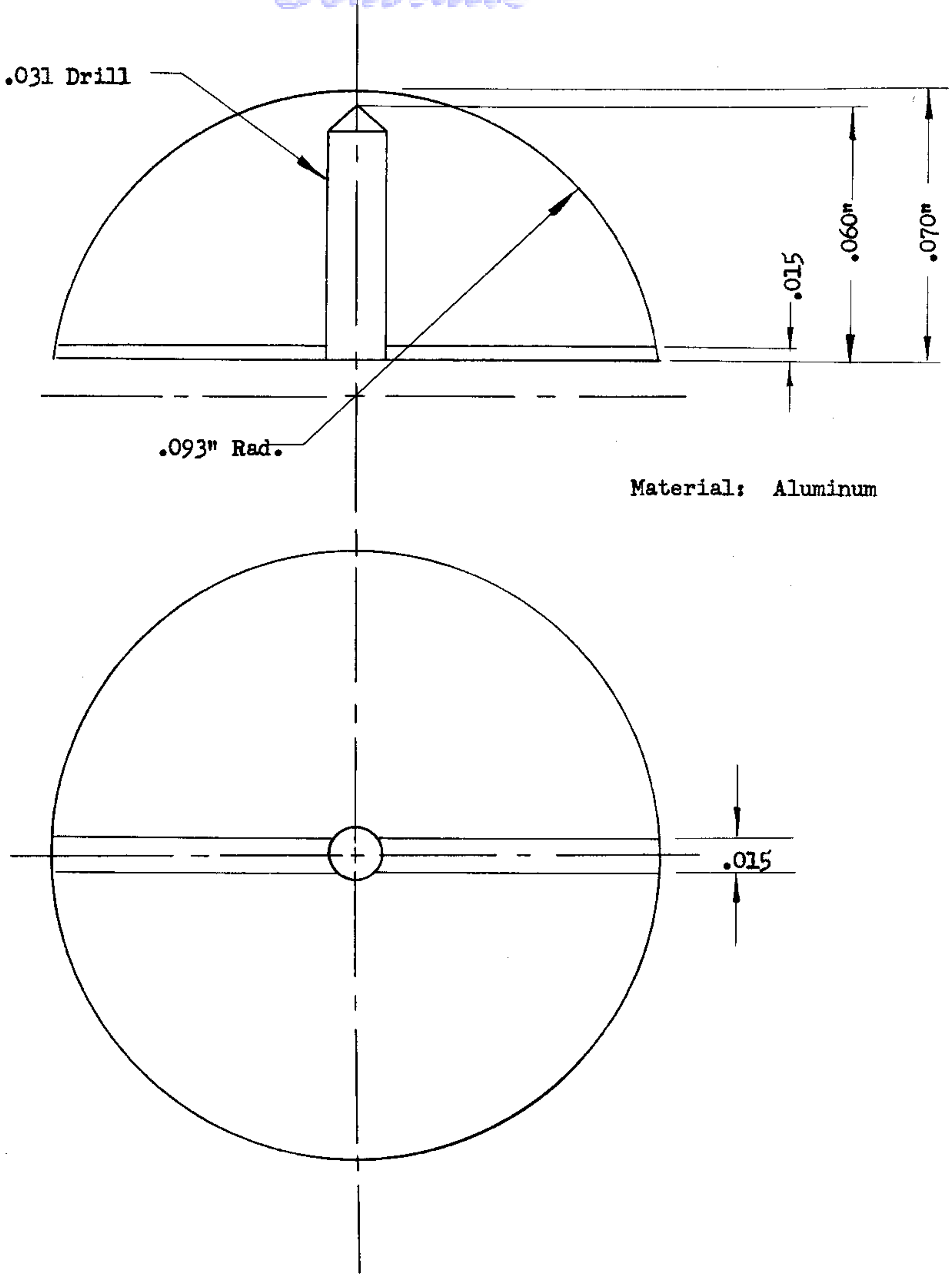


Fig. 8 Cross Section of Aluminum Thermocouple Cap

VII. TEST RESULTS

The results of the test were reduced for analysis from the oscillograph traces, recording automatically the time-temperature relationship during the period of shock. The oscillograph frame previous to failure was compared with the oscillograph frame in which failure took place for each specimen.

Test results for failures were plotted as a pair of curves; the time-temperature curve of the shock in the test previous to failure was compared to a similar curve during failure. A pair of curves was drawn for all samples tested. These pairs of curves were grouped as one figure for each type of glass.

A. Annealed Glass

On each of the figures, a line representing the theoretical shock temperature[1] associated with a stress of 5500 psi (the minimum strength of glass), was drawn. The intersection of this "minimum failure stress line" with the failure associated temperature curve establishes approximately the maximum time in which the temperature could be dropped and still cause failure. This time is used to calculate the approximate shock rate associated with failure. The calculation is made by dividing the temperature differential (starting temperature minus theoretical shock temperature equivalent to failure stress) by the longest elapsed time. Figures 10 to 13 inclusive are the plotted curves for the four types of glass tested.

Table II is a summary of the "average" shock rates established by the above method.

TABLE II

MINIMUM SHOCK RATES REQUIRED TO FAIL ANNEALED GLASS

Type of Glass	Thermal Expansion Coefficient, in/in/°C x 10^{-7}	Temperature Differential, ΔT, °F	Time, sec	"Average" Shock Rate, °F/sec
Blue Ridge Lime	90	85	0.25	340
Blue Ridge Aklo	74	104	0.27	385
Pittsburgh 3235	65	117	0.28	418
Corning Pyrex	32	238	0.35	680

1 Calculated by Equation 1, page 1

A curve of the minimum values of temperature drop causing failure versus time for all four types of glass is shown in Fig. 14.

B. Tempered Glass

Tests performed on Blue Ridge Lime tempered glass required initial temperature of 700°F. This temperature represented the upper safe-operating limit of the equipment which had been designed around the 600°F limit specified in the contract. Pairs of curves described above were drawn and intersected by a line representing the assumed 27,000 psi strength of tempered glass. The three remaining types of tempered glass were tested under these conditions, but no failure occurred. Fig. 15 is a temperature-drop-versus- time-curve for the failed Blue Ridge specimens.

Various methods of shocking with sub-zero fluid mixtures were attempted, but the heat transfer properties were inadequate and no failures occurred.

In a final effort to obtain some relationship of the remaining three glasses, the unheated side of the glass was insulated with asbestos paper to attain a higher initial temperature, but no shock failures occurred. One Blue Ridge Aklo specimen failed approximately 5 seconds after the completed shock. Pittsburgh 3235 and Corning Pyrex did not fail even though they were heated at various temperatures up to 850°F.

