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I am submitting herewith a thesis written by James E. Hackney entitled "Modeling and Control of a Resistometer with a Microcomputer." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Chemical Engineering.

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MODELING AND CONTROL OF A RESISTOMETER
WITH A MICROCOMPUTER

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Presented for the

Master of Science

Degree

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ABSTRACT

Microcomputer control, as an extension of direct digital control (DDC), is currently finding application in many laboratory research programs. One such application is in the Resistivity Laboratory in the Department of Chemical, Metallurgical, and Polymer Engineering at The University of Tennessee, Knoxville where a PDP-11 micromputer is to replace a PDP-15 minicomputer. The computer is used for data acquisition and temperature control of a resistometer: a device that measures the electrical resistivity of a sample as a function of temperature.

This study was a specific application of DDC to the resistometer for a Ni_4Mo sample. The study involved both the computer simulation and modeling of the system as well as the development of a viable temperature control algorithm using advanced control techniques. The study concluded that a feedforward-feedback control scheme was sufficient for proper control. The feedforward element was taken to be a model of the system based upon a heat balance, and the feedback element was the discrete approximation to the PI controller. Two feedback controllers were used: a temperature PI controller for isothermal regimes and a rate controller for heating or cooling regimes. Overall, the control eliminated any appreciable overshoot and achieved control in the isothermal regime.

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INTRODUCTION

The computer revolution has provided a vast impetus to process control, especially to those processes that are complex, nonlinear, and/or multivariable with significant coupling. Many such processes cannot be adequately controlled with conventional analog equipment. Thus, there is a great need, and has been for quite sometime, for direct-digital control (DDC). This is not to say that it is absolutely necessary; after all, operators have manually controlled distillation columns for many years. However, DDC is not only often cost effective, but it can often achieve higher product quality.

Though these ideas are certainly not new, they take on a new light with the advent of the low cost microcomputer. With memory and speed rivaling (or exceeding) the minicomputers of ten years ago, DDC can enter into areas heretofore untouched. In addition, microcomputers can replace many practically obsolete minicomputers. In this manner, many laboratory experiments limited by computer timesharing can acquire more freedom with microcomputers. And for those previously having no access to computers, DDC, on-line analyses, and rapid data acquisition and storage are now possible with microcomputers. One example of a changeover from a minicomputer to a microcomputer is in the Resistivity Measurement Laboratory in the Department of Chemical, Metallurgical, and Polymer Engineering at The University of Tennessee, Knoxville where a PDP-15 minicomputer is being phased out in favor of a PDP-11 microcomputer.

This changeover offers an excellent opportunity to improve the temperature control of the resistometer using advanced control techniques (feedforward control, for example). Thus, this project is a control study

of the resistometer which includes the mechanistic modeling of the system. The modeling involves both a heat balance of the system, and the phase transition kinetics of the Ni-Mo alloy (the Hastelloys) used in the resistivity measurements. The control study involves developing a viable control algorithm, and simulating the control system using the system model.

CHAPTER I

BACKGROUND

Electrical resistivity measurements have been used somewhat extensively as a means of studying the order-disorder phase transition in Ni-Mo alloys (1-7). Such studies are important for the understanding of mechanical properties and phase transition kinetics. Such studies are also of industrial importance because of the corrosion resistant properties of the Ni-Mo-Fe alloys (8-10). Two particular examples of such alloys are Hastelloy B and Hastelloy B2, each containing mostly Ni-Mo with an atomic ratio of 4:1.

The resistivity studies of the Ni-Mo alloys performed in the Department of Chemical, Metallurgical, and Polymer Engineering of The University of Tennessee, Knoxville (UTK) (1-5) employ what can be termed a "resistometer." The device not only measures the resistivity and temperature of a sample, but also heats and cools the sample at various rates. A computer (PDP-15 by the Digital Equipment Corporation) presently is used to control the current to the sample (the heating mechanism) and collect and store data. The storage device can be a magnetic tape, teletype printout, or an X-Y plot of resistivity versus temperature. The PDP-15 is being replaced by a PDP-11 microcomputer. The reasons for the transition are many, including the PDP-15's analog-to-digital converters increasing amount of downtime.

The resistometer, when connected to a computer, offers an excellent opportunity to utilize some advanced computer control concepts such as adaptive tuning and feedforward predictive control. Although the control

algorithm may be complicated, the system as a whole is quite simple in that it is a single input, single output process (SISO) with temperature as the control variable and the current to a Ni-Mo alloy as the manipulated variable. The kinetic modeling of the system is interesting due to a particular phase transition and the nonlinear aspects of radiative heat transfer. Consequently, the objectives of this study were the modeling of the resistometer at UTK and the development of a computer control algorithm to be incorporated with the PDP-11.

Metallurgy

This study focused on the Ni-Mo alloy with 20 atomic percent Mo. Before the modeling and control of the system, it was first important to understand the structure of the alloy and to be familiar with various physical properties, such as resistivity and heat capacity and the effect of temperature on such properties. The work by Lei (1) contains a review of the Ni rich alloys, and the following discussion is based upon the continuing resistivity research at The University of Tennessee (UTK).

Figure I-1 is the phase diagram of the Ni-Mo system for 16 to 40 weight percent Mo (5). Since the molecular weights of Ni and Mo are 58.71 and 95.94 gm/gm-mole, respectively, this corresponds to approximately 10 to 29 atomic percent Mo. The point of interest (20 atomic percent Mo) thus occurs at 29 weight percent Mo. There are two phases of interest at this composition: α and β .

The β phase exists as body-centered tetragonal (b.c.t.) and exhibits a long range ordering (LRO). Figure I-2 gives a qualitative description of the Ni-Mo distribution in this phase. As can be seen, lattice sites

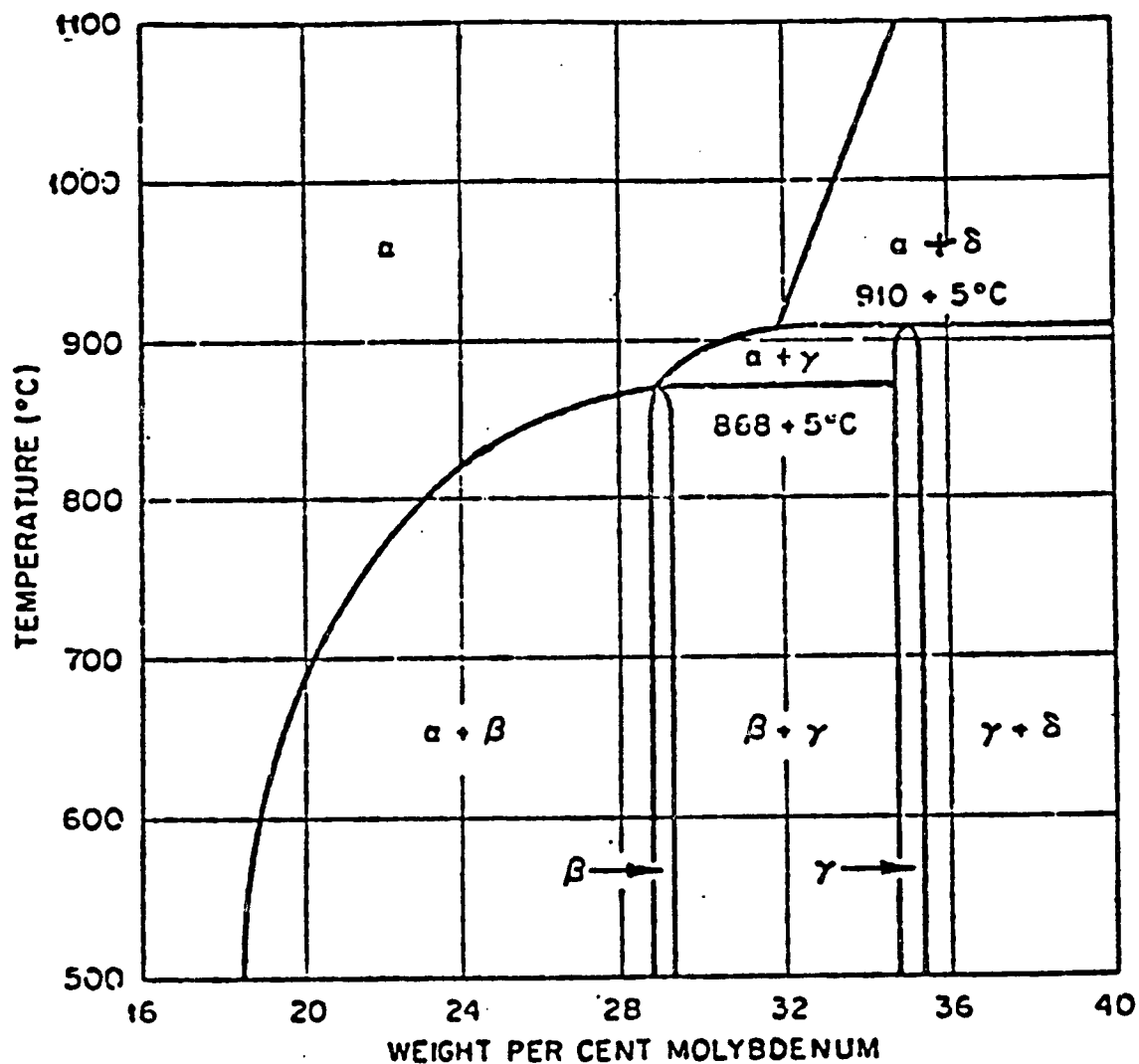


Figure I-1. Phase diagram of Ni-Mo system from 16 to 40 weight percent Mo.

