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RESEARCH AND DEVELOPMENT OF A HIGH TEMPERATURE CAPACITANCE STRAIN GAGE

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FOREWORD

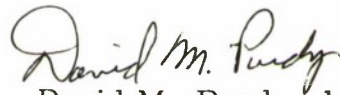
This research and development program was performed by the Space Systems Division of Hughes Aircraft Company, El Segundo, California, under Air Force Contract No. F33615-67-C-1448.

The work was supervised and directed by O. Larry Gillette, Program Manager. The report was prepared by he and Lester E. Vaughn. This project was initiated by the Air Force Flight Dynamics Laboratory, and was administered under the technical coordination of James. L. Mullineaux, FDTE.

The high temperature strain gages were developed, fabricated, and tested by the Structural Test Section of the Engineering Mechanics Laboratory, Space Systems Division, Hughes Aircraft Company. Acknowledgement is also given for the helpful assistance and technical guidance provided by Richard Harvuot, Supervisor, Structural Test Laboratory, and Raul J. Mondragon, Research Assistant.

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This technical report has been reviewed and approved.



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ABSTRACT

This report describes the research and development of a high temperature capacitance strain gage. The investigation consisted of a material and configuration study followed by a manufacturing and evaluation phase. The final configuration was a stress frame with a capacitor element composed of stainless steel plates and mica dielectric insulators. The overall size of the stress frame was 1 by 1 by 0.1 inch. Of the 40 sensors constructed, 15 were evaluated and 25 were delivered to the Air Force Flight Dynamics Laboratory. The gages were tested from 75 °F (24 °C) to 1500 °F (816 °C) on a constant moment bending beam with strains up to 0.0015 inch per inch. From the results obtained it can be concluded that the developed capacitance gage provides a positive and accurate means of measuring strain at temperatures up to at least 1500 °F (816 °C). Not all of the contract target specifications were met but the unique configuration of the gage allows for precalibration which does provide a gage that outperforms the intent of the target specifications in every respect.

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SECTION I

INTRODUCTION

High temperature strain measurement is needed to support the development and qualification testing of aircraft, missiles, and space vehicles. These vehicles are subjected to component and full-scale test programs where flight environments of external loads and temperatures are simulated. The structural test facilities achieve the simulation of these temperatures through the use of radiant heat lamps as a heat source and reflectors to direct the radiant energy to the areas to be heated. The temperatures achieved are a function of speed and altitude. Temperatures associated with present day vehicles are in the 1000° to 1500°F range. It is anticipated that in the 1970's this requirement will increase to 3500° to 4000°F. Quantitative strain measurements in the static and quasi-static region are presently limited to temperatures less than 1000°F.

Although attachment techniques, such as the Rockide or Metco processes have been developed for use up to 2000°F, the resistance strain gage, which is the standard technique used today, has been limited by the performance of the alloys available. All alloys that can be used to measure strains and temperatures experience a phase change between 800° and 1000°F which destroys their temperature compensation. Above this temperature, they become unstable and unsuitable for the measurement of static strain. Other alloys or metals, such as platinum, are stable and repeatable within limits, but their outputs resulting from temperatures are several orders of magnitude greater than their outputs resulting from strain, thus making the resulting accuracies unacceptable for strain measurement. A desirable extension of the present state of the art would be the development of a new method for measuring strains. This new method must be suitable for the measurement of static strains at temperatures up to and including 1500 °F.

In September 1966, Hughes Aircraft Company, under Company funds, began the development of such a gage. This gage was designated "high temperature capacitance strain gage" and was based on the principle of a change in strain producing an equivalent change in capacitance. Feasibility of such a gage was further investigated under an Air Force funded contract known as F33615-67-C-1448. A two-phase program was established. The first phase was a material evaluation and configuration phase, and the second was the gage evaluation phase. The entire program was keyed to a target specification which set the goals for the development of a high temperature capacitance strain gage.

During the material evaluation and configuration selection phase, many materials were evaluated for their dielectric properties, and a series of gage configurations was selected for a preliminary evaluation. The end result of the first phase was the selection, in concurrence with the contract monitor, of a final configuration. During the second phase, the selected gage configuration was evaluated in accordance with a previously published

preliminary test plan. Since there were no standards available for the evaluation of capacitance strain gages, new standards and methods of testing were established. These test standards and methods were based primarily on previously approved strain standards, such as NAS 942, which is currently being used for the evaluation of the resistance strain gage.

SECTION II

TARGET SPECIFICATIONS

The following target specifications were established prior to the start of the contract as the design goals for the high temperature capacitance strain gage. A general consideration given to all the items listed below was that the design of a high temperature capacitance gage would be compatible with remote operation on a major structural air frame which is completely surrounded by radiant heat lamps.

- 1) The maximum gage length or width shall not exceed 1 inch.
- 2) The gage capacitance shall be between 10 and 100 picofarads (reproducible within 2 percent gage to gage).
- 3) The gage factor $(\Delta C/C)/(\Delta L/L)$ (strain sensitivity) shall not be less than 25.
- 4) The gages shall have a predictable and repeatable gage factor variation of 2 percent per 100°F or less at temperatures below 600°F (316°C), and 5 percent per 100°F or less at temperatures above 600°F (316°C).
- 5) The maximum gage factor change with temperature tolerance shall be 2 percent per 100°F.
- 6) The minimum strain limit at 1500°F (816°C) shall be ± 0.5 percent (5000 microstrains).
- 7) The drift rate (change of output at constant temperature) shall not exceed 300 microstrains per hour at temperatures below 600°F (316°C) or 900 microstrains at temperatures above 600°F (316°C).
- 8) The minimum resistance to ground shall be 10 megohms at 1500°F (816°C).
- 9) The apparent strain (temperature sensitivity) shall not exceed 5 microstrains per degree Fahrenheit at the maximum heating rate.
- 10) The bond cure process, if required, shall need less than 6 hours at a temperature no more than 50°F above the maximum operating temperature of the gage.
- 11) The maximum gage zero shift per cycle shall be 50 microstrains.

- 12) The output due to thermal electric effect shall not exceed 0.2 millivolt at 1500°F (816°C).
- 13) The maximum temperature rise rate on the gage shall be 10°F per second.
- 14) The maximum continuous time at 1500°F (816°C) shall be 1 hour.
- 15) The gage signal conditioning to the gage circuits shall be sufficient to provide a minimum of 1 microvolt per microstrain at 1500°F (816°C).

SECTION III

GAGE CONFIGURATION

The capacitance strain gage was initially developed before the advent of the resistance strain gage, and its use as a strain measuring device is not new. However, the use of capacitance gages for measurement of strains at high temperature is new, and special attention has been given to the selection of a configuration for measurements in the extreme environments of temperatures up to 1500. F (816 °C).

The basic equation for a parallel plate capacitor is given by

$$C = \frac{AK}{3.6 \pi X} \quad (1)$$

where

C = capacitance, picofarads

A = area of plate, square centimeters

X = separation between plates, centimeters

K = dielectric constant of material between plates

The basic principal is that variations in dimensions caused by strain generate changes in capacitance. It is apparent from Equation 1 that there are two primary variables that can be used in the strain gage: the area of the plates, and the separation between them.

Selection of the final gage configuration was based on a preliminary evaluation conducted during the initial phase of this program. In all, seven gage configurations were studied. All the gages used stainless steel as the capacitive plate materials; however, various materials were used as the dielectric. In some cases, three or four different dielectrics were used in a single configuration before a final one was selected. A discussion of the dielectric materials evaluated and their results is contained in the material section of this report.

The first configuration evaluated was a sawtooth configuration which varied the parameters of area and distance. The second configuration was a variable area gage consisting of three horizontal rectangular plates. The third configuration was a modification of the variable area gage, using triangular plates to increase the sensitivity. The fourth configuration was the variable area gage (configuration 2) mounted on an hourglass strain frame. This frame was designed so that an applied axial tension strain on the frame produced a magnified tension strain in the capacitance element. The fifth configuration evaluated was the triangular plates (configuration 3) mounted in a rhombic frame. The sixth configuration was a parallel plate or variable

distance gage mounted in the hourglass strain frame. The seventh configuration was the parallel plate gage mounted in the rhombic frame.

Each of the seven configurations was evaluated for its response to the following parameters: 1) gage length, 2) gage capacitance, 3) gage factor, 4) gage factor change with temperature, 5) resistance to ground, 6) zero shift per cycle, 7) thermal electric output, and 8) apparent strain with temperatures. All the gage configurations achieved some degree of success as a 1500 °F strain gage. Configurations 1, 2, and 3 experienced a considerable amount of nonlinearity. Configurations 4 and 5 were basically the same gage as configurations 2 and 3; however, they did show a marked improvement in performance. Configuration 6 was a very successful gage. Configuration 7 was, in all respects, an outstanding gage in comparison with the previous gages and it was selected as the final design for evaluation in the second phase of the program.

The gage consists of a capacitance wafer of four stainless steel plates and five mica dielectric insulators mounted in a rhombic stress frame. The stress frame, as shown in Figure 1, has several purposes, including: 1) applying an initial compression on the capacitance plates, and 2) acting as a strain intensifier, by its geometric configuration, applying a 2 to 1 multiplication to the specimen strain. The rhombic frame at first appears to be very stiff, and seemingly would influence the strain output. However, in actual application, it is a very flexible member and requires forces on the order of 3 to 5 pounds to apply strains in excess of 5000 microinches. The rhombic frame is made from 310 stainless steel. Design of this frame and its capacitive element is such that an applied axial tension strain to the frame produces a compressive strain to the capacitive element. Small stainless steel shims are welded to the corners of the frame in the direction of the applied strain. To attach the gage, these tabs are welded to the test specimen by four small spot welds. This grounds the entire frame to the test specimen but the outer plys of mica in the capacitive element insulate the capacitive plates from the frame and test specimen.

The basic advantage of the final design is found in the rhombic frame. Examination of Equation 1 shows that as the distance, X , between the plates is increased, the capacitance, C , is decreased. Conversely, when the distance, X , is decreased, the capacitance is increased. The use of the rhombic frame has allowed a tension on the gage to decrease the gap, X , between the plates, and therefore increases the capacitance. Besides placing the readings in their normal order of tension increasing and compression decreasing, it allows for a built-in correction of apparent strain. As the gage is heated, it experiences radical changes in the dielectric constant, which approaches ∞ as the temperature increases. In order to correct for this effect, it is necessary to move the plates apart by some predetermined amount. By proper selection of the materials used, it is theoretically possible to provide the necessary correction. An attempt was made to do this by using a frame of stainless steel 310 with a coefficient of thermal expansion of approximately 10 ppm/°F in conjunction with the Inconel 718 test bar with a coefficient of 8.9 ppm/°F. This combination provided a differential expansion of -1 ppm on the gage. This was a first rough cut at the correction since, prior to

evaluation, it was not known what exact amount of negative correction should be used to provide a minimum apparent strain at 1500 °F (816 °C).

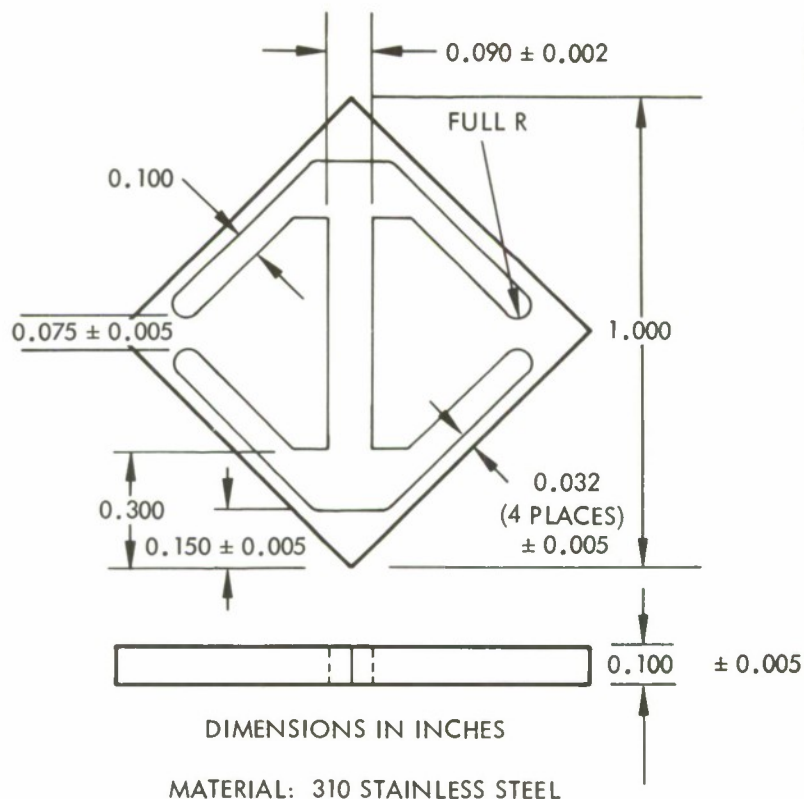


Figure 1. Rhombic Frame

SECTION IV

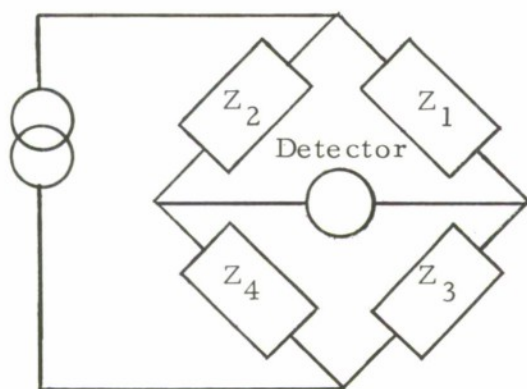
CAPACITANCE MEASUREMENTS

Precise capacitance measurements are possible if care is exercised in the circuit arrangement, and if the measurement is made with properly designed instrumentation. The National Bureau of Standards (NBS) is presently making measurements on the order of 1 micropicofarad (1). The technique described here is basically that used by the NBS.

The capacitance between any two conductors in space is not clearly defined as long as there are other conductors in the area. Measurements on this type of capacitor are difficult, and errors on the order of 0.1 picofarad are normal (2). This lack of definition may be eliminated by the introduction of a third conductor which completely surrounds one conductor of the capacitor. This configuration is known as a three-terminal capacitor, and the capacitance between the conductors, C_{12} , in Figure 2, is called direct capacitance (3). Capacitances C_{13} and C_{23} are called grounded capacitances. The direct capacitance is not affected by anything external to the third conductor; however, the grounded capacitances are affected by anything connected to the terminals, such as the coaxial leads.

Any device or method used for the measurement of direct capacitance must make allowances for the ground capacitances. One device that has achieved wide acceptance is the ratio arm or direct capacitance bridge. This bridge is one of the alternating current bridge family, but it incorporates design techniques that virtually eliminate the effects of ground capacitance. The prime feature of the ratio arm bridge is the ratio transformer that excites the bridge. Careful design and manufacture have resulted in extremely tight coupling and low resistance in the secondary of these transformers.

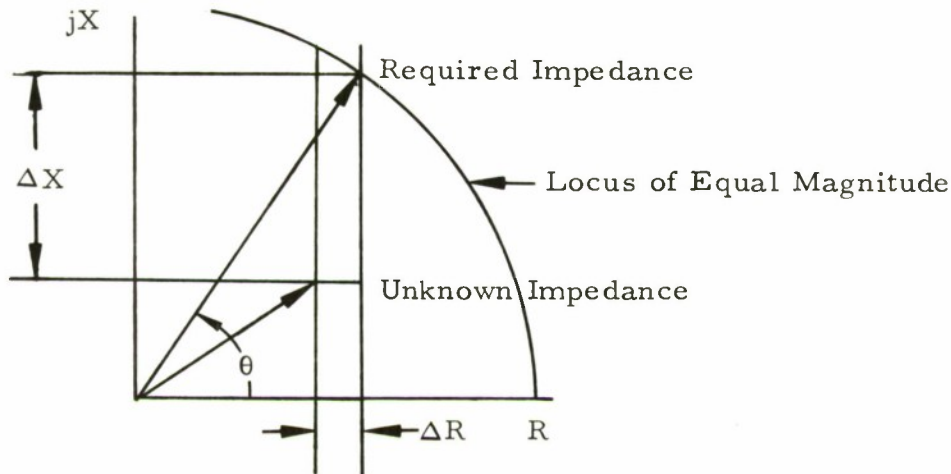
The operation of an ac bridge (sometimes referred to as an impedance or reactance bridge) is in principal the same as a dc bridge (wheatstone) used for measuring pure resistive elements. The general form of the balance equations are the same and are shown below.



Balance Equation

$$\frac{Z_1}{Z_2} = \frac{Z_3}{Z_4}$$

In a dc excited bridge the current and voltage are in phase through the elements and all that is required to make the potential differences across the detector equal to zero is an adjustment of the voltage magnitudes. In a bridge that has reactive elements such as capacitors or inductors the bridge must be ac excited as these elements are inherently frequency sensitive. It is in the balancing of an ac bridge that the difference between an ac and dc bridge becomes apparent. In an ac bridge it is not enough to balance the voltage magnitudes but in addition a phase balance is required. The voltage across and the current through a complex impedance experiences a phase shift that is proportional to the ratio of the reactive component to the resistive component of the impedance. Therefore, to achieve a complete null in an ac bridge alternate adjustment of resistive and reactive components is required. Since balancing is primarily the adjustment of impedance in one leg of the bridge this can, perhaps, be better illustrated in the vector plot of impedance as shown below.



It can be seen from the diagram that matching the magnitude does not necessarily match the phase angle and the adjustment of both resistance and reactance is necessary to match the unknown impedance to the required impedance.

The variations possible in ac bridge configurations are manifold and beyond the scope of this section. However, the derivation of the balance equations of a circuit similar to the one used in the gage evaluation (Figure 3) is shown below.

$$Z_1 = R - j \frac{1}{\omega C_{12}} ; Z_3 = R_x - j \frac{1}{\omega C_x}$$

$$Z_2 = j\omega L_1 ; Z_4 = j\omega L_2$$

$$\frac{R - j \frac{1}{\omega C}}{j\omega L_1} = \frac{R_x - j \frac{1}{\omega C_x}}{j\omega L_2}$$

$$j\omega R L_2 + \frac{L_2}{C_{12}} = j\omega R_x L_1 + \frac{L_1}{C_x}$$

Equating real and imaginary parts, then:

$$\frac{L_2}{C_{12}} = \frac{L_1}{C_x}$$

Therefore,

$$C_x = \frac{L_1}{L_2} C_{12}$$

and

$$\omega R_1 L_2 = \omega R_x L_1$$

therefore,

$$R_x = \frac{L_2}{L_1} R_1$$

When the three-terminal capacitor is connected to the terminals of this bridge, one ground capacitance is shunted (see Figure 3) across one ratio arm, and the other is shunted across the bridge detector. Since, at balance, the impedance of the ratio arms reduces to the small resistances of the matched windings, the effect of the shunt is negligible so long as it is of a reasonable value (4). In the case of a coaxial cable of 30 picofarad per foot capacitance connected to one side of the measured capacitor, C_{23} could have values on the order of 200 picofarads. This would result in a reactance of approximately 800 ohms at 1 megacycle. The resistance of the ratio winding at null is on the order of a few hundredths of an ohm. In addition, at null the current through the detector is zero, and no error is produced by C_{13} which is shunting the detector. A slight reduction in sensitivity is a result of this shunting effect, but it is negligible (5).

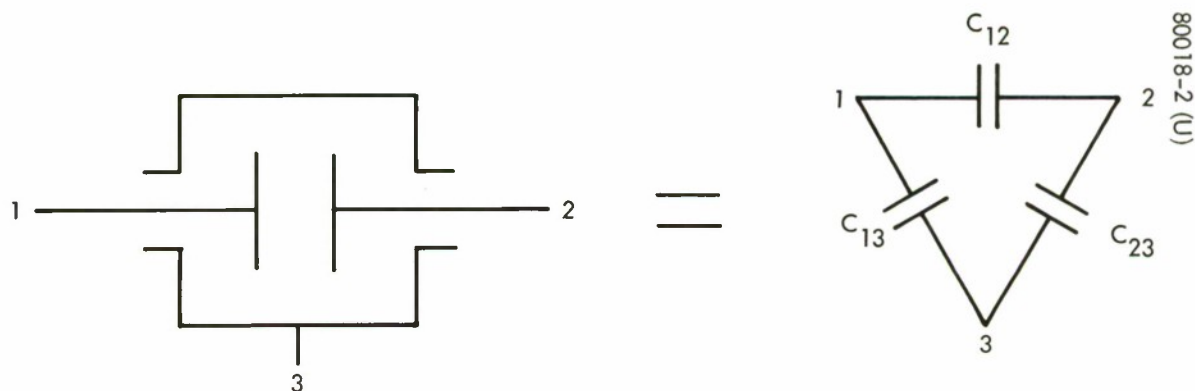
The losses in the dielectric of a capacitor, usually denoted in the literature as "loss factor", "dissipation factor", or "loss tangent", make the measured capacitor behave as if shunted by a pure resistive element. The result is an in-phase and quadrature current through the element. The effects of these losses are balanced with a resistive balance in the bridge. This control is usually direct reading in equivalent resistance and conductance from which the losses are computed. Since these losses are temperature dependent, some difficulty is experienced in nulling the bridge with the capacitor in a transient temperature environment.

The aforementioned techniques were all incorporated in the evaluation apparatus used at Hughes. When the capacitance gage was mounted to the test bar, it was enclosed by a metal box constructed of 5-mil stainless steel spot welded at one end to the test bar; this constituted the third conductor. Coaxial leads capable of withstanding high temperatures were attached to the gage, with their ends projecting inside the metal box. These leads were made from stainless steel tubing with a 28-gage Nichrome wire inserted through the center. Glasrock slurry was used as a dielectric material and support for the Nichrome wire. The tubes were spot welded together so that a constant spacing was maintained at all times. The entire lead assembly was post-

cured to 1500 °F. Commercial coaxial leads capable of withstanding 1000 °F have been developed by Amphenol-Borg Electronics Corporation and should be available at this time (6). Outside the thermal environment, a transition was made to standard RG-58/u coaxial cable which carried through to the bridge (see Figure 4). In this manner, the shield integrity was maintained throughout. The system proved very stable, and any conductors brought into the immediate area of the gage had no effect. Measurements were made with a ratio arm bridge.

