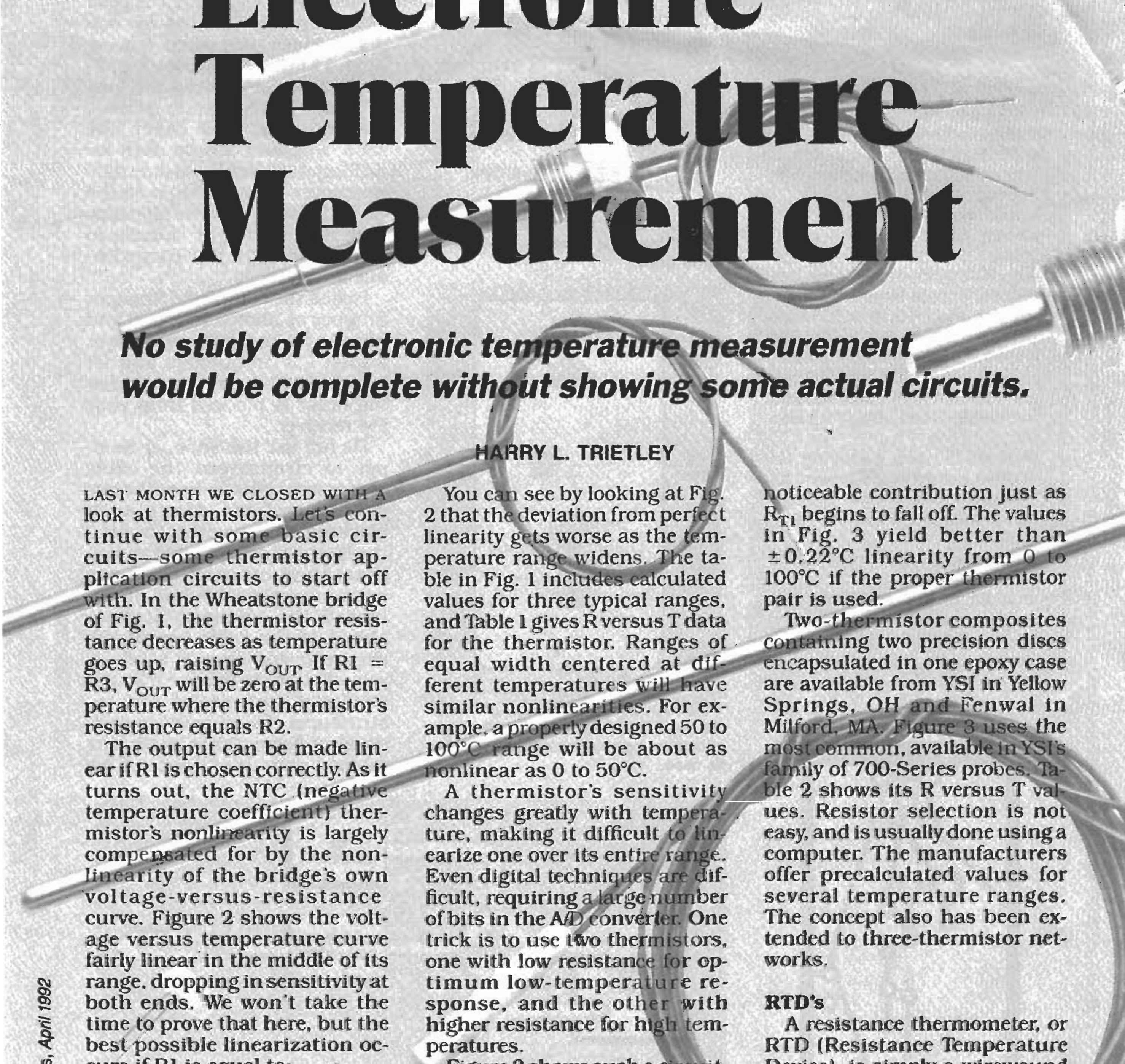
Electronic Temperature Measurement



No study of electronic temperature measurement would be complete without showing some actual circuits.

HARRY L. TRIETLEY

LAST MONTH WE CLOSED WITH A look at thermistors. Let's continue with some basic circuits—some thermistor application circuits to start off with. In the Wheatstone bridge of Fig. 1, the thermistor resistance decreases as temperature goes up, raising V_{OUT}. If R1 = R3, V_{OUT} will be zero at the temperature where the thermistor's resistance equals R2.

The output can be made linear if R1 is chosen correctly. As it turns out, the NTC (negative temperature coefficient) thermistor's nonlinearity is largely compensated for by the nonlinearity of the bridge's own voltage-versus-resistance curve. Figure 2 shows the voltage versus temperature curve fairly linear in the middle of its range, dropping in sensitivity at both ends. We won't take the time to prove that here, but the best possible linearization occurs if R1 is equal to:

$$\frac{R_{T1}R_{T2}+R_{T2}R_{T3}-2R_{T1}R_{T3}}{R_{T1}+R_{T3}-2R_{T2}}$$

where R_{T1}, R_{T2}, and R_{T3} are the thermistor's resistance at the low end, midpoint, and high end of the temperature range respectively. (Remember, R_{T1} is higher than R_{T3}.)

You can see by looking at Fig. 2 that the deviation from perfect linearity gets worse as the temperature range widens. The table in Fig. 1 includes calculated values for three typical ranges, and Table 1 gives R versus T data for the thermistor. Ranges of equal width centered at different temperatures will have similar nonlinearities. For example, a properly designed 50 to 100°C range will be about as nonlinear as 0 to 50°C.

