Electronic Temperature Measurement

What is temperature and how can it be measured electronically?

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TEMPERATURE IS PERHAPS THE most common of all physical measurements. From weather forecasts to industrial processes to patient monitoring, its measurement pervades our lives. Yet, unless our jobs directly involve temperature measurement, most of us don't give much thought to what temperature is or how it's measured. In this article we will look briefly at how temperature is defined and survey the field of electronic temperature measurement. We'll then begin an in-depth study of temperature sensors and application circuits, closing with a look at noncontact infrared thermometry.

What is temperature?

Any grade school science student knows that heat is molecular motion. The hotter something is, the faster its molecules move; absolute zero is defined as the point where all molecular motion ceases. All well and good but, since we can't see molecules move, how do we measure temperature?

The bedrock standard used by the NIST (National Institute of Standards and Technology, formerly the National Bureau of Standards) is based on the perfect gas law. The law states that as temperature rises, either the pressure or volume of the gas must increase in proportion. Mathematically, $P \times V = kT$, where P = pressure, V = volume, T = absolute temperature, and k is a constant. Doubling the molecular velocity in a constant volume results in twice as many molecular collisions per second, or twice the pressure. At absolute zero a perfect gas would collapse to zero volume and pressure.

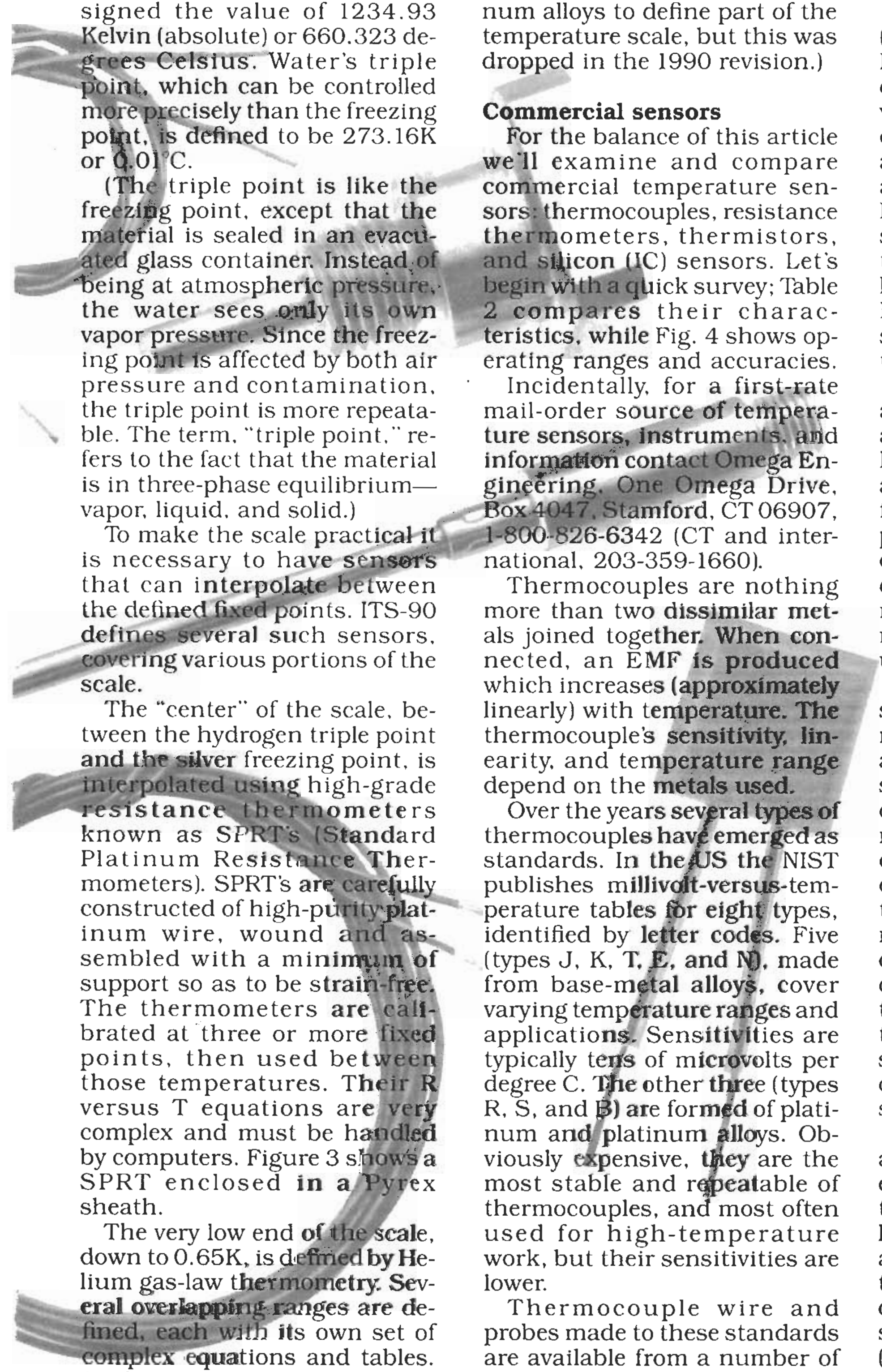
Figure 1 illustrates the concept of a constant-volume helium gas thermometer. (Perfect gases do not exist, but helium comes close.) A mercury manometer—a device used for measuring the pressure of gasses and vapors—with an adjustable reservoir measures the gas pressure of a helium-filled bulb. As temperature changes, a plunger in the reservoir is adjusted to maintain the left leg of the manometer at a constant height, thus maintaining the helium at a constant volume. When a vacuum is pulled above the right leg, the mercury height indicates the gas pressure, and thus the temperature of the helium.

