CIRCUITS

ALL ABOUT THERMISTORS

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We conclude our look at thermistors with two simple but practical projects—a digital thermometer and a temperature-to-frequency converter—that you can build.

Part 3 BEFORE WE MOVE ON to our thermistor-based projects, let's finish up our discussion of matched thermistor sets.

At least two manufacturers, Yellow Springs Instrument Co. (Box 279, Yellow Springs, OH 45387) and Fenwal (63 Fountain St., Framingham, MA 01701), sell preselected and precalculated sets of components. The thermistor pair is constructed as a single component and looks just like an ordinary small, epoxy-coated disc, except that it has three leads instead of two. Internally, the two thermistors are connected in common on one side. The resistors are low temperature-coefficient, 0.1% metal film resistors.

Table 3 lists the values of four different component sets from the Yellow Springs Instrument Co. that are intended to be used with either the *44018* thermistor-pair or the 700-series thermistor probe. The selected values of R1 and R2 optimize the linearity over several temperature ranges. Table 3 also lists a *resistance mode* equation—we will get to this a bit later. The thermistor-pair itself has an accuracy of ± 0.15 °C (± 0.27 °F), which should be added to the linearity deviation to find worst-case error. Other prepackaged thermistor sets are available, including a three-thermistor set for even better linearity.

Table 4 lists the bridge component values (R3, R4, and V_S) needed for an output of 10 mV-per-°C or 5 mV-per-°F. You can get 10 mV-per-°F by doubling the supply voltage, but that's not recommended—the power dissipation in the thermistors may become high enough to affect accuracy.

Resistor-thermistor networks

It is often useful to create a network whose resistance changes linearly with temperature. Such networks are used to temperature-compensate other circuit values or to measure temperature using an ohmmeter-like circuit. An NTC thermistor may be linearized by simply connecting a resistor in parallel as shown in Fig. 14.

