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The Development of a PdCr Integral Weldable Strain Measurement System Based on NASA Lewis PdCr/Pt Strain Sensor for User-Friendly Elevated Temperature Strain Measurements

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THE DEVELOPMENT OF A PdCr INTEGRAL WELDABLE STRAIN MEASUREMENT SYSTEM BASED ON NASA LEWIS PdCr/Pt STRAIN SENSOR FOR USER-FRIENDLY ELEVATED TEMPERATURE STRAIN MEASUREMENTS

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SUMMARY

This report describes the development of a user friendly weldable strain gage employing the NASA Lewis PdCr/Pt wire strain sensor. The NASA sensors are preattached to Hastelloy X or Titanium alloy shims using flame spray techniques developed under previous NASA programs. The weldable sensors are then prestabilized for 50 hr at 1440 °F in air. A weldable terminal and high temperature cable is then connected to the sensor and the assembly is precalibrated over the full test temperature range. Calibrated resistors are inserted into a bridge completion module at the cool end of the cable to condition the sensor in half or full bridge configuration. The sensor is attached to the structure using a common capacitive discharge spot welder. No additional high temperature stabilization or calibration is required. The resultant device is a precalibrated strain transducer which can be plugged into any common variety strain instrumentation.

INTRODUCTION

The development of PdCr wire strain gages make possible static strain measurements to 1400 °F. The development of these gages revolutionized attachment techniques rendering all prior art obsolete. A totally new and comprehensively different set of procedures and new materials were developed. In order to use these gages successfully, every strain gage installer must undergo a thorough reorientation, abandon familiar materials and procedures, and adopt completely new practices, the details of which are discussed in references 1 and 2.

In addition to strict observance of installation procedures, the PdCr strain gages must be prestabilized at elevated temperatures (1440 °F for 50 hr). Care must be exercised not to overtemp the gages because a momentary excursion above the critical temperature (ref. 7) will destroy the gage compensation. The special flame sprayed alumina/zirconia ceramic matrix provides superior resistance stability. However, excessive under temperature will result in insufficient stabilization of the PdCr and resistance changes less than expected. This causes an unbalanced bridge, thus an improper value for the balast resistor R_B, (either too low or too high) which distorts the apparent strain curve. An R_B value which produces a near perfect balanced bridge produces the least amount of strain. Therefore, it is imperative to hold stabilization temperatures at each gage location within the specified tolerance. This is difficult to do on large structures.

Therefore, the installation of PdCr/Pt gages onto thin shims which can be prestabilized in a closely controlled oven is an attractive alternative for several reasons:

1. Gages are installed by trained technicians in a closely controlled laboratory environment.
2. Gages are stabilized in a very closely controlled programmable furnace.
3. With a terminal and high temperature cable attached, the gages on a shim can be precalibrated for R_B over the desired temperature range.
4. With the selected R_B value inserted into a miniature signal conditioning module at the cool end of the high temperature cable; the gage can be precalibrated for apparent strain versus temperature. Using the calibration method developed by Hofstötter (ref. 3) the gage can be calibrated on a sample coupon of test article material.

GAGE DESCRIPTION

The weldable gage consists of a free filament PdCr/Pt strain gage flame spray (shown in fig. 1) bonded to a 5 mil thick shim using bonding procedures described in reference 2. A thin metalized precoat of nickel chrome aluminum alloy is applied to the gage bonding area of the shim to enhance ceramic bonding. Rokide HTZ rod, a special flame spray rod developed specifically for use with PdCr is used for gage attachment. A margin of shim material extends around the perimeter of the gage and is the weld area used to attach the shim to the test structure. The gage is attached to the structure using capacitive discharge spot welding equipment ordinarily used for this purpose.

The gage is available in two sizes, a small, 60 Ω unit and a standard 120 Ω size. The 60 Ω units are only 0.5-in. long by 0.4-in. wide. See table I for nomenclature and dimensions. Two shim materials are standard, Hastelloy X for compensation on 6 ppm/°F materials and Ti6Al4V for compensation on Titanium matrix composites.