When the system is developed up to the point just described, one additional spurious capacitance must be accounted for and this is the distributed capacitance between the two coaxial leads. Capacitance bridges of the Boonton type 75A, as used in this program, have a feature for balancing out this lead capacitance. The unterminated leads are hooked to the bridge and the lead capacitance (and loss effect) is balanced out with a small trimmer capacitor and resistor in the bridge circuit. This balancing must be done each time the instrument range setting is changed. In cases where it is impractical to unterminate the leads, as in the case of the high temperature leads which are spot welded to the sensor, the value of the leads should be measured beforehand and subtracted from the final reading.

In the event capacitive strain gages should gain wide acceptance, modifications of measuring systems such as that described by E. B. Baker (7) could be developed which would overcome the present difficulty in measuring capacitance change in a transient load or temperature condition. Development of systems of this type would certainly have to pace advances in the capacitive strain sensor if the full potential is to be realized.



C_{12} IS CALLED DIRECT CAPACITANCE

C_{13} AND C_{23} ARE CALLED GROUND CAPACITANCE

Figure 2. Equivalent Circuit of Three-Terminal Capacitor

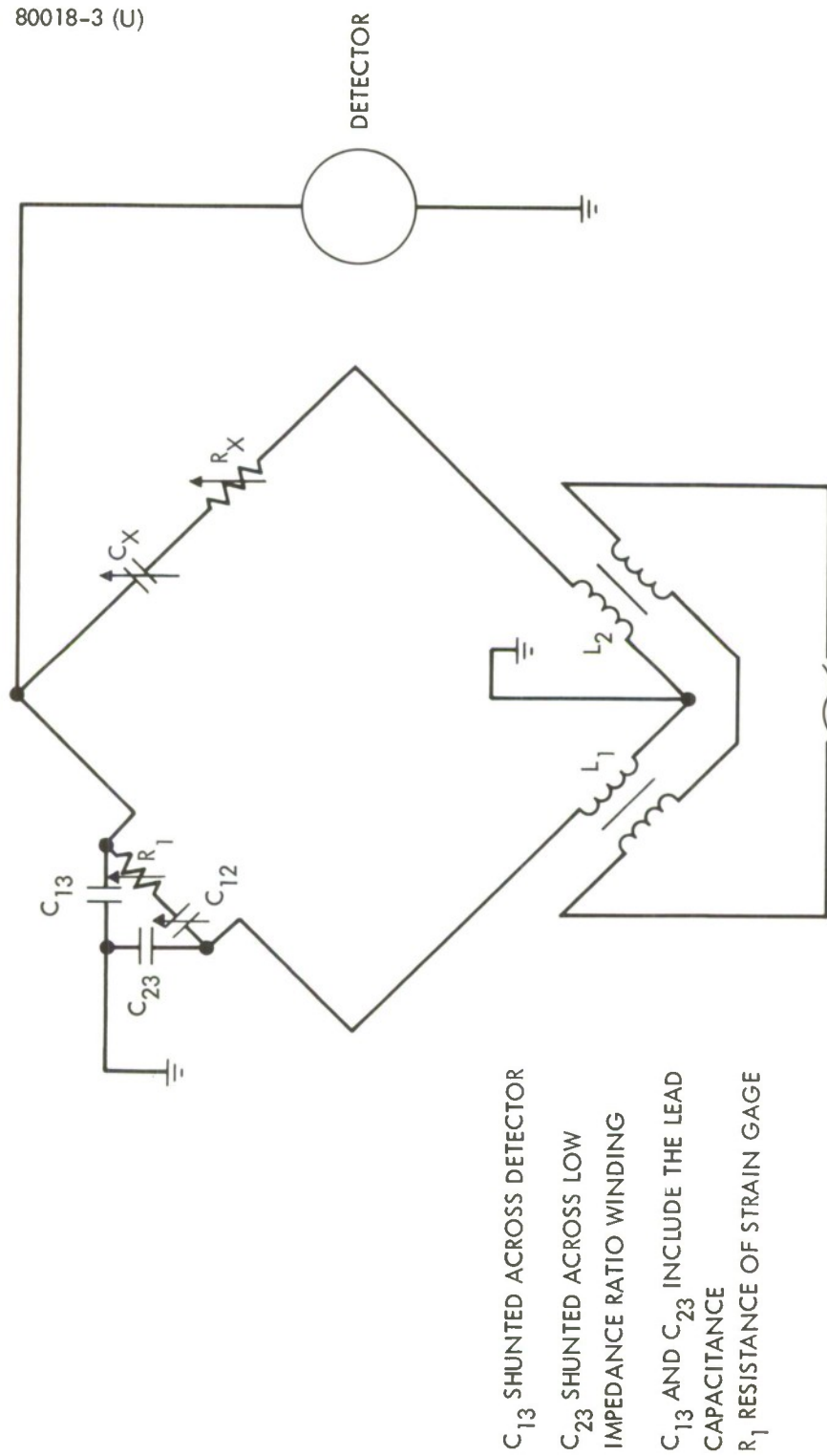


Figure 3. Bridge Circuit For Measurement of Direct Capacitance

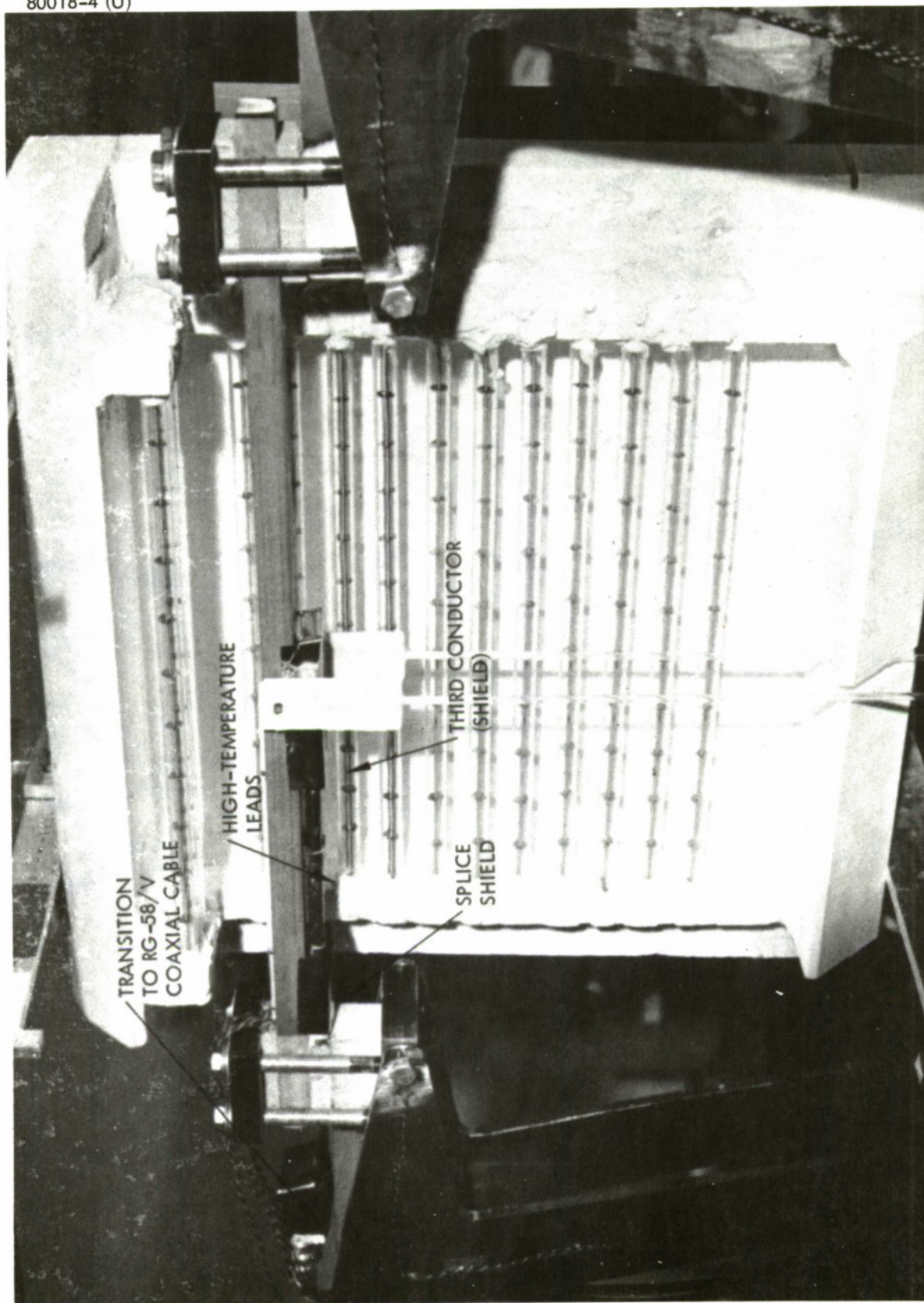


Figure 4. Capacitive Strain Gage Mounted as a Three-Terminal Capacitor For High Temperature Evaluation
(Photo 293-15A)

SECTION V

MATERIAL EVALUATION

The primary purpose of the material evaluation phase was to determine which dielectric material had the best electrical properties over the entire 1500°F range. In view of application in a gage assembly, however, other properties, such as mechanical and handling (e. g. , machineability, mechanical attachment, etc.), had to be considered. Some tradoff was necessary between good electrical properties, and good mechanical and handling properties.

The basis for good electrical properties was an initially high and stable dielectric constant and low losses over the 1500°F spectrum. The mechanical requirements were a low modulus, since the dielectric must necessarily be deformed in the gage, low thermal expansion to minimize change in capacitance, and ease of handling, since the capacitive element must be physically small. With these objectives in mind, many materials were surveyed prior to the evaluation, and the most promising were selected for the actual evaluation. The materials selected are presented in Table I. In actual fact, investigation indicates that very few materials meet both of the foregoing requirements.

Since cost and time were important factors, it was decided that the evaluation procedure would be a modified version of that outlined in the ASTM standards (8) and, instead of trying for precise values, relative values would suffice. The results obtained with the final fixture used were in good agreement with available values published by the manufacturer.

The initial method used was to clamp a dielectric wafer between two ground steel conductors. A screw reaction frame was used to provide clamping pressure. The conductors were surrounded by a shield to make a three-terminal capacitor. This fixture proved unsatisfactory for two reasons: 1) the clamping pressure varied due to the differential expansion of fixture and dielectric, and 2) the steel used in the plates formed oxides and scale at the elevated temperatures. The fixture was redesigned so that one plate was spring loaded for constant pressure, and 302 stainless steel was used as plate material, eliminating the scale problem. The specimen size was standardized to a 1-inch square by approximately 1/8-inch thick wafer. The specimen thickness varied from specimen to specimen, depending upon material availability.

To eliminate the presence of air dielectric between the conductors and the dielectric wafer, a technique was developed to flame spray, using the Metco process, nickel aluminide (a conductor) on each face of the dielectric wafer. An outgrowth of this technique is a means of attaching, by spotwelding, small metal conductors, such as foil leads or thermocouples, to ceramics. Leads attached in this manner have sustained shear

forces of several pounds without noticeable effect. The thermal environment was provided by an ignitron-controlled electric furnace controlled by a thermocouple on one plate of the capacitor. Capacitance readings were taken with a direct capacitance bridge. All data were taken at a frequency of 1 megacycle, since much of the published data was taken at this frequency and offered a basis for comparison. Both the dielectric constant and loss factors are frequency dependent, but the 1 megacycle frequency offers median values between the extremes.

The results of the material evaluations are shown in Figures 5 and 6. Based on the data shown, the material Glasrock shows the best electric properties, but, unfortunately, it is very brittle and extremely difficult to cast in sheets thin enough to be practical in a capacitor of small physical size. The other runners up, such as Lava 1136, Lucalox and AL 300 aluminum oxide, are extremely hard to machine and are virtually incompressible, which renders them unacceptable in the gage configuration. The best compromise seemed to be mica which has reasonable electrical properties coupled with ease of handling.

TABLE I. MATERIALS EVALUATION SUMMARY

Name	Primary Material	Coefficient of Expansion, ppm/° F, (Nominal Value)	Tensile Strength, Ksi	Compressive Strength, Ksi	Dielectric Constant at 1MC and 75°F	Dissipation Factor at 1MC and 75°F	Loss Factor at 1MC and 75°F
Mica	Muscovite	---	---	---	4.6	0.003	0.013
AL-300	98 percent Al_2O_3	4.5	---	---	7.3	0.002	0.013
Vycor 7900	96 percent Silica	0.44	---	---	3.8	0.001	0.004
Glasrock, 50 pound	98 percent SiO_2	0.30	2	20	2.0	0.001	0.003
Metco 105	Al_2O_3	---	---	---	3.5	0.006	0.021
Lava 1136	Magnesium Silicate	6.3	---	25	5.8	0.003	0.002
Eccofoam SM-25	Silica	---	---	---	3.6	0.004	0.016
Bean type "H"	Al_2O_3	---	---	---	3.68	0.007	0.026

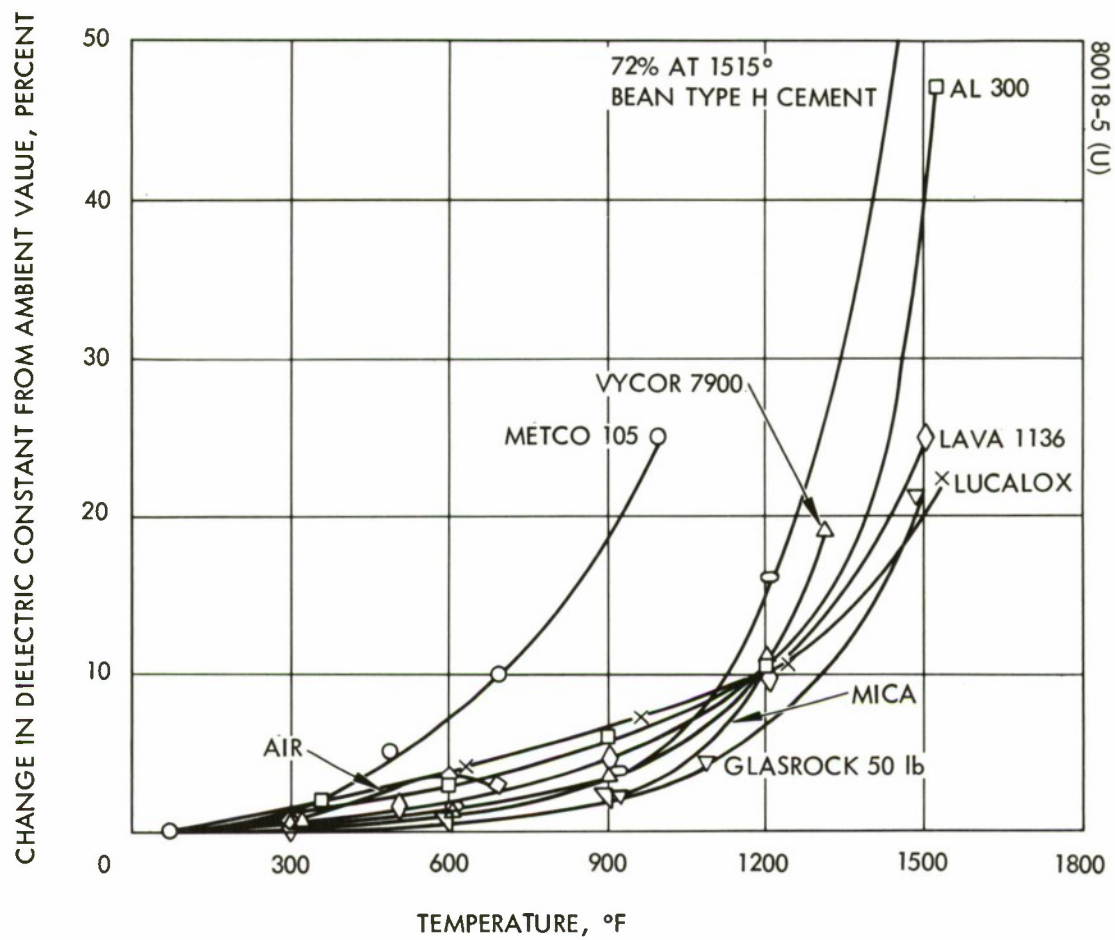


Figure 5. Dielectric Constant Versus Temperature

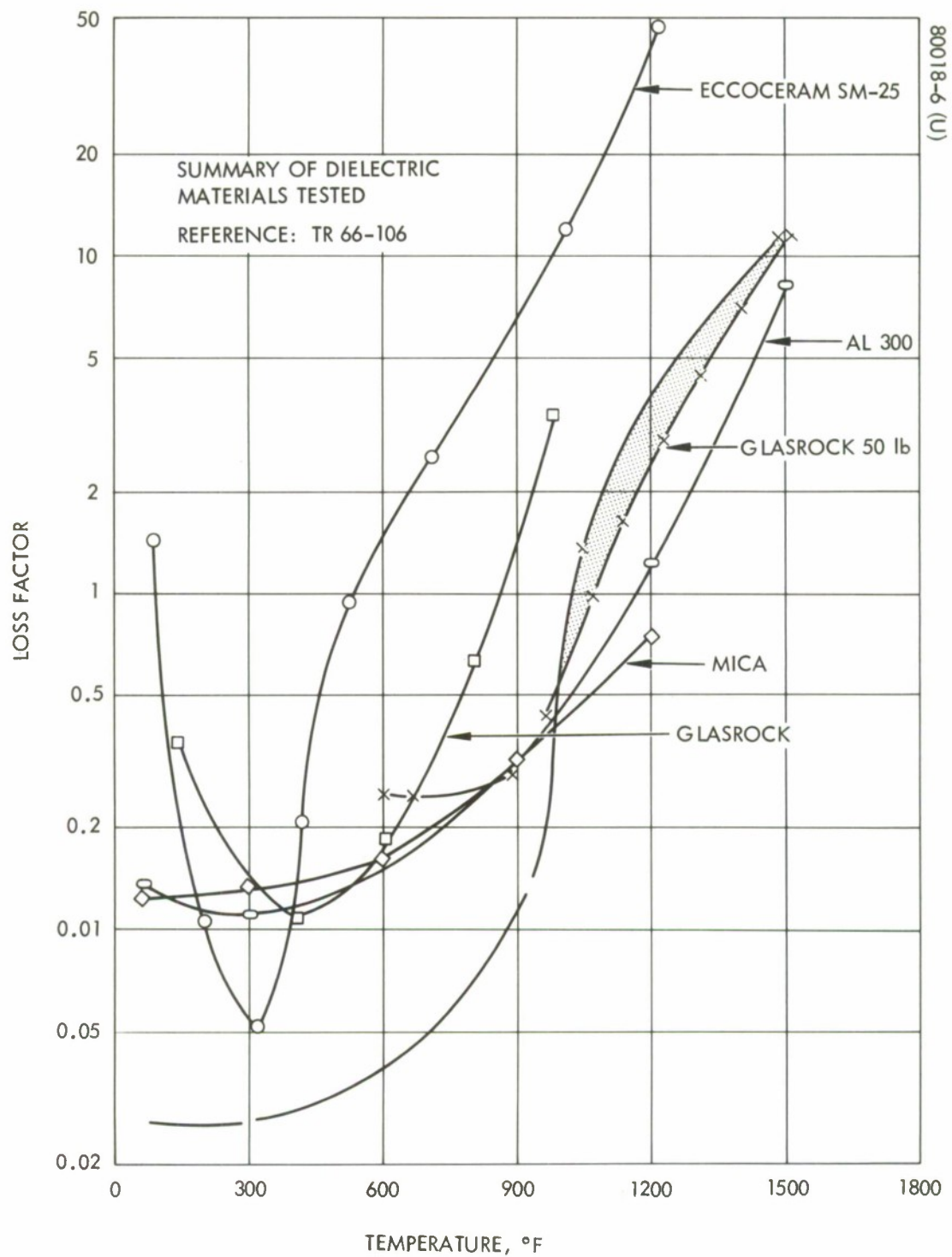


Figure 6. Loss Factor Versus Temperature

SECTION VI

GAGE MANUFACTURING AND ASSEMBLY PROCEDURE

Forty of the configuration No. 7 high temperature capacitance strain gages selected during Phase I were manufactured, and the first fifteen of these gages were tested and evaluated at Hughes. The second group of 25 gages were delivered to Air Force Flight Dynamics Laboratory. The manufacturing sequence and assembly consisted of machining 50 of the rhombic frames to the drawing and dimensions shown in Figure 7. The next phase was to cut and assemble the capacitance strain element as described in Section III. This capacitive element consisted of four 310 stainless steel shims, welded together in pairs, and sandwiched with seven 6- to 14-mil mica sheets to make an eleven-ply sandwich. This element was then installed in the rhombic frame, which was placed under a slight precompression of approximately 3 pounds in order to deflect the gap (as shown in Figure 7) approximately 6 mils. The entire assembly was then installed in an oven and cured for 1 hour at 1500°F. The gages used in the test and evaluation program at Hughes are numbered 1 through 16. Gage No. 7 was rejected during the manufacturing procedure and was eliminated from the program. Gages 17 through 41 were the 25 gages delivered to AFFDL.

During the final inspection of the gages, slight warpage of the rhombic frame was noted. This occurred as a result of the 1 hour heat cure at 1500°F. Since no information was known as to the required acceptance criteria, the deviations were noted and the gages tested as is.