A thermistor's sensitivity changes greatly with temperature, making it difficult to linearize one over its entire range. Even digital techniques are difficult, requiring a large number of bits in the A/D converter. One trick is to use two thermistors, one with low resistance for optimum low-temperature response, and the other with higher resistance for high temperatures.

Figure 3 shows such a circuit. At very low temperatures R_{T2} is so large that R_{T1} and R2 dominate. At higher temperatures the opposite is true: R_{T1} becomes small in comparison with R2, and R_{T2} shunts the R2-R_{T1} combination. If the component values are properly chosen, R_{T2} begins to make a noticeable contribution just as R_{T1} begins to fall off. The values in Fig. 3 yield better than ±0.22°C linearity from 0 to 100°C if the proper thermistor pair is used.

Two-thermistor composites containing two precision discs encapsulated in one epoxy case are available from YSI in Yellow Springs, OH and Fenwal in Milford, MA. Figure 3 uses the most common, available in YSI's family of 700-Series probes. Table 2 shows its R versus T values. Resistor selection is not easy, and is usually done using a computer. The manufacturers offer precalculated values for several temperature ranges. The concept also has been extended to three-thermistor networks.

RTD's

A resistance thermometer, or RTD (Resistance Temperature Device), is simply a wirewound coil or metal film whose resistance increases with temperature. As we saw last month, platinum is the most widely used material, offering the best stability and widest temperature range, while nickel is sometimes used for moderate industrial temperature measurements. Platinum thermometers are sometimes known as PRT's (Platinum Resistance Thermometers).

Table 3 gives R versus T tables and typical accuracies for platinum and nickel RTD's per the German DIN (Deutsche Industrie Normenausschuss) standard. Other curves exist, but those in Table 3 have achieved world-wide recognition. Most manufacturers offer platinum matching the DIN R versus T table, but often with tighter or looser accuracies. Not all platinum thermometers cover the entire −200 to 850°C range, and a 500 or 600°C upper limit is common.

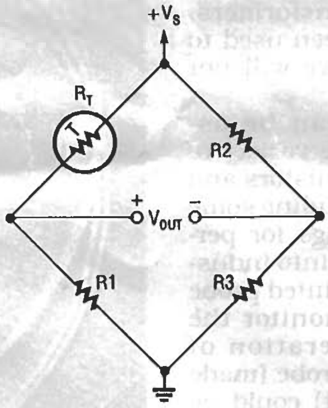
Sensors of 100 ohms (at 0°C) are most common, but others exist. At 100 ohms, platinum's sensitivity is 0.385 ohms/°C between 0 and 100°C, decreasing slightly as temperature rises. Nickel's sensitivity is 0.618 ohms/°C, increasing with temperature. Higher resistance sensors provide proportionally higher ohms per degree.

Platinum is expensive, but very little metal is used in making RTD's. Typical 100-ohm elements use about 22 inches of 0.001-inch diameter wire wound on a small ceramic bobbin.

Manufacturing details vary, but the wire must be constrained well enough to avoid shorts between turns, yet free enough to minimize strain-gage effects due to thermal expansion. The finished element is usually encased within an outer ceramic or glass housing. Most elements are under 0.1-inch diameter and a fraction of an inch long. Figure 4 shows some typical elements.

The biggest challenge for manufacturers is accuracy, and 0.25°C accuracy corresponds to 0.1% resistance, or about 0.022 inch of wire. Some manufacturers carefully control the wire length while others have developed methods to trim at a known temperature. The wire composition itself must be carefully controlled; very slight amounts of impurities are alloyed with the platinum to achieve the correct temperature coefficient. Pure platinum sensors having slightly higher sensitivity are also available.

Platinum-film elements are a more recent development. Most are made by vacuum-depositing platinum onto ceramic substrates, although silk-screened thick-film pastes have also been used. Film elements are not as stable as wire at high temperatures, but they cost less. Deposited film uses less platinum and can be bulk manufactured and laser trimmed. The elements can be made smaller—as small as thermistors—and can be supplied in resistances to 2 kilohms for higher sensitivity.



EXAMPLES OF BRIDGE DESIGNS

Temperature range	10 to 30°C	0 to 50°C	0 to 70°C
Temperature for zero output	10°C	0°C	0°C
Sensitivity	10 mV/°C	10mV/°C	10mV/°C
Bridge supply (V_s)	916.2 mV	1017.3 mV	1147.0 mV
R1	2,168 ohms	1,763 ohms	1,164 ohms
R2	4,482 ohms	7,355 ohms	7,355 ohms
R3	2,168 ohms	1,763 ohms	1,164 ohms
Maximum nonlinearity	+0.07 −0.06°C	+0.85 −0.95°C	+2.0 −2.3°C

Note: Thermistor is a YSI 44004, 400 series probe or equivalent, 2,252 ohms at 25°C.

FIG. 1—A WHEATSTONE BRIDGE with a thermistor arm will produce an output that increases with temperature. The table shows three practical ranges.

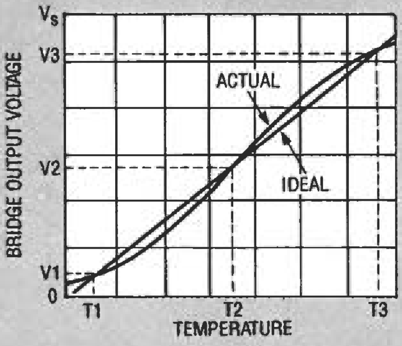


FIG. 2—THE WHEATSTONE BRIDGE OUTPUT is fairly linear near the middle of its range.

