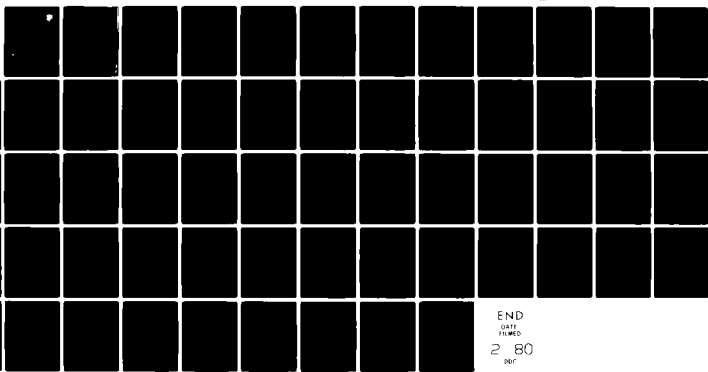


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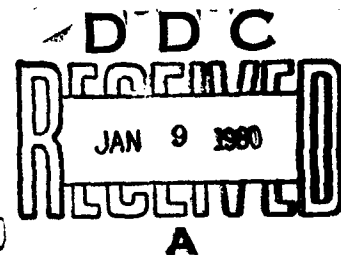
# **A COMPUTER-AUTOMATED TEMPERATURE CONTROL SYSTEM FOR SEMICONDUCTOR MEASUREMENTS**

Roger Nohl Switzer  
Philip C. H. Chan  
C. T. Sah

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| 20. ABSTRACT (Continue on reverse side if necessary and identify by block number)<br>A computer-automated temperature control system is described in this report to completely automate data acquisition for the characterization of electrical properties of semiconductor devices and materials. Temperature is monitored by a type T thermocouple embedded in a heat sink surrounding the sample. Liquid nitrogen provides a reference temperature for the thermocouple. Steady state is established by computer control of the current in a heater wire wrapped around a block of copper on which the solid state device is mounted. A proportional plus integral control is implemented as a computer (Cont'd) |                       |                                                                                       |

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program. The system is capable of controlling the sample temperature with a precision of  $\pm 0.1$  K in the temperature range from 85 K to 300 K with a settling time of better than 600 seconds with a temperature change of as much as 50 K.

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## Chapter 1. SYSTEM OVERVIEW

### 1.1 Importance of Temperature in Semiconductor Measurements

It is well known that most electrical properties of semiconductor materials are dependent in some manner on temperature. One example is the rate of thermal emission of trapped holes or electrons from generation-recombination-trapping centers. The transient capacitance method can be used to measure the thermal emission rate. This measurement is more conveniently accomplished at low temperatures since the emission rate is smaller and thus the duration of the capacitance transient is longer. [1] It is clear that if accurate measurements of such temperature dependent properties are to be obtained, the temperature must be accurately maintained.

The purpose of this thesis work is to design, implement, and test a computerized temperature control system which will become part of a highly automated data acquisition system. This data acquisition system was previously developed by the author and other members of the Solid State Electronics Laboratory. Stable temperatures in the range from 85 K to 300 K are obtainable with this system. In actual use, the most common input to the controller will be the step input. Therefore, the design is aimed at obtaining a suitable step response.

### 1.2 Thesis Organization

In the remaining sections of this chapter a description of the physical apparatus used to construct the control system is presented. An approximate model of the thermal portion of the system is obtained.

Two design techniques were employed in the search for a suitable control algorithm to be executed by the computer. Chapter 2 covers

the design of a discrete-time controller using the z-transform. In Chapter 3 the system is treated as an approximation to a continuous-time system. The design of a controller is carried out using the Laplace transform. The controller which gave the best performance was designed using Laplace transform techniques. Testing of this version of the temperature control system is also covered in Chapter 3. Chapter 4 is the conclusion in which the capabilities and limitations of the system are summarized.

### 1.3 The Data Acquisition System

The heart of the automated data acquisition system mentioned in Section 1.1 is a Hewlett-Packard 1000M minicomputer system. Programs are executed under control of the Hewlett-Packard Real Time Executive IV (RTE-IV) operating system. In order to gather data related to the properties of semiconductor materials, various instruments and meters must be interfaced to the computer. The Hewlett-Packard Multiprogrammer Model 6940B provides an easy and efficient solution to this interface problem.

The purpose of the 6940B Multiprogrammer is to extend the capability of one computer I/O channel. It is a bidirectional I/O interface which facilitates communication between the computer and several input/output circuit cards. Each 6940B can contain up to fifteen input/output cards. In addition, up to fifteen 6941B Extender units, each capable of holding fifteen cards, can be connected to the 6940B. In this manner one computer I/O channel can be expanded to a total of 240 subchannels. The digital data sent to the Multiprogrammer is used to:

- (1) control the mode of operation of the system, for example

- to select whether data is to be input or output,
- (2) address output cards and supply the output quantity in binary encoded form, or
  - (3) address input cards so that binary encoded data may be received from the card.

Examples of the functions of output cards are resistance programming of power supplies and digital-to-analog voltage conversion. Conversion of an analog voltage to digital data is an example of the functions of input cards. [2]

A block diagram of the data acquisition system hardware is shown in Figure 1.1. A detailed drawing of the probe which holds the semiconductor device-under-test and also constitutes the thermal portion of the temperature control system is shown in Figure 1.2. Power supplies No. 1 and No. 2 are programmed by the value of resistance set on the resistance programming cards in slots 403 and 404. The outputs of these power supplies are routed to the relay-readback card in slot 406. Relay closures on this card select which power supply voltage is applied to the bias terminals of the Boonton capacitance meter. The polarity of the bias voltage is also determined by the relay-readback card. The power supply voltages are also sent to one of the voltage monitor (A/D) cards in slots 411 through 413 when the appropriate relay is closed. Voltage monitors 001, 010, and 102 can measure voltages in the ranges +1.0235V to -1.0240V in 0.5mV steps, +10.235V to -10.240V in 5mV steps, and +102.35V to -102.40V in 50mV steps respectively. Voltage monitor 001 may also receive the analog output of the Boonton capacitance meter through the relay card in slot 406. The bias voltage and analog output of the Boonton capacitance meter are multiplexed to the input of the

Figure 1.1 Block diagram of the data acquisition system.

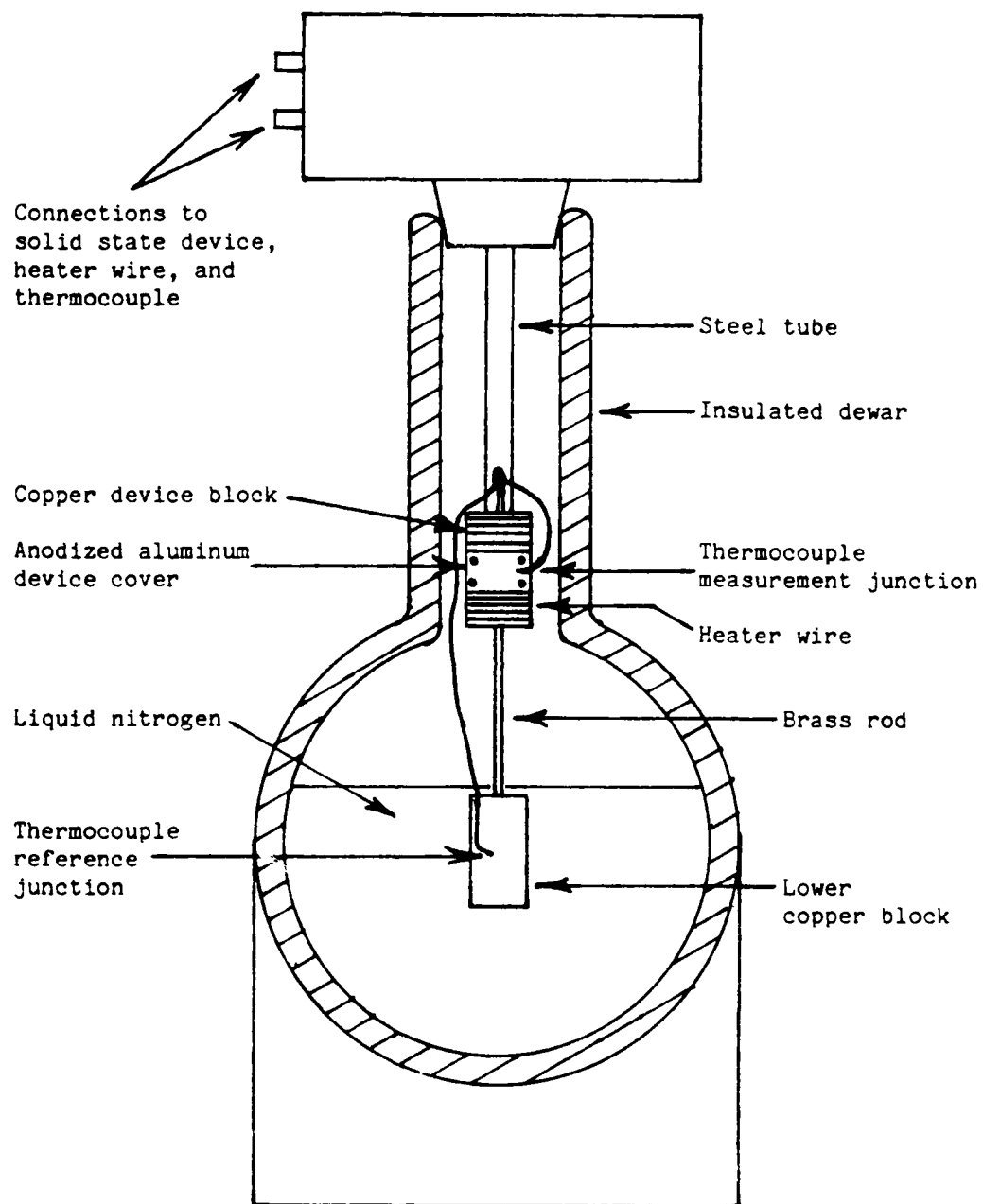


Figure 1.2 Probe to hold semiconductor device-under-test.

Data Precision 3500 digital voltmeter, labelled DVM 2, by the relay-readback card in slot 405. The maximum resolution of the Data Precision DVM is one microvolt. DVM 1 is dedicated to reading the thermocouple voltage from which the device temperature can be determined. Binary-coded-decimal data from DVM 1 and DVM 2 is fed to the optically-isolated digital input cards in slots 407 through 410.

A library of relocatable subroutines which either control or receive data from the instruments in the system has been previously developed by the author. These subroutines make the job of writing data acquisition programs much less tedious and reduce the chances for program errors.

#### 1.4 Temperature Control System Hardware

The hardware units specifically related to the temperature control system are the D/A voltage converter card, the HP 6224B power supply (Figure 1.1) and the probe which holds the semiconductor device-under-test and also forms the thermal portion of the system (Figure 1.2). Hereafter, this probe will be referred to as the thermal plant. The D/A voltage converter is capable of delivering a DC voltage in the range -10.240V to +10.235V in 5mV steps. It is used to voltage program the 6224B power supply with a gain of two. Power is supplied to the heater wire of the thermal plant by the 6224B. Its output voltage is controlled by the software subroutine SETVH which also limits the output to 20V. A listing of the subroutine SETVH is included in Appendix A. The resistance of the heater wire is 13.35 ohms. Therefore, the maximum power which can be supplied to the thermal plant is about 30 Watts. Since energy cannot be removed from the plant via the heater wire, the minimum power is zero Watts. The unipolarity and saturation of the power which

can be supplied to the thermal plant result in a limited region of linear operation. Small quantization errors also exist in the power supplied to the heater and the measured temperature due to the use of digital signals to represent these quantities.

The thermal plant was designed by previous members of the Solid State Electronics Laboratory. On the upper copper device block there is a socket which accepts an eight-pin TO-5 can which contains one to four solid state devices. An anodized aluminum cover is placed over the device can and is in direct thermal contact with the copper block. The layer of aluminum oxide prevents any electrical contact to the TO-5 can. The measurement thermocouple junction is imbedded in the aluminum device cover and is also electrically insulated. Since the device is completely surrounded by the thermal mass of the copper block and the aluminum cover, the temperature measured in the aluminum cover will accurately reflect the temperature of the semiconductor device. Due to this large thermal mass, the device is not subject to rapid temperature fluctuations. The copper block at the lower end of the brass rod is used to reduce the sensitivity of the plant parameters to the level of liquid nitrogen in the dewar. In normal use, the nitrogen level should be even with the top of the lower copper block. In order to maintain a constant temperature at the device block, the power supplied through the heater wire and also from the outside environment must be equal to the power which flows out of the device block through the brass rod and also to the air in the dewar.

#### 1.5 Temperature Measurement with a Copper-Constantan Thermocouple

When two dissimilar metals are joined, a voltage is developed across the junction. This phenomenon is called the Seebeck effect and is the

basis of the operation of thermocouples. A thermocouple consists of two wires of different types of metals, twisted together, and heated at the junction until the two wires begin to alloy. A Seebeck voltage is generated at the junction of the two wires, whose magnitude depends on the composition of the metals and the temperature of the junction. As the temperature of the junction increases so does the voltage at the open ends of the wires. Two thermocouple junctions connected in series are used in the temperature measuring circuit. When one of the junctions is held at a known, constant temperature, the voltage produced by the pair of junctions can be used to determine the temperature of the non-reference junction. [3]

The thermocouples used in this temperature control system are type T (copper vs. constantan). Constantan is a copper-nickel alloy. The copper wire has a positive potential with respect to the constantan wire. The temperature measurement circuit is shown in Figure 1.3. Note in the figure that junctions of dissimilar metals also occur where the coaxial cable leading to the input of the digital voltmeter connects to the copper thermocouple wires. These junctions are, however, in close proximity and should be at the same temperature so that the voltages generated at these junctions will cancel each other. The lower reference junction is immersed at all times in liquid nitrogen which is at its boiling point, 77.348 K, according to the International Practical Temperature Scale adopted in 1968 (IPTS-68). [4]

The type T thermocouple is the only one of the standardized types for which limits of error are set below  $0^{\circ}\text{C}$ . The thermocouple wires used in this temperature control system are specified by the manufacturer (Claud S. Gordon Co., Richmond, IL) to meet the special limits of