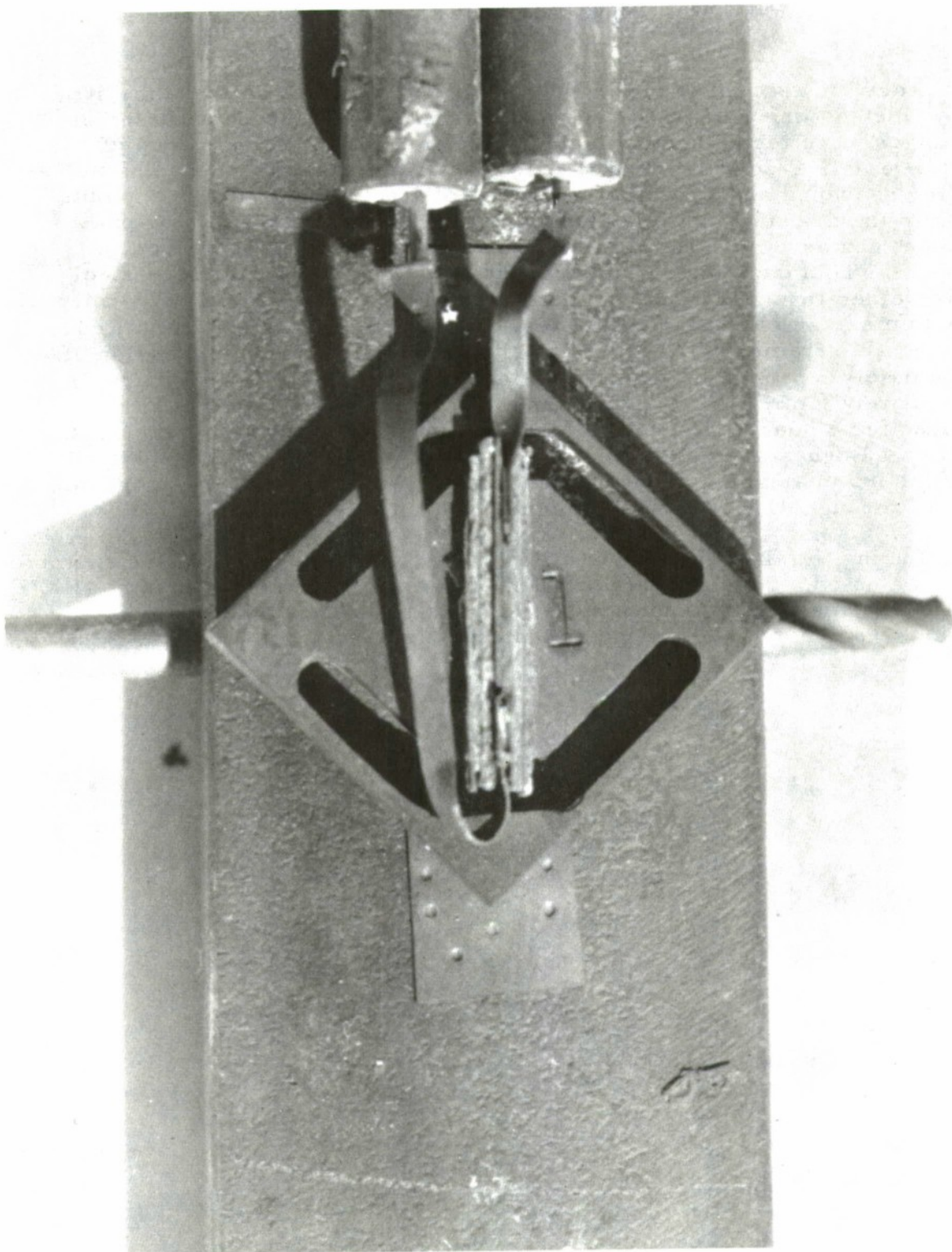


Figure 7. Capacitance Strain Gage
(Photo 297-3A)

SECTION VII

INSTALLATION PROCEDURE

The gage is constructed in two parts: the stress frame, and the sensing element. The stress frame has two tabs which are welded to the test part. The sensing element is constructed from stainless shim, which make up the capacitor plates. The dielectric is mica. The sensing element is placed in the stress frame slot while the stress frame is slightly compressed. The prestress is approximately 0.002 inch. Excessive force on the gage leads can displace the sensing element and change the initial capacitance; therefore, it is important that the gage be handled with reasonable care.

The equipment required to mount the capacitive strain gage is as follows:

- 1) Weldmatic model 1016C, or equivalent
- 2) Stainless steel shim stock, 5 mils, type 302
- 3) High temperature signal leads
- 4) BNC adapter.

The strain gage is installed in the following manner:

- 1) Align the capacitance strain gage tabs along the strain axis. Weld one tab four equal places, using a setting of 16 to 20 watt-seconds (Refer to Figure 8). This setting depends on the tab thickness, sharpness of electrode, and the material being welded. For practice, try welding 5-mil stainless to the test part to get an optimum setting. Weld the other tab in the same manner, avoiding bending the tabs.
- 2) Weld gage leads to signal leads (Refer to Figure 9). Keep signal lead lengths to a minimum. Use a setting of 7 to 12 watt-seconds. One good weld is sufficient.
- 3) Weld gage shield over gage area (refer to Figure 10). This shield eliminates any capacitive effects from any external conductor adjacent to the gage and high temperature signal leads. This shield can be made from 5- or 10-mil stainless, and should be high enough to clear the capacitance strain gage leads by 1/4 inch. The setting of the welder depends on the thickness of the shield, but settings of from 7 to 20 watt-seconds should be sufficient.

- 4) In order to connect the high temperature signal leads to the measuring instrument, construct an adapter that terminates with UG-625 B/u BNC connectors (refer to Figure 11). The connections between high temperature leads and adapter leads are welded with 5-mil stainless ribbon, which can be made from shim stock. Two connectors are required, signal lead to signal lead, and tube to tube. The tube-to-tube welded connection carries the ground through to the measuring instrument.
- 5) A shield similar to that in Figure 10 is used to shield the welded connection of Figure 11. The RG 58 C/u cable will complete the connection to the measuring instrument. The RG 58 C/u cable must be external of the furnace, since the cable cannot withstand high temperatures. The completed installation is shown in Figure 12.
- 6) Use of intermedial lead such as Amphenol-Borg may be made.

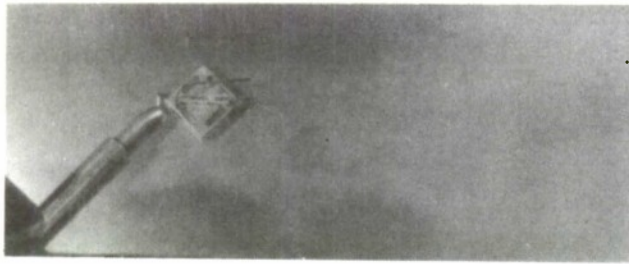


Figure 8. Capacitive Strain Gage Being Welded to Stainless Sheet. Resistance Welder Set to 16 to 20 Watt-Seconds
(Photo 318-8)

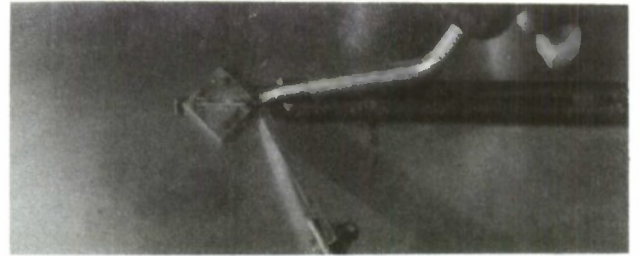


Figure 9. Welding Gage Leads to High Temperature Leads. Resistance Welder Set to 7 to 12 Watt-Seconds
(Photo 318-9)

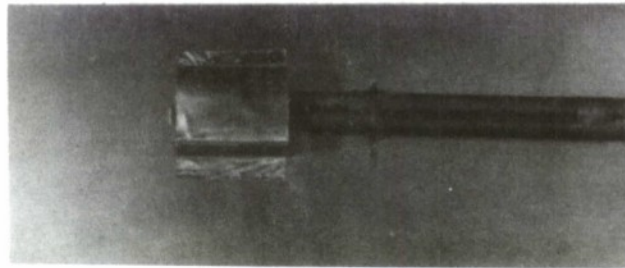


Figure 10. Capacitance Strain Gage Shield Welded Over Gage Area Completing Third Terminal
(Photo 318-10)

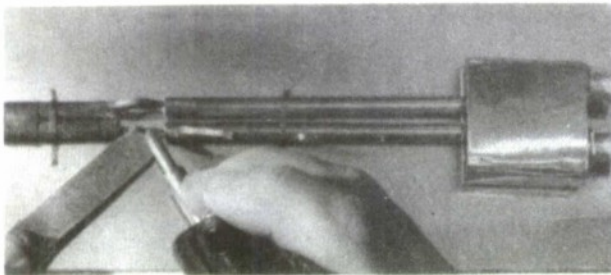


Figure 11. Weld Signal Leads and Shield Leads to High Temperature BNC Adapter
(Photo 318-6)



Figure 12. Shield Welded Over Connection
(Photo 318-5)

SECTION VIII

TEST PROCEDURE

APPARATUS

Gages evaluated were mounted on an Inconel 718 test bar and strained in a constant moment apparatus (see Figure 13).

HIGH TEMPERATURE LEAD WIRE

The lead wire in the thermal environment consisted of 28-gage Nichrome wire inserted through 1/4-inch stainless steel tubing. Glasrock was used as an insulator and support for the Nichrome wire. The tubes were spot welded together to maintain constant spacing and, hence, constant capacitance. The unterminated capacitance of these leads was 0.03 picofarad per inch, and is the C_L indicated in subsection 1.A. Measurements. The change in capacitance of these leads from ambient to 1500°F was only 0.003 picofarad, and is considered negligible.

TEST EQUIPMENT

The test equipment used was as follows:

- 1) Capacitance bridge, Model 75A, manufactured by Boonton Electronics Corp., or equivalent.
 - a) Resolution: 0.02 picofarad
 - b) Accuracy: 0.25 percent
- 2) Potentiometer, Model 8686, Manufactured by Leeds and Northrup, Philadelphia, Pennsylvania.
 - a) Resolution: 0.1 millivolt
 - b) Accuracy: 1 percent
- 3) Multimeter, Model 260, manufactured by Simpson Electric Co., Detroit, Michigan.
 - a) Resolution: 1 ohm
 - b) Accuracy: 5 percent

- 4) Potentiometer temperature recorder, Model IPG 560, manufactured by Bristol Co., Waterbury, Conn.
 - a) Resolution: 5°F
 - b) Accuracy: 1 percent of full scale
- 5) Thermocouple, Chrome-Alumel, Type 301, manufactured by Claude S. Gorden, El Segundo, Calif.
 - a) Resolution: 1°F
 - b) Accuracy: ±0.75 percent
- 6) Dial indicator, Type 656-341, Manufactured by Starret Company, Athol, Mass.
 - a) Resolution: 0.001 inch
 - b) Accuracy: 0.3 percent
- 7) Hydrometer, Model 310, Manufactured by Serdex Co., Boston, Mass.
 - a) Resolution: 2 percent
 - b) Accuracy: 1 percent

Certification

All foregoing instruments were calibrated by Hughes Aircraft Company Primary Standards Laboratory, using standards traceable to NBS.

TEMPERATURE CONTROL

Temperature rates and levels were controlled by Research Inc. controllers and Data-Trak function generators. Heating elements were 1000-watt and 2000-watt infrared heat lamps.

METHODS

The following methods were used in the evaluation of gages in Phase I and Phase II.

1. Gage Capacitance

The gage capacitance, C_G , is defined as the capacitance exhibited at the terminals of the gage while mounted to the test bar, and exclusive of any distributed capacitance exhibited by lead wire.

A. Measurements

The following measurements were taken prior to capacitance evaluation:

- 1) Capacitance, C_L , of high-temperature lead wire while unterminated. Capacitance of coaxial leads up to high-temperature leads are balanced out at the bridge.
- 2) Room temperature and relative humidity.

After the foregoing readings were taken, lead wires were attached to the gage and measurement of the total system capacitance C_T was taken.

B. Data

Tabulated gage capacitance as:

$$C_G = C_T - C_L \quad (2)$$

2. Gage Factor and Zero Shift per Cycle at Room Temperature

The test bar, with gage mounted, was installed in the constant moment apparatus. The bar was strained in $300 \mu\epsilon$ increments to a maximum of $1500 \mu\epsilon$, and in $300 \mu\epsilon$ decrements to zero. The bar was cycled a total of five times, but only zero readings were taken on the last two cycles. Six of the gages were tested in compression and tension.

A. Measurements

The following measurements were taken during the evaluation.

- 1) The deflection of the bar at each increment, including zero
- 2) Gage capacitance at each increment, including zero
- 3) Room temperature and relative humidity before and after evaluation.

B. Data

The incremental data was plotted as unit change of capacitance (ordinate) versus mechanical strain (abscissa) for all points up and down. The gage factor for each of three runs was found in accordance with the definition

$$G. F. = \frac{\Delta C / C_G}{\epsilon} \quad (3)$$

The gage factor of each gage was the average of the three values found above.

Hysteresis and repeatability data was extracted from the same plots (see Figures 14 and 15).

The zero shift per cycle data was plotted as change in capacitance from initial unstrained capacitance value (ordinate) versus number of cycles (abscissa) (see Figure 24).

3. Strain Limit at Room Temperature

In attempting to measure strain limit of the gages in tension, a different procedure than normally used was developed. Repeated thermal cycling of the Inconel test bars reduced them to an annealed condition so that the bars yielded before the strain limit of the gage was reached. The rigidity of the gage precluded bending a test bar around a radius. The method finally used was to weld each end of the gage to separate bars and then place a microformer extensometer across the gage. The bars were placed in a test machine and the strain in the gage controlled by the extensometer until a 10 percent deviation in indicated strain was achieved.

The gages tested in compression were placed in the constant moment apparatus and strained in 200 $\mu\epsilon$ increments until a 10 percent deviation was achieved.

A. Measurements

The following measurements were taken during evaluation.

- 1) The deflection of the beam at each increment, including zero
- 2) Gage capacitance at each increment, including zero
- 3) Temperature and relative humidity before and after evaluation

B. Data

The capacitance readings were converted to indicated strain, using gage factor determined previously in subsection 2.B. Data, above, and plotted versus

mechanical strain. A difference of 10 percent between indicated and actual strain was defined as strain limit. Strain limit was given in terms of mechanical strain.

4. Effect of Temperature on Apparent Strain, Gage Factor, Drift, Resistance to Ground, and Thermoelectric Output at 1500°F

For this series of evaluations, the test bars had thermocouples spot-welded to each corner of the gage area. A radiant oven was placed around the beam while in the moment apparatus.

Temperatures were controlled by the "set point" mode on the thermal controllers. One of the four thermocouples was used for feedback. The beam temperature was raised in 250°F increments and allowed to stabilize. The beam was considered stabilized when all thermocouples read within $\pm 5^\circ\text{F}$. The maximum temperature was 1500°F.

Starting at ambient temperature, the beam was cycled in 200 $\mu\epsilon$ increments to a strain level of 1000 $\mu\epsilon$ at each temperature plateau.

Six of the gages were strained in both tension and compression.

A. Measurements

Starting at ambient temperature, the following readings were taken at each cycle:

- 1) Capacitance reading while beam was unstrained
- 2) Capacitance reading while beam was strained
- 3) Beam deflection, strained and unstrained
- 4) Resistance to ground and equivalent resistance

When the extreme temperature of 1500°F was reached, the fore-mentioned readings were taken, but in addition, the thermoelectric output was measured. The unstrained beam was held at this temperature for 1 hour, and capacitance measurements taken every 10 minutes as soon as other readings were completed. This constituted drift data.

B. Data

The incremental data at each temperature was plotted as unit change of capacitance (ordinate) versus mechanical strain (abscissa) for all points up and down. The gage factor was determined as in subsection 2.B. for each temperature increment. This data was in turn plotted as gage factor (ordinate) versus temperature (abscissa).

The change in capacitance of the unstrained gage at each temperature was converted to indicated strain (ordinate), using the data from that determined in subsection 2.B. Data. and plotted versus temperature (abscissa).

The change in capacitance versus time at 1500 °F was converted to indicated strain (ordinate) and plotted versus time (abscissa). Resistance to ground and the thermoelectric output were also measured and recorded.

5. Effects of Heating Rate on Apparent Strain

The same apparatus used in subsection Effect of Temperature on Apparent Strain, Gage Factor, Drift, Resistance to Ground, and Thermoelectric Output at 1500 °F was utilized, except that the oven was controlled by Data-Trak function generators. One program was utilized and had a slope of 10 °F per second. The peak temperature was 1500 °F. The program was run a total of five times.

A. Data

The data was plotted as $\Delta L/L$ (ordinate) versus temperature (abscissa).

6. Effect of Temperature on Strain Limit

The same problem existed as in Strain Limit at Room Temperature for the tension strain limit; however, the extreme temperatures precluded the use of the extensometer. The bar temperature was raised to 1500 °F and stabilized, and the gage strained in 200 $\mu\epsilon$ steps until a 10 percent deviation in indicated strain was achieved.

A. Measurements

The following readings were taken at each increment, beginning at zero strain:

- 1) Capacitance
- 2) Deflection of beam

B. Data

The capacitance readings were converted to indicated strain using the gage factor determined in subsection 2.B. Data and plotted versus mechanical strain.

The strain limit is the point where the difference between indicated strain and mechanical strain is greater than 10 percent, or at the point where bond failure occurs.



Figure 13. Constant Moment Apparatus
(Photo 319-7)

SECTION IX

TEST RESULTS

The results of the Phase II evaluation of the 15 high temperature capacitance strain gages is arranged here in the same order as the target specifications. Table II presents a test matrix of the tests conducted on the 15 gages. In summary, the first nine gages were evaluated at both room and elevated temperature. These gages were not destroyed but were used to measure all the pertinent properties at both room and elevated temperatures. The order of testing was varied slightly from gage to gage in order to gain the maximum amount of data from the nine available gages. Gage 7 was rejected in Manufacturing and was not tested. Gages 11, 12, and 13 were used to measure the strain limit at room temperature. Gages 14, 15, and 16 were used to determine the strain limit at elevated temperatures.

GAGE LENGTH

All of the gages fell within the prescribed drawing tolerances indicated in Figure 1 for the rhombic frame. This is well within the target specification of a 1-inch square.

GAGE CAPACITANCE

Table III presents the initial gage capacitance of all 40 gages manufactured, as part of this program. The nominal gage capacitance as indicated in the table is 14 picofarads, which is within the range of 10 to 100 picofarads as set by the target specification. The reproducibility gage to gage was outside the target of ± 2 percent. The capacitance varied from a low of 11.17 to a high of 16.42 picofarad.

GAGE FACTOR (STRAIN SENSITIVITY)

A summary of the room temperature gage factors is presented in Table IV. Tension gage factor is given for gages 1 through 16. Gage factor in compression is given for gages 1 through 6 only. The gage factor varied from a low of 19.5 to a high of 40.5. The target specification was arbitrarily set at 25. At the completion of evaluation of gage 2 it was removed from the test bar by carefully prying up the welded tabs. The gage was then reinstalled and the room temperature gage factor measured. This second run is included in the strain limit data. The gage factor for both calibrations on gage 2 were the same, within the accuracy of the measuring equipment.

A second important consideration is the repeatability, run to run, of any particular gage. This data is presented in Figure 14 for the tension runs, and in Figure 15 for the compression runs. This data is presented as an envelope which encompasses the run to run deviations for all gages tested.

TABLE II. TEST MATRIX

Tests	Capacitance Strain Gage															
	1	2	3	4	5	6	8	9	10	11	12	13	14	15	16	
<u>Ambient Temperature</u>																
Initial capacitance	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
Equivalent gage resistance at IMC	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
Resistance to ground	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
Gage factor	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
Zero shift per cycle	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
Strain limit										X	X	X				
<u>Elevated Temperature</u>																
Capacitance	X	X	X	X	X	X	X	X	X				X	X	X	
Equivalent gage resistance at IMC	X	X	X	X	X	X	X	X	X							
Resistance to ground	X	X	X	X	X	X	X	X	X							
Change in gage factor at various temperatures	X	X	X	X	X	X	X	X	X							
Zero shift per cycle	X	X	X	X	X	X	X	X	X							
Apparent strain at various temperatures	X	X	X	X	X	X	X	X	X							
Drift versus time at 1500°F	X	X	X	X	X	X	X	X	X							
Effect of heating rate on apparent strain			X					X	X	X	X	X	X	X	X	
Strain limit at 1500°F													X	X	X	
Gage factor at 1500°F only													X	X	X	
Thermoelectric output	X	X	X	X	X	X	X	X	X							

Note: Gages tested in:

- 1) Tension: 8 through 12; 14 and 15
- 2) Compression: 13 and 16
- 3) Tension and Compression: 1 through 6

TABLE III. INITIAL GAGE CAPACITANCE

Gage No.	Capacitance, Picofarad	Gage No.	Capacitance, Picofarad
1	12.95	21	12.50
2	14.04	22	13.04
3	15.46	23	12.50
4	15.65	24	13.40
5	14.72	25	11.17
6	15.63	26	12.91
7	---	27	12.78
8	15.74	28	13.10
9	16.42	29	12.34
10	15.00	30	12.87
11	15.45	31	12.77
12	14.07	32	13.15
13	14.40	33	12.01
14	12.96	34	12.15
15	14.08	35	13.42
16	13.76	36	12.28
17	14.74	37	12.46
18	12.66	38	12.72
19	12.40	39	14.72
20	12.92	40	13.25
		41	13.10

TABLE IV. ROOM TEMPERATURE GAGE FACTOR

Gage No.	Gage Factor	
	Tension	Compression
1	25.4	33.0
2	27.0	22.8
3	40.5	40.5
4	25.2	30.3
5	35.2	27.0
6	20.7	25.7
7	---	---
8	19.5	---
9	23.2	---
10	29.5	---
11	31.8	---
12	27.3	---
13	29.3	---
14	28.25	---
15	27.1	---
16	29.0	---

The lightly shaded area on each figure represents the deviation experienced from the first load cycle at room temperature. These curves represent a deviation from the mean gage output run to run on three to five runs per gage of a maximum of 150 to 200 microinches. Most of this deviation is experienced on the first cycle at any given test temperature. The second and third cycles are considerably closer together, with a deviation of approximately ± 25 microinches. The target specification allowed for a deviation (gage factor tolerance) of ± 2 percent per 100 °F. This represents a minimum allowable deviation of $\pm 0.004 \Delta C/C$, assuming a 1000 microinch strain. This is outside the limits of the plot shown in Figures 14 and 15.

