

Heat Pen Project

**Measure temperature directly with your digital voltmeter;
build this simple add-on.**

By Geoff Phillips

THE HEAT PEN is a low cost temperature probe that transforms a standard DVM into a digital thermometer. Just plug the Heat Pen into any digital voltmeter, place the tip onto a surface, and the DVM shows its temperature directly in degrees C. Its range is from -50 to +150 degrees C.

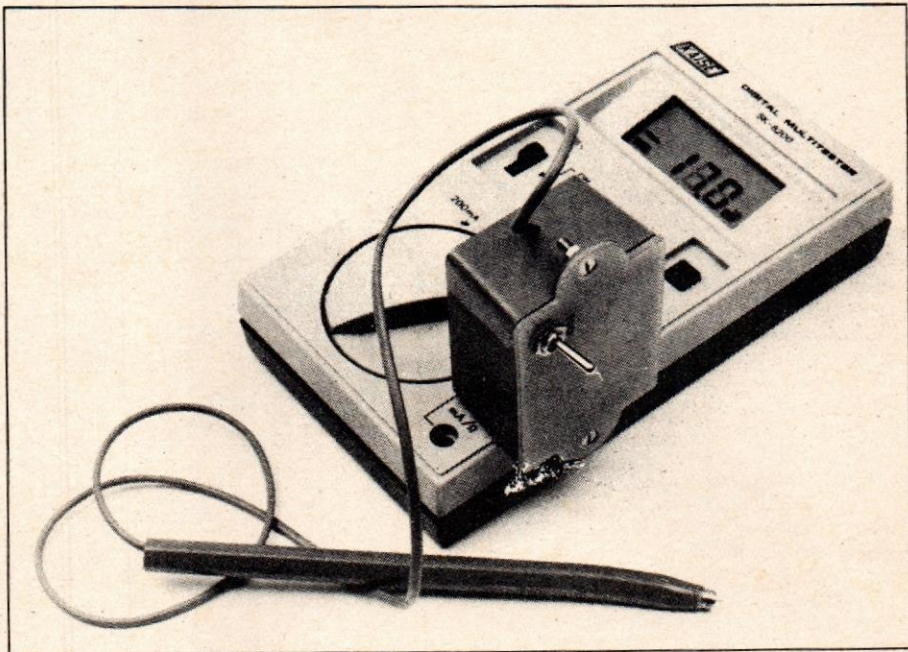
Thermocouples are messy; they require cold junction compensation and scale conversion. Stick-on labels have their uses but they are expensive and can only be used once. The Heat Pen is an inexpensive solution to your temperature measurement problems.

Temperatures of power transistors can be measured easily. Balance your central heating equipment by measuring inlet and outlet temperatures. Take your own temperature by placing the Heat Pen under your tongue. The uses are endless.

A semiconductor temperature sensor is used as the probe tip. It gives a nominal 1uA per degree Kelvin. This is converted to 10mV per degree Kelvin. A bandgap voltage reference is amplified to 2.73V; this is subtracted from the voltage signal derived from the probe tip so that the remaining voltage is equivalent to 10mV per degree C. Low power semiconductors are used, making the quiescent current drain of the Heat Pen less than 1mA.

Nearly all DVMs are fitted with 4mm input sockets which are pitched 3/4" apart. The Heat Pen's PCB, as well as

housing the circuitry, also has two 4mm plugs firmly fitted at the 3/4" pitch. The PCB, along with a 9V battery, fits neatly into a plastic utility box. The probe is mounted in a ball point pen casing and is connected to the PCB via a shielded cable.



Construction

Fit the resistors, capacitor, then IC1 and ZD1 to the PCB. No special precautions are required. Remove the plastic casing from the two 4mm terminals and using a small hacksaw, cut 1mm of the hexagonal sections of the terminals so that approximately 12mm remains. The terminals already have one hole drilled in the hexagonal section. Ideally a second hole should be drilled 8mm from the first. If you have metric taps, drill these holes for an M3 tap and then tap out the holes. Secure the two 4mm terminals to the PCB with M3 x 6mm screws. If you cannot lay your hands on metric taps then the terminal may be fixed to the PCB by passing short lengths of heavy gauge copper wire through the holes and soldering the wires in place. The wires are then passed through the holes in the PCB and soldered in place.

Solder the -ve lead of the 9V battery clip to the 0V terminal of the PCB and solder a 2' lead to the +9V terminal. Solder the conductor of the shielded lead to the PCB and the screen to +9V terminal. The case must now be prepared for the fitting of the PCB.

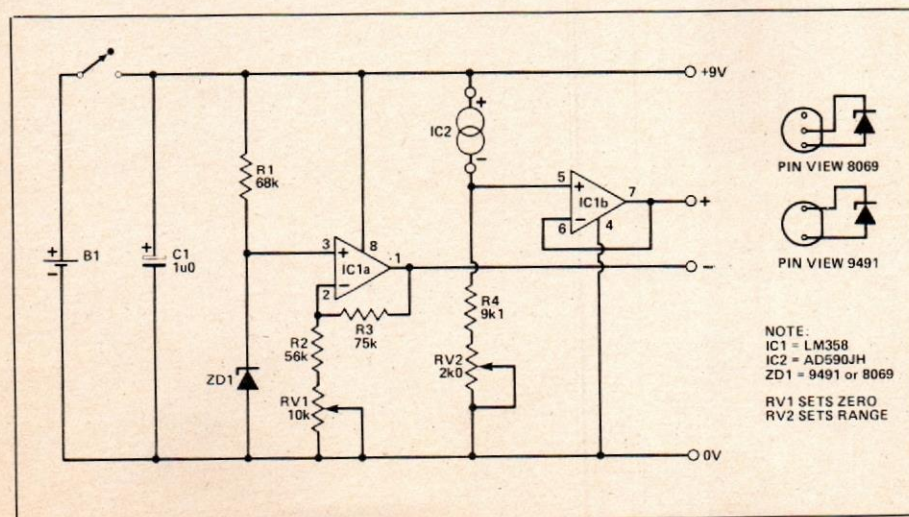


Fig. 1 Circuit diagram of the heat pen.

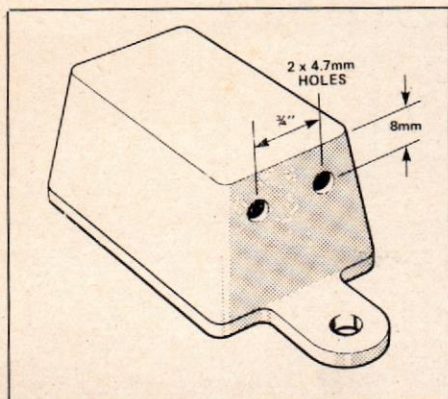


Fig. 2 Case details for the heat pen.

First of all it is necessary to make a cover for the box. This may be made from glass fibre sheet or plastic sheet. Use the box as a template and draw around its shape on the plastic sheet with a scribe. Cut out the shape with a hacksaw. After dressing up the cover with a file, temporarily clamp it to the box and drill two mounting holes through the lugs of the box and cover. Drill and file a hole in the cover for the on/off switch.

The hole will have to be carefully positioned so that the switch does not foul the 9V battery when the unit is assembled. Fit the switch to the cover. Drill two 4.7mm holes in the side of the box (Fig. 2) to allow the 4mm terminals to protrude from the box and one small hole in the opposite end of the box for the shielded cable.

Tie a knot in the shielded cable about 25mm away from the PCB and then pass the cable through the small hole in the box. Pass the two 4mm terminals on the PCB through the two holes in the box and continue to pull the shielded cable through the hole until the PCB is positioned at the bottom of the box.

Pass the shielded cable through the empty ball point pen casing and solder it carefully to the Intersil temperature sensor. The AD590JH has an accuracy of 5 degrees, the AD590IH is 10 degrees, and the AD590KH is 2.5 degrees. The 590-type ICs will be about five dollars, except for the KH version, which will be about ten. The Intersil ICL8069 is available in various tolerances, with the suffix DCZR indicating .01 percent and a price of about two dollars.

Connect the shield to the +ve lead and the case lead of the sensor. Connect the core to the -ve lead of the sensor. Insulate the leads from each other with sleeving; then the sensor can be positioned at the tip of the pen casing and secured with adhesive. Solder the +ve lead of the battery clip and the +ve lead from the PCB to the two switch terminals. The Heat Pen is now ready for calibration.

Calibration

A crude but effective way of calibrating the Heat Pen is in iced water. Ideally the water should be distilled and free from contaminants which may alter the freezing

point temperature. It is important to ensure that water does not penetrate the leads of the temperature sensor as it will cause a leakage current to flow and thus give an erroneous reading. Therefore place the heat pen probe in a plastic bag and place in a vessel of iced water. Switch on the Heat Pen and with your DVM monitor the voltage at pin 7 of IC1 with respect to OV. Adjust RV2 for 2.73V.

Now plug the Heat Pen into the DVM. Adjust RV1 until 0.00V is obtained. The unit is now calibrated to 0 degrees C. Cut out a piece of foam rubber to fit on top of the PCB in the box. This is to prevent the battery casing from short circuiting the components, and also to prevent everything from rattling around inside the box. Fit the battery on top of the foam rubber and fit the cover with its switch to the box and secure with two nuts and bolts.

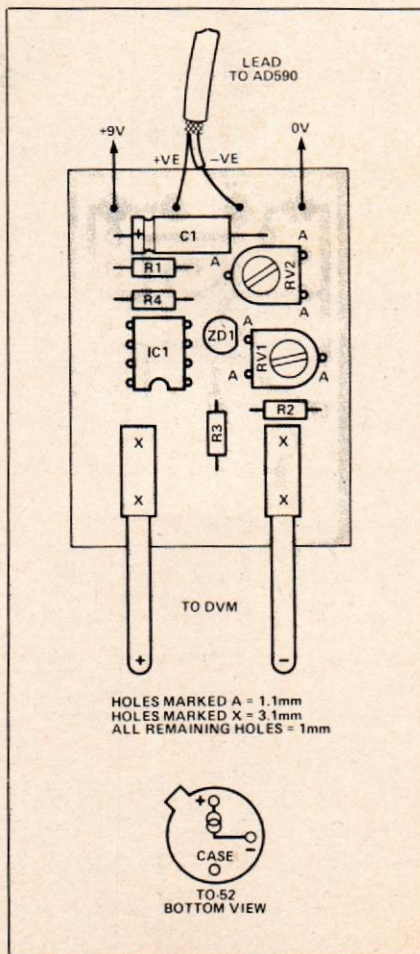
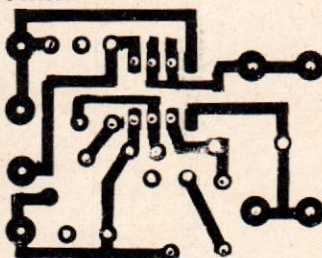


Fig. 3 Overlay diagram and pin-out of the AD590 temperature transducer.

PARTS LIST

Resistors (All 1% metal film)

R1	.....68	.....68k
R2	.....	.....56k
R3	.....	.....75k
R4	.....	.....9k1
RV1	.....	10k horizontal line pre-set
RV2	2k horizontal line pre-set

Capacitors

C1	1u0 16V axial electrolytic
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Semiconductors

IC1	LM358N
IC2	AD590JH
ZD1	TSC9491BJ or ICL8069DCZR or any 1.225V bandgap voltage reference with tolerance $\pm 2\%$ and temperature coefficient of 100ppm/degC

Miscellaneous

PCB; 4mm terminals; battery clip; small on/off toggle switch; 9V battery; ball point pen casing.

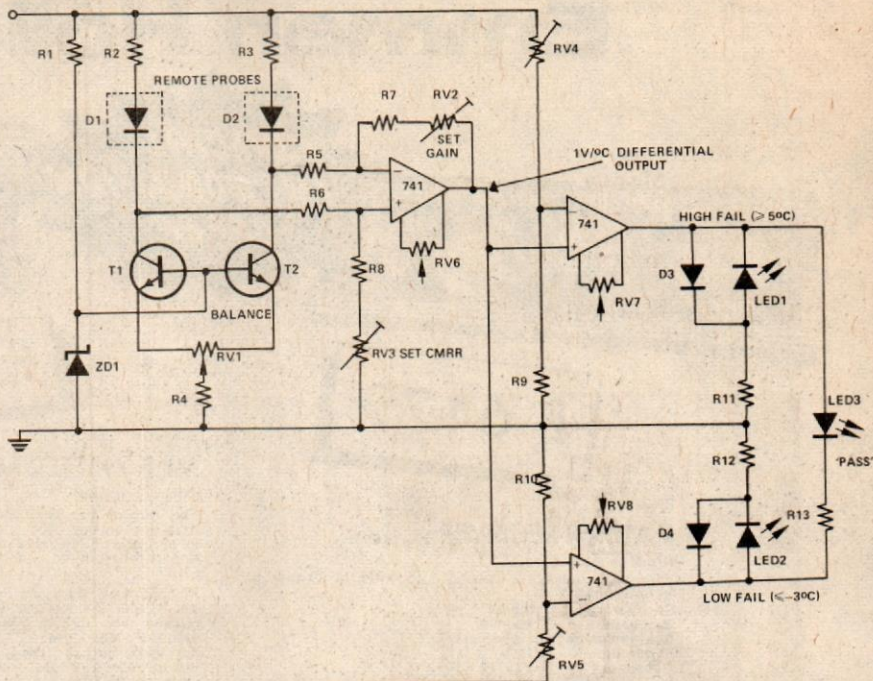
DIFFERENTIAL TEMPERATURE SENSOR AND ALARM SYSTEM

The circuit is comprised of three parts (i) the differential temperature sensor (ii) a differential amplifier to provide gain (iii) a switching circuit to monitor the output from the differential amplifier.

Two diodes D1 and D2 are used as probes for the sensor. A small preset, RV1 provides fine adjustment of the current through each branch so as to give zero differential output between D1 and D2 when they are at the same temperature.

A gain of 500 must be provided at the differential output to provide a useful voltage to switch the LED's (....ie 1V corresponding to 1°C.) RV2 provides fine adjustment of the gain and RV3 adjusts the CMRR.

A potential divider network is set up by RV4, R9, R10, RV5 to provide the necessary switching voltages for the voltage comparators, thus enabling LED1 or LED2 or LED3 for voltages set up by RV4 and RV5 ..ie.. -3V and +5V.



SETTING UP

1. Adjust offset-null on all Op. Amps for zero output by connecting input terminals together and taking to ground and adjusting either RV6, RV7 and RV8.
2. Adjust CMRR for differential amplifier by shorting input terminals and connecting to +15V line, then adjusting RV3.
3. Apply probes D1 and D2 to a liquid, say at room temperature, and adjust RV1 until there is zero output across collectors of T1 and T2.

COMPONENT LIST

RESISTORS

R1	2.2k
R2,R3	51k
R4,R10,R13	1k
R5,R6	2k
R7,R8	910k
R9	390Ω
R11,R12	1.2k
PRESETS	
RV1	100Ω
RV2,RV3	100k

RV4,RV5

2.2k

RV6,RV7,RV8

10k

TRANSISTORS

T1,T2

BC108

DIODES

D1,D2

1N4004

D3,D4

1N914

LED1,LED2

miniature RED

LED3

miniature GREEN

ZD1

400mW,3V3

3 Operational Amplifiers

741

4. Apply probe D1 to a liquid at a temperature 10°C different from above, then adjust gain control RV2 until there is 10V at the diff. amplifier output. The CMRR

should again be set.

5. Adjust RV4 and RV5 so that the comparators switch at -3V and +5V corresponding to -30°C and +50°C.

Direct-reading converter yields temperature

by James Williams and Thomas Durgavich
Massachusetts Institute of Technology, Cambridge, Mass.

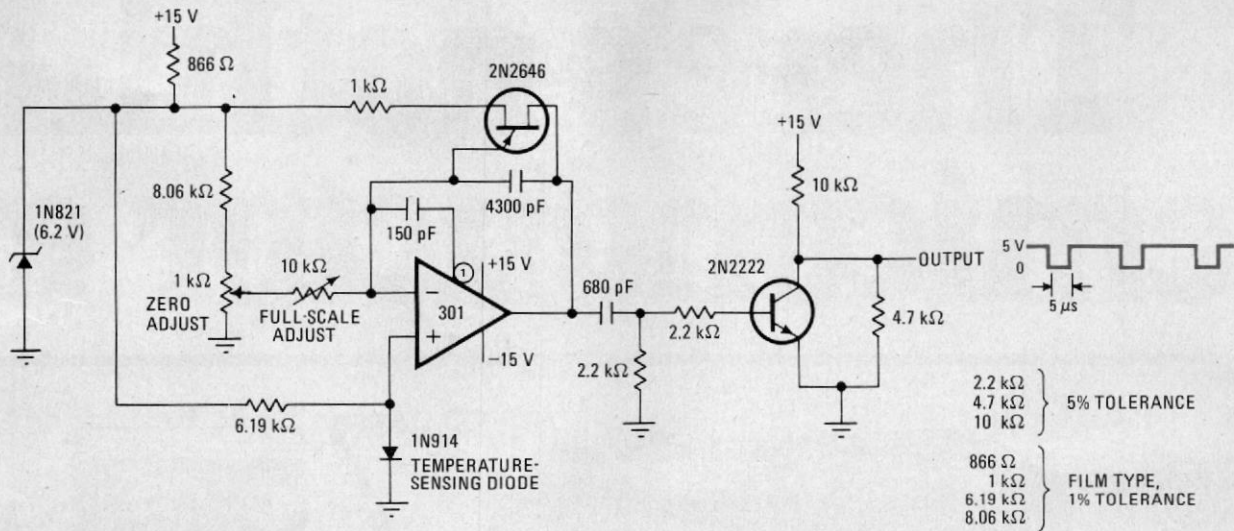
It's possible to convert temperature accurately to a numerically equivalent frequency for direct display or for instrumentation. The circuit described here uses an 1N914 temperature-sensing diode to provide 0.1°C resolution from 0°C to 100°C , with accuracy of $\pm 0.3^{\circ}\text{C}$ over the entire range.

