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RESEARCH AND DEVELOPMENT
OF A
HIGH TEMPERATURE
CAPACITANCE STRAIN GAGE
FOR
OPERATION AT 2000°F

O. LARRY GILLETTE
HUGHES AIRCRAFT COMPANY

TECHNICAL REPORT AFFDL-TR-71-103

OCTOBER 1971

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AIR FORCE FLIGHT DYNAMICS LABORATORY
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

TASK 317007-004

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FOREWORD


This research and development program was performed by the Technology Division of the Space and Communications Group, Hughes Aircraft Company, El Segundo, California, under Air Force Contract No. F 33615-70-C-1181. The contract was initiated under Project 3170, "Flight Dynamics Laboratory Instrumentation," Task 317007, "Development of Structural Test Instrumentation."

The work was supervised and directed by O. L. Gillette, Program Manager. This report was prepared by Mr. Gillette. This project was initiated by the Air Force Flight Dynamics Laboratory and was administered under the technical coordination of J. L. Mullineaux, AFFDL/FBT.

The high temperature capacitance strain gages were developed, fabricated, and tested by the Structural Test Section of the Engineering Mechanics Laboratory, Technology Division, Hughes Aircraft Company. Acknowledgment is also given for the helpful assistance and technical guidance provided by L. E. Vaughn, Supervisor, Structural Test Laboratory, R. J. Mondragon and N. Svalina, Research Assistants.

This document was submitted by the author in June 1971. The report covers work conducted from February 1970 to June 1971 and is the final report under Contract F 33615-70-C-1181. The Contractor's report number is SCG 10273R.

This technical report has been reviewed and is approved.


Robert L. Cavanagh
Chief, Experimental Branch
Structures Division
Air Force Flight Dynamics Laboratory

AD-745449

This report describes the research and development of a high temperature capacitance strain gage. The investigation consisted of a materials, configuration, and attachment study; a cable evaluation; and a manufacturing and evaluation phase. The final configuration was a rhombic strain frame with a capacitor element composed of Inconel plates and mica dielectric insulators. The overall gage length was 1/2 inch. A total of 50 sensors were constructed; 25 were tested at Hughes and 25 were delivered to the Air Force Flight Dynamics Laboratory. The gages were tested from 75°F (24°C) to 2000°F (1093°C). From the results obtained, it can be concluded that the capacitance gage provides a positive and accurate means of measuring strain at temperatures up to 1750°F (954°C). Under specified conditions, some data can be obtained at reduced accuracies at temperatures of 2000°F (1093°C).

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1. INTRODUCTION

High speed aircraft, missiles, and space vehicles are subjected to stresses generated by the combined actions of aerodynamic forces and temperature gradients. During the developmental and qualification testing of these structures in the laboratory with simulated mechanical and thermal loads, it is necessary to determine the stresses at many critical locations. Since it is not easy to obtain stress directly, strain is generally the measured parameter. Therefore, the structures test laboratory must have a dependable, remote reading strain gage which will operate under static or quasi-static mechanical loads in conjunction with static or transient thermal environments up to and including 2000°F (1093° C).

In February 1970, Hughes Aircraft Company began development of a high temperature capacitance strain gage to meet the objectives. This program required 1) research of dielectric and metallic components to determine the optimum materials to meet the requirement, 2) study of attachment techniques for various structural materials, 3) investigation of cables to withstand the temperature, 4) manufacture of high quality strain gages in sufficient quantity to permit evaluation, 5) provision of a test plan and procedure for evaluation, and 6) adequate testing to determine gage-to-gage and cycle-to-cycle characteristics. This program was funded under Air Force contract F33615-70-C-1181. The work performed and reported herein was based on earlier work accomplished at Hughes Aircraft Company and reported in an Air Force Flight Dynamics Technical Report AFFDL-TR-68-27, April 1968 (Reference 1).

The primary objectives of this program were to expand the useful temperature range of the capacitance strain gage (Reference 1) and to reduce its size from a 1 inch gage length to a 0.5 inch gage length.

2. TARGET SPECIFICATION

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

- 1) The maximum gage length or width shall not exceed one half inch.
- 2) The gage capacitance shall be between 10 and 50 picofarads (reproducible within 2 percent gage-to-gage).
- 3) The gage factor $(\Delta C/C)/(\Delta L/L)$ shall not be less than 25 (reproducible within 10 percent gage-to-gage).
- 4) The gages shall have a predictable and repeatable gage factor change with temperature cycling. The gage factor shall not vary more than 5 percent from the room temperature gage factor at temperatures less than 1000°F (538°C) or 10 percent at temperatures above 1000°F (538°C).
- 5) The maximum gage factor variation, gage-to-gage, shall be 2 percent per 100°F.
- 6) The strain limit at 1500°F (816°C) shall be ± 0.5 percent (5000 microstrain). The strain limit at 2000°F (1093°C) shall be ± 0.2 percent (2000 microstrain).
- 7) The drift rate (change of output at constant temperature) shall not exceed 300 microstrain per hour.
- 8) The minimum resistance to ground shall be 10 megohms at 2000°F (1093°C).
- 9) The apparent strain (temperature sensitivity) shall not exceed 5 microstrain per °F at the maximum heating rate.
- 10) The bond curing 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 microstrain.
- 12) The output due to thermoelectric effects shall not exceed 0.2 millivolts at 2000°F (1093°C).
- 13) The maximum temperature rise rate on the gages shall be 10°F per second.
- 14) The maximum continuous time at 2000°F (1093°C) shall be 30 minutes.
- 15) The gages shall operate at frequencies from 1 kilohertz to 1 megahertz.

3. GAGE CONFIGURATION

The basic gage configuration developed in Reference 1 was a parallel plate capacitor with a variable gap held in a rhombic frame. This gage had a 1 inch gage length and an area of 0.50 square inch. It was desirable to reduce the gage length to 0.50 inch and the area to 0.125 square inch.

An analytical study was undertaken to determine the most promising gage and frame configurations. Each configuration was assigned a merit figure based on its analytical gage factor. The following configurations were evaluated:

Gage Configurations


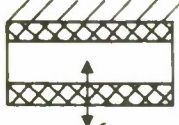
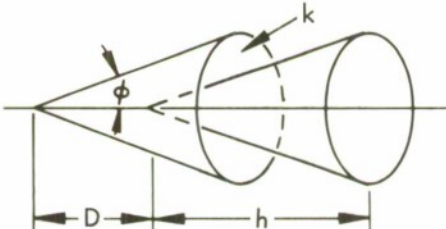
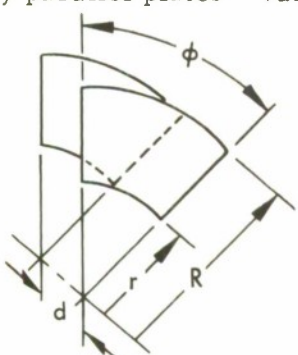
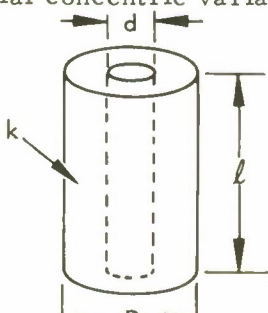
- 1) Parallel plate
 - a) Rectangular plate, variable area
 - b) Triangular plate, variable area
 - c) Variable gap
- 2) Coaxial cones, variable gap/area
- 3) Rotary parallel plates, variable area
- 4) Coaxial concentric, variable length

Frame Configurations

- 1) Rhombic strain frame 1
- 2) Rhombic strain frame 2
- 3) Circular strain frame

The merit number was calculated on the basis of a unit change in capacitance, $\Delta C/C$, as a function of a unit change in length or strain, $\Delta L/L$. It was assumed that all the strain would be seen by the sensing element. All numbers were calculated on the basis of a strain of 1000 microinches per inch. The comparison of the gage configurations is shown in Table I.

TABLE I. COMPARISON OF GAGE CONFIGURATIONS

Configuration	Capacitance Formula	Merit Number (K)
<p>1a) Parallel plate variable area</p>  <p>rectangular plate</p>	$C = \frac{kA(n-1)}{3.6 \pi t}$ <p>k = dielectric constant A = plate area n = number of plates t = distance between plates</p>	<p>K = 1</p>
<p>1b) Triangular plate variable area</p>	<p>Same as 1a</p>	<p>K = 2</p>
<p>1c) Parallel plate variable t</p> 	<p>Same as 1a</p>	$K \approx \frac{1}{(n+1)t}$
<p>2) Coaxial cones variable D</p> 	$C = \frac{1.41 h}{\log \left[1 + 2 \frac{D}{h} \cos^2 \theta \right]}$	<p>Assume: h = 0.5 inch D = 0.010 inch theta = 20 degrees Delta D = 0.001 inch</p> <p>then K = 99.6</p>
<p>3) Rotary parallel plates - variable A</p> 	$C = \frac{0.00196 k(R^2 - r^2) \phi}{d}$	<p>K = 1</p>
<p>4) Coaxial concentric variable length</p> 	$C = \frac{0.614 k l}{\log D/d}$	<p>K = 1</p>

Using the configuration shown in 1c, (parallel plate, variable gap) and assuming a four-plate sensing element, a curve can be developed by gage factor (merit number) versus the thickness of the gap between plates. This curve is shown in Figure 1. From this curve it can be seen that a gap of 5 mils will produce a gage factor of 40, assuming that all the strain of a 1 inch gage length is seen across the sensor.

In order to assure that the sensing element sees the strain of a 1 inch gage length, a strain frame must be used. Several strain frames were evaluated analytically as listed above. The strain frame used in Reference 1 will produce a sensitivity (amplification) as a function of the included angle of the frame and the ratio of the gage length to the frame gap (L/X). This produces the family of curves shown in Figure 2. The dashed line represents a $\theta/2$ of 45 degrees, which is representative of the frames used in Reference 1. The equation for sensitivity of this frame can be reduced to:

$$\text{Sensitivity} = \frac{\Delta X/X}{\Delta L/L} \approx \frac{L}{X} \cdot \cot \frac{\theta}{2} = K_1 \quad (1)$$

In the case where $\theta/2$ is equal to 45 degrees, the sensitivity reduces to L/X. A second frame design evaluated is shown in Figure 3. The sensitivity of this design is

$$\text{Sensitivity} = \frac{\Delta X_2/X_2}{\Delta L_2/L_2} = \frac{L}{X} \cos \frac{\theta}{2} \left(2 + \frac{\Delta \ell}{\ell} \right) = K_2 \quad (2)$$

and assuming a $\theta/2$ equal to 45 degrees, the sensitivity of frame 2 with respect to frame 1 is

$$\frac{K_2}{K_1} = 0.707 \left(2 + \frac{\Delta \ell}{\ell} \right) \approx 1.4 \quad (3)$$

It is important to note that this second frame design will produce either positive or negative deflections with a strain expansion, depending on which corners are strained.

A third strain frame evaluated was a circular frame whose sensitivity was $K_C = -0.92 D/X$, where D is the diameter of the frame. The minus sign indicates a sign reversal between the strain $\Delta L/L$ and the strain at $\Delta X/X$. It can be seen from the above equation that the circular frame is less efficient than either of the rhombic frames.

Based on the analysis of the sensors and frames, the parallel plate capacitor with a variable gap and rhombic frames were selected as the best possible candidates for the final gage configuration.

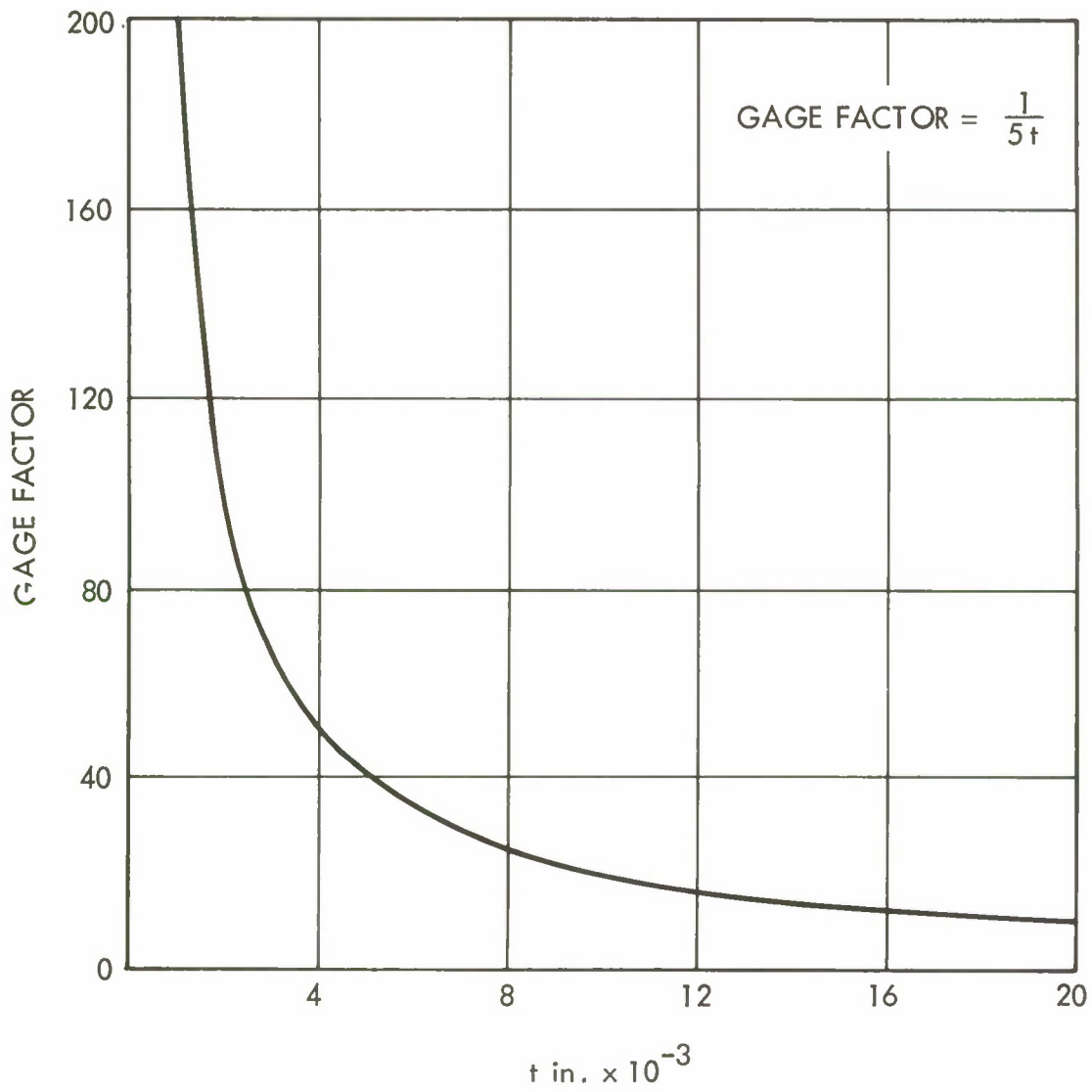


Figure 1. Gage Factor Versus Variable t

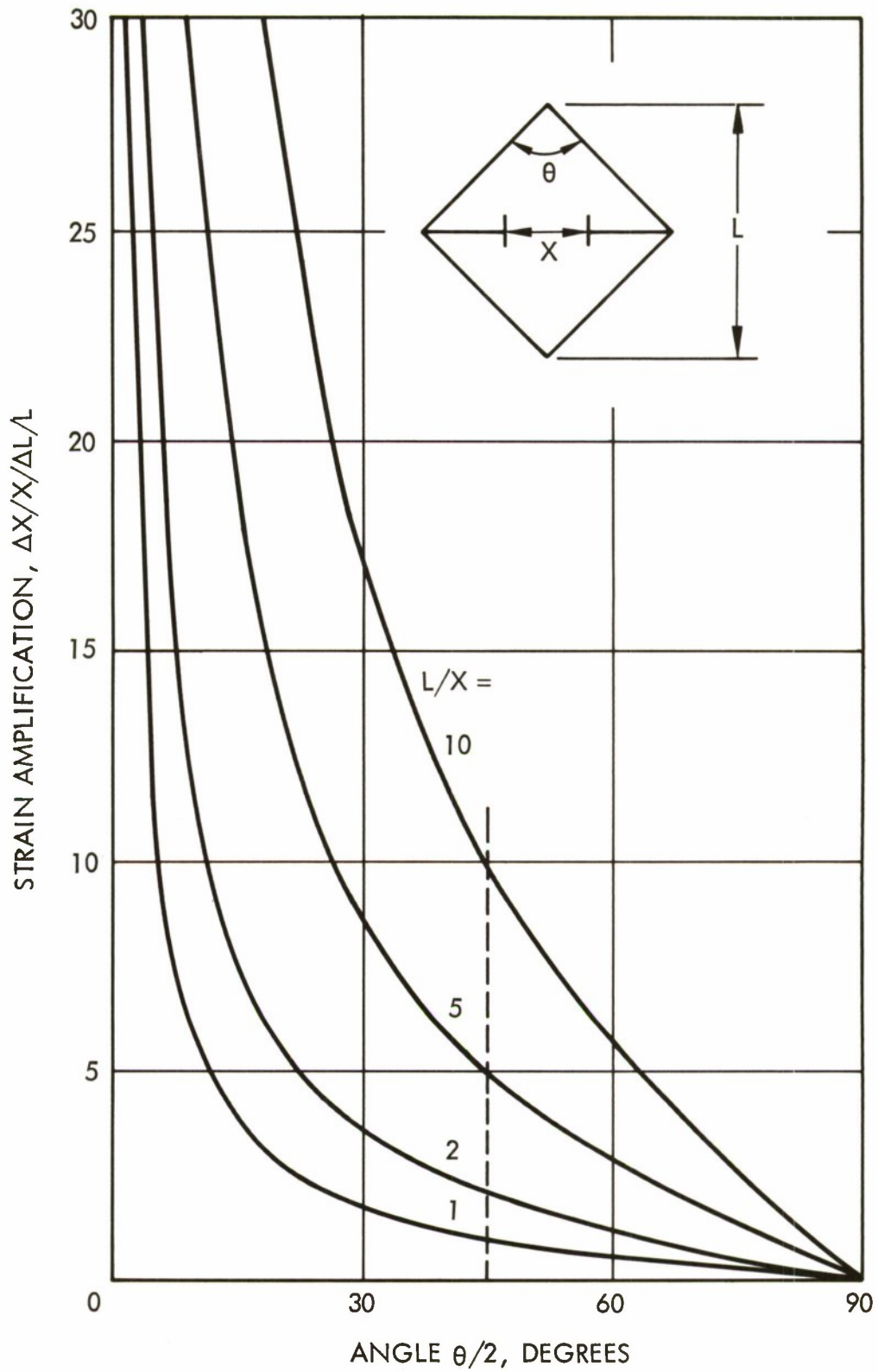


Figure 2. Rhombic Strain Frame No. 1 Amplification

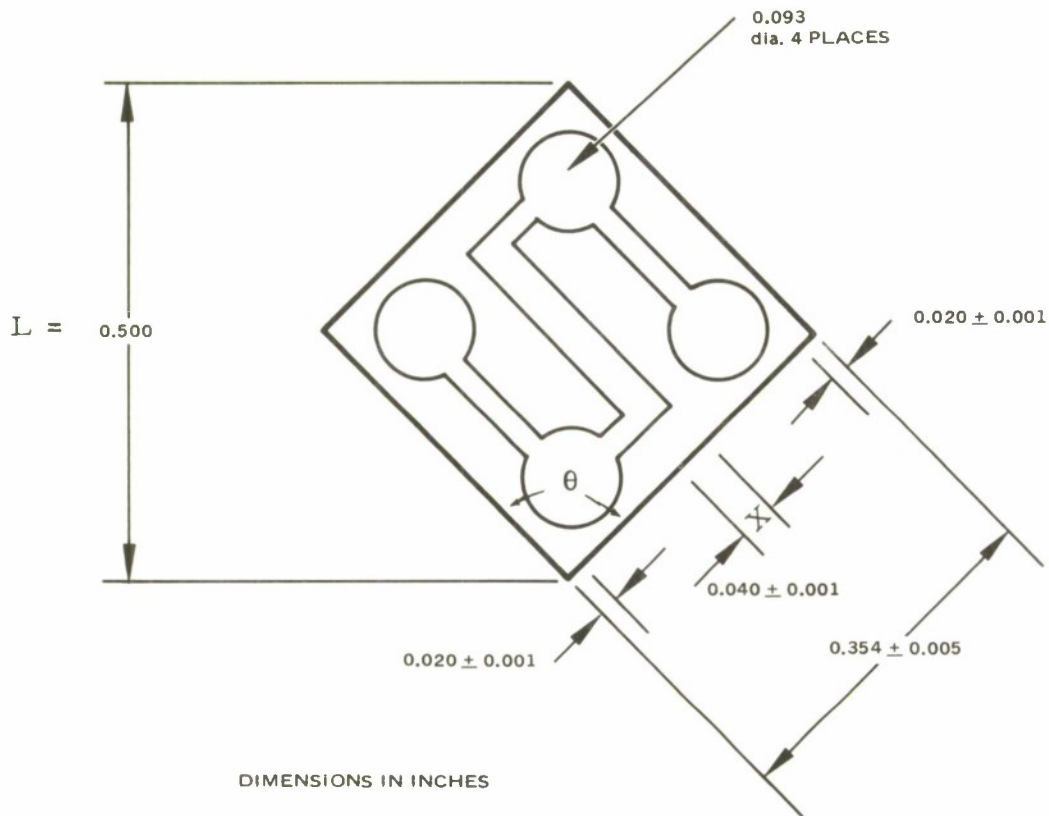


Figure 3. Rhombic Frame No. 2

In order to confirm the analysis and to develop more data on the effect of gage variables, 12 experimental gages were constructed and tested. Results indicated that the 1 inch gage length of rhombic frame 1 was the most stable and rhombic frame 2 was a close second but with greater sensitivity.

Rhombic frame 2 also performed well with a 3/4 inch gage length and a 1/2 inch gage length. Based on results of these tests, it was decided to standardize on a gage length of 1/2 inch, using rhombic frame 2.

4. MATERIAL STUDY

A material study was conducted to determine the dielectric properties of candidate dielectric materials as a function of temperature and frequency. The materials selected for evaluation on the basis of literature search were:

- 1) Air
- 2) Mica (phlogopite)
- 3) Silica
- 4) Titania (titanium oxide)
- 5) AD 99 (alumina)
- 6) Glasrock
- 7) Barium titanate

Of these materials, mica, Glasrock, silica, and AD 99 were the only materials providing usable results at 2000°F. The other materials all exhibited low resistance values at temperatures between 1400°F and 1650°F, which prevented measurement of capacitance at higher temperatures.

Of these materials, mica and Glasrock still looked like the best dielectric for strain gage use at 2000°F. Mica was the preferred material because of its relative ease in handling and was used as the dielectric material in the final gage configuration.

The dielectric properties of the material evaluated as a function of temperature is plotted in Figure 4.

The effect of frequency is shown in Figure 5. The effect of frequency on the dielectric property as a function of temperature appears to be minimal except for a small perturbation at elevated temperatures and at frequencies below 50 kHz.

During this phase of the program, the following materials were also selected for the attachment evaluation and for use as the base structure material:

- 1) Super alloy - L605
- 2) Dispersion strengthened material - TD Nichrome
- 3) Coated refractory - niobium with a sylvor coating.