GAGE FACTOR VARIATION WITH TEMPERATURE

The gage factor variation with temperature is also demonstrated in Figures 14 and 15. The curves represent the maximum deviation from an average curve. This deviation occurred in all cases at the maximum strain recorded, and therefore represents a change in slope for consecutive runs at any given temperature. Since these figures represent an envelope of all test data recorded, it is the worst case, with the majority of data being a less severe case. The data shows that at 250°F, a maximum deviation, $\Delta C/C$ (compression), of $+0.18 \times 10^{-2}$ and -0.12×10^{-2} were recorded. These values correspond to a total $\Delta C/C$ change 40×10^{-2} (gage 3), or a gage factor variation of 4.5 percent, compared with a target specification of 2 percent per 100°F at temperatures below 600°F, or ± 3.5 percent for a test temperature of 250°F. The gage is therefore outside the target specification at 250°F. However, as the temperature is increased, the deviation remains almost constant, providing a gage far superior to the target which was set for a deviation ranging from ± 10.5 percent at 500°F to ± 55.5 percent at 1500°F.

MAXIMUM GAGE FACTOR CHANGE WITH TEMPERATURE

The gage factor change with temperature is plotted in Figure 16 for tension and Figure 17 for compression. It is noted that this variation is extremely nonlinear and nonrepeatable gage to gage. However, as noted in the previous section, it is very repeatable run to run. The target specification was a linear change of a maximum of 2 percent per 100°F. Careful examination of Figures 16 and 17 reveal that approximately half of the gages fall within the specification, which would allow, for example, on a gage with an initial gage factor of 25, a maximum change of ± 7.1 at 1500°F.

STRAIN LIMIT AT 1500 °F

Gages 14 and 15 were tested for strain limit in tension. The gages were taken to 2600 $\mu\epsilon$ without a 10-percent deviation, at which point yielding in the test bar occurred. The data is shown in Figure 18. Gage 16 was tested for strain limit in compression and the 10 percent deviation occurred at 2260 $\mu\epsilon$ of real strain (see Figure 19). This is outside the target specification of 5000 $\mu\epsilon$. The real strain limit of gage 13, tested at room temperature in compression, was 2040 $\mu\epsilon$, as shown in Figure 20. In an attempt to measure the real strain limit in tension, gage 2 was welded between two steel bars (which forced all of the load to go through the gage) and tested as described in the test procedure. The gage experienced 16,000 microinches before it exceeded the 10 percent nonlinearity.

DRIFT RATE AT 1500°F

Gages 1 through 10 were tested for drift rate, and the composite data is shown in Figure 21. The entire data envelope for the 9 gages is from $-20 \mu\epsilon$ to $+125 \mu\epsilon$ over a 1-hour time duration. This is well within the target specification of $300 \mu\epsilon$ per hour below 600°F , and $900 \mu\epsilon$ per hour above 600°F .

MINIMUM RESISTANCE TO GROUND

Resistance to ground measurements were taken as a function of temperature for gages 1 through 10. This resistance degraded from nominal values of 1 megohm down to values as low as 0.04 megohm, which is well outside the target of 10 megohms in the specification. However, a further discussion is required when considering resistance to ground in connection with a capacitive strain gage. The effects of resistance to ground were not known at the time the target specifications were written, and as it turns out, it has no effect on gage performance. Resistances to ground are actually shunts across the grounded capacitances and are effectively eliminated in the bridge circuit.

APPARENT STRAIN AS A FUNCTION OF HEATING RATE (TEMPERATURE SENSITIVITY)

Gages 3, and 9 through 16 were evaluated at a heating rate of $10^\circ\text{F}/\text{sec}$, and a typical family of curves is shown for gage 11 in Figure 22. The drop in the curve from ambient to 300°F represents apparent strains of the order of $1200 \mu\epsilon$ to $2000 \mu\epsilon$, which is outside the target specification of $5 \mu\epsilon/^\circ\text{F}$, or $1000 \mu\epsilon$ at 300°F . However, all gages evaluated, with the exception of gages 10, 14, and 16, crossed the zero apparent strain axis in a temperature band from 1000°F to 1400°F . Gages 10, 14, and 16 approached the zero axis to within $700 \mu\epsilon$ at 1500°F . The gages tended to stabilize after the first two thermal cycles.

A comparison of the effect of the transient heating with the results of static temperature conditions can be taken from Figure 23. Figure 23 presents the apparent strain resulting from quasisteady-state heating. Only gages 1 through 5 are plotted, but they represent the results of all 9 gages tested in this manner. The data from Figures 22 and 23 both represent gages welded to an Inconel 718 test bar. With the exception of the initial offset seen in the transient condition, all the gages exhibit the same trend of a gradually increasing apparent strain. This trend is a direct duplicate of the dielectric constant change with temperature curve (Figure 5) and can be attributed to this effect. The effect of the thermal expansion of the test bar can be corrected by constructing the rhombic frame from a material with a similar coefficient of thermal expansion. In the case of gages evaluated, the thermal expansion of Inconel 718 bar and stainless steel 310 gage are 8.9 and 10 ppm, respectively. This would result in a differential expansion of $-1 \text{ ppm}/^\circ\text{F}$ with respect to the gage, which would put the rhombic frame in

compression and provide the opposite effect of the change in dielectric. The ideal combination would appear to be a gage with a slightly higher coefficient of expansion than the test specimen; i. e. , 1 to 2 ppm/ °F.

The initial shift of the apparent strain seen in the transient condition apparently results from the differential heating of the specimen and gage resulting from the shielded configuration of the gage.

BOND PROCESS

The gages are mounted by spot welding and no other attachment methods are intended, so the target specification of a 6-hour cure cycle is met.

ZERO SHIFT PER CYCLE

Figure 24 represents the total data envelope of the 15 gages evaluated for zero shift. The maximum zero shift occurs on the first cycle with values from -100 $\mu\epsilon$ to 250 $\mu\epsilon$, with the exception of gage 8. Succeeding cycles are within the target specification of 50 $\mu\epsilon$ per cycle, with the exception of gages 3 and 8. This data indicates the need for initial cycling of the gage before any data is taken.

THERMOELECTRIC OUTPUT

Measurements with a millivolt potentiometer, were made on gages 1 through 9. In every instance the output was zero. It is felt that differential emfs generated in a capacitance circuit would not be troublesome, as the capacitor would block dc current and it would not show up in the ac excited bridge network.

ADDITIONAL TEST RESULTS

Supplemental data showing the strain sensitivity of gages 1 through 6 and 8 through 10, versus temperature are provided for detailed comparison in Figure 25. This data is for applied tensile strains.

In addition, Figure 26 shows the strain sensitivity of gages 11 through 16 for tensile strain at room temperature.

Figure 27 shows the strain sensitivity of gages 1 through 6 versus temperature.

The data presented in Figures 25, 26, and 27 represent the average of a minimum of three data runs.

