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High Temperature Strain Gage Technology for Hypersonic Aircraft Development Applications

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FOREWORD

This report presents the results of an experimental evaluation of two types of wire strain gages each on two types of substrate materials applicable to hypersonic aircraft development. The evaluation was conducted under the "High Temperature Strain Gage for Hypersonic Aircraft Development Application" program under Contract NAS3-25410.

The original Pratt & Whitney Program Manager was Howard P. Grant who retired in September 1989. He was replaced by Mr. Wilbur L. Anderson who served as Program Manager for the remainder of the program. Acknowledgements are given to Mr. Richard G. Claing and Mr. Armand J. Latraverse who were involved in the test preparation and strain gage installation, respectively.

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SECTION 1.0
SUMMARY

A program was conducted to evaluate two types of wire strain gages each on two types of substrate materials applicable to hypersonic aircraft development. The program was conducted under Contract NAS3-25410, "High Temperature Strain Gage for Hypersonic Aircraft Development Applications" with the objective of establishing the extent to which the temperature limitation of 700K (801°F) can be overcome by employing two advanced gage alloys: a new palladium-13% chromium alloy and a baseline iron-chromium-aluminum alloy. The specific objective was to establish the durability and accuracy of wire strain gage systems under simulated hypersonic aircraft operating conditions.

Two alloy wire strain gages, Pd 13% Cr (by weight) and BCL-3, on IN100 and Cu .15% Zr alloy substrates were evaluated. The PdCr and BCL-3 strain gages were designed by Pratt & Whitney and Battelle-Columbus Labs, respectively, and installed on test bars. The gages were connected to Wheatstone bridge circuits and the outputs were recorded on a microcomputer based acquisition system.

Four types of testing were conducted on the strain gages:

1. Apparent strain testing: zero shift with temperature.
2. Drift testing: zero shift with time, without strain.
3. Gage factor testing: strain sensitivity.
4. Creep testing: zero shift with time, with strain.

Results of the testing have shown the strain gages to have good resistance stability as summarized below:

- PdCr gages have good resistance stability below 866K (1100°F), the Pt temperature compensation element is effective and the drift rate is reduced by a NiCrAl coating.

- BCL-3 gages have good resistance stability above 800K (981°F) but the drift is high at 700K (800°F).

- Insulation resistance is less then one megohm above 900K (1161°F) and the thermo-electric effects of both gage types are low with the lead configurations tested.

SECTION 2.0
INTRODUCTION

The objective of this work is to establish a technology base for use of high-temperature wire-form static strain gages on materials applicable to hypersonic aircraft development at temperatures above 800K (981°F).

A goal in the field of aeronautical research is the development of hypersonic aircraft capable of flying take-off to orbit or transporting people to the far Pacific basin in a few hours. Because of the high speeds involved, such aircraft will have structures that are subject to high temperatures (more than 800K) and very high heat fluxes. In the development of such aircraft, there will be a need for high-temperature static strain measurement which is beyond the state-of-the-art strain gage technology. This work is intended to contribute to the technology of high-temperature static strain measurement on materials and under conditions that are pertinent to hypersonic aircraft development needs.

The strain gage alloys which have the highest potential for static strain measurements at temperatures above 800K are those of the FeCrAl family and those of newly developed PdCr. The FeCrAl alloys have a relatively low but nonlinear electrical-resistance-versus-temperature character and good oxidation resistance. The FeCrAl alloy selected for this work is BCL-3, developed under NASA sponsorship at Battelle-Columbus Labs (Ref. 1). The PdCr alloy has a fairly linear electrical-resistance-versus-temperature character, but a temperature-coefficient-of-resistance high enough that a thermal compensation scheme is needed. It also has fair oxidation resistance. The PdCr alloy selected for this work is 87% Pd and 13% Cr (by weight), developed under NASA sponsorship by the United Technologies Research Center (Ref. 2).

Because of the high temperature and very high heat flux expected in the hypersonic aircraft structure, the structure must be fabricated of an uncooled high-temperature material or a cooled low-temperature material. If a cooled material is used, the thermal conductivity should be high. The high temperature material selected for this work is IN100 (59% Ni, 15% Co, 9.5% Cr, 5.5% Al, 4.8 Ti, 3% Mo, 1% Fe, 1% V and 1.2% other) and the low temperature material 99.85% Cu and .15% Zr.

SECTION 3.0
EXPERIMENTAL DESIGN AND TEST PLAN FORMULATION

Test specimens were designed for use with existing test fixtures and for the four types of tests listed below to be conducted on the strain gages:

1. Apparent strain testing: zero shift with temperature.
2. Drift testing: zero shift with time, without strain.
3. Gage factor testing: strain sensitivity.
4. Creep testing: zero shift with time, with strain.

TEST EQUIPMENT

Existing strain gage test equipment, shown in Figure 1, was used for all four types of tests. It includes the bar bending mechanism, a 25.4 cm (10") long tube furnace, a temperature indicator, an oven temperature control, a bridge connection box and a Hewlett-Packard data acquisition system. The test bar bending mechanism, shown in Figure 2, consists of a vise to hold the clamping fixture and a stepping motor driven deflection device. The clamping fixture, with a test bar (old design) installed, is shown in Figure 3.

TEST SPECIMEN DESIGN

Test bars 20.3 cm (8") long, 3.5 cm (1-3/8") wide and .64 cm (1/4") thick were fabricated as shown in Figure 4. Only bars intended for gage factor and creep testing were fabricated with the tapered section, the others being rectangular. The purpose of the taper is to provide constant strain over the active length.

The PdCr strain gages were designed by Pratt & Whitney as shown in Figure 5. The large grid size, .76 cm (.3") square, is needed to obtain a high enough gage resistance (about 58 Ohms) for good measurement with the large wire diameter (and low resistance). Pt was selected for the thermal compensation element because of the stable resistance characteristics and high temperature coefficient of resistance. The 3.3 Ohm resistance is designed to provide the right amount of compensation in a 1:1 bridge. The .16 mm (6.3 mil) diameter Ni 20% Cr leadwires are larger than desirable, but necessary to keep the resistance low relative to that of the gage grid. Lead resistance is about 4.6 ohms.

The BCL-3 strain gages were designed by Battelle-Columbus Labs as shown in Figure 6. The grid size is standard for this 120 Ohm gage. The FeCrAl ribbon (Hoskins alloy 875) lead is a standard used by Battelle. Lead resistance is about 2.9 ohms.

Installation of the gages and thermocouples on the test bars is shown in Figure 7. The gage leads are about 6.35 cm (2.5") long, being spliced to Ni Clad Cu wire about 2.54 cm (1.0") from the end of the bar. The splice is brazed with Nicrobraz 150 (from Wall Colmonoy Corp.). The prep coat of NiCrAl (Metco 443), precoat and overcoat cover the shaded areas. The thermocouples are made of .2 mm (8 mil) diameter, type K wire, with the junction welded prior to installation on the precoat. A non-precoated area was left on side 1 for the installation of a reference strain gage (WK-06-062AP-350 from Measurements Group) prior to the gage factor tests. The types of bars gages, precoats and overcoats are as follows:

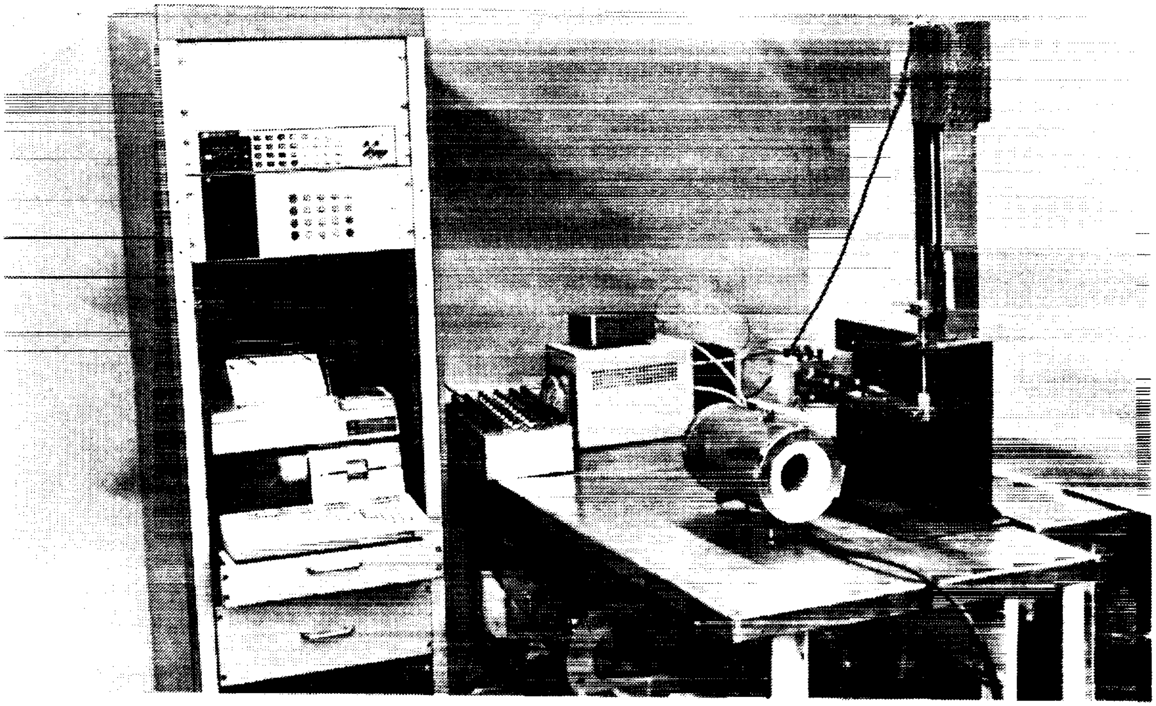

Figure 1.- Strain Gage Test Equipment

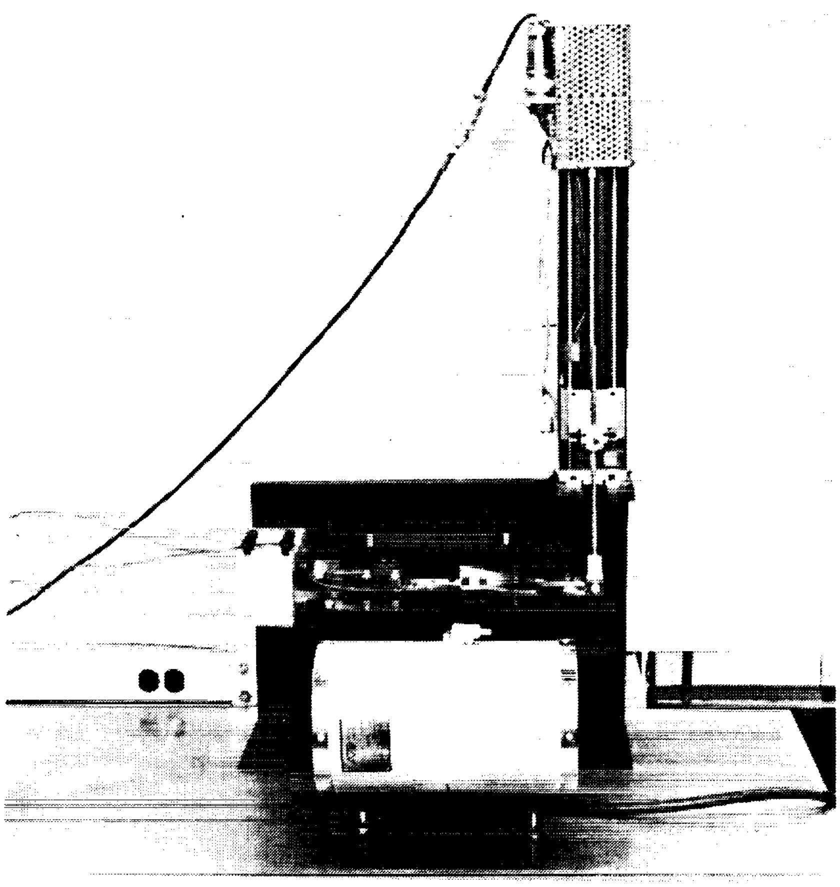

Figure 2.- Test Bar Bending Mechanism

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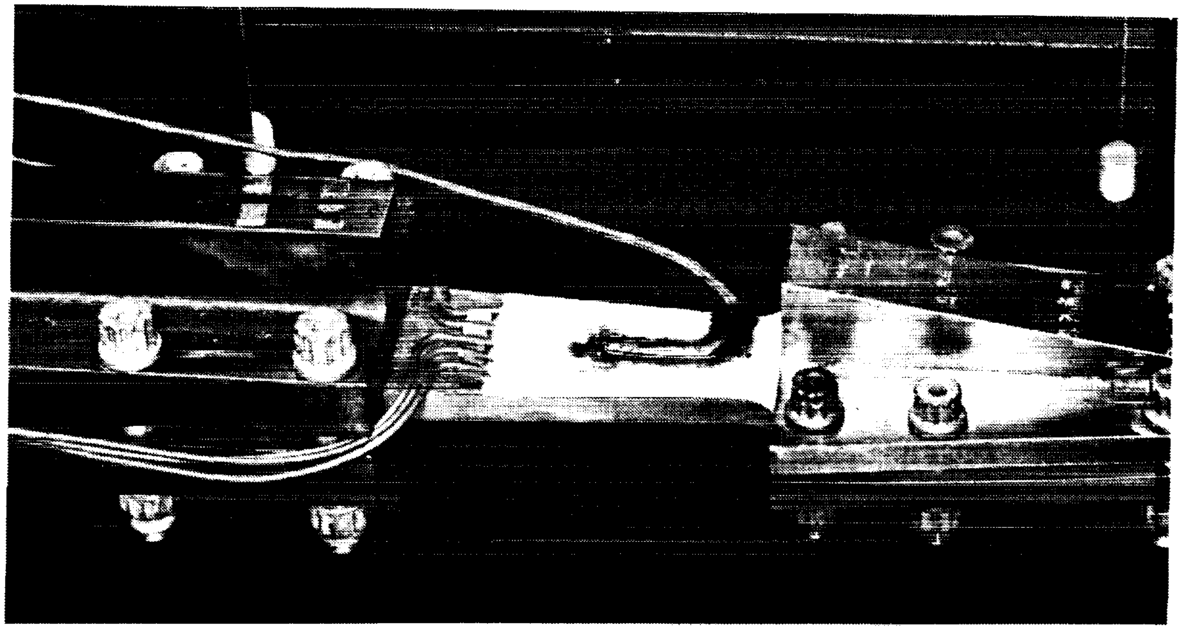


