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Instruments

AEC RESEARCH AND DEVELOPMENT REPORT

MASTER

A STANDARD LEAK TEMPERATURE CONTROLLER

F. W. Henson

UNION CARBIDE CORPORATION
NUCLEAR DIVISION
OAK RIDGE Y-12 PLANT

operated for the ATOMIC ENERGY COMMISSION under U. S. GOVERNMENT Contract W-7405 eng 26

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Nuclear Division

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F. W. Henson

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ABSTRACT

Standard leaks with leak-rate values of 1×10^{-8} cubic centimeters of volume per second or less require permeation leak-rate elements. To achieve the desired stability of standard leaks in this range requiring permeation elements, a standard leak temperature controller was developed. The electronic circuit which was designed, constructed, and tested for use in controlling the standard leak temperature included a differential amplifier with a thermistor bridge input, a single-phase silicon-controlled rectifier with a unijunction transistor trigger to phase control the 110-volt, 60-Hertz power applied to a resistance heater, a power supply, and an independent temperature measuring bridge. Of the several possible methods considered for controlling the unijunction transistor trigger angle, the shunt control transistor method was selected due to its high gain at minimum output.

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SUMMARY

Two types of standard leaks were investigated to determine their sensitivity to temperature changes. A standard leak with a glass permeation element was found to have a sensitivity of 3.9 percent per degree Celsius, while a standard leak with a glass capillary element was found to have a sensitivity of only 0.65 percent per degree Celsius.

Standard leaks with leak-rate values of 1×10^{-8} cubic centimeters of volume per second or less require permeation leak-rate elements. To achieve the desired stability of standard leaks in this range requiring permeation elements, a standard leak temperature controller was developed. The electronic circuit which was designed, constructed, and tested for use in controlling the standard leak temperature included a differential amplifier with a thermistor bridge input, a single-phase silicon-controlled rectifier with a unijunction transistor trigger to phase control the 110-volt, 60-Hertz power applied to a resistance heater, a power supply, and an independent temperature measuring bridge. Of the several possible methods considered for controlling the unijunction transistor trigger angle, the shunt control transistor method was selected due to its high gain at minimum output.

The temperature controller was analyzed by both theoretical and experimental methods. A phase plane trajectory and experimental results indicated a small oscillation in the system output. However, this small oscillation was not objectionable since a relatively large thermal lag existed between the point of oscillation in the control loop and the glass element which was to be temperature controlled. Measurement of the temperature at the glass element with equipment capable of sensing 0.1 degree Celsius variations revealed no oscillation.

The final test of the temperature controller indicated that ambient temperature could experience changes of up to 25 degrees Celsius with the output of the standard leak remaining constant within about one percent, which was the limitation of the equipment.

INTRODUCTION

A leak detection system which uses a mass spectrometer for sensing traces of a particular gas in a vacuum is calibrated with a known leak rate generally referred to as a standard leak. Construction of standard leaks by Y-12 prior to 1968 was based on a method established by Y-12 Development, which consisted of enclosing a glass capillary leak element in a metal reservoir containing the desired gas. The standard leaks were calibrated either by a volumetric method or by comparison with another known standard leak. This method has proved quite satisfactory for leak-rate standards with values above 1×10^{-8} cubic centimeter per second at one standard atmosphere of pressure and a room temperature of 25 degrees Celsius (atmos cc/sec).

Standard helium leaks with values below 1×10^{-8} atmos cc/sec require further consideration as to construction methods. The permeation of helium through the glass element walls adds to the intended capillary leak rate and substantially increases the overall leak-rate value. This permeation of helium through the glass walls is not evident when the standard leak is first constructed and calibrated. However, after the standard leak is placed in service, and after a differential pressure has existed across the glass element for a period of time, an increasing leak rate is observed. The time required for this increase and the value of the new leak rate after stability depends on the physical characteristics of the glass and the differential pressure across it. A typical standard leak constructed with a capillary element was observed to increase from 1×10^{-8} to 1.2×10^{-8} atmos cc/sec over a period of ten days and at a temperature of about 23 degrees Celsius.

Since the permeation of helium through the glass of a capillary element is in the range of 0.2×10^{-8} atmos cc/sec, construction of a capillary standard leak in the range of 1×10^{-8} atmos cc/sec requires a prediction of the permeation leak rate along with a delicate capillary construction. Permeation elements with no capillary have been constructed from glass tubes with one end closed. These elements have been used in several standard leaks ranging from 1×10^{-10} to 1×10^{-8} atmos cc/sec and have proved satisfactory in regard to physical construction and leak rate.

Helium standard leaks have been observed during calibration to have a sensitivity to temperature change. This sensitivity to temperature has not been sufficiently large to cause concern on capillary standard leaks; however, preliminary data indicate a temperature coefficient of leak rate for the permeation element of about three percent per degree Celsius as opposed to 0.3 percent for the capillary leak element. Normal temperature variations encountered in the calibration and use of standard leaks can produce output changes in permeation leaks of sufficient magnitude to warrant further consideration.

The purpose of this study was to further evaluate the temperature sensitivity of standard helium leaks with permeation elements; to design, build, and test an electronic temperature controller; and to evaluate the use of the controller in reducing the effect of temperature on the standard leaks.

TEMPERATURE SENSITIVITY OF STANDARD LEAKS

The temperature sensitivity of standard leaks with glass permeation elements was determined from the work of Norton⁽¹⁾ and compared with experimental data on selected standard leaks. The temperature-control requirement was determined from the temperature sensitivity and the maximum allowable variation in leak rate due to temperature change.