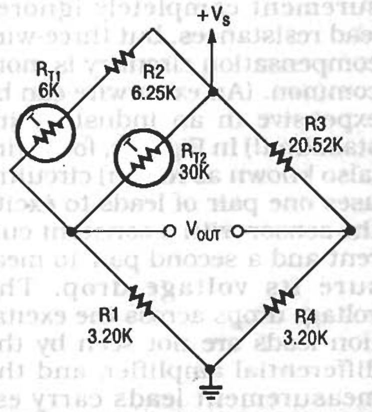


FIG. 3—A THERMISTOR-PAIR can be used in a Wheatstone bridge to improve the output linearity. This circuit is linear to within ±0.216°C from 0–100°C.

Copper, in general, is a poor choice for temperature measurement due to its limited temperature range and very low resistance. Its most common application is monitoring the temperature rise of motors, generators, and transformers. Other alloys have been used to create RTD's, but we will not cover them here.

RTD elements can be assembled into a wide variety of probes, as can thermistors and thermocouples, including some with threaded fittings for permanent installation into industrial processes. A pointed probe could be used to monitor the cooking or refrigeration of foods, while a flat probe (made from a film element) could be used to measure surface temperatures. Other styles are available, including laboratory types and probes with bends.

RTD circuits

RTD readout circuits are basically ohmmeters, specialized to ignore lead-wire resistance and (sometimes) to compensate for R versus T nonlinearity. Since typical RTD sensitivities are 0.4 or 0.6 ohms per degree, each ohm of lead resistance contributes about 2°C measurement error. Therefore, compensation circuitry must be used.

Four-wire resistance measurement completely ignores lead resistances, but three-wire compensation circuitry is more common. (An extra wire can be expensive in an industrial installation!) In Fig. 5-*a*, four-wire (also known as Kelvin) circuitry uses one pair of leads to excite the sensor with a constant current and a second pair to measure its voltage drop. The voltage drops across the excitation leads are not seen by the differential amplifier, and the measurement leads carry essentially no current, so their voltage drop is zero. Therefore, the amplifier's input sees only the voltage drop across the RTD itself. The circuit also performs linearization, but we'll come back to that in a moment.

The three-wire circuit in Fig. 5-*b* uses an identical controlled current source but different readout circuitry. The main amplifier's "+" input sees the combined voltage drop of the RTD and the two excitation leads. The second (×2) amplifier sees

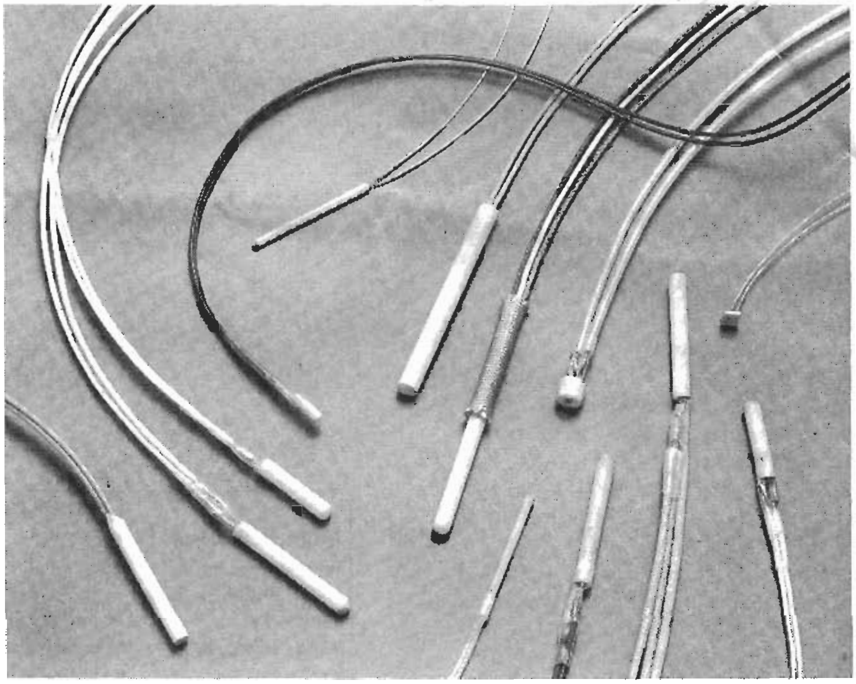


FIG. 4—TYPICAL RTD ELEMENTS, with leads attached. The small square element toward the right of the picture is a platinum-film element. (Courtesy of Sensing Devices Inc.)

