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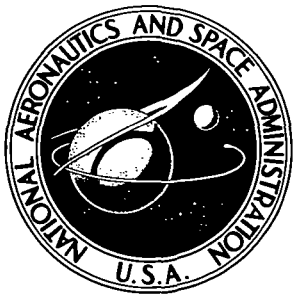

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IMPLEMENTATION OF A SELF-CONTROLLING HEATER

by Maxwell G. Strange

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16. Abstract

Temperature control of radiation sensors, targets, and other critical components is a common requirement in modern scientific instruments. Conventional control systems use a heater and a temperature sensor mounted on the body to be controlled. For proportional control, the sensor provides feedback to circuitry which drives the heater with an amount of power proportional to the temperature error.

It is impractical or undesirable to mount both a heater and a sensor on certain components such as ultra-small parts or thin filaments. In these cases, a single element may serve simultaneously as the heater and sensor. In principle, a variable current through the element is used for heating, and the change in voltage drop due to the element's temperature coefficient is separated and used to monitor or control its own temperature. Since there are no thermal propagation delays between heater and sensor, such control systems are exceptionally stable.

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CONTENTS

	Page
ABSTRACT	i
INTRODUCTION	1
THEORY	1
SELF-MONITORING HEATER	3
SELF-CONTROLLING HEATER	5
EXPERIMENTAL RESULTS	8
APPLICATIONS	12
CONCLUSION	13

IMPLEMENTATION OF A SELF-CONTROLLING ELECTRIC HEATER

Maxwell G. Strange
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INTRODUCTION

Precision temperature control is a common requirement in modern instrumentation. Proportional control is usually preferred to simple on-off thermostating, as it avoids a cyclical temperature excursion in the controlled body and the possibility of generating electrical interference.

Basically, a proportional control system functions to maintain a known, stable relationship between the controlled parameter (temperature in this case) and an input or reference signal. To accomplish this, the reference is compared with a signal indicating actual temperature; the amplified difference, or error signal, then controls heater power in a direction to reduce the error.

The self-controlling heater concept uses the heater's temperature coefficient for the sensing function. If heating current varies, as it must to maintain a constant temperature in the presence of disturbances, the heater voltage drop due to its temperature must be separated from the component due to the varying drive current. This can be done by a simple analog computation, and the resulting measure of actual temperature can then be used as an input to the control system's error comparator. Thus the heater controls itself, using its own temperature coefficient for sensing.

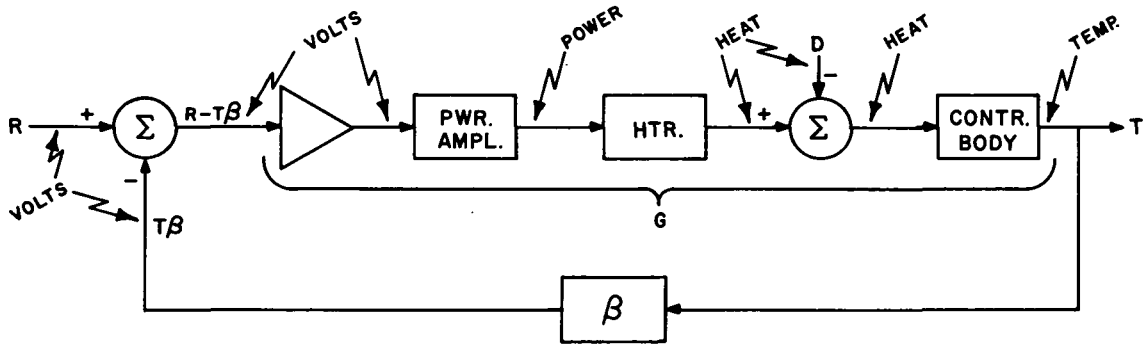
The circuit is implemented in a straightforward manner using analog techniques. Control accuracy is basically limited only by the stability of the heater/sensor. Since there is no thermal propagation delay between heater and sensor, excellent dynamic loop behavior results.

THEORY

Figure 1 shows an elementary proportional temperature control system. The error comparator in this case will have inputs in the form of voltage. The feedback path, β, converts a measure of actual temperature back to voltage (e.g., by a current-biased thermistor) for error comparison.

The closed-loop transfer function of the control system of Figure 1 is of the familiar form

$$\frac{T}{R} = \frac{G}{1 + G\beta}$$



R = REFERENCE, OR INPUT
G = FORWARD GAIN
β = FEEDBACK FUNCTION
$G\beta$ = LOOP GAIN
D = DISTURBANCE (HEAT LOSS) DUE TO AMBIENT TEMP., AIR FLOW, ETC.
T = CONTROLLED TEMP.

$$\frac{T}{R} = \frac{G}{1+G\beta}$$

IF $G\beta >> 1$,

$$T = \frac{R}{\beta}$$

Figure 1. Elementary proportional temperature control system.