The concept sounds simple, but precision measurements are difficult. Temperature affects the volume of the bulb and the interconnecting tube is not at the same temperature as the bulb. Also, the relatively small change in mercury level, plus the meniscus of the mercury's surface, limits measurement accuracy. On top of all that, corrections must be made for helium's deviations from the perfect gas law. Therefore, gas-law thermometry is used primarily by national standards laboratories such as the NIST.

Temperature scales

Companies and laboratories which manufacture or calibrate thermometers need a more practical standard. For that reason, the International Temperature Scale (ITS) was established. Previously known as the International Practical Temperature Scale to distinguish it from the fundamental gas-law scale, it is regularly reviewed and revised by international conferences involving a number of national standards laboratories. The latest revision, published in 1990, is known as ITS-90.

The scale begins with a series of agreed-upon fundamental temperatures, or fixed points. The freezing (or melting) point—or, in some cases, a variation known as the triple point—of certain high-purity materials have been assigned precise temperature values by agreement among the participating labs. Figure 2 shows



a typical fixed-point cell. A graphite crucible containing a high-purity metal is sealed in a quartz envelope filled with argon or some other inert gas.

Table 1 lists several fixed points. The freezing point of silver, for example, has been assigned the value of 1234.93 Kelvin (absolute) or 660.323 degrees Celsius. Water's triple point, which can be controlled more precisely than the freezing point, is defined to be 273.16K or 0.01°C.

(The triple point is like the freezing point, except that the material is sealed in an evacuated glass container. Instead of being at atmospheric pressure, the water sees only its own vapor pressure. Since the freezing point is affected by both air pressure and contamination, the triple point is more repeatable. The term, "triple point," refers to the fact that the material is in three-phase equilibrium—vapor, liquid, and solid.)

To make the scale practical it is necessary to have sensors that can interpolate between the defined fixed points. ITS-90 defines several such sensors, covering various portions of the scale.

The "center" of the scale, between the hydrogen triple point and the silver freezing point, is interpolated using high-grade resistance thermometers known as SPRT's (Standard Platinum Resistance Thermometers). SPRT's are carefully constructed of high-purity platinum wire, wound and assembled with a minimum of support so as to be strain-free. The thermometers are calibrated at three or more fixed points, then used between those temperatures. Their R versus T equations are very complex and must be handled by computers. Figure 3 shows a SPRT enclosed in a Pyrex sheath.

The very low end of the scale, down to 0.65K, is defined by Helium gas-law thermometry. Several overlapping ranges are defined, each with its own set of complex equations and tables. At the high end, temperatures above the silver freezing point are defined using radiation thermometry. We'll look at radiation thermometry next month, but basically it makes use of the fact that infrared or optical radiation increases with temperature. (The older IPTS also used thermocouples made of platinum alloys to define part of the temperature scale, but this was dropped in the 1990 revision.)

Commercial sensors

For the balance of this article we'll examine and compare commercial temperature sensors: thermocouples, resistance thermometers, thermistors, and silicon (IC) sensors. Let's begin with a quick survey; Table 2 compares their characteristics, while Fig. 4 shows operating ranges and accuracies.

Incidentally, for a first-rate mail-order source of temperature sensors, instruments, and information contact Omega Engineering, One Omega Drive, Box 4047, Stamford, CT 06907, 1-800-826-6342 (CT and international, 203-359-1660).

Thermocouples are nothing more than two dissimilar metals joined together. When connected, an EMF is produced which increases (approximately linearly) with temperature. The thermocouple's sensitivity, linearity, and temperature range depend on the metals used.

