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**A STRAIN-GAGE TECHNIQUE FOR MEASURING
THE THERMAL EXPANSION OF SOLIDS**

M. W. Poore
K. F. Kesterson

February 1977

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OAK RIDGE Y-12 PLANT
OAK RIDGE, TENNESSEE

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ABSTRACT

A technique was developed to measure the thermal expansion of solids in the temperature range from -50 to 175°C . The technique utilizes strain gages to measure expansion and Type J (iron/constantan) thermocouples to measure temperature. Measurements were made on pure platinum and on copper and tungsten standards obtained from the National Bureau of Standards.

CONTENTS

SUMMARY	4
INTRODUCTION	5
MEASURING THE THERMAL EXPANSION OF SOLIDS	6
Experimental Measurements	6
The Strain Gage	6
Equipment and Specimen Containment Chamber	6
Equipment Calibration	7
Experimental Procedure	7
Calculations	10
Standard Reference Materials	11
Analysis of Data	11
Discussion of Error and Results	12
Discussion of Error	12
Discussion of Results	12
Conclusions	14
BIBLIOGRAPHY	15
ACKNOWLEDGEMENTS	16
APPENDIX A	17
Tables	17
APPENDIX B	21
List of Symbols	21

SUMMARY

A technique was developed to measure the thermal expansion of solids in the temperature range from -50 to 175°C . The technique utilizes strain gages to measure expansion and Type J (iron/constantan) thermocouples to measure temperature. Measurements were made on pure platinum and on copper and tungsten standards obtained from the National Bureau of Standards.

Results were compared with the published values of expansivity. The maximum difference in measurements made in this study and the standard values was $0.22\ \mu^{\circ}\text{C}^{-1}$ ($0.22 \times 10^{-6}/^{\circ}\text{C}$) for the mean coefficients and $0.31\ \mu^{\circ}\text{C}^{-1}$ for the calculated instantaneous coefficients. The repeatability of the measurement of the mean coefficient of linear thermal expansion was one standard deviation of $\pm 0.14\ \mu^{\circ}\text{C}^{-1}$.

INTRODUCTION

A strain-gage technique was developed at the Oak Ridge Y-12 Plant^(a) to determine the thermal-expansion values of parts having a varied shape. These values were determined in the range from -50 to 175° C. It was required that the technique be relatively inexpensive and versatile enough to measure expansion in several directions simultaneously.

A strain gage, if properly compensated, may be used to measure thermal expansion of a material in the same manner it measures the applied strain of that material. In this technique for measuring thermal expansion, the active strain gage measuring the expansion was compensated for by an identical strain gage mounted on a low-expansion NBS standard of fused silica. Both the active and compensative gages were subjected to the same temperature. To prove out this technique, using strain gages to measure the expansion and Type J (iron/constantan) thermocouples to measure temperature, measurements were made on tungsten, copper, and platinum standards in the range from -50 to 175° C and the results, after correction for the expansion of the compensator (fused silica), were compared with the published values of expansivity.

(a) Operated by the Union Carbide Corporation's Nuclear Division for the US Energy Research and Development Administration.

MEASURING THE THERMAL EXPANSION OF SOLIDS

EXPERIMENTAL MEASUREMENTS

The Strain Gage

Micro-Measurement EA-06-500BH-120 (Option W) gages were chosen for this work. This strain gage is a constantan-foil-type gage with a polyimide backing which shows a relatively small amount of thermally induced apparent microstrain, as noted in Figure 1, and is stable in the -50 to 175°C range. The strain-gage adhesive used was the Micro-Measurement M-Bond 610. This particular adhesive is a two-component, solvent-thinned epoxy phenolic which has a temperature range from deep cryogenic to over 370°C and is capable of extremely thin, hard, and void-free glue lines that minimize creep, hysteresis, and linearity problems.

Strain gages from the same lot were bonded to the specimens per bonding instructions (M-M Bulletin B-130). After the gages were cured and post cured, two complete temperature cycles were run on them. The purpose of this thermal cycling was to minimize the zero-shift and hysteresis errors. All temperature cycling as well as the post cure was done in an argon-purged system. A view of the strain gages bonded to the four standards, along with their lead-wire attachments, is presented in Figure 2.

Figure 1. APPARENT STRAIN AS A FUNCTION OF THE TEMPERATURE FOR MICRO-MEASUREMENT CONSTANTAN GAGES.