The leak rate of helium through a glass membrane is reported by Norton to be directly proportional to a permeation constant, K , with units of cubic centimeters (cm^3) of gas volume per second (sec) per square centimeter (cm^2) of glass area per millimeter (mm) of glass thickness per centimeter (cm) of mercury gas pressure difference across the membrane. The constant, K , varies exponentially with temperature as follows:

$$K = Ae^{-\frac{Q}{RT}}, \quad (1)$$

where:

Q represents the activation energy in calories per mole,

R the gas constant in calories per mole per degree Kelvin, and

T the absolute temperature in degrees Kelvin. A is a constant.

Values of K for a variety of glass compositions were plotted by Norton as a logarithm of K versus the reciprocal of the absolute temperature. The resulting curves were straight lines with slopes indicating the activation energy of the particular glass. Temperature sensitivities were calculated from data from these curves for two types of glass. A chemical grade of Pyrex was determined to have a sensitivity of six percent degree Celsius; a borosilicate glass a sensitivity of 16 percent per degree Celsius. Both were determined at 25 degrees Celsius.

An experimental determination of standard leak temperature sensitivity was made. A standard helium leak with a permeation element was selected and installed in a variable temperature chamber along with a second helium leak with a capillary element. The outputs of both standard leaks were connected with stainless steel tubing to a mass spectrometer leak detector through a valve arrangement which allowed the selection of either standard leak output. The leak rates of both standard leaks were measured with the mass spectrometer leak detector at several temperatures between 15 and 40 degrees Celsius. Results are indicated in Figure 1. Several hours were required for the leak rate to stabilize at a new value after changing the chamber temperature. Measurement of the slopes of the curves in Figure 1 at 25 degrees Celsius indicates a rate of change in leak rate with temperature of 0.65 percent per degree Celsius for the standard leak with the capillary element and 3.9 percent per degree Celsius for the standard leak with the permeation element.

Figure 1. LEAK RATE AS A FUNCTION OF THE TEMPERATURE FOR TYPICAL PERMEATION AND CAPILLARY STANDARD LEAKS.

To limit the variation in leak rate due to temperature change to ten percent of the calibrated value, the permeation leak which was examined experimentally would require temperature control to within 2.5 degrees Celsius. To achieve the same stability using borosilicate glass would require temperature control to within 0.6 degree Celsius. A reasonable design requirement of the temperature controller was imposed which allowed a variation in temperature of the glass element of not more than 0.5 degree Celsius for ambient temperature changes between 20 and 30 degrees Celsius.

ELECTRONIC TEMPERATURE CONTROLLER

CIRCUIT DESCRIPTION

The circuit which was designed to control the temperature of standard leaks with permeation elements included a differential amplifier with a thermistor bridge input; a single-phase silicon-controlled rectifier (SCR) to phase control the 110-volt, 60-Hertz power applied to a resistance heater; a unijunction transistor (UJT) trigger circuit; and a direct current (dc) power supply. A thermistor bridge which was independent of the active control circuit was included in the electronic package to provide a calibrated millivolt output versus standard-leak temperature to aid in the adjustment and calibration of the temperature controller.

The circuit has a minimum number of components for a compact package, low circuit power requirements, and ease of construction along with the desired temperature control capability for the standard leaks. For temperature control applications other than standard leaks, the circuit is capable of controlling up to 50 watts of power over a range from about 0 to 50 degrees Celsius with no circuit changes. Use of a higher-rated SCR would allow control of larger quantities of power.

PHASE CONTROL CIRCUIT

The nominal standard leak control temperature was selected to be 40 degrees Celsius in order to establish a low-level power requirement at the control point while operating the standard leak in ambient temperatures around 20 to 25 degrees Celsius. A test standard leak with polystyrene foam insulation required 0.73 watt of input power to maintain the 40-degree temperature.

Proportional control of power from the 110-volt, 60-Hertz power source into the resistance heater in the standard leak temperature controller was accomplished with a half-wave silicon-controlled rectifier (SCR). The SCR circuit power output is found⁽²⁾ by determining the root-mean-square (rms) value of voltage across the load. This voltage is a function of the delay angle, as shown in Figure 2. The rms value of load voltage, E_a , is:

$$E_a = \left[\frac{\int_{\alpha}^{\pi} (E \sin \omega t)^2 d(\omega t)}{\int_0^{2\pi} d(\omega t)} \right]^{\frac{1}{2}}, \quad (2)$$

Figure 2. HALF-WAVE SILICON-CONTROLLED RECTIFIER CIRCUIT SHOWING THE WAVE FORM OF THE LOAD VOLTAGE.

$$E_a = E \left[\frac{\int_{\alpha}^{\pi} \left(\frac{1}{2} - \frac{1}{2} \cos 2(\omega t) \right) d(\omega t)}{(\omega t) \Big|_0^{2\pi}} \right]^{\frac{1}{2}}, \quad (3)$$

$$E_a = E \left[\frac{\frac{1}{2} \left(\omega t - \frac{\sin 2(\omega t)}{2} \right) \Big|_{\alpha}^{\pi}}{2\pi} \right]^{\frac{1}{2}}, \text{ or } \quad (4)$$

$$E_a = \frac{E}{2\sqrt{\pi}} \left(\pi - \alpha + \frac{1}{2} \sin 2\alpha \right)^{\frac{1}{2}}. \quad (5)$$

Since E_a maximum occurs when α equals 0, the ratio of the rms value of load voltage at a particular angle, α , to E_a maximum is:

$$\frac{E_a}{E_{a_{\max}}} = \frac{\frac{E}{2\sqrt{\pi}} \left(\pi - \alpha + \frac{\sin 2\alpha}{2} \right)^{\frac{1}{2}}}{\frac{E}{2}}, \text{ or} \quad (6)$$

$$\frac{E_a}{E_{a_{\max}}} = \frac{\left(\pi - \alpha + \frac{\sin 2\alpha}{2} \right)^{\frac{1}{2}}}{\pi} \quad (7)$$

Figure 3 shows the relation of the ratio $\frac{E_a}{E_{a_{\max}}}$ to the trigger delay angle α .

