Designer's Guide to: Temperature measurement

Having selected the optimum sensor for your application, you now must convert its output into a useable signal.

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Part 1 of this tutorial reviewed the characteristics of the various transducers that can sense levels of heat. But whatever device you choose for your temperature-measurement application, you will also need signal-conditioning circuitry—the subject of this article.

Signal-conditioning circuitry must accurately convert the sensor's output into information meaningful to the user. Requirements for such circuitry vary considerably. In some applications, the electronics exists in a low-noise laboratory environment but must perform ultra-precise measurements. In others, it's located thousands of feet from the sensor and in a high-noise environment, but the accuracy requirements are relaxed. Whatever the case, you should recognize that sensor characteristics, signal conditioning and qualitative results are interrelated, inseparable issues.

For straightforward problems—simple solutions

Designers can take simple and reliable "GO/NO-GO"-type temperature measurements with thermoswitches and electrical-output mercury thermometers. A single thermoswitch can determine if an object or process has reached a predetermined temperature, or it can also perform dual limit functions. **Fig. 1a** shows how a mercury thermometer with two switch contacts can be used on an assembly line to inexpensively check the temperature of an instrument's component ovens. The technician inserts the thermometer bulb into a well in the oven, then the bulb will light only if the temperature lies within preset limits.

Fig. 1b shows a similar arrangement. Here, two thermoswitches monitor the wall temperature of a chemical vat that must remain between 45 and 60°C while being filled. If the wall temperature is within these limits, the relay is energized and issues a command to fill the vat. At lower or higher temperatures, the relay deenergizes, stopping the filling process.

Analog readouts are easily obtained with a thermistor or other resistive sensor in a simple, uncalibrated deviation bridge **(Fig. 2).** Here the meter reads zero when $R_t = R_2$ and indicates deviations from this point. This type of readout serves "ballpark" checks of equipment. Despite the fact that both the sensor and bridge responses are nonlinear, the meter reading will be approximately linear for small deviations and/or can be calibrated for large spans.

An unreferenced thermocouple can also read deviations from a reference temperature. In **Fig. 3,** a thermocouple monitors temperatures inside a furnace. Of course, the exact temperature proves difficult to determine because the thermocouple is unreferenced. But since the meter is only calibrated in terms of "hot" and "cold," the measurement scheme sufficies. The op amp

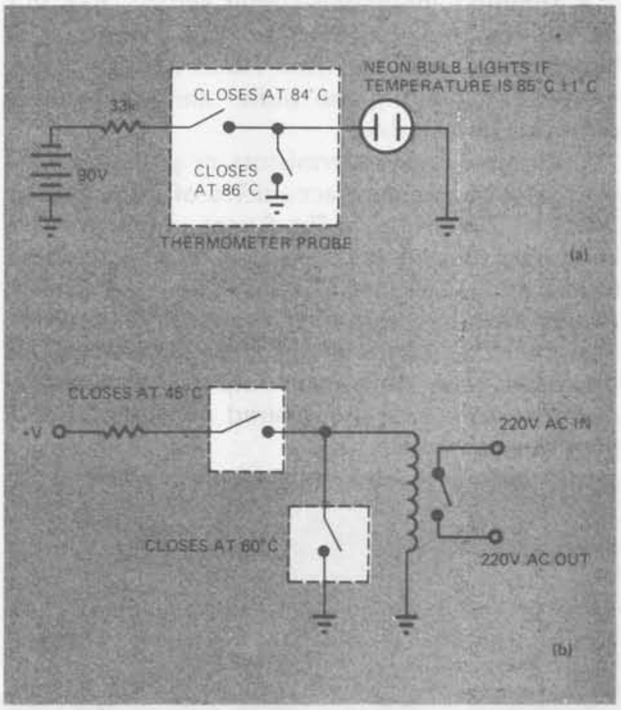


Fig. 1—Thermoswitches can measure temperatures for GO/NO-GO situations. In **a,** a mercury thermometer with two switched contacts provides a ±1° check on crystal ovens during assembly. In **b,** an arrangement of snap-action devices determines the temperature in a vat and issues switching commands to a fill control relay.