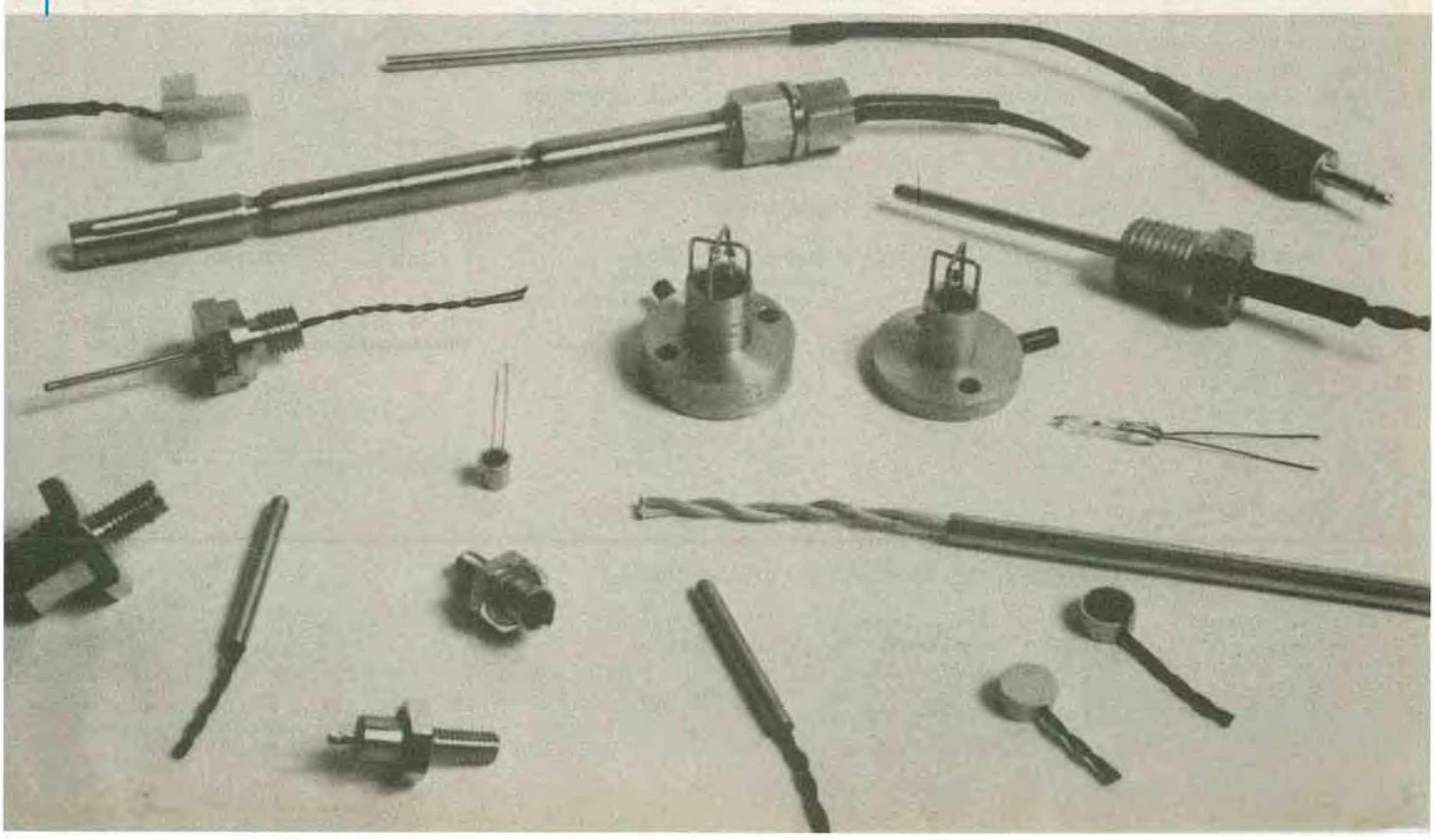


TABLE 3—MULTIPLE THERMISTOR LINEAR NETWORKS

Linear temperature range	R1	R2	Bridge equation* (V_{out}, volts, when V_s equals 1 volt.)	Resistance mode* equation (ohms)	Linearity deviation	Manufacturer's component set no.
0 to 100°C or 32 to 212°F	3.20K	6.25K	0.0053483 T + 0.13493 or 0.00297127 T + 0.03985	2768.23 − 17.115 T or 3072.48 − 9.508 T	±0.216°C or ±0.388°F	YSI 44201
−5 to 45°C or 23 to 113°F	5.70K	12.0K	0.0056846 T + 0.194142 or 0.0031581 T + 0.093083	4593.39 − 32.402 T or 5169.42 − 18.001 T	±0.065°C or ±0.12°F	YSI 44202
−30 to 50°C or −22 to 122°F	18.7K	35.25K	0.0067966 T + 0.34893 or 0.00377588 T + 0.228102	12175 − 127.096 T or 14435 − 70.608 T	±0.16°C or ±0.29°F	YSI 44203
−2 to 38°C or 30 to 100°F	5.70K	12.4K	0.00563179 T + 0.192437 or 0.0031289 T + 0.09232	4603.11 − 32.1012 T or 5173.8 − 17.834 T	±0.03°C or ±0.055°F	YSI 44204

The values shown work with YSI 44018 thermistor-pair. Resistors must be 0.1% or better.

Bridge equation refers to Fig. 13. Resistance mode equation refers to Fig. 16.

Figure 15 shows the resistance-versus-temperature curve for such a network. You can see that it is the same S-shaped curve as was seen earlier for a thermistor bridge, only inverted. As it turns out, the same rules apply for linearization: you can get good linearization over narrow ranges by simply choosing the resistor to be equal to the thermistor's value at mid-scale. For best possible linearization, you can use the same equation as was used earlier to linearize the bridge.

Table 5 lists the resistance equations and linearity deviation for three temperature ranges. Just as with the bridge, linearity becomes worse as the temperature range increases. Of course, sensitivity and zero-offset are not adjustable, although you can add a resistor in series with the network without affecting linearity. Only negative-going slopes are possible, since the thermistors' resistance decreases with increasing temperature.

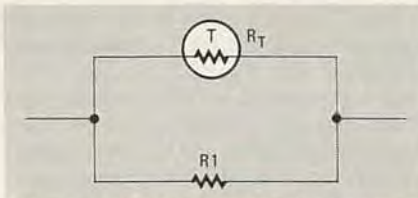


FIG. 14—A THERMISTOR'S RESISTANCE can be linearized over small temperature ranges simply by placing a fixed resistor in parallel with it.

Networks like those are useful if you need to generate a gain or an offset voltage that changes with temperature. They also may be used in series with a coil such as a meter-movement or a TV deflection coil. Since the resistance of copper increases with temperature, the series thermistor network can be designed to keep the total resistance constant despite temperature fluctuations.