Source: Lei, T. S., The Effect of 0-8 Wt. % Iron on Transformations of Alpha Phase Ni-Mo-Fe Alloys with Ni:Mo Ratio Equal to 4:1, Ph. D. Dissertation, The University of Tennessee, Knoxville, (1979).

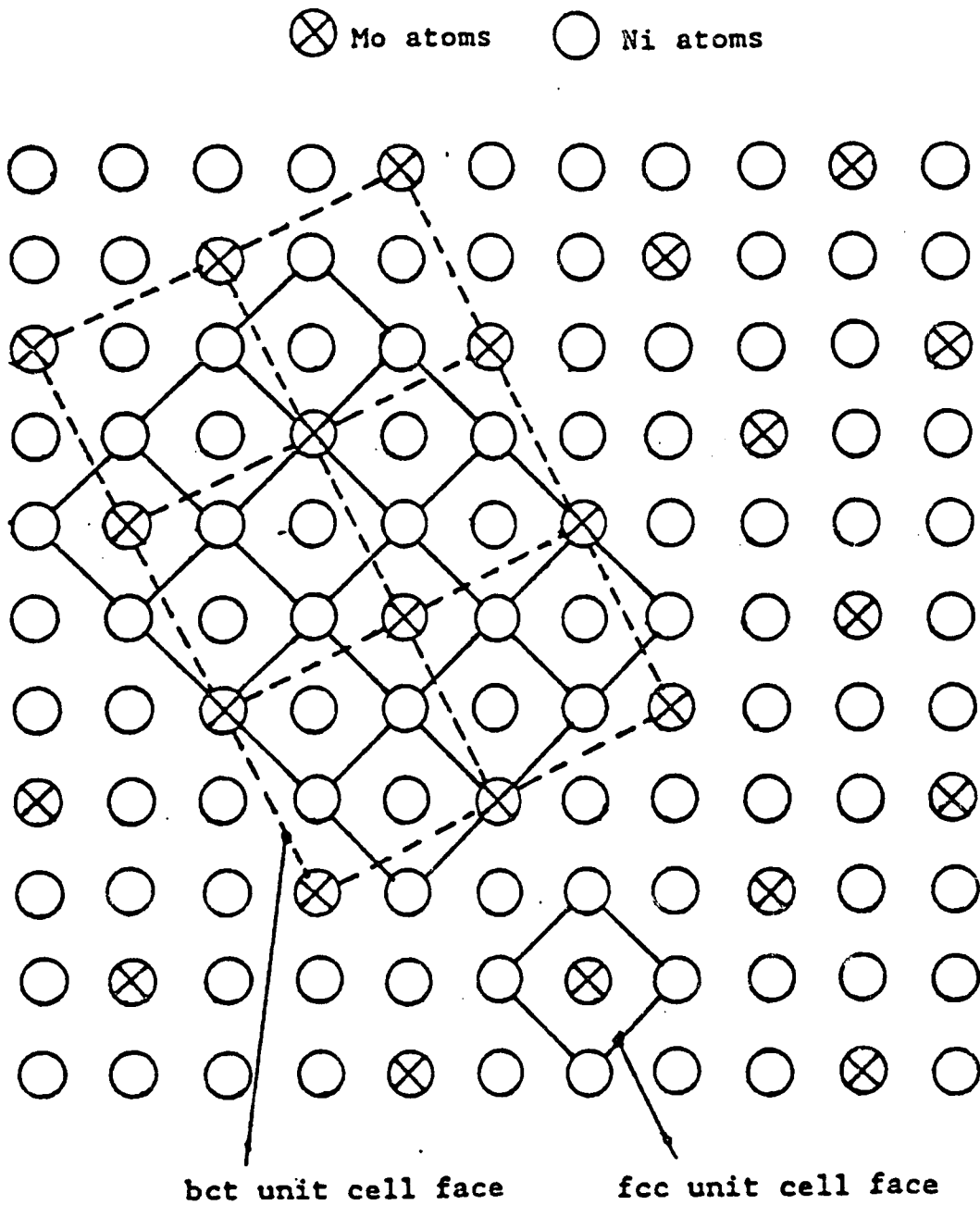


Figure I-2. Schematic diagram of a cube plane of α phase showing the Ni_4Mo .

associated with the b.c.t. structure, are revealed by an overlaying structure based upon the position of the Mo atoms in the basic structure: the long range ordering. One can easily see that, although the basic structure is four Ni atoms to a single Mo atom and that randomly the probability that two Mo atoms are located next to each other is $1/5$, there are in fact no two Mo atoms adjacent to one another. Such "supersymmetry" in the LRO phase thus implies that the Mo atoms prefer Ni neighbors to Mo. Obviously, the actual lattice structure is not perfect, and irregularities such as grain boundaries, dislocations, and thermal vibrations occur.

The α phase exists as face centered cubic (f.c.c.) and exhibits short-range order (SRO) behavior. This SRO behavior is a function of temperature and heating/cooling rate as well as the history of the material. Figure I-3 shows, qualitatively, the f.c.c. structure of the SRO phase. Note that if the center atom is a Mo atom and the distribution of atoms surrounding the Mo atom is completely random then the probability of another Mo atom being a "nearest neighbor" (in the first coordination shell) is $1/5$, as discussed earlier for the LRO phase. The idea of SRO is that the probability is less than $1/5$, though not necessarily zero; i.e., the distribution of Ni and Mo atoms is not completely random. The Mo atoms might be said to prefer Ni neighbors. The degree of SRO increases as the temperature decreases with tendency to LRO starting at the α - β phase transition temperature ($T_C \sim 868^\circ\text{C}$). Based on the Gibbs free energy, this can be explained from the balance between the entropy of mixing of Ni and Mo atoms and the Ni-Mo interaction energy as the temperature increases. This can be seen from $\Delta G = \Delta H - T\Delta S$, where G is the

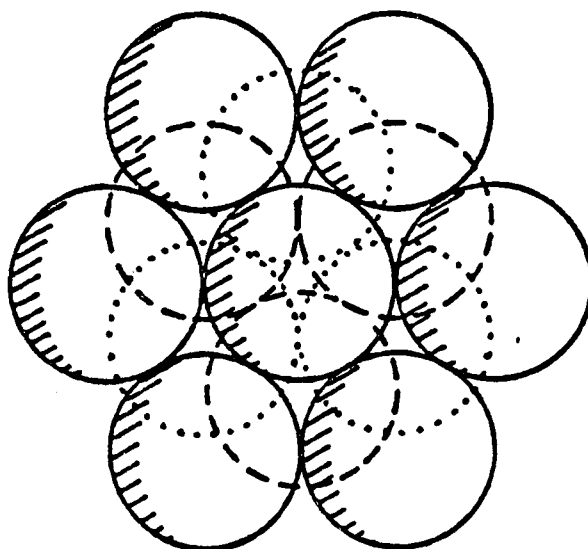


Figure I-3. Schematic diagram of the atom arrangement of the SRO phase. Three atoms (---) are shown above and three atoms below (···) the intermediate plane of 7 atoms. The center atom has 12 closest neighbors.

Gibbs free energy, H is enthalpy, and S is entropy. At low temperatures, ΔH (associated with the Ni-Mo interaction energy) dominates; thus, there is a tendency toward ordering. At higher temperatures, the temperature effect of the $T\Delta S$ term dominates; thus, there is a tendency toward disorder. The increased thermal energy therefore increases the randomness (decreases the ordering) of the distribution of Ni and Mo atoms. Since the resistivity of a material is a function of the lattice structure, one might expect a correlation between changes in resistivity with changes in ordering. Such a relationship can be seen in Figure I-4, the resistivity versus temperature diagram for Ni_4Mo .