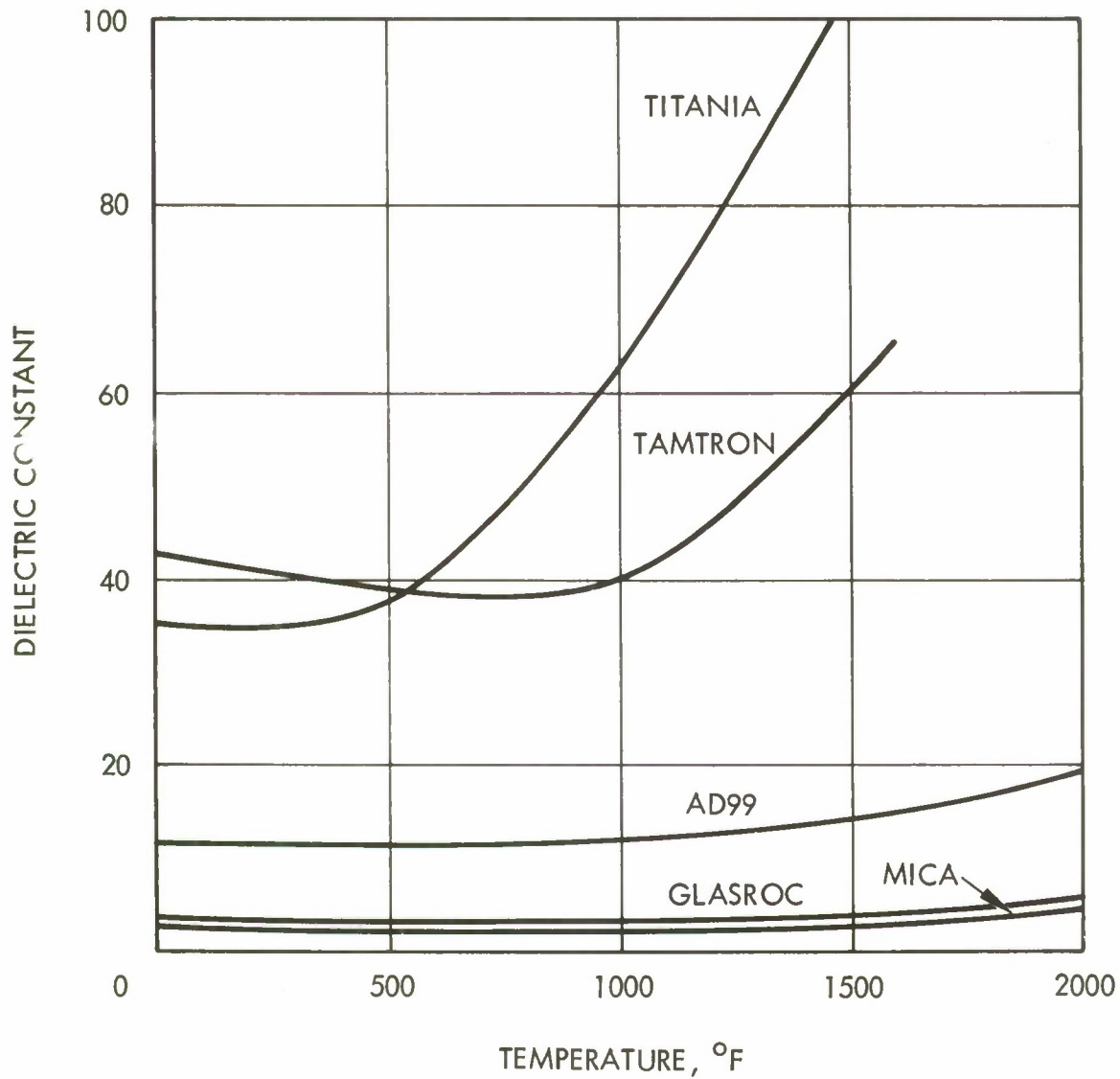


Figure 4 .. Dielectric Properties Versus Temperature

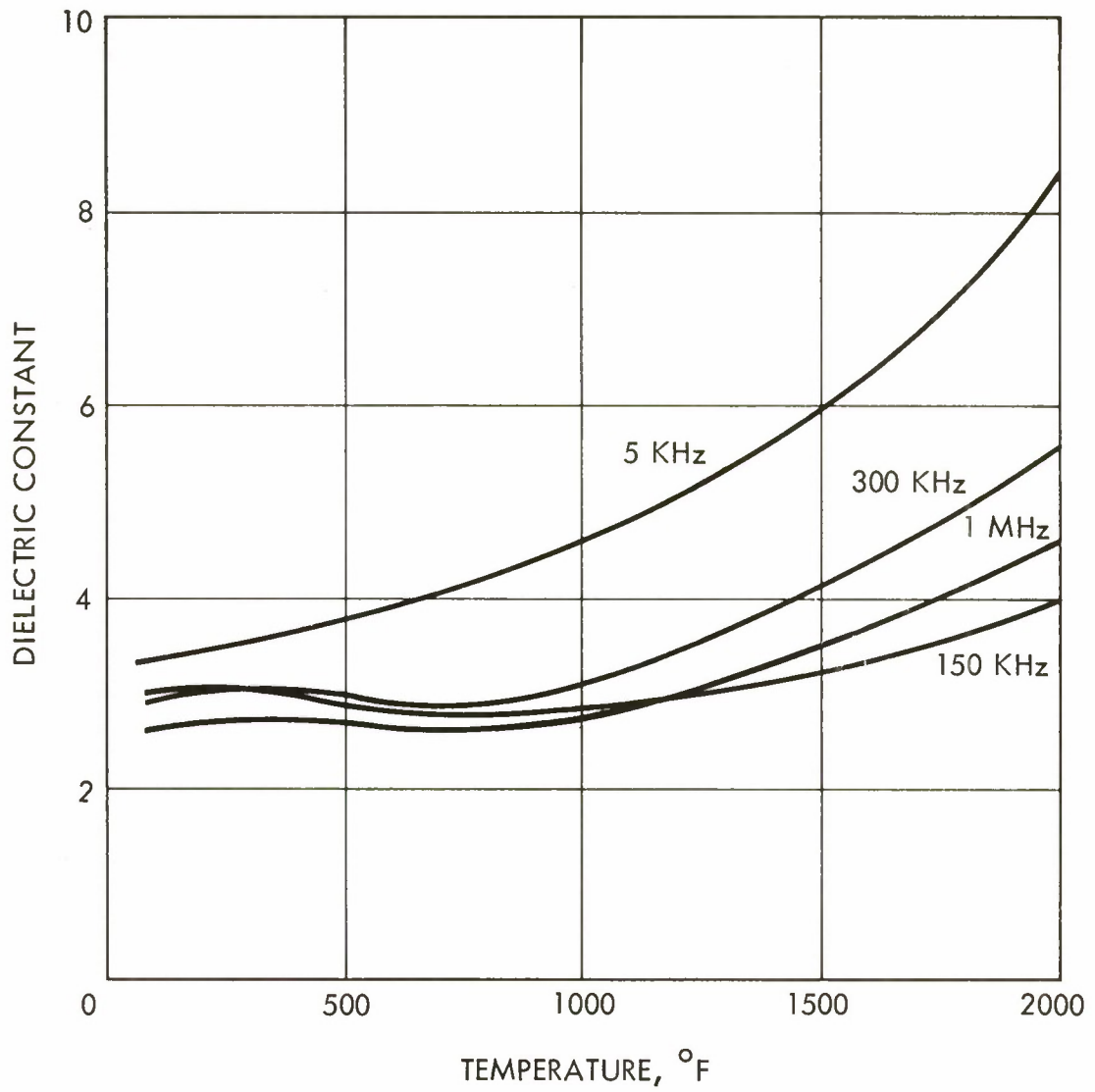


Figure 5 . Frequency Versus Temperature Effects on Dielectric Properties of Mica

5. ATTACHMENT TECHNIQUES

One serious problem facing the strain gage user when he is attempting to measure strains at very high temperatures is the problem of attaching the strain sensor. These problems are aggravated by the fact that many of the base materials must be coated to prevent serious oxidation or other chemical reactions from occurring at the elevated temperatures. Another contributing circumstance is that welding the gage in many cases creates a secondary fatigue problem.

Over 20 different attachment configurations were evaluated. The techniques and configurations can be grouped into three different classifications:

- 1) Welded attachment
- 2) Flame sprayed attachment
- 3) Bonded attachment

The 20 configurations are shown in Figure 6. The attachment techniques were all evaluated on all three of the base materials selected for capability tests. The three materials were TD-Nichrome, L605, and coated niobium. The niobium material was coated with Sylvania sylcor coating. The specimen attachment techniques were all made by using 302 stainless steel ribbon 0.30 inch wide and 0.005 inch thick to simulate the attachment tabs of the strain frame. The specimen was brought up to test temperature (70°F, 1000°F, 1500°F, and 2000°F) and a shear test was conducted on the joint. In order to conserve the coated niobium material, survey tests of configurations 12 and 13 were conducted on stainless steel coated with Metco 450.

WELDED ATTACHMENT

Nine different spot weld groupings were evaluated. In the case of the niobium base material, two basic techniques were evaluated: first, scraping the sylcor coating from the niobium and then welding the ribbon to the base material; second, coating the sylcor with a flame spray coating of Metco 450 nickel aluminum and then welding to the coating. All of the weld techniques proved to be adequate for use as a strain gage attachment. A minimum shear strength of 80 psi at 2000°F was established as a requirement for this study. This was based on a 4.8 pound load and a shear area of 0.06 inch.

ATTACHMENT CONFIGURATION

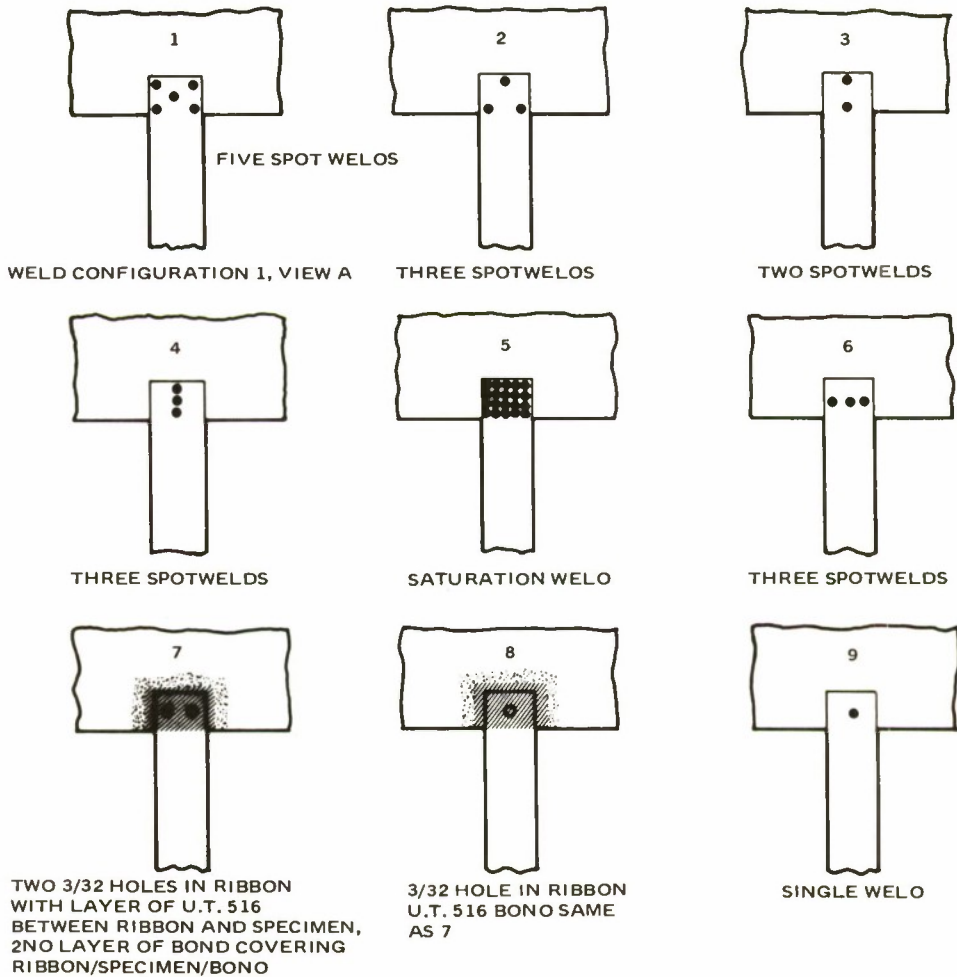
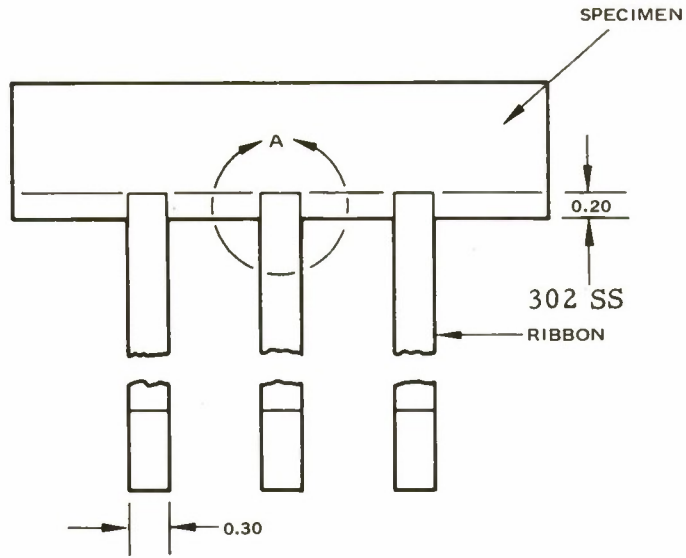
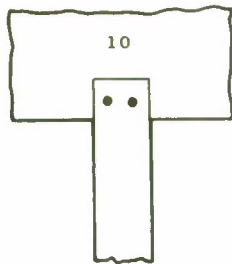
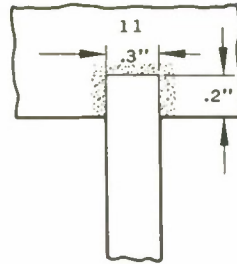


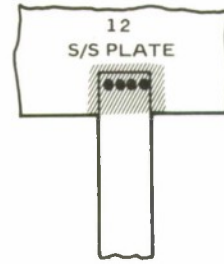
Figure 6. High Temperature Strain Gage Attachment



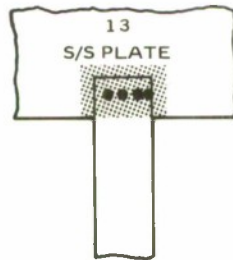
10
TWD WELDS SIDE BY SIDE



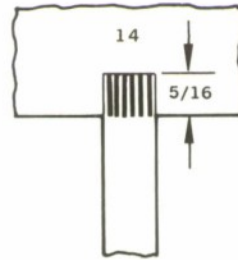
11
S/S RIBBON BONDED TO BASE MATERIAL WITH ND. 29 SAUERISEN



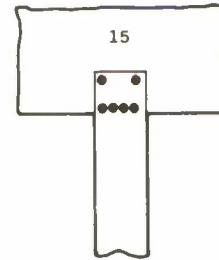
12
S/S PLATE
FIRST A THIN COAT OF NICKEL ALUMINUM TYPE 450 WAS FLAME SPRAYED ON S/S PLATE. THEN NICKEL ALUMINUM WAS SANDED SMOOTH AND RIBBON WELDED TO NICKEL ALUMINUM AT 35 w-sec.



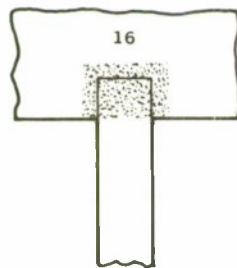
13
S/S PLATE
FIRST METCD 105 CERAMIC THEN NICKEL ALUMINUM WAS FLAME SPRAYED, THEN RIBBON WAS WELDED TO NICKEL ALUMINUM AT 35 w-sec.



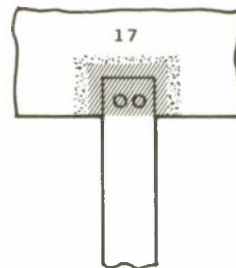
14
5/16
0.30 INCHES S/S RIBBON SPLIT INTO 6 PARTS AT ATTACHED END BONDED WITH U. T. 516



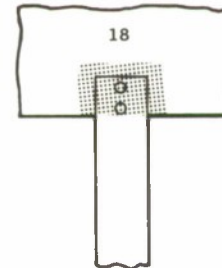
15
6 SPDTWELDS



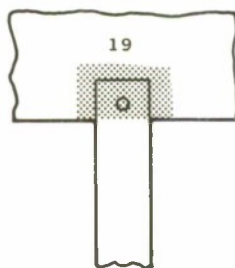
16
BOND WITH U.T. 516



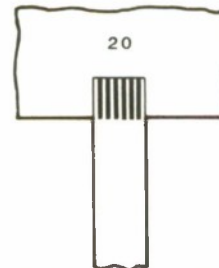
17
SAME AS 7 EXCEPT FLAME SPRAYED WITH METCD 450



18
2 HDLES IN SERIES FLAME SPRAYED WITH METCD 450



19
SAME AS 18 WITH ONLY 1 HDLE



20
SAME AS 14 EXCEPT FLAME SPRAYED WITH METCD 450

Figure 6. (Continued) High Temperature Strain Gage Attachment

FLAME SPRAY ATTACHMENT

The flame spray attachments were all made using the Metco flame spray gun and spray materials. The most successful spray technique was configuration 18 (Figure 6). This consisted of a thin precoat spray of the base material using the Metco 450 material. Two $3/32$ inch holes were stamped in the end of the stainless steel ribbon and the ribbon was then taped in place on the base material. A coating of about 10 to 15 mils was then sprayed over the ribbon, filling the holes. This technique proved to be very successful at the 2000°F test temperature.

BONDED ATTACHMENT

A number of different adhesives were evaluated as attachment agents. The materials evaluated were:

- 1) Sauerizen 29
- 2) Ultra Temp 516
- 3) Allen P-1

These materials were selected on the basis of a literature search. The adhesives were evaluated at room temperature and Ultra Temp 516 was selected as the best adhesive. Based on this selection, tests were conducted on the 516 material at 2000°F.

A comparison of the results of the three attachments studied is shown in Figure 7, where all three methods were satisfactory on the TD-Nichrome material with only the bonding method dropping out on the L-605 and niobium materials. The flame spray method appears to be the strongest attachment. Welding is the preferred attachment method because of its ease of application. However, it appears that some oxidation occurred on the welded specimens, which would have reduced their strength. The flame spray method would be used only when welding would not be permissible because of a fatigue environment or for some other reason.

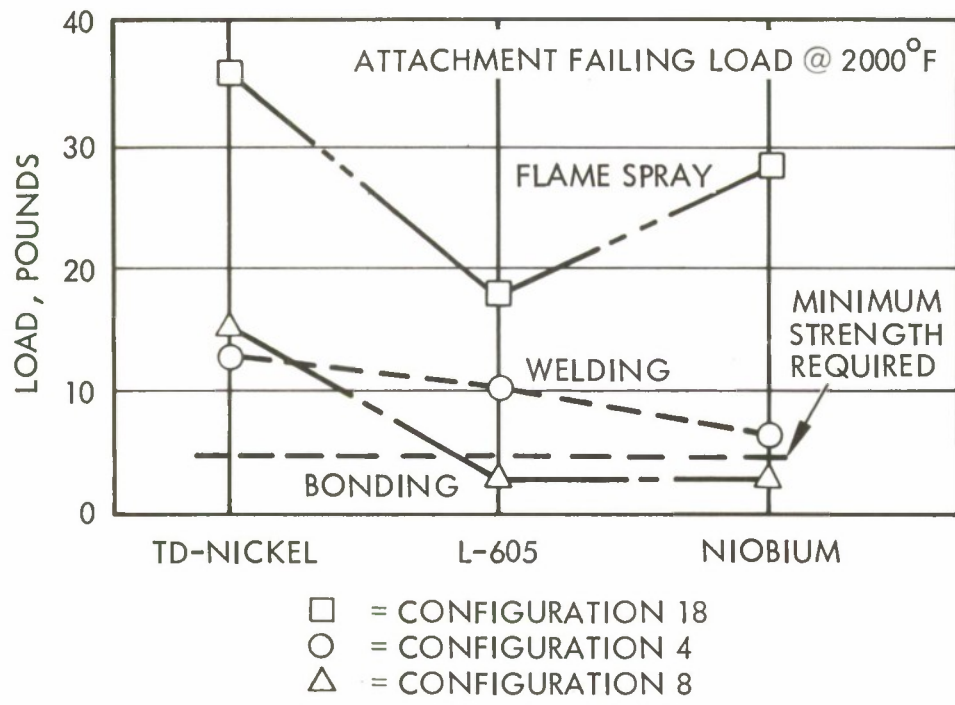


Figure 7. Comparison of Attachment Methods

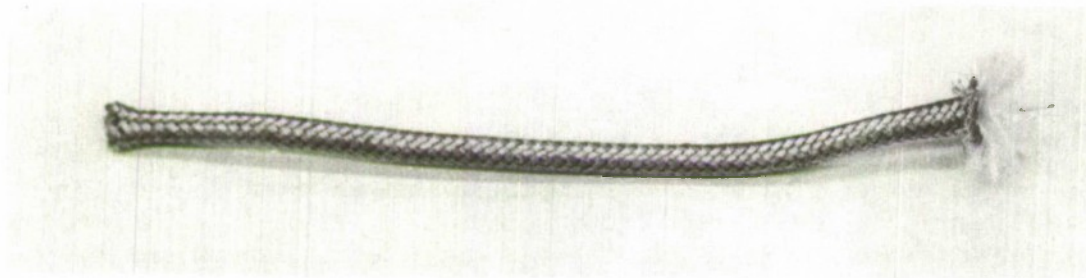
6. CABLE EVALUATION

The cable evaluation portion of this program was limited to a survey of commercial cable to select the best one available for the specific task. A literature search was conducted, which is summarized in Reference 2.

Four vendors were selected from the literature search on high temperature cables. Letters were sent to the vendors requesting information and assistance. All four vendors declined to comment or participate in a program requiring cables to operate at 2000°F.

A fifth vendor, Maser Rex Hi Temp Wire Company from Monrovia, California, submitted a sample of wire which they designed to our applications. This was a 0.020 inch stainless steel conductor insulated with G. E. quartz fiber and shielded with braided 304 stainless steel. The cable was exposed to repeated temperature cycles to 2000°F, where it was held at maximum temperature for 30 minutes. A photograph of the Maser Rex cable before and after temperature exposure is shown in Figure 8. The Maser Rex cable was used for all evaluation tests reported here.

The Maser Rex cable was found to remain flexible after repeated exposures to 2000°F. Its initial capacitance remained low enough not to affect the gage output, since it is essentially balanced out during the test setup (Reference 1).



HIGH TEMPERATURE CABLE BEFORE HEATING



HIGH TEMPERATURE CABLE AFTER 1 HOUR AT 2000 °F—STILL FLEXIBLE

Figure 8. High Temperature Cable

7. GAGE MANUFACTURE AND ASSEMBLY PROCEDURES

The gages manufactured in Reference 1 showed a wide spread in their initial capacitance. Gages varied from a high of 16.42 picofarads to a low of 11.17 picofarads. An analytical study was conducted to determine the variables affecting the initial capacitance and to determine what controls could be placed on these variables. This is a manufacturing quality control problem. Before a quality control program can be established it is necessary to know what parameters affect the gage performance, and the magnitude of the influence these parameters have on the gage accuracies.

The variable parameters have been grouped as follows:

Dimensional Tolerances

- 1) Gage length
- 2) Plate area
- 3) Dielectric thickness (d)
- 4) Strain frame gap (X)

Process Tolerances

- 1) Heat soak — heating rate
 - time at soak
 - maximum temperature
 - number of cycles

Electrical Properties Tolerances

- 1) Final gage configuration

DIMENSIONAL TOLERANCES

Gage Length

The measure of the influence of the gage length variations on performance is the gage factor (G. F.) where:

$$G. F. = \frac{\Delta C/C}{\Delta L/L} \quad (4)$$

where L is the gage length, since any change in L is accompanied by an equivalent change in ΔC . $\Delta L/L$ is the strain in the base structure and independent of the actual value of L (assuming a uniform strain field). Therefore the gage length variations will have no effect on the output as long as other parameters are not affected by the change in L.

Plate Area

The measure of the effect of initial deviation in plate area is the percent change in the initial capacitance, dC/C , where dC is the variation in capacitance and C is the mean or average capacitance. Assuming that the width of the plate remains constant and the height, h , is the variable, then:

$$\frac{dC}{C} = \frac{h_1 - h_2}{h_1} \quad (5)$$

where

h_1 = mean height

h_2 = actual height

Assuming

$$h_1 = 0.100 \text{ inch}$$

$$h_2 = 0.0995 \text{ inch}$$

then $dC/C = 0.005$, or 0.5 percent change in initial capacitance. On a 10 picofarad initial capacitance, deviations of 0.0005 inch in the plate height would produce capacitance changes of 0.05 picofarad.

Dielectric Thickness

Variation in the dielectric thickness affects both the initial capacitance and the gage factor of the gage. Since the capacitance is inversely proportional to the dielectric thickness

$$\frac{dC}{C} = \frac{d_2 - d_1}{d_2} \quad (6)$$

where

$$d_1 = \text{desired thickness} = 0.004$$

$$d_2 = \text{actual thickness} = 0.0043$$

The effect of dielectric thickness changes $\frac{dC}{C} = 0.07$, or 7% change in the initial capacitance. The effects of these variations are shown plotted in Figure 9. The plot is shown as a function of X where X can be taken as either the dielectric thickness (d), the height (h), or the width of the plate. From the family of curves in Figure 9, it can be seen that dimensional errors or variations on the order of 0.001 inch can produce large errors in the initial capacitance when the basic dimensions are small.