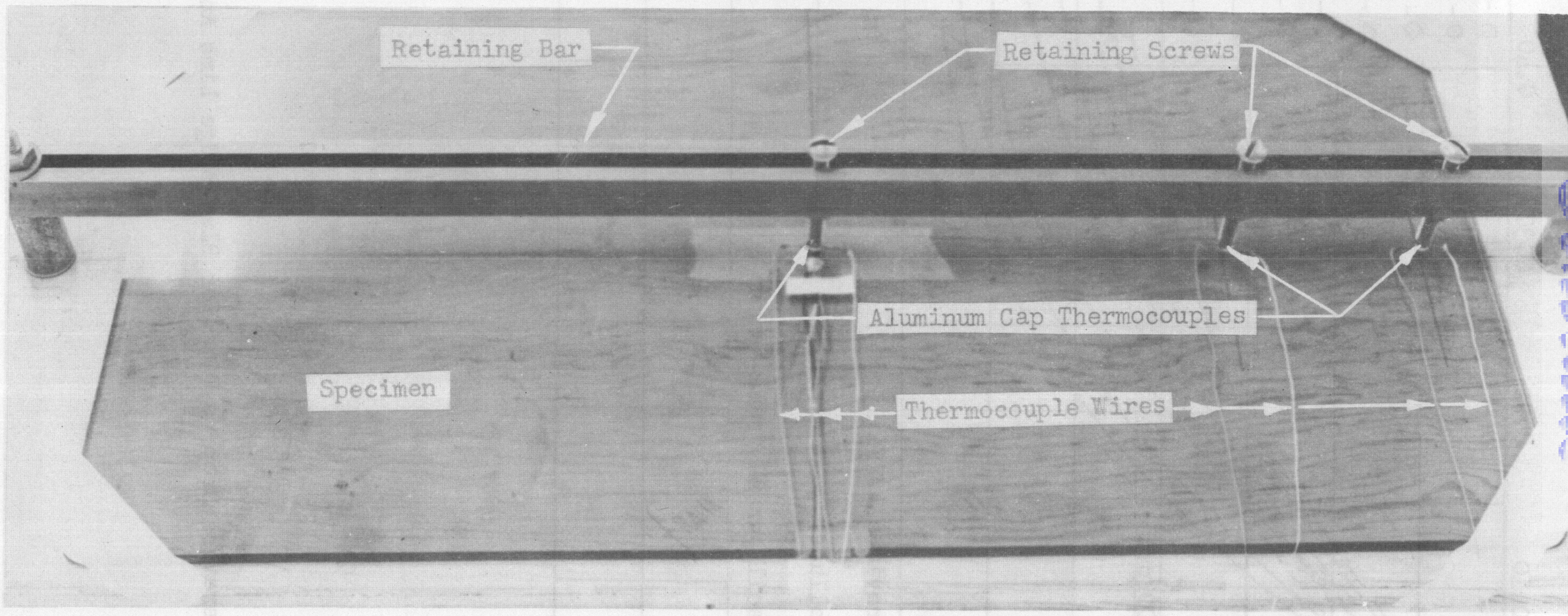


Fig. 9 Thermocouple Mounting Fixture

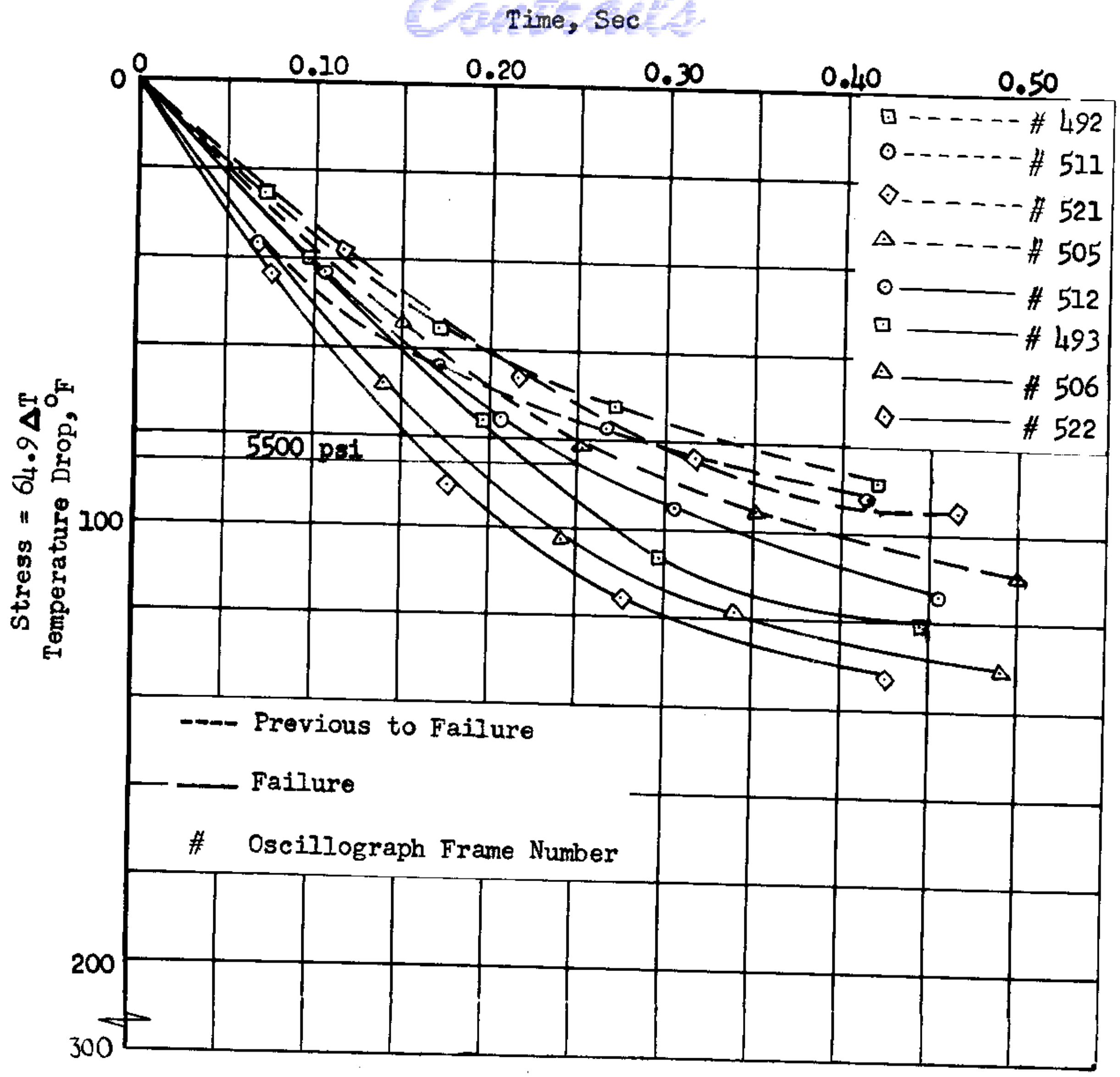


Fig. 10 Temperature Drop vs Time for Blue Ridge Lime Annealed Glass

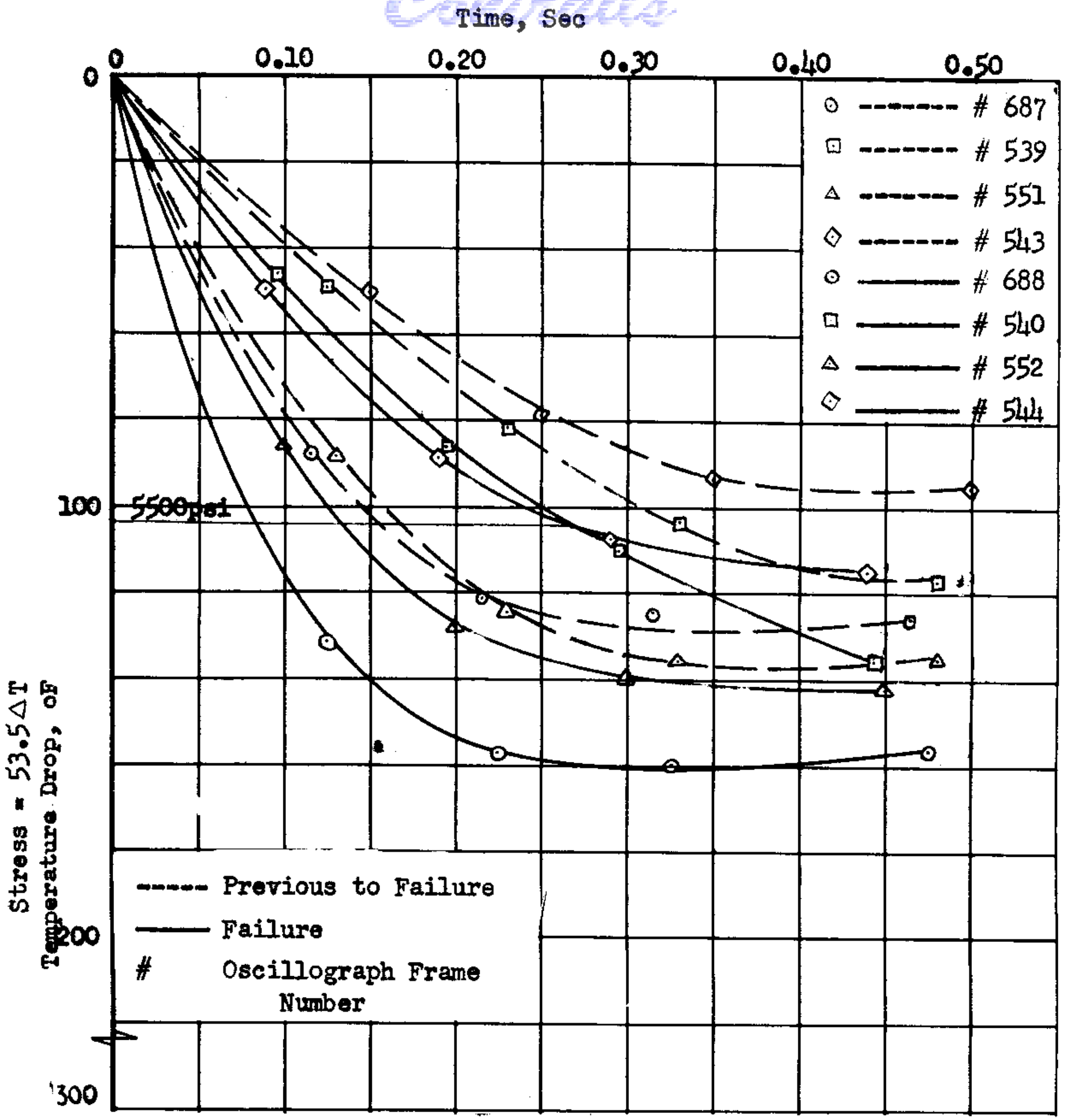


Fig. 11 Temperature Drop vs Time for Blue Ridge Aklo Annealed Glass

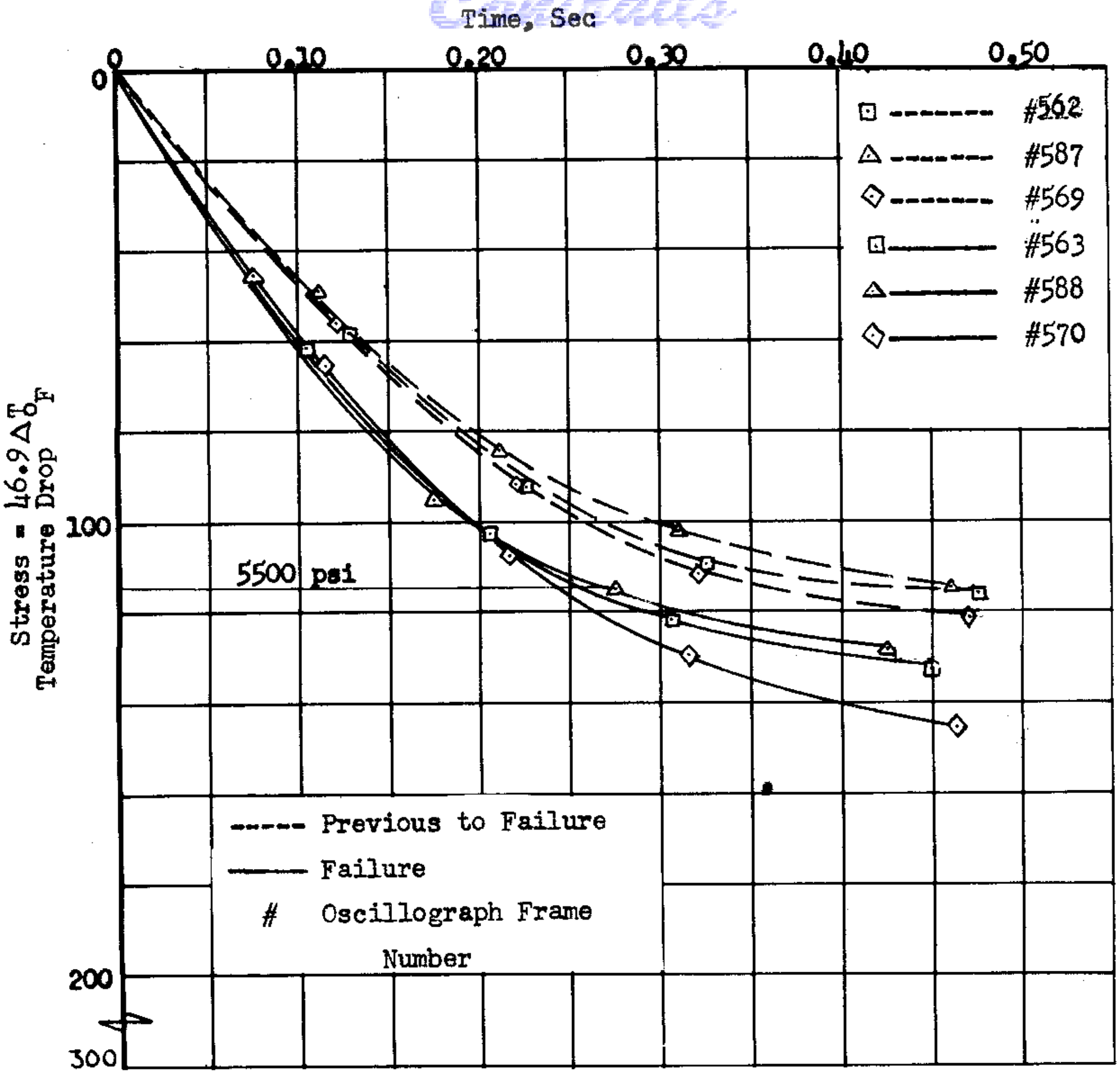


Fig. 12 Temperature Drop vs Time for Pittsburgh 3235 Annealed Glass

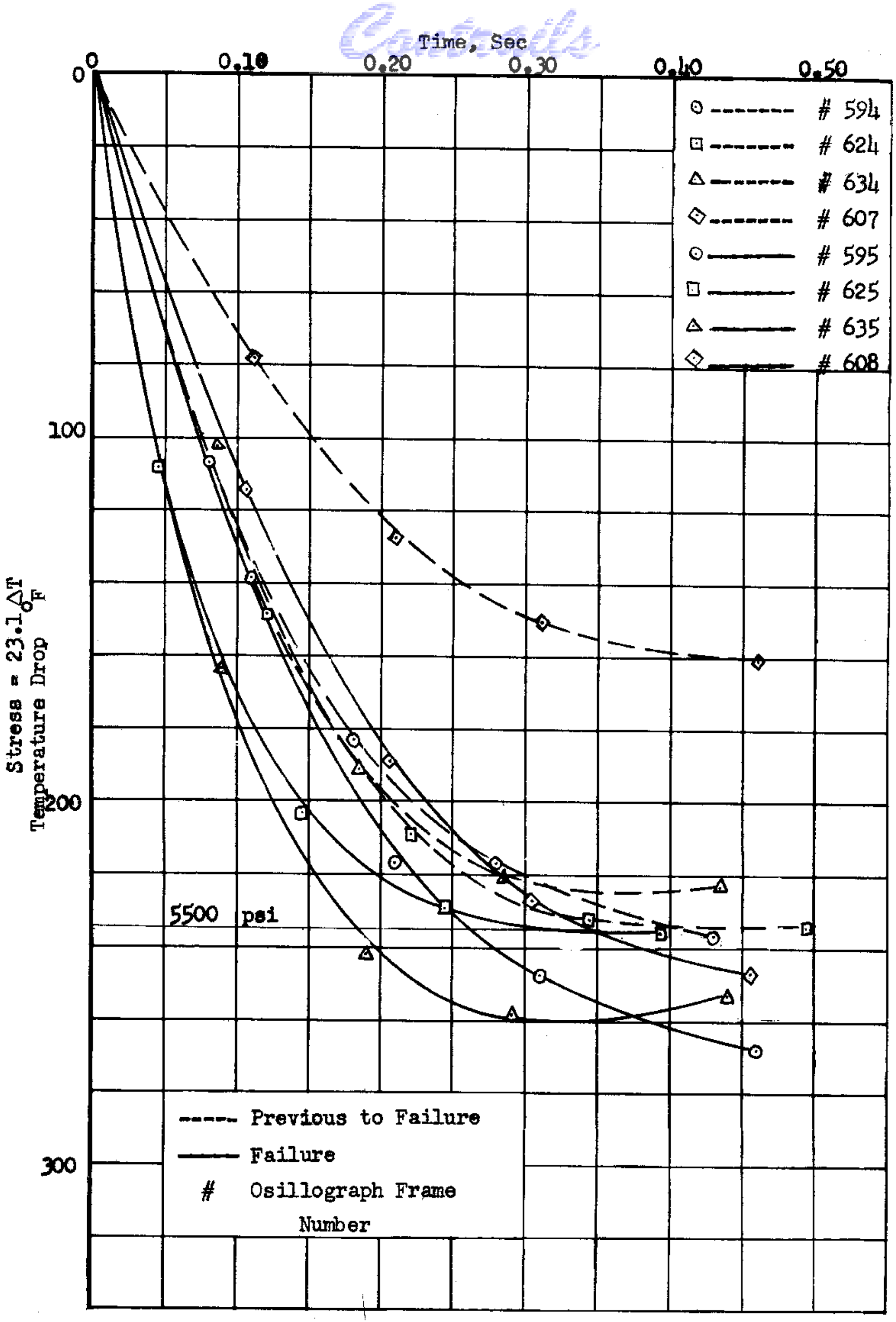


Fig. 13 Temperature Drop vs Time for Corning Pyrex Annealed Glass

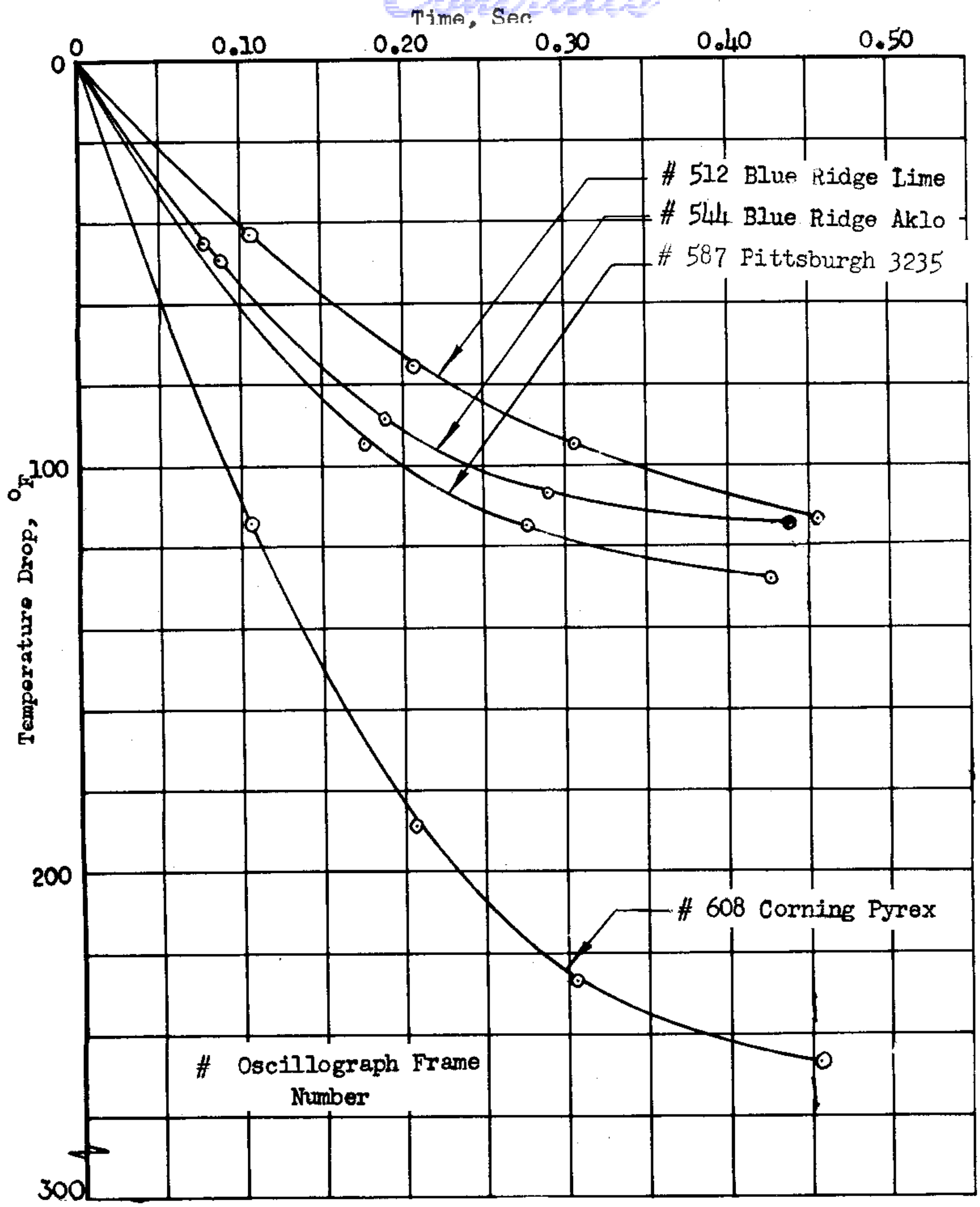


Fig. 14 Minimum Temperature Drop Causing Failure vs Time for Four Types of Annealed Glass

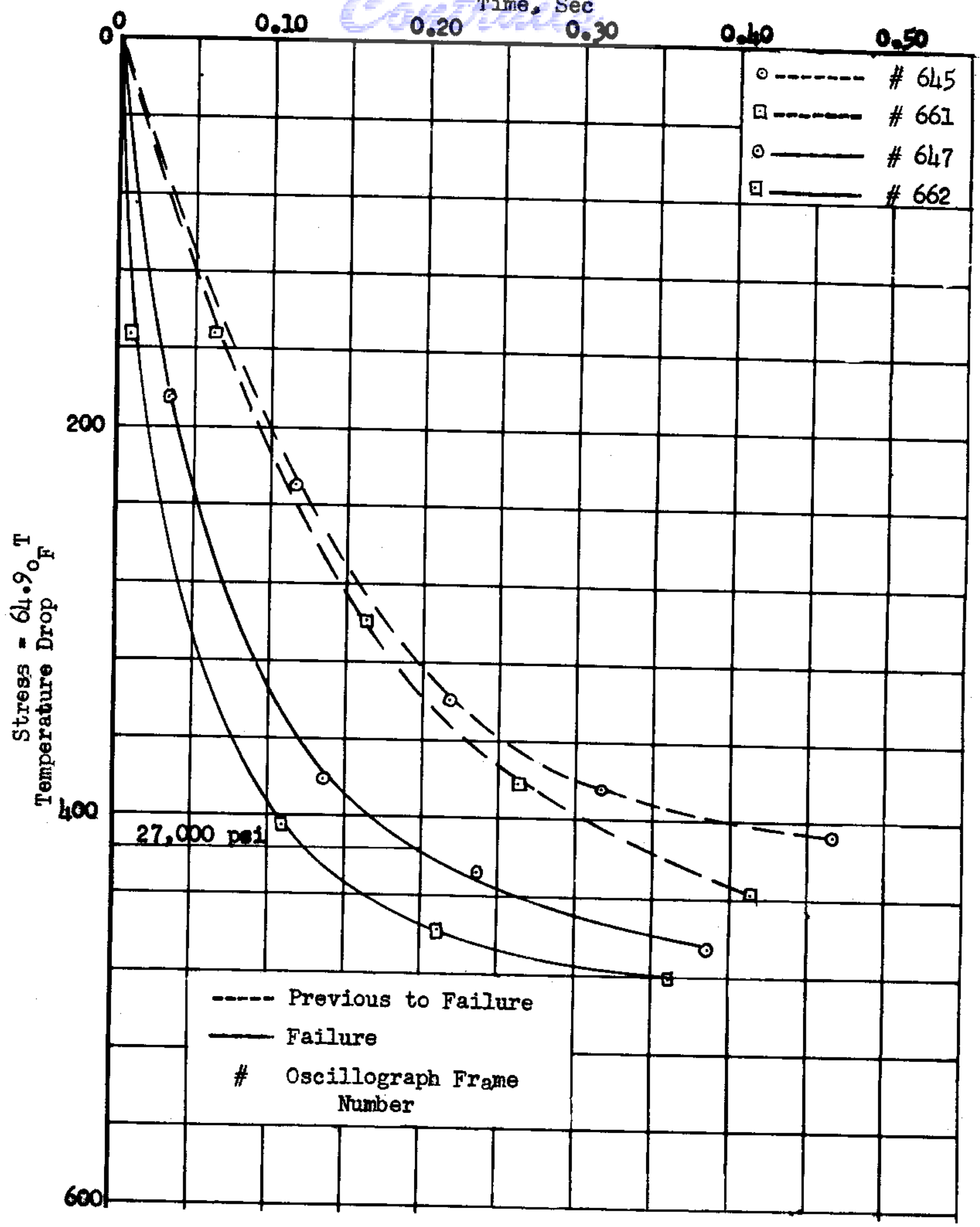


Fig. 15 Temperature Drop vs Time for Blue Ridge Lime Tempered Glass

VIII. DISCUSSION

The test results generally indicated that increasingly greater shock rates are required to cause failure in glasses of lower coefficients of thermal expansion. Since greater shock rates are associated with greater temperature drops, it follows that the temperature differential required to fail glass generally varies inversely with the thermal expansion coefficient.

Unless mediums are encountered which have a higher heat transfer coefficient than water, Pittsburgh 3235 and Corning Pyrex tempered glasses should be able to withstand any thermal shocks of the type studied which may be encountered by supersonic aircraft developing skin temperatures in the 600°F range. However, thermal shocks are not the only potential causes of failure of glass. Mechanical stresses due to edge mounting and pressure loading are additional factors. Non-uniform temperature distribution induced in the plane of the glass may very well be a more important factor in service than theoretical uniform surface shock.

Thermal shock stresses produced by non-linear temperature distributions through thickness of a glass pane are derived from parameters similar to those associated with stresses produced by non-uniform temperature distribution in the plane of the glass. Therefore, it is reasonable to assume that those glasses which have the greatest resistance to thermal shock will best resist the combination of non-uniform planar, steady-state and shock stresses.

Approaching the critical temperature distribution curve $T(c)_1$, which generates the rupture stress, by increasing the initial temperature in each successive test, provides a method of producing shock failures from a "threshold" initial temperature. Maximum (surface) shock stress generated by the temperature distribution $T(c)_1$ is increased with successively higher test temperature until the magnitude of maximum stress produced by this type of distribution is sufficiently large to cause failure.

IX. CONCLUSIONS

1. The test method developed under this program generally permits the selection of glass for windshield application, which possesses the greatest resistance to failure under thermal shock conditions uniformly applied to one surface.