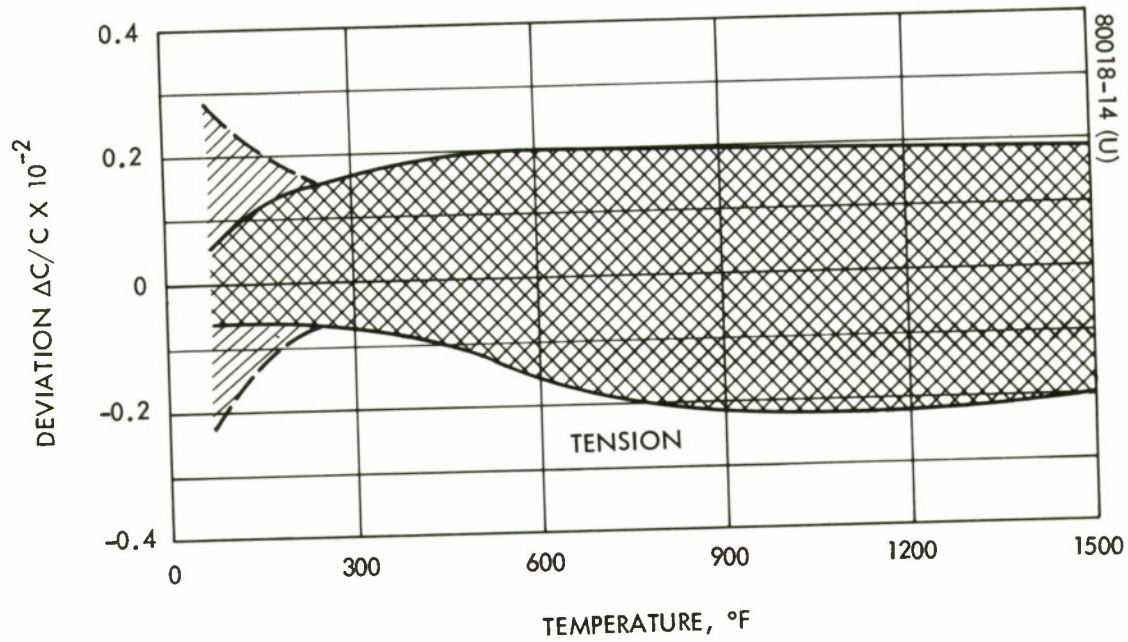


Figure 14. Repeatability, Run-to-Run For 15 Gages In Tension

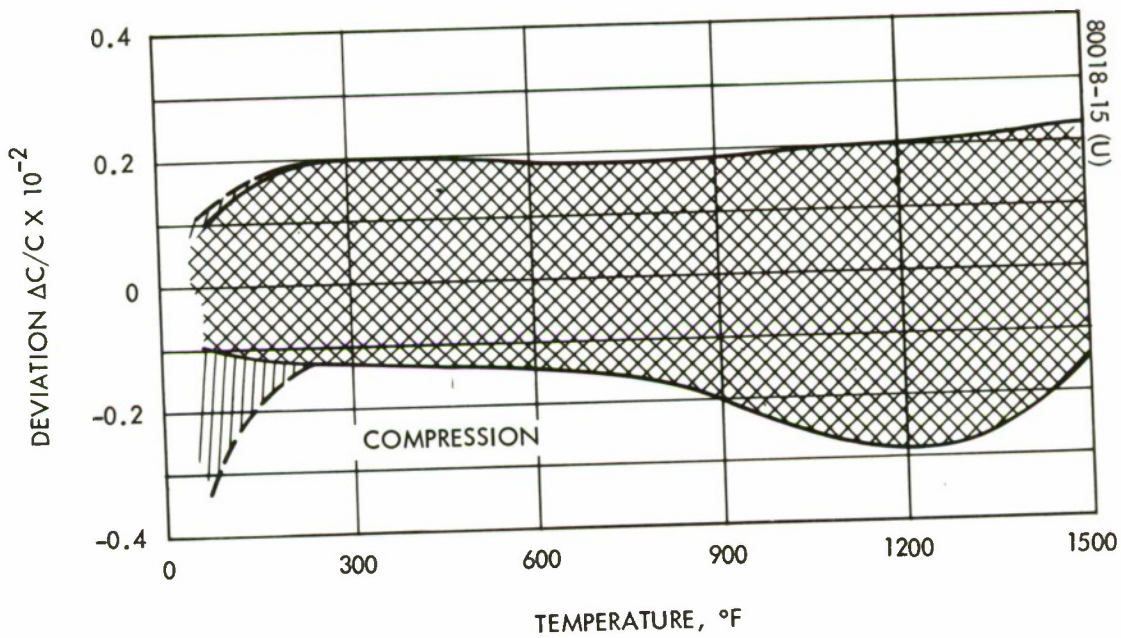


Figure 15. Repeatability, Run-to-Run For Gages 1 Through 6 In Compression

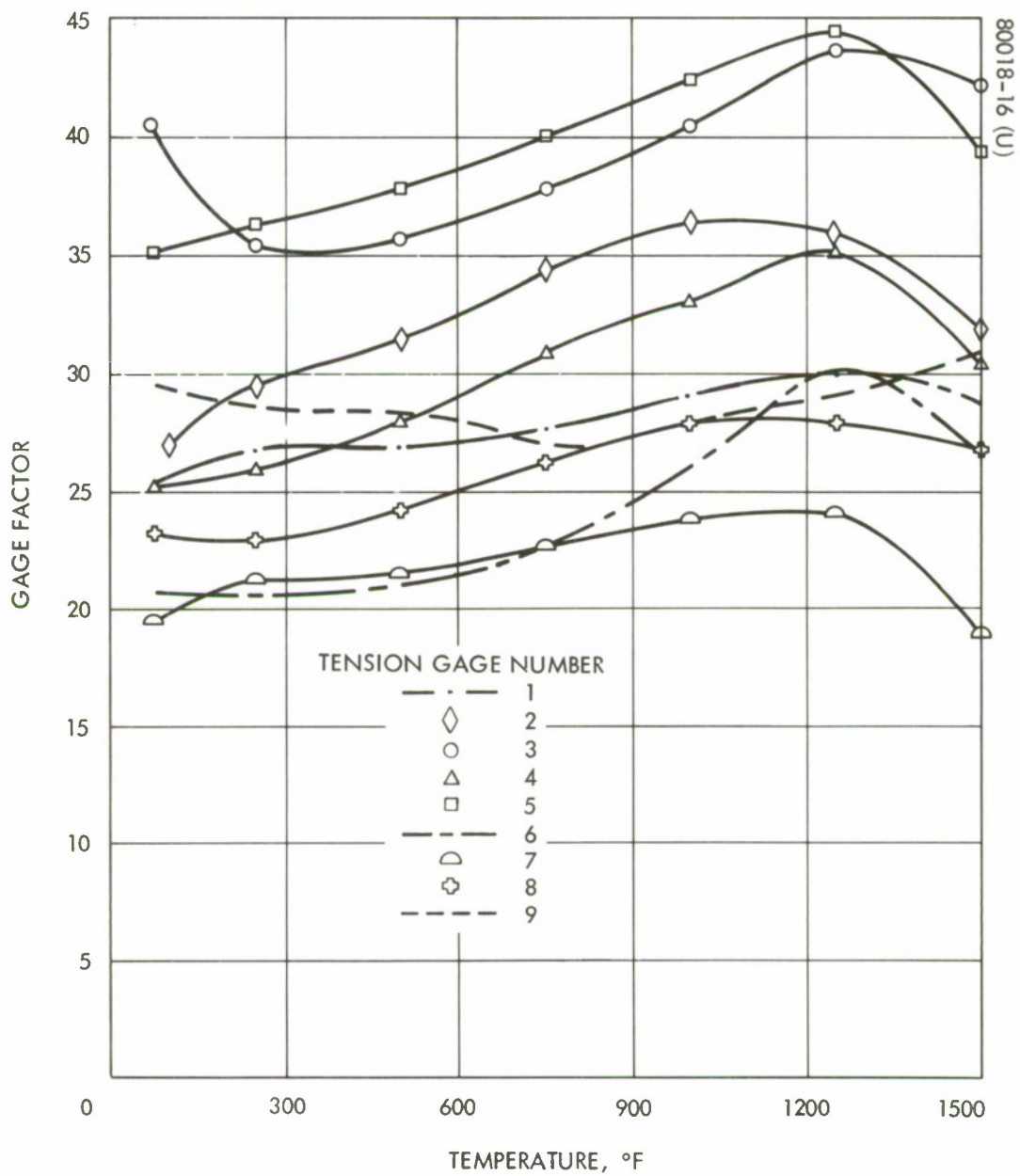


Figure 16. Gage Factor Versus Temperature, Gages 1 Through 10, In Tension

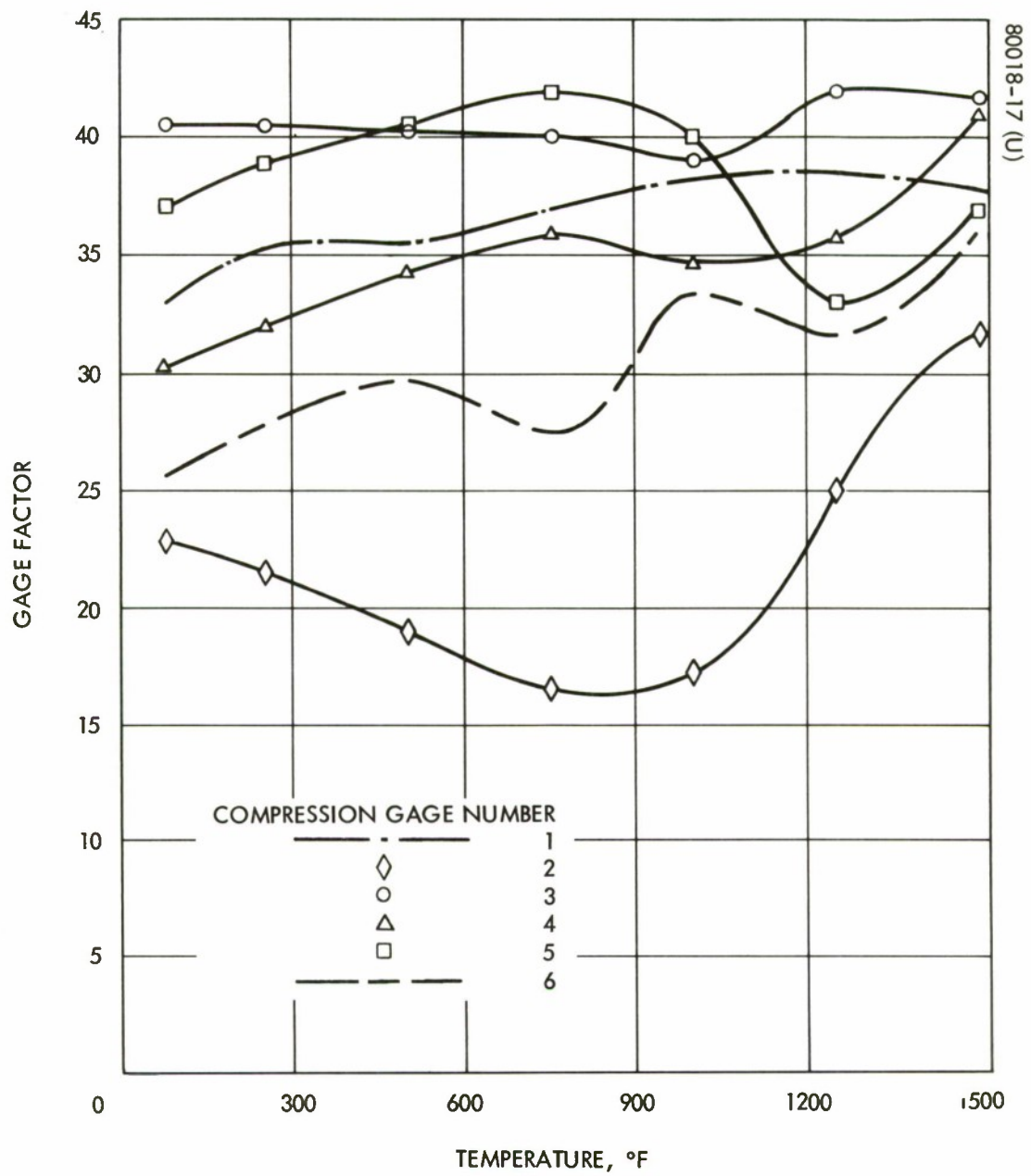


Figure 17. Gage Factor Versus Temperature, Gages 1 Through 6, In Compression

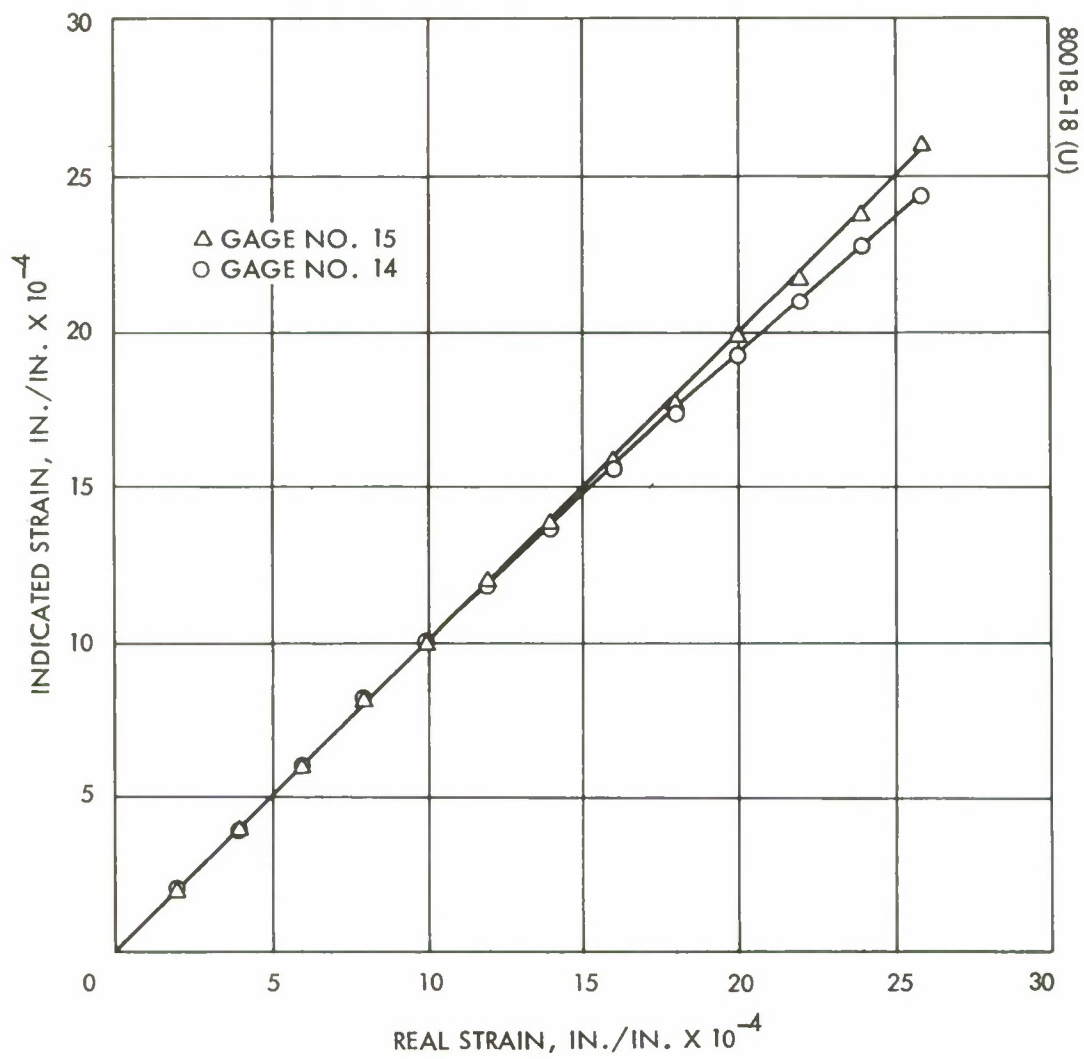


Figure 18. Strain Limit, 1500°F (Tension), Gages 14 and 15

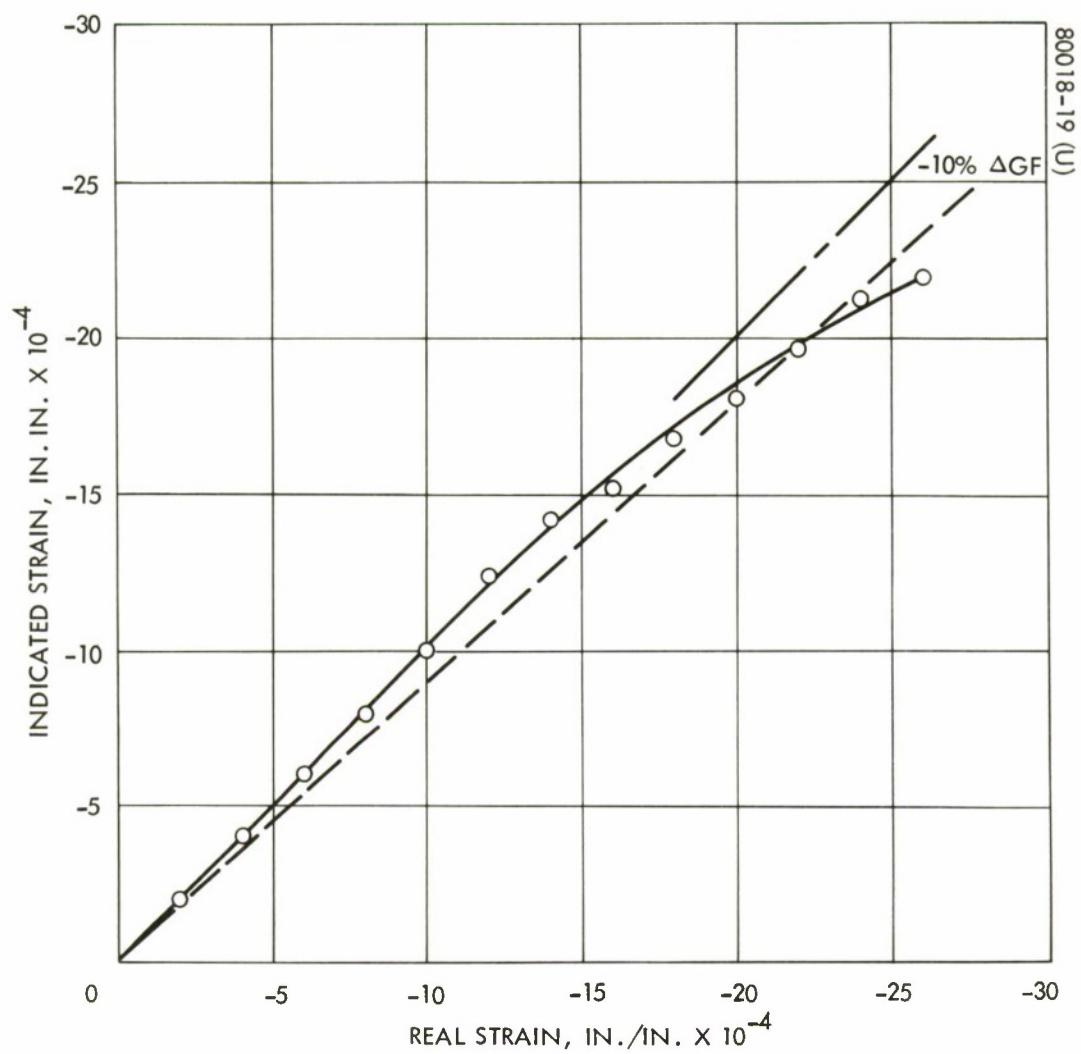


Figure 19. Strain Limit, 1500°F (Compression), Gage 16

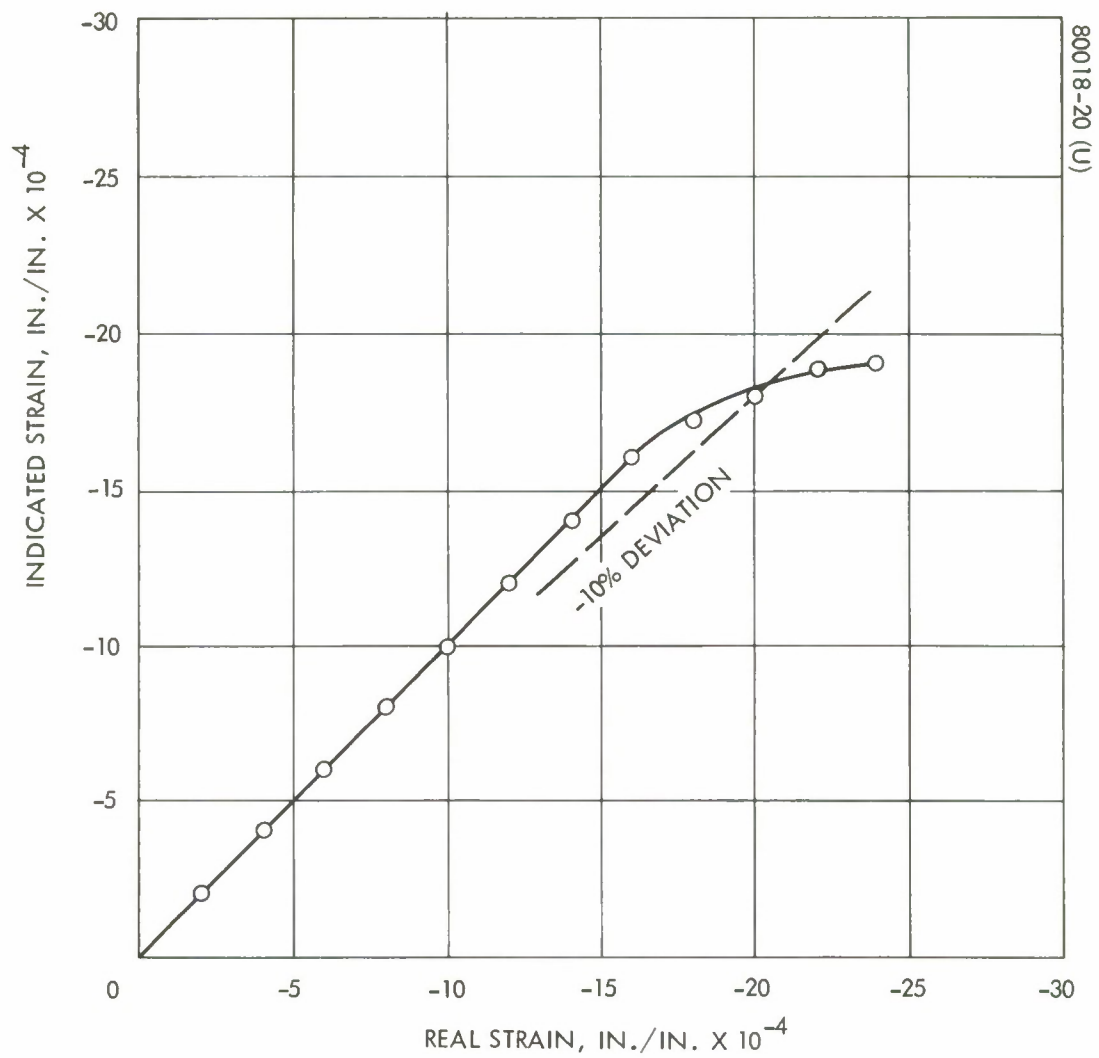


Figure 20. Strain Limit, Room Temperature (Compression), Gage 13