Strain Frame Gap

The effect of variation in the strain frame gap is to alter the preload in the sensing element. Tests were conducted to determine the effect of preload on the gage factor, linearity, and hysteresis. The preload consisted of interference fit of:

0.002 inch

0.003 inch

0.004 inch

0.007 inch

Tests were conducted in both tension and compression. A preload of 0.003 inch gave the best results of both linearity and the best average gage factor for tension and compression.

PROCESS TOLERANCE

Heat Soak

The heat soak or preheat cure gives the gage the only process variable. The heating rate, time at soak, maximum temperature, and the number of heating cycles are all independent variables of the heat soak. In order to establish a standard for the test gages, various combinations of heat soak were applied to five developmental gages of the 1/2 inch rhombic 2 design.

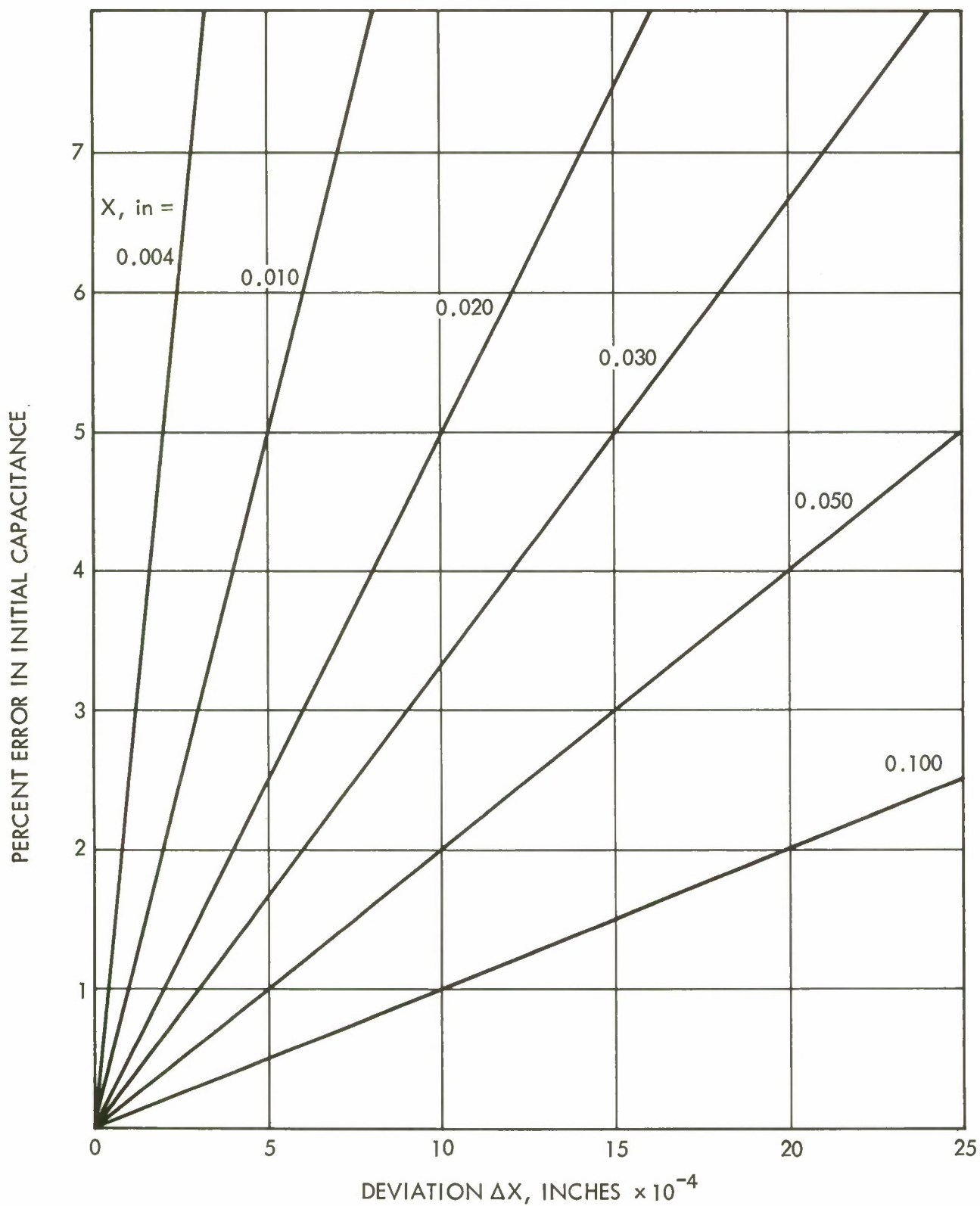


Figure 9. Dimensional Tolerances

The first gage was heated to 1500°F (816°C) and held at temperature for 30 minutes, then cooled to room temperature. This heat cycle was repeated three times with gage factor readings taken before and after each cycle. Gages 2 and 3 were heated to 1625°F (885°C) at different heating rates and held at temperature for 30 minutes, then cooled to room temperature. Again gage factor readings were taken before and after each run with the cycle being repeated three times. Gage 4 was heated to 1625°F (885°C) and held for 1 hour then cooled to room temperature and the gage factor was checked. Gages 2, 3, and 4 were then tested for gage factor versus temperature at room temperature, 1000°F (538°C), 1500°F (816°C), 1625°F (885°C), 1750°F (954°C), 1875°F (1024°C), and 2000°F (1093°C). A fifth gage was heat cycled to 2000°F (1093°C) three times, with maximum temperature being held for 15 minutes. Following the heat cure on gage 5, it was tested at ambient and elevated temperatures in the same manner as gages 2, 3, and 4.

Based on the results which showed the 1625°F (885°C) cure to be the most stable but limited in maximum temperature response, it was decided to split the 25 test gates into two groups as far as the heat cure was concerned. Twenty of the gages were heat cured at 1625 degrees, three cycles for 15 minutes each. The last five gages were heat cured at 2000°F, three cycles for 15 minutes each. The heating rate for all production gages was held at approximately 100°F/minutes, since the preliminary results of the 5 test gages indicated that temperature cycle was considerably more significant than heating rate or time at temperature.

ELECTRICAL PROPERTIES TOLERANCE

The electrical properties tolerances are measured properties unique to each configuration and were measured as accurately as allowed by the state of the art. Capacitances were measured to within 0.001 picofarad.

Final Gage Configuration

The final gage configuration (Figure 10) was constructed in two parts: the strain frame and the sensing element. The strain frame was a 1/2 inch gage length rhombic frame configuration number 2 made of TD Nickel. The frame had two welded stainless steel tabs at opposite corners which were in turn welded to the test part. The sensing element plates were constructed from Inconel shim stock. The dielectric was 4 mil phlogopite mica. Both the plates and mica dielectric were diecut to hold maximum dimensional accuracy. The sensing element was placed in the **strain** frame slot while the **strain** frame was slightly compressed. The prestress was held to exactly 0.003 ± 0.0005 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 gage leads were made from thin strips of 5 mil Nichrome foil.



Figure 10. Final Gage Configuration

8. INSTALLATION PROCEDURE

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 three equal places, using a setting of 16 to 20 watt-seconds. 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 11). 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 12). 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 2 to 5 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. 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.

- 5) A shield similar to that in Figure 12 is used to shield the welded connection. The RG 58 C/u cable will complete the connection to the measuring instrument. The RG 58 C/u cable must be external to the furnace, since the cable cannot withstand high temperatures.
- 6) Use of intermedial lead such as Amphenol-Borg in the unheated zone may be made.



Figure 11. Lead Wire Attachment

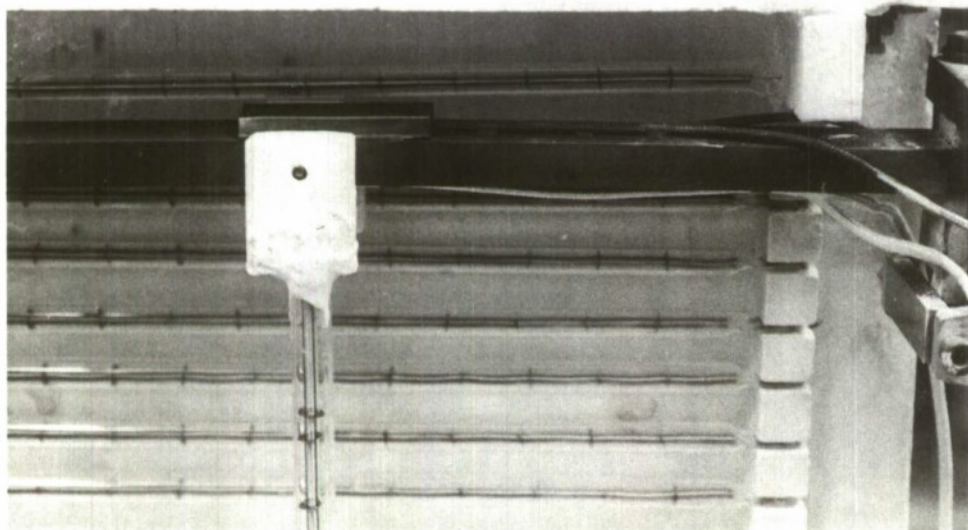


Figure 12. Shielded Gage Installation

9. TEST PROCEDURE

APPARATUS

Gages to be evaluated were mounted on test bars of TD Nichrome. The specimen bar thickness was 0.500 ± 0.002 inch, width 1.000 ± 0.006 inch and length 18.00 inches. The test bars were placed in a constant moment apparatus as shown in Figure 13 for evaluation. The moment apparatus was precalibrated by instrumenting one test bar with resistance strain gages. Three strain gages were installed, one on center and the others, 1 inch either side of center. The installation was repeated on the other side of the bar for a total of six strain gages. The instrumented bar was placed in the moment apparatus and strained incrementally to 2500 $\mu\epsilon$ in 500 $\mu\epsilon$ steps. All gage outputs and the beam deflection were recorded at each increment, for a total of three strain cycles.

Prior to any elevated temperature evaluations, the TD Nichrome, test bar was thermally surveyed at test temperatures of 1000, 1500, 1625, 1750, 1875, and 2000°F. The bars were instrumented with thermocouples every 2.0 inches on top and bottom for a total of 16 thermocouples. The instrumented beams were placed in the radiant oven, mounted to the moment apparatus, and thermocouples recorded at each temperature plateau. A thermocouple near the bar center was used as a temperature control, and the bar was held at each plateau a sufficient length of time for the system to stabilize.

LEAD CABLES

Lead cables in the thermal environment were the Maser Rex commercial coaxial cable capable of withstanding 2000°F.

TEST EQUIPMENT

The test equipment was generally as follows:

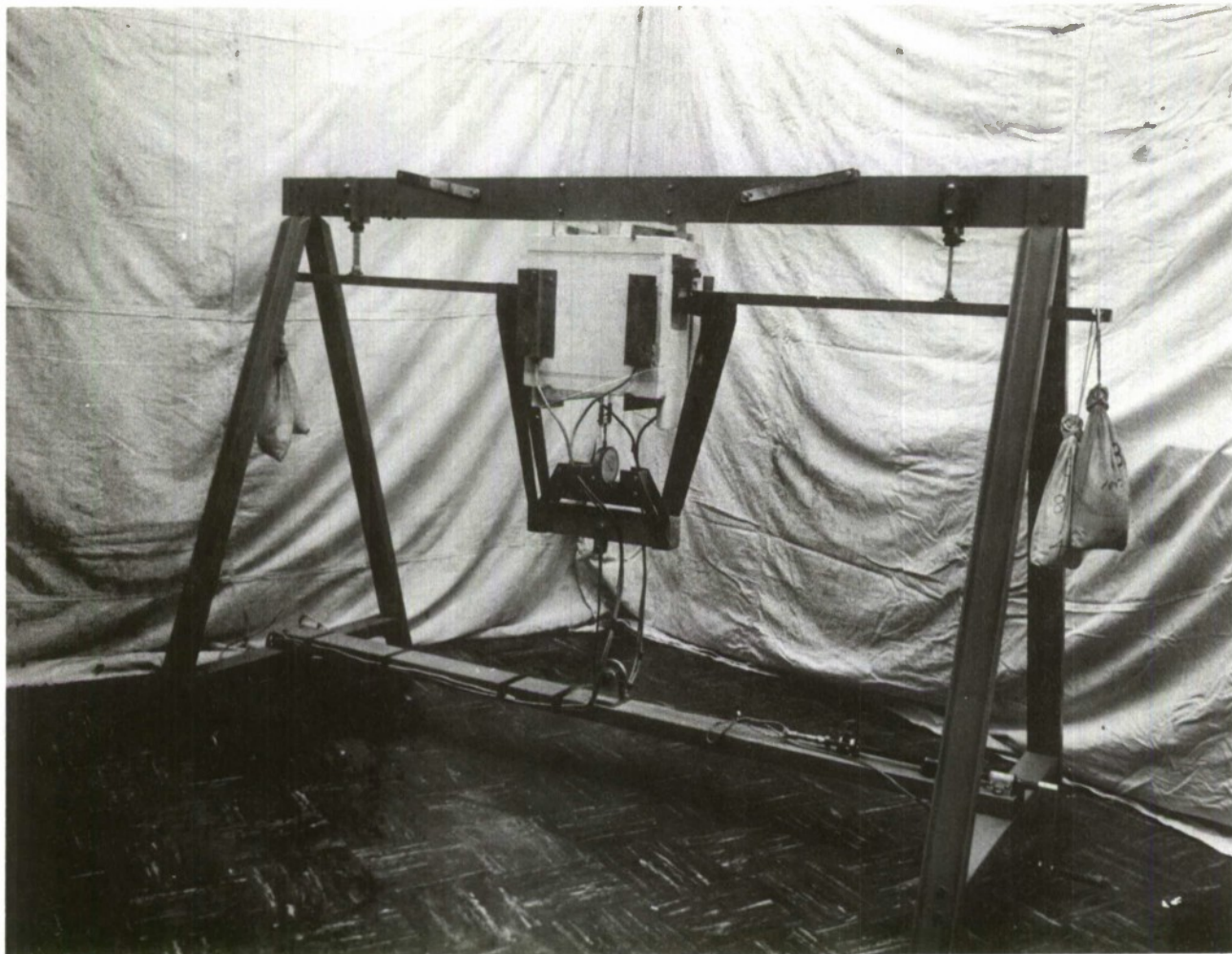


Figure 13. Constant Moment Apparatus

- 1) Capacitance bridge, Model 75C, Boonton Electronics Corp.
 - a) Resolution: 0.02 picofarad
 - b) Accuracy: 0.25 percent
 - c) Frequency range: 5 kHz to 500 kHz
- 2) Capacitance bridge, Model 75A, Boonton Electronics Corp.
 - a) Resolution: 0.02 picofarad
 - b) Accuracy: 0.25 percent
 - c) Frequency range: 1000 kHz
- 3) Potentiometer temperature recorder, Model IPG 560, Bristol Co., Waterbury, Connecticut
 - a) Resolution: 5° F
 - b) Accuracy: 1 percent of full scale
- 4) Thermocouple wire, Chromel-Alumel, Type 301, Claude S. Gordon Co., El Segundo, California
 - a) Resolution: 1° F
 - b) Accuracy: 0.75 percent
- 5) Dial indicator, type 656-341, Starrett Co., Altral, Mass.
 - a) Resolution: 0.001 inch
 - b) Accuracy: 0.3 percent
- 6) Vacuum tube voltmeter, Volt Ohmyst, RCA
 - a) Resolution: 1 ohm
 - b) Accuracy: 5 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 Quartz T-3 radiant lamps.

INSTRUMENTATION CIRCUITRY

The gage was always connected as a three terminal device and readout instrumentation was compatible with this configuration (Reference 1).

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 plate terminals of the gage while mounted to the test bar, and exclusive of any distributed capacitance exhibited by lead cables.

a) Measurements

The following measurements were taken prior to capacitance evaluation:

- 1) Distributed capacitance C_L of coaxial pair lead cables while unterminated, including all cable from instrument to gage.

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

b) Data

Tabulate gage capacitance as:

$$C_G = C_T - C_L$$

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

The test bar with gage mounted was installed in the constant moment apparatus shown in Figure 13. The bar was strained in 500 $\mu\epsilon$ increments to a maximum of 2500 $\mu\epsilon$ and in 500 $\mu\epsilon$ decrements to zero. The bar was cycled a total of five times, but output was only read at maximum and zero on the last two cycles.

The first three gages (Table II) evaluated were tested at source frequencies of 5, 50, 150, 300, 500, and 1000 kHz. Based on the results of these evaluations, the remainder of the gages were tested at the source frequency of 150 kHz which optimized their performance.

Forty percent of the gages were tested in compression.

a) Measurements

The following measurements were taken during evaluation.

- 1) The deflection of the bar at each increment including zero
- 2) Gage capacitance at each increment including zero

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 five runs was found in accordance with the definition:

$$G.F. = \frac{\Delta C_G / C_G}{\epsilon}$$

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

Repeatability data was extracted from the data plots.

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

3) Strain Limit at Room Temperature

The gaged test bar was placed in the moment apparatus and strained in 10 percent increments of maximum strain. In this evaluation the maximum strain was 5000 $\mu\epsilon$ or 80 percent of the yield strain of test bar, whichever was lower. This evaluation was performed at the optimum source frequency selected in (2). A special titanium test bar was used for this test.

Forty percent of the gages were tested in compression as the construction of the gage could produce difference strain limit values for each mode.

a) Measurements

The following measurements were taken during evaluation. The load apparatus was as in Figure 13.

- 1) The deflection of the beam at each increment, including zero
- 2) Gage capacitance at each increment including zero

b) Data

The capacitance readings were converted to indicated strain using gage factor determined previously in Section 2, and plotted versus mechanical strain. A difference of 10 percent between indicated and actual strain was defined as strain limit.

4) Effect of Temperature on Apparent Strain, Gage Factor, Zero Shift, Drift, and Resistance to Ground at 2000°F

For this series of evaluations, the test bar had thermocouples attached to each corner of the gage area. One was used for temperature feedback. The beam temperature was raised to the levels specified above and allowed to stabilize. The beam was considered stabilized when all thermocouples read within ± 2 percent. The maximum temperature was 2000°F.

Starting at ambient temperature, the beam was cycled to 1000 $\mu\epsilon$ three times and repeated at each temperature plateau.

Forty percent of the gages were tested in both tension and compression.

a) Measurements

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

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

When extreme temperature of 2000°F was reached, the forementioned readings were taken. The unstrained beam was held at this temperature for 1 hour and capacitance measurements taken every 10 minutes beginning as soon as bar was stabilized.

b) Data

The change in the unstrained capacitance readings was converted to indicated strain using gage factor from Section 2 and plotted versus temperature.

The unit change of capacitance due to strain was found for each temperature increment. Each value was shown as a percentage change from the ambient temperature value and plotted versus temperature.

The change in the unstrained capacitance readings was plotted versus time.

The zero shift change in capacitance was plotted versus cycles.

5) Effects of Heating Rate on Apparent Strain

The same apparatus used in Section 4 was utilized except that oven was controlled by the Data-Trak function generators. One program was utilized having a slope of $10^{\circ}\text{F}/\text{sec}$. The peak temperature was 2000°F .

a) Measurements

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

- 1) Capacitance
- 2) Deflection of beam

b) Data

The ordinate of the plot obtained was converted to indicated strain using gage factor from Section 2.

6) Effect of Temperature on Strain Limit

The same apparatus used in Section 4 was utilized. The test bar temperature was raised to 2000°F and stabilized. The bar was strained in 10 percent increments of maximum expected strain, which is defined as a point below the yield strength of the test bar at 2000°F .

Forty percent of the gages were tested in both tension and compression.

a) Measurement

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 Section 2 and plotted versus mechanical strain.

The strain limit is the mechanical strain at the point where indicated strain differs $\pm 10\%$ from mechanical strain plus the thermal expansion of the test bar.

10. TEST RESULTS

The results of the Phase II evaluation of the 25 high temperature capacitance strain gages are arranged here in the same order as the target specifications. Table II presents a test matrix of the tests conducted on the 25 gages. All gages were manufactured exactly the same, holding tolerances as closely as possible. The following is a list of the dimensional parameters and the accuracy to which they were held:

- 1) Gage length, 0.500 ± 0.002 inch
- 2) Plate area, 0.0150 ± 0.0006 square inch
- 3) Dielectric thickness, 0.004 ± 0.0003 inch
- 4) Strain frame gap, 0.039 ± 0.003 inch

Each frame was individually measured for its gap to ± 0.0003 inch and the sensor sized to that frame such that every gage held a preload of 0.003 ± 0.0005 inch.

All of the gages were heat soaked for three cycles to 1625°F (885°C) for 15 minutes except for gages 6, 10, 13, 17, and 18, which were heat cured to 2000°F (1093°C) as previously described.

GAGE LENGTH

All of the gages fell within the prescribed tolerances indicated in Figure 3 for the rhombic frame. That was the target specification of a $1/2$ inch gage length.

GAGE CAPACITANCE

Table III presents the initial gage capacitance of all 25 gages tested during Phase II of this program. The nominal gage capacitance as indicated in the table is 8.305 picofarads. The reproducibility gage-to-gage was ± 34 percent. These values were outside the target specification of 10 picofarads ± 2 percent. Section 7 indicated the tolerances to which a gage must be held to meet the capacitance specifications. Some of those tolerances are beyond the present state of the art in manufacturing and measuring tolerances.

TABLE II. TEST MATRIX - HIGH TEMPERATURE CAPACITANCE STRAIN GAGE PROGRAM

Test Parameter	Gage Numbers																														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
Room temperature	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
C _g	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
R _g	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
R _{ground}	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
K _t -tension	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
K _c -compression	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Zero shift/cycle	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Strain limit - tension	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
- compression	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Frequency versus K	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Elevated temperature	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Test temperature 1000°F	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Test temperature 1500°F	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Test temperature 1625°F	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Test temperature 1750°F	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Test temperature 1875°F	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Test temperature 2000°F (maximum)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Measure C _g	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Measure R _g	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Measure R _{ground}	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Measure K _t -tension	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Measure K _c -compression	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Apparent strain - static	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
- 10° F/S	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Strain limit - tension	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
- compression	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Drift - maximum temperature, 1 hour	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

TABLE III. INITIAL GAGE CAPACITANCE

Gage No.	Capacitance, picofarads	Gage No.	Capacitance, picofarads
1	8.686	14	6.188
2	5.420	15	9.227
3	7.962	16	7.594
4	9.039	17	7.251
5	8.362	18	8.192
6	7.923	19	9.534
7	7.508	20	10.178
8	8.398	21	10.205
9	8.147	22	8.960
10	6.005	23	9.066
11	10.982	24	9.150
12	7.302	25	7.579
13	8.783	—	
		Average C = 8.305	

GAGE FACTOR (STRAIN SENSITIVITY)

A summary of the room temperature gage factors is presented in Table IV. Tension gage factor was measured on all gages except 11 and 12. Compression gage factor was measured on gages 7, 8, 11, 12, 14, 15, 16, 23, 24, and 25. The gage factors varied from a low of 22.2 to a high of 69.5 with an average of 44.2 (tension). Gages 2, 3, and 11 were installed on the TD Nichrome bar, calibrated, then removed and reinstalled on another bar of different material. Gages 2 and 3 were reinstalled on a stainless steel bar, and gage 11 was reinstalled on a titanium bar. The gage factor comparison was as follows:

<u>Gage Number</u>	<u>Gage Factor</u>	
	<u>First Bar</u>	<u>Second Bar</u>
2	58.7	62.5
3	69.5	69.0
11	28.9	29.5

TABLE IV. ROOM TEMPERATURE GAGE FACTOR

Gage Number	Gage Factor	
	Tension	Compression
1	48.0	—
2	58.7	—
3	69.5	—
4	67.4	—
5	42.3	—
6	41.3	—
7	32.5	38.5
8	56.5	61.5
9	48.3	—
10	34.3	—
11	—	28.9
12	—	67.0
13	22.2	—
14	68.6	63.0
15	40.0	54.0
16	45.0	34.0
17	40.3	—
18	32.8	—
19	44.7	—
20	21.6	—
21	25.0	—
22	58.1	—
23	47.8	44.2
24	34.5	49.7
25	40.0	55.0

Secondary variables related to the gage factor are the linearity, zero shift, repeatability, drift, and hysteresis of the gage. Considerable non-linearity was experienced with some of the gages in this 1/2 inch configuration. No attempt was made to linearize the gage except in the calculation of the room temperature gage factor presented in Table IV. All of the data are presented as a best fit curve to the data. Most of the room temperature data

showed the gages to be linear within ± 1 percent. The worst case was gage 15, which had a room temperature nonlinearity of ± 5.3 percent. These variables are discussed in greater detail in the following paragraphs.