2. Specifically, the apparatus used for this program did not have sufficient heating capacity to permit thermal differentials adequate for breaking the most shock-resistant glass specimens tested. However, the technique for both testing and interpreting could be extended if this became desirable.

3. The magnitude of surface stress caused by thermal shocks is dependent on both temperature drop and duration. The analysis indicates that temperature drops achieved in short shock periods develop higher surface stresses than comparable drops over longer periods. Test results corroborate this prediction in that failures resulted from short duration shocks but not from comparable temperature drops occurring over longer periods. From this it may be inferred that shock failure can be attained only by achieving a shock rate at least as great as the "threshold" or "critical" rate.

4. The time-versus-"surface"-temperature curves associated with failure are essentially linear functions in the range investigated. Therefore, they may be expressed in numerical terms as critical shock rates. These critical shock rates, having the following properties: (1) being based on a critical temperature distribution $T(c)_1$ which will cause failure, (2) representing the minimum shock rate which will cause failure, and (3) being approximately linear, provide a simple, direct measure of thermal shock resistance.

5. The experimental results indicate that the critical shock rate required to fail annealed glass is related inversely to the linear thermal expansion coefficient.

APPENDIX A

THERMAL TRANSDUCERS FOR RECORDING APPROXIMATE SURFACE SHOCK

by

G. NAGUMO

I. INTRODUCTION

The purpose of this Appendix is to present a summary of an investigation to develop a thermal transducer which was compatible with the thermal shock-testing equipment and would approximate dynamic surface temperature.

The copper-button technique used in early heat transfer experiments was excellent for measurement of surface temperature under steady-state conditions but proved to be unreliable and unstable when used in a water-spray system. This unsatisfactory behavior is obvious upon consideration of the heat transfer system peculiar to the copper-button transducer, as illustrated in Fig. 16.

The problem is essentially one of rapid heat flow from a thin plate which is insulated from the glass by a film of adhesive. For practical purposes the transient temperature registered by the thermocouple is independent of the glass temperature. Therefore, it is doubtful that dynamic glass surface temperature can be represented with acceptable reliability with this type of thermal transducer. The unsuitability of the copper-button transducer created the need for a satisfactory thermal transducer compatible with the thermal shock equipment.

Ideally, the most accurate system would be one in which a thermocouple, having thermal properties similar to the glass, was embedded in the glass immediately below the shocked surface. It would be desirable to devise a thermocouple which would simulate the measurement of temperature in the glass as close to the shock surface as practicable.

