Designer's Guide to: Temperature sensing

Part 1 of a 3-part tutorial on temperature explores the wide variety of sensors available, from basic to exotic, both analog and digital.

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Temperature plays a critical role in the performance of every electronic circuit. It's the one environmental parameter you can never ignore. Yet the moment you acknowledge its importance, temperature becomes fair game for systems that can sense, measure and control it. And that, fellow designers, is exactly what this 3-part series is all about.

This installment details the many types of sensors and transducers that convert heat into inputs for electronic circuits. Fundamentally, we can define temperature, as a statistical entity, as the number of molecular collisions in an environment per unit of time. All heat-sensing devices trace their performance to this basic physical fact.

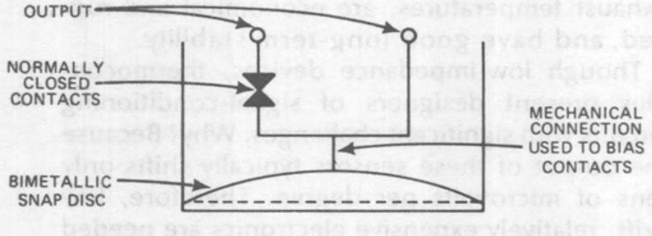

Fig. 1—Bimetallic disc snaps into the position shown by the dotted line when the ambient reaches the thermoswitch's transition temperature.

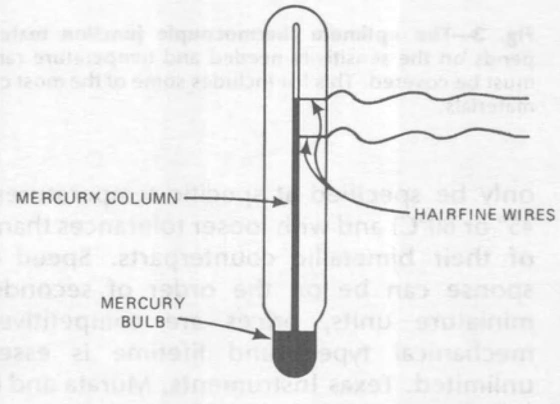

Fig. 2—Electrical contact is established when heat causes the mercury in this electrical output mercury thermometer to bridge both hairfine wires.

Thermostatic devices are a snap

Perhaps the most elementary component developed to convert temperature into an electrically measureable quantity is the bimetallic thermal switch. It uses metals with differing thermal coefficients of expansion to physically make or break an electrical contact at a preset temperature. Disc-shaped, bimetal elements provide snap action **(Fig. 1)**.

Bimetallic thermal switches function from subzero temperatures to almost +300°C. Contacts come in a variety of forms and can handle dry-circuit switching as well as currents beyond 15A. In addition, the hysteresis of the switching point can be specified.

Although inexpensive and reliable, bimetallic switches won't work in many situations because of their slow thermal response. Nevertheless, they still suit control applications such as crystal ovens and gyros, and. find extensive use as temperature limit and override sensors. Manufacturers include Elmwood Sensors, Fenwal and Texas Instruments' Klixon Division.

Solid-state thermostatic devices take advantage of the exceedingly steep resistance curve of special ceramics. These materials are relatively unaffacted by temperature until that point where the resistance suddenly increases by orders of magnitude. Typically, solid-state thermostats can only be specified at specific temperatures (i.e., 45° or 80°C) and with looser tolerances than those of their bimetallic counterparts. Speed of response can be on the order of seconds with miniature units, prices are competitive with mechanical types, and lifetime is essentially unlimited. Texas Instruments, Murata and others sell these solid-state digital sensors.

JUNCTION MATERIALS	USEFUL TEMPERATURE RANGE (°C)	VOLTAGE SWING OVER RANGE
COPPER–CONSTANTAN	−270 TO + 600°C	25.0 mV
IRON–CONSTANTAN	−270 TO +1000°C	60.0 mV
CHROMEL–ALUMEL	−270 TO +1300°C	55.0 mV
CHROMEL–CONSTANTAN	−270 TO +1000°C	75.0 mV
PLATINUM 10%–RHODIUM/PLATINUM	0 TO +1550°C	16.0 mV
PLATINUM 13%–RHODIUM/PLATINUM	0 TO +1600°C	19.0 mV
PLATINUM 30%–RHODIUM/PLATINUM	+38 TO +1800°C	13.0 mV
PLATINEL 1813–PLATINEL 1503	0 TO +1300°C	51.0 mV
IRIDIUM–RHODIUM	+1400 TO + 1850°C	2.5 mV
TUNGSTEN–RHENIUM	0 TO +2700°C	30.0 mV

Fig. 3—The optimum thermocouple junction material depends on the sensitivity needed and temperature range that must be covered. This list includes some of the most common materials.