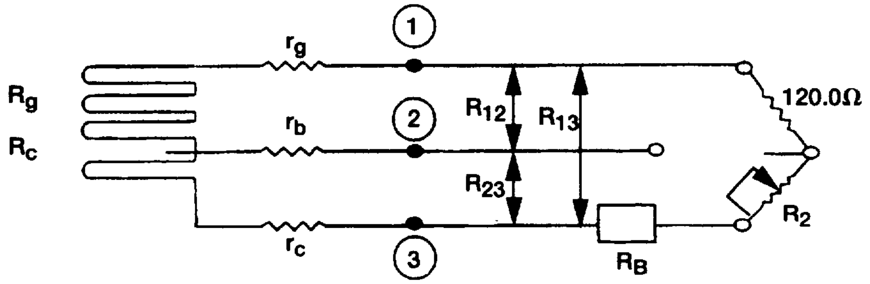
Although available without cables, the gages are usually supplied with an integral weldable terminal, high temperature cable, and a bridge completion module on the cold end of the cable.

The gage may be attached to the terminal located axially or transversely to the cable. See figure 4. The terminal consists of a weldable base shim with three high purity alumina insulators and the hot end of the cable strap welded to the base shim (fig. 2). The three cable wires are threaded through the insulators and bonded to the inside of the insulator using a high alumina ceramic cement. The bonding prevents movement of the conductors when the cable is twisted, pulled or vibrated. The ceramic cement is also applied to the exterior of the insulators to bond them to each other and to the weld straps. The cement is heat cured prior to attachment of the terminal to the gage.

The terminal is attached to the gage with two wire flexures welded to the edge of the gage shim and the edge of the terminal. The flextures consist of 10 mil diameter Nichrome[*] wires bent in a "U" shape. The flextures are used to hold the gage and terminal together without imposing stresses on the PdCr/Hoskins weld joint. The 3 mil PdCr leads are spot welded to the Hoskins alloy conductors. The high temperature cable consists of three number 25 AWG Hoskins alloy 875 conductors individually insulated with Nextel[†] fiber-braided insulation and held together with a tightly wound Nextel braid over the three individual cables. The cable is heat cleaned prior to assembly. A small PC board module (fig. 3) which contains the bridge completion resistors is attached to the cool end of the high temperature cable. The gage with terminal, and completion module can be temperature calibrated at the user's facility or they may be supplied precalibrated.

Determination of R_B

The first step in the calibration process is the determination of R_B and other bridge completion resistor values. The gage is mounted in a calibration fixture attached to a sample of test material (if calibration on a specific material is desired), or it can be calibrated on the shim only. Referring to the Sketch below, R_{12}, R_{23} and R_{13} are measured at points ①, ②, and ③ at room temperature and at maximum temperature using a meter with at least 2 decimal place resolution.



R is measured at end of leads at points ①, ② and ③.

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[*] T.M. Driver Harris

[†] TM 3M Co.

From the resistance measurements, R_B is calculated using the equations given in reference 4. A sample calculation is included in the appendix. The calculated value of R_B is verified using a temporary bridge completion network of precision decade resistors such as the General Radio model 1432 or Vishay model V-40. R_B is placed in series with the compensating gage. The other two resistors completing the full bridge also utilize precision decade resistors. The resistor adjacent to R_g is set at 120 Ω (or 60 Ω for 60 Ω gages), and the resistor R_2 is adjusted to balance the bridge. Bridge balance is read out on a Vishay P-3500 strain indicator. The bridge balance resistor within the indicator is disconnected for this procedure.

Calibration

With the gage connected to the precision resistor network the gage on the test bar (Hastelloy X for 6 ppm/°F gages) is placed into a cool furnace. It is necessary to keep the gage shim flat during calibration. In addition to tack welding the four corners, the gage may be clamped to the test bar using the methods developed by Hofstötter (ref. 3). A type K thermocouple is also spot welded to the test bar and connected to the X axis of an X-Y plotter. The temperature is also read out on a digital meter. A thin layer of alumina felt insulation is placed over the gage to prevent spurious signals due to thermal convection within the furnace. The output of the P-3500 strain indicator is connected into the Y axis of the X-Y plotter.