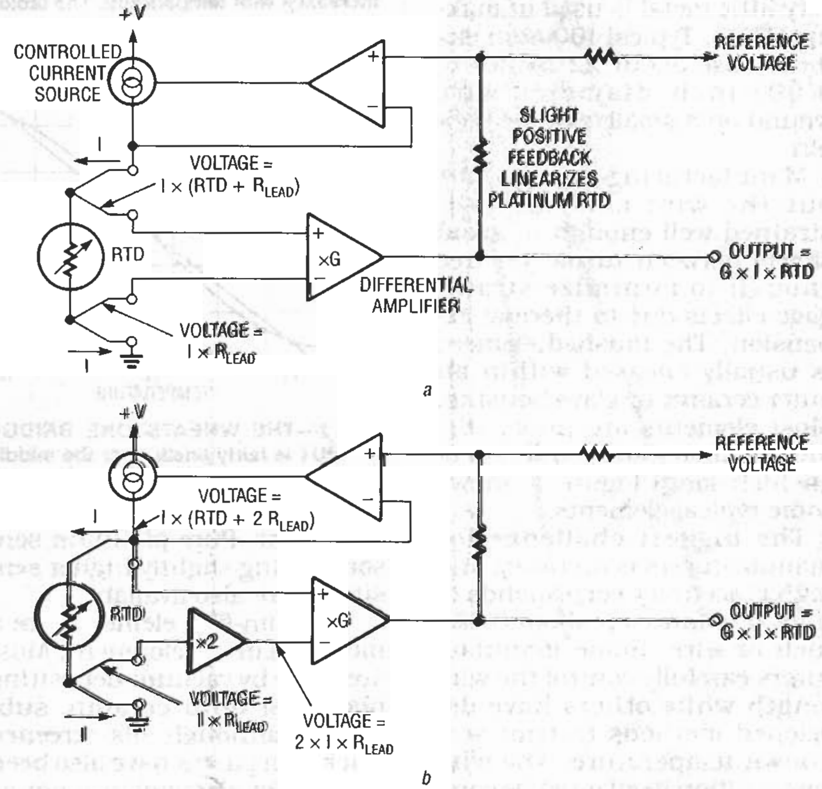


FIG. 5—FOUR-WIRE MEASUREMENT (*a*) measures the RTD's resistance and ignores lead wire resistances completely; it also includes linearization for platinum RTD's. Three-wire circuitry (*b*) compensates for voltage drops in the lead wires.

TABLE 1—CHARACTERISTICS 2252-OHM PRECISION THERMISTOR

Temperature °C	°F	Resistance Ohms
−80	(−112)	1660K
−70	(−94)	702.3K
−60	(−76)	316.5K
−50	(−58)	151.0K
−40	(−40)	75.79K
−30	(−22)	39.86K
−20	(−4)	21.87K
−10	(14)	12.46K
0	(32)	7.355K
10	(50)	4.482K
20	(68)	2.814K
25	(77)	2.252K
30	(86)	1.815K
40	(104)	1.200K
50	(122)	811.3
60	(140)	560.3
70	(158)	394.5
80	(176)	282.7
90	(194)	206.1
100	(212)	152.8
110	(230)	115.0
120	(248)	87.7
130	(266)	67.8
140	(283)	53.0
150	(302)	41.9

TABLE 2—700-SERIES THERMISTOR PAIR

Temperature °C	°F	T1 (Ohms) (6K at 25°C)	T2 (Ohms) (30K at 25°C)
−30	(−22)	106.2K	481.0K
−20	(−4)	58.26K	271.2K
−10	(14)	33.20K	158.0K
0	(32)	19.59K	94.98K
10	(50)	11.94K	58.75K
20	(68)	7496	37.30K
30	(86)	4834	24.27K
40	(104)	3196	16.15K
50	(122)	2162	10.97K
60	(140)	1493	7599
70	(158)	1051	5359
80	(176)	753.8	3843
90	(194)	549.8	2799
100	(212)	407.6	2069

TABLE 3—PLATINUM AND NICKEL RTD'S (DIN STANDARD 43760)

Temperature (°C)	Platinum (Ohms)	Tolerance (°C)	Nickel (Ohms)	Tolerance (°C)
−200	18.49	1.3		
−100	60.25	0.8		
−60	76.33	0.6	69.5	2.1
−50	80.31	0.55	74.3	1.8
0	100.00	0.3	100.0	0.4
50	119.40	0.55	129.1	0.75
100	138.50	0.8	161.8	1.1
150	157.31	1.05	198.7	1.45
180	168.46	1.2	223.2	1.7
200	175.84	1.3		
400	247.90	2.3		
600	313.59	3.3		
800	375.51	4.3		
850	380.26	4.55		

only the IR drop of the lower excitation lead. The ×2 amplifier doubles that voltage and presents it to the main amplifier, which subtracts it from the total. Thus, the signal seen by the main amplifier is $(I \times (RTD + 2R_{LEAD})) - (2 \times I \times R_{LEAD})$, which equals $I \times RTD$. Compensation will be perfect as long as the resistances of the leads and their connections are equal.

Now back to linearization. Platinum RTD's decrease in sensitivity (ohms per degree) as temperature rises. That can be compensated for by causing the current source to increase slightly with temperature. In Fig. 5-*a*, a slight amount of positive DC feedback (much too small to cause oscillation) increases the controlled current source as the output rises.

Figure 6 shows a practical circuit. The controlled current source consists of IC1-b and Q1; IC1-b compares the voltage drop across R2 to the voltage on R7's wiper and controls Q1 to keep the two equal. Resistors R3 and R4 "pad" the value of R2; when properly adjusted, the net resistance of R2, R3, and R4 is 100 ohms. Filter R5-C2 removes 60 Hz or other noise picked up by the RTD leads. The main amplifier, IC2, is a differential amplifier with a gain of 1. The positive feedback from R16 increases the RTD current with output, linearizing the platinum curve to better than ±0.5°C between 0 and 500°C. Linearization degrades somewhat at higher and lower temperatures.