If the loop gain, $G\beta$, is made large compared to one, this expression reduces to

$$T = \frac{R}{\beta}$$

and controlled temperature becomes independent of the forward gain path G. This path includes disturbances such as electrical gain variations and, most importantly, the effect of ambient temperature on controlled body temperature. Note, however, that error comparison must remain accurate and β must be stable. If the above conditions are met, this system will serve to control temperature as a stable function of the reference input voltage R.

Dynamic stability depends upon the phase characteristics of the loop. Control is accomplished by negative, or out-of-phase, feedback. If feedback becomes in-phase (shifted 180°) at any frequency at which the loop gain exceeds one, the system will, of course, be unstable and will oscillate continuously. Normally, phase shift at unity gain should be between 90° and 135° (90° to 45° phase margin) for minimum overshoot in response to a step input, and yet fairly fast response.

Poor stability, manifested as a tendency to oscillate or as excessive "ringing" in response to sudden input changes, usually is caused by the thermal characteristics of the controlled body. Heat propagation through a solid is analogous to current through a transmission line; it is a distributed parameter medium through which very large phase lags can occur.

The general cures are to mount the heater centrally (or distributed so that the temperature gradients are minimized) and in good thermal contact with the controlled body. The sensor should be located close to (but usually not directly on) the heater. Loop gain should not be greatly in excess of that actually needed for adequate control accuracy. Of course, when the heater itself doubles as a sensor, no propagation delay exists and dynamic stability is assured.

SELF-MONITORING HEATER

Before discussing the self-controlling heater, the method of deriving a temperature measurement from the heater will be detailed. Figure 2 shows the principle of a self-monitoring heater. The heater is actually used like a constant-current-biased resistance sensor, except the current is made much higher in order to produce a desired power dissipation. As heater temperature changes, its resistance changes due to its temperature coefficient of resistivity. Resistance changes are reflected as proportional changes in voltage drop across the heater. This voltage is simply offset and amplified to obtain the desired monitor voltage range.

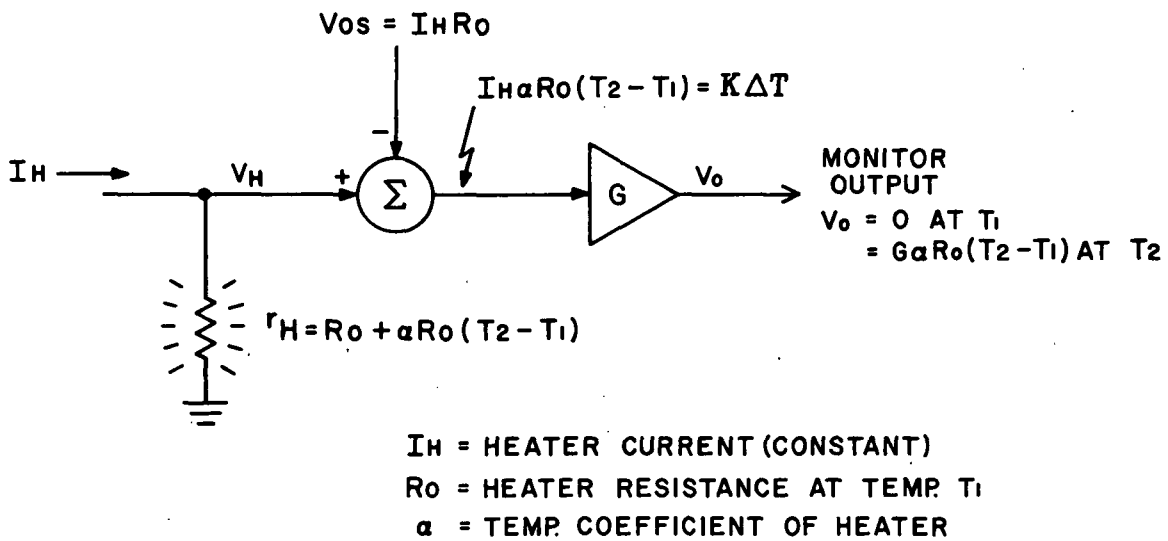


Figure 2. Principle of the self-monitoring heater. Offset voltage V_{os} subtracts the heater voltage due to heating current at reference temperature T_1.

As a design example, Figure 3 shows a practical circuit which was breadboarded and tested using a copper wire heater constructed as shown in Figure 4. Amplifier A_1 and the current boost transistor comprise an operational current source for driving the heater. Heater current I_H was set, quite arbitrarily, at 0.130 ampere by choosing R_D for V = 0.130 volt.