The 301A operational amplifier is set up as an integrator. The 150-picofarad capacitor from the inverting input to pin 1 provides feed-forward compensation for high slew rate. The 2N2646 unijunction transistor resets the integrator when the 4300-pF capacitor charges to about -10 volts. The 1N821 temperature-compensated diode provides a voltage reference that determines the firing point of the unijunction transistor, provides stable zero and full-scale references, and sends a 1-milliam-

pere current through the 1N914 temperature-sensing diode. The 2N2222 transistor and its associated components provide an output pulse that is compatible with transistor-transistor logic.

In operation, the circuit functions as a voltage-to-frequency converter. The voltage at the wiper arm of the 1-kilohm potentiometer is integrated until the transistor's firing point is reached. When the transistor fires, it resets the capacitor. The frequency of oscillation is related to temperature because the diode voltage biases the integrator via the noninverting input. The only variable voltage available to the amplifier is the temperature-dependent (-2.2 millivolts per $^{\circ}\text{C}$) potential from the 1N914 diode. To adjust the circuit, put the diode in a 100°C environment and turn the 10-kilohm potentiometer till the output frequency is 1,000 hertz. Then put the diode in a 0°C environment, and turn the 1-kilohm potentiometer for 0 Hz out. This procedure must be repeated two or three times, until the adjustments cease to interact. Once the circuit is adjusted, its output frequency is 10 times the sensed temperature within 0.3°C from 0° to 100°C . For example, if the temperature is 37.5°C , the meter will read 375 Hz.

The output frequency can be counted by TTL count-



Temperature-to-frequency converter. Frequency of relaxation oscillator varies with temperature-dependent voltage across 1N914 diode. Over 0°C-to-100°C temperature range, frequency changes linearly from 0 to 1,000 Hz. Therefore frequency meter at output can show temperature directly. Accuracy is $\pm 0.3^\circ\text{C}$. Excellent performance and low cost (less than \$5 for parts) make this circuit outstanding.

ers and a 1-Hz square wave. The 1-Hz square wave can be fed to the base of the 2N2222 through a 2.2-kilohm

resistor, and the resultant gated pulses at the output can then be fed to TTL counters. □

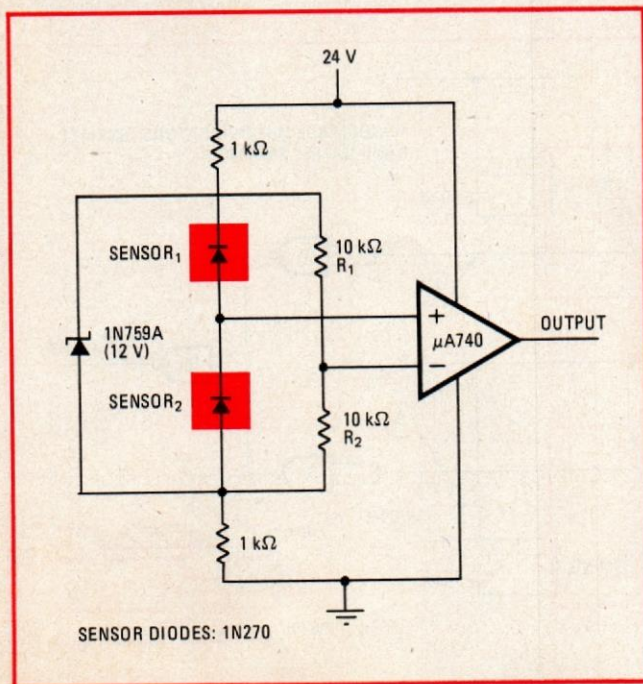
Diode pair senses differential temperature

by Don DeKold
Dekolabs, Gainesville, Fla.

Normally, a germanium diode functioning as a temperature sensor relies on the linear variation of its forward voltage with temperature. But a pair of germanium diodes can be made to serve as a differential-temperature comparator if the circuit exploits a much less used temperature-dependent diode property—the logarithmic variation with temperature of the reverse saturation current. The resulting circuit is useful for industrial-control applications.

When one diode (SENSOR₁) is at temperature T_1 and the other diode (SENSOR₂) is at temperature T_2 , the circuit output will change state as the temperature differential ($T_1 - T_2$) approaches and crosses a differential threshold, $\Delta T_{1,2}$. For the circuit shown here, $\Delta T_{1,2}$ is 13°C—when ($T_1 - T_2$) is less than 13°C, the circuit's output is low; and when ($T_1 - T_2$) is greater than 13°C, the output goes high. The circuit has a fairly wide and useful temperature range of 20°C to 120°C.

The two diodes, along with resistors R_1 and R_2 , form a resistance bridge. The right-hand side of the bridge consists of equal resistances that divide the bridge voltage in half, establishing a reference voltage at the inverting terminal of the FET-input operational amplifier. The noninverting op-amp terminal receives the temperature-dependent voltage, which is derived from the division of the bridge voltage across the diode temperature sensors.

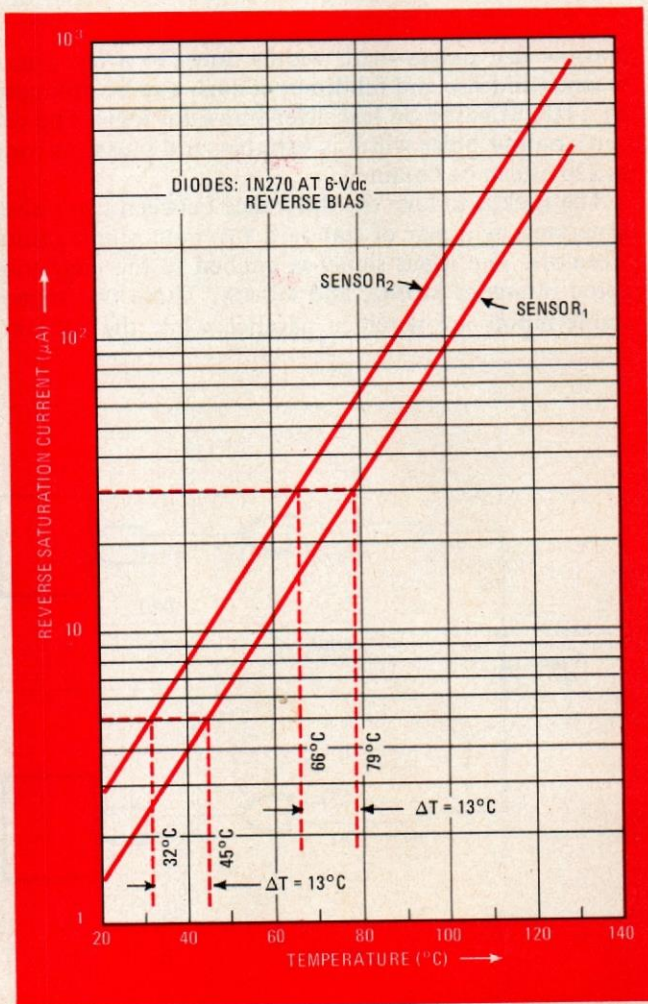


Temperature comparator. Unmatched germanium diodes have different reverse saturation currents at the same temperature. But this difference remains proportionate with changing temperature so that the temperature differential between the two currents stays the same, as shown by the graph. A differential-temperature comparator can be built by connecting two unmatched diodes in a bridge configuration.

In general, the reverse saturation currents of two unmatched diodes are different at a single temperature. However, when plotted as a function of temperature on semilog paper, the two reverse-current characteristics will be parallel to each other. That is, a diode's reverse current may vary from one unit to the next at a single temperature, but it will increase in an identically proportional manner from one unit to the next as a function of temperature.

For instance, for the type 1N270 germanium diodes used here, the current doubles every 13°C. The doubling is highly regular, producing a nearly linear semilog plot over a fairly wide temperature range, as shown by the graph of reverse saturation current versus temperature for two type 1N270 diodes.

Now, when a diode is reverse-biased, it in effect becomes a temperature-dependent current source with a reverse saturation current that is only negligibly influenced by the actual magnitude of the reverse voltage. But as the reverse voltage approaches zero, the reverse current decreases. When two diodes are connected in series, therefore, the voltage across them will divide equally only when their currents are the same, a condition that occurs at a fixed temperature difference between the two. This equal-current temperature differ-



ential is the $\Delta T_{1,2}$ threshold for the circuit.

The diode having the lower reverse saturation current acts here as $SENSOR_1$, so that practically all of the bridge voltage will be dropped across it. This keeps the voltage at the noninverting op-amp input below that of the inverting op-amp input, and the circuit's output is low. As the temperature of $SENSOR_1$ increases, its reverse leakage current will also rise.

When $SENSOR_1$ is $\Delta T_{1,2}$ degrees celsius above $SENSOR_2$, the voltages at the op-amp inputs will be equal. With an additional temperature increase of $SENSOR_1$, most of the bridge voltage will then be dropped across $SENSOR_2$. This raises the voltage of the noninverting op-amp input above that of the inverting op-amp input, causing the circuit's output to go high.

Various operating conditions can be set up for the differential-temperature comparator by interchanging the locations of the low-current and high-current diodes or by switching the input connections to the op amp. Different diode pairs will provide different values of threshold temperature. Basically, $\Delta T_{1,2}$ is determined by the ratio of diode leakage currents at a fixed temperature, and this current ratio increases as the comparator differential increases. Diodes with identical reverse currents at the same temperature produce a $\Delta T_{1,2}$ of 0°C .

A FET-input op amp must be used here to assure that there is practically no loading of the bridge diode divider. Minimal loading is particularly important if the absolute temperatures to be compared differentially are low. □

Generating nanosecond pulses with TTL monostables

by Robert J. Broughton
Yale University, New Haven, Conn.

Narrow fast pulses—with widths down to a few nanoseconds and rise and fall times of 2 ns—can be produced by a circuit based on transistor-transistor logic. The circuit's output pulse width is variable, and pulses as wide as 220 ns can be obtained.

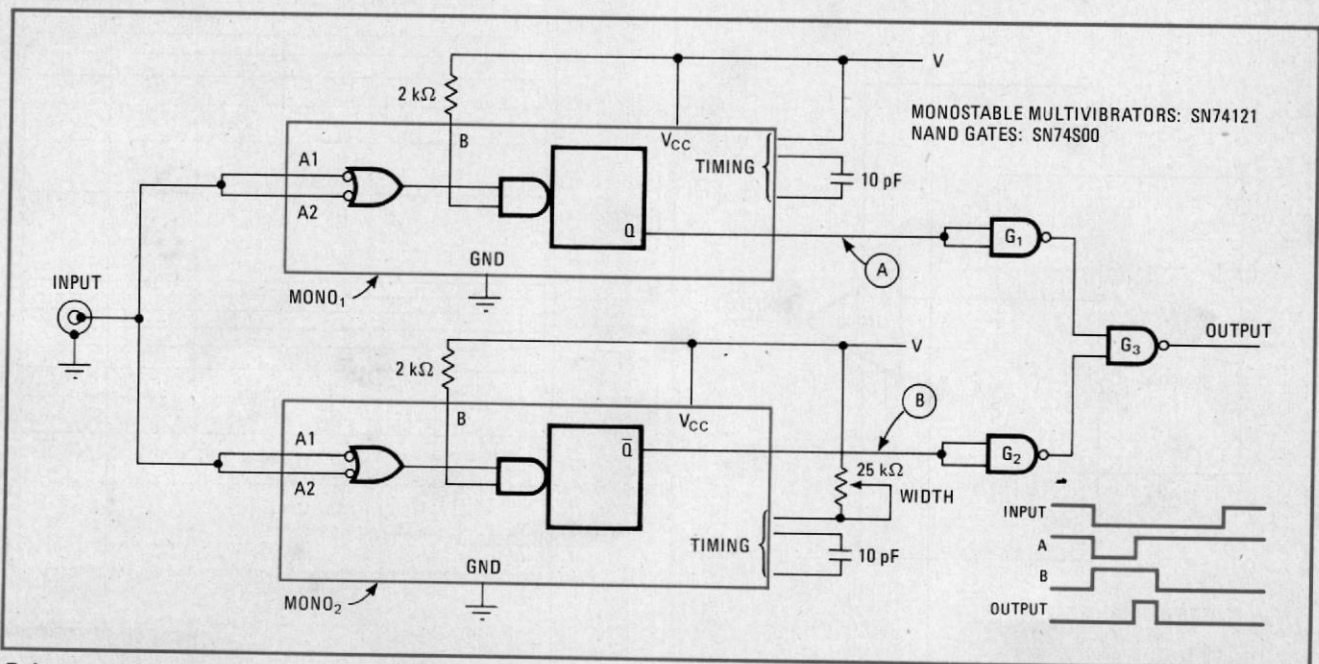
The trick is to take the difference between two pulses generated by a pair of standard TTL monostable multivibrators. The input signal is applied to the edge-triggered inputs of $MONO_1$ and $MONO_2$. Those two monostable inputs are wired in parallel, while the Schmitt-

trigger monostable inputs are kept high by the 2-kilohm resistors tied to the supply voltage.

$MONO_1$ is wired to produce a 30-ns pulse, which is conditioned by a Schottky-TTL NAND gate, G_1 , to speed up its rise and fall times. Similarly, $MONO_2$ generates an output pulse that is complementary to the one generated by $MONO_1$ and that is conditioned by a second Schottky-TTL NAND gate, G_2 . The width of this pulse is adjustable from 30 ns to more than 250 ns.

The third and last Schottky-TTL NAND gate, G_3 , accepts the conditioned pulses from gates G_1 and G_2 . The output of this gate is a fast narrow pulse whose width is the difference between the pulses produced by $MONO_1$ and $MONO_2$. An output pulse having a width of 8 ns and rise and fall times of 2 ns can be easily obtained with the generator circuit. □

Designer's casebook is a regular feature in Electronics. We invite readers to submit original and unpublished circuit ideas and solutions to design problems. Explain briefly but thoroughly the circuit's operating principle and purpose. We'll pay \$50 for each item published.



Pulse generator. A pair of standard TTL monostables can be made to produce sharp nanosecond pulses by using a Schottky-TTL NAND gate to accept their complementary outputs. The pulse width of $MONO_1$ is fixed at 30 ns, while the pulse width of $MONO_2$ is variable from around 30 ns to better than 250 ns. Gate G_3 takes the difference between these two pulse widths. Output rise and fall times are 2 ns.

Integrated temperature transducers

Within their limited temperature range, new ICs are cheap and easy to use because they have large linear outputs

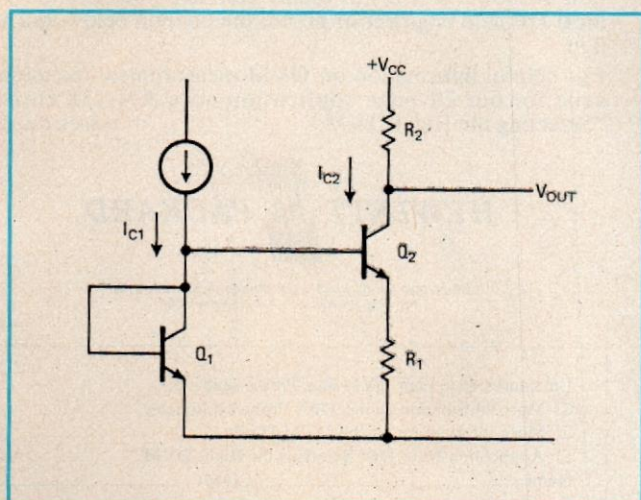
by Michael J. Riezenman, *Industrial Editor*

□ The electrical temperature transducer, characterized for many years by slow, evolutionary development, has at last entered the semiconductor age. During all this time, there has been no serious competitor to these sensors—thermocouples, resistance-temperature devices (RTD)s, and thermistors.

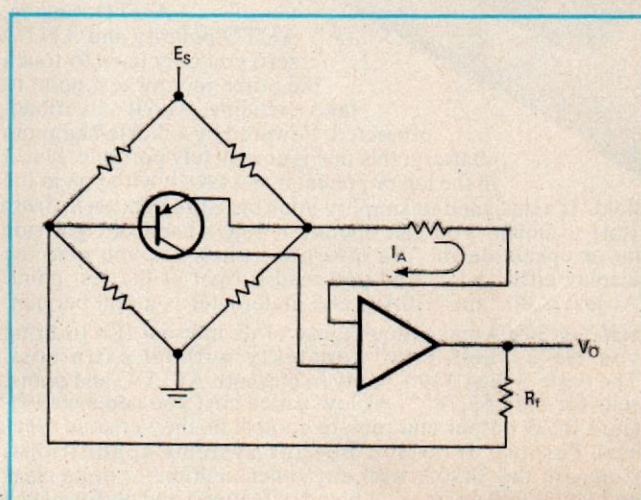
Despite their newness and relatively limited temperature range of -100 to $+150^{\circ}\text{C}$ at best, the new silicon devices are creating a good deal of interest because of their large and linear outputs—typically 10 millivolts per degree Celsius. The new transducers are cheap and easy to use because of these two attributes, which eliminate the need for signal-conditioning amplifiers, cold-junction compensators, and other accessories.

Further, such highly integrated units as the LX5600/LX5700 from National Semiconductor Corp., Santa Clara, Calif., include output operational amplifiers. When an externally set voltage is applied to one of its inputs, this transducer acts as an adjustable temperature-sensitive switch.

The key to temperature measurement by semiconductors is the exploitation of the temperature sensitivity of a transistor's base-emitter voltage. Although the effect is well-known, difficulties arise when it comes to



1. Measuring temperature. So long as Q_1 and Q_2 are a matched pair and I_{C1} and I_{C2} are not equal, the difference in the base-emitter drops across R_1 is proportional to the absolute temperature.



