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# A NEW DESIGN APPROACH FOR WIDE-RANGE TEMPERATURE MONITORING AND COMPENSATING NETWORKS IN SCIENTIFIC SATELLITES

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## ABSTRACT

An analytical design method is presented for thermistor-resistance temperature monitoring and compensating networks, providing good linearity over wide temperature ranges. These networks have the advantages of design simplicity, low power operation, small physical size, and low cost. Network equations are established in terms of a desired operating characteristic, and unknown network parameters are determined by means of a simultaneous solution of these equations.

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# A NEW DESIGN APPROACH FOR WIDE-RANGE TEMPERATURE MONITORING AND COMPENSATING NETWORKS IN SCIENTIFIC SATELLITES

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## INTRODUCTION

On scientific satellites and space probes the temperature may vary under normal orbital conditions from 120°C to 10°C inside the spacecraft and from 10°C to −40°C outside the spacecraft, with low extremes exceeding −125°C in extended earth shadow conditions. Until now any temperature below −50°C was monitored by tungsten, platinum, or thermocouple type sensors. These sensors require an operational amplifier due to their low temperature coefficients. Because of the relatively large temperature coefficient of a thermistor an operational amplifier is not needed for monitoring and compensating networks using thermistors.

The purpose of this paper is to present a new design approach for single and multi compensated thermistor networks. The multi network given in the design example is capable of monitoring a temperature from 100°C to −100°C with good linearity. This design method which greatly simplifies the mathematical solution of thermistor-resistor compensation networks has been found to work equally well for extended temperature ranges down to −150°C. The equations developed in this report are by no means the exact mathematical solution. The thermistor sensitivity $k$ is obtained from the thermistor temperature-resistance ratio characteristic curves, and the values $R_A$, $R_B$, and etc. are approximate as can be seen from the equations. Despite these limitations this design yields temperature monitoring networks that have a wide temperature range with accuracies ±1%.

The multi thermistor-resistance compensated network presented in this paper was used to monitor temperatures on Explorer XVIII, Explorer XXI, and Explorer XXVIII, Orbiting Geophysical Observatory C and D, and a few military spacecraft. This same design could be employed, however, to monitor temperature or compensate any electronic circuit over a temperature range of 100°C to −100°C with good linearity and stability.

## CIRCUIT OPERATION

The sensitivity $k$, of a thermistor is expressed as the ratio of its resistance at a given temperature to its resistance at 25°C. Sensitivity as a function of temperature for three different thermistors is plotted in Figure 1. Curve A represents maximum sensitivity and curve C represents minimum sensitivity of commercially available thermistors. Curve B is characteristic of a thermistor

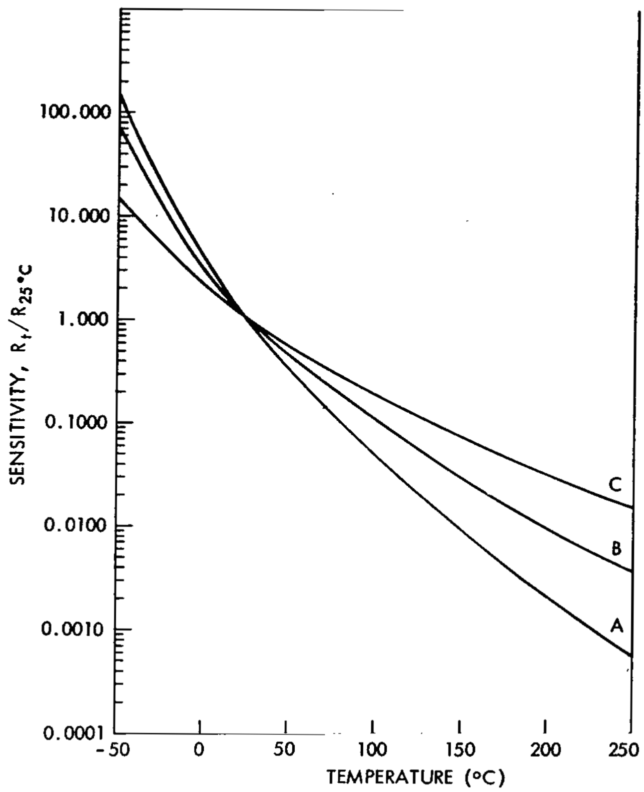


Figure 1—Thermistor temperature-resistance ratio characteristics.

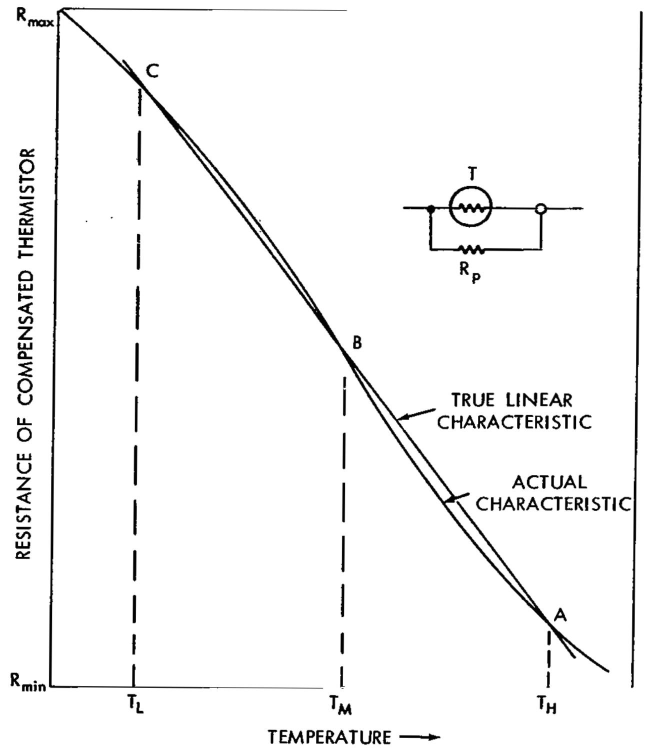


Figure 2—Compensated thermistor and its temperature-resistance characteristic.

with medium sensitivity. The nearly linear characteristic of resistance as a function of temperature shown in Figure 2 may be obtained by placing an appropriate resistance in parallel with a thermistor (Reference 1).