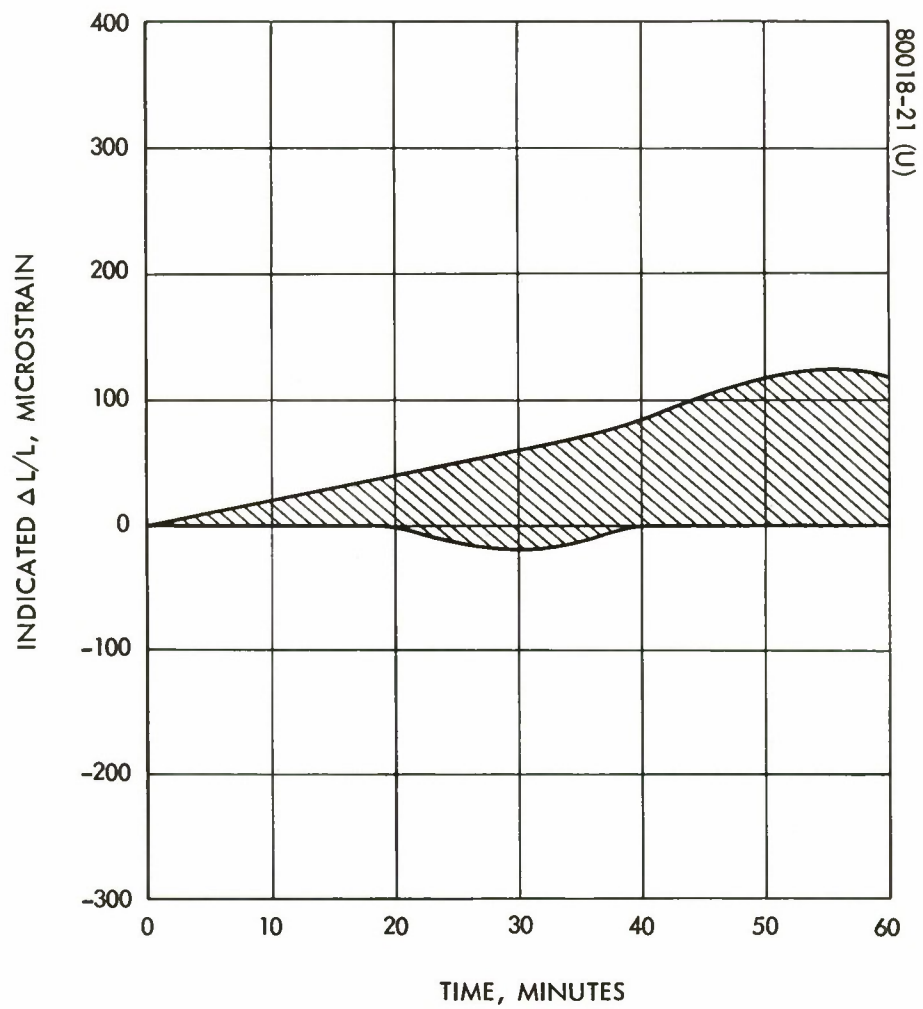


Figure 21. Drift at 1500°F, Gages 1 Through 10

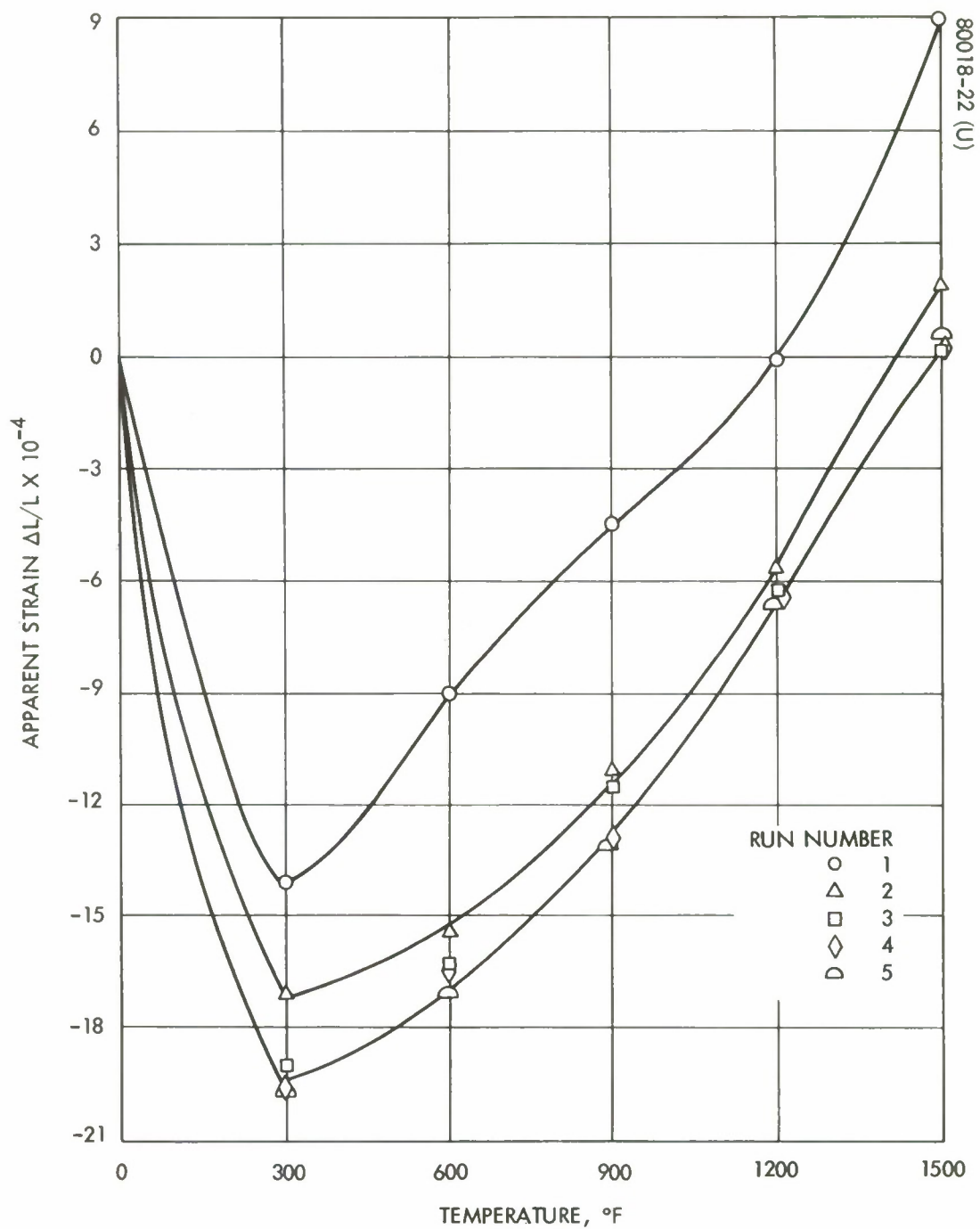


Figure 22. Apparent Strain (10°F/second), Gage 11

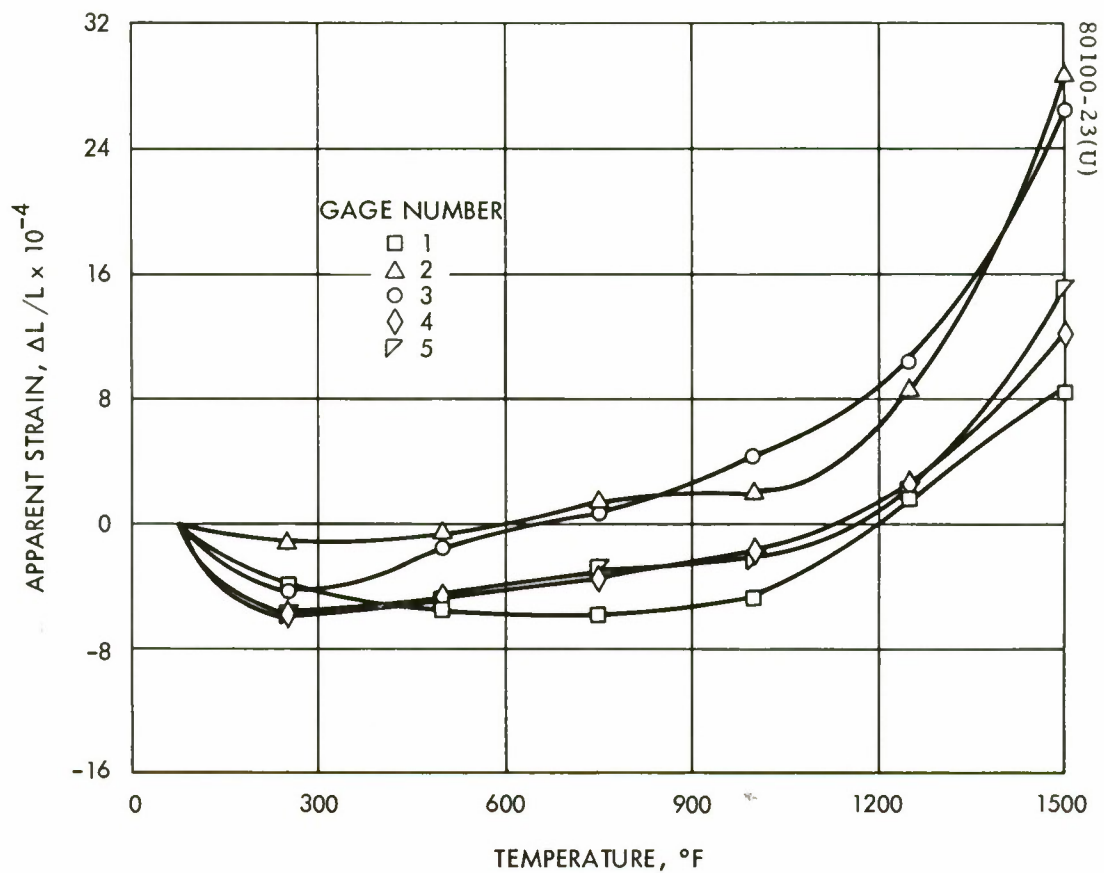


Figure 23. Apparent Strain (Steady State Heating), Gages 1 Through 5

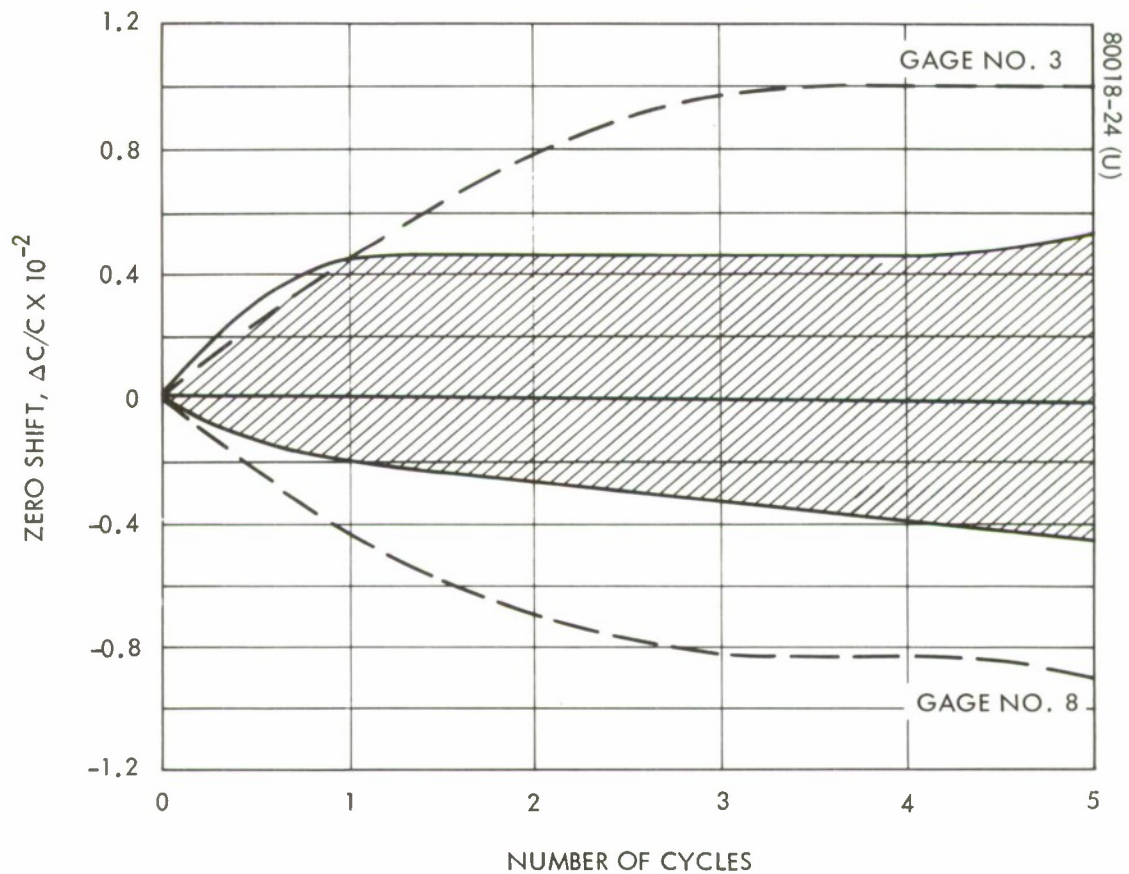


Figure 24. Zero Shift Total Data

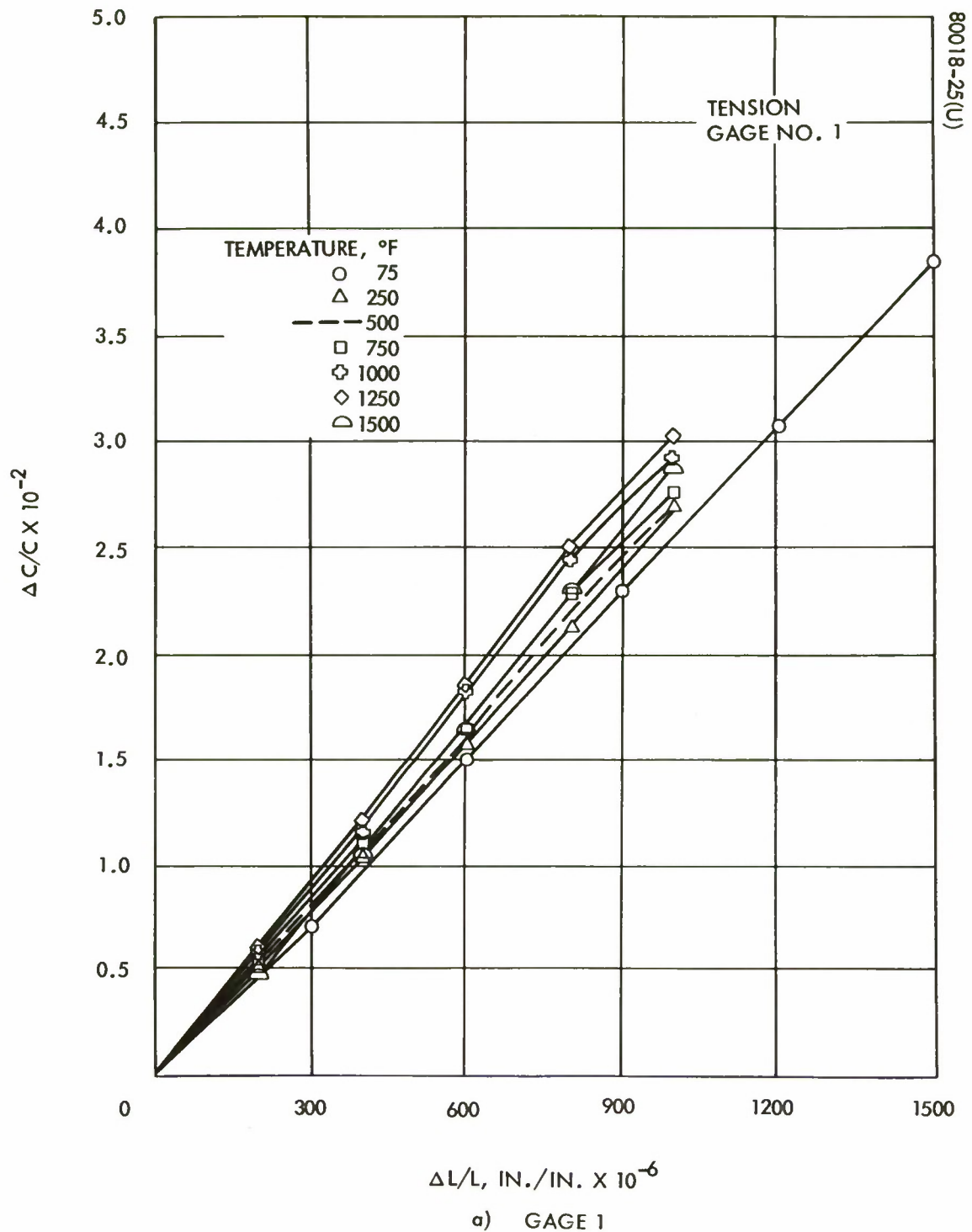
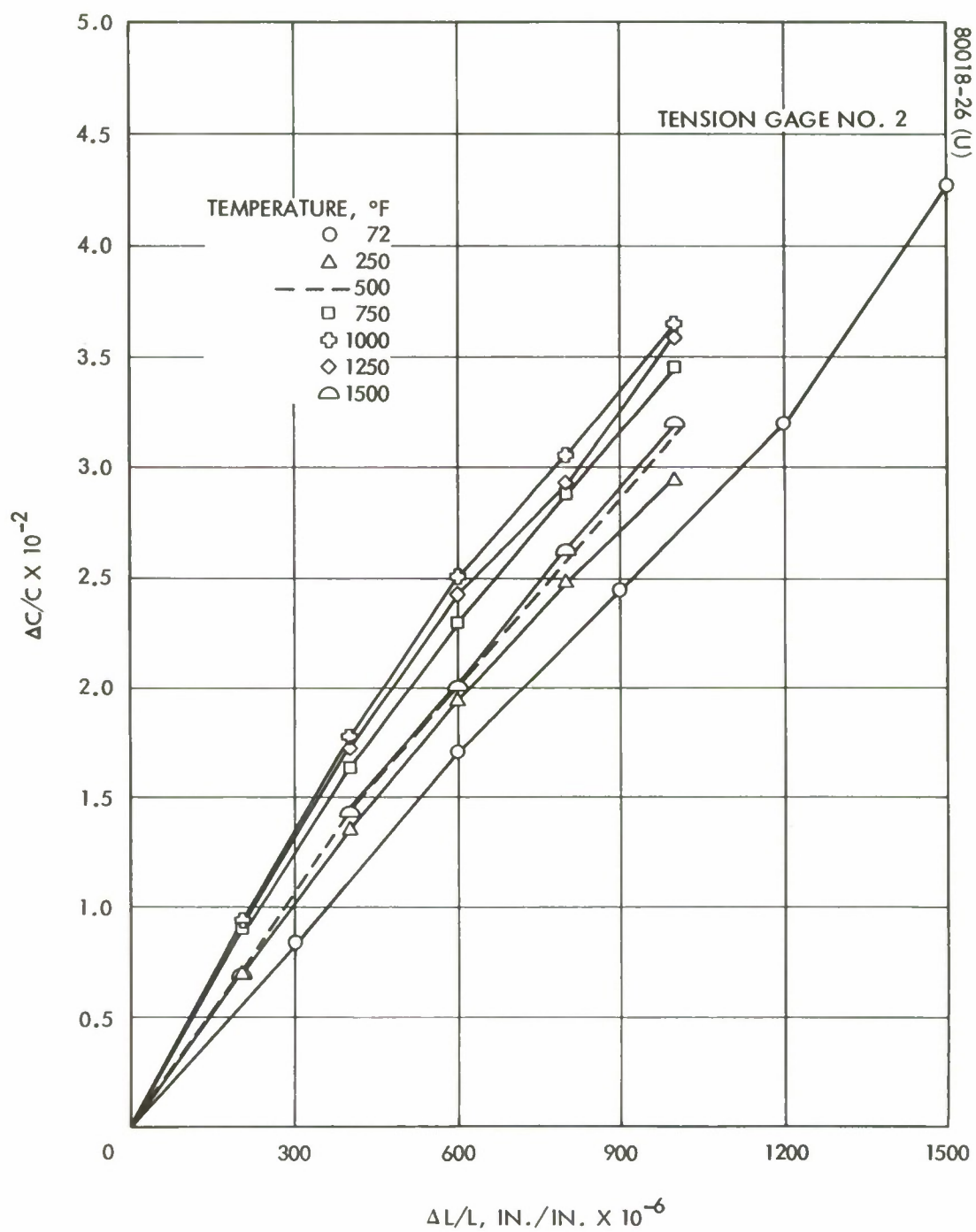
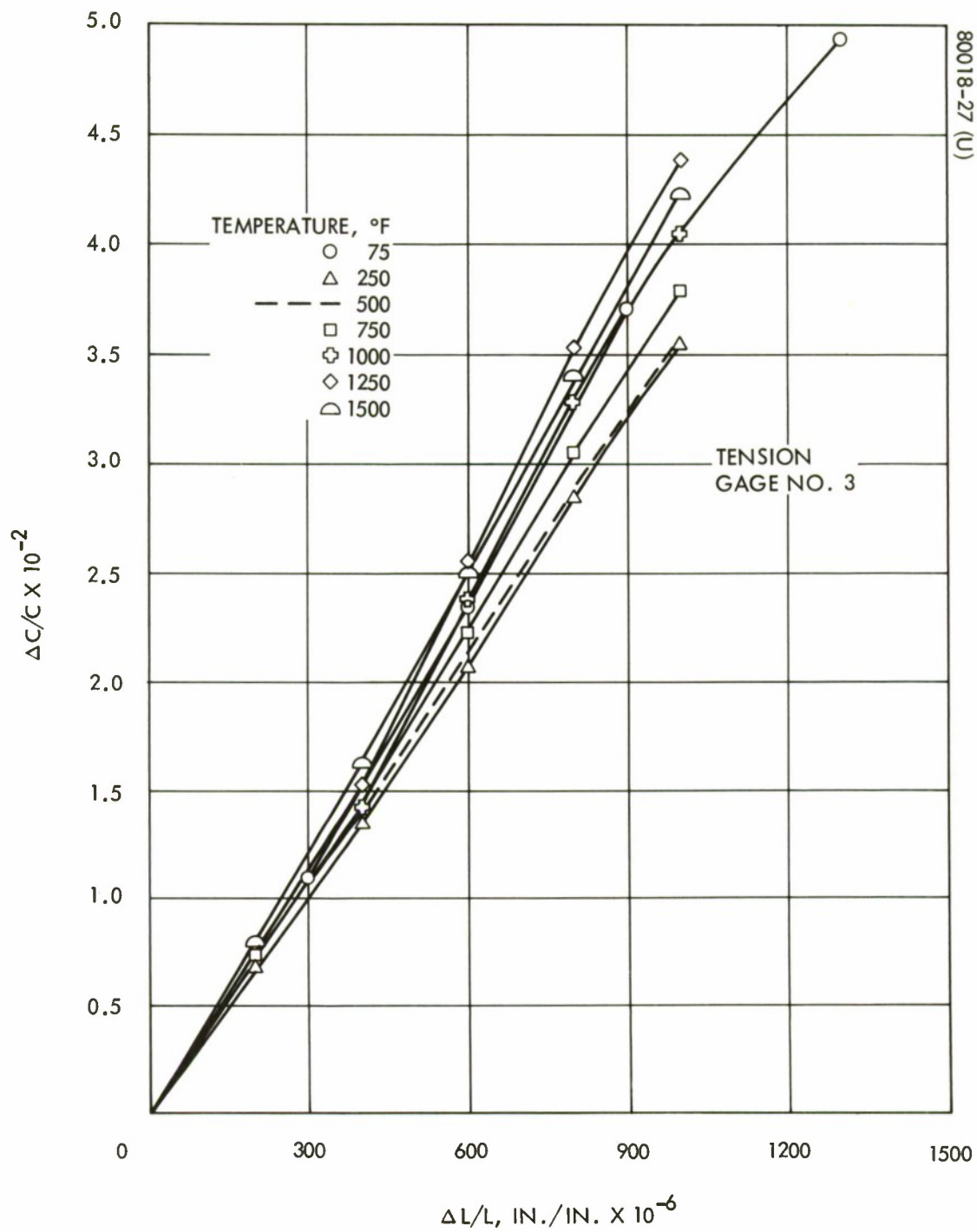


Figure 25. Gage Sensitivity Versus Temperature (In Tension)



b) GAGE 2

Figure 25 - Continued



c) GAGE 3

Figure 25 - Continued

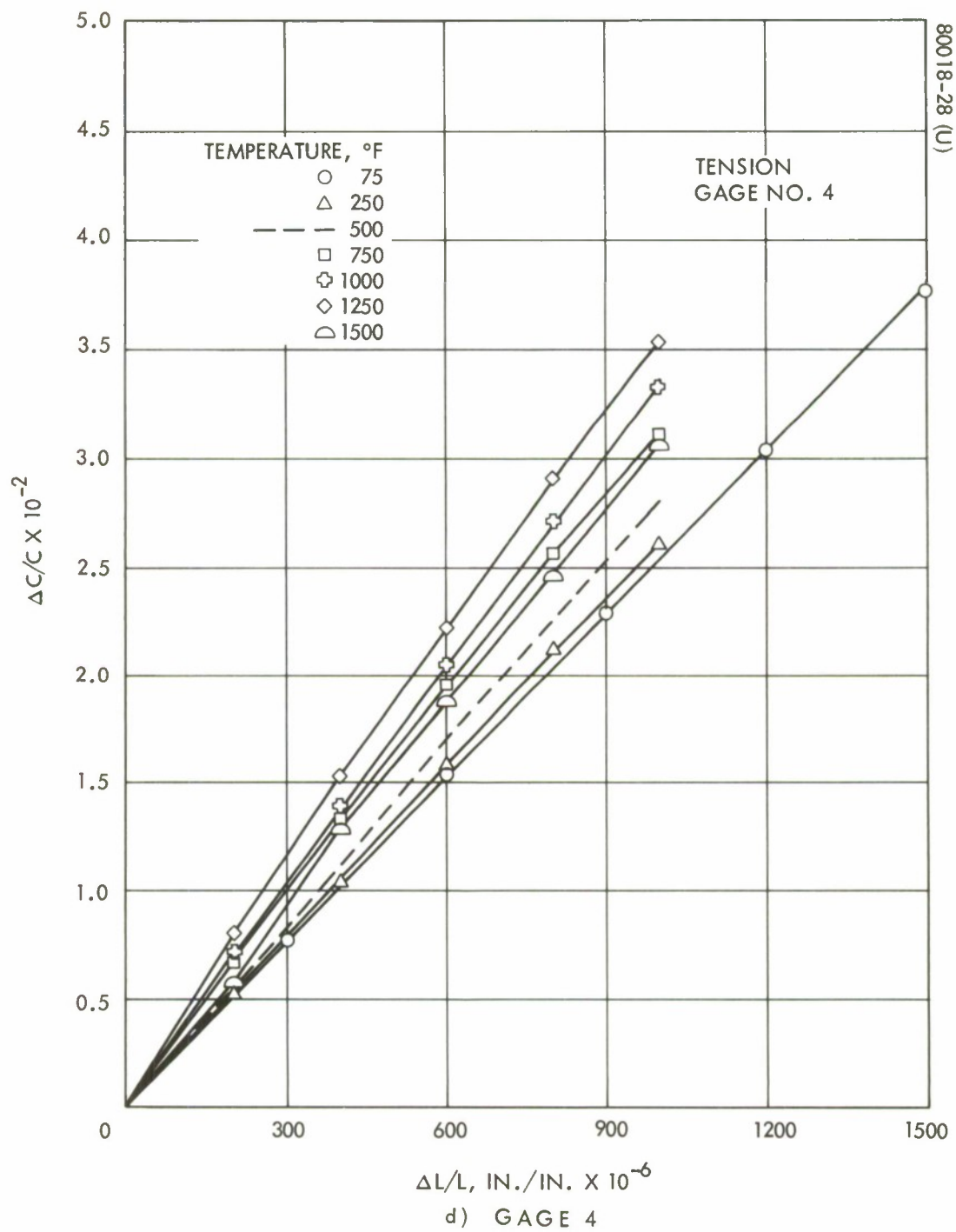
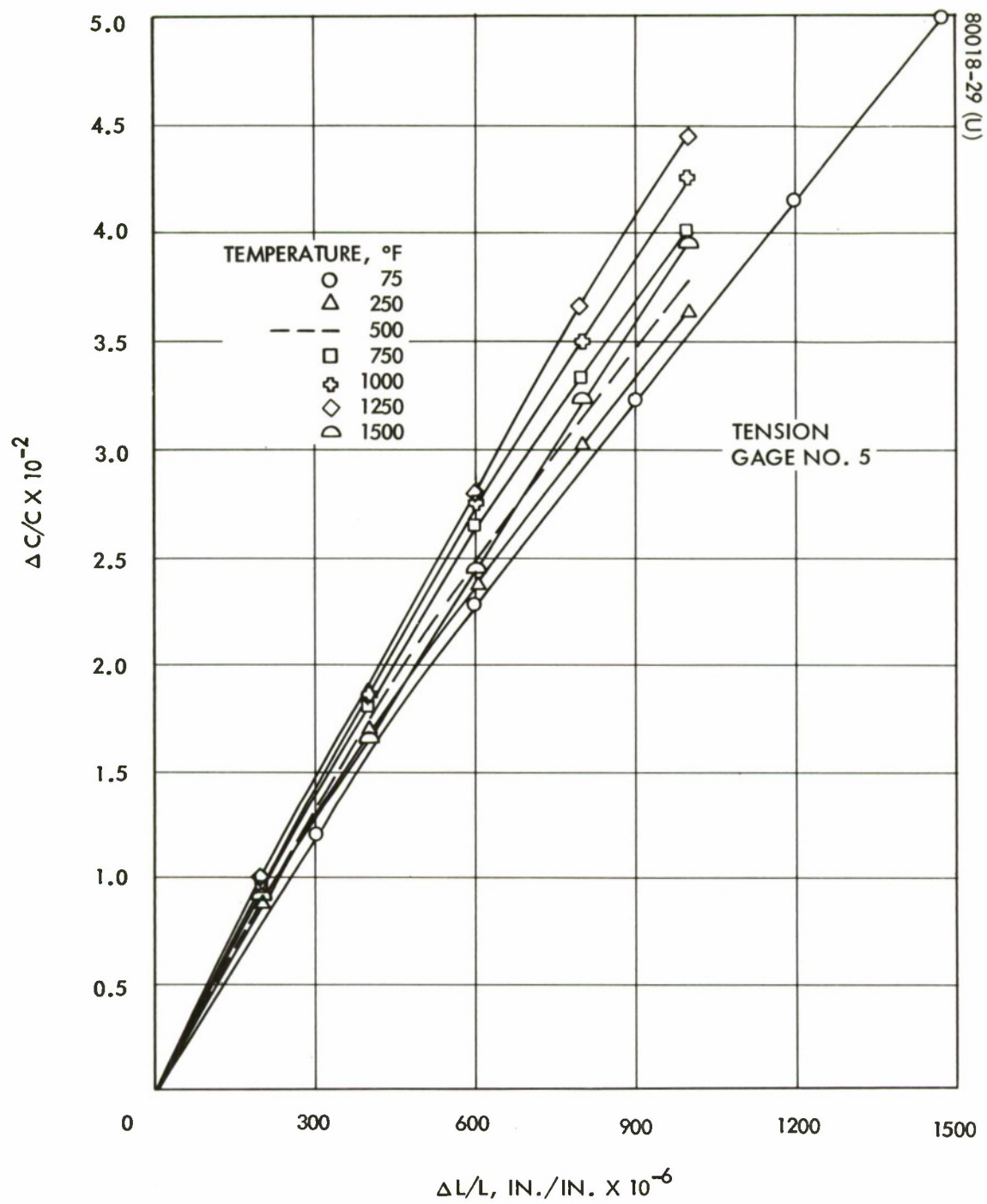
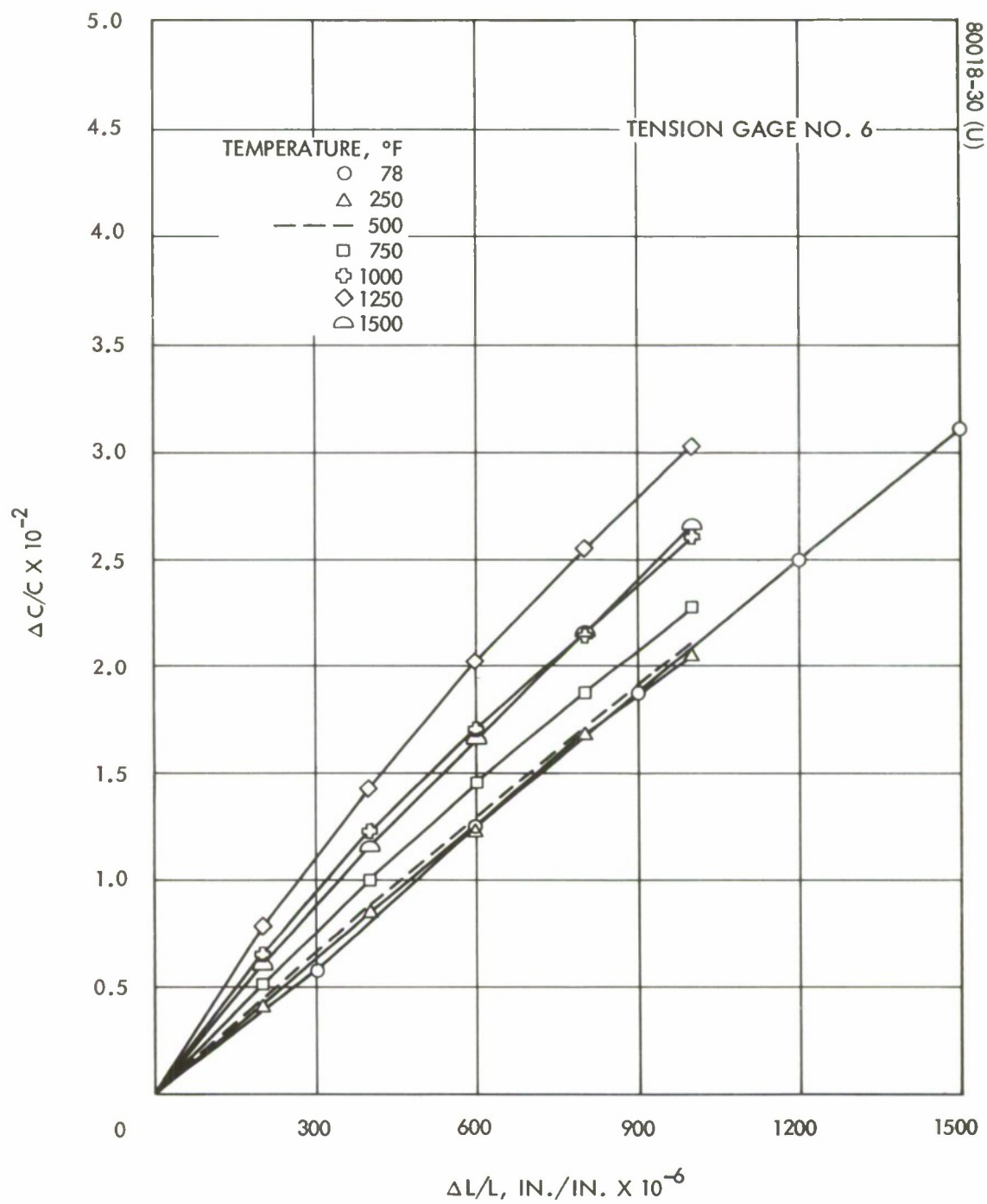