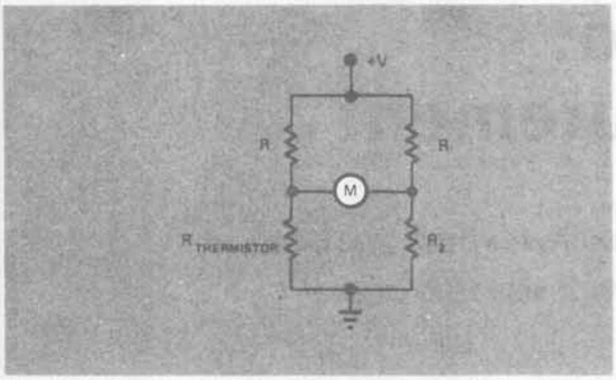


Fig. 2—As the thermistor's value approaches that of R_2, the meter reading approaches zero. Despite nonlinearities in the bridge and sensor response, a linearly calibrated meter proves quite accurate for small temperature ranges.

provides the gain needed to drive the meter.

When greater accuracies are needed....

Calibrated systems require more sophistication. In **Fig. 4,** a low-cost sensor (1N914 diode) provides ±1° accuracy over 0 to +100°C. Calibration is simple: Put the diode in a 0°C environment and adjust the zero potentiometer for 0V output, then place the diode in a 100°C environment and adjust the F.S. potentiometer for a 10V output. (This procedure should be repeated until interaction between the adjustments ceases.) Although this circuit is inexpensive, its calibration is time consuming.

A trimmed integrated-circuit sensor, like the AD590, requires no calibration at all. The circuit of **Fig. 5** reads within ±1° from 148 to 473°K (−125 to +200°C). Offsetting the buffer amplifier makes other scales possible.

Calibrated linear thermistors or platinum sensors provide absolute accuracies of from 0.15 to >0.01°C. The circuit of **Fig. 6** uses an inexpensive linearized thermistor composite to achieve absolute accuracy of 0.15°C over 0 to +100°C. The AD580 band-gap reference drives the 741J, which has the YSI 44018 temperature sensor in its feedback loop. The voltage output of A_1 feeds A_2, and the latter sets the desired output gain and provides zeroing.

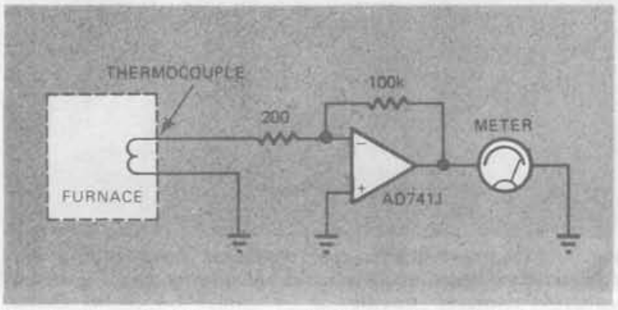


Fig. 3—To get a "hot" or "cold" indication of the heat in a furnace, an unreferenced thermocouple driving a simple amplifier suffices.

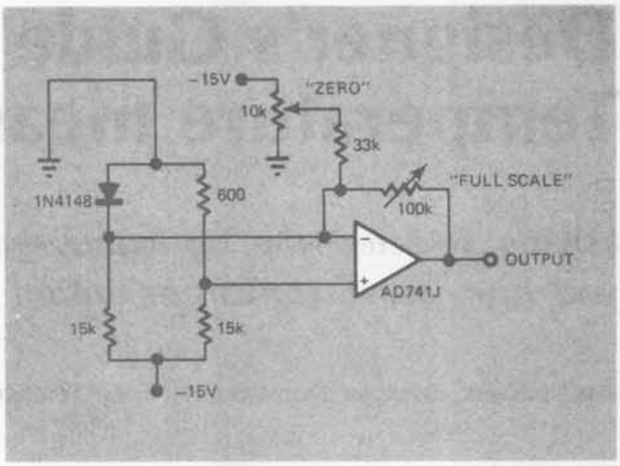


Fig. 4—After a 2-point calibration, this circuit provides ±1° accuracy over 0 to +100°C.

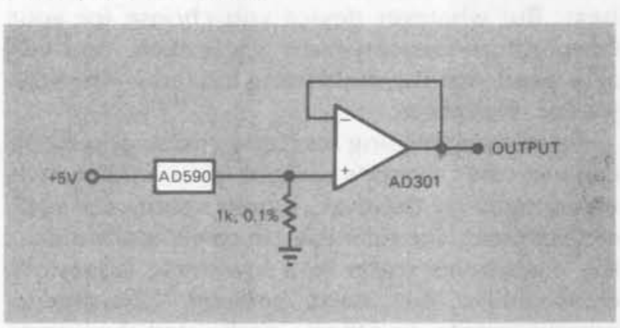


Fig. 5—Factory trimming of the AD590 IC temperature sensor permits this circuit to measure temperatures from −125 to +200°C with 1° accuracy.

