TECHNOLOGY

Bondable Resistance Temperature Sensors and Associated Circuitry

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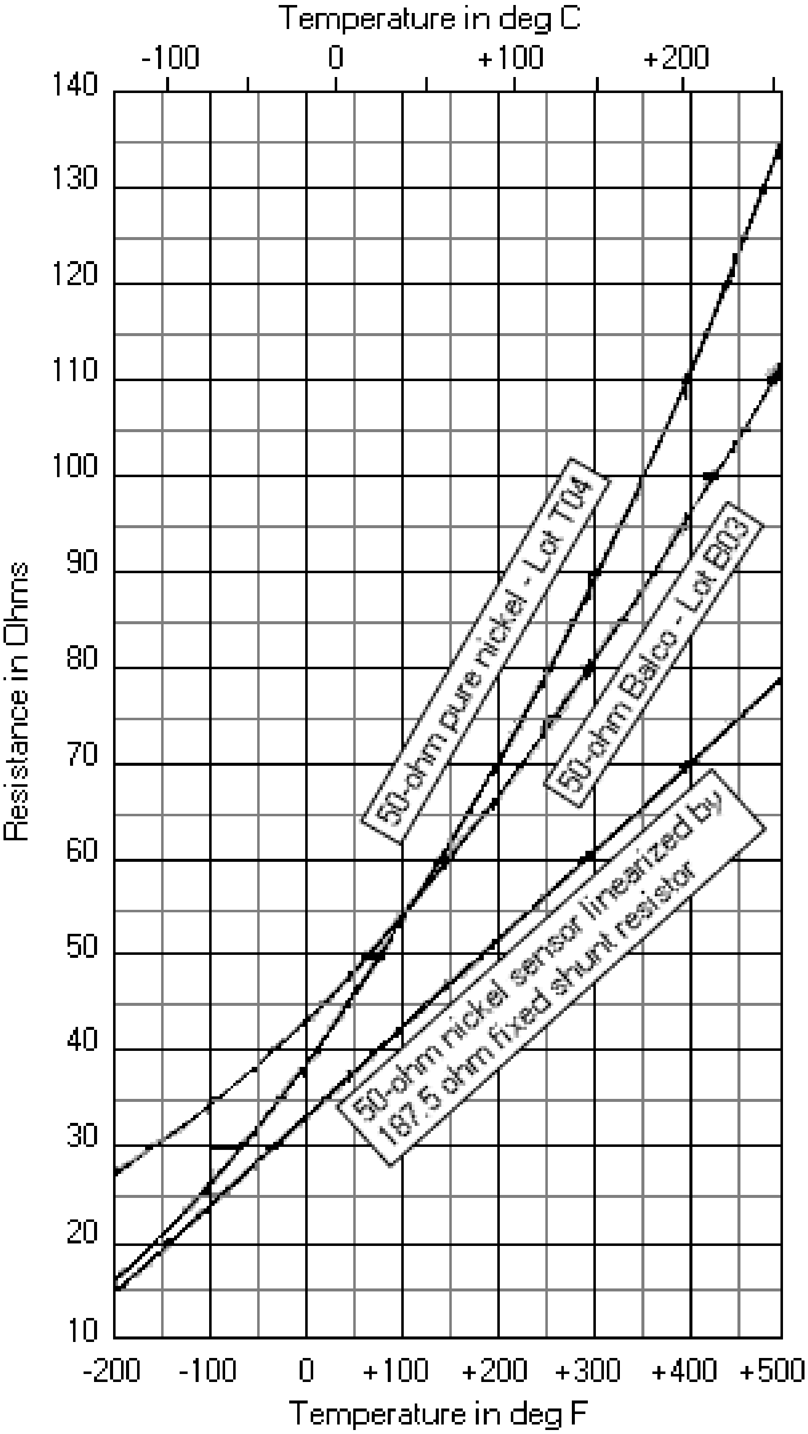
Bondable Resistance Temperature Sensors and Associated Circuitry

Introduction

Micro-Measurements manufactures a line of resistance temperature sensors which are constructed much like wide-temperature-range strain gages, but which utilize high-purity nickel foil sensing grids. These temperature sensors are bonded to structures using standard strain gage installation techniques, and can measure surface temperatures from -320° to approximately +500° F (-195° to +260° C).

This Tech Note discusses the operational characteristics of nickel temperature sensors, as well as various methods of data readout. The standard line of temperature sensors and matching networks for use with strain indicators is listed in Catalog 500.

The resistance of high-purity nickel increases rapidly with temperature, following a repeatable and stable curve to over +500° F (+260° C). As shown below, the resistance changes are quite large, resulting in high signal levels. Also shown below is a curve for Balco alloy, which will be discussed later. Note that a reference value of 50.0 ohms occurs at a temperature of +75.0° F (+23.9° C) in the graph.



Variation of resistance with temperature for 50-ohm sensors mounted on 1018 steel.

All standard Micro-Measurements TG temperature sensors are manufactured to this nominal value, but gages of other resistance values are available on special order. The resistance-versus-temperature characteristic of sensors having nonstandard reference resistances can be expressed directly as a percentage of the nominal +75.0° F (+23.9° C) value by multiplying the ordinate shown above by a factor of 2.0.

Tables are given later in this publication for obtaining resistance values of TG sensors at various temperatures to a higher accuracy than is readable in the figure above. These tables are also referenced to a value of 50.0 ohms at +75.0° F (+23.9° C) and can be multiplied by a factor of 2.0 to obtain resistances of nonstandard sensors as a percentage of their +75.0° F (+23.9° C) value.

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Sensor Installation

TG temperature sensors are installed with the same techniques and materials used for installation of wide-temperature range strain gages. M-Bond 600 or 610 adhesives are usually employed because they are useful over the entire temperature range of the sensor itself. Surface preparation techniques are given in Instruction Bulletin B-129, *Surface Preparation for Strain Gage Bonding*, and specific installation procedures are included in the selected adhesive kit.

Leadwires are normally handled in the same way as those for strain gages, with one significant difference. The three-wire system used with strain gages to eliminate errors due to temperature-induced resistance changes in the leadwires is not generally effective with TG sensors.