GAGE FACTOR CHANGE WITH TEMPERATURE, RUN-TO-RUN

The run-to-run gage factor change or variation is presented in the repeatability plots of Figures 14 and 15. These data are presented as an envelope which encompasses the run-to-run deviations for all gages tested up to and including 1875°F (1023°C). The lightly shaded area on Figure 14 represents the tension deviation experienced on the five gages heat cured to 2000°F (1093°C). It should be noted that at temperatures above 1750°F (954°C), the gages stabilized at 1625°F (883°C) became erratic and could not be measured. The gages proved to be more stable in compression as shown in Figure 15. The shaded area in Figure 15 includes both groups of gages tested.

Each gage was load cycled five times at each temperature level. This load cycling required approximately 15 minutes to complete. An example of the type of excursion that occurred at the maximum temperature on the gages cured at 2000°F (1093°C) is shown in Figures 16 and 17, which give the tension outputs of gages 13 and 18. The large change in $\Delta C/C$ experienced by the gage during the reading can be seen at the zero strain level and is due mainly to gage drift. This drift continues at about this same rate over the period of time the gage is exposed to the very high temperatures. Lines, parallel to a line drawn from the midpoint of the zero reading before and after run 5, can be passed through the maximum strain point of each cycle. This resulting information gives an approximate gage factor and an estimate of the drift rate during the 15 minute reading time. The estimated gage factor for gage 13 at 2000°F is 22.5, with a drift rate of approximately 200 microinches per inch per minute. Gage 18 has an estimated gage factor of 46.0 at 2000°F , with a drift rate of approximately 70 microinches per inch per minute.

The drift and instability on the gages cured at 1625°F was far greater than gages 13 and 18, and the gage could not be tracked at temperatures above 1750°F (954°C).

GAGE FACTOR CHANGE WITH TEMPERATURE, GAGE-TO-GAGE

Figure 18 presents the gage factor versus temperature plot of gages 9, 13, 18, 23, and 24 in tension. Figure 19 is the gage factor in compression plot of gages 14, 16, 23, and 24. A comparison of the tension and compression gage factor for gage 23 is shown in Figure 20. From these gage factor plots, which were selected at random, it can be seen that the gage-to-gage repeatability is still poor for the 1/2-inch gage configuration. Some of the gages, like gage 23 and 9, have a reasonably flat gage factor versus temperature plot. Other gages, like gage 24, have a very poor curve. One factor that is still an advantage of the gage is that it can be precalibrated. Figure 21 presents the gage factor versus temperature plot for gage 25. These data were obtained on two different days with repeatable results.

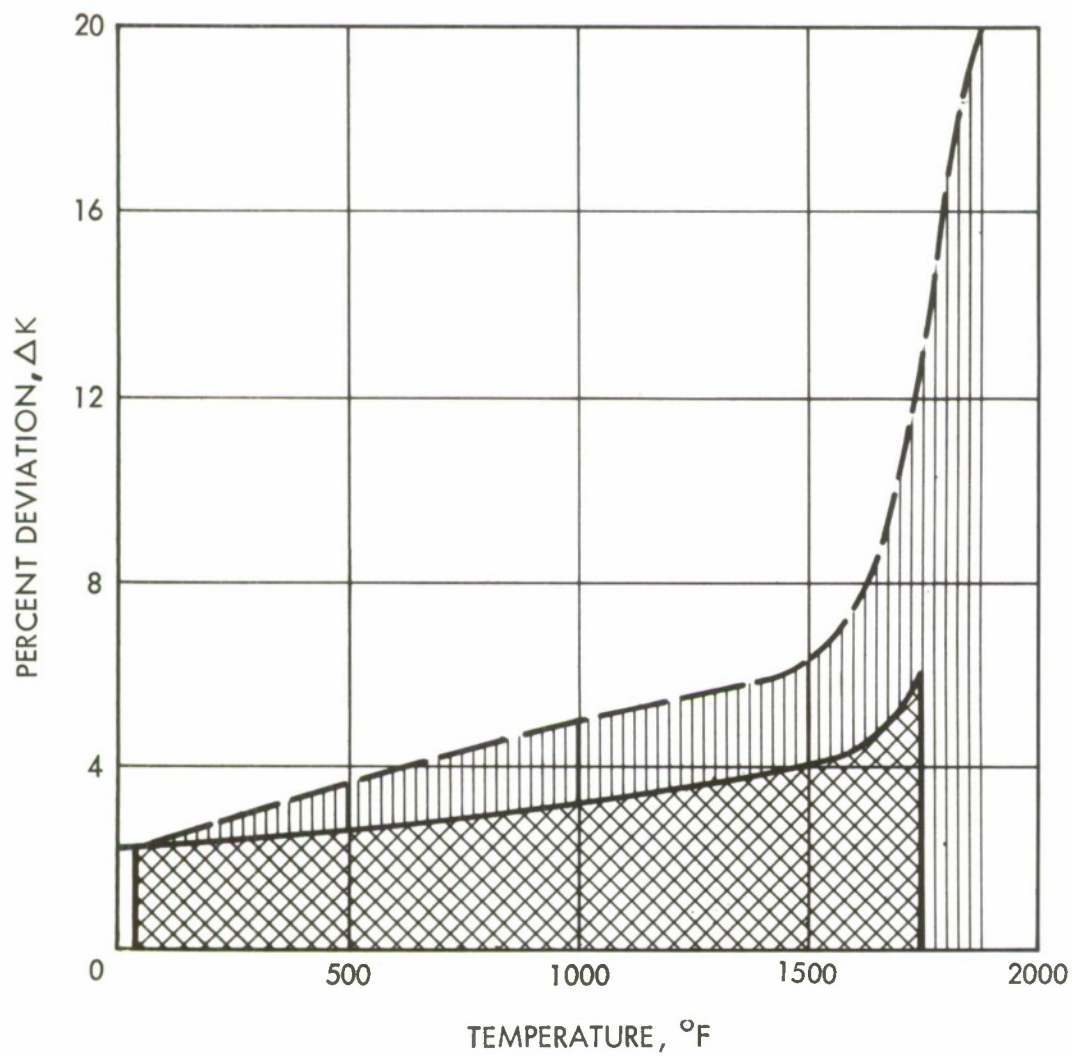


Figure 14. Repeatability, Run-to-Run (Tension)

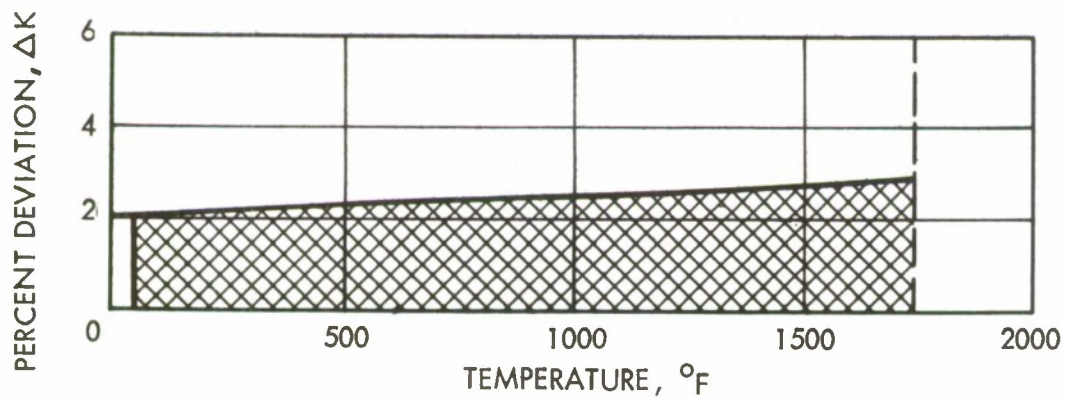


Figure 15. Repeatability, Run-to-Run (Compression)

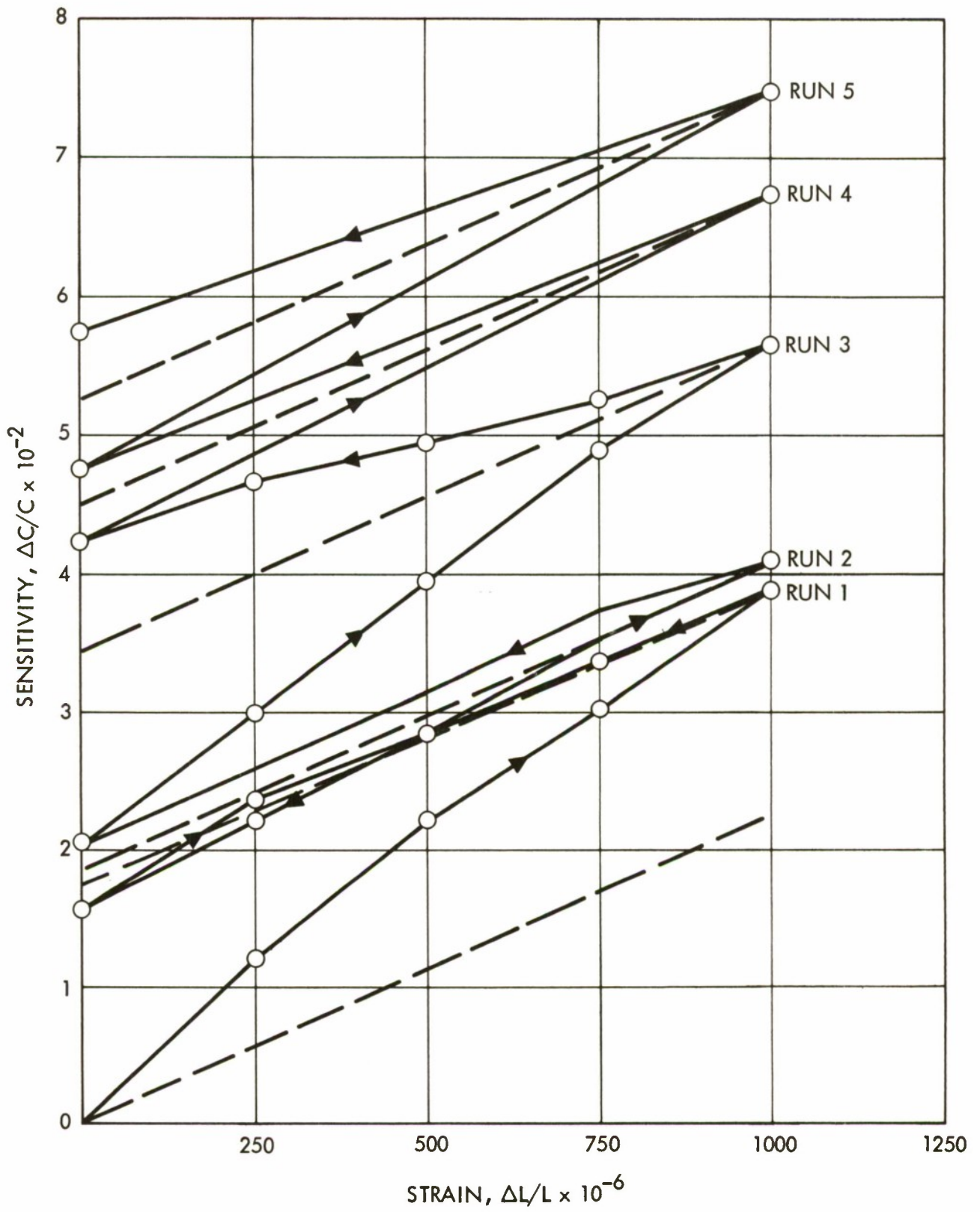


Figure 16. Gage Sensitivity, Gage 13 (2000 °F)

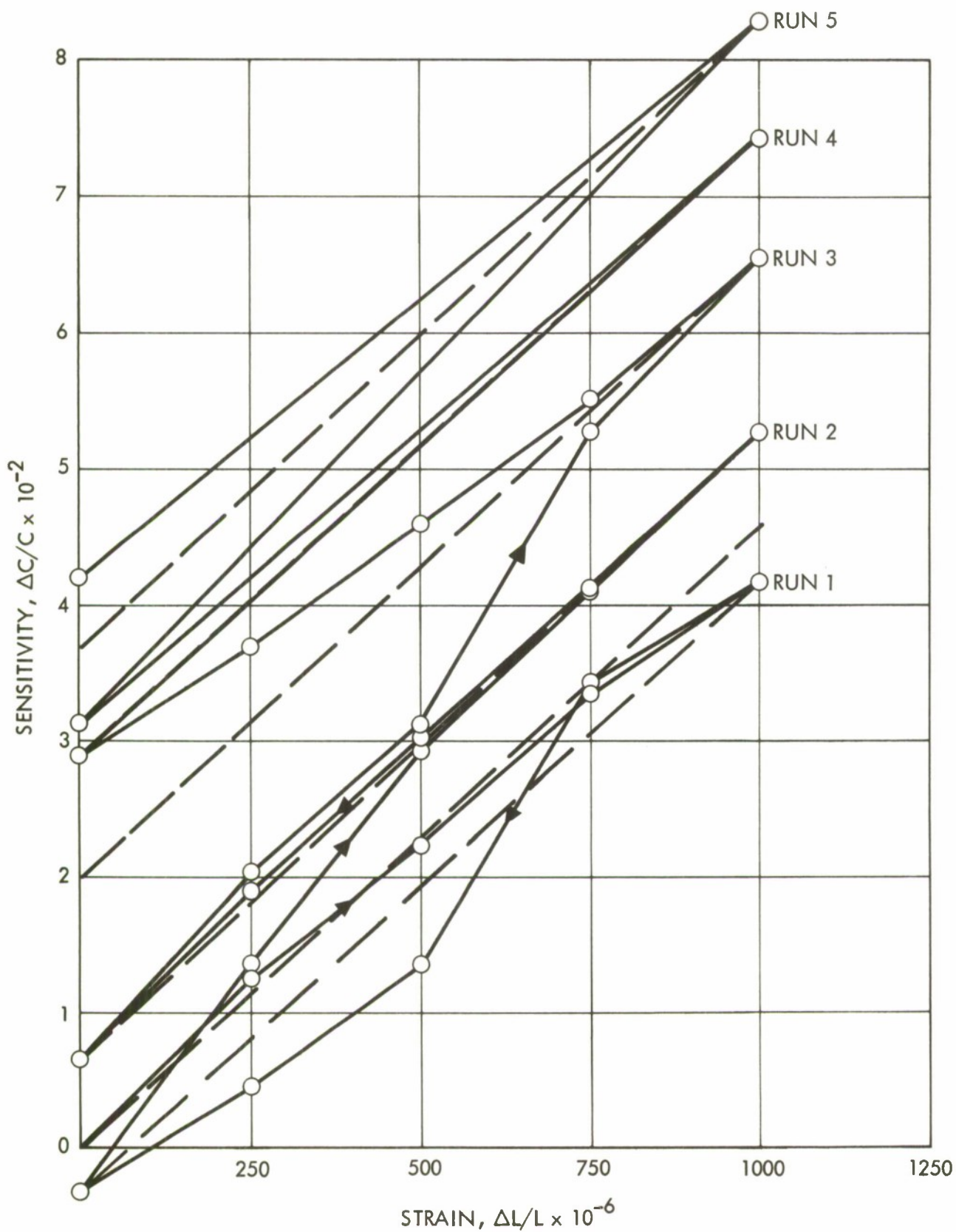


Figure 17. Gage Sensitivity, Gage 18 (2000 °F)

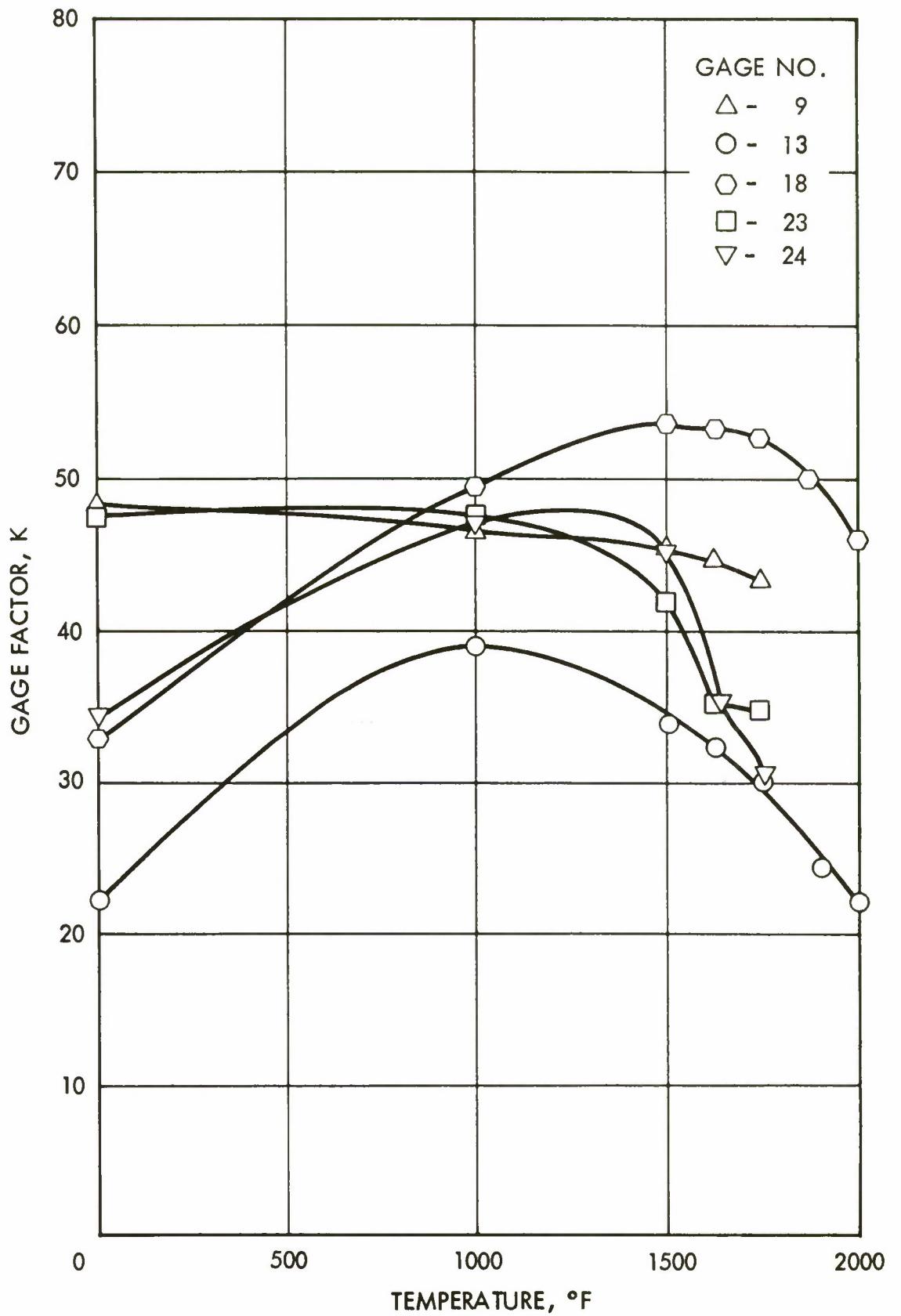


Figure 18. Gage Factor Versus Temperature (Tension)

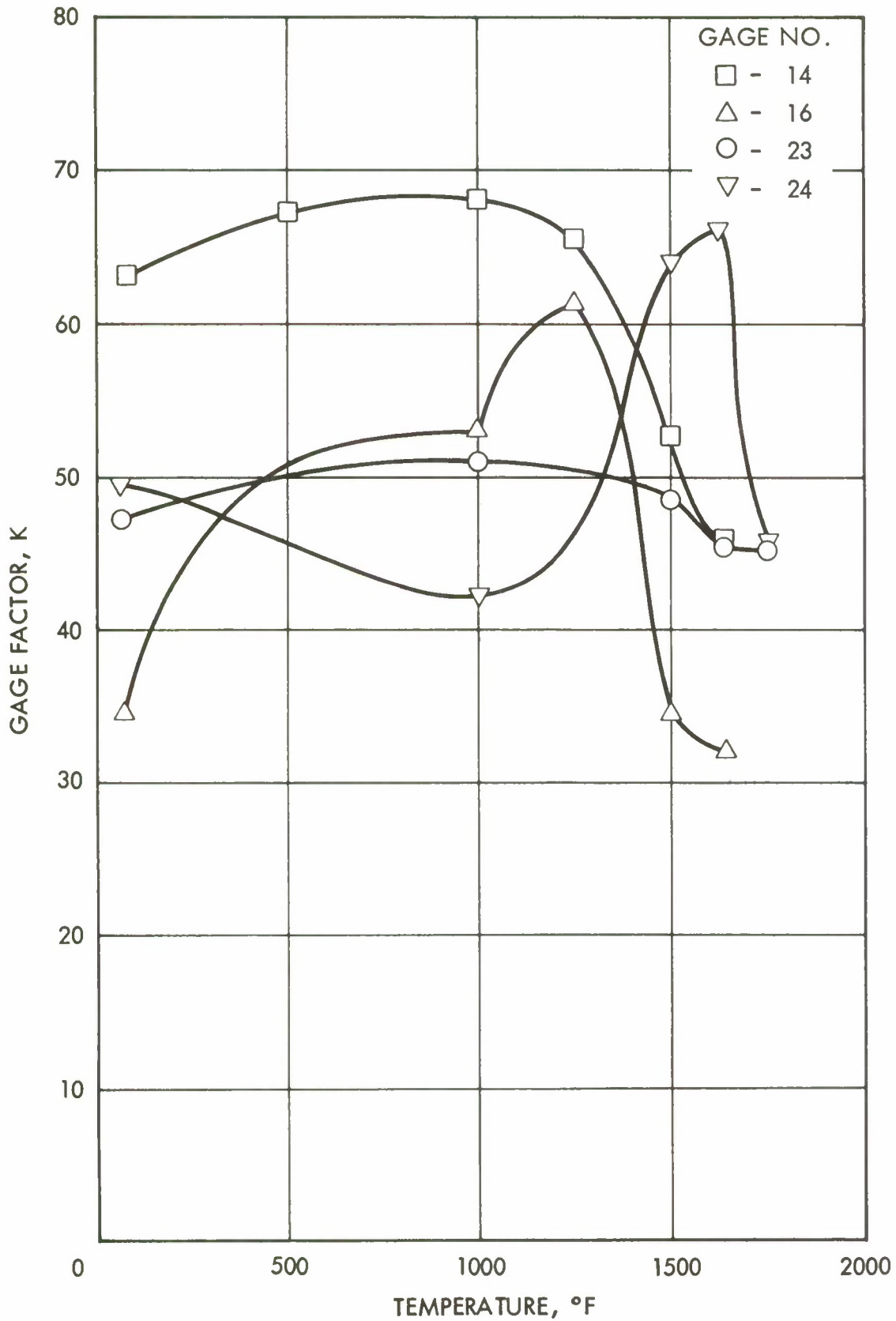


Figure 19. Gage Factor Versus Temperature (Compression)