A commonly used thermistor temperature monitoring network where output voltage v is a linear function of temperature is shown in Figure 3. Normally, E and $R_L$ are fixed, and the circuit is designed to give a voltage drop v = V at the maximum temperature $T_H$, v = $V_c$ at a temperature $T_B$ near 25°C, and v = V/2 (near zero) at the minimum temperature $T_L$. It can be shown that $R_s$ sets the value of V, and $R_p$ determines the slope of the curve (Reference 2). It is possible to design a network with a desired characteristic in a limited temperature range of approximately 130°C by appropriate selection of a thermistor and resistance values for $R_s$ and $R_p$.

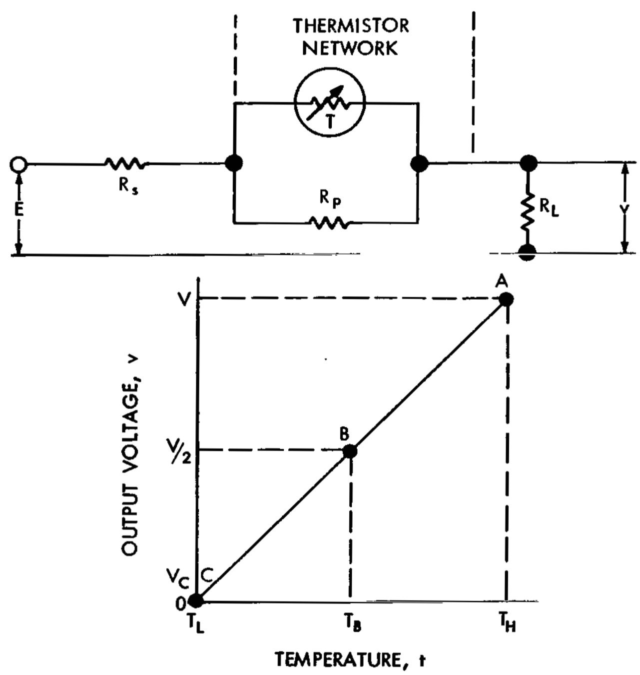


Figure 3—Thermistor temperature monitoring circuit and its temperature-voltage characteristic.

The most common temperature ranges to be encountered in spacecraft are -20°C to +70°C, -40°C to +80°C, and -100°C to +100°C. A single network as shown in Figure 3 can be designed to cover each of the first two limited ranges. Furthermore, two or more of these single networks may be connected in series; appropriate values of $R_s$ and $R_p$ can be chosen to give a nearly linear voltage-temperature characteristic over the wide range -100°C to +100°C.

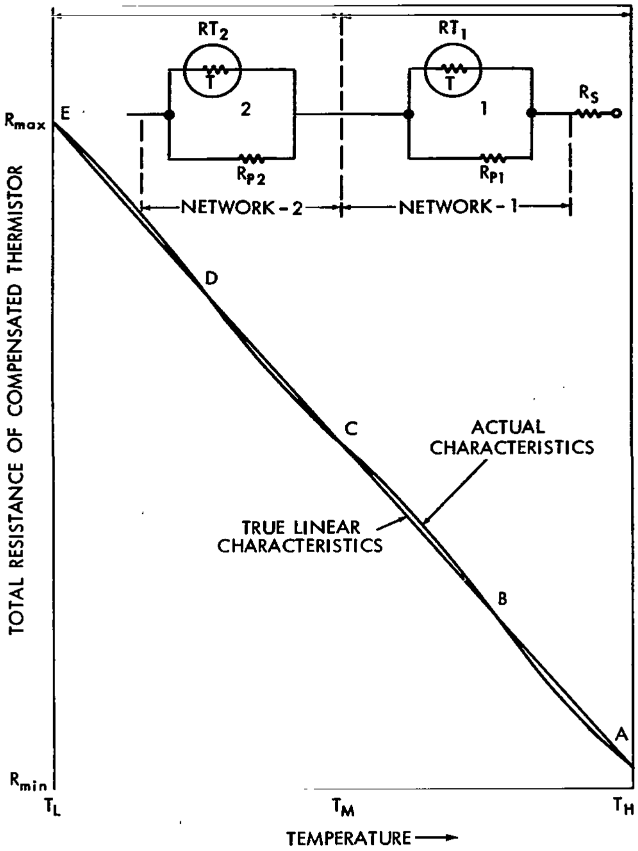


Figure 4—Two compensated-thermistor networks and the resultant temperature-resistance characteristic.

Figure 4 shows two compensated thermistors connected in series and the resulting wide range temperature-resistance characteristic. The temperature range to be covered is divided into four equal segments which determine the points A, B, C, D, and E on the characteristic. Thermistor $RT_2$ is chosen so that its resistance is small at the mid-point temperature $T_M$ and essentially zero at $T_H$. The effect of $RT_2$ decreases between $T_M$ and $T_H$ and is negligible at point A on the characteristic. The equivalent circuit at $T_H$ is $R_s$ in series with network 1, and the characteristic between points A and C is very nearly the same as that obtained from this equivalent circuit. Thermistor $RT_1$ is chosen so that its resistance is very high at $T_M$ and greatly increases at lower temperatures. The effect of $RT_1$ decreases between $T_M$ and the minimum temperature $T_L$ and is negligible at point E on the characteristic. The equivalent circuit at $T_L$ is $R_s$ in series with $R_{p1}$ and network 2, and the characteristic between points C and E is very nearly the same as that of this equivalent circuit.