Curve 1, the region below T_C and corresponding to a sample with no SRO, shows the effect of thermal vibrations of the lattice on resistivity: the resistivity increases somewhat linearly with increasing temperature. Most metals exhibit this phenomena, and it can be explained as the thermal lattice vibrations interfering with electron flow through electron scattering (11). At T_C , however, there is a discontinuity in the resistivity due to the phase change from LRO to SRO. The SRO state has a higher resistivity at T_C than the LRO. This is consistent with the theory of electrical conductivity which predicts a decrease in electron scattering with increase in long range periodicity of the lattice. A very interesting SRO phenomena is that the resistivity actually decreases with increasing temperature (curve 2). This is taken as experimental evidence that the amount of SRO decreases with increasing temperature. Although the resistivity as a function of SRO increases in some alloys and decreases in others, the more random the Ni-Mo distribution in the f.c.c structure, the lower the resistivity.

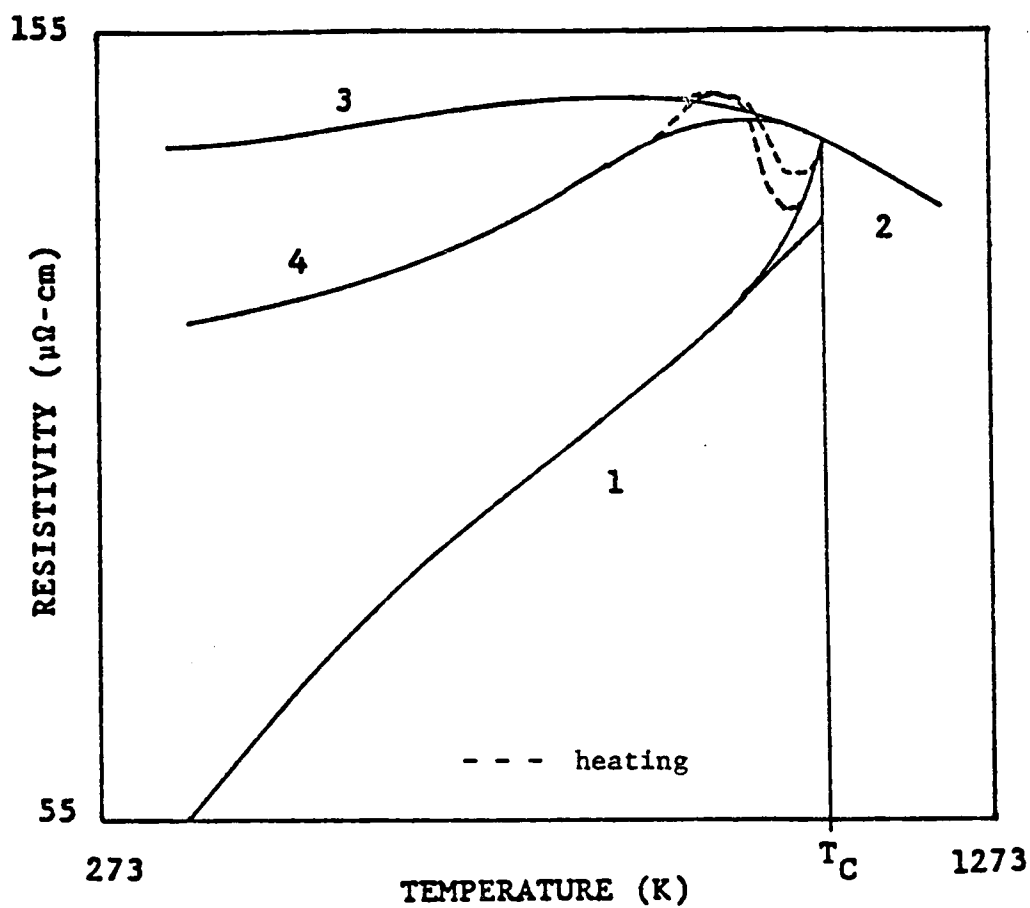


Figure I-4. Schematic resistivity versus temperature diagram for Ni_4Mo showing various heating and cooling rates.

The relative amounts of the α and β phases strongly affects the resistivity versus temperature curve. Curves 3 and 4 (Figure I-4) show the effect of cooling rate on resistivity. Curve 3 represents a high cooling rate (~ 60 $^{\circ}\text{C}/\text{min.}$) and curve 4 represents a lower cooling rate. Each of these curves originates above T_C and thus starts with all SRO. Once the sample has been cooled below T_C , LRO regions tend to nucleate and grow. There are two driving forces for the phase change: the degree of supersaturation and the difference in the free energies of the two phases at that temperature (12). For fast cooling, such transitions can become kinetically inhibited before much LRO material has nucleated. Thus, these samples retain most of their SRO characteristics (the SRO phase can be said to be "frozen in"). For slow cooling, the resistivity curve follows curve 1, and the sample is almost all LRO. For intermediate cooling rates, the resistivity curve generally lies somewhere between 1 and 3. The above analysis also applies qualitatively to the dotted lines of curves 3 and 4. The dotted lines represent the path upon reheating. Such lines are coincident with the cooling curves except near T_C . In fact, all of curves 1 and 2 apply to both heating and cooling under equilibrium. Consider, however, the driving forces upon heating the material cooled according to curve 3. At low temperatures, the kinetic activity (atom jump frequency) is low, even though there is a large thermodynamic driving force (large supersaturation). As temperatures approach T_C , the atom jump rate increases, enhancing the phase transformation by growth from existing LRO nuclei; thus, the transformation rate increases to yield increased LRO (thus lowering the resistivity).

One anomaly to the situation is that the resistivity can actually increase upon heating along curve 3 or 4 just before the decrease toward the LRO value. It is attributed to additional SRO formation in this region before nucleation of LRO; however, this phenomena is not completely understood.

It should be noted that not only resistivity has been used to study LRO-SRO transformations in Ni-Mo alloys, but heat capacity has also been used (2) as well as metallographic techniques (1-5).

Control

Microcomputer control has begun to invade the laboratories (13,14). Such use of the computer has many advantages including relatively low cost data acquisition and the possibility of advanced control techniques for systems that, due only to economic reasons, do not merit computer control by minicomputers. In fact, as memory and speed increase in microcomputers, it is logical to assume that control algorithms will generally become more complex in the quest for "optimum" control. At the present, microcomputer control can be found anywhere from temperature control in platinum resistance thermometry to controlling large-scale astronomical instruments (15-18).

This is not to say that direct digital control (DDC) is new, even for the laboratory. In fact, it is about as old as digital computers themselves. Some basic theory even predates the digital computer, such as the z-transform. In the Department of Chemical, Metallurgical, and Polymer Engineering at UTK, applications of DDC have been a major research area since the early 1970's (19-25). These projects range from dead-time

compensation (19,20) to applications of singular-value decomposition (24,25).

As stated earlier, the basic aim of this research is the modeling and computer control of the resistometer of UTK. A process by which one can logically develop a control system is given below (26):

- (1) establish process objectives
- (2) define control objectives
- (3) determine constraints
- (4) identify sources and characteristics of disturbances
- (5) determine dynamic characteristics
- (6) examine technical and economic feasibility
- (7) consider alternate solutions
- (8) finalize control-system design
- (9) complete control-system development

The first has already been discussed in the previous section: to measure the resistivity of a Ni-Mo alloy for various heating and cooling rates and temperatures. The control objectives may be stated as follows:

- (1) develop a mechanistic, dynamic model of the resistometer for a Ni_4Mo sample,
- (2) develop a control algorithm that would allow heating and cooling at desired rates (for changes in isothermal set points, there should be no overshoot, if possible, and quick response).

As for the constraints, the maximum current available for heating is 90 amps, and the maximum rate of cooling is limited by heat loss by radiation (since the sample is contained in a vacuum). These correspond to about 40 °C/sec for heating and -2 °C/sec for cooling. These values, however,

change dramatically depending upon temperature as the system is quite nonlinear.

The reason for the idea of no overshoot and yet a quick response can be seen in the time-temperature-transformation (TTT) diagram (Figure I-5). Three hypothetical control responses are labeled. The first shows what a "good" response would be. The second illustrates the danger of overshoot. Since the phase transformation is being studied at T_{sp} , one would want to make sure that no transformation has occurred before reaching a steady-state T_{sp} . An overshoot might allow the sample to enter a region of relatively fast transformation times. Thus, there is a chance of collecting misleading isothermal transformation data. The third curve also results in partial transformation before T_{sp} has been reached. Thus, a relatively fast response with no significant overshoot is necessary for the collection of reliable data.

It will be shown later that the known disturbances to the system are rather small. The known possible disturbances are current surges, electromagnetic noise, the quality of thermocouple welds, and the noise due to the computer (A/D and D/A converters). Since great care was taken to limit process noise when the equipment was first assembled, the quality of the data acquisition is relatively high (the system was checked, however, and is noted in Chapter II).