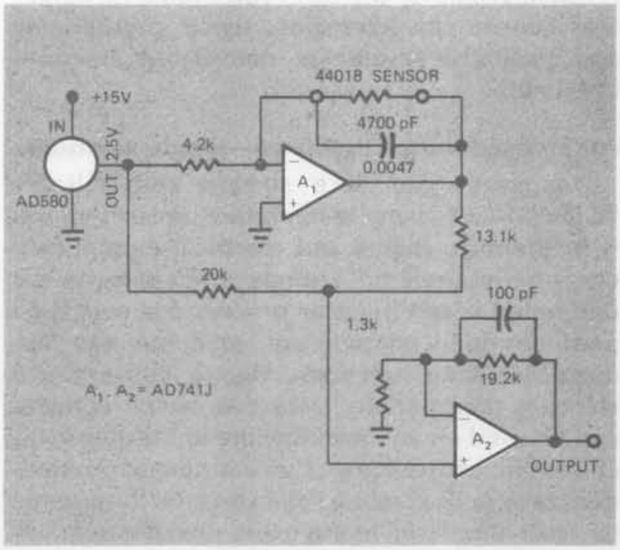


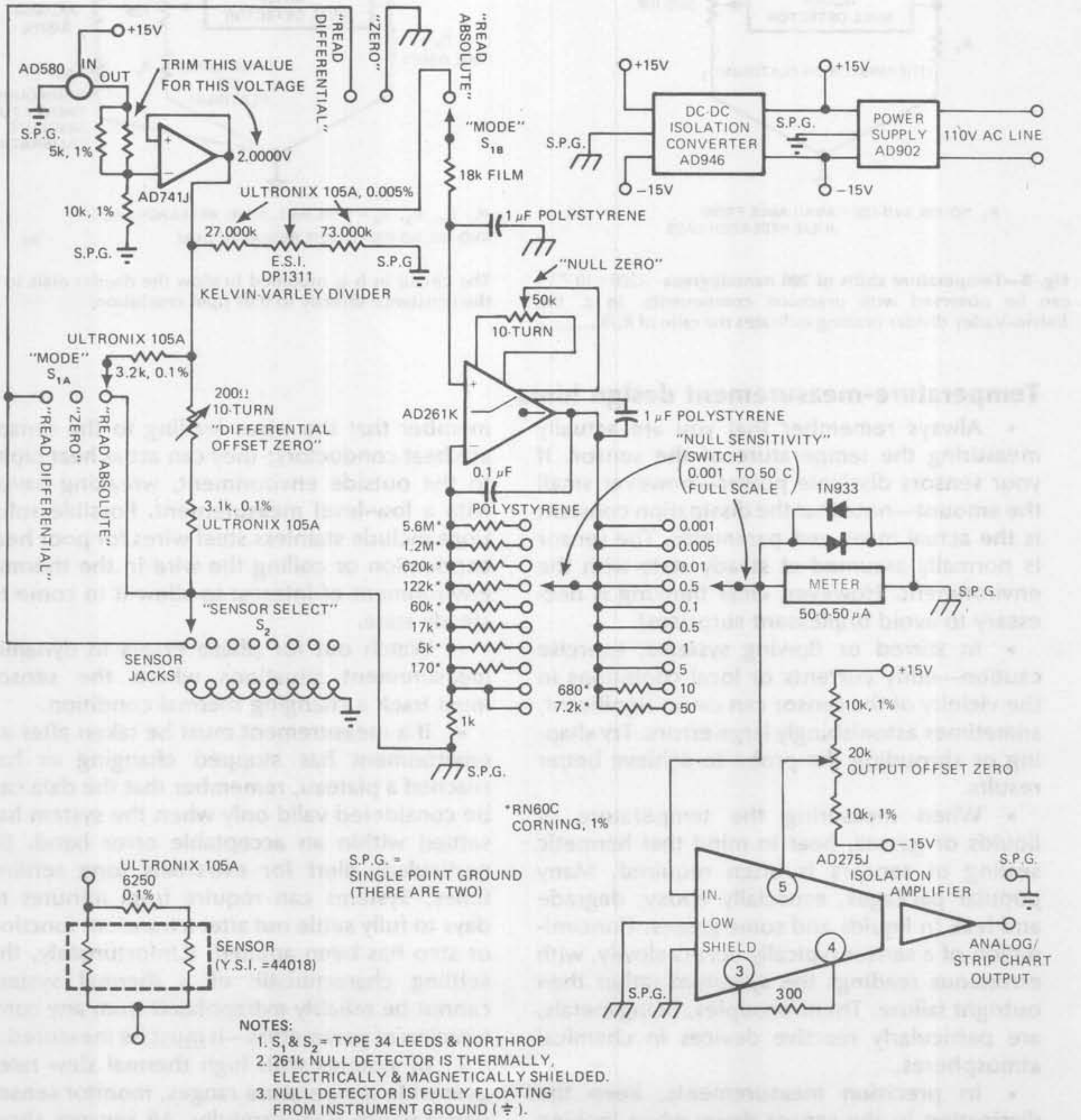
Fig. 6—An inexpensive, linearized thermistor generates the temperature-dependent signal, then A_2 provides needed gain and offset. Circuit achieves 0.15°C absolute accuracy over 0 to +100°C.