Components IC1-a, R10, and R11 form the ×2 amplifier, with R1 and C1 providing filtering. Notice that IC1-a amplifies the voltage drop across R2 as well as that of the current-carrying lead. Its output is:

$$2 \times I \times (R_{LEAD} + 100\Omega)$$

Now notice that the main amplifier's input is:

$$I \times (RTD + 2R_{LEAD} + 100\Omega)$$

IC2's output is the difference: $I \times (RTD - 100\Omega)$. Since the RTD is 100 ohms at 0°C, the output at zero degrees is zero millivolts. With the circuit values shown, sensitivity is 1 mV/°C, which is handy for measuring temperature with a DVM.

Zero is set by providing a 100-ohm input and setting R4 for a 0-mV output. The gain is adjusted via R7 for 500 mV output at 280.90 ohms (500°C). Because RTD's are interchangeable, you do not need known temperatures or a reference thermometer for calibration.

Thermocouples

A thermocouple is simply two unlike metals joined together. The junction produces a voltage that increases with tempera-

TABLE 4—STANDARD THERMOCOUPLES

Thermocouple Type	Specified Temperature Range	Specified Error (Above 0°C)	Applications
Base Metal Thermocouples:			
J: Iron vs. Constantan	−210 to 760°C	Std: 2.2°C or .75% Special: 1.1°C or .375%	Reducing and inert atmospheres. Avoid oxidation and moisture.
K: Chromel vs. Alumel	−270 to 1372°C	(Same as type J)	Oxidizing and inert atmospheres.
T: Copper vs. Constantan	−270 to 400°C	Std: 0.83°C or .75% Special: 42°C or .375%	Most atmospheres. Best choice below 0°C. Moisture ok.
E: Chromel vs. Constantan	−270 to 1000°C	Std. 2.2°C or .5% Special: 1.1°C or .375%	Oxidizing and inert atmospheres. Highest sensitivity.
N: Nicrosil vs. Nisil	−270 to 1300°C	Std: 2.2°C or .75% Special: 1.1°C or .4%	Hi temp and oxidizing. More stable than type K.
Platinum Alloy Thermocouples:			
R: Pt/13% rhodium vs. pure pt.	−50 to 1768°C	1.4°C or 0.25%	Oxidizing & inert atmospheres. Avoid reducing atmospheres, metallic vapors.
S: Pt/10% rhodium vs. pure pt.	(Same as type R)	(Same as type R)	(Same as type R)
B: Pt/30% rhodium vs. pt/6% rhodium.	0 to 1820°C	0.5%	(Same as type R)

ture. Almost any pair of dissimilar metals can be used to make a thermocouple, but some will be more stable and accurate than others. Eight types are documented by NIST (formerly NBS) as standards, but specialized nonstandard thermocouples are available as well.

Table 4 lists the eight standard types, which are identified by letter codes. The first five (types J, K, T, E, and N) are pairs of base-metal alloys. Type K covers the widest range and is most popular. (Handheld DVM-like thermocouple thermometers most often use type K.) Type N, the newest, is similar to K but is more stable at high temperatures and in oxidizing atmospheres. Type T is best below freezing and in moist atmospheres, but is very limited at the upper end because one lead is copper. Type J includes iron and should not be used in moist or oxidizing environments. It is the best choice for inert or reducing atmospheres. Type E is the most sensitive of the standard thermocouples.

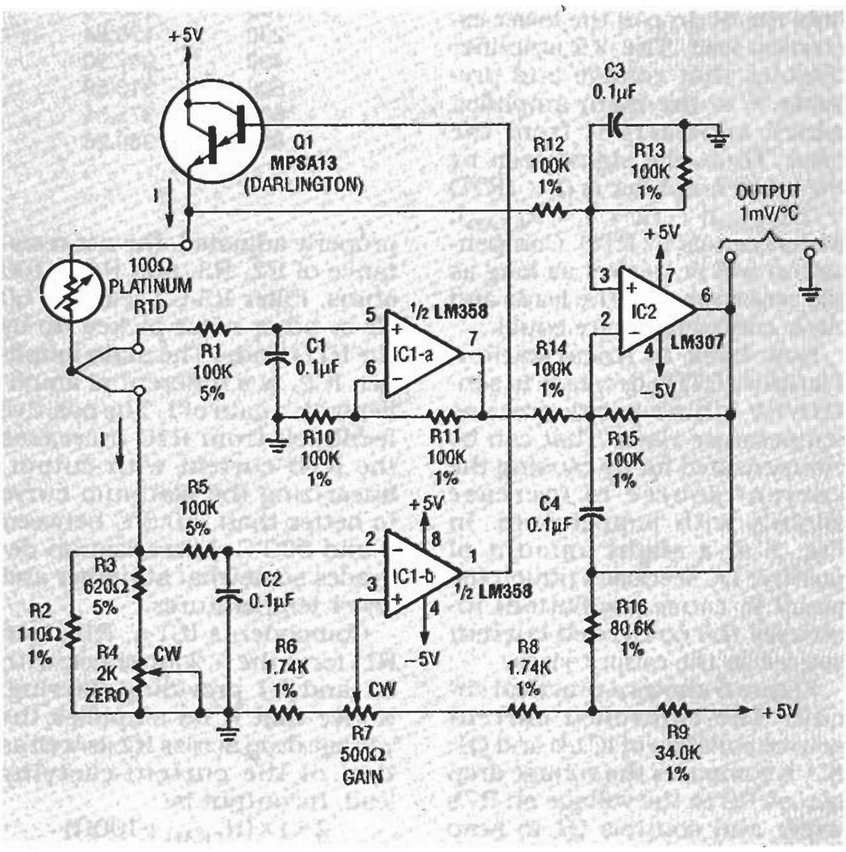


FIG. 6—THIS CIRCUIT INCLUDES 3-WIRE lead compensation, linearizes a platinum RTD, and produces a 1 mV/°C output.