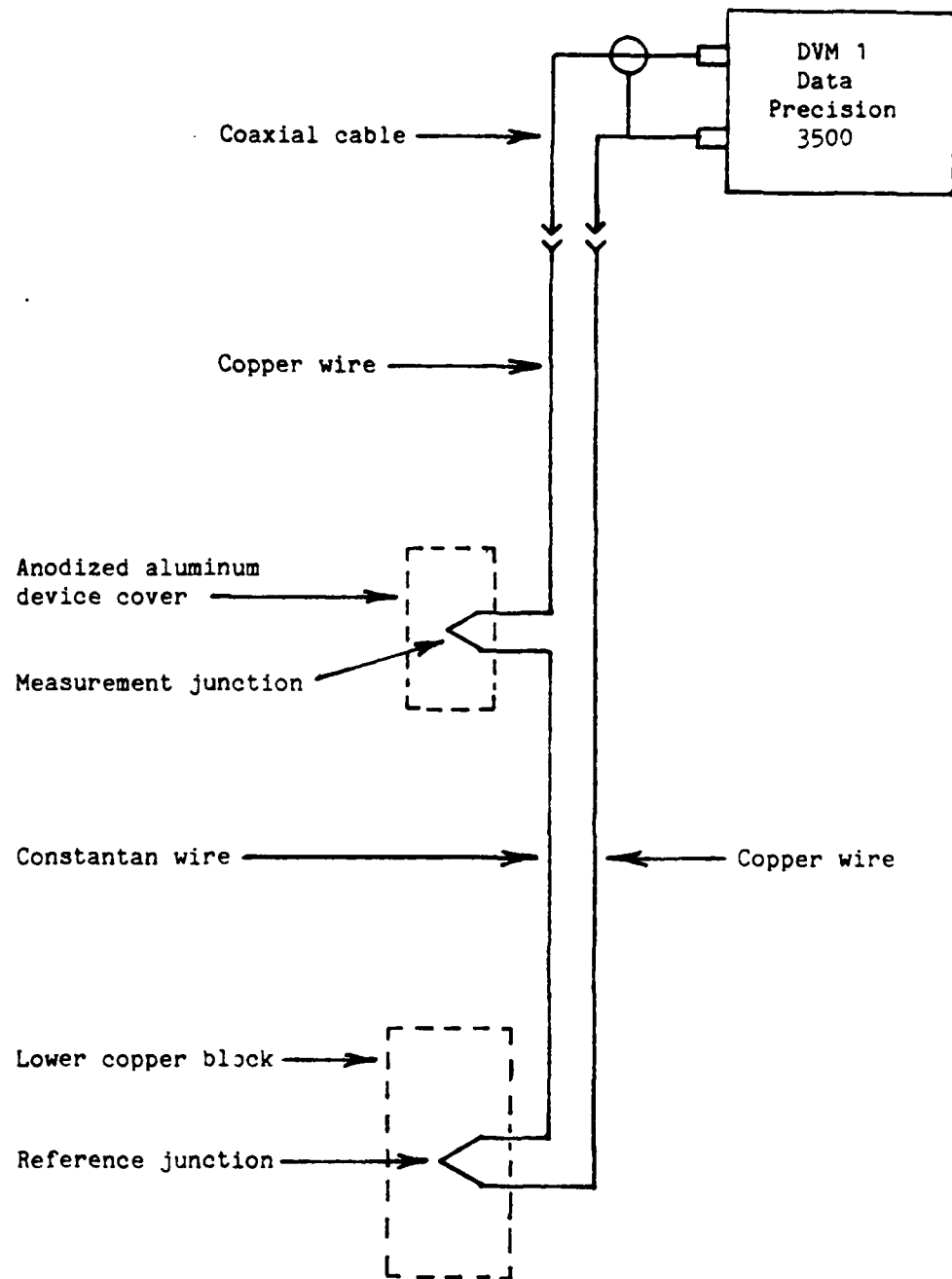


Figure 1.3 Temperature measurement circuit.

error which are plus or minus one percent of the measured temperature between  $-184$  and  $-59^{\circ}\text{C}$  and plus or minus  $0.8^{\circ}\text{C}$  between  $-59$  and  $93^{\circ}\text{C}$  when the reference junction is at  $0^{\circ}\text{C}$ . [4] With these limits in mind, the absolute accuracy of the measured temperature should not be considered to be better than plus or minus one percent of the measured temperature. Calibration of the thermocouple against a platinum resistance thermometer may improve the absolute accuracy.

A fourteen term power series expansion for the thermoelectric voltage in microvolts of type T thermocouples is given in Reference [4]. The series is not repeated here. This power series with temperature in degrees Celsius as the independent variable is for the reference junction at  $0^{\circ}\text{C}$ . To adapt this series to the reference junction at the boiling point of nitrogen, all that needs to be done is to calculate the thermoelectric voltage at the reference temperature ( $-195.802^{\circ}\text{C}$ ) and subtract this value from the voltage obtained from the series. Of course, the temperature used as the argument of the series must still be in degrees Celsius. The temperature may be determined from the measured thermocouple voltage by solving the equation

$$f(T) - f(-195.802) - (\text{thermocouple voltage}) = 0 \quad (1.1)$$

where  $f$  denotes the power series,  $T$  is the temperature in degrees Celsius, and the thermocouple voltage is in microvolts. The function TEMP, listed with the control program in Appendix A, uses the Newton-Raphson Technique to solve Equation (1.1) for the temperature in degrees Kelvin. Function TEMP converges in less than seven iterations.

#### 1.6 Approximate Model of the Thermal Plant

Before one can go about designing a feedback control system, one must have a good model of the process to be controlled. In order to

formulate a model of the thermal plant, step response data was taken for several input power levels. The mathematical form of the step responses was determined using a fitting program based on a subroutine called CURFIT from Reference [5]. The data was successfully fitted to a function consisting of two exponential terms and a constant term of the form

$$T(t) = A_1 \exp(-A_2 t) + A_3 \exp(-A_4 t) + A_5. \quad (1.2)$$

This is the same form of response which would be obtained when a step function is the input to a system with transfer function of the form

$$G(s) = \frac{T(s)}{P(s)} = \frac{A(s + z_1)}{(s + p_1)(s + p_2)}, \quad (1.3)$$

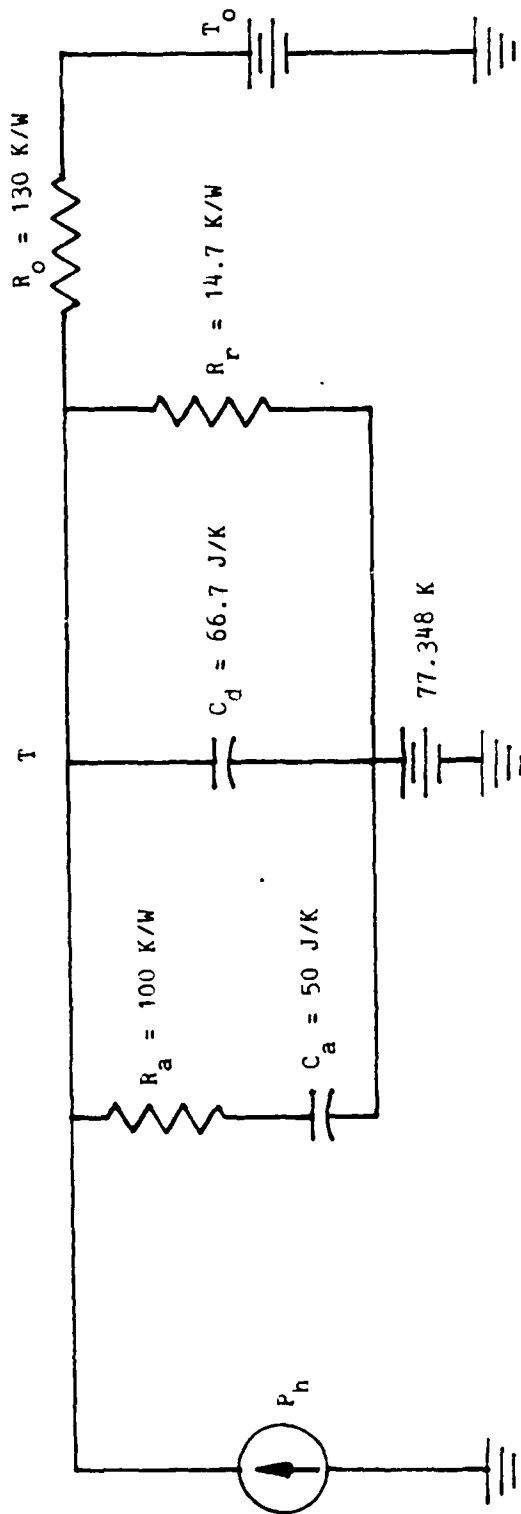
where  $T(s)$  is the Laplace transform of the temperature response and  $P(s)$  is the Laplace transform of the input power. From the information provided by the fitted parameters of Equation (1.2), the following approximate values were found for the parameters of the transfer function in Equation (1.3):  $A = 0.015$ ,  $z_1 = 0.0002$ ,  $p_1 = 0.0012$ , and  $p_2 = 0.00017$ .

A lumped model of the thermal plant was obtained from this approximate transfer function. Figure 1.4 shows this lumped model in electrical analog form. The values of all the elements of the model except  $R_o$  were obtained by equating the transfer function of Equation (1.3) to the transfer function of the model, given by Equation (1.4) and solving for the parameters of the model.

$$\frac{T(s)}{P_h(s)} = \frac{(s + 1/R_a C_a)/C_d}{s^2 + s(1/R_r C_d + 1/R_a C_a + 1/R_a C_d) + 1/R_a C_a R_r C_d} \quad (1.4)$$

The value of  $R_o$  was calculated from the temperature of the device block when  $P_h = 0$  W according to the following.

$$R_o = R_r(T_o - T)/(T - 77.348) \quad (1.5)$$



$P_h$  - power supplied to the heater wire

$R_a$  - thermal resistance of the air in the dewar

$C_a$  - thermal capacitance of the air in the dewar

$C_d$  - thermal capacitance of the device block and cover

$R_r$  - thermal resistance of the brass rod

$R_o$  - thermal resistance between device block and outside environment

$T_o$  - temperature of the outside environment

$T$  - temperature of the device block and cover

Figure 1.4 Lumped model of the thermal plant.

When a brass rod is used,  $R_p$  is 14.7 K/W and  $T$  is about 100 K with  $P_h = 0$ . If  $T_o$  is taken as 300 K then  $R_o$  is found to be about 130 K/W. So the power entering the system from the outside environment is given by

$$P_o = (T_o - T)/130 \text{ W.} \quad (1.6)$$

To check the validity of this model, the thermal resistance of the brass rod,  $R_p$ , and the thermal capacitance of the device block and cover,  $C_d$ , were calculated from the dimensions and the thermal conductivity or specific heat capacity of these elements. The thermal resistance of the brass rod assuming no heat loss from the sides of the rod was calculated to be 19.6 K/W. Of course if heat loss from the sides of the rod was considered, the calculated value would be significantly less. Thus the experimental value of 14.7 K/W for  $R_p$  in the model is roughly correct. The calculated thermal capacitance of the device block and cover assuming no temperature gradients within the block was 80 J/K. When one considers that temperature gradients do exist within the device block during the rise time of the step response, it is logical that the apparent thermal capacitance will be smaller since the outside regions of the device block where the temperature is measured are heated before the inside of the block. Less power will be required to cause a given change in temperature in a given time near the outside of the block than if the temperature were measured in the middle of the block. In non-equilibrium conditions the effective thermal capacitance of the block will be reduced. When this point is considered, the experimental value of 66.7 J/K for  $C_d$  used in the model is also seen to be reasonable.

It must be pointed out that this model is only approximate. The use of a lumped model for a system which is obviously distributed is,

strictly speaking, incorrect. There is a time delay in the actual system which is not accounted for in the lumped model. However, the simplification of the design procedures which results from using a lumped model is a benefit which outweighs the disadvantage of the inaccuracy in the model.

## Chapter 2. CONTROLLER DESIGN USING DISCRETE-TIME TECHNIQUES

### 2.1 Discrete-Time Design Procedure

The sampled signals present within the temperature control system are not continuous functions of time and are difficult to handle using Laplace transforms. The z-transform method is useful in simplifying the analysis and design of sampled-data systems. This technique is employed in the design of a digital discrete-time controller in this chapter. It was pointed out in Chapter 1 that the temperature control system has non-ideal properties such as quantization errors and saturation of the power which can be supplied to the thermal plant. These characteristics will be neglected in order to simplify the analysis and design. The quantization errors may be neglected since they are small in comparison to the magnitudes of the signals present in the system. The saturation effect in the power available to the heater will come into play only for large temperature steps in the reference input.

The design procedures described below follow closely those given in Reference [6] and Chapter 9 of Reference [7]. Only the major points used in arriving at a design algorithm are repeated here.

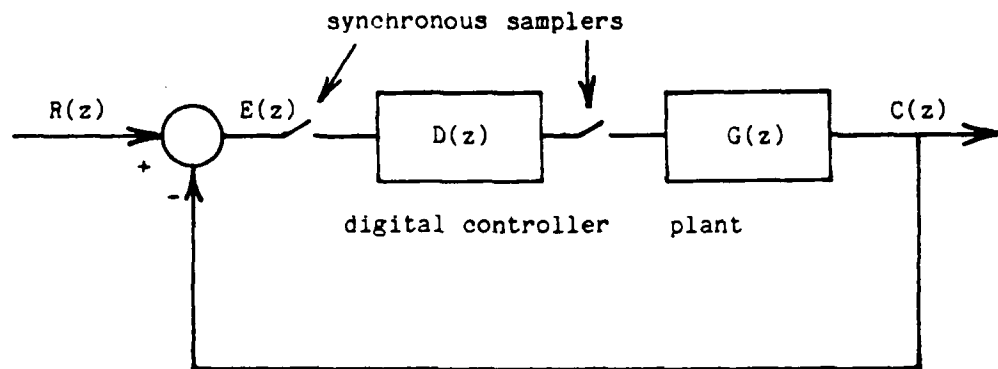
Consider the closed loop sampled-data system in Figure 2.1.

The transfer function of the closed loop system is given by

$$M(z) = \frac{C(z)}{R(z)} = \frac{D(z)G(z)}{1 + D(z)G(z)} \quad (2.1)$$

If  $M(z)$  can be selected so that the closed loop system meets certain design specifications such as percent overshoot or rise time, then the appropriate digital controller transfer function,  $D(z)$ , can be found by

$$D(z) = \frac{M(z)}{1 - M(z)} \frac{1}{G(z)} \quad (2.2)$$



$R(z)$  - reference input

$C(z)$  - controlled variable

$E(z)$  - error signal

$D(z)$  - digital controller transfer function

$G(z)$  - plant transfer function

Figure 2.1 Sampled-data control system with digital controller.

The choice of  $M(z)$  cannot be made without regard to the transfer function of the plant,  $G(z)$ . The controller transfer function found from Equation (2.2) must be physically realizable and should also be stable. Physical realizability of  $D(z)$  implies that the degree of the numerator must not exceed that of the denominator. The digital controller will be stable if the poles of  $D(z)$  lie inside the unit circle in the  $z$ -plane.

