NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

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ERRORS IN INDICATED STRAIN FOR A TYPICAL WIRE STRAIN GAGE CAUSED BY PRESTRAINING, TEMPERATURE CHANGES, AND WEATHERING

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National Bureau of Standards

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ERRORS IN INDICATED STRAIN FOR A TYPICAL WIRE STRAIN GAGE CAUSED BY PRESTRAINING, TEMPERATURE CHANGES, AND WEATHERING

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SUMMARY

Tests were made on a wire strain gage of representative design to determine zero shift after straining at room temperature, error in indicated strains at high and low temperature, and changes in calibration factor and zero shift after exposure to severe weathering.

The measured zero shifts after the first cycle of prestraining to 34.8 × 10^{-4} in tension or compression were less than 2.1 × 10^{-4}; after the fourth cycle they were less than 0.15 × 10^{-4}. The zero shift was always opposite to the direction of the applied strain; a cycle of tensile strain resulted in a decrease in the resistance of the wire strain gage corresponding to zero strain and a cycle of compressive strain resulted in an increase.

The errors in indicating a strain up to 40 × 10^{-4} at temperatures between −50° and 64° C were less than 1 × 10^{-4}. These errors could be ascribed entirely to imperfect matching of the thermal coefficients of resistance of the working gage and the compensating gage.

Calibrations and zero shift measurements on 18 gages, 12 of which were exposed to 32 days of severe winter weather, showed that the changes in calibration factor of individual gages due to the weathering did not exceed ±1 percent even for gages with no waterproofing. Gages attached with Duco cement and waterproofed showed negligible zero shift following the period of weathering; whereas unwaterproofed gages gave zero shifts of the order of $\Delta R/R = +2 \times 10^{-4}$ corresponding to an apparent tensile strain of 1 × 10^{-4}.

INTRODUCTION

The National Advisory Committee for Aeronautics requested the National Bureau of Standards to make a series of tests on a wire strain gage of representative design which would indicate the order of magnitude of the errors that might be expected when this type of gage is used in the measurement of strains under flight conditions.

After consideration of the problem it was decided to make the following three groups of tests.

I. Determination of zero shift at room temperature as a function of

(a) Maximum tensile and compressive strain

(b) Number of cycles of strain

(c) Time, with repeated cycles of strain over a period of several weeks

II. Determination of errors in indicated strain at high and low temperature when strain gage and compensating gage are subjected to repeated cycles of heating and cooling between approximately −60° and 60° C as a function of

(a) Maximum tensile and compressive strain

(b) Number of cycles of temperature variation

III. Determination of changes in calibration factor and of zero shift of gages after severe weathering by measuring zero shift and calibration factors of gages with and without waterproofing exposed to the weather for several weeks and of gages stored at room temperature in the laboratory.

The three groups of tests are described as parts I, II, and III of this report.

This investigation, conducted at the National Bureau of Standards, was sponsored by and conducted with the financial assistance of the National Advisory Committee for Aeronautics.

NOTATION

ϵ	axial strain
ϵ_b	extreme fiber bending strain
ϵ_s	extreme fiber permanent set
$\Delta\epsilon$	change in axial strain
$\Delta\epsilon_b$	change in extreme fiber bending strain
R	gage resistance, ohms
ΔR	change in gage resistance, ohms
μ	Poisson's ratio
$K = (\Delta R/R)(1/\Delta\epsilon)$	calibration factor for uniaxial stress increment producing a change in strain $\Delta\epsilon$ parallel to the gage axis and a change in strain $-\mu\Delta\epsilon$ transverse to the gage axis
ΔK	change in calibration factor
n	subscript denoting the nth measurement of gage resistance on a given gage in the unstrained condition.

I – ZERO SHIFT AFTER PRESTRAINING AT ROOM TEMPERATURE

The zero shift $(\Delta R/R)_n$ is defined in this report as the relative change in gage resistance between two successive conditions of zero strain or

$$\left(\frac{\Delta R}{R}\right)_n = \frac{R_{(n+1)} - R_n}{R_n} \qquad (1)$$

where n signifies that the zero shift occurred during the nth cycle of straining.

TESTS AND PROCEDURE

Zero shift measurements for both tensile and compressive strains were obtained on eight gages attached to the extreme fibers of 18- by 1- by 0.125-inch strips of 24S-T aluminum alloy which were subjected to bending moments. Two gages were attached to each strip, one at the center of each face at midlength. The gages were attached with "Duco Household Cement" following the procedure given in appendix 1. A constant bending moment was applied to the portion of the strip to which the gages were attached by applying transverse forces at approximately the third points. A different strip was used for each of four values of applied strain.

The laboratory setup for the zero shift measurements is shown in figure 1. The gage G on strip S is being subjected to a compressive strain of 9 × 10^{-4} by loading the strip with the 5-pound weights W. The gage G' on strip S' is a compensating gage. Other strips were loaded in the same manner with 10-, 15-, and 20-pound loads, respectively, which produced strains $\epsilon_b = 17.3 \times 10^{-4}$, 25.8×10^{-4}, and 34.8×10^{-4}, respectively. Cycles of strain were applied to the gages by successively loading and unloading the strips. The total load was left on only a few seconds before unloading. After each cycle of loading, the two test gages (tension and compression) were alternately substituted in the test arm of a Wheatstone brdige by means of a mercury film switch M and the zero shifts from the preceding zeros were determined. The Tuckerman strain gage T was used to measure the extreme fiber compressive strain along gage G, and to check the strip for permanent set during each cycle; the readings of the Tuckerman gage were corrected for shortening caused by the curvature of the strip (reference 1) where necessary. The measured zero shift $(\Delta R/R)_{meas}$ was corrected for permanent set ϵ_s in the test strip by substitution in,

$$\left(\frac{\Delta R}{R}\right)_{corr} = \left(\frac{\Delta R}{R}\right)_{meas} - K\epsilon_s \qquad (2)$$

where the calibration factor K was taken as 2.06 for all gages.

The relative change in gage resistance corresponding to the zero shift of each gage was measured with a Wenner type ratio set in a direct current Wheatstone bridge, using a high-sensitivity moving coil galvanometer as a null indicator. The ratio set and its use in the bridge circuit for measuring percentage changes in resistance is described in reference 2. The voltage drop across the test gage was 1.5 volts.

Similar tests were made on six additional gages to determine whether or not the zero shift which had been reduced or eliminated by prestraining, reappeared after gages were allowed to "rest," unstrained, for various intervals of time. Two gages were attached as before to each of three strips, and each pair of gages was strained 10 times to a strain $\epsilon_b = 25.8 \times 10^{-4}$, and the zero shift was measured after each cycle. The gages were retested at the same strain, beginning with the eleventh cycle, after remaining unstrained for 2, 5, and 24 days, respectively.

RESULTS AND DISCUSSION

The results of the measurements of zero shift after 1 to 10 cycles of straining are shown in figure 2. The figure shows that for all values of strain there was a pronounced zero shift during the first cycle of strain; it decreased rapidly during successive cycles of strain. After 4 cycles, the zero shift did not exceed $\Delta R/R = 0.15 \times 10^{-4}$. It was estimated that the maximum error in the measurement of zero shift did not exceed 0.04×10^{-4}. Figure 2 also shows that for the first three cycles the zero shifts, as defined by equation (1), were opposite in direction (sign) to the applied strain; gages strained in compression were observed to have positive zero shifts, and gages strained in tension were observed to have negative zero shifts.

The zero shifts measured during the first and fourth cycles for the eight gages of figure 2 are plotted in figure 3 against the maximum strain to which the gages were subjected. The curve of zero shift versus strain for the fourth cycle shows the zero shift reduced to a negligible value. The curve for the first cycle shows that the zero shift increased exponentially with strain. For an applied strain of 34.8×10^{-4} the zero shifts of the tension and compression gages after 1 cycle of strain amounted to about 3 percent of gage output, $\Delta R/R$, corresponding to that strain.

Tests on a few gages showed that although the zero shift associated with a given strain may be reduced to a negligible value by prestraining, further zero shift occurs if the the "prestrain" is exceeded in subsequent straining cycles. This unfortunately removes the possibility of eliminating zero shift by preloading structures to low strains. It was also found that a gage that is first prestrained in tension shows a larger zero shift when subsequently strained in compression (and vice versa) than does a gage which has not been prestrained. This effect of reversing the direction of the applied strain is shown in figure 4. The curves at the left in figure 4 are the curves that are shown in figure 2 for the gages which were strained to $\varepsilon_b = 34.8 \times 10^{-4}$. After the tenth strain cycle on these two gages, the strip to which the gages were attached was turned over so that the gage which had just been strained in tension would be strained in compression and the gage which had been strained in compression would be strained in tension. The gages were then strained an additional 10 cycles to the same magnitude of strain as before. The curves on the right in figure 4 show the zero shifts which accompanied the reversal of the applied strain. "The zero shifts during the first cycle with reversed strain (cycle 11) were about 45 percent larger than those measured during the first cycle following the attachment of the gages.