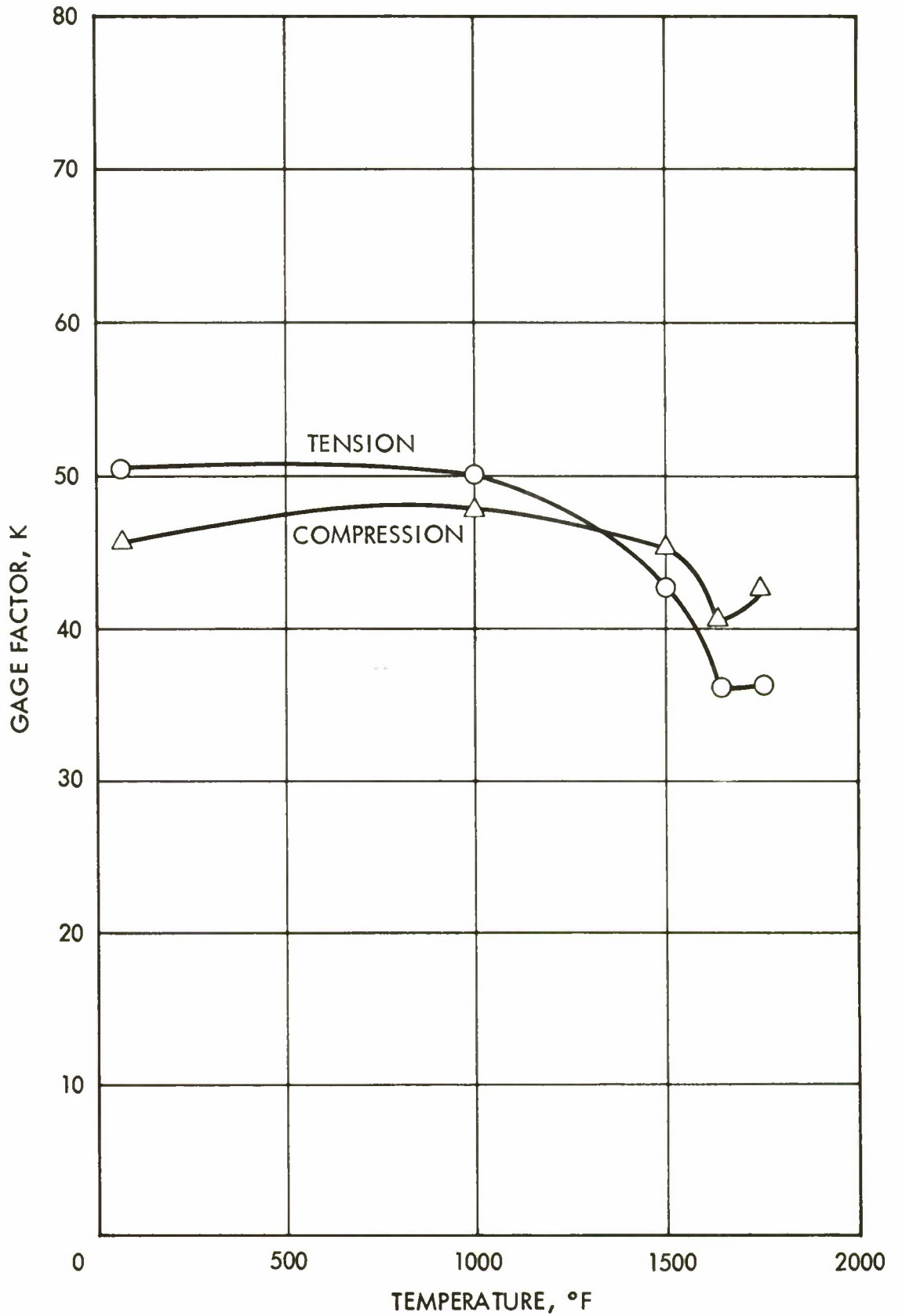


Figure 20. Gage Factor Versus Temperature, Gage 23

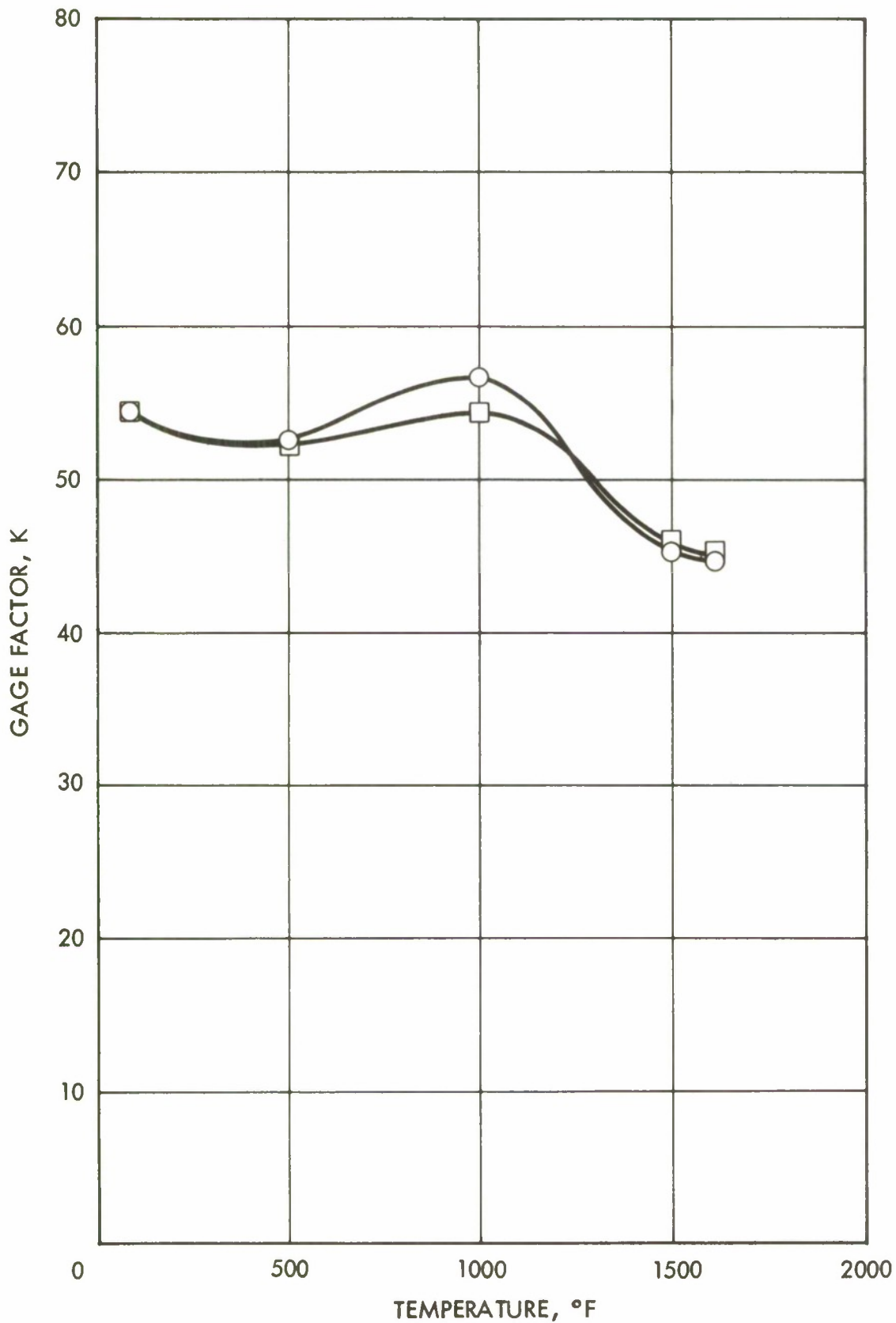


Figure 21. Gage Factor Versus Temperature, Gage 25 (Compression) Tested on 2 Different Days

Figures 22 through 26 present the average gage sensitivity versus temperature data for selected gages, including gage 15, which was the most nonlinear of all the gages tested.

STRAIN LIMIT

The strain limit was defined as 5000 microinches per inch at room temperature and 2000 microinches at maximum temperature. Gages 1, 2, and 3 were used to measure the room temperature strain limit in tension (Figure 27). The gages were tested on a titanium bar for the room temperature tests and on the standard TD-Nichrome bar for the elevated temperature test. The maximum temperature data were limited to 1750°F (954°C) because of the instability of the gage above that temperature. The strain limit for compression at room temperature and the elevated temperature strain limit data are presented in Figures 28 and 29. The strain limit in tension is greater than compression. The strain limit at room temperature is between 2000 to 5000 microinches/inch. At elevated temperature and in compression at room temperature, the gage is limited to approximately 2000 microinches/inch.

DRIFT

Drift is a very serious problem with the present configurations of the capacitance strain gage. At the present time, this seems to be the limiting parameter of the gage. Those gages cured at 1625°F became unstable above 1750°F. This means that the drift rate was so high that the gage could not be tracked. Gages cured at 2000°F were readable, but the drift is still so rapid as to make the resulting data questionable. The drift data have been plotted for gage 13 in Figure 30. Figures 31 and 32 present an envelope of the drift rates for all gages tested at their respective maximum usable temperature, 2000°F and 1750°F. Assuming an average gage factor of 35, this would represent a minimum drift rate of 6000 microinches per inch per hour for the gages cured at 2000°F and tested at 2000°F. The gages cured at 1625°F have a maximum drift rate at 1750°F of 1200 microinches/inch per hour.

APPARENT STRAIN

Apparent strain is the induced output of the gage caused by a temperature shift on an unstrained member. The apparent strain of the gage cured at 1625°F is reasonably repeatable gage-to-gage as shown in Figures 33, 34, and 35. Figures 33 and 34 are the apparent strain resulting from static temperature shifts where the new temperature is allowed to stabilize before readings are taken. Figure 35 is the apparent strain resulting from a 10°F/sec thermal transient. Careful examination of these figures shows that both curves are approximately the same.

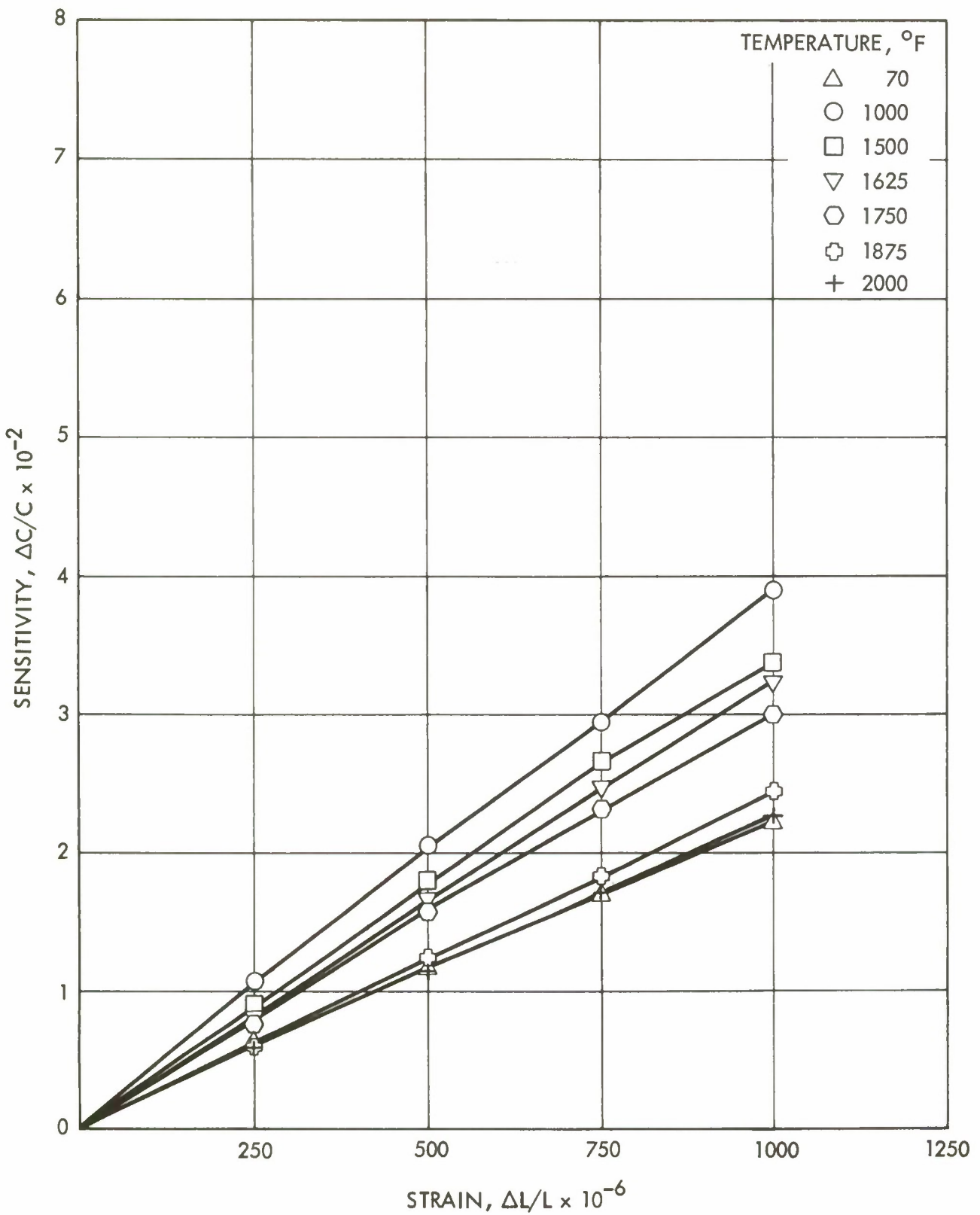


Figure 22. Gage Sensitivity Versus Temperature, Gage 13 (Tension)

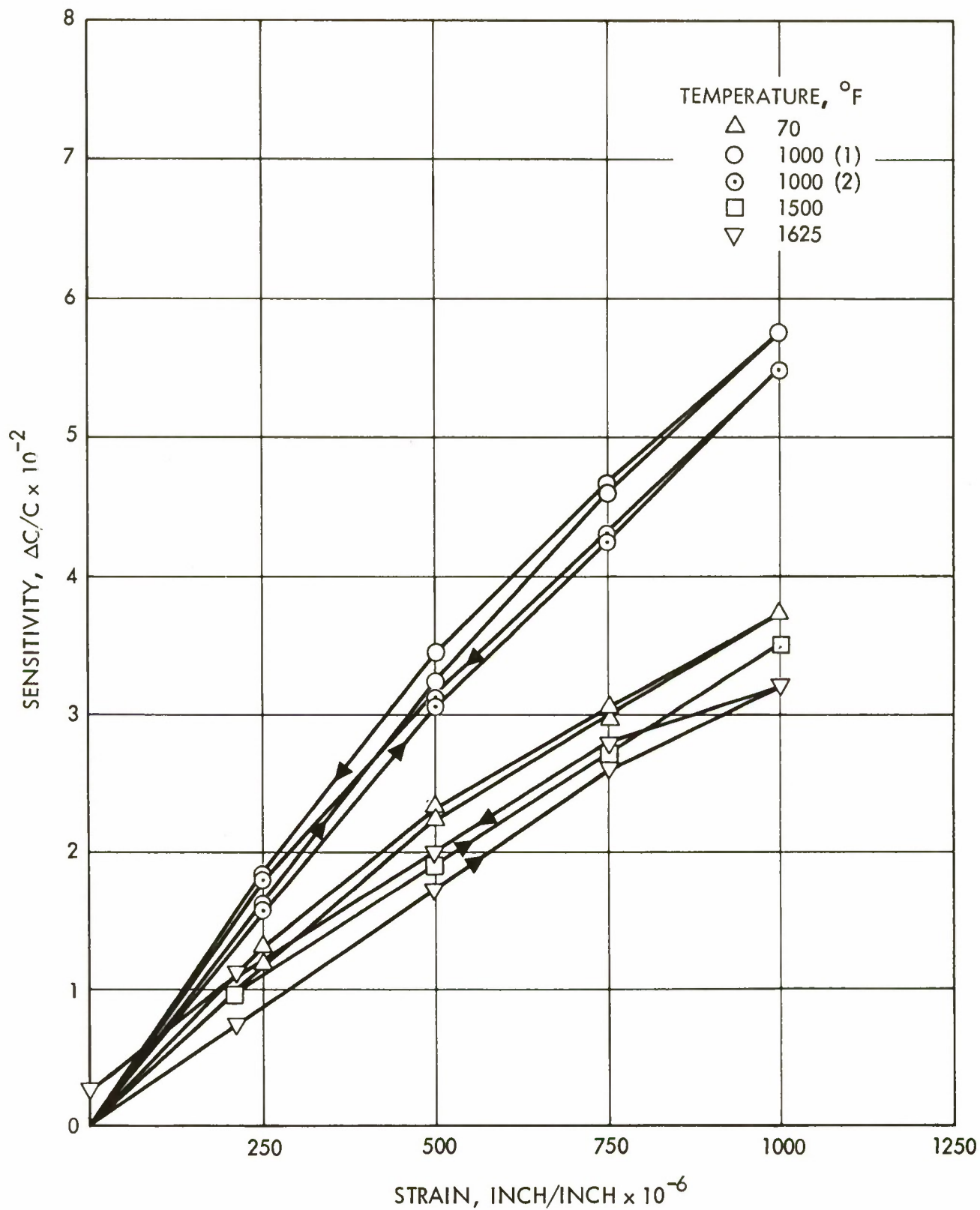


Figure 23. Gage Sensitivity Versus Temperature, Gage 15 (Tension)

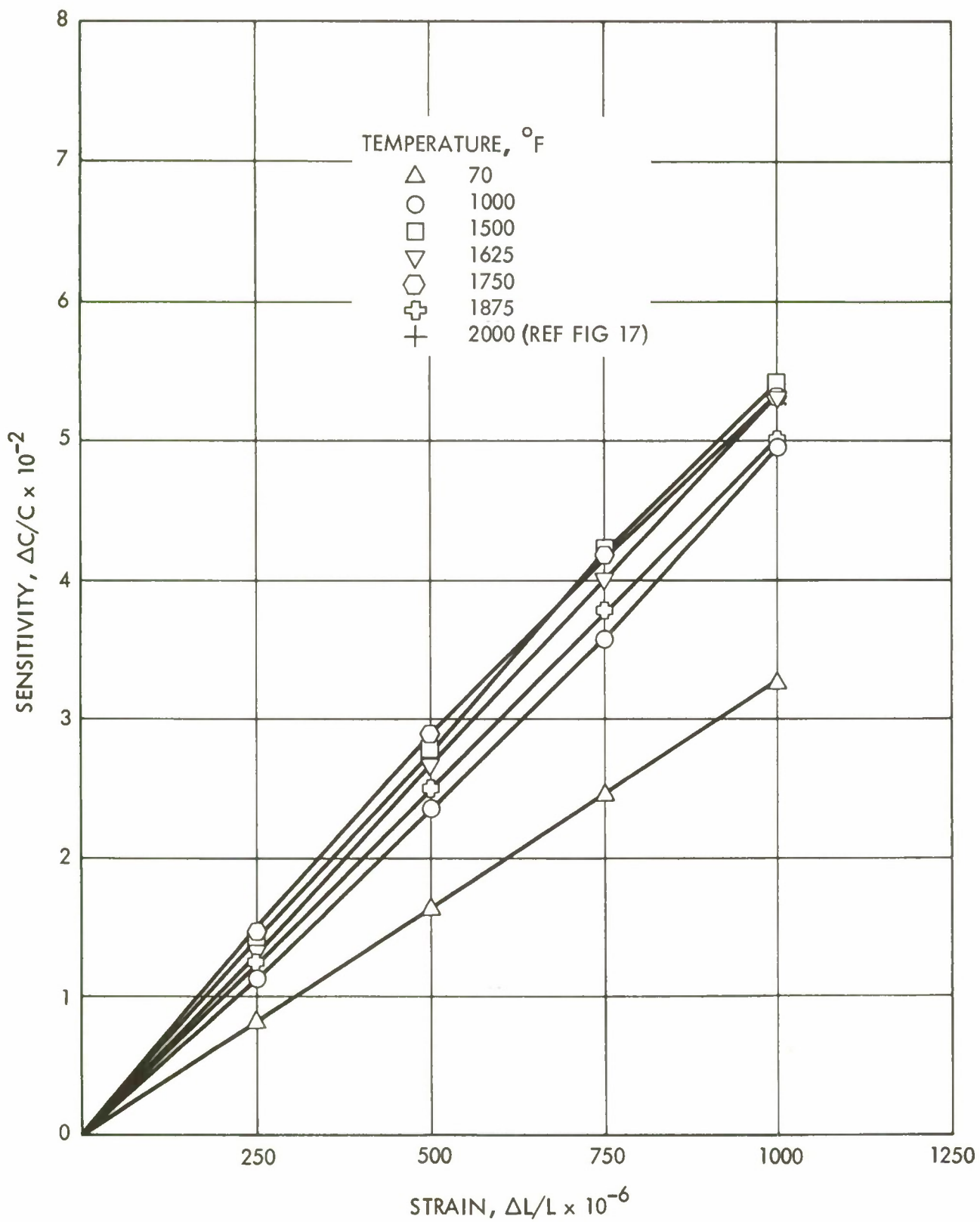


Figure 24. Sensitivity Versus Temperature, Gage 18 (Tension)

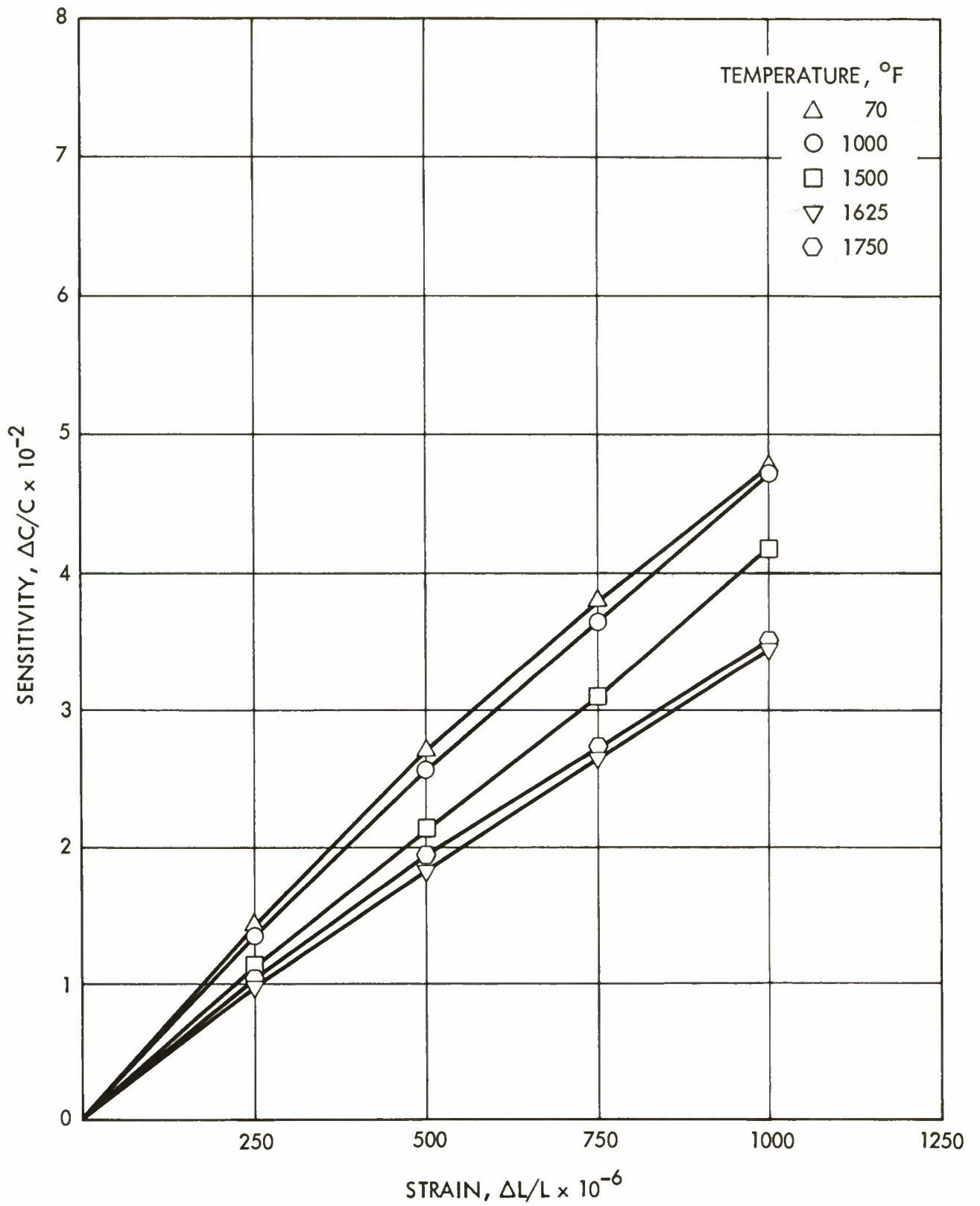


Figure 25. Gage Sensitivity Versus Temperature, Gage 23 (Tension)