For best linearity over wide temperature ranges, two thermistors (or a single thermistor-pair) can be used as shown in Fig. 16. The resistor values for the circuit shown in Fig. 16 turn out to be the same as were used earlier in the bridge circuit. Therefore, you can use the same pre-selected component sets that are available from the manufacturers. Table 3 can again be used to select the optimum value of R1 and R2. The total resistance of that circuit is calculated using the resistance-mode equation listed in Table 3.

Analog-to-digital conversion

You can connect the output of a thermistor bridge directly to the input of an

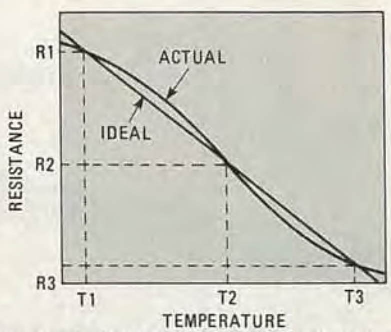


FIG. 15—RESISTANCE VS. TEMPERATURE of the resistor-thermistor combination of Fig. 4

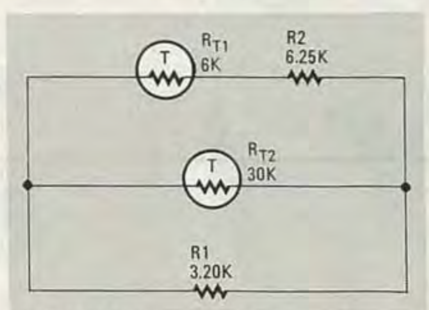


FIG. 16—FOR BETTER LINEARITY, you can use two thermistors in parallel. This circuit provides a linearity of ±0.216°C from 0–100 °C.

TABLE 4—LINEAR BRIDGE COMPONENTS

Temperature range	Resistors R3, R4	Supply voltage V_s	Bridge output
0 to 100°C	20.52K, 3.20K	1.8698 V	10 mV/°C
32 to 212°F	77.10K, 3.20K	1.6828 V	5 mV/°F
−5 to 45°C	23.66K, 5.70K	1.7591 V	10 mV/°C
23 to 113°F	55.54K, 5.70K	1.5832 V	5 mV/°F
−30 to 50°C	34.89K, 18.7K	1.4713 V	10 mV/°C
−22 to 122°F	63.28K, 18.7K	1.3242 V	5 mV/°F
−2 to 38°C	23.92K, 5.70K	1.7756 V	10 mV/°C
30 to 100°F	56.04K, 5.70K	1.5980 V	5 mV/°F

Note: Resistors should be 0.1% or better. For values of R1 and R2 see Table 2a.

TABLE 5—LINEARIZED THERMISTOR-RESISTOR NETWORK VALUES

Temperature range	R1	Linear resistance equation (ohms)	Linearity deviation
10 to 30°C	2,168 ohms	1697.84 − 23.664 T	+0.07, −0.06°C
0 to 50°C	1,763 ohms	1422.12 − 17.330 T	+0.86, −0.95°C
0 to 70°C	1,164 ohms	1004.96 − 10.147T	+2.0, −2.3°C

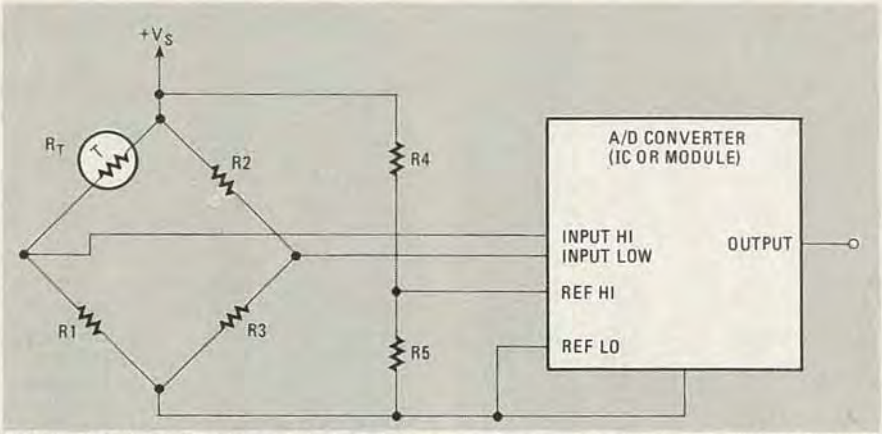


FIG. 17—CONNECTING THE BRIDGE OUTPUT to an A/D converter provides digital temperature information.