Figure 5 gives the results of tests to determine whether or not the zero shift which was removed by prestraining reappeared after the gages were left unstrained for a period of time. After a period of as much as 24 days, the zero shift during a cycle of strain did not exceed $\Delta R/R = 0.14 \times 10^{-4}$. This zero shift was only 16 percent of the shift during the first cycle, without prestraining (cycle 1); it corresponds to about 0.2 percent of gage output $\Delta R/R$ for the applied strain.

CONCLUSIONS FROM MEASUREMENTS OF ZERO SHIFT

AFTER PRESTRAINING AT ROOM TEMPERATURE

The tests showed zero shifts during the first cycle of strain which did not exceed 3 percent of gage output corresponding to the maximum strain applied, for strains up to 34.8×10^{-4}. The zero shift was opposite to the direction of the applied strain. Repeated prestraining to a given strain resulted in negligible zero shift during the fourth cycle, provided the maximum "prestrain" was not exceeded. Gages which were prestrained in tension to remove zero shift showed larger zero shift when strained in compression (and vice versa) than did new gages which had not been prestrained. Gages which had been prestrained to remove zero shift showed a slight tendency to recover zero shift after remaining in an unstrained condition for 24 days.

II — ERROR IN INDICATED STRAIN AT HIGH AND LOW TEMPERATURES

The following tests were made to determine the errors in indicated strains which may be expected in the presence of variations in ambient temperature between − 50° and 64° C. The applied strains were varied from 40 × 10^{-4} in compression to 40 × 10^{-4} in tension.

APPARATUS AND PROCEDURE

The device for straining the gages is shown in figure 6. Twelve test gages were attached to six 24S-T aluminum alloy cantilever beams 4 by 1 by 0.125 inch which were racked in a steel frame to form a compact assembly that could be heated and cooled as a unit. The free ends of the beams were slotted and were slipped over a 1/4-inch threaded rod which was anchored at each end in the steel frame. Nuts spaced along the threaded rod between the projecting ends of the test beams were used to deflect the beams to obtain various strains at the test gages. The frame was mounted on the ends of two bolts which were fastened at the other end in four layers of fiber board that formed the door to separate heating and cooling cabinets.

Two dummy gages were attached to the short beam in figure 6. One of these gages was used to compensate for the variation in temperature of the test gages. The other dummy gage served as a check on the compensating gage. All gages were waterproofed with "Gargoyle Petrosene A" following the procedure given in appendix 1 for gages attached with Duco cement. The six test beams were numbered 1 to 3 and 4 to 6 outward from the short beam. The gages on each beam were identified by the number of the beam to which they were attached, plus the letter T or C (T1, T2, — C1, C2, —) to designate tensile or compressive strain.

The strains ϵ_{bi} indicated by each wire gage and change in indicated strain $\Delta\epsilon_{bi}$ were measured with a Baldwin-Southwark portable strain indicator (reference 3). Measurements were made at six values of strain, 0, 5×10^{-4}, 10×10^{-4}, 20×10^{-4}, 40×10^{-4}, and for 3 cycles of temperature variation at each strain except at 40×10^{-4} at which only 2 cycles were applied.

The measurements were started at room temperature (24° C) by successively connecting the test gages to the strain indicator and determining the balance position with the cantilevers undeflected. With the beams still undeflected, the unit was subjected to 3 cycles of temperature variation (beginning with the cold half of the cycle) and strain indicator readings were taken on each gage at the two extreme temperatures during every cycle. After the third cycle the unit was returned to room temperature and indicator readings were again taken on each gage. The two gages on each beam were then strained to 5×10^{-4} in tension and compression, respectively, by turning the nuts on the threaded rod and deflecting the beams. Strain indicator readings were again taken on each gage at room temperature, at the extreme temperatures during 3 temperature cycles, and again at room temperature. Following these readings the beams were returned to the undeflected position for zero readings at room temperature. Measurements at higher strains were made in the same manner. At a strain of about 25×10^{-4} the two beams on either side of the short beam (1 and 4) contacted at the ends and beam 4 was therefore adjusted to only 22×10^{-4}. Beams 1 and 4 were later removed from the unit to permit measurements at 40×10^{-4} on the remaining gages.

CALCULATIONS

The error in indicated strain was defined as

$$\Delta\epsilon_{bi} = \epsilon_{biT} - \epsilon_{bi0} \qquad (3)$$

where

ϵ_{biT} indicated strain at low and high temperature with beam in deflected position

ϵ_{bi0} indicated strain upon return to room temperature with beam in same deflected position

For all measurements the indicator was balanced using the calibration factor furnished with the gage. Separate calculations were made at each value of applied strain. The quantity ϵ_{bi0} was taken as the indicated strain upon returning to room temperature rather than the indicated strain before applying the low and high temperature, in order to avoid errors caused by changes in the deflection of the beams during the first application of the low temperature.

RESULTS AND DISCUSSION

Changes in indicated strain $\Delta\epsilon_{bi}$ for each gage at low temperature and high temperature are shown in figures 7 to 12 as circles and as triangles, respectively. The squares in these figures show the changes in indicated strain after cycles of temperature variations with increasing values of strain.

Examination of figures 7 to 12 shows that similar results were obtained with all 12 of the test gages. Differences between the temperature coefficients of the test gages and the compensating gage are shown by the intercepts of the curves of $\Delta\epsilon_{bi}$ versus ϵ_{bi} for high and low temperature on the axis of $\Delta\epsilon_{bi}$. Gages C2 and T2 (fig. 8) illustrate this point. Gage C2, at the left in figure 8, shows a wide separation between the high and low temperature curves of $\Delta\epsilon_{bi}$ versus ϵ_{bi}. The intercepts of these curves on the vertical axis indicates the error which resulted from imperfect temperature compensation alone since at the ordinate axis the applied strain is zero. Gage T2, at the right, shows only a small separation between the intercepts of the two curves indicating nearly equal thermal coefficients of resistance for gage T2 and the compensating gage. Although there is considerable experimental scatter, the points on the high and low temperature curves for gage C2 are nearly equidistant at all values of strain, being separated by the sum of the intercepts. This shows that the error in indicated strain could be assigned entirely to the imperfect matching of thermal coefficients for the working gage and the compensating gage. In gage T2 the matching of thermal coefficients is much better and the error in indicated strain is much smaller.

In general, the curves of $\Delta\epsilon_{bi}$ versus ϵ_{bi} showed that for all gages the change in indicated strain with changes in temperature was constant for all values of strain and equal to the change caused by imperfect temperature compensation. There was no evidence of creep in the gages under sustained strain at 64° C.

Changes in indicated strain due to differences in temperature compensation ranged from 0 to about 0.85×10^{-4} for the change in temperature from −50° to 64° C. The maximum change was therefore of the order of 0.0075×10^{-4} per degree centigrade.

The fact that the intercepts are positive for the high temperature and negative for the low temperature may be ascribed to having a compensating gage with a thermal coefficient equal to or less than the coefficient of any of the test gages.

In figures 7 to 12 it is seen that the intercepts associated with the curves for −50° C are greater than the intercepts for 64° C by more than the ratio of the respective temperature changes from room temperature, that is, −74/40 or −1.85. This indicates that the thermal coefficients increase with decreasing temperature. Measurement of the output of the compensating gage for changes in temperature showed that the curve of $\Delta R/R$ versus temperature was not linear and that the slope of this curve, equal to the thermal coefficient, was appreciably greater at low temperatures than the slope above room temperature.

The squares in figures 7 to 12 show differences in strain obtained by substracting final from initial readings of the strain indicator at room temperature. These differences may be due either to a permanent change within the structure of each gage or to a permanent change in the deflection of each beam which occurred on the initial cooling. The differences were ascribed to changes in the deflection of the beams rather than to changes within the gages for the following reasons. The differences were approximately equal and opposite for gages attached to opposite extreme fibers of a given beam, as would be expected for a change in the deflection of the beam. All the differences corresponded to a small decrease in the deflection of the beams, such as might be produced by a slight yielding in the center portion of the screw passing through the slots at the ends of the beams. Yielding in this portion of the screw may be expected since the screw was drawn up tightly during assembly and since the center portion was stressed in addition by the forces required to deflect the cantilever beams.