All the strain measurements were made using a Model P-350 digital strain indicator in connection with a Model SB-1 switch and balance unit (both instruments are manufactured by the Budd Company). A fused-silica specimen was utilized as the compensator, and the specimen under test was connected on the switch and balance unit as the active gage. This arrangement of active and compensative gages, which is a Wheatstone bridge circuit, is illustrated in Figure 3.

Equipment and Specimen Containment Chamber

For this experiment, a special containment vessel was fabricated with grating $1\frac{1}{2}$ inches off the bottom and with perforated copper tubing beneath the grating to allow for argon purging of the system during temperature cycles. The grating was lined with aluminum foil to give a better temperature distribution. Six iron/constantan (Type J) thermocouples

were welded at different locations along the grating of the vessel. All lead wires to the thermocouples and strain gages were passed through an opening in the bottom half of the container and then this opening was sealed with tape. A typical specimen arrangement is seen in Figure 4.

The containment vessel was located in a Thermotron Temperature Test Chamber with a controllable temperature range of -300 to 600°F . Figure 5 is an overall view of this arrangement. Also used was a digital voltmeter, two thermocouple references for iron/constantan, Type J (reference temperature 0°C) thermocouples, and a Hewlett-Packard X-Y-Y strip-chart recorder. Figure 6 indicates the arrangement of the equipment for the experiment.

Equipment Calibration

Representative thermocouples from the group used in this experiment were calibration checked at several different temperatures within the range from -45 to 190°C . The maximum difference from the standard reference thermocouple was $+0.85^{\circ}\text{C}$, which occurred at the 190°C temperature level. The digital voltmeter and recorders used in this experiment were calibrated over the useful range by a voltage standard reference traceable to the National Bureau of Standards (NBS). The thermocouple reference junction (reference temperature 0°C) was checked by utilizing an ice bath and a reference thermocouple with a digital voltmeter readout. Items of equipment used in this experiment were all found to be within tolerance and were used without any calibration adjustments.

Experimental Procedure

The approach used in this thermal-expansion procedure was to heat the specimens in a stepwise manner, allowing thermal equilibrium to occur at each intervening temperature. A thermal cycle for purposes of measuring thermal expansion consisted of stabilizing at six different temperatures. This number of temperature readings does not include the room-temperature point at which the digital strain indicator was initially zeroed. (The room temperature from day to day varied about 1°C .) The initial stabilizing temperature was approximately -45°C . This temperature was defined as the base or reference temperature in all calculations. The heating rate during a cycle was approximately 2°C per minute, not including the stabilization period. To determine when stabilization occurred at a particular temperature, the X-Y-Y strip-chart recorder was used to monitor time versus the temperature on one of the Y axes and strain on the other Y axis. Stabilization was defined as that point when the chart-recorded temperature varied less than $1/2^{\circ}\text{C}$ and the strain varied no more than about 5 microinches per inch over a five-minute period.

The complete measurement consisted of three thermal cycles. This procedure was followed to determine if there was any noticeable effect due to the method of cycling. The first cycle consisted of overshooting each temperature level by approximately 10°C and then coming back to stabilize; the second cycle consisted of approaching each temperature level and stabilizing; the third cycle was a downward cycle that was actually part of the second cycle in that the temperature was brought down from the high level ($\sim 175^{\circ}\text{C}$) to the reference

167014
Figure 2. STANDARD REFERENCE MATERIALS WITH BONDED STRAIN GAGES AND LEADWIRES ATTACHED.

Figure 3. WHEATSTONE-BRIDGE ARRANGEMENT OF ACTIVE AND COMPENSATIVE GAGES FOR ELIMINATING TEMPERATURE-INDUCED APPARENT STRAIN.

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Figure 4. SPECIMEN ARRANGEMENT INSIDE THE CONTAINMENT VESSEL.

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Figure 5. CONTAINMENT VESSEL USED FOR THE THERMAL MEASUREMENTS AS IT WAS LOCATED INSIDE THE FURNACE.

Figure 6. EQUIPMENT ARRANGEMENT FOR THE THERMAL-EXPANSION EXPERIMENT.

level by slowly approaching each level from above and stabilizing. As a check on the variation of different strain gages, the four reference materials were strain gaged again from strain gages of the same lot used before, and the complete measurement was repeated.