Figure 25 - Continued



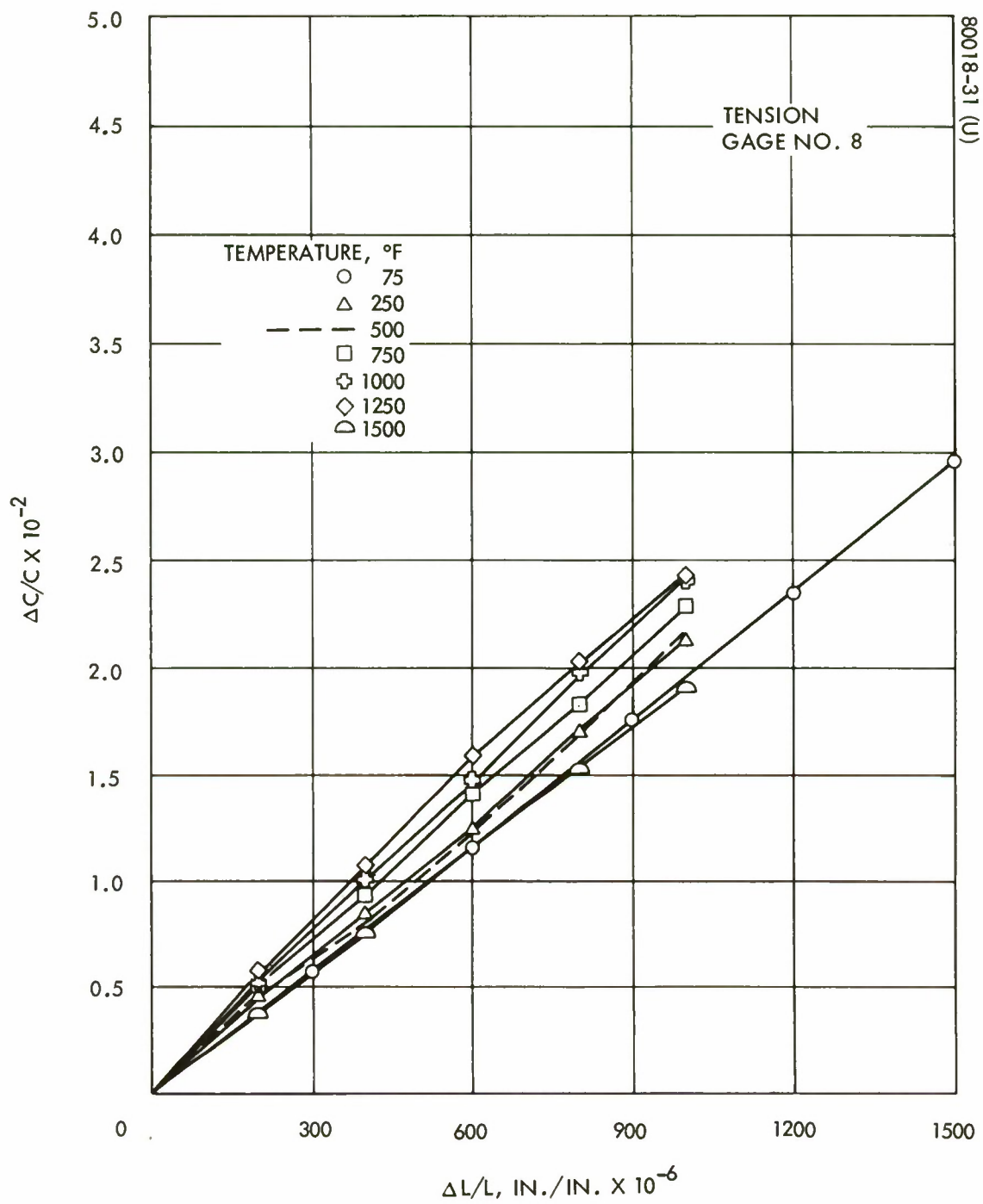
e) GAGE 5

Figure 25 - Continued



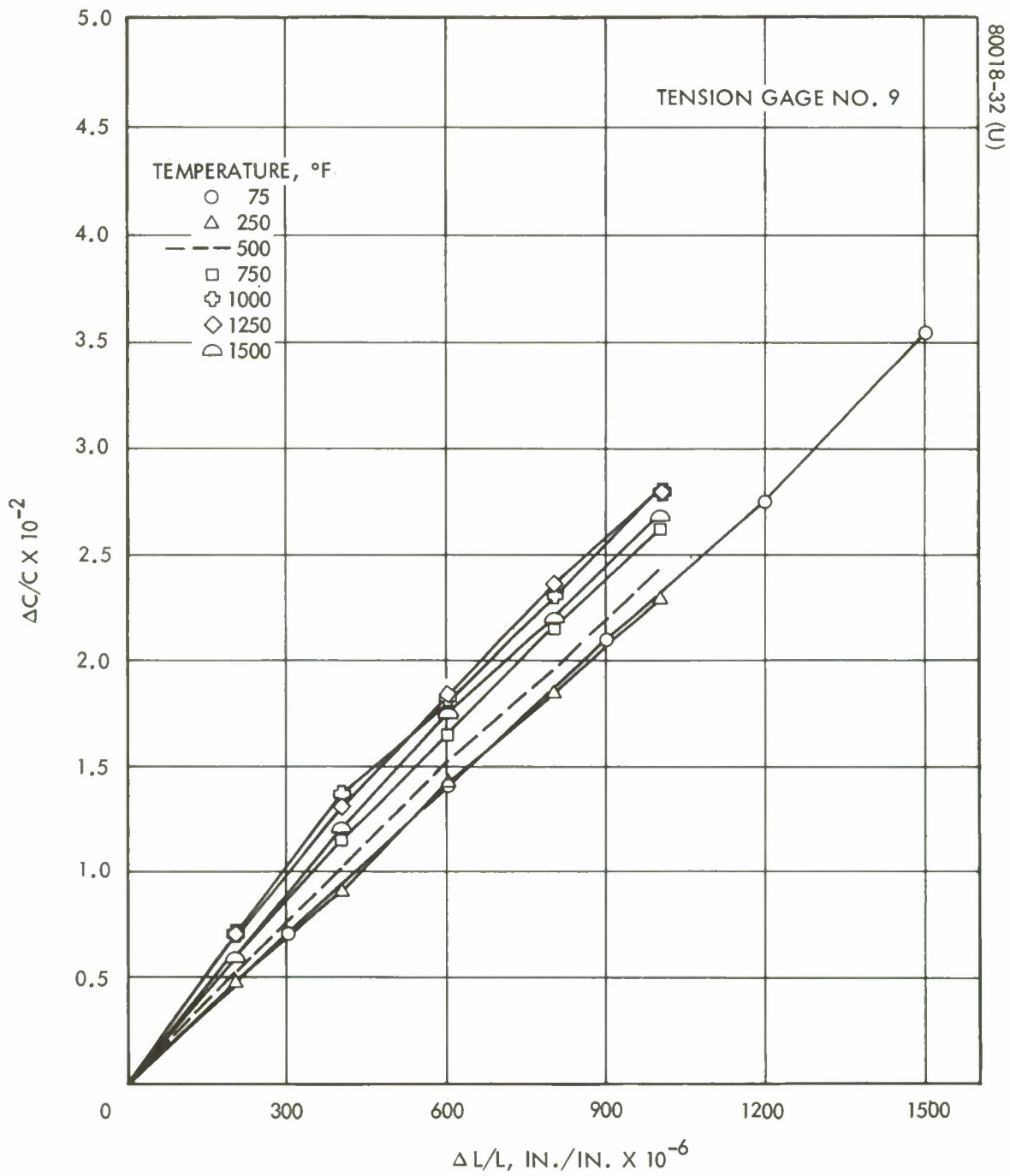
f) GAGE 6

Figure 25 - Continued



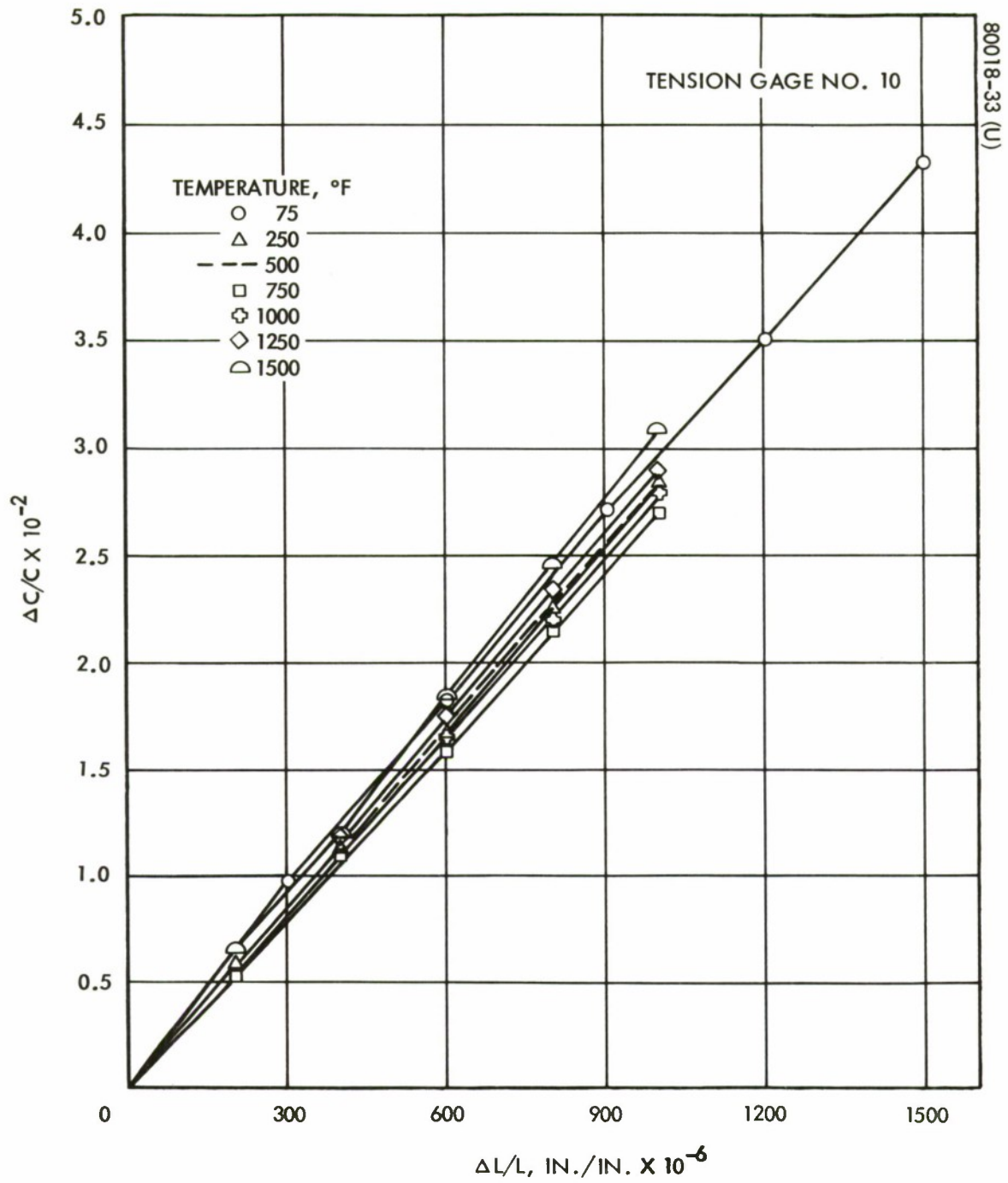
g) GAGE 8

Figure 25 - Continued



h) GAGE 9

Figure 25 - Continued



i) GAGE 10

Figure 25 - Concluded.

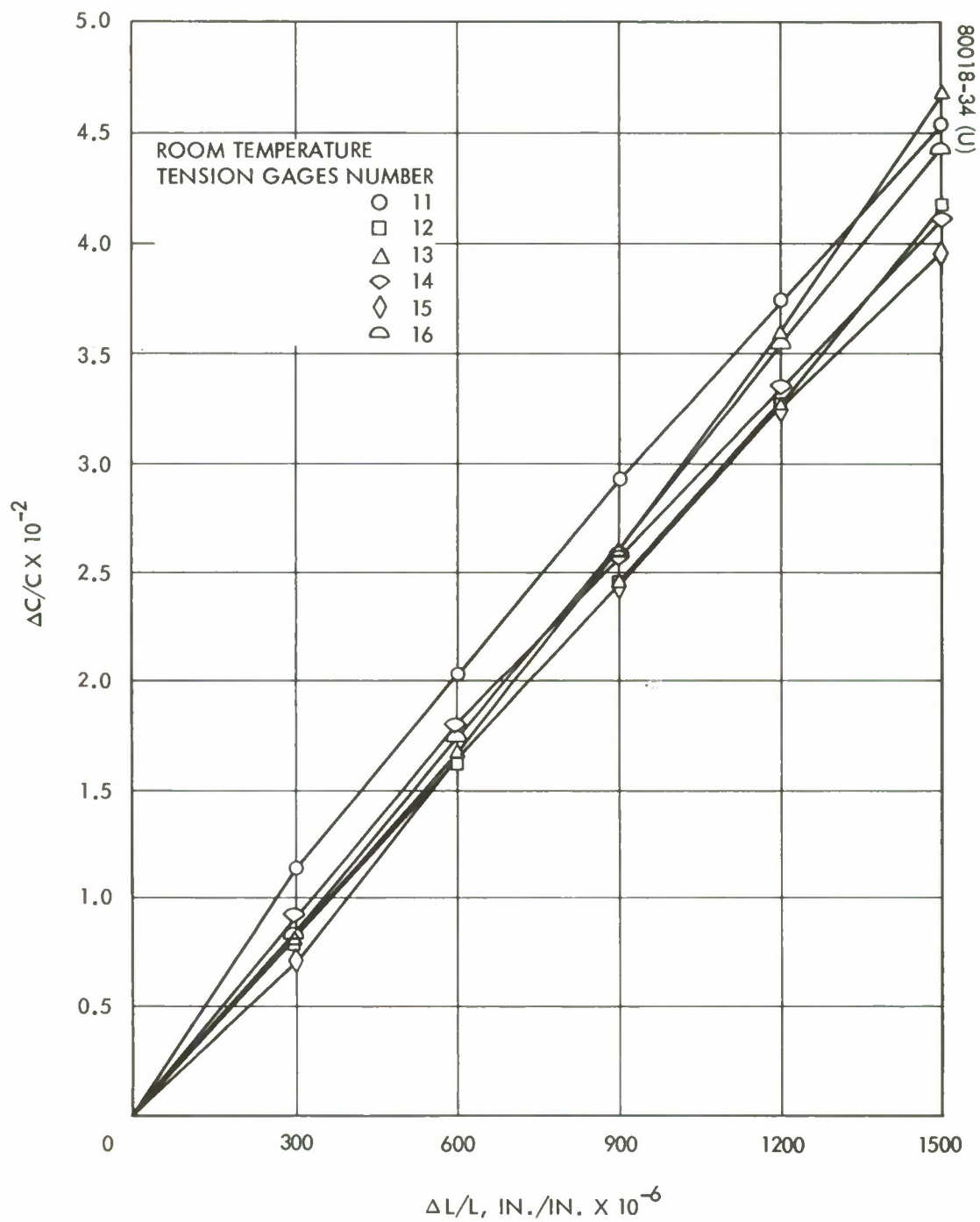


Figure 26. Gage Sensitivity At Room Temperature (In Tension),
Gages 11 Through 16

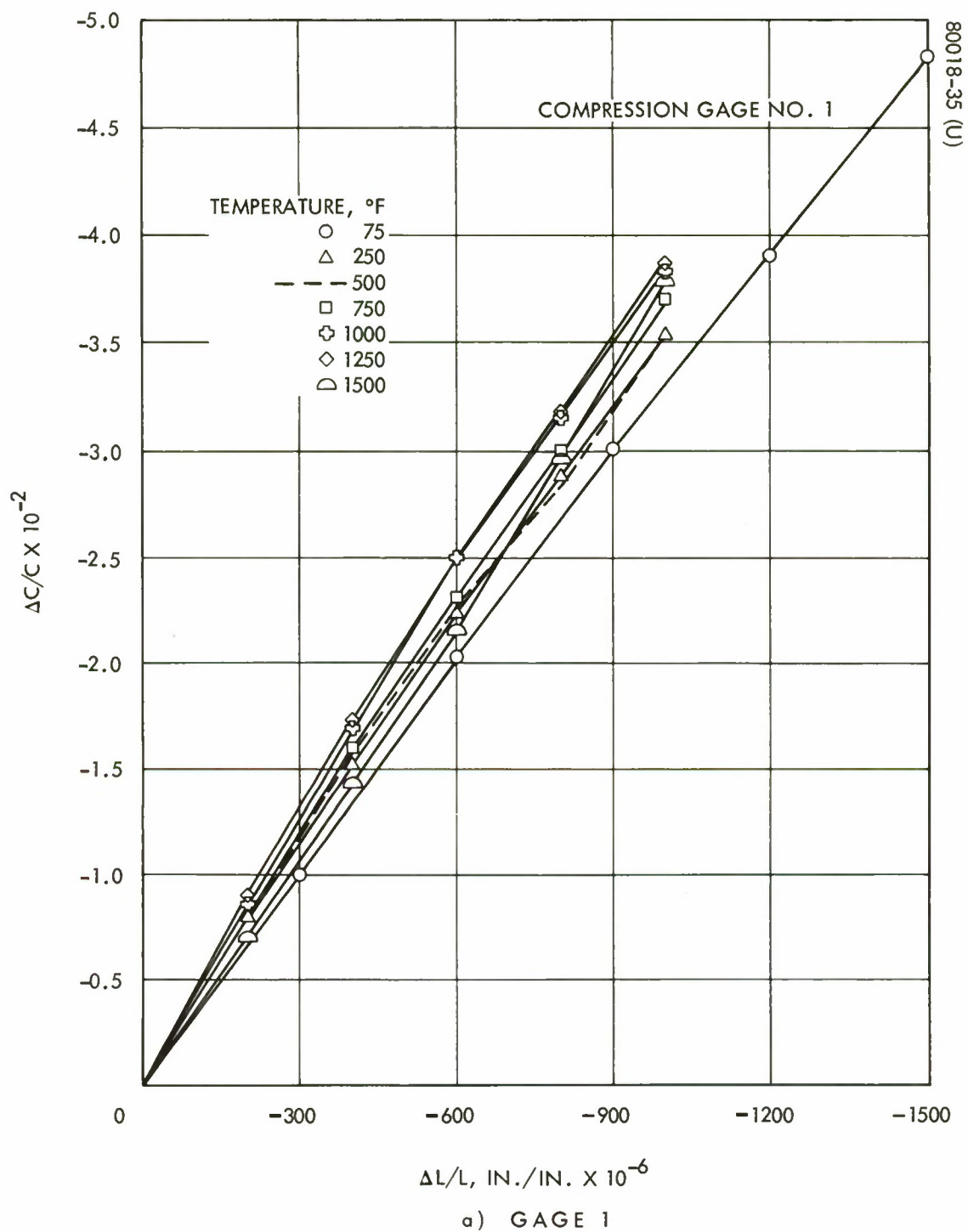
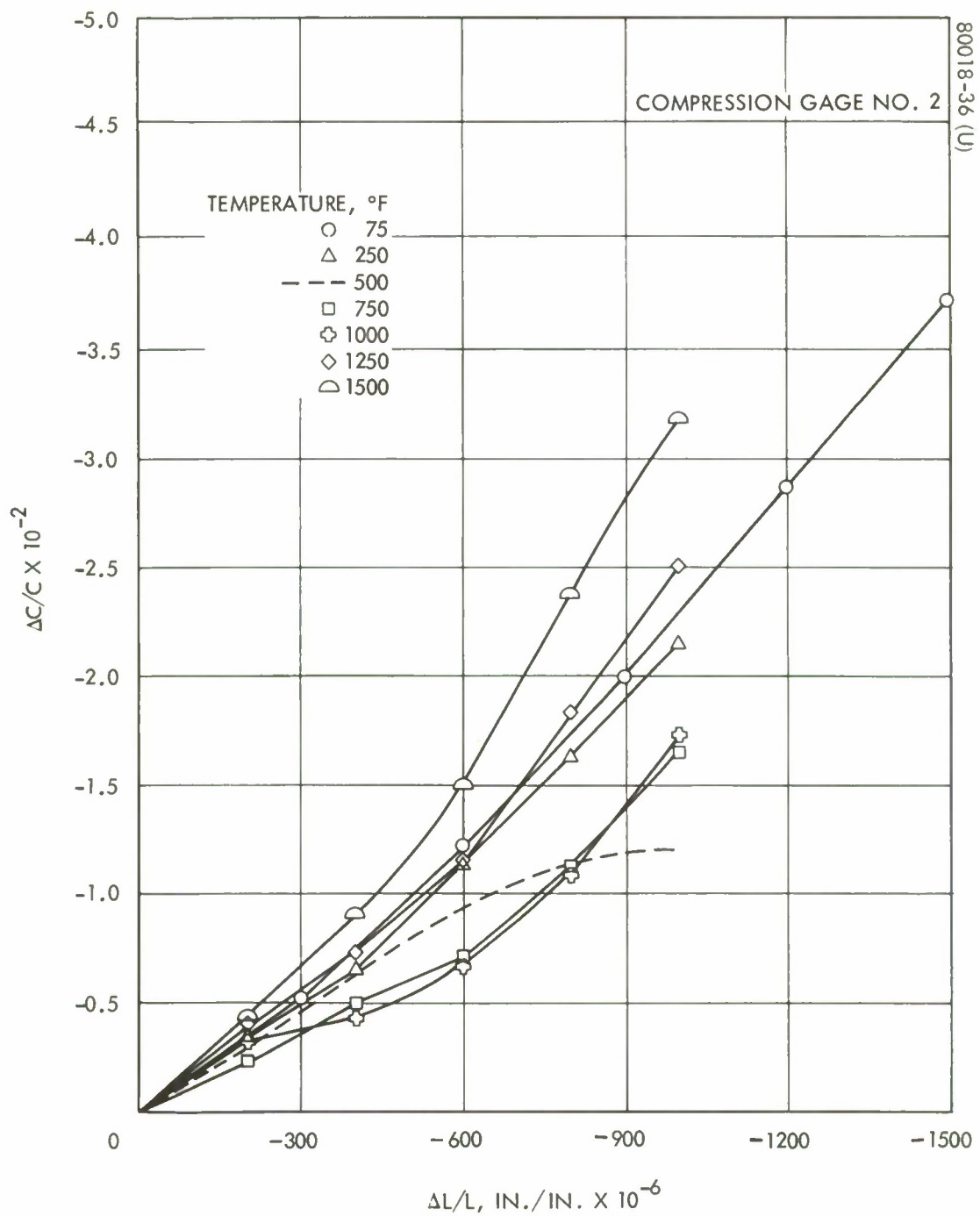