2. Feedback. Bridge circuit operates sensing transistor (a selected 2N2484) at a constant current so that its V_{BE} is a linear function of absolute temperature. Op amp is usually an LM-308.

actually using this phenomenon as the basis for a thermometer. The main problem is that it is difficult to control the V_{BE} of any transistor with sufficient precision to make a useful measuring device. The V_{BE} can vary as much as ± 100 millivolts over a single production run. Nevertheless, both National Semiconductor and Relco Products Inc., Denver, Colo., have successfully exploited the phenomenon, and they did it in completely different ways.

A hot idea

National's solution is to measure the difference in base-emitter voltages of two matched transistors operating at different collector currents. This quantity is directly proportional to the absolute temperature of the transistors and to the natural logarithm of the ratio of their collector currents. In the simplified temperature-sensing circuit of Fig. 1, it can be shown that if Q_1 and Q_2 are matched transistors, and if they are operated at different collector currents, then the difference in base-emitter voltage appearing across R_1 will be given by

$$\Delta V_{BE} = (kT/q) \ln(I_{C1}/I_{C2})$$

where k is Boltzmann's constant, T is the absolute tem-

perature, and q is the electronic charge.

If the transistors' betas are high enough and the ratio of the collector currents is kept constant—two relatively easy tasks in the fabrication of modern monolithic circuitry—then the voltage across R_2 is proportional to the absolute temperature, and an appropriate choice of R_2 can provide a readout directly in the Kelvin scale.

Constant current

Relco uses a bridge-type feedback circuit to keep the sensing transistor's emitter current constant (Fig. 2). Since it can be shown that operating a transistor at a constant current makes its V_{BE} a linear function of temperature, the illustrated feedback circuit constitutes a linear temperature-to-voltage transducer.

To avoid self-heating problems, which would compromise the maximum error of 0.1°C , Relco builds its transducer out of discrete components, rather than integrating the entire circuit onto a single chip. As a result, it is easy to compensate for variations in V_{BE} between various transistors by simply choosing the correct value of R_f , the feedback resistor. Alternatively, R_f can be made variable, allowing the sensitivity of the transducer to be changed by the user. In this fashion,

CHARACTERISTICS OF TEMPERATURE TRANSDUCERS

PARAMETER	THERMISTOR	RESISTANCE-TEMPERATURE DEVICE	THERMOCOUPLE	SILICON TEMPERATURE TRANSDUCER
Sensitivity/ $^\circ\text{C}$	-4 %	+0.4 %	+60 μV	+10 mV to +200 nV
Linearity	Highly exponential	Very linear	Somewhat nonlinear	Very linear
Room-temperature resistance range	5 Ω to 20 M Ω	10 Ω to 1 k Ω	N/A	N/A
Sensitivity to changes in ambient temperature	No effect	No effect	Needs cold-junction compensation	No effect
Minimum temperature	Liquid-oxygen temperatures	Liquid-oxygen temperatures	Liquid-oxygen temperatures	-100 $^\circ\text{C}$
Maximum temperature	300 $^\circ\text{C}$	750 $^\circ\text{C}$	3,000 $^\circ\text{C}$	+150 $^\circ\text{C}$
Minimum size	0.005 in. dia beads	Small coil	Small wire (smallest)	TO-5 or TO-46 transistor package
Room-temperature error	Typically ± 20 %	Usually wound to $\pm 0.25^\circ\text{C}$	About 2 $^\circ\text{C}$	8 $^\circ\text{C}$ to 0.1 $^\circ\text{C}$
Cost	\$ 5	\$ 25	\$ 2	\$ 3 to \$ 30

sensitivities from less than 10 mv/°C to more than 200 mv/°C can be obtained.

Choosing a transducer

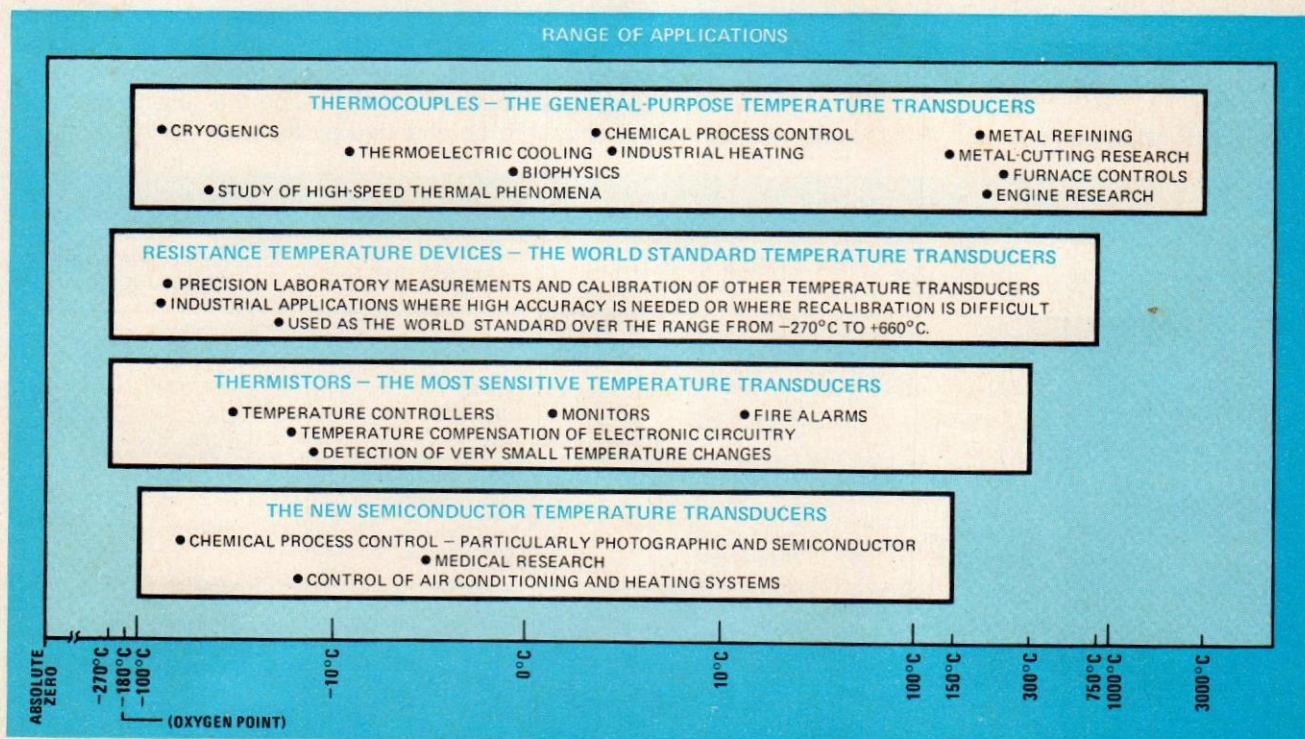
Where do the new semiconductor devices fit into the grand scheme of temperature measurement? As the table indicates, right in the middle. They're no good for extremely high or low temperatures. They're not the most accurate devices available. And they're not the smallest or fastest-responding transducers. But as the applications chart shows, their low cost and ease of use make them ideal for a large number of applications in the middle.

If low price is the main consideration, cheap thermocouples are available for temperatures as high as about 1,200°C. Above that, more-expensive platinum and tungsten units must be used. If accuracy is most important, the RTD is the way to go. Although usually wound to an error tolerance of $\pm 0.25^\circ\text{C}$, the RTD will normally

drift less than 0.05°C over a long period and hence can be calibrated to much greater accuracy. It is obvious that since the increased accuracy requires greater care and time in calibration, it comes at an increased price.

Nearly anything except a semiconductor transducer can be used at cryogenic temperatures, while nothing but a tungsten-based thermocouple can withstand temperatures above about $2,000^\circ\text{C}$. The thermistor, while highly nonlinear, is extremely small, rugged, and sensitive. Furthermore, although not as stable as an RTD, a properly used thermistor will actually improve with age. Thermistors, of course, are also useful as temperature-compensating devices in all kinds of electronic circuitry.

Finally, if an extremely small device is needed, if the fastest possible response is essential, or if it is necessary to locate the transducer far from the rest of the measuring circuitry, the thermocouple again is the best choice. □



Diode or transistor makes fully linear thermometer

by Cameron J. Koch

Ontario Cancer Foundation, London, Ont., Canada

An electronic thermometer circuit that uses a semiconductor diode or a transistor as its sensor can produce an output voltage that varies linearly with temperature. The voltage across the diode or the base-to-emitter junction of the transistor changes at -2.2 millivolts per degree celsius if the current through the junction is held constant. Previous circuits with such sensors have been nonlinear at low temperatures [*Electronics*, March 20, 1975], but this difficulty is easy to overcome.

The trick is to use a bipolar power supply so that the sensor's amplifier is not forced to operate near its V -supply voltage. The thermometers described here use this kind of supply, and both are linear and accurate to within 0.05°C . Self-heating of the sensors is extremely small, because they operate at about 50-microwatt power levels.

In the transistor-sensor circuit (Fig. 1a), the potential of the noninverting input of the op amp is set by resistor divider R_4 and R_5 between ground and B^- . The output of the amplifier then drives the R_1 - R_2 divider and the base of the sensing transistor via R_6 . As a result, enough current flows through emitter resistor R_3 to make the potential at the emitter (and hence at the inverting input of the amplifier) the same as the potential at the noninverting input.

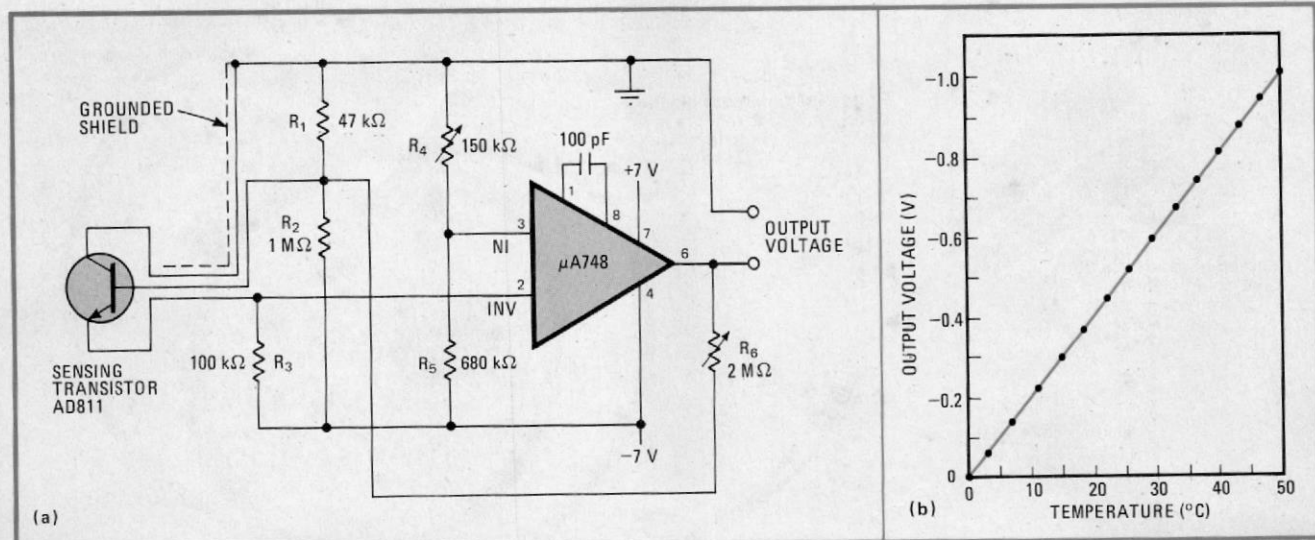
The operation of the circuit depends on the necessity for the emitter current I_E to remain constant in order to provide a constant potential at the inverting input of the amplifier. The base current I_B is just $I_E/(1+h_{FE})$; since I_B is constant, the base-to-emitter voltage depends only on the temperature of the transistor. Hence the output, which is proportional to the base-emitter voltage, is in turn proportional to the absolute temperature.

Neither the temperature variation of h_{FE} nor the collector-to-base leakage current affects the operation of the thermometer circuit significantly. The value of h_{FE} varies very slowly with temperature, and I_{CBO} is much smaller than the forward base-emitter current. The Analog Devices AD811 transistor used for the sensor has extremely low leakage.

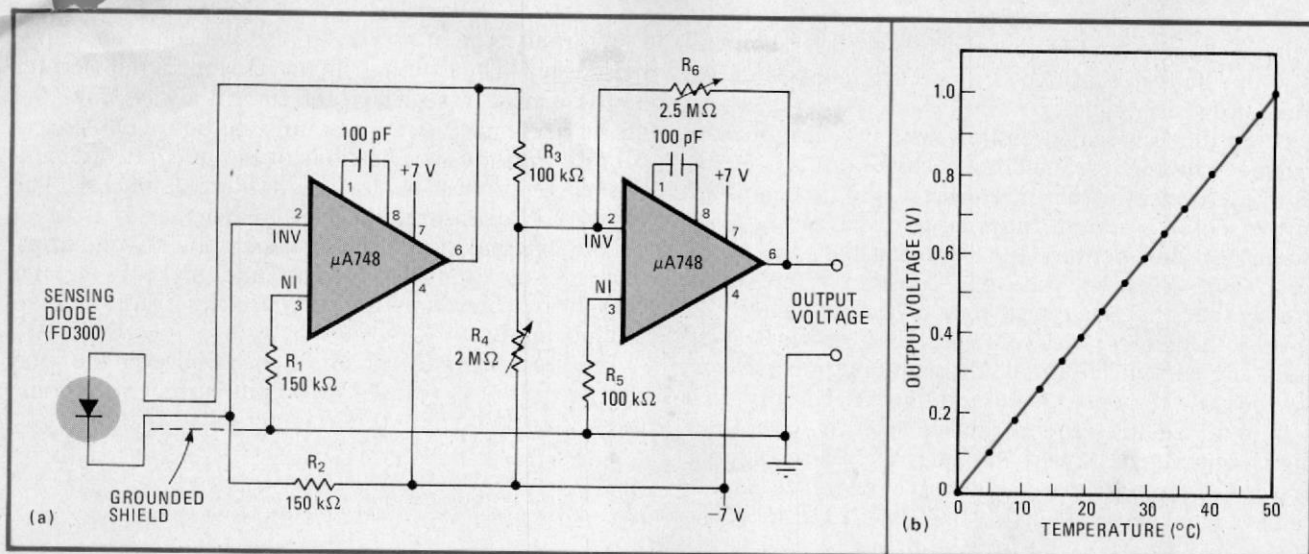
The zero point is set by potentiometer R_4 and the gain by potentiometer R_6 . Since the two adjustments interact somewhat, two or three iterations of the calibration are necessary. At the slight expense of an increased output impedance, it's possible to remove the interdependence of zero and gain controls by using a fixed feedback resistor for R_6 and connecting a 10-kilohm potentiometer between the output of the amplifier and ground. Then the overall circuit output becomes the wiper and ground terminals of the pot.

Figure 1b shows the output voltage as a function of ambient temperature at the transistor. The calibration adjustments were set for an output of -1 volt at 50°C . The line connecting the experimental points was drawn with a straight edge.

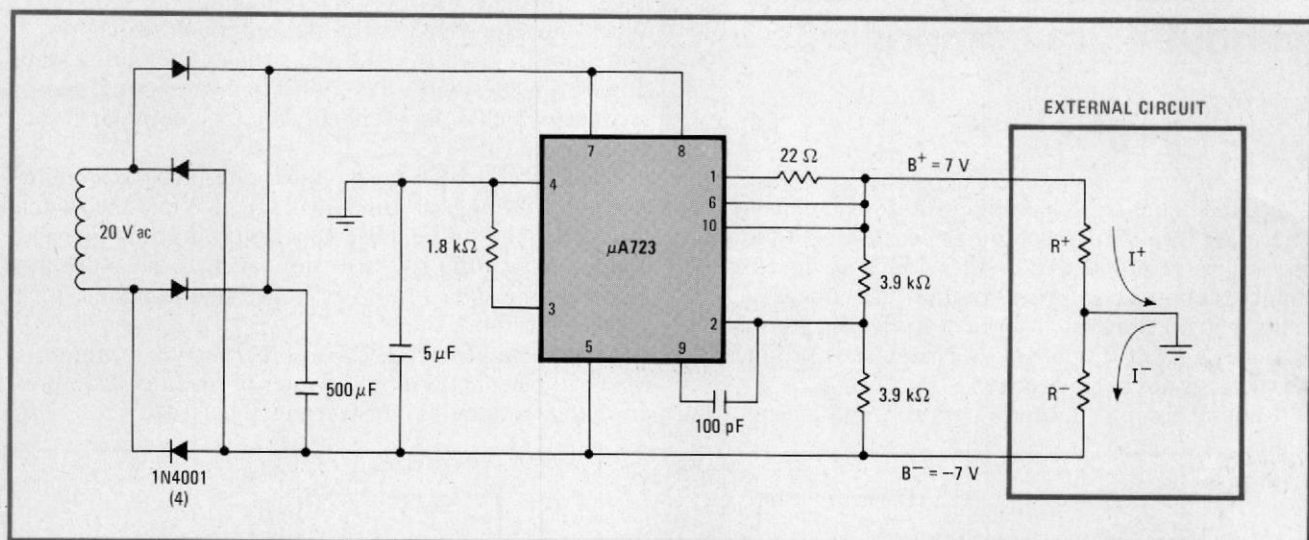
The sensor is fabricated by sealing the transistor—preferably along with a little dessicant—into thin stainless steel tubing with silicone rubber. Both the tubing and the collector are grounded. The unit operates satis-



1. Transistor sensor. Electronic thermometer circuit (a) uses a low-leakage transistor to produce an output voltage that varies linearly with temperature. The fixed voltage applied to the noninverting input of op amp is matched by the constant emitter-current drop through R_3 . Output voltage varies with temperature-dependent junction voltage to hold emitter current constant. Zero point is set by R_4 and gain by R_6 . Response curve (b) is linear to within the 0.05°C accuracy of calibrating thermometers.