CONCLUSIONS FROM MEASUREMENTS OF INDICATED STRAIN AT HIGH AND LOW TEMPERATURES

Changes in indicated strains for strains up to 40 × 10^{-4} with temperature variations between −50° and 64° C, could be ascribed entirely to differences between the thermal coefficients of resistance of the test gage and the compensating gage. The changes were observed to be nearly constant at all values of applied strain for a given change in temperature. The maximum change in indicated strain was of the order of 0.0075 × 10^{-4} per degree centigrade. There was no evidence of creep under sustained strain at temperatures up to 64° C for strains up to 40 × 10^{-4}.

III – EFFECT OF GAGE EXPOSURE TO SEVERE WEATHER ON CALIBRATION FACTOR AND ZERO SHIFT

The following tests were made to indicate the changes in calibration factor and the zero shifts which may be expected after gages have been exposed to severe weather conditions.

TESTS AND PROCEDURE

Tests were made on 18 gages, separated into two groups, a group of 12 gages exposed to weather and a control group of 6 gages protected from the weather. The tests on the first group consisted of measuring the calibration factor in tension and the resistance corresponding to zero strain for each gage before and after the gages were exposed to 32 days of winter weather. The tests on the control group consisted of the same measurements on gages that were stored in the laboratory at room temperature while gages of the first group were weathering. Both groups included waterproofed and unwaterproofed gages attached with two different cements, "Duco Household Cement" and "De Khotinsky (Cementyte A)."

Each of the test gages was attached at the center of one face of eighteen 18- by 1- by 0.125-inch 24S-T aluminum alloy strips. Table 1 gives a list of the test gages, numbered 1 to 18, and shows the attaching cement and provisions for waterproofing. The waterproofing compound was "Gargoyle Petrosene A." Details of the procedure used in attaching and waterproofing gages are given in appendix I.

After attachment, the gages were prestrained in tension to a strain of 22×10^{-4} for 4 cycles of loading to minimize zero shift and improve linearity. The gages were then calibrated for tensile strains between 0 and 20×10^{-4} for both increasing and decreasing strain using the procedure described in reference 2. Calibration factors K_u for increasing strain and K_d for decreasing strain, where

$$K = \frac{\Delta R}{R} \frac{1}{\Delta \epsilon} \qquad (4)$$

were determined for each gage as the slopes of two straight lines fitted by least squares to plots of $\Delta R/R$ versus ϵ for increasing strain and decreasing strain, respectively.

Following the calibrations on all gages, the resistances corresponding to zero strain were measured. A Rubicon resistance decade of the type shown in the background in figure 1 was substituted for the compensating wire strain gage in the Wheatstone bridge and adjusted to within 0.1 ohm of the resistance of each gage as the gages were successively substituted in the test arm of the bridge. The decade reading and the ratio of the resistance of the decade to the resistance of the test gage, as measured with a Wenner type ratio set, were recorded for each gage. After determining the ratios for the wire strain gages, a second decade box was substituted in the test arm of the bridge and, with both decades set at 120.0 ohms, the ratio was measured for the sum of all the resistances in the two arms of the bridge (decade coils, dial switches, cables, and binding post contacts). The differences between this ratio and the same as measured after the weathering period was used to correct measured zero shifts for changes in contact resistance in the bridge arms.

Gages 1 to 6 were then stored in the laboratory at room temperature in the unstrained condition. Gages 7 to 18 were taken to the roof of the laboratory and exposed, unstrained, to open winter weather for 32 days. The strips to which the gages were attached were supported horizontally with the gages skyward. Temperatures, humidity, and precipitation for the weathering period, as recorded by the U. S. Weather Bureau, are given in figure 13. After weathering, gages 7 to 18 were stored at room temperature in the laboratory with gages 1 to 6 for 2 days. This allowed the weathered gages to reach laboratory temperature and permitted the unwaterproofed gages to dry before making measurements for zero shift.

Zero shifts were measured by redetermining the ratios of gage resistance to decade resistance with the decade adjusted to the same resistance for each gage that was used for the initial ratio. The zero shift $\Delta R/R$ was computed from the initial and final ratios on each of the 18 gages after applying a correction $\Delta R/R = -0.09 \times 10^{-4}$ for changes in contact resistance at the binding posts in the arms of the bridge. Variations in the dial switch resistance of the decade used with the test gages were considered in the estimate of the accuracy of measurements. After the zero shift determinations, calibration factors were redetermined on both the control gages and the weathered gages.

RESULTS AND DISCUSSION

The zero shifts which occurred on all gages after weathering or storage are given in table 1 together with calibration factors K_u and K_d before and after weathering or storage and percentage changes in calibration factor.

Examination of table 1 shows that no calibration factor changed by more than 1 percent. There was no marked difference between the changes in calibration factor for the weathered gages and for the control gages. In several cases the factors for a weathered gage, even without waterproofing, were more stable than the factors for a control gage. The factors for all gages, both control and weathered, were definitely more stable for decreasing strain (K_d) than for increasing strain (K_u).

Zero shifts after the weathering period showed substantial differences between gages depending on the attaching cement used, the waterproofing, and the weathering. Gages which were attached with Duco cement and were not weathered (gages 1 to 4) showed practically no zero shift. Gages which were attached with De Khotinsky cement and were not weathered (5 and 6) showed zero shifts of the order of $\Delta R/R = +2 \times 10^{-4}$. Weathered gages attached with Duco cement and waterproofed (7 to 10) showed negligible zero shift, while unwaterproofed gages (11 to 14) with the same attachment gave zero shifts ranging from $+1.37 \times 10^{-4}$ to $+2.68 \times 10^{-4}$. Weathered gages, both waterproofed and unwaterproofed, attached with De Khotinsky cement (15 to 18) gave somewhat inconsistent zero shifts ranging from small to large values. One of these gages (15) showed the extremely large shift of $\Delta R/R = 31.57 \times 10^{-4}$ (0.38 ohm). This shift was so much larger than the shifts measured on other gages that the measurement is open to question.

CONCLUSIONS OF TESTS ON EFFECTS OF EXPOSURE TO SEVERE WEATHER

Calibrations on 18 gages, 12 of which had been exposed to 32 days of severe winter weather, showed that the changes in calibration factor of individual gages due to weathering did not exceed ±1 percent even for gages with no waterproofing.

Waterproofing was advantageous in that weathered gages attached with Duco cement and protected by waterproofing showed negligible zero shift; whereas unwaterproofed gages gave zero shifts of the order of $\Delta R/R = +2 \times 10^{-4}$. Unwaterproofed gages attached with Duco cement and left unstrained at room temperature for 32 days after calibration showed negligible zero shift. It was found that gages attached with De Khotinsky cement were subject to zero shift with time at room temperature, although calibration factors of such gages were constant within 1 percent even after severe weathering.

National Bureau of Standards,
Washington, D. C., May 23, 1945.

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APPENDIX I

ATTACHMENT OF GAGES

Duco Household Cement

The procedure used in attaching gages with Duco cement consisted of the following steps:

1. The calibration strip was cleaned with acetone and the surface film was removed by rubbing the strip lightly with emery cloth so as to produce a dense mesh of fine scratches.

2. The prepared surface was cleaned again with a cloth moistened with acetone.

3. A bead of Duco cement was squeezed from the tube along the center of the strip for a length equal to the over-all length of the gage to be attached.

4. The gage, with edges moistened with acetone, was placed on top of the cement and was pressed down firmly with a flat stick. The excess cement was worked from under the exposed paper with the end of the stick. The area of gage under the felt was pressed down repeatedly by placing the flat of the stick over the gage and applying pressure to the upper surface with the fingers.

5. The gage was allowed to dry at room temperature for 48 hours before straining (or waterproofing).

Waterproofing of gages attached with Duco cement was accomplished by heating the strip to which a gage was attached to 160° F for 1 hour. After 1 hour and with the gage still hot, hot petrosene wax (Gargoyle Petrosene A) was painted over the gage and over the strip at the edges of the gage. The strip was then cooled in air before use.

De Khotinsky (Cementyte A)

The procedure for attaching gages with De Khotinsky cement consisted of the following steps:

1. Same as steps 1 and 2 for gages attached with Duco cement.

2. The strip was heated slowly on an electric plate while a stick of the De Khotinsky cement was rubbed over the attachment area until the cement had softened to a pasty state. The pasty cement was then smeared over the attachment area.

3. As soon as the cement became liquid, the gage was pressed firmly in place using a flat stick and pressure on the felt area of the gage.

4. The strip was immediately removed from the electric plate and the gage was again pressed down while the cement cooled and hardened.

