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CHARACTERISTICS AND BEHAVIOR OF BONDED WIRE RESISTANCE STRAIN GAGES IN THERMAL COEFFICIENT OF EXPANSION MEASUREMENTS

PART I SR-4 PAPER BONDED A-7 AND BAKELITE BONDED AB-19 GAGES

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Physics Division

CHARACTERISTICS AND BEHAVIOR OF BONDED WIRE RESISTANCE STRAIN GAGES IN THERMAL COEFFICIENT OF EXPANSION MEASUREMENTS

PART I SR-4 PAPER BONDED A-7 AND BAKELITE BONDED AB-19 GAGES

by

Martin R. Goodman

Date Issued: MAY 31 1950

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CHARACTERISTICS AND BEHAVIOR OF BONDED WIRE RESISTANCE STRAIN GAGES IN THERMAL COEFFICIENT OF EXPANSION MEASUREMENTS*

PART I SR-4 PAPER BONDED A-7 AND BAKELITE BONDED AB-19 GAGES

Martin R. Goodman

Oak Ridge National Laboratory**

ABSTRACT

The thermal coefficient of expansion of metals can be measured to at least $\pm 0.1 \times 10^{-6}$ over the range 32.5 - 60.0°C by means of bonded wire resistance strain gages. The strain gages are found to exhibit gage creep and zero shift. Such gage malfunctions have to be differentiated from the performance of specimens under investigation. Methods are suggested to overcome these adverse gage properties so as to obtain greater strain gage stability and accuracy.

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* Most of this paper originally appeared as classified document ORNL-518, Dec. 1949. It appears here in revised form suitable for an unclassified report.

** Work performed under Contract Number W-7405, eng. 26 for the Atomic Energy Project.

SECTION A - STRAIN GAGE PERFORMANCE AND RELIABILITY FOR MEASUREMENT OF THERMAL COEFFICIENT OF EXPANSION OF METALS

Introduction

Problems associated with work carried on in the Oak Ridge National Laboratory made imperative an investigation of thermal coefficient of expansion and dimensional instability of various types of metals and alloys under a variety of pertinent conditions. A survey of the existing methods and devices to carry out such a program indicated that bonded wire resistance strain gages might be most appropriate and practical for this work.

Strain Gage Equations and Variables*

The derivation of the bonded wire resistance strain gage basic working equation is as follows:

Let R_g = initial gage resistance

ΔR_g = change in gage resistance

Δt = temperature change

e_g = temperature coefficient of expansion of the gage wire.

e_x = temperature coefficient of expansion of the material under test.

α_g = temperature coefficient of resistance of the gage wire

Γ = the gage factor or strain sensitivity

---

* References (1) and (2) at the end of this paper contain the fine points and the theory of strain gages.

In addition, let L_i = the initial length of a material at a temperature t_i

L_f = the length of a material at a temperature t_f

e = the temperature coefficient of expansion of a material

R_i = the initial resistance of a material

For any material $$\frac{\Delta R}{R_i} = \Gamma \frac{\Delta L}{L_i} \tag{1}$$

Also $$L_f = L_i (1 + e\Delta t) \tag{2}$$

$$\Delta L = L_f - L_i = L_i + L_i e\Delta t - L_i = L_i e\Delta t \tag{3}$$

Therefore $$\frac{\Delta R}{R_i} = \Gamma \frac{L_i e\Delta t}{L_i} = \Gamma e\Delta t \tag{4}$$

For a strain gage made from one material cemented on a specimen made from another material, we have, due to temperature change

$$\frac{\Delta R_g}{R_g} = \Gamma (e_x - e_g) \Delta t \tag{5}$$

The gage wire is insulated from the test specimen by bakelite or bonded paper and also the cement. But it must be remembered that the gage wire has a temperature coeff. of resistance α_g. This term has to be added to equation (5) in order to fully account for the change in resistance of the gage wire due to temperature.

We therefore get $$\frac{\Delta R_g}{R_g} = \alpha_g \Delta t + \Gamma (e_x - e_g) \Delta t \tag{6}$$

This is the basic working equation and can be written in various ways, as required. Thus, the temperature coeff. of expansion of any material can be found by means of the equation $$e_x = \frac{\frac{\Delta R_g}{R_g} - \alpha_g \Delta t}{\Gamma \Delta t} + e_g \tag{7}$$

R_g, ΔR_g and Δt can be directly measured. The value of Γ for each gage is supplied by the strain gage manufacturer. The temperature coeff. of expansion e_g of the gage wire depends upon the composition of the wire and the temperature range used. The value of α_g depends upon the type of gage wire employed and varies from spool to spool. It also depends on the drawing and annealing process used.

A mathematical substitution makes it unnecessary to know separately the values of the doubtful constants α_g and e_g in order to obtain e_x. Dividing equation (6) by Δt we get

$$\frac{1}{\Delta t}\frac{\Delta R_g}{R_g} = \alpha_g - \Gamma e_g + \Gamma e_x \tag{8}$$

Let

$$\alpha_g - \Gamma e_g = \beta \tag{9}$$

Then

$$\frac{1}{\Delta t}\frac{\Delta R_g}{R_g} = \Gamma e_x + \beta \tag{10}$$

and

$$e_x = \frac{\frac{1}{\Delta t}\frac{\Delta R_g}{R_g} - \beta}{\Gamma} \tag{11}$$

β can be found by solving equation (11) for a known substance: experimentally by cementing the gages on any specimen with a known coeff. of expansion e_x. Using this value of β the unknown coeff. of expansion can be determined if gages of the same type and from the same lot are used.

Strain Gage Specifications

Description of Strain Gages Used

SR-4 Strain Gage	Gage Wire Material	Nominal Gage Wire Length	Type of Wire Winding	Gage Wire Bonding Material	Nominal Gage Resistance	Approx. Gage Factor	Gage to Specimen Application Cement
AB-19	.001 inch Advance	1/16 in.	Helical grid	Bakelite	60 ohms	1.82±3%	Bakelite #6035 Poly.
A-7	.001 inch Advance	1/4 in.	Helical grid	Paper	120 ohms	1.92±2%	Duco (Household)

Cementing of Strain Gages to Specimens

Bakelite Bonded Gages

The following procedure was used in cementing bakelite bonded gages to test specimens:

1. Specimens were cleaned with acetone, the surface slightly roughened with emery cloth, and again cleaned with acetone.

2. A thin coat of bakelite cement was applied to the surface to which the gages were to be cemented.

3. The gages, cleaned in acetone, were applied to the desired location. A piece of cellophane was placed over each gage and a small piece of 1/8" neoprene over the cellophane. Metal plates designed to fit the gages and specimens were clamped over the gages by means of compression springs and pressures up to 500 lbs/in^2 were applied, depending on the area of the gages.* A very thin cement film and excellent bonding was thus obtained.

4. The gages, while still clamped, were baked respectively for 1 hour at 175°F, 2 hours at 250°F and 1 hour at 300°F.

Paper Bonded Gages

The same general procedure as for bakelite bonded gages was followed except that Duco cement was used, the spring pressure was lowered to 150 lbs/in^2, and the gages were air dried at 70°F for 2 hours, baked at 120°F for 3 hours, and at 170°F for 8 hours.

Precision of Experimental Measurements

The following data give the precision of experimental measurements:

$\Delta R_g \pm .0001$ ohm

$R_g \pm .0001$ ohm

$\Delta t \pm 0.1°C$

$\Gamma \pm$ 2% or 3%, as stated by the manufacturer.

e_x Depends upon gages used.

Metals Used

2S Aluminum - annealed and unannealed. Coeff. of expansion 24.0×10^{-6}

Copper - annealed and unannealed. Coeff. of expansion 16.8×10^{-6}

Nilvar - Coeff. of expansion 1×10^{-6}

Special metals under investigation

---

* See photograph #1.

Temperature Mediums

Transformer oil bath controlled to ± 0.1°C.

Air at room temperature controlled to ± 0.5°C.

Cyclic Character

Runs at random constant temperatures and runs between fixed constant temperatures of 32.6 and 60.1°C. Readings taken over as many as 8 cycles.

Duration of Readings at Constant Temperature

A few hours to over 3 months.

Apparatus

Leeds and Northrup G-2 Mueller resistance bridge. Direct current Wheatstone bridge arrangement using a high sensitivity moving coil galvanometer as a null indicator. Bridge range 0 to 111.111 ohms in steps of 0.0001 ohm. Limit of error less than 0.0001 ohm. Thermostatically controlled built in heater keeps bridge at approximately 35°C constant within ±0.01°C. Mercury contact commutator provides means for reversing the connections to four lead resistance thermometers for the purpose of cancelling the effect of lead resistance.*

Leeds and Northrup 12 channel switching unit. Contact resistance very low and its effect eliminated by Mueller bridge.

Leeds and Northrup precision standard 100 ohm resistor, calibrated by Bureau of Standards, used to check resistance variation due to temperature change or circuit misbehavior.

Leeds and Northrup K-2 potentiometer.

---

* For further details about the G-2 Mueller bridge, including the bridge circuit and operation, one is advised to see the Leeds and Northrup catalog E-33C (1), 1943, and also the direction book 77-2-1-1.

Sensitivity

Can easily detect a change in strain of 1×10^{-6} in/in.

Insulation Resistance

Greater than 1000 megohms in any part of the circuit, including the oil bath.

Waterproofing

None deemed necessary under the test conditions used.

Photographs of Laboratory Set-Up

Photograph #1 shows the strain gage application device.

Photograph #2 shows the general set-up of the experiment in action.