This is impossible because: (1) the high heat transfer rates of known thermocouple materials, and (2) the weakening effect on the glass by the presence of a foreign body having different thermal and mechanical properties.

II. STATEMENT OF PROBLEM

The problem essentially resolves into a design for a thermal transducer which incorporates the following characteristics: (1) sensitive and stable response, (2) not unduly influenced by shock fluid temperature, and (3) simulation of temperature measurement in the glass as close to the shock surface as practicable. Some of the difficulties encountered in solving this problem are presented below.

Since it is impossible to incorporate maximum sensitivity and maximum stability into a single unit, due to the inherent nature of measuring systems, a good transducer must be the product of a fine balance between sensitivity and stability.

The ability to measure approximate surface temperature rather than shock fluid temperature is based on a fundamental criterion; namely, the insulation of the EMF generating surfaces. Because of the many unknown parameters, any standard established by analytical methods can, at best, represent the expected order of magnitude of performance. Therefore, such a standard is not quantitatively applicable to experimental results. Transducers with the following physical properties were required: (1) complete insulation from the shock fluid, (2) a size small enough to leave the instrumented surface completely free and accessible to the shock fluid, (3) perfect heat transfer between the transducer and surface, thereby permitting the transducer and surface to maintain identical temperatures, and (4) production which would be simple and economical.

The economic aspects of this problem are mentioned primarily as a factor influencing the present program. The degree of refinement achieved in the solution of a problem of this nature is dependent largely on the financial resources and time available. It is likely that greater refinement could be achieved in subsequent applications if justified by performance and reliability of results.

In selecting the optimum measuring technique for this program, development cost plus total cost of all installations versus accuracy and response was considered. In the present program each test specimen required a minimum of four transducers and all were discarded with the tested specimen. The time and expense expended in production and installation are important under any similar test program.

III. BASIS OF EVALUATION

Evaluation of the thermal transducers was made on the basis of comparative response characteristics and agreement with analytical values derived from the solution of the Fournier heat flow equation which was solved for specific boundary conditions applicable to the present test program. The assumptions and limitations for the mathematical model are presented below, together with the complete solution of an example treated in the analytical discussion.

A. Mathematical Solution

1. Statement of the Problem

Given a glass pane at any equilibrium temperature, find the transient temperature distribution through its thickness at the time the "outer" surface of the pane is sprayed with a cooling medium.

2. Assumptions

The following assumptions were made: (1) the pane is infinite in extent, (2) the thermal and mechanical properties of the pane are independent of temperature and position, (3) temperature differences are not great enough to produce buckling, (4) the pane is free to expand in any direction in a plane parallel to its surface, (5) the cold surface of the glass pane changes temperature instantaneously under cold shock, and (6) the minimum surface temperature used in all calculations are those obtained during preliminary experimentation under suddenly short duration cold shock conditions.

The temperature change with time at the glass surface subjected to cold shock is illustrated in Fig. 17.

B. General Field of Heat Conduction Based Upon the Wave Equation

The Fournier heat flow equation[1] was applied to the temperature-time relation of Fig. 17 to determine the temperature at any distance from the shock surface at any time after shock, subject to the following boundary conditions: The initial temperature distribution is $U(x, 0)$, and the surfaces at $x = 0$ and $x = L$ were assumed to have constant temperatures U_0 and U_L, respectively.

---

[1] Churchill, Ruel V. "Fournier Series and Boundary Value Problems," McGraw-Hill Book Company, Inc., New York, 1941.

1. Boundary Conditions

$$U\ (0,\ t) = U_0 \qquad \text{at } x = 0$$

$$U\ (L,\ t) = U_L \qquad \text{at } x = L$$

$$U = U\ (x, 0\ ) \qquad \text{at } t = 0$$

2. Method of Attack

If we assume that U (x, t) is the sum of a transient solution (x, t), and a steady-state solution v (x) then

$$U\ (x,\ t) = v\ (x) + W\ (x,\ t) \tag{4}$$

a. Solution of v (x)

The transient solution decays exponentially with time, hence U (x, t) approaches v (x) as t approaches infinity. The function v (x) is a solution of the Laplace equation

$$\frac{d^2\ v}{d\ x^2} = 0 \tag{5}$$

subject to the boundary conditions;

$$\text{(i) } v\ (0) = U_0 \qquad \text{when } x = 0$$

$$\text{(ii) } v\ (L) = U_L \qquad \text{when } x = L$$

since the solution of the Laplace equation is

$$v = K_1\ x + K_2$$

from boundary conditions i,

$$K_2 = U_0$$

from boundary conditions ii,

$$K_1 = \frac{U_L - U_0}{L}$$

so that

$$v(x) = (U_L - U_0)\frac{x}{L} + U_0 \tag{6}$$

b. Solution of w(x, t)

The heat flow equation where there are no heat sources or sinks is

$$\frac{\partial^2 w}{\partial x^2} = \frac{1}{\alpha}\frac{\partial w}{\partial t}. \tag{7}$$

Where

$\alpha = \frac{K}{c\rho}$ is called the diffusivity of the material.

Where c and p are specific heat and density respectively the method of separation of variables assumes a solution in the form

$$w(x, t) = T(t)\,F(x) \tag{8}$$

If Equation 8 is substituted into Equation 7 assuming that T(t) is independent of space coordinates and F(x) is independent of time,

$$T\frac{\partial^2 F(x)}{\partial x^2} = \frac{1}{\alpha}F(x)\frac{\partial T}{\partial t}. \tag{9}$$

This equality exists if both the right and lefthand side equal a constant. Designate this constant as $-a_x^2$ and let

$$\gamma^2 = -a_x^2$$

$$\gamma = \pm\, i\, a_x$$

$$\frac{1}{F(x)}\frac{\partial^2 F(x)}{\partial x^2} = \frac{1}{\partial T}\frac{\partial T}{\partial t} = \gamma^2 \tag{10}$$

It then follows from Equation 10,

$$\frac{1}{\alpha T} \frac{\partial T}{\partial t} = \gamma^2$$

$$\frac{d T}{T} = \alpha \gamma^2 \, dt$$

$$\log T = \alpha \gamma^2 t + K$$

or

$$T(t) = A e^{\alpha \gamma^2 t} \tag{11}$$

and from the relation in Equation 10,

$$\frac{1}{F(x)} \frac{\partial^2 F(x)}{dx^2} = \gamma^2$$

or

$$\frac{\partial^2 F(x)}{\partial x^2} = \gamma^2 F(x).$$

The solution by classical or operator methods is

$$F(x) = K_x' \, e^{\gamma x} + K_x'' \, e^{-\gamma x} \tag{12}$$

$$F(x) = K_x' \cos a_x x + K_x'' \sin a_x x.$$

Therefore, from Equations 8, 11, and 12,

$$w(x, t) = A e^{\alpha \gamma^2} t \, (K_x' \cos a_x x + K_x'' \sin a_x x) \, . \tag{13}$$

Subject to the following boundary conditions:

i) $w(0, t) = 0$ at $x = 0$

ii) $w(L, t) = 0$ at $x = L$

iii) $w(x, 0) = U(x, 0) - v(x)$ at $t = 0$

By boundary condition i

$$K_x' = 0 \,.$$

By boundary condition ii

$$a_x = \frac{n\pi}{L} \quad \text{or} \quad \gamma^2 = \frac{n^2 \pi^2}{L^2} \,.$$

Applying i and ii to Equation 13 and summing from $n = 1$ to $n = \infty$ we have

$$w(x,\ t) = \sum_{n=1}^{\infty} C_n \ e^{-\frac{\alpha n^2 \pi^2}{L^2} t} \sin \frac{n \pi x}{L} \tag{14}$$

in order to evaluate C_n we note that at $t = 0$

$$w(x,\ 0) = \sum_{n=1}^{\infty} C_n \sin \frac{n \pi x}{L} \,.$$

This is a Fournier sine series where the coefficients are given by

$$C_n = \frac{2}{L} \int_0^L w(x',\ 0) \sin \frac{n \pi x'}{L} \, dx'. \tag{15}$$

By boundary condition, iii

$$w(x,\ 0) = U(x,\ 0) - v(x) \qquad \text{at } t = 0 \,.$$

Replacing x by x' for $t = 0$

$$w(x',\ 0) = u(x',\ 0) - (U_L - U_0) \frac{x'}{L} - U_0$$

substituting into Equation 15 for C_n

$$\begin{aligned} C_n &= \frac{2}{L} \int_0^L \left[U(x',\ 0) - (U_L - U_0) \frac{x'}{L} - U_0 \right] \sin \frac{n \pi x'}{L} \\ &= \frac{2}{L} \int_0^L U(x',\ 0) \sin \frac{n \pi x'}{L} \, dx' + \frac{2}{n} \left[(-1)^n U_L - U_0 \right] \end{aligned} \tag{16}$$

$n = 1,2,3\ldots\ldots$

Hence, from Equations 4, 6, 14, and 16,

$$U(x, t) = (U_L - U_0)\frac{x}{L} + U_0 + \sum_{n=1}^{\infty}\left[\frac{2}{L}\int_0^L U(x', 0)\sin\frac{n\pi x'}{L}dx' - \frac{2}{L}\int_0^L U(x', 0)\sin\frac{n\pi x'}{L}dx + \frac{2}{n\pi}\left[(-1)^n U_L - U_0\right] e^{-\frac{\alpha n^2 \pi^2 t}{L^2}} \sin\frac{n\pi x}{L}\right]. \quad (17)$$

Upon integration

$$U(x, t) = (U_L - U_0)\frac{x}{L} + U_0 + \sum_{n=1}^{\infty}\left[\frac{2}{n\pi} U(x', 0) - (-1)^n U(x', 0) + (-1)^n U_L - U_0\right] e^{-\frac{\alpha n^2 \pi^2 t}{L^2}} \sin\frac{n\pi x}{L}.$$

For all practical purposes, the present test program assumes

$$U(x', 0) = U_L$$

therefore,

$$U(x, t) = (U_L - U_0)\frac{x}{L} + \frac{2}{\pi}(U(x', 0) - U_0)\sum_{n=1}^{\infty}\frac{1}{n} e^{-\frac{\alpha n^2 \pi^2 t}{L^2}} \sin\frac{n\pi x}{L} \quad (18)$$

C. Numerical Solution and Examples

For the numerical solution incorporating parameters applicable to a representative test specimen, we consider the determination of the temperature distribution through the glass plate tested as recorded on oscillograph frame No. 591. This particular specimen was a Pyrex annealed glass plate with the following physical properties:

(1) Over-all dimension is 10 by 20 in.
(2) 0.25 in. thick
(3) $\alpha = 0.016\ ft^2/hr$
(4) coefficient of linear thermal expansion = 90×10^{-7} in./° C.

The boundary conditions to be satisfied are:

$$v(x) = 170°F \qquad \text{at } x = 0$$
$$U_0 = 159°F \qquad \text{at } x = 0$$
$$U_L = U(x, 0) = 417°F \qquad \text{when } t = 0.$$

The complete solution is given in Section A, Equation 18.

The numerical value of the exponential term is

$$e^{-\frac{\alpha n^2 \pi^2 t}{L^2}} = e^{-\frac{0.016\,(3.14)^2\, n^2\, t}{\left(\frac{1}{48}\right)^2}} = e^{-0.101\, n^2\, t}$$

where t is in seconds.

If the above results are inserted in Equation 18 then

$$U(x, t) = \left[U(x', 0) - U_0\right] \frac{x}{L}$$
$$+ U_0 + \frac{2}{\pi} (U(x', 0) - U_0) \sum_{n=1}^{\infty} \frac{1}{n} e^{-0.101\, n^2\, t} \sin \frac{n \pi x}{L}$$

Also, if we are to determine the temperature distribution at a depth of .01 inch below the surface, $x = 0.01$ and $\frac{x}{L} = \frac{0.01}{0.25} = \frac{1}{25}$.