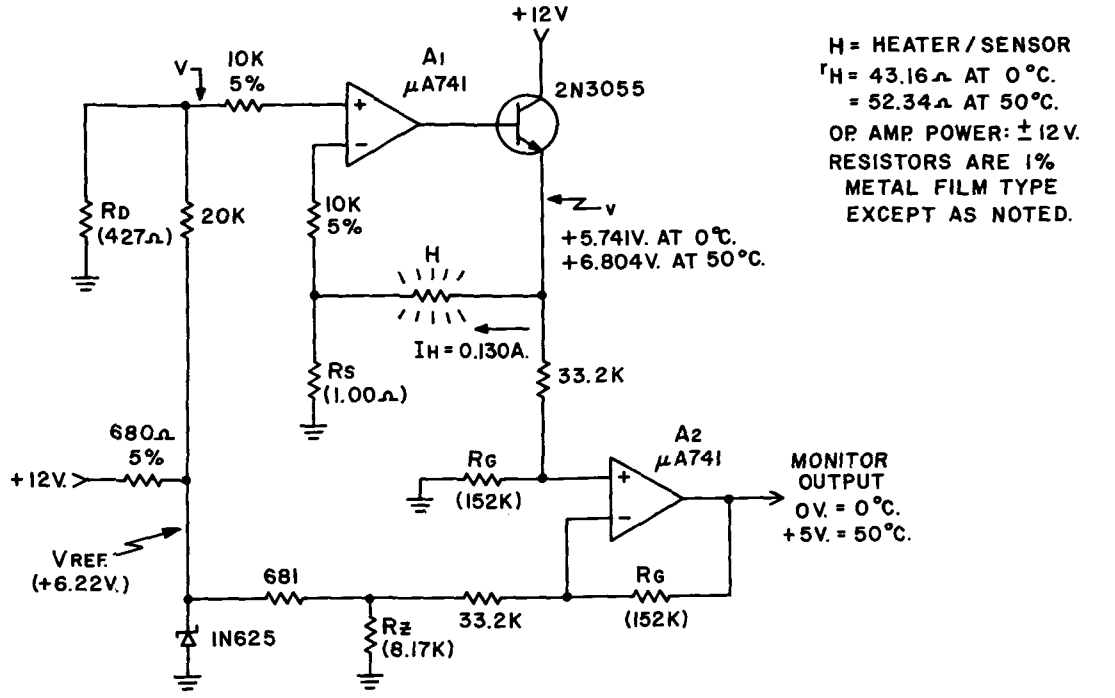
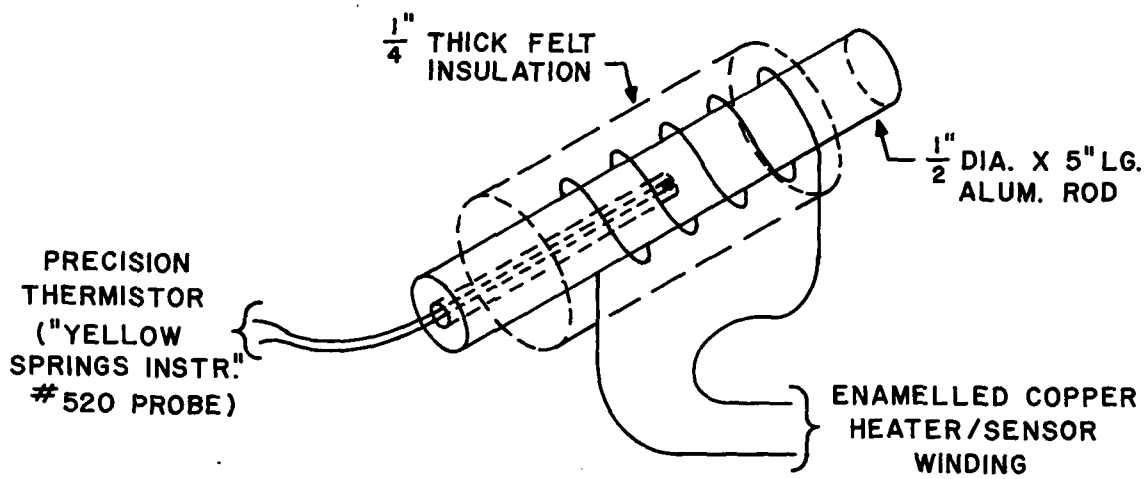


Figure 3. Complete circuit for a self-monitoring heater.



NOTE: HEATER/SENSOR WIRE IS WOUND IN A FILM OF "WAKEFIELD" No. 128 THERMAL-CONDUCTIVE PASTE TO FILL ALL VOIDS.

Figure 4. Heater/sensor used for circuit evaluation.

The circuit then functions to maintain 0.130 volt across the 1-ohm current sampling resistor R_s.

Since I_H is constant, voltage V follows temperature-induced changes in heater resistance. Amplifier A_2 is used as a difference amplifier with gain (set by R_G) and offset (set by R_Z) adjusted to provide a 0 to +5 volt output corresponding to a heater temperature range of 0 to 50 degrees C. Calculated component values were based upon measured heater resistance at 0° and 50°C.