Dummy Control Gages

When measuring strain produced by applied loads it is necessary to eliminate all errors that may be introduced by the gage itself, by the measuring instruments, and by temperature fluctuations. This is usually accomplished by employing what may be called dummy control or compensating gages. Similar gages are cemented on the material to be tested under strain and on a sample of this material to be left unstrained, with the sample being placed along side the material undergoing strain. This means that the difference in readings between the active and dummy gages should be due to the actual strain as measured by the active gages on the strained material. Gage characteristics are assumed to be the same and unchanged by the conditions of test. Temperature difference between dummy and active gages is assumed to be negligible. Instrument zero shift and contact resistance are eliminated by reversing the positions of the active and dummy gages in the circuit and averaging the readings.

The experiments at the Oak Ridge National Laboratory did not involve the placing of load on the specimens, changes being effected merely by

change of temperature or by irradiation, so that in reality all test gages were active dummy gages. This meant that the dummy gage principle could not be used and that it was necessary to know the strain gage behavior under the conditions of test so that the effects to be measured could be differentiated from the strain gage characteristics.

The Value and Reliability of β for A-7 Paper Bonded Strain Gages on Copper

To calibrate and check the A-7 strain gages it was decided to determine β with the gages mounted on a copper specimen, in which case e_x is 16.8×10^{-6}. This work was started in air at room temperature and employed a Leeds and Northrup K-2 potentiometer hook up. It was noted that the readings appeared to vary with time. This fact together with the temperature being constant to only $\pm 0.5^{\circ}C$ decided us in favor of a constant temperature oil bath. Accordingly, a new copper specimen was made, A-7 paper bonded gages attached with Duco cement, and 10 runs were made in oil at various temperatures between 20 and $41^{\circ}C$ to determine β for the type of gage used. Results are presented in Table 1.

Table 1

Gage # (Same specimen)	Average β for 10 runs with A-7 paper bonded strain gages on copper
1	-28.9×10^{-6}
2	-28.9
3	-29.1
4	-28.7
5	-28.4
6	-29.1
	Av. $-28.9 \pm 0.2 \times 10^{-6}$

The average value of β for all the gages includes the 50% probable error of $\pm$ 0.2 x 10^{-6}. The probable error in β for each individual gage was $\pm$ 0.2 x 10^{-6}.

The calculation of the thermal coeff. of expansion of the special metals under investigation were based upon the average value of β from Table 1. ΔR was taken as the difference between the reading immediately preceding temperature change and the peak reading upon reaching temperature equilibrium at the new temperature. Substitution of measured values in equation (11) gives the desired value for the unknown coeff. of expansion. The SR-4 paper bonded A-7 strain gage thus appears to give coeff. of expansion values to a 50% probable error of $\pm$ 0.1 x 10^{-6}.

Changes to Increase Experimental Precision

Similar to the runs in air, the readings at constant oil temperature varied with time and appeared to simulate some sort of relaxation phenomenon. The same type of effect appeared in runs with the special metals under investigation.

To increase the precision of further experiments two major changes were made. (1) The K-2 potentiometer was replaced by the G-2 Mueller bridge and the circuit changed accordingly. This meant that the measuring instrument was always at constant temperature and that gage resistance could be read directly instead of reading potentials. (2) Bakelite strain gages were used instead of paper bonded strain gages. This was to insure greater gage stability and to check whether the observed "relaxation" effects were characteristic of the specimens or of the strain gages being used.

The Value and Reliability of β for AB-19 Bakelite Bonded Strain Gages

Bakelite AB-19 gages were applied with bakelite cement to samples of annealed copper, annealed 2S aluminum, unannealed Nilvar (coeff. of expansion 1 x 10^{-6}), and the special metals under investigation. All Specimens were

placed together in an oil bath and simultaneously underwent the same treatment for 5 cycles. A temperature cycle consisted of 4 days at 32.6°C and 4 days at 60.1°C. The time for temperature increase and decrease was one hour.* To check temperature and circuit stability a Leeds and Northrup precision standard 100 ohm resistor was also added in the circuit and cycled with the specimens. Results are presented in Table 2.

Table 2

Gage #	Specimen	AB-19 Bakelite strain gages. Average β for 10 runs or 5 complete cycles
6	Copper	-27.9×10^{-6}
7 (Same specimen)	Copper	-29.2
8	2S Aluminum	-32.5**
10	Nilvar	-23.8
		Av. $-28.4 \pm 2.1 \times 10^{-6}$

The calculation of the thermal coeff. of expansion of the special metals was based upon the average value of $\beta = -28.4 \times 10^{-6}$. The 50% probable error in β for each individual gage was $\pm 0.1 \times 10^{-6}$. However, it was found that the value of β between similar gages varied and that the 50% probable error of the average β between gages was $\pm 2.1 \times 10^{-6}$. This rather large uncertainty enters in the determination of the coefficient of expansion, with

* The gage wires from one of the special metal specimens were accidentally broken off after $1\frac{1}{2}$ cycles. Since the wires were broken off at the base of the gages they could not be repaired. The specimen was therefore removed and replaced by two plain gages, one with and one without cement, unattached to any specimen and hanging freely in the oil bath. The results of the unattached gages will be discussed in Section B of this paper.

** One value obtained was so low as to indicate a possible malfunction of the gage.

the result that the uncertainty in any coefficient of expansion measurement is 1.2×10^{-6}. It should be pointed out that the special metals coeff. of expansion values, as given by each individual gage, repeated themselves within a 50% probable error of $\pm 0.03 \times 10^{-6}$.

Conclusions for Section A

Employing any individual SR-4 paper bonded A-7 and bakelite bonded AB-19 wire resistance strain gage the observed 50% probable error in gage β was ± 0.2 and $\pm 0.1 \times 10^{-6}$ respectively. Gage β values and in turn specimen thermal coefficient of expansion values were found to repeat within these limits regardless of the number of cycles, regardless of the varying time duration of the cycles, and regardless of whether the readings represented either an increasing or decreasing temperature.

For A-7 gages there appears to be no difference in gage β value between the individual gage and the same lot of gages whereas for AB-19 gages β appears to vary appreciably within the lot.

The large varience in β for the AB-19 gages may perhaps be attributed to the type of gage used since very small gages are thought to be less stable than larger gages. It is also possible that perhaps a bad or unstable lot of gages were employed although the gages were supposed to come from a typically representative lot. Further tests with this type of gage on materials of known coefficient of expansion should give better statistics and more information as to the suitability of this type of gage for coefficient of expansion measurements.

Provided that an appropriate strain gage is employed, thermal coefficient of expansion should be able to be measured to at least $\pm 0.1 \times 10^{-6}$ over the range 32.5 - 60.0°C.

SECTION B - STRAIN GAGE CREEP AT CONSTANT TEMPERATURE

Relaxations or Gage Creep

Throughout all measurements of the coeff. of expansion it was always noted that the readings either decreased or increased with time if readings were continued after temperature equilibrium had been reached. Apparently some sort of strain relaxation phenomenon was taking place. At first this was attributed to a characteristic of the special metals but since in the experiments with the known calibrating metals the same type of relaxation patterns were found (except for magnitude) it was concluded that perhaps evidence of a creep of the gage itself was responsible. This relaxation or creep was observed both in air and in oil, both in paper bonded and in bakelite bonded strain gages, and using either the potentiometer or the resistance bridge circuit.

To check circuit stability and temperature, as mentioned in Section A, a Leeds and Northrup precision standard 100 ohm resistor was inserted in the oil bath next to the specimens. This standard was hooked up in the strain gage circuit so that for all practical purposes it could be considered as another strain gage. During cyclic temperature changes the resistance of this standard repeated itself within 1×10^{-6} and showed no creep effects.

The above information was interpreted as meaning that the circuit was behaving properly, that there was no measurable metallic creep,* and that therefore the peculiar creep or relaxations observed were probably a manifestation of strain gage characteristics under the conditions of test.

---

* The question of metallic creep in the sample itself was discussed with the staff of the Metallurgy Division. According to expert opinion there was very little likelihood of an appreciable contribution to creep of such small magnitudes by the various metal specimens used since no load was applied and the temperature was much too low.

Typical Gage Creep Curves

Figure 1 shows a typical gage creep or relaxation curve obtained in oil with paper bonded A-7 gages on special metal under investigation at a constant temperature of 60.0°C.

Work on coefficient of expansion measurements and on creep curves was simultaneously done with AB-19 bakelite gages on copper, 2S aluminum, Nilvar, and special metals. Apparent creep was closely followed for all specimens at the temperatures of 32.6°C and 60.1°C. The time duration of each half of the temperature cycle was exactly the same, this being 4 days. The complete cycle was consecutively repeated 5 times without interruption.

Figure 2 shows typical creep curves of AB-19 gages on various control metals during the first of the 5 complete cycles. It will be noted that the direction of creep at 32.6°C is opposite to that at 60.1°C. It will also be observed that the general creep patterns for all metals are the same and differ only in magnitude.

A comparison of Figures 1 and 2 and other graphs not shown indicates that under similar conditions the paper bonded gages creep about 3 times as much as the bakelite gages.

A graphical analysis* of the creep curves indicated 2 apparent relaxation times, these being of the order of 1.4 hours and then 50 to 320 hours for the A-7 gages at 60.0°C. The AB-19 gages had relaxation times of from 7 to 14 hours and then from 45 to 165 hours at 60.1°C.

---

* Log $(R_g - R_\infty)$ was plotted against Time. R_g is the measured gage resistance and R_∞ is the gage resistance extrapolated to infinitely long time of observation.

Effect of Continued Temperature Cycling on Gage Creep

Figure 3 shows what happens to the creep curves due to continued temperature cycling. It will be noted that gage creep appears to decrease in magnitude and tends to approach a straight line.

Figure 4 shows a somewhat unusual type of creep curve at 60°C which reverses its direction. It will be noted, however, that continued cycling appears to reduce creep, with the curves tending to approach a straight line.

The above results suggest a need for at least 10 cycles of curing* at temperatures equal to or above expected experimental use in order to bring about better gage stability. The number of curing cycles necessary will probably vary depending on the gage application and baking procedure, the type of gage used, and the contemplated experimental temperature.