Strain readings are taken every 100 °F and an analog plot is made of the apparent strain calibration on the X-Y plotter. Slow furnace heat up and cool down rates are used to eliminate thermal stresses within the test bar. Thermal EMFs are checked periodically by turning off bridge power momentarily. If the apparent strain calibration is satisfactory, a permanent bridge completion module is made up using adjustable bridge completion resistors available from strain gage manufacturers. The values of these adjustable resistors are made identical to the values on the precision decade resistors. If the apparent strain curve is not satisfactory, R_B is re-adjusted and another calibration run is made. This process is repeated, if necessary, until a satisfactory calibration curve is achieved. The adjustable resistors are inserted into the bridge completion module in place of the precision decade resistors and calibration curve recorded. A second cycle is run to check repeatability and to verify that the maximum and zero return strain readings are repeatable. The gage is then removed from the test bar and packaged for shipment along with the analog calibration curve.

RESULTS

Figure 2 is a photograph of the weldable gage, terminal, and high temperature cable. Figure 3 is a photograph of the bridge completion module. Figure 4 shows two sketches of the weldable strain gage assembly with half bridge and full bridge signal conditioning modules. A typical analog plot of apparent strain versus temperature recorded on an X-Y plotter is shown in figure 5. Note that the zero shift at room temperature is only 22 $\mu\varepsilon$, after a thermal cycle to 1380 °F.

DISCUSSION OF RESULTS

Possibly the most common problem faced by today's experimental engineer is obtaining enough time to perform the testing. The development of the precalibrated weldable strain gage assembly goes a long way to easing the burden of the test engineer. While one might be interested in how calibrations are done, project time schedules often preclude the test engineer from conducting extensive apparent strain calibrations on the test article. Often users are not interested in conducting temperature calibrations; they want to install the instrumentation and run the test. The development of the precalibrated weldable strain gage assembly allows the user to do just that - install the strain gage and run the test.

BENEFITS

1. A major benefit of the preinstalled strain gage is that the stabilization treatment takes place with the PdCr/Pt wires in contact with a 96 percent alumina, 4 percent zirconia ceramic matrix. This zirconia oxide additive to alumina significantly reduces oxidation of the wire as compared to the same wires oxidized in air (refs. 5 and 6).
2. Another benefit of precalibrated weldable gages is improved accuracy. It is extremely difficult in practice to generate accurate apparent strain calibration curves on the structure because it is virtually impossible to maintain isothermal conditions within the structure during heat up and cool down. Temperature gradients cause thermal stresses which result in a hysteresis between heat up and cool down cycles. It is only when the structure is reduced in size to that of a gage on a shim (which is also well insulated during this test) that the hysteresis between heat up and cool down disappears.
3. The greatest benefit of the precalibrated weldable strain gage is that it is user friendly. The test engineer is not expected to have the expertise of the strain gage vendor. He/she should not have to be a strain gage guru in order to achieve good results. A calibrated gage with understandable specifications and easy to follow installation instructions with no unexpected, unforeseen operational surprises, is essential for good results.

CONCLUSIONS

A user friendly weldable strain measurement system based on the NASA Lewis PdCr/Pt wire strain gage has been developed for high temperature strain measurements up to 1400 °F.

Technology Transfer

The strain measurement system developed under this and other NASA Lewis contracts has been made commercially available in accordance with the Space Act Agreements between NASA Lewis and Hitec Products, Inc.

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APPENDIX

SAMPLE CALCULATION

Calculate value for ballast resistor R_B from reference below:

$$R_B = \frac{\acute{R}_{c_o}\left(\acute{\alpha}_c - \acute{\alpha}_g\right)}{\alpha'_g}$$

where

$$\acute{\alpha}_g = \frac{\acute{R}_{g_T} - \acute{R}_{g_o}}{\acute{R}_{g_o}\,\Delta T}$$

$$\acute{R}_{g_T} = \frac{R_{12} + R_{13} - R_{23}}{2}$$

with R_{12}, R_{13} and R_{23} readings taken at temperature T. $\acute{R}_{g_o} = \frac{R_{12} + R_{13} - R_{23}}{2}$ at "0" or room temperature

ΔT = Tempeature at T - T_o; T_o = room temperature.