The closed loop transfer function,  $M(z)$ , must now be related to the performance specifications of the system. Consider  $M(z)$  in the form

$$M(z) = \frac{K(z - z_1)}{(z - p_1)(z - \overline{p_1})} \quad (2.3)$$

where  $p_1$  and  $\overline{p_1}$  are a pair of complex conjugate poles.  $K$  is chosen so that the steady state error for a step input is zero. By application of the Final-Value Theorem,  $K$  is found to be

$$K = \frac{(1 - p_1)(1 - \overline{p_1})}{1 - z_1} \quad (2.4)$$

The step response of the closed loop system is found to be

$$c(nT) = 1 + \sec \alpha |p_1|^n \cos(n\phi + \alpha - \pi) \quad \text{for } n=0,1,2,\dots \quad (2.5)$$

where  $\phi = \arg(p_1)$  and  $\alpha = \arg(p_1 - z_1) - \arg(p_1 - 1) + \pi/2$ . The complex pole  $p_1$  has a counterpart in the  $s$ -plane denoted  $p'_1$  such that

$$p_1 = \exp(p'_1 T) = \exp(-\zeta \omega_n T) \exp(j\omega_n \sqrt{1-\zeta^2} T) \quad (2.6)$$

where  $\zeta$  is the damping ratio and  $\omega_n$  is the natural frequency of the system. From this relation it is seen that

$$|p_1| = \exp(-\zeta \omega_n T) \quad \text{and} \quad \phi = \omega_n \sqrt{1-\zeta^2} T \quad (2.7)$$

When these relations are substituted into Equation (2.5), a continuous function which passes through the sampled points is obtained by replacing  $nT$  with  $t$ .

$$c(t) = 1 + \sec \alpha \exp(-\zeta \omega_n t) \cos(\omega_n \sqrt{1-\zeta^2} t + \alpha - \pi) \quad (2.8)$$

This equation can be solved for the time at which the maximum response occurs.

$$t_{\max} = \frac{1}{\omega_n \sqrt{1-\zeta^2}} \left\{ \arctan\left(\frac{-\zeta}{\sqrt{1-\zeta^2}}\right) - \alpha + \pi \right\} \quad (2.9)$$

Substituting this expression for  $t_{\max}$  in Equation (2.8), it is found that the overshoot, abbreviated O.S., for a unit step input is

$$\text{O.S.} = \sqrt{1-\zeta^2} \sec \alpha \exp\left\{ \frac{-\zeta}{\sqrt{1-\zeta^2}} \left( \arctan\left(\frac{-\zeta}{\sqrt{1-\zeta^2}}\right) - \alpha + \pi \right) \right\} \quad (2.10)$$

For a given damping ratio,  $\zeta$ , the value of  $\alpha$  which gives the minimum overshoot is given by

$$\alpha = \arctan(-\zeta / \sqrt{1-\zeta^2}) \quad (2.11)$$

If  $\alpha$  is chosen by (2.11), using (2.8) Equation (2.9) may be written as

$$t_{\max} = \pi T / \phi \quad (2.12)$$

The angle of the complex pole,  $p_1$ , may be found from Equation (2.12) for a specified  $t_{\max}$ . The magnitude of  $p_1$  can be found by combining the two relations of (2.7) to obtain

$$|p_1| = \exp(-\phi \zeta / \sqrt{1-\zeta^2}) \quad (2.13)$$

The zero,  $z_1$ , lies on the real axis of the z-plane and can be found from the relation

$$\alpha = \arg(p_1 - z_1) - \arg(p_1 - 1) + \pi/2 \quad (2.14)$$

The constant  $K$  can now be found from Equation (2.4). At this point, all of the parameters of the closed loop transfer function have been found for any choice of  $\zeta$  and  $t_{\max}$ . The discrete-time controller transfer function,  $D(z)$ , can be found from Equation (2.2) provided the transfer function of the plant,  $G(z)$ , is known. The design procedure may be developed into a point-by-point design

algorithm suitable for execution by a computer program. This is done in Appendix B.

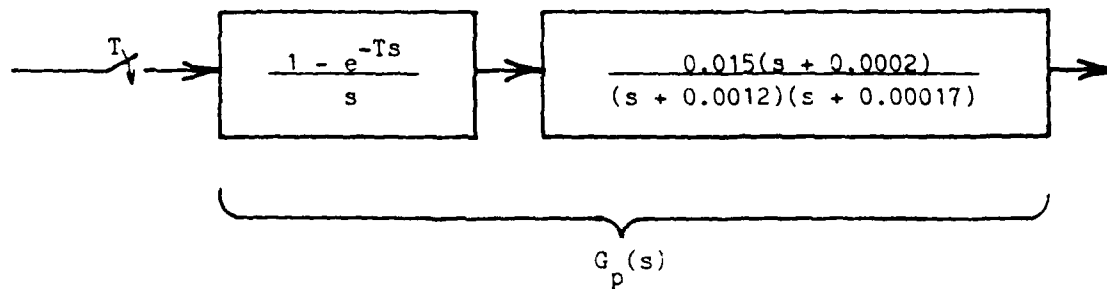
## 2.2 Discrete-Time Temperature Controller Design

The design procedures developed in Section 2.1 and Appendix B will be applied to the temperature control system in this section. The voltage applied to the heater wire of the thermal plant is held constant until the next sampling instant when a new voltage is set. Thus, the power input to the thermal plant is subjected to a sample-and-hold operation commonly referred to as the zero-order hold. A block diagram portraying this action is shown in Figure 2.2 (a). The z-transformed counterpart is shown in Figure 2.2 (b) for a sampling period of two seconds. The zero-order hold may be considered as a part of the plant. The transfer function of the plant with the zero-order hold included is denoted by  $G_p(z)$ .

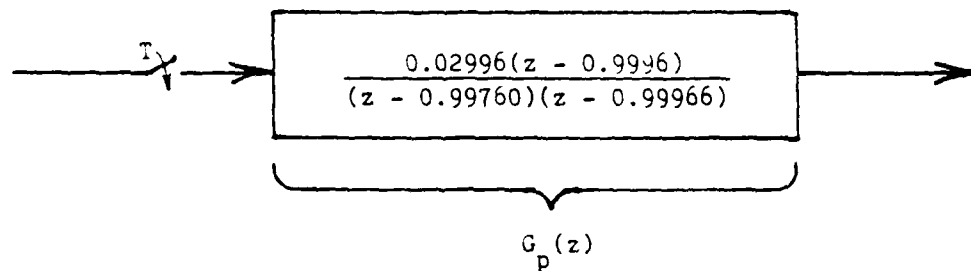
With this knowledge of the transfer function of the plant, the design algorithm described in Appendix B may be applied to the temperature control system to find the controller transfer function. The controller transfer function may be written in the form

$$D(z) = \frac{P(z)}{E(z)} = \frac{a_0 + a_1 z^{-1} + a_2 z^{-2} + a_3 z^{-3}}{1 + b_1 z^{-1} + b_2 z^{-2} + b_3 z^{-3}} \quad (2.15)$$

where  $P(z)$  is the power output of the controller and  $E(z)$  is the error signal input to the controller. In Equation (2.15), the factor  $z^{-n}$  implies a time delay of  $nT$  seconds.  $D(z)$  may easily be implemented by a computer program. The operation of the computer program is depicted in block diagram form in Figure 2.3. The output sequence of the digital discrete-time controller depends on the past outputs as well as the past and present inputs.



(a)



(b)

Figure 2.2 Block diagram of thermal plant with zero-order sample-and-hold. (a) Laplace transform diagram, and (b) z-transform diagram. The plant transfer function was found experimentally.

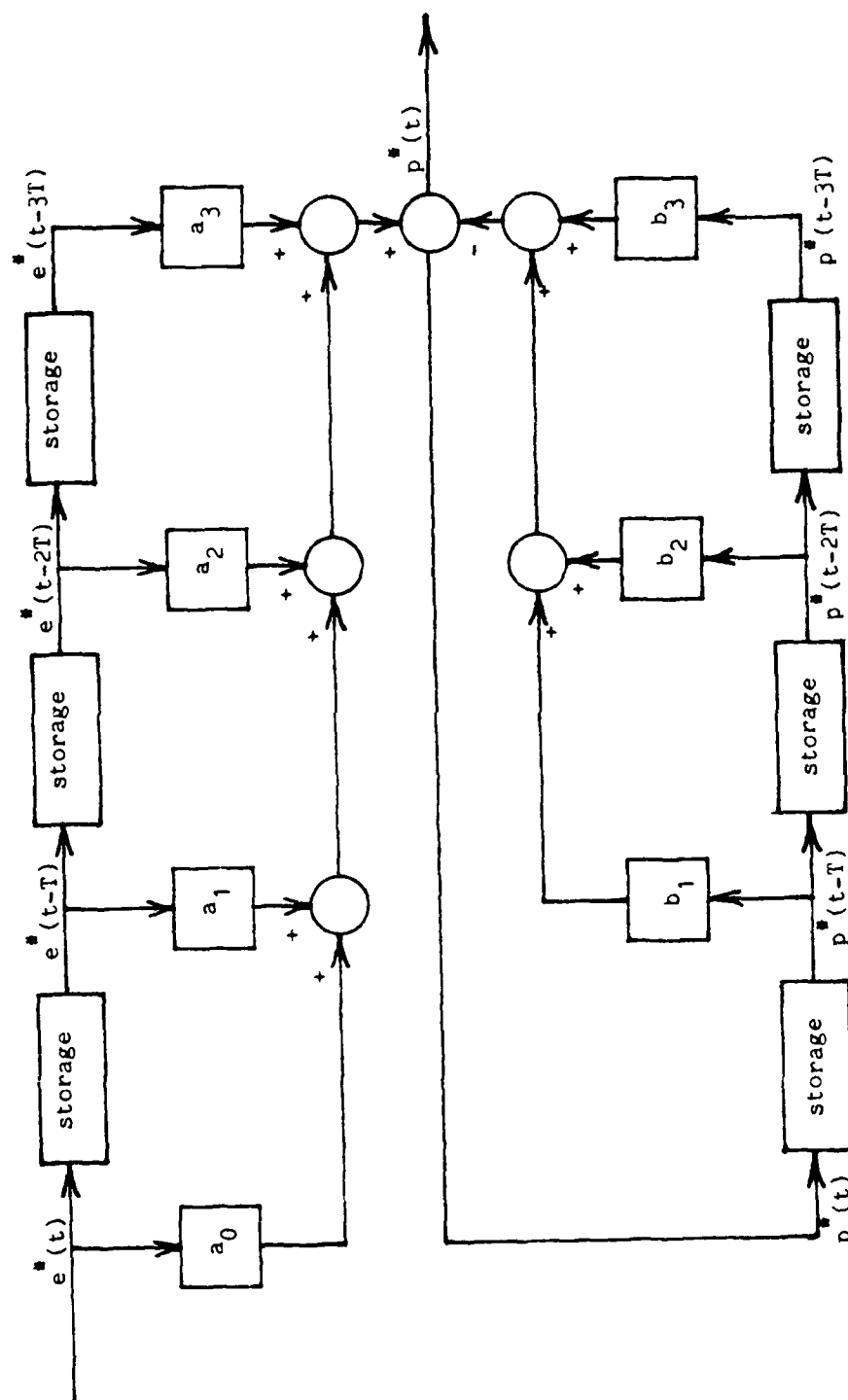


Figure 2.3 Block diagram of computer program implementation of  $D(z)$ .  $e^*(t)$  denotes the error signal input and  $p^*(t)$  denotes the power output. After Kuo [7].

Several discrete-time controllers were designed with the aid of program DSN, listed in Appendix B, and tested. None of the discrete-time controllers exhibited totally satisfactory responses. An example of the step response of one of the discrete-time controllers is shown in Figure 2.4. The transfer function of the controller which produced this response is given in the sample output of program DSN in Appendix B. The response shown in Figure 2.4 is unsatisfactory for the following reasons:

- (i) there is a steady state error of 0.5 K,
- (ii) the response is oscillatory before reaching the steady state,
- (iii) the settling time of about 30 minutes is excessive.

The most serious of these deficiencies is the non-zero steady state error. A deeper consideration of the design algorithm reveals why the steady state error is not zero. Referring to Equation (2.2) it is seen that the determination of  $D(z)$  which should give the desired closed loop transfer function,  $M(z)$ , depends on a rather precise knowledge of the plant transfer function,  $G(z)$ . In the case of the temperature control system,  $G(z)$  is only approximately known. The constant  $K$  of the closed loop transfer function was chosen for zero steady state error using Equation (2.4). The values used for the poles and zero in this equation are calculated values which may not be equal to the actual poles or zero of the closed loop system due to the inexact knowledge of the plant transfer function. Therefore,  $D(z)$  found from Equation (2.2) may not yield the desired closed loop transfer function which would produce a response with zero steady state error. Since this particular discrete-time design approach does not produce a closed loop system which meets the design goals, some other techniques must be used to design the control system. In Chapter 3 the control system is treated as an approximation to a continuous-time system.

TEMPERATURE CONTROLLER STEP RESPONSE  
CONTROLLER VERSION CN06

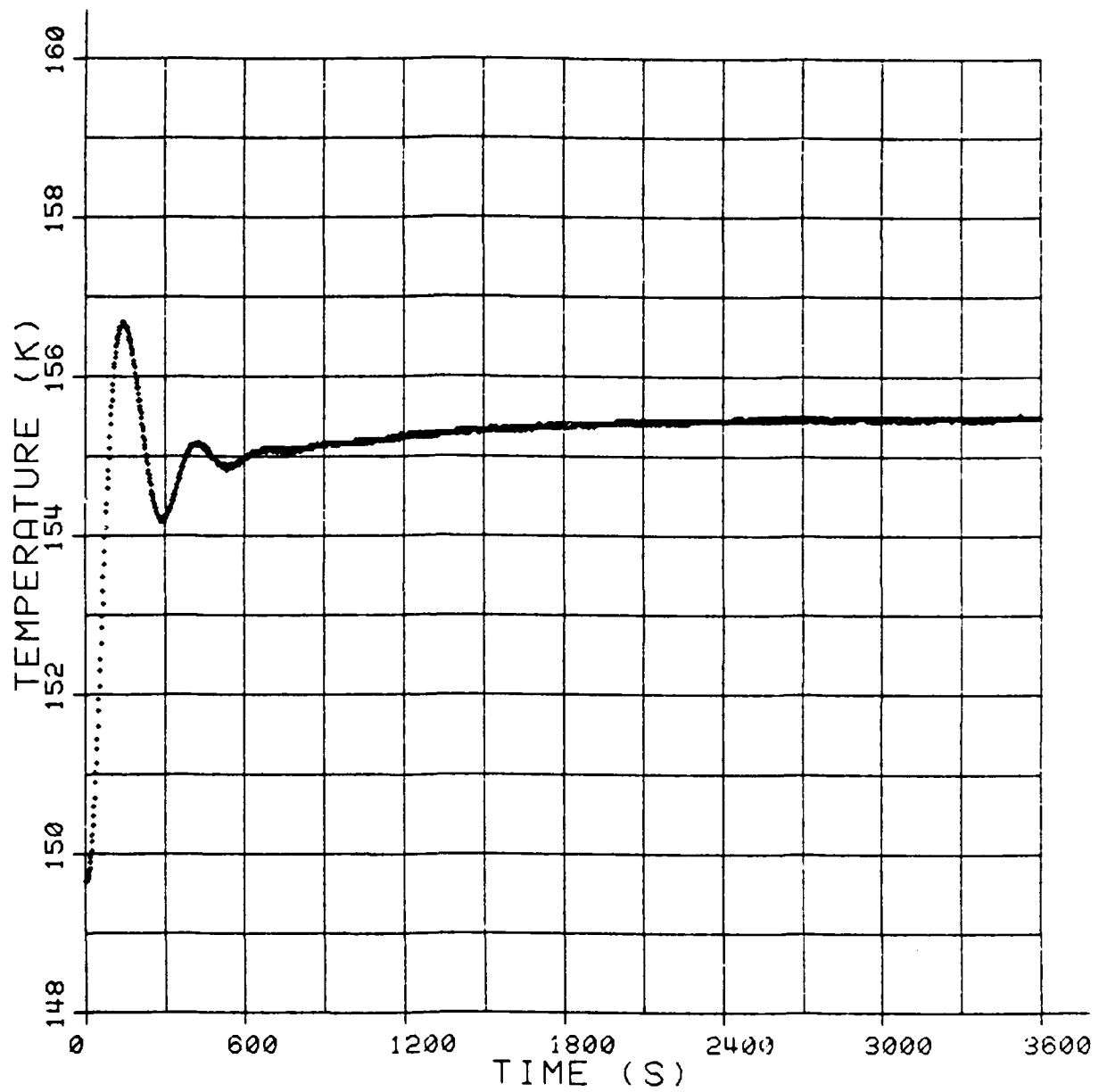


Figure 2.4 Response of temperature control system with a digital controller to a step input from 150 to 155 K.