Figure 3.- Test Bar Clamp Fixture

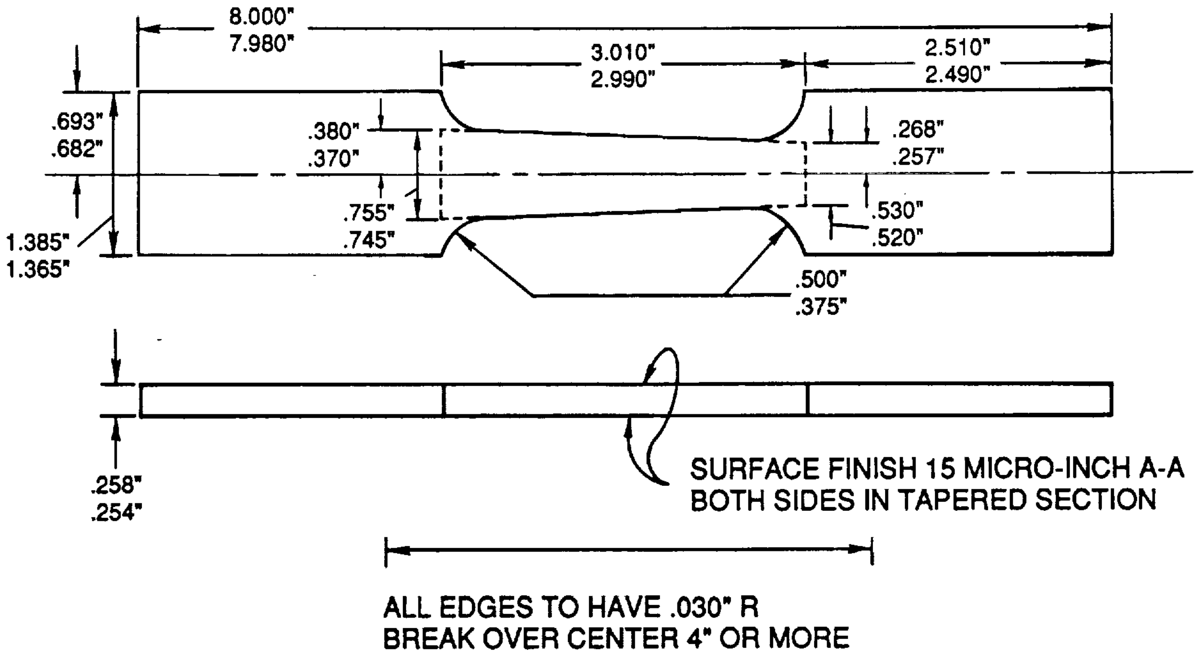


Figure 4.- Strain Gage Test Bar

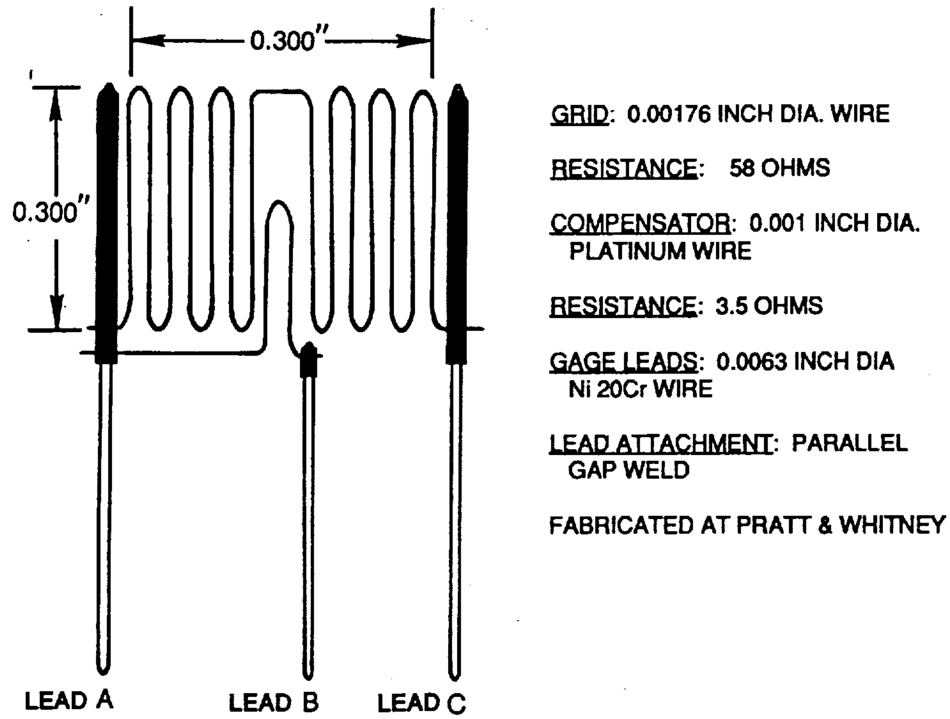


Figure 5.- Palladium 13% Chromium Dual Element Strain Gage

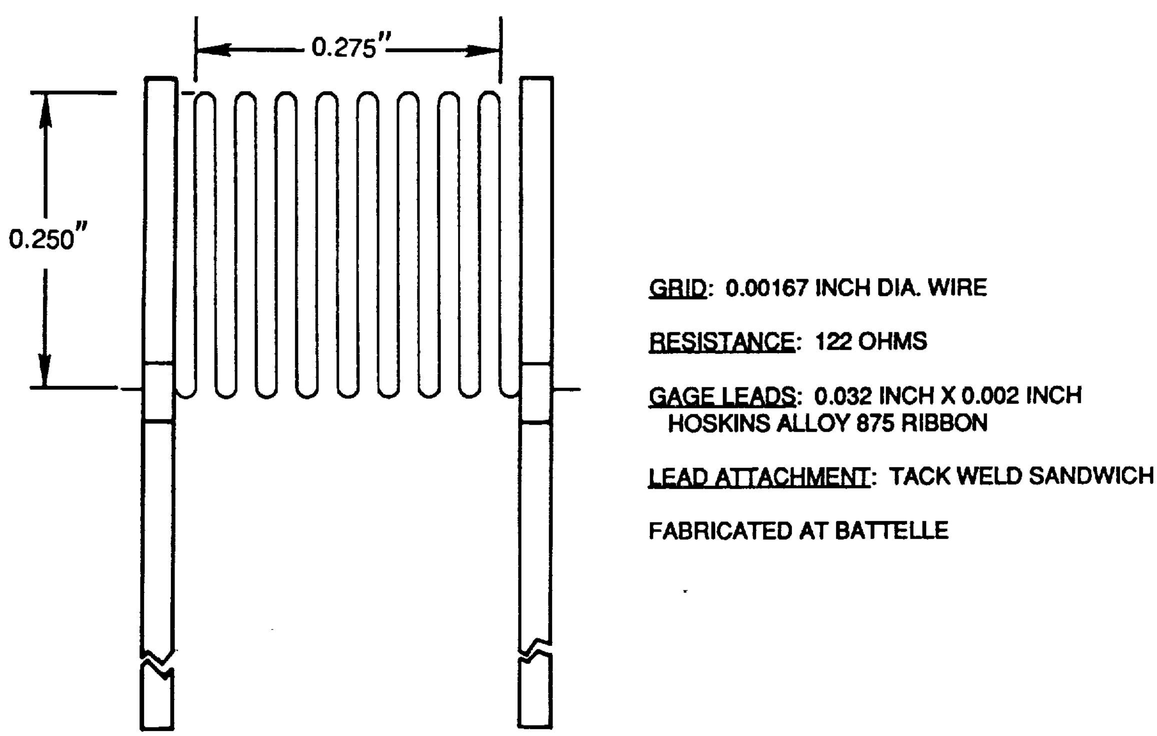


Figure 6.- FeCrAl (BCL-3) Strain Gage

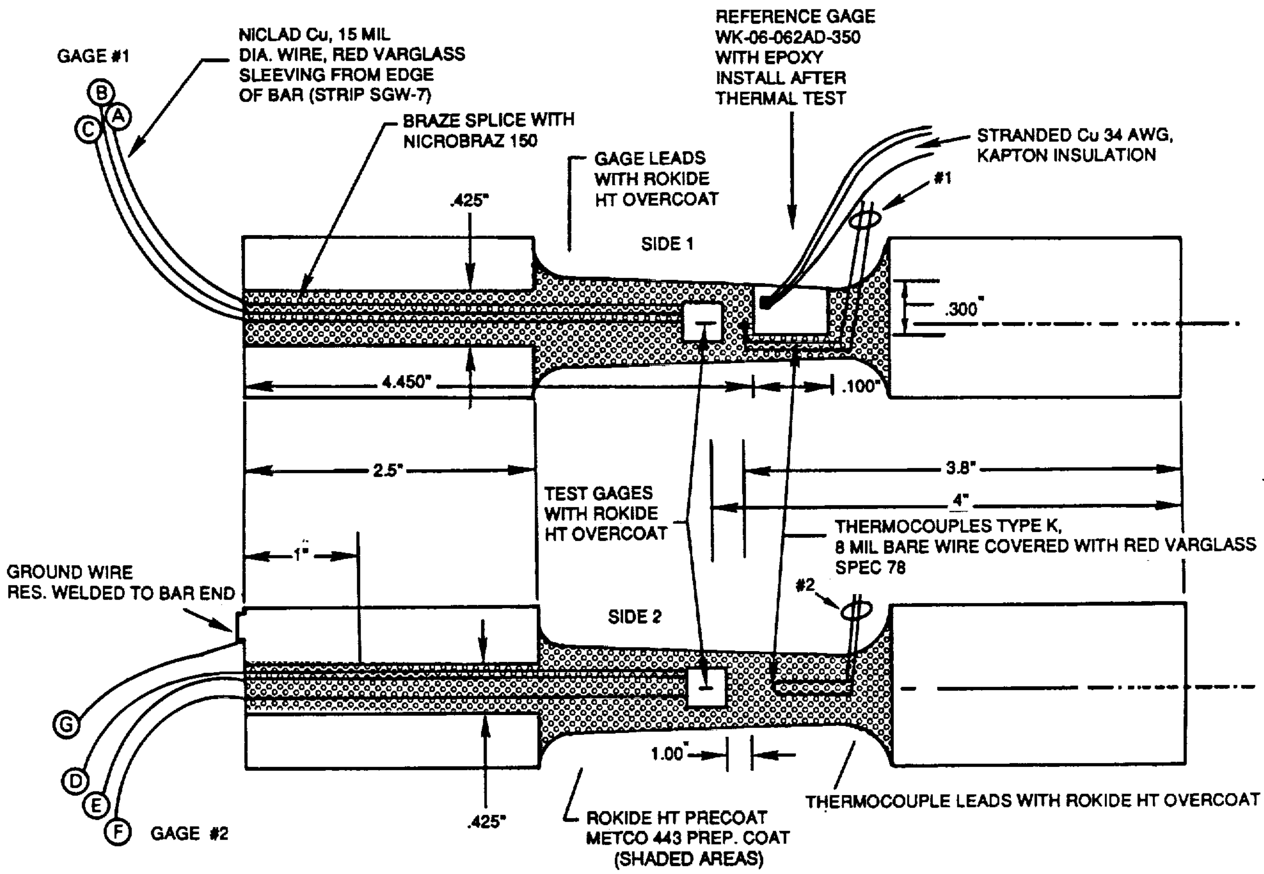


Figure 7.- Test Bar With Strain Gage And Thermocouple Installation

Bar Numbers	Gage Material	Bar Material	Precoat	Overcoat
01 02 03 04	PdCr	IN100	Rokide	Rokide
05	PdCr	IN100	Rokide	Rokide & NiCrAl
06 26	PdCr	IN100	Al_2O_3/ZrO_2	Al_2O_3/ZrO_2
18	PdCr	IN100	Rokide	Al_2O_3/ZrO_2
25	PdCr	IN100	Al_2O_3/ZrO_2	Al_2O_3/ZrO_2 & NiCrAl
07 08 09 10 11 12	PdCr	CuZr	Rokide	Rokide
13 14 15 16 17	BCL-3	IN100	Rokide	Rokide
19 20 21 22 23 24	BCL-3	CuZr	Rokide	Rokide

The Al_2O_3/ZrO_2 is a mixture of 96% alumina and 4% zirconia powder flame spray coating intended to provide improved oxidation protection to the PdCr gages. The NiCrAl (Metco 443) coating is the same as that of the prep coat and is also intended to provide oxidation protection.

INSTRUMENTATION OF TEST BARS

The PdCr gages were fabricated by Pratt & Whitney using gage wire provided by NASA. The BCL-3 gages, with the FeCrAl ribbon leads attached, were purchased from Batelle-Columbus Labs. All gages were installed in the Pratt & Whitney Strain Gage Lab, except for PdCr gages with alumina/zirconia overcoat which were installed by HITEC Products, Inc. The two bars with NiCrAl oxidation-resistant coating were overcoated at Pratt & Whitney.

TEST PROCEDURE

Apparent strain, drift, gage factor and creep testing were conducted as described below. At every test point, the strain gage bridge output for each gage (with both positive and negative excitation) was recorded along with the two thermocouples, insulation resistance and time. Oven temperature, excitation (5v dc) polarity and precise bar deflection were controlled by the data acquisition system. The excitation was applied to each gage circuit only when a measurement was to be made (not continuously).

Apparent Strain Testing

Data were recorded during at least three heating and cooling cycles on all of the gages. The first cycle was the heat-treating cycle and the heat-treating temperature was higher than that of the other cycles by 22K (40°F) for PdCr and 28K (50°F) for BCL-3 gages. The heat-treating period was 30 minutes. Data were recorded at equal time intervals during the temperature cycles.

Drift Testing

Data were recorded during constant temperature periods of 10 hours. Testing at three different temperatures (five for BCL-3 on IN100) was conducted. Each drift test was preceded by a heating cycle to the maximum temperature (for each gage/bar type) and a cooling cycle to the drift temperature. Data were recorded at equal time intervals during the drift and temperature cycles.

Gage Factor Testing

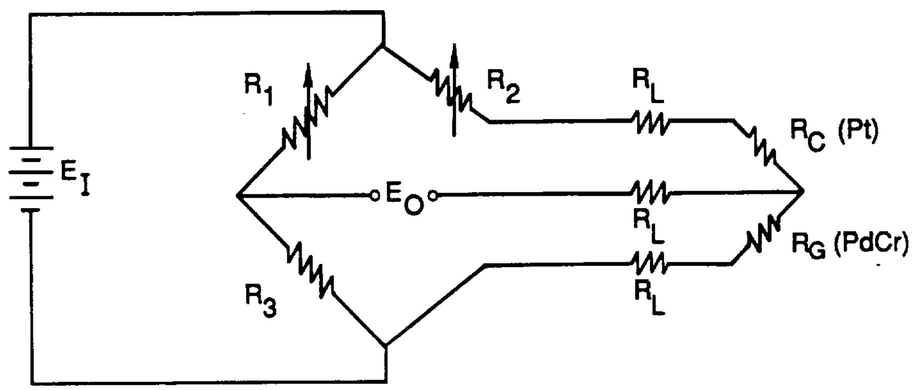
Data were recorded at room temperature, four intermediate temperatures and maximum temperature for each gage/bar type. Stabilization time was 30 minutes at each temperature. The temperature sequence was room, first, second, third, fourth, maximum, fourth, third, second, first, room, maximum, fourth, third, second, first and room. At each temperature, measurements were made in both compression and tension using a 0, +, 0, -, 0, +, 0, -, 0 bar deflection sequence (nine readings per sequence producing four compression and four tension measurements. The deflection sequence was run at both approximately 500 and 1000 micro-strain. The exact strain level for each deflection was measured at room temperature using reference (commercial) foil gages.

Creep Testing

Data were recorded during constant temperature periods of 10 hours, during which a strain level of 1000 micro-strain was applied (gage 1 in tension and gage 2 in compression). Testing at three different temperatures was conducted. Each creep test was preceded by a heating cycle to the maximum temperature (for each gage/bar type) and a cooling cycle to the creep temperature. The strain was applied at the beginning of the cooling cycle. Data were recorded at equal time intervals during the creep and temperature cycles.

TEST CIRCUITRY

All gages were connected to a Wheatstone bridge circuit as shown in Figure 8. The BCL-3 gages required setting $R_2 = R_G$ for a 1:1 bridge (because they have no R_C). The temperature compensated PdCr gages required setting $R_2+R_C= R_G$ (R_2 being approximately 55 Ohms) for a 1:1 bridge. Use of other than a 1:1 bridge ratio results in a more complex bridge sensitivity factor, as shown in Figure 9, and in lead-resistance changes not canceling in the two bridge arms.



GAGE DESIGNED FOR 1:1 BRIDGE $(R_2 + R_L + R_C = R_L + R_G)$

Figure 8.- Bridge Circuit - Temperature Compensation

$R_B = R_2 + R_C$

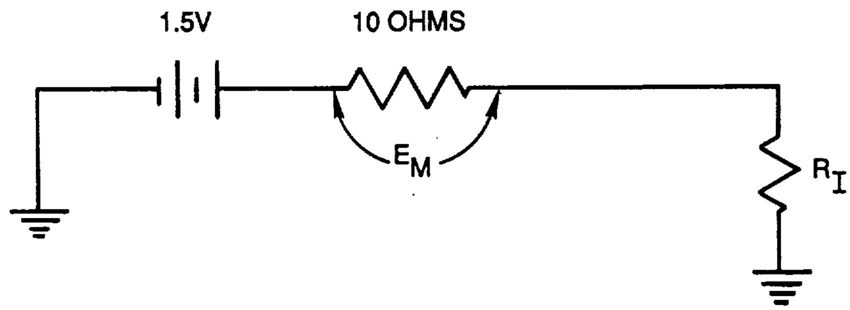
$$\Delta E_O = E_I \frac{\Delta R_G}{R_G} \frac{\left(\frac{R_L}{R_G} + \frac{R_B}{R_G}\right)}{\left(1 + \frac{2R_L}{R_G} + \frac{R_B}{R_G}\right)^2}$$

FOR A 1:1 BRIDGE: $\frac{R_B}{R_G} = 1$

$$\Delta E_O = E_I \frac{\Delta R_G}{R_G} \frac{1}{4\left(1 + \frac{R_L}{R_G}\right)}$$

Figure 9.- Bridge Formula

Insulation resistance was measured using the Ohmmeter-type circuit shown in Figure 10. The gage was switched out of the bridge circuit during this measurement (switches are not shown in Figure 8). Measurements were made between each of the two gage leads (in the case of PdCr, leads B and C in Figure 5), and the ground wire attached to the test bar. For each lead, two measurements were made: one with plus and one with minus polarity (of the 1.5 volt dc supply) and the two averaged.



$$R_I = \frac{1.5}{E_M}(10) - 10 \text{ OHMS}$$

Figure 10.- Insulation Resistance Measurement Circuit

SECTION 4.0
TEST PERFORMANCE AND ANALYSIS OF RESULTS

Planned and revised maximum test temperatures are shown below. Maximum temperature for the PdCr alloy was revised after excessive drift was measured at 1150K and above.

Gage	Bar	Original	Revised
PdCr	IN100	1144K (1600°F)	866K (1100°F)
PdCr	CuZr	811K (1000°F)	
BCL-3	IN100	1144K (1600°F)	
BCL-3	CuZr	811K (1000°F)	

Apparent strain, drift, gage factor and creep testing were conducted and the test data were recorded on a Hewlett-Packard microcomputer based data acquisition system. Data files, containing voltmeter readings, were converted to ASCII format and transferred to IBM MS-DOS files for import into Lotus 123 (worksheet software). Conversion to engineering units and plotting were done using Lotus 123. In most cases, the thermal cycles were identified on the plots by the cycle number and A for heating, B for cooling, HT for heat treat, DR for drift and CR for creep.

PALLADIUM CHROMIUM GAGES

Maximum test temperatures for each test is shown in Table I.

Apparent Strain Data (PdCr)

Apparent strain data for PdCr gages on IN100 bars are shown in Figures 11 and 12. The first tests were conducted on bars 03, 01, 02 and 04 (Figure 11) to determine the time and temperature effect on apparent strain. From these results, the maximum test temperature for PdCr gages was reduced to 866K (1100°F) from the originally planned 1144K (1600°F). Bars 05, 06, 18 and 26 (Figure 12) were then tested within the revised maximum temperature.

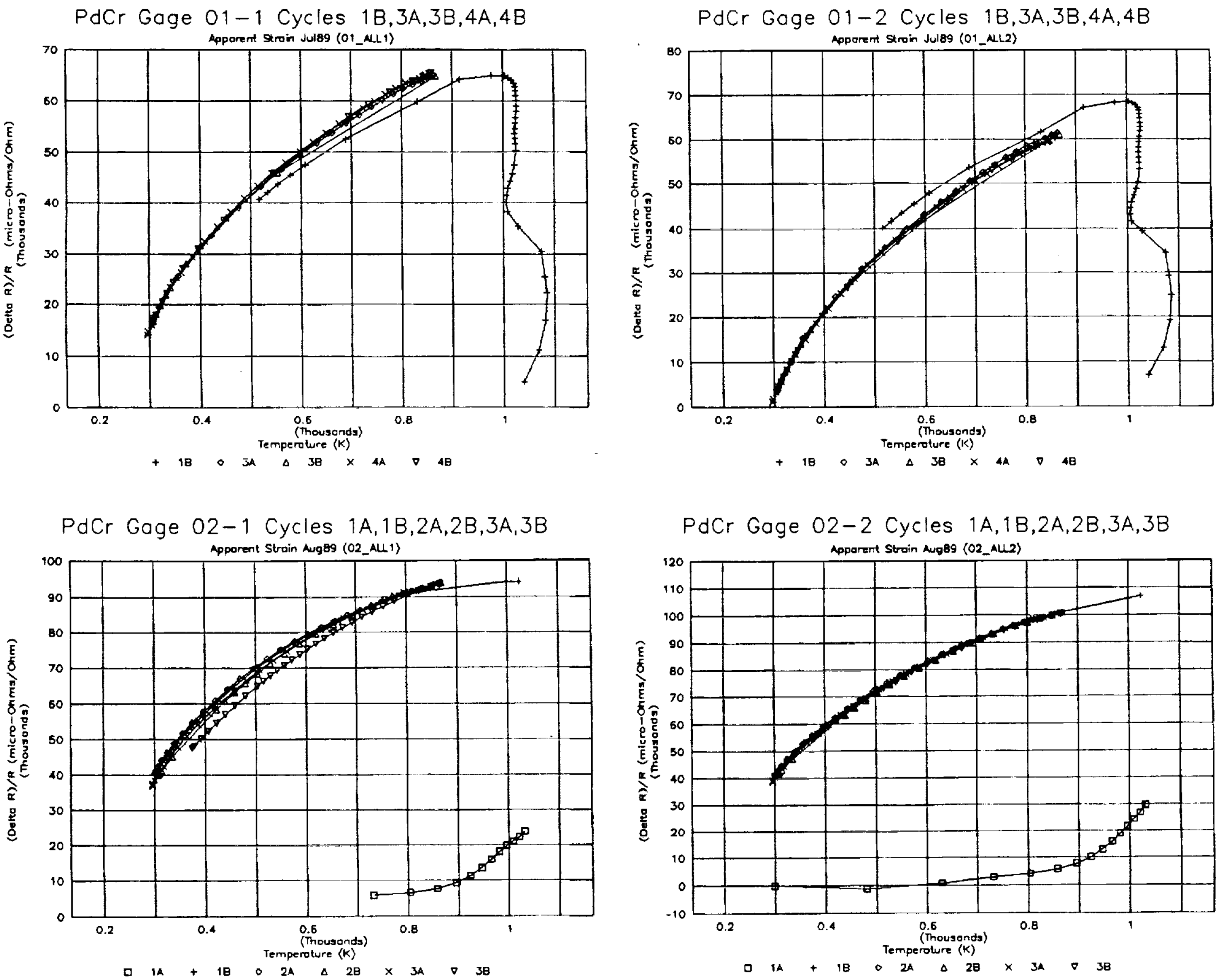
Bar 03 (gage 03-1 only) was subjected to 14 temperature cycles to 894K (1150°F) before and temperature cycles to 873K (1112°F) after a 50-hour soak at 873K. Before the soak, there was a steady increase in the slope with each cycle (2 of the 6 plotted). The 50-hour soak resulted in greater resistance stability but with great loss of temperature compensation. Most data for bar 03 were acquired with a hand-balance strain indicator because the data system was not ready for use when testing started. Gage 03-2 is not shown because the analysis was not fully completed, but enough points were analyzed to show that the trend was the same.

Bar 01 was subjected to one thermal cycle to 1023K (1382°F), with a one hour dwell at 1023K and three cycles (only two shown) to 873K (1112°F). The initial heating cycle is not shown because of a data system malfunction. The dwell at 1023K resulted in good resistance stability but with a large loss of temperature compensation.

TABLE I.- PdCr STRAIN GAGES: TESTS CONDUCTED AND MAXIMUM TEMPERATURES (K)

Bar Number	Bar Material	Heat Treat	Apparent Strain	Drift	Gage Factor	Creep
01	IN100	1022	853			
02	IN100	1023	853	1023		
03	IN100	894	894	894	866	
04	IN100	894	866		866	700 755 866
05 N	IN100	889	866	700 811	866	
06 AZ	IN100	889	866			
18 R	IN100	889	866	700 811	866	
25 R,N	IN100	Not Tested				
26 AZ	IN100	889	866	700 811		
07	CuZr	822	811			
08	CuZr	822	811	700 755 811		
09	CuZr	833	811		811	
10	CuZr	833	811		811	
11	CuZr	833	811		811	
12	CuZr	833	811		297	700 755 811

AZ: Alumina/Zirconia Precoat and Overcoat
R: Rokide Precoat and Alumina/Zirconia Overcaot
N: NiCrAl Overcoat



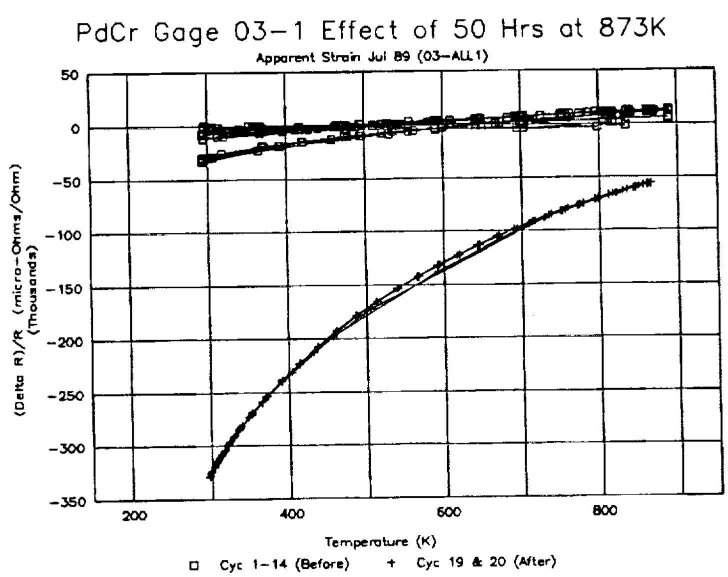
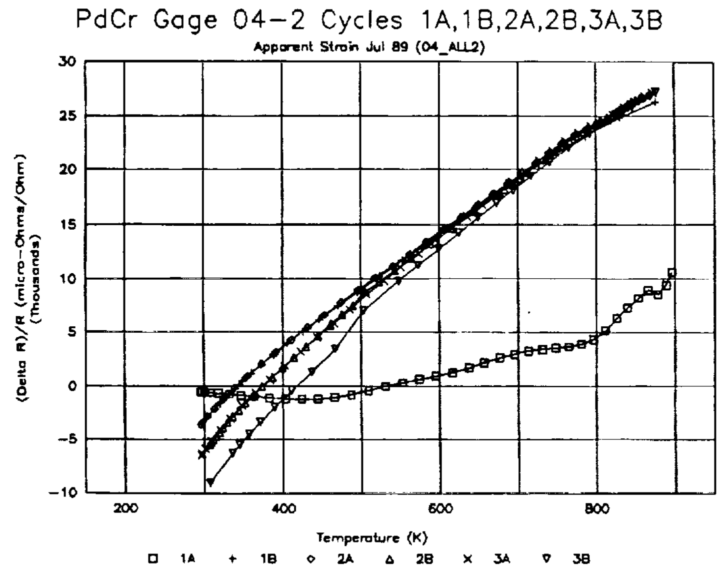