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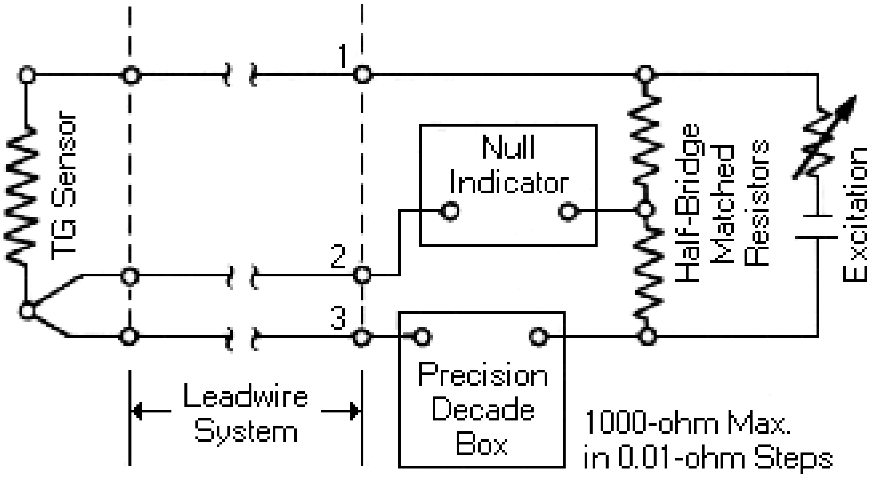
Readout Methods

One method of reading temperature with TG temperature sensors is to connect the sensor to a Wheatstone resistance bridge, and convert the resistance readings to equivalent temperatures with the tables given in this publication. But, the leadwires can cause two different errors in a Wheatstone bridge. First, the resistance of the leads, which can be appreciable with remote gages, produces an initial offset error, and desensitizes the arm of the bridge containing the temperature sensor. The second error is the result of resistance change in the leads caused by temperature variations. Except under unusual conditions, errors of this type are very small. In cases where long leadwires are necessary, special calibration techniques or compensation systems can be used (Ref. 1 and 2).

A variation of the above method is capable of providing accurate compensation for leadwire resistances with a three-wire system. The circuit is shown below, in which a precision decade box is used in place of one resistor in the Wheatstone bridge.

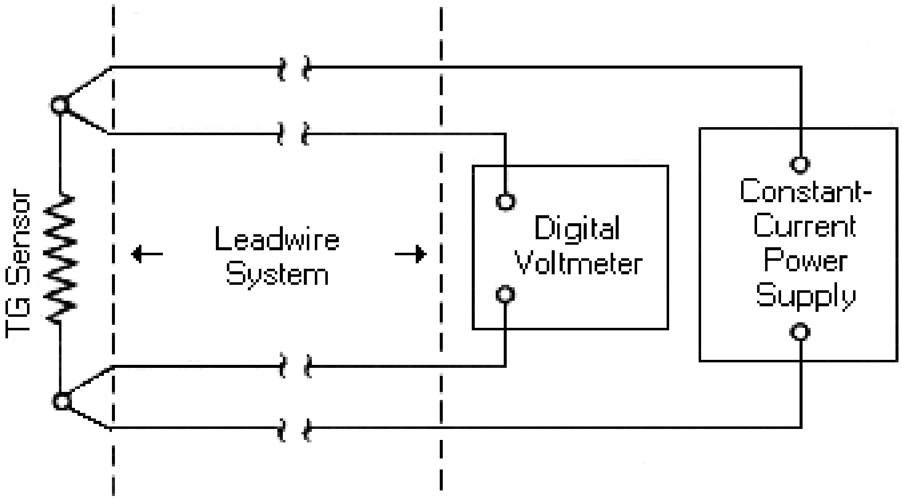


Three-wire null-balance circuit for TG sensor.

The decade box in this circuit is varied to keep the output at null, and the indicated decade resistance is therefore the same as the sensor resistance. Provided leads 1 and 3 are of the same length and size, resistance changes in the leadwire circuit caused by temperature changes common to all wires will not create errors in the reading. Three-wire compensation is effective in this case because this is a true null-balance system in which the bridge arm adjacent to the sensor (the decade box) is always set to the sensor resistance at the time of readout.

Excitation power can be either dc or ac, depending on the null indicator chosen. Excessive excitation can create errors due to self-heating in the sensor, but this error is easily avoided or corrected as discussed later.

A more sophisticated readout system, which eliminates the need for manual rebalance, is shown below. This arrangement eliminates leadwire errors by use of a four-wire system.



Four-wire circuit for TG sensor.

If the digital voltmeter has a high enough input impedance, the readings will be a known function of sensor resistance, regardless of resistance change in any of the leadwires. A current level of one mA will allow the voltmeter to read sensor resistance in terms of mV (50.0 ohms reads as 50.0 mV).