### Chapter 3. CONTROLLER DESIGN USING CONTINUOUS-TIME TECHNIQUES

#### 3.1 Proportional, Integral, and Proportional plus Integral Control

Consider a closed loop system of the form shown in Figure 3.1(a). If the sampling period,  $T_s$ , is small compared to the system time constants, the system may be treated as a continuous-time system for the purposes of analysis and design (Figure 3.1(b)). This approach is applied to the temperature control system in this chapter.

The plant transfer function was found in Chapter 1. The controller transfer function,  $D(s)$ , must be determined so that the desired response of the closed loop system can be obtained. In this temperature control system,  $D(s)$  will be implemented using a digital computer (HP 1000M). The saturation effect in the power which can be supplied to the thermal plant is neglected in the initial design. The design goals are:

- (1) the system should be stable,
- (2) the steady state error for a step input must be zero, and
- (3) the step response overshoot and settling time should be reasonable.

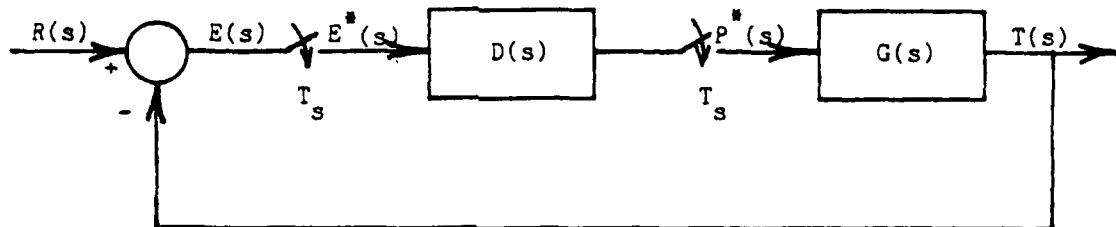
The question which arises now is what form the controller transfer function should take so that the design goals are met.

The plant transfer function is of the form

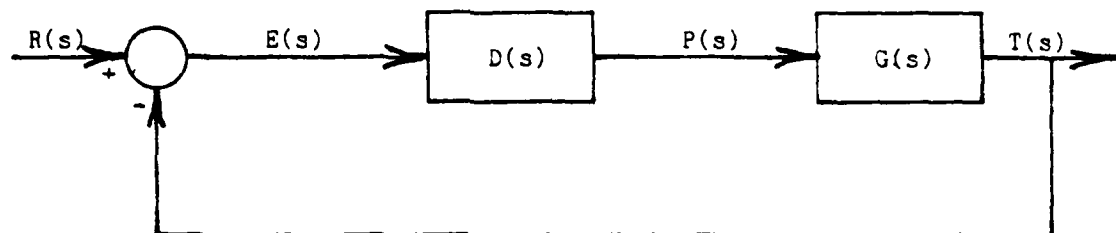
$$G(s) = \frac{A(s + z_1)}{(s + p_1)(s + p_2)} \quad (3.1)$$

where  $A = 0.015$ ,  $z_1 = 0.0002$ ,  $p_1 = 0.0012$ , and  $p_2 = 0.00017$ .

If proportional control is used the controller transfer function will simply be a fixed gain,  $K_p$ , as shown in Figure 3.2(a). The closed loop transfer function is of the form

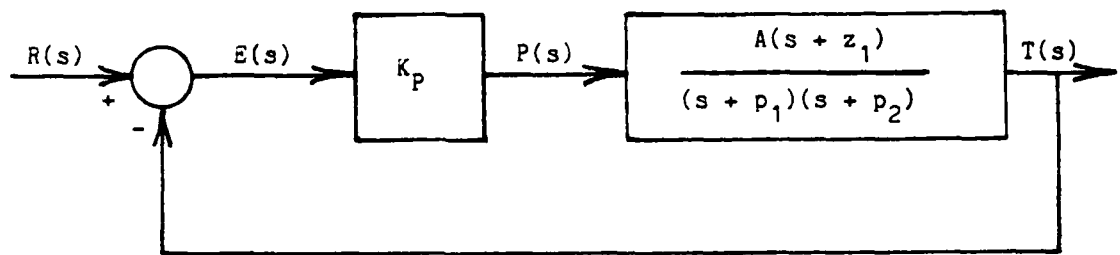


(a)

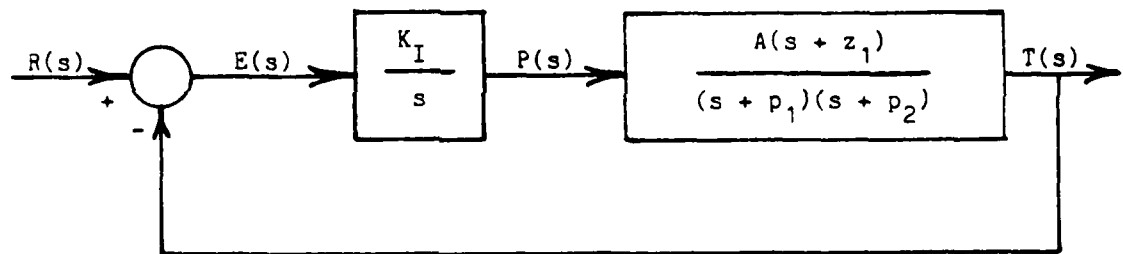


(b)

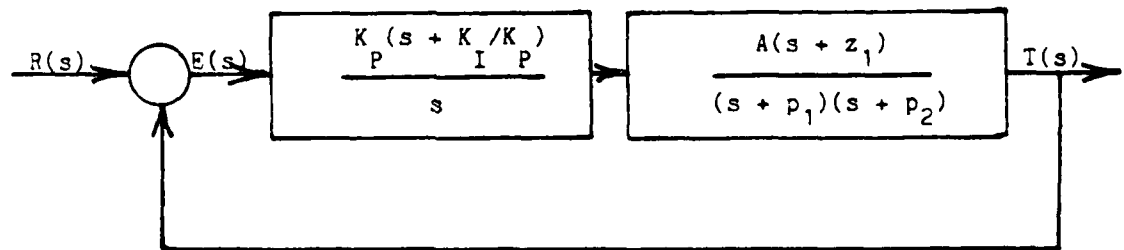
Figure 3.1 (a) Discrete-time representation of the temperature control system, and (b) Continuous-time representation of the temperature control system.



(a)



(b)



(c)

Figure 3.2 Temperature control system block diagram with  
 (a) proportional control, (b) integral control,  
 (c) proportional plus integral control.

$$\frac{T(s)}{P(s)} = \frac{AK_p(s + z_1)}{s^2 + (p_1 + p_2 + AK_p)s + p_1p_2 + AK_pz_1} \quad (3.2)$$

The Routh-Hurwitz stability test shows that this system will be stable for  $K_p > 0$ . The steady state error for a unit step input is non-zero for finite values of  $K_p$ . [8]

$$E_{ss} = p_1p_2 / (p_1p_2 + AK_pz_1) \quad (3.3)$$

It is seen that the proportional controller cannot meet design goal number 2.

If integral control is used the controller transfer function will take the form  $K_I/s$  as shown in Figure 3.2(b). The closed loop transfer function becomes

$$\frac{T(s)}{R(s)} = \frac{AK_I(s + z_1)}{s^3 + (p_1 + p_2)s^2 + (p_1p_2 + AK_I)s + AK_Iz_1} \quad (3.4)$$

This system will be stable for  $K_I > 0$  according to the Routh-Hurwitz test. The steady state error for a unit step input is found to be zero by application of the Final-Value Theorem. Integral control was tested on the control system and it was found that design goal number 3 could not be satisfied. The overshoot of the step response was excessive and the settling time was much too long.

If proportional plus integral control are employed, the controller transfer function will be of the form shown in Figure 3.2(c). The closed loop transfer function is

$$\frac{T(s)}{P(s)} = \frac{AK_p(s + K_I/K_p)(s + z_1)}{s^3 + (p_1 + p_2 + AK_p)s^2 + (p_1p_2 + AK_I + AK_pz_1)s + AK_Iz_1} \quad (3.5)$$

For  $p_1 + p_2 - z_1 > 0$ , the system is stable for  $K_p > 0$  and  $K_I > 0$ . These conditions are met by the temperature control system. The steady state error for a unit step input is zero. Thus, a proportional plus integral

controller meets design goals 1 and 2. Root locus and Laplace transform techniques can be used to study the form of responses which will be obtained as  $K_p$  and  $K_I$  are varied. Proportional plus integral control is definitely the best choice for the temperature control system.

### 3.2 Design Using Root Locus Techniques

Information on how the proportional constant,  $K_p$ , and the integral constant,  $K_I$ , should be chosen may be obtained from the loci of the poles of the closed loop transfer function. To get this information  $K_p$  can be fixed at a chosen value and  $K_I$  varied from zero upward. The characteristic equation is obtained by setting the denominator of Equation (3.5) equal to zero.

$$s^3 + (p_1 + p_2 + AK_p)s^2 + (p_1p_2 + AK_I + AK_pz_1)s + AK_Iz_1 = 0 \quad (3.6)$$

The zeros of the characteristic equation which are the poles of the transfer function are found and plotted in the s-plane for each value of  $K_p$  and  $K_I$ .

Figure 3.3 shows the behavior of the poles in the s-plane for  $K_p = 2.0$  and  $K_I$  varied from 0 to 0.05 in steps of 0.0001. The behavior of the poles near the closed loop zero at  $s = -0.0002$  is shown in Figure 3.4. This feature is not visible in Figure 3.3 due to the plotting scale. The points on the real axis where two poles meet and become a pair of complex conjugate poles are called breakaway points. As the fixed value of  $K_p$  is increased, the breakaway point shown in Figure 3.3 moves to the left in the s-plane. One of the poles approaches the zero at  $s = -0.0002$  very rapidly as  $K_I$  is varied so that there will be a pole-zero cancellation except when  $K_I$  is very small. For  $K_p = 2.0$ , the breakaway point occurs at  $s = -0.0156$  when  $K_I = 0.0162$ . For  $K_I < 0.0162$ , the two uncanceled poles will be on the real axis and the step response

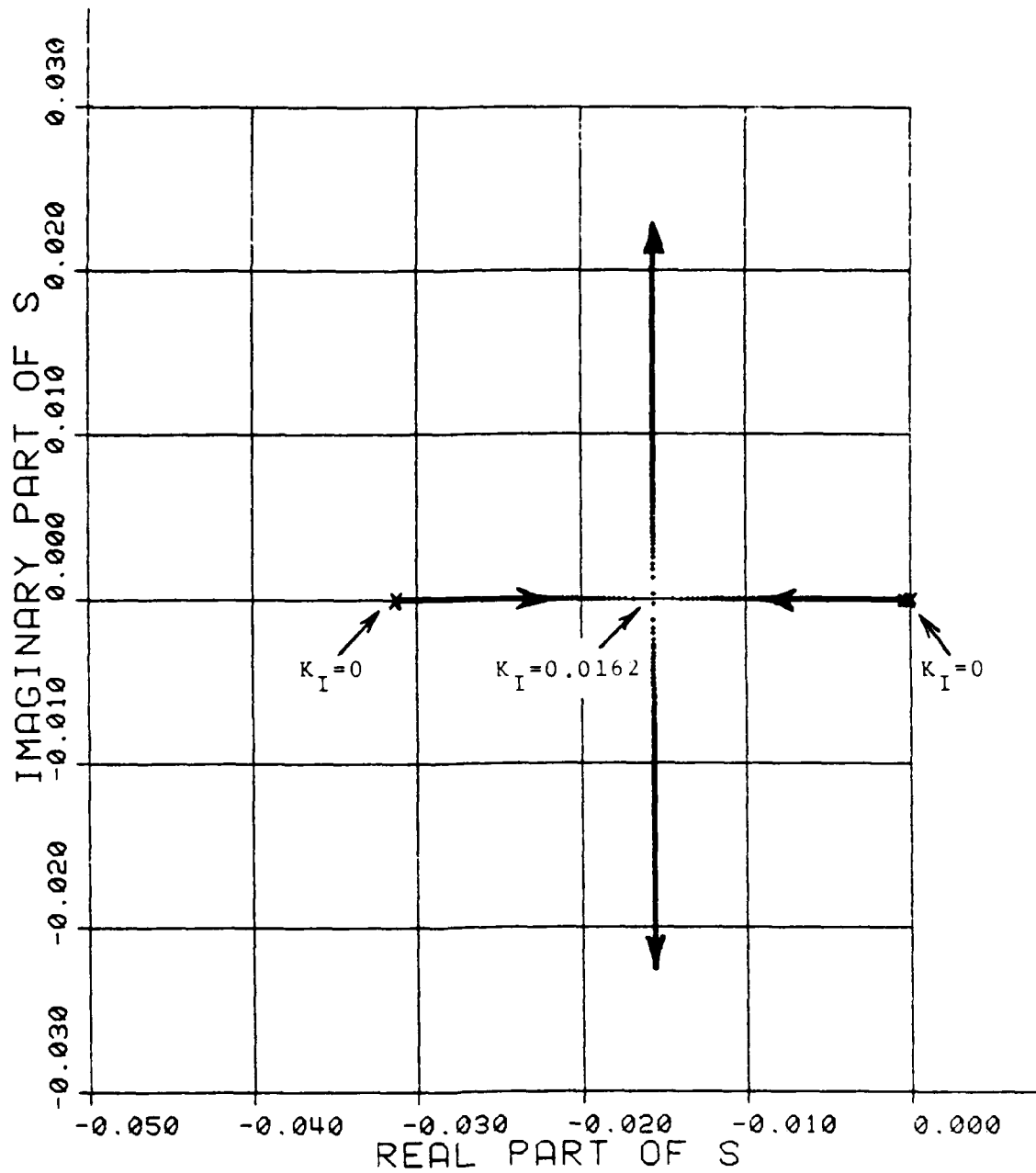


Figure 3.3 Loci of poles of temperature control system with a proportional plus integral controller.  $K_p = 2.0$ ,  $K_I$  varied from 0.00 to 0.05 in steps of 0.0001.