## CIRCUIT DESIGN

Circuits employed in scientific satellites are designed with reliability and low power consumption as major factors. In designing reliable low power thermistor networks, the current-voltage characteristic of a typical thermistor shown in Figure 5 should be considered. The thermistor resistance is constant and positive for currents up to approximately 250 microamperes, and remains positive for currents up to one milliampere. When the current exceeds one milliampere, the thermistor exhibits a negative resistance characteristic (Reference 3). If the thermistor is allowed to operate in this region for an extended time, it will eventually be destroyed due to thermal runaway. Therefore, thermistor networks must be designed so that maximum thermistor current is limited well below one milliampere.

## Parameters

In the design of thermistor networks for temperature monitoring or compensation, the known parameters are temperature range to be monitored, input voltage, load, output voltage range, and maximum allowed power dissipation. The parameters to be determined are series resistance $R_s$, parallel resistance $R_p$, and thermistor resistance at 25°C $R_T$.

## Single Compensated Thermistor Network

The three unknown parameters $R_s$, $R_p$, and $R_T$ may be computed from three simultaneous equations which give the network equivalent resistance at three specific temperatures in terms of these parameters. For example, consider the single thermistor network in the temperature monitoring circuit of Figure 3. The equivalent circuit for design purposes is shown in Figure 6 where the thermistor network and series resistance is replaced by a variable resistor R. The required values for R at points A, B, and C on the desired output voltage characteristic are designated $R_A$, $R_B$, and $R_C$ respectively. These may be determined either analytically or experimentally from the circuit of Figure 6. At the highest temperature $T_H$ the compensated thermistor network equation is

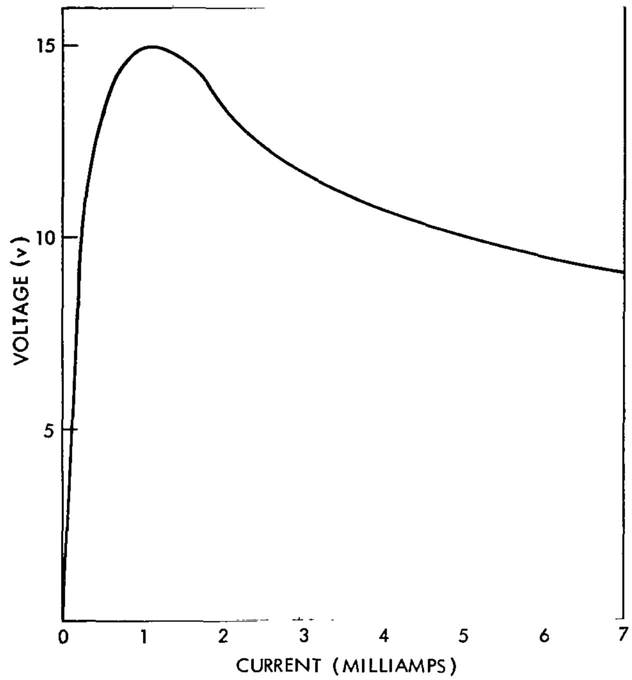


Figure 5—Voltage-current characteristic for a typical thermistor.

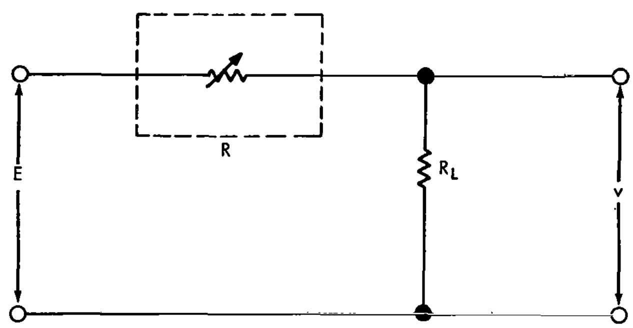


Figure 6—Equivalent temperature monitoring circuit.

$$R_A = R_s + \frac{k_A R_T R_p}{k_A R_T + R_p} ,$$

where $k_A$ is the thermistor constant obtained from Figure 1 at the temperature $T_H$. Similarly at point B we have

$$R_B = R_s + \frac{k_B R_T R_p}{k_B R_T + R_p} \approx R_s + \frac{R_T R_p}{R_T + R_p} ,$$

where $k_B$ is unity at the temperature $T_B$ = 25°C. At point C the thermistor constant $k_C$ is very large and the product $K_C R_T >> R_p$. The network equation may therefore be written as

$$R_C = R_s + \frac{k_C R_T R_p}{k_C R_T + R_p} \approx R_s + R_p .$$

Solving Equations 1, 2, and 3 simultaneously, we obtain

$$R_s = \frac{k_A R_B \left(R_A - R_C\right) + R_A \left(R_C - R_B\right)}{k_A \left(R_A - R_C\right) + \left(R_C - R_B\right)} , \tag{4}$$

$$R_p = R_C - R_s , \tag{5}$$

$$R_T = \frac{\left(R_s - R_C\right)\left(R_A - R_s\right)}{k_A \left(R_A - R_C\right)} . \tag{6}$$

This same procedure may be followed when the thermistor network is to be designed for temperature compensating circuits such as the series arrangement shown in Figure 7 or the parallel arrangement shown in Figure 8. The three values for R for Equations 1, 2, and 3 may be determined experimentally by placing the device or circuit to be compensated in a temperature chamber and adjusting R to give a constant performance at three different temperatures in the range to be covered.