The uncorrected data for the experimentation are reported in Tables A-1 through A-3 (see Appendix A). Also given in these tables is the temperature standard deviation for the six thermocouples used.

Calculations

Properties of the strain gages and the test part which contribute to the apparent strain variation with temperature and related definitions include:

- β the coefficient of thermal resistivity of the grid conductor,
- α the coefficient of thermal expansion of the base materials or test part,
- α_G the coefficient of thermal expansion of the gage material,
- F gage factor or strain sensitivity of the strain gage,
- ΔT temperature change from the arbitrary initial reference temperature, and
- ϵ_{App} the apparent strain of the strain gage. (A full list of symbols and their definitions is presented in Appendix B.

Using these definitions, the net temperature-induced apparent strain can be expressed as follows:

$$\epsilon_{App} = (\alpha - \alpha_G) \Delta T + \frac{\beta}{F} \Delta T. \quad (1)$$

Temperature-induced apparent strain can be minimized by employing a "compensating" strain gage in conjunction with the "active" strain gage. The compensative gage must be connected in an adjacent arm of the Wheatstone bridge circuit. In theory, the compensating gage must be identical with the active gage mounted on an unstrained specimen made from the identical material as the test part, and both the active and compensative gages must be subjected to the same temperature. Because of leadwire resistivity changes, the leadwires to the active and compensative gages must be the same length and routed together so that any temperature changes affect them identically. This arrangement of active and compensative gages is illustrated in Figure 3.

In this experimentation, the problem was to eliminate all temperature-induced apparent strain except for the thermal expansion of the test part (α). To accomplish this goal, a very-low-expansion material with a well-known coefficient of thermal expansion [$\alpha(c)$] was used as the mounting material for the compensating gage. Fused-Silica Standard Reference

Material 739 from the NBS was employed. When the two strain gages were arranged, as in Figure 3, an output calibrated to be equivalent to the algebraic difference in the apparent strains (ϵ') resulted. From Equation 1, this difference is determined to be:

$$\epsilon' = [\alpha - \alpha(c)] \Delta T. \quad (2)$$

The term, $\alpha(c)$, by definition, is a well-known parameter, and ϵ' and ΔT can be measured accurately by instrumentation. By manipulation of Equation 2, an expression for α is obtained:

$$\alpha = \epsilon'/\Delta T + \alpha(c). \quad (3)$$

Defining ϵ' as the uncorrected thermal expansion of the base material and $\epsilon'/\Delta T$ as the uncorrected coefficient of thermal expansion (α'), another expression for α is obtained:

$$\alpha = \alpha' + \alpha(c) \quad (4)$$

From this expression, the parameter of interest in this experiment can be calculated.

Standard Reference Materials

In order to evaluate the strain-gage technique as a means of determining thermal expansion, it was necessary to obtain materials for which the thermal expansion was well known. Copper, tungsten, and fused-silica rods (1/4 inch in diameter by 2 inches long) were obtained from the NBS Office of Standard Reference Materials. Platinum (in the form of 1/4-inch-diameter, 3.8-inch-long rods) was also used as a standard. The published thermal expansion data for the NBS copper, fused-silica, and tungsten specimens was given in SRM (Standard Reference Material) 736, 737, and 739, respectively. Data for the platinum was obtained from Table A2 of ASTM E228-71 (Linear Thermal Expansion of Rigid Solids with a Vitreous Silica Dilatometer). A summary of the thermal expansion data in the range of interest is presented in Table A-4. Expansion at the temperatures of interest was estimated using a third-degree-polynomial least-squares fit of published data obtained in the range from 220 to 480 K. Also calculated and presented in Table A-4 is the mean coefficient of thermal expansion (α_m) computed for each ΔT from a common reference temperature, being the low or base temperature.

Analysis of Data

Each standard was separately analyzed. At each temperature level, the average temperature and the uncorrected average mean coefficient of linear thermal expansion (α'_m) for the complete experiment was determined. The average α'_m value at each level was then corrected by adding to it the corresponding $\alpha_m(c)$ value for fused silica (SRM 739), as found in Table A-4 (see Equation 4 calculations). Table A-5 gives this corrected mean coefficient of linear thermal expansion (α_m) and its standard deviation. The experimental thermal expansion for each material was then approximated, using the α_m values. These

thermal expansion values are also given in Table A-5. Figures 7 through 9 compare the experimental thermal expansion curves taken from Table A-5 with the published thermal expansion curves from Table A-4. These curves were estimated by using a third-degree-polynomial least-squares fit. In Table A-6, a comparison is made between the experimentally determined α_m values and the α_m values determined from published data.