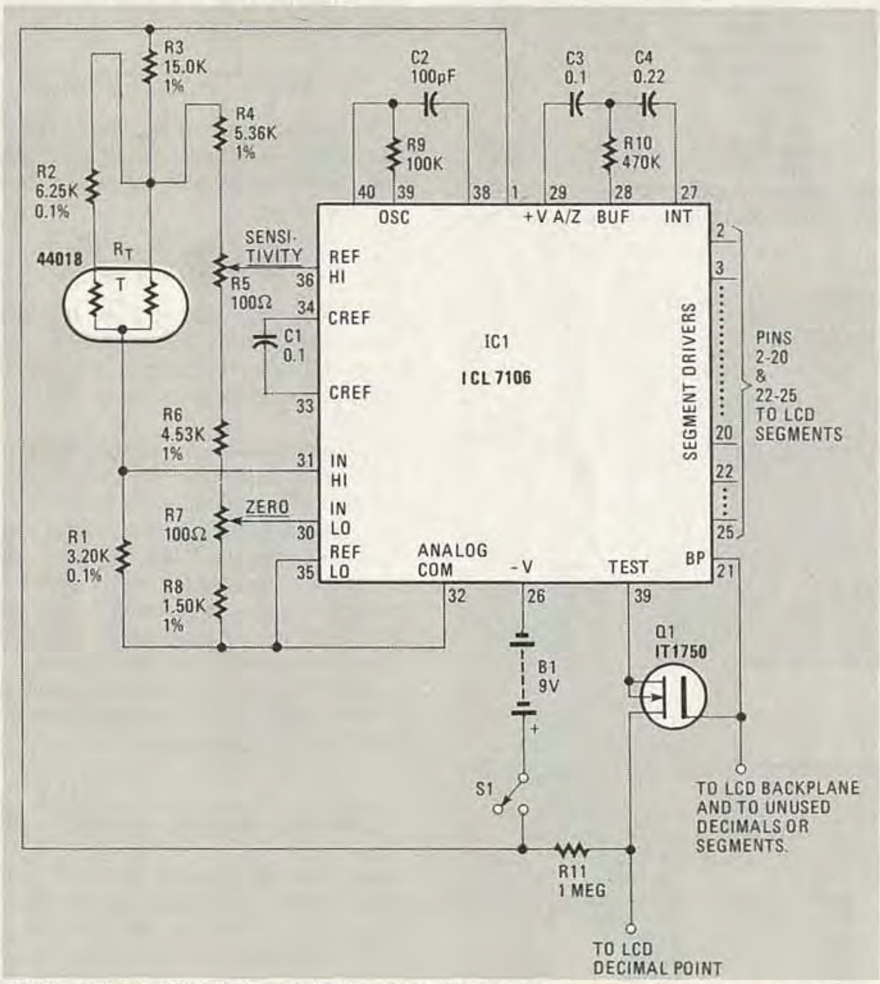


FIG. 18—A BATTERY-POWERED DIGITAL THERMOMETER using a single IC and a thermistor-pair.

analog-to-digital converter IC or module as shown in Fig. 17. The bridge values are selected as before to provide best linearity, needed voltage sensitivity, zero offset, etc. Either a single thermistor or a thermistor-pair may be used, and the component values of Tables 2 and 3 will work just as well here. The reference voltage input should be set for the desired sensitivity or for the desired full-scale output.

One interesting observation results from the fact that an analog-to-digital converter is really a ratio device; that is,

$$\text{Output} = K \times \frac{\text{Input}}{\text{Reference}}$$

If the supply voltage, V_S, varies, the input and reference voltages will vary by equal percentages, leaving the output unchanged. That means that the regulation, and even the exact value of V_S, are not critical—an inexpensive zener diode or regulator may be used. In fact, if the circuit's power supply is only moderately regulated, you may be able to use a simple voltage divider to create V_S. We will see this in the next example. A very simple circuit can give accurate and stable results.

Digital thermometer

If we replace the A/D converter with an digital voltmeter IC, we can produces a simple, accurate, battery-powered thermometer. Figure 18 shows the complete circuit we need. It uses an Intersil ICL7106 A/D converter IC and a two-thermistor linear network.