Therefore,

$$U(x, t) = (U_L - U_0)\frac{1}{25} + U_0$$

$$+ \frac{2}{\pi}(U\ (x', 0 - U_0) \sum_{n=1}^{\infty} \frac{1}{n}\ e^{-0.101\ n^2\ t} \sin\ (7.2n)°.$$

With the values of the boundary conditions inserted, $U(x, t)$ becomes

$$U(x, t) = \frac{417 - 159}{25} + 159 + (417 - 159) \sum_{n=1}^{\infty} \frac{2}{n\pi} e^{-0.101\ n^2\ t} \sin\ (7.2n)°.$$

To simplify the handling of the solution, the summation of the Fournier series coefficients is presented in Table III where $\psi_n = \frac{2}{n\pi}\sin\ (7.2n)°$

and

t (sec)	$e^{-0.101n^2\ t}$
0.05	$e^{-0.005n^2} = \phi^n_{0.15}$
0.15	$e^{-0.015n^2} \equiv \phi^n_{0.15}$
0.25	$e^{-0.025n^2} = \phi^n_{0.25}$
0.35	$e^{-0.035n^2} = \phi^n_{0.35}$

Then

$$U(0.01,\ 0.05) = \frac{258}{25} + 159 + 258 \sum_{n=1}^{\infty} \frac{2}{n\pi} \sin\ (7.2n)°\ \ \phi^n_{0.05}$$

$$U(0.01,\ 0.15) = \frac{258}{25} + 159 + 258 \sum_{n=1}^{\infty} \frac{2}{n\pi} \sin\ (7.2n)°\ \ \phi^n_{0.15}$$

TABLE III

SUMMATION OF THE FOURNIER SERIES COEFFICIENTS

n	ψ	ϕ 0.05	ϕ 0.15	ϕ 0.25	ϕ 0.35	$\psi\phi$ 0.05	$\psi\phi$ 0.15	$\psi\phi$ 0.25	$\psi\phi$ 0.35
1	0.0800	1.00	0.98	0.97	0.96	0.080	0.078	0.078	0.077
2	0.0797	0.98	0.94	0.90	0.86	0.078	0.075	0.072	0.068
3.	0.0773	0.95	0.87	0.79	0.73	0.073	0.067	0.061	0.056
4	0.0771	0.92	0.79	0.66	0.57	0.091	0.061	0.051	0.044
5	0.0964	0.88	0.68	0.53	0.41	0.067	0.052	0.041	0.031
6	0.0752	0.84	0.61	0.40	0.28	0.063	0.046	0.030	0.021
7	0.0693	0.78	0.47	0.20	0.17	0.054	0.033	0.014	0.012
8	0.0619	0.72	0.38	0.19	0.10	0.045	0.024	0.012	0.006
9	0.0634	0.66	0.29	0.13	0.06	0.042	0.018	0.008	0.004
10	0.0571	0.61	0.22	0.08	0.03	0.035	0.013	0.004	0.002
11	0.0589	0.54	0.16	0.05	0.01	0.032	0.009	0.003	0.001
12	0.0499	0.48	0.11	0.03		0.024	0.006	0.002	
13	0.0499	0.42	0.08	0.01		0.021	0.044	0.001	
14	0.0394	0.37	0.05			0.015	0.002		
15	0.0380	0.32	0.03			0.012	0.001		
16	0.0362	0.27				0.010			
17	0.0338	0.23				0.008			
18	0.0308	0.19				0.006			
19	0.0305	0.16				0.005			
20	0.0176	0.13				0.002			
					$\sum \psi_n \phi_t^n$	0.763	0.489	0.377	0.322

$$U(0.01,\ 0.25) = \frac{258}{25} + 159 + 258 \sum_{n=1}^{\infty} \frac{2}{n\pi} \sin\,(7.2n)^\circ \quad \phi^n_{0.25}$$

$$U(0.01,\ 0.35) = \frac{258}{25} + 159 + 258 \sum_{n=1}^{\infty} \frac{2}{n\pi} \sin\,(7.2n)^\circ \quad \phi^n_{0.35}\ .$$

Therefore,

$$U(0.01,\ 0.05) = 169.3 + 258\ (0.763) = 169.3 + 196.85 = 366^\circ F$$

$$U(0.01,\ 0.15) = 169.3 + 258\ (0.489) = 169.3 + 126.16 = 295^\circ F$$

$$U(0.01,\ 0.25) = 169.3 + 258\ (0.377) = 169.3 + 97.27 = 267^\circ F$$

$$U(0.01,\ 0.35) = 169.3 + 258\ (0.322) = 169.3 + 83.08 = 252^\circ F$$

The temperature distributions determined as above have been plotted against the actual test results in Fig. 23.

IV. EXPERIMENTAL INVESTIGATION

The development program consisted of stepwise modifications of the copper-button thermal transducer, wherein physical modifications were refined and incorporated into each succeeding model which had improved thermal characteristics. Preliminary investigations with the copper-button transducer included tests wherein the amount of insulation, type of adhesive, and mounting techniques were varied to determine their effect on dynamic response. The results of the preliminary investigation also lead to the design of a special clamping fixture to hold the transducers in place on the glass specimens during the drying or curing period. A standard mounting technique was developed, thereby insuring uniformity and providing a reliable and systematic basis for the evaluation of succeeding results.

The laboratory test program consisted of thermal shock tests to evaluate the performance of various thermal transducers mounted on glass specimens. Each type of transducer was affixed to the "outer" or "shock" surface of a test specimen with epoxy resin. The resin was applied only about the base and not over or under the transducers, thereby keeping the active heat transfer areas free of insulation. The transducers were tightly clamped onto the surface while the adhesive was allowed to dry for four to five hours at room temperature.

Instrumented specimens were placed in the thermal shock fixture and shocked from several temperatures by a cold spray of ice-water (32°F). Each type of transducer was tested several times under different shock conditions before final evaluations were made.

The dynamic EMF values were recorded by an oscillograph and the records read with a glass optical gage. For all tests it was assumed that the oscillograph galvanometers would equally respond to the output of the thermocouples, both in magnitude and time with negligible error. In addition, it was assumed that the thermocouples were generating or functioning within the limits set forth by the specifications of the Leeds & Northrup Company for their copper and constantan thermocouple wire.

The following is a summary description of the transducers tested including the construction and evaluation of each. Sketches of each type are shown in Fig. 18. Each type of transducer was operated and compared with a bare thermocouple.

Type A-1

Construction: The thermocouple was soldered to the center of a 1/4 in. diameter disc stamped out of 0.007 in. copper shim stock.

Evaluation: The fabrication was simple and economical. The thermal response characteristics were excellent for steady-state conditions; however, the dynamic shock response was varied and unpredictable, depending partially on the adhesive line insulation

Type A-2

Construction: The type A-2 transducer is a type A-1 with a copper cap soldered over the thermocouple to protect it from the direct flow of the shock fluid. The leads were well insulated to prevent shorting through the cap.

Evaluation: Fabrication was difficult and time-consuming. The dynamic thermal response of a few was satisfactory; however, most of the units were unstable and erratic.

Type A-3

Construction: An 0.500 in. diameter by 0.0065 in. thick biological glass coverslip was glued over a type A-1 thermocouple to protect it from the direct flow of the shock fluid.

Evaluation: There were no fabrication difficulties and expense other than the nominal cost of the coverslips. The thermal response characteristics depended largely upon the type and amount of adhesive used for mounting. For those units which operated properly, the response was good but usually the coverslips shattered under the thermal shock spray. Further, this size coverslip insulated the specimen unduly from the shock fluid.

Type A-4

Construction: The cylinders were made from 1/4 in. aluminum rod cut to lengths of 3/16 in. and drilled with an 0.030 in. drill. In the two-hole model a groove connected the two lead holes on the base, thus permitting the thermocouple to be in contact with the "active" surface.

Evaluation: Fabrication was simple and economical; however, the thermal-response was unsatisfactory. The time lag between shock and response was too great; also the amplitude of response was greatly attenuated by the mass of the aluminum cylinders.

Type A-5

Construction: The domes were machined from 1/4 in. aluminum rod. The height of the dome was approximately 1/8 in. Holes were drilled with an 0.030 in. drill.

Evaluation: The response of both models was good; however, the solid model was in general more stable and uniform. The experimental results approach the analytical temperature distribution at a depth of 0.015 in. below the shock surface. However, from the calculations made, it was believed that reduction of the button mass would bring the theoretical depth of simulation closer to the surface of the specimen.

Type A-6

Construction: The dome was cut from 1/4 in. aluminum stock with a special cutter ground to a radius of 0.093 in. Holes were drilled with a drill. The slot was 0.015 in. deep and 0.031 in. wide.

Evaluation: After the special production tools were made, fabrication was easy and economical. The response was good with a short time lag and stable uniform response throughout the temperatures ranges of the thermal shock region. The experimental results agree favorably with the analytical temperature distribution at a depth of 0.01 in. below the shock surface.

V. RESULTS

The results of the thermal-shock tests to determine the dynamic response of the thermal transducers tested are summarized in Table IV, where the temperature response versus time of each type of transducer is presented. Test results are compared graphically with analytical results in Figs. 19 to 24.

TABLE IV

TEMPERATURE VERSUS TIME

FOR VARIOUS TYPES OF TRANSDUCERS

Type of Thermocouple	Oscilograph Frame No.	Galvanometer No.	Temperature, °F Initial Temperature	Time After Shock (sec) 0.15	0.25	0.35	0.50
A-1	399	3	211	110	95		
	606	7	349	125	100		
	607	7	397	112	112		
	608	7	430	136	120		
	609	7	490	155			
A-2	399	5	220	154	140	125	110
	399	9	222	135	119	110	100
	402	5	198	115	102	97	92
	402	9	214	143	119	112	104
	406	5	187	105	94	92	86
	406	9	252	143	115	100	95
	406	3	252	180	150	116	102
	407	5	274	120	102	86	86
	458	4	163	146	141	130	125
	458	5	160	138	120	105	99
	458	8	156	126	112	102	98
	460	4	230	210	196	176	157
	460	5	230	180	156	150	137
	460	8	252	155	135	121	110
A-3 Ribbon Thermocouple Under One Glass Cover-slip = 0.007 in.	421	4	481	194	179	155	
	421	7	260	190	180	170	
	421	8	260	202	187	170	
	433	6	254	184	165	151	
	440	7	265	208	182	170	
	440	9	285	177	145	130	
Ribbon Thermo-couple Under Two Glass Cover-slips = 0.0013 in.	424	5	483	300	269	238	
	433	5	363	300	265	195	
Three Cover-slips = 0.02 in.	424	6	490	413	-		
3/16 x 1/8 in. Aluminum Dome with Slot on Bottom	453	6	338	292	273	250	232
	453	7	345	310	290	268	242
	453	13	325	290	267	248	218
	453	14	350	317	245	212	166
	454	6	415	388	363	333	305
A-5	454	7	423	394	366	348	326
	454	13	392	338	277	230	195
	454	14	423	383	330	314	282
A-5 Aluminum Dome with Two Holes	453	8	356	305	261	230	200
	454	8	432	387	315	279	240
A-6 Aluminum Dome with Hole and Slot for Thermo-couple	591	3	208	154	132	123	116
	591	4	243	204	179	165	155
	591	5	255	194	163	145	140
	594	3	326	214	168	150	140
	594	4	392	296	243	216	205
	594	5	417	295	232	197	178
Bare Thermocouple	404	6	185	135	73	-	-
	405	6	253	145	75	-	-
	409	6	373	203	153		-
	411	6	375	183	155	-	-
	414	6	485	225	195	-	-
	426	3	511	250	214	-	-
	439	4	194	111	-	-	-
	439	11	185	93	88		
	439	12	185	106	-	-	-

VI. CONCLUSIONS

On the basis of these investigations, the most satisfactory method developed for measuring dynamic surface temperatures in this program was found to be the thermal transducer type A-6; however, this method is not necessarily the best technique for measuring all dynamic surface temperature change phenomenon.

Due to the time scheduled for this phase of the program, the investigation of surface temperature measurement was terminated with the completion of the A-6 thermal transducer, since its response closely approximated the analytically predicted temperature distribution at 0.01 in. below the shock surface. It is suggested that work could be continued along the lines initiated above. Other techniques touched on, which warrant serious consideration, include: (1) the use of ribbon thermocouples, (2) metallic spray techniques, (3) conducting paint thermisters, and (4) printed circuit techniques utilizing impedance variations as a function of the coefficient of expansion.