Experimental instantaneous coefficients (α_I) were calculated (Hahn, 1970) using the thermal expansion data in Table A-5, and a third-degree polynomial was least-squares fitted to each set of data. All α_I values were found to fit the following equations:

Tungsten:

$$\alpha_I \times 10^6 = 4.4532 - 2.9193 \times 10^{-3}T - 7.2398 \times 10^{-6}T^2 + 1.5531 \times 10^{-7}T^3. \quad (5)$$

Copper:

$$\alpha_I \times 10^6 = 16.458 + 9.9294 \times 10^{-3}T - 3.1552 \times 10^{-5}T^2 + 1.553 \times 10^{-7}T^3. \quad (6)$$

Platinum:

$$\alpha_I \times 10^6 = 8.6990 + 2.3300 \times 10^{-3}T + 2.0636 \times 10^{-5}T^2 - 7.2916 \times 10^{-8}T^3. \quad (7)$$

The standard deviation of the data points which the three equations fit is $\pm 0.14 \mu^{\circ} \text{C}^{-1}$ ($\pm 0.14 \times 10^{-6} / ^{\circ} \text{C}$). Figure 10 is a plot of the difference between Equation 5 and the NBS certification of SRM 737; Figure 11 is a plot of the difference between Equation 6 and the NBS certification of SRM 736, and Figure 12 is the difference between Equation 7 and the α_I' values calculated from Table A2 of ASTM E-228-71.

DISCUSSION OF ERROR AND RESULTS

Discussion of Error

Errors in the thermal expansion data due to the variation in gage factor with temperature ranged from -0.5 to 1.1%. This range of values related to a mean coefficient error of 0.4 to -0.6%. There was also a small, fixed, bridge excitation error in the opposite direction (a maximum error on the order of about 0.2%).

Major contributing errors to the experiment were: (1) the measurement accuracy of the temperature, and (2) the apparent strain variability of the constantan gages used (Micro-Measurement, TN-128-2). The estimated maximum uncertainties for the temperature and the strain gages are given in Table A-7.

Discussion of Results

Examination of Tables A-2 through A-4 indicate no noticeable effect due to the method of temperature cycling.

From Table A-5, the repeatability of the mean coefficient of thermal expansion (α_m) shows an overall pooled standard deviation or repeatability of $\pm 0.14 \mu^{\circ} \text{C}^{-1}$. Assuming that the NBS certifications and ASTM values are correct, the maximum error for the mean coefficient is $0.22 \mu^{\circ} \text{C}^{-1}$ (Table A-6), which occurred for the copper. In a more descriptive

Figure 7. COMPARISON OF THE EXPERIMENTAL AND PUBLISHED THERMAL-EXPANSION DATA FOR TUNGSTEN.

Figure 8. COMPARISON OF THE EXPERIMENTAL AND PUBLISHED THERMAL-EXPANSION DATA FOR PLATINUM.

Figure 9. COMPARISON OF THE EXPERIMENTAL AND PUBLISHED THERMAL-EXPANSION DATA FOR COPPER.

Figure 10. DIFFERENCE BETWEEN EQUATION 1 AND THE NATIONAL BUREAU OF STANDARDS INSTANTANEOUS COEFFICIENTS OF SRM 737 (TUNGSTEN).

Figure 11. DIFFERENCE BETWEEN EQUATION 2 AND THE NATIONAL BUREAU OF STANDARDS INSTANTANEOUS COEFFICIENTS OF SRM 736 (COPPER).

Figure 12. DIFFERENCE BETWEEN EQUATION 3 AND THE INSTANTANEOUS COEFFICIENTS CALCULATED FROM TABLE A2 ASTM E 228-71 (PLATINUM).

comparison, the maximum instantaneous coefficient error is $0.31 \mu^{\circ} \text{C}^{-1}$ (Figures 10 through 12) which occurred for the tungsten. The instantaneous errors all fall within the estimated uncertainties of $\pm 0.53 \mu^{\circ} \text{C}^{-1}$ for copper, $\pm 0.41 \mu^{\circ} \text{C}^{-1}$ for platinum, and $\pm 0.34 \mu^{\circ} \text{C}^{-1}$ for tungsten (Table A-7). The maximum error, which occurred for the tungsten standard, would normally be expected to occur for copper because of the larger expansion values. However, this larger error for tungsten is not unreasonable, considering that the major portion of the error is due to the uncertainty between the constantan gages ($\pm 0.27 \mu^{\circ} \text{C}^{-1}$) and is independent of the expansion of the base material.