Figure 11.- Apparent Strain of PdCr Strain Gages on IN100 Bars



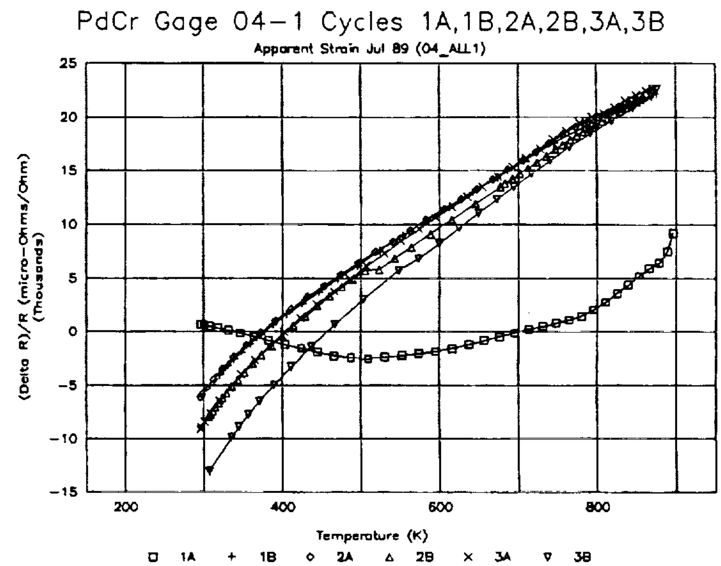


Figure 11.- Continued

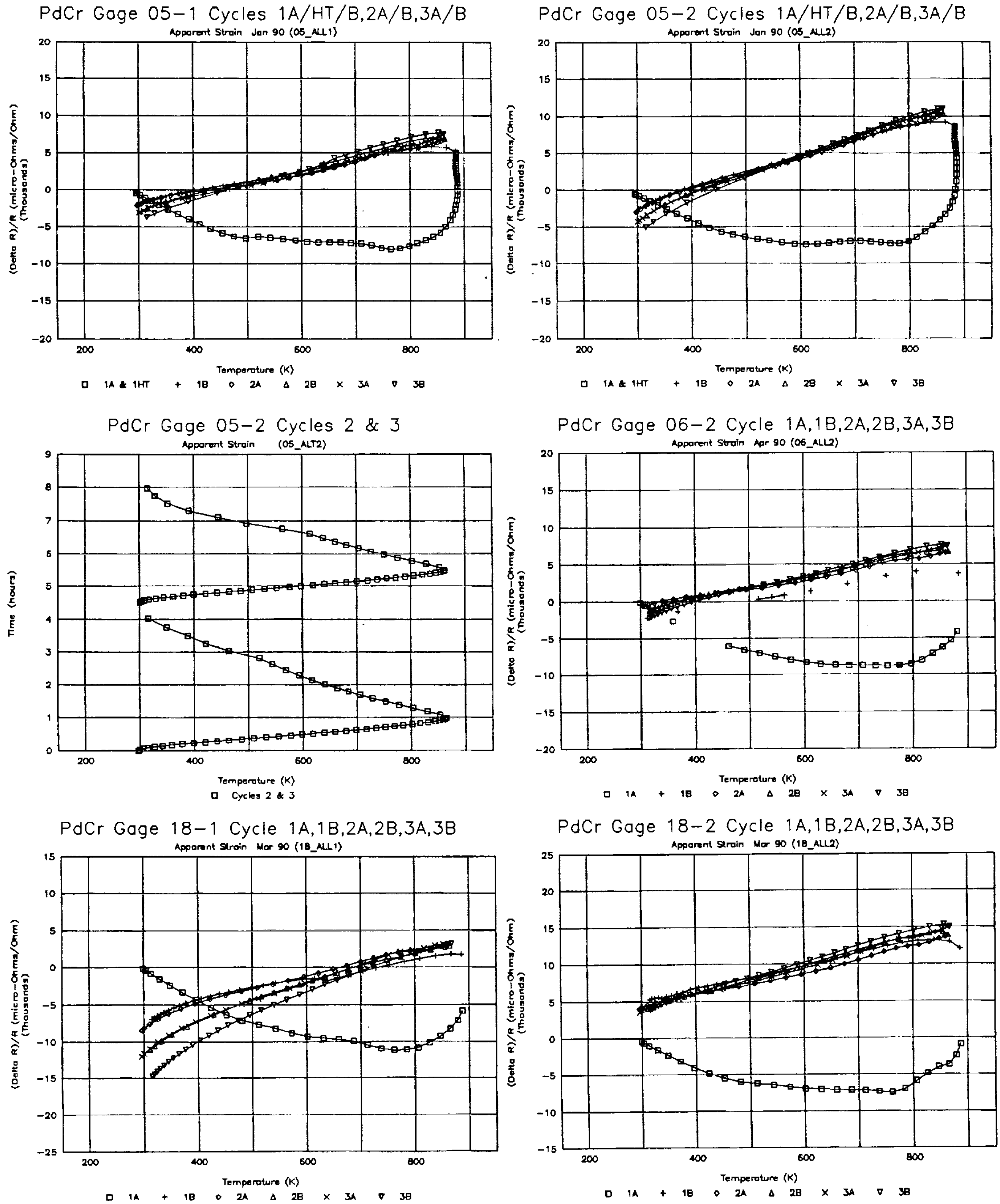


Figure 12.- Apparent Strain of PdCr Strain Gages on IN100 Bars with Oxidation Preventive Overcoat

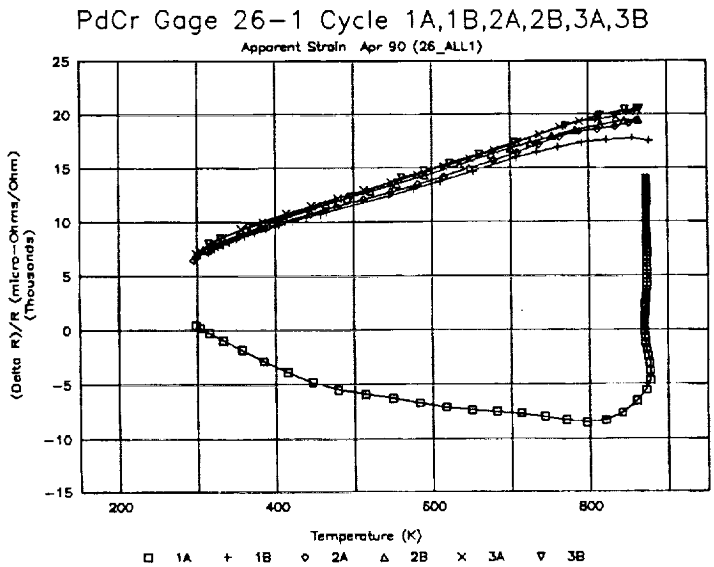


Figure 12.- Continued

Bar 02 was subjected to one cycle to 1023K (1382°F), with a 16 hour dwell at 1023K, and three cycles to 873K (1112°F). The increased exposure time was intended to further improve resistance stability, but resulted in a greater loss of temperature compensation.

Bar 04 was subjected to one cycle to 893K (1148°F), with a one hour dwell and two cycles to 866K (1100°F). The temperature compensation was much better, but there was still a significant increase in slope on each cycle. The maximum test temperatures of 886K (1140°F) for the heat treat cycle and 866K (1100°F) for the apparent strain cycles were established for the other gages/bars of this type. The heat treat duration was established at 30 minutes.

Bars 05, 06, 18 and 26 incorporated two oxidation resistant schemes as described in the "Test Specimen Design" of Section 3.0. The apparent strain results for these bars are shown in Figure 12. On bar 05, a coating of NiCrAl flame spray was applied over the Rokide overcoat as an oxygen barrier. The increase in slope on cycles 2 and 3 was slightly less than shown on bar 04 (standard overcoat and same temperature cycles). A typical time vs temperature plot is also shown for two cycles of bar 05. Bar 06 was instrumented with a precoat and overcoat of alumina/zirconia for oxidation resistance (same as bar 26). The increase in slope on cycles 2 and 3 was slightly less than shown on bar 04 (standard overcoat and same temperature cycles). Because gage 06-1 had an open circuit after installation, no data were acquired. Bar 18 was instrumented with a standard Rokide precoat and an alumina/zirconia overcoat for oxidation resistance. The Rokide precoat was used because of extreme difficulty in installing the alumina/zirconia precoats on bars 06 and 26. Although the two gages were identical, gage 18-1 experienced a much greater increase in slope, on cycles 2 and 3, than gage 18-2. This difference has not been explained. Bar 26 was instrumented with a precoat and overcoat of alumina/zirconia for oxidation resistance (same as bar 06). The increase in slope on cycles 2 and 3 was slightly less than shown on bar 04 (standard overcoat and same temperature cycles).

Apparent strain data for PdCr gages on CuZr bars are shown in Figure 13. Bars 07, 08, 09, 10, 11 and 12 were all instrumented with the standard Rokide precoat and overcoat and were subjected to a heat treat cycle to approximately 833K (1040°F) and two apparent strain cycles to approximately 811K (1000°F). The heat-treat period was 30 minutes. The exact maximum test temperatures for each bar are shown in Table I. For bar 07, data from all three cycles for both gages were lost because of a data system malfunction. Three additional cycles (4, 5 and 6) were run and data for gage 07-2 are shown. The change in slope was small, but this stability may be due to the additional cycles run. However, data from gage 07-1 was not properly recorded. For bar 08, data for cycles 2, 3 and 4 are shown. Data from cycle 1 were lost because of a recorder malfunction. Cycles 3 and 4 were run after making a slight adjustment of the temperature compensation circuit to increase the compensation (reduce R_2). On cycle 2, R_2 was inadvertantly set too high (70.1 and 65.8 ohms for gages 1 and 2, respectively). Prior to cycles 3 and 4, R_2 was set to the proper value such that $R_2+R_C = R_G$ (54.2 and 53.3 ohms, respectively). The results show that the 3.3 ohm compensator is about the correct value for the 58 ohm gage ($R_G/R_C = 17.6$). Bar 09 had the lowest (negative) slope of all the PdCr gages. The increase in slope on cycles 2 and 3 was similar to the other gages, however. The data from bar 10 shows a premature temperature drop and recovery on cycle 3A. This additional time at temperature may account for the slope on cycle 3B being greater than that of the other cycles. On bar 11, the data of cycle 1B were lost because of a data system malfunction. The heat treat dwell (30 minutes) is plotted so that the end points of cycle 1B may be determined. Bar 12 had near optimum thermal compensation (nearly zero slope). This happened by chance because the resistances of the gage and compensation grids cannot be controlled any better than they were in this program.

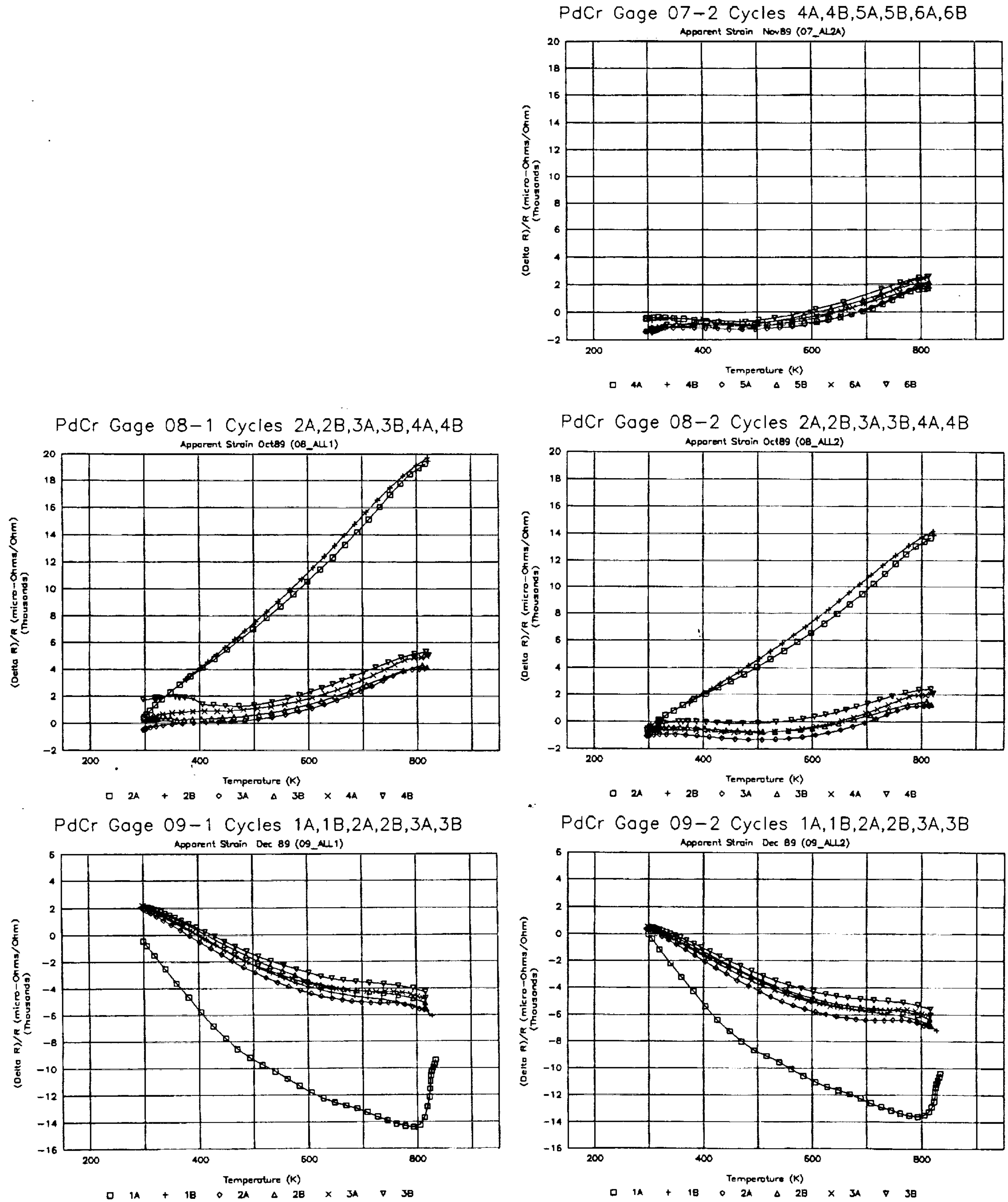


Figure 13.- Apparent Strain of PdCr Strain Gages on CuZr Bars

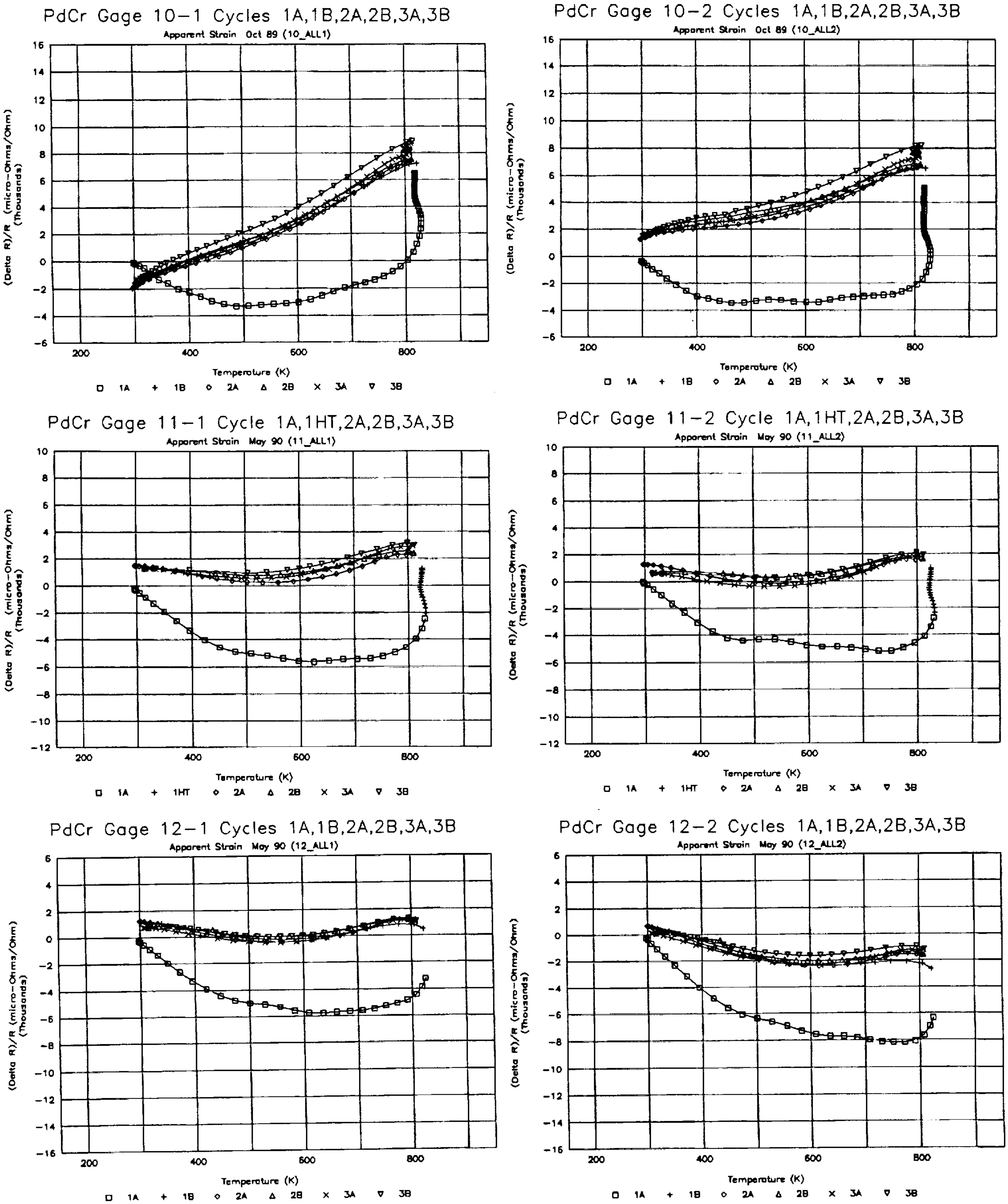


Figure 13.- Continued

Drift Data (PdCr)

Drift data for PdCr gages are shown in Figure 14. In each plot, data shown for approximately the first hour represent the period of cooling from the maximum temperature to the drift temperature, and the next 10 hours (1 through 11) is the drift test period. Bar 08 was instrumented with the standard Rokide precoat and overcoat. Bar 05 was instrumented the same as Bar 08 but with the addition of a coating of flame sprayed NiCrAl. No data were acquired from gage 05-2 at 700K because of a data system malfunction. Bar 18 was instrumented with a Rokide precoat and alumina/zirconia overcoat. Bar 26 was instrumented with both precoat and overcoat of alumina/zirconia.

The following is a summary of the drift rates (in micro-Ohms/Ohm per hour).

Bar-Gage	Precoat	Overcoat	700K (800°F)	755K (900°F)	811K (1000°F)
08-1 CuZr	Rokide	Rokide	+100	+100	+600
08-2 CuZr	Rokide	Rokide	+100	+100	+600
05-1 IN100	Rokide	Rokide/NiCrAl	+50	-	-100
05-2 IN100	Rokide	Rokide/NiCrAl	-	-	-100
18-1 IN100	Rokide	Al_2O_3/ZrO_2	+50	-	-600
18-2 IN100	Rokide	Al_2O_3/ZrO_2	+50	-	+400
26-1 IN100	Al_2O_3/ZrO_2	Al_2O_3/ZrO_2	+100	-	+550

Gage Factor Data (PdCr)

Gage factor data for PdCr gages on IN100 bars are shown in Figures 15 and 16 and on CuZr bars in Figure 17. For each gage, the gage factor and gage factor variation are shown. Each point on the gage factor plot is the mean of the four measurements described in the "Test Procedure" of Section 3.0. The variation is defined as two times the standard deviation of those four measurements as a percent of the mean.

Strain levels, measured at room temperature with reference gages, were repeated at elevated temperature with precise control of bar deflection and while maintaining uniform temperature over the active bar length of 7.62 cm (3"). Bar deflection is 5.94 mm (.234 inches) for 1000 micro-strain and is repeatable within $\pm$ 13 μm (.5 mil). Bar temperature was held constant within a 17K (30°F) range as determined from a temperature test on a similar bar several years ago and shown in Figure 18.

The measured gage factor of 1.4 for the Pt compensated PdCr gage was about as expected from published gage factors of 1.8 for Pd Cr and 4.8 for Pt. A compensation element with a lower (than Pt) gage factor would desensitize the PdCr less, but the resistance stability of Pt was worth the sensitivity reduction.