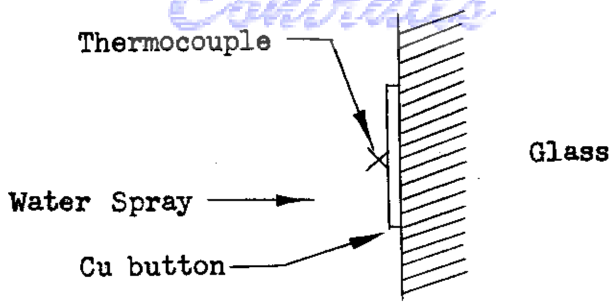


Fig. 16 Heat Transfer System

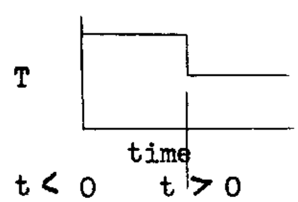


Fig. 17 Temperature Distribution Induced at Surface of Glass Pane

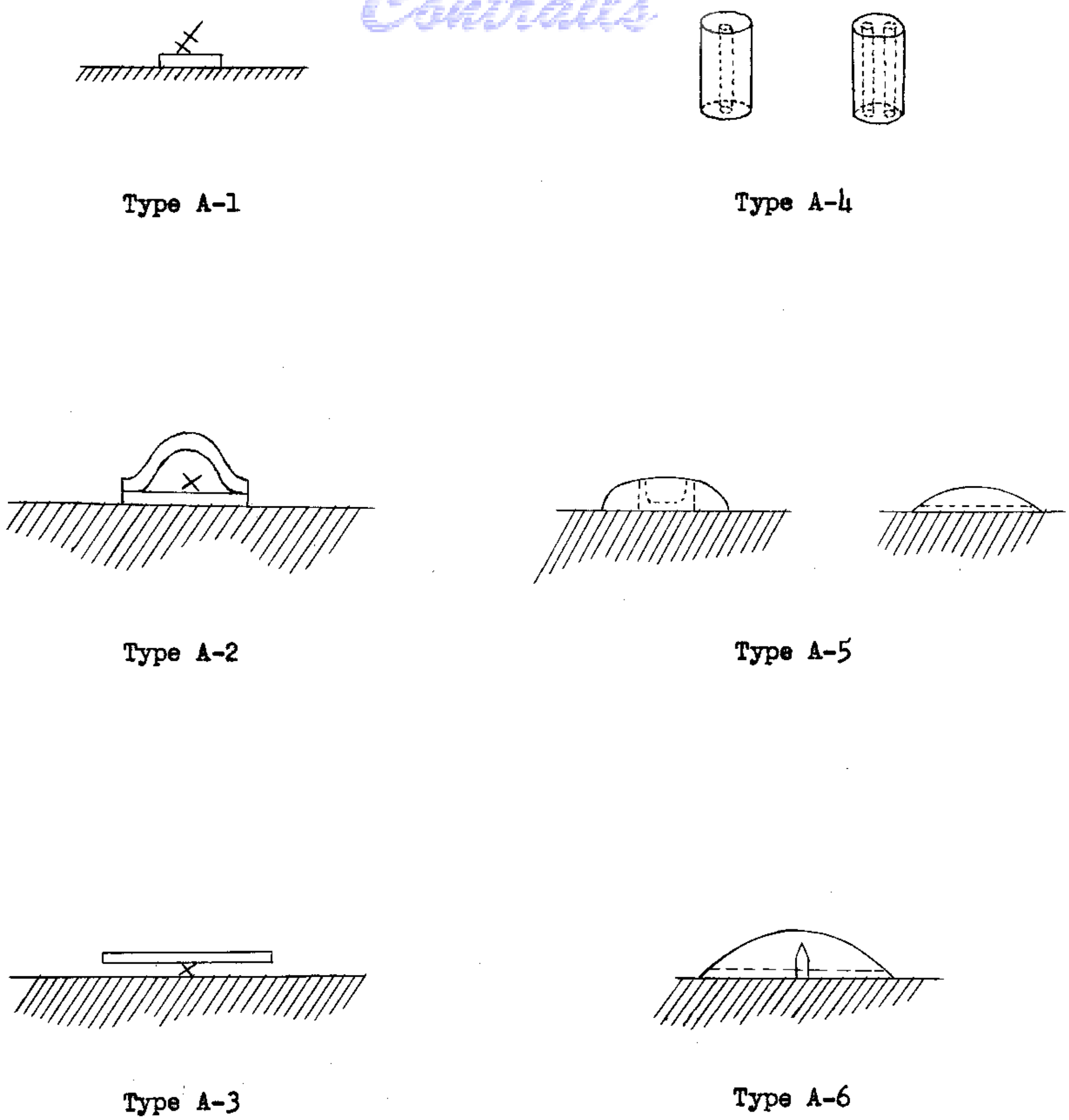


Fig. 18 Sketches of the Various Types of Transducers

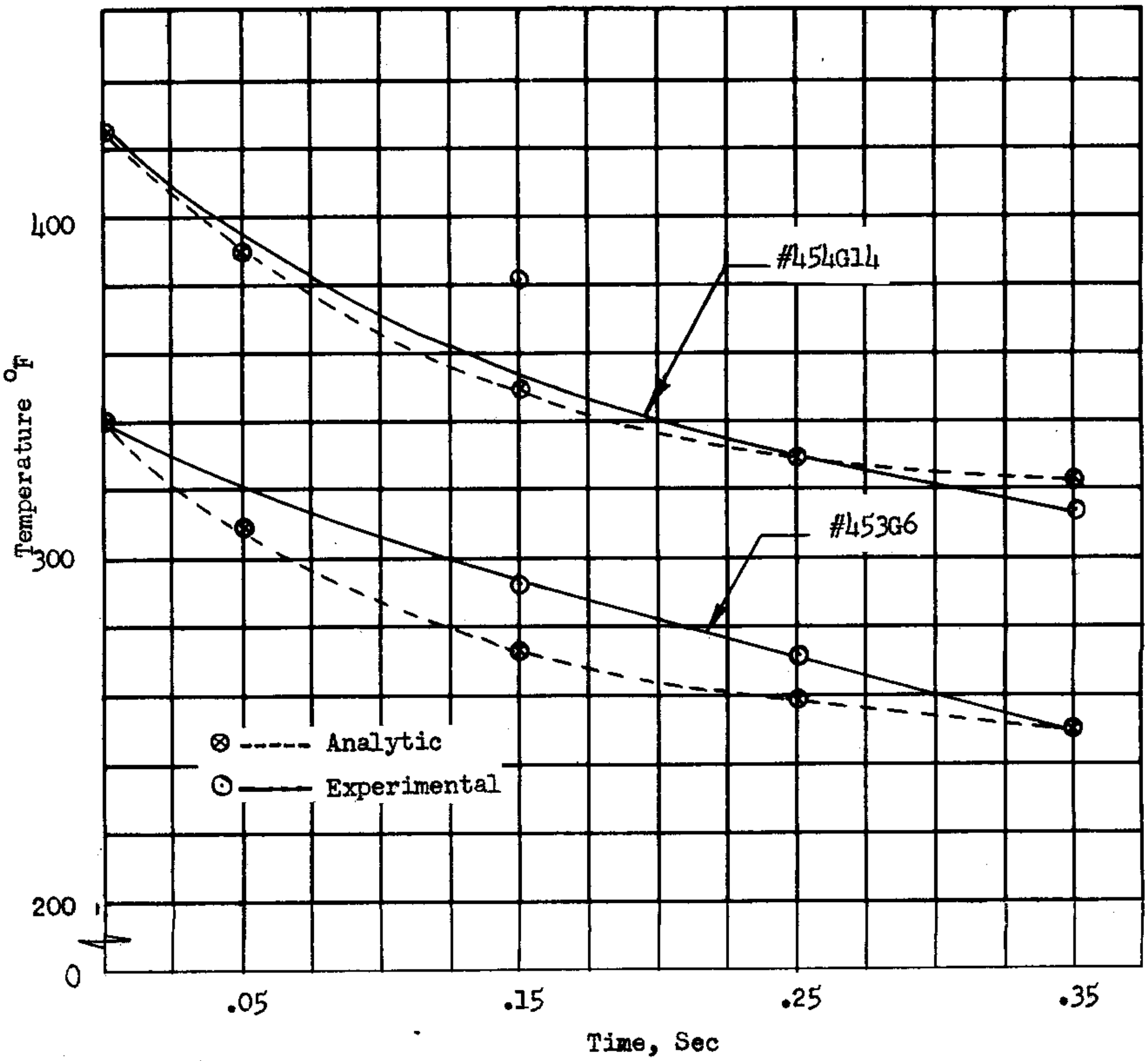


Fig. 19 Type A-2 Aluminum Dome With Slot

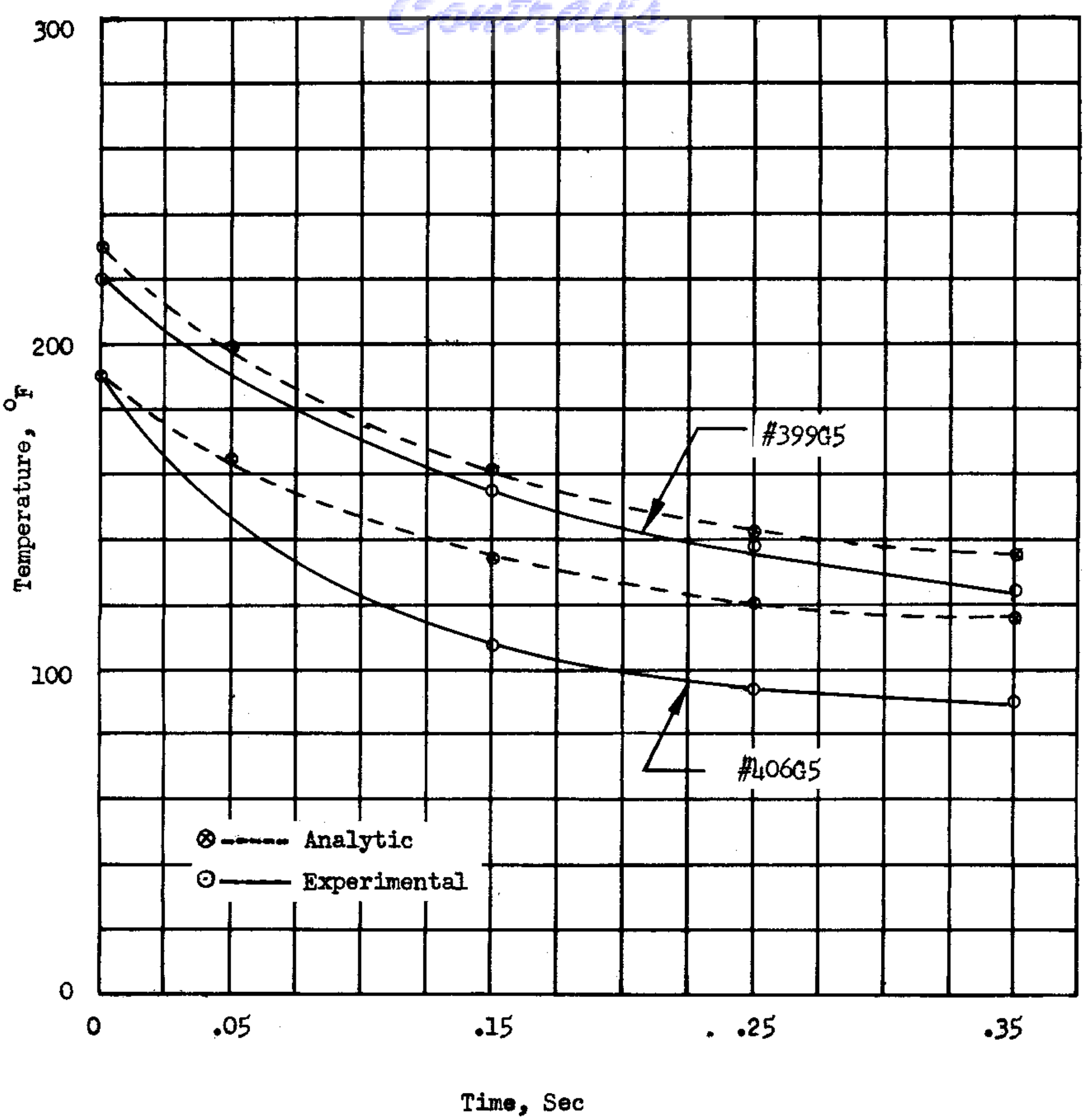


Fig. 20 Type A-2 Copper Dome Over Copper Button

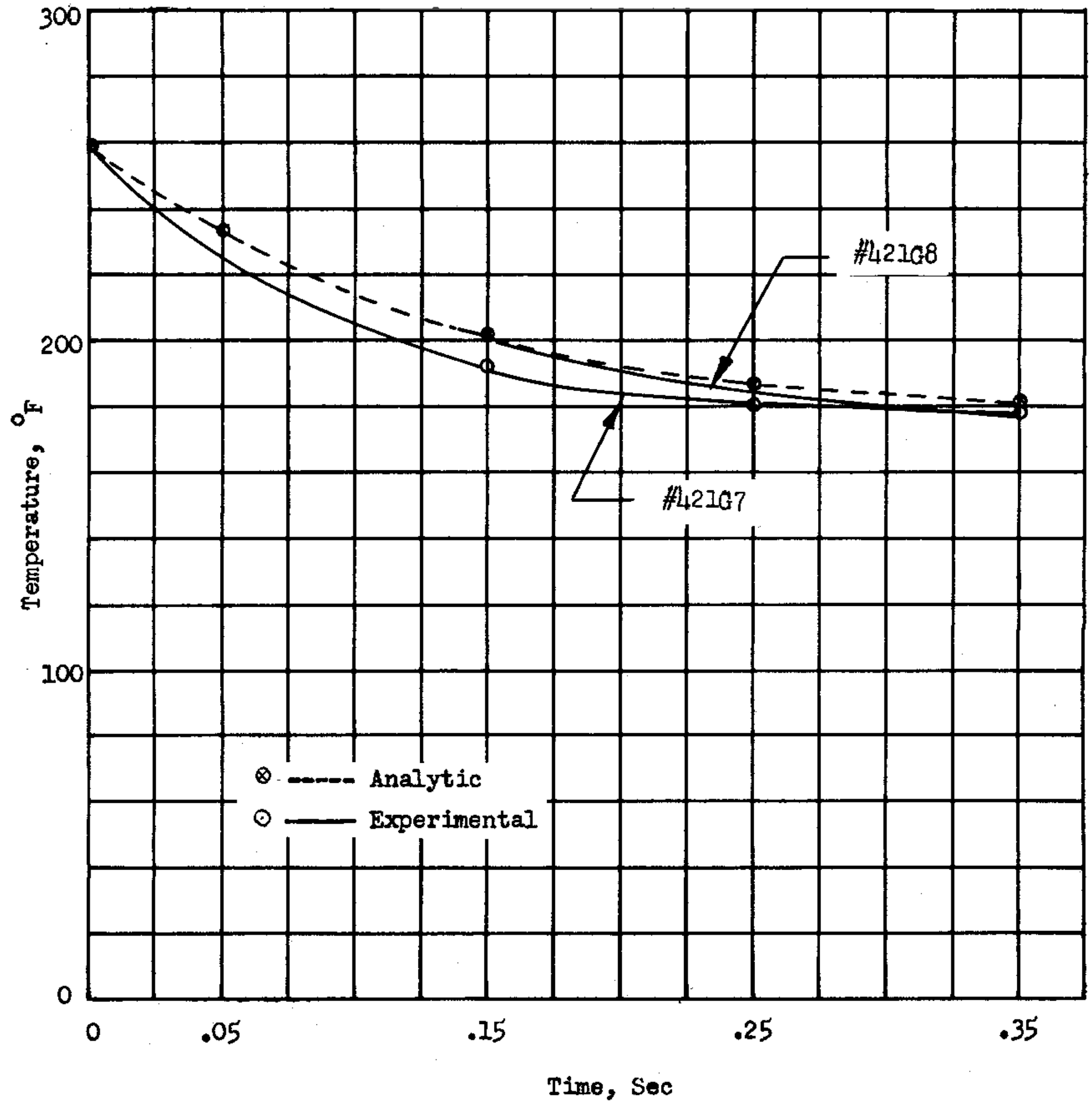


Fig. 21 Type A-3 One Glass Cover Slip = .007 inch thick

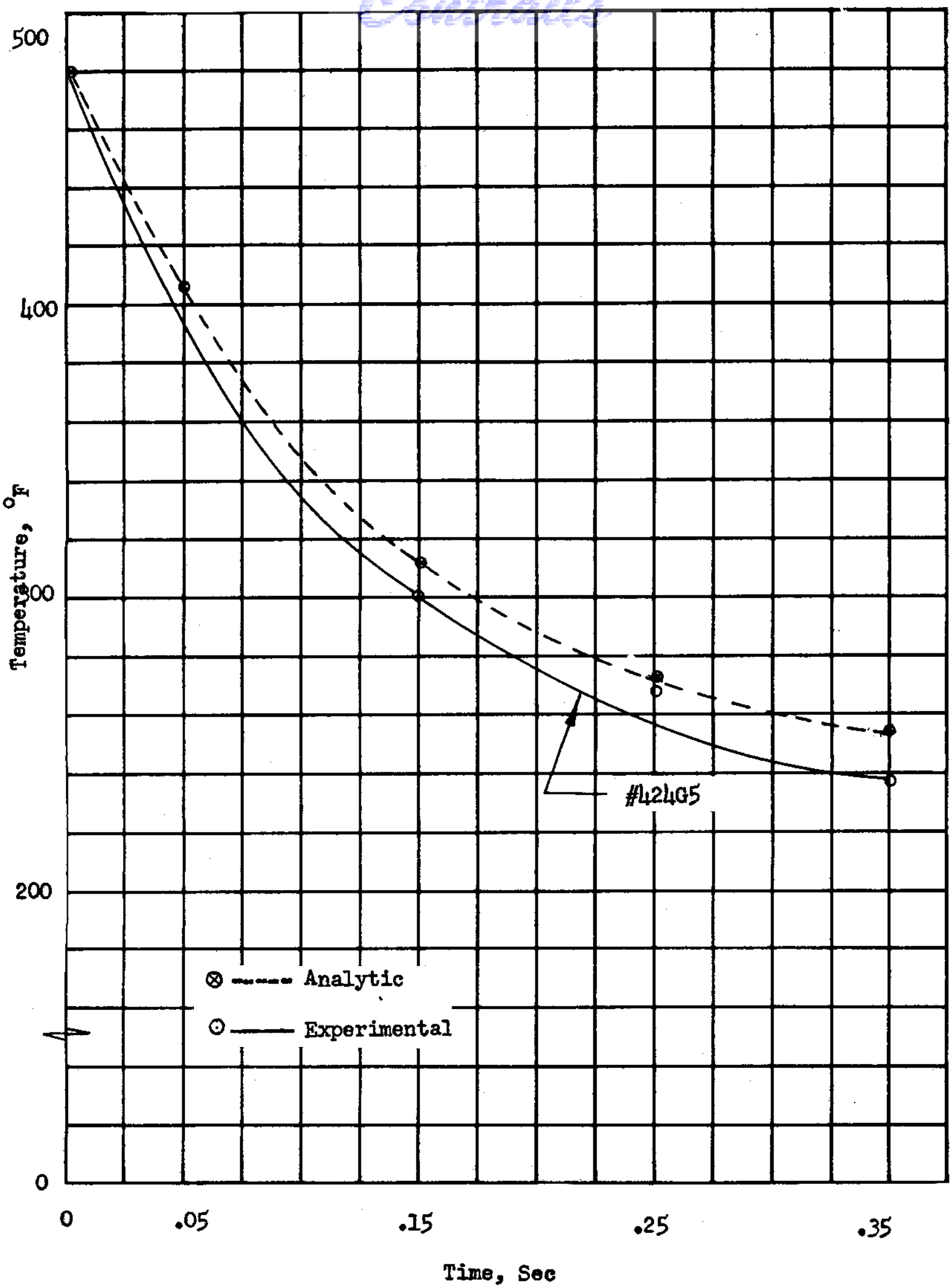


Fig. 22 Type A-3 Two Glass Cover Slips = .013 inch thick

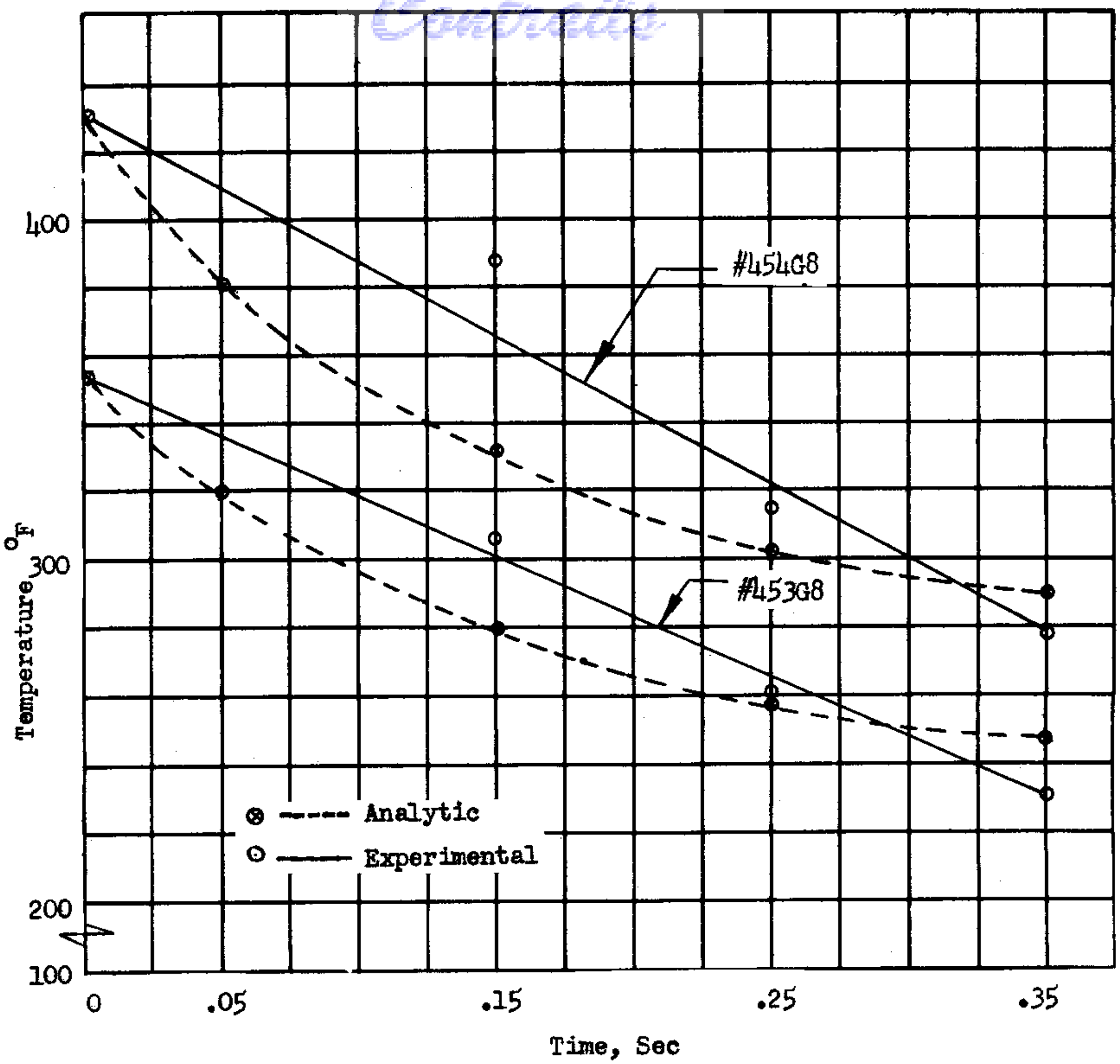


Fig. 23 Type A-5 Aluminum Dome With Two Holes

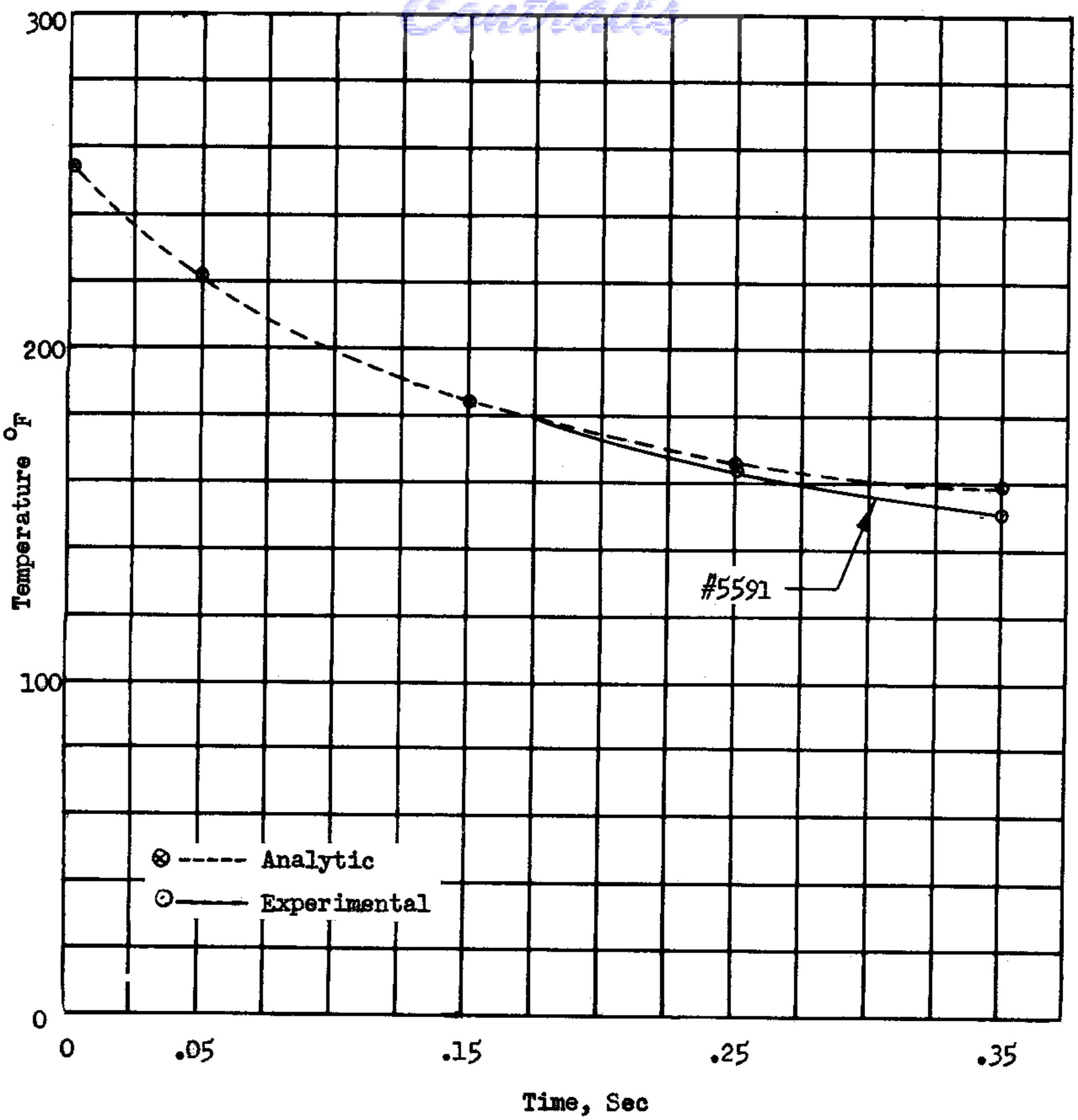


Fig. 24 Type A-6 Aluminum Dome With Slot and Hole

APPENDIX B

HEAT TRANSFER COEFFICIENT RELATIONSHIP FOR ATTACKING FLUIDS

D. Horwitz

I. STATEMENT OF PROBLEM

The purpose of this study is to compare the relative effectiveness of various gases and liquids as heat transfer or cooling media when employed in the manner contemplated for the experimental phase of this program. The problem considered is that of unsteady-state heat transfer from a heated glass plate to a fluid impinging normal to the heated surface. Initial and boundary conditions for this system have been specified and are listed:

1. The surface exposed to the coolant fluid is at a maximum temperature of 600°F initially.

2. The surface that is shielded from the coolant fluid loses heat by natural convection to an ambient at 70°F.

3. The minimum thermal shock rate to be attained at the exposed surface is 100°F/min.

4. The plate thickness is 1/4 in.

A sketch of the system is given in Fig. 25.

The rate of temperature fall at the exposed plate surface is a function of the physical properties of the plate, and the driving force for the flow of heat as provided by the product (h) (Δt).* The minimum rate of temperature decrease at the surface of the plate has been specified to be 100°F/min. Then this minimum rate is given by:

$$\left(\frac{\partial t}{\partial \theta}\right)_{x=0} = 100^{\circ}F/min = \phi\,(h\Delta t, \Delta_p, \delta_i) \qquad (19)$$

The system has been defined with regard to $\frac{\partial t}{\partial \theta}$, Δ_p, and δ_i, so that the product (h) (Δt) is determined by Equation 19 and from correlations which exist in the literature, the heat transfer coefficient can be expressed in terms of velocity of the attacking fluid. These correlations can be presented in the general form:

$$N_{Nu} = C_0 (N_{Re})^m \, (N_{Pr})^n \qquad (20)$$

$$\left(\frac{hD}{k}\right) = C_0 \left(\frac{VD\rho}{\mu}\right)^m \left(\frac{c_p \cdot \mu}{k}\right) \qquad (21)$$

---

* See Section III: Nomenclature

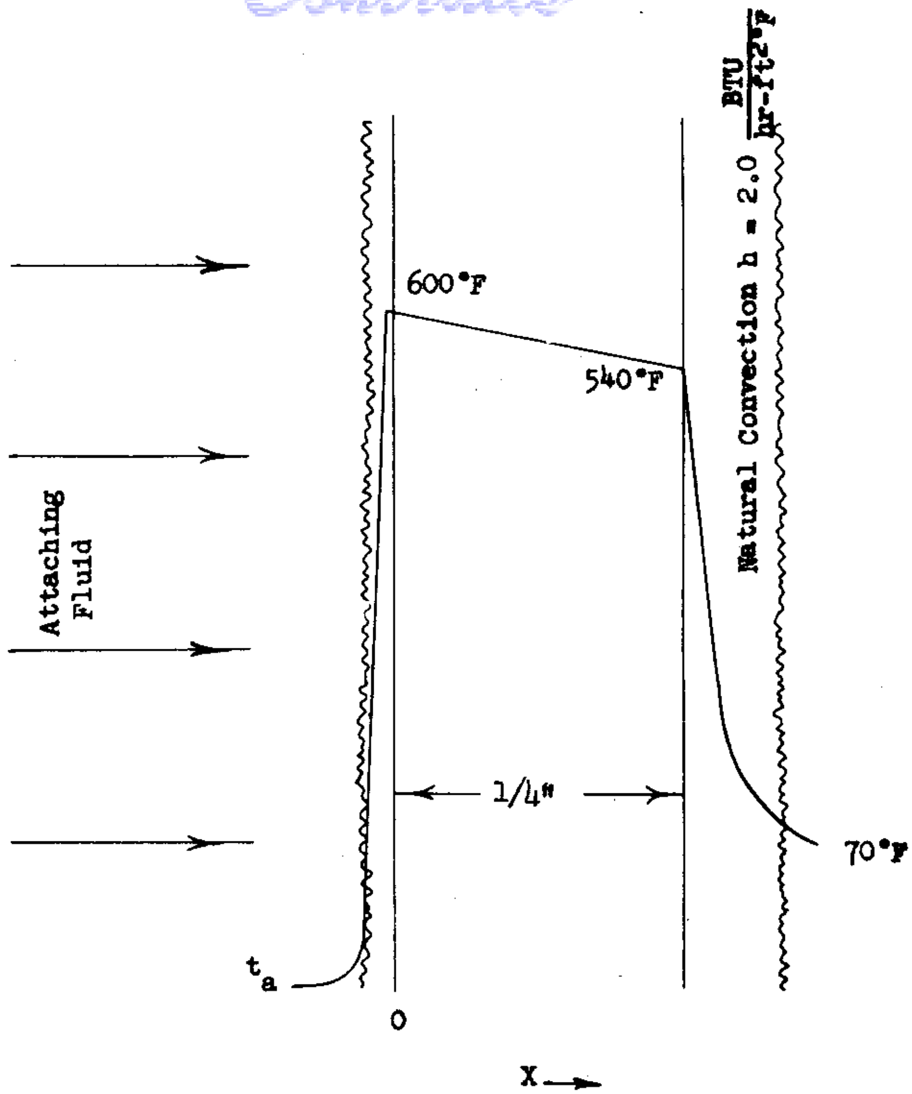


Fig. 25 Geometry and Boundary Conditions of Heat Transfer System

For our purposes this correlation is most useful in the form:

$$h = \left(\frac{C_0 k}{D}\right) \left(\frac{D\rho V}{\mu}\right)^m \left(N_{Pr}\right)^n \qquad (22)$$

For a specific fluid Equation 19 can be written as:

$$\left(\frac{\partial t}{\partial \theta}\right)_{x=0} = 100^\circ F/\min = \phi \left(\left(\frac{C_0 k}{D}\right) \left(\frac{D\rho}{\mu}\right)^m \left(N_{Pr}\right)^n V^m \Delta t, \quad \Delta p, \quad \delta_i \right) \qquad (23)$$

A comparison between any two fluids can be made with the aid of Equation 23 by comparing the Prandtl numbers and their thermal conductivities.

To compare the heat transfer coefficient for different fluids, the ratio $h_1 : h_2$ is formed:

$$\frac{h_1}{h_2} = \frac{k_1}{k_2} \frac{(N_{Pr})_1^n}{(N_{Pr})_2^n} \qquad (24)$$

This equation is based on equivalent Reynolds numbers, where the subscripts represent two different fluids.

II. HEAT TRANSFER RELATIONSHIP

The heat transfer coefficient is directly proportional to the thermal conductivity of the attacking fluid. The thermal conductivity of various fluids are presented in Table V.