Gages attached with De Khotinsky were waterproofed by painting hot petrosene wax over the gage area after the cement hardened.

TABLE 1.- RESULTS OF TESTS

Gage No.	Attaching cement	Calibration factors[1] [2]				Change in Calibration factor		Zero shift[3]
		Before weathering or storage		After weathering or storage		$\frac{\Delta K_u}{K_u}$	$\frac{\Delta K_d}{K_d}$	$\frac{\Delta R}{R} \times 10^{-4}$
		K_u	K_d	K_u	K_d	(percent)		
Control gages								
1	Duco	2.038	2.045	2.030	2.054	-0.4	+0.4	-0.14
2	"	2.061	2.067	2.052	2.068	-0.4	0.0	+0.14
[4] 3	"	2.061	2.071	2.051	2.061	-0.5	-0.5	-0.09
[4] 4	"	2.061	2.062	2.042	2.060	-0.9	-0.1	-0.09
5	DeKhotinsky	2.044	2.068	2.055	2.054	+0.5	-0.2	+1.67
6	"	2.048	2.054	2.041	2.054	-0.3	0.0	+2.51
Weathered gages								
[4] 7	Duco	2.063	2.063	2.046	2.059	-0.8	-0.2	+0.15
[4] 8	"	2.040	2.043	2.027	2.041	-0.6	-0.1	+0.38
[4] 9	"	2.059	2.062	2.054	2.062	-0.2	0.0	+0.10
[4] 10	"	2.050	2.053	2.056	2.053	+0.3	0.0	-0.09
11	"	2.062	2.072	2.041	2.056	-1.0	-0.8	+1.56
12	"	2.060	2.065	2.041	2.063	-0.9	-0.1	+2.68
13	"	2.062	2.065	2.063	2.068	0.0	+0.1	+1.37
14	"	2.073	2.078	2.058	2.077	-0.7	0.0	+1.69
[4] 15	DeKhotinsky	2.046	2.049	2.046	2.054	0.0	+0.2	[5] +31.57
[4] 16	"	2.043	2.043	2.036	2.046	-0.3	+0.1	+0.11
17	"	2.038	2.052	2.031	2.055	-0.3	+0.1	+0.77
18	"	2.055	2.060	2.063	2.060	+0.4	0.0	+3.00

[1] K_u (increasing strain).
K_d (decreasing strain).

[2] Estimated accuracy, ±0.5 percent.

[3] Estimated accuracy, $\pm 0.10 \times 10^{-4}$.

[4] Waterproofed with Petrosene.

[5] Questionable measurement.

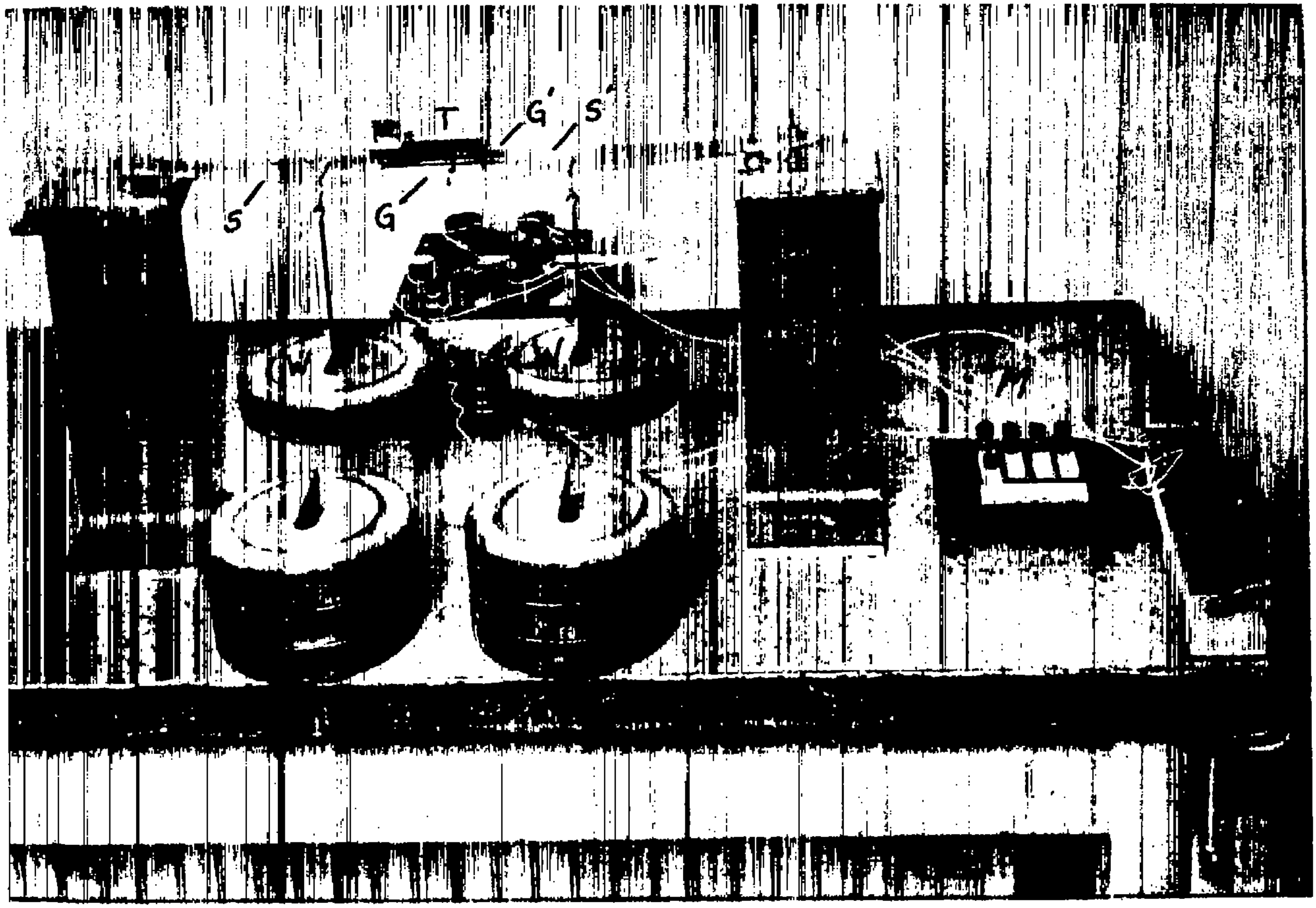

Figure 1.- Setup for zero shift measurements.