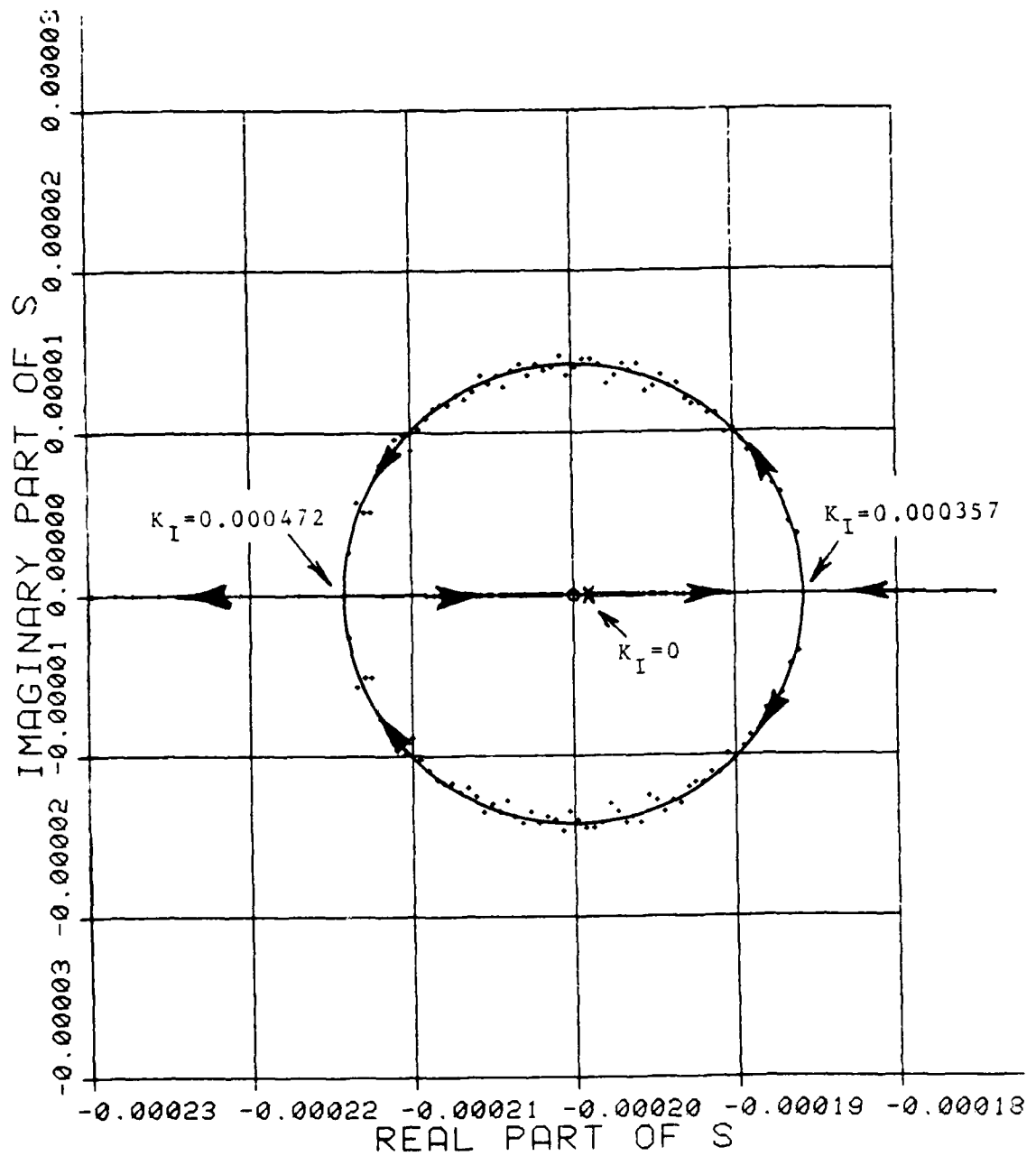


Figure 3.4 Behavior of poles near the zero at  $s = -0.0002$ .  
 $K_p = 2.0$ ,  $K_I$  varied in steps of 0.000002.

will consist of two decaying exponential terms plus a constant. For example, when  $K_p = 2.0$  and  $K_I = 0.01$  the response to a unit step input is

$$T(t) = 1 - 1.248 \exp(-0.02522 t) + 0.247 \exp(-0.005945 t) \quad (3.7)$$

For  $K_I > 0.0162$  the step response will consist of a damped sinusoid plus a constant term.

The methods described above can be used to investigate the theoretical system responses as  $K_p$  and  $K_I$  are varied, but in order to choose the values of  $K_p$  and  $K_I$  which yield the best performance for the actual system, several controllers must be implemented and tested with the system.

### 3.3 Computer Implementation of the Temperature Controller

The transfer function of the proportional plus integral controller may be implemented using a computer program. The reference input to the controller is passed to it in the form of digital data by a monitor or or data acquisition program by means of Class I/O calls which permit communication between separate programs. Class I/O is provided in the RTE-IV operating system. [9] Class I/O communication between the two programs is illustrated in Figure 3.5.

The sampling period is also passed to the controller program along with the reference temperature. This flexibility in choosing the sampling period is a definite advantage. A data acquisition program might instruct the temperature control program to run every two seconds. When the data acquisition program reached a point where the sampling of data on the semiconductor device became very time-critical, it could set the sampling period of the temperature control program to some larger value so that the temperature control program would not use any

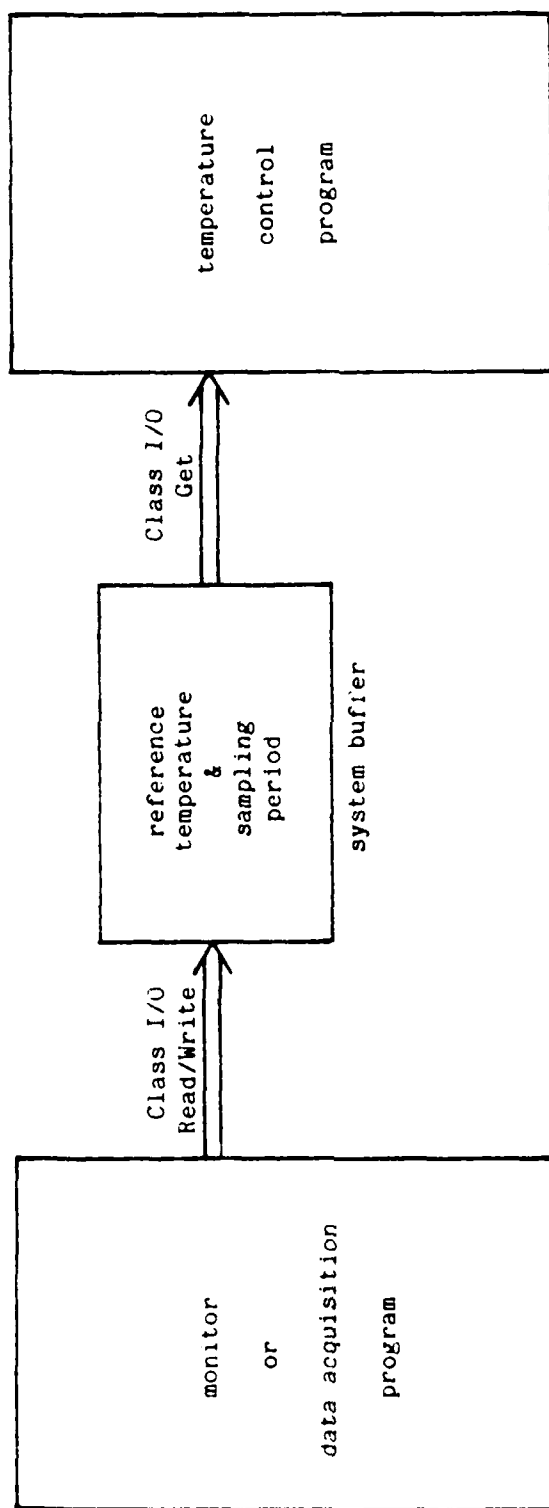


Figure 3.5 Illustration of communication with temperature control program using Class I/O.

CPU time during this critical period. After the data has been taken, the temperature sampling period could be reset to two seconds.

In the temperature control program, the trapezoidal approximation is used to compute the integral of the error signal. A flow chart showing the operations performed by the temperature control program is shown in Figure 3.6. The temperature control program is listed in Appendix A along with a sample monitor program which serves as an example of how to use the control program.

### 3.4 Testing of the Temperature Control System

The actual response of the temperature control system to a step input from 195 K to 200 K, with  $K_p = 2.0$  and  $K_I = 0.01$  is shown in Figure 3.7. The theoretical step response for the same values of  $K_p$  and  $K_I$  and the same input is shown in Figure 3.8. The overshoot of the actual response is due to the time delay in the thermal plant which is not accounted for in the lumped model. The best values of  $K_p$  and  $K_I$  were found to be  $K_p = 2.0$  and  $K_I = 0.01$  with a brass rod used in the thermal plant.

It was mentioned in Chapter 1 that the power which can be supplied to the thermal plant saturates at about 30 W. For steps in the input larger than 15 K, saturation of the applied power will occur. Large overshoots and long settling times are the results of this nonlinearity. A simple correction can be made to compensate for this nonlinearity. Whenever the magnitude of the error signal is greater than 15 K, the integral of the error signal is not updated. Response to a 50 K step in the input without this correction is shown in Figure 3.9. The improvement of the response with the correction for the nonlinearity included is very significant as shown in Figure 3.10.

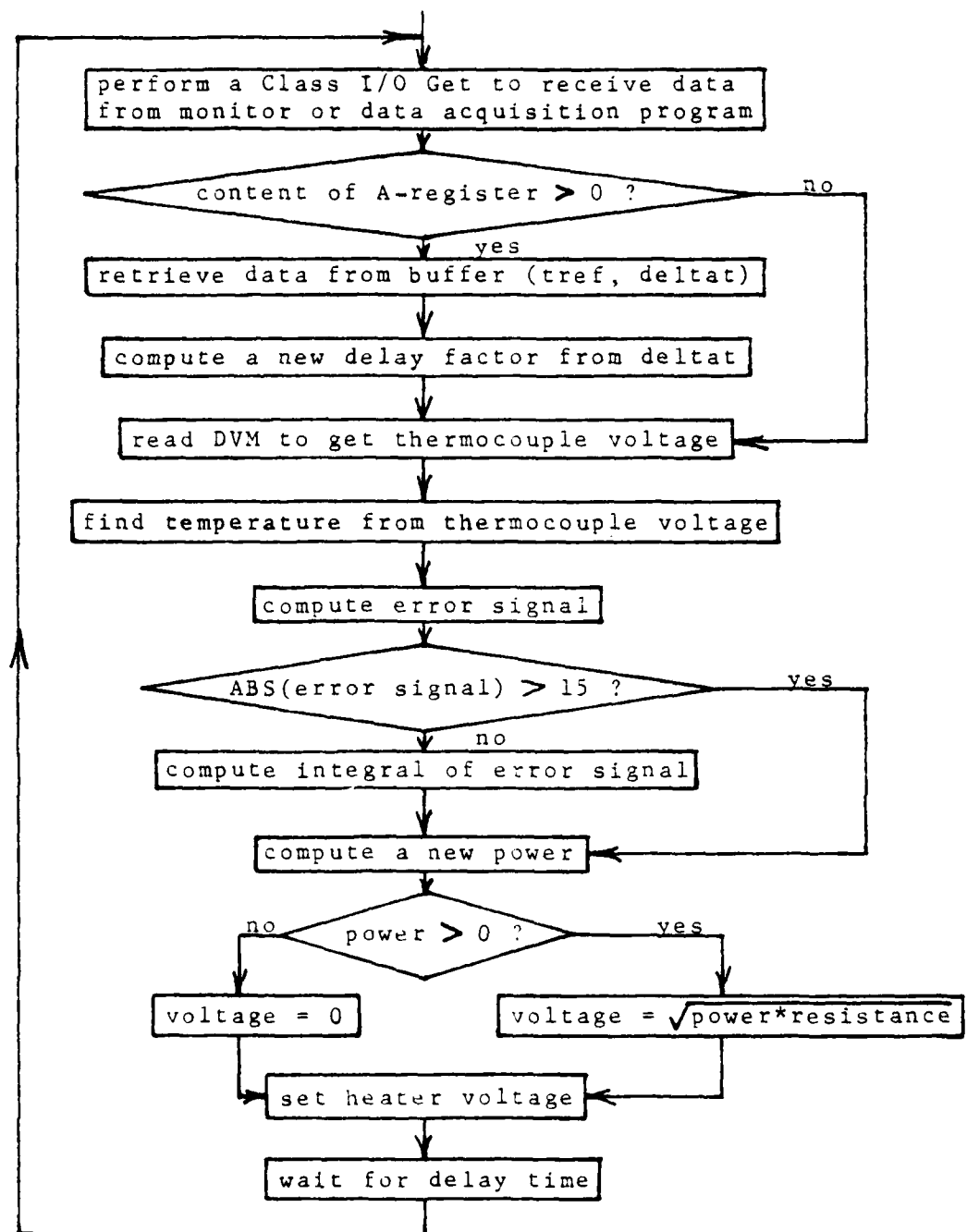


Figure 3.6 Flow chart of temperature control program.