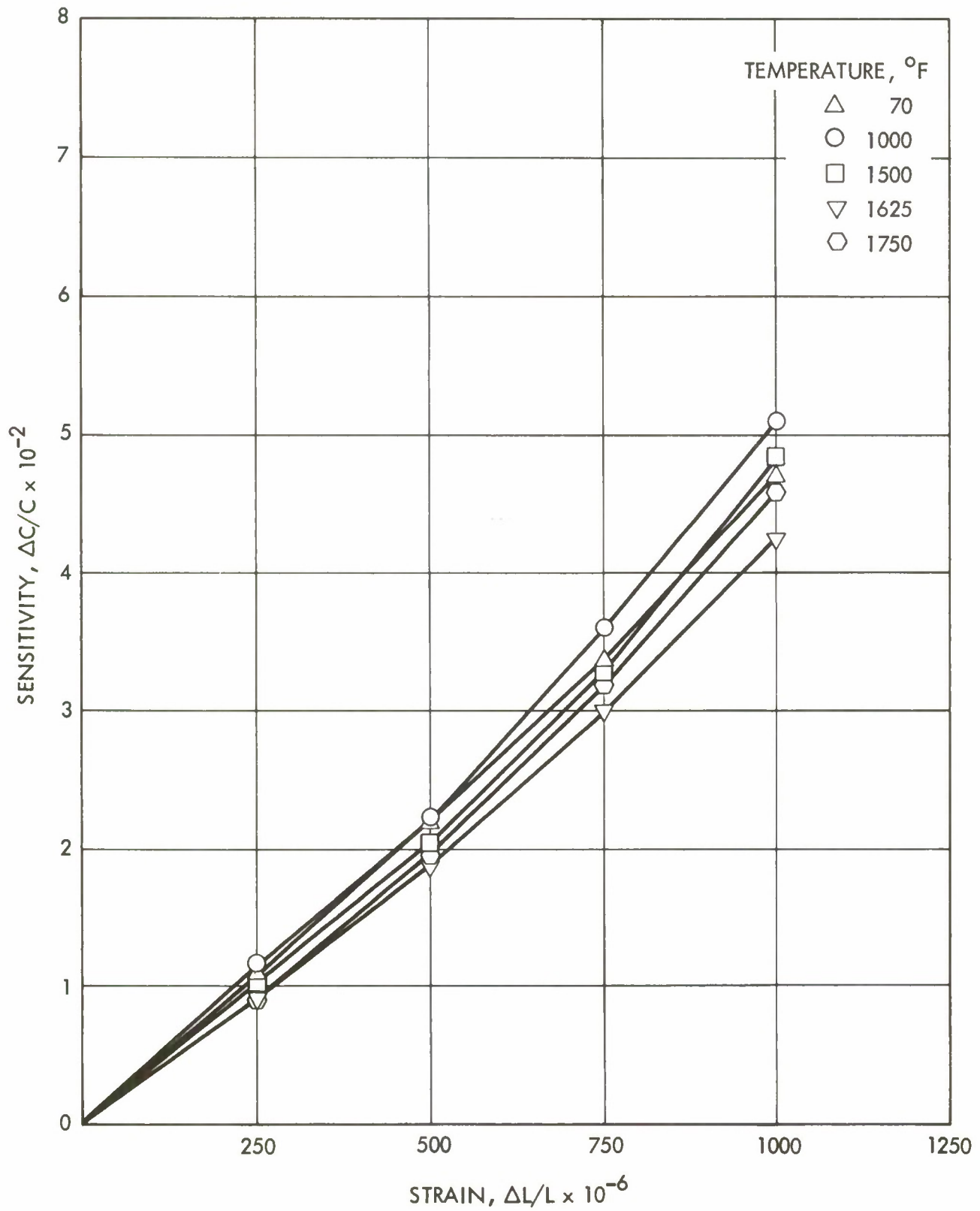


Figure 26. Gage Sensitivity Versus Temperature, Gage 23 (Compression)

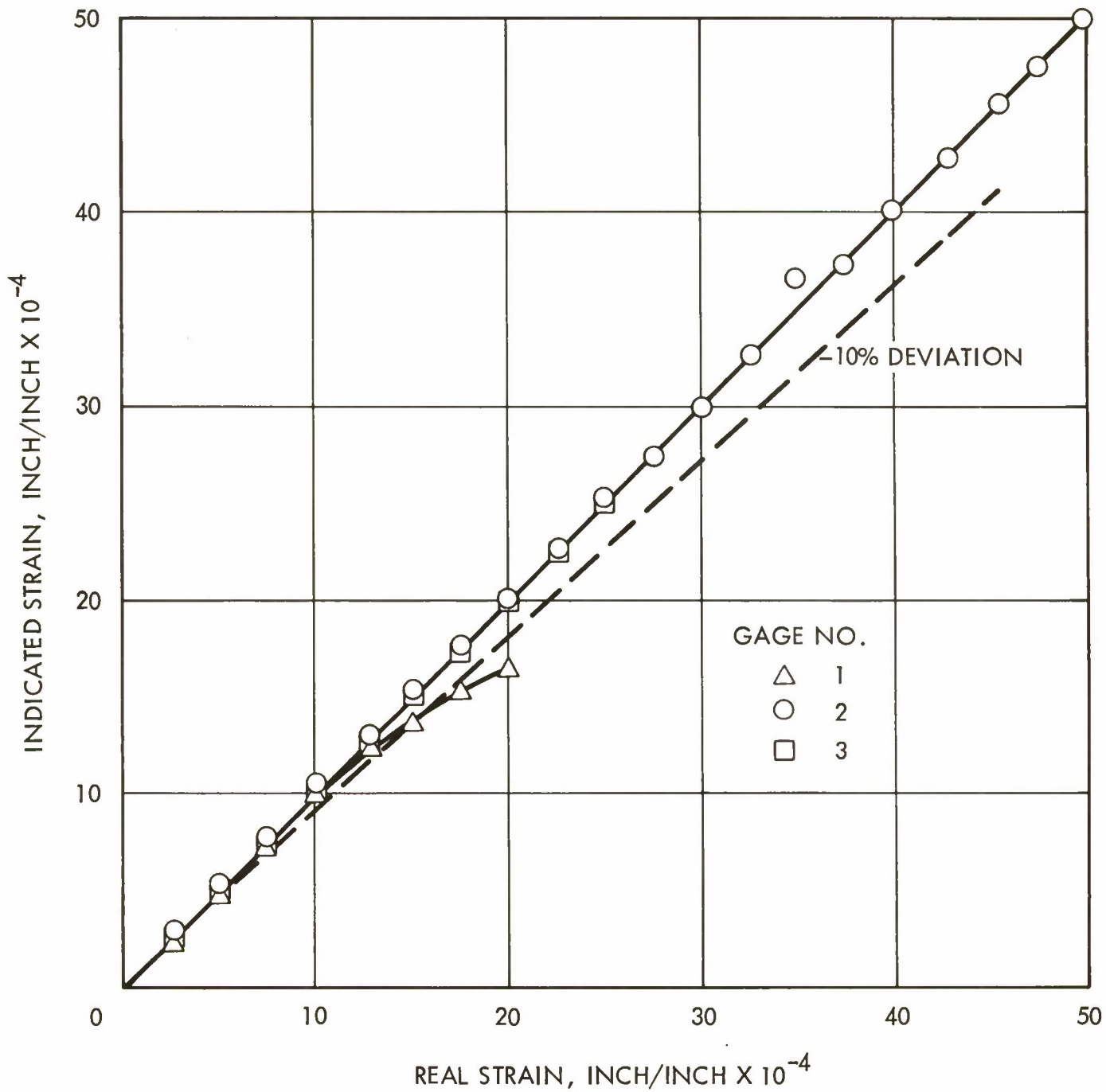


Figure 27. Strain Limit-Tension (Room Temperature)

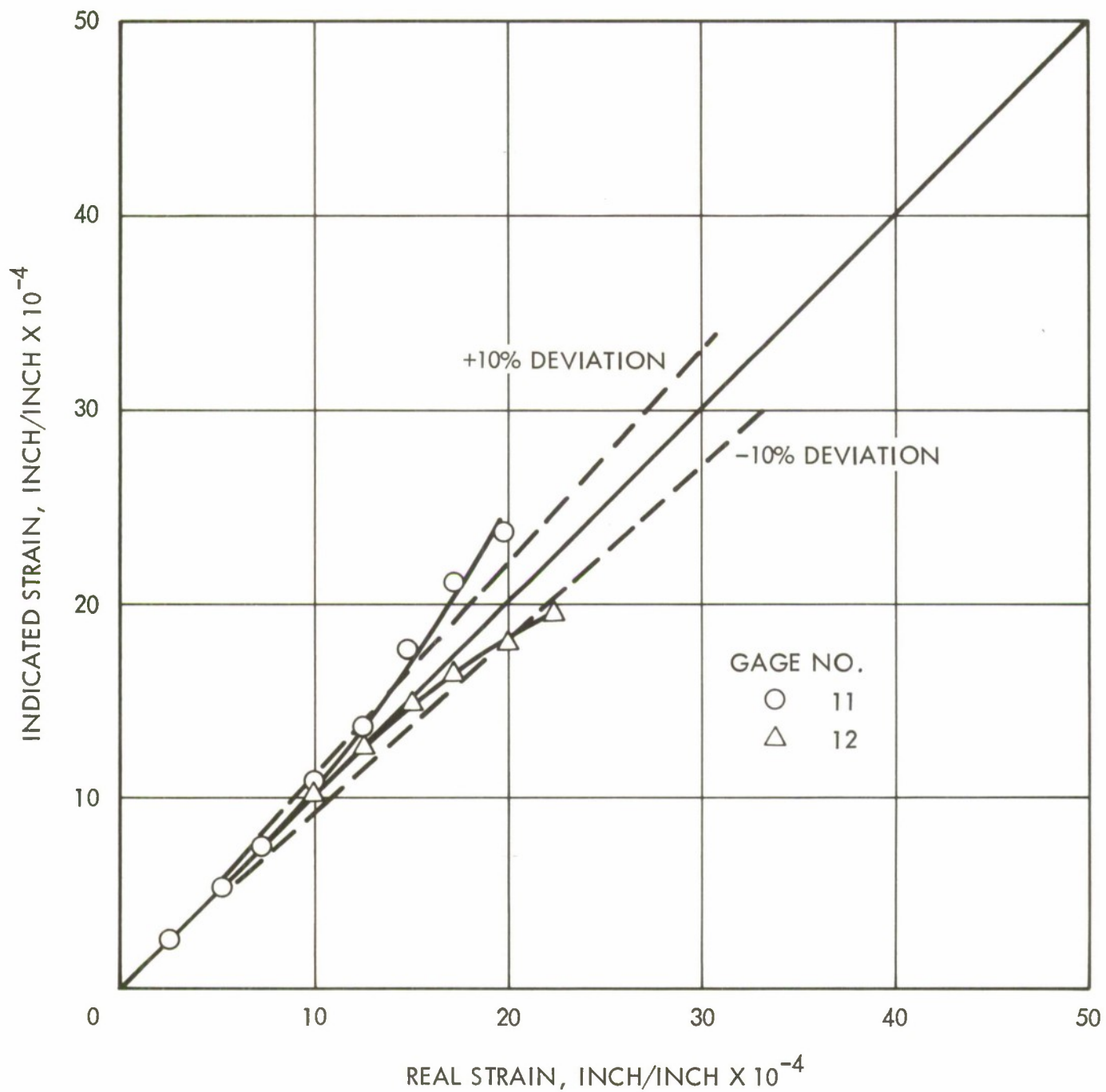


Figure 28. Strain Limit-Compression (Room Temperature)

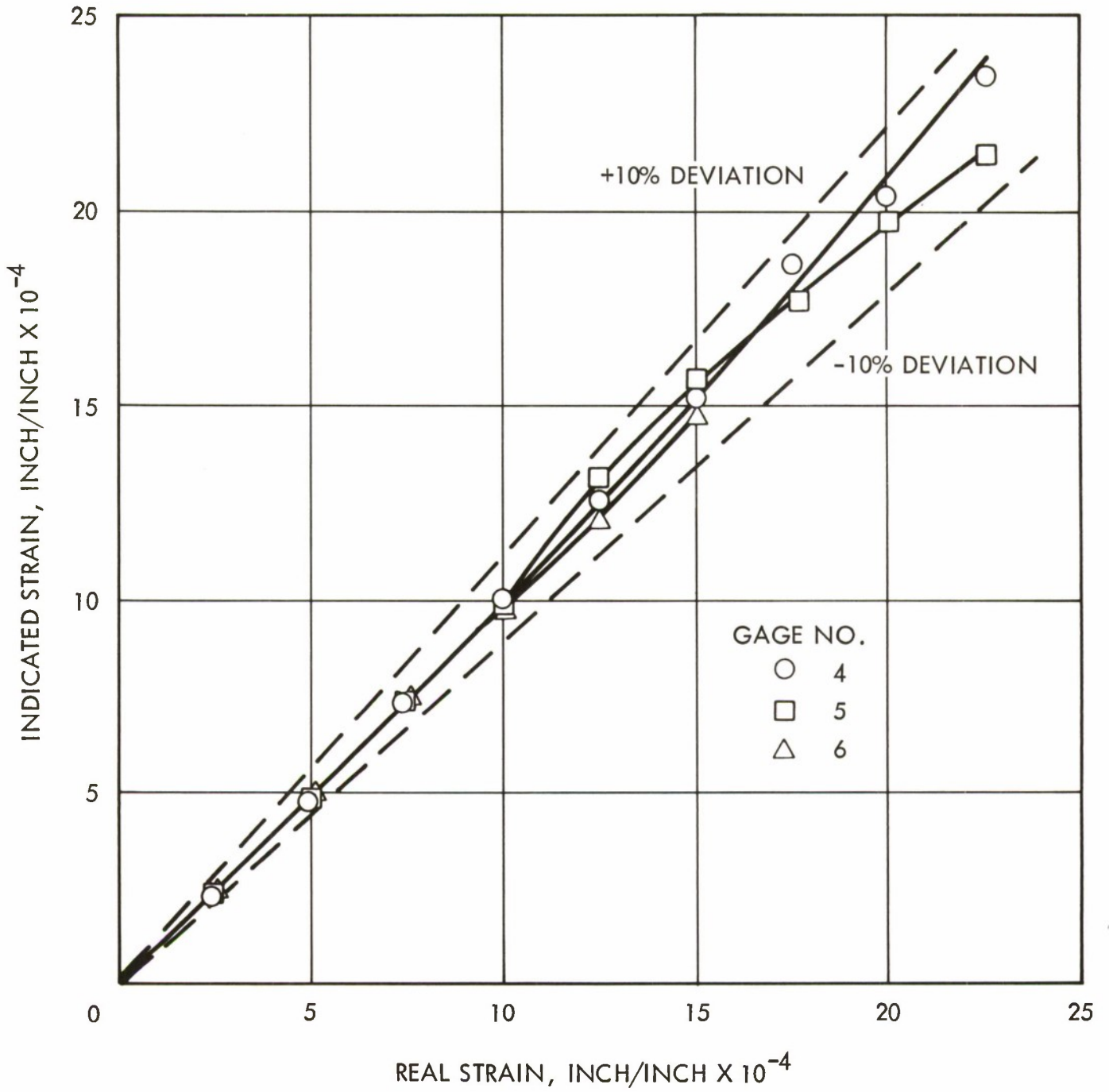


Figure 29. Strain Limit-Tension (1750°F)

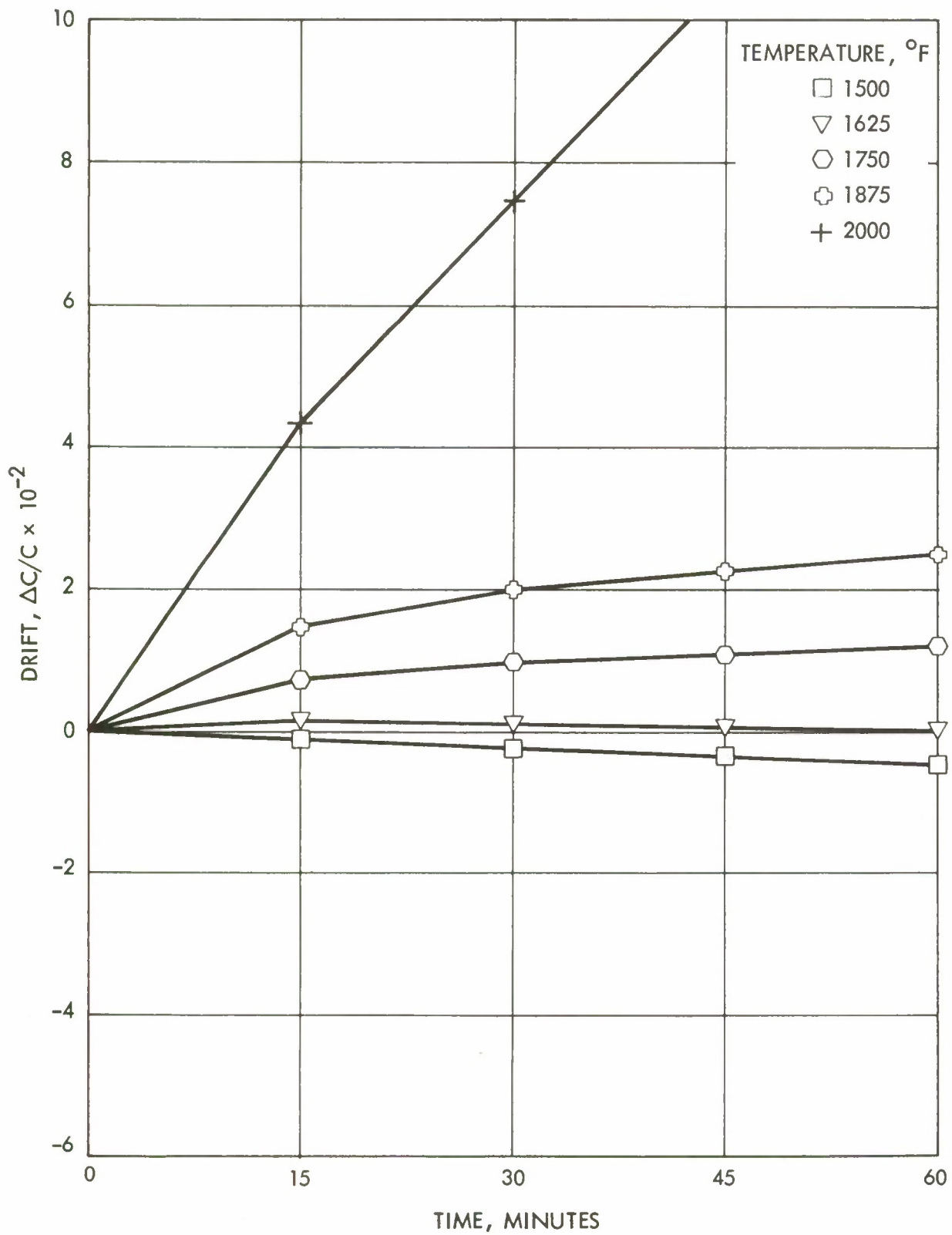


Figure 30. Drift Versus Temperature, Gage 13 (Heat Cured at 2000°F)

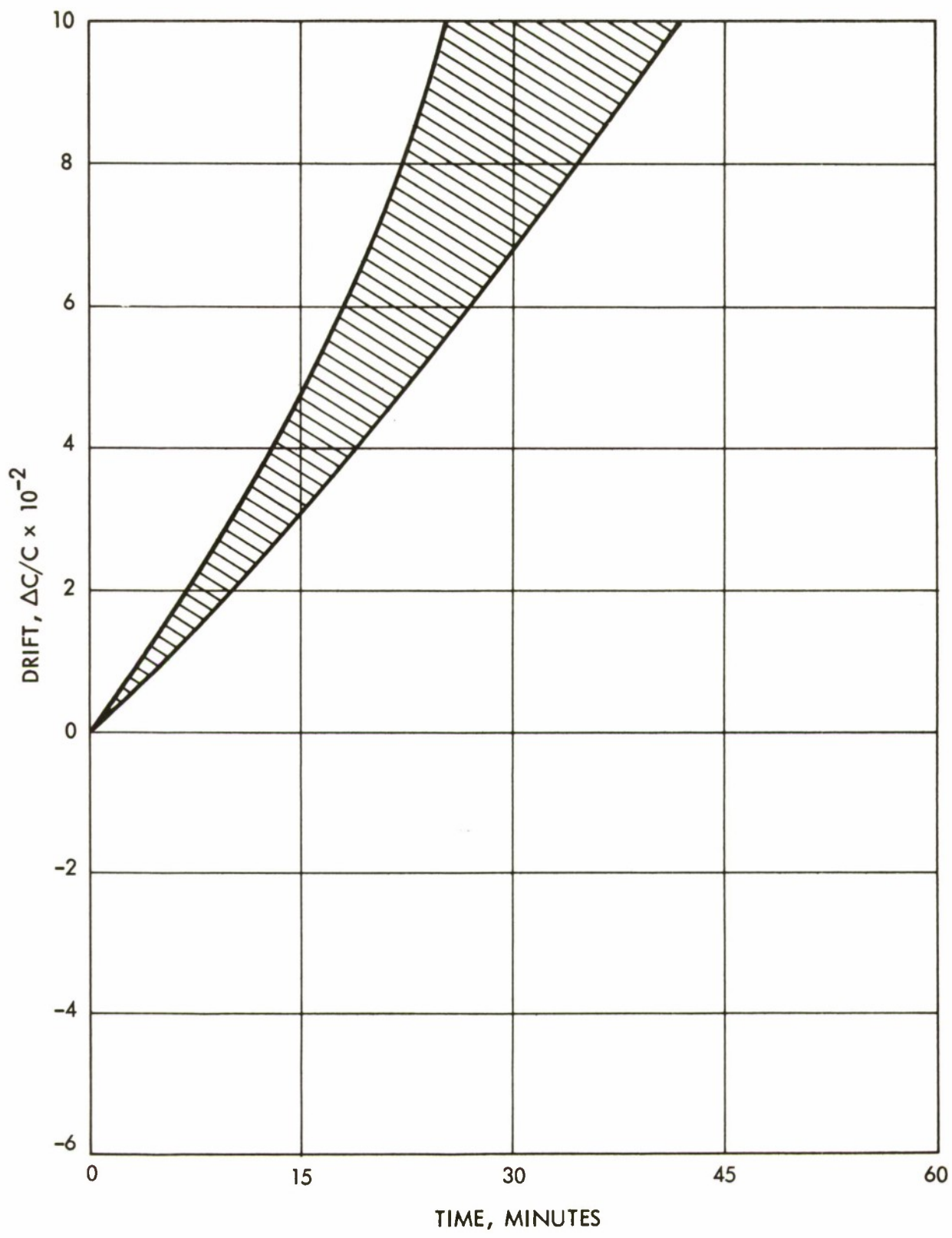


Figure 31. Drift at 2000°F (Heat Cured at 2000°F)