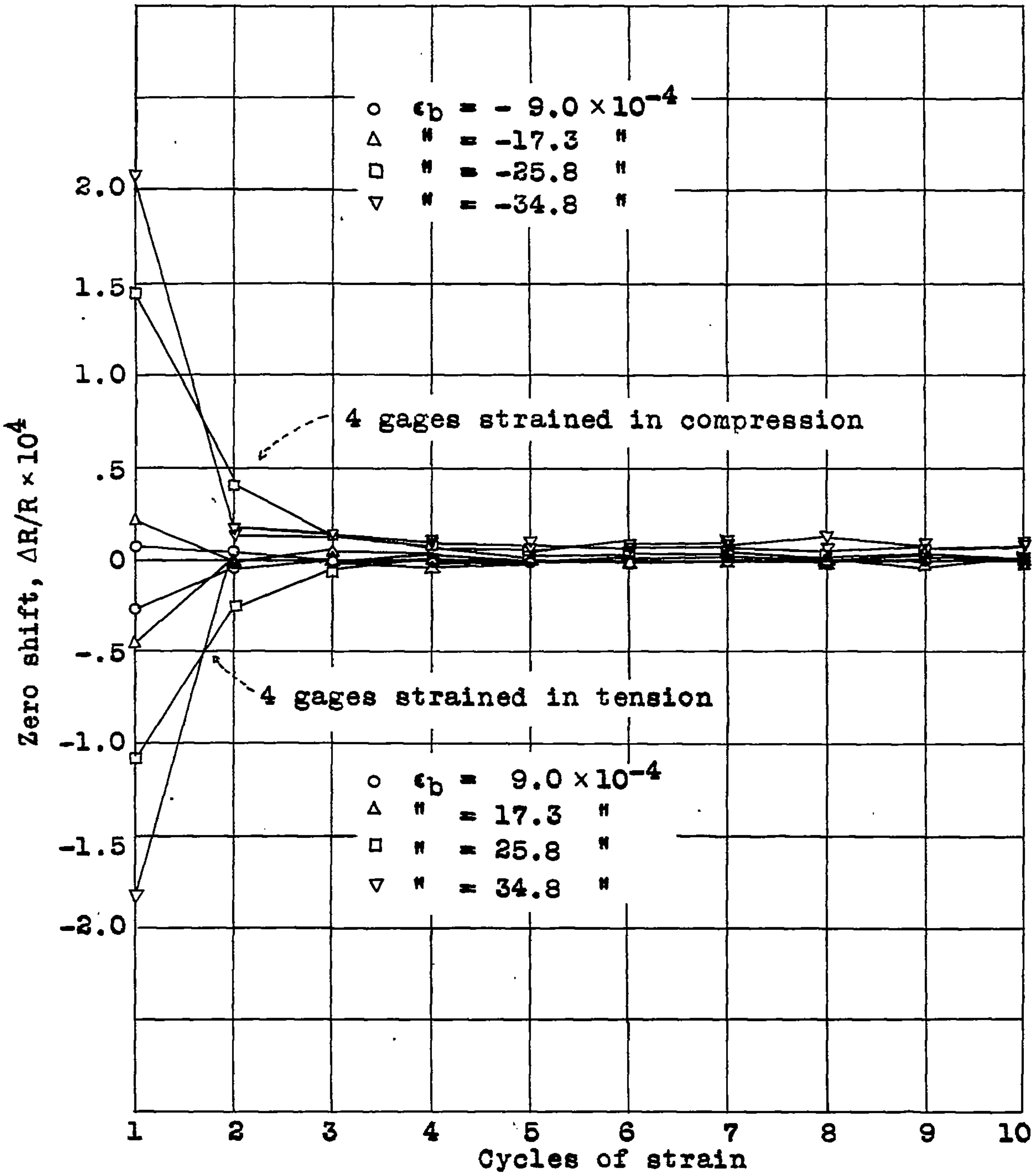

Figure 2.- Effect of strain cycling on zero shift.

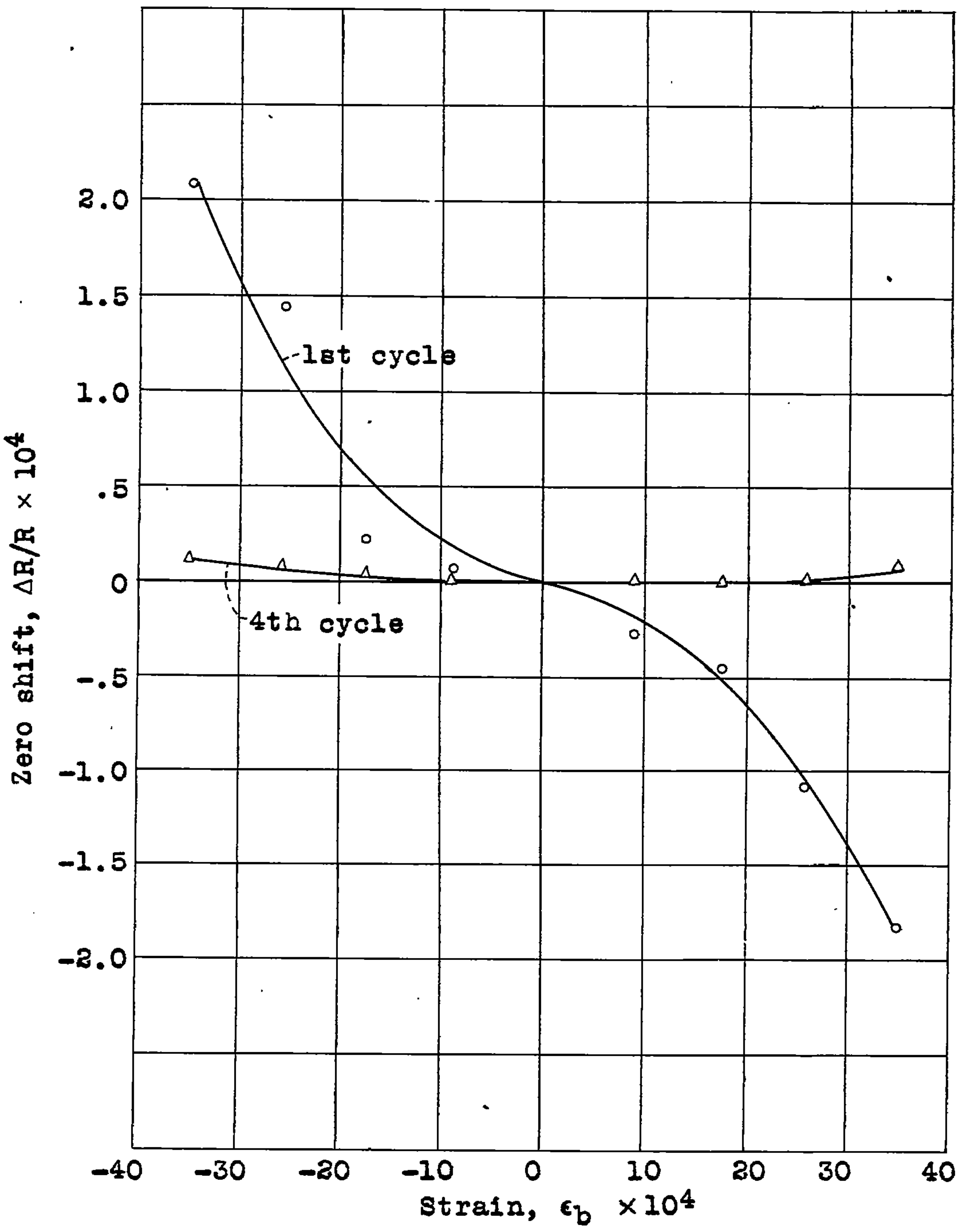

Figure 3.- Zero shift against strain.

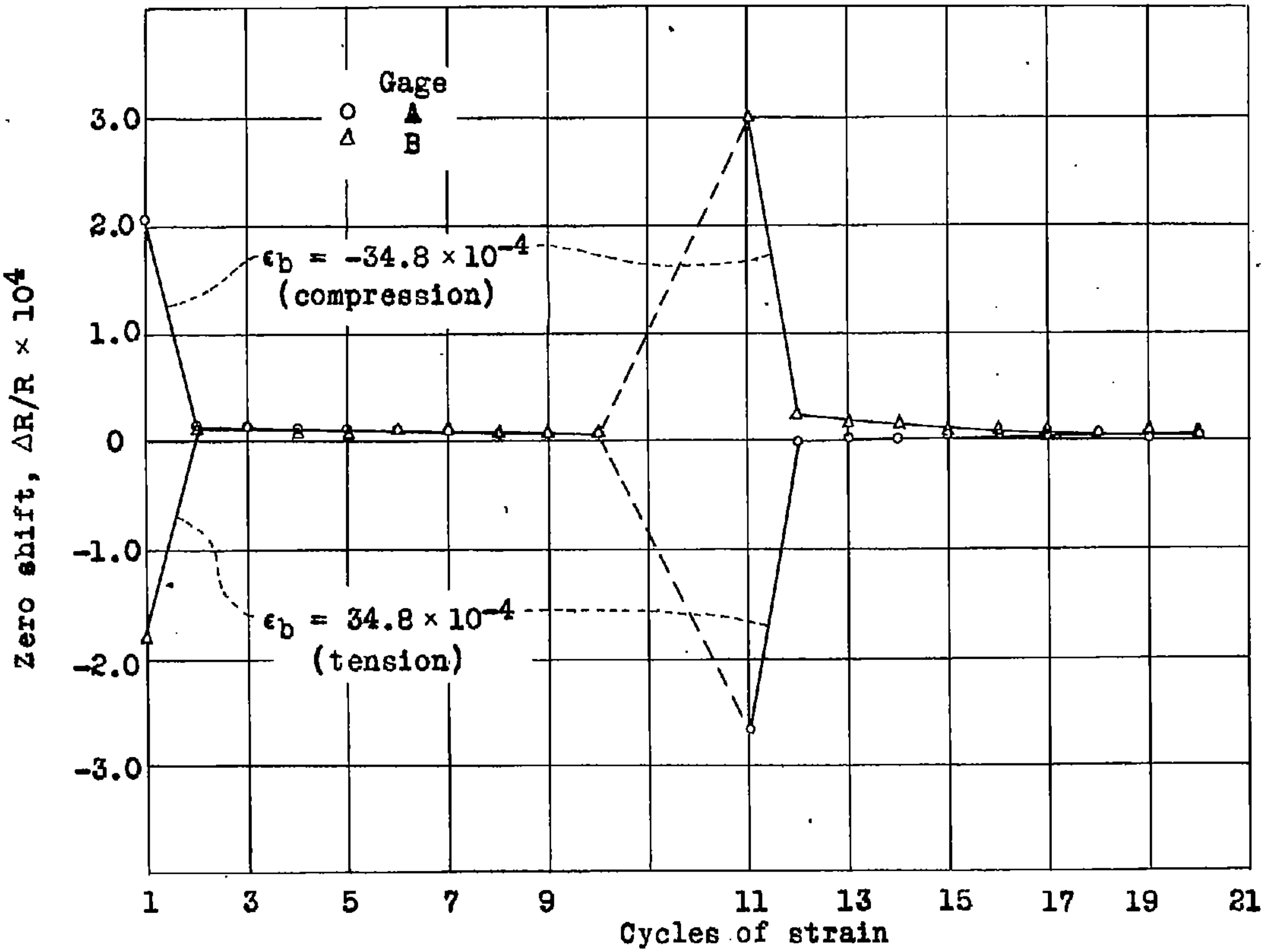

Figure 4.- Effect of reversal of applied strain on zero shift.