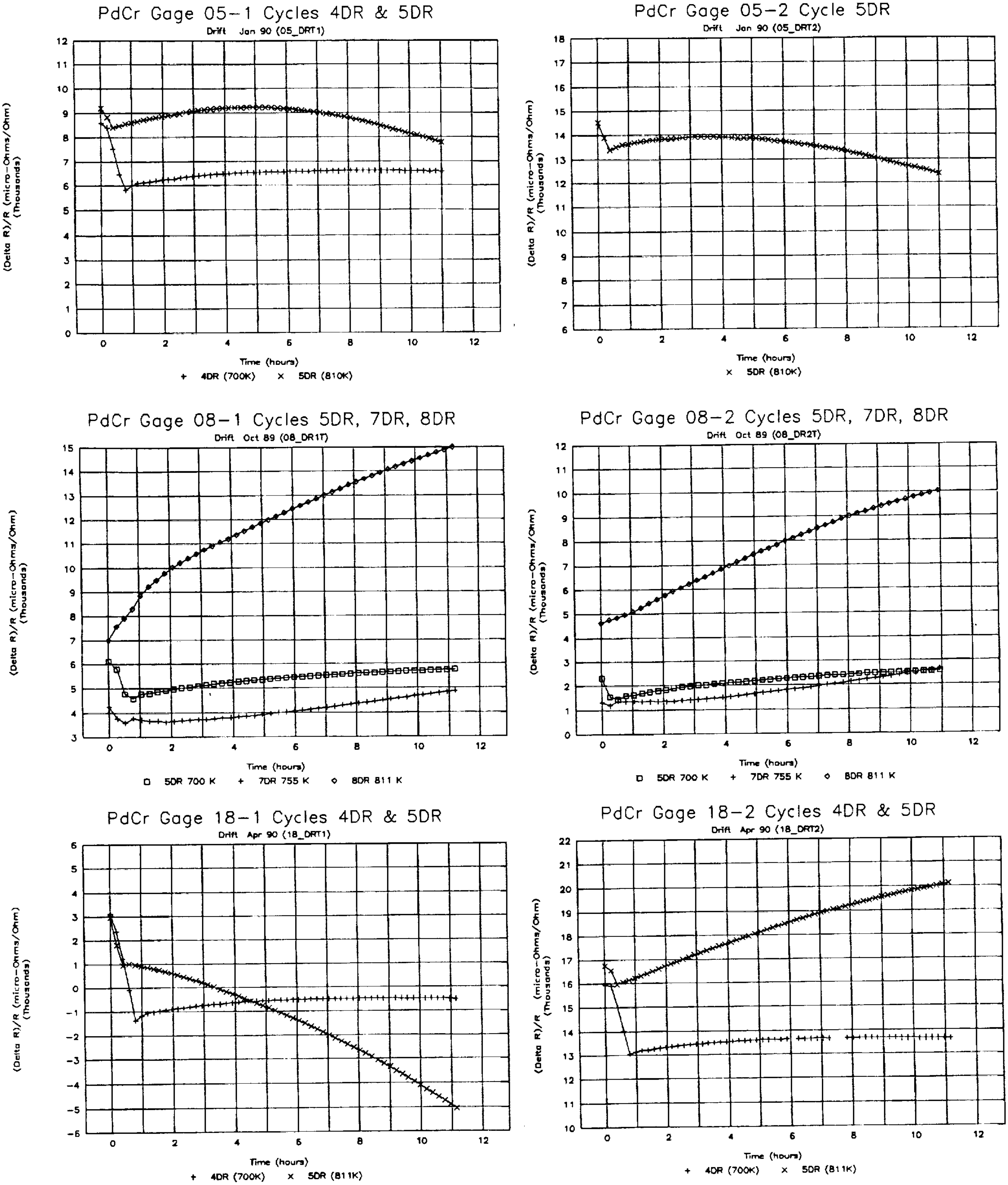
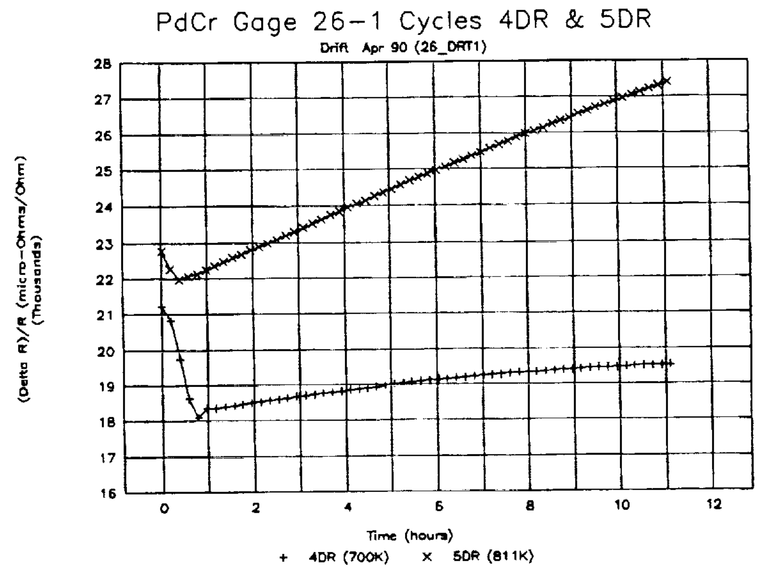


Figure 14.- Drift of PdCr Strain Gages



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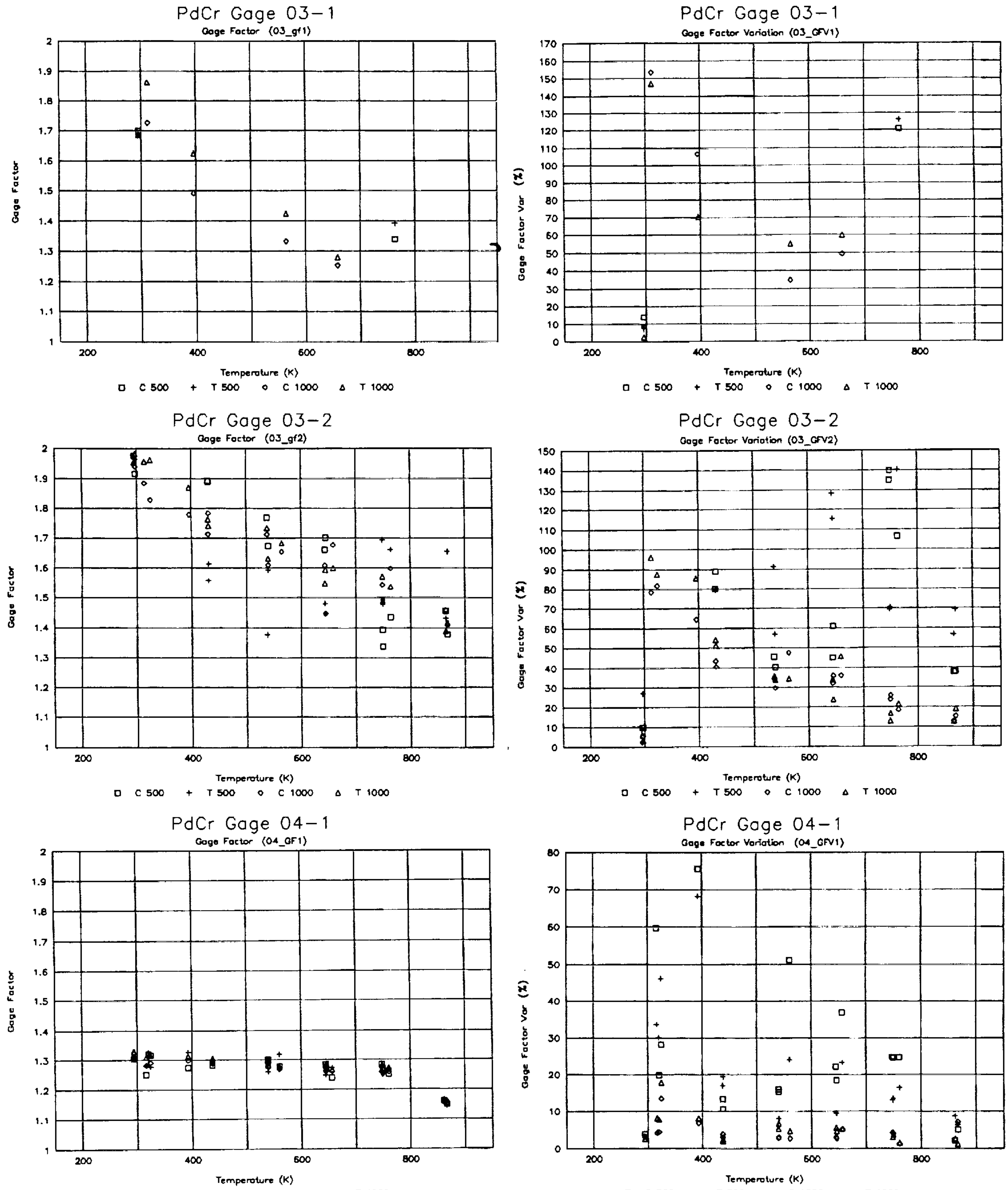
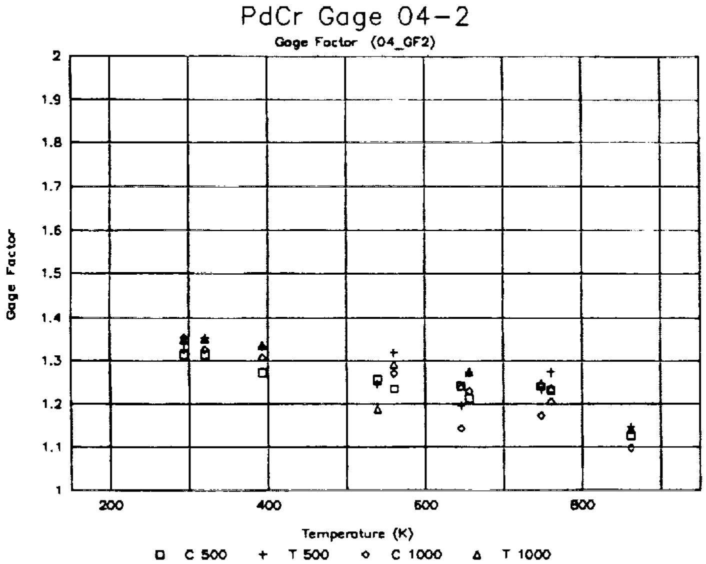
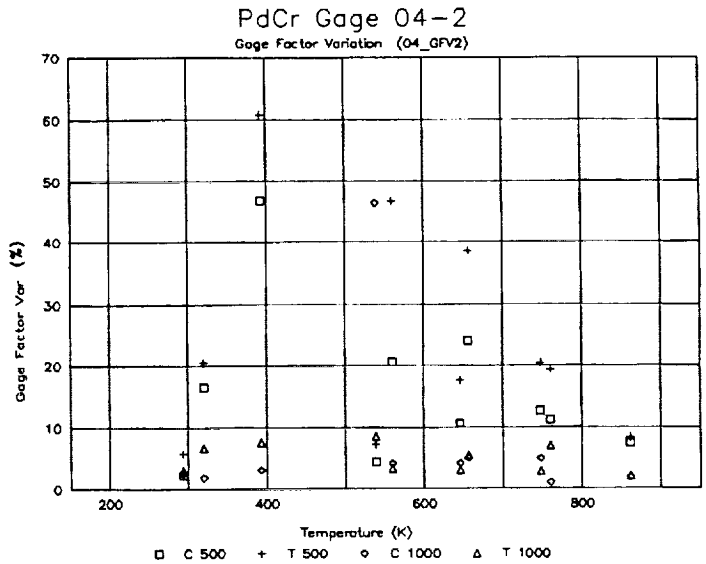


Figure 15.- Gage Factor and Variation of PdCr Strain Gages on IN100 Bars





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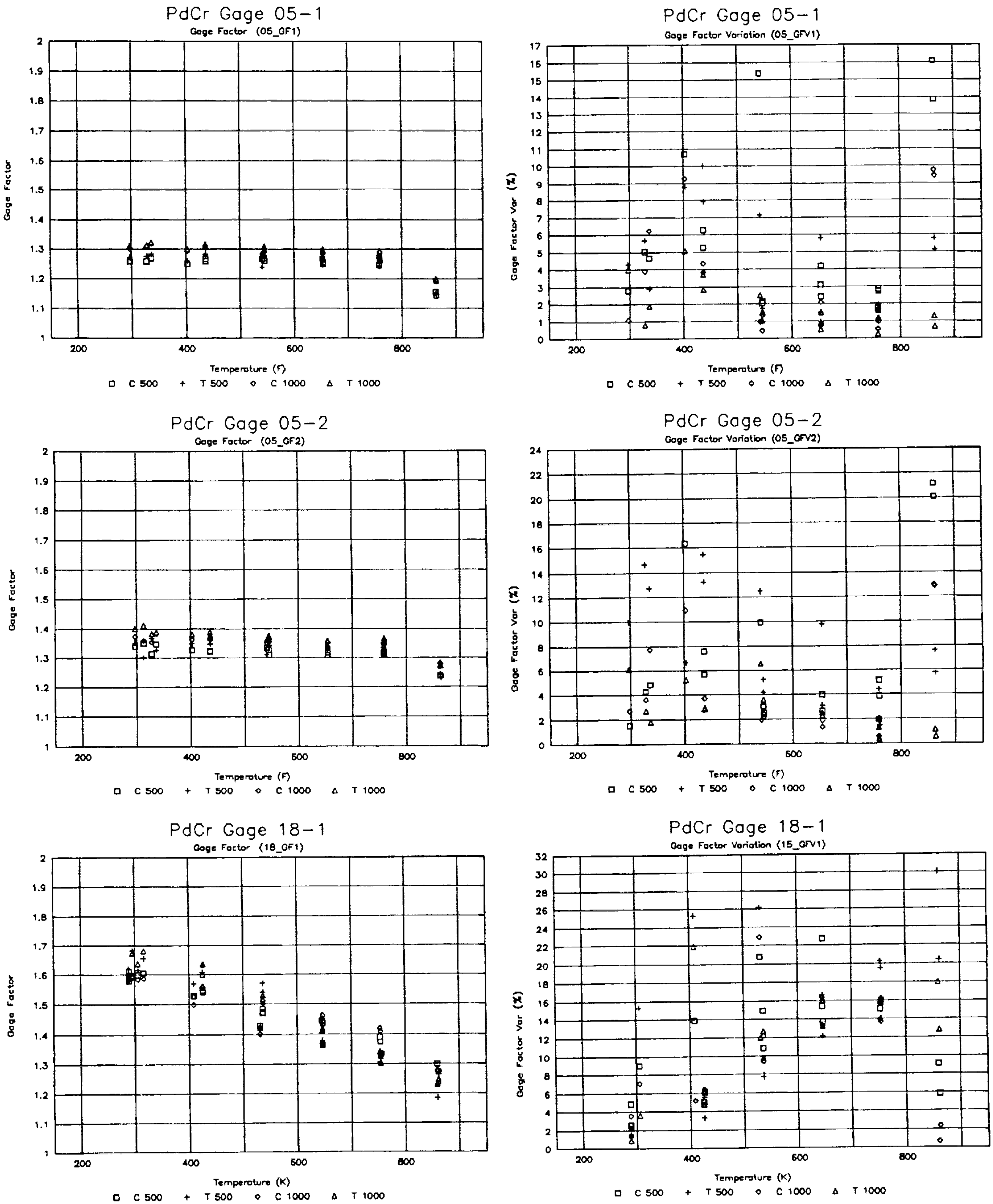
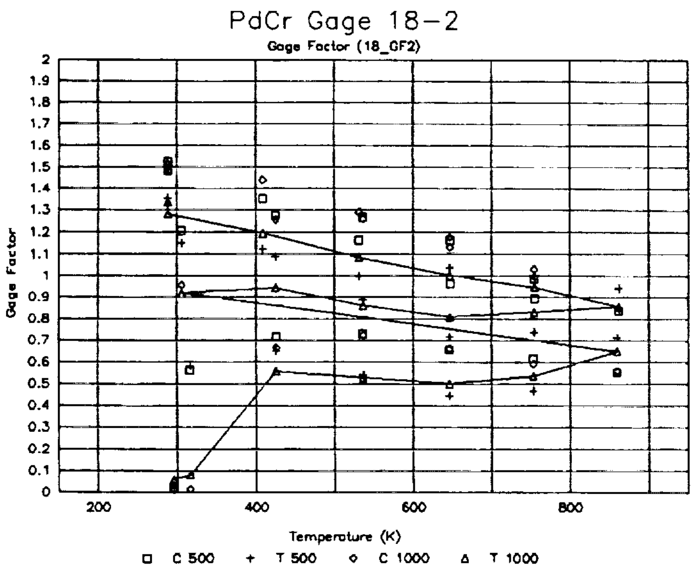
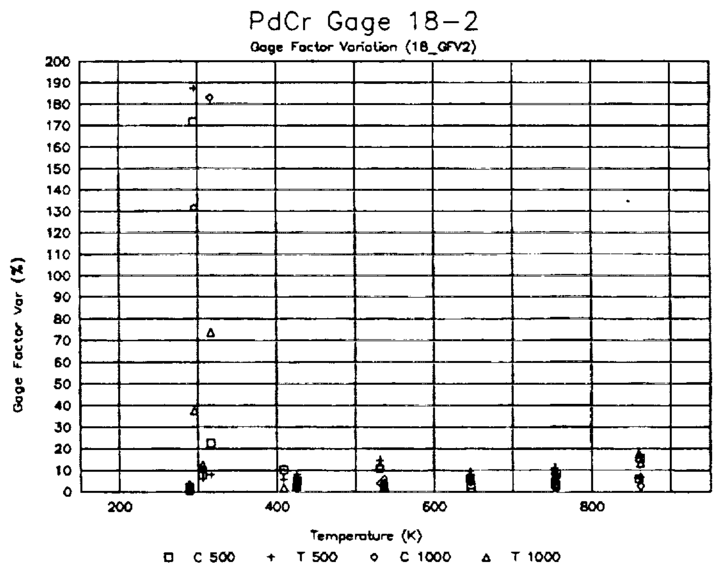


Figure 16.- Gage Factor and Variation of PdCr Strain Gages on IN100 Bars with Oxidation Protective Overcoat