A high-resolution differential thermometer

Fig. 7 diagrams a high-performance, extremely versatile temperature-measuring instrument that can handle applications ranging from determining heat-sink temperature rise to performing microcalorimetry. It reads a thermistor sensor from any of eight switch-selected inputs to 100 μ° resolution over a 0 to +100°C range with 0.15°C absolute accuracy. Additionally, this device measures the temperature difference between two sensors to 100 μ° sensitivity.

The circuit is basically the thermometric equivalent of a differential voltmeter. Temperature is directly dialed out on the 5-decade Kelvin-Varley voltage divider. Differences between this temperature and that of the sensor are observed on the meter. Full-scale sensitivity of the meter varies from 50 to 0.001°C and is controlled by the gain of the chopper-stabilized null detector. Fully floated from instrument ground, the null detector provides high sensitivity and low noise and drives both the meter and a 275J isolation amplifier. The latter supplies a ground-referenced strip chart recorder output.

In the "Read Absolute" mode, the null detector compares the voltage from the sensor network to that at the Kelvin-Varley divider output. Since both the sensor network and K-V divider are driven from the same potential, the measurement is ratiometric and a stable reference is not



NOTES:
1. S_1 & S_2 = TYPE 34 LEEDS & NORTHROP
2. 261k NULL DETECTOR IS THERMALLY, ELECTRICALLY & MAGNETICALLY SHIELDED.
3. NULL DETECTOR IS FULLY FLOATING FROM INSTRUMENT GROUND (⏚).

Fig. 7—Kelvin-Varley voltage divider setting reads temperature directly in this differential thermometer. Gain of the null detector varies the F.S. sensitivity from 0.001 to 50°C. Unit can indicate 100 μ° shifts in sensitivity.

required. In this mode, the temperature of an environment or surface can be determined to 0.15°C absolute accuracy. Moreover, shifts in stability of 100 μ° are directly readable.

In the "zero" mode, the null detector offset can be trimmed out with the "zero" control.

In the "Read Differential" mode, sensor number 1 reads differentially against any of the other seven switch-selected sensors. This mode can be used for microcalorimetry, where both sensors are in close physical proximity in a controlled thermal environment. Typically, one sensor is