A 2N1597 SCR was used in a half-wave circuit to control a 30-watt, cartridge-type heater, as shown in Figure 4. The 2N1597 has an rms current capability of up to 1.6 amperes and a peak reverse voltage rating of 200 volts. The 10-ohm resistor in the cathode circuit of the SCR was used to monitor the current into the heater with an oscilloscope during the adjustment and test of the circuit.

Figure 3. VARIATION OF ROOT MEAN SQUARE LOAD VOLTAGE ACROSS A RESISTIVE LOAD WITH DELAY ANGLE α FOR A HALF-WAVE SILICON-CONTROLLED RECTIFIER CIRCUIT.

Figure 4. HALF-WAVE PHASE-CONTROLLED SILICON-CONTROLLED RECTIFIER CIRCUIT.

TRIGGER CIRCUIT

A unijunction transistor (UJT) was used as a relaxation oscillator trigger which was synchronized by a 60-Hertz line frequency. Analysis of this type of trigger is developed⁽²⁾ from the basic circuit, as shown in Figure 5. From Equation 7 the ratio of

Figure 5. PHASE CONTROL WITH A UNIJUNCTION TRANSISTOR AND A SERIES RESISTANCE CONTROL.

the rms voltage of the SCR firing at an angle, α , to the maximum rms voltage when $\alpha = 0$ can be rewritten as:

$$\frac{E_a}{E_{a_{\max}}} = \left(1 - \frac{\alpha}{\pi} + \frac{\sin 2\alpha}{2\pi} \right)^{\frac{1}{2}}. \quad (8)$$

The ratio may be expressed as a function of the RC time constant in Figure 5, the intrinsic standoff ratio, η , of the uni-junction transistor, and the supply line frequency, f . Since:

$$\eta = \frac{V_E}{V_{BB}} = \frac{v_c}{V_{BB}}, \text{ and} \quad (9)$$

$$v_c = V_{BB} \left(1 - e^{-\frac{t}{RC}} \right), \text{ then} \quad (10)$$

$$\eta = 1 - e^{-\frac{t}{RC}}. \quad (11)$$

Solving Equation 11 for t gives:

$$t = RC \ln \frac{1}{1 - \eta}. \quad (12)$$

Since:

$$\omega t = \alpha, \text{ and} \quad (13)$$

$$\omega = 2\pi f, \text{ then} \quad (14)$$

$$\alpha = 2\pi f t. \quad (15)$$

Substituting the expression for α and t into Equation 8 gives the ratio:

$$\frac{E_a}{E_{a_{\max}}} = \left(1 - 2fRC \ln \frac{1}{1 - \eta} + \frac{\sin 4\pi fRC \ln \frac{1}{1 - \eta}}{2\pi} \right)^{\frac{1}{2}}. \quad (16)$$

Equation 16 indicates the relation of the ratio $\frac{E_a}{E_{a_{\max}}}$ to R and C for a particular frequency and intrinsic standoff ratio.

While a thermistor could be used in place of R to directly control the UJT trigger angle, a more flexible arrangement with a higher gain capability is achieved by using a transistor in series with or in shunt across the timing capacitance. A transistor operating in a common-emitter configuration, as in Figure 6, replaces R and allows voltage control of the UJT trigger angle. To develop the transfer characteristic for this circuit, (2) the collector current, i_c , of the transistor is approximated by:

$$i_c \approx \frac{v}{R}, \quad (17)$$

assuming that v is much greater than V_{BE} and that β_0 is much greater than one. Since the voltage across the capacitor, C , is:

$$v_c = \frac{1}{C} \int_0^t i_c dt = \frac{v}{RC} \int_0^t dt = \frac{vt}{RC}, \text{ and} \quad (18)$$

$$t = \frac{\alpha}{\omega} = \frac{\alpha}{2\pi f}, \text{ then} \quad (19)$$

$$v_c = \frac{v\alpha}{2\pi fRC}. \quad (20)$$

Solving for α gives:

$$\alpha = \frac{v_c 2\pi fRC}{v}. \quad (21)$$

Figure 6. PHASE CONTROL WITH A UNIJUNCTION TRANSISTOR AND A SERIES TRANSISTOR.

But, from Equation 9 and Figure 6,

$$v_c = V_1 \eta; \text{ therefore,} \quad (22)$$

$$\alpha = \frac{V_1 2\pi fRC}{v}. \quad (23)$$

Substituting Equation 23 into Equation 8 gives:

$$\frac{E_a}{E_{a_{\max}}} = \left(1 - \frac{\eta V_1 2fRC}{v} + \frac{\sin \frac{4\pi\eta V_1 fRC}{v}}{2\pi} \right)^{\frac{1}{2}}, \quad (24)$$

which is the rms voltage ratio transfer characteristic for the series transistor control circuit. The transfer characteristic for the series transistor control circuit is shown in Figure 7.

A method offering high power gain with a sacrifice of linearity is illustrated in Figure 8. The control transistor is connected in shunt across the timing capacitor and diverts

Figure 7. TRANSFER CHARACTERISTIC FOR SERIES TRANSISTOR CONTROL.