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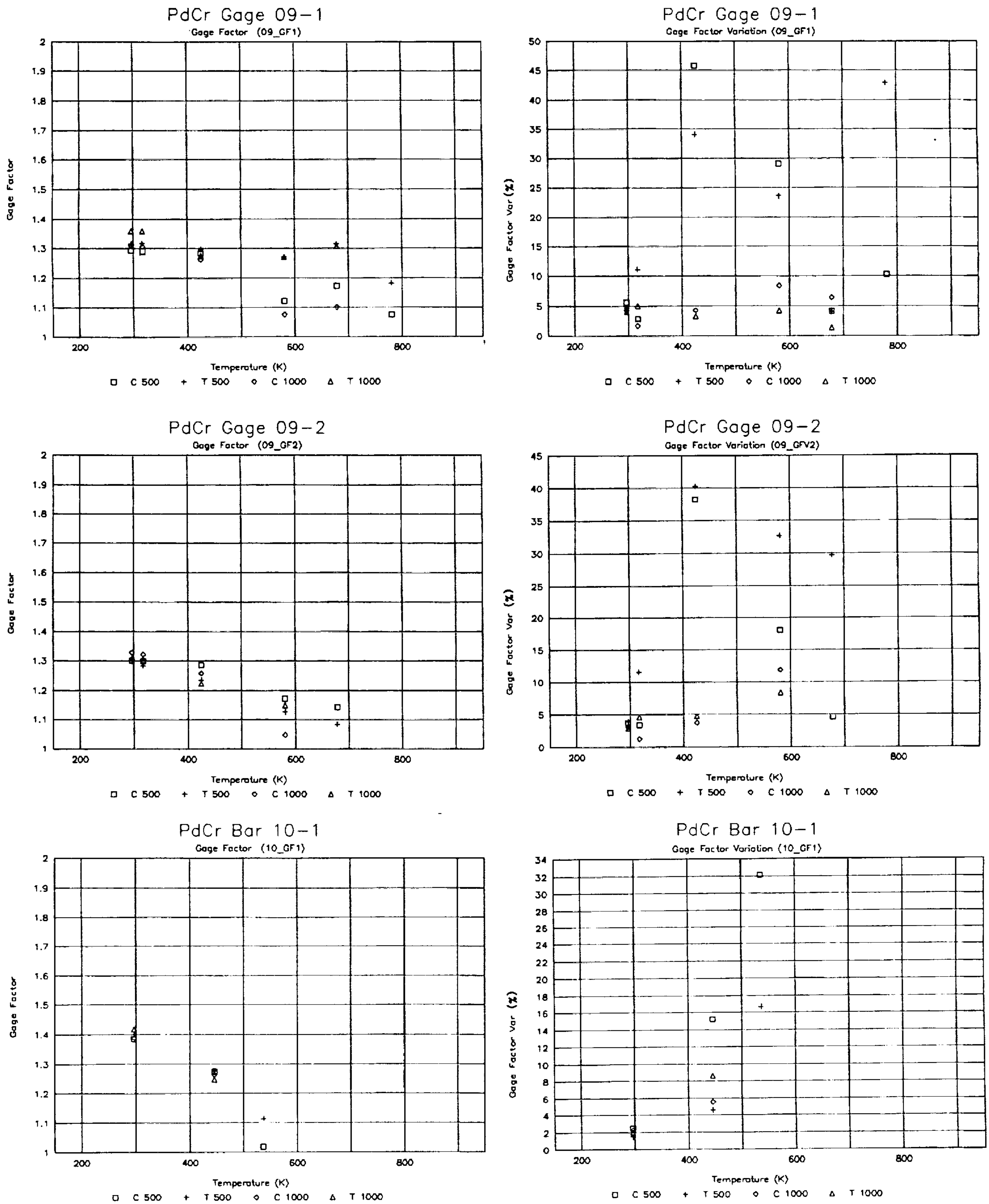
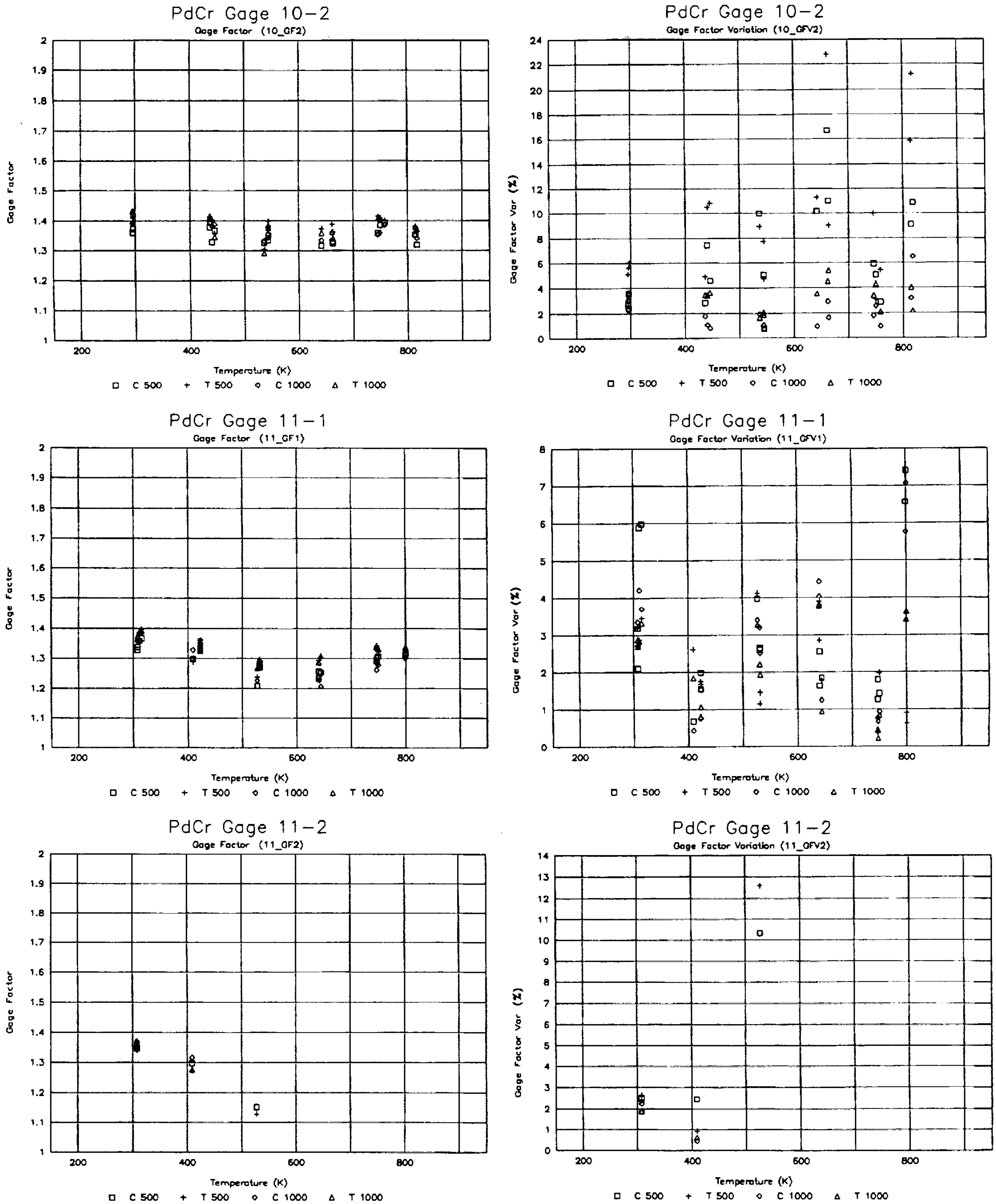


Figure 17.- Gage Factor and Variation of PdCr Strain Gages on CuZr Bars



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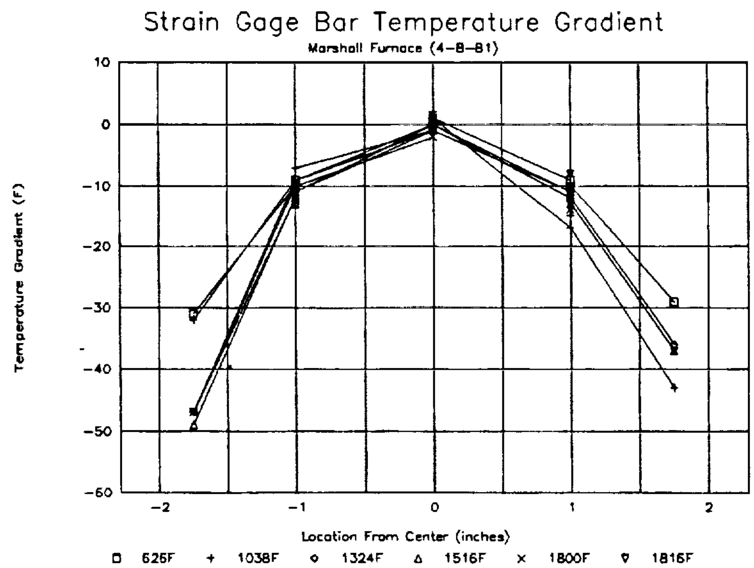


Figure 18.- Axial Temperature Distribution On A Test Bar

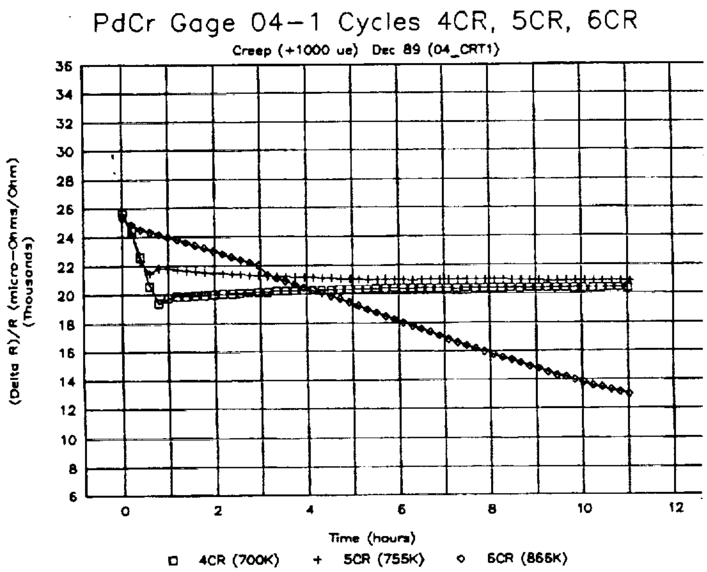
The gage factor results from bar 03 indicated a higher gage factor than from other PdCr gages (about 1.9 compared to 1.4). This was possibly because of Cr depletion due to oxidation from long exposure to elevated temperature during previous apparent strain testing. Additional evidence of this was a gage resistance that decreased from about 60 to 40 Ohms during the apparent strain testing. Also, it is possible that the Pd diffused to the wire surface, resulting in electrical shunting of the PdCr wire. The gage factor results from gage 18-2 indicated a continuous reduction in gage factor with time, the last measurement being near zero. This was due to delamination of the Rokide overcoat and loss of the gage bond to the precoat. Results from gages 10-1 and 11-2 indicate erratic readings above 533K (500°F). For gage 10-1, the reason was not found but could be a recording malfunction or a loose connection in the circuitry. For gage 11-2, the reason is probably a loose connection in the gage circuitry (the gage was found to have an open circuit during the post-test inspection).

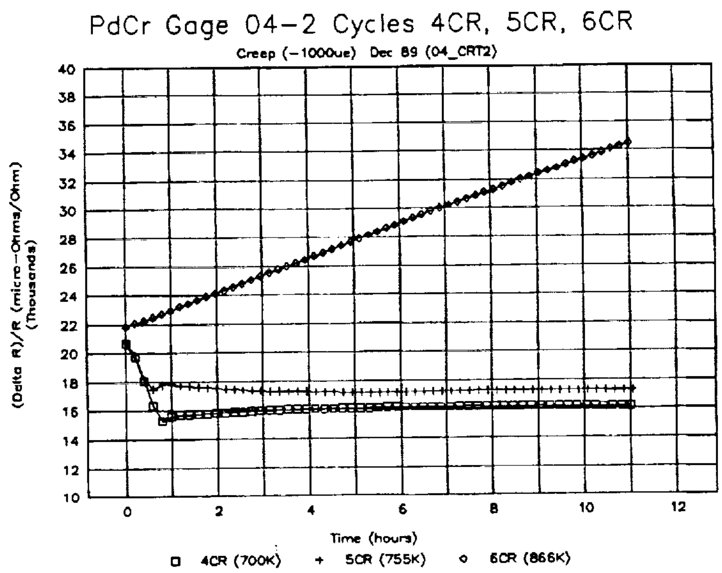
Creep Data (PdCr)

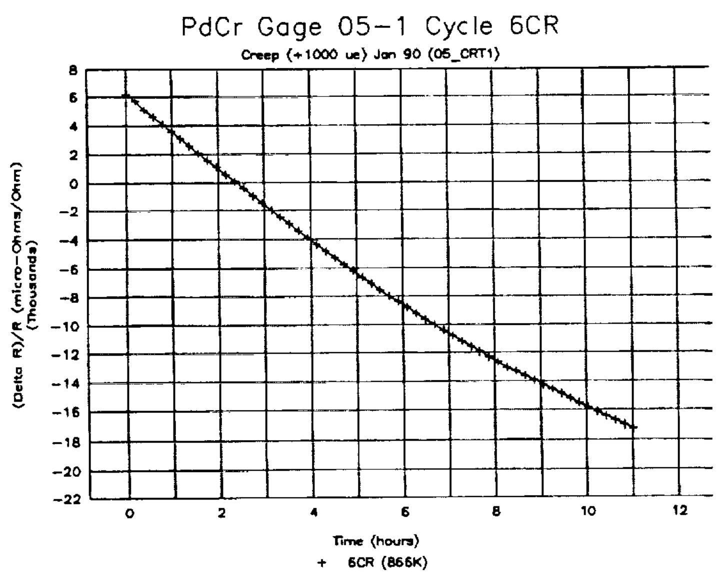
Creep data for PdCr gages are shown in Figure 19. In each plot, data shown for approximately the first hour represent the period of cooling from the maximum temperature to the creep temperature, and the next 10 hours (1 through 11) is the creep test period. The creep strain of 1000 micro-strain resulted in about 1400 micro-Ohms/Ohm (gage factor is about 1.4) of delta-R/R. Because creep is the relaxation of strain in the cement and gage, creep must be in the opposite direction from and no greater than the applied strain. The creep direction would be minus for gage 1 and plus for gage 2 because of the bending strain. The data shows that the drift is too great to measure any creep if it exists. Except for the 700 and 755K results from gage 12-2, the direction or magnitude does not fit the creep character.

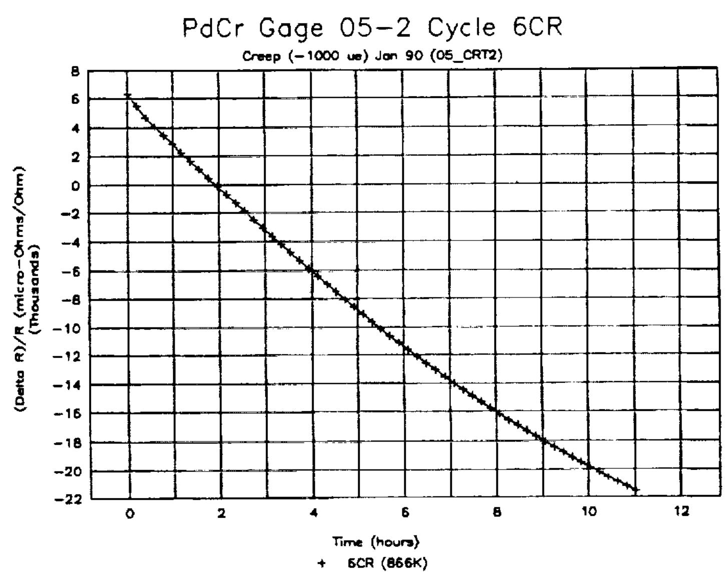
BCL-3 GAGES

Maximum test temperature for each test is shown in Table II.









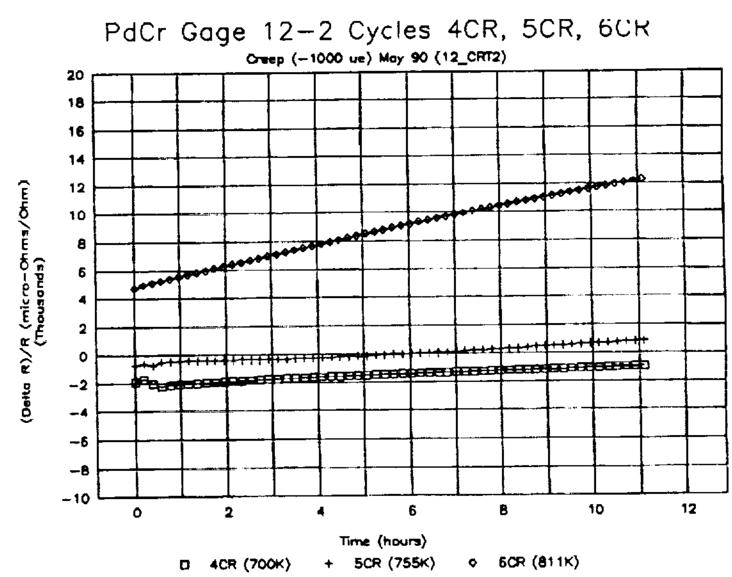


Figure 19.- Creep of PdCr Strain Gages

TABLE II.- BCL-3 STRAIN GAGES:
TESTS CONDUCTED AND MAXIMUM TEMPERATURES (K)

Bar Number	Bar Material	Heat Treat	Apparent Strain	Drift	Gage Factor	Creep
13	IN100	1172	1144	616		
				700		
				755		
				811		
				1144		
14	IN100	1172	1144			
15	IN100	1172	1144	1144		
16	IN100	1172	1144		1144	700
						866
						1144
17	IN100	1172	1144		1144	
19	CuZr	839	811			
20	CuZr	839	811	700		
				755		
				811		
21	CuZr	833	811		811	700
						755
						811
22	CuZr	839	811		811	
23	CuZr	839	811		811	
24	CuZr	839	811			

Apparent Strain (BCL-3)

Apparent strain data for BCL-3 gages on IN100 bars are shown in Figure 20 and on CuZr bars in Figure 21. On the first cycle, the bars were subjected to a heat treat of 50°F above the established maximum test temperature for 30 minutes. This is the heat treatment recommended by the gage producer, Batelle-Columbus Labs.

The results from gages on IN100 bars indicate a large change in slope between the heat treat and the other two cycles. The second and third cycles are about the same when the heating and cooling time histories are similar (bar 15, for example). Time vs temperature plots for bars 13 and 15 are shown. Differences between the second and third cycles are due to longer than planned heating or cooling times caused by improper oven control (bar 13, for example). These differences are due to the known time/temperature dependency of the resistance of the FeCrAl family of gage alloys. Data from the third cycle of gage 16-1 and from all three cycles of gage 16-2 were lost due to a data system malfunction. Data from the first cycle, below 900K, from bar 17 were lost because of an electrical power failure (local circuit breaker).

The results from gages on CuZr bars indicate better uniformity of the three cycles because of more uniform temperature histories and low drift in the range of 811K (1000°F).