Over the years several types of thermocouples have emerged as standards. In the US the NIST publishes millivolt-versus-temperature tables for eight types, identified by letter codes. Five (types J, K, T, E, and N), made from base-metal alloys, cover varying temperature ranges and applications. Sensitivities are typically tens of microvolts per degree C. The other three (types R, S, and B) are formed of platinum and platinum alloys. Obviously expensive, they are the most stable and repeatable of thermocouples, and most often used for high-temperature work, but their sensitivities are lower.

Thermocouple wire and probes made to these standards are available from a number of manufacturers and distributors. In addition, some manufacturers produce special thermocouples for high temperature, cryogenic, and other specialized applications. Most common of these are tungsten alloy thermocouples which allow measurements as high as 2315°C (4200°F).

A resistance thermometer (commonly called an RTD, or Resistance Temperature Device) consists of a coil of fine-gauge wire or metal film. Most metals change resistance with temperature, but platinum or nickel are most often used to make RTD's. RTD's generally are more stable, accurate, and sensitive than thermocouples, but are limited to lower temperatures. Platinum RTD's are the most stable and accurate and cover the highest temperature range.

Nickel's lower cost has made it attractive for moderate-temperature industrial applications; however, recent advances in the art of manufacturing platinum-film elements (similar in principle to metal-film resistors) has eliminated the cost advantage of nickel. Other metals, primarily copper and an alloy named Balco, are sometimes used as well.

Thermistors are probably somewhat familiar to most readers. Unlike thermocouples and RTD's, they are highly sensitive, highly nonlinear, and cover limited temperature ranges. Positive temperature coefficient (PTC) thermistors exist, but those best suited to temperature measurement are negative temperature coefficient (NTC) devices which decrease in resistance by about 3 to 5% per °C. Thermistors offer the widest variety of sizes, shapes, accuracies, and prices of any commercial temperature sensors.

Integrated circuit (IC) temperature sensors are newest and easiest for most experimenters to apply. They are sensitive and linear, and interface easily to op-amps and A/D converters. On the flip side, IC's have not become as standardized as other sensors. Precisely-calibrated (selected) grades tend to get expensive. Their temperature range is about the same as ep-

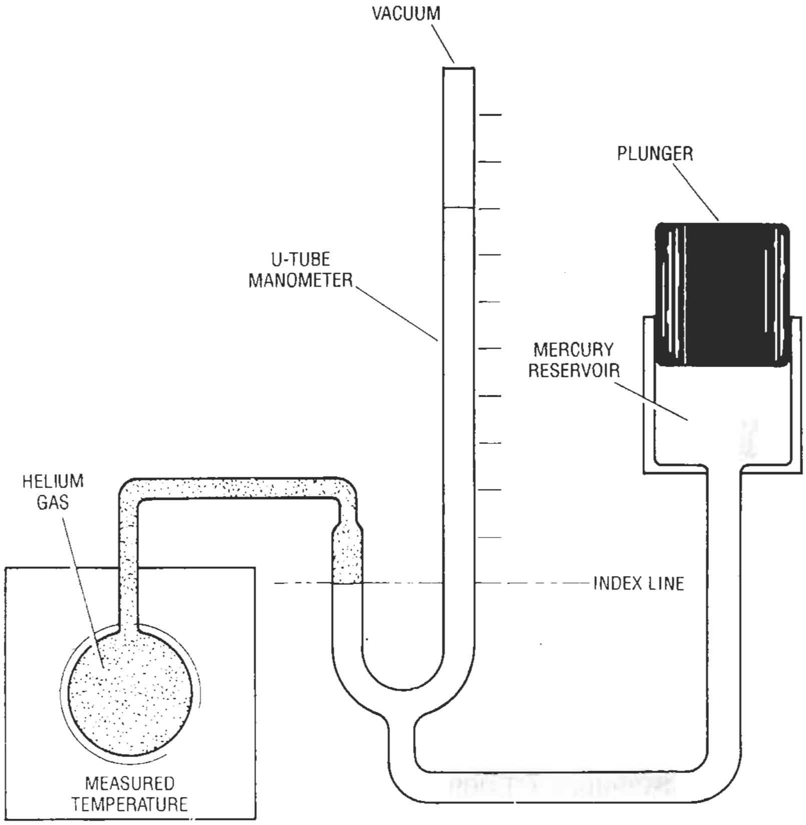


FIG. 1—CONSTANT-VOLUME GAS THERMOMETER. The plunger is adjusted to maintain the left leg of the manometer at the index line as the gas pressure changes.