Effect of Time on Gage Creep

Figure 5 shows a continuation of creep with time in the 5th cycle at 32.6°C. That is, measurements were continued after the 4th day of the 5th cycle at 32.6°C without change of temperature. The curves appear to consist of two component parts, one indicating a relatively fast creep lasting 4 days and the other part indicating a slow constant creep rate which seems to continue.

Tests were made to determine whether gage creep would be affected by change of the period of thermal cycle duration. The temperature of 60°C was always held constant for 4 days whereas the temperature at 32.5°C was held from 1 to 18 days. Unfortunately the creep readings were not followed at the lower temperature but the results at 60°C are rather interesting, as shown in Figure 6.

---

* We are indebted to Mr. F. Hines for information regarding the baking and curing procedure followed in the Ruge-De Forest Laboratories, Cambridge, Massachusetts.

It is seen that whenever the time at 32.5°C was increased the resulting gage creep greatly increased after change to 60°C. The initial creep for cycle I at 60°C is exceeded by the creep for cycle VII at 60°C after having remained for 18 days at 32.5°C before change to 60°C.

Creep of Uncemented Strain Gages

As mentioned in a footnote in Section A, two AB-19 gages not cemented to any specimen were cycled in the oil bath. The strain changes for these gages between 32.6 and 60.1°C. are in the same range as the gages cemented to specimens but do not repeat and are erratic. The magnitude of creep at constant temperature is 10 times greater than that for any gage cemented to a specimen and indicates an apparent strain of about 1000×10^{-6} in/in after 4 days. Such results are to be expected due to the nature of the tests. It should be remembered that while the gage bonding material and the cement are very thin compared with the sample of metal under test, they are not thin compared with the gage wire. When the gage is properly cemented to a specimen it is expected to follow the dimensional changes of the specimen so that the properties of the gage bonding material and cement are suppressed. Any gage not cemented to a specimen would therefore be expected to follow the large and erratic dimensional changes of the gage bonding material and the cement. The occurrence of gage creep appears to indicate that the gage properties are not completely suppressed by being bonded to the specimen.

Direction of Gage Creep Curves

The general trend of the gage creep curves at constant temperature remains to be accounted for. This can perhaps be accomplished by first considering the direction of $\frac{\Delta R_g}{R_g}$ during actual change of temperature and then matching the gage creep curves with the immediate previous history of the gage. Experimental results give the following types of curves:

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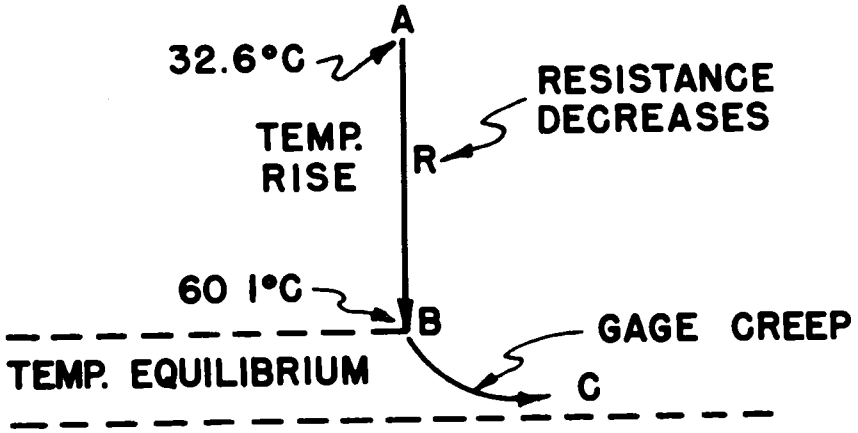
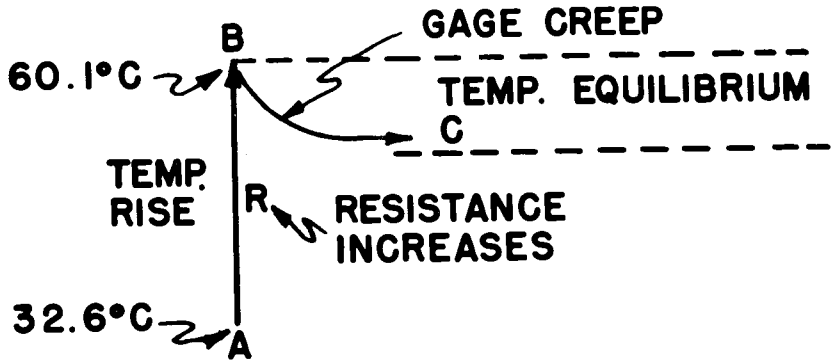
CASE A-1 RISE IN TEMP., $\frac{\Delta R_g}{R_g}$ NEGATIVE



OCCURRENCE

NILVAR — COEFF. OF EXPANSION 1×10^{-6}
SPECIAL METALS — COEFF. OF EXPANSION FROM 5.0 TO 14.9×10^{-6}

CASE B-1 RISE IN TEMP., $\frac{\Delta R_g}{R_g}$ POSITIVE



OCCURRENCE

2 S ALUMINUM — COEFF. OF EXPANSION 24.0×10^{-6}
COPPER — COEFF. OF EXPANSION 16.8×10^{-6}
SPECIAL METALS — COEFF. OF EXPANSION FROM 15.5 TO 30.1×10^{-6}

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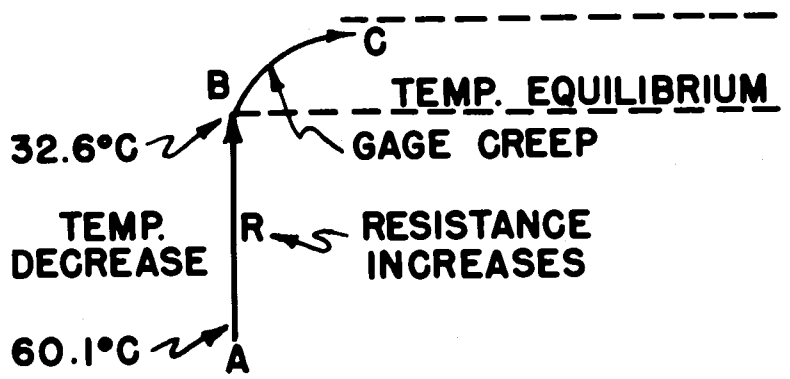
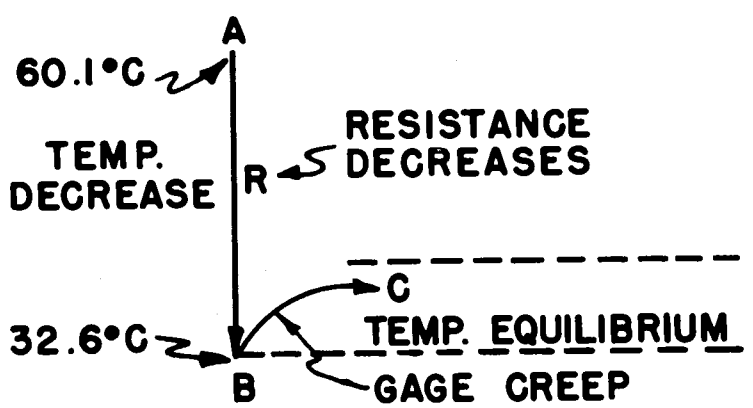
CASE A-2 DECREASE IN TEMP., $\frac{\Delta R_g}{R_g}$ POSITIVE



OCCURRENCE

NILVAR – COEFF. OF EXPANSION 1×10^{-6}
SPECIAL METALS – COEFF. OF EXPANSION
FROM 5.0 TO 9.9×10^{-6}

CASE B-2 DECREASE IN TEMP., $\frac{\Delta R_g}{R_g}$ NEGATIVE



OCCURRENCE

2 S ALUMINUM – COEFF. OF EXPANSION 24.0×10^{-6}
COPPER – COEFF. OF EXPANSION 16.8×10^{-6}
SPECIAL METALS – COEFF. OF EXPANSION
FROM 18.8 TO 19.9×10^{-6}

Please clip and insert the following omission as paragraph 3 on page 21:

For Case B-1 the specimen coeff. of expansion is always greater than the coeff. of expansion of the gage wire. For a temp. increase the specimen expands more than the gage wire, putting the gage wire under tension, and resulting in an increase of gage resistance (line AB).

The above cases can perhaps be analyzed, in part, by considering what happens to the gage when a change of temperature is brought about.

For Case A-1 the specimen coeff. of expansion is always less than the coeff. of expansion of the gage wire (approx. 14.8×10^{-6}) so that for a temp. increase the specimen expands less than the gage wire, putting the gage wire under compression, and resulting in a decrease of gage resistance (line AB).

During actual temperature change the bakelite material only serves to transmit the dimensional change in the specimen to the gage wire. At temp. equilibrium a gage creep BC is observed in the same direction for Cases A-1 and B-1. Since creep of the specimen or the gage wire has been ruled out as highly unlikely it appears that creep of the bakelite would explain the observed results at constant temp. Let us assume that the bakelite material used for the gages has a coeff. of expansion greater than that of any of our specimens, say, for example, 40×10^{-6}. On reaching temp. equilibrium the bakelite material is put under great tension by means of the more rigid specimen, which prevents the bakelite from expanding to assume its normal length at the higher temperature. The strains in the bakelite are relieved by a creep contraction which in turn forces the gage wire to contract and the resistance to decrease (BC).

Case A-2 is the reverse of Case A-1 due to temp. decrease. Now the specimen contracts less than the gage wire, putting the gage wire under tension, and resulting in an increase of gage resistance (line AB).

Case B-2 is the reverse of Case B-1 due to a temp. decrease. Here the specimen contracts more than the gage wire, putting the gage wire under compression, and resulting in a decrease of resistance (line AB).