The circuit worked as predicted. As soon as power was applied, the monitor output voltage continuously indicated the heater's temperature as it warmed up. Since copper has a very nearly constant temperature coefficient over the 0° to 50°C range, output voltage could be read directly as °C/10; it compared with the independent monitor within ±1 degree. With the heater in an environmental chamber, monitored temperature was found accurate from considerably below 0°C (negative output voltage) to at least 80°C. Calculated circuit values, with a very slight adjustment of R_Z to zero the output at 0°C, produced the measured curve of Figure 5.

SELF-CONTROLLING HEATER

The next step is to utilize the temperature monitor voltage in a feedback control loop so that the heater becomes self-controlling. To do this, a voltage representing actual temperature must be compared with a reference voltage representing desired temperature, and the difference or error signal used to control heater current. The simple monitor circuit of Figure 2, however, cannot be used to supply the feedback signal directly, as it assumes a fixed heater current. Heater voltage will now fluctuate from two effects, that of varying drive current, and that due to temperature. It is necessary to remove the component due to changing current in order to recover the temperature information.

The simplified schematic of a self-controlling heater (Figure 6) shows how this is done. Amplifiers A_1 and A_2 perform the current drive and offset/gain functions as in the self-monitoring heater of Figure 3. Amplifier A_3 has been added for error comparison; reference voltage V_R sets the temperature control point. Voltage v_x, which corresponds to the monitor output of Figure 3, contains the extraneous heater drive factor. This is eliminated with an analog divider using v_y, which linearly determines instantaneous heater current, as a divisor. The A_v attenuator provides for proper scaling of this signal.

For design purposes, we need an equation of the form

$$V_R = f(T_2, T_1, R_o, R_s, A_d, \alpha)$$

where V_R = Temperature set reference voltage

T_2 = Desired temperature

T_1 = Temperature at which $r_H = R_o$

R_S = Current-sampling resistance

A_D = Gain of difference amplifier A_2

α = Temperature coefficient of resistivity of the heater

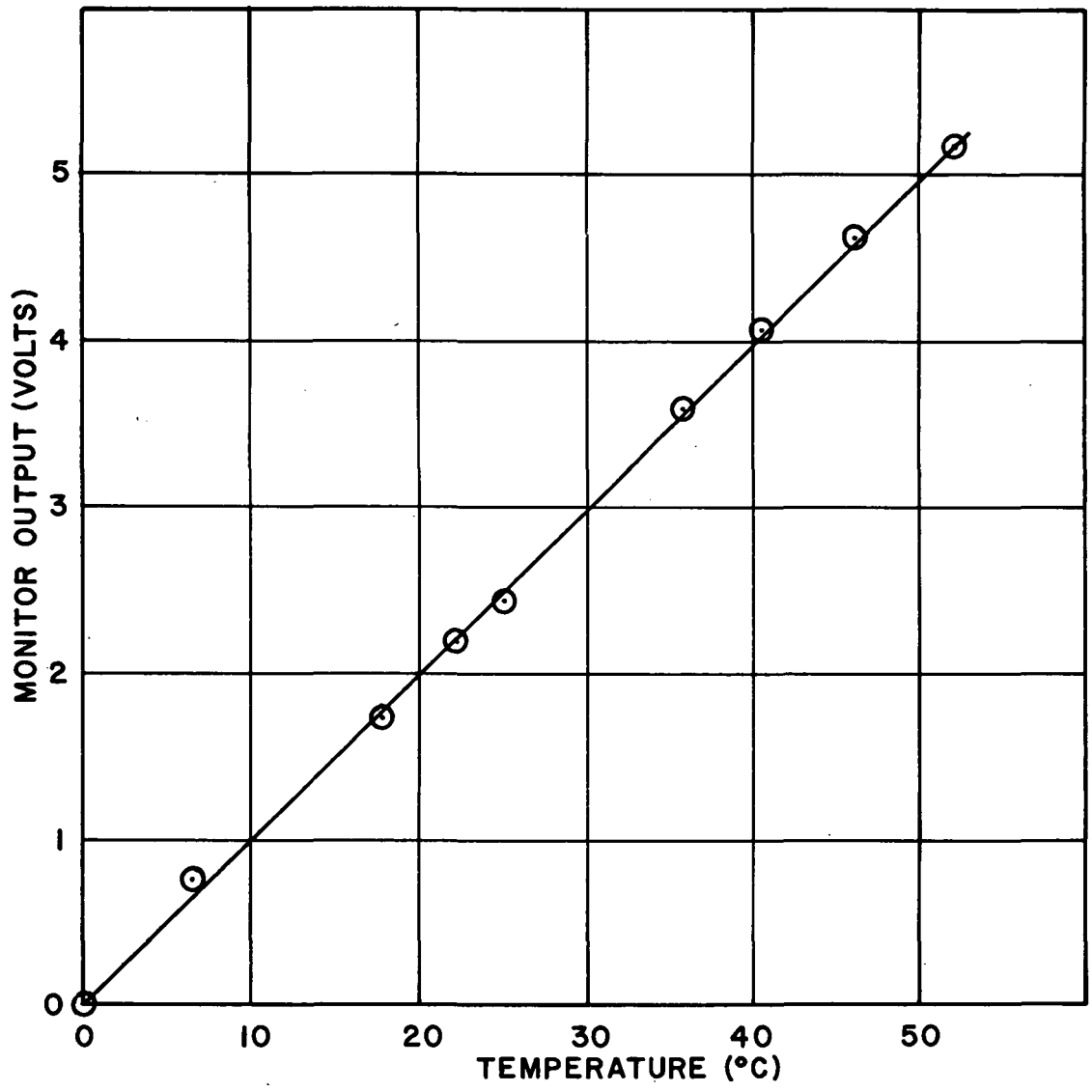


Figure 5. Measured performance of the self-monitoring heater.