Figure 8. PHASE CONTROL WITH A UNIJUNCTION TRANSISTOR AND A SHUNT TRANSISTOR.

charging current from the capacitor. A subsequent increase in the time required to trigger the UJT is produced, which is adjustable by the voltage input to the control transistor. The current, i_c , is approximated by:

$$i_c \approx \frac{v}{R_2}, \text{ where} \quad (25)$$

$$v = v_i - V_{BE} \quad (26)$$

The final voltage, V_F , to which the capacitor can charge is given by:

$$V_F = V_1 - R_1 \left(\frac{v}{R_2} \right), \quad (27)$$

and the instantaneous voltage across Capacitor C is given by:

$$v_c = V_F \left(1 - e^{-\frac{t}{RC}} \right), \quad (28)$$

which assumes that there is no initial charge on the capacitor. Then:

$$v_c = \left[V_1 - R_1 \left(\frac{v}{R_2} \right) \right] \left(1 - e^{-\frac{t}{R_1 C}} \right). \quad (29)$$

Since:

$$\eta = \frac{v_c}{V_1}, \quad (30)$$

$$\eta V_1 = \left[V_1 - R_1 \left(\frac{v}{R_2} \right) \right] \left(1 - e^{-\frac{t}{R_1 C}} \right), \text{ and} \quad (31)$$

$$\frac{\eta V_1}{V_1 - R_1 \left(\frac{v}{R_2} \right)} = 1 - e^{-\frac{t}{R_1 C}}. \quad (32)$$

Further rearrangement gives:

$$e^{-\frac{t}{R_1 C}} = \frac{V_1 R_2 - v R_1 - \eta V_1 R_2}{V_1 R_2 - v R_1}. \quad (33)$$

Taking the natural logarithm of the reciprocal of both sides and then solving for t yields:

$$t = R_1 C \ln \frac{V_1 R_2 - v R_1}{V_1 R_2 - v R_1 - \eta V_1 R_2}. \quad (34)$$

Since:

$$\alpha = 2\pi f t, \quad (35)$$

α may be expressed as:

$$\alpha = 2\pi f R_1 C \ln \frac{V_1 R_2 - v R_1}{V_1 R_2 - v R_1 - \eta V_1 R_2}. \quad (36)$$

Substituting Equation 36 for α in Equation 8 gives the rms voltage ratio for the shunt transistor control circuit as the function:

$$\frac{E_a}{E_{a_{\max}}} = \left[1 - 2fR_1 C \ln \frac{V_1 R_2 - v R_1}{V_1 R_2 - v R_1 - \eta V_1 R_2} + \frac{\sin^2 \left(\frac{2\pi f R_1 C \ln \frac{V_1 R_2 - v R_1}{V_1 R_2 - v R_1 - \eta V_1 R_2}}{2\pi} \right)}{2\pi} \right]^{\frac{1}{2}} \quad (37)$$

Figure 9 indicates the transfer characteristic for the shunt transistor control circuit.

Figure 9. TRANSFER CHARACTERISTIC FOR SHUNT TRANSISTOR CONTROL.

The trigger circuit developed for the standard leak temperature controller is shown in Figure 10. The shunt transistor control method was used since only a small amount of power is required to offset the heat loss from the standard leak through the polystyrene insulation. The shunt transistor method offers a higher gain around a minimum output as indicated by the transfer characteristic in Figure 9. A 2N1671B unijunction transistor was used for the trigger oscillator along with a 2N930 shunt control transistor. To keep the peak emitter voltage constant over the operating temperature range of the UJT,⁽³⁾ the resistor, R_4 , was calculated from:

$$R_4 \approx \frac{0.70 R_{BB}}{\eta V_1} \quad (38)$$

Figure 10. COMPLETE PHASE CONTROL TRIGGER CIRCUIT USED ON THE STANDARD LEAK TEMPERATURE CONTROLLER.

where:

R_{BB} represents interbase resistance, and

V_1 the dc supply voltage.

The 2N1671B had a measured intrinsic standoff ratio of 0.55 and an interbase resistance, R_{BB} , of 7,000 ohms. (4) With a V_1 of 20 volts, R_4 is calculated to be 437 ohms. A value of 464 ohms was used from available sizes. The time constant resistor, R_1 , was made 14,700 ohms and the capacitor 0.18 microfarad, which limited the conduction period to an equivalent nine watts maximum power with no collector current being drawn by the control transistor. The 10,000-ohm, three-watt resistor, R_5 , was used to drop the voltage required by the 1N4747A, 20-volt zener diode. The 1N4004 diode was used to block the forward current flow through the zener, which reduces the power dissipated in R_5 . About 12 milliwatts of minimum power is dissipated in the heater at all times due to the average current drawn by the UJT, the zener diode, and the SCR leakage current. Twelve milliwatts are not sufficient to cause a noticeable temperature rise in the standard leak. Wave forms of the trigger circuit are shown in Figure 11 with the numbers keyed to Figure 10.

THERMISTOR BRIDGE AND DIFFERENTIAL AMPLIFIER

Equation 37 and the transfer function shown in Figure 9 indicate the required input voltage to the trigger control transistor for various heater power levels. The source

Figure 11. WAVE FORMS OF THE TRIGGER CIRCUIT.

of this input at Points A and B was provided by the output of a differential amplifier, as shown in Figure 12. The output voltage of the differential amplifier can swing from + 2 to - 2 volts, which is more than adequate to drive the trigger control transistor.