$$\acute{\alpha}_c = \frac{\acute{R}_{c_T} - R_{c_o}}{\acute{R}_{c_o} \cdot \Delta T}$$

$$\acute{R}_{c_T} = \frac{R_{23} + R_{13} - R_{12}}{2}$$

(Readings taken at temperature T)

$$\acute{R}_{c_o} = \frac{R_{23} + R_{13} - R_{12}}{2}$$

(Readings taken at room temperature)

For gages bonded to Alumina specimen:

T	R_{12}	R_{23}	R_{13}
T_o = 73 °F	131.4	22.6	138.9
T_T = 1125 °F	146.3	36.4	167.2

Therefore,

$$R_{g_o} = \frac{R_{12} + R_{13} - R_{23}}{2} = \frac{131.4 + 138.9 - 22.6}{2} = 123.85$$

$$R_{g_T} = \frac{R_{12} + R_{13} - R_{23}}{2} = \frac{146.3 + 167.2 - 36.4}{2} = 138.55$$

$$\Delta T = 1125 - 73 = 1052$$

$$\acute{\alpha}_g = \frac{\acute{R}_{g_T} - \acute{R}_{g_o}}{\acute{R}_{g_o} \cdot \Delta T} = \frac{138.55 - 123.85}{123.85 \times 1052} = 0.000112$$

$$\acute{\alpha}_c = \frac{\acute{R}_{c_T} - \acute{R}_{c_o}}{\acute{R}_{c_o} \cdot \Delta T}$$

$$\acute{R}_{c_T} = \frac{R_{23} + R_{13} - R_{12}}{2} = \frac{36.4 + 167.2 - 146.3}{2} = 28.65$$

$$\acute{R}_{c_o} = \frac{R_{23} + R_{13} - R_{12}}{2} = \frac{22.6 + 138.9 - 131.4}{2} = 15.05$$

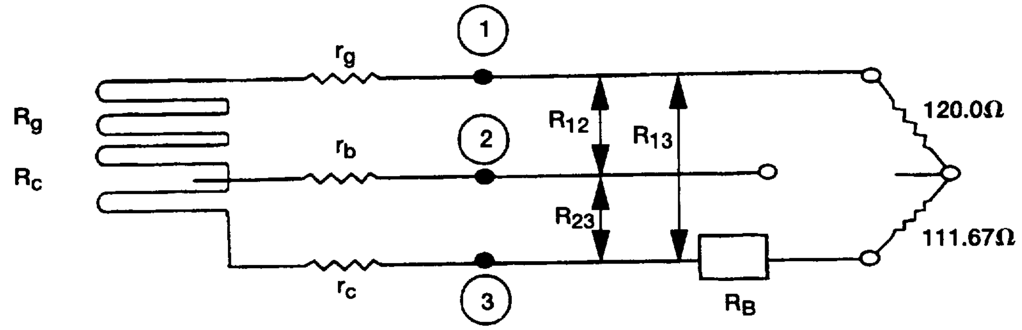
$$\acute{\alpha}_c = \frac{28.65 - 15.05}{15.05 \times 1052} = 0.000858$$

Then

$$R_B = \frac{\acute{R}_{c_o}\left(\acute{\alpha}_c - \acute{\alpha}_g\right)}{\acute{\alpha}_g} = \frac{15.05(0.000858 - 0.000112)}{0.000112}$$

$$R_B = 100.2\Omega$$

Using a decade resistor, set $R_B = 100.2\Omega$



R is measured at end of leads at points ①, ② and ③.

The 2nd decade is set at 120.0Ω and the bridge is balanced by adjusting the adjacent decade, which resulted in 111.67Ω.

The gage is placed in the furnace and experimental determination of the apparent strain between room temperature and 1100 °F is made as follows. A Vishay P3500 Strain Indicator, with GF set to 1.30, is used to record strain, and a chromel alumel thermocouple is used to measure temperature.

T	μS	
70°F	0000	
150°F	-630	
200°F	-975	
300°F	-1525	
400°F	-1850	
460°F	-1912	Max (-)
500°F	-1880	
600°F	-1675	
700°F	-1275	
800°F	-720	
900°F	0000	
1000°F	+485	
1100°F	+260	

APPENDIX REFERENCE

Jih-Fen Lei, D.R. Englund and C. Croom: "The Temperature Compensation Techniques for a PdCr Resistance Strain Gage," Society for Experimental Mechanics, Fall Conference 1991.