2. Diode sensor. In thermometer circuit with diode (a), constant diode-junction current through R_2 keeps inverting terminal of first op amp at same potential as grounded noninverting terminal. Output voltage varies with temperature-dependent diode drop to hold current constant. Second op amp allows zero adjustment through R_4 and gain control through R_6 . Response curve (b) is linear within measurement accuracy.



3. Supplying power. Precision voltage regulator IC is heart of this ± 7 -V power supply for low-current instrumentation circuits. The -7 -V line is a stable reference for the thermometer circuits because it is just the reference voltage of the integrated circuit, with no temperature-dependent elements to reduce stability; the $+7$ -V stability is limited by the temperature dependence of the output transistor in the device.

factorily, even in boiling water.

In the diode-sensor circuit (Fig. 2a), the first operational amplifier acts as a simple constant-current source for the diode. The noninverting input is grounded through R_1 , so the output always moves sufficiently positive to keep the inverting input at ground potential as well. Thus the current through R_2 is set at about -50 microamperes by the ground-to- B^- reference voltage (-7 V/ 150 kilohms). The input current requirement of the amplifier is very small (less than 50 nanoamperes), so virtually all of this (constant) current flows through the diode. Therefore, the voltage drop across the diode depends only on temperature, and hence the output of the first amplifier is proportional to the absolute temperature.

Since most temperature measurements are made in the range of 270 to 370 K (0 – 100°C), a second amplifier is used to offset the diode voltage to whatever tempera-

ture range is desired and also to provide gain. Potentiometer R_4 between the input of the second amplifier and ground sets the output at zero for whatever temperature is chosen (i.e. 0°C), and feedback resistor R_6 sets the gain. The input resistor to this stage, R_3 , is 100 kilohms, so the maximum gain is about 25 . Figure 2b shows the voltage-vs-temperature curve for a circuit adjusted to give 1 V at 50°C .

Compared to the transistor, the diode sensor is a little harder to fabricate and shield effectively by using commercial high-quality devices like the Fairchild FD300 because the cathode is only at virtual ground in the circuit. However, the diode circuitry does have two advantages. The zeroing and gain potentiometers are completely independent, resulting in a simple calibration procedure, and since both the diode input current and zeroing current are set by the -7 -V reference voltage, any slight changes in these currents caused by reference

voltage changes tend to cancel. Thus the overall circuit is about half as sensitive to reference changes as the transistor-sensor circuit.

If the diode is sealed entirely within a thin piece of grounded tubing, the shielding becomes just as effective as in the transistor sensor. However, the time constant of the sensor is several times larger because of the reduced heat flow between the diode and the external environment. Even so, this time constant is not much greater than that of a typical mercury thermometer.

In both of these electronic temperature-sensing circuits, the current requirements of the outputs are very low because the operational amplifiers need only drive a high-impedance readout device such as a recorder, digital voltmeter, or microammeter. Therefore a bipolar power supply and extremely stable reference can be achieved inexpensively with a single $\mu A723$ (Fig. 3).

With this type of power supply, two conditions must be satisfied. The external circuit resistances (labeled R^+ and R^-) must be such that the current always flows out of the reference (i.e., $I^- - I^+$ must be positive). Also, to comply with the specifications of the integrated circuit, this current must be less than 5 milliamperes. The easiest way to ensure that I^- is greater than I^+ is to set up the external circuit under maximum I^+ conditions, then measure the two currents and make I^- greater than I^+ by connecting an appropriate resistor between ground and B^- .

The second condition can be met wherever the total change in $I^- - I^+$ (caused by output current variations) is less than 5 mA, as in these circuits. \square

Engineer's Notebook is a regular feature in Electronics. We invite readers to submit original design shortcuts, calculation aids, measurement and test techniques, and other ideas for saving engineering time or cost. We'll pay \$50 for each item published.

Touch switch enters data without extra components

by Kim Rubin

University of California, Berkeley, Calif.

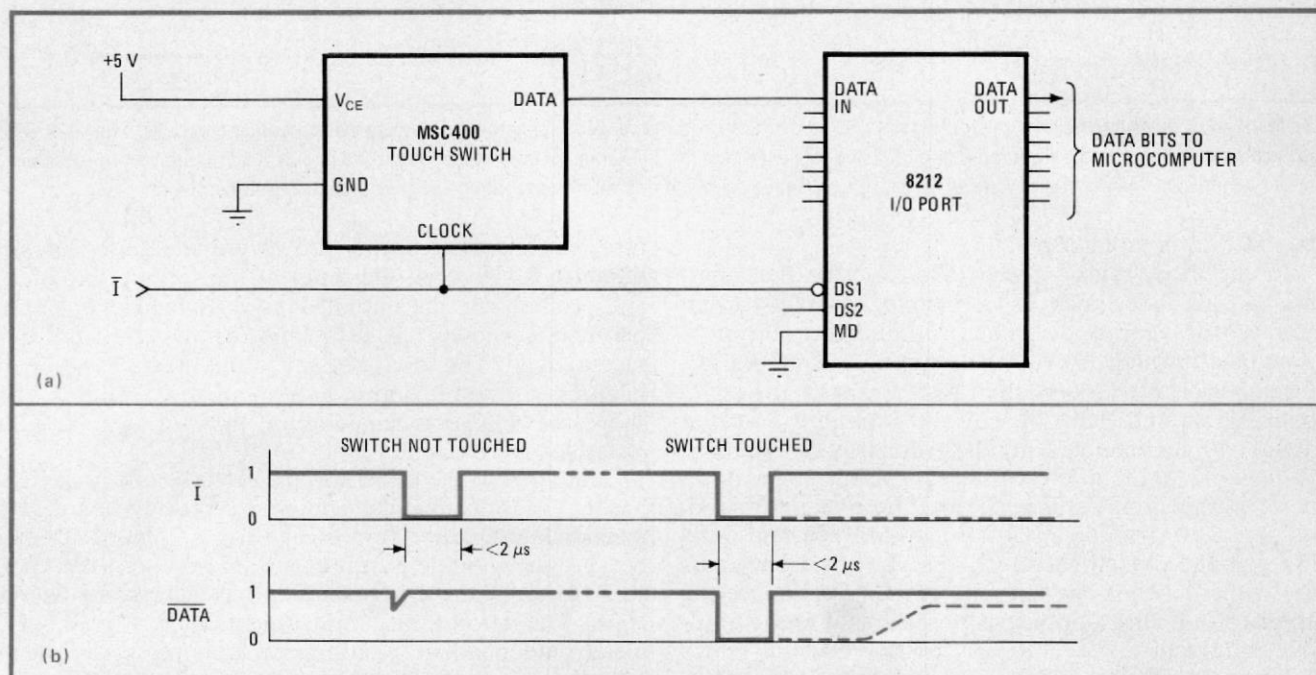
A clocked touch switch provides a convenient way to enter data into a microcomputer because no additional circuitry is required. And, since touch switches don't bounce, debounce software routines are unnecessary. If a finger is on the switch when it is clocked, the switch produces a short output pulse. No pulse is produced if the switch is not being touched.

A microcomputer receives data through an input in-

struction that typically entails the use of a negative-going input pulse \bar{I} . This pulse strobes the latch that connects the data bus or data source to the computer. When the data source is the clocked touch switch, the \bar{I} pulse can be used to clock the switch. The output data pulse from the switch has a duration of about 2 microseconds, which is long enough for the computer to accept the data.

The figure shows a touch switch interfaced to a microcomputer through an Intel 8212 latch. While the switch is touched, the strobe pulse appears on the data line as a logic 0. When the switch is not touched, no pulse appears on the data line in response to the strobe, so a logic 1 is read in.

Although an Intel 8212 I/O port is shown, a Motorola MC6820 peripheral input adapter or an Intel 8255 programmable peripheral interface may be used. \square



Data at a fingertip. Clocked touch switch feeds logic 1s or 0s into computer through I/O latch (a). Strobe that enables latch also clocks the touch switch and appears on data line as a logic 0 if switch is touched (b). Dashed line indicates what happens when the strobe stays low.

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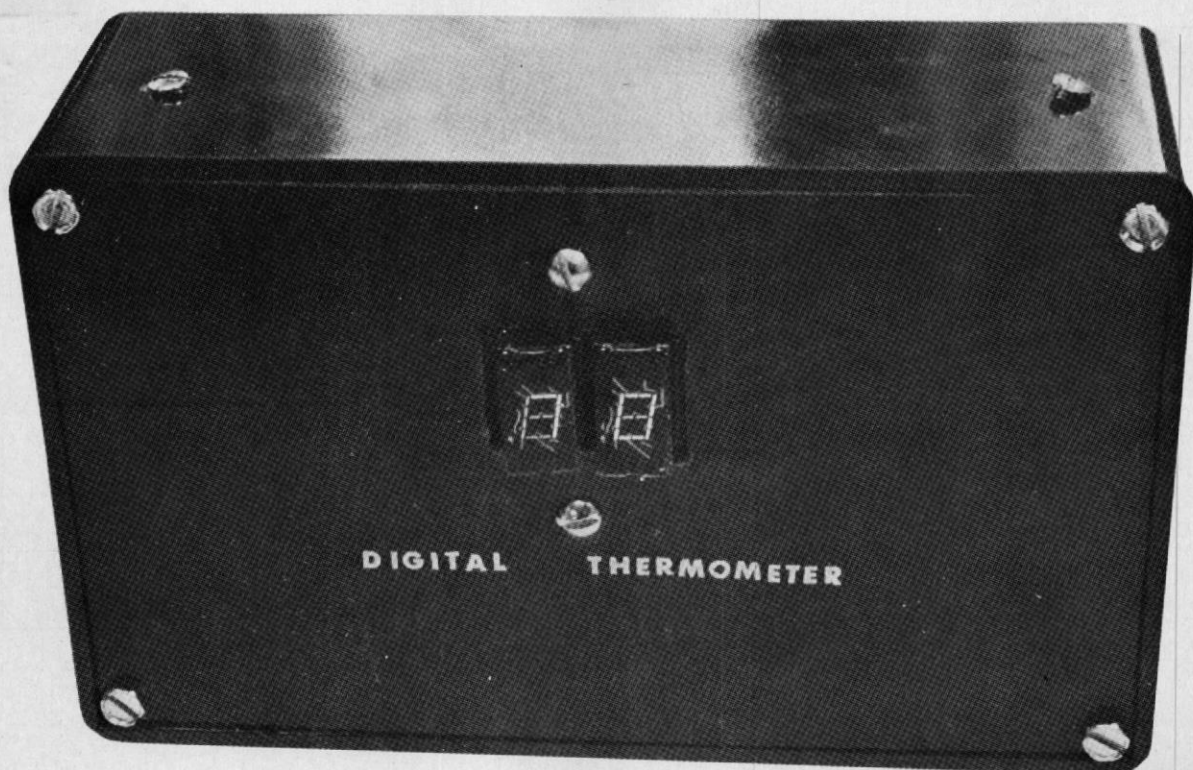
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Our *LED Short Form Catalog* is free for the asking. Simply check the box on this issue's VIP card.



Build a VERSATILE DIGITAL LED THERMOMETER

Low-cost, accurate device can be used as

- *indoor/outdoor thermometer*
- *heater/cooler thermostat*
- *temperature alarm*
- *fishing thermometer*

BY THOMAS R. FOX

THE digital thermometer described here was designed for low cost and simplicity, as well as accuracy. If you check the semiconductor sales ads in this magazine and use a conventional thermistor, you can build the thermometer for about \$15. If you decide to use a precision thermistor, the cost will be about \$20. Since the thermometer operates from a +5-volt line, it can be used in a car,

boat, or camper. With a line-powered 5-volt supply, it can be used in the home.

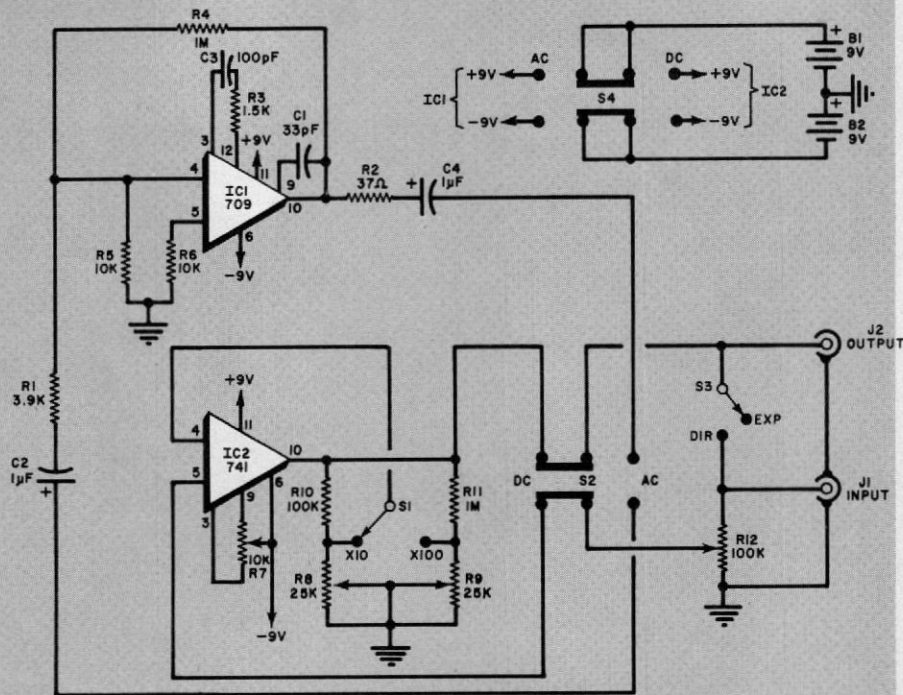
It is possible to use two switchable thermistors to check temperature differentials—such as between the outside and inside, or between two rooms. If a long lead is used between the thermistor and the electronic circuit, the project can be used as a fishing thermometer.

How It Works. The frequency of the CMOS multivibrator (Fig. 1) depends on the resistance of thermistor *TDR1*, which is determined by the ambient temperature. Thus, if the temperature goes up, the frequency of the multivibrator goes up, and vice versa. Trimmer potentiometer *R23* is used to adjust the linearity.

The two-transistor multivibrator (*Q1* and *Q2*) automatically resets the two

PARTS LIST

B1, B2—9-volt battery
 C1—3-pF capacitor
 C2, C4—1- μ F, 15-volt electrolytic capacitor
 C3—100-pF capacitor
 IC1—709 operational amplifier
 IC2—741 operational amplifier
 J1, J2—Phono jack
 R1—3900-ohm, 1/4-watt resistor
 R2—37-ohm, 1/2-watt resistor
 R3—1500-ohm, 1/4-watt resistor
 R4, R11—1-megohm, 1/4-watt resistor
 R5, R6—10,000-ohm, 1/4-watt resistor
 R7—10,000-ohm trimmer potentiometer
 R8, R9—25,000-ohm trimmer potentiometer
 R10—100,000-ohm potentiometer
 R12—100,000-ohm linear potentiometer
 S1—Spdt toggle or slide switch
 S2—Dpdt slide or toggle switch
 S3—Spst toggle or slide switch
 S4—4-position, double-throw slide switch
 Misc.—Chassis box, 9-volt transistor battery clips, shielded cable and audio phono plugs (for test cables), IC sockets or Molex Soldercons®, pc board or perforated phenolic board and solder clips, hookup wire, solder, hardware, control knob, etc.



Two operational amplifiers (IC1 and IC2) form heart of expander.

meter. You can even use the range expander to measure the output voltage of a phono cartridge. Try that with an ordinary multimeter.

About the Circuit. The range expander makes use of two operational amplifier IC's (IC1 and IC2 in the schematic), exploiting the particular advantages of the types 709 and 741 op amps. A monolithic amplifier using bipolar transistors appears to the signal being processed as a series of resistances and shunting capacitances. An RC system like this forms a phase-shift network that at some frequency will cause the amplifier to oscillate.

Compensation is required to insure low gain at the frequency at which oscillation occurs. The 741 op amp is unconditionally compensated. (Gain is reduced to unity at the point where oscillation is possible.) The 709 op amp is not internally compensated, requiring external components to obtain the necessary compensation. However, it can be compensated for frequencies up to 1 MHz, while the 741 is restricted to a top-end frequency of about 1 kHz by its internal compensation.

The 741 op amp has provisions for input offset nulling, which makes it operate well as a dc amplifier. In the range expander, the 741 (IC2) is used as a dc amplifier with output nulling

and a feedback network that minimizes drift. The 741 has input overvoltage protection and output short-circuit protection, while the 709 has neither. To provide input overvoltage and output short-circuit protection for the 709, R1 and R2 are used.

The 709 (IC1) in the range expander is compensated for a 40-dB gain up to about 200 kHz by C1, C3, and R3. It has a feedback network consisting of R4 and R5. Both ac and dc amplifiers (IC1 and IC2) have a common vernier control (R12) that can be used where exact values of gain are not required.

The incoming signal (or voltage) is applied via J1, while the mode of operation (ac or dc) is selected with S2. Switch S1 permits selection of X10 or X100 in the dc mode, while switch S3 applies power to either the IC1 or the IC2 circuit. The final switch, S4, permits the range expander to be bypassed when in the DIR position. In this position, it routes the incoming signal at J1 directly to output jack J2. (Note: When S3 is in the DIR position, S4 can be switched to off to conserve battery life.)

Construction. Assembling the range expander is relatively easy, owing to the simplicity of the circuit. The entire circuit can be easily accommodated inside a 4 in. by 2 3/4 in. by 2 in. metal utility box, with the four switches and vernier control R12 mounted on the

top of the box for convenience.

You can use a printed circuit board of your own design or perforated phenolic board and solder clips for mounting the IC1 and IC2 amplifier circuits inside the box. Jacks J1 and J2 can be mounted at one end of the box.

When the circuit has been fully assembled and all parts are mounted in place, use dry-transfer letters to label the control, switches, and jacks.