TABLE V

THERMAL CONDUCTIVITY OF VARIOUS FLUIDS

Fluid	Thermal Conductivity, BTU/hr-ft/°F
Air	0.0140 at 32°F
Carbon Dioxide	0.0085 at 32°F
Nitrogen	0.0140 at 32°F
Water	0.330 at 32°F
Ethylene Glycol	0.153 at 32°F
Isopropyl Alcohol	0.091 at 86°F

A comparison of the heat transfer coefficient for different fluids is made by Equation 24

$$\frac{h_1}{h_2} = \frac{k_1}{k_2} \frac{(N_{Pr})_1^n}{(N_{Pr_2})^n}$$

According to this ratio ethylene glycol has a heat transfer coefficient about 70 times that of air, water has a coefficient 45 times that of air.

III. NOMENCLATURE

The following symbols were used in this Appendix.

c_p = specific heat of attacking fluid, BTU/lb/°F

c_g = specific heat of glass plate, BTU/lb/°F

D = diameter of nozzle through which attacking fluid flows, ft

h = heat transfer coefficient at surface of glass plate (x = 0), BTU/hr-ft^2/°F

h_{nc} = natural convection heat transfer coefficient at shielded plate surface (x = ℓ), BTU/hr-ft^2/°F

k = thermal conductivity of attacking fluid, BTU/hr-ft/°F

k_g = thermal conductivity of glass plate, BTU/hr-ft/°F

T_a = temperature of attacking fluid, °F

$T_{x=0}$ = temperature of glass plate at x = 0, θ = 0, °F

$\Delta t = (T_{x=0} - T_a)$, °F

$(\frac{\partial t}{\partial \theta})_{x=0}$ = rate of temperature fall with respect to time at x = 0, °F/min

V = linear velocity of attacking fluid, ft/sec

N_{Nu} = Nusselt Number $(\frac{hD}{k})$

N_{Pr} = Prandtl Number $\frac{c_p \mu}{k}$

N_{Re} = Reynolds Number $\frac{D V \rho}{\mu}$

Δ_p = physical properties of the plate

δ_i = initial and boundary conditions

ρ = density of attacking fluid, lb/ft^3

μ = viscosity of attacking fluid, lb/ft-sec

IV. PHYSICAL PROPERTIES OF THE GLASS

The physical properties of the plate do not vary appreciably with composition. Typical values were obtained from the text: "Properties of Glass," by G. W. Morey.

1. Density = 140 lb/ft^3

2. Specific heat = 0.250 BTU/lb/^{o}F

3. Thermal conductivity = 0.50 BTU/hr-ft/^{o}F