TABLE 1

Fixed Point	Temp (K)	Temp (°C)
Hydrogen Triple Point	13.8033	−259.3467
Neon Triple Point	24.5561	−248.5939
Oxygen Triple Point	54.3584	−218.7916
Argon Triple Point	83.8058	−189.3442
Mercury Triple Point	234.3156	−38.8344
Water Triple Point	273.16	0.01
Gallium Melt Point	302.9146	29.7646
Indium Freeze Point	429.7485	156.5985
Tin Freeze Point	505.078	231.928
Zinc Freeze Point	692.677	419.527
Aluminum Freeze Point	933.473	660.323
Silver Freeze Point	1234.93	961.78
Gold Freeze Point	1337.33	1064.18
Copper Freeze Point	1357.77	1084.62

oxy-coated thermistors.

Which sensor is best?

It depends upon temperature, application and accuracy. At high temperatures thermocouples may be the only choice. Best accuracy generally is given by platinum RTD's, although precision thermistors may excel near room temperature. Thermistors, because of their high sensitivity, are superb in narrow-range applications such as medical thermometers. Thermistors and IC's both serve well for moderate accuracy measurements and temperature compensation applications.

IC's and, to a lesser extent, RTD's offer limited package selections. For small size and fast response, glass-bead thermistors are available in diameters from 0.014 down to 0.005 inch while uninsulated thermocouple wire is available down to 0.0005-inch diameter. At the other end of the scale, thermistor washers and discs are offered with diameters up to 1 inch. Thermocouple wire is available to 14 AWG and even larger, with insulations ranging from PVC to ceramic fibers or beads. Surface temperatures may be measured by ribbon-style thermocouples, or thermocouple wires may be welded directly to metal surfaces.

Now that our survey is complete, let's look at each in detail.

IC sensors

Forward-biased silicon diodes and base-emitter junctions have often been used to measure temperature. At room temperature, a forward-biased

FIG. 2—FIXED POINT CELL. The graphite crucible, visible through the quartz enclosure, contains a high-purity metal. (Courtesy of YSI Inc.)

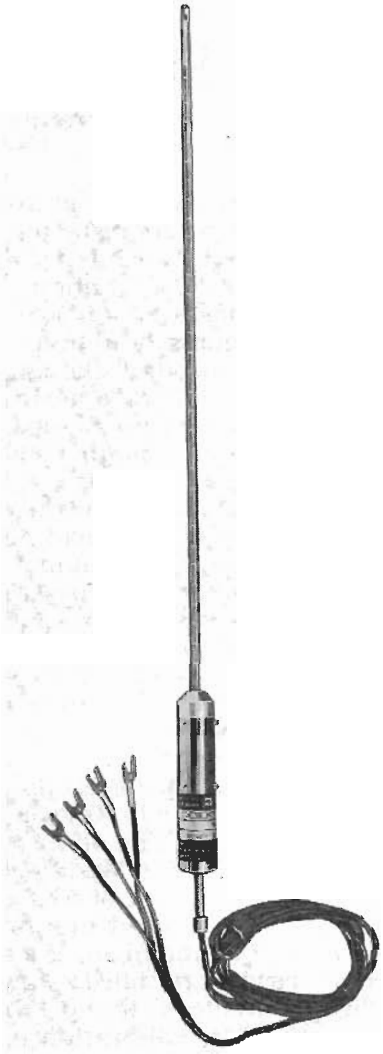


FIG. 3—STANDARDS-QUALITY SPRT, assembled into a quartz sheath. (Courtesy of YSI Inc.)

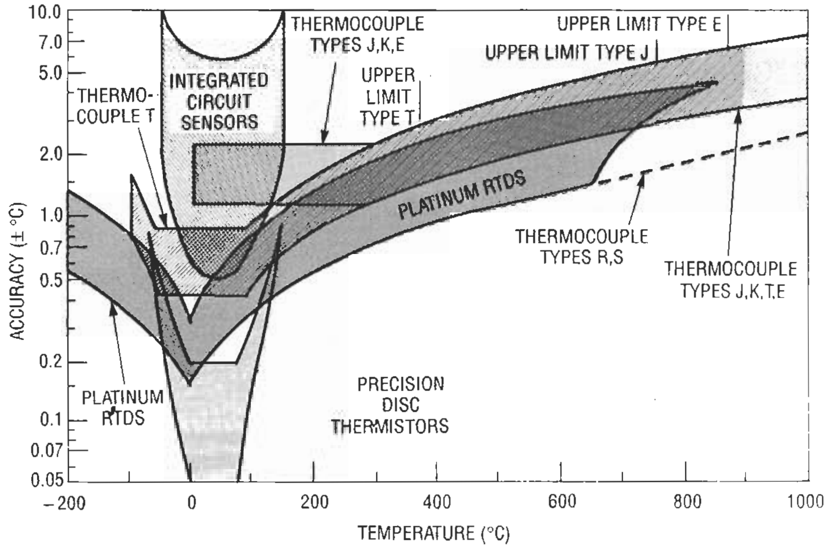


FIG. 4—THE "BEST" TEMPERATURE SENSOR depends on the temperature range and accuracy required.