Another generic relative of bimetallic thermoswitches, the electrical output mercury thermometer, is elegantly simple—just a glass-stem thermometer with very fine wires extending into the path of the mercury column **(Fig. 2).** Heat sensors of this type respond in 1-5 sec (at the trip point), have a sharply defined trip point with almost no hysteresis and boast nearly infinite life. Units with an absolute accuracy of 0.05°C are available, as are multiple and adjustable contact units.

Manufactured by P.S.G. Industries, thermometer-based thermoswitches make excellent choices for controlling ovens. For instance, they can control a thermodynamically properly designed crystal oven to 0.01°C stability to keep the crystal at its zero temperature-coefficient "turning point."

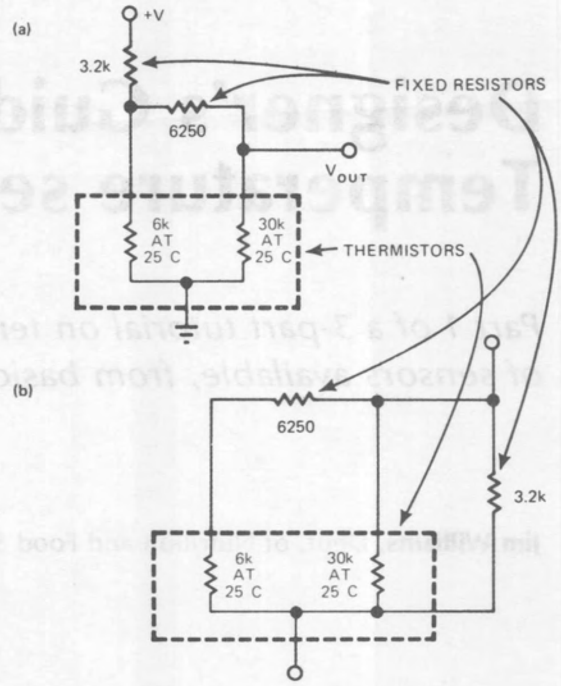

Fig. 4—Linear, accurate response can be obtained by combining two thermistors with fixed resistors. The penalty is decreased sensitivity. In **a,** the 3-terminal network functions as a temperature-dependent voltage source. In **b,** the same network is used in the 2-terminal mode to provide a shift in resistance that is linear with temperature.

Thermocouples handle wide temperature ranges

Thermocouples, a common form of a true analog-output temperature sensor, rely on the fact that junctions of dissimilar metals generate predictable low-level voltages as a function of temperature (Seeback effect). Of course, different combinations of metals produce junctions with varying characteristics **(Fig. 3).**

Because of their small size, thermocouples are fast devices and thus suit applications that emphasize speed of response. In addition, they function from cryogenic to well above jet-engine exhaust temperatures, are economical and rugged, and have good long-term stability.

Though low-impedance devices, thermocouples present designers of signal-conditioning circuits with significant challenges. Why? Because the output of these sensors typically shifts only tens of microvolts per degree. Therefore, low drift, relatively expensive electronics are needed to achieve resolutions better than 1°C.

Linearity of many thermocouple types is poor. Fortunately, however, the curves are predictable and repeatable, allowing designers to use either digital or analog linearization techniques.

The one serious drawback to thermocouples is that they require a reference to a known temperature for use in absolute temperature measurements; i.e., the circuitry must compare the output of the "signal" thermocouple with that of a similar "reference" thermocouple. Of course, the latter must be held at a known temperature.

Each signal thermocouple must have its own reference junction. Normally, all reference junctions are placed in the same constant temperature bath of 0.01°C (32.02°F), which is the triple point of water. "Black box" electronic equivalents of these triple-point baths are available from Omega, Acromag and others.

Every connection ("junction") between dissimilar metals represents a de-facto thermocouple, intended or not. Therefore, customary engineering practice in thermocouple cabling makes each signal wire (and all connections through which it passes) of the same metal as the side of the junction(s) to which it connects. Complex and expensive, these special cables and connectors run between the measuring thermocouple and reference junction.

It is worth noting that most of the world's thermocouples are junctions of solder and copper. These "thermocouples," usually unintentional and overlooked, can easily generate 20 times the offset drift of the low-drift amplifier in a precision preamp.