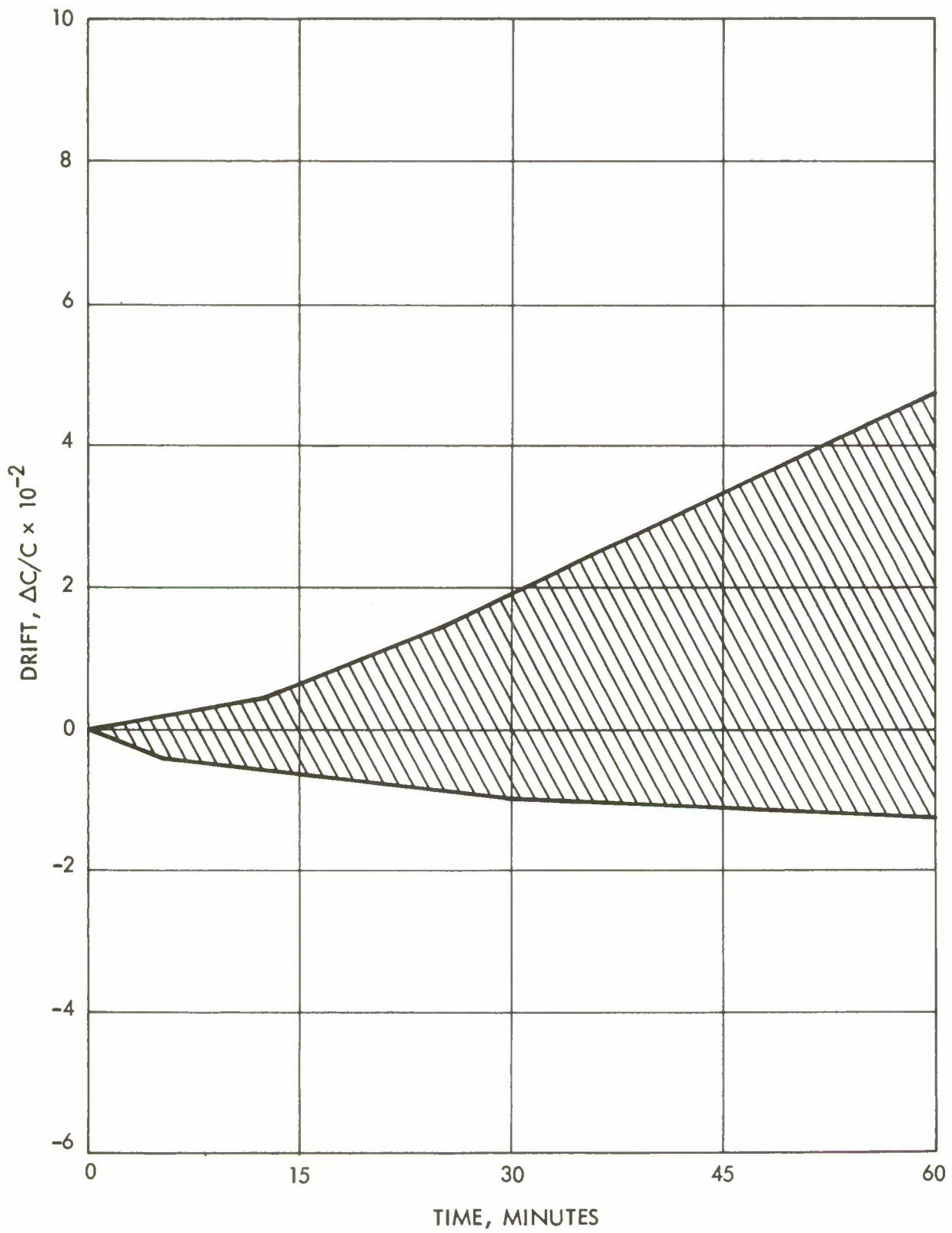


Figure 32. Drift at 1750°F (Gages Heat Cured at 1625°F)

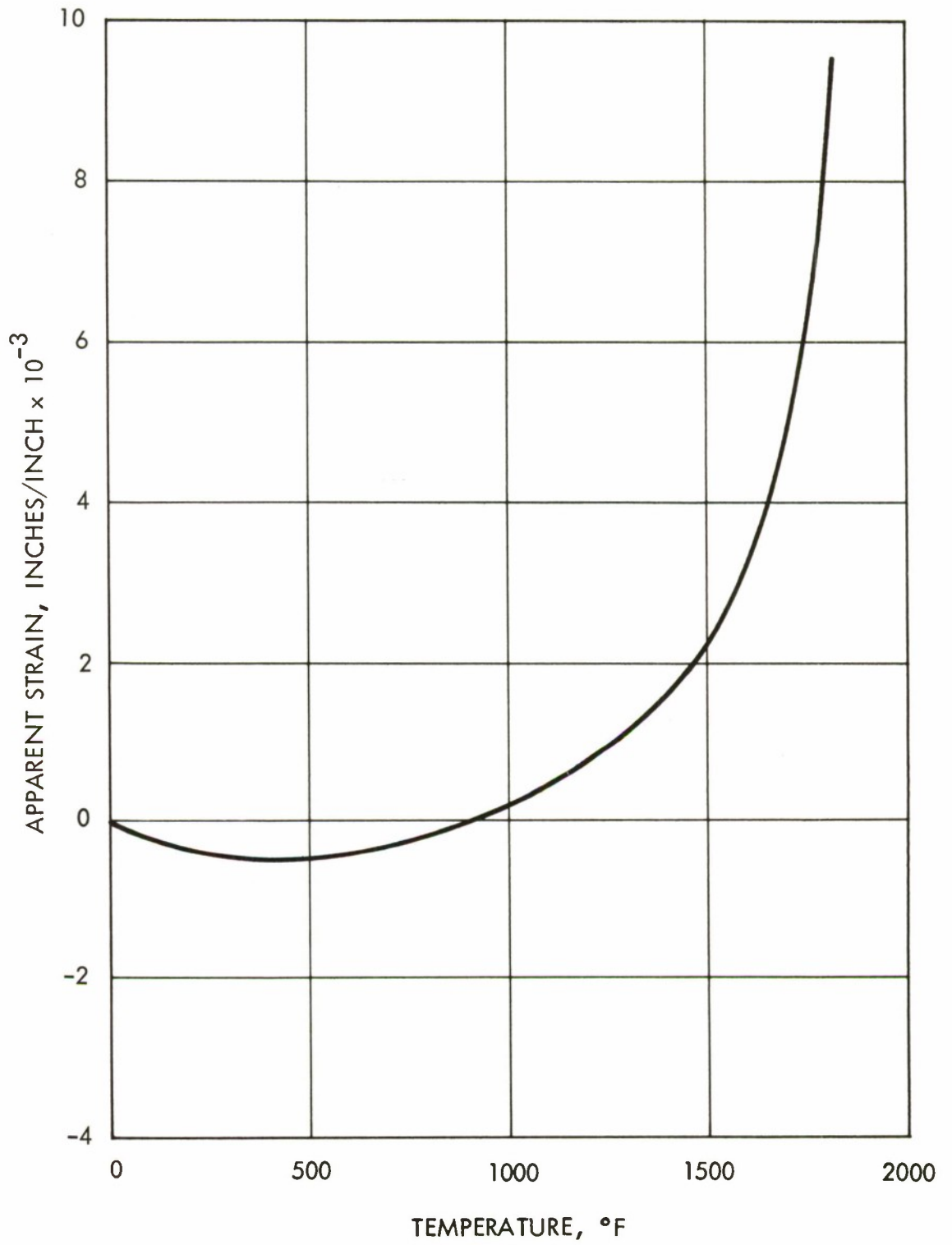


Figure 33. Apparent Strain Versus Temperature, Gage 23

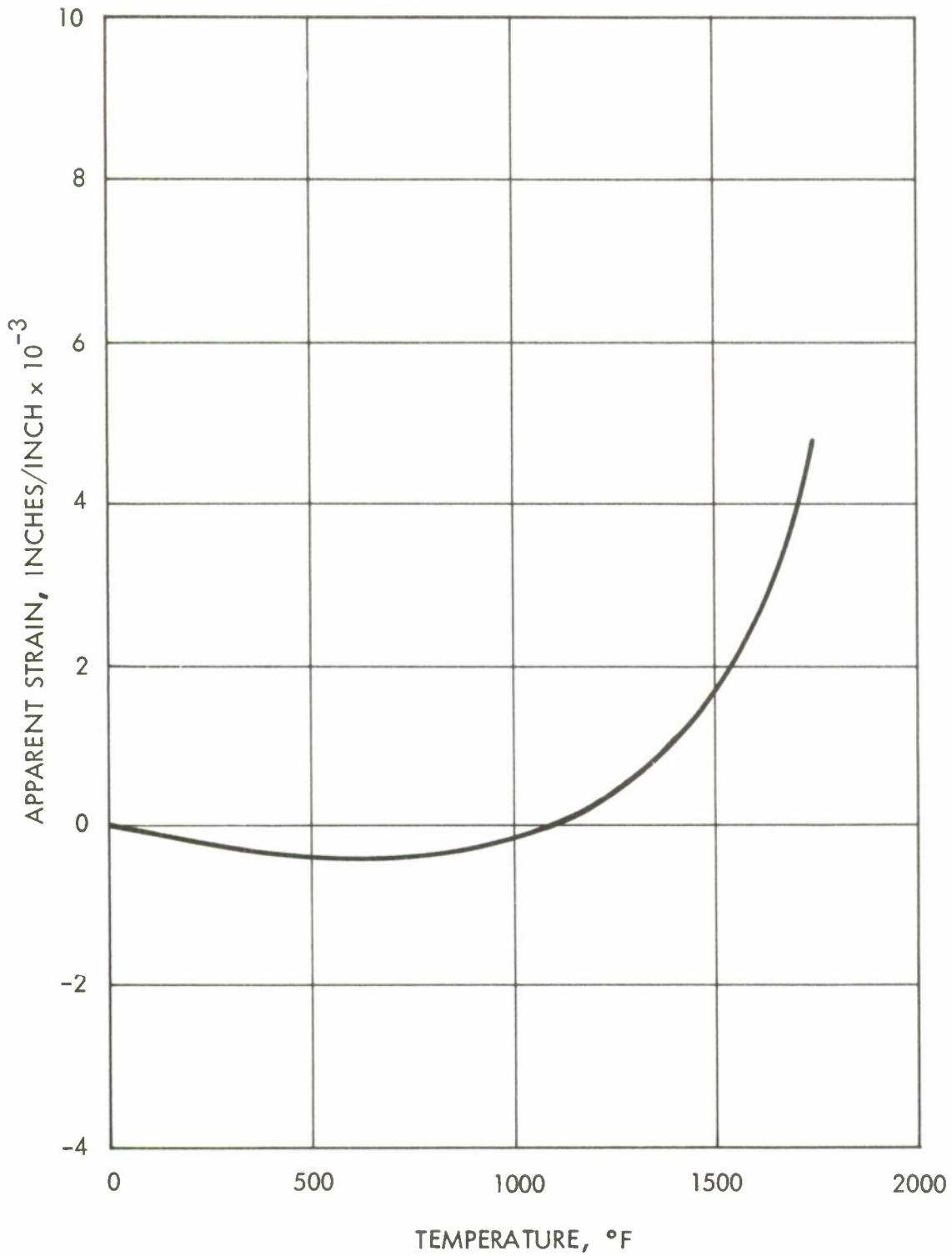


Figure 34. Apparent Strain Versus Temperature, Gage 19

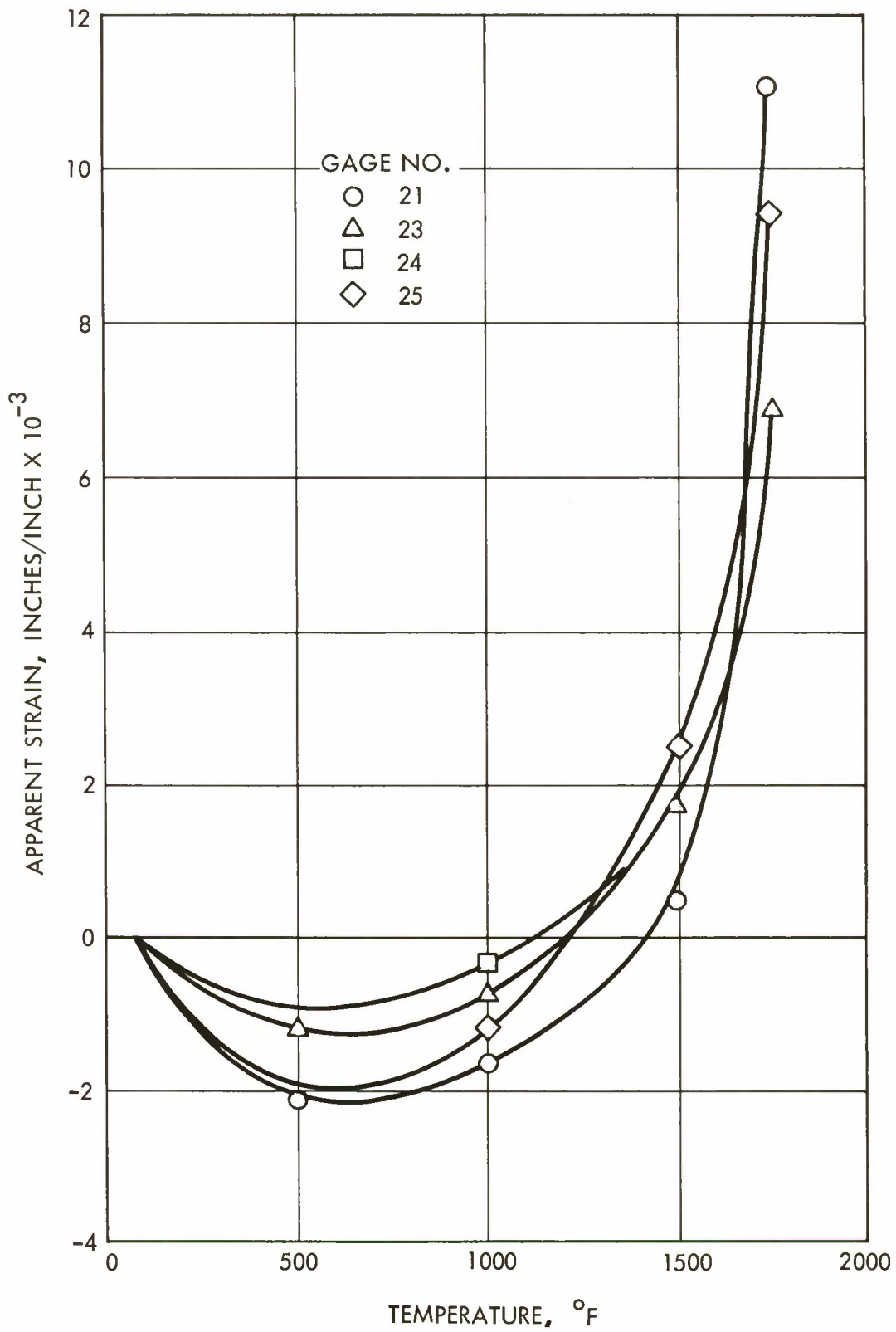


Figure 35. Apparent Strain, 10^0 F/sec Heat Rate

The apparent strain of gages cured at 2000°F becomes a serious problem, since the apparent strain becomes an order of magnitude greater than the real strain. The apparent strain of gages cured at 2000°F is presented in Figure 36.

ZERO SHIFT

The zero shift with temperature data also includes the effect of gage drift that occurred during the loading cycle. The gages cured at 1625°F (883°C) were more stable than those cured at 2000°F (1093°C). Figure 37 presents a history of the zero drift of gage 9 as a function of temperature. With the exception of the test at 1750°F (954°C), the zero shift was most prominent on the first cycle. Very little difference was found between zero shift in tension and compression. The zero shift of gages 19 through 25 at 1750°F (954°C) is presented in Figure 38. In all but one gage, the first cycle zero shift at temperature was less than .001 unit change in capacitance.

The gages cured at 2000°F (1093°C) exhibited considerable zero shift. No attempt was made to correct for the drift experienced by the gage in plotting the data. Figures 39 through 42 present the zero shift data on these gages at room temperature, 1750°F (954°C), 1875°F (1023°C), and 2000°F (1093°C). Zero shift and drift are a serious problem with this gage and must be handled carefully if meaningful data is to be gathered at the very high temperatures (above 1500°F (816°C)).

THERMOELECTRIC OUTPUT AND RESISTANCE TO GROUND

Thermoelectric output with a capacitance gage is not a problem as long as the gage continues to act as a capacitor; that is, it continues to have a very high resistance across the element. In all cases, the gage element started out above 10 megohms resistance. In the gages cured at 1625°F (883°C), this resistance was decreased at 1750°F (954°C) to approximately 50,000 ohms. The gages cured at 2000°F (1093°C) had a resistance at 1750°F (954°C) of about 40,000 ohms, reducing to 8000 ohms at 2000°C (1093°C). These resistances are still high enough to hold the thermoelectric effects of the high temperature tests to a negligible value, which could not be measured during test.

In all cases the resistance to ground remained above 10 megohms and was not a significant parameter in these tests.

FREQUENCY EFFECT

The effect of varying the frequency on the present gage configuration has little or no effect at frequencies above 50 kHz, with only a slight increase in output noted at frequencies tested below 50 kHz (Figure 43). It was decided to standardize the frequency of testing at 150 kHz, as this frequency matched equipment being developed for AFFDL under other contracts.

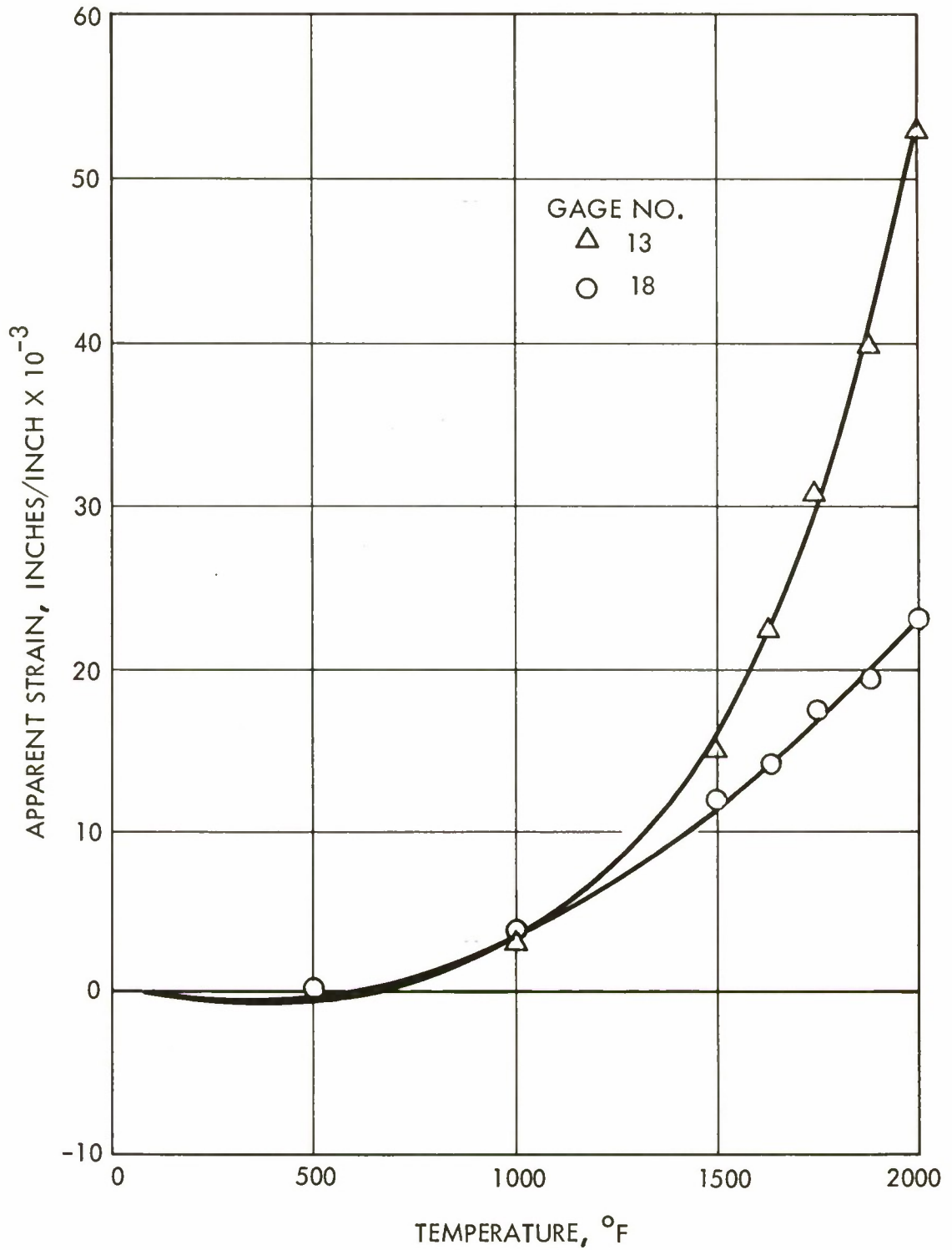


Figure 36. Apparent Strain Versus Temperature, Gages 13 and 18

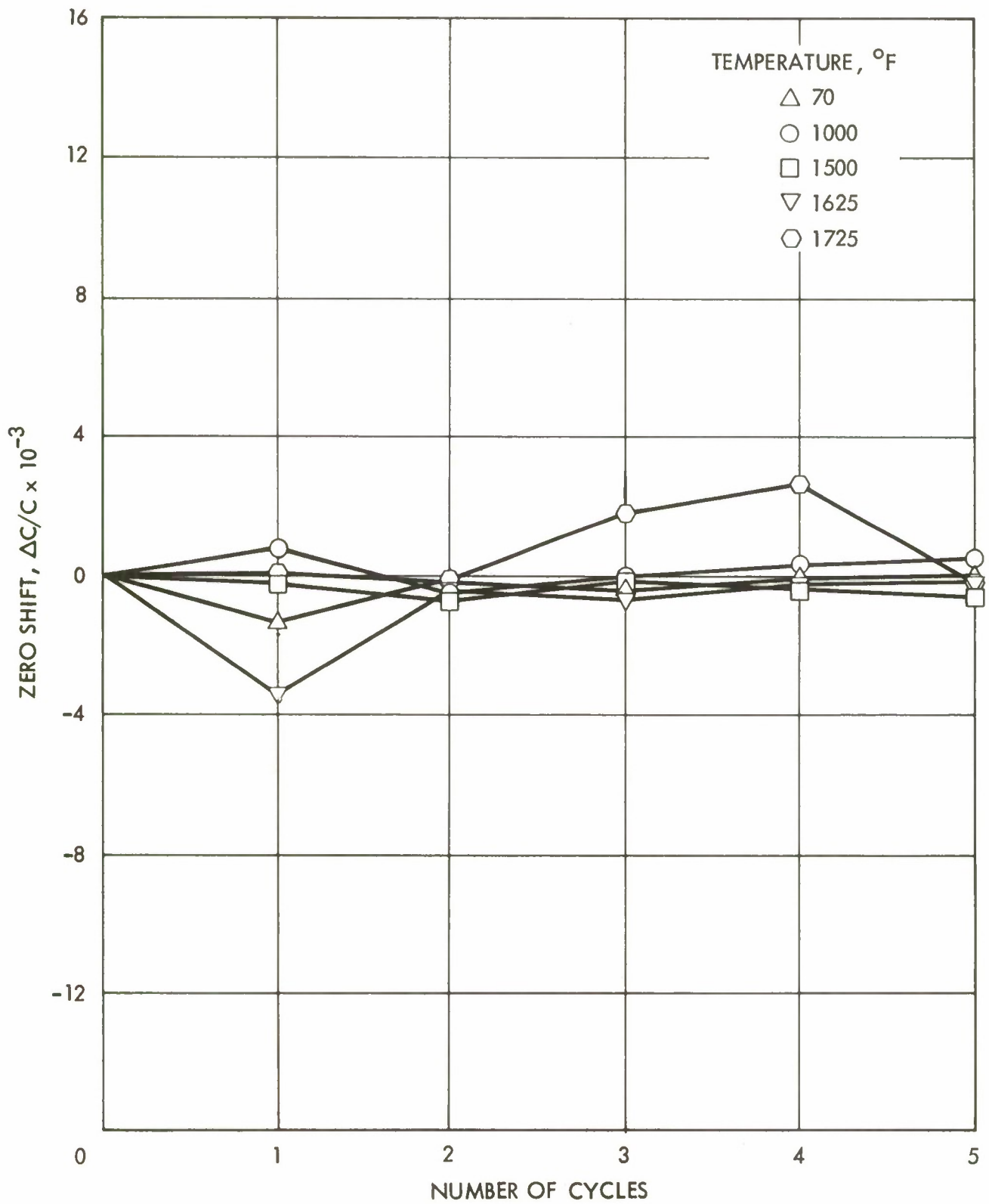


Figure 37. Zero Shift Versus Temperature, Gage 9 (Tension)