TABLE 2—SENSOR COMPARISON CHART

Sensor Type	Typical Sensitivity	Temperature Range	Midrange Accuracy	Non-Linearity
Base Metal Thermocouples Types J, K, T, E, N	40 to 70 μV/°C	−270 to 1372°C	1.1 to 2.2°C	1 to 5%
Platinum Alloy Thermocouples Types R, S, B	7 to 12 μV/°C	−50 to 1820°C	0.6 to 1.5°C	1 to 5%
Tungsten Alloy Thermocouples	10 to 21 μV/°C	−17 to 2315°C	4.5°C	2 to 7%
Platinum Resistance Thermometers (100Ω)	0.4Ω/°C	−200 to 650°C	0.1 to 0.25°C	1 to 3%
Nickel Resistance Thermometers (100Ω)	0.7Ω/°C	−60 to 180°C	0.4°C	1 to 5%
Precision Disc Thermistors	−3 to −5 %/°C	−80 to 150°C	0.1 to 0.2°C	Inherently Nonlinear
Glass Bead Thermistors	−3 to −5 %/°C	−60 to 300°C	Noninterchangeable	Inherently Nonlinear
Integrated Circuit Sensors	1μA/°C or 1 to 10mV/°C	−50 to 150°C	0.5 to 5°C	0.3 to 3°C

junction drops about 0.7 volts, with a negative temperature coefficient of approximately −2mV/°C. The exact voltage and temperature coefficient depends upon the junction's geometry, current density, and other factors.

Precise calibration requires individual measurement of each diode or transistor at known temperatures. The basic equation for a P-N junction is:

$$I = I_o\left(e^{\frac{qV}{kT}} - 1\right)$$

where q is the charge of an electron, k is a physical constant known as the Boltzmann constant, and T is the absolute temperature (Kelvins). I_O is a constant, basically equal to the reverse-biased leakage current. At room temperature, the quantity kT/q is about 26 mV. Under normal forward-biased conditions the −1 term is insignificant and can be ignored, so:

$$I \cong I_o e^{\frac{qV}{kT}}$$

so

$$\ln\left(\frac{I}{I_o}\right) = V$$

An IC temperature sensor's operation is based on the difference between two base-emitter voltage drops where the junction currents are maintained at a constant ratio, I2/I1. Applying a little algebra to that equation shows that the voltage difference is given by:

$$V_2 - V_1 = \frac{kT}{q}\ln\left(\frac{I2}{I1}\right)$$

Circuits within the IC use that difference to create an output voltage or current which is proportional to temperature.

Table 3 lists four IC's. The AD590 and AD592 behave iden-

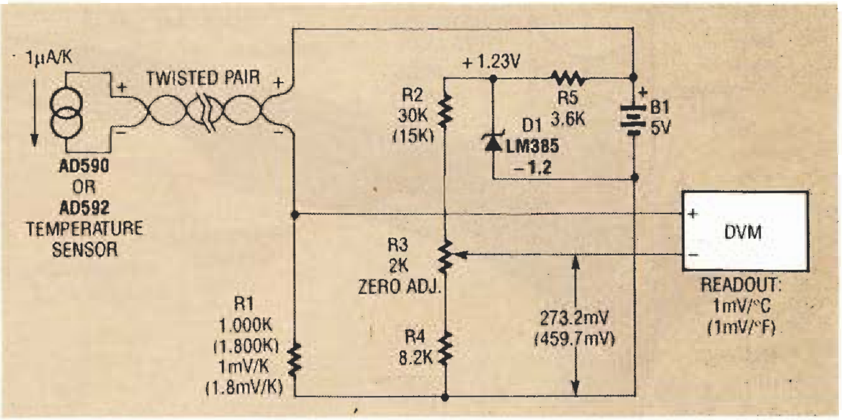


FIG. 5—AN AD590 OR AD592 makes it easy to transmit temperature data over a pair of wires. The circuit produces 1mV/°C (or 1mV/°F using the values in parentheses).