Calibration. With the range expander switched to DC (both S2 and S4 must be set to this position) and R12 set for maximum sensitivity, connect a multimeter set to a low-voltage range across J2. Adjust R7 for a zero indication on the multimeter's scale.

Connect a variable-output power supply or a potentiometer in parallel with a 1.5-volt battery to J1 and adjust the supply or pot for a 0.1- to 0.5-volt indication on the multimeter's scale. Adjust R8 for an indication of 10 times the reading of the input voltage level. (Use the multimeter to monitor both the input and output voltage levels.)

Now, decrease the output voltage of the power supply (or battery/pot setup) again for a meter reading of 0.1 to 0.5 volt and switch S1 to the X100 position. Adjust R9 for a reading of 10 times the previous meter reading. With the input disconnected, recheck the null produced by adjustment of R7. If necessary, readjust the null. ♦

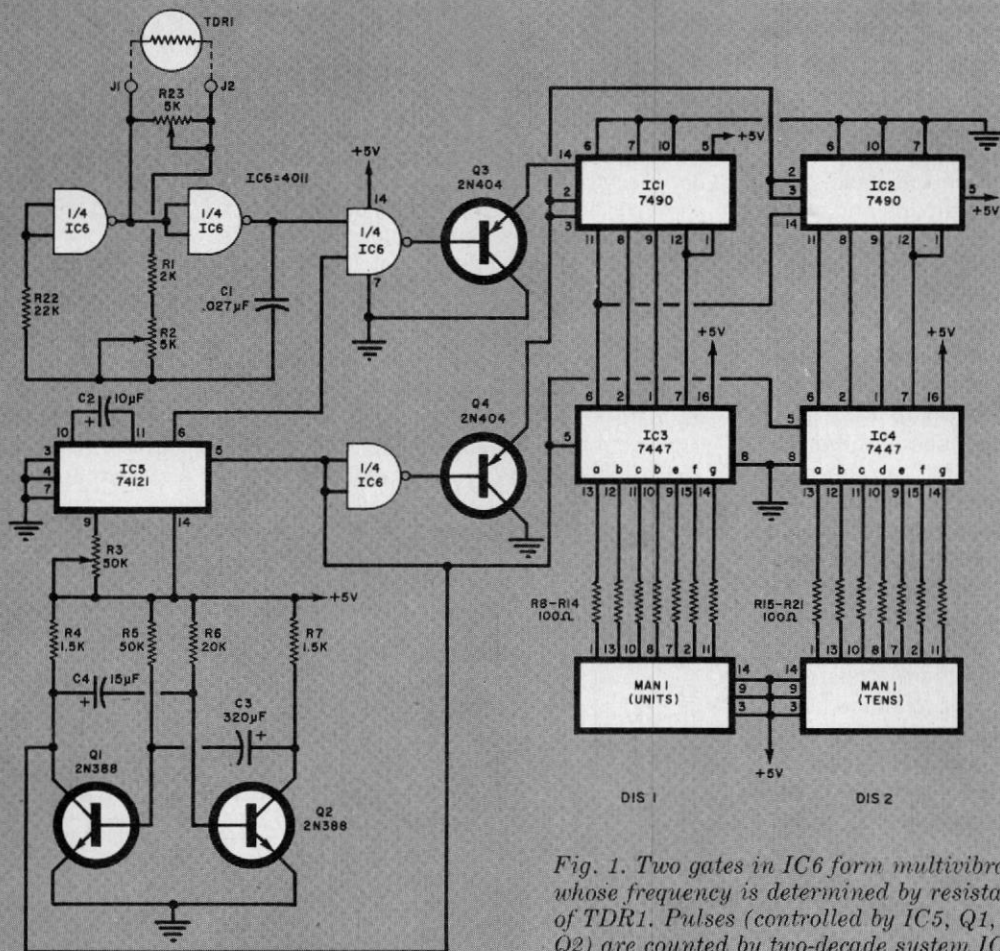


Fig. 1. Two gates in IC6 form multivibrator whose frequency is determined by resistance of TDR1. Pulses (controlled by IC5, Q1, and Q2) are counted by two-decade system IC1, IC2.

PARTS LIST

C1—0.027- μ F silver mica capacitor
C2—10- μ F, 10-V tantalum capacitor
C3—320- μ F, 10-V electrolytic capacitor
C4—15- μ F, 10-V electrolytic capacitor
DIS1, DIS2—LED display (Monsanto MAN-1 or similar)
IC1, IC2—7490 TTL decade counter
IC3, IC4—7447 TTL decoder/7-segment driver
IC5—74121 TTL monostable multivibrator

IC6—Quad NAND gate (RCA CD4011 or similar)
J1, J2—Banana jacks
Q1, Q2—2N388, HEP641 or similar
Q3, Q4—2N404, HEP739 or similar
R1—2000-ohm, 5%, 1/4-watt resistor
R2, R23—5000-ohm miniature trimmer potentiometer
R3—50,000-ohm miniature trimmer potentiometer
R4, R7—1500-ohm, 1/4-watt resistor
R5—50,000-ohm, 1/4-watt resistor

R6—20,000-ohm, 1/4-watt resistor
R8-R21—100-ohm, 1/4-watt resistor
R22—22,000-ohm, 5% 1/4-watt resistor
TDR1—1000-ohm, negative coefficient thermistor (USI 44004, available from Yellow Springs Instruments, Box 279, Yellow Springs, OH 45387)
Misc.—Suitable enclosure, flexible wire for thermistor leads, rubber glue, optional 9-oz plastic jar and cover, optional switch for two thermistors, mounting hardware and sockets.

decade counters (IC1 and IC2) and IC5, which triggers the monostable multivibrator. When IC5 operates, it closes the CMOS AND gate and allows the output of the temperature-dependent multivibrator to pass to the counters. The length of time that IC5 is on is determined by the value of C2 and the setting of R3.

Construction. The circuit can be assembled on perforated board, using sockets for the IC's and transistors. Everything is on one board except the power supply and thermistor.

Choose an enclosure that will accommodate the board, the power

supply, and the two readouts. Be sure you have access to the three trimmer potentiometers (R2, R3, and R23) through suitable holes. If you use the thermistor called for in the Parts List, you can use an 1800-ohm fixed resistor for R23. Other 1000-ohm thermistors will require some adjustment of R23. For stability, C1 should be silver mica and C2 should be tantalum.

The on and off times of the display are determined by the values of R5/C3 and R6/C4, respectively. These can be varied to suit individual choice of times.

If the temperature of more than one area is to be measured, a simple

switching scheme can be arranged between J1 and J2.

Carefully solder the flexible two-wire cable to the thermistor and insulate the joints. If the thermistor is to be used only indoors, coat it with some rubber glue. If it is to be used outside, it must be protected from the direct rays of the sun and other weather conditions. In this case, mount the thermistor in a plastic jar (about 9-oz capacity), being sure to drill many ventilation holes. The thermistor (mounted through the cover) should not come in contact with the jar. The jar must be positioned so that it does not get the direct rays of the sun.

Power Supplies. Three possible power supplies are shown in Fig. 2. Select the one that suits your needs. Any 5-volt supply that can deliver at least 300 mA can be used. If the digital thermometer is for fishing, use the ac-powered circuit. In this case, omit the transformer and diodes and use a battery holder to mount four 1.35-volt mercury cells, with an spst switch to control power.

Calibration. Connect the thermistor to J1 and J2 and apply power to the circuit. Allow it to warm up for at least 30 minutes. You will see a numerical display that will "blink" as the multivibrator operates every few seconds.

Fill a glass with ice cubes and top it off with cold water. Fill another glass with water that is as close to 90 degrees as possible. (Use an accurate mercury thermometer.) Set R23 to its midpoint; and place the thermistor in the ice water *adjacent* to an ice cube. Without disturbing the glass or thermistor, adjust R3 until the display indicates 33. Place the thermistor in the 90° water. If the display shows greater than 90, increase the value of R2 until a reading of 90 is obtained. If the display indicates below 90, decrease the value of R2.

Insert the thermistor back in the ice water and touch up R3 if the reading is less than 33. These adjustments will have to be repeated several times to

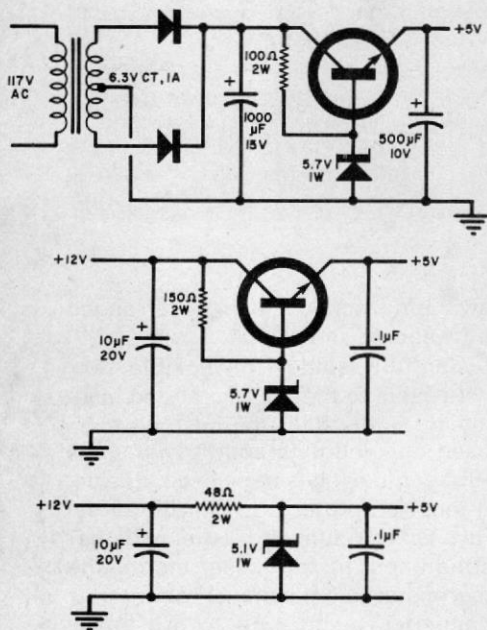


Fig. 2. Three typical power sources for thermometer. Top is for line power, other two are for mobile operation.

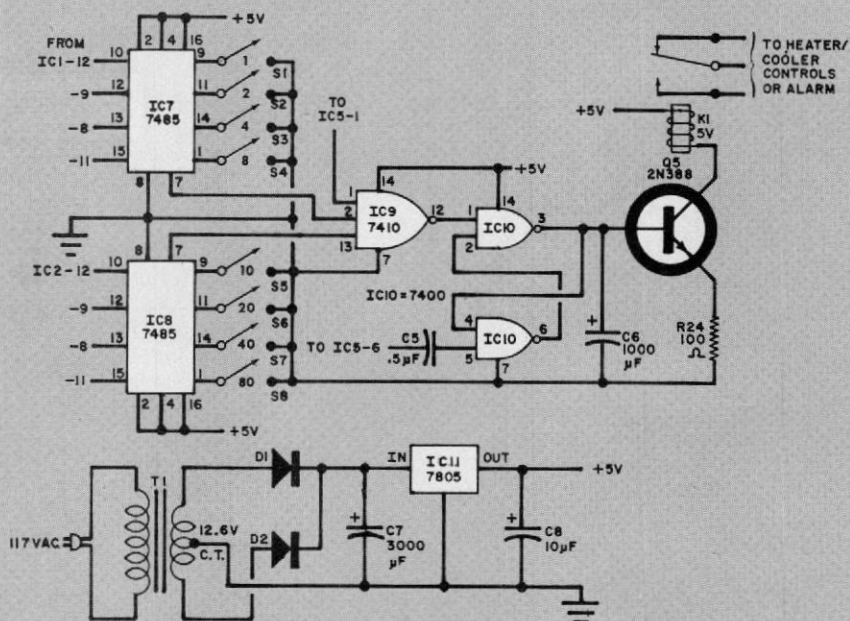
THERMOSTAT CONTROL MODIFICATION

You can convert the digital thermometer described in this article into a multi-purpose heating/cooling thermostat control with a 0° to 99° F temperature range by adding to it the circuit shown below. Relay K1 and any alarm or circuit connected to it can be made to trip at any temperature selected by switches S1 through S8.

The reference temperature selected by the switches is the sum of the closed-switch designations. For example, to set the system up for 34° F, you would close S3, S5, and S6 ($4° + 10° + 20° = 34°$). If the sensed temperature falls below 34°,

K1 will sound an alarm or turn on the heat. Conversely, if the reference temperature is 99° and the sensed temperature rises to 101°, K1 can sound a different type of alarm or turn on the cooling system.

The use of a 5-volt relay for K1 and suitable connections for its contacts to the heating/cooling controls produces a state-of-the-art environmental control system that eliminates troublesome mechanical thermostats. For the most reliable thermostatic operation, increase the value of C3 to at least 2000-μF and change the value of R5 to 100,000 ohms. Also surround thermistor TDR1 with ¼-in. (6.35 mm) of insulating material and protect it from drafts.



ADD-ON PARTS LIST

- C5—0.5-μF disc capacitor
- C6—1000-μF, 10-volt electrolytic capacitor
- C7—3000-μF, 20-volt electrolytic capacitor
- C8—10-μF, 15-volt electrolytic capacitor
- D1, D2—1-ampere silicon diode (1N4001 or similar)
- IC7, IC8—7485 magnitude comparator integrated circuit

- IC9—7410 triple 3-input NAND integrated circuit
- IC10—7400 quad 2-input NAND integrated circuit
- IC11—7805 5-volt regulator integrated circuit
- K1—5-volt relay with spdt contacts
- Q5—2N388 (or similar) transistor
- R24—100-ohm, ½-watt resistor
- S1-S8—Spst switch
- T1—12.6-volt, 1-ampere filament transformer

get the readings as accurate as possible. If you encounter difficulty in attaining a linear display, adjust R23. In general, a decrease of resistance in R23 results in an increase in sensitivity near the high end and a decrease in sensitivity at the low end.

Once calibration is complete, the digital thermometer should be within 1 degree between 0° and 90° F and

usable between -50° and 130° F. Although this project was designed for the 0-90 range, it could be used to take readings of temperatures below zero and above 100° F. A reading of 90 on a bitter-cold winter day would mean that the true temperature is $-(100-90)$ or -10°F. A display of 5 on a hot summer day means the temperature is $100 + 5$ or 105° F.

Solid-state temperature sensor outperforms previous transducers

Temperature detector profits from linear heat sensitivity of a transistor's base-emitter voltage; the result is a low-cost package with a stable, accurate output that needs no amplification

by Robert A. Ruehle, *Relco Products Inc., Denver, Colo.*

□ Although the inexpensive silicon transducer has become available to industry only in the past year or so, the military has used it for nearly 10 years. It has traveled aboard scientific satellites and high-altitude balloons, survived the steam and hot water of an active volcano, and dived into the ocean to measure temperatures in an undersea habitat.

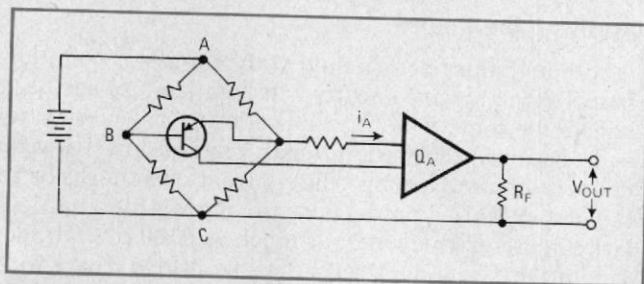
Until the past couple of years, the costs of the high-quality components required for the silicon transducer

have been so high that the device was impractical for the commercial market, which could be served by cheaper, existing transducers. What's more, the military until recently bought most of the output from the manufacturers that were making the unit.

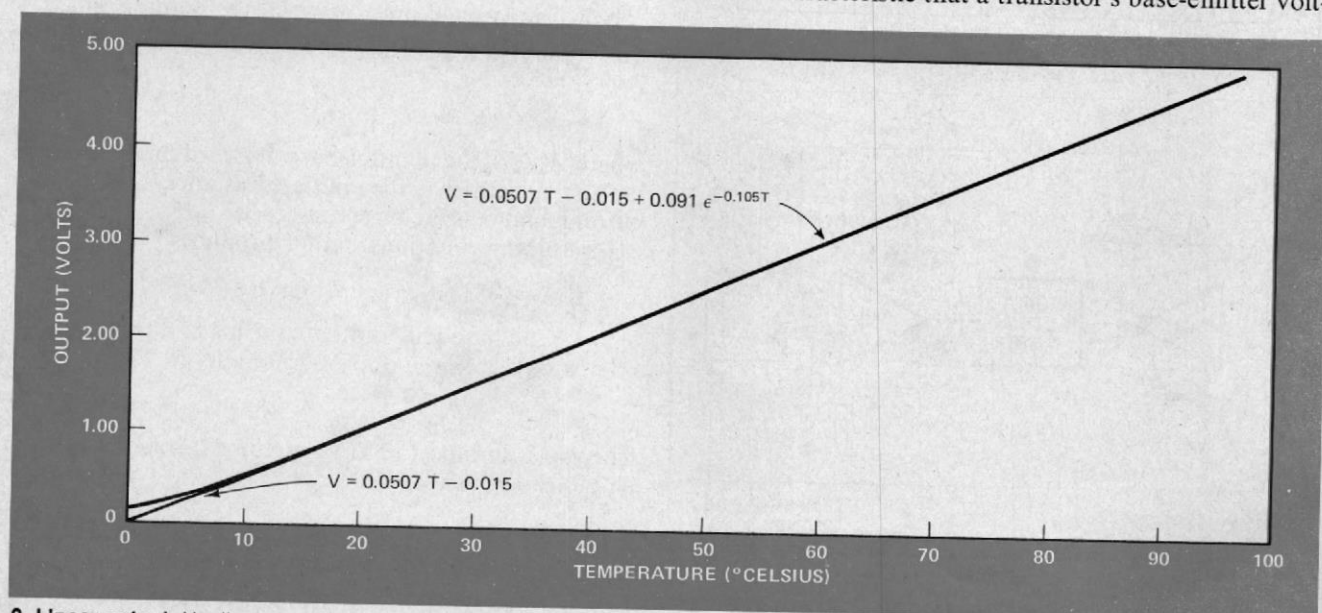
But now the new transducer, which can be purchased for about \$15, is being built into instruments—among them a digital thermometer. Although this transducer outperforms traditional temperature-measurement devices, its temperature range is limited to a range of -100°C to 150°C . Its most notable characteristic is its large and highly linear output, adjustable from 10 millivolts per degree celsius to $360\text{ mV}/^{\circ}\text{C}$. Measurements made with the instrument are highly accurate, and the output remains exceptionally stable for long periods.

Good sensitivity and a wide range of temperatures have been offered for many years by thermocouples, thermistors, and resistance-temperature devices. However, the thermocouple requires cold-junction temperature compensation, the thermistor is extremely non-linear, and the RTD is relatively expensive.