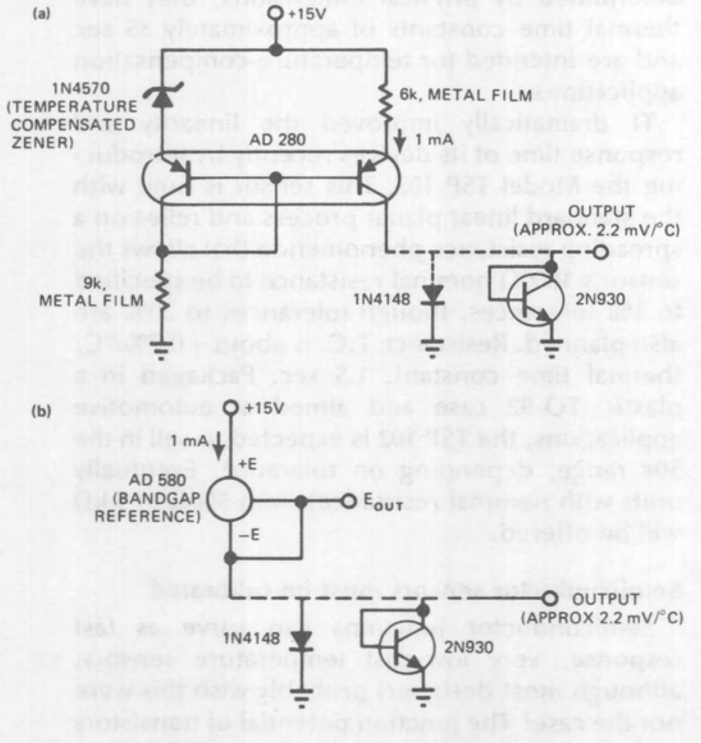

Fig. 5—Standard diodes and transistors can function as temperature sensors. The AD 820 transistor pair and associated components in **a** form a typical current source that can drive either diode or transistor sensors. For simplicity, these devices can be driven from voltage sources, but linearity decreases. An alternate current-source design, the band-gap reference circuit of **b** is extremely simple yet offers reasonably good performance.

Platinum sets the standard

Designers generally acknowledge platinum resistance wire as the standard for accuracy and repeatability in a temperature sensor. Some units have histories of years of agreement within 0.1 millidegree with the National Bureau of Standards calibration facilities. These generic cousins of wirewound resistors find heavy use in transfer-type measurements and provide linearity within

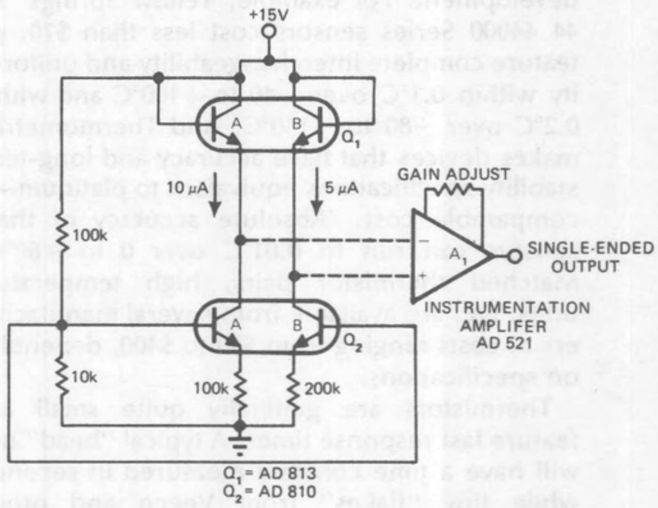

Fig. 6—In this practical current-ratio differential pair temperature sensor, dual transistor Q_2 provides currents of 10 and 5 μA through Q_{1A} and Q_{1B}, respectively. The difference between the V_{be} of Q_{1A} and that of Q_{1B} is a function highly linear and predictable with temperature. Instrumentation amplifier A_1 provides a single-ended output.

several degrees over a 100° range.

The absolute accuracy of platinum sensors can run to better than 0.01°C for standards-lab units. Resistance at 25°C ranges from tens to hundreds of ohms. Temperature coefficients are positive and typically run 0.5% of value/°C.

Because they are wirewound devices, platinum sensors tend to be large. However, versions about the size of 1/8W resistor are readily available.

Industrial versions of platinum sensors are reliable and retain much of the performance of premium units, yet they cost much less. A good industrial-grade sensor sells from $20-$100, while a *ne-plus-ultra* standards unit with a documented aging history can cost up to $1000.

Thermistors boast high sensitivities

Thermistors have the highest sensitivity of any common temperature transducer—at 25°C a typical unit shifts its resistance at a −5%/°C rate. The response curve is nonlinear, but predictable. Commercially available thermistors function over a range of −100 to +450°C and come in values from tens of ohms to megohms. Because of their high sensitivity, they frequently make the best choice in high-resolution measurement and control apparatus.

Designers often unjustly label thermistors as wild and unstable devices because of difficulties with early and some present commercial devices. But firms like Yellow Springs Instrument Co. and Thermometrics pursue serious research programs and have made great progress in thermistor development. For example, Yellow Springs' YSI 44 44000 Series sensors cost less than $10, yet feature complete interchangeability and uniformity within 0.1°C over −40 to +100°C and within 0.2°C over −80 to +150°C. And Thermometrics makes devices that have accuracy and long-term stability specifications equivalent to platinum—at comparable cost. (Absolute accuracy of these sensors can run to 0.01°C over 0 to +60°C.) Matched thermistor pairs, high temperature units, etc. are available from several manufacturers at costs ranging from $50 to $400, depending on specifications.