Again the effect of the bakelite may be neglected during actual temperature change. On reaching temp. equilibrium the bakelite material is put under great tension by means of the more rigid specimen, which prevents the bakelite from contracting to assume its normal length at the lower temperature. The strains in the bakelite are relieved by a creep expansion which in turn forces the gage wire to expand and the resistance to increase (BC).

The analysis presented* has been greatly simplified. No account is taken of the contribution by the coeff. of resistance α_g of the gage wire. But α_g should be eliminated at temp. equilibrium. It is assumed that the gage has a finite thickness, with the interface being rigidly bonded to the specimen by means of the gage application cement and its bakelite body being subject to creep under certain conditions. The assumption that the bakelite has a coefficient expansion greater than that of any of our specimens appears valid in that the magnitude of creep (see Figure 2) appears to be smaller the greater the coefficient of expansion of the test specimen. Presumably this suggests that if the gage were cemented to a specimen with the same coefficient of thermal expansion as the bakelite there would be no creep of the gage.

This paper makes no attempt to develop a quantitative theory of gage creep since the utility of the gage rather than the gage itself was the object of importance. However, it was found necessary to investigate gage behavior in so far as one must be able to differentiate between effects due to the specimens investigated and those due to the gage employed.

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* We are indebted to Dr. T. A. Read of Columbia University for suggesting this explanation of the results obtained.

Conclusions for Section B

The strain gages used are found to exhibit gage creep. Such gage malfunctions have to be differentiated from the performance results of the specimens investigated. The indications are that greater stability against gage creep can be obtained by a number of curing cycles at temperatures greater than expected in experimental use.

SECTION C - STRAIN GAGE ZERO SHIFT DUE TO TEMPERATURE CYCLING

The apparent characteristics of the strain gages used show that in addition to gage creep there is also a gage zero shift to contend with. Zero shift refers to the failure of the gage resistance to come back to its starting point after being completely relieved of strain. In our experiments this means a failure of the gage to come back to its original resistance after a complete temperature cycle. The zero shift has been found to occur both in the same and in the opposite direction to the applied gage strain.

Figure 7 shows typical examples of zero shift. For each cycle the zero shift is determined by comparing the initial maximum strain immediately after reaching temperature equilibrium with the equivalent value in the preceding cycle. Experimental results indicate a random zero shift with no particular tendency to decrease in magnitude due to changes in strain produced by thermal cycling. Zero shift will be discussed further in Section D of this paper.

SECTION D - DISCUSSION OF STRAIN GAGE BEHAVIOR

Let us compare the strain gage behavior thus far described with the data appearing in published literature. It should be born in mind that none of the gages used in our experiments measured strain due to applied load but that

strain was produced only by temperature effects. These gages can therefore be considered equivalent to dummy control gages at constant temperature when equilibrium has been reached.

Zero Shift of Paper Bonded Strain Gages

Perhaps the most detailed investigations of bonded wire resistance strain gages were published by W. R. Campbell of the National Bureau of Standards. His experiments on strain gages indicate results very similar to those found by this writer. For paper bonded gages held at room temperature, if a load producing a strain of 3480×10^{-6} in/in is applied for a few seconds and then removed a zero shift of -180×10^{-6} in/in is found.[3] Zero shift increased with magnitude of applied load. Load cycling sharply reduced zero shift so that after the 4th cycle the zero shift was less than -15×10^{-6} in/in. The zero shift was always opposite to the direction of the applied strain. Similar magnitudes and patterns were obtained for tension and compression strains, the zero shift being somewhat larger for compressive strains.

It was found that the zero shift stability due to cyclic prestraining can be upset if a strain gareater than the prestrain is applied during the test. This indicates the desirability of applying cyclic prestraining equivalent to or greater than the experimental strain expected if zero shift is to be greatly reduced.

Zero shift which was greatly decreased by prestraining reappeared after the gages were left unstrained for as much as 24 days.

Reversal of applied strain from tension to compression or vice versa produced a larger zero shift than the same strain on a gage that had not been prestrained.

It can be seen that the above results produced by applied loads are quite similar to the strains and effects produced by temperature cycling observed in our experiments wherein gage creep and zero shift take place. Reversing the temperature reverses the strain so that gage stability is continually upset and works against gage conditioning which tends to bring about gage stability. Nevertheless, from our work one may conclude that many prestraining temperature cycles will bring about gage stabilization.

Weather Exposure of Paper Bonded Strain Gages

Another interesting part of Campbell's work (reference #3) is his exposure of prestrained waterproofed and unwaterproofed gages to 32 days of winter weather. Results for waterproofed gages showed a zero shift of 15×10^{-6} in/in and a change in gage factor Γ of less than 1%. Unwaterproofed gages showed a zero shift of 200×10^{-6} in/in and a change in gage factor of also less than 1%. These results indicate gage factor stability against moisture and suggest a criterion for determining from zero shift when gages may be unsatisfactory due to moisture absorption.

Bakelite Bonded Strain Gages

For Bakelite bonded gages[4] Campbell again finds that prestraining greatly reduces zero shift. At a strain of 2000×10^{-6} in/in (at room temperature) the gage factor of any one type of gage did not differ by more than 1.6% from the average value. It was found that hysteresis effects were greater for gages having shorter gage lengths, due, presumably, to the more compact wires transmitting greater stress to the cement. Changes in gage factor Γ with temperature were also greater for gages with shorter gage lengths. At a strain of 1000×10^{-6} in/in gages of 15/16" and 1/2" gage length showed no change in Γ from 30-140°C and only a 3% decrease at 170°C. The 1/4" gage decreased in Γ

by 1% from 30-60°C, by 5% at 120°C, and by 25% at 167°C. In our experiments it is not known whether the change in the 1/16" AB-19 gage factor Γ exceeds the degree of accuracy of $\pm 3\%$ usually associated with this type of gage.

On bakelite gages made from iso-elastic wire, creep tests applied at strains of 500 and 1000 x 10^{-6} in/in showed creep of less than 1% of the applied strain at a temperature of 140°C and 6% of the applied strain at 170°C.(4) Unfortunately these tests were run for only one hour's duration and no such tests were reported for gages made of advance wire.

Strain Gage Properties on Theoretical Zero Coeff. of Expansion Materials

For similar gages on different unstressed materials the difference in $\frac{\Delta R_g}{R_g}$ with changing temperature is due to the difference in thermal coeff. of expansion e_x of the materials. If, therefore, one subtracts $\Gamma e_x \Delta t$ from the values of $\frac{\Delta R_g}{R_g}$ for materials of known e_x, all results should now be the same, within experimental error, and a curve should be obtained corresponding to the output of the gage alone when attached to a material with a thermal expansion coefficient $e_x = 0$. Campbell has performed such experiments over the range -73 to + 93°C and obtained curves in agreement with the above exposition(5). The resulting curves for $e_x = 0$ show that the change in gage resistance with temperature is non-linear for most gages. Provided gage zero shift and gage creep can be greatly reduced, such curves can be utilized for determining unknown coefficients of expansion on any material over various temperature ranges.*

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* We have no temperature runs available and can only compare results at one temperature difference (32.5 to 60.0°C). If the above relation holds rigorously the results obtained with strain gages from the same lot should be identical. While our values all fall into the range observed by Campbell there is quite a variation from gage to gage. This may be due, in part, to the small size (1/16") of the gages used in our experiments.

There is much other interesting information concerning bonded wire resistance strain gages in other reports by Campbell[6,7,8,9,10] but only the information most pertinent to this writer's experiments have been discussed.

Effect of Increasing Temperature on Gage Creep Under Load

The late Eric Jones (see reference #1) published a very interesting report on wire resistance strain gages. The effect of temperature on gage creep under load was investigated. Tension and compression strains were held constant at 2000 x 10^{-6} in/in and the temperature varied from 19 to 95°C. A family of creep curves were obtained which increased progressively with temperature and with time and was greater in compression than in tension. After 4 hours at 95°C errors in indicated strain due to gage creep were 11% for tension and 16% for compression. The creep was explained as "due presumably to the gradual breakdown in the strain transmission from test surface to gage wire."

According to the report by Savic (see reference #2) creep or relaxation curves are obtained at zero load when bakelite gages are cemented with DeKhotinsky cement. The curves are rather unusual in that they show creep occuring only above 32°C.

The above mentioned curves of Jones and Savic can be considered very similar to those obtained by the author. Our conditions are different from those of Jones in that no load was applied to the specimens. Also a cyclic temperature change was applied instead of a continuously increasing temperature under a tension or compression. Apparently the cyclic temperature change was equivalent to placing the specimens alternately under tension and compression and would account for the repeated reversal of direction of the creep curves obtained. (See Figures 2, and 3).

Other effects already presented have also been found by Jones and Savic and therefore will not be discussed.

Conditions not Effecting Strain Gage Stability

Boodberg[11] and associates have carried out experiments over a period of 40 months in order to determine the stability of SR-4 paper bonded strain gages under various conditions. Among their many results the following are of interest:

1. Varying drying times and temperatures after gage cementing application and prior to waterproofing indicated no difference in gage stability. Maximum deviation from the original reading was $\pm 20 \times 10^{-6}$ in/in.

2. Ordinary room humidity had no apparent effect on stability of gages, even unprotected ones. However, gages that were to serve in damp conditions must be waterproofed to avoid damage.

3. Waterproofing agents showed no detrimental effects on gage stability in air and in sea water.

4. A check of waterproofed dummy compensating gages subjected to temperatures ranging from - 1 to $+38^{\circ}$C as well as rain, fog, and salt-water spray showed only minor fluctuations but no drift trend during the period of observations. The maximum deviations from the median was $\pm 20 \times 10^{-6}$ in/in.

It should be pointed out that the above and other results of Boodberg's tests indicating very good gage stability were obtained at a temperature usually less than 33°C and that higher temperatures may produce less stability.