TEMPERATURE CONTROLLER STEP RESPONSE  
CONTROLLER VERSION CN22

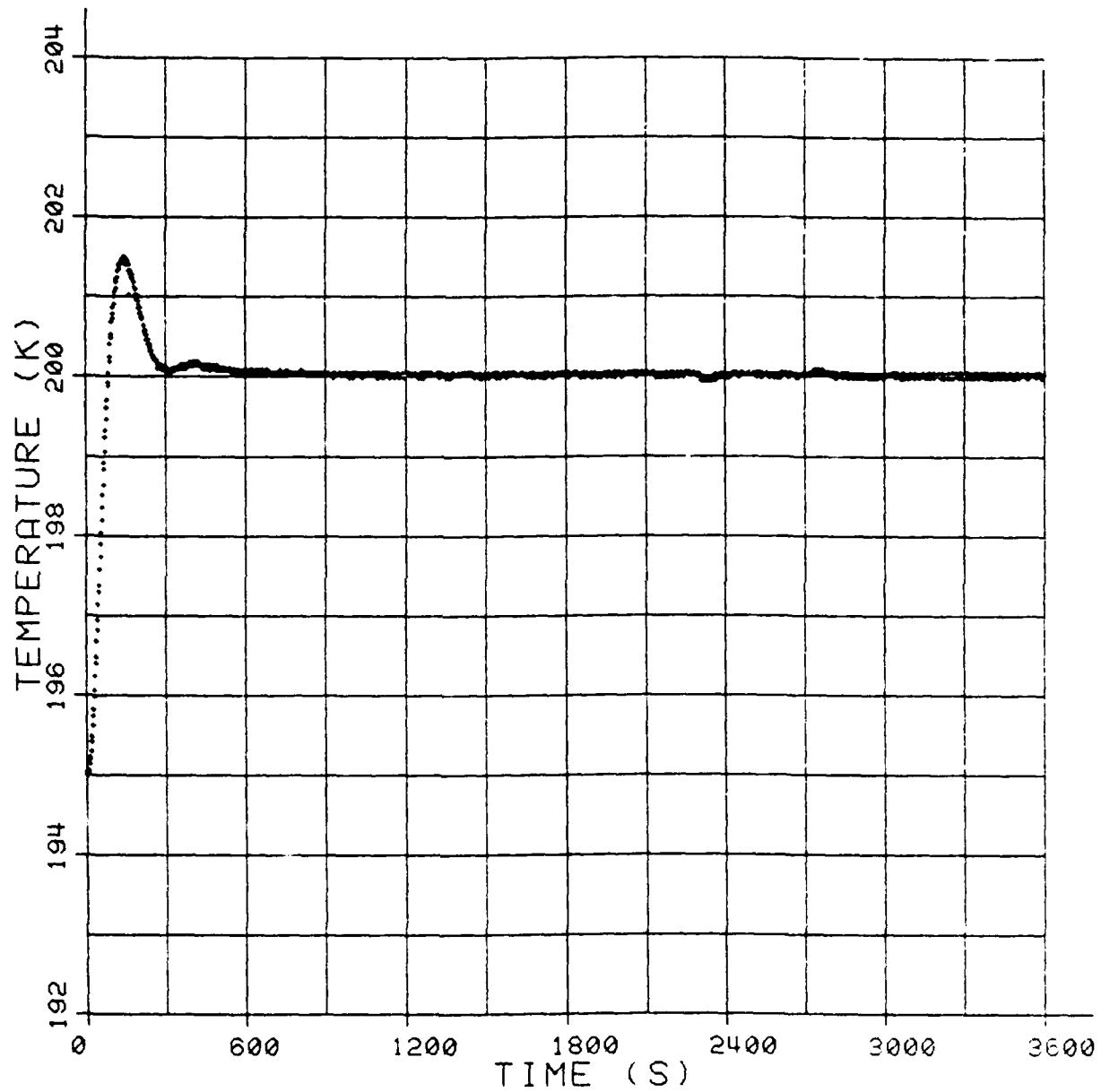


Figure 3.7 Response of temperature control system to a step input from 195 K to 200 K.  $K_P = 2.0$ ,  $K_I = 0.01$ .

THEORETICAL STEP RESPONSE  
CONTROLLER VERSION CN22

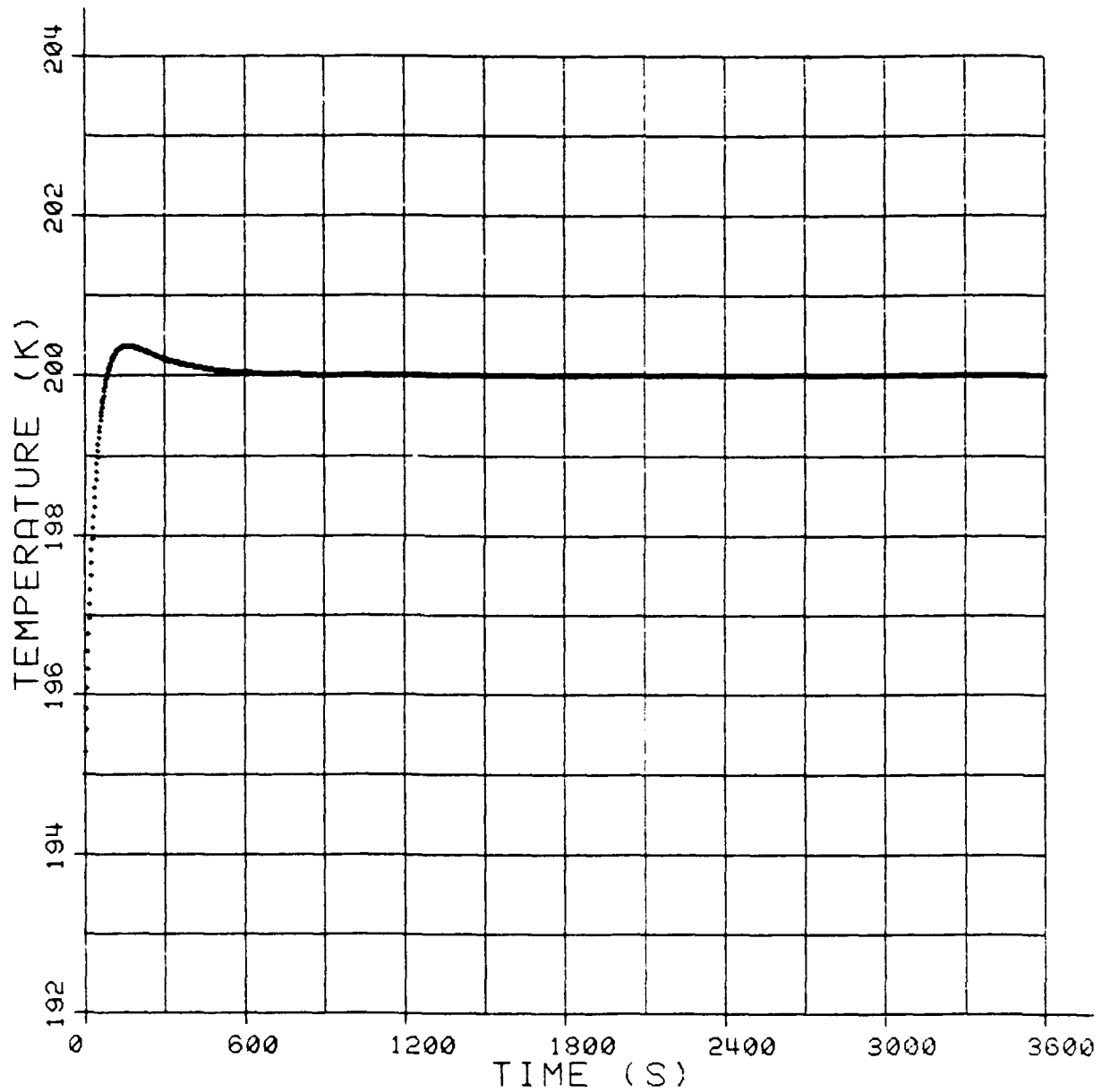


Figure 3.6 Theoretical step response based on the model of the thermal plant for the same conditions as Figure 3.7.

TEMPERATURE CONTROLLER STEP RESPONSE  
CONTROLLER VERSION CN22

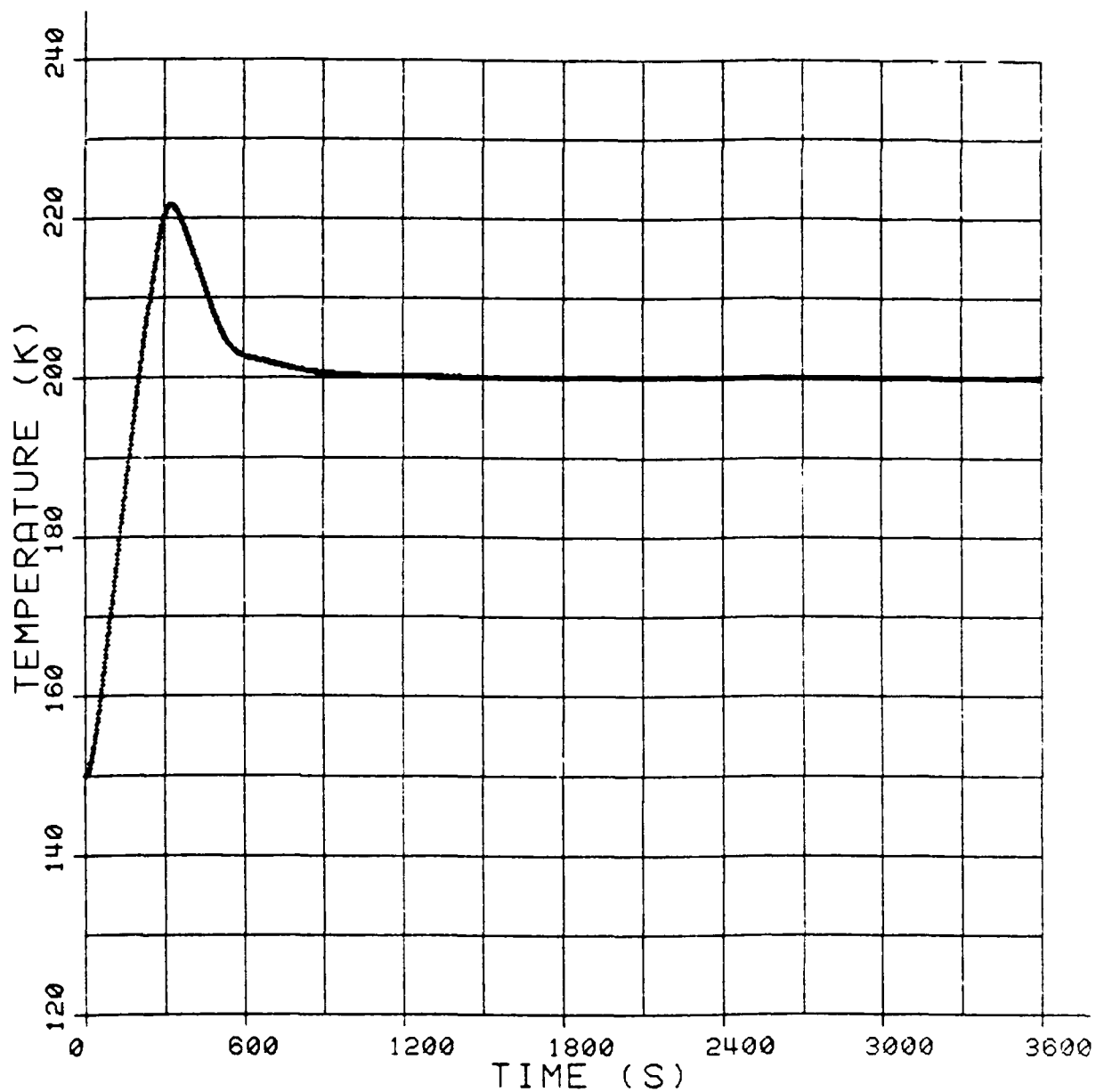


Figure 3.9 Response to a 50 K step input without the correction for saturation of heater power.

TEMPERATURE CONTROLLER STEP RESPONSE  
CONTROLLER VERSION CN22

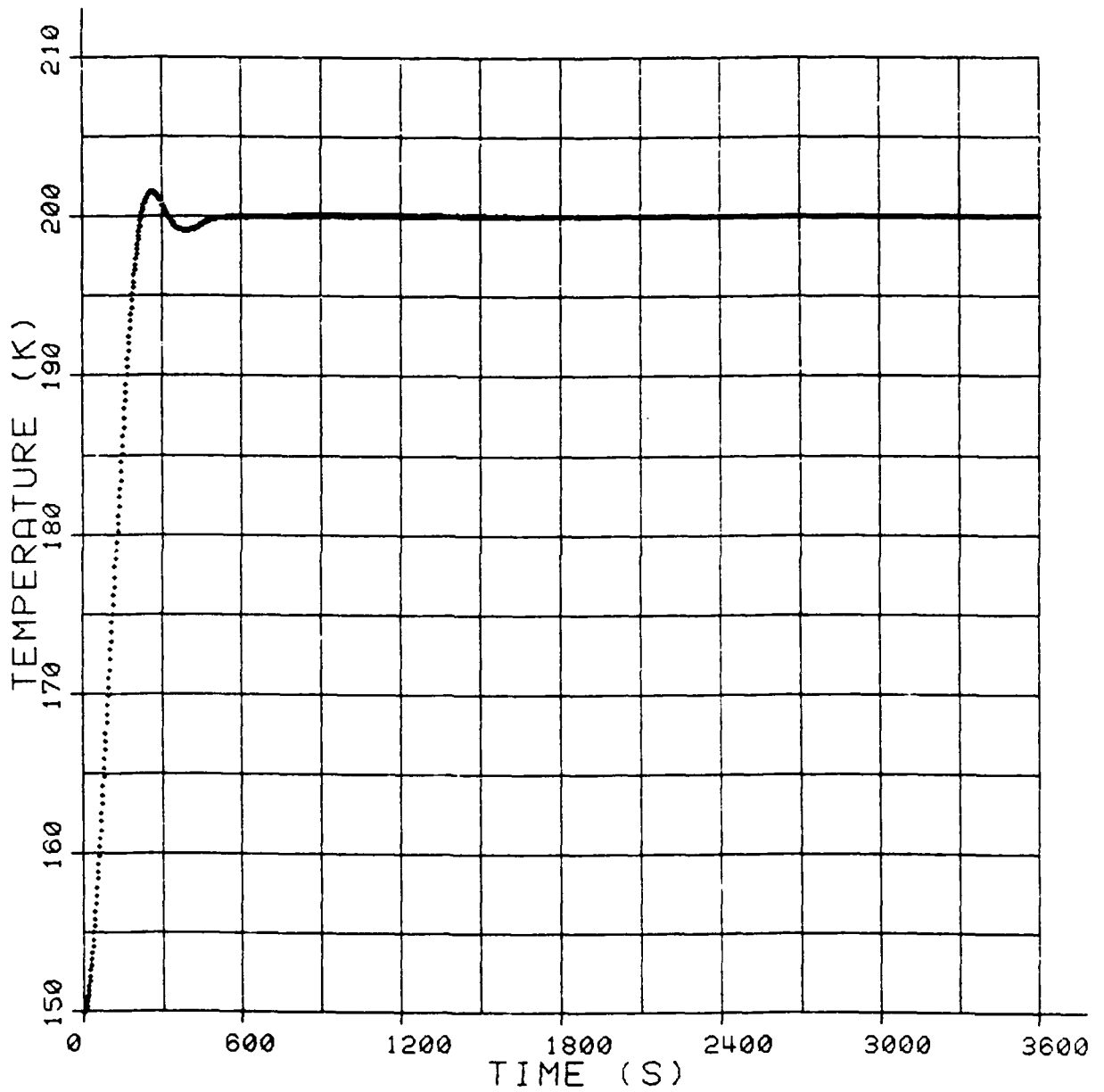


Figure 3.10 Response to a 50 K step input with the correction for saturation of heater power.