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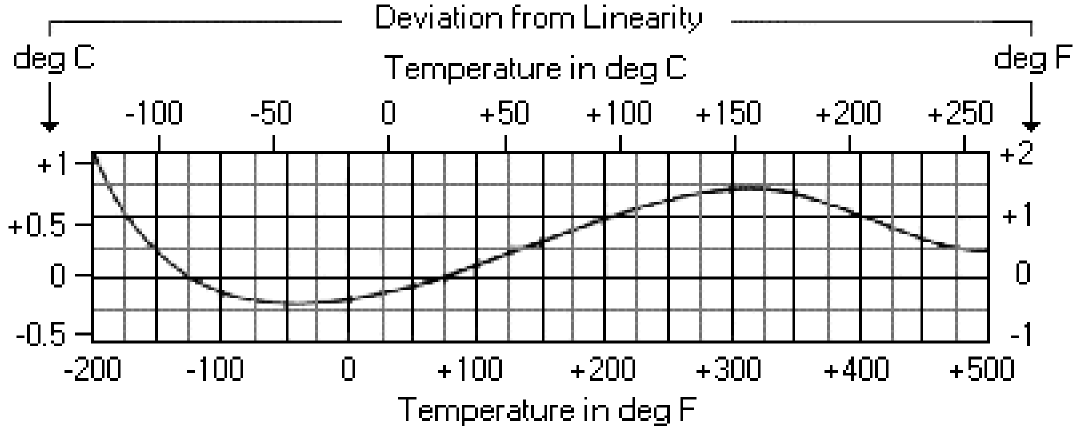
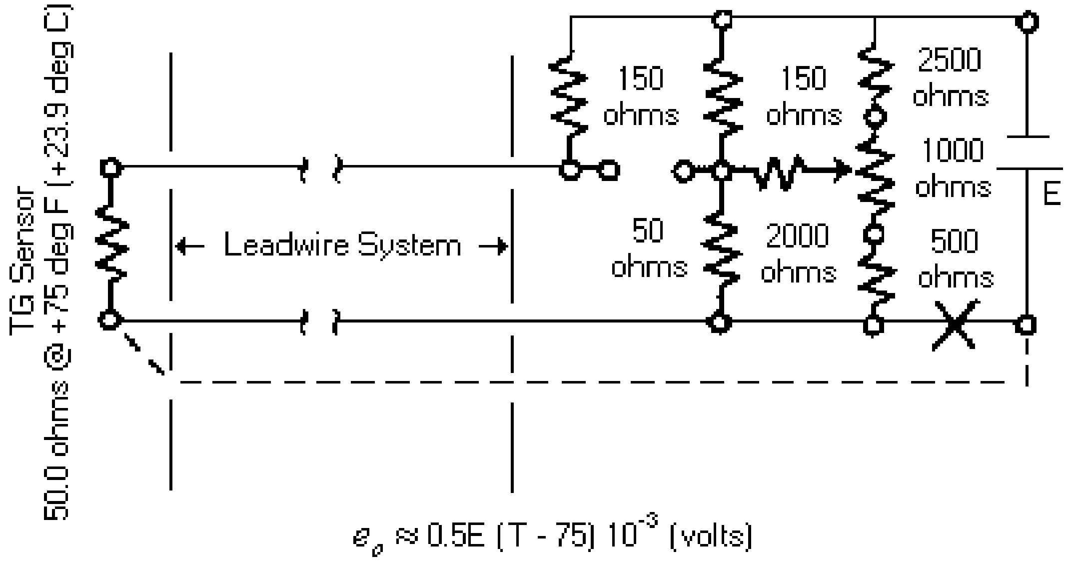
Linearization of Sensor Response

The readout methods shown previously can be quite accurate, but are somewhat awkward to use in that they read sensor resistance directly, and the nonlinear characteristic of sensor resistance-versus-temperature requires the use of tabulated data to convert resistance values to the equivalent temperatures. A very simple method exists for converting the nonlinear sensor to a linear resistance change with temperature with good practical accuracy. This is accomplished by shunting the sensor with a fixed resistor equal in value to 3.75 times the +75.0° F (+23.9° C) value of sensor resistance, or 187.5 ohms for standard TG sensors. The resultant resistance change with temperature has a lower slope, but is quite linear as shown earlier. A plot of deviation from linearity for this circuit is shown below, and provides much higher error readability.



Deviation from linearity for shunted TG sensor.

A useful application of shunt linearization is to provide an asymmetrical bridge circuit that has a linear output voltage with temperature. This circuit can be used with a digital voltmeter for direct temperature readings (expressed in mV) or to drive one axis of an X-Y recorder for directly plotting temperature against another variable. A simplified version of this circuit is shown below.



$e_o \approx 0.5E\ (T - 75)\ 10^{-3}$ (volts)

[$e_o \approx 0.9E\ (T - 24)\ 10^{-3}$ (volts)]

where: T = Sensor Temperature in deg F and [deg C]

Linearization circuit.

This linearization circuit requires a constant-voltage excitation source, and this can be conveniently provided by a single silver-oxide battery. The output factor is 0.5 mV/V/° F (0.9 mV/V/° C), which can be scaled down by use of a high-resistance voltage divider at the output terminals. A balance potentiometer is incorporated for balancing out the tolerance on the nominal sensor resistance and the offset caused by leadwire resistance. (When the Celsius temperature scale is used, it is more convenient to balance at +24° C, rather than +23.9° C, so that the readings are in round numbers.) Calibration can be checked by substituting a precision decade box for the TG sensor and dialing in resistances equivalent to various temperatures from the resistance-versus-temperature tables.

Because of the asymmetrical bridge, a three-wire lead system cannot be used effectively with the linearization circuit shown above to eliminate the errors from a temperature-induced leadwire resistance change. However, it is possible to use the three-wire method for the more limited purpose of compensating the initial offset error caused by the leadwire resistance. This is accomplished by adding the third wire (shown dashed) and breaking the connection at the point marked X.

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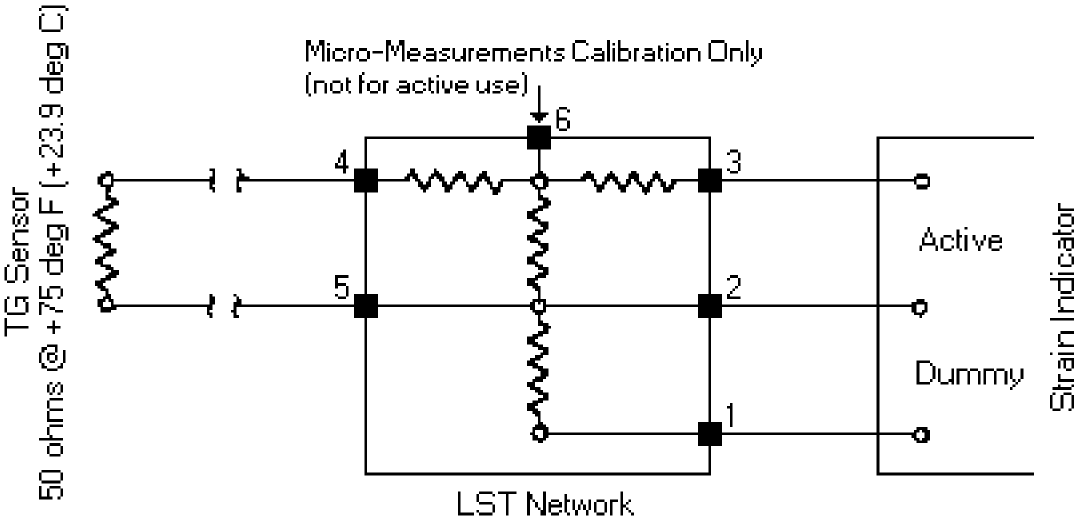
LST Matching Networks

Commercial single- or multiple-channel strain indicators are excellent readout devices for TG temperature sensors, and are particularly convenient when combinations of strain and temperature are to be measured or recorded simultaneously. This readout method requires the use of an interface signal conditioning network, referred to as an LST network, to "match" the temperature sensor response to that of the strain indicator. The arrangement is shown below.