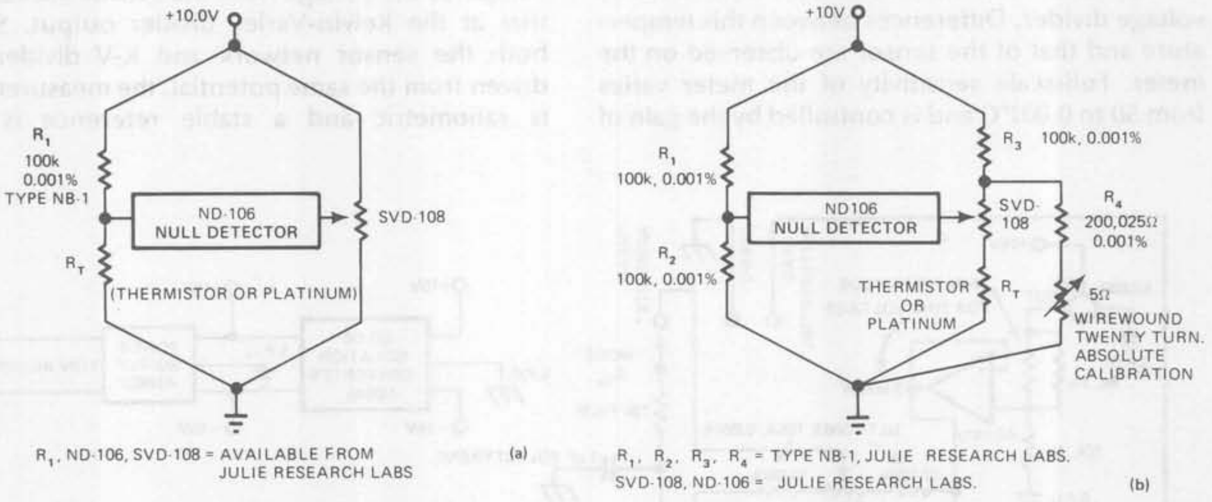


Fig. 8—Temperature shifts of 200 nanodegrees (200×10^{-7}°C) can be observed with precision components. In **a,** the Kelvin-Varley divider reading indicates the ratio of $R_1/R_{thermistor}$.

The circuit in **b** is modified to allow the divider dials to read the resistance directly to 0.01 ppm resolution.

Temperature-measurement design hints

- Always remember that you are actually measuring the temperature of the sensor. If your sensors dissipate power—however small the amount—note that the dissipation constant is the actual measured parameter. The sensor is normally assumed at steady state with the environment. However, clear thinking is necessary to avoid unpleasant surprises!
- In stirred or flowing systems, exercise caution—eddy currents or local conditions in the vicinity of the sensor can cause significant, sometimes astonishingly large errors. Try shaping or shrouding the probe to achieve better results.
- When measuring the temperature of liquids or gasses, bear in mind that hermetic sealing of sensors is often required. Many popular packages, especially epoxy, degrade and leak in liquids and some gasses. Contamination of a sensor typically occurs slowly, with erroneous readings the symptom rather than outright failure. Thermocouples, being metals, are particularly reactive devices in chemical atmospheres.
- In precision measurements, keep the dissipation in the sensor down when looking for high absolute accuracy or when attempting to detect small changes in temperature. Remember that the wires leading to the sensor are heat conductors; they can act as heat pipes to the outside environment, wreaking havoc with a low-level measurement. Possible solutions include stainless steel wires for poor heat conduction or coiling the wire in the thermal environment of interest to allow it to come to steady state.
- Watch out for phase errors in dynamic measurement situations where the sensor must track a changing thermal condition.
- If a measurement must be taken after an environment has stopped changing or has reached a plateau, remember that the data can be considered valid only when the system has settled within an acceptable error band. Be particularly alert for extremely long settling times. Systems can require from minutes to days to fully settle out after a transient function or step has been applied. (Unfortunately, the settling characteristic of a thermal system cannot be reliably extrapolated from any combination of parameters—it must be measured.)
- In systems with high thermal slew rates over wide temperature ranges, monitor sensor performance very carefully. All sensors show some calibration shift after repeated exposure to thermal shock.

coated with reactive biochemicals, while its uncoated twin serves as a reference. When additional biochemical agents are introduced, the coated sensor becomes 100 to 300 $\mu°$ warmer than the reference (due to heat of reaction), and the instrument reads this difference. The "Read Differential" mode can also serve such common applications as determining the gradient between a power transistor and various points on its heat sink.

Taking good ideas one step further

Really precise measurements of absolute temperature and temperature deviations call for state-of-the-art components. **Fig. 8** shows an arrangement for reading a thermistor or platinum sensor to better than 0.01 ppm resolution. The 8-decade resolution Kelvin-Varley divider allows tracking of 0.001Ω shifts in a 100 kΩ thermistor. This arrangement provides the electronic capability to detect 200 nanodegree (200×10^{-9}°C!) temperature shifts and has been used to perform 500 pW microcalorimetry. (A single human cell operates at about the nanowatt level.)

The K-V divider readout gives the ratio of the sensor to R_{std}, from which the absolute value of the sensor can be calculated. If you alter the bridge structure **(Fig. 8b),** the divider dials can indicate the absolute value of the sensor directly in ohms.

Note that the concepts employed in these ultra-precision circuits are merely extensions of the simple circuits presented in the beginning of this article—the major differences being the greater difficulty of manufacture and the substantial increase in cost.