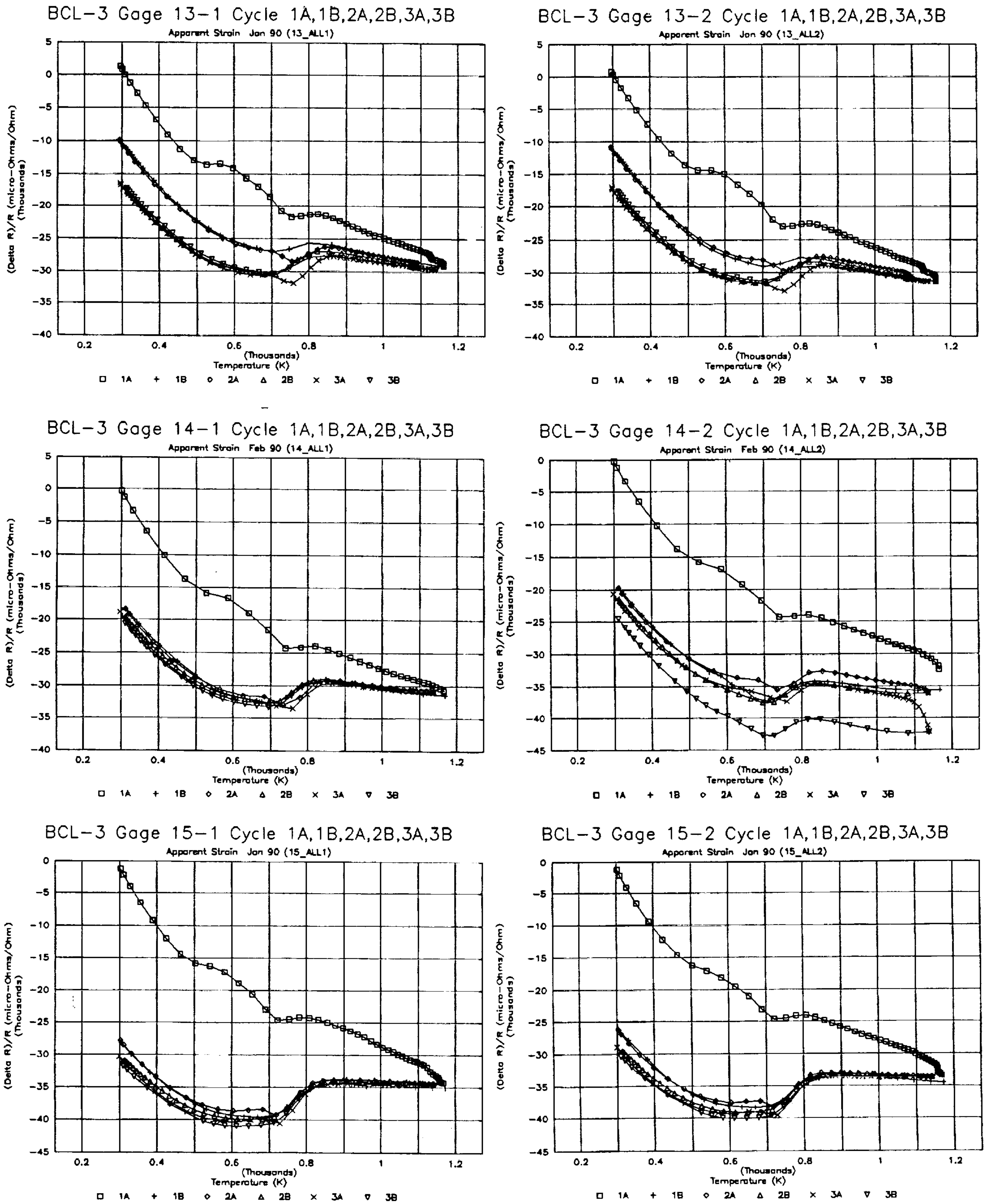


Figure 20.- Apparent Strain of BCL-3 Strain Gages on IN100 Bars

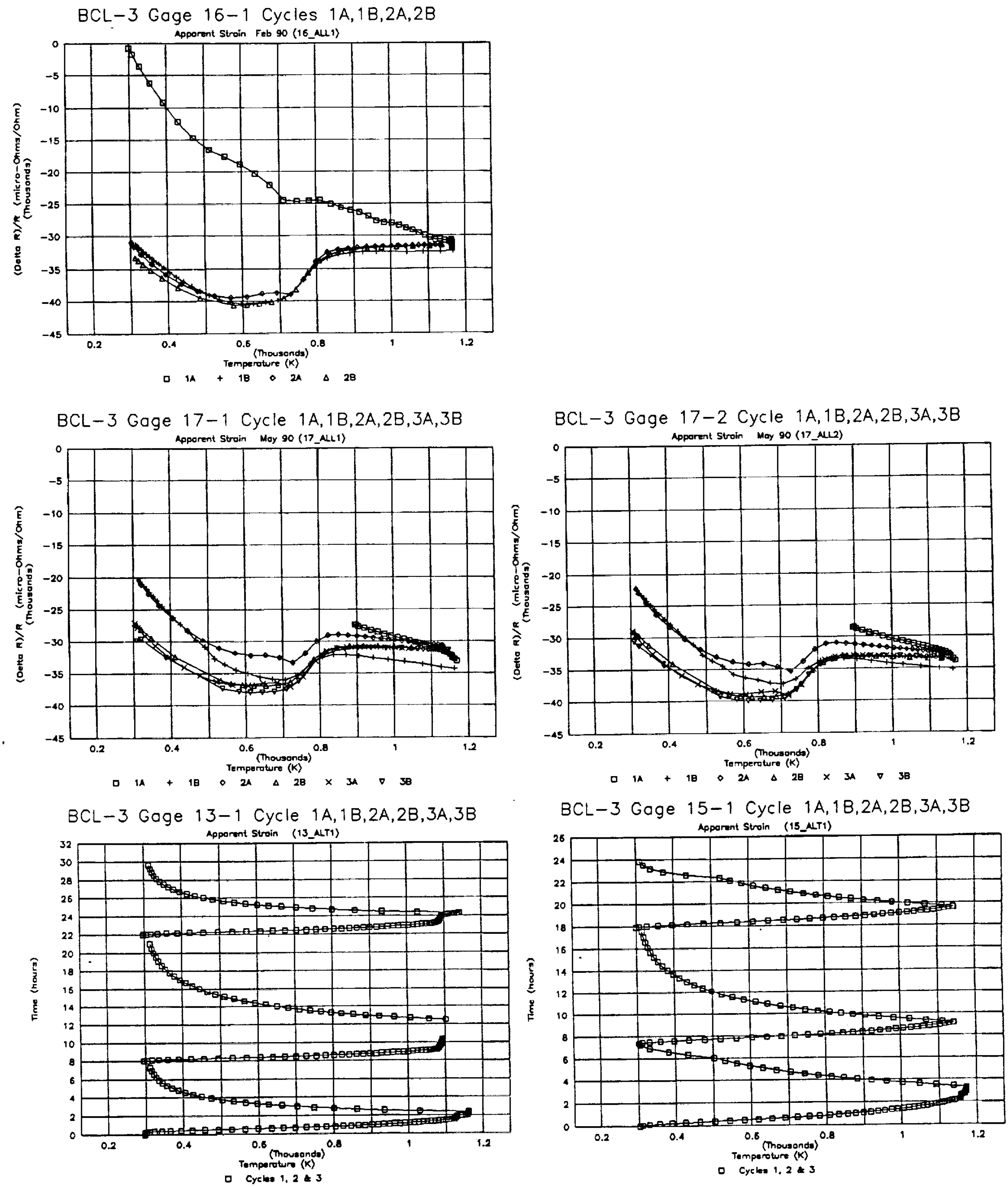


Figure 20.- Continued

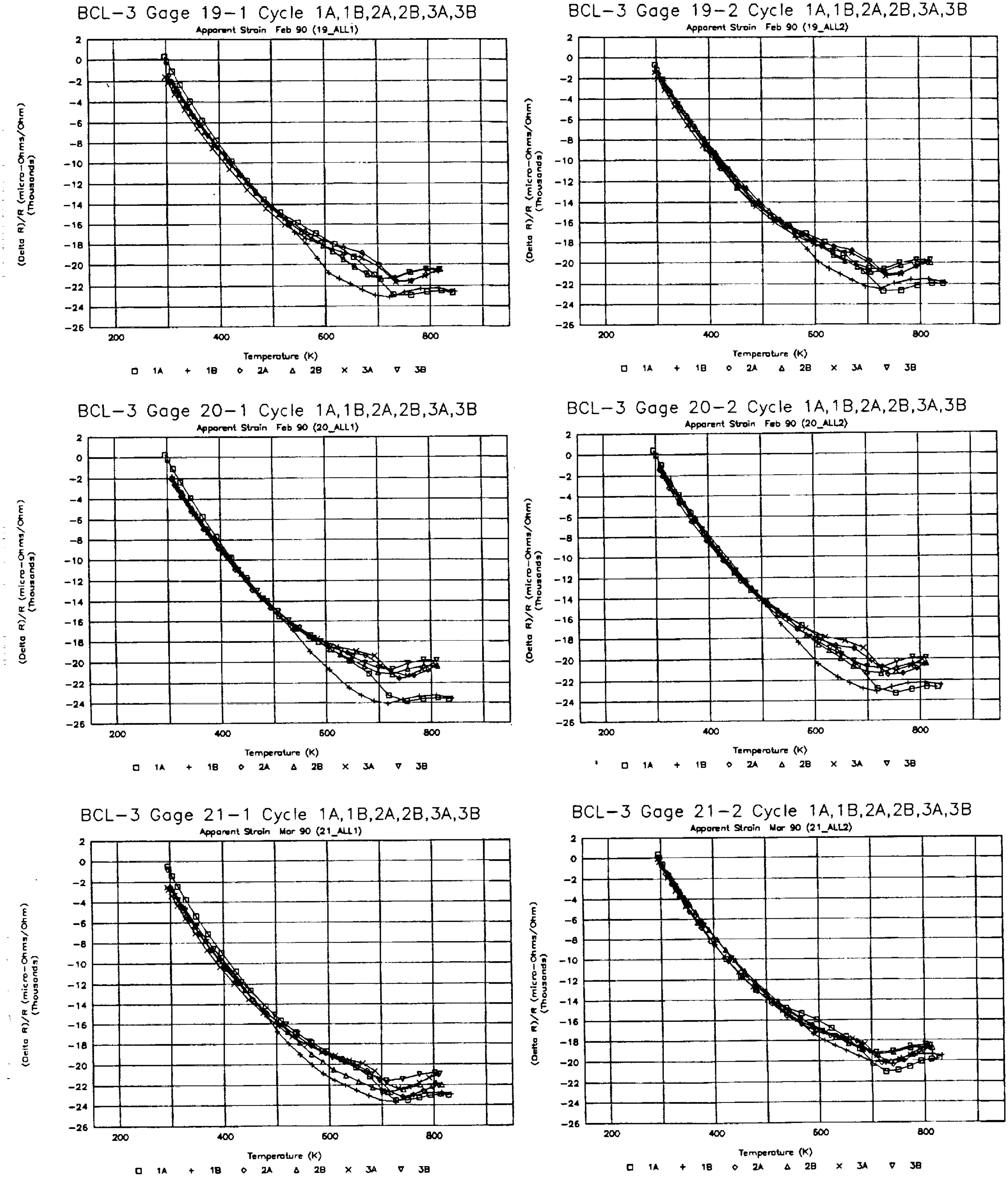


Figure 21.- Apparent Strain Of BCL-3 Strain Gages On CuZr Bars

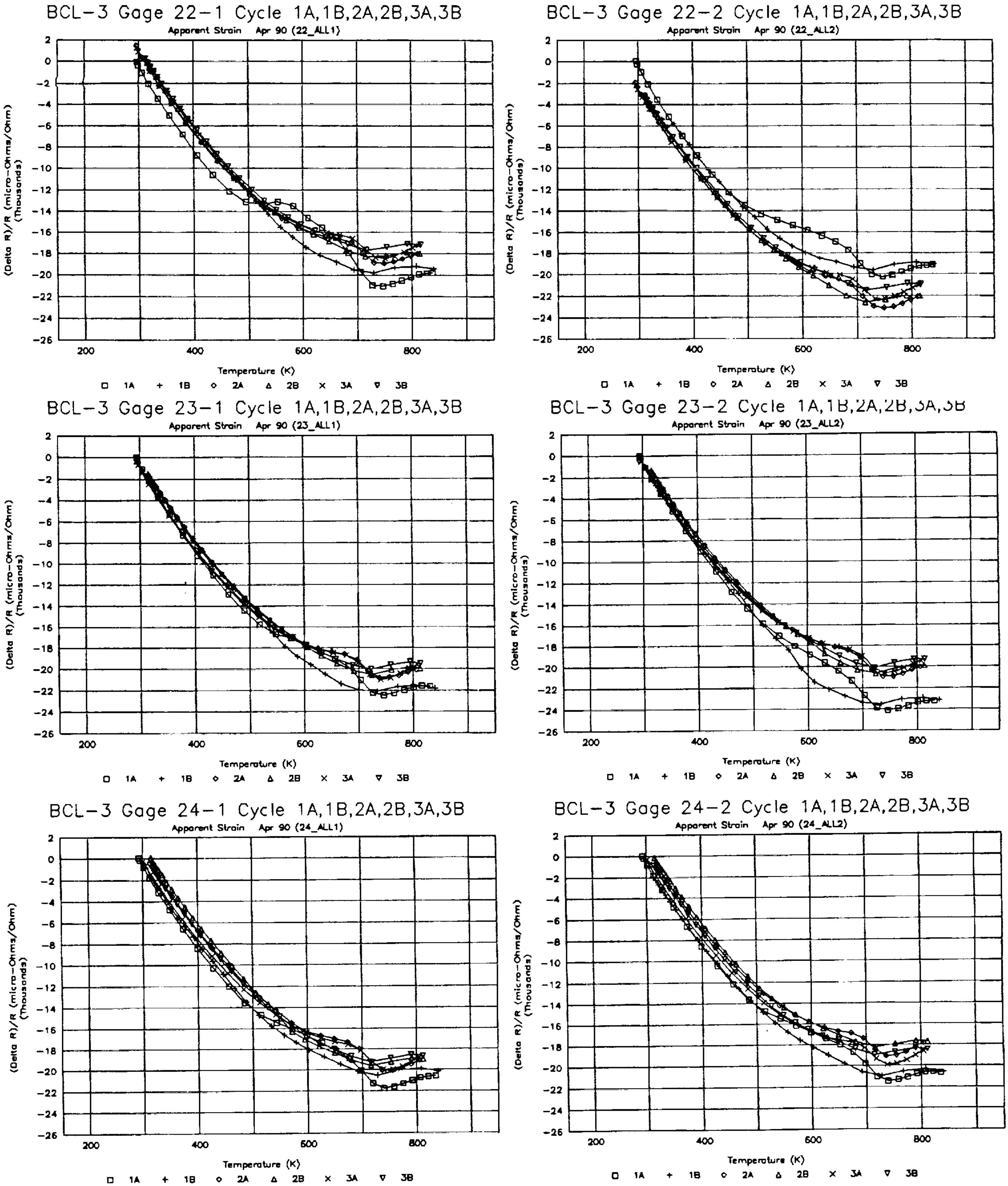


Figure 21.- Continued

Drift Data (BCL-3)

Data for BCL-3 gages are shown in Figure 22. In each plot, data shown for approximately the first hour represents the period of cooling from the maximum temperature to the drift temperature, and the next 10 hours (1 through 11) is the drift test period.

The following is a summary of the drift rates (in micro-Ohms/Ohm per hour).

Bar-Gage	Type	616K (650°F)	700K (800°F)	755K (900°F)	811K (1000°F)	1144K (1600°F)
13-1	IN100	+100	-550	-260	-20	-230
13-2	IN100	+100	-550	-260	-20	-220
20-1	CuZr	-	-410	-5	+40	-
20-2	CuZr	-	-420	-5	+30	-

Gage Factor Data (BCL-3)

Gage factor data for BCL-3 gages on IN100 bars are shown in Figure 23 and on CuZr bars in Figure 24. For each gage, the gage factor and gage factor variation are shown. Each point on the gage factor plot is the mean of the four measurements described in the "Test Procedure" of Section 3. The variation is defined as two times the standard deviation of those four measurements as a percent of the mean.

The results from IN100 bar 15 indicate a lower than expected measurement and from IN100 bar 16, a higher than expected measurement of gage factor, based on the published value of about 2.4 (room temperature). On bar 16, the reference strain measurement was repeated twice (with new reference gages), but the excessive measured gage factor was not explained. Simple bend load testing was conducted in an attempt to varify the results, but the results indicate that the high measured values are invalid (see Appendix). The measurements could be due to defects in the cast material. The gage factors of the gages on the CuZr bars agreed more closely with each other.

Creep Data (BCL-3)

Creep data for BCL-3 gages are shown in Figure 25. In each plot, data shown for approximately the first hour represents the period of cooling from the maximum temperature to the creep temperature, and the next 10 hours (1 through 11) is the creep test period. The creep strain of 1000 micro-strain resulted in about 2400 micro-Ohms/Ohm (gage factor is about 2.4) of $\Delta R/R$. Because creep is the relaxation of strain in the cement and gage, creep must be in the opposite direction from and no greater than the applied strain. The creep direction would be minus for gage 1 and plus for gage 2 because of the bending strain.

At all temperatures, the change in $\Delta R/R$ was in the same direction for both gages 1 and 2. This indicated that the change was due to drift and not creep. At 755, 811 and 866K (900, 1000 and 1100°F), the change was very small, indicating that any creep or drift that may be present was very small.