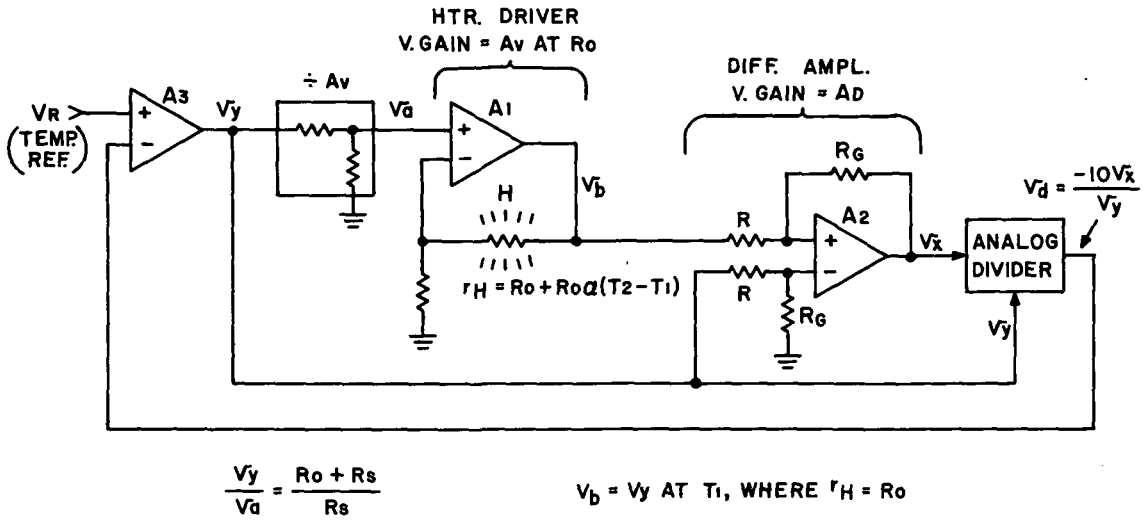


Figure 6. Simplified schematic of the self-controlling heater.

From Figure 6 we can immediately write the following relations:

$$A_V = \frac{v_y}{v_a} = \frac{R_o + R_s}{R_s}$$

$$v_d = V_R = -\frac{10v_x}{v_y}$$ (transfer function of typical analog divider)

$$v_x = A_D (v_y - v_b)$$

$$v_b = \frac{v_a}{R_s}(R_s + r_H)$$

$$r_H = R_o + R_o\alpha(T_2 - T_1)$$

From these, the most useful form of design equation is easily derived as

$$V_R = \frac{10A_D\alpha R_o(T_2 - T_1)}{R_o + R_s}$$

Values of the constants are selected from the following considerations:

1. α is a function of the heater material. Desirable materials have high α, good stability, and good linearity (constant α) between temperatures T_1 and T_2.
2. The best value of R_o is simply determined by the required maximum heating power and available supply voltage.

3. T_1 may be any convenient reference temperature for measuring R_o. It should preferably be near the low end of the possible operating range.

4. R_s should be small compared to R_o to minimize power dissipation. However, it should be large enough to develop a voltage drop much larger than the input voltage offset stability of amplifier A_1. R_s must also be stable with temperature and time.

5. A_D should be set so that the analog divider operates at a fairly high level to minimize errors. Typical maximum signal levels are ±10 volts at the divider inputs and output.

EXPERIMENTAL RESULTS

Another test heater using a copper wire winding was prepared for experimental evaluation of the self-controlling heater circuit. It is similar to the self-monitoring test heater, but has lower resistance for higher power levels. Its parameters were measured as:

α = 0.003811 (25° to 90° C)
R_o = 9.333 ohms (25.0° C)

The circuit of Figure 7 was breadboarded for test purposes. Analog division was instrumented with a standard circuit (network B) using an operational amplifier interconnected with an inexpensive multiplier. This multiplier requires ±15 volts dc stable within ±0.1%; otherwise, unregulated supplies could be used to power the circuit, with a zener reference supplying V_R.

Care must be taken to keep the analog divider inputs at fairly high levels, or small offsets in the multiplier may produce an output error. Since the divider is part of the feedback function, an error in it will produce a proportional error in controlled temperature. v_x and v_y levels depend upon the choice of difference amplifier gain A_D, current-sampling resistor R_S, and heater parameters.