The dynamic characteristics will be discussed in Chapter III (Modeling of the Resistometer with a Ni_4Mo Sample). system, and steps 7 through 9 will constitute part of the control studies. Step 6, the technical and economical feasibility, is rather simple since the equipment (resistometer, computer, operating algorithm, etc.) already

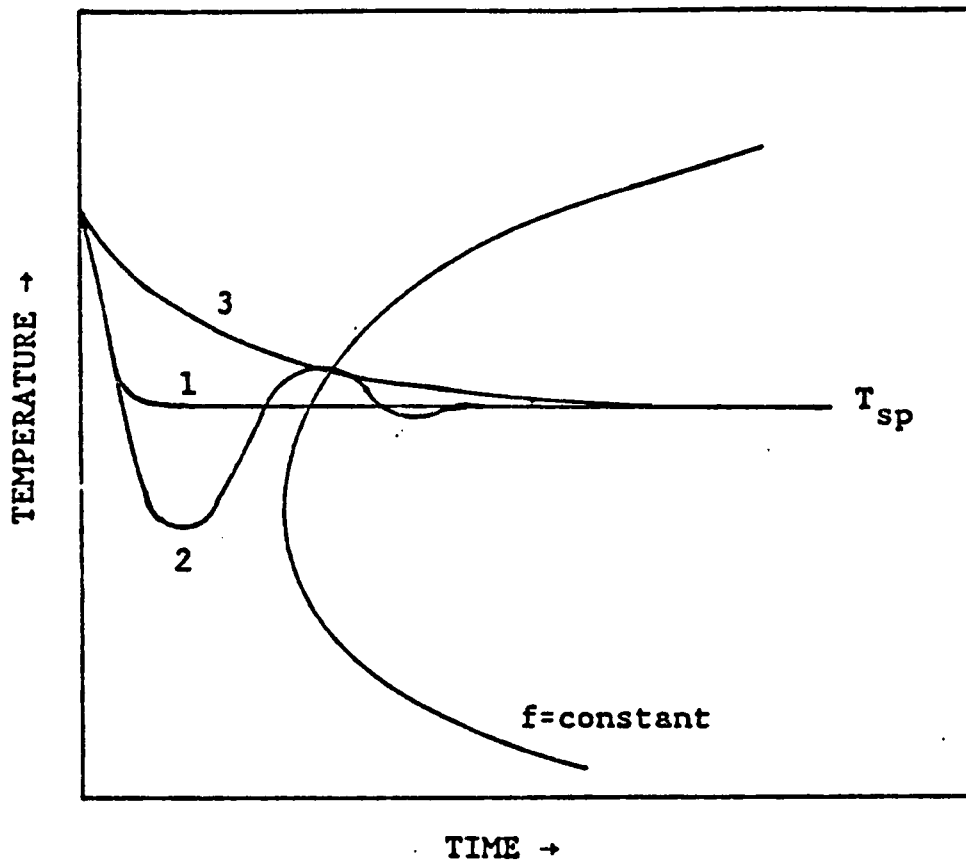


Figure I-5. Schematic TTT diagram showing hypothetical control responses.

exists. Thus, as long a control algorithm could be developed, such a project is definitely feasible.

The simplest case of computer control is the digital equivalent to the conventional proportional + integral + derivative (PID) controller (27-30). The basic idea is as follows. For a continuous sampler (a pneumatic control system, for example),

$$Y = Y_0 + K_C(E + \int E dt / T_I + T_D \frac{dE}{dt}) \quad (I-1)$$

where

Y = manipulated variable

Y_0 = Y at steady-state conditions

E = error (difference between control variable and set point)

K_C = controller gain

T_I = integral time

T_D = derivative time

The integral can be approximated by a summation and the derivative by the Euler relationship

$$\frac{dE}{dt} = \frac{\Delta E}{\Delta t} = \frac{\Delta E}{T} \quad (I-2)$$

where T is the sampling period. Thus, Equation II-2 becomes

$$Y_n = Y_0 + K_C(E_n + \sum(E_i T) / T_I) + T_D(E_n - E_{n-1}) / T \quad (I-3)$$

Thus, by keeping track of the summation, the previous error, and the steady-state conditions, the digital controller can approximate a conventional controller. The Y_0 term, however, may be difficult to accurately predict. For this reason, and to protect against reset windup (continuing integration when the controller is saturated), the velocity

algorithm may be employed (27,30). It may be derived by subtracting the n-1-th control equation from the n-th, giving

$$Y_n = Y_{n-1} + K_C[E_n - E_{n-1} + E_n T/T_I + T_D(E_n - 2E_{n-1} + E_{n-2})/T] \quad (I-4)$$

For nonlinear processes, the control parameters (K_C , T_I , and T_D) at one set of operating conditions may be inappropriate or even disastrous for another set of conditions. Thus, a logical next step might be an algorithm or an equation that would change the control parameters as needed for varying operating conditions. This is the idea behind adaptive tuning (26-33). The approaches one can take in adaptive tuning vary appreciably. One method is to take a process model and apply a mathematical tuning form, such as Zeigler-Nichols or Cohen-Coon (31), on the model gain and time constant. Thus, one obtains a quasi-theoretical adaptively tuned controller. A rather simplistic approach might be to search for the optimum control parameters, minimizing some criteria (such as the integral of the absolute error) for various operating conditions and fitting such data to an empirical expression. More sophisticated techniques exist where the search for the control parameters is performed on-line, sometimes called "self-tuning" controllers.

Another advanced control strategy is the feedforward predictive controller (26-33). A schematic block diagram of such a controller is given in Figure I-6. The basic idea is that some type of model predicts the effects of disturbances before or as they happen. The manipulated variable is then changed to offset the disturbance. It can be easily seen, however, that not only should the model be accurate, but that all important disturbances be known and accounted for in the model.

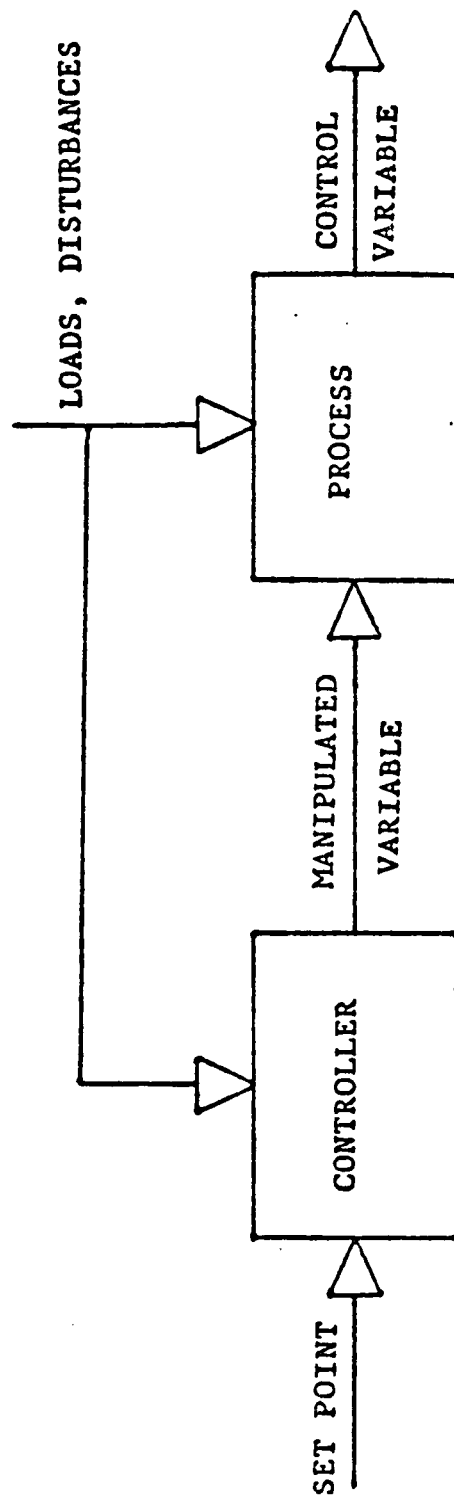


Figure I-6. Schematic block diagram for feedforward control.

One can correct for model inaccuracies via a feedforward-feedback combination. Figure I-7 gives a schematic block diagram of such a control system. Although there are many different schemes as to where the feedback loop should be located, the basic idea is the same: the feedforward loop attempts to correct for disturbances and set point changes while the feedback loop attempts to correct for the feedforward inaccuracies. Given a model in terms of a computer algorithm, the feedforward-feedback controller and adaptive tuning thus offer an excellent opportunity to utilize the flexibility of DDC.