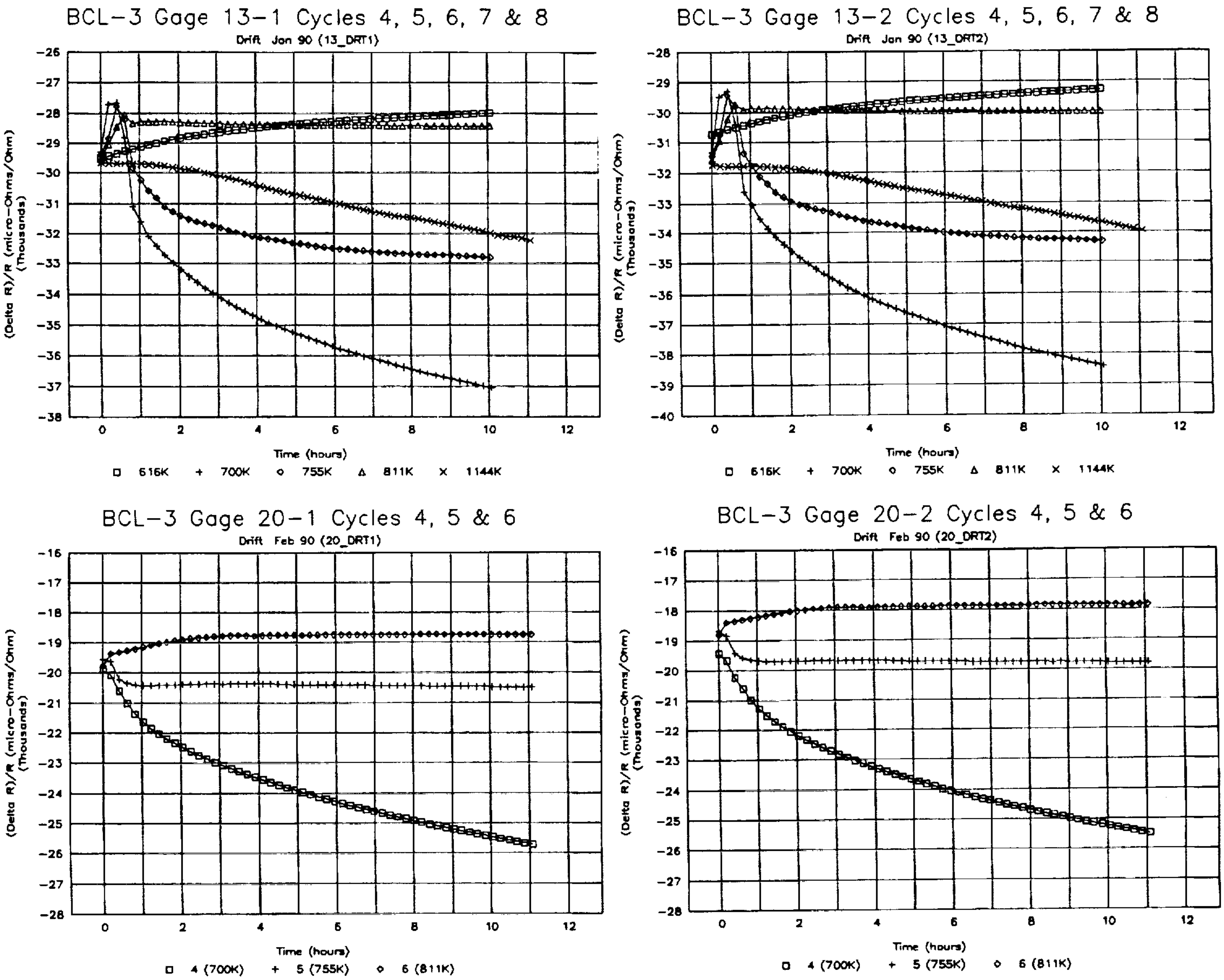


Figure 22.- Drift of BCL-3 Strain Gages

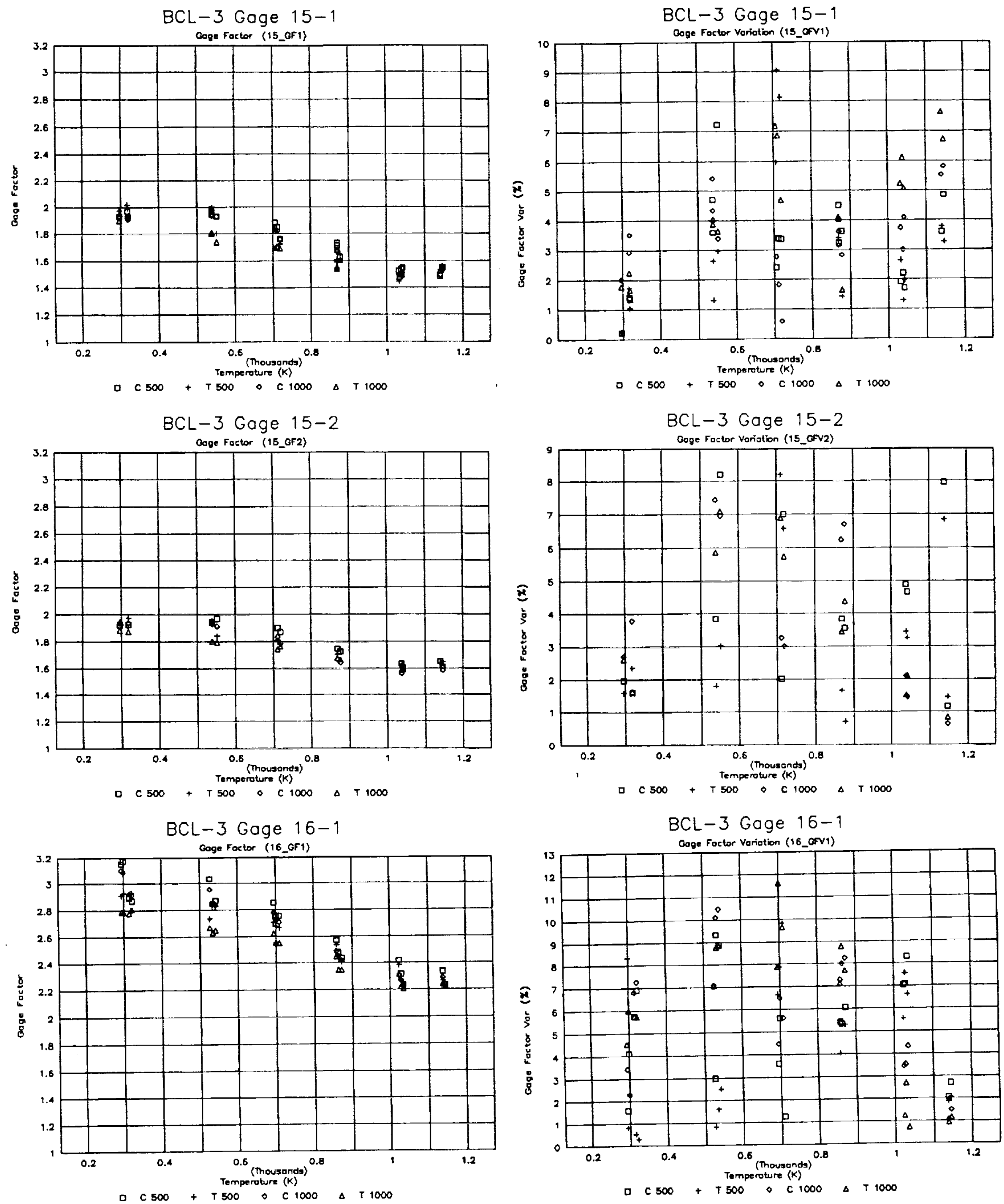


Figure 23.- Gage Factor and Variation of BCL-3 Strain Gages on IN100 Bars

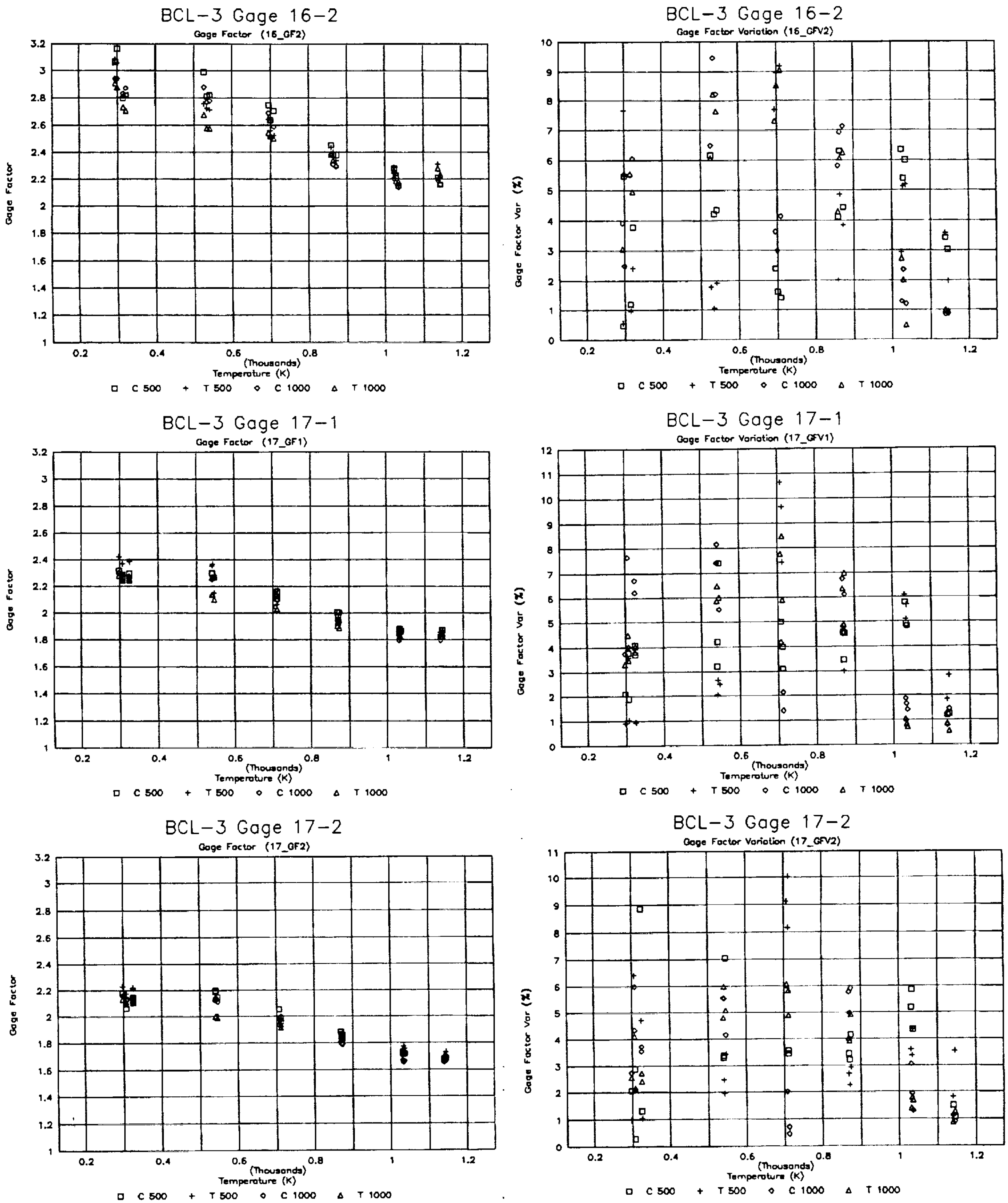


Figure 23.- Continued

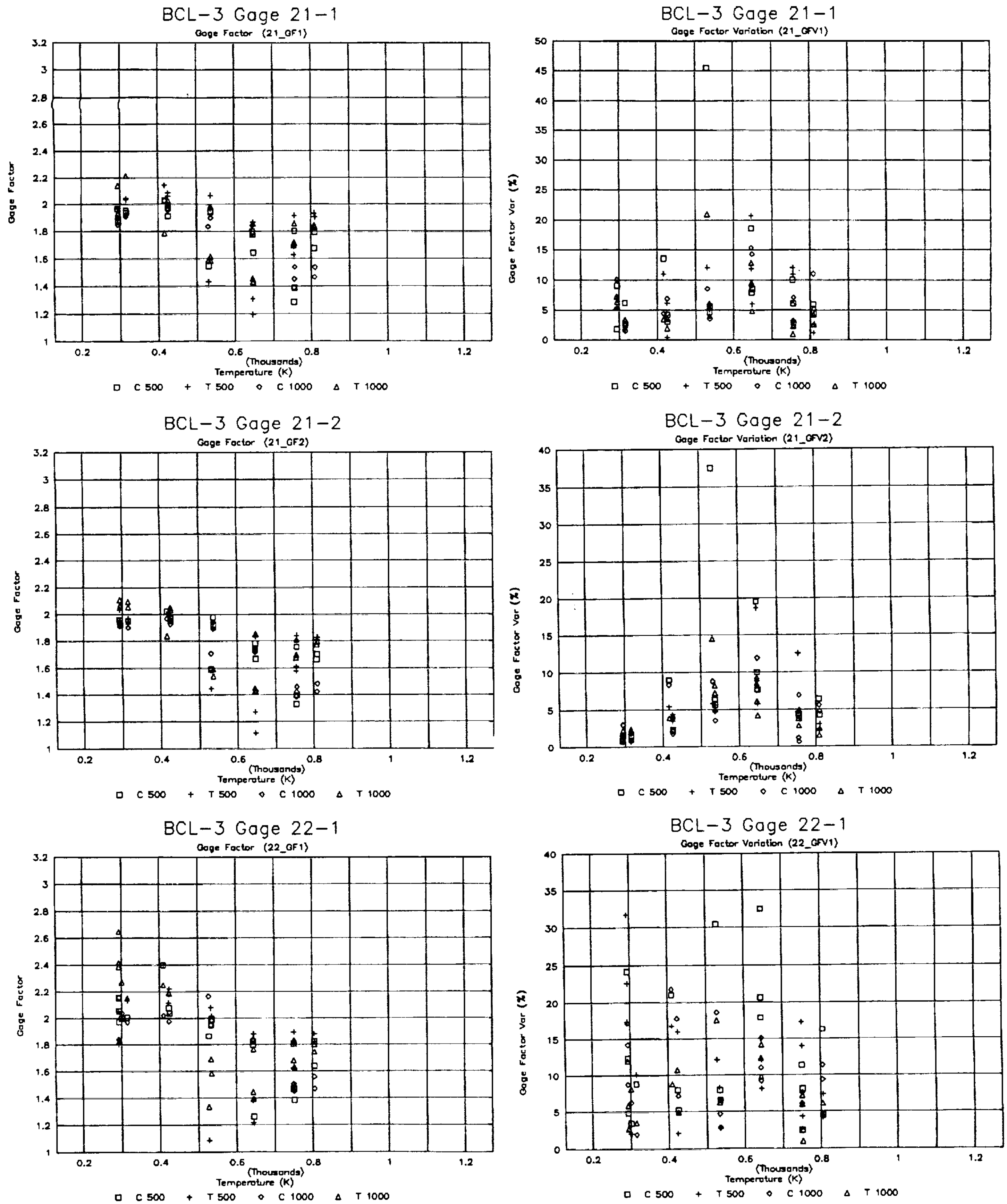


Figure 24.- Gage Factor and Variation of BCL-3 Strain Gages on CuZr Bars

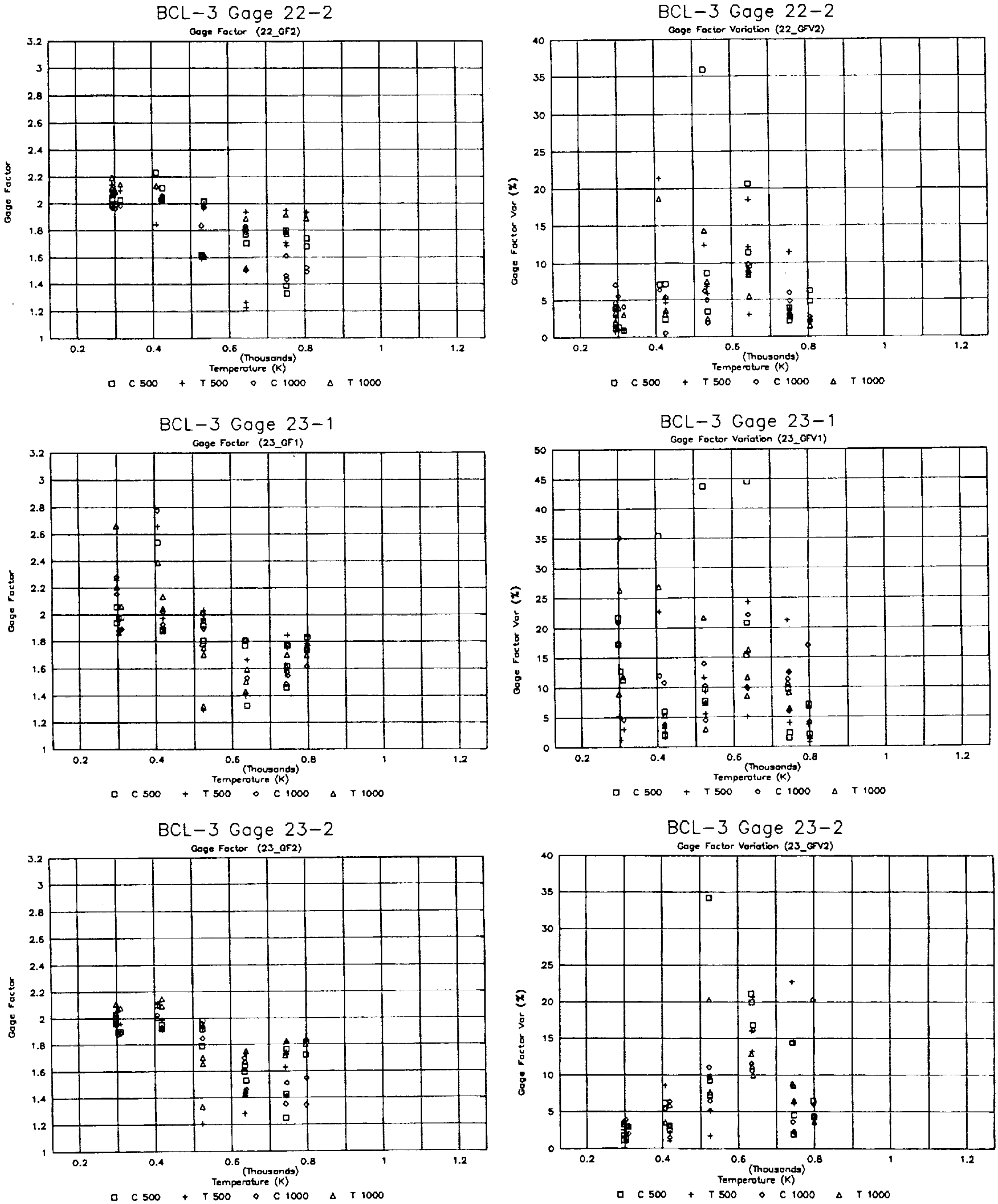


Figure 24.- Continued

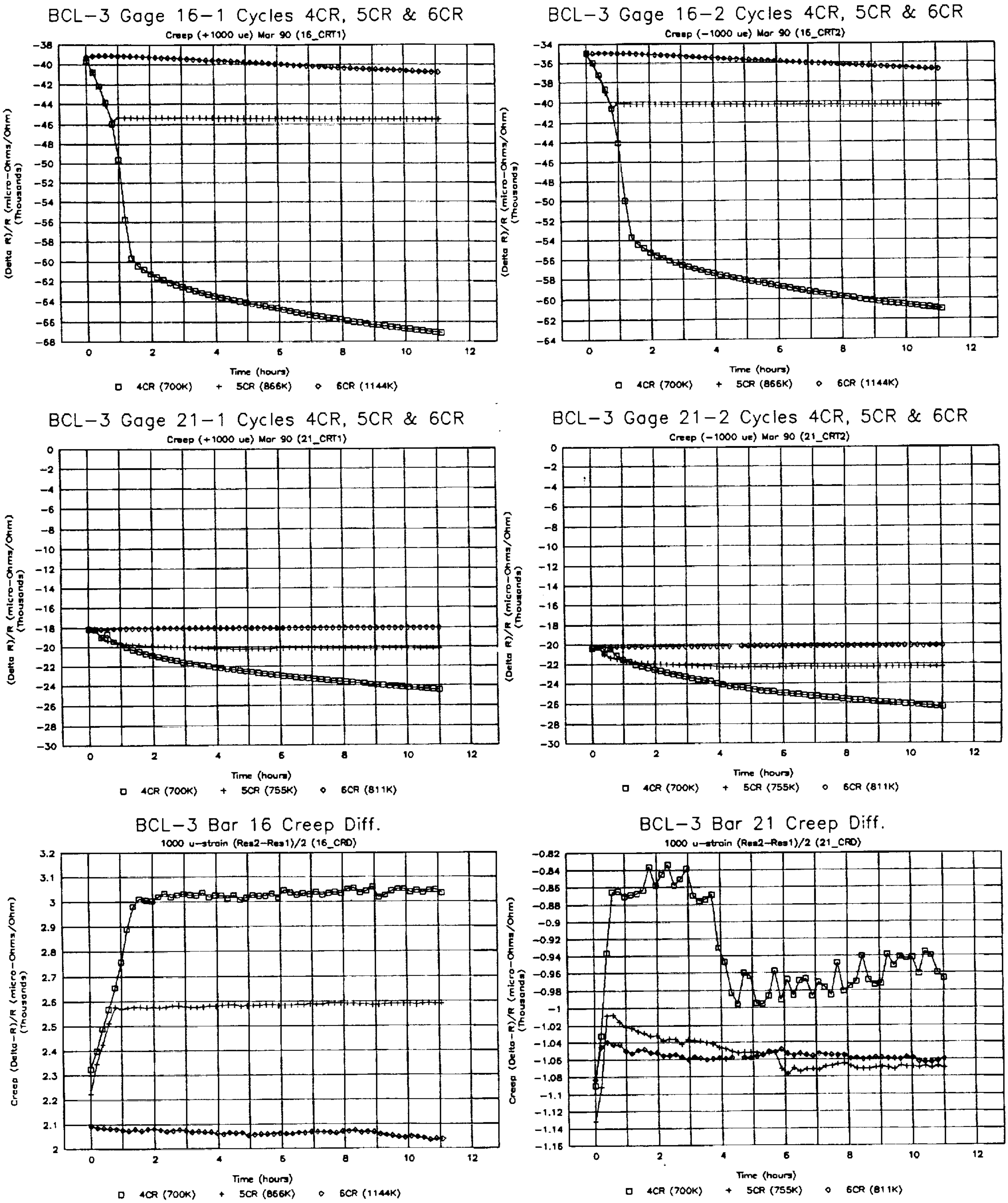


Figure 25.- Creep of BCL-3 Strain Gages

Some additional analysis was performed on data from bars on which both gages were functional. If the drift character was the same on both gages, the drift and creep would be separable because the strains are equal and opposite. Therefore, the creep would be found from half of the difference of the signals (and the drift from half of the sum). This type of analysis was done for BCL-3 bars 16 and 21. (The PdCr gages with high drift did not have good enough uniformity to obtain meaningful results.) The BCL-3 gages did have good uniformity and the results indicated very low (less than 5 micro-Ohms/Ohm per hour) creep. The results of this differential analysis for bars 16 and 21 are shown in Figure 25.

COMPARISON OF RESULTS

Comparison of PdCr to BCL-3 on IN100

Apparent strain of PdCr is less than that of BCL-3 up to the temperature limit of PdCr, 866K (1100°F). Above that temperature, BCL-3 has better apparent strain stability, probably due to better oxidation resistance. Drift of PdCr is less than that of BCL-3, but they cannot be compared above 811K (1000°F), the maximum drift-test temperature for PdCr. Gage factor of PdCr is less than that of BCL-3 (1.4 vs 2.4), because of slightly lower strain sensitivity of the PdCr wire and the desensitization caused by the platinum temperature compensation element. Creep of the two gage types can not be compared because, for the PdCr, drift hides any creep that may be present. Creep of BCL-3 is very small.

Comparison of PdCr to BCL-3 on CuZr

Comparison may be made only up to the temperature limit of the CuZr substrate, 811K (1000°F). Apparent strain of PdCr is less than that of the BCL-3. Drift of PdCr is less than that of BCL-3. Gage factor and creep comparisons are the same as for IN100, above.

Comparison of IN100 to CuZr for PdCr

Apparent strain, drift and gage factor results for PdCr were similar for IN100 and CuZr. Creep results can not be compared because drift hides any creep that may be present.

Comparison of IN100 to CuZr for BCL-3

Apparent strain and apparent strain stability were greater for IN100, due to the higher maximum test temperature, 1144K (1600°F) vs 811K (1000°F). Thermal expansion accounts for only a small fraction of the apparent strain. Differences due to the slightly higher temperature-coefficient-of-expansion of CuZr would not be noticeable. Drift results were similar for the two substrates at the same temperatures. Gage factor consistency, gage to gage, was better for CuZr. However, variation among the four readings for individual gages (gage factor variation plots) was worse for CuZr. This was thought to possibly be related to yield of the CuZr bar, but no evidence of yield was found. Review of the material properties (from Nippert) indicates that the yield strain is higher than 1000 micro-strain, even at 811K (1000°F). Also, the strain measurements, made during gage factor testing, were compared to determine if the first deflection differed from subsequent deflections. No differences were found. The large gage factor variation has not been explained. Creep was very low for both substrates.

INSULATION RESISTANCE DATA

During testing, insulation resistance was measured for each gage at each data point. These data were plotted for selected apparent strain cycles of PdCr bar 06 and BCL-3 bars 15, 17 and 24. The results indicate that the insulation resistance drops below 1 megohm at about 900K (1161°F). This is shown for bar 17 (BCL-3 on IN100) in Figure 26. The results for the alumina/zirconia powder mix were similar to Rokide up to 866K (1100°F), the maximum temperature for those bars. The measurement method inherently provided better accuracy at low resistance levels than at high. This accounted for the scatter at low temperature (and high resistance).

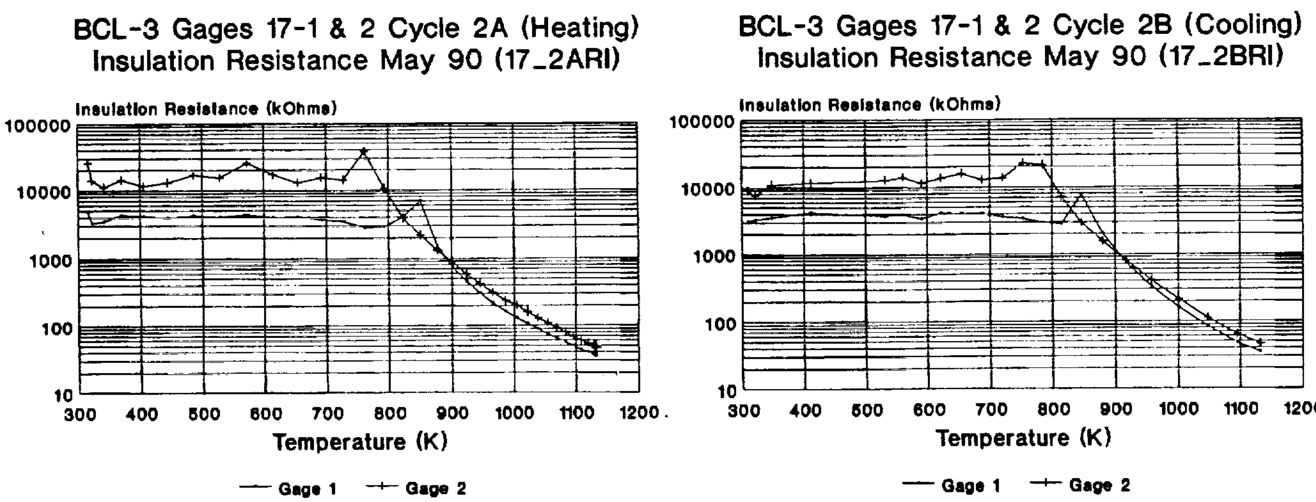


Figure 26.- Insulation Resistance

THERMO-ELECTRICITY DATA

Thermo-electricity was measured at each data point by measuring the bridge signal with both positive and negative excitation. This was calculated in the same way as the resistance change (-R/R) except that the signal difference (rather than the sum) was used. The units represent the equivalent -R/R indicated by the bridge signal due to thermo-electricity. This parameter was plotted for selected apparent strain cycles for PdCr bar 05 and BCL-3 bars 17 and 24. The thermo-electricity range during heating and cooling cycles are as follows:

Type	Cycle	Range (micro-Ohms/Ohm)
PdCr	Heating	30
PdCr	Cooling	30
BCL-3	Heating	270
BCL-3	Cooling	120

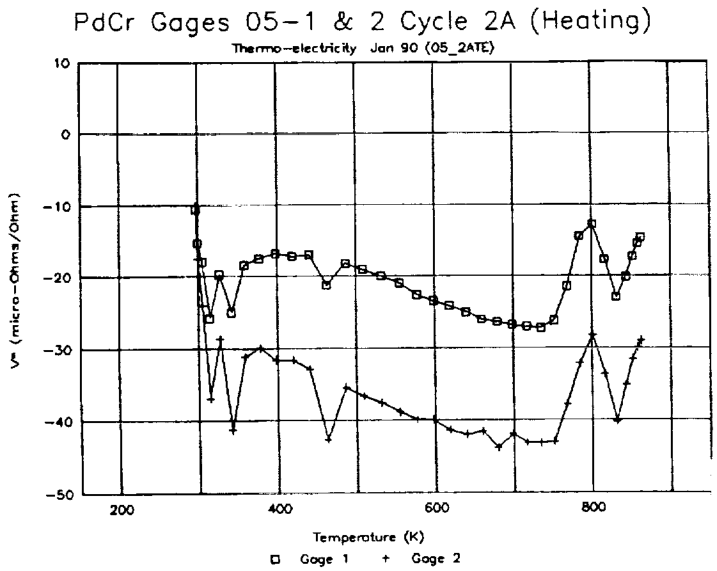
The amount of thermo-electricity depend on the type of grid and lead wire and on the temperature gradient along the path. It is generally less during cooling cycles than heating cycles because cooling cycle are slower and the gradients less. Results are shown in Figure 27.