As divisor v_y approaches zero, divider gain becomes very high. However, this is offset by the fact that heater current (sensor bias) approaches zero at the same time so that heater (sensor) responsivity approaches zero. At zero (or very low) v_y values, loop gain will become indeterminate and the circuit may either oscillate electrically or latch in an inoperative state. Network C prevents this by biasing the system slightly so that a little heat is always demanded. This effect limits the lowest operating point to a few degrees above ambient temperature.

The trim potentiometer R′ is set so that $v_b = v_y$ at temperature T_1, or, with the parameters of the present circuit and heater, for

$$\frac{v_y}{v_a} = \frac{R_o + R_S}{R_S} = 10.333.$$

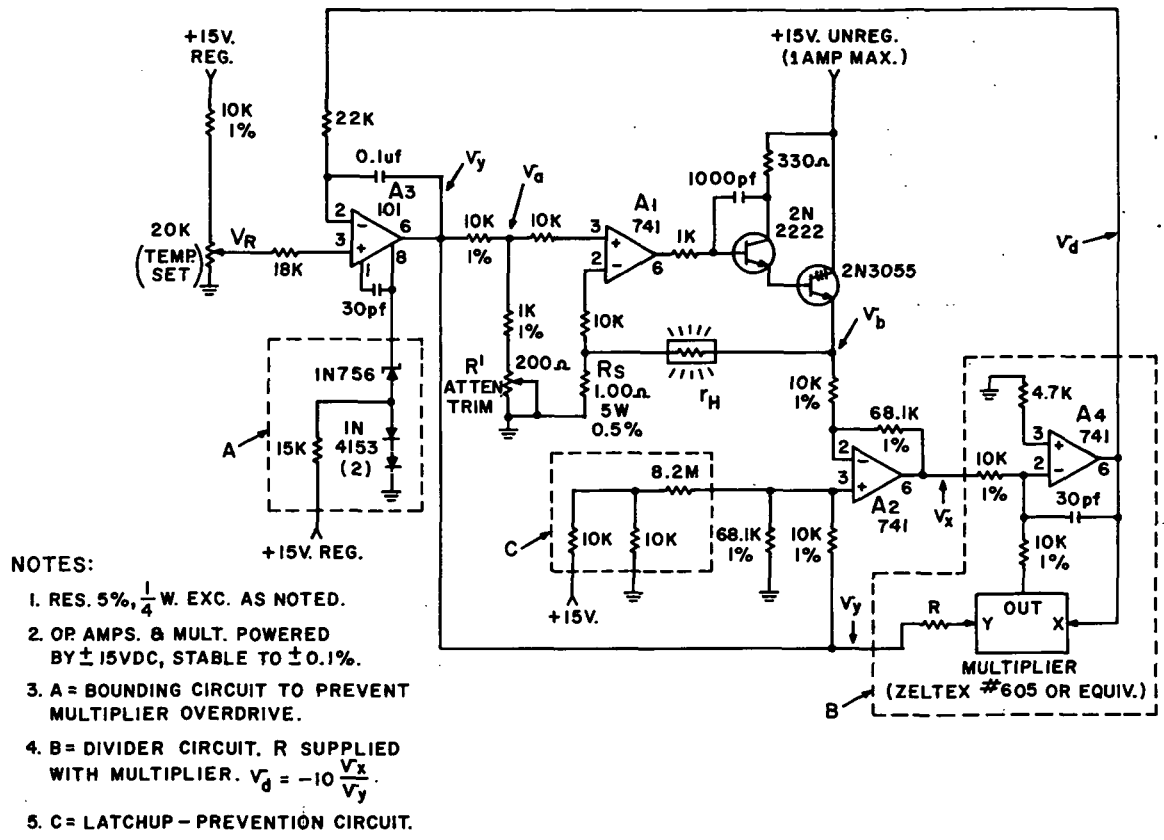


Figure 7. Complete schematic of the self-controlling heater.

This adjustment may be touched up experimentally to compensate for component tolerances.

Loop gain at low temperature settings is about 10^4. If there were no disturbances other than varying ambient temperature, this would be sufficient to maintain control within 0.01° over a 100° ambient range.

Figure 8 shows controlled temperature measured as a function of temperature-set input, V_R. The curve follows the design equation within measurement accuracy (±0.3°) over the measured range. Table 1 shows circuit voltages at various control points. For this test the heater was insulated with several layers of felt in a room-temperature environment.

Figure 9 shows measured control accuracy for an arbitrarily set control point. Control within 2 degrees over a 90° ambient range is achieved. The unexpected negative slope is caused by an error in the multiplier; otherwise control would be much better. Data taken during this run show that multiplier output v_d drops slightly from the proper output of

$-10v_x/v_y$ at the v_x and v_y values encountered at lower temperatures. This error in v_d, when compared with the fixed reference V_R, is just enough to produce the observed negative slope. The error could be trimmed out, or a more accurate multiplier used. This run shows that a negative control slope can easily be achieved if desired.