Thermistors are generally quite small and feature fast response times. A typical "bead" unit will have a time constant measured in seconds, while tiny "flakes" from Veeco and others respond in milliseconds.

Networks trade sensitivity for linearity

Manufacturers combine one or two thermistors in a single package with external fixed resistor shunts to produce sensor networks with highly linear response curves. Such networks are available over the −45 to +100°C range. One model, the Yellow Springs Instrument "Thermilinear" 44018, operates from 0 to +100°C with 0.15°C absolute accuracy and linearity. It costs about $15.

The penalty for the linearized response of composite thermistor/resistor networks is a drop of approximately an order of magnitude in sensitivity. These units can function as linearly temperature-dependent resistors or can operate in a potentiometric mode to produce an output voltage linear with temperature **(Fig. 4)**. Composite beads containing two thermistors are not much larger than single thermistor units and have response times measured in seconds.

These thermistors think positive

A special class of thermistors, available from Texas Instruments and Pennsylvania Electronic Technology, has a positive 0.7%/°C temperature coefficient. TI's "Sensistors" are about the size of

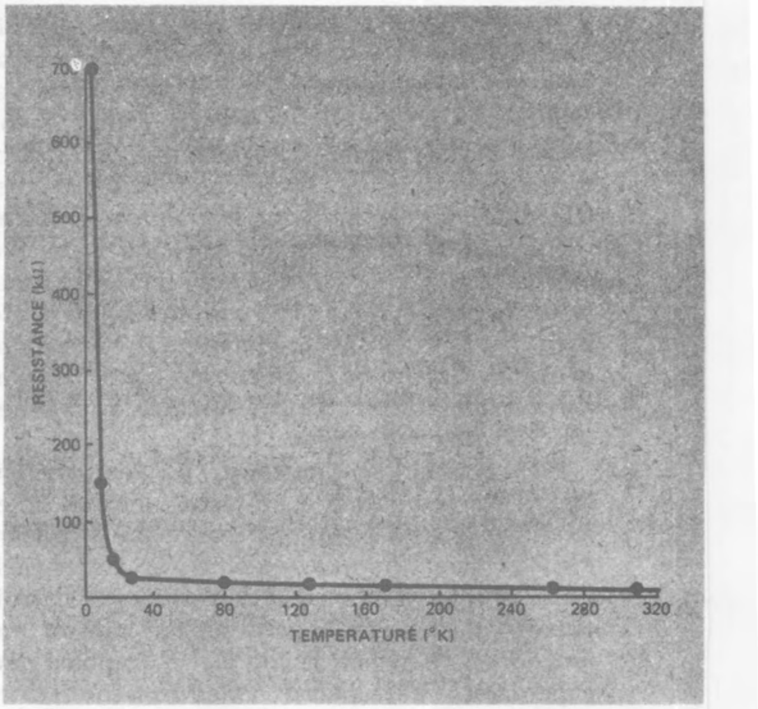

Fig. 7—Even a 1/4W resistor can be used to sense temperature. This curve was plotted for an 820Ω unit from Allen-Bradley.

1/4W resistors and are linear within 5° over −75 to +150°C. Bulk silicon devices with resistances determined by physical dimensions, they have thermal time constants of approximately 35 sec and are intended for temperature-compensation applications.

TI dramatically improved the linearity and response time of its devices recently by introducing the Model TSP 102. This sensor is built with the standard linear planar process and relies on a spreading resistance phenomenon that allows the sensor's 1000Ω nominal resistance to be specified to 1% tolerances, though tolerances to 20% are also planned. Resistance T.C. is about +0.7%/°C; thermal time constant, 1.5 sec. Packaged in a plastic TO-92 case and aimed at automotive applications, the TSP 102 is expected to sell in the 50¢ range, depending on tolerance. Eventually units with nominal resistances from 500Ω to 5 kΩ will be offered.

Semiconductor sensors must be calibrated

Semiconductor junctions can serve as fast response, very low-cost temperature sensors, although most designers probably wish this were not the case! The junction potential of transistors and diodes changes at about 2.2 mV/°C over a wide range of temperature. Linearity of within 2° is possible over −85 to +125°C with constant-current junction biasing techniques **(Fig. 5)**. Source impedance is low and the output is a medium-level signal with 25 to 100 times the voltage T.C. of a thermocouple.

Unfortunately, every semiconductor junction has its own initial offset and gain, so each individual device must be calibrated—a process that can easily outweigh the initial cost advantage. Recently, however, manufacturers have devised "clever" circuits to solve this problem. ECD Corp., for instance, uses diodes as sensors for a hand-held thermometer, yet achieves 0.5°C accuracy over −55 to +125°C with interchangeable probes.

The most sophisticated form of semiconductor sensor is the current-ratio differential pair **(Fig. 6).** Here transistor Q_{1A} is biased at higher collector current than Q_{1B}. The difference in V_{be}'s vs. temperature is theoretically predictable and extremely linear. Sensors based on this approach can afford >1°C accuracy over 300°C temperature ranges. National Semiconductor introduced an IC version of this circuit several years ago, the LX5600. It combines on chip, current-ratio differential pair and associated signal-conditioning electronics, and produces a scalable output voltage.