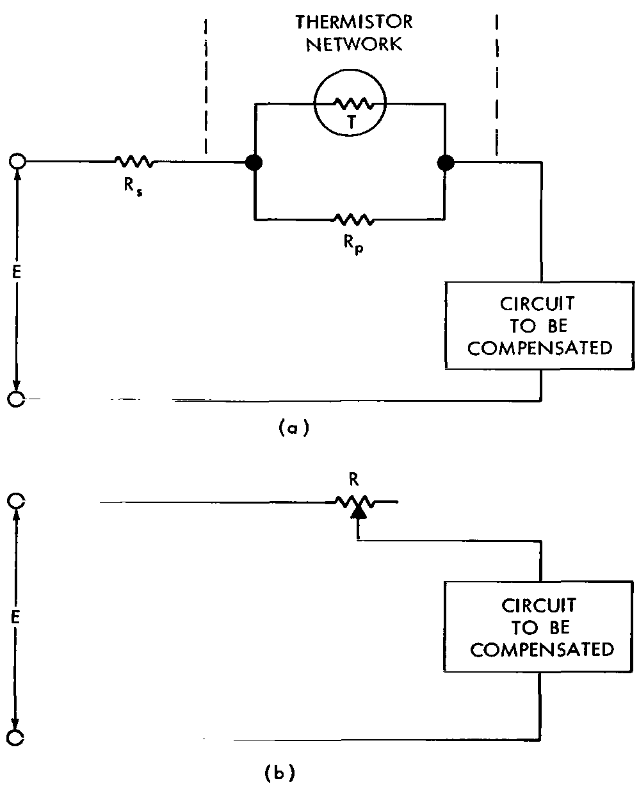


Figure 7—Temperature compensation with a series circuit: (a) Actual compensating circuit, (b) Equivalent circuit for design purposes.

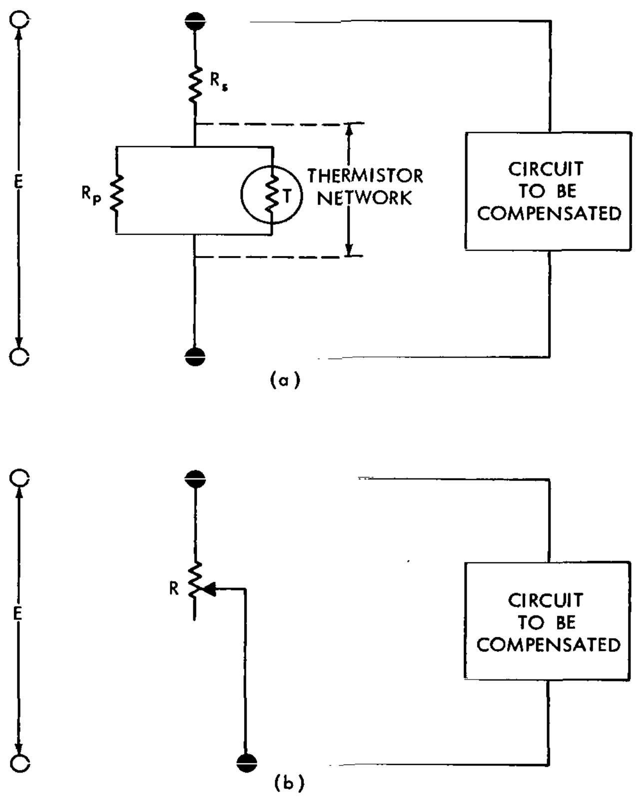


Figure 8—Temperature compensation with a parallel circuit: (a) Actual compensating circuit, (b) Equivalent circuit for design purposes.

## Multiple Networks

The design approach just described may also be used to design temperature monitoring or compensating circuits with two or more compensated thermistors. A multiple network circuit has two parameters for each thermistor, $R_T$ and $R_P$, plus the unknown series resistance $R_s$. Thus, a circuit with N networks has 2N + 1 unknown parameters and consequently requires 2N + 1 simultaneous equations. Illustrated in Figure 9 is the design procedure with a simplified two network temperature monitoring circuit to cover the range -100°C to +100°C, with an output voltage variation of 0.3 volts to 5.0 volts. The five points A, B, C, D, and E on the characteristic are selected to simplify the simultaneous equations as much as possible as follows:

A Corresponds to $T_H$ = 100°C,

B Corresponds to +25°C where the constant k for any thermistor is unity,

C Corresponds to -30°C which establishes the range of 130°C to be covered by thermistor $RT_1$,

D Corresponds to -65°C, the mid-point between -30°C and -100°C, and

E Corresponds to $T_L$ = -100°C.