Strain Gage Waterproofing

The question of waterproofing the gages has been brought up many times. While it can be said that waterproofing is a good general procedure the literature discussed indicates that it is not always necessary for gage stability. Oil had been found to affect gage waterproofing agents and result in unstable gages.[11, 12] On the other hand, unwaterproofed gages were found to function satisfactorily in oil.[12, 13] It was therefore decided not to waterproof the

gages. During our experiments the oil and gage insulation resistance were continually checked and found to be always greater than 1000 megohms. No difference in general gage behavior was noted between paper and bakelite bonded gages in oil or in air. In view of such results and the fact that observed changes were very small and could be repeated, it was concluded that moisture did not effect the results of our experiments.

Strain Gage Coefficient of Expansion Measurements

If coefficient of expansion measurements are to be taken by means of bonded wire resistance strain gages it is very important to take readings immediately before temperature change and immediately upon reaching temperature equilibrium. Temperature change and equilibrium ought not to take more than a total of one hour if errors are to be avoided which would otherwise be caused by gage creep. However, if one succeeds in largely eliminating gage creep, then readings should be relatively constant with time and can be taken more leisurely. With judicious choice of gages and the knowledge of or the performing of gage calibrating experiments at higher temperatures (60-150°C), one can still probably obtain low errors in coefficient of expansion measurements over this temperature range.

Simultaneous Use of Many Strain Gages

In instruments available now, but at a sacrifice of some accuracy, as many as 48 strain gages can be hooked up to a self-balancing recording device and automatic readings can be taken. The knowledge of what happens in many places at the same time is in many instances more advantageous than very precise measurements at only one place at one time by means of using interferometric methods or X-ray analysis, etc. However, for the greatest accuracy, as in our experiments, a number of gages can be hooked up and readings taken manually, allowing a few minutes for each gage reading.

Creep Measurements by Means of Strain Gages

Interest has been indicated in the possible use of bonded wire resistance strain gages for creep measurements. Although some creep work with these gages has been performed[14] further work on this subject is recommended. For creep measurements in the range of total deformation 0 to 100 x 10^{-6} in/in it would be important to be able to separate the inherent gage creep from the creep of the test specimen. For very large creep measurements the inherent gage creep, if unknown, may only introduce errors of a few percent. It should be pointed out that the limit of measurements with bonded wire resistance strain gages corresponds to a 1% dimensional change in the test specimen. This corresponds to a strain of 10,000 x 10^{-6} in/in.

Conclusions for Section D

Cyclic prestraining by means of loads greater than expected in experimental use has been shown by Campbell to bring about fairly good stability against gage zero shift.

Strain gage accuracy and stability are likely to be increased by use of larger gages than the 1/4" paper bonded and 1/16" bakelite bonded gages used in our experiments.

The higher the temperature the greater will be the gage inaccuracy.

ACKNOWLEDGEMENTS

Dr. T. A. Read of Columbia University, formerly of Oak Ridge National Laboratory, had initiated this investigation. The author is much indebted to him for his guidance in this work.

Appreciation is expressed to Dr. Karl Lark-Horovitz of Purdue University for his interest and advice. Acknowledgement is also made to Prof. G. P. Tschebotarioff of Princeton University, Mr. W. V. Bassett of the Bethlehem Steel Company, Mr. W. R. Campbell of the National Bureau of Standards, Prof. A. C. Ruge and Mr. F. F. Hines of Ruge-De Forest, Inc., and Mr. F. G. Tatnall of the

Baldwin Locomotive Works for their informative correspondence with the author.

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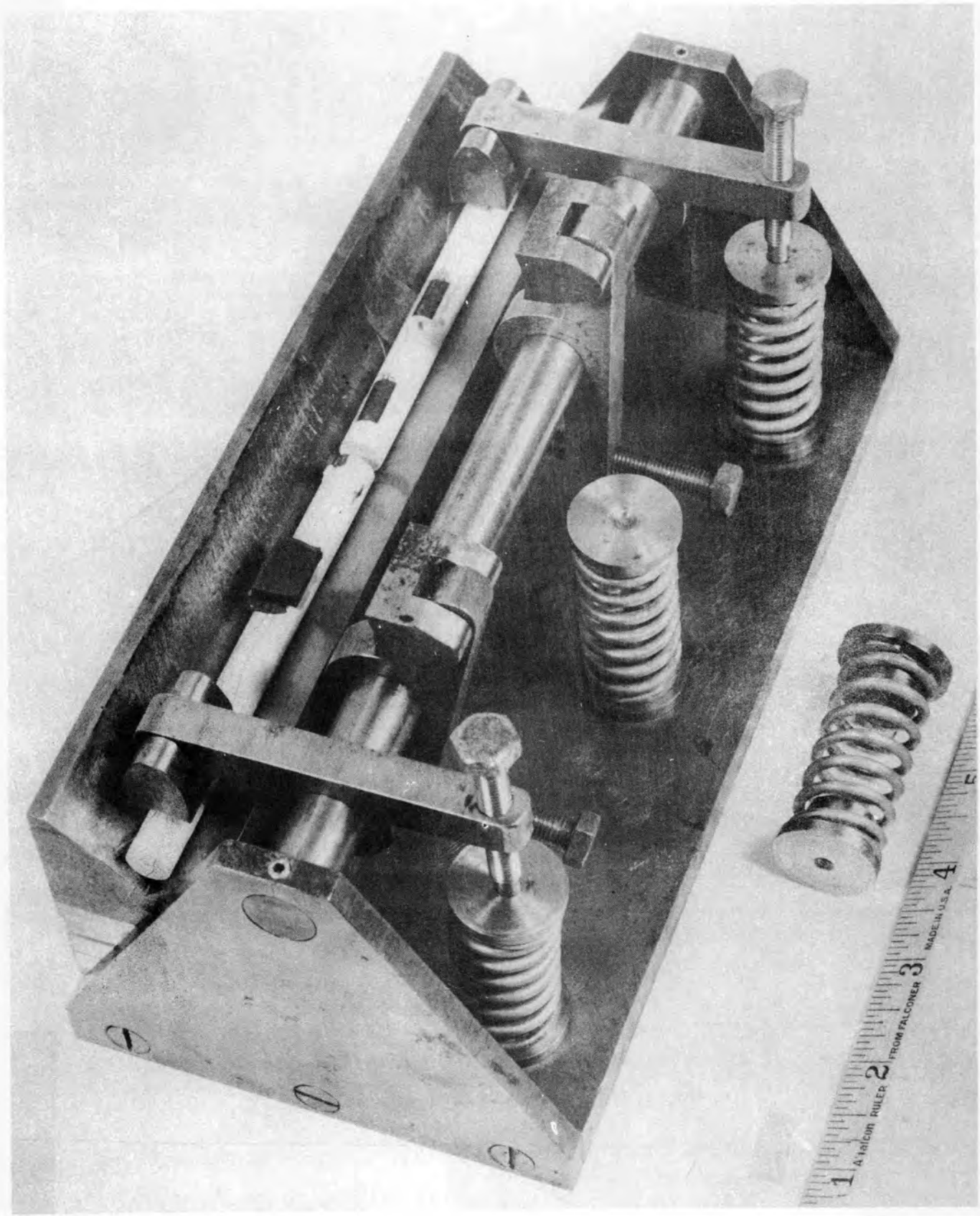