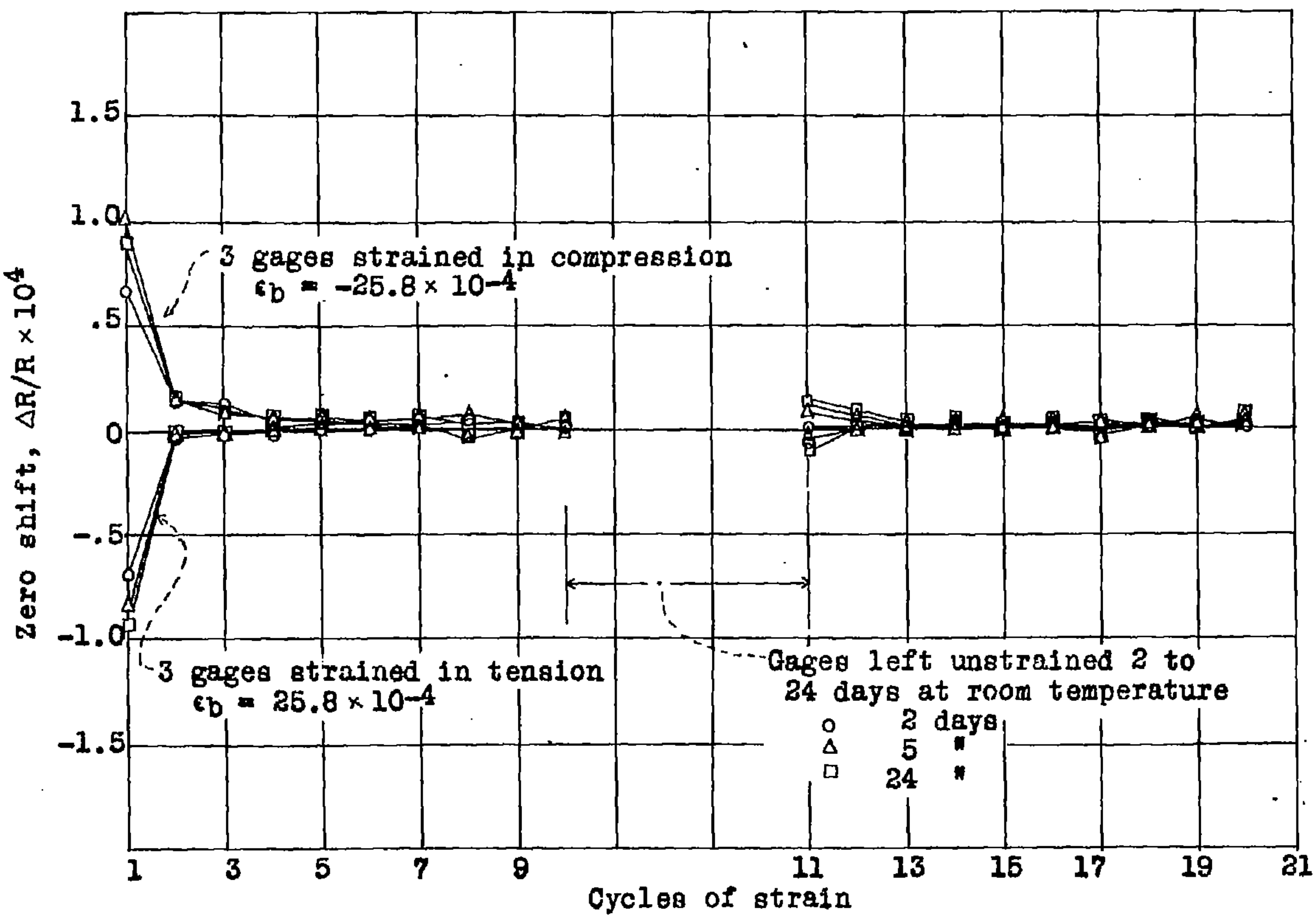

Figure 5.- Effect of time on zero shift.

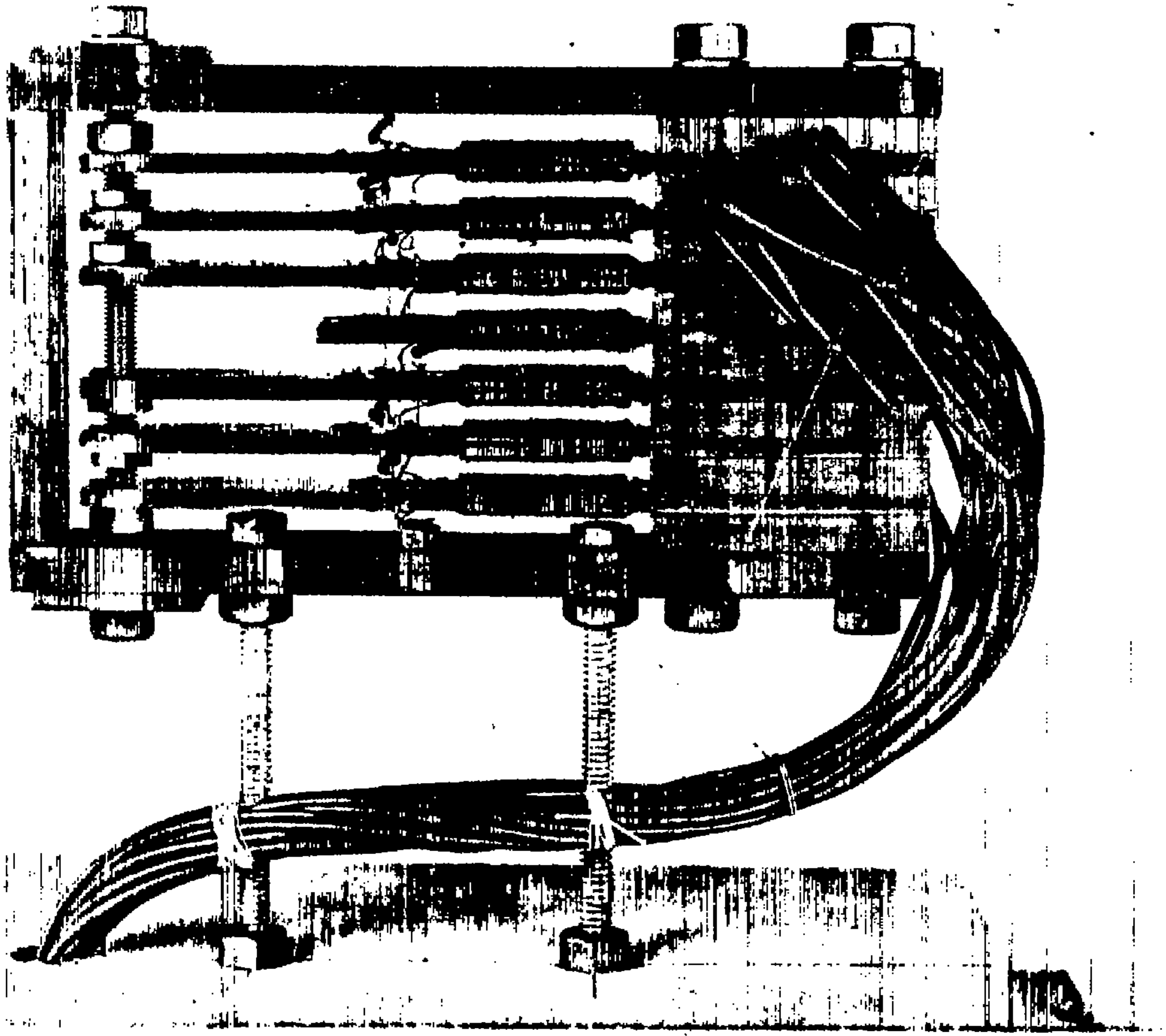

Figure 6.- Device for straining gages at high and low temperature.