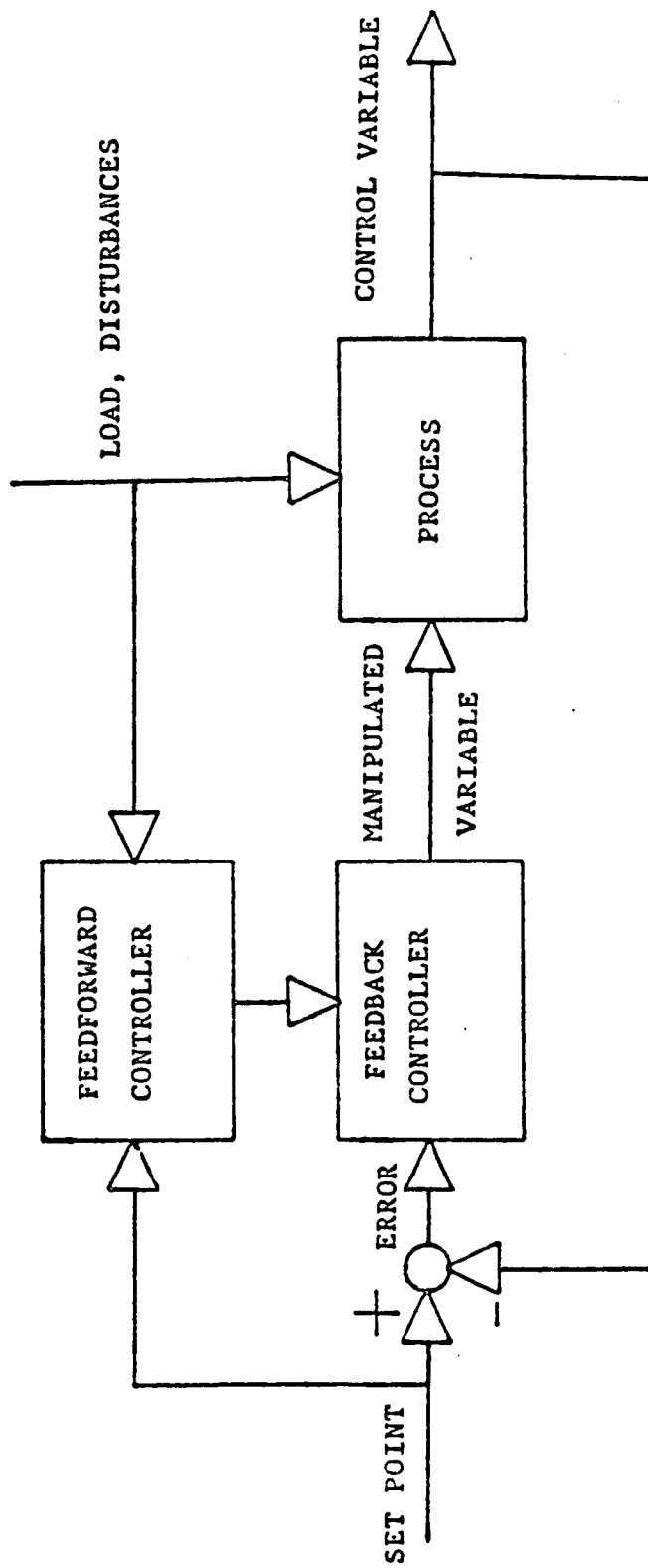


Figure I-7. Schematic diagram for a feedforward-feedback control strategy.

CHAPTER II

PROCESS EQUIPMENT

A schematic diagram of the overall equipment is given in Figure II-1. The temperature of the sample, in terms of control, is the control variable, and the current to the sample is the manipulated variable. In terms of the metallurgical implications, the main variables to be measured are the resistivity of the sample and the temperature. The temperature of the sample can be read with two separate thermocouples, designated TC_1 and TC_2 . The thermocouple wires also offer a method of obtaining the potential drop across the sample. Thus, by knowing the sample dimensions and the current, the resistivity of the sample can be calculated. The general flow of the process is as follows.

The thermocouple voltages are sent through a relay system, a James Micro-scan relay system designed for low level signals, and thus eliminate the need and cost of separate amplifiers for each thermocouple. The signals are then sent through a suppression unit where they are suppressed 5 or 15 mV according to the magnitude of the signal so that the resulting voltage lies between -5 and +5 mV. The signals are then sent back through the relays and to a Preston isolation amplifier (8300 XWB, Model D) whose gain is 1000. The Preston amplifier is of a very high quality, and is capable of reliable signals in the mV range.

Upon amplification, the signals are in the range of 5 V. From the Preston amplifier, the signals are sent to the PDP-11 via the computer's analog-to-digital (A/D) converter where they are converted into computer "counts" ranging from -2048 to +2047, corresponding to -5 and +5 volts,

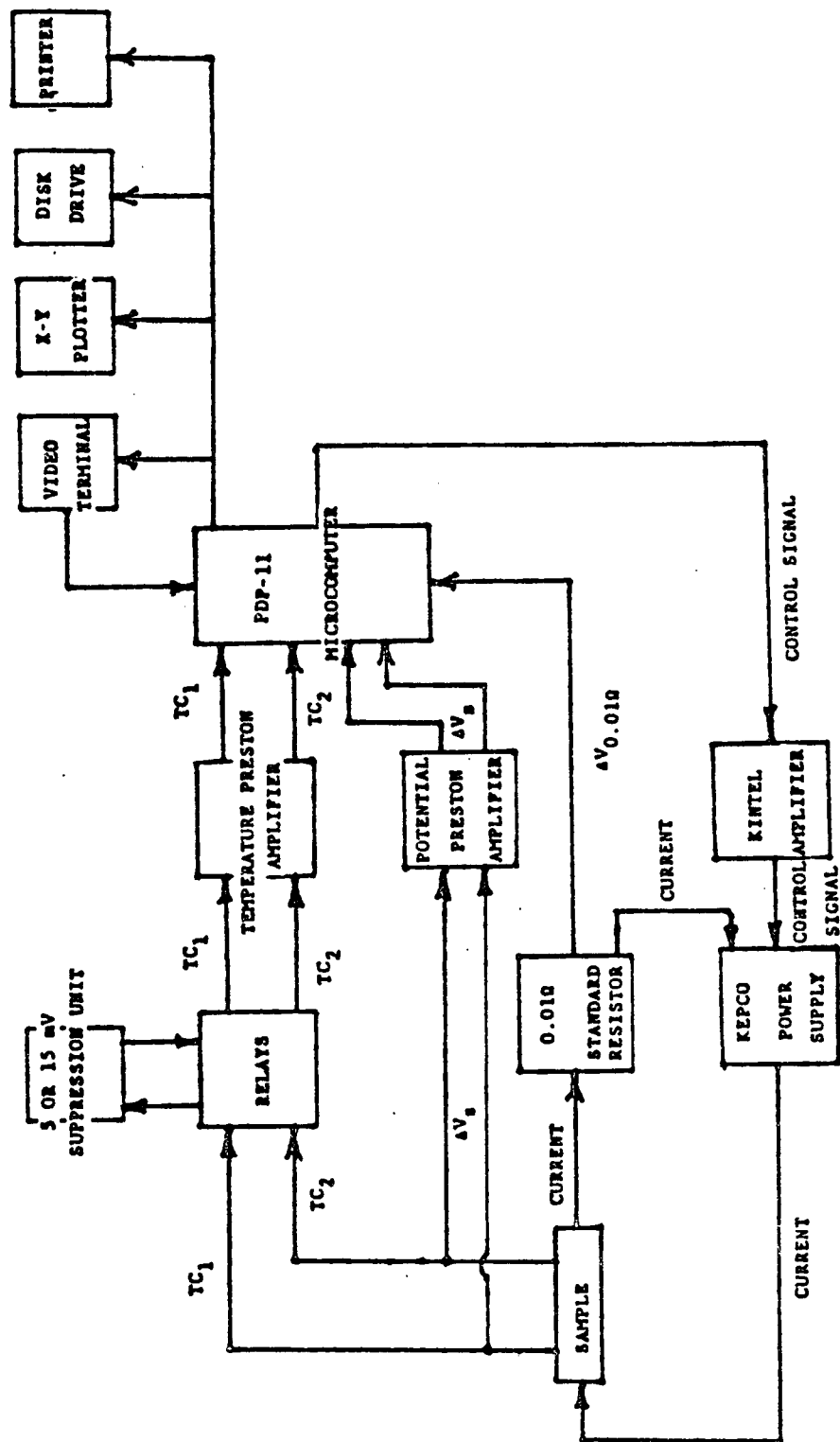


Figure II-1. Schematic diagram of the process equipment.

respectively. The digital counts can be related to a thermal emf/temperature table within computer's memory, and the "looked-up" temperature recorded and/or used within the temperature control algorithm. However, within the control algorithm, a time-saving consideration is to use the digital counts as the control variable and the digital-to-analog (D/A) digital counts as the manipulated variable. The temperature sampling process occurs four times at 0.1 intervals every 2 seconds. The four temperature values are then averaged, reducing measurement noise, before they are sent to the control algorithm. The controller thus sees a sampling period of 2 seconds.