Figure 27. Gage Sensitivity Versus Temperature (In Compression)



b) GAGE 2

Figure 27 - Continued

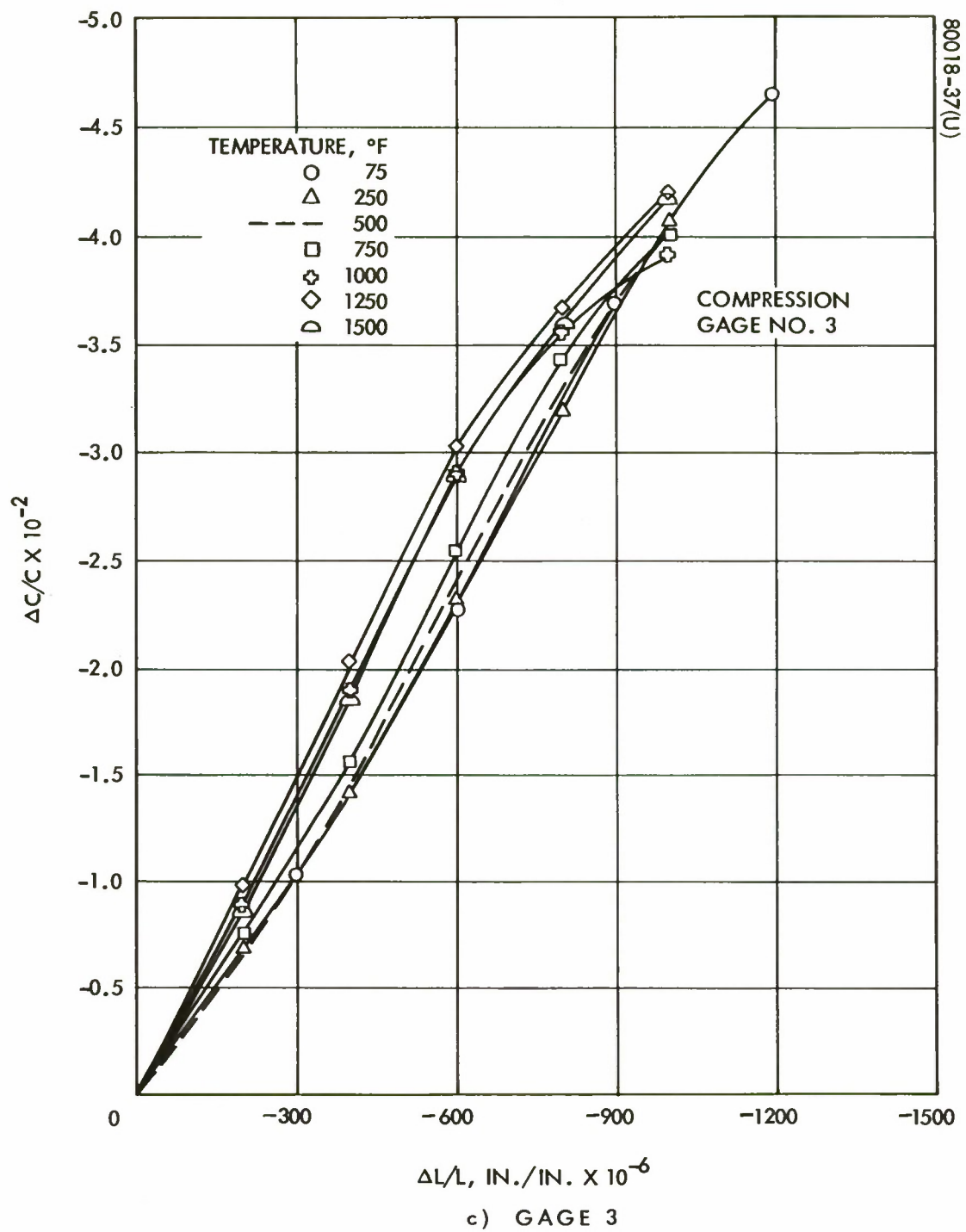


Figure 27 - Continued

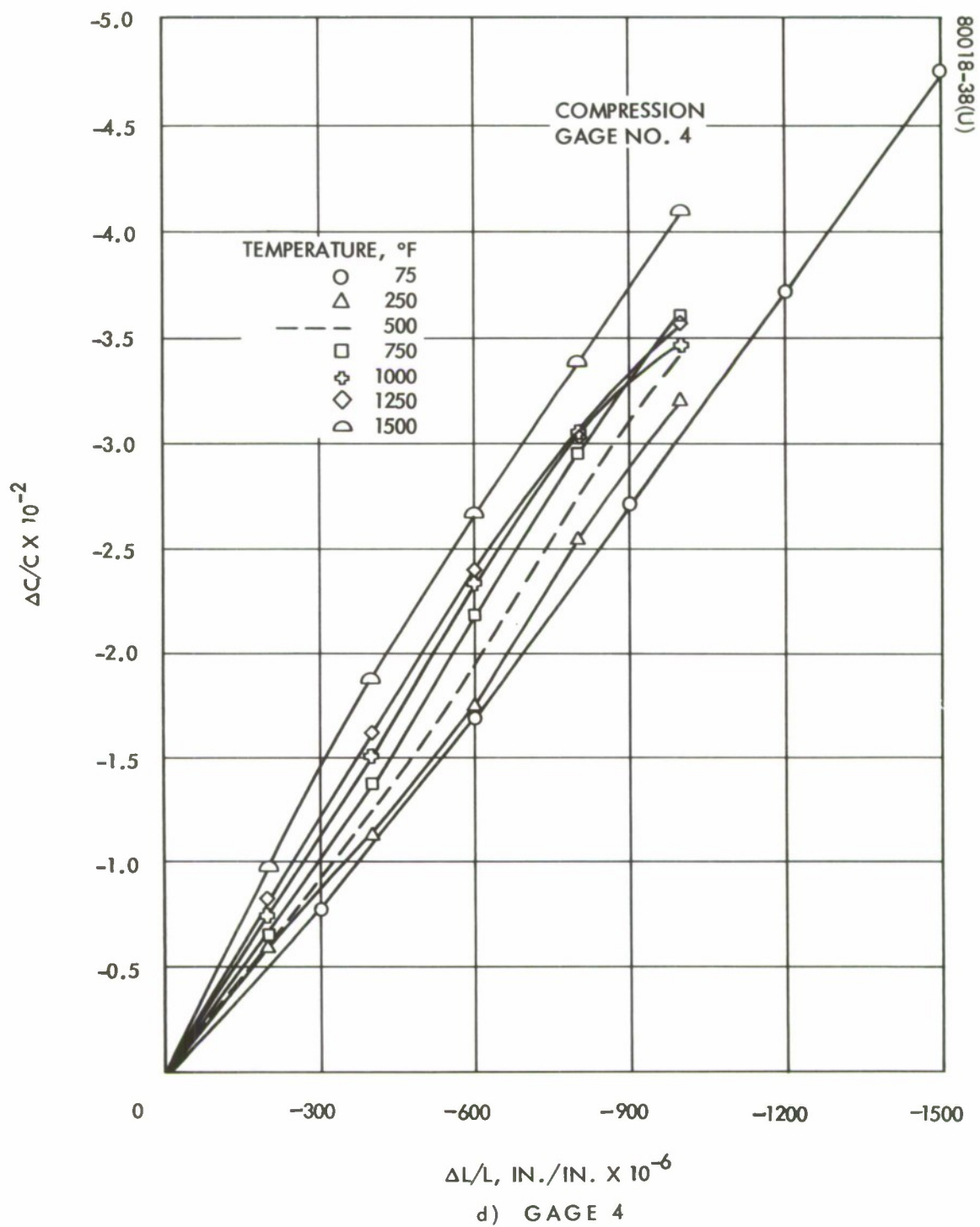


Figure 27 - Continued

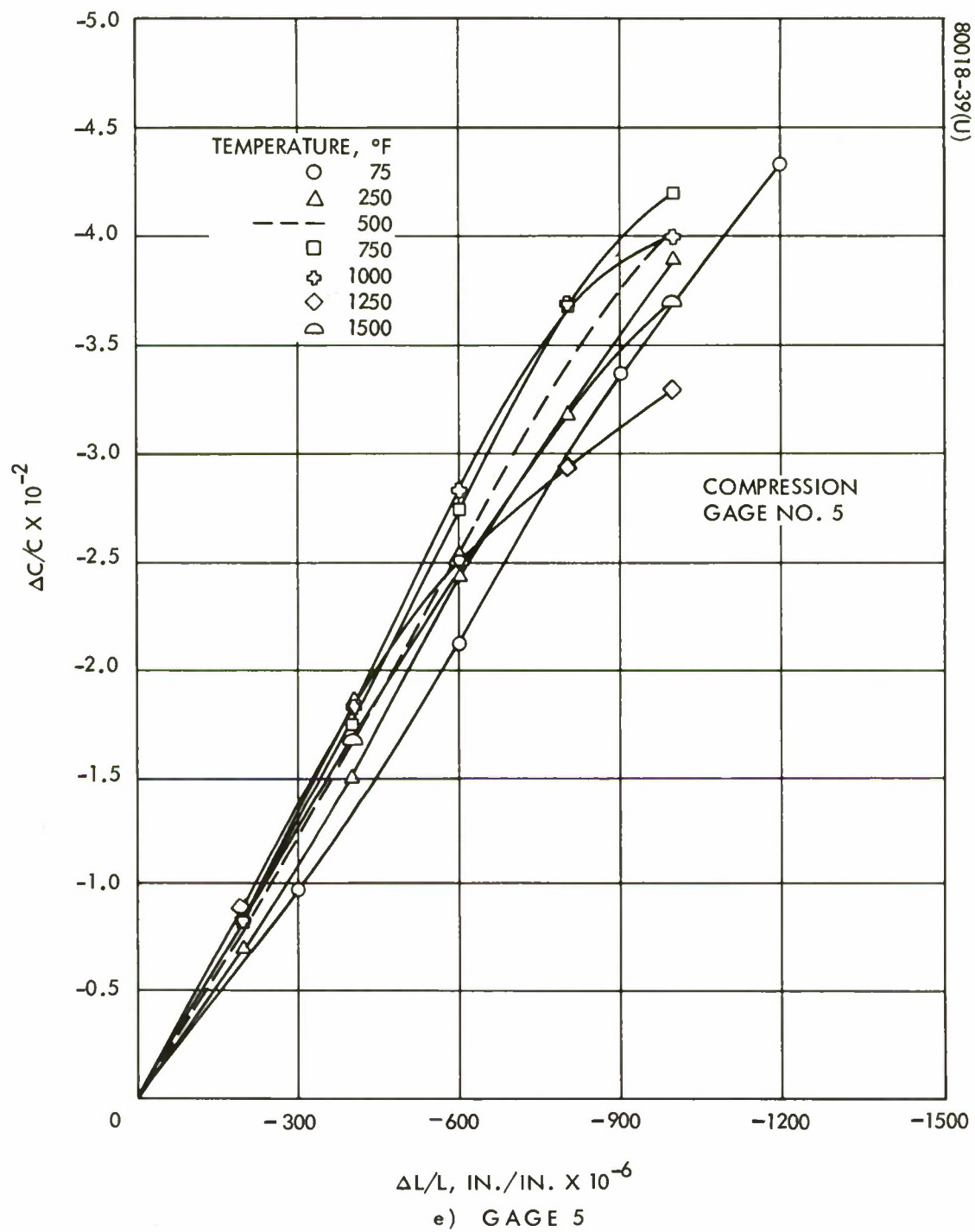
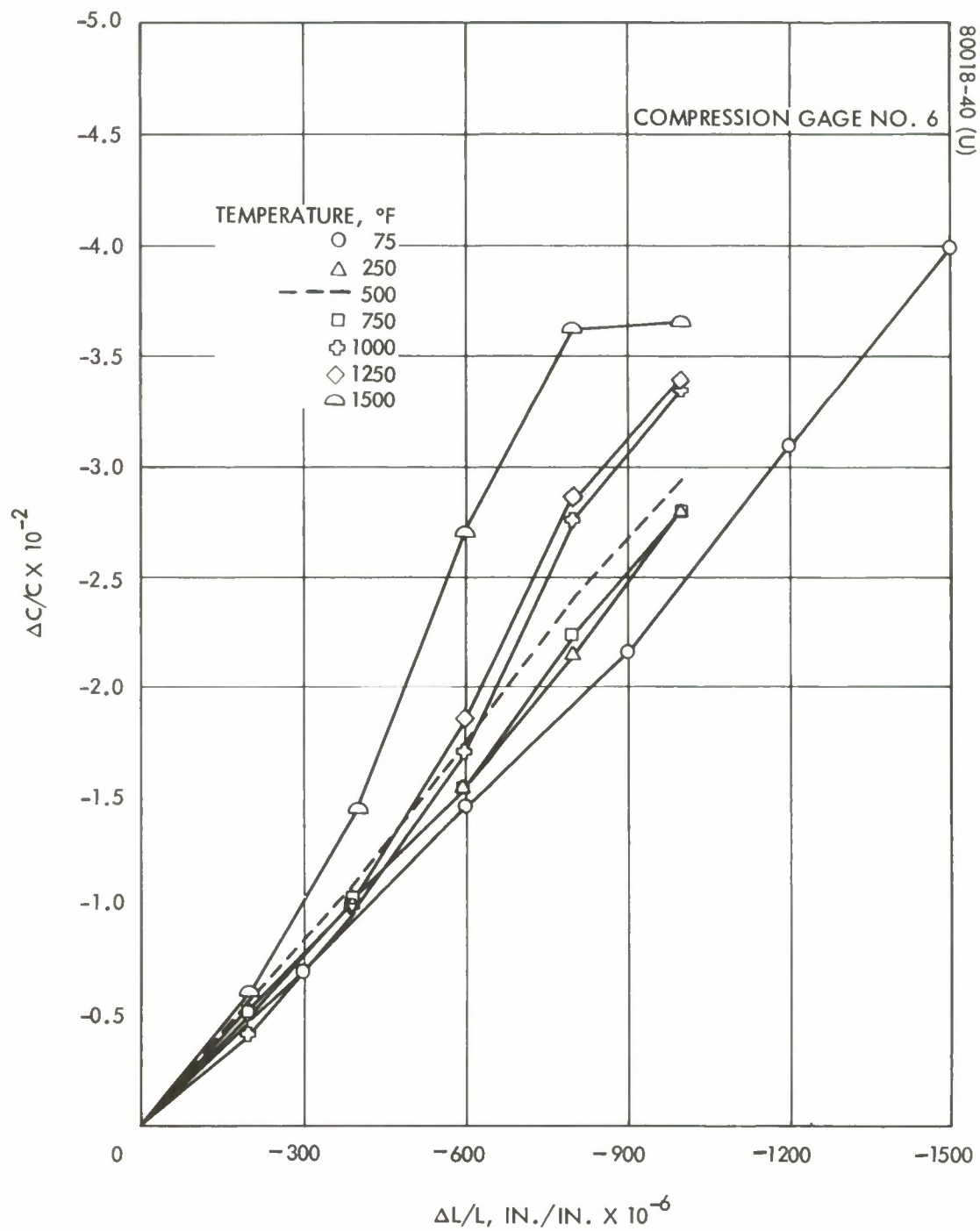


Figure 27 - Continued



f) GAGE 6

Figure 27 - Concluded

SECTION X

SUMMARY AND CONCLUSIONS

The performance of the high temperature capacitance strain gage as developed to date has shown it to meet most of the requirements of the target specification. The most notable exceptions are its gage to gage repeatability in gage factor, the effects of temperature on the gage factor, and apparent strain. This appears to be a manufacturing problem which can probably be solved with more rigorous controls and procedures. While this nonrepeatability, gage to gage, of the capacitance gage is a drawback for use as a strain gage, according to the accepted procedures of the state of the art today, use of the gage as a transducer will eliminate these disadvantages. The capacitance gage has shown itself to be repeatable on a run to run basis. The gage has also demonstrated its ability to be installed, calibrated, removed, and reinstalled with the ability to repeat the original calibration. Use of the gage as a transducer therefore offers the greatest potential today. The incorporation of the rhombic frame has therefore allowed for this calibration by providing a reusable configuration. It has also allowed for correction of the apparent strain when installed on any specific material. A second examination can be made of the high temperature capacitance strain gage when used as a transducer by comparing it with the target specification. This has been done in Table V.

This gage is not a cureall. Capacitance is considerably more difficult to measure than resistance. However, the state of the art today does allow measurement of changes in capacitance of as low as 0.02 picofarad, which is equivalent in this gage to approximately ± 50 microstrain. With strain readings of 1000 to 2000 microstrain, this is equivalent to accuracies of from $\pm 2\frac{1}{2}$ to 5 percent. Care must be taken in the installation of the gage, in the use of shielding, and lead wires. However, the gage is apparently insensitive to bending effects and can be used without corrections as long as the material stays within the elastic limit. The evaluation was conducted on a welded configuration; however, it is adaptable to other bonding techniques such as flame spraying.

No correlation could be made with the test results and the warpage noted on the gages. It is felt that more accurate measurements are needed in quality control and that a strict rejection criteria could possibly eliminate some of the gage-to-gage nonrepeatability.

In summary, the capacitance gage is repeatable and accurate, in its present configuration, to within ± 5 to 10 percent of the readings at temperatures up to 1500 °F as long as the necessary precalibration is performed. This gage has made a considerable step forward in the state of the art. It provides for the first time an accurate means of measuring static strains in the 1000 to 1500.F temperature range.

TABLE V. PERFORMANCE SUMMARY – HIGH TEMPERATURE
CAPACITANCE STRAIN GAGE

Item	Requirement	Performance
Gage length	< 1 inch	1 inch
Gage capacitance	$10 < C < 100$ picofarad	$11 < C < 16$ picofarad
Gage factor	25	~25
Repeatability	± 2 percent/100°F	± 5 percent overall
Gage factor change with temperature	± 2 percent/100°F	± 4 percent/100°F
Strain limit (1500°F)	$\pm 5000 \mu \text{ in/in}$	+5000 -2000
Drift rate	$900 \mu \text{ in/in/hr}$ at 1500°F	$100 \mu \text{ in/in/hr}$ at 1500°F
Minimum resistance to ground	10 meg Ω	N.C.
Apparent strain	$5 \mu \text{ in/in/}^\circ\text{F}$	$< 5 \mu \text{ in/in/}^\circ\text{F}$ at 1500°F
Maximum zero shift	$< 50 \mu \text{ in/in}$	$< 50 \mu \text{ in/in}$

REFERENCES

1. M.C. McGregor, et al, "New Apparatus at the National Bureau of Standards for Absolute Capacitance Measurement", IRE Transactions, December 1958.
2. J.F. Hersh, "A Close Look at Connection Errors in Capacitance Measurements", General Radio Experimenter, Volume 33, No. 7, July 1959.
3. G.A. Campbell, "Direct Capacity Measurement", Bell System Tech. Journal, Volume 1, July 1922.
4. F.K. Harris, Electrical Measurements, chapter 15, Wiley, 1952.
5. A.M. Thompson, "The Precise Measurement of Small Capacitances", IRE Transactions, December 1958.
6. C. Camillo, "Flexible Coaxial Cable Takes 1000°F", Electronics, Page 64, June 26, 1959.
7. Edward B. Baker, "Automatic Measurement Computation and Recording of Dielectric Constant and Loss Factor Against Temperature", Review of Scientific Instruments, Volume 22, No. 6, June 1951.
8. ASTM Standard, Vol. 9, D150-54T "AC Capacitance Dielectric Constant and Loss Characteristics of Electrical Insulating Materials".

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13. ABSTRACT This report describes the research and development of a high temperature capacitance strain gage. The investigation consisted of a material and configuration study followed by a manufacturing and evaluation phase. The final configuration was a stress frame with a capacitor element composed of stainless steel plates and mica dielectric insulators. The overall size of the stress frame was 1 by 1 by 0.1 inch. Of the 40 sensors constructed, 15 were evaluated and 25 were delivered to the Air Force Flight Dynamics Laboratory. The gages were tested from 75 °F (24 °C) to 1500 °F (816 °C) on a constant moment bending beam with strains up to 0.0015 inch per inch. From the results obtained it can be concluded that the developed capacitance gage provides a positive and accurate means of measuring strain at temperatures up to at least 1500 °F (816 °C). Not all of the contract target specifications were met but the unique configuration of the gage allows for precalibration which does provide a gage that outperforms the intent of the target specifications in every respect. Distribution of this abstract is unlimited.			

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
strain gages high temperature capacitance capacitance measurements dielectric material						