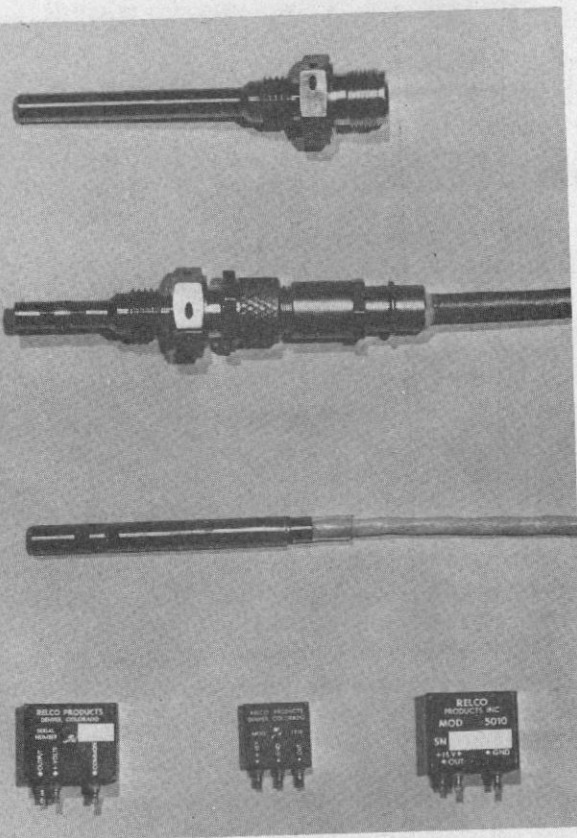
The silicon temperature transducer takes advantage of the characteristic that a transistor's base-emitter volt-



1. Solid-state transducer. A self-adjusting bridge circuit holds base current constant; the base current, in turn, keeps the collector current constant. As a result, the emitter-base voltage is a linear function with respect to temperature.



2. Linear output. Nonlinear portion of transfer function becomes negligible at higher outputs. And between 1 and 5 volts, output deviates from straight line by less than $\pm 0.1\%$. The value of constants in transfer function depends on the specific transistor used.



3. Temperature transducer. Units come in a variety of sizes, shapes, and housings to fit the application.

age varies directly with temperature. In a transistor, the collector current, I_c , is proportional to the emitter current, I_e .

$$-I_c = \gamma I_e - I_{co} \quad (1)$$

where the constant γ is the short-circuit forward-transfer ratio, and I_{co} is the collector reverse current. The emitter current, in turn, is proportional to the emitter's reverse current I_{eo} , the absolute temperature, T , and the emitter-base forward-bias voltage, V_{eb} . This relationship is shown by the equation

$$I_e = I_{eo}(e^{qV_{eb}/nKT} - 1) \quad (2)$$

where q is the electronic charge, n is a number ranging from 1 to 2, and K represents the Boltzman constant.

Taking the logarithm of Eq. 2 and rearranging the result yields

$$V_{eb} = \frac{nK}{q} \ln \left[\frac{I_e + I_{eo}}{I_{eo}} \right] T \quad (3)$$

If the emitter current is held constant, the term in brackets becomes a constant, and the emitter-base voltage becomes a linear function of temperature. As a result, theoretically, a transistor can serve as a linear precision temperature transducer.

Applying the theory

Although this phenomenon of the transistor's emitter-base voltage to vary linearly with temperature has been known for some time, its application hasn't been practical because the proportional relationship between temperature and voltage differs from one transistor to the next. Within a production run, the V_{be} for a particular temperature may vary as much as ± 100 mv. To factor out this variation, a self-adjusting bridge circuit with negative feedback has been developed (Fig. 1). In this circuit

$$V_{AB} = V_{AD} + V_{DB} \quad (4)$$

Now the voltage drop between the emitter and base of transistor Q can be considered to be made up of three parts.

$$V_{DB} = V_{eb} + i_e r_e + i_b r_b \quad (5)$$

where V_{eb} is the emitter-base forward bias, i_e is the emitter current, r_e is the emitter resistance, i_b is the base current, and r_b is the base resistance.

Combining equations 4 and 5 produces

$$V_{AB} = V_{AD} + V_{eb} + i_e r_e + i_b r_b \quad (6)$$

Since the base and emitter currents of a transistor are related by a constant of proportionality β

$$i_e = (1 + \beta) i_b \quad (7)$$

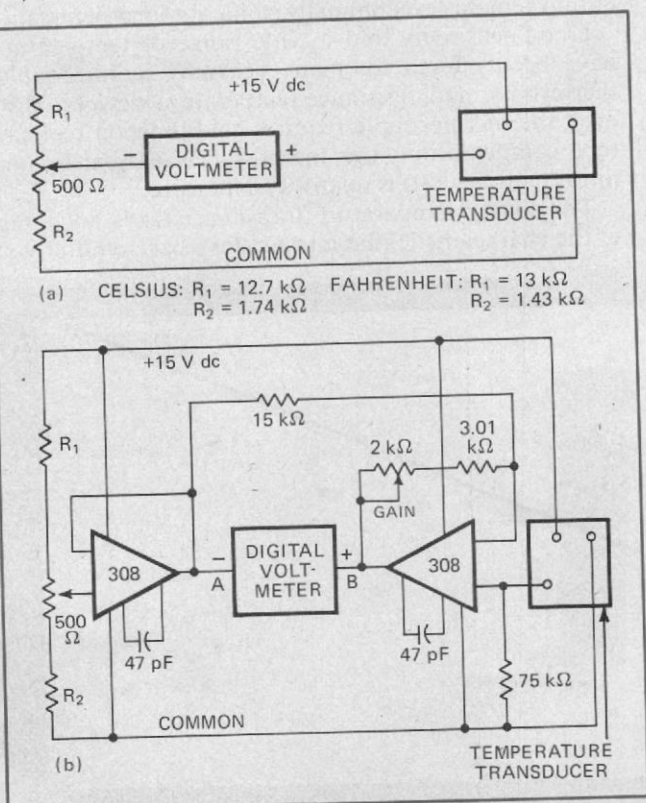
where β is termed the forward-current-transfer ratio or amplification factor and

$$\beta = i_c / i_b \quad (8)$$

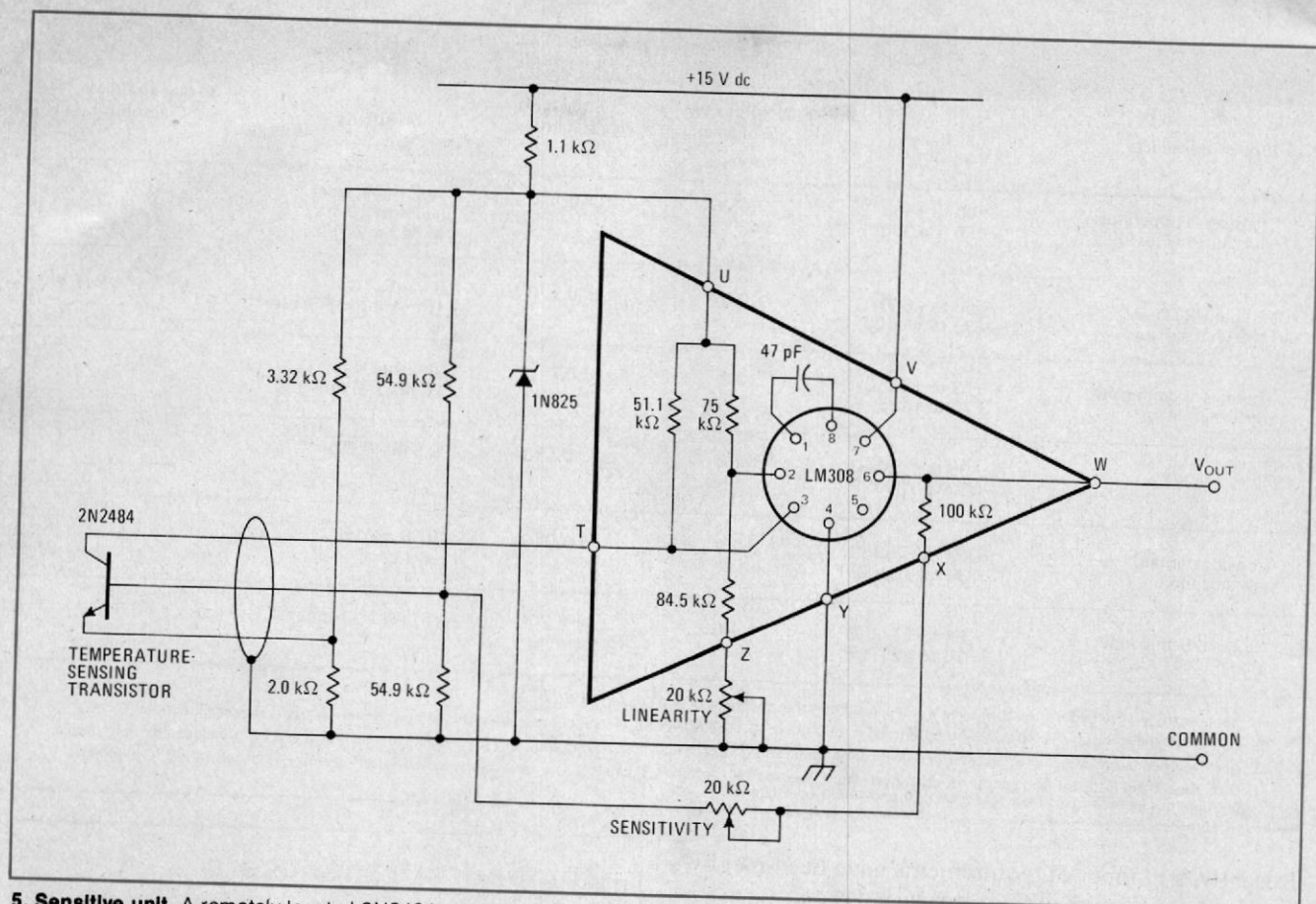
Eq. 7 can be substituted into Eq. 6 to yield

$$V_{AB} = V_{AD} + V_{eb} + i_b [(1 + \beta) r_e + r_b] \quad (9)$$

By definition, the term inside the brackets is the emit-



4. Digital thermometer. Adjustment of potentiometer and internal gain of digital panel meter in (a) trims out manufacturing variations in slope and zero-intercept. Where it is not practical to adjust the DPM's gain to trim system sensitivity, the circuit in (b) can be used.



5. Sensitive unit. A remotely located 2N2484 serves as the temperature-sensing element. To eliminate collector-base leakage current, the collector-base voltage is adjusted to zero with the linearity potentiometer; the sensitivity pot adjusts circuit gain. Linearity is typically within $\pm 0.05\%$. If better linearity is required, the open-loop gain must be increased by using an amplifier with a higher gain feedback.

ter-base resistance, r_{eb} ; therefore, Eq. 9 can be expressed as

$$V_{AB} = V_{AD} + V_{eb} + i_b r_{eb} \quad (10)$$

The circuit is set up initially at some operating point so that any change in the collector current appears greatly amplified as the current, i_A through the resistor, R . And any change in V_{AB} is accompanied by an equivalent change in V_{AD} . V_{AB} is constant for a constant supply voltage and fixed values of R_1 , R_2 , R_3 , and R_4 , so that

$$\Delta V_{DB} = \Delta i_b r_{eb} + \Delta V_{eb} \quad (11)$$

Since the operation of the circuit is based on maintaining the transistor current at a constant level, Eq. 11 reduces to

$$\Delta V_{DB} = \Delta V_{eb}$$

Further mathematical manipulation can show that the change in the current i_A is proportional to ΔV_{eb} . By making the output voltage of the amplifier, Q_A , equal to the change in i_A , the output of the transducer can be expressed as

$$V_{OUT} = MGT$$

where M is a constant equal to the value in the brackets of Eq. 3 and G is a constant determined by the closed loop gain of the circuit. This equation shows that it is,

indeed, possible to obtain a linear voltage signal proportional to temperature by using a transistor operated under constant-current conditions.

Experimental results

Tests made on several hundred silicon temperature transducers fabricated in various configurations have verified that the transfer function can be expressed by the equation

$$V_{OUT} = AT + B + Ce^{-\alpha(T-T_0)}$$

where A , B , C and α are constants and T is equal to or greater than T_0 .

Figure 2 graphs the output of a typical transducer at various temperatures, along with its transfer function. While the mathematical analysis assumes that the closed-loop gain is much greater than unity, this is not true at very low output voltages.

A drop in the open-loop gain initially causes a small nonlinearity to appear in the output. This nonlinearity becomes negligible at higher outputs, and between 1 to 5 volts, the output deviates from a straight line by less than $\pm 0.1\%$.

At first, all transducers were built for temperature-telemetry applications where an output of 0 to 5 v was typically required. As shown in Fig. 3, these transducers are built in a variety of sizes, shapes, and housings to fit the applications for which they were designed.

COMPARING TEMPERATURE TRANSDUCERS

Type of transducer	Range	Nonlinearity (% of span) (Note 1)	Long-term stability (Note 2)	Sensitivity	30-day accuracy (°C absolute) (Note 3)
Transistor temperature transducer (Fig. 5)	-100 to +150°C -150 to +300°F	± 0.05	± 0.1°C	Adjustable from less than 10 mV/°C to 360 mV/°C	± 0.1
Platinum RTD (100-ohm ice point)	-200 to +600°C -330 to +1,100°F	± 0.5	± 0.1°C	0.4 mV/°C (1 mA through sensor)	± 0.1
Thermistor composite (dual thermistor)	-55 to +85°C -70 to +185°F	± 0.8	± 0.1°C	Adjustable to 20 mV/°C max	± 0.15
Silicon diode	-100 to +150°C -150 to +300°F	± 1.0	± 0.1°C	2.5 mV/°C	± 0.5
Iron-constantan thermocouple	-200 to +750°C -330 to +1,400°F	± 2.0	± 1.0°C	0.05 mV/°C	± 1.2
National Semiconductor Model LX5700 (Note 4)	-55 to +125°C -70 to +257°F	± 1.0	± 0.2°C	10 mV/°C nominal	± 3.8

1. Nonlinearity is specified for the span, which is the lesser of either the range or -100 to +150°C.
 2. Data on IC thermocouple is estimated from limits of error given in ISA Standard C96.1, together with stability data on commonly used reference junctions.
 3. Accuracy figures are based on using external signal-conditioning and readout electronics having approximately equal cost. Self-heating error is included for each device.
 4. Data taken from National Semiconductor data sheet dated August 1974. Accuracy figure includes uncertainty caused by self-heating device, which is 2°C minimum, but does not include errors from reference drift and amplifier instability.

Recently, a number of requirements have been met by a standardized version of the aerospace design.

One of these applications was a low-cost precision digital thermometer with a slope of 10 mV/°C and an intercept of +2 V at 0°C. A digital panel voltmeter connected to the transducer output as shown in Fig. 4(a) is calibrated so that the display changes one unit for every 10 mV change at the input so that temperature can be read directly to within ±0.1°C.

To calibrate the DPM, the temperature is held at 0°C while the potentiometer is adjusted until the display reads zero. This trims out the manufacturing tolerances on the zero intercept. To trim out the manufacturing tolerance on the slope, the temperature is raised to 100°C, and the gain of the DPM is adjusted until the display reads 100.0.

In applications where it is not practical to adjust the gain of the digital panel meter to trim system sensitivity, the circuit of Fig. 4(b) can be used. Here a buffer amplifier at the transducer output and a 2-kilohm potentiometer correct system sensitivity to yield 10 millivolts per degree at points A and B.

The circuits in (a) and (b) both require a regulated voltage source, divider networks, buffer amplifiers, and trimming potentiometers, together with a transducer and readout. All these items have been combined into a single instrument that operates off either ac line power or internal batteries.

Figure 5 is a schematic diagram of one version of the new transducer. This design uses a remotely located 2N2484 as the temperature sensor. As was pointed out in the theory of operation, the circuit maintains a constant base current in the sensing transistor in order to obtain a linear output signal proportional to tempera-

Comparing transducers

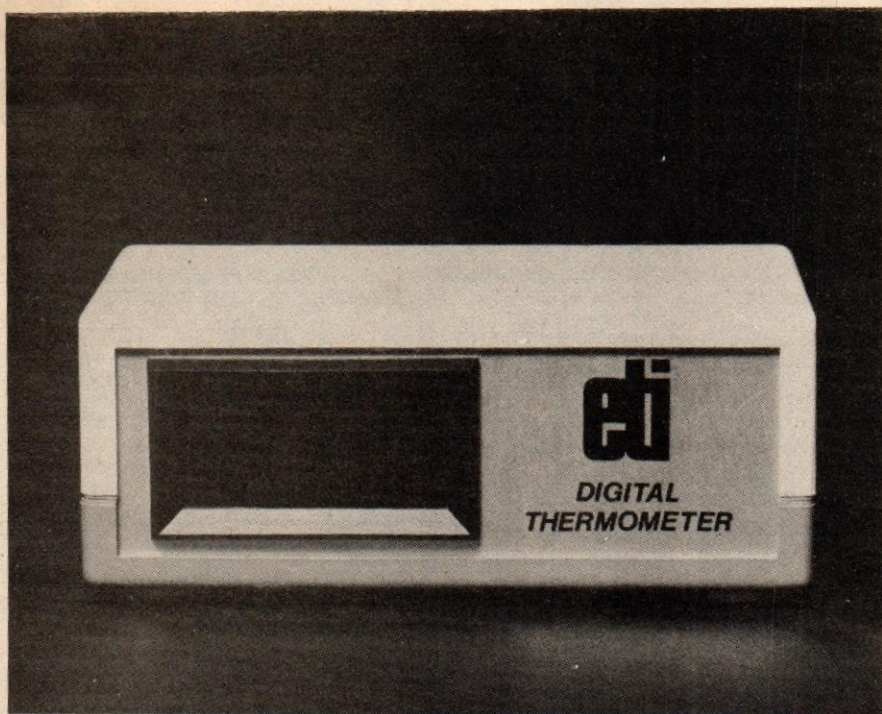
Another version of the solid-state temperature transducer can be seen in the LX5600 and the LX5700 from National Semiconductor [*Electronics*, Nov. 14, 1974, p. 130]. These units exploit the temperature sensitivity of the emitter-base voltage, but in an entirely different manner from Relco's device. National uses a pair of matched transistors operating at different collector currents. The difference in their base-emitter voltages can be shown to be proportional to the absolute temperature of the transistors and to the natural logarithm of the ratio of their collector currents.