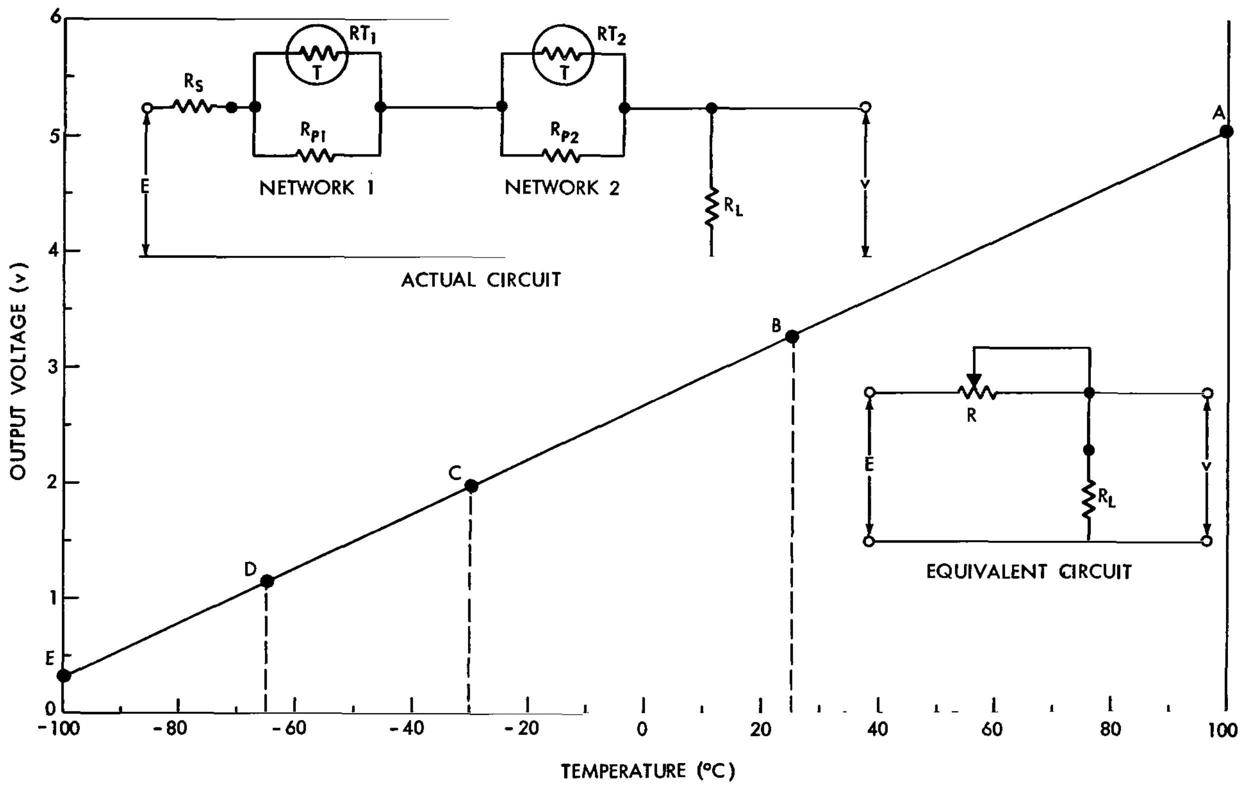


Figure 9—Two-network temperature monitoring circuit and its temperature-voltage characteristic.

As described earlier, the two thermistors are selected such that at -30°C the resistance of $RT_1$ is high and the resistance of $RT_2$ is low, and at +100°C the resistance of $RT_1$ is low and $RT_2$ is essentially zero. At +100°C the equivalent resistance R in Figure 9 is

$$R_A = R_s + \frac{k_{A1} R_{T1} R_{p1}}{k_{A1} R_{T1} + R_{p1}} , \tag{7}$$

where the subscript 1 indicates parameters for network 1 and $k_A$ is the thermistor constant obtained from Figure 1 at +100°C.

At +25°C the expression for the equivalent resistance is

$$R_B = R_s + \frac{R_{T1} R_{p1}}{R_{T1} + R_{p1}} + \frac{R_{T2} R_{p2}}{R_{T2} + R_{p2}} ,$$

where the subscript 2 indicates parameters for network 2. The third term in the right-hand member of this expression is very small; therefore the expression may be written,

$$R_B \approx R_s + \frac{R_{T1} R_{p1}}{R_{T1} + R_{p1}} . \tag{8}$$

At -30°C the resistance of $RT_1$ is high compared with $R_{p1}$; therefore, the expression for equivalent resistance is

$$R_C \approx R_s + R_{p1} + \frac{k_{C2} R_{T2} R_{p2}}{k_{C2} R_{T2} + R_{p2}} , \tag{9}$$

where $k_C$ is the thermistor constant obtained from Figure 1 at -30°C.

At -65°C the resistance of $RT_1$ is even higher than at -30°C; therefore, the expression for equivalent resistance is

$$R_D \approx R_s + R_{p1} + \frac{k_{D2} R_{T2} R_{p2}}{k_{D2} R_{T2} + R_{p2}} , \tag{10}$$

where $k_D$ is the thermistor constant extrapolated from Figure 1 at -65°C.

At -100°C both thermistors have very high resistance; the equivalent resistance is

$$R_E \approx R_s + R_{p1} + R_{p2} . \tag{11}$$

Solving Equations 7, 8, 9, 10, and 11 simultaneously, we obtain

$$\delta = \frac{R_D k_C (R_E - R_C) - R_C k_D (R_E - R_D)}{k_C (R_E - R_C) - k_D (R_E - R_D)} , \qquad (12)$$

where

$$R_s = \frac{R_A (R_B - \delta) - R_B k_A (R_A - \delta)}{(R_B - \delta) - k_A (R_A - \delta)} , \qquad (13)$$

$$R_{p1} = \delta - R_s , \qquad (14)$$

$$R_{T1} = \frac{(R_s - \delta)(R_B - R_s)}{R_B - \delta} , \qquad (15)$$

$$R_{p2} = R_E - \delta , \qquad (16)$$

and

$$R_{T2} = \frac{(R_E - \delta)(R_D - \delta)}{k_D (R_E - R_D)} . \qquad (17)$$

## DESIGN EXAMPLE

The design and measured performance of two temperature monitoring circuits and a temperature compensating circuit are discussed here.

### Single Network Monitoring Circuit

In the steps which follow, a temperature monitor, using the circuit in Figure 10, is designed. The known parameters are:

1. temperature range -20°C to +75°C
2. $E$ = +7.0 vdc ±1%
3. $R_L$ = 10 kilohms,
4. $v$ = output voltage range between 0 and 5 vdc, and
5. Maximum allowed power dissipation $P_m$ = 3.5 mw.