Once the control algorithm has calculated a current setting, the control signal is sent, via the D/A converter in the computer, to a Kintell (Model 114A) amplifier. The signal is within the range of -10 to +10 V, and, although the signal is not actually amplified, the amplifier does help reduce process noise by separating the computer's noise from the rest of the processes' noise. The signal is then sent to a Kepco power supply (Model OPS 6-90M). The Kepco is capable of output currents ranging from 0 to 90 amps at 0 to 6 V, corresponding to an input range of 0 to 10 V, respectively. This current is then sent to the sample for heating.

Once every 30 seconds, the resistivity of the sample is measured. To do this, the current is momentarily raised to about 40 amps (the actual duration is 3 computer clock ticks, corresponding to 0.05 seconds which is not enough time to disrupt the sample's heating or cooling). The voltage drop along the sample between the two thermocouples (designated ΔV_s in Figure II-1) is then measured by connecting the platinum leads of the thermocouple system through suitable relays. The signal thus obtained is

sent through another Preston amplifier and sent to the computer. To calculate an accurate resistivity, an accurate value of the current must be obtained. This is done by measuring the voltage drop across a 0.01Ω standard resistor in series with the power supply output and the sample. Since the current range is 0 to 90 amps, the voltage range going to the computer is 0 to 0.9 V.

The resistivity measurements, taken every 30 seconds, are displayed and/or stored by one or more of three devices: (1) terminal or teletype, (2) X-Y plotter, and (3) magnetic disk or tape. After the routine is completed, the system resumes the temperature sampling and control every 2 seconds.

A schematic electronic diagram of the system is given in Figure II-2. Two interesting points should be made about the diagram. First, the wires are shielded so as to eliminate foreign noise from such sources as fluorescent lights, radio waves, and building currents. Also, the shielding and grounding were designed to eliminate local noise, such as "cross talk" between wires. Morrison (34) gives a theoretical and practical analysis of grounding and shielding techniques. Second, there is an electronic switch designed so that the equipment could be run by either the PDP-15 or the PDP-11 during the phasing out of the PDP-15 according to switch selection.

Tests were performed to check the noise in the relay and amplifier system by sending a signal from a quiet potentiometer through the system as though it were a thermocouple reading, except for the suppression unit. The signal eventually reached the A/D converter of the PDP-11, where it was recorded by the computer. The user could vary the amount of time

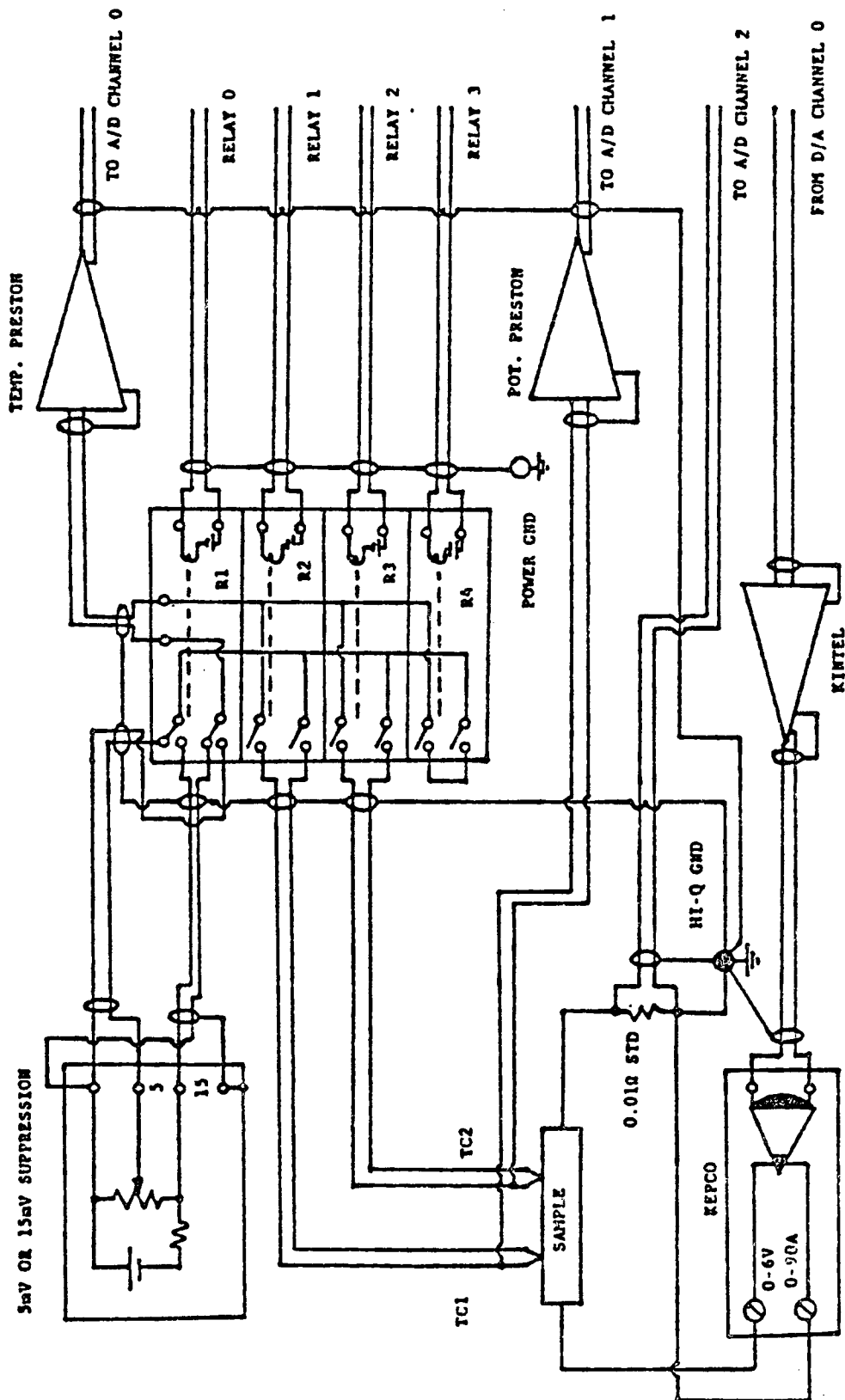


Figure II-2. Schematic electronic diagram of the process equipment.
Computer not shown.

between samples readings. The results showed that noise presented no significant error to the measurements.

PDP-11 Microcomputer

The PDP-11 microcomputer by the Digital Equipment Corporation is not only a powerful computational tool for a small package (64K RAM, 16 bit CPU), but it can also be a very useful data acquisition system. Up to 8 A/D channels, 4 D/A channels, and 16 relays can be used to interface with various equipment. A diagram of the computing system of the resistivity lab is shown in Figure II-3. The various input/output (IO) devices are labeled. In no specific order they are (1) a Zenith Model Z19 Video Terminal, (2) an Anadex Model DP-9501 dot-matrix printer, (3) a Houston Instruments HI PLOT Model DMP-6 X-Y plotter, and (4) a Digital RX02 dual floppy disk drive, in addition to the converters and relays. The processor is Digital's LSI-11 by Heath. In addition to the hardware, various system software packages, either purchased or developed in house, are available. These include BASIC, FORTRAN, full-screen editors, and the RT-11 operating system subroutines.

Figure II-4 shows a general flow sheet of the computer program that runs the resistometer. There are three major areas of function: (1) the IO routines which control output to the terminal, printer, and plotter and control the input of such information as sample dimensions and heating/cooling rates; (2) the temperature control algorithm; and (3) the data acquisition and processing of information.