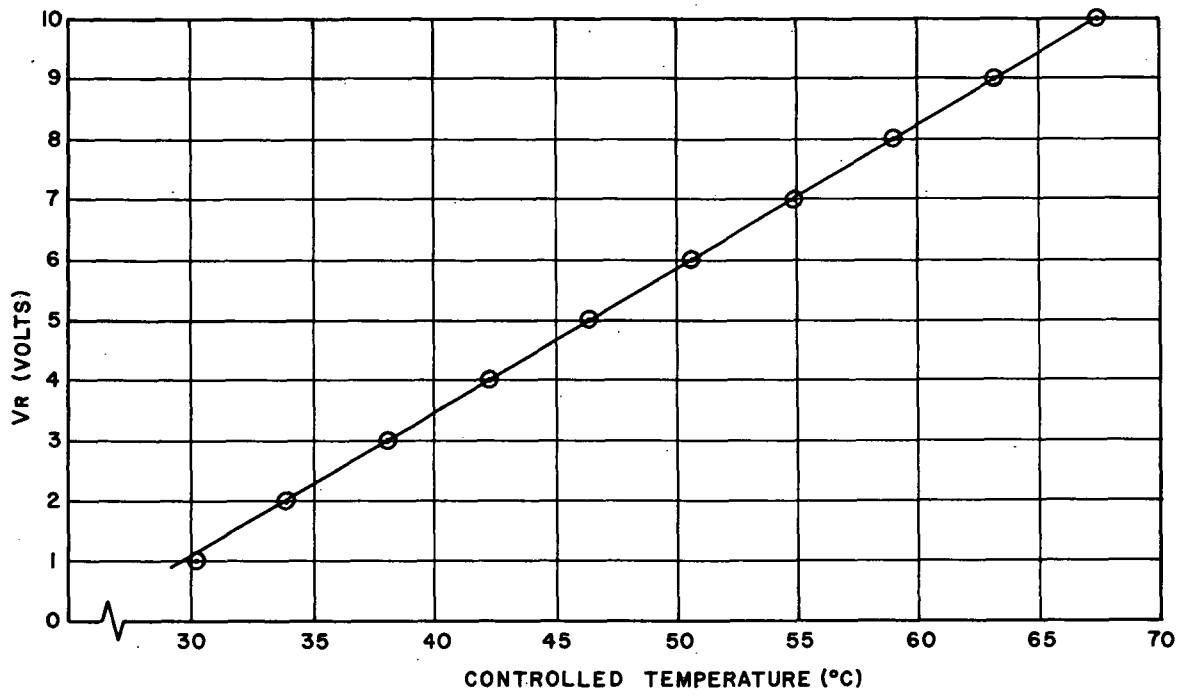


Figure 8. Measured temperature control point versus temperature set reference V_R for the self-controlling heater.

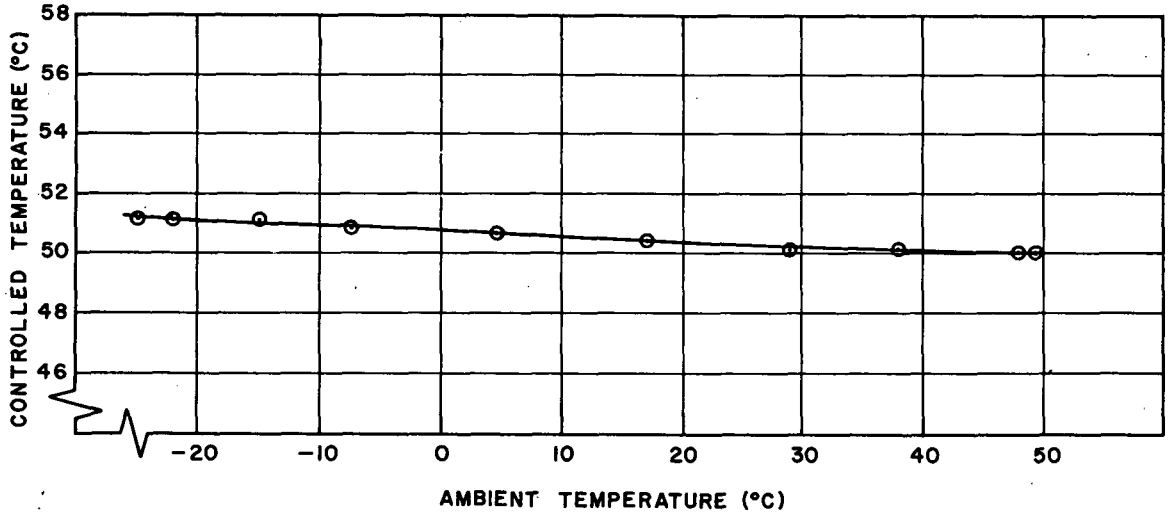


Figure 9. Temperature control characteristics for V_R = 5.92 volts. The slight negative slope is caused by an error in the analog multiplier.