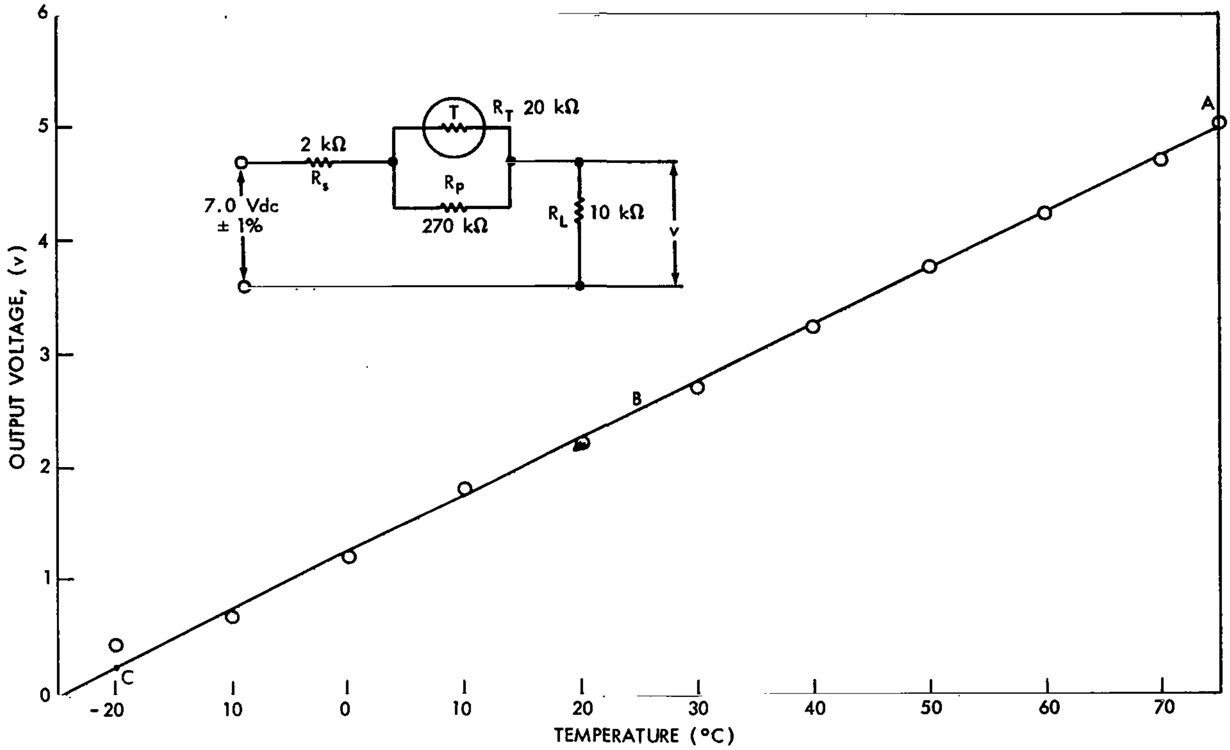


Figure 10—Single thermistor temperature monitor design example.

*Step 1. Desired Linear Characteristic*

The desired linear characteristic in Figure 10 is drawn from 0 volts at -25°C to point A corresponding to +5vdc at 75°C. For design purposes point B is selected at +25°C, and point C is selected at -20°C.

*Step 2. Equivalent Network Resistance Values*

Values for the equivalent network resistance R at points A, B, and C are determined analytically as

$$R_A = 4\,k\Omega\ ,$$

$$R_B = 18\,k\Omega\ ,$$

and

$$R_C = 270\,k\Omega\ .$$

*Step 3. Selection of Thermistor*

From Figure 1 it can be seen that at 75°C a thermistor with maximum sensitivity (curve A) has a resistance ratio $k_A = 0.12$ and a thermistor with minimum sensitivity (curve C) has $k_A = 0.131$. Furthermore, curve A shows that the resistance of a thermistor with high sensitivity will become excessively high at very low temperatures. In the present example covering the relatively warm range -20°C to +75°C, however, we may select a thermistor with maximum sensitivity in order to obtain a maximum output voltage swing over the temperature range. From curve A in Figure 1 $k_A = 0.12$.

*Step 4. Network Parameters $R_s$, $R_p$ and $R_T$*

We substitute the values for equivalent resistance and resistance ratio from Steps 2 and 3 into Equations 4, 5, and 6 to obtain

$$R_s = \frac{k_A R_B (R_A - R_C) + R_A (R_C - R_B)}{k_A (R_A - R_C) + (R_C - R_B)} = 1970\,\Omega ,$$

$$R_p = R_C - R_s = 268\text{ k}\Omega ,$$

$$R_T = \frac{(R_s - R_C)(R_A - R_s)}{k_A (R_A - R_C)} = 17.04\text{ k}\Omega .$$

A breadboard circuit was constructed using commercially available components having the values

$$R_s = 2.0\text{ k}\Omega ,$$

$$R_p = 270\text{ k}\Omega ,$$

$$R_T = 20\text{ k}\Omega .$$

Actual measured output voltage readings at ten-degree intervals over the range -20°C to +75°C are plotted as points in Figure 10. These show good agreement with the desired linear characteristic. Maximum deviation from the linear characteristic is 0.42 volt at -20°C. This could be improved by selecting a thermistor resistance value closer to the computed value. Maximum power dissipation occurs at 75°C when $R_A = 4\text{ k}\Omega$

$$P_m = \frac{E^2}{R_A + R_L} = 3.5\text{ mw} .$$

## Double Network Monitoring Circuit

In the steps which follow, a temperature monitoring circuit, using the schematics in Figure 11, lesigned. The known parameters are:

1. temperature range -100°C to +100°C,
2. $E$ = +7.0 vdc ±1%,
3. $R_L$ = 10 kΩ,
4. $v$ = output voltage range between 0 and 5 vdc, and
5. Maximum allowed power dissipation $P_m$ = 3.5 mw.