TABLE 5—VOLTAGE VS. TEMPERATURE

Temperature (°C)	Type K Chromel vs. Alumel (mV)	Type R Pt-13% Rhodium vs. Platinum (mV)	Tungsten vs. Tungsten-26% Rhenium (mV)
−270	−6.548		
−200	−5.891		
−100	−3.553		
0	0	0	0
100	4.095	0.647	0.334
200	8.137	1.468	1.037
400	16.395	3.407	3.339
600	24.902	5.582	6.529
800	33.277	7.949	10.296
1000	41.269	10.503	14.389
1200	48.828	13.224	18.607
1372	54.875	15.639	22.213
1400		16.035	22.792
1600		18.842	26.820
1768		21.108	30.009
1800			30.592
2000			34.022
2200			36.884
2315			38.556

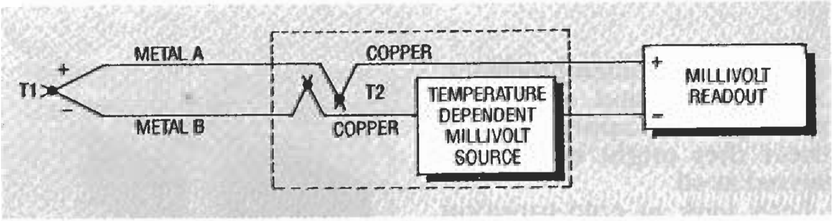


FIG. 7—COLD-JUNCTION COMPENSATION is necessary to offset EMF's generated by the unwanted thermocouples at the readout connections.

Types R, S and B consist of various platinum-rhodium alloys. They are more stable and accurate, and operate to higher temperatures. They also are less sensitive and, of course, more expensive. Types R and S are very similar to each other. Type B goes a bit higher in temperature, but falls off drastically in sensitivity below several hundred degrees. All three lose sensitivity near room temperature.

We do not have room here for data on all thermocouples, but Table 5 gives abbreviated millivolt versus temperature tables for types K, R, and a nonstandard high-temperature tungsten alloy thermocouple. (The catalog from Omega Engineering, Stamford, CT, mentioned last month, contains complete thermocouple reference data.)

Thermocouples offer more variety in size, shape, and configuration than any other sensors. Preassembled probes are available in many styles, and wire is available bare or insulated with such material as PVC, Teflon and ceramics. Various diameters are available from 14 AWG to 0.0005 inch, and ribbon thermocouples serve for surface temperature measurement.

The junction is usually formed by welding the two wires together, although twisting works for temporary purposes. One-shot measurement of molten steel can be made by simply plunging the two wires into the steel. Wires may be welded to metal surfaces or epoxied in place. One precaution when making surface measurements: place some of the connecting wire along the surface to make sure it does not conduct heat away from the junction.

Two final notes on wire: First, it can be expensive. Less-expensive extension-grade wire is sometimes used in industrial installations to connect remote measurement points to the readout instruments. Measurement-grade wire is used to make the measurement and runs out to locations at ambient temperature, where it is spliced to extension wire. The extension wire runs the rest of the distance to the readout or control devices. Extension wire matches measurement wire at ambient temperatures, but is not suitable for high- or low-temperature use.

Second, thermocouple cable is often coded by insulation color. Type K, for example, is identified by yellow on the positive wire and red on the negative. An outer brown jacket identifies measurement-grade wire: type K extension wire is yellow. Note that all color-coded thermocouples use red to identify the negative wire, which seems backwards to most of us in electronics.

Thermocouple circuit

A thermocouple circuit must do three things: amplify millivolt-level signals, correct for nonlinearities in the millivolt-versus-temperature table, and provide cold-junction compensation. Accurate amplification of millivolt-level signals requires stable, low-drift op-amps.

Thermocouples are not as easily linearized as RTD's, but we will not show specific circuits here. A wide variety of analog techniques have been used, the most common being diode breakpoint circuits. Those circuits use op-amps, diodes, precision resistors, and trimmer potentiometers to create an output versus input function consisting of a series of straight-line segments which approximate the required curve. Other approaches use one or several computational IC's (exponential, logarithmic, etc.) as part of the linearization circuitry.