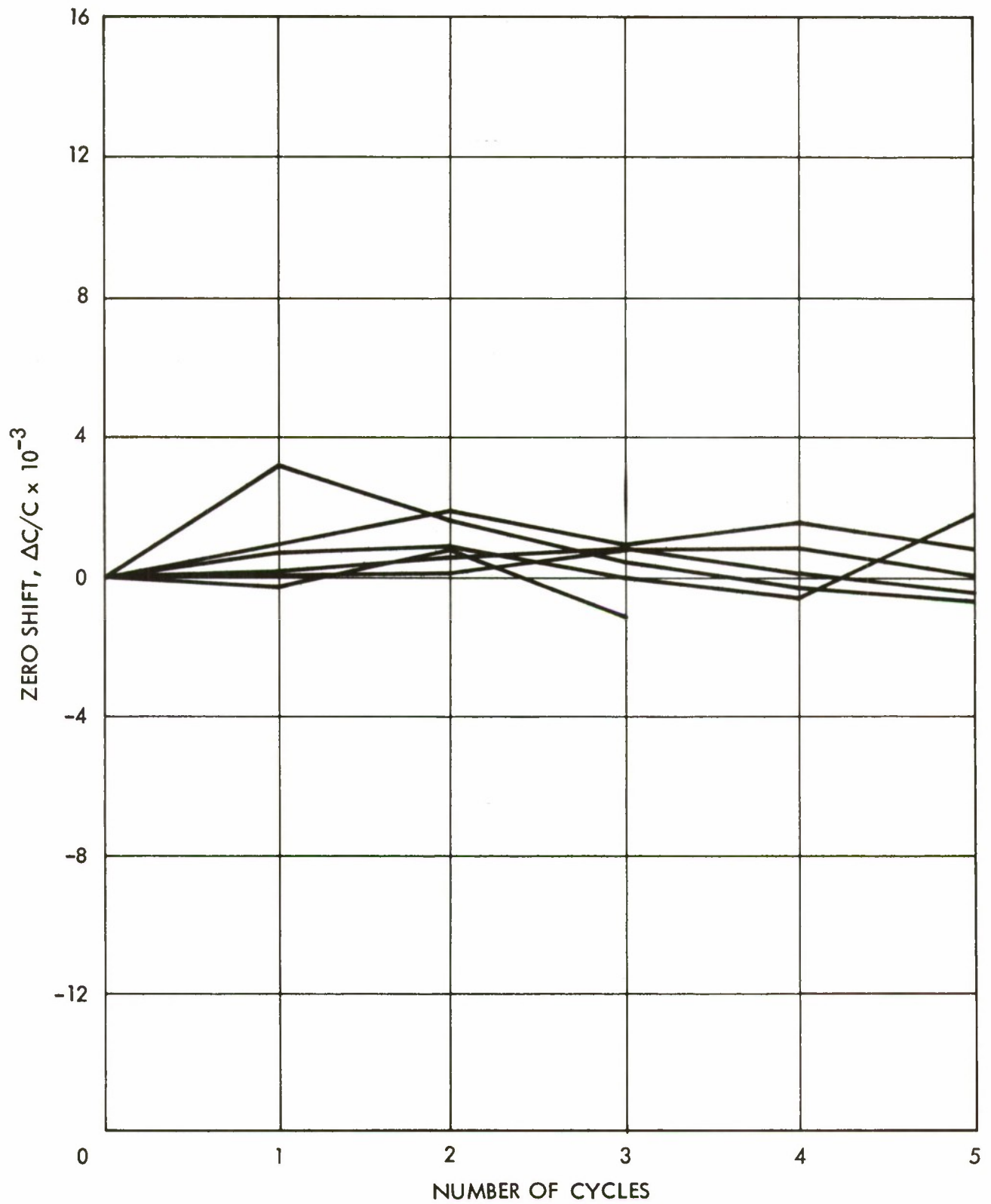


Figure 38. Zero Shift at 1750°F, Gages 19 Through 25

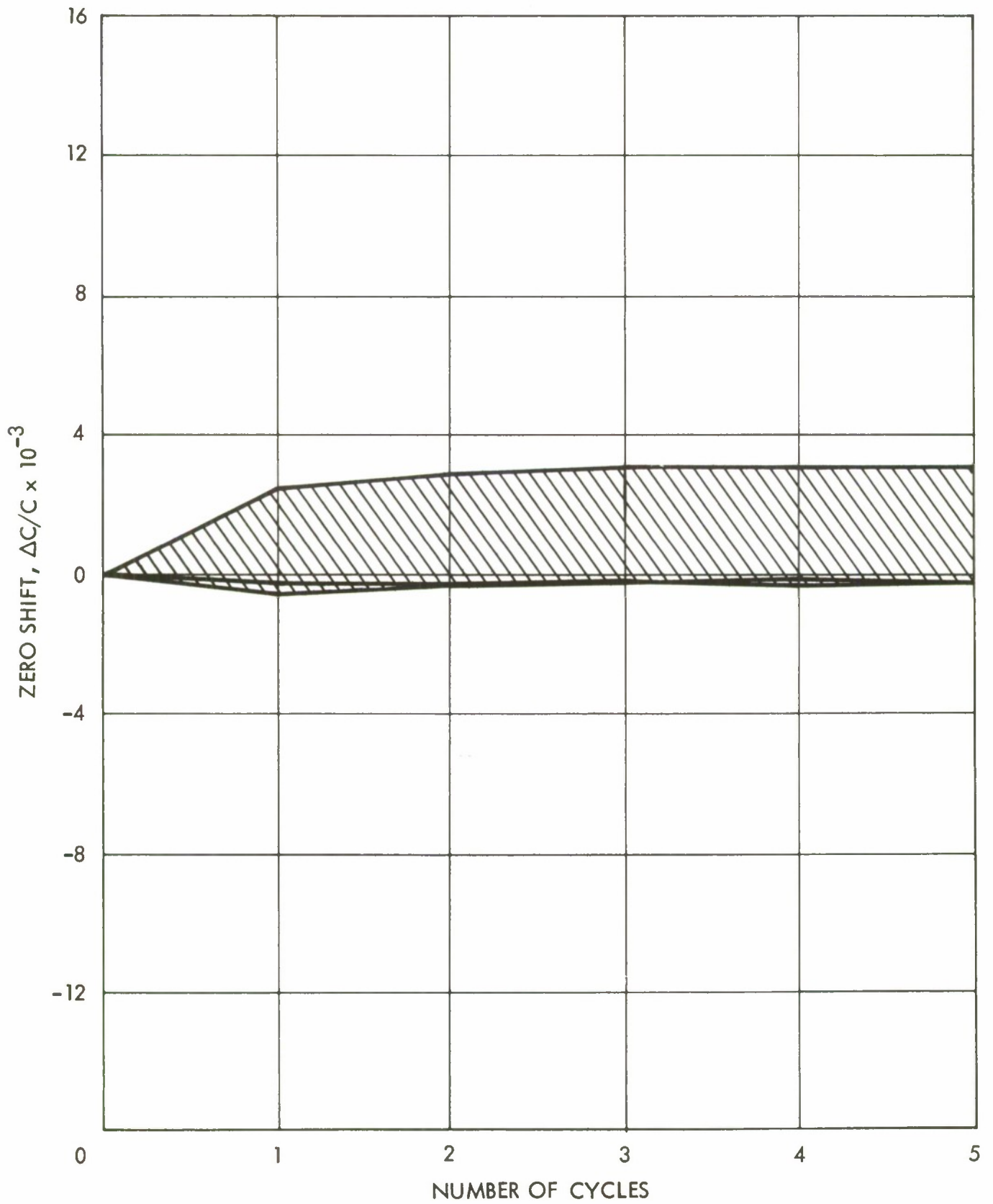


Figure 39. Zero Shift at Room Temperature, Gages Stabilized at 2000°F

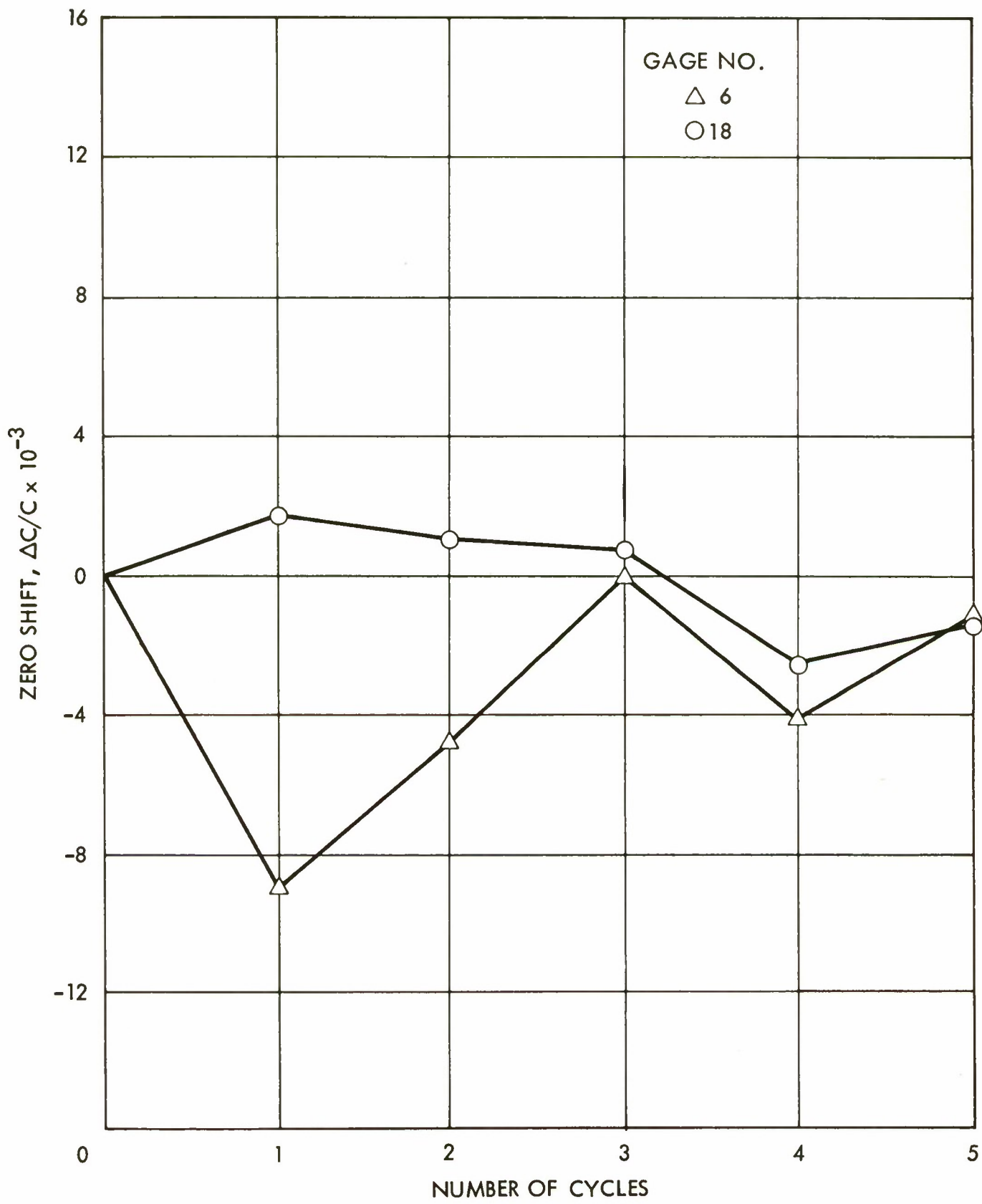


Figure 40. Zero Shift , 1750°F (954°C), Gages Stabilized at 2000°F (1092°C)

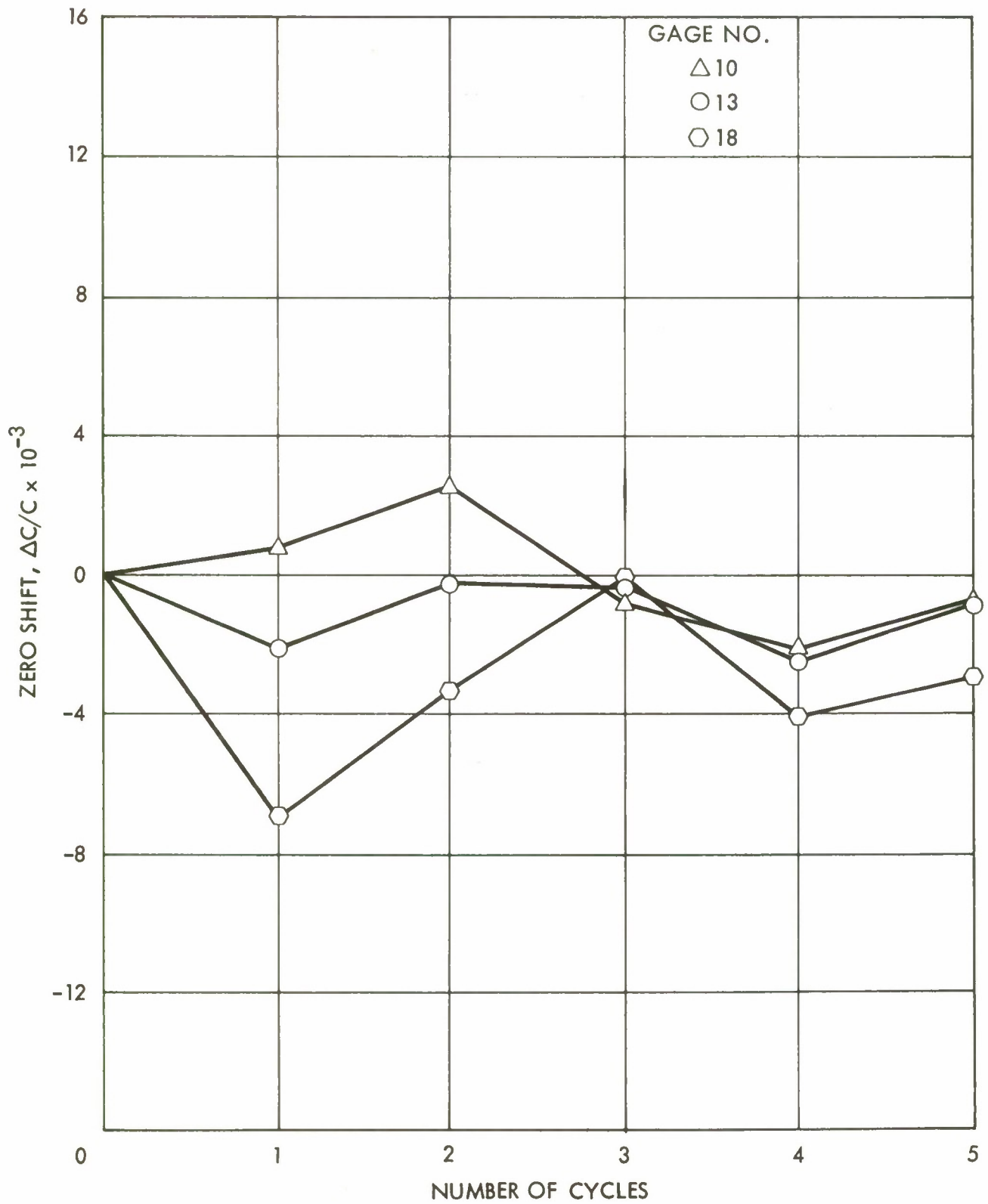


Figure 41. Zero Shift, 1875°F (1023°C), Gages Stabilized at 2000°F (1093°C)

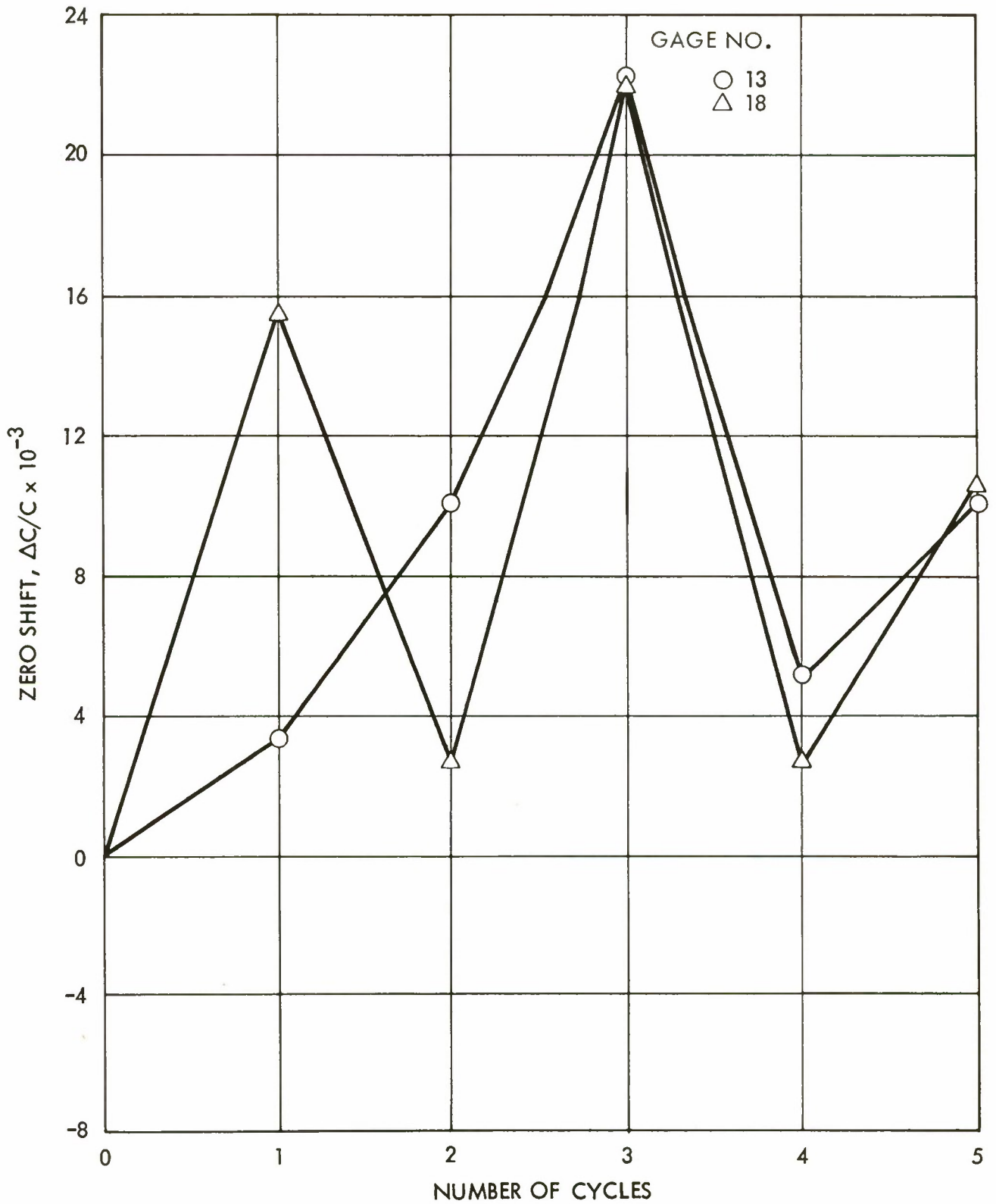


Figure 42. Zero Shift, 2000°F (1093°C), Gages Stabilized at 2000°F (1093°C)

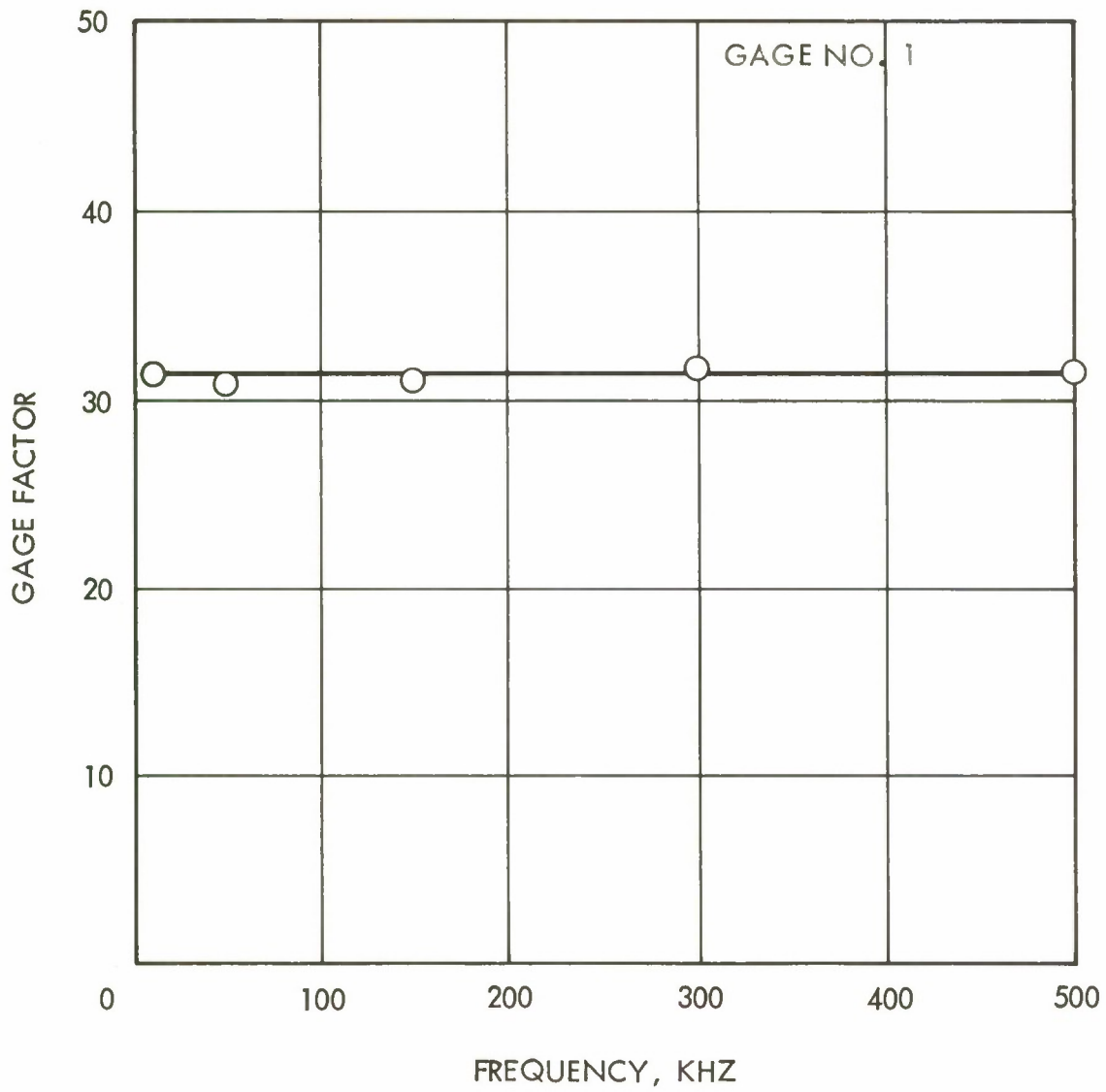


Figure 43. Frequency Versus Gage Factor (Room Temperature)

11. SUMMARY

A high temperature capacitance gage has been developed with a gage length of 1/2 inch. This gage is compatible for operation within the design environment of a structural testing laboratory using infrared heat lamps as a heat source. The performance of the gage must be considered in two parts: those gages cured at 1625°F (883°C) and those gages cured at 2000°F (1093°C).

Performance of the gages cured at 1625°F (883°C) is limited to a maximum temperature of 1750°F (954°C). The initial capacitance of the gage is generally below the target specification of 10 to 50 picofarads, with an average value of 8 picofarads. The gage factor variation gage-to-gage was very poor but, again, since the gage can be precalibrated and is repeatable within 5 percent, the effect is a gage performance of better than the target specification of 2 percent per 1000°F. The strain limit on the gage is +5000 microstrain, -2000 microstrain at room temperature and \pm 1500 to 2000 microstrain at 1750°F (954°C). The drift rate was greater than the target specification of 300 microstrain per hour at temperature. In the worst case, drift was 1000 microstrain in one hour at 1750°F (954°C). The resistance to ground was always greater than the specification of 10 megohms at temperature. The apparent strain was within the target specification of 5 microstrain per °F at the maximum heating rate. The zero shift per cycle was better than specification. Finally, the gage will operate within the frequency range of 5 kHz to 1 MHz. In summary, a gage that will operate at temperatures up to 1750°F (954°C) and meets most of the target specifications, providing an overall gage accuracy of better than \pm 10 percent, has been achieved.

The gages cured at 2000°F (1093°C) will provide data at temperatures up to 2000°F, but considerable accuracy has been lost. The gages are very sensitive to drift and apparent strain such that the initial gage capacitance will more than double by the time the gage has reached 2000°F (1093°C), and the temperature has been allowed to stabilize. This gage should only be used when it is necessary to provide data at the maximum temperature of 2000°F (1093°C).

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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 materials, configuration, and attachment study; a cable evaluation; and a manufacturing and evaluation phase. The final configuration was a rhombic strain frame with a capacitor element composed of Inconel plates and mica dielectric insulators. The overall gage length was 1/2 inch. A total of 50 sensors were constructed; 25 were tested at Hughes and 25 were delivered to the Air Force Flight Dynamics Laboratory. The gages were tested from 75°F (24°C) to 2000°F (1093°C). From the results obtained, it can be concluded that the capacitance gage provides a positive and accurate means of measuring strain at temperatures up to 1750°F (954°C). Under specified conditions, some data can be obtained at reduced accuracies at temperatures of 2000°F (1093°C).			

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
High Temperature Strain Measurement High Temperature Strain Gage Capacitance Capacitance Strain Gage						