The output voltage between the two collectors of a differential amplifier will not drift⁽⁵⁾ if identical transistors are used, if the circuit is symmetrical, and if the junction temperatures are equal. A 2N4004 monolithic, dual, silicon, planar transistor was used for the differential amplifier circuit to provide identical units and equal junction temperature. Symmetry was maintained with the exception of the potentiometer and the thermistor, which were the input elements. Holding the values of collector current and element voltages low tends to aid in drift reduction.⁽⁶⁾ The differential amplifier was designed for one milliampere of collector current in each side of the

circuit when in balance. An eight-volt, isolated dc power supply was used, which provided quiescent voltages, as indicated in Figure 12.

Baxandall and Shallow⁽⁷⁾ describe a constant-current source which has an unusually high internal impedance. Such a circuit, shown in Figure 13, was used as the constant-current source in the emitter circuit of the differential amplifier. An MD6002 silicon complementary pair in a single package provided the electrical similarity between the two transistors, which is desirable for cancellation of temperature effects on the emitter-base voltages.

The temperature sensing device selected for the control circuit was a bead-type thermistor with a negative temperature coefficient. The resistance of the thermistor at the control point of 40 degrees Celsius is about 5,000 ohms. Figure 12 shows a 10,000-ohm, microminiature, humidity-proof, wire-wound potentiometer in the bridge circuit opposite the thermistor. Adjustment of the potentiometer allows a 10-degree-Celsius variation in the temperature control point. Resolution of the 11-turn potentiometer is 0.27 percent of the potentiometer resistance, or the equivalent of 0.12 degree Celsius at the control point of the thermistor.

Figure 12. DIFFERENTIAL AMPLIFIER AND THERMISTOR BRIDGE.

TEMPERATURE MEASURING CIRCUIT

A temperature measuring circuit which was independent of the control circuit was desirable to observe the controller performance and to establish a relative temperature set point for the controller as a part of the standard leak calibration. A thermistor bridge circuit was designed and constructed (Figure 14). A calibration of the bridge was performed from 15 to 43 degrees Celsius, with the resulting calibration curve indicated in Figure 15. A high impedance recorder with an adjustable range and adjustable zero was calibrated and used to indicate the standard leak temperature during subsequent tests of the controller.

Figure 13. CONSTANT CURRENT SOURCE.

POWER SUPPLY

An eight-volt, isolated dc power supply was designed for the controller differential amplifier, controlling thermistor bridge circuit, and for the temperature measuring circuit. The circuit used two 1N4004 rectifiers in a full-wave configuration with Resistor R selected to set the current through the eight-volt zener diode at a reasonable value. The final circuit values along with the resulting currents are indicated in Figure 16.

Figure 14. TEMPERATURE MEASURING CIRCUIT.

Figure 15. VOLTAGE OUTPUT AS A FUNCTION OF TEMPERATURE FOR THE TEMPERATURE MEASURING CIRCUIT.

Figure 16. POWER SUPPLY.

CONSTRUCTION OF THE TEMPERATURE CONTROLLER

A water-bath temperature controller is described by Larsen⁽⁸⁾ which achieves extremely good stability, primarily due to locating all temperature-dependent components within the temperature-controlled environment. The small number and small physical size of the electronic components used in the standard-leak temperature controller allowed the construction of a small package of components which was included in the temperature-controlled zone. Only the power-supply transformer; the three-watt, 10,000-ohm resistor; two 1N4004 rectifiers; and an 18-microfarad filter capacitor were placed externally to the temperature-controlled zone. Figure 17 shows the printed circuit construction which was used to reduce the size of the electronic package and to aid in the construction of the controller circuit. Figure 18 presents a view of the expandable polystyrene foam insulation which was molded in a steam chest for use as the controller insulation material. Cavities were molded in the foam for the electronic package which would be a part of the temperature-controlled zone, for the power-

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Figure 17. PRINTED CIRCUIT CONSTRUCTION OF THE ELECTRONIC CONTROL CIRCUIT.

supply transformer and other components external to the controlled zone, for the heater cartridge, and for the two thermistor sensors. A chrome-plated brass case, shown in Figure 19, was fabricated to house the complete assembly.

Access to a miniature electrical connector was provided under a removable metal plug through which the outlet valve was installed. The electrical connection provided means of monitoring the output of the temperature measuring bridge during calibration. The electrical connection also provided leads from the 10-ohm resistor in series with the cathode of the SCR, which allowed observation of the heater current wave form and phase angle.

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Figure 18. MOLDED EXPANDABLE POLYSTYRENE INSULATION WITH A STANDARD LEAK.

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Figure 19. COMPLETED CONTROLLER.

ANALYSIS OF THE TEMPERATURE CONTROLLER

METHOD OF ANALYSIS

The analysis of the standard-leak temperature controller consisted of both a theoretical and an experimental examination of the system. The theoretical effort was applied to the nonlinear portion, which consisted of the phase-controlled SCR trigger circuit shown in Figure 20; while the more linear sections, including the differential amplifier, thermistor bridge, and heater, were examined experimentally. Both open-loop and closed-loop operation of the system were investigated.

Figure 20. THE TEMPERATURE CONTROLLER.

THERMISTOR BRIDGE AND DIFFERENTIAL AMPLIFIER

The transfer function of the thermistor bridge and differential amplifier is indicated by Figure 20 to have a temperature input and voltage output. Figure 21 shows the experimentally determined transfer function for this section. The curve was linearized by approximating the transfer function by a straight-line tangent to the experimentally determined curve at the operating point.⁽⁹⁾ The slope at the operating point of 40 degrees Celsius was measured from the curve to be:

$$\frac{\Delta V}{\Delta T} = 1.44 \text{ volts/degree Celsius.} \quad (39)$$

Figure 21. TRANSFER CHARACTERISTIC OF THE DIFFERENTIAL AMPLIFIER AND THERMISTOR BRIDGE.