For measurements on the NBS standards made in this study (Figures 10 and 11), a systematic variation in the instantaneous coefficients can be seen. In the region from 70 to 145°C , the change in $\alpha_I - \alpha_I$ NBS is small ($0.07 \mu^{\circ} \text{C}^{-1}$ for tungsten and $0.05 \mu^{\circ} \text{C}^{-1}$ for copper). Outside this region, the change in $\alpha_I - \alpha_I$ NBS increases sharply. These systematic variations can be explained by examining the apparent strain-versus-temperature curve for constantan gages approximated in Figure 1. In the 70 to 145°C region, the apparent strain slope is relatively constant; thus, there is a constant difference between the active and compensative gages. Outside this temperature region, the slope changes drastically and the difference between the active and compensative gages has more variation. This inconsistency results in the larger variations in $\alpha_I - \alpha_I$ NBS outside the 70 to 145°C region, as seen in Figures 10 and 11.

CONCLUSIONS

This strain-gage technique is an accurate and relatively inexpensive method for determining thermal-expansion characteristics in the range from -50 to 175°C . There are more accurate techniques for measuring thermal expansion, but none is as inexpensive as this one, considering that the strain-gage application to varied geometries is neither limited by location or direction.

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APPENDIX A**TABLES**

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Table A-1

UNCORRECTED THERMAL-EXPANSION DATA FOR THE TUNGSTEN STANDARD (SRM 737) AS TAKEN FOR THE TWO DIFFERENT GAGE SETS OVER THREE DIFFERENT CYCLES

Order of Temperature Cycle	First Cycle			Second Cycle			Third Cycle		
	Temperature ± σ ⁽¹⁾ (° C)	ε' ⁽²⁾ (μin/in)	α _m ' ⁽³⁾ (μ° C ⁻¹)	Temperature ± σ (° C)	ε' (μin/in)	α _m ' (μ° C ⁻¹)	Temperature ± σ (° C)	ε' (μin/in)	α _m ' (μ° C ⁻¹)
First Gage Set									
1	23.3 ± 0.1	0	3.90	22.5 ± 0.1	0	3.95	171.3 ± 1.6	543	3.73
2	- 45.4 ± 0.3	- 268	-	- 47.6 ± 0.2	- 277	-	137.3 ± 0.7	423	3.73
3	3.8 ± 0.2	- 71	4.00	1.8 ± 0.1	- 79	4.01	98.8 ± 0.4	283	3.80
4	54.2 ± 0.3	118	3.88	52.7 ± 0.3	112	3.88	54.3 ± 0.4	124	3.90
5	100.5 ± 0.4	286	3.80	98.1 ± 0.6	278	3.81	4.4 ± 0.2	- 66	4.00
6	138.7 ± 0.8	425	3.76	134.8 ± 1.0	410	3.77	- 45.9 ± 0.4	- 267	-
7	174.0 ± 1.0	553	3.76	171.3 ± 1.6	543	3.75			
Second Gage Set									
1	24.5 ± 0.1	0	4.05	23.8 ± 0	0	4.22	173.4 ± 1.9	580	3.98
2	- 45.2 ± 0.4	- 232	-	- 44.7 ± 0.6	- 289	-	137.6 ± 1.0	428	3.93
3	4.5 ± 0.4	- 75	4.16	2.8 ± 0.3	80	4.40	100.0 ± 0.5	295	4.03
4	55.5 ± 0.4	121	4.00	54.2 ± 0.4	123	4.17	54.6 ± 0.4	123	4.14
5	98.7 ± 0.9	276	3.88	99.6 ± 1.0	301	4.09	6.7 ± 0.9	- 68	4.29
6	135.6 ± 1.2	435	3.97	135.2 ± 1.2	435	4.02	- 43.8 ± 0.7	- 284	-
7	175.3 ± 1.4	575	3.89	173.4 ± 1.9	580	3.99			

(1) σ = Standard deviation.

(2) ε' = Uncorrected thermal expansion of the standard material.