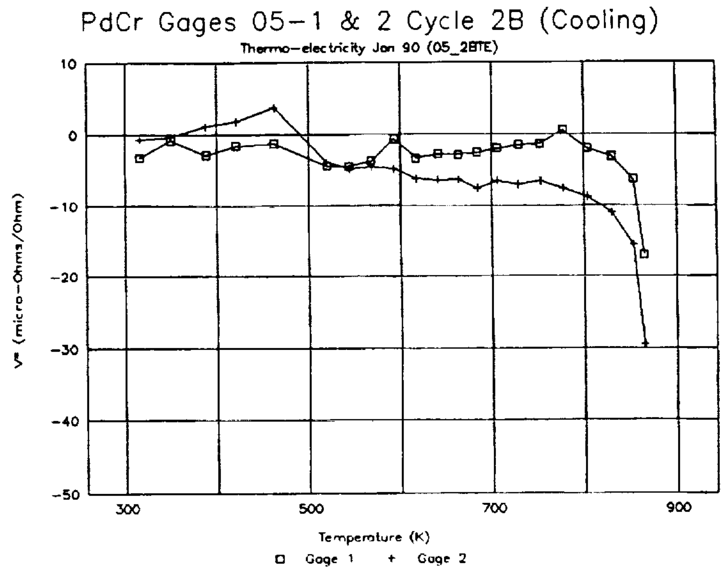
POST-TEST INSPECTION

For each test bar, gage circuit and insulation resistance were measured and the installation was visually examined for defects. Of the 26 tested PdCr gages, five were found to have an open circuit. All open circuits were located at the weld of the Pt grid to the noncommon lead wire. Of the 22 tested BCL-3 gages, one was found to have an open circuit. It was located near the center of the grid. All gages were found to have insulation resistance greater than 20 megohms except for two gages with about one megohm. The general appearance of the precoats and overcoats was excellent. Only one gage had evidence of overcoat delamination.

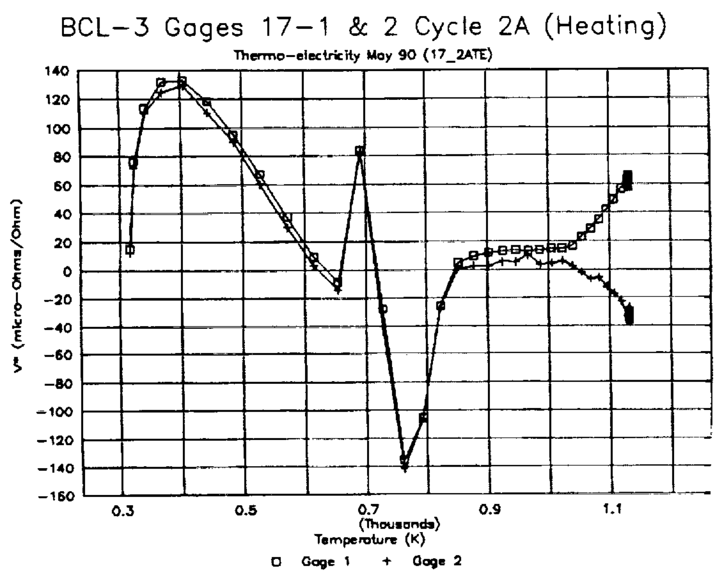
Resistance measurements of all the gages and compensation elements were made after testing and compared to those made prior to testing. The results are shown in Figure 28.

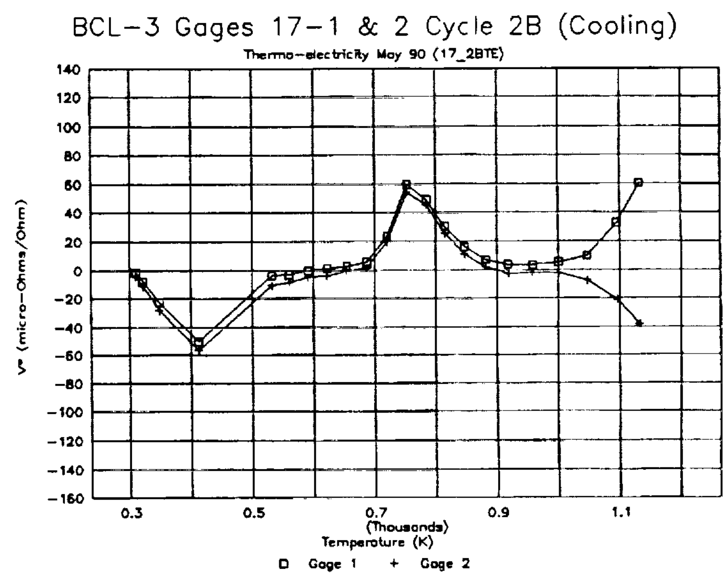
Two additional tests were conducted to determine the thermal stability of the gage connection box and the self-heating character of the gages. In the first test, with gages connected to the system, the connection box was heated to measure any output caused by temperature change of the bridge resistors. The box was heated over a range of 11K (20°F) and the output was small (about 200 micro-Ohms per Ohm) compared to the thermal performance of the gages, but significant relative to strain measurement accuracy objectives. The results are shown in Figure 29. In the second, with PdCr gages connected to the system, output was recorded with several levels of excitation to determine the shift due to gage heating. The results are shown in Figure 30. The two data points at each excitation level were recorded about 80 seconds apart. At the 5-volt level used in this program, the self-heating effect was small (about 20 micro-Ohms/Ohm). The power density of the gages as used in this program was considered acceptable (about .76 watts per square inch for BCL-3 and 1.16 watts per square inch for PdCr).



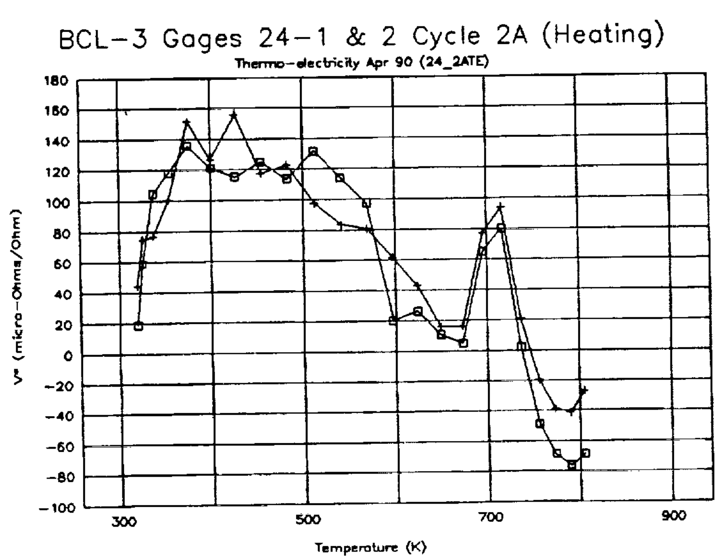


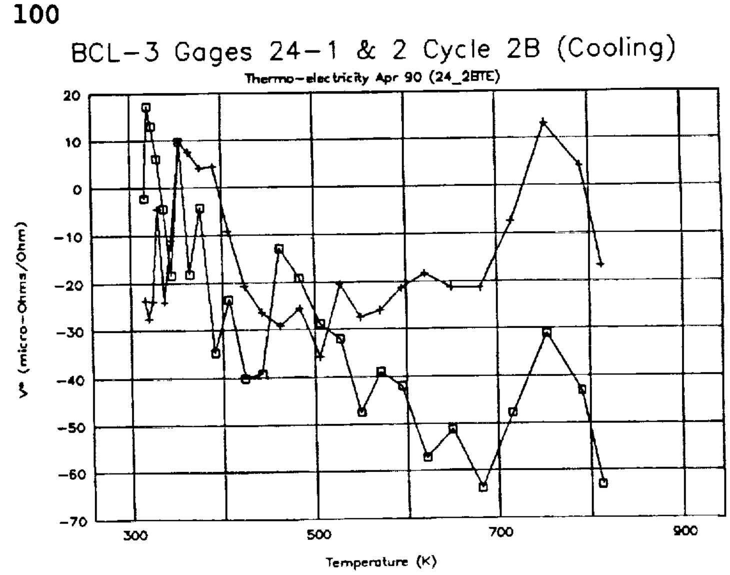
IN 100





IN 100





CuZr

Figure 27.- Thermo-electricity

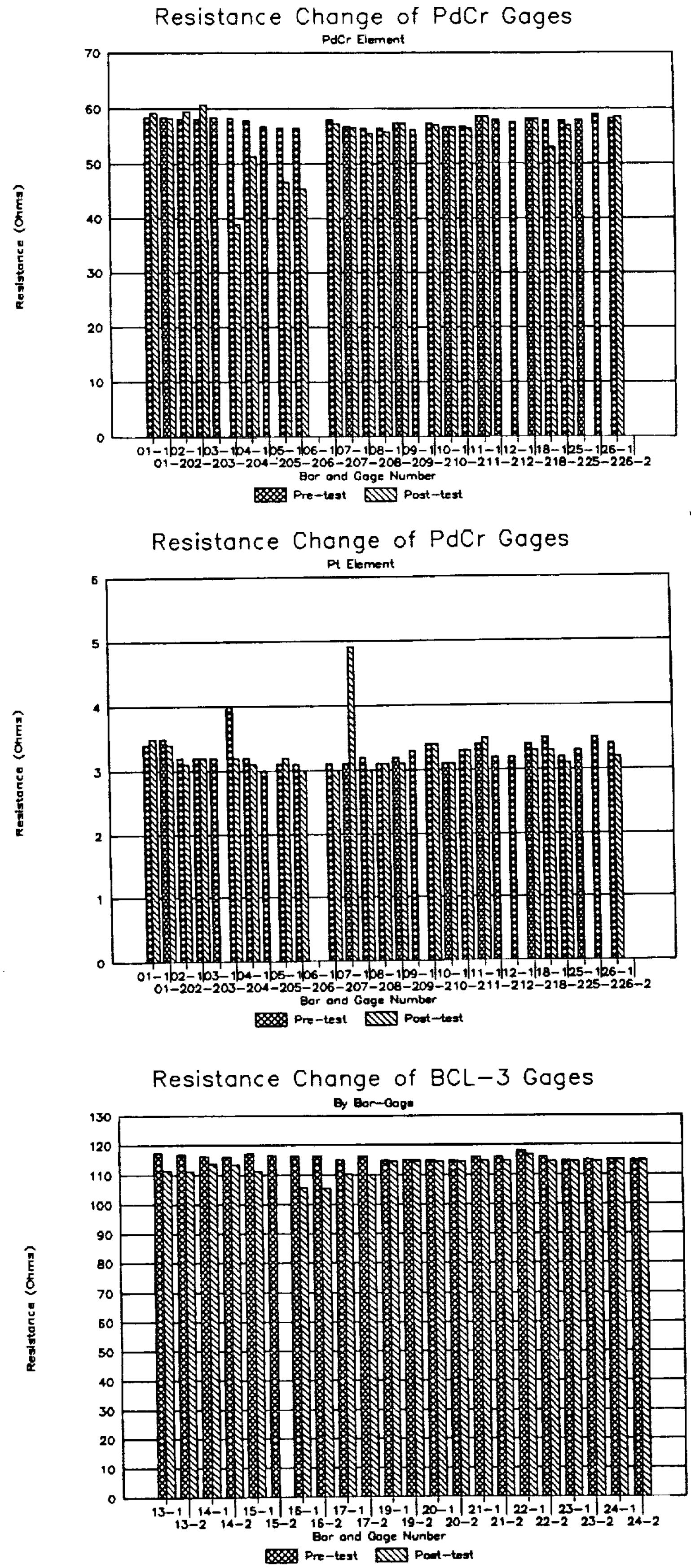


Figure 28.- Strain Gage Resistance Before and After Testing

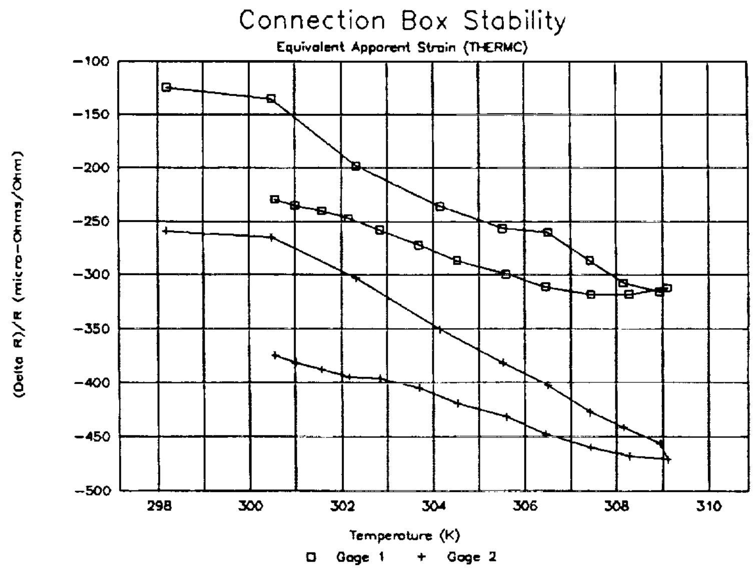


Figure 29.- Strain Gage Zero Shift from Heating due to Excitation

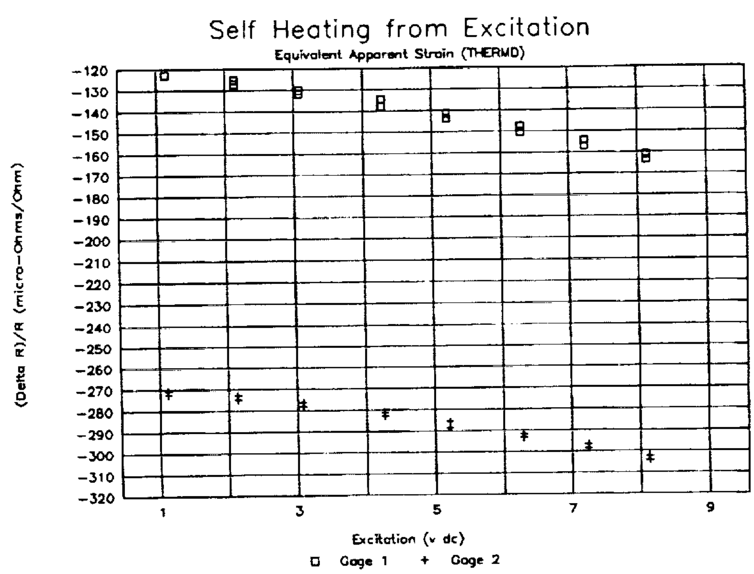


Figure 30.- Bridge Completion Network Thermal Stability

SECTION 5.0
CONCLUSIONS

PdCr GAGES

- o Exposure to temperatures above 866K (1100°F) resulted in an increase in the temperature-coefficient-of-resistance (TCR), probably due to selective oxidation of the Cr.

- o Pt is an effective thermal compensation material. The resistance ratio of PdCr to Pt should be about 18:1. This will allow a bridge ratio of 1:1 and provide compensation for thermal resistance change in the leads.

- o The drift rate was reduced by adding a NiCrAl coating to the Rokide overcoat. Use of flame spray Al_2O_3/ZrO_2 overcoat did not reduce drift rate significantly within the limits of this program.

BCL-3 GAGES

- o Resistance stability is good above 800K (981°F). For measurement between 800 and 1144K (981 and 1600°F), BCL-3 can be a useful gage wire.

- o Drift is high in the temperature range of 700 to 755K (800 to 900°F). This results in time-dependent apparent-strain character, similar to other FeCrAl strain gage alloys.

GENERAL

- o Insulation resistance is less than one megohm above 900K (1161°F). This agrees with other experience with Rokide.

- o Thermo-electric effect for both gage/lead combinations is low, but that of PdCr is less than BCL-3.

6.0 REFERENCES

1. Hulse, C. O., Bailey, R. S. and Lemkey, F. D., "High Temperature Static Strain Gage Development Program", R85-915952-13, United Technologies Research Center, NASA Contract NAS3-23169, March, 1985.

2. Lemcoe, M. M., "Development of Electrical Resistance Strain Gage System for Use to 2000°F", Paper 75-572 Instrument Society of America, 1975.

APPENDIX

ATTEMPTED GAGE FACTOR VERIFICATION OF BAR 16 (BCL-3 ON IN100)

Because the gage factor measurements are higher than expected (approximately 3.0 rather than the published 2.4), simple room temperature bend load tests were conducted on bars 15, 16 and 17 in an attempt to verify the measurements. However, the high measurements were not substantiated by these tests and are probably invalid (although not explained).

The bars were clamped in a fixture and vise and a 27 pound weight was hung on the other end while measurements were made with a portable strain indicator. Reference gages were not used because in this loading mode, strain is not constant along the length (and would be lower at the reference gage location). Therefore, the exact strain of the bar was not measured, but the relative sensitivity of the five gages was determined. These measurements were made for gages 15-1, 16-1, 16-2, 17-1 and 17-2 (gage 15-2 was found to have on open circuit at the end of the scheduled test program). All the measurements were referenced to gage 15-1 (ratios of sensitivities of the other gage to that of gage 15-1 were calculated). Similar ratios were calculated for the original gage factor data for these gages.

The results, shown in Figure A-1, indicate that the sensitivities of all of these gages are within about 20% of that of gage 15-1. The original gage factor data indicates that gages 16-1 and 16-2 have sensitivities about 60% higher than gage 15-1.

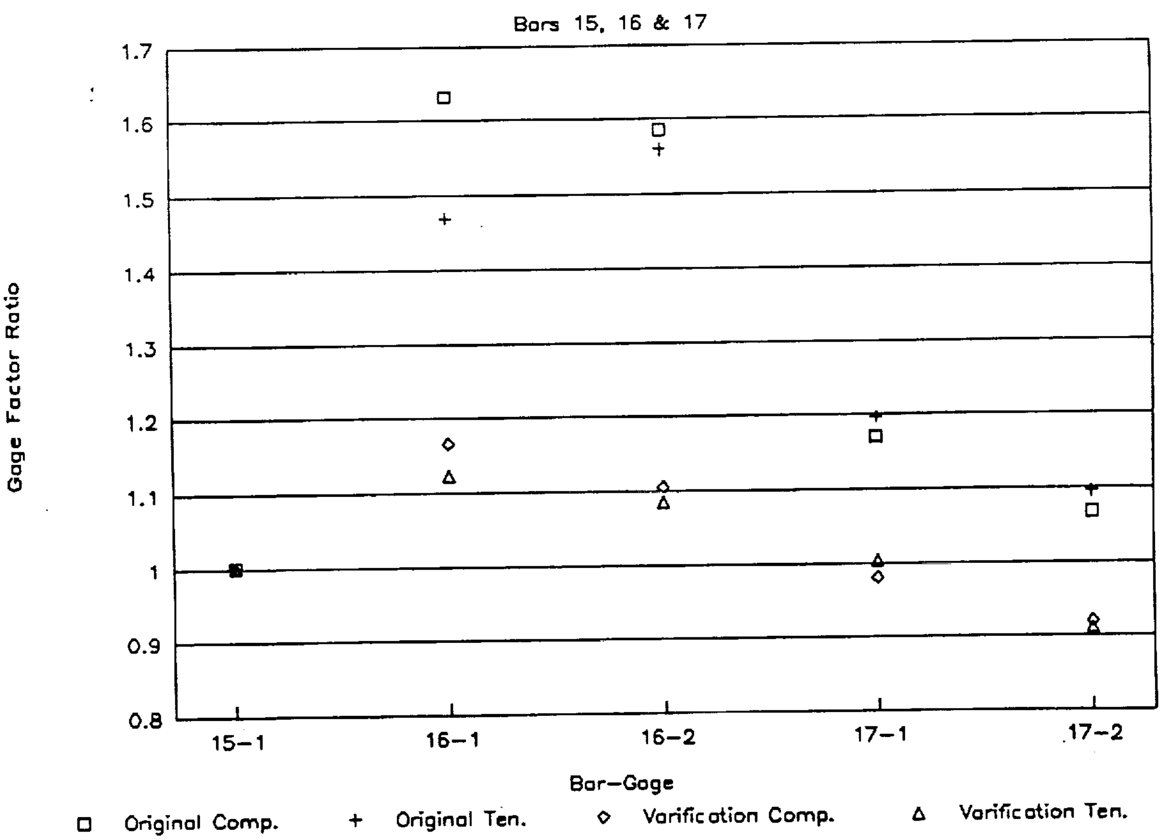


Figure A1.- Gage Factor Verification Test Data for BCL-3 Gages on IN100 Bars at Room Temperature. Ratio of Sensitivities of Gages are Relative to that of Gage 15-1

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16. ABSTRACT

An experimental evaluation of Pd13% Cr and of BCL-3 alloy wire strain gages was conducted on IN100 and Cu .15% Zr alloy substrates. Testing included apparent strain, drift, gage factor and creep. Maximum test temperature was 1144K (1600°F). The PdCr gages incorporated Pt temperature-compensation elements. The PdCr gages were found to have good resistance stability below 866K (1100°F). The BCL-3 gages were found to have good resistance stability above 800K (981°F), but high drift around 700K (800°F).

17. KEY WORDS (SUGGESTED BY AUTHOR(S) Strain Gages, PdCr Gages, BCL-3 Gages, Apparent Strain, Drift, Gage Factor, Creep	18. DISTRIBUTION STATEMENT

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