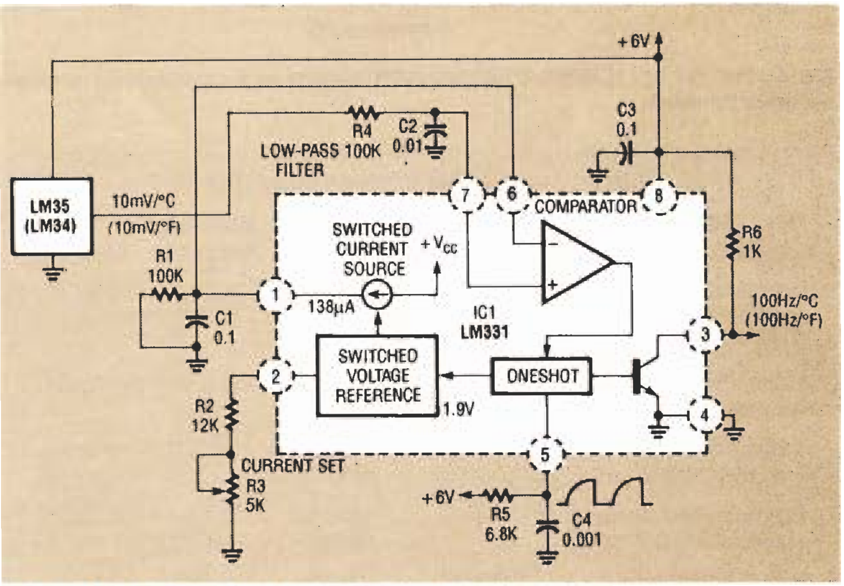


FIG. 6—AN LM35 OR LM34 PLUS A V/F IC produces a frequency proportional to temperature.

TABLE 3—TEMPERATURE SENSORS

Type & Mfr	Description	Available Ranges	Available Accuracies
AD590: Analog Devices, Harris	Two terminal current source 1µA/K	−55 to 150°C	1.7 to 10°C (0.5 to 5°C @ 25°C)
AD592: Analog Devices	Two terminal current source 1µA/K	−25 to 105°C	1 to 3.5°C (0.5 to 2.5°C @ 0 to 70°C)
LM34, LM35: National	Three terminal current source 10mV/°F (LM34) 10mV/°C (LM35)	−55 to 150°C	1.5 to 2°C (0.5 to 1°C @ 25°C)
LM135/235/335: National	Two terminal voltage regulator 10mV/K, calibratable	−40 to 100°C −40 to 125°C −55 to 150°C	2.7 to 9°C (1 to 6°C @ 25°C) without user calibration

tically, but the newer AD592 is less expensive (plastic T0-92 case), covers a narrower range, and, over that range, offers tighter accuracy. National's LM34/LM35 is a three-terminal device having zero output voltage at 0°F or C, while the LM135/235/335 is a Zener-like device with an output proportional to absolute temperature.

Let's start with the AD590/592.

The AD590 and AD592 are two-terminal current regulators with an output of 1 µA/K (273.15 µA at 0°C). Calibrated by the manufacturer at 5 volts, operation is guaranteed from 4 to 30V. Keep in mind, though, that raising the voltage increases internal power dissipation and leads to slight measurement errors.

Figure 5 illustrates their use in a simple circuit providing DVM temperature readout in °C or °F. The 1 µA/K current passes through R1, which converts it to voltage with a sensitivity of 1 mV/°C (1.000K) or 1 mV/°F (1.800K). The voltage across R1 is proportional to absolute temperature.

Resistors R2, R3, and R4 provide an offset equal to R1's voltage at 0°C or 0°F. The offset is adjusted using the DVM: simply set R3 for an output of 273.2 mV for Celsius readings or 459.7 mV for Fahrenheit. If R1 is purchased (or trimmed using a digital ohmmeter) to ±0.1%, no temperature calibration is required to achieve the IC's rated accuracy.

If you want to achieve superior accuracy using a lower grade (looser tolerance) IC, you can make R1 adjustable. Place the IC at a known temperature, connect the DVM across R1, and adjust it for the correct reading based on 1 mV/degree. (Suggestion: place the IC in a closed-end sheath and let it come to equilibrium in a stirred ice-and-water bath. Trim R1 until the voltage across it is 273.2 at 0°C

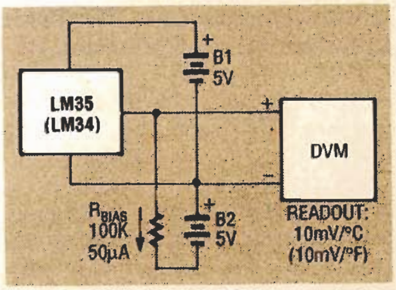


FIG. 7—A NEGATIVE BIAS is needed for readings below zero degrees.