The general voltage range of the equipment to the A/D and D/A converters is given in Figure II-5. The thermocouple voltages range from

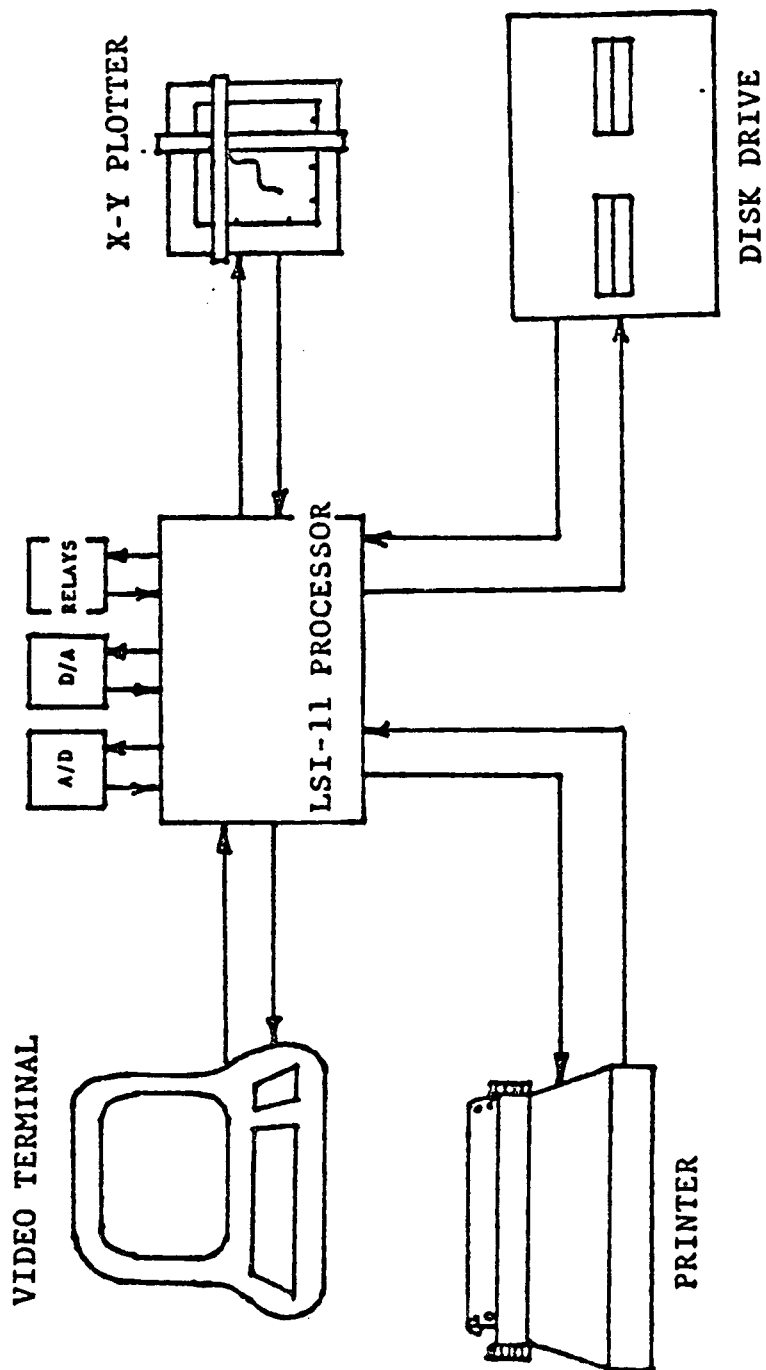


Figure II-3. Schematic diagram of the computer and its peripherals.

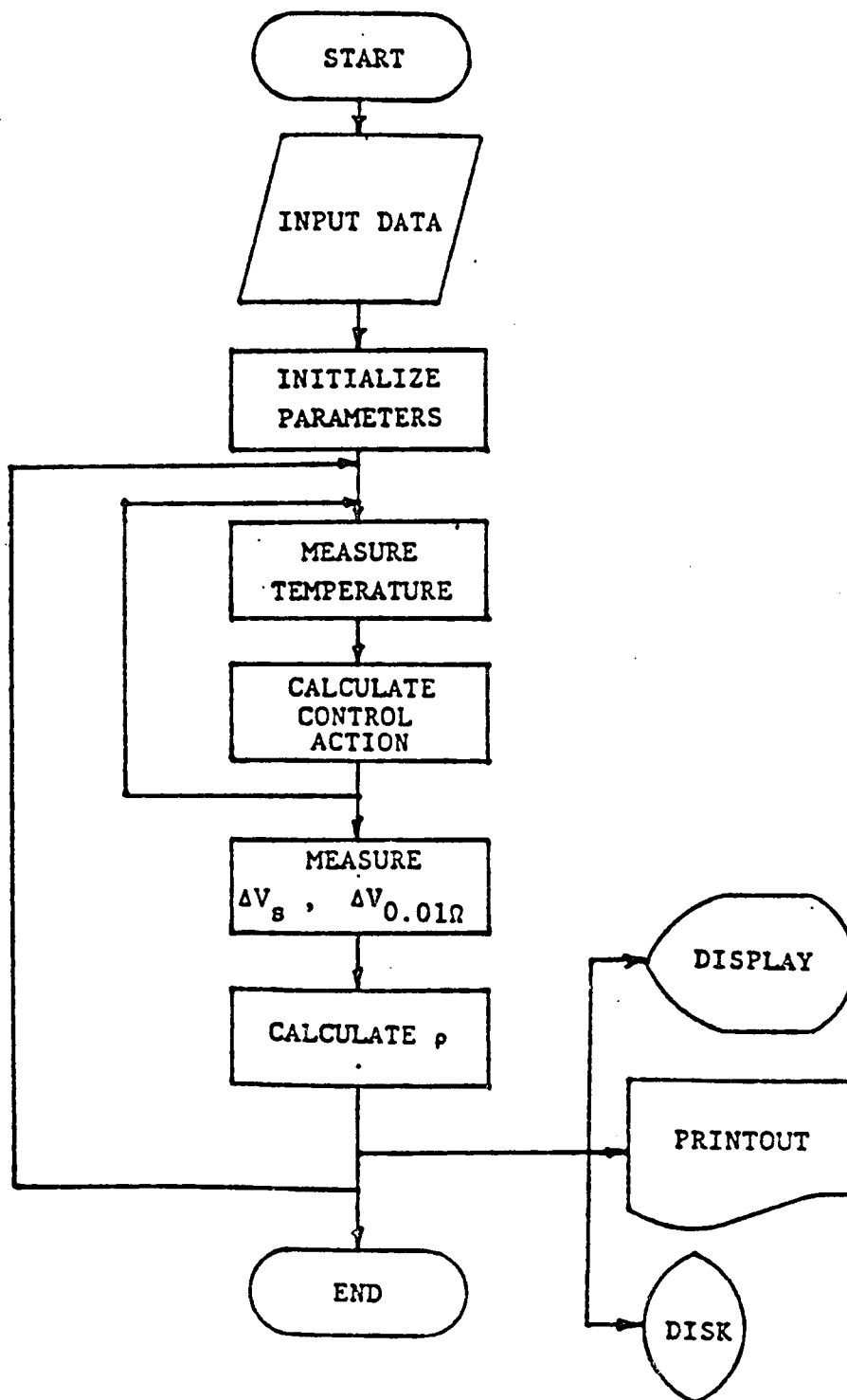


Figure II-4. Schematic diagram of the general governing computer program.

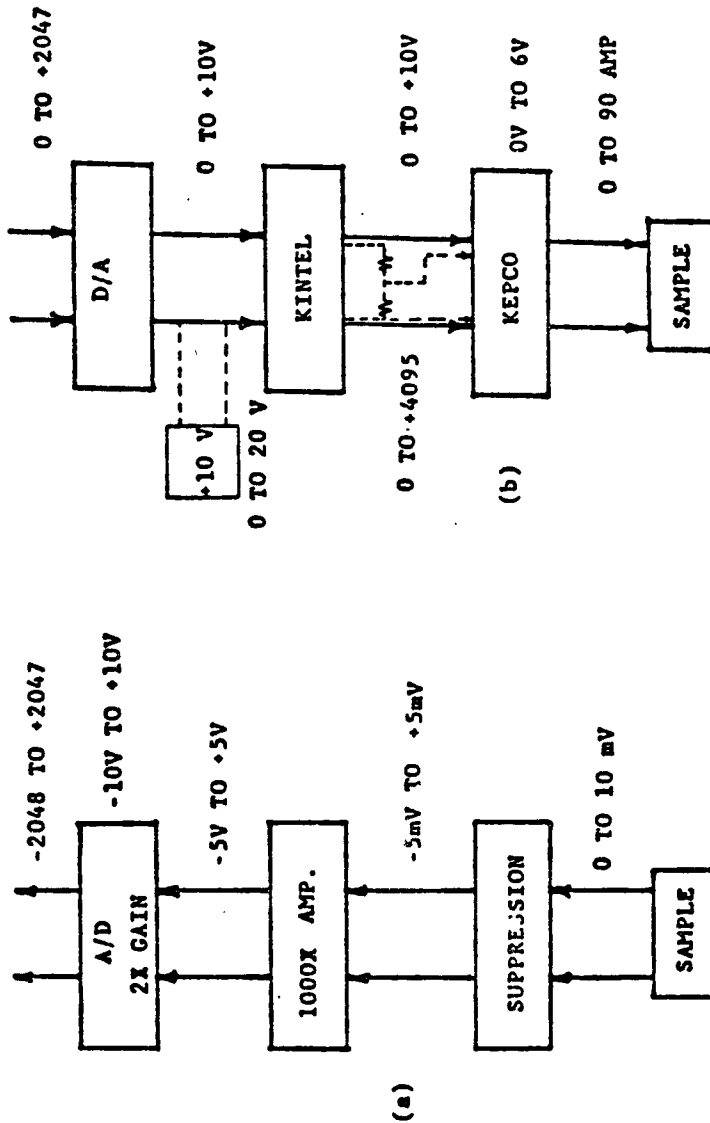


Figure II-5. Schematic block diagram of (a) A/D converter signal paths and (b) D/A converter signal paths. Reasonable voltage ranges for each step are shown. Also shown are additions (dotted lines) designed to utilize the entire range of the computer's digital counts of the D/A converter.