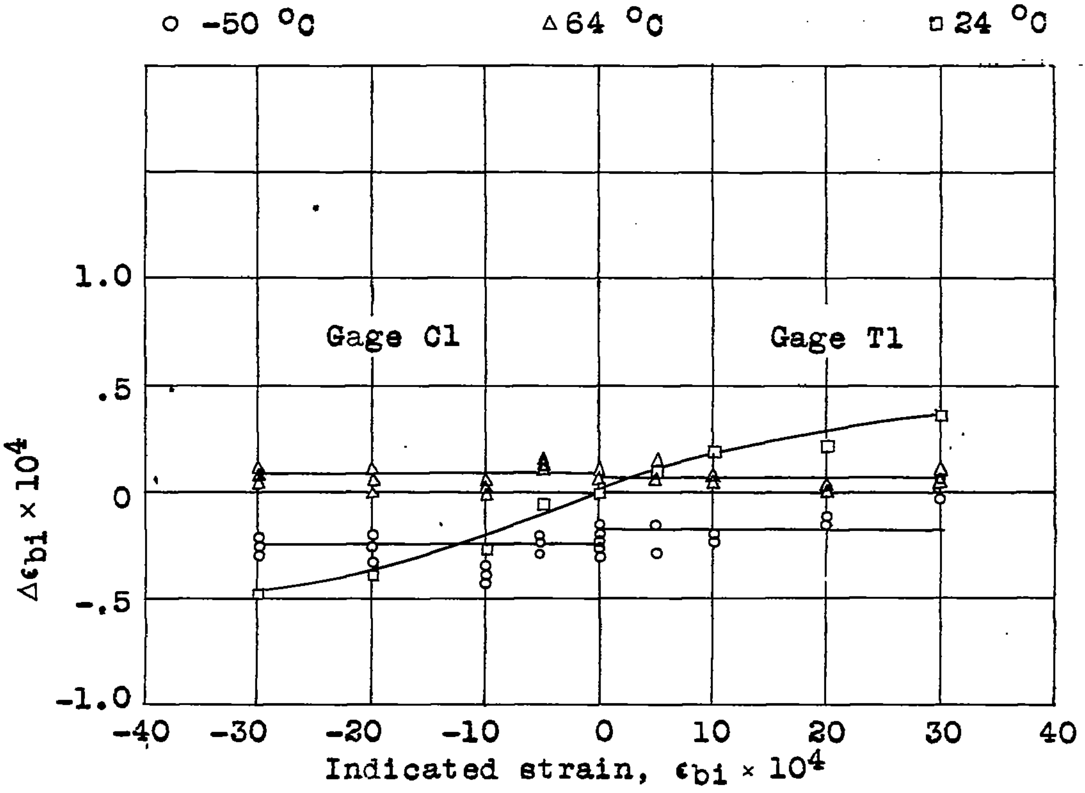

Figure 7.- Change in indicated strain against indicated strain.

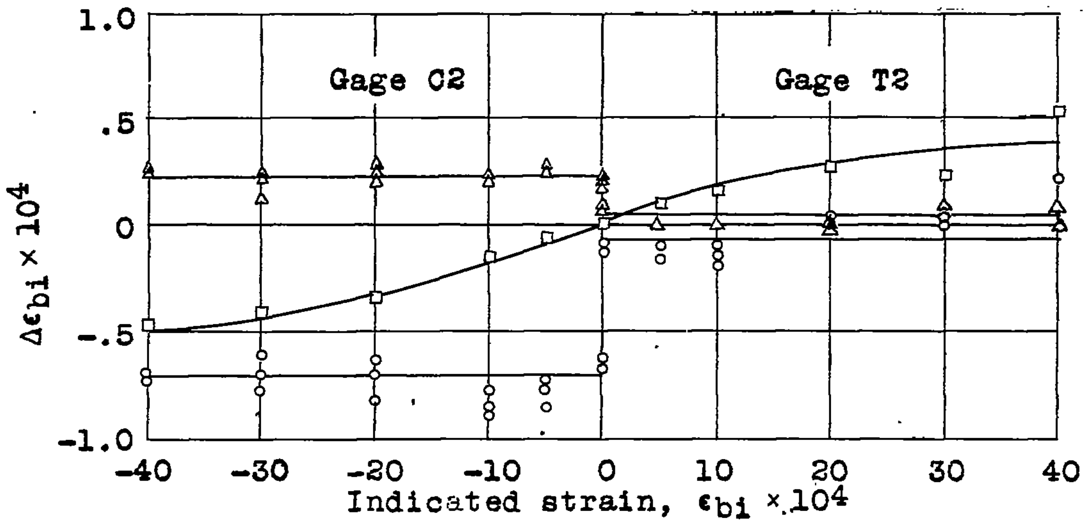

Figure 8.- Change in indiated strain against indicated strain.

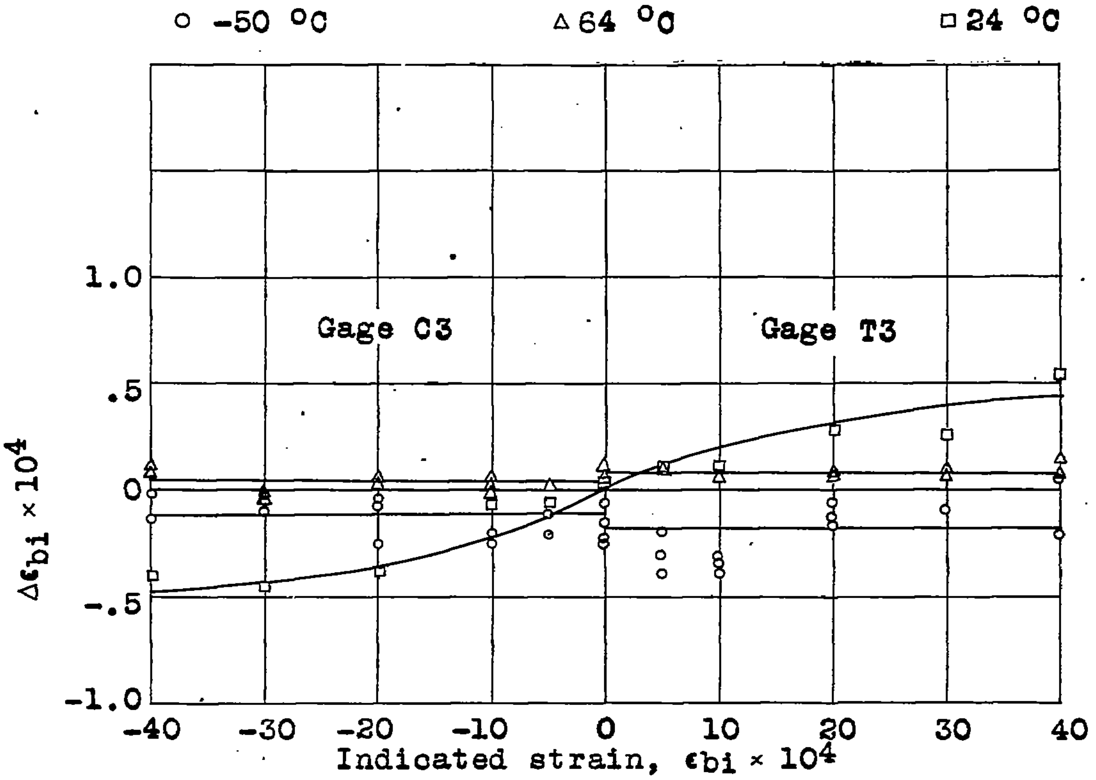

Figure 9.- Change in indicated strain against indicated strain.