The highest performance IC version of the current-ratio differential pair sensor, Analog Devices' new Model AD 590, is a 2-terminal device that guarantees 1°C accuracy over −125 to +200°C and features a scaled current-source output. For remote sensing, a 5 to 15V supply can power the device down thousands of feet of wire, while the current output returns on another wire. The current output is scaled in degrees Kelvin (298.2 μA = 298.2°K), but other temperature scales are available by offsetting the output.

The AD 590 is an extremely low-noise device; preliminary studies indicate a noise level below (10^{-5})°C at 50°C. The sensor's TO-18 package provides reasonably fast thermal response, although other package designs (such as epoxy-coated or glass-passivated chips) may result in an extremely fast sensor. Sensitivity is about 0.3%/°C at 25°C.

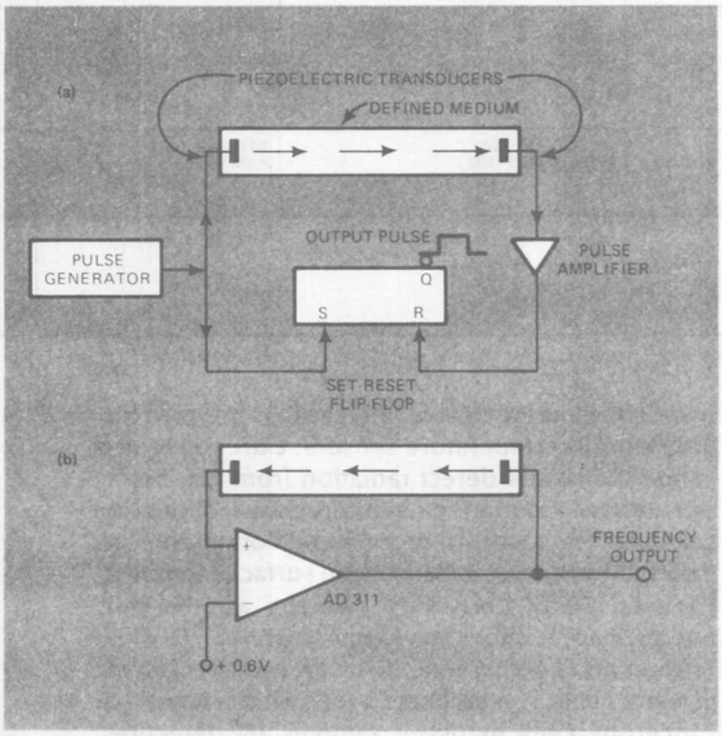

Fig. 8—In the acoustical thermometer diagrammed in **a** the pulse generator drives the "send" piezoelectric transducer, while simultaneously setting the output of the flip-flop to the ONE state. The sound wave propagates through the known medium and strikes the "receive" piezoelectric transducer, generating a small pulse. After amplification, this pulse resets the flip-flop to ZERO. Because the speed of sound varies with temperature in a predictable and reproducible manner, the temperature can be determined from the pulse width. In **b**, the acoustic thermometer is placed between the "+" input of a comparator and the output, causing an oscillation whose frequency varies with temperature.

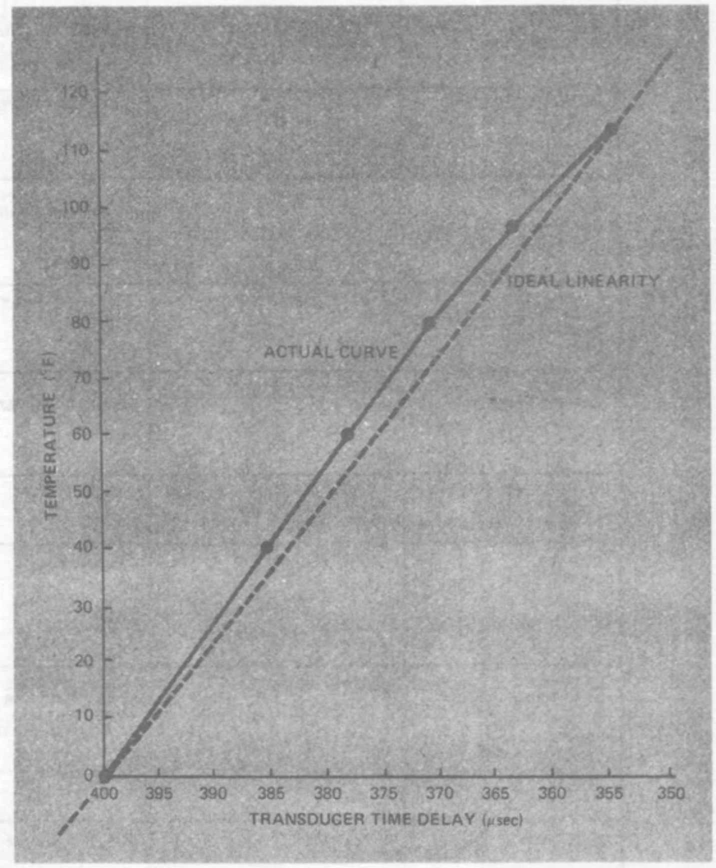

Fig. 9—A 3.6-in. tube filled with dry air and capped with piezoelectric sonic transducers produced this delay time plot.