0 to +10 mV (small enough so that proper shielding is a necessity). Since the A/D converters of the computer can handle voltages ranging from -10 to +10 V, the suppression unit is used to transform the signals within the range of -5 to +5 mV. By the time the signal is actually converted to digital counts, the voltage range is -10 to +10 mV.

The D/A converter signal path (Figure II-5(b)) is somewhat different in that no signal amplification is needed. The D/A converter has a range of -10 to +10 V, and the range of the Kepco power supply input is 0 to 6V. This unfortunately means that most of the digital counts of the D/A converter are not utilized. As will be shown later, this may be important. The Kepco then outputs a current in the range of 0 to 90 amps to the sample.

The accuracy of the A/D converters was found to be at worst within 2 counts. This corresponds to an accuracy of 0.0025 mV from the sample, since the A/D digital counts range from -2048 to +2047. Since the sample generally varies as 0.01 mV/°C, the accuracy is correspondingly 0.25 °C. Although the accuracy of the D/A converter was not as good as the A/D, it was found to be generally within 2 counts also. The range of the digital counts used for the Kepco is not 4096, as in the A/D converter, but only 1129, which corresponds to an accuracy of 0.15 amps. In terms of temperature of the sample, 0 to 90 amps corresponds roughly to 300 to 1300 K, respectively, at steady state. Although this relationship is not linear, for a rough estimate of the D/A converters it will suffice for the simple calculation to yield an accuracy of 1.5 °C. This value, therefore, sets a limit on the control accuracy. The accuracy can easily be improved if the entire range of the D/A converter were utilized. This

would correspond roughly to an accuracy of 0.75 °C. This study assumed the specification of a control algorithm within 1 °C.

Sample and Environment

A schematic diagram of the sample is shown in Figure II-6. The entire sample structure is placed within a cylindrical Ni housing (approximately 4 in. in diameter) which is evacuated to approximately 5×10^{-5} torr by a vacuum pump (Welch Scientific Co. Model 1397). Two large copper leads carry the current (from the Kepco power supply) to the sample for heating. The leads are welded to separate ends of the sample bar. Two Pt/Pt-Rh thermocouples are welded to the sample approximately 0.5 cm apart on the 8 cm. sample bar, thus corresponding to a sample length to the sample bar length of about 1:40. The reference junction for the thermocouples is an ice water bath. Each thermocouple wire is encased in a ceramic insulator, as are the current leads. Radiation shields help to prevent heat loss through the ends of the housing, and with the temperature of the sample measuring up to about 1300 K and the housing temperature between 300 and 800 K, radiation within the housing is significant.

The accuracy of the temperature measurement is greatly dependent upon the quality of the thermocouple welds. The quality of the welds is a function of the location of the effective junction, whether it is at the sample or not. Thus, a weld in which the thermocouple wires are attached before the weld to the sample is considered of a lower quality than a weld in which the wires are attached separately to the sample (and yet close together). The thermocouple readings may differ by 2 or 3 degrees. This

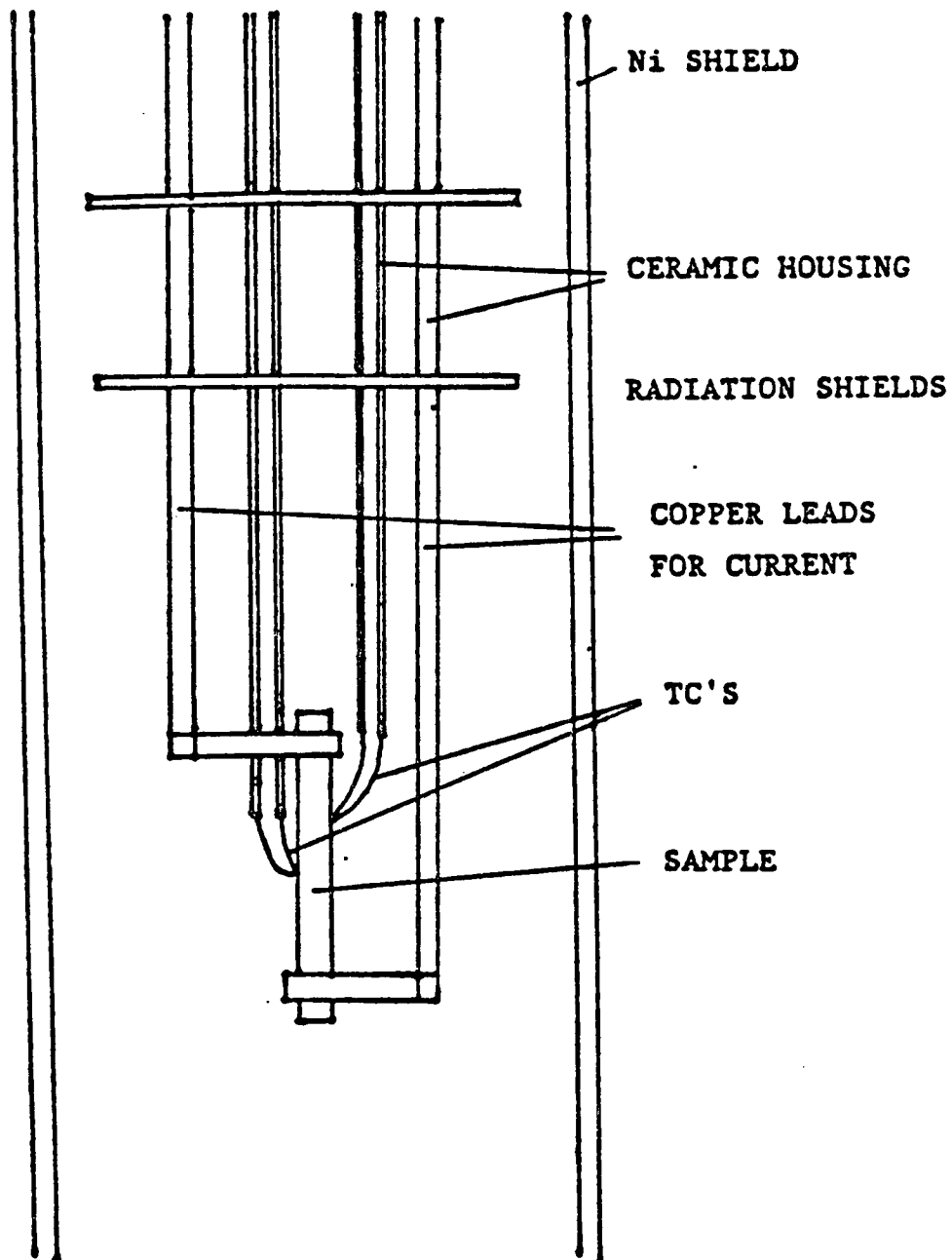


Figure II-6. Schematic diagram of the sample and its environment.

is probably not due to any conduction along the sample bar within the spacial separation of the thermocouples (since the sample length is relatively small), but rather to the difference in the quality of the welds. Good welds have been known not to significantly differ in temperature measurements.

CHAPTER III

MODELING OF THE RESISTOMETER WITH A Ni_4Mo SAMPLE

The purpose of modeling the resistometer with a Ni_4Mo sample was to provide a simulation for computer analysis, eg. step tests, ramp tests, and parameter sensitivity studies, with the idea of temperature control in mind. Such modeling may also be used to develop feedforward controller. It may be possible, however, to make some conclusions concerning the ordering kinetics of the Ni_4Mo alloy.

The approach used to model the system was as follows: (1) make a heat balance of the sample, including current, radiation, and conduction effects, (2) obtain a model of the SRO to LRO phase change kinetics from literature, and (3) compare the models to actual data to obtain various parameters. The last step may be instrumental in determining the validity of the models and, if the models are valid, interpreting the physical meaning of the parameter values.

Heat Balance

For the purpose of doing a heat balance on the system, the system was first defined. Figure III-1 is a schematic diagram of the system and the possible modes of heat exchange. The system was defined as the actual sample between the thermocouples (shaded region). For the system, the heat balance is given by

$$Q_{\text{in}} - Q_{\text{out}} = \text{accumulation} - \text{latent heat} \quad (\text{III-1})$$

The left hand side can be thought of as sensible heat. The heat balance for individual terms becomes