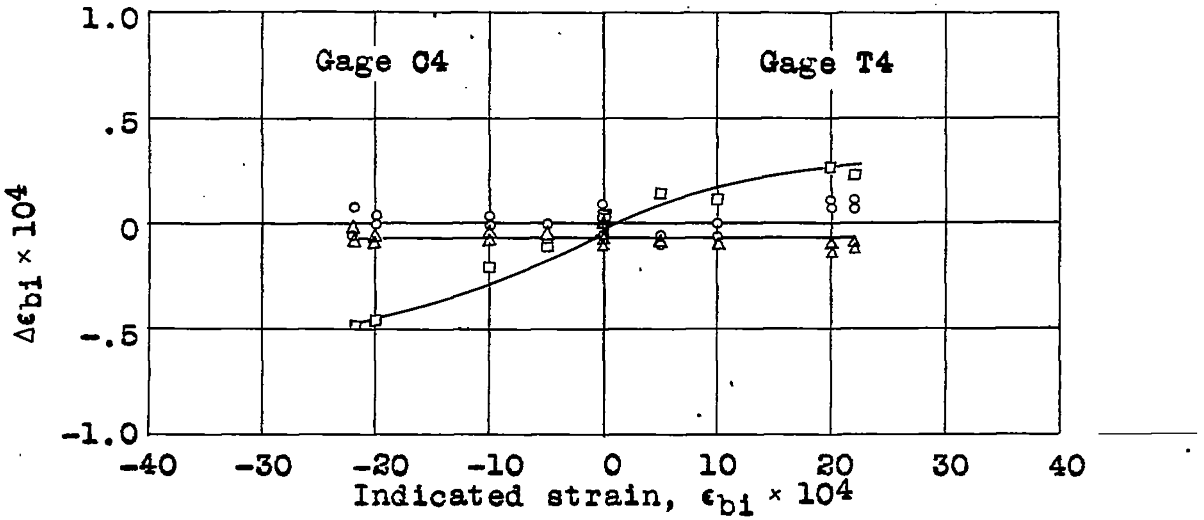

Figure 10.- Change in indicated strain against indicated strain.

○ −50 °C △ 64 °C □ 24 °C

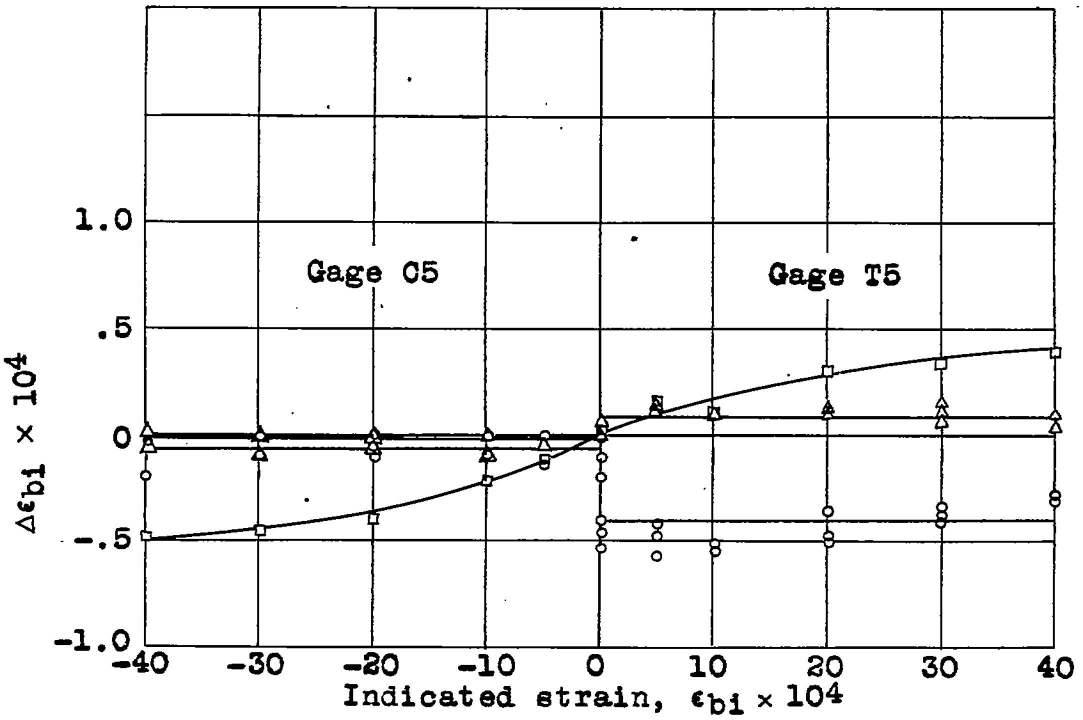

Figure 11.- Change in indicated strain against indicated strain.

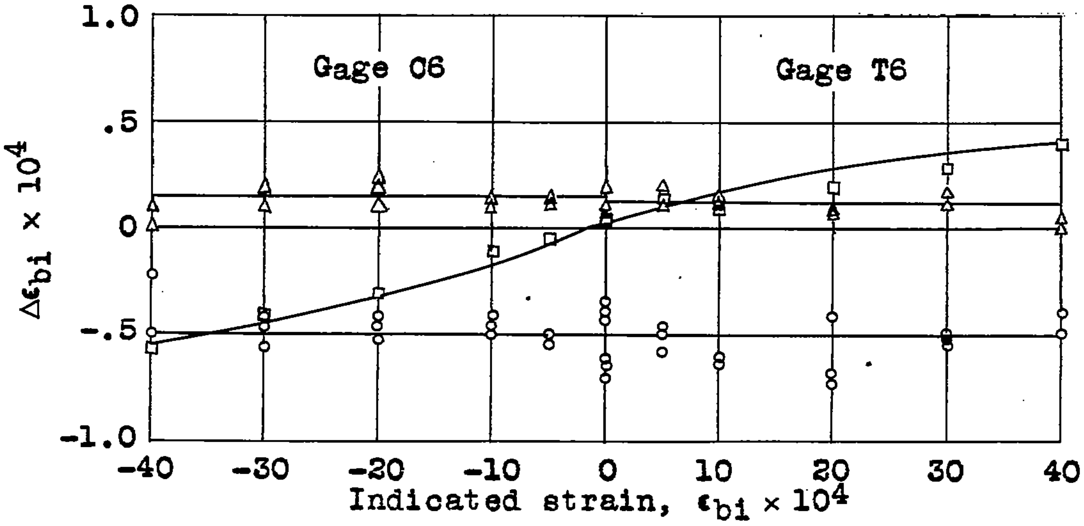

Figure 12.- Change in indicated strain against indicated strain.

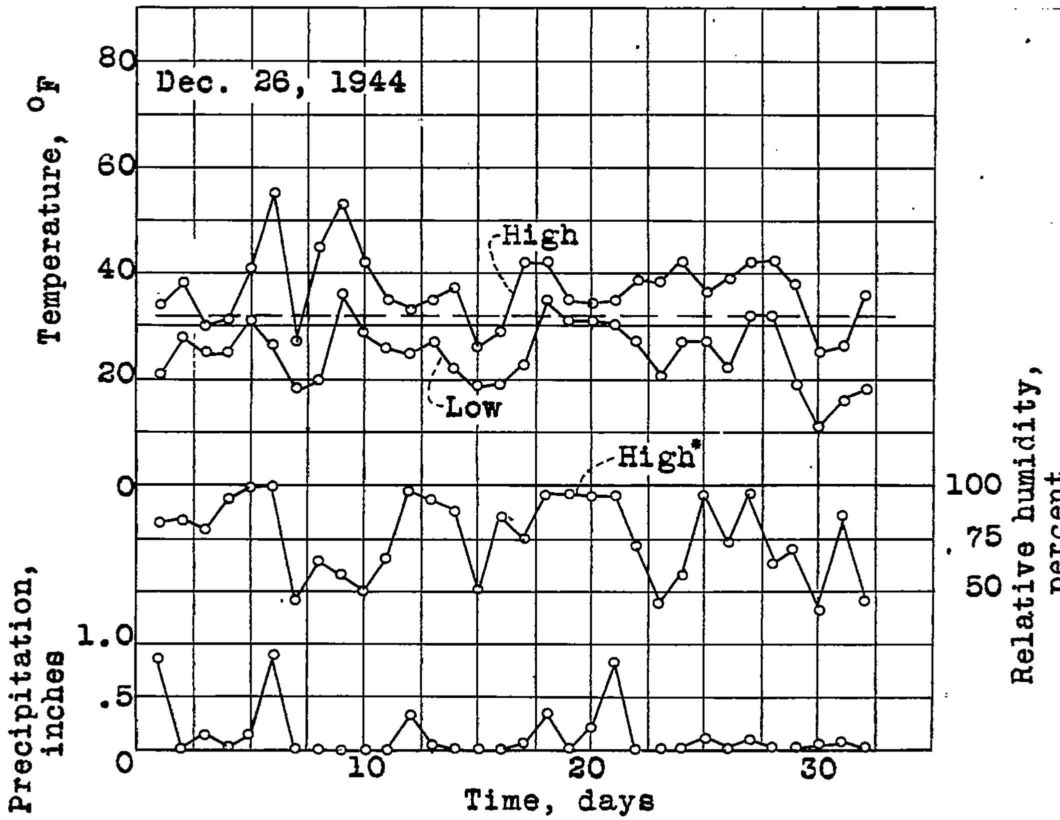

Figure 13.- U. S. Weather Bureau data for weathering period.

*Highest of four daily readings