With carbon resistors, you can go low

Standard carbon resistors are often used as cryogenic temperature sensors. Depending on the manufacturer and process control, units can be reasonably uniform from batch to batch. **Fig. 7** shows the response of a 1/4W Allan-Bradley resistor to a range of temperatures.

Carbon resistors can also provide inexpensive

TYPE	RANGE OF OPERATION	SENSITIVITY AT +25°C	ACCURACY	LINEARITY
THERMOSWITCHES & ELECTRICAL OUTPUT THERMOMETERS	−25 TO +265°C FOR BIMETALLICS; −35 TO +390°C FOR THERMOMETERS	HYSTERESIS AS LOW AS ±1°C IN BIMETALLIC UNITS. NO HYSTERESIS IN THERMOMETER TYPES	AS GOOD AS ±0.05°C FOR THERMOMETERS; ±2° FOR BIMETALLICS	NOT APPLICABLE
THERMOCOUPLES (ALL TYPES)	−270 TO +1800°C	TYPICALLY 1%/°C	±0.5°C WITH REFERENCE	POOR
THERMISTORS AND THERMISTOR COMPOSITES	−100 TO +450°C	−5%/°C FOR THERMISTORS; −0.5%/°C FOR LINEARIZED UNITS	±0.1°C STANDARD FROM −40 TO +100°C; ±0.01°C FROM 0 TO +60°C AVAILABLE	±0.2°C FOR LINEARIZED COMPOSITE UNITS OVER 100°C RANGES
PLATINUM RESISTANCE WIRE	−250 TO +900°C	APPROXIMATELY +0.5%/°C	±0.1°C READILY AVAILABLE; ±0.01°C IN PRECISION STANDARDS–LAB UNITS	NEARLY LINEAR OVER LARGE SPANS; TYPICALLY WITHIN 1° OVER 200°C RANGES
DIODES & TRANSISTORS	−250 TO +175°C	−2.2 μV/°C (APPROX. −0.37%/°C)	±2 TO ±5°C OVER −85 TO +125°C	WITHIN 5% OVER OPERATING RANGE
INTEGRATED CIRCUIT (CURRENT RATIO DIFFERENTIAL PAIR)	−125 TO +200°C FOR AD 590; −85 TO +125°C FOR OTHERS	0.4%/°C TYPICAL	±1° OVER −125 TO +200°C FOR AD 290	WITHIN 1° FOR TYPE AD 290 (0.2° FROM 0 TO +70°C)
QUARTZ CRYSTALS	−80 TO +250°C	0.0035%/°C	±0.03°C ACHIEVEABLE	0.01° ACHIEVABLE OVER 100°C RANGES
CARBON RESISTORS	−250 TO +200°C	0.05%/°C (VARIES WITH MANUFACTURER AND POWER RATING); 300%/°C AT CRYOGENIC TEMPERATURES	VERY POOR	POOR OVER LARGE RANGE; AS GOOD AS 5°C OVER 0 TO +75°C; WILDLY NON-LINEAR AT CRYOGENIC TEMPERATURES
INFRARED	0 TO +3500°C	NOT APPLICABLE	±0.4% FOR HIGH QUALITY UNITS; ±5 TO ±10% FOR LOW COST UNITS	POOR
ACOUSTIC THERMOMETERS	−250 TO +4000°C	0.05%/°C (DRY AIR)	AS GOOD AS ±0.01°C OVER +10 TO +100°C	WITHIN 2° FROM +10 TO +100°C
PYROELECTRIC	−270 TO +200°C	20V/1° STEP	NOT APPLICABLE	NOT APPLICABLE

Fig. 10—To help you select the temperature sensor that best meets your needs, this chart summarizes the important characteristics of the most common types.

low-order temperature compensation in circuitry. However, note that a significant difference exists between the T.C.'s of various brands and wattage sizes. Further, resistor manufacturers will not likely guarantee any curve with temperature. Generally speaking, a standard 1/2W resistor will provide an average of −500 ppm/°C from 0 to +100°C.

Special sensors for special problems

Under certain conditions, the standard temperature sensors previously described do not provide the necessary characteristics to make a measurement. Fortunately, a number of exotic sensors have been developed to meet special needs. We will now describe four of the most interesting types.