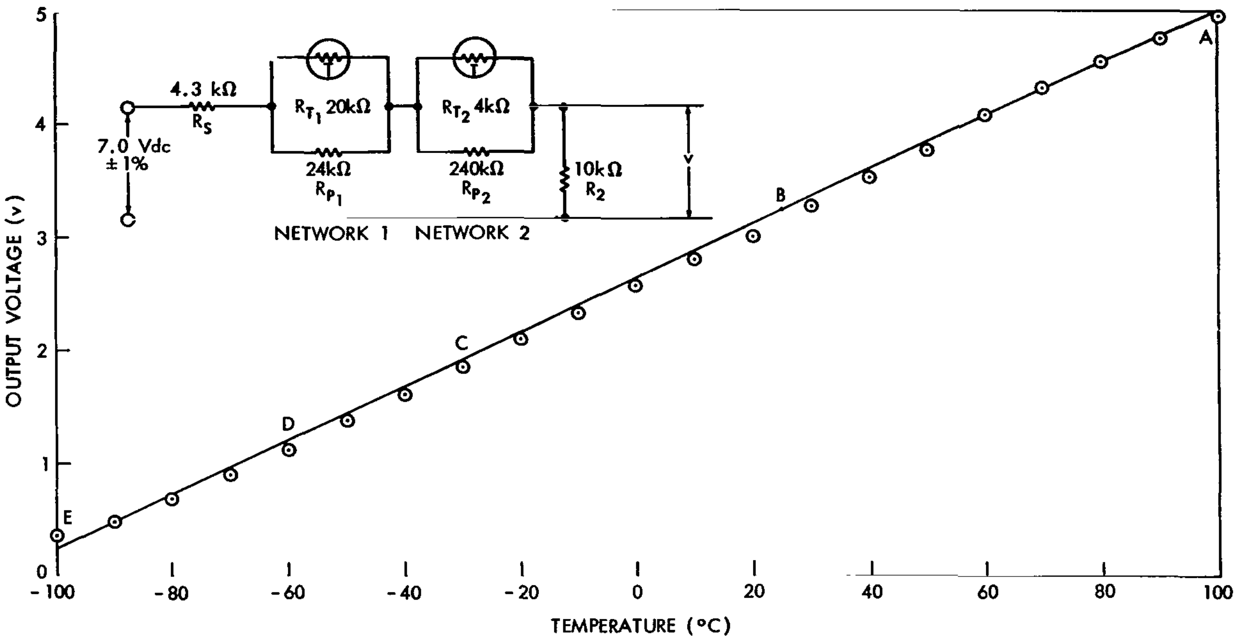


Figure 11—Double thermistor temperature monitoring design example.

*Step 1. Desired Linear Characteristic*

The desired linear characteristic in Figure 11 is drawn from point E corresponding to 0.25 volts at -100°C to point A corresponding to +5 volts at +100°C.

*Step 2. Equivalent Network Resistance Values*

Values for equivalent network resistance R at points A, B, C, D, and E are determined analytically and the results are

$$R_A = 4\,k\Omega \,,$$

$$R_B = 12\,k\Omega\ ,$$

$$R_C = 30\,k\Omega\ ,$$

$$R_D = 68\,k\Omega\ ,$$

and

$$R_E = 270\,k\Omega\ .$$

*Step 3. Selection of Thermistors*

If it is possible to design the double network circuit so that one of the thermistors covers the low temperature range without becoming an excessively high resistance, then both networks may have high sensitivity thermistors with the same k values. In this example with the extended temperature range, -100°C to +100°C, such a design is possible and, therefore, high sensitivity thermistors are selected for both networks. From curve A in Figure 1 we obtain

$$k_{A1} = k_{A2} = k_A = 0.048\ ,$$

$$k_{C1} = k_{C2} = k_C = 29.0\ ,$$

and

$$k_{D1} = k_{D2} = k_D = 120\ .$$

*Step 4. Network Parameters $R_s$, $R_{p1}$, $R_{T1}$, $R_{p2}$, and $R_{T2}$*

We substitute the values for equivalent resistance and resistance ratios into Equations 12 through 17 to obtain

$$\delta = 27\,k\Omega\ ,$$

$$R_s = 4.5\,k\Omega\ ,$$

$$R_{p1} = 22.5\,k\Omega\ ,$$

$$R_{T1} = 11.2\,k\Omega\ ,$$

$$R_{p2} = 243\,k\Omega\ ,$$

$$R_{T2} = 400\,\Omega\ .$$

A breadboard circuit was constructed using commercially available components with the values

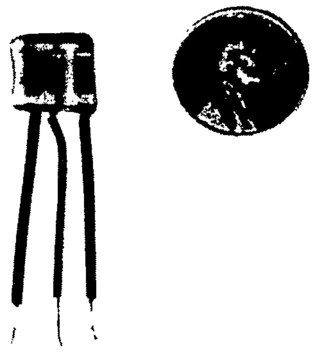

Figure 12—Double thermistor temperature monitor in package form.

$$R_s = 4.3\,k\Omega ,$$

$$R_{p1} = 24\,k\Omega ,$$

$$R_{T1} = 10\,k\Omega ,$$

$$R_{p2} = 240\,k\Omega ,$$

and

$$R_{T2} = 400\,\Omega .$$

Actual measured output voltage readings at ten-degree intervals over a -100°C to +100°C range are plotted in Figure 11. These show good agreement with the desired linear characteristic. Maximum deviation from the linear characteristic is 0.15 volts at -100°C. This could be minimized by selecting a thermistor resistance value closer to the computed value.

The maximum power dissipation occurs at 100°C when

$$R_A = 4.5\,k\Omega ,$$

$$P_m = \frac{E^2}{R_A + R_L} = 3.4 \text{ mw} .$$

One means of packaging the temperature monitoring circuit is depicted in Figure 12.

## Temperature Compensating a Magnetic Core Oscillator

A compensating circuit to stabilize the frequency of the saturable core magnetic multivibrator is shown in Figure 13. The operating frequency of such an oscillator is

$$f = \frac{e}{4\Phi_m N_s} ,$$

where

$\Phi_m$ = saturation flux, webers,

$N_s$ = number of turns on each switching winding, and

$e$ = voltage across each switching winding.