Table 1

Temperature Control Circuit Test Data.

V_R (volts)	Measured v_y (volts)	Measured $v_b - v_y$ (volts)	Measured v_A (volts)	Measured v_d (volts)	Calculated* v_d (volts)	Htr. Pwr. (watts)	T_{meas} (°C)	T_{calc} (°C)	Error (°C)
1.000	1.15	0.015	-0.115	1.000	0.89	0.11	30.1	29.3	+.8
2.000	1.73	0.051	-0.35	2.000	2.01	0.27	33.9	33.5	+.4
3.000	2.17	0.098	-0.65	3.000	3.08	0.43	38.0	37.8	+.2
4.000	2.57	0.151	-1.03	4.001	4.00	0.60	42.2	42.1	+.1
5.000	2.91	0.214	-1.45	5.002	5.01	0.79	46.4	46.3	+.1
6.000	3.21	0.281	-1.93	6.002	5.96	0.97	50.6	50.6	0
7.000	3.45	0.354	-2.41	7.003	6.99	1.14	54.9	54.9	0
8.000	3.69	0.434	-2.95	8.004	8.01	1.32	59.0	59.1	-.1
9.000	3.92	0.517	-3.53	9.004	8.98	1.51	63.2	63.4	-.2
10.000	4.15	0.609	-4.16	10.004	9.99	1.72	67.5	67.7	-.2
11.000	4.36	0.705	-4.80	11.004	11.01	1.93	71.8	71.9	-.1

*As a check, $v_d = V_R = 68.1\ (v_b - v_y)/v_y$

NOTE: Data taken from circuit of Figure 7. Heater was in room temperature environment. Ambient temperature changes during run may have perturbed readings slightly. V_R versus T_{meas} is shown in Figure 8.

APPLICATIONS

Obviously, the majority of temperature-control requirements do not justify the complexity of the self-controlling heater (or even a proportional-control system). In fact, the ultimate in control accuracy is usually best accomplished using conventional design techniques. However, there are control applications in which it is impractical to use a separate sensor to supply feedback information.

As one example, it is difficult to control or monitor the temperature of a thin wire filament with conventional approaches. Here, the filament itself can be the self-controlling heater. Thus the average filament temperature is maintained at a preset or programmed average temperature, independent of ambient temperature or air flow. Open wire filaments are often used in gas conductance and flow gauges. Here, it would be advantageous to hold filament temperature constant and to monitor input power (or current) as a measure of rate of heat loss. Linearity of the resistance change versus temperature would be unimportant and the filament material could be chosen entirely on the basis of maximum coefficient and mechanical characteristics.

Temperature-controlled filaments have applications in several areas of research. For example, electron emission studies can be made with better temperature control than is possible using optical pyrometry. Also, changes in strength, evaporation rates, or other properties of metal samples at controlled high temperatures may be conveniently studied.

As an example of a different application, it is often necessary to accurately control the temperature of radiation-cooled infrared detectors on space vehicles by electrical heating. These detectors are in delicate heat balance, and the extra mass and electrical leads required for a separate sensing element are detrimental to thermal performance. There is also a definite expense and risk attached to the installation of such an element. Using the self-controlling heater, a single tiny thermistor or platinum resistance sensor can serve heating, control, and monitoring functions.

The self-controlling heater may also be used advantageously in many "ordinary" applications. Very high accuracy can be achieved where temperatures are low enough to permit using a relatively high-coefficient, stable wire such as platinum or nickel. Freedom from oscillation due to heat propagation time is assured. However, it is very important that good thermal contact between the heater/sensor and heated body be maintained, since the thermal gradient at this interface will represent a temperature error. A very low gradient may be achieved with glass-covered or enameled heater wire wound in a close-fitting milled groove, well-distributed over the controlled body and epoxy-encapsulated. For example, the gradient between the heater wire and aluminum body for the design shown in Figure 3, assuming 5.5 meters of No. 37 double-enamelled wire and a 2 watt input, is less than 0.2° C.

Heater-body gradient may cause a significant error in high-power systems, or where the thermal interface cannot be controlled. Here an entirely different design approach would be required if the heater must still double as a sensor. For example, heater current can be

turned off long enough to allow the gradient to subside, and the temperature quickly sampled on turn-on before heater temperature rises. Or the heater can be switched periodically to a separate sensing circuit of conventional design. These approaches would disturb controlled temperature to some degree, and the required heater current switching could generate interference when used with sensitive instruments.

CONCLUSION

The self-controlling heater has been shown to be feasible and advantageous in certain applications. Relatively simple, reliable circuitry results from the use of modern integrated circuit components.

The circuits presented are intended only to demonstrate a concept. Many variations are possible. Much better performance is certainly possible with a more accurate analog divider and better operational amplifiers and resistors; these are readily available. Control accuracy is limited in a fundamental sense only by heater/sensor stability and, in some configurations, by the mounting interface temperature gradient.

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