This T-to-F converter uses a diode sensor

Many measurement situations call for digital output of temperature information. **Fig. 9a** depicts a direct temperature-to-frequency converter that can be built for a parts cost of less than $5. The circuit uses a diode sensor for economy and responds with a 0 to 1 kHz output for 0 to +100.0°F. Accuracy is ±0.3°F.

Operation is basically that of an operational-amplifier controlled relaxation oscillator, where the -2.2 mV/°C temperature shift of the diode determines the charging rate of the 4300 pF capacitor. The 100 pF capacitor provides feed-forward compensation for the 301 amplifier, decreasing the oscillator's reset time to ensure linearity. A 1N821 compensated zener stabilizes the circuit against supply-voltage changes. At the output, the 680 pF/2.2 kΩ network differentiates the 400 nsec reset edge of the op amp's negative-going output ramp and drives the single transistor inverter.

Note that a current source does not drive the sensor diode as you might expect. Instead, the loading error that the "−" input resistor imposes on the 1k potentiometer's output has been calculated to offset the slightly nonlinear response of the voltage-driven 1N4148.

Variations of T-to-F's abound. **Fig. 9b** shows a circuit that uses the current-source output of a current-ratioed, differential pair IC temperature transducer for low parts count. This scheme provides 125 to 470 Hz for 125 to 470°K. But if even greater simplicity is desired, **Fig. 9c** shows how the on-chip temperature sensor in an AD537 IC voltage-to-frequency converter can perform direct T-to-F conversion using only four external parts.

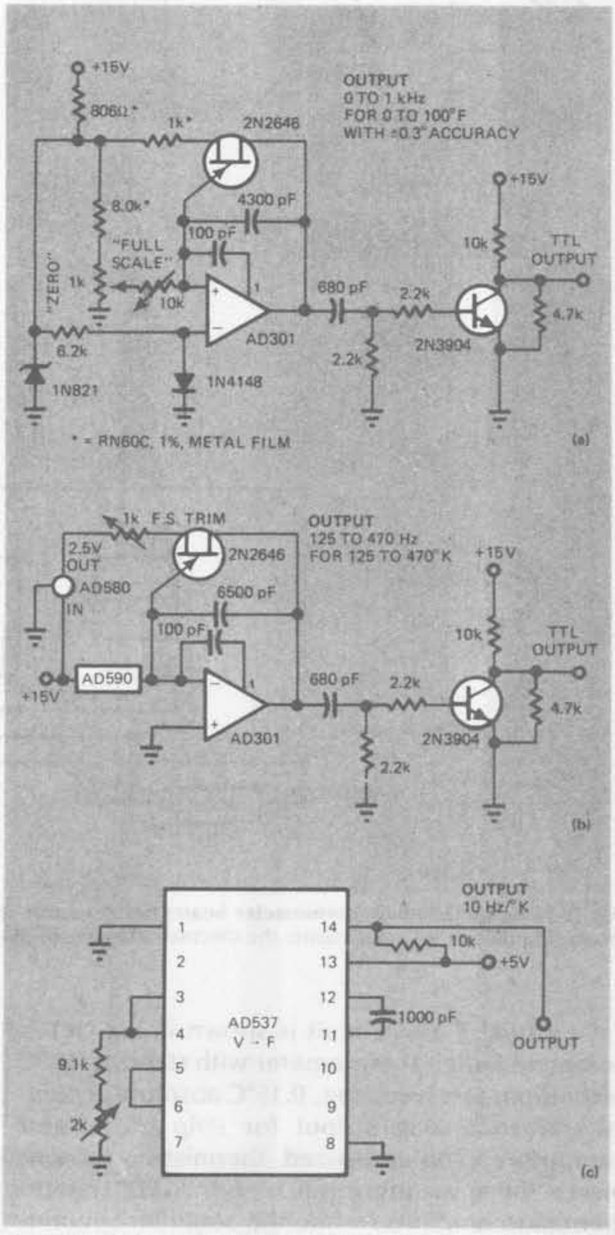


Fig. 9—Variations on a theme: Each of these circuits produces an output pulse train whose frequency is proportional to temperature.