LST network circuit.

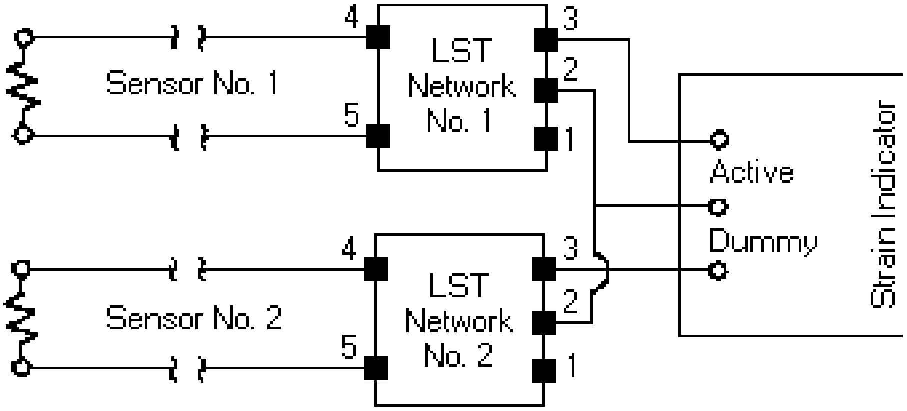
The LST network is a small, completely encapsulated unit consisting of four special precision resistors. When used with standard 50-ohm nickel TG temperature sensors, it performs the following three functions:

1. Provides a linear resistance change at the output terminals.
2. Attenuates the resistance change slope to the equivalent of 10 or 100 $\mu\varepsilon$/° for a gage factor setting of 2.00 on the strain indicator. It is usually most

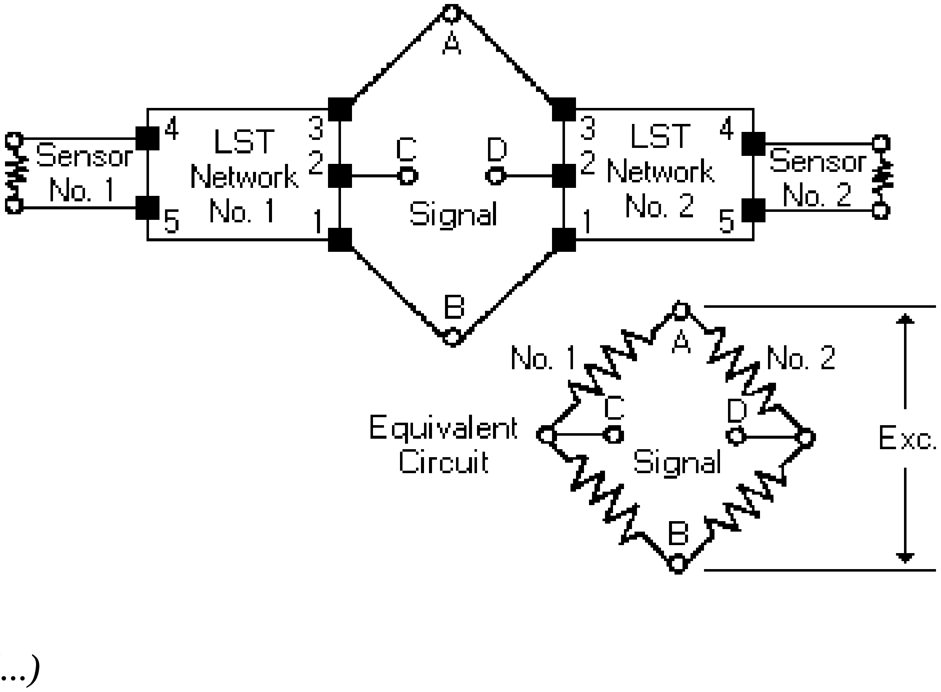
practical to use 10µε/° networks when a large temperature range is involved, and 100µε/° networks for high resolution of small temperature spans.

3. Presents a complete 350-ohm half-bridge circuit to the strain indicator.

Differential temperature measurements can be made by combining two TG sensors and two LST networks. The arrangement shown below provides a half-bridge circuit to the strain indicator in which the ACTIVE arm responds to sensor 1, and the DUMMY arm to sensor 2.



An alternate method is to arrange the networks to form a full-bridge circuit as shown below, which may be preferred for some types of readout equipment.



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Bondable Resistance Temperature Sensors and Associated Circuitry

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Calibration and balancing of circuits containing LST networks can be handled in various ways. Initial balance is usually obtained by setting the BALANCE dial of the strain indicator channel so that the instrument reading corresponds to the initial temperature of the TG sensor. When it is not possible to control or measure the initial temperature of the sensor, it can be temporarily replaced by a precision 50.0-ohm resistor. The BALANCE dial is then set to create an equivalent readout of +75.0° F (Fahrenheit networks) or +23.9° C (Celsius networks). The sensor can then be reconnected to the network. The first procedure has the obvious advantage of correcting for the error due to tolerance limits on initial TG-sensor resistance.

Resistance shunt calibration 3 can be applied to the output terminals of the LST network in order to verify linearity and span accuracy of the associated instrumentation. It is also useful in setting the GAGE FACTOR dial or in correcting for leadwire desensitization when the LST network is remote from the readout instrument. In this latter case, note that shunt resistors must be placed across the leadwire terminals at the network end, not at the instrument end.