The thermistor-pair R_T forms the left-hand side of a Wheatstone bridge. The right-hand side of the bridge is formed by the voltage-divider string R4 through R8. That same string provides the reference voltage for the A/D converter.

The ICL7106 maintains its ANALOG COMMON (pin 32) 2.8 volts below the supply voltage. Resistor R3 reduces the voltage for the bridge, to minimize thermistor self-heating. You will notice that the bridge voltage varies as the thermistors change with temperature, from about one volt at 0°C to 0.5 volt at 100°C. In a normal analog situation, that would be disastrous. In this case, however, the A/D converter's output equals the input divided by the reference and, since the input and reference vary by equal percentages, the output is unaffected.

The IC itself is a dual-slope A/D converter with an auto-zero cycle. Its output will directly drive a 3-1/2-digit, seven-segment LCD readout. The output (as seen on the display) is given by:

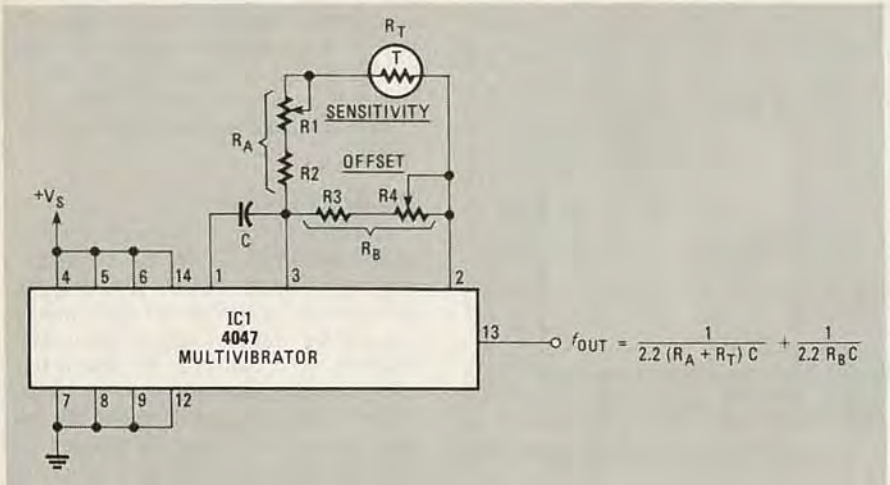
$$\text{Output} = \frac{\text{Input}}{\text{Reference}} \times 1000$$

The IC's clock timing is set by R9 and C2 to 48 kHz, which results in three readings per second. Transistor Q1 inverts the backplane waveform to drive the decimal point. The thermistor-pair shown is a 44018 or 700-series probe from Yellow Springs Instrument Co.

To calibrate the thermometer, you first have to know the R versus T values of the thermistor-pair. That information is shown in Table 6. Once you know their characteristics, you can replace two thermistors of the pair with accurate, known resistances (from precision decade resistors, for example). Set both to the zero-degree resistances, then adjust R7 (zero control) for a reading of 0.2 (the setting for minimum nonlinearity error). Next, set the decades to 100°C and adjust R5 (sensitivity) until the reading is 100.0. Repeat as necessary.

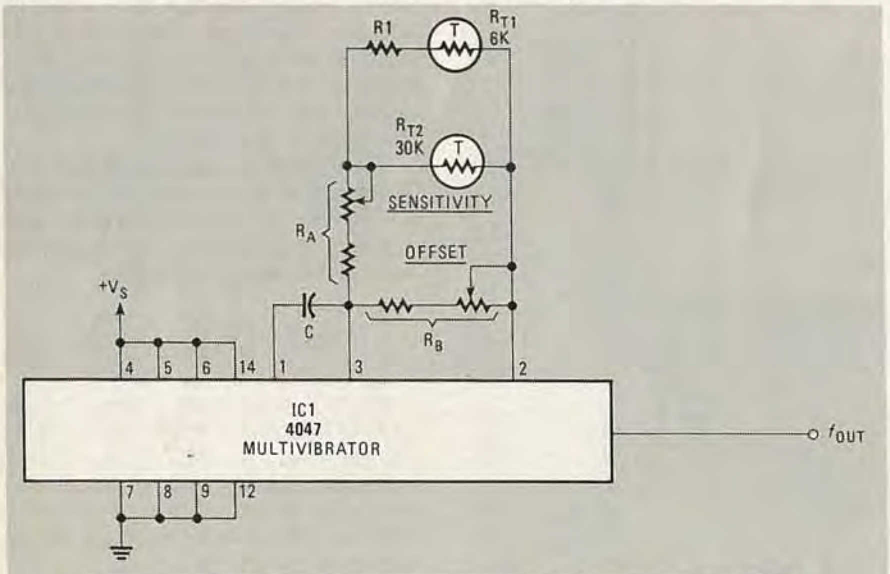
Temperature to frequency converters

You can make a temperature-to-frequency converted by replacing the A/D converter of Fig. 17 with a voltage-to-