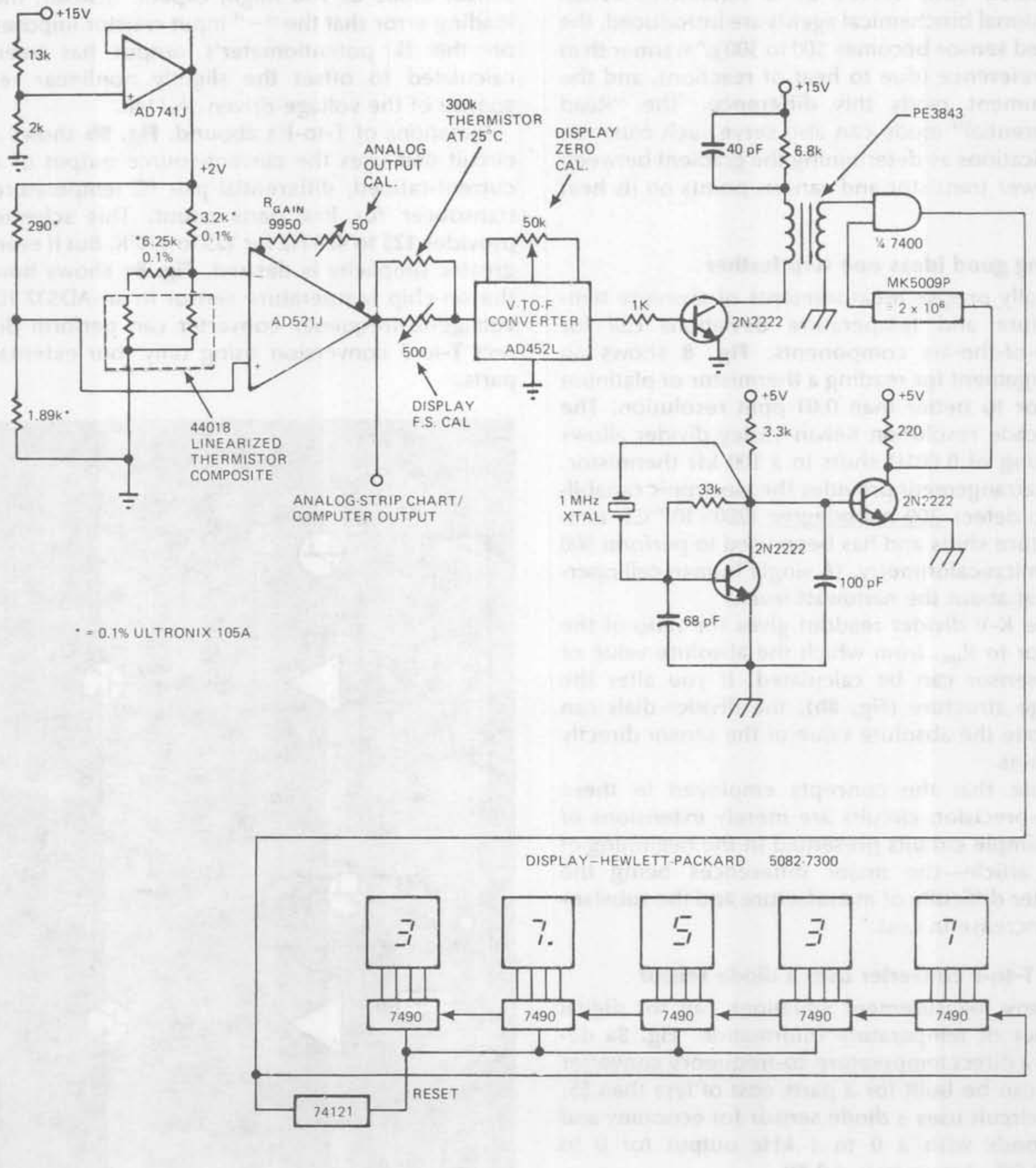


Fig. 10—Complete 5-digit thermometer boasts fast response, stable 0.001°C resolution and 0.15°C absolute accuracy. The 2-sec readout update rate complements the thermal response of the thermistor network.

One final T-to-F circuit is shown in **Fig. 10**—a complete 5-digit thermometer with stable 0.001°C resolution, fast response, 0.15°C absolute accuracy and an analog output for strip charts and computers. The linearized thermistor network biases the inverting input of the AD521 instrumentation amplifier, while the amplifier's noninverting input is driven from the same reference that drives the sensor. Output of the AD521—a precise 0 to 10V for 0 to +100°C—feeds the voltage-to-frequency converter that digitizes the analog signal.