Because of significant resistance changes in the ACTIVE arm with temperature, shunt calibration across network terminals 2 and 3 will be correct only when the sensor temperature is near +75° F (+24° C). So, it is preferable that calibration resistors be shunted across the DUMMY arm (network terminals 1 and 2). When it is desired to calibrate across both arms to simulate both plus and minus temperature changes, and it is not convenient to stabilize sensor temperature near +75° F (+24° C), the sensor can be replaced by a precision 50.0-ohm resistor during calibration.

When applying shunt calibration to the differential temperature measurement circuit shown earlier, it will be necessary to calibrate across the ACTIVE arms (network terminals 2 and 3). Shunting network 1 will simulate a temperature decrease for sensor 1 or an increase for sensor 2. Under these conditions the nominal or common-mode temperature for both sensors must be near +75° F (+24° C) if it is desired to calibrate across both networks. If this cannot be conveniently arranged, the sensors should be temporarily replaced by 50.0-ohm resistors during calibration. If the alternate full-bridge connection is used for a differential operation, shunt calibration steps can be applied to either DUMMY arm, terminals

1 and 2, regardless of temperature.

For best accuracy, it is always advisable to select shunt calibration values which are close to the temperature span of greatest interest. When the instrument readings are not in agreement with the simulated calibration temperature, the GAGE FACTOR dial can be adjusted to eliminate the error.

Custom LST networks can be tailored for special temperature ranges or output slopes, and for impedance matching. Consult the Measurements Group Applications Engineering Department for details.

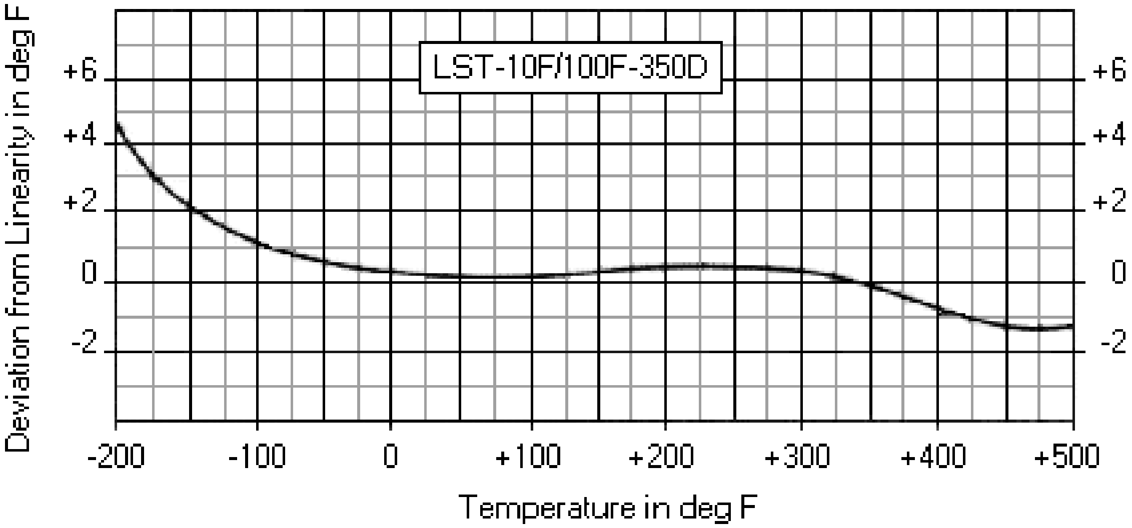
Bondable Resistance Temperature Sensors and Associated Circuitry

Sources of Error

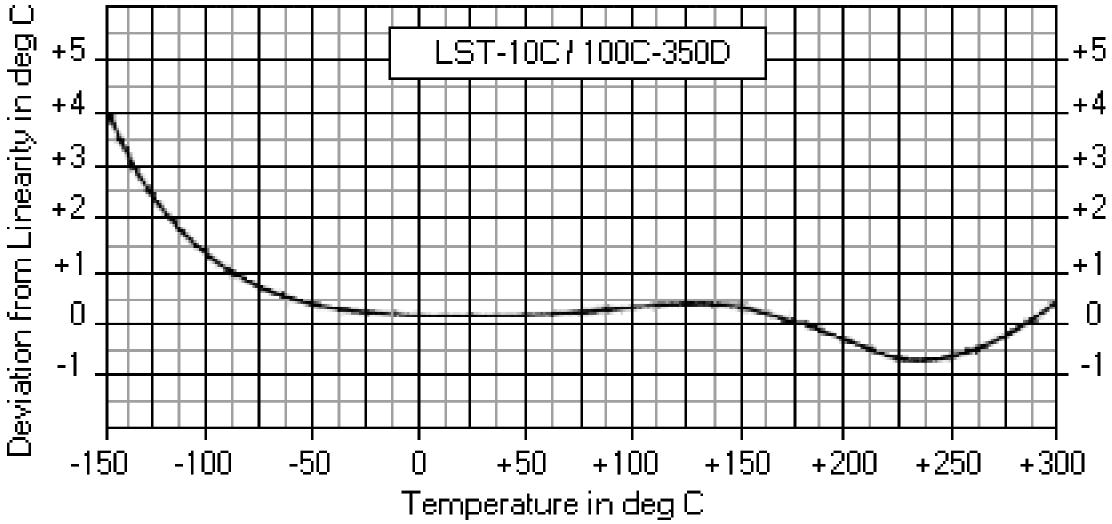
Deviations from Linearity

Linearization of TG-Series sensors with passive resistance circuits characteristically leaves small deviations from true linearity. To assure optimum correction for nonlinearity of the nickel, the user may select from four temperature ranges:

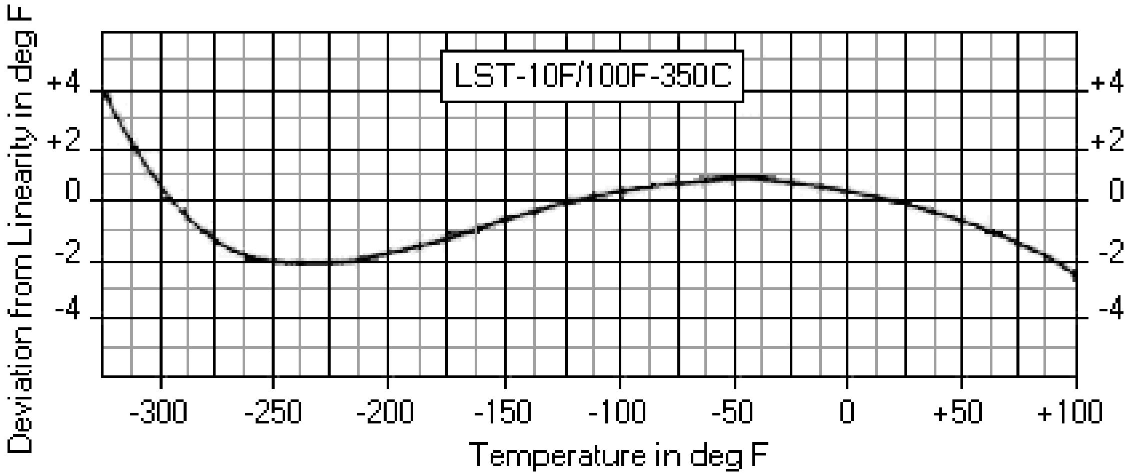
-200° to +500° F, use LST-10F/100F-350D



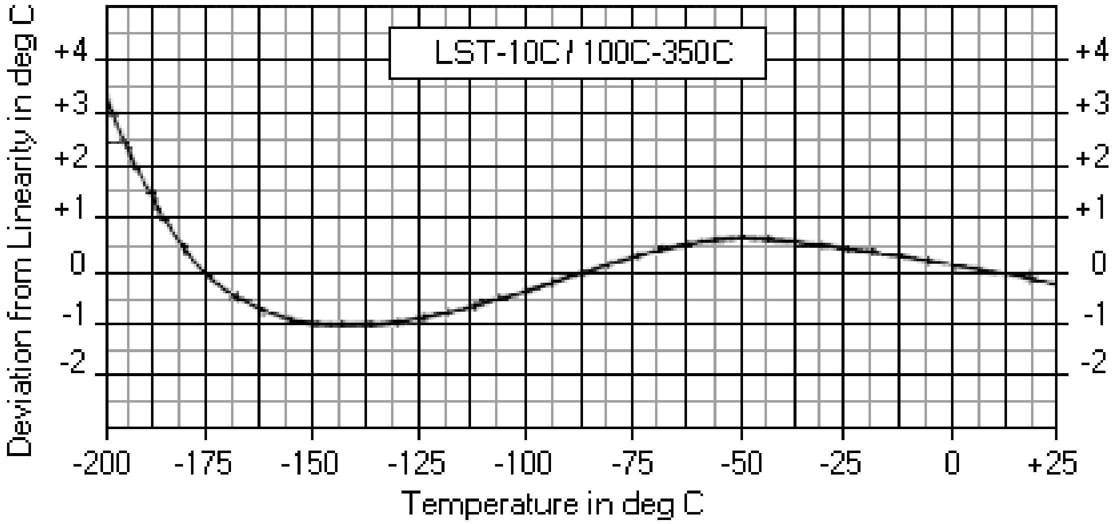
-320° to +100° F, use LST-10F/100F-350C



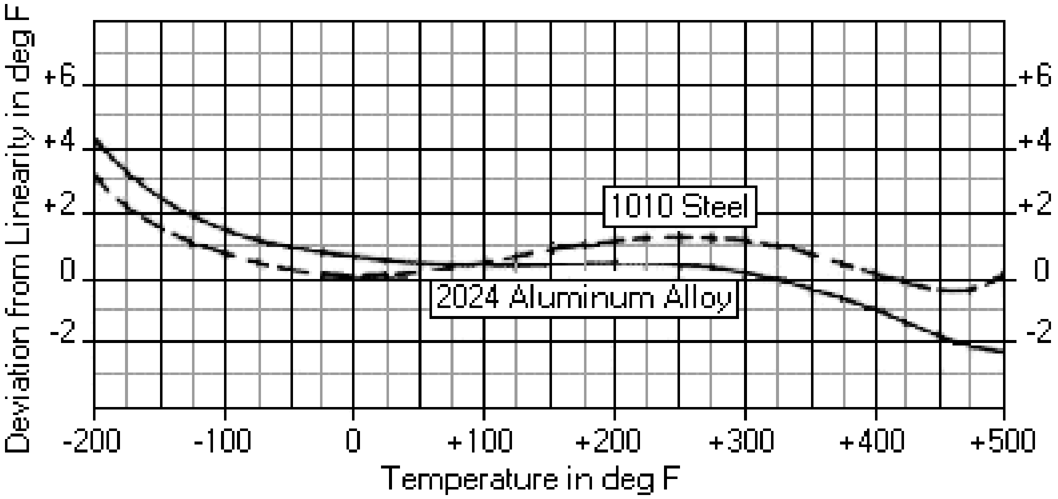
-150° to +260° C, use LST-10C/100C-350D



-200° to +25° C, use LST-10C/100C-350C



The expansion coefficient of the structure to which the temperature sensor is bonded will affect linearity, and the deviation of TG sensors with LST-10F-350D conditioning networks on 1018 steel and 2024 aluminum alloy is shown below.



Typical deviation from linearity for TG-Series sensors mounted on 1018 steel and on 2024 aluminum alloy.

For highest accuracy it is necessary to calibrate sensor/LST systems on the material to be used. In most work, however, the average curves (shown above) are satisfactory.

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Leadwire Effects and Related Errors

Leadwires are a source of error in all circuits using TG sensors, except three-wire null-balance and four-wire circuits. To minimize these errors, leadwires between the sensor and the readout device (or LST network) should be of low resistance and no longer than necessary. A total two-wire resistance of 0.5 ohm will introduce a shift or offset of about +4° F (+2° C) at room temperature. This leadwire resistance corresponds to 25 ft (7.5 m) of AWG No. 20 (0.8-mm diameter) copper double leads, or 100 ft (30 m) of AWG No. 14 (1.6-mm diameter) double leads.