Today it is common to digitize the amplified signal and lin-

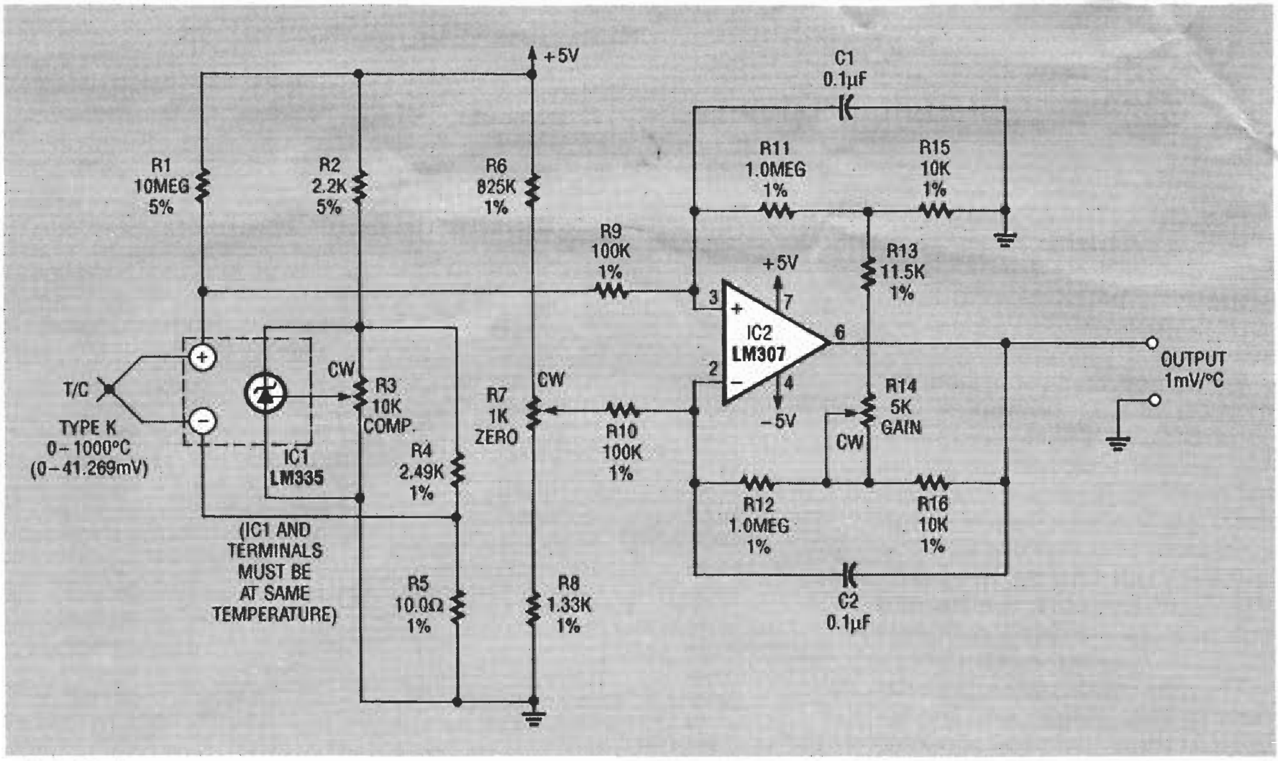


FIG. 8—THIS CIRCUIT PROVIDES cold-junction compensation and amplifies a type-K thermocouple to 1 mV/°C.

earize it with a microprocessor. On the other hand, since thermocouples are approximately linear they might not be linearized at all.

Let's look at cold-junction compensation. Remember that any connection between two unlike metals generates thermocouple voltage. Figure 7 shows that two unwanted thermocouples (cold junctions) are formed where the wires are connected to the readout's copper circuitry (T2). As the T2 temperature changes, the reading will be affected, even if T1 remains constant.

The cold-junction voltage is predictable, however, in fact, its temperature coefficient is equal and opposite to that of the thermocouple itself. (If T1 and T2 are equal, the net voltage will be zero.) It is a fairly simple matter to use a semiconductor or thermistor temperature sensor with circuitry creating an offsetting millivolt signal.

Figure 8 shows a complete circuit capable of producing a 1mV/°C output from a type-K thermocouple. It includes cold-junction compensation, but does not linearize the thermocouple curve. It would make an ideal circuit to turn your DMM into a thermometer.

FIG. 9—THIS HANDHELD DEVICE measures temperature using noncontact infrared, radiation thermometry.

Let's start with the cold junction compensation. An LM335 temperature sensor IC (discussed last month) generates 10 mV/K (273.15 mV at 0°C). Potentiometer R3 adjusts the precise sensitivity of the IC—you can omit it if you use a tight-tolerance grade LM335. R4 and R5 divide the signal down to 40 µV/K, equivalent to type K's sensitivity at room temperatures.

Without R13 and R14, the gain of IC2, a modified differential amplifier, would be 1 megohm/100K, or 10. Resistors R13 and R14 work with R15 and R16 to divide the feedback signal by 2.42:1, which multiplies the closed-loop gain by the same factor. The resulting 24.2 gain produces a 1000-mV output from the 41.269-mV (1000°C) input signal. The zero offset provided by R6, R7, and R8 is needed because the cold-junction compensation voltage is not zero at 0°C.

Note that IC1 must be at the same temperature as the thermocouple connections. One construction technique is to epoxy the IC to the terminal block. To calibrate, measure the ambient temperature, then set R3 for the proper voltage across IC1 (10 mV/K, which is 2.732 volts plus 0.01V/°C).

Zero and gain calibration is tricky because disconnecting

continued on page 83

R-E Engineering Admart

Rates: Ads are 2¼" × 2⅞". **One** i each. **Six** insertions **$950** each. **Twelve** insertions **$925** each. Closing date same as regular rate card. Send order with remittance to **Engineering Admart**, Radio-Electronics Magazine, 500-B Bi-County Blvd., Farmingdale, NY 11735. Direct telephone inquiries to Arline Fishman, area code-**1-516-293-3000. FAX 1-516-293-3115.** ***Only 100% Engineering ads are accepted for this Admart.***

MIDI Projects

MIDI PROJECTS

BP182—MIDI interfacing enables any so equipped instruments, regardless of the manufacturer, to be easily connected together and used as a system with easy computer control of these music systems. Combine a computer and some MIDI instruments and you can have what is virtually a programmable orchestra. To order your copy **send $6.95 plus $2.50 for shipping** in the U.S. to **Electronic Technology Today Inc., P.O. Box 240, Massapequa Park, NY 11762-0240.**

DR. "CHIP" MUNK SAYS

6805 / 68HC05 / 68HC11 DEVELOPMENT TOOLS + QUALITY and SERVICE + AFFORDABILITY = TECI

"Chip" experts agree with Dr. Munk. TECI's PC based microcontroller development tools are the most cost effective for veterans or beginners.