Since the range of operation of the system after reaching stability was very narrow, the slope was considered constant. The curve indicates a voltage output of about two volts negative when the temperature is well below the set point. The negative two volts is sufficient to turn the shunt control transistor off, which results in the shortest possible time constant in the trigger circuit and, consequently, the longest conduction period for the SCR. This condition provides the maximum power that the circuit can supply to the heater with a particular set of circuit component values. When the temperature is well above the set point, the voltage output approaches a positive two volts, which causes the control transistor to divert sufficient current from the time constant capacitor to prevent the capacitor voltage to charge up to:

$$v_c = \eta V_{1'} \quad (40)$$

which is the firing voltage of the UJT.

The thermistor-bridge and differential-amplifier section performs the intended function of providing an output voltage swing sufficiently large to completely cut off the power to the heater at one extreme and to allow full power input for the other extreme, while providing a reasonably linear transfer function in the steady-state operating range.

PHASE-CONTROLLED SILICON-CONTROLLED RECTIFIER AND TRIGGER CIRCUIT

The ratio of the rms voltage output developed across the standard leak temperature-controller heater to the maximum rms voltage was expressed in terms of several component values and a variable input voltage, v , in Equation 37. To aid in component selection, this equation was programmed for a computer solution of rms voltage ratios for various ranges of input voltage, v , and various component values. After the component values had been assigned to provide a maximum power of nine watts, the program was utilized to provide ratios for various input voltages over the operating range of the circuit. The power levels, P , were calculated from the voltage ratios by:

$$P = 9 \left(\frac{E_a}{E_{a_{\max}}} \right)^2 \quad (41)$$

The power levels were plotted for various shunt control transistor input voltages, v_i , as shown by Curve B in Figure 22 after correcting for a base-to-emitter voltage, V_{BE} , of 0.62 volt by:

$$v = v_i - V_{BE} = v_i - 0.62. \quad (42)$$

Figure 22. TRANSFER CHARACTERISTIC OF THE SILICON-CONTROLLED RECTIFIER AND TRIGGER CIRCUIT.

Equation 41 and Figure 23 were found to give a closer approximation of the shunt-control transistor collector current than that used by Gutzwiller⁽²⁾ which did not take into account the base-to-emitter junction voltage, V_{BE} .

Further examination of Equation 37 reveals that if the logarithmic term is rearranged to give:

$$\ln \frac{V_1 R_2 - v R_1}{V_1 R_2 - v R_1 - \eta V_1 R_2} = \ln \frac{1}{1 - \frac{\eta V_1 R_2}{V_1 R_2 - v R_1}}, \text{ the ratio:} \quad (43)$$

$$\frac{\eta V_1 R_2}{V_1 R_2 - v R_1} \quad (44)$$

must always be less than 1 to prevent taking the logarithm of a negative number. The significance of this limitation on the ratio in Equation 44 is found in one of the requirements necessary for the UJT to trigger. This requirement is that its emitter voltage exceed the intrinsic stand-off ratio times the interbase voltage as expressed by:

$$v > \eta V_1. \quad (45)$$

Figure 23. SHUNT CONTROL TRANSISTOR CIRCUIT.

Since the voltage:

$$v = v_c, \text{ then} \quad (46)$$

$$v_c > \eta V_1. \quad (47)$$

The voltage across the capacitor was given as:

$$v_c = \left(V_1 - R_1 \frac{v}{R_2} \right) \left(1 - e^{-\frac{t}{RC}} \right); \text{ therefore,} \quad (29)$$

$$\eta V_1 < \left(V_1 - R_1 \frac{v}{R_2} \right) \left(1 - e^{-\frac{t}{RC}} \right), \text{ and} \quad (48)$$

$$\eta V_1 < V_1 - R_1 \frac{v}{R_2}. \quad (49)$$

Rearrangement of terms gives:

$$\eta V_1 R_2 < V_1 R_2 - R_1 v_1, \text{ or} \quad (50)$$

$$\frac{\eta V_1 R_2}{V_1 R_2 - R_1 v} < 1. \quad (51)$$

Further examination of Equation 43 reveals that in the term:

$$\ln \frac{1}{1 - \frac{\eta V_1 R_2}{V_1 R_2 - v R_1}}, \quad (52)$$

$$V_1 R_2 \neq v R_1. \quad (53)$$

The significance of this limitation is found by rearranging Equation 27 to give:

$$V_F = \frac{1}{R_2} \left(V_1 R_2 - v R_1 \right). \quad (54)$$

If:

$$V_1 R_2 = v R_1, \quad (55)$$

then the charging voltage, V_F , is zero or:

$$V_F = V_1 R_2 - v R_1 = 0, \quad (56)$$

and the capacitor could not charge to the required positive value to trigger the UJT. Substituting component values into Equation 51 gives:

$$v < 0.6 \text{ volt.} \quad (57)$$

Then, by Equation 42:

$$v_i < 1.22 \text{ volts.} \quad (58)$$

Substituting component values into Equation 53 gives:

$$v \neq 1.36, \quad (59)$$

and by Equation 42:

$$v_i \neq 1.98. \quad (60)$$

Since Equation 58 must hold true, then the largest value v_i can have and the UJT still trigger is 1.22 volts. When

$$v_i > 1.22 \text{ volts,} \quad (61)$$

no power is allowed to be applied to the heater since the UJT cannot trigger; and, when v_i is as specified by Equation 58, power is applied to the heater up to the maximum value of nine watts, depending on v_i . Curve B of Figure 22 shows the theoretical variation in power input to the heater with various values of the input voltage, v_i , to the shunt control transistor base, as calculated by computer from Equation 37 and Equation 42 with component values substituted. Curve A of Figure 22 indicates measured power values for measured values of the input voltage. If the effect of emitter current on V_{BE} was taken into consideration in plotting Curve B of Figure 22, a closer agreement between the theoretical and experimental results might be obtained.