PHOTO 1. STRAIN GAGE APPLICATION DEVICE

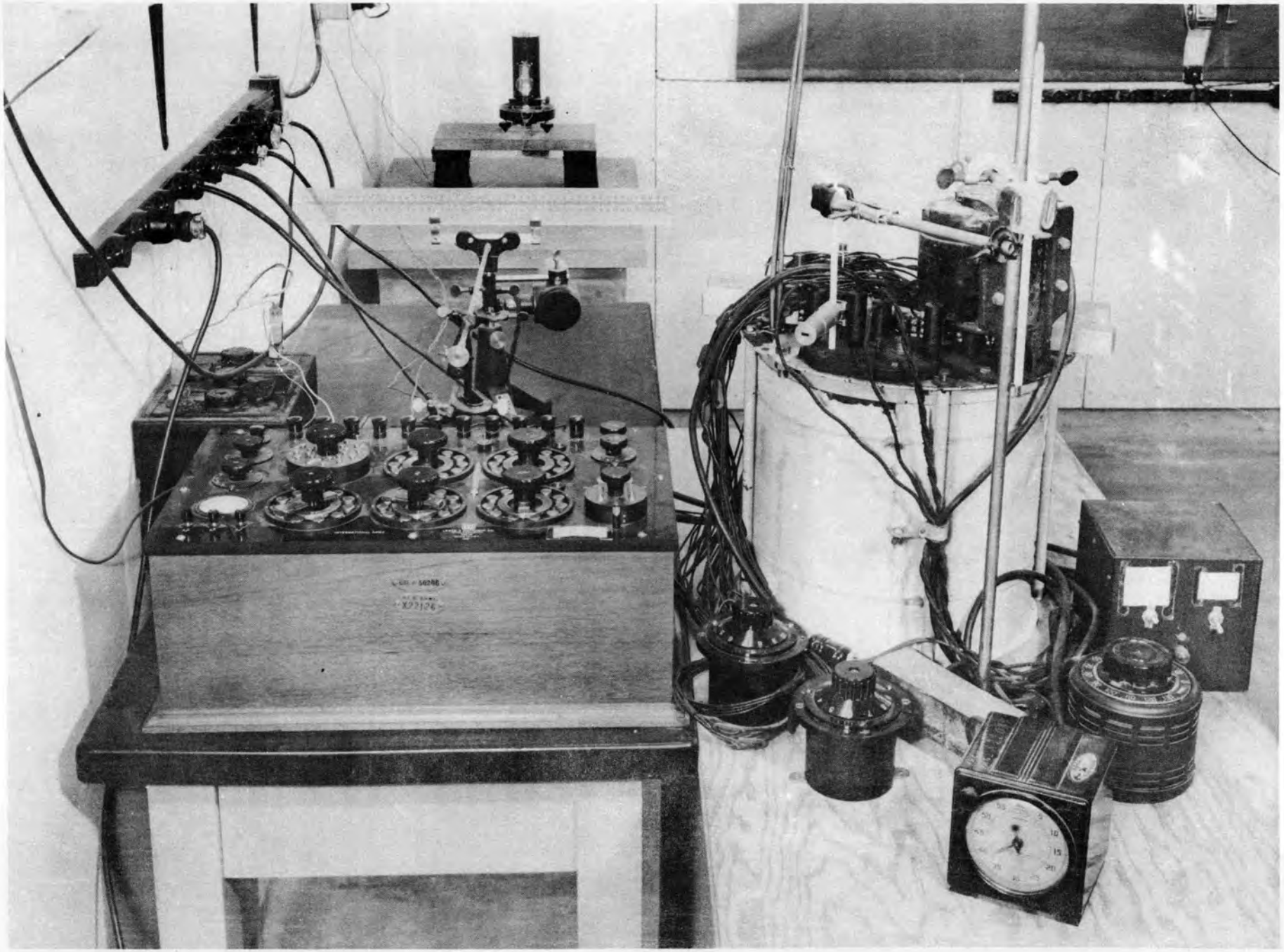

PHOTO 2. SET-UP FOR COEFFICIENT OF EXPANSION MEASUREMENTS

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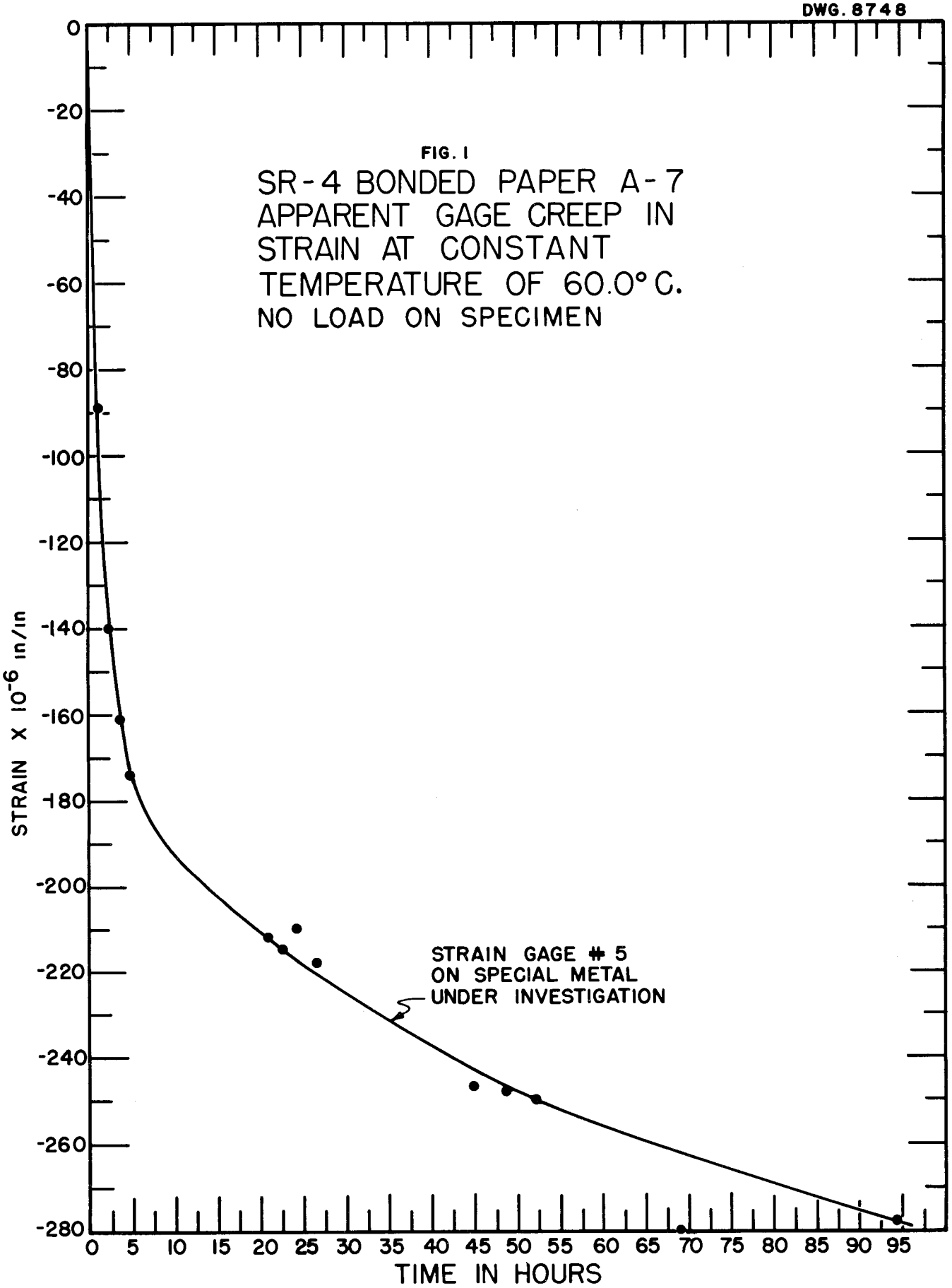

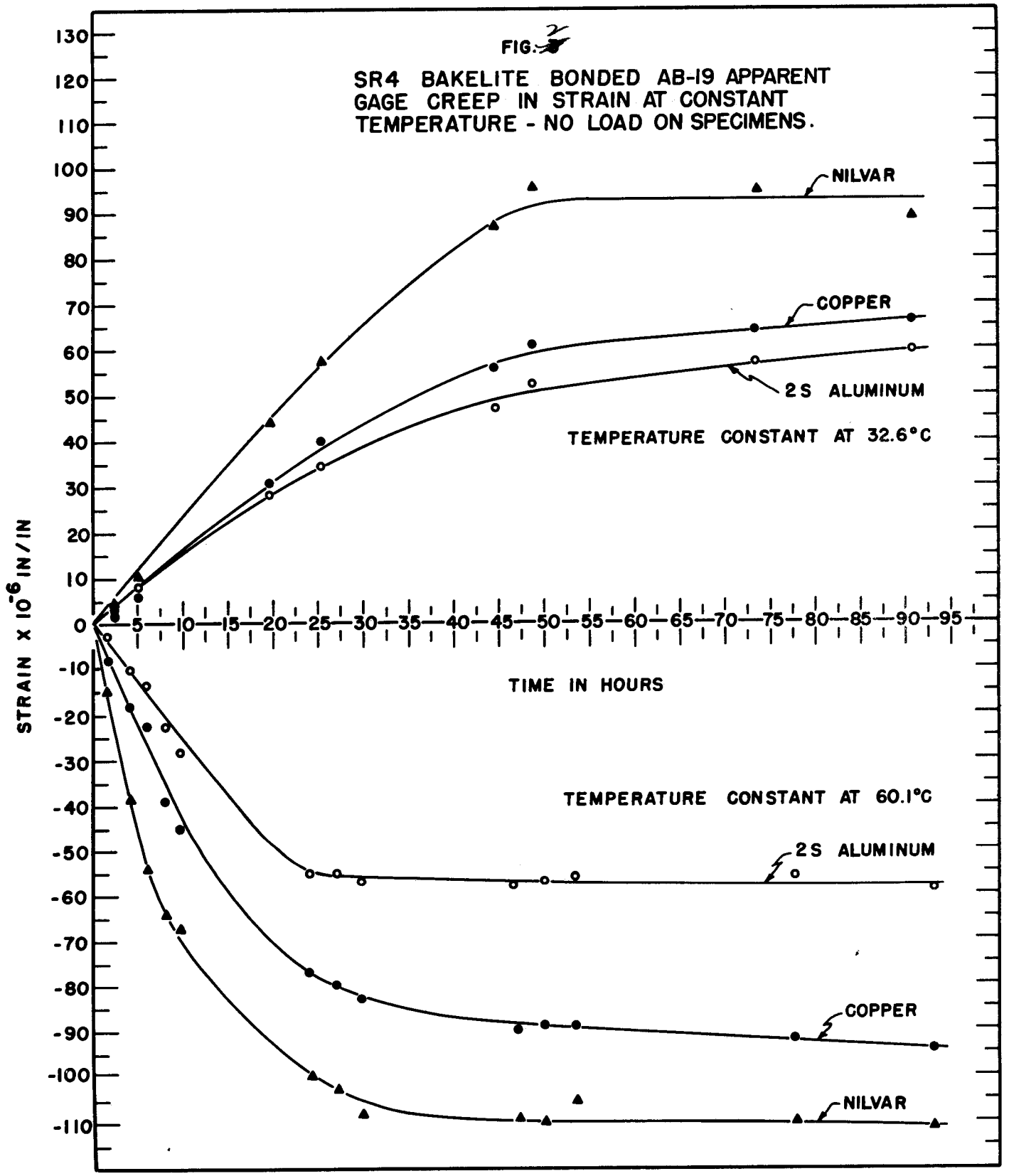
FIG. 2
SR4 BAKELITE BONDED AB-19 APPARENT GAGE CREEP IN STRAIN AT CONSTANT TEMPERATURE - NO LOAD ON SPECIMENS.
NILVAR
COPPER
2S ALUMINUM
TEMPERATURE CONSTANT AT 32.6°C
TEMPERATURE CONSTANT AT 60.1°C
2S ALUMINUM
COPPER
NILVAR
TIME IN HOURS
STRAIN X 10^-6 IN/IN
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
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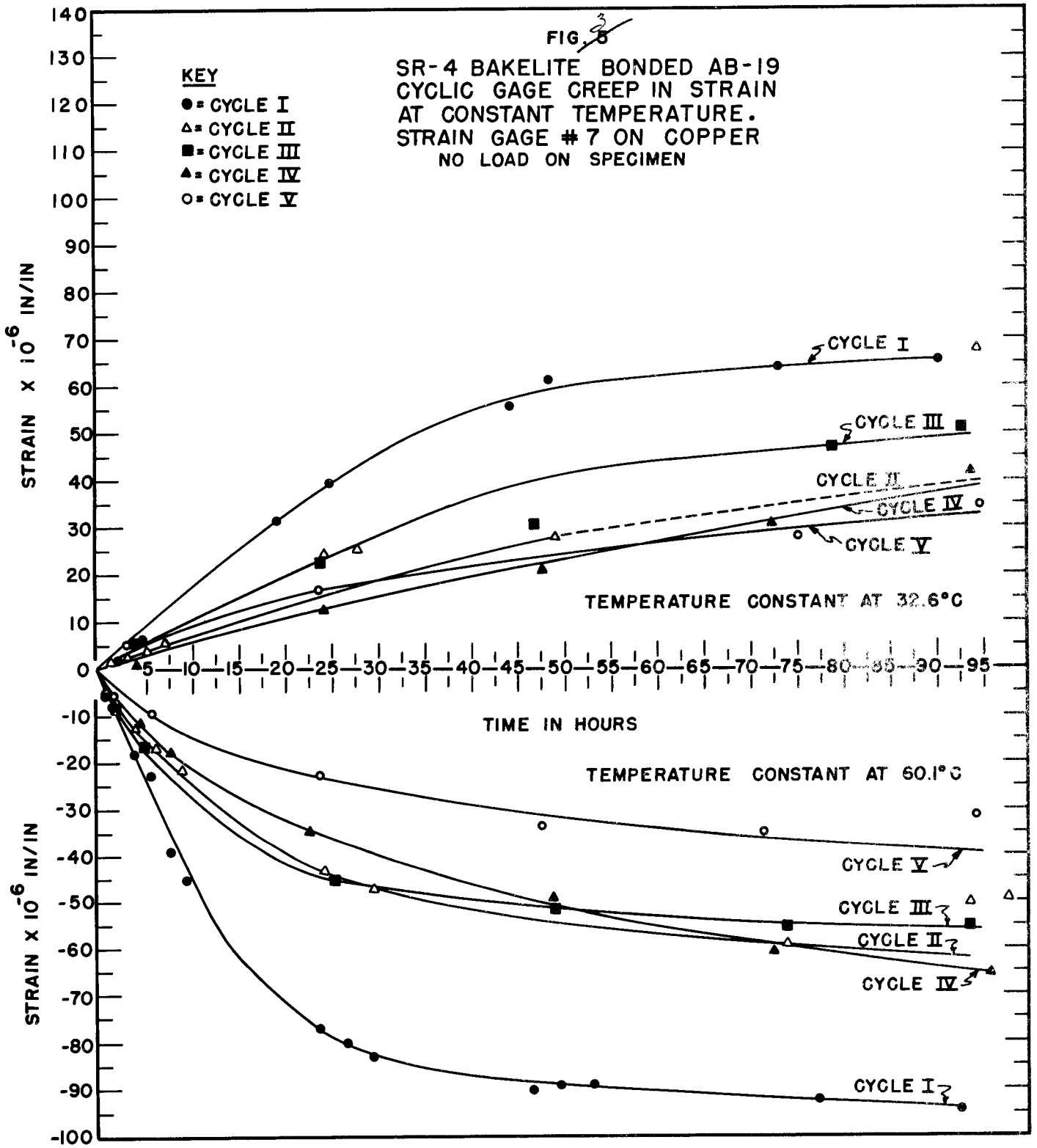
FIG. 3
SR-4 BAKELITE BONDED AB-19
CYCLIC GAGE CREEP IN STRAIN
AT CONSTANT TEMPERATURE.
STRAIN GAGE # 7 ON COPPER
NO LOAD ON SPECIMEN
KEY
● = CYCLE I
△ = CYCLE II
■ = CYCLE III
▲ = CYCLE IV
○ = CYCLE V
STRAIN X 10^-6 IN/IN
CYCLE I
CYCLE III
CYCLE II
CYCLE IV
CYCLE V
TEMPERATURE CONSTANT AT 32.6°C
TIME IN HOURS
TEMPERATURE CONSTANT AT 60.1°C
CYCLE V
CYCLE III
CYCLE II
CYCLE IV
CYCLE I