(3) α_m' = Uncorrected mean coefficient of thermal expansion referenced to the low temperature (T₁) and calculated by (ε'₂ - ε'₁)/(T₂ - T₁).

Table A-2

UNCORRECTED THERMAL-EXPANSION DATA FOR THE PLATINUM STANDARD AS TAKEN FOR THE TWO DIFFERENT GAGE SETS OVER THREE DIFFERENT CYCLES

Order of Temperature Cycle	First Cycle			Second Cycle			Third Cycle		
	Temperature ± σ ⁽¹⁾ (° C)	ε' ⁽²⁾ (μin/in)	α _m ' ⁽³⁾ (μ° C ⁻¹)	Temperature ± σ (° C)	ε' (μin/in)	α _m ' (μ° C ⁻¹)	Temperature ± σ (° C)	ε' (μin/in)	α _m ' (μ° C ⁻¹)
First Gage Set									
1	23.3 ± 0.1	0	8.11	22.5 ± 0.1	0	8.16	171.3 ± 1.6	1250	8.32
2	- 45.4 ± 0.3	- 557	-	- 47.6 ± 0.2	- 572	-	137.3 ± 0.7	959	8.26
3	3.8 ± 0.2	- 159	8.09	1.8 ± 0.1	- 170	8.14	98.8 ± 0.4	631	8.21
4	54.2 ± 0.3	254	8.14	52.7 ± 0.3	248	8.18	54.3 ± 0.4	266	8.21
5	100.5 ± 0.4	645	8.24	98.1 ± 0.6	628	8.24	4.4 ± 0.4	- 147	8.15
6	138.7 ± 0.8	967	8.28	134.8 ± 1.0	938	8.28	- 45.9 ± 0.2	- 557	-
7	174.0 ± 1.0	1267	8.31	171.3 ± 1.6	1250	8.32			
Second Gage Set									
1	24.5 ± 0.1	0	7.92	23.8 ± 0	0	8.42	173.4 ± 1.9	1288	8.54
2	- 45.2 ± 0.4	- 552	-	- 44.7 ± 0.6	- 557	-	137.6 ± 1.0	961	8.43
3	4.5 ± 0.4	- 139	8.31	2.8 ± 0.3	- 168	8.61	100.0 ± 0.5	644	8.43
4	55.5 ± 0.4	280	8.26	54.2 ± 0.4	261	8.47	54.6 ± 0.4	260	8.41
5	98.7 ± 0.9	656	8.39	99.6 ± 1.0	646	8.48	6.7 ± 0.9	- 139	8.49
6	135.6 ± 1.2	370	8.42	135.2 ± 1.2	955	8.52	- 43.8 ± 0.7	- 566	-
7	175.3 ± 1.4	1309	8.44	173.4 ± 1.9	1288	8.56			

(1) σ = Standard deviation.

(2) ε' = Uncorrected thermal expansion of the standard material.

(3) α_m' = Uncorrected mean coefficient of thermal expansion referenced to the low temperature (T₁) and calculated by (ε'₂ - ε'₁)/(T₂ - T₁).

Table A-3

UNCORRECTED THERMAL-EXPANSION DATA FOR THE COPPER STANDARD (SRM 736) AS TAKEN FOR THE TWO DIFFERENT GAGE SETS OVER THREE DIFFERENT CYCLES