The temperature control system gives very satisfactory performance over the temperature range from 100 K to 300 K with a brass rod used between the device block and the lower copper block of the thermal plant. The temperature in this range can be controlled with a precision of better than plus or minus 0.1 K. In order to obtain stable temperatures lower than 100 K, a copper rod which has a smaller thermal resistance must be substituted for the brass rod. The copper rod has a length of 7.635 cm. and a diameter of 1.275 cm. The thermal resistance of this rod is calculated to be 1.46 K/W. When this thermal resistance is substituted into the model and the design is performed and tested as described earlier, it is found that  $K_p = 2.0$  and  $K_I = 0.01$  gives very good results. The theory shows that 0.02 would be a better value for  $K_I$ . However, experiments showed that  $K_I = 0.01$  gave a better steady state response. Accumulation of the integral of the error signal has an averaging effect on any noise in the system. As the integral control constant is increased, this averaging effect is diminished and response to the noise in the system becomes apparent in the form of small oscillations in the temperature.  $K_I$  is chosen equal to 0.01 to obtain better immunity to noise. The minimum stable temperature which can be maintained is about 85 K. The precision of the temperature control is the same as that for the brass rod.

Of course there is a limit on how long a certain temperature can be maintained with either type of rod due to the evaporation of the liquid nitrogen. Usually the liquid nitrogen will last six to eight hours before it must be replenished.

Several sampling periods were tested. The temperature control system performed well with sampling periods less than or equal to fifteen seconds.

The response to a ramp input  $R(t) = 100 + 0.05t$  K where  $t$  is in seconds is shown in Figure 3.11. The ramp response is of interest if Thermally Stimulated Capacitance (TSCAP) measurements are to be taken. [1] The response to faster ramp inputs is nonlinear due to the saturation of the power supplied to the heater wire of the thermal plant.

TEMPERATURE CONTROLLER RAMP RESPONSE  
CONTROLLER VERSION CN22

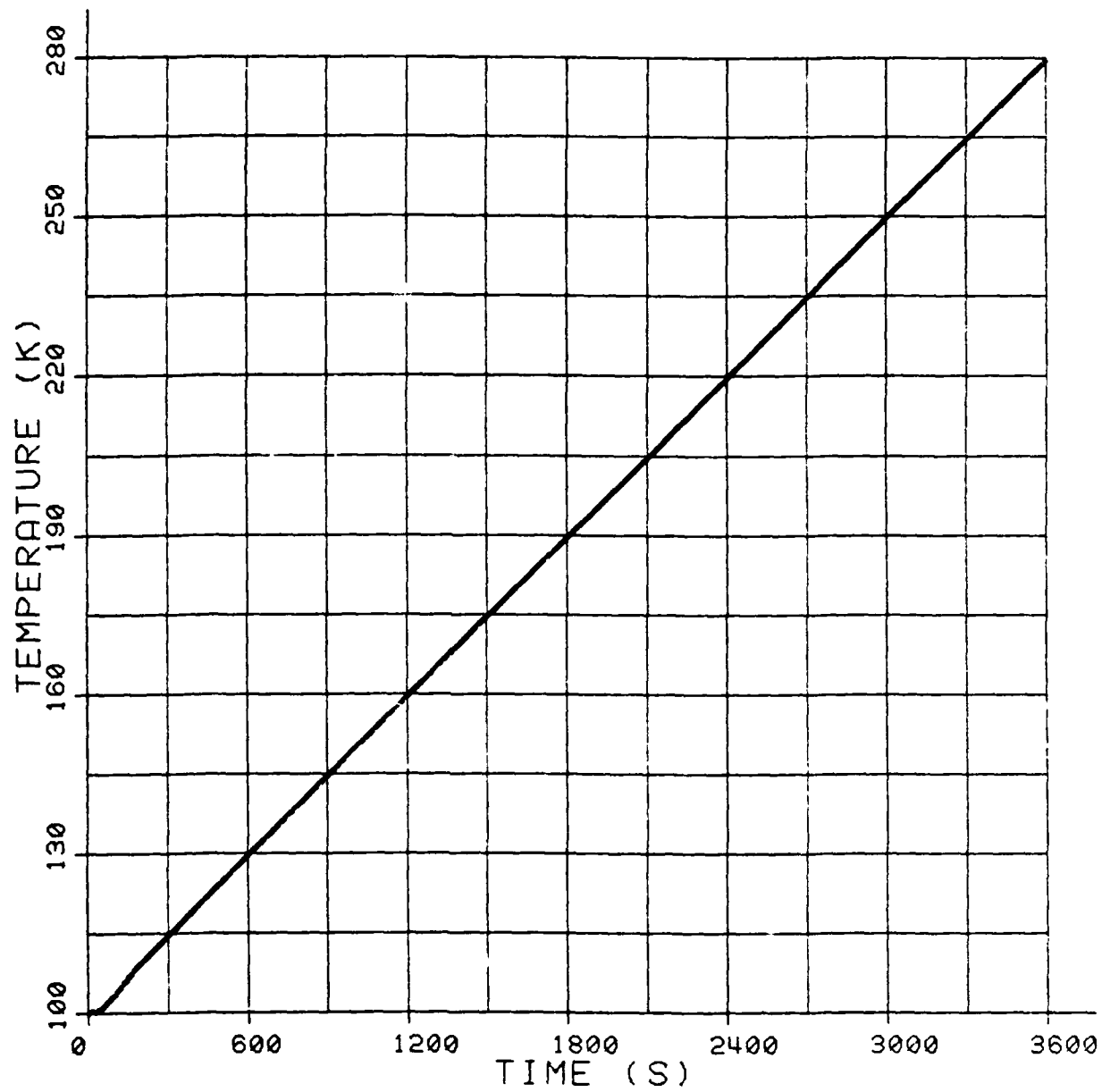


Figure 3.11 Response to a ramp input,  $R(t) = 100 + 0.05t$  K.

The computer-automated temperature control system described in this thesis is a significant step toward complete automation of data acquisition for the characterization of fundamental electrical properties of semiconductor materials.

The completion of this project required work in a wide range of topics including system identification and modeling, control system design using both discrete and continuous-time techniques, and computer implementation of the temperature controller.

A design algorithm was developed for a controller using discrete-time techniques. This algorithm did not produce a controller which performed satisfactorily because it required knowledge of the plant transfer function with more accuracy than was obtainable. A controller which met all of the system design goals was designed by application of continuous-time techniques. This controller used both proportional and integral control. Strictly speaking, the temperature control system is a discrete-time system. However, since the sampling period is very small compared to the system time constants, this system can be approximated by a continuous-time system.

The final implementation of the temperature control system is capable of controlling temperature, with a precision of  $\pm 0.1$  K, in the range from 100 K to 300 K using a brass rod in the thermal plant. A copper rod must be substituted for the brass rod to obtain temperatures below 100 K. The temperature may be maintained within  $\pm 0.1$  K of the reference input for temperatures down to 85 K using the copper rod. The absolute accuracy of the measured temperature is determined by the manufacturer's specifications for the thermocouple wire, which is plus

or minus one percent of the measured temperature. Better absolute accuracy of the measured temperature may be obtained by calibrating the thermocouple against a platinum resistor which is a very stable and linear temperature transducer. This method has been used by members of our laboratory to obtain absolute accuracy of  $\pm 0.1$  K.

## APPENDIX A.

Listing of Temperature Control Program and Monitor Program

```

FTN4,L
C
C***** RNS790802 - 51      SOURCE FILE : RNTCON
C
C *****
C *
C      PROGRAM TCON
C *
C *****
C
C***** THIS IS THE TEMPERATURE CONTROL PROGRAM TO BE USED
C      WITH A BRASS OR COPPER ROD IN THE THERMAL PLANT OF THE
C      SYSTEM. THIS PROGRAM IS FOR USE ON THE MULTIPROGRAMMER 6940B
C      MAINFRAME (UNIT ADDRESS 00).
C
C***** THIS PROGRAM COMMUNICATES WITH A MONITOR OR DATA
C      ACQUISITION PROGRAM VIA CLASS I/O CALLS PROVIDED BY
C      THE RTE IV OPERATING SYSTEM. THIS PROGRAM RECEIVES
C      THE REFERENCE TEMPERATURE, TREF, AND THE SAMPLING
C      PERIOD, DELTAT, FROM THE MONITOR OR DATA ACQUISITION
C      PROGRAM. THE MAXIMUM SAMPLING PERIOD SHOULD BE 15 SEC.
C      THE MONITOR OR DATA ACQUISITION PROGRAM HAS THE JOB OF
C      OBTAINING A CLASS NUMBER AND SCHEDULING THE TEMPERATURE
C      CONTROL PROGRAM. THE MONITOR OR DATA ACQUISITION PROGRAM
C      MUST ALSO RELEASE THE CLASS NUMBER AND KILL THE CONTROL
C      PROGRAM WHEN IT IS DESIRED TO END THE TEMPERATURE CONTROL.
C      THIS ROUTINE TAKES APPROXIMATELY 40 MILLISECONDS TO RUN.
C
C***** IMPORTANT VARIABLES
C      TREF --- REFERENCE TEMPERATURE IN DEGREES KELVIN
C      TMEAS -- MEASURED TEMPERATURE IN DEGREES KELVIN
C      DELTAT - SAMPLING PERIOD
C      ERRSIG - ERROR SIGNAL (TREF - TMEAS)
C      OLDERR - LAST VALUE OF ERRSIG
C      INTERR - INTEGRAL OF THE ERROR SIGNAL
C      TCV ---- THERMOCOUPLE VOLTAGE
C      KP ----- PROPORTIONAL GAIN
C      KI ----- INTEGRAL GAIN
C      RH ----- HEATER RESISTANCE
C      VH ----- VOLTAGE APPLIED TO HEATER
C      POWER -- POWER TO BE APPLIED TO THERMAL PLANT
C
C      INTEGER CLASS, A, B, DELAY, ERR, PARAM(5)
C      REAL TREF, DELTAT, TMEAS, ERRSIG, OLDERR, INTERR
C      REAL TCV, VH, RH, POWER, KP, KI, MESSAG(2)
C
C      DATA KP/2.0/, KI/1.0E-2/, RH/13.35/
C
C***** GET THE CLASS NUMBER
C      CALL RMPAR(PARAM)

```

```

        CLASS = PARAM(1)
C
C***** SET BITS 15 AND 13 IN CLASS WORD
C      (NO WAIT BIT AND DE-ALLOCATE BIT)
        CLASS = IOR (CLASS, 120000B)
C
C***** INITIALIZE OLDERR AND INTERR
        OLDERR = 0.0
        INTERR = 0.0
C
C***** DO A CLASS I/O GET TO RETRIEVE TREF AND DELTAT
100    CALL EXEC(21, CLASS, MESSAG, 4)
C
C***** CHECK CONTENT OF A-REGISTER TO SEE IF NEW DATA
C      WAS RECEIVED
        CALL ABREG (A, B)
        IF (A .LT. 0) GOTO 200
C
C***** NEW DATA WAS OBTAINED IF A >= 0
        TREF = MESSAG(1)
        DELTAT = MESSAG(2)
C
C***** COMPUTE THE DELAY FROM DELTAT
        DELAY = IFIX (100.0*DELTAT - 4.0)
C
C***** READ THE TEMPERATURE AND COMPUTE ERRSIG
200    CALL RDVM (TCV)
        TMEAS = TEMP (TCV)
        ERRSIG = TREF - TMEAS
C
C***** CORRECTION FOR NONLINEARITY
        IF (ABS(ERRSIG) .GT. 15.0) GOTO 500
C
C***** UPDATE THE INTEGRAL OF THE ERROR SIGNAL
        INTERR = INTERR + (ERRSIG + OLDERR)/2.0 * DELTAT
C
C***** COMPUTE THE NEW POWER AND SET HEATER VOLTAGE
500    POWER = KP * ERRSIG + KI * INTERR
C
C***** POWER IS UNIPOLAR
        IF (POWER .LT. 0.0) GOTO 10
        VH = SQRT (POWER * RH)
        GOTO 20
10     VH = 0.0
20     CALL SETVH (VH)
C
C***** SAVE VALUE OF ERRSIG
        OLDERR = ERRSIG
C
C***** WAIT FOR DELAY*10 MILLISECONDS
        CALL WAIT (DELAY, 0, ERR)
        GOTO 100
END

```





```

TNEW=TOLD-EMFK/DEDT
IF(DABS(TNEW-TOLD).LE.1.0D-5) GOTO 1
100 CONTINUE
WRITE (1,10)
10 FORMAT (" FUNCTION TEMP DID NOT CONVERGE  TEMP SET TO 0.0 ")
TNEW=0.0D0
1 TEMP=SNGL(TNEW)
RETURN
END

```

SUBROUTINE SETVH (VH)

C-----PURPOSE-----

```

C      THIS SUBROUTINE SETS THE VOLTAGE APPLIED TO THE HEATER COIL
C      OF THE TEMPERATURE CONTROLLER FROM THE HP 6224B POWER SUPPLY
C      BY SETTING THE PROGRAMMING VOLTAGE GENERATED BY THE A/D CARD
C      IN SLOT 2 OF THE MULTIPROGRAMMER MAINFRAME.  WHEN THE A/D CARD
C      IS PROGRAMMED TO ZERO VOLTS, THE OUTPUT OF THE 6224B POWER
C      SUPPLY IS -0.048.  THEREFORE AN OFFSET VOLTAGE IS ADDED TO THE
C      PROGRAMMED VOLTAGE.  THE VOLTAGE GAIN IS SET TO 2.0.