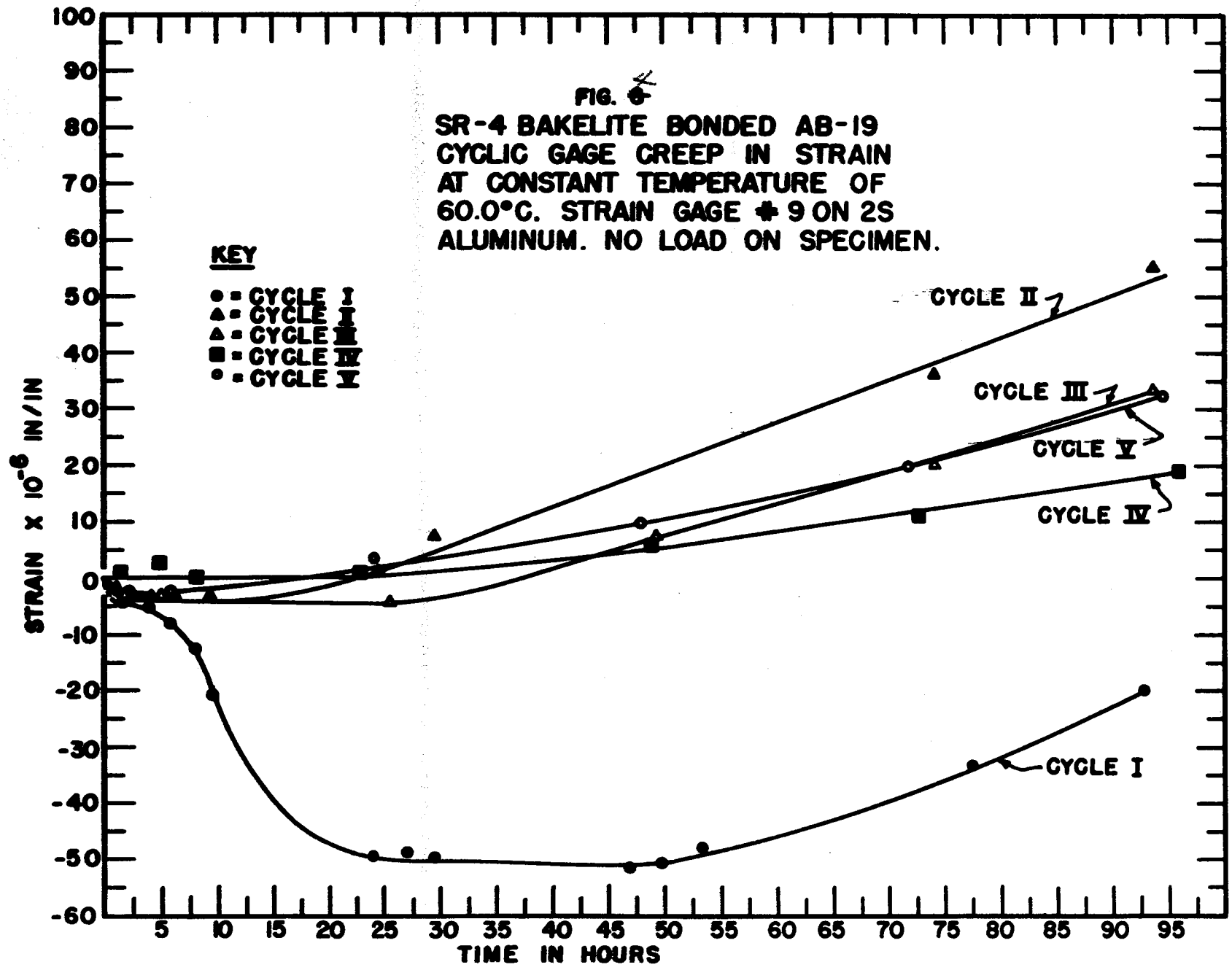

FIG. 4

SR-4 BAKELITE BONDED AB-19 CYCLIC GAGE CREEP IN STRAIN AT CONSTANT TEMPERATURE OF 60.0°C. STRAIN GAGE # 9 ON 2S ALUMINUM. NO LOAD ON SPECIMEN.