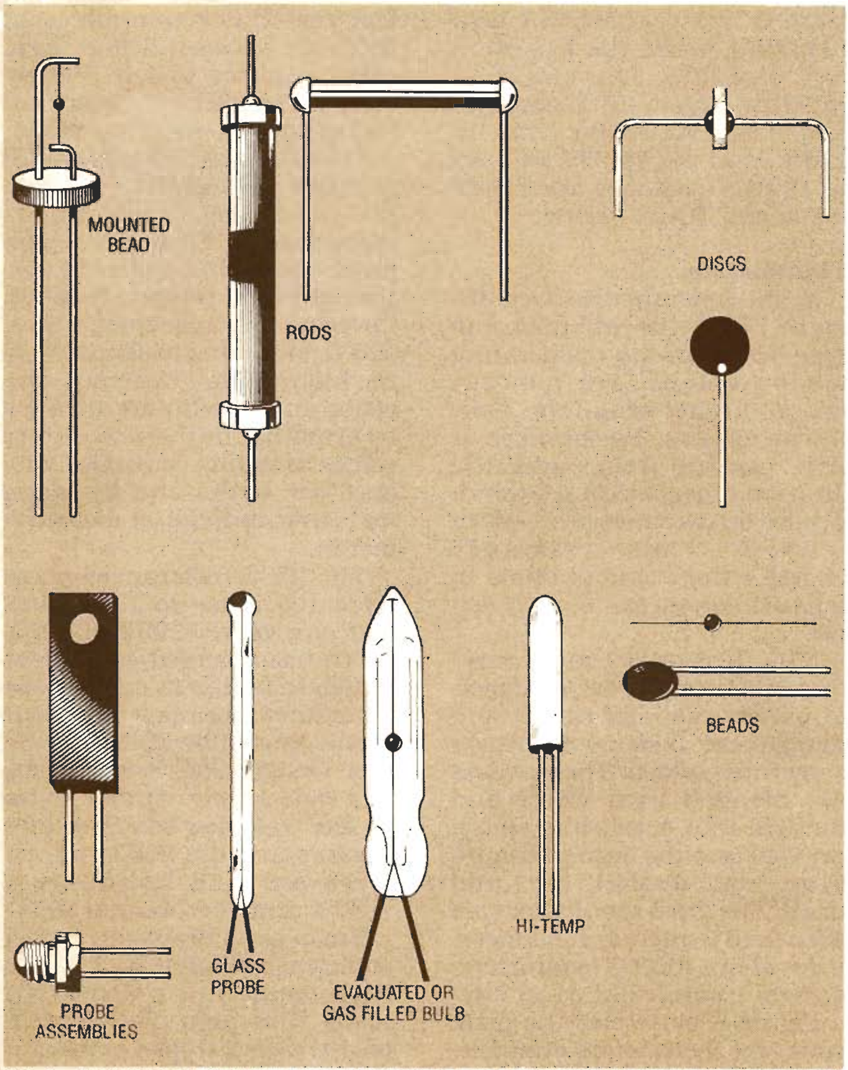


FIG. 8—A BROAD VARIETY of thermistor styles are available. Shown here are some of the more common ones.

TABLE 4—THERMISTOR CHARACTERISTICS

Thermistor Type	Available Resistances	Mid-Range Accuracy	Typical Temperature Range
Low Cost	100 ohms to 200K	5 to 20% (1 to 5°C)	−50 to 150°C
Precision Interchangeable Disc	100 ohms to 1 megohm	0.1 to 0.2°C (0.5 to 1%)	−80 to 150°C
Glass Bead	200 ohms to 1 megohm	20% (5°C)	−60 to 300°C
Glass Coated Interchangeable Disc	2.2K to 30K	0.05 to 0.2°C (0.2 to 1%)	−80 to 250°C

or 491.7 mV at 32°F.) Adjust R3 as described earlier.

The AD590 is available in several grades from ±5°C (AD590J) to ±0.5°C at 25°C (AD590M). The AD592's guaranteed 25°C accuracies range from ±2.5°C (AD592AN) to ±0.5°C (AD592CD). The AD590 is available in TO-52 transistor can or flat-pack enclosures, while the AD592 is sold in a TO-92 plastic transistor package. Both are sold as unpackaged, trimmed chips.

National's LM34/35 series is even easier to use. A three-terminal IC, it outputs 10 mV/°F (LM34) or 10 mV/°C (LM35) and is zero-based (zero millivolts at zero degrees). All that is needed to read temperature is a DVM and a battery or voltage source (anywhere from 4 to 30 volts).

Figure 6 combines an LM34 or LM35 with an LM331 voltage-to-frequency converter to provide a frequency proportional to temperature. The component values shown produce an output of 100 Hz/degree (10 kHz at 100°F or C). For more information on the LM331 and other V/F converters see "V/F Converters," **Radio-Electronics**, June 1991.