Order of Temperature Cycle	First Cycle			Second Cycle			Third Cycle		
	Temperature ± σ ⁽¹⁾ (° C)	ε' ⁽²⁾ (μin/in)	α _m ' ⁽³⁾ (μ° C ⁻¹)	Temperature ± σ (° C)	ε' (μin/in)	α _m ' (μ° C ⁻¹)	Temperature ± σ (° C)	ε' (μin/in)	α _m ' (μ° C ⁻¹)
First Gage Set									
1	23.3 ± 0.1	0	15.87	22.5 ± 0.1	0	15.81	171.3 ± 1.6	2480	16.38
2	- 45.4 ± 0.3	- 1090	-	- 47.6 ± 0.2	- 1108	-	137.3 ± 0.7	1903	16.27
3	3.8 ± 0.2	- 313	15.79	1.8 ± 0.1	- 334	15.67	98.8 ± 0.4	1257	16.13
4	54.2 ± 0.3	500	15.96	52.7 ± 0.3	488	15.91	54.3 ± 0.4	524	15.98
5	100.5 ± 0.4	1269	16.17	98.1 ± 0.6	1238	16.10	4.4 ± 0.2	- 285	15.75
6	138.7 ± 0.8	1913	16.31	134.8 ± 1.0	1856	16.25	- 45.9 ± 0.4	- 1077	-
7	174.0 ± 1.0	2515	16.43	171.3 ± 1.6	2480	16.38			
Second Gage Set									
1	24.5 ± 0	0	16.01	23.8 ± 0	0	16.12	173.4 ± 1.9	2517	16.64
2	- 45.2 ± 0.4	- 1116	-	- 44.7 ± 0.6	- 1104	-	137.6 ± 1.0	1884	16.43
3	4.5 ± 0.4	- 332	15.77	2.8 ± 0.3	- 342	16.04	100.0 ± 0.5	1248	16.31
4	55.5 ± 0.4	490	15.95	54.2 ± 0.4	495	16.17	54.6 ± 0.4	495	16.18
5	98.7 ± 0.9	1220	16.23	99.6 ± 1.0	1251	16.32	6.7 ± 0.9	- 279	16.20
6	135.6 ± 1.2	1830	16.29	135.2 ± 1.2	1854	16.44	- 43.8 ± 0.7	- 1094	-
7	175.3 ± 1.4	2513	16.46	173.4 ± 1.9	2517	16.60			

(1) σ = Standard deviation.

(2) ε' = Uncorrected thermal expansion of the standard material.

(3) α_m' = Uncorrected mean coefficient of thermal expansion referenced to the low temperature (T₁) and calculated by (ε'₂ - ε'₁)/(T₂ - T₁).

Table A-4

THERMAL-EXPANSION DATA CALCULATED FROM PUBLISHED REPORTS ON THE STANDARD MATERIALS USED

Temperature (° C)	Tungsten (SRM 737)		Platinum (ASTM-E-228-71)		Copper (SRM 736)		Fused-Silica (SRM 739)	
	ε ⁽¹⁾ (μin/in)	α _m ⁽²⁾ (μ° C ⁻¹)	ε (μin/in)	α _m (μ° C ⁻¹)	ε (μin/in)	α _m (μ° C ⁻¹)	ε (μin/in)	α _m (μ° C ⁻¹)
- 45	- 282	-	- 398	-	- 1048	-	- 25.6	-
4	- 70	4.33	35	8.84	- 236	16.02	- 7.3	0.37
54	151	4.37	482	8.89	568	16.32	17.2	0.43
99	355	4.42	891	8.95	1339	16.58	42.8	0.48
136	524	4.45	1231	9.00	1987	16.77	65.4	0.50
173	695	4.48	1575	9.05	2645	16.94	88.4	0.52

(1) α_m = Mean coefficient of thermal expansion calculated from the reference temperature (- 45° C).

(2) ε = Thermal expansion of the standard materials.

Table A-5
EXPERIMENTALLY DETERMINED AND CORRECTED THERMAL EXPANSION DATA FOR THE STANDARDS

Average Temperature (° C)	Tungsten (SRM 737)			Platinum (ASTM-E-288-71)			Copper (SRM 736)		
	Average α_m ⁽¹⁾ ($\mu^\circ\text{C}^{-1}$)	σ ⁽²⁾ ($\mu^\circ\text{C}^{-1}$)	ϵ ⁽³⁾ ($\mu\text{in/in}$)	Average α_m ($\mu^\circ\text{C}^{-1}$)	σ ($\mu^\circ\text{C}^{-1}$)	ϵ ($\mu\text{in/in}$)	Average α_m ($\mu^\circ\text{C}^{-1}$)	σ ($\mu^\circ\text{C}^{-1}$)	ϵ ($\mu\text{in/in}$)
- 45	-	-	- 282	-	-	- 398	-	-	- 1048
4	4.51	0.17	- 61	8.67	0.21	27	16.24	0.20	- 252
54	4.43	0.13	157	8.71	0.13	454	16.46	0.12	582
99	4.38	0.13	349	8.81	0.12	871	16.69	0.09	1355
136	4.36	0.12	507	8.87	0.11	1207	16.83	0.08	1998
173	4.37	0.12	671	8.94	0.12	1551	17.00	0.11	2658

(1) α_m = Mean coefficient of thermal expansion calculated from the reference temperature (- 45° C).
(2) σ = Standard deviation for α_m .
(3) ϵ = Thermal expansion of the standard materials as approximated from the average α_m value.