The transfer function of the SCR and trigger circuit was determined by linearization of the experimentally established Curve A in Figure 22. This transfer function was found to be:

$$\frac{\Delta P}{\Delta v_i} = 32 \text{ watts/volt.} \quad (62)$$

HEATER AND THERMAL LAG

From a final value standpoint, the power input versus temperature output of the heater was linear and relatively easy to determine; however, the lag time between a power-level change and the resulting temperature change involved many variables. These variables included the quality of the thermal contact of the heater and the control thermistor with the standard leak body, the type of insulation around the complete assembly, and, probably the most important, the physical location of the controlling thermistor with respect to the heater.

The heater and thermal-lag section of the control loop may be simulated by a simple resistance and capacitance circuit.⁽⁹⁾ The resistance, R , represents an energy dissipation element and the capacitance, C , an energy storage element. Referring to Figure 24 it is clear that:

$$i_R(t) = \frac{e_i(t) - e_o(t)}{R}, \quad (63)$$

where $e_i(t)$ and $e_o(t)$ are the input and output voltages and $i_R(t)$ the current through the dissipation element, R . The current $i_C(t)$ through the storage element, C , is:

$$i_C(t) = C \frac{de_o(t)}{dt}. \quad (64)$$

Figure 24. ELECTRICAL ANALOG OF THE THERMAL SYSTEM.

In the thermal system voltages are analogous to temperatures and currents to thermal energy. In Equation 63 and 64, if $e_o(t)$ is loaded by a high impedance,

$$i_R = i_c, \text{ then} \quad (65)$$

$$\frac{e_i(t) - e_o(t)}{R} = C \frac{de_o(t)}{dt}, \text{ or} \quad (66)$$

$$e_i(t) - e_o(t) = RC \frac{de_o(t)}{dt}. \quad (67)$$

Let:

$$\tau = RC, \text{ and} \quad (68)$$

$$e_o(t) = e_i(t) - \tau \frac{de_o(t)}{dt}. \quad (69)$$

The response function:

$$g(t) = \frac{e_o(t)}{e_i(t)} \quad (70)$$

may be found by taking the Laplace transform which gives:

$$e_o(s) = e_i(s) - \tau s e_o(s). \quad (71)$$

Solving for $g(s)$ gives:

$$g(s) = \frac{e_o(s)}{e_i(s)} = \frac{1}{1 + \tau s}. \quad (72)$$

The well-known time response of Equation 72 is:

$$e_o(t) = E \left(1 - e^{-\frac{t}{\tau}} \right), \quad (73)$$

which is the desired expression. Equation 73 indicates that a step change in energy into the thermal system results in an exponentially rising output temperature. Both a step function and an impulse function were applied to the thermal system with the results indicated in Figures 25 and 26. The time constant for the thermal system was

Figure 25. TEMPERATURE RESPONSE TO A STEP-FUNCTION POWER INPUT.

measured to be 75 minutes for 63 percent of the final temperature change to occur. This time constant was subject to drastic changes due to changes in the quality of the thermal contacts and the physical arrangement of the standard leak and insulation.

The transfer function for the heater and time-lag section was experimentally determined to be that shown in Figure 27. With linearization at 40 degrees Celsius, a gain of

Figure 26. TEMPERATURE RESPONSE TO AN IMPULSE-FUNCTION POWER INPUT.

Figure 27. TRANSFER CHARACTERISTIC OF THE HEATER AND THERMAL LAG.

$$\frac{\Delta T}{\Delta P} = 19 \text{ degrees/watt} \quad (74)$$

was measured.

SYSTEM RESPONSE

The open-loop response of the system was determined by multiplying together the three response functions for the three sections of the standard-leak temperature controller. Figure 20 shows the three sections which result in an open loop gain of:

$$G_{OL} = G_1 G_2 G_3, \text{ or} \quad (75)$$

$$G_{OL} = (1.44 \text{ volts/degree}) (32 \text{ watts/volt}) (19 \text{ degrees/watt}), \text{ or} \quad (76)$$

$$G_{OL} = 876. \quad (77)$$

The expected results of enclosing the control loop would be to speed up the time response of the system. This prediction was examined by a closed-loop startup of the system with the results given in Figure 28. A rise of 63 percent of the final temperature change occurred in four minutes, with the final temperature settling into an oscillation with magnitude and repetition, as shown in Figure 29. The temperature

Figure 28. CLOSED LOOP STARTUP OF THE STANDARD-LEAK TEMPERATURE CONTROLLER.

cycle indicated by Figure 29 was that cycle which was present at the controlling thermistor and not the glass permeation element. An additional temperature lag exists between the thermistor and the element, as shown by the R_2C_2 filter in Figure 30. This additional filter reduced the oscillation to the extent that no measurable oscillation was observed at the permeation element of the standard leak.

The low-amplitude oscillation was further investigated to determine its cause. D'Azzo and Houpis⁽¹⁰⁾ describe a number of nonlinearities which are referred to as fast nonlinearities with respect to the response time of the system. The nonlinearities include dead zone, relay, backlash, and hysteresis, each of which is shown in Figure 31. The response of the trigger and SCR circuit is also shown in Figure 31, along with the range over which the input, v_i , swings during the temperature oscillation after stability is reached. The response of the trigger and SCR circuit contains a combination of dead zone at the lower swing of the input voltage and relay action at the upper portion of the swing. The relay action is not instantaneous due to the slope of the response curve; however, the long time constant of the system allows the action to be considered instantaneous. The saturation region of the trigger and SCR circuit is not reached by the voltage swing except for the first few cycles after the system is turned on. Figure 32 shows the power cycles of the system with respect to the resulting temperature cycles after making a temperature set-point increase at time, t_0 .