The characteristic of the uncompensated circuit, Figure 14, shows that frequency increases as temperature increases to +60°C and decreases as temperature decreases to -10°C. Suitable

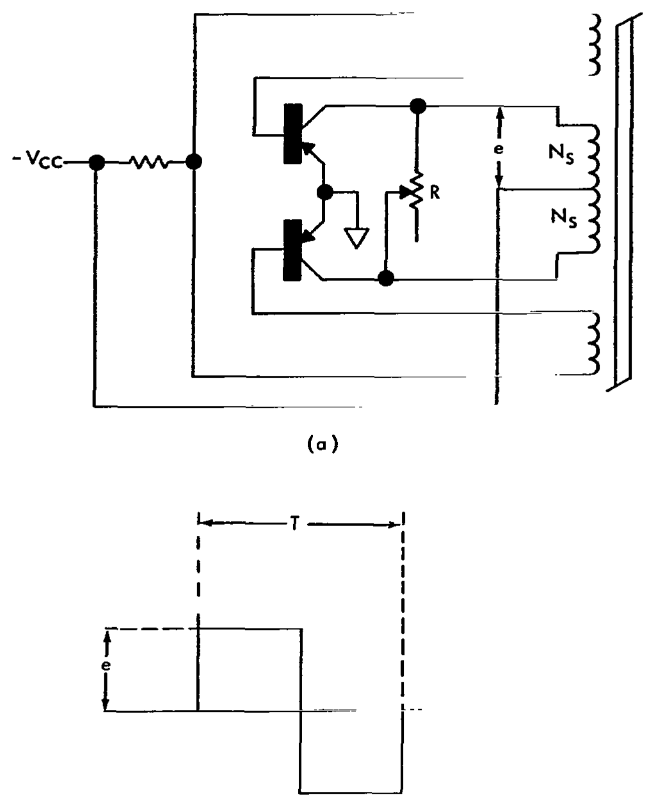


Figure 13—Magnetic core oscillator: (a) Basic RL oscillator, (b) Square wave cycle.

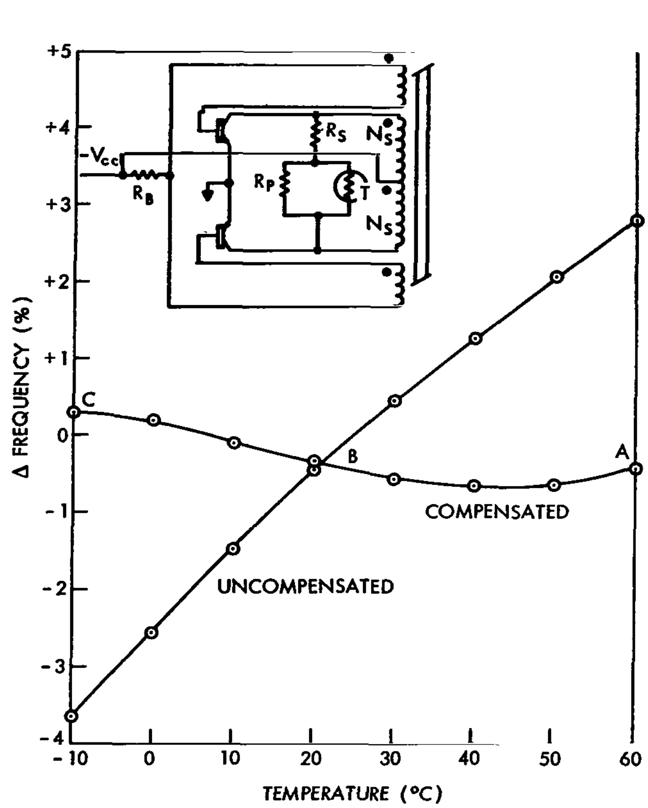


Figure 14—Percentage change in output frequency with temperature.

adjustment of the load R may be made to compensate for the frequency variation over this temperature range. In Figure 14, a single-thermistor network is shown connected in place of R to compensate for frequency variation when appropriate values of $R_s$, $R_p$, and $R_T$ are used.

*Step 1. Determining Network Resistance Values*

The three values for the equivalent network resistor determined experimentally are

$$R_A = 5611 ,$$

$$R_B = 6850 ,$$

$$R_C = 7353 .$$

*Step 2. Selection of Thermistor*

It is apparent that over the relatively small temperature range -10°C to +60°C, the required variation of net resistance is small, and a high sensitivity thermistor will therefore operate satisfactorily. According to curve A, Figure 1, a high sensitivity thermistor at +60°C has $k_A = 0.21$.

*Step 3. Network Parameters $R_s$, $R_p$, and $R_T$*

We substitute the values for required equivalent resistance and resistance ratio from the above into Equations 4, 5, and 6 to obtain

$$R_s \cong 6.13\,\mathrm{k\Omega}\ ,$$

$$R_p = 953\,\Omega\ ,$$

$$R_T \cong 725\,\Omega\ .$$

A breadboard circuit was constructed using commercially available components with the values

$$R_s = 6.2\,\mathrm{k\Omega}\ ,$$

$$R_p = 1\,\mathrm{k\Omega}\ ,$$

and

$$R_T = 800\,\Omega\ .$$

Actual measured output frequency variation at ten-degree intervals over the -10°C to +60°C were plotted as points in Figure 14. The uncompensated curve shows the percentage of frequency variation versus temperature of an uncompensated RL oscillator. The compensated curve shows the percentage of frequency variation versus temperature of the compensated RL oscillator.

## ACKNOWLEDGMENTS

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NASA-Langley, 1966 G-723

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—National Aeronautics and Space Act of 1958

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