IR sensors take a "hands-off" approach

A number of applications require a noncontact heat measurement—a job easily handled by infrared (IR) temperature sensors. Extremely sensitive, IR sensors detect radiation from an object or surface. Combined with precision optics in satellites that study environmental conditions on earth, they can determine ocean surface temperature to 0.5°C precision. And in a "thermal microscope" under development at M.I.T.'s Nutrition and Food Science Instrumentation Lab, IR sensors allow researchers to follow the spread of cancerous cells in tissue samples by detecting 0.01°C temperature differences in the tissue. This same instrument could serve to quantitatively measure thermal gradients in a power transistor or integrated circuit. Key to its performance is an Indium-Antimonide detector cooled by liquid nitrogen to obtain low noise.

High-performance IR sensors have unit costs ranging from hundreds to thousands of dollars. Further, they usually require complex and expen-

SPEED IN STIRRED OIL	SIZE	PACKAGE	COST	COMMENTS
5 TO 30 SEC FOR BIMETALLIC TYPES; 1 TO 5 SEC FOR MERCURY TYPE (AT THE TRIP POINT)	BIMETALLIC UNITS TYPICALLY ARE 3/32 x 3/4 x 1/4 IN.; THERMOMETERS CAN BE AS SMALL AS 0.1 IN. DIA. x 1 IN. LONG	BIMETALLIC–METAL, GLASS, CERAMIC, PLASTIC. THERMOMETER–GLASS	\$1 TO \$85	BIMETALLIC UNITS INEXPENSIVE. THERMOMETERS COME IN CALIBRATED ADJUSTABLE TYPES IF DESIRED.
TYPICALLY 1 SEC; SOME TYPES ARE FASTER	0.02 IN. BEAD TYPICAL; 0.0005 IN. UNITS ARE AVAILABLE	METALLIC BEAD	\$1 TO \$50 DEPENDING ON TYPE AND SPECIFICATIONS	REQUIRES REFERENCE. LOW LEVEL OUTPUT REQUIRES STABLE SIGNAL CONDITIONING COMPONENTS.
1 TO 10 SEC IS STANDARD; 3 TO 100 mSEC TYPES ARE AVAILABLE	BEADS CAN BE AS SMALL AS 0.005 IN., BUT 0.04 TO 0.1 IN. IS TYPICAL; "FLAKE" TYPES ARE ONLY 0.001 IN. THICK	GLASS, EPOLY, TEFLON ENCAPSULATED, METAL HOUSING, ETC.	\$2 TO \$10 FOR STANDARD UNITS; \$10 TO \$350 FOR HIGH PRECISION TYPES AND SPECIALS	HIGHEST TEMPERATURE SENSITIVITY OF ANY COMON SENSOR. SPECIAL UNITS REQUIRED FOR LONG TERM STABILITY ABOVE +100°C.
TYPICALLY SEVERAL SECONDS	1/8 TO 1/4 IN. TYPICAL; SMALLER SIZES AVAILABLE	GLASS, EPOXY, CERAMIC, TEFLON, METAL, ETC.	\$25 TO \$1000, DEPENDING ON SPECS; MOST INDUSTRIAL TYPES BELOW \$100	SETS STANDARD FOR STABILITY OVER LONG TERM. HAS WIDER TEMP. RANGE THAN THERMISTOR, BUT LOWER SENSITIVITY.
1 TO 10 SEC IS STANDARD; SMALL DIODE PACKAGES PERMIT SPEEDS IN mSEC RANGE	STANDARD DIODE AND TRANSISTOR CASE SIZES; GLASS PASSIVATED CHIPS PERMIT EXTREMELY SMALL SIZES	GLASS, METAL	BELOW 50¢	REQUIRE INDIVIDUAL CALIBRATION. MUST BE DRIVEN FROM CURRENT SOURCE FOR OPTIMUM PERFORMANCE. EXTREMELY INEXPENSIVE.
SEVERAL SECONDS	TO-18 TRANSISTOR PACKAGE SIZE; ALSO MINI-DIP	METAL, PLASTIC	\$2 TO \$10	AD 590 IS A 2-TERMINAL CURRENT-OUTPUT DEVICE.
2 TO 5 SEC ACHIEVABLE	AS SMALL AS 0.5 IN. DIA. x 0.75 IN. LONG	GLASS, METAL	\$75 TO \$350	NOT READILY AVAILABLE COMMERCIALLY. REQUIRES SIGNIFICANT SIGNAL CONDITIONING. PARASITICS IN CABLES PRESENT PROBLEMS. EXCELLENT LINEARITY AND ACCURACY.
3 TO 10 SEC	1/4W, 1/2W RESISTOR SIZES	TYPICAL RESISTOR PACKAGE	5¢	WILL PROVIDE SECOND ORDER TEMP. COMPENSATION FOR CIRCUITS. INEXPENSIVE CRYOGENIC SENSOR. WHILE UNIT-TO-UNIT UNIFORMITY IN A GIVEN BATCH MAY BE GOOD, MANUFACTURERS WILL NOT GUARANTEE SPECS.
LESS THAN 1 SEC	THERMISTOR TYPE SENSORS TYPICALLY 0.01 IN. FLAKE; SOPHISTICATED UNITS AS LARGE AS 12 x 3 IN., INCLUDING LIQUID NITROGEN DEWAR FLASK, ETC.	GLASS	\$10 TO \$2500	NON-CONTACT TEMP. SENSOR. SOPHISTICATED SENSORS REQUIRE EXPENSIVE SUPPORT OPTICS AND ELECTRONICS.
<1 mSEC UNDER IDEAL CONDITIONS. TYPICALLY SEVERAL SECONDS	TYPICALLY 1.5 x 0.25 IN.	SOME TYPES HAVE NO PACKAGE; OTHERS USE METAL, GLASS, CERAMIC, QUARTZ, ETC.	\$5 TO \$1000, DEPENDING ON DESIRED PERFORMANCE	NOT COMMERCIALLY AVAILABLE. HIGH PERFORMANCE TYPES REQUIRE FULL DESIGN OF TRANSDUCERS AND PACKAGE.
TYPICALLY 10 SEC TO 1 MINUTE	0.75 IN. DIA. DISC IS TYPICAL	CERAMIC	\$10	HIGHEST GAIN TEMP. SENSOR KNOWN, BUT SENSES RATE OF CHANGE ONLY. NO OUTPUT FOR CONSTANT TEMP. A TRUE AC COUPLED DEVICE. OUTPUT IMPEDANCE IS $10^{12}\Omega$.