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2. Wnuk, S.P. Jr., “Final report on Procedure for Installation of PdCr Gages by Flame Spraying,” NASA CR–195389, Oct. 1994.
3. Hofstötter, P, “The Use of Encapsulated High-Temperature Strain Gages at Temperatures up to 315 °C,” Experimental Techniques, August 1985.
4. Lei, J.F., Englund, D.R., Croom, C., “The Temperature Compensation Techniques for a PdCr Resistance Strain Gage,” Society for Experimental Mechanics, Fall Conference 1991.
5. Lei, Jih-Fen, “Protective Coats for High Temperature Strain Gages”, NASA Technical Briefs, p. 94, Sept. 1993.

6. Leca, L., “Physical and Structural Properties Of Palladium-Chromium Layers Obtained by Cathodic Sputtering: Resitive Element for a High Temperature Strain Gage,” Note Technique 1995-14, Office National D’Etudes Et De Recherches Aerospatiales, 29 Avenue de la Division Leclirc, 92320 Chatillon (France).
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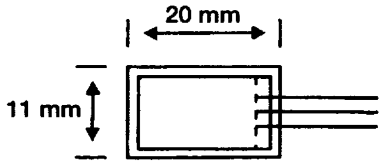
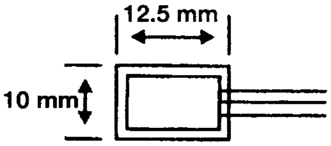
TABLE I.—PALLADIUM CHROME WELDABLE STRAIN GAGES

Designation	Resistance, W		Compensation	Carrier	L, mm	W, mm
	Sensor	Thermometer				
HBWAPd-06-130-In-SPdW	60	4	Inconel	Hastelloy X Shim	12.5	10
HBWAPd-06-130-Ti-SPdW	68	4	TMC*	Ti6A14V Shim	12.5	10
HBWAPd-12-300-In-SPdW	120	8	Inconel	Hastelloy X Shim	20	11
HBWAPd-13-300-Ti-SPdW	135	8	TMC*	Ti6A14V Shim	20	11



120Ω weldable
(actual size)



60Ω weldable
(actual size)

Leads are 0.07 mm diameter PdCr, 25 mm long.

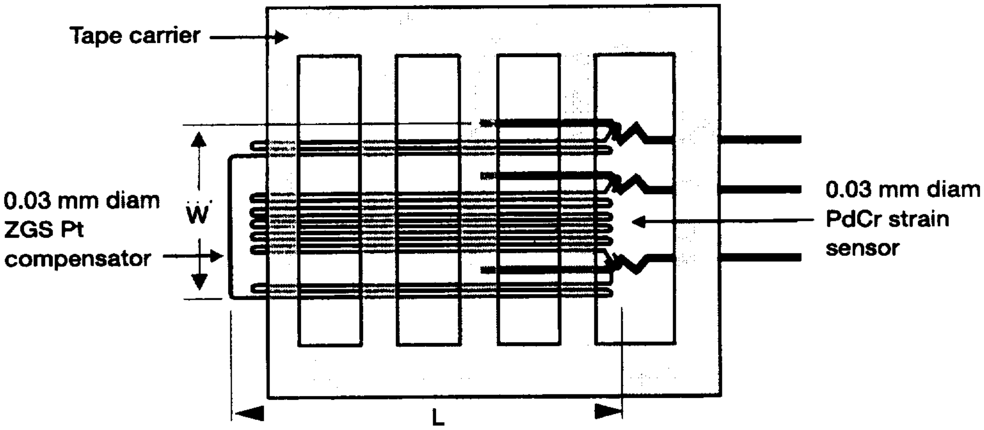


Figure 1.—Free filament PdCr strain gage (6x larger than actual size).