6805 PRIMER FOR BEGINNERS. $195.00
6805/68HC05/68HC11 CROSS ASSEMBLERS. $99.00
6805/68HC05 SIMULATOR / DEBUGGERS $99.00
68705P3,P5,U3,U5,R3,R5 PROGRAMMERS FROM $349.00
68HC705/68HC805 PROGRAMMERS FROM $395.00
COMPLETE PC BASED DEV. SYSTEMS FROM $449.00
68HC05/68HC11 REAL TIME EMULATORS FROM $895.00

TECI

CALL TOLL FREE 1-800-336-8321
The Engineers Collaborative, Inc.
Rt #3 Box 8C, Barton, VT 05822 USA
TEL:(802)525-3458 FAX:(802)525-3451

CIRCLE 189 ON FREE INFORMATION CARD

FCC LICENSE PREPARATION

The FCC has revised and updated the commercial license exam. The NEW EXAM covers updated marine and aviation rules and regulations, transistor and digital circuitry. THE GENERAL RADIOTELEPHONE OPERATOR LICENSE - STUDY GUIDE contains vital information. VIDEO SEMINAR KITS ARE NOW AVAILABLE.

WPT PUBLICATIONS
7015 N.E. 61st Ave.
Vancouver, WA 98661
Phone (206) 750-9933 Dept. 50

CIRCLE 177 ON FREE INFORMATION CARD

TEMPERATURE

continued from page 46

the thermocouple changes the net cold-junction voltage. With the input shorted (0 mV), set R7 for an output equal to room temperature; for example, 25 mV at 25°C (77°F). Connect 41.269 mV to the input and set R14 for 100 mV plus the room temperature (1025 mV at 25°C).

Resistor R1's small bias current has no effect on normal operation, but causes the output to go high if the thermocouple breaks or burns out.

Noncontact thermometry

We've finished our study of temperature sensors, but let's close with a quick look at noncontact infrared radiation thermometry. Figure 9 shows a handheld device and Fig. 10 illustrates its principle.

Any object warmer than absolute zero radiates energy. Both the intensity and the spectral distribution of that radiation increase with temperature. (We're all familiar with "red hot" and "white hot" temperatures, but even "cold" objects radiate energy.) According to the Stefan-Boltzmann law, the radiated energy density is proportional to T^4, where T is absolute temperature. It is that law which allows scientists to determine the temperature of the sun's surface.

In Fig. 10 the radiated energy is focused on a temperature sensor. Designs vary, but in general the sensor should be small and have a low mass for good response time. Some designs insulate the sensor by placing it in a vacuum. The lens material might need to be specially chosen to pass long-wavelength infrared, especially for low-temperature measurement. Some designs might not use a lens at all, substituting a focusing mirror instead. A red or infrared filter might be added to minimize interference from ambient light.

The Stefan-Boltzmann law applies perfectly only to "blackbody" radiators. In reality, the ability of surfaces to radiate energy varies. Every surface has a reflectivity and an emissivity. A perfectly reflective surface has a

continued on page 92

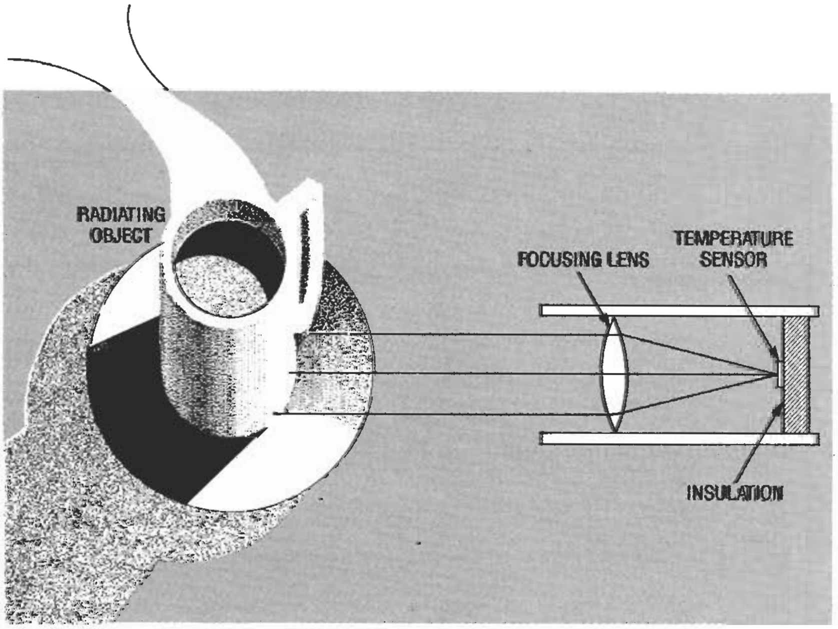


FIG. 10—ANY OBJECT WARMER than absolute zero radiates energy. The radiated energy is focused on a temperature sensor.