Table A-6
COMPARISON BETWEEN THE EXPERIMENTAL AND PUBLISHED MEAN COEFFICIENT OF THERMAL EXPANSION CALCULATIONS

Temperature (° C)	Tungsten (SRM 737)			Platinum (ASTM-E-228-71)			Copper (SRM 736)		
	α_m ⁽¹⁾ SRM 737 ($\mu^\circ\text{C}^{-1}$)	α_m Experimental ($\mu^\circ\text{C}^{-1}$)	$\Delta\alpha_m$ ⁽²⁾ ($\mu^\circ\text{C}^{-1}$)	α_m ASTM-E-228-71 ($\mu^\circ\text{C}^{-1}$)	α_m Experimental ($\mu^\circ\text{C}^{-1}$)	$\Delta\alpha_m$ ($\mu^\circ\text{C}^{-1}$)	α_m SRM 736 ($\mu^\circ\text{C}^{-1}$)	α_m Experimental ($\mu^\circ\text{C}^{-1}$)	$\Delta\alpha_m$ ($\mu^\circ\text{C}^{-1}$)
- 45	-	-	-	-	-	-	-	-	-
4	4.33	4.51	0.18	8.84	8.67	- 0.17	16.02	16.24	0.22
54	4.37	4.43	0.06	8.85	8.71	- 0.18	16.32	16.46	0.14
99	4.42	4.38	- 0.04	8.95	8.81	- 0.14	16.58	16.69	0.11
136	4.45	4.35	- 0.09	9.00	8.87	- 0.13	16.77	16.83	0.06
173	4.48	4.37	- 0.18	9.05	8.94	- 0.11	16.94	17.00	0.06

(1) α_m = Mean coefficient of thermal expansion calculated from the reference temperature (- 45° C).
(2) $\Delta\alpha_m$ = Difference between the experimental and published mean coefficient of thermal expansion.

Table A-7
ESTIMATED MAXIMUM UNCERTAINTIES IN MEASUREMENT OF THERMAL EXPANSION COEFFICIENTS OF THE STANDARDS USED

Standard	Quantity	Uncertainty ($\mu^\circ\text{C}^{-1}$)
Copper ($\alpha = 17.00\ \mu^\circ\text{C}^{-1}$)	ΔT ⁽¹⁾	± 0.26 (0.7° C)
	$\epsilon_{\text{App}}/\Delta T$ ⁽²⁾	± 0.27
	Total	± 0.53
Platinum ($\alpha = 9.00\ \mu^\circ\text{C}^{-1}$)	ΔT	± 0.14 (0.7° C)
	$\epsilon_{\text{App}}/\Delta T$	± 0.27
	Total	± 0.41
Tungsten ($\alpha = 4.40\ \mu^\circ\text{C}^{-1}$)	ΔT	± 0.07 (0.7° C)
	$\epsilon_{\text{App}}/\Delta T$	± 0.27
	Total	± 0.34

(1) Uncertainty is given for a temperature interval of 45° C.
(2) Apparent strain of the strain gage for an arbitrary temperature change.

APPENDIX B
LIST OF SYMBOLS

Symbol	Definition	Units
β	Coefficient of resistivity of the grid conductor.	ohm/ohm/degree
α	Coefficient of linear thermal expansion of the base material.	inch/inch/degree
α_G	Coefficient of linear thermal expansion of the gage material.	inch/inch/degree
$\alpha(c)$	Coefficient of linear thermal expansion of the compensating material.	inch/inch/degree
α'	Uncorrected coefficient of linear thermal expansion of the base material.	inch/inch/degree
α'_m	Uncorrected mean coefficient of linear thermal expansion of the standard material.	inch/inch/degree
α_m	Mean coefficient of linear thermal expansion of the standard material.	inch/inch/degree
α_l	Instantaneous coefficient of linear thermal expansion.	inch/inch/degree
F	Gage factor or strain sensitivity of the strain gage.	ohm/ohm/inch/inch
ΔT	Temperature change from the arbitrary reference temperature.	degrees
ϵ_{App}	Apparent strain of the strain gage.	inch/inch
ϵ'	Uncorrected thermal expansion of the base or standard material.	inch/inch
ϵ	Thermal expansion of the base or standard material.	inch/inch
σ	Standard deviation.	Same as Average
μ	Micro units (10^{-6}).	None

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