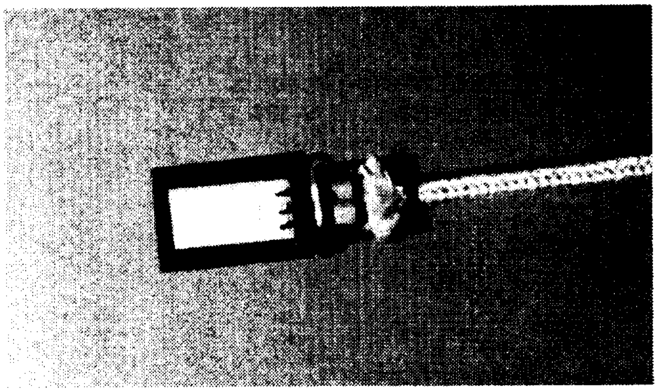


Figure 2.—Photograph of PdCr weldable gage with terminal and cable.

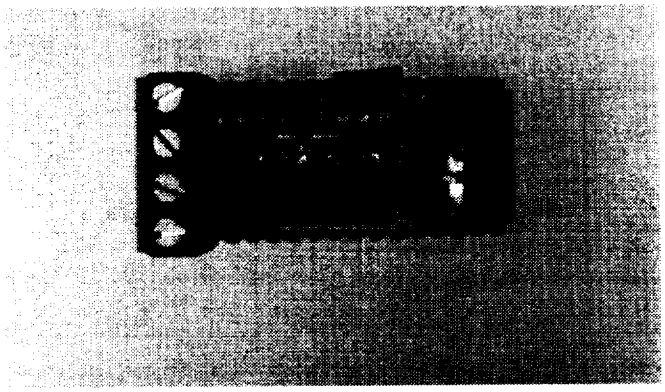


Figure 3.—Photograph of bridge completion module.