```

C-----PARAMETERS-----

C        VH ----- HEATER VOLTAGE TO BE SET

C-----IMPORTANT VARIABLES-----

```
C      GAIN    --- VOLTAGE GAIN = 6224B VOLTAGE / PROGRAMMING VOLTAGE
C      OFFSET  --- NEGATIVE OF 6224B VOLTAGE WHEN ZERO VOLTS IS PROGRAMMED
C      RES     --- RESOLUTION OF A/D CARD = 5 MV PER BIT
C      MAXVH   --- MAXIMUM POSSIBLE HEATER VOLTAGE
```

```
REAL VH, GAIN, OFFSET, RES, MAXVH
INTEGER BUF(2), SLOT, BITS
```

DATA GAIN/2.0/, OFFSET/0.0475/, RES/0.005/, MAXVH/20.0/  
DATA BUF/170140B/, SLOT/20000B/

```
IF (VH.GT.MAXVH) VH = MAXVH
IF (VH.LT.0.0) VH = 0.0
BITS = IFIX ((VH + OFFSET) / GAIN / RES + 0.5)
BUF(2) = IOR (SLOT, BITS)
```

C  
C-----BUF ELEMENTS

```
C      BUF(1) = 170140B -- CONTROL WORD   DTE, SYE ON
C      BUF(2) = 2XXXXXE -- A/D CARD DATA WORD
```

C-----MAKE A WRITE WITH HANDSHAKE REQUEST

```
C      ICODE=2      CONTROL WORD=124B      BUFFER LENGTH=2      IFUNC=1
      CALL EXEC (2,124B,BUF,2,1)
      RETURN
      END
      END$
```

```

FTN4,L
C
C***** RNS790802 - 60      SOURCE FILE : RNTMON
C
C *****
C *
C   PROGRAM TMON
C *
C *****
C
C***** THE PURPOSE OF THIS PROGRAM IS TO ACT AS AN INTERFACE
C   BETWEEN THE OPERATOR AND TEMPERATURE CONTROL PROGRAM.
C
C***** THE MONITOR COMMANDS ARE AS FOLLOWS:
C
C       T -- CHANGE TEMPERATURE SET POINT
C           AND/OR SAMPLING PERIOD
C       N -- NO CHANGE
C       S -- STOP TEMPERATURE CONTROL PROGRAM
C           AND THIS PROGRAM
C
C***** THE SUBROUTINES RDVM, TEMP AND MSTOP ARE INCLUDED IN
C   MULTIPROGRAMMER LIBRARY. TO LOAD THEM WITH THIS PROGRAM
C   USE THE LOADER COMMAND SE,%MPLIB TWO TIMES.
C
C   INTEGER PARAM(5), LU, CLASS, COMAND, NAME(3)
C   INTEGER T, N, S, DUMY1, DUMY2, I, ERR, CDELAY, PDELAY
C   REAL MESSAG(2), TCV, TEMPER
C
C
C   DATA I/2HT /, N/2HN /, S/2HS /
C
C   CALL RMPAR(PARAM)
C   LU = PARAM(1)
C   WRITE (LU,1)
1   FORMAT ("INPUT THE NAME OF THE CONTROL PROGRAM")
C   READ (LU,2) (NAME(I), I=1,3)
2   FORMAT (3A2)
C   WRITE (LU,3)
3   FORMAT ("INPUT REFERENCE TEMPERATURE AND SAMPLING PERIOD")
C   READ (LU,*) (MESSAG(I), I=1,2)
C   WRITE (LU,4)
4   FORMAT ("AT WHAT INTERVAL IN SECONDS DO YOU WANT "
$       "THE TEMPERATURE PRINTED AT THIS TERMINAL ?")
C   READ (LU,*) PDELAY
C   WRITE (LU,5)
5   FORMAT ("AT WHAT INTERVAL IN MINUTES DO YOU WANT "
$       "TO BE PROMPTED FOR A COMMAND ?")
C   READ (LU,*) CDELAY
C
C***** GET A CLASS NUMBER AND PUT MESSAG IN SYSTEM BUFFER
C   CLASS = 0
C   CALL EXEC (20,0,MESSAG,4,DUMY1,DUMY2,CLASS)
C

```

```

C***** SCHEDULE THE CONTROL PROGRAM AND PASS IT THE CLASS NO.
      CALL EXEC (10, NAME, CLASS)
      GOTO 300

C
C***** ENTER THE COMMAND INPUT LOOP
100  WRITE (LU,6)
6    FORMAT ("TMON COMMAND ?" )
      READ (LU,2) COMAND
      IF (COMAND .EQ. N) GOTO 300
      IF (COMAND .NE. T) GOTO 500
      WRITE (LU,3)
      READ (LU,*) (MESSAG(I), I=1,2)
      WRITE (LU,4)
      READ (LU,*) PDELAY
      WRITE (LU,5)
      READ (LU,*) CDELAY

C
C***** DO A CLASS I/O WRITE/READ
      CALL EXEC (20,0,MESSAG,4,DUMY1,DUMY2,CLASS)

C
C***** FEAD THE TEMPERATURE AND PRINT AT THE TERMINAL
300  I = 0
400  CALL RDVM(TCV)
      TEMPER = TEMP (TCV)
      WRITE (LU,99) TEMPER
99   FORMAT ("TEMPERATURE ="F10.3" K")
      CALL WAIT (PDELAY, 2, ERR)
      I = I + 1
      IF (I*PDELAY/60 .LT. CDELAY) GOTO 400
      GOTO 100

C
500  IF (CCMAND .EQ. S) GOTO 600
      WRITE (LU,7)
7    FORMAT ("ILLEGAL COMMAND")
      GOTO 100

C
C***** KILL THE CONTROL PROGRAM AND RELEASE THE CLASS NUMBER
600  CALL EXEC (6, NAME, 2)
      CALL EXEC (21, CLASS, MESSAG, 4)
      CALL MSTOP
      END
      END$

```

## APPENDIX B.

Design Algorithm for the Discrete-Time Controller

The design procedures covered in Section 2.1 may be put in the form of a simple design algorithm given below:

1. Choose the damping ratio  $\zeta$  between 0 and 1. A damping ratio near 1 gives smaller overshoots of the step response.
2. Find  $\alpha$  for minimum overshoot with the given value of  $\zeta$  from Equation (2.11).
3. Choose the sampling period  $T$ .
4. Pick a reasonable time for the maximum response,  $t_{\max}$ . This time should be greater than 5% of the plant time constant.
5. Find the angle of the closed loop pole  $p_1$  from Equation (2.12).
6. Find the magnitude of the closed loop pole  $p_1$  from Equation (2.13).
7. Find the closed loop zero  $z_1$  from Equation (2.14).
8. Find the closed loop constant  $K$  from Equation (2.4).
9. Find the controller transfer function  $D(z)$  from Equation (2.2).

This algorithm is ideal for execution by a computer design program. A program which performs this algorithm is listed on the following pages. A sample output of the program is also given in this appendix.

FTN4,L

C

C RNS790630 - 16 SOURCE FILE : RNSDN

C

C \*\*\*\*\*

C \* \*

C PROGRAM DSN

C \* \*

C \*\*\*\*\*

C

C

THIS PROGRAM PERFORMS THE DESIGN ALGORITHM FOR A DIGITAL  
CONTROLLER WHICH RESULTS IN A CLOSED LOOP SYSTEM WITH  
MINIMUM STEP RESPONSE OVERSHOOT FOR A GIVEN VALUE OF THE  
DAMPING RATIO, ZETA. THE CLOSED LOOP SYSTEM ALSO POSSESSES  
THE MINIMUM BANDWIDTH NECESSARY FOR THE PEAK OF THE STEP  
RESPONSE TO BE REACHED AT OR BEFORE A SPECIFIED TIME, TM.

C

C THE CLOSED LOOP Z-TRANSFER FUNCTION IS OF THE FORM:

C

$$M(Z) = \frac{K * (Z - Z1)}{(Z - P1) * (Z - P1*)}$$

C

C WHERE P1 AND P1\* ARE A PAIR OF COMPLEX CONJUGATE POLES.

C

C THE Z-TRANSFER FUNCTION OF THE PLANT IS OF THE FORM:

C

$$GP(Z) = \frac{GPK * (Z - GPZ1)}{(Z - GPP1) * (Z - GPP2)}$$

C

THE RESULT OF THE CALCULATION IS THE TRANSFER FUNCTION  
OF THE DIGITAL CONTROLLER :

C

$$D(Z) = \frac{NC(1)*Z**3 + NC(2)*Z**2 + NC(3)*Z + NC(4)}{DC(1)*Z**3 + DC(2)*Z**2 + DC(3)*Z + DC(4)}$$

C

C

C

C

C

C

C

C

C

C

C

C

C

C

C

C

C

C

## DESCRIPTION OF THE VARIABLES

Z1 ---- CLOSED LOOP ZERO

P1 ---- CLOSED LOOP COMPLEX POLE

K ----- CONSTANT OF THE CLOSED LOOP TRANSFER FUNCTION

PHI --- ARG(P1)

MAGP1 - MAGNITUDE OF P1

RE P1 -- REAL PART OF P1

IM P1 -- IMAGINARY PART OF P1

GPK --- CONSTANT OF THE PLANT TRANSFER FUNCTION

GPZ1 -- ZERO OF THE PLANT TRANSFER FUNCTION

GPP1 -- POLE OF THE PLANT TRANSFER FUNCTION

GPP2 -- POLE OF THE PLANT TRANSFER FUNCTION

ZETA -- DAMPING RATIO

ZETA2 - SORT(1 - ZETA\*\*2)

```

C      ALPHA - ARG(P1 - Z1) - ARG(P1 - 1) + PI/2
C      ALPHA IS CHOSEN FOR MINIMUM OVERSHOOT
C      T ----- SAMPLING PERIOD IN SECONDS
C      TM ----- DESIRED TIME OF PEAK OF STEP RESPONSE
C      NC ----- ARRAY OF NUMERATOR COEFFICIENTS OF D(Z)
C      DC ----- ARRAY OF DENOMINATOR COEFFICIENTS OF D(Z)
C      A ----- TEMPORARY VARIABLE
C      B ----- TEMPORARY VARIABLE
C      BETA -- TEMPORARY VARIABLE
C
C      - - - - -
C
C      DOUBLE PRECISION PI, ZETA, ZETA2, T, TM, PHI, BETA
C      DOUBLE PRECISION MAGP1, REP1, IMP1, Z1, K
C      DOUBLE PRECISION GPK, GPZ1, GPP1, GPP2
C      DOUBLE PRECISION NC(4), DC(4), A, B
C
C      INTEGER LU, PARAM(5), I
C
C      DATA PI/3.141592654D0/
C
C      CALL RMPAR(PARAM)
C      LU = PARAM(1)
C
C      GET THE DESIGN PARAMETERS FROM THE USER
C      WRITE (LU,1)
1      FORMAT(" DIGITAL CONTROLLER DESIGN PROGRAM"//)
C      WRITE (LU,2)
2      FORMAT(" THE Z-TRANSFER FUNCTION OF THE PLANT IS OF THE FORM :"/)
C      WRITE (LU,3)
3      FORMAT(12X,"GPK * (Z - GPZ1)")
C      WRITE (LU,4)
4      FORMAT(" GP(Z) = -----")
C      WRITE (LU,5)
5      FORMAT(9X,"(Z - GPP1) * (Z - GPP2)"/)
C      WRITE (LU,6)
6      FORMAT(" ENTER THE PARAMETERS: GPK, GPZ1, GPP1, GPP2")
C      READ (LU,*) GPK, GPZ1, GPP1, GPP2
100     WRITE (LU,7)
7      FORMAT("/" ENTER THE DAMPING RATIO, ZETA, BETWEEN 0 AND 1")
C      READ (LU,*) ZETA
C      IF (ZETA.LE.0.0D0 .OR. ZETA.GE.1.0D0) GOTO 100
200     WRITE (LU,8)
8      FORMAT("/" ENTER THE SAMPLING PERIOD, T, IN SECONDS")
C      READ (LU,*) T
C      IF (T.LE.0.0D0) GOTO 200
300     WRITE (LU,9)
9      FORMAT("/" ENTER THE DESIRED TIME OF THE PEAK STEP RESPONSE, TM")
C      READ (LU,*) TM
C      IF (TM.LE.0.0D0) GOTO 300
C
C      CALCULATE ALPHA FOR MINIMUM OVERSHOOT
C      ZETA2 = DSCRT(1.0D0 - ZETA**2)
C      ALPHA = DATN2(-ZETA, ZETA2)

```

```

C
C   CHOOSE PHI FOR MINIMUM NECESSARY BANDWIDTH
C   PHI = PI * T / TM
C
C   FIND THE CLOSED LOOP POLE, P1
C   MAGP1 = DEXP(-PHI * ZETA / ZETA2)
C   REP1 = MAGP1 * DCOS(PHI)
C   IMP1 = MAGP1 * DSIN(PHI)
C
C   FIND THE CLOSED LOOP ZERO, Z1
C   BETA = ALPHA + DATN2(IMP1, REP1 - 1.0D0) - PI / 2.0D0
C   Z1 = REP1 - IMP1 * DCOS(BETA) / DSIN(BETA)
C
C   FIND THE CLOSED LOOP CONSTANT, K
C   K = ((1.0D0 - REP1)**2 + IMP1**2) / (1.0D0 - Z1)
C
C   COMPUTE THE DENOMINATOR COEFFICIENTS OF D(Z)
C   A = 2.0D0 * REP1 + K
C   B = REP1**2 + IMP1**2 + K * Z1
C   DC(4) = -B * GPZ1
C   DC(3) = B + A * GPZ1
C   DC(2) = -A - GPZ1
C   DC(1) = 1.0D0
C
C   COMPUTE THE NUMERATOR COEFFICIENTS OF D(Z)
C   A = GPP1 + GPP2
C   B = GPP1 * GPP2
C   NC(1) = K / GPK
C   NC(2) = -NC(1) * (Z1 + A)
C   NC(3) = NC(1) * (Z1 * A + B)
C   NC(4) = -NC(1) * Z1 * B
C
C   PRINT THE RESULTS
C   WRITE (LU,10)
10  FORMAT("//" THE TRANSFER FUNCTION OF THE DIGITAL CONTROLLER IS:"/)
C   WRITE (LU,11)
11  FORMAT(3X,"A0*Z**3 + A1*Z**2 + A2*Z + /3")
C   WRITE (LU,12)
12  FORMAT(" D(Z) = -----")
C   WRITE (LU,13)
13  FORMAT(3X,"B0*Z**3 + B1*Z**2 + B2*Z + B3"/)
C   WRITE (LU,14)
14  FORMAT(" WHERE :"/)
C   DO 400 I=0,3
400  WRITE (LU,15) I, NC(I+1)
15  FORMAT(" A"I1" = "F10.6)
C   DO 500 I=0,3
500  WRITE (LU,16) I, DC(I+1)
16  FORMAT(" B"I1" = "F10.6)
C   ENI
C   ENI$

```

A sample output of the program DSN is given below:

# DIGITAL CONTROLLER DESIGN PROGRAM

THE Z-TRANSFER FUNCTION OF THE PLANT IS OF THE FORM :

$$GP(Z) = \frac{GPK * (Z - GPZ1)}{(Z - GPP1) * (Z - GPP2)}$$

ENTER THE PARAMETERS: GPK, GPZ1, GPP1, GPP2  
0.029964, 0.999600, 0.997603, 0.999660

ENTER THE DAMPING RATIO, ZETA, BETWEEN 0 AND 1  
0.8

ENTER THE SAMPLING PERIOD, T, IN SECONDS  
2.0

ENTER THE DESIRED TIME OF THE PEAK STEP RESPONSE, TM  
90.0

THE TRANSFER FUNCTION OF THE DIGITAL CONTROLLER IS:

$$D(Z) = \frac{A0*Z**3 + A1*Z**2 + A2*Z + A3}{B0*Z**3 + B1*Z**2 + B2*Z + B3}$$

WHERE :

A0 = .212287  
A1 = -.224481  
A2 = -.186770  
A3 = .198965  
B0 = 1.000000  
B1 = -2.823756  
B2 = 2.647582  
B3 = -.823826

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