Since the National unit is packaged as one IC, a self-heating error amounts to several degrees. Relco uses discrete components to reduce self-heating and also mounts the temperature-sensing transistor away from the amplifying circuit.

—Margaret Maas

ture. To do this, the collector-base leakage current must be eliminated from the collector circuit. This is accomplished by adjusting the collector-base voltage to zero with the linearity potentiometer. The sensitivity potentiometer is used to adjust the circuit gain for an output signal sensitivity of 10 mV/°C. The linearity of the circuit is typically ±.05%. If better linearity is required, the open-loop gain must be increased by substituting a higher gain feedback amplifier, such as the type AD508.

The table, which compares the transistor temperature transducer with other common methods of measuring temperature, shows that the circuit of Fig. 1 provides the best performance within its range of operation. This new transducer system is also the most economical. □



DIGITAL

THERMOMETER

WE HAVE FOR some time been considering the construction of an accurate electronic thermometer, and the announcement of the new National LM3911 temperature controller was enough to spur us into action and get down to building the thing.

The LM3911 is a highly accurate measurement system for use over the -25°C to $+85^{\circ}\text{C}$ temperature range. It is fabricated on a single monolithic chip and includes a temperature sensor, stable reference voltage and operational amplifier on chip.

SENSING ATTRACTION

The characteristics of this device make it ideal as the basis for an accurate and easily calibrated thermometer. The chip produces an output of $10\text{mV}/^{\circ}\text{K}$ and all that is necessary to convert the 3911 into an electronic thermometer is to connect it to a scaled voltmeter.

In its simplest form the voltmeter would consist of a moving coil meter with as large a deflection as possible.

It soon became apparent that if we were to make use of the full measurement range available, we would need a very large meter scale. A smaller scale would mean that the temperature could not be read to within a couple of degrees. We wanted our thermometer to be more accurate than this.

Now while we are not in favour of going digital for the sake of it, in this case it seemed that the potential accuracy of a digital display was required.

We threw out our analogue measurement stage and started thinking in terms of VCOs and 7400s. This line of approach seemed very attractive until we looked at the final design.

THERMAL EXPANSION

The component count had gone up dramatically and the accuracy

The circuit for the digital thermometer may conveniently be broken down into three separate building blocks. These are the temperature sensing block, the A to D convertor including the display and the power supply.

We shall start by considering the temperature sensor.

THE TEMPERATURE SENSOR

The LM3911 temperature controller used in this project provides an output voltage which is linearly related to the temperature at which the chip's sensing element is maintained. This output voltage is given by the relationship:

$$V_{\text{out}} = T \cdot 10^{-2} \text{ volts}$$

Where T is the temperature in degrees Kelvin.

The Kelvin and centigrade scales are related by the following relationship:

$$^{\circ}\text{K} = ^{\circ}\text{C} + 273.16$$

Thus at room temperature (about 20°C) the output of the LM3911 will be:

$$V_{\text{out}} = (273.16 + 20) \cdot 10^{-2} \text{ volts}$$

$$\approx 3 \text{ volts.}$$

For the A/D convertor to give readings in $^{\circ}\text{C}$, and to correctly display temperatures below zero, it is necessary to arrange so that at 0°C the output of the LM3911 is 0V.

The components R2, R3, R4, and R5 together with RV1 allow for this adjustment. They enable an adjustable 'offset' voltage to be added to the output of the temperature sensor. This offset is trimmed during the calibration procedure described in the main text.

For more detailed data on the LM3911 see the Data Sheet on page 59 of our September 1977 issue.

THE A/D CONVERTOR

The A/D convertor is based on the new Intersil ICL7107 $3\frac{1}{2}$ digit, single chip panel meter. It is intended to drive an LED display directly with a segment current of about 8mA. In addition to a precision dual slope convertor, it contains BCD to seven segment decoders, a clock and a reference voltage.

The detailed operation of this chip is something known only to the design team who produced the IC's mask, so we will have to content ourselves with a brief look at the function of the external components.

The components associated with pins 38, 39 and 40 (C4 and R9), determine the oscillator frequency, which is designed to run at approximately 50 kHz.

The reference voltage for the system is set up using RV2. The chip internally regulates the voltage between pins 1 and 32 at about 2.8 volts. This stable voltage is used as the systems reference.

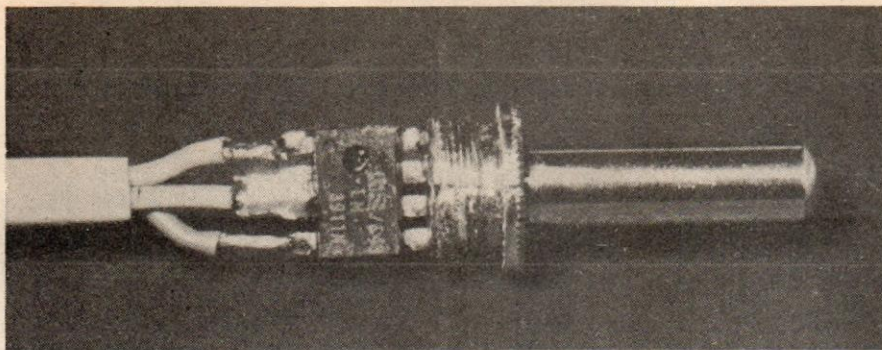
We shall see later that we require the 7107 to have an f.s.d of 2.000 V. For this f.s.d reading we must arrange for the voltage between pins 35 and 36 to be 1.000 V.

Adjustment of RV2 allows this to be accomplished.

The components not yet mentioned take care of auto zero, polarity, etc., and Intersil do not provide details of their exact functions.

The displays are directly connected to the appropriate pins with no interfacing required.

21



Interior view of our temperature probe. Pins 5, 6, 7 and 8 of the LM3911, those connected to the internal temperature sensing element, have been soldered into a jack plug from which the shaft has been removed. This provides good thermal contact between the probe tip and the sensor chip.

of the unit would have been seriously degraded as many of the new components would drift with temperature and time.

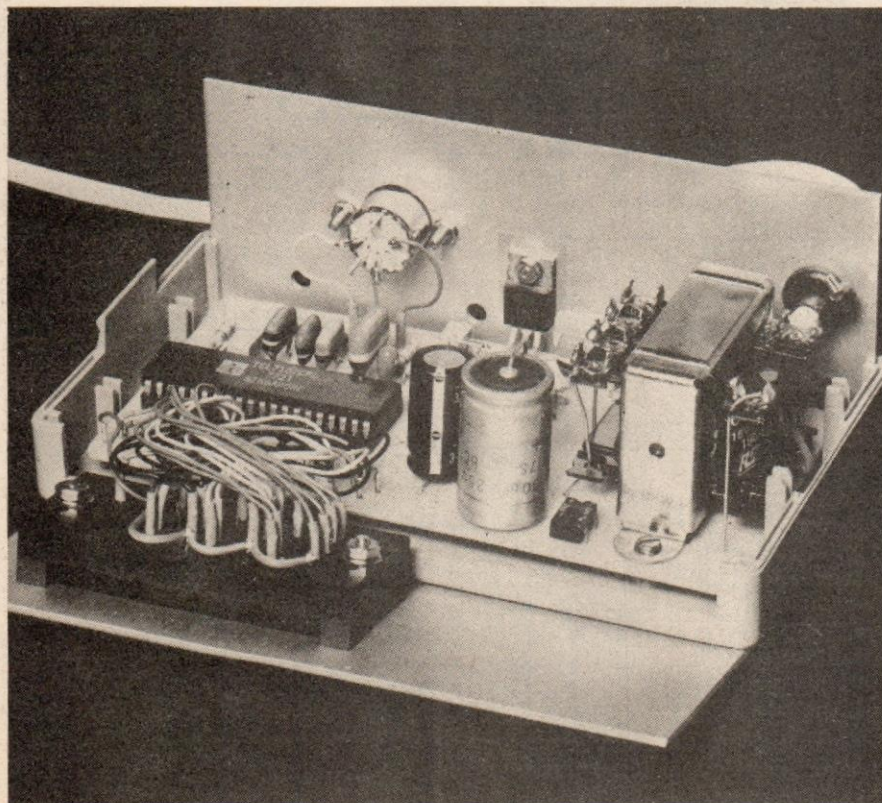
Having firstly rejected the analogue approach, and now come to the conclusion that the digital approach was also out, we were beginning to worry....

It was at this point that a new chip from Intel came to our rescue. The 7107 is a single chip DVM with three and a half digit resolution. The chip needs only a few passive external components to function as a DVM — unlike some single chip DVM's of the past which were little more than overpriced VCO's.

BUY LINES

The 7107 is available from Rapid Recall at Betterston Street, Drury Lane, London WC2H 9BS. The LM3911 should be obtainable from National Semiconductors Distributors. The voltage regulators we used we obtained from Doram.

The rest of the components should be available from good component shops or from any of the larger mail order suppliers advertising in this magazine.



A view of the interior of the thermometer. The seven segment displays are mounted in the display mounting hardware described in the text and hard wired to the PCB board. The probe is connected to the thermometer via the DIN socket shown on the rear panel.

This looked very promising. the component count would be low and the DVM chip was stable over a wide range of temperatures. In theory all we had to do was hook the temperature chip up to the DVM, add a power supply and we would have a thermometer capable of resolving temperature in 0.1°C steps.

All the components with the exception of IC2 should be mounted on the PCB according to the component overlay shown.

IC2 is a CMOS device and we recommend that it be mounted in an IC socket. As a further concession to the sensitive nature of this chip it is best not to insert the IC into its socket until all other constructional work has been completed.

After finishing the PCB assembly the display should be wired to the board. The display mounting hardware we used was from Elbar (see page 23 of the August issue).

Indication of negative temperature is by means of a LED which is mounted in the vacant position of the display mount.

The mounting arrangement for the sensor is largely a matter of choice. We mounted ours in a jack plug from which the central shaft had been removed. If the distance between the sensor and thermometer is large, then screened lead should be used for the interconnection.

There are two adjustments to be made before the thermometer will display the temperature correctly.

The first is to adjust RV1 so that, with the sensor held at 0°C, the display will read all zeros.

The best way of ensuring that the sensor is at 0°C is to immerse the device into a plastic container (flower pot) that has been half-filled with crushed ice, and topped up with cold water to the three-quarter full mark. Care must be taken to ensure that no water can reach the electrical connections to the sensor.

Leave the mixture for five to ten minutes, stirring gently, and at the end of this time adjust RV1 to give an all zero display.

The second adjustment to be made is to RV2. There are two different ways of accomplishing this. The first is to hold the sensor at a second known temperature, well away from zero, and then to adjust RV2 to bring the known temperature, and the reading on the digital thermometer into agreement.

Probably the best way of meeting the above requirement, is to obtain an accurate, limited range thermometer — a clinical thermometer should be ideal.

Place the sensor and clinical thermometer in a container of cool water and slowly add warm water to bring the mixture into the temperature range covered by the clinical thermometer.

When the mixture appears to have settled at the same temperature for a few minutes, adjust RV2 accordingly.

Another source of a stable, known,

temperature is the human body. A healthy person's under arm temperature is fairly constant at 37.4°C.

The male members of the ETI staff, for some reason the women would not take part in this test, must be a healthy lot because this method agreed very closely with the first.

The second and perhaps the most

accurate procedure, which relies not on a second temperature but upon the accurate trimming of the voltage between two pins on IC2.

If an accurate DVM is used to measure the voltage between pins 35 & 36, then adjustment of RV2 to bring the voltage reading to 1.000 V will complete calibration.

PARTS LIST

RESISTORS (all 1/4W 5%)

R1	470R
R2	12k
R3	5k6
R4	27k
R5	39k
R6	1M
R7	1k5
R8	470k
R9	100k
R10	150R

CAPACITORS

C1	220u 35V electrolytic
C2	1000u 25V electrolytic
C3,4,10	100n polyester
C5,6	10u 25V electrolytic
C7,13	220n polyester
C8	470n polyester
C9	10u 16V tantalum
C11	10n polyester
C12	47n polyester
C14	100p polystyrene

POTENTIOMETERS

RV1	5k Multiturn Bourne type (Doram: 62-701-4)
RV2	1k Multiturn Bourne type (Doram: 62-700-7)

SEMICONDUCTORS

BR1	4 pin DIL type: 0.9A 400V (from RS stockists), or other types, ie W04 will fit.
REG1	±15V regulator (Doram 65-360-0)
REG2	7805
IC1	LM3911 (see 'Buy Lines')
IC2	ICL 7107 (see 'Buy Lines')
LED1	TIL209 or similar
DISPLAYS	3 DL707 or similar (see text for mounting unit)
ZD1	4V7 400mW zener

TRANSFORMERS

T1	240V: 0-15V, 0-15V 6VA (Doram 66-113-5)
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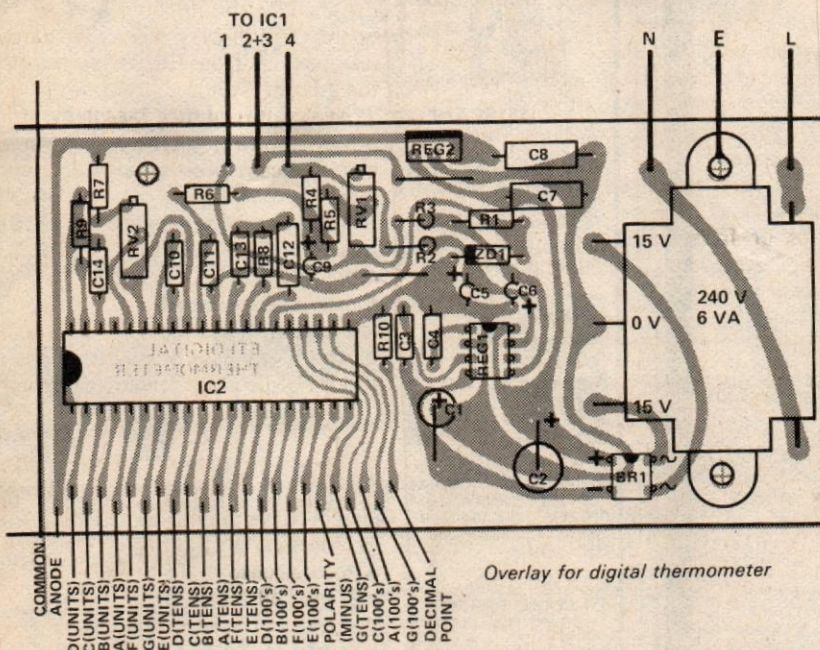
CASE
VEROCASE type 75-1238D

PROBE

1/4" mono Jack plug, Japanese type (see text)

MISCELLANEOUS

PC board as pattern. 5 pin DIN plug and chassis socket.
3 core mains flex, screened lead, nuts, bolts, etc., insulator kit for REG2, connecting wire, grommets.



Foil pattern
shown full
size (138 x 70mm).

—SHORT CIRCUITS—

TEMPERATURE ALARM

A SIMPLE BUT VERSATILE monitor to provide for over or under alarm was the main aim of this circuit. It may be used to keep an eye on fish tanks, deep freezes (by monitoring the heat exchanger), cooking vessels, incubators etc etc.

The temperature at which an alarm is given is adjustable over a range predetermined by the combined values of the components RV1 and R1. RV1 is a potentiometer which is used to adjust the final 'set point' (the temperature at which the alarm is given).

Actual temperature sensing is done by a device called a 'thermistor'. This is basically a resistor in which the resistance value varies with changes in temperature. Thermistors are obtainable in innumerable shapes, sizes and temperature ranges.

The unit may be built so that a small loudspeaker provides an audible warning when the set limit is reached.

OVER + UNDER

The unit can be constructed so that the warning (or relay action) takes place as temperature *exceeds* the set limit - or so that the warning (or relay action) takes place as temperature falls *below* the preset level.

All that is required to convert either unit from one mode of oper-

ation to the other is simply to change over the position in the circuit of the thermistor and the combination RV1 and R1.

Figure 1a shows the unit with loudspeaker set up to warn if the temperature exceeds the limit preset by RV1. Figure 1b shows the circuit set up to warn when the temperature falls below the preset limit.

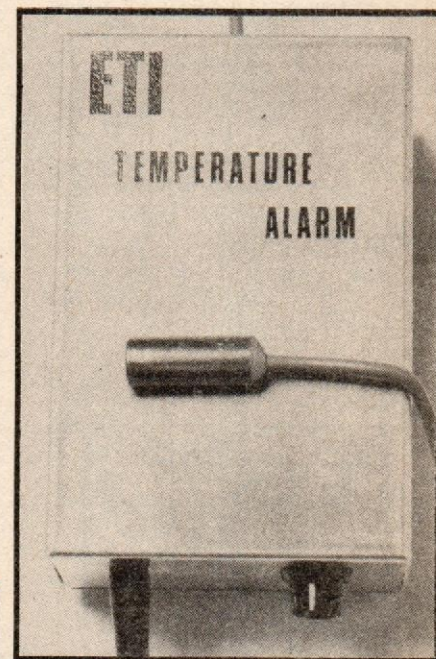
Figure 2 shows the circuit for adding a relay to enable a blower or heater depending on the circuit chosen, to be switched on.

How it works

Temperature is sensed via a thermistor. This is a resistor which varies its resistance as temperature changes. The one chosen for this application is an NTC (negative temperature coefficient) type in which resistance falls as temperature rises. The resistance at 25°C is about 47k falling to about 3k at 100°C. This thermistor forms a voltage divider with RV1 and R1.