Changes in leadwire temperature are normally a minor source of error. A change of 50° F (28° C) over the entire length of a 0.5-ohm copper leadwire circuit will create an offset error of approximately 0.4° F (0.2° C) when the sensor temperature is near +75° F (+24° C). This error decreases at higher sensor temperatures and increases at lower sensor temperatures. Accurate measurements in the cryogenic temperature region may require three-wire null-balance or four-wire circuits when long lengths of small diameter leadwire must be employed.

Initial "zero" errors or offsets due to the tolerances applicable to LST networks and the TG sensors themselves can be eliminated by stabilizing the sensor installation at any known temperature close to +75° F (+24° C), and then setting the instrument BALANCE dial so that the reading corresponds to this known temperature. This procedure also eliminates offset error caused by initial leadwire resistance.

In certain circumstances it may be necessary to locate the instrumentation at a long distance from the sensor installations. When LST networks are employed under these conditions, it is preferable to position the network close to its associated sensor and use a three-wire lead circuit between the network and the remote indicator (this should not be done if the test temperature exceeds the temperature capability of the LST network). This type of hookup will eliminate first-order offset errors due to leadwire resistance and leadwire temperature changes. Desensitization or slope-change error is greatly reduced and can be eliminated by setting the strain indicator GAGE FACTOR dial properly. The correct setting can be calculated on the basis of known leadwire resistance or directly determined by applying shunt calibration to the remote network terminals.

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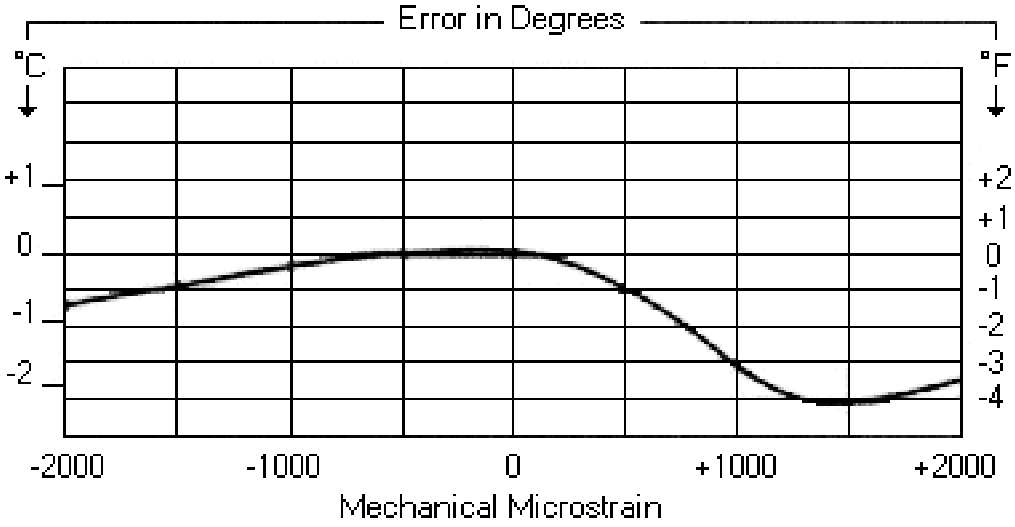
Strain Sensitivity Errors
The strain sensitivity of pure nickel can create error signals when TG sensors are installed in areas of high mechanical strain. The magnitude of this effect is fairly small, however, as shown below.



Typical error signal caused by strain applied to TG sensor. Data applies to sensor temperatures near +75° F (+24° C).

The shape of this curve is caused by the nonlinear response of pure nickel. The strain-sensitivity coefficient has a high negative value in the central portion of the elastic region and tends toward a much smaller positive value on either side of this region. It will be observed that compressive strains result in smaller error signals, and this strain field orientation should therefore be selected for sensor placement when possible. The center of symmetry of this curve is located at approximately +750$\mu\varepsilon$, because the manufacturing process leaves the sensor with a residual compression of this value.

It is important to realize that the center of symmetry can be shifted by installing the gage on materials of different thermal expansion coefficients and/or with different adhesive cure temperatures. It is for this reason that gage response when mounted on aluminum alloy will differ slightly from that obtained when mounted on steel. These tables demonstrate the change in resistance-versus-temperature characteristic created by these two mounting conditions.

It has been shown that repeatability of properly installed TG sensors can be better than ±0.05% of applied temperature span. To take full advantage of this repeatability, and of the other intrinsic features of TG temperature sensors, it is always advisable to conduct a calibration run of the sensor mounted on a specific material when highest measurement accuracy is required.

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Stability

In common with most other organic resin systems, the matrix of TG sensors will slowly sublimate and lose strength when aged at elevated temperatures. When properly installed, life will be essentially infinite below +250° F (+120° C), and will be approximately 10 000 hours at +400° F (+205° C). At +500° F (+260° C), life can be estimated at 1000 hours in the presence of air, and will be considerably extended if an inert atmosphere is used.

The sensing grids are quite stable under the aging conditions described above. If exposed to temperatures above +500° F (+260° C), however, a slight shift in resistivity will occur, together with a small change in temperature coefficient. For example, if the WTG-Series sensor is exposed to a temperature of +600° F (+315° C) for one hour, the +75.0° F (+23.9° C) resistance will shift from 50 ohms to approximately 50.6 ohms. On a normalized basis, the resistance increase from +75.0° to +450° F (+23.9° to +232° C) will become 140% instead of the previous 143%. Operation at temperatures below +550° F (+290° C) will thereafter be stable and repeatable.

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Bondable Resistance Temperature Sensors and Associated Circuitry

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Self-Heating
In order to obtain a useful output from passive transducers such as TG temperature sensors, it is necessary to apply an excitation voltage, which results in self-heating of the sensors. This will cause a certain temperature rise in the surface to which the sensor is bonded, thus creating an error signal. Since TG sensors have a high temperature coefficient of resistance, it is not necessary to utilize high excitation levels to develop large outputs, and self-heating errors can easily be kept to insignificant values. When it is necessary to use high excitation levels to obtain maximum output signals, it should be noted that the largest practical sensor grid size should be chosen. The thermal conductivity and thermal capacity of the specimen will then determine the highest excitation level that can be used for a given self-heating error.