As with the AD590/592, no temperature calibration is necessary. To calibrate it, you temporarily disconnect the sensor, provide a precise 1.000 volt input, and adjust R3 for 10.00-kHz output. No zero adjustment is necessary. For improved accuracy using loose-tolerance IC's, you can place the IC at an accurately-known temperature near the high end of its range and adjust R3 for the proper output.

The LM34/35 needs a negative bias to track temperatures below zero. Figure 7 shows the basics: the IC is powered by a positive supply, but a negative bias current of approximately 50 μA is added to the output.

The LM35 is available with temperature ranges of −55 to 150°C, −40 to 110°C (suffix C), and 0 to 100°C (suffix D), and with 25°C guaranteed accuracies of ±1°C and ±0.5°C (suffix A). Similar grades are available for the LM34 Fahrenheit version. Packages are TO-46 metal and TO-92 plastic. The last IC in the table is National's LM135/235/335 series.

The LM135 operates as a Zener-like two-terminal voltage regulator IC, similar to an LM185 reference. A third terminal allows a potentiometer to be added for user calibration. The bias or "Zener" current may be anywhere from 400 μA to 5 mA. Its output is proportional to absolute temperature, 10 mV/K (2.73 volts at 0°C).

The tightest 25°C guaranteed accuracy without user calibration is ±1°C (LM135A and LM235A), while the loosest is ±°C (LM335). The LM135 is rated for −55 to 150°C continuous, the LM235 for −40 to 125°C, and the LM335 for −40 to 100°C. Packages are TO-46 metal and TO-92 plastic.

Thermistors

Negative temperature coefficient (NTC) thermistors, the type best suited to temperature measurement, are narrow-range, highly sensitive, nonlinear devices. Resistances at 25°C can run from under 100 ohms to 1 megohm and beyond. Typical sensitivities are −3% to −5%/°C. Thus resistance changes from tens of ohms to tens of kilohms per °C are possible.

NTC thermistors are formed from mixtures of powdered metal oxides, usually nickel and manganese oxides with others sometimes added. The powders are blended with water and binders into a clay-like slurry, pressed into the desired shapes (disc, rod, washer, etc.) and dried. The dried thermistors are then fired (sintered) at temperatures above 1000°C to form a resistive, ceramic-like structure.

Figure 8 illustrates the great variety of thermistors available. Most common for temperature measurement applications are epoxy-coated discs, generally under 0.1-inch in diameter. Similarly-sized glass-coated discs perform at higher temperatures. Bead thermistors, both glass-coated and bare, offer small size and fast response. Sizes vary from around 0.05 inch down to 0.005 inch. At the other end of the spectrum, thermistor rods are available as well as disc and washer shapes up to 1-inch diameter. In addition, several manufacturers offer thermistor sensor assemblies ranging from straight-stick probes to bolt-on and surface-mount assemblies to transistor cans.

Specifications vary greatly, but Table 4 summarizes several types. Thermistors have a reputation of being not too accurate or stable—and that is true of most inexpensive devices. Typical resistance tolerances at 25°C are between 5 and 20%, corresponding to 1 to 5°C accuracy. The tolerance loosens at high and low temperatures.

At least three companies (YSI in Yellow Springs OH, Fenwal in Milford MA, and Thermometrics in Edison NJ) offer precision interchangeable disc thermistors (epoxy coated). Covering the range from −80 to 150°C, loosening to about 1°C at the high and low extremes. Precision and stability are achieved by grinding the discs to precise values in tightly-controlled temperature baths and by aging tests and individual measurements.

The 25°C resistances range from 100 ohms to 1 megohm, but one value (2252 ohms at 25°C) has emerged as a quasi-standard for use in medical and laboratory thermometers. Commonly known by YSI's "400 Series" designation, it is available in a wide variety of probe styles. To illustrate how sensitive thermistors are, the 2252-ohm devices are 1.66 megohms at −80°C and 41.9 ohms at 150°C.

Small glass beads are formed somewhat differently. A pair of high-temperature wires (typically fine-gage platinum) is coated with a droplet of the slurry, fired, and then dipped into molten glass. The result is a high-temperature device which typically is more stable than epoxy-coated discs but which cannot be ground or trimmed. For precision applications thermistors may be supplied by the manufacturer with individual test measurements. For interchangeability, the manufacturer may select and preassemble two thermistors in parallel to match a specific calibration curve. Glass beads generally are specified to about 300°C.

Next month we'll look at some thermistor application circuits, then move on to resistance thermometers and thermocouples. We will conclude with a look at noncontact radiation thermometry. If you want to study thermistors in detail, look at **Radio-Electronics**' three-part series, "All About Thermistors," January—March 1985. **R-E**