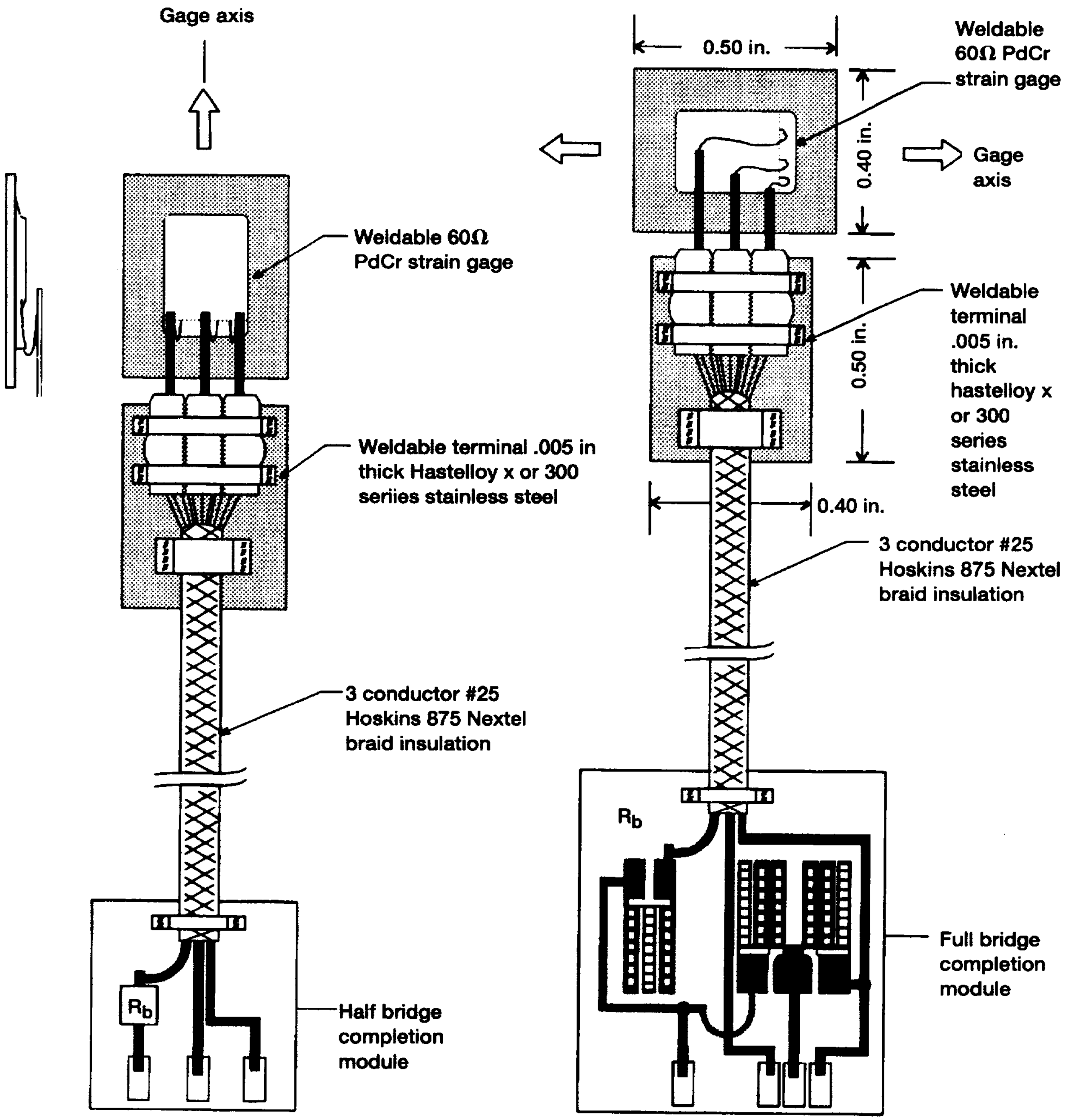
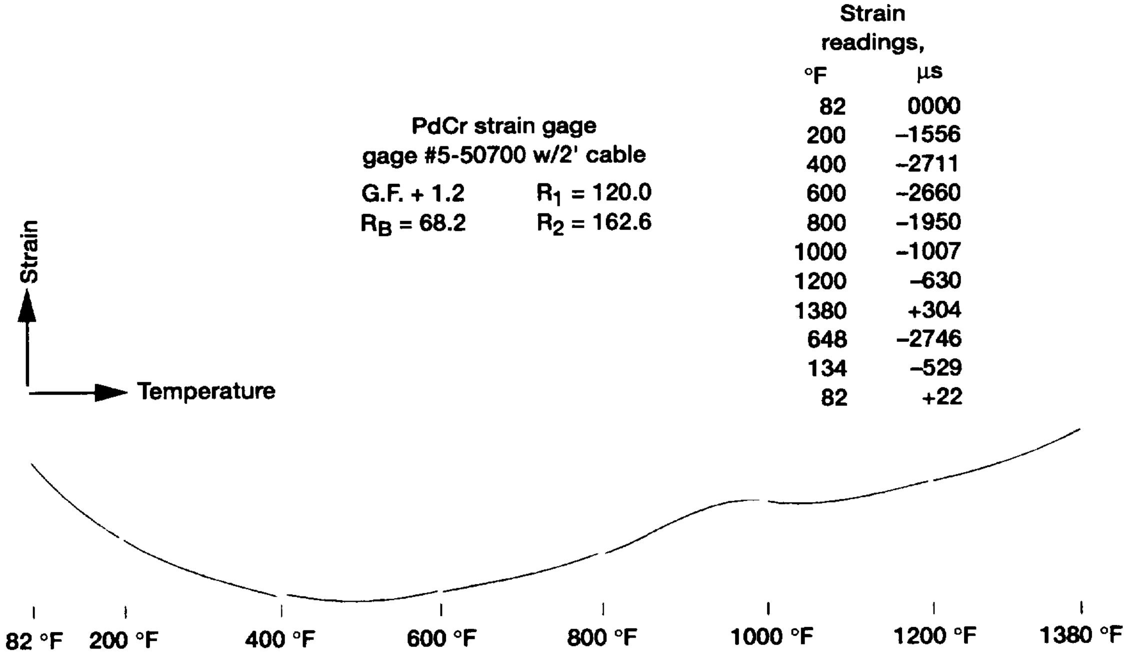


Figure 4.—High temperature PdCr/Pt weldable strain gage with terminal, cable, and bridge completion module.



Strain readings,

°F	μs
82	0000
200	–1556
400	–2711
600	–2660
800	–1950
1000	–1007
1200	–630
1380	+304
648	–2746
134	–529
82	+22

Figure 5.—Analog plot of apparent strain versus temperature.

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