It is usually very simple to measure self-heating errors directly with TG sensors because the excitation can be varied under constant ambient temperature conditions while observing the change in output indication in degrees. A bridge excitation of 0.25V or less will usually produce self-heating errors of a fraction of one degree for standard sensors mounted on metallic specimens. Special attention should be given to self-heating errors when accurate measurements must be made on low thermal conductivity materials such as plastic or glass.

The attenuation factor incorporated into LST networks greatly reduces the excitation voltage from strain gage instrumentation, and self-heating errors are seldom encountered when this readout method is used with TG sensors.

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Special Sensors

In addition to the standard line of TG sensors described in Catalog 500, Micro-Measurements can furnish almost any sensor pattern desired, and a wide range of resistances. Setup charges will be minimized when the special pattern design corresponds to one of the patterns in the line of EA-Series strain gages, although resistances available are sometimes limited.

Balco® an alloy of nickel and iron with a high temperature coefficient-of-resistance and a resistivity 2.4 times that of pure nickel, can also be furnished on special order for measurement or control functions. This alloy is frequently used for temperature compensation of transducer gage circuits.

Two fixed bondable Balco resistors are commonly inserted in the excitation leadwires of a transducer bridge circuit to provide automatic compensation for the combined effects of elastic modulus variation (in the transducer) and gage factor variation (in the strain gage,) with temperature. A series of adjustable, bondable resistor patterns is available, and permits trimming to the exact value of resistance required. Both resistor types are also available in nickel.

While Balco has a slightly lower temperature coefficient of resistance than high-purity nickel (as shown previously), its lower cost and higher resistivity permit smaller size and better economy.

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Calibration

Nickel foil lots are calibrated with specially designed test equipment consisting of a carefully controlled, uniform temperature bath, and a platinum resistance standard having calibration results traceable to the National Institute of Standards and Technology. Accuracy of calibration during these tests is 0.5° F (0.3° C). The temperature range used is -320° to +500° F (-195° to +260° C). The test data from TG sensors shows that their behavior can be described generally by a polynomial equation of the form:

$$R = A + BT + CT^2 + DT^3 + ET^4 + FT^5 + GT^6 \quad (1)$$

where:

R = Resistance of the gage
T = Temperature
A through G = Constants determined using regression analysis curve fitting

When the RTD's are being used to indicate temperature, the equation must be entered in the transposed form:

$$T = A' + B'R + C'R^2 + D'R^3 + E'R^4 + F'R^5 + G'R^6 \quad (2)$$

Values of the constants for Eqs. (1) and (2) for 50-ohm [at +75° F (+23.9° C)] nickel TG sensors are listed in the following tables.

Notes

1. The constants A' through G' in Eq. (2) are not the same as A through G in Eq. (1).

2. Curve-fit Eqs. 1 and 2 are best-fit equations.

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TABLE 1A -- Coefficients for Eq. (1)

TABLE 1B -- Coefficients for Eq. (2)

🟦 = °F
⬜ = °C

Coef.	Lot T04 Nickel	
	1018	2024
A	3.946795 x 10^{1}	3.939097 x 10^{1}
	4.384157 x 10^{1}	4.378630 x 10^{1}
B	1.33972 x 10^{-1}	1.34525 x 10^{-1}
	2.50996 x 10^{-1}	2.52373 x 10^{-1}
C	8.31445 x 10^{-5}	8.63411 x 10^{-5}
	2.84885 x 10^{-4}	2.95290 x 10^{-4}
D	4.72396 x 10^{-8}	5.02142 x 10^{-8}
	3.00807 x 10^{-7}	2.88453 x 10^{-7}
E	4.93933 x 10^{-11}	1.21108 x 10^{-11}
	2.03720 x 10^{-10}	2.13625 x 10^{-10}

Coef.	Lot T04 Nickel	
	1018	2024
A'	-3.87148 x 10^{2}	-3.85275 x 10^{2}
	-2.32852 x 10^{2}	-2.31809 x 10^{2}
B'	1.437356 x 10^{1}	1.423312 x 10^{1}
	79.8384 x 10^{-1}	79.0495 x 10^{-1}
C'	-20.6576 x 10^{-2}	-1.96463 x 10^{-1}
	-11.4693 x 10^{-2}	-1.09006 x 10^{-1}
D'	3.47019 x 10^{-3}	3.14370 x 10^{-3}
	1.92684 x 10^{-3}	1.74321 x 10^{-3}
E'	-3.70193 x 10^{-5}	-3.23587 x 10^{-5}
	-2.05640 x 10^{-5}	-1.79412 x 10^{-5}

F	-2.16840 x 10^{-13}	-2.51606 x 10^{-13}
	-2.95460 x 10^{-12}	-2.97514 x 10^{-12}
G	3.15935 x 10^{-16}	4.88934 x 10^{-16}
	1.07663 x 10^{-14}	1.65922 x 10^{-14}

F'	2.05767 x 10^{-7}	1.75570 x 10^{-7}
	1.14362 x 10^{-7}	9.73545 x 10^{-8}
G'	-4.55192 x 10^{-10}	-3.82500 x 10^{-10}
	-2.53118 x 10^{-10}	-2.12139 x 10^{-10}

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References

1. Watson, Robert B., James Dorsey, James E. Starr, "Conditioning Circuits for Bondable RTD's," 30th International Instrumentation Symposium, *Instrument Society, of America*, Denver, Colorado, May 1984.

2. American National Standard ASTM E-644, "Standard Methods for Testing Industrial Resistance Thermometers." American Society for Testing and Materials. 1916 Race Street, Philadelphia, Pennsylvania 19103, 1978.

3. Measurements Group, Inc., Tech Note TN-514, "*Shunt Calibration of Strain Gage Instrumentation*," 1988.