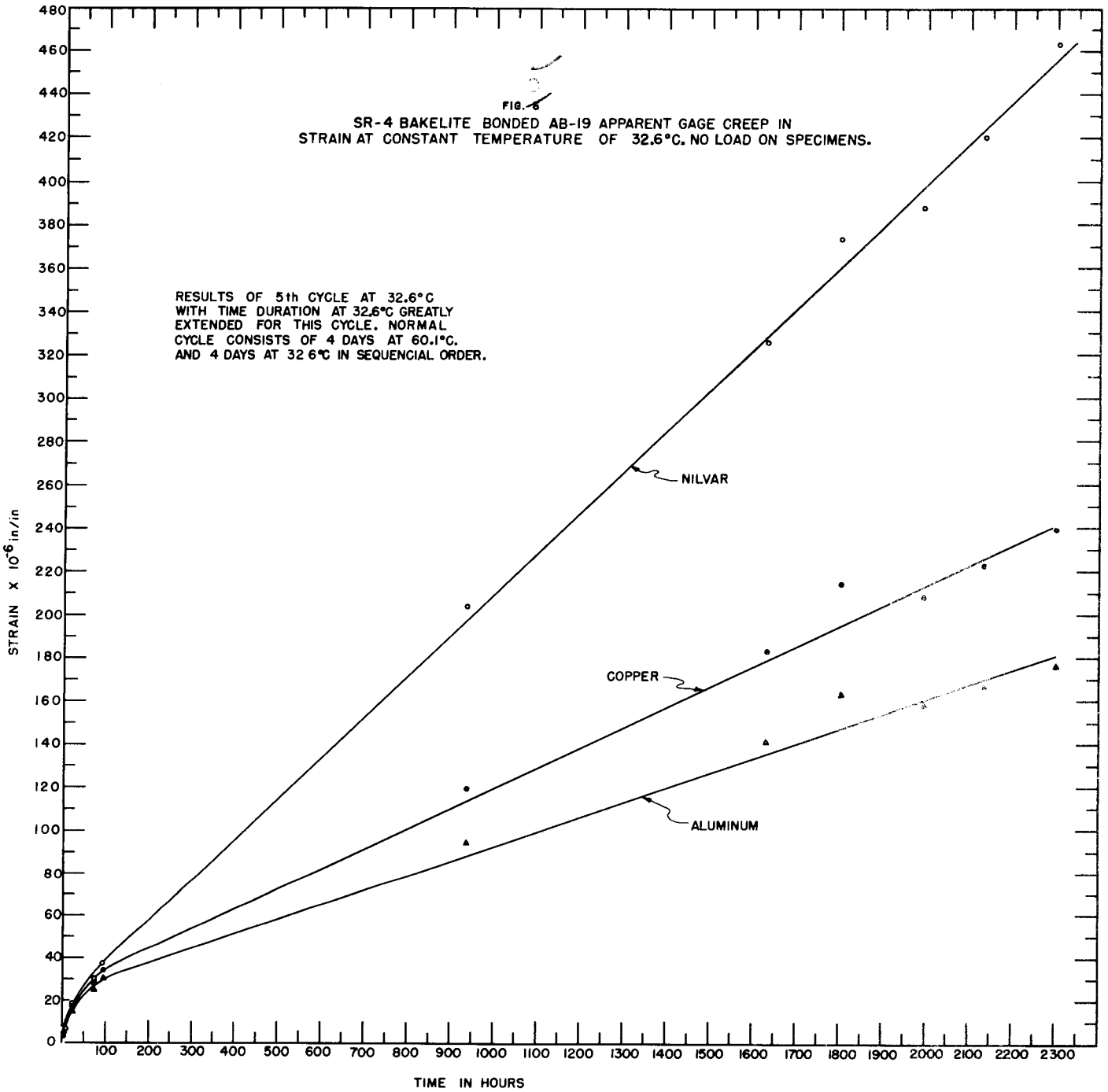
FIG. 6
SR-4 BAKELITE BONDED AB-19 APPARENT GAGE CREEP IN STRAIN AT CONSTANT TEMPERATURE OF 32.6°C. NO LOAD ON SPECIMENS.
RESULTS OF 5th CYCLE AT 32.6°C WITH TIME DURATION AT 32.6°C GREATLY EXTENDED FOR THIS CYCLE. NORMAL CYCLE CONSISTS OF 4 DAYS AT 60.1°C. AND 4 DAYS AT 32.6°C IN SEQUENCIAL ORDER.
NILVAR
COPPER
ALUMINUM
STRAIN X 10^-6 in/in
TIME IN HOURS
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
400
420
440
460
480
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
2200
2300

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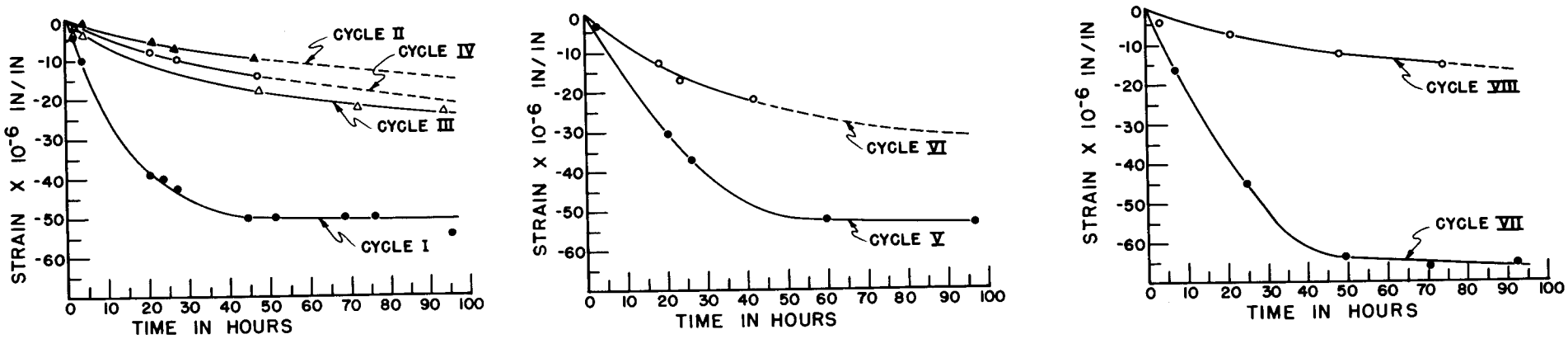
FIG. 6

EFFECT OF CHANGE OF CYCLE TIME ON APPARENT GAGE CREEP. SR-4 BAKELITE BONDED AB-19 STRAIN GAGE AT CONSTANT TEMPERATURE OF 60.0°C. STRAIN GAGE # 4 ON SPECIAL METAL UNDER INVESTIGATION. NO LOAD ON SPECIMEN

NORMAL CYCLES (I, II, III, IV, VI) CONSIST OF 4 DAYS AT 60.0°C AND 1 DAY AT 32.5°C. DURING CYCLES V AND VII THE STRAIN GAGES WERE KEPT AT 32.5°C. FOR 2 DAYS AND 18 DAYS RESPECTIVELY BEFORE THE TEMPERATURE WAS RAISED TO 60.0°C AND HELD FOR 4 DAYS.



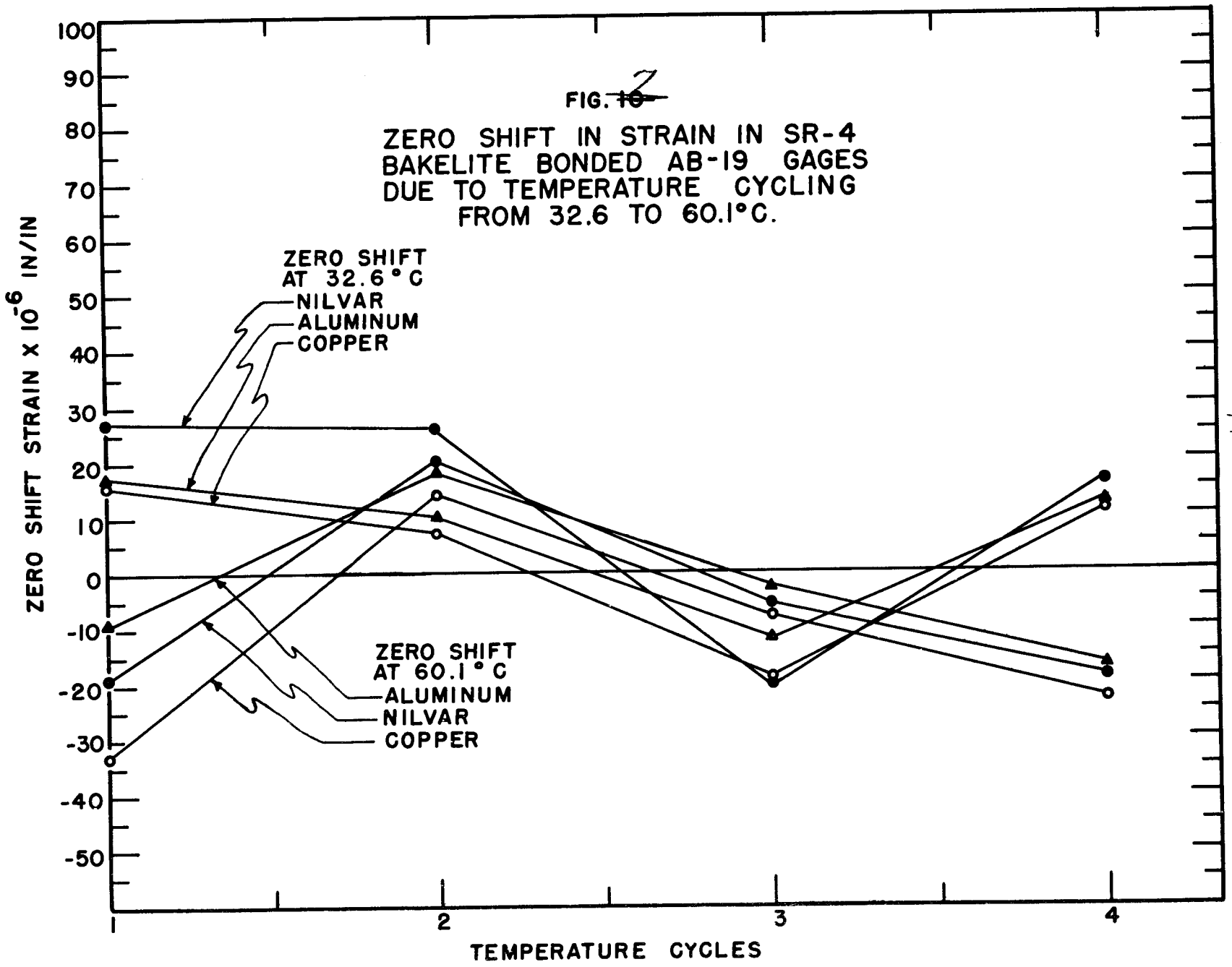


FIG. ~~10~~ 2

ZERO SHIFT IN STRAIN IN SR-4 BAKELITE BONDED AB-19 GAGES DUE TO TEMPERATURE CYCLING FROM 32.6 TO 60.1°C.