Figure 29. TEMPERATURE CYCLE AT THE CONTROL THERMISTOR.

Figure 30. CONTROL LOOP WITH THE ADDITIONAL THERMAL LAG.

Figure 31. NONLINEARITIES.

Figure 32. POWER CYCLES WITH RESPECT TO THE TEMPERATURE CYCLES.

The phase plane is useful for investigating the time response of second-order systems with nonlinearities. Eckman,⁽¹¹⁾ Kalman,⁽¹²⁾ and Gibson⁽¹³⁾ apply the phase plane to a variety of control problems. A phase-plane plot is the rate of change of the deviation of the variable with the deviation of the variable. Figure 33 shows a

Figure 33. PHASE-PLANE DIAGRAMS.

phase-plane plot of a stable system in which the oscillation reduces to zero deviation, one for a system which reduces to a steady oscillation, and one for an unstable system in which the oscillation increases after a disturbance. Eckman⁽¹¹⁾ shows that if the differential gap, G , or the amount of deviation required to initiate a response change is not zero, or if there is a finite dead zone or lag in the control system, the result will be a steady oscillation. The standard-leak temperature-control system has a zero differential gap over the portion of the response curve in which power is being applied to the heater. A differential gap exists during the part of the cycle at which no power is being applied. A time lag after a power change is the dominating factor which results in the steady oscillation. A phase plane plot of the steady oscillation can be seen in Figure 34.

Figure 34. PHASE-PLANE TRAJECTORY AND TIME-DOMAIN PLOT OF THE SYSTEM.

PERFORMANCE TESTS

Performance of the standard-leak temperature controller was examined by installing a standard leak in the controller and placing a small temperature measuring probe into the glass permeation element of the standard leak. The controller was turned on; and, with an ambient temperature of 25 degrees Celsius, the permeation-element temperature was observed to stabilize at 40 degrees Celsius in 15 minutes. While the controller was stabilized at 40 degrees Celsius, a five-degree Celsius change in the set point was made in the controller by adjusting the potentiometer in the differential amplifier thermistor bridge. Temperature stability of the glass permeation element was achieved in five minutes. The standard leak was placed in a temperature chamber; and, with the controller operating, the chamber temperature was adjusted to several values between 15 and 40 degrees Celsius. The resulting temperature changes of the glass element are indicated in Figure 35. The times required for both the warmup and set-point change were typical values for the particular standard leak under test. Factors influencing this time response include the mass of the standard leak, quality of the thermal contact between the heater and the standard leak body, and thermal contact between the temperature sensor and standard leak body.

Figure 35. STANDARD-LEAK ELEMENT TEMPERATURE FOR VARIOUS CHAMBER TEMPERATURES.

The temperature sensitivity of a standard leak with a permeation element is indicated in Figure 1. The same standard leak was installed in the temperature controller, and complete assembly placed in the variable temperature chamber. The chamber was varied over a wide range of temperatures while the leak-rate output of the temperature-controlled standard leak was monitored by a mass-spectrometer leak detector. The curve indicating leak rate versus temperature for the permeation leak with the controller operating is shown in Figure 36. The original curve of the permeation leak from Figure 1 is included for comparison. Figure 36 indicates that the leak rate for the permeation-element standard leak with the temperature control operating is no longer a function of ambient temperature within the temperature range over which the standard leak was tested.

Figure 36. LEAK RATE AS A FUNCTION OF THE TEMPERATURE.

CONCLUSIONS

A mass-spectrometer leak detector may be calibrated by a known gas leak-rate standard which consists of a reservoir of gas with a leak element. The basic problem with which this study was concerned was that of investigating and reducing the sensitivity of certain of these standard leaks to changes in the ambient temperature. The reduction in sensitivity to temperature was accomplished by means of an electronic temperature controller of miniature design. With the controller, the temperature of the standard leak element was held essentially constant at 40 degrees Celsius over a 25-degree range of ambient temperatures which allows the temperature effects to be neglected. The design of the electronic temperature controller included a resistance heater with a phase-controlled SCR and UJT trigger circuit. The transfer functions were developed for the various methods of unijunction transistor trigger delay angle control. The shunt transistor control method, which offers higher gain at minimum power output, was chosen with a sacrifice of overall response linearity. The temperature sensing circuit was a thermistor bridge which served as the input circuit to a differential amplifier. The output of the differential amplifier was the input to the UJT trigger circuit. Circuit analysis was achieved by both theoretical and experimental methods. A small oscillation was present in the steady-state condition of the control system. This small oscillation was not objectionable since a relatively long thermal lag existed between the control thermistor and glass element which was to be temperature controlled. Measurements of the temperature at the glass element revealed no oscillation.

An effort was made to miniaturize the circuit by holding the power consumption of the circuit components to a minimum and by utilizing high-quality miniature components mounted on printed circuit boards.

The circuit which was designed for the purpose of controlling the standard leak temperature could be applied to a wide variety of temperature-control problems. Little modification of the circuit would be required to achieve a wide range or high temperature control. Further work on this subject might include the packaging of the circuit in such a manner that various input thermistors, SCR devices, and heaters could be adapted for a wide range of temperature-control work. Another study which should be made is that of providing variable output standard leaks by adjusting the temperature of the glass elements.

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