TEMPERATURE RANGE	20 TO 40°C	-20 to 30°C	0 TO 70°C
FREQUENCY RANGE	4,000 TO 6,000 Hz	800 TO 1300 Hz	200 TO 900 Hz
f_{OUT}	100 T +2000 Hz	10 T + 1000 Hz	10 T + 200 Hz
THERMISTOR	30K AT 25°C	10K AT 25°C	30K AT 25°C
RA	18.83K	18.67K	15.82K
RB	268.3K	30.39K	530.0K
C	0.002448 μF	0.02452 μF	0.0248μF
MAXIMUM NONLINEARITY	+0.062, -0.054°C	+0.9, -1.0°C	+2.0, -2.2°C

FIG. 19—A MULTIVIBRATOR can be used to give a frequency output that varies linearly with temperature.



TEMPERATURE RANGE	0 TO 100°C	-5 TO 45°C	-30 TO 50°C
FREQUENCY RANGE	1000 TO 2000 Hz	4500 TO 9500 Hz	700 TO 1500 Hz
f_{OUT}	10T + 1000 Hz	100 T + 5000 Hz	10 T + 1000 Hz
RA	3.2K	5.7K	18.7K
R1	6.25K	12K	35.25K
RB	8K	63.28K	56.55K
C	0.07597 μF	0.004533 μF	0.01652 μF
LINEARITY	±0.216°C	±0.065°C	±0.16°C

FIG. 20—USING TWO THERMISTORS improves the linearity of the temperature-to-frequency converter of Fig. 19

frequency converter. Even simpler and less expensive, though, is a circuit that uses a thermistor as part of the resistance in an R-C multivibrator circuit.

Temperature-to-frequency converters are useful in telemetry applications because the frequency signal is not affected by line resistance or by normal amounts of noise pickup. They are especially useful if temperature data must be transmitted by RF, through telephone lines or optical cable, (where D.C. transmission is impossible). The frequency range can be tailored to suit the transmission medium.

Figure 19 shows a temperature-to-frequency converter built around a 4047 CMOS multivibrator IC. The 4047's out-

TABLE 6—R VERSUS T VALUES

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

put frequency (pin 13) is given by $f = 1/(2.2RC)$. Therefore:

$$f = \frac{1}{2.2\,(R_A + R_T)C} + \frac{1}{2.2\,(R_B)C}$$

The combination of R_A and C affects the circuit's sensitivity, while R_B affects only the frequency offset. Resistor R1 is selected using:

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

where R_{T1}, R_{T2}, and R_{T3} are the thermistor's resistances at the low-end, mid-scale, and high-end temperatures, respectively. Linearity is the same as shown in Fig. 12.

A high-resistance thermistor should be used for this temperature-to-frequency converter. Depending on the supply voltage, the 4047 will generate several volts between terminals 2 and 3, and a low resistance thermistor will self-heat enough to cause large errors. Once the thermistor and the temperature range are chosen, compute R_A for best linearity.

Next, the capacitor must be chosen to give the right sensitivity (Hertz per degree). In the circuit shown:

$$C = \frac{1}{2.2S}\left[\frac{1}{R_A + R_{T3}} - \frac{1}{R_A + R_{T1}}\right]\left[\frac{1}{T3 - T1}\right]$$

where S has the units of Hz/°C, C is in farads and all resistances are in ohms. Finally, R2 is found by substituting R_A, R_{T1} and C in the original frequency equation and solving for the value of R_B that gives the desired frequency at T1. Figure 19 includes a table of component values for three temperature ranges. Notice that the calculations generally produce odd component values. The needed value of C must be created by using a parallel combination of capacitors; R_A and R_B include trimmer potentiometers.

Just as with the bridge, linearity and range of the temperature-to-frequency converter may be improved by using a two-thermistor network. The design process is complex, but Fig. 20 shows such a circuit. R-E