The familiar 555 IC is the basis of the unit. The IC will oscillate if pins 2 and 6 are allowed to exceed approximately two-thirds of the supply voltage. However, the voltage divider, along with diode D1 can prevent this and while it does so the alarm will be off.

As temperature increases thermistor resistance falls and the voltage begins to rise at the junction of D1, the thermistor, and R1. When the voltage reaches $2/3 V_s - 0.6V$, the 555 begins to oscillate and causes the



loudspeaker to sound (at about 1.2kHz). If an 8 ohm speaker is available then R4 must be included. However if an 80 ohm speaker is available then R4 may be left out - the sound will then be much louder.

The circuit may be arranged so that a relay is actuated rather than an alarm. Figure 2 shows how this is done. Here diode D2 and capacitor C2 rectify the output of the 555 IC. Resistor R4 is added to ensure that there is some overlap between pull-in and drop-out set points. The lower the value of R4 the greater the difference there will be between these two points (this effect is known technically as 'hysteresis').

TABLE 1
APPROXIMATE VALUES
OF R1 + RV1 FOR
DIFFERENT TEMPERATURES

°C	OVER ALARM	°C	UNDER ALARM
20	85k	12	37k
25	75k	14	35k
35	50k	16	31k
45	30k	18	29k
55	18k	21	27k
65	10k	24	25k
75	6k5	27	23k
85	4k	30	18k
95	2k5		
100	1k8		

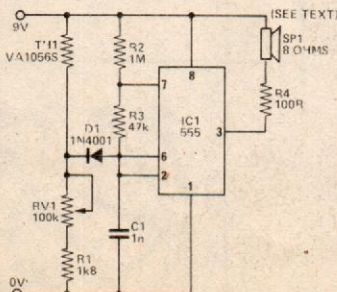


Fig. 1a OVER ALARM

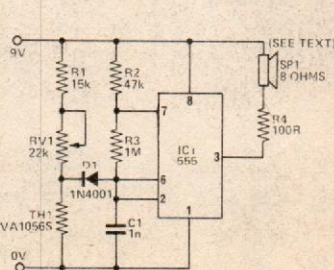


Fig. 1b UNDER ALARM

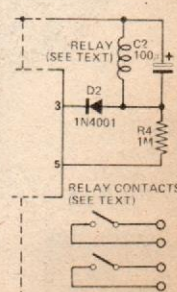


Fig. 2 ADDING A RELAY

Short Circuits

The relay is external to the board, and should be a 6V, 185R (min.) coil type. The contact rating needed will depend on the application.

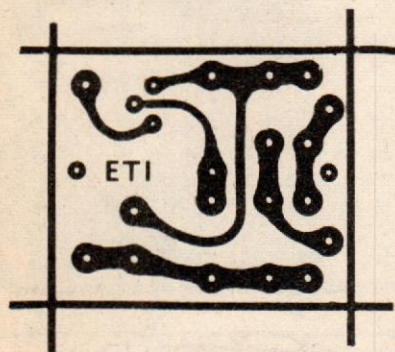
CONSTRUCTION

The thermistor should be mounted in some thin-walled glass tube, say an old perfume bottle (or cap!). If this component is not sealed, its working life will be very truncated to say the least! Electrolytic action quickly dissolves the leads. Our's lasted a day!

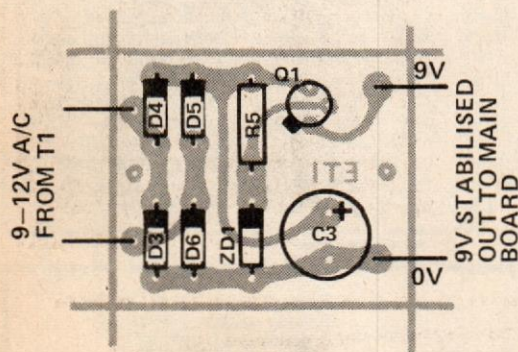
Obviously though, if all you're monitoring is air temperature, then sealing is unnecessary.

The power supply is a conventional series-pass circuit, and no comment is needed. The stabilisation components are included on the PCB. The use of a supply is recommended as the standing current is quite high.

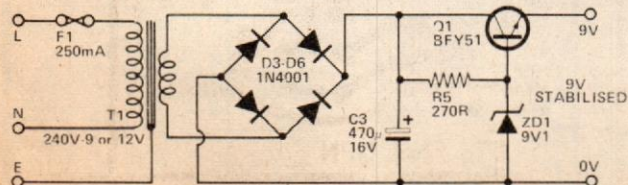
Table 1 shows the approximate values of RV1 and R1 to cause triggering at various temperatures.



Temp Alarm P.S.U. Board Foil Pattern — Full Size



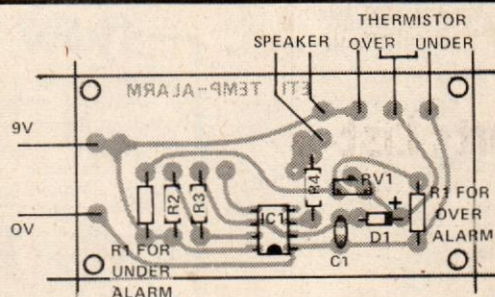
Temp Alarm P.S.U. Overlay



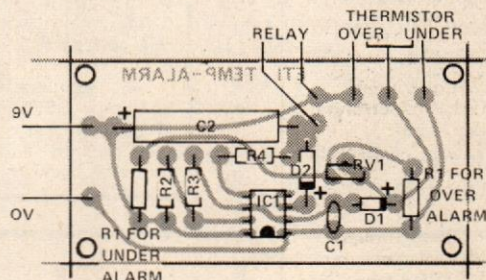
Temp Alarm Power Supply Circuit

Parts List

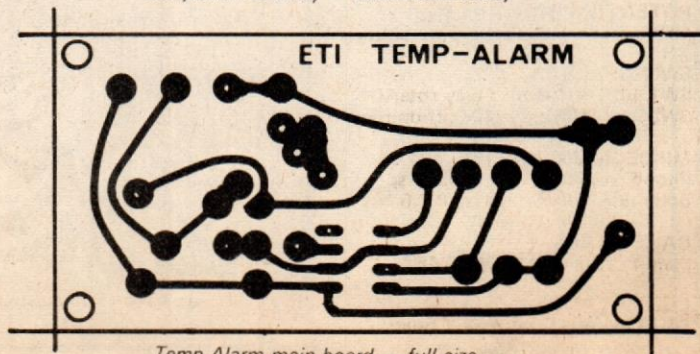
	OVER ALARM WITH 8Ω SPEAKER	UNDER ALARM WITH 8Ω SPEAKER	CHANGES FOR USING RELAY
RESISTORS			
R1	1k8	15k	----
R2	1M	47k	----
R3	47k	1M	----
R4	100R	100R	1M
R5	270R	270R	----
	All ½W 5%	All ½W 5%	
CAPACITORS			
C1	1n ceramic	1n ceramic	----
C2	----	----	100u 16V electrolytic
C3	470u 16V electrolytic	470u 16V electrolytic	----
SEMICONDUCTORS			
Q1	BFY 51	BFY 51	----
IC1	555 Timer	555 Timer	----
D1, 3 - 6	1N4001	1N4001	----
D2	----	----	1N4001
ZD1	9V1 400mW Zener	9V1 400mW Zener	----
POTENTIOMETER			
RV1	100k Mini Trim	22k Mini Trim	----
THERMISTOR			
TH1	VA 1056s (N.T.C.)	VA 1056s (N.T.C.)	----
TRANSFORMER			
T1	240V - 9V - 150mA	240V - 9V - 150mA	----
FUSE/HOLDER			
F1	To suit 250mA fuse	To suit 250mA fuse	----
BOX			
	4½" x 3" x 2"	4½" x 3" x 2"	----
	114 x 75 x 52mm.	114 x 75 x 52mm.	
RELAY			
			To suit applications with 6V 185Ω (min) coil.
MISCELLANEOUS			
3-core flex, 2-core flex, P.C. board spacers, glass tube, grommets, etc.			
Cost £4-£6			



Component Overlay — Alarm with Speaker



Component Overlay — Alarm with Relay



Temp Alarm main board — full size

AN ELECTRONIC circuit including a triac and/or an SCR (connected to a suitable sensor) is often considered a desirable substitute for a bimetallic thermostat. However, the radio frequency interference (RFI) generated by such a circuit has impeded any large-scale movement toward its use. Presented here is a thyristor thermostat which generates no RFI, uses inexpensive components, and is mechanically stable.

- Uses true zero firing of the thyristor.
- Provides symmetrical line loading (an even number of half cycles).
- Is adaptable to any size triac and load.
- Has essentially no deadband (hysteresis).

by the minimum control temperature required.

When $R1$ turns on, the cathode of $D1$ becomes highly positive with respect to point A. The value of the voltage developed on the cathode of $D1$

depends on the required "firing" voltage of $R1$. This in turn depends only on sensor temperature.

If a sufficiently positive voltage develops on the cathode of *D1* (referenced to point A) and voltage divider

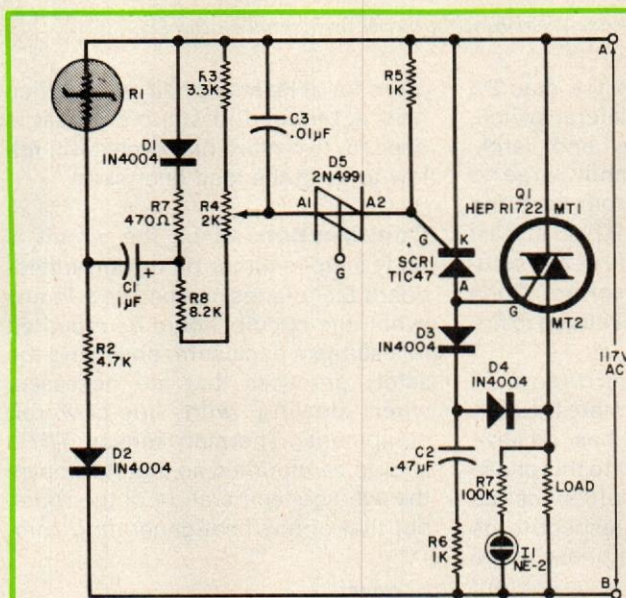


Fig. 1. Sensor R1 triggers thyristor firing circuit when heat is needed

C1—1- μ F, 200-WVDC electrolytic capacitor
C2—0.47- μ F, 200-WVDC Mylar film capacitor
C3—0.01- μ F, 25 WVDC disc capacitor
D1 to D4—1N4004 rectifier
D5—2N4991, ECG6404 (Sylvania) silicon bilateral switch
I1—NE-2 neon indicator
Q1—HEP R1723 triac (see text)
R1—TS53-57S Moxie™ thermal sensor
R2—4700-ohm, 2-watt resistor
R3—3300-ohm, 1/4-watt resistor
R4—20,000-ohm, 1-watt, linear taper, 10% tolerance potentiometer

R5—1000-ohm, ¼-watt resistor
R6—1000-ohm, 2-watt resistor
R7—100,000-ohm, ¼-watt resistor
R8—8200-ohm, ¼-watt resistor
SCR1—TIC47, ECG5404
Misc.—Printed circuit or perforated board, solder, hookup wire, suitable enclosure, thermal paste, machine hardware, etc.
Note—The Moxie thermal sensor is available for \$1.09 from Elcom Sales, Box 9112, Rochester, NY 14625, and from Multi-State Devices Ltd., 1330 Trans Canada Highway S., Dorval, P. Q., Canada, H9P 1H8.

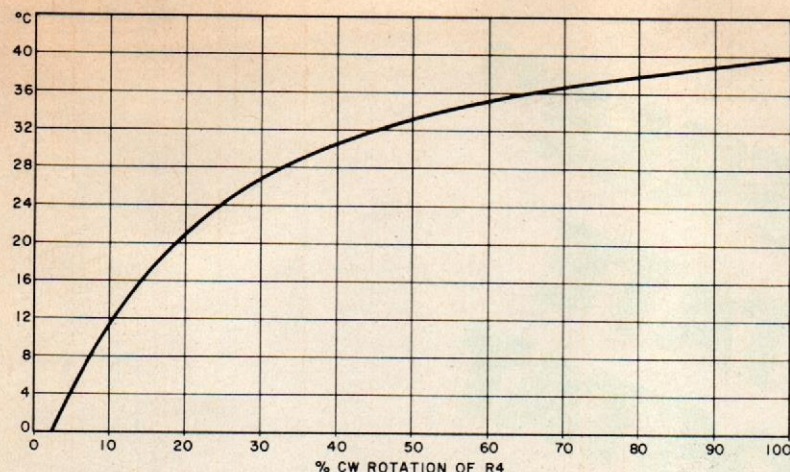


Fig. 2. Curve shows how thermostat setting is affected by $R4$.

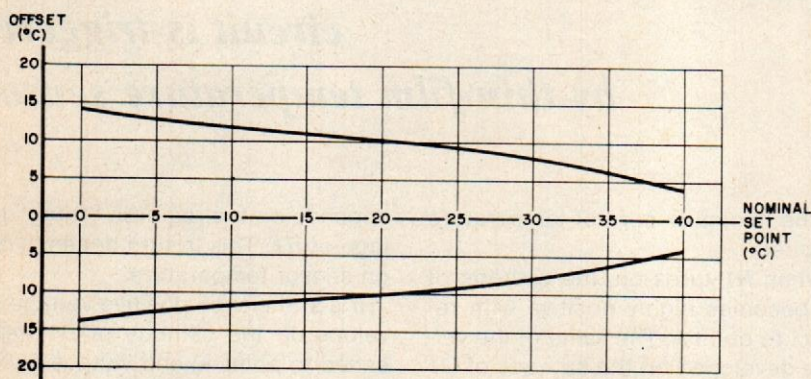


Fig. 3. Worst-case recalibration curve for a non-typical $D5$.

$R4$ is set properly, then the diac $D5$ (also called a silicon bilateral switch, or SBS) will turn on and latch. Capacitor $C1$ is sufficiently large to hold $D5$ in its on state from the firing point of $TDR1$ (less than 90°) to at least 180° . Of course, if $TDR1$ fires at a sufficiently low voltage (sensor hot), then there will not be enough voltage to fire diode $D5$.

But if $D5$ does fire, it will do so prior to 90° and remain in this state through 180° . Therefore, $SCR1$ has positive gate current at 180° . Prior to this phase angle, $SCR1$ remains off since its anode is negative with respect to its cathode. As soon as the phase angle passes 180° , $SCR1$ conducts current into the gate of the triac $Q1$. The current through $SCR1$ is limited to the minimum turn-on current of $Q1$, as it serves as a shunt around $SCR1$.

So, the triac is on from 180° to 360° , when the current through it falls below its holding point. The slaving circuit consisting of $D3$, $D4$, $C2$, and $R6$ serves to store the peak voltage across the load on $C2$. This stored voltage provides the triac with gate current between 270° and 450° , insuring zero-cross firing at 360° .

In this way, the load will be ener-

gized for at least two half cycles when heat is required. If still more heat is needed, two more half cycles will follow to keep the load energized.

Construction. Since the circuit is fairly simple, either pc or perforated-board techniques can be used. In any event, the circuit should be mounted in a suitable enclosure, observing the safety practices that are necessary when dealing with line-powered equipment. Thermal sensor $TDR1$ should be mounted so that it samples the average temperature of the room, not that of any heat-generating com-

ponent in the circuit. For example, it could be mounted in one corner of the enclosure away from triac $Q1$, with numerous holes drilled around it for unimpeded air flow. Alternatively, it could be mounted in a small metal box a short distance away from the rest of the circuit, with short interconnecting leads between the two. Thermal paste could then be used to keep sensor and enclosure at the same temperature.

Calibration and Use. Potentiometer $R4$ acts as the thermostat's sensitivity control. Figure 2 shows how the thermostat's set point varies as $R4$ is rotated. This curve is valid when all components are at their "typical" values. Of course, solid-state and thin-film devices are subject to some variations. Figure 3 shows the worst-case recalibration required with a "non-typical" $D5$. Worst-case variations of the thermal sensor will affect the calibration curve as well, and the resulting recalibration is shown in Fig. 4. All thermostats can be calibrated to within 2°C of Fig. 2 by trimming $R3$ and $R8$.

You will most probably want to make a calibrated dial for adjusting $R4$ to the desired room temperature. This is best done empirically. Thermally couple a good-quality thermometer to $R1$ and adjust $R4$ until the neon indicator $I1$ flickers or glows. At that point current is flowing through the heating element (LOAD), and the temperature of the sensor can be read off the thermometer. For temperatures higher than the room temperature, $R1$ can be gently heated.

One final note—the triac specified for $Q1$ (HEP R1722) is rated at 10 amperes forward current. If your heating element draws more current, simply use a higher-power triac. Of course, adequate heat-sinking is necessary for any thyristor. ♦

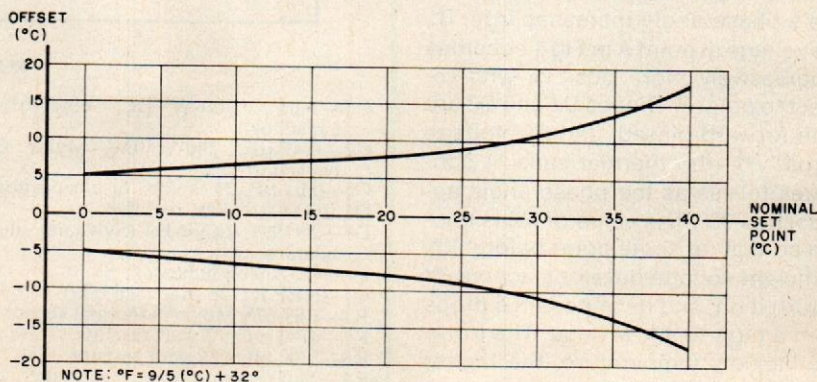


Fig. 4. Variations in $R1$ can be corrected using these curves.