sive optics, cooling equipment and signal-conditioning electronics.

The manufacture of IR sensing devices is a specialized, difficult art, and elements of witchcraft seem necessary to produce high-performance devices. Santa Barbara Research Corp. and Barnes Engineering number among the leading innovators in this field.

Acoustic thermometers go to extremes

Acoustic thermometers operate on the principle that the speed of sound varies with temperature in a medium in a highly predictable and reproducible manner over temperatures ranging from cryogenic to thousands of degrees. These devices usually operate as either clocked systems or oscillators **(Fig. 8).** In both modes, the sensor effects a temperature-dependent delay line.

Acoustic sensors function at temperature extremes that other sensors cannot tolerate. Linearity is good over small ranges, but over extremely wide dynamic ranges or for precision work, the output must be linearized by digital methods.

An acoustic thermometer composed of a 3.6-in. dry-air-filled tube with piezoelectric sonic transducers produced the data in **Fig. 9.** Precise acoustic thermometers require considerable engineering to compensate for temperature errors in the sonic transducers, thermal expansion effects in the tube walls and wave dispersion inside the device. Acoustic thermometers are not available commercially, although a number of experimental designs have been published. They can be made as small as 1/8×1/4 in. with time constants of 0.5 to 15 sec.

Pyroelectrics measure minute changes

Pyroelectric materials boast the highest sensitivity of any known sensor. Pyroelectric thermometers consist of crystalline solids that respond to the time derivative of temperature (Δtemperature/Δtime). One typical unit can produce a 20V peak pulse for a 1°C step change, and temperature rate deltas as small as 60 nanodegrees/sec have been measured with devices of this type.

Unfortunately, pyroelectric sensors are relatively unknown and commercial versions are not readily available. Their output impedance is around $10^{12}\Omega$, so high-performance FET or varactor-bridge input amplifiers must be used for signal conditioning. Since they are extraordinarily high-gain ac devices, pyroelectrics hold promise as detectors for low-level micro-calorimetry.

Quartz crystals—results worth the effort

The resonant frequency of quartz crystals changes with temperature. However, even inexpensive crystals have a temperature coefficient of only 1 ppm/°C. To get higher sensitivities, the "LC" cut was devised to raise the temperature coefficient to 35 ppm/°C over −80 to +250°C. This is still low sensitivity, but the availability of crystal time bases with 1×10^{-9} stability means that temperature shifts of (10^{-4})°C can be observed. Hewlett-Packard's Model 2801A thermometer uses this type of sensor.

The problems involved in designing around quartz crystals as temperature sensors are formidable: Many crystal manufacturers do not even want to make the "LC" cut. Capacitance shifts in the cable can easily cause erratic operation and incorrect readings. And a precision time base that's difficult to make and expensive to buy is required for high-resolution work. For the latter two reasons quartz sensors usually require dedicated cables and sometimes include the oscillator circuit in the cable.

On the positive side—as would be expected of quartz—long-term stability, accuracy and linearity characteristics are all excellent.

More to come....

Fig. 10 summarizes the key characteristics of all temperature sensors discussed in this article.

Part 2 of this series will appear in our May 20, 1977 issue. It will match specific signal-conditioning circuits with popular temperature-sensor types, as well as provide practical design hints and typical performance details. **Part 3,** scheduled to appear in our June 20, 1977 issue, will describe the application of measurement schemes to temperature controllers, including one capable of very spectacular performance. □

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