The circuit's 2-sec update rate complements the sensor's thermal response. Further, the thermistor across the V-to-F's gain setting resistor provides sufficient temperature compensation to achieve stable 0.001°C resolution over a 20 to 30°C instrument ambient.

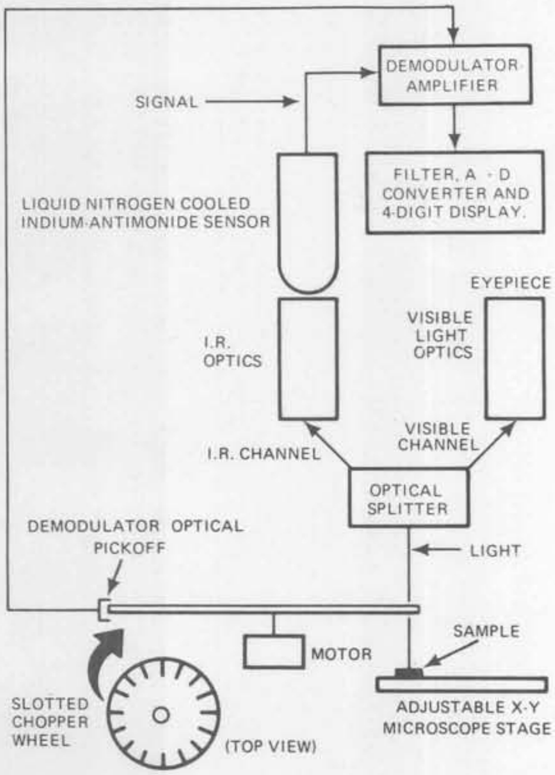


Fig. 11—Noncontact temperature measurements to 0.01°C resolution can be achieved by this IR thermal microscope.

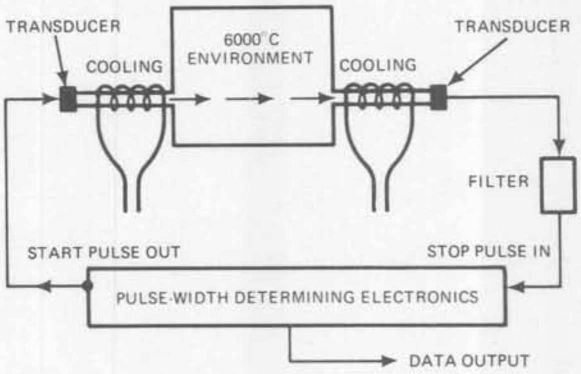


Fig. 12—For measurements at temperature extremes, an acoustic thermometer fills the bill. The medium through which the pulse must travel must be known, however.

Look, but don't touch...

Part 1, the May 5th article, described applications that require noncontact temperature measurements, detailed the infrared (IR) sensors that can be used in such cases and briefly mentioned an IR thermal microscope being developed at M.I.T.'s Nutrition and Food Science Instrumentation Laboratory. **Fig. 11** block diagrams that unit. Its 0.01°C resolution and digital display will permit researchers to monitor the progress of cancerous cells across a piece of tissue. The unit can also be used in IC design to determine the exact temperature difference between the input transistors of a low-drift op amp. From this data the optimum thermal layout can be determined.

In operation, a slotted wheel optically chops the light from the sample. The chopped light is then split into infrared and visible channels, the latter being used in the normal fashion. The IR channel, however, is sensed by a high-performance detector which is cooled by liquid nitrogen to keep noise as low as possible. The detector's output feeds an amplifier that is switched at the chopping frequency. The resultant synchronously demodulated output is filtered, converted to digital and displayed on a 4-digit readout.

Acoustic thermometers can also take accurate noncontact measurements at temperature extremes if the medium through which the sonic pulse must travel is known. **Fig. 12** shows an acoustic thermometer being used to determine the temperature of a 6000°C environment. The sonic transducers are maintained at relatively low temperatures outside the super-hot area. Of course, the pathlengths of the extension tubes must be thermally and sonically defined, because they must be subtracted out as an offset by the circuitry that determines the temperature-related pulse width.

Control comes next....

In our June 20, 1977 issue, Part 3 will conclude this series with an in-depth treatment of thermal control systems. We will emphasize practice rather than theory: Nine different actual working circuits will be presented, including one that can hold the temperature in an oven to within 3.3 μ° over a 3-hr period. A potpourri of general design hints will provide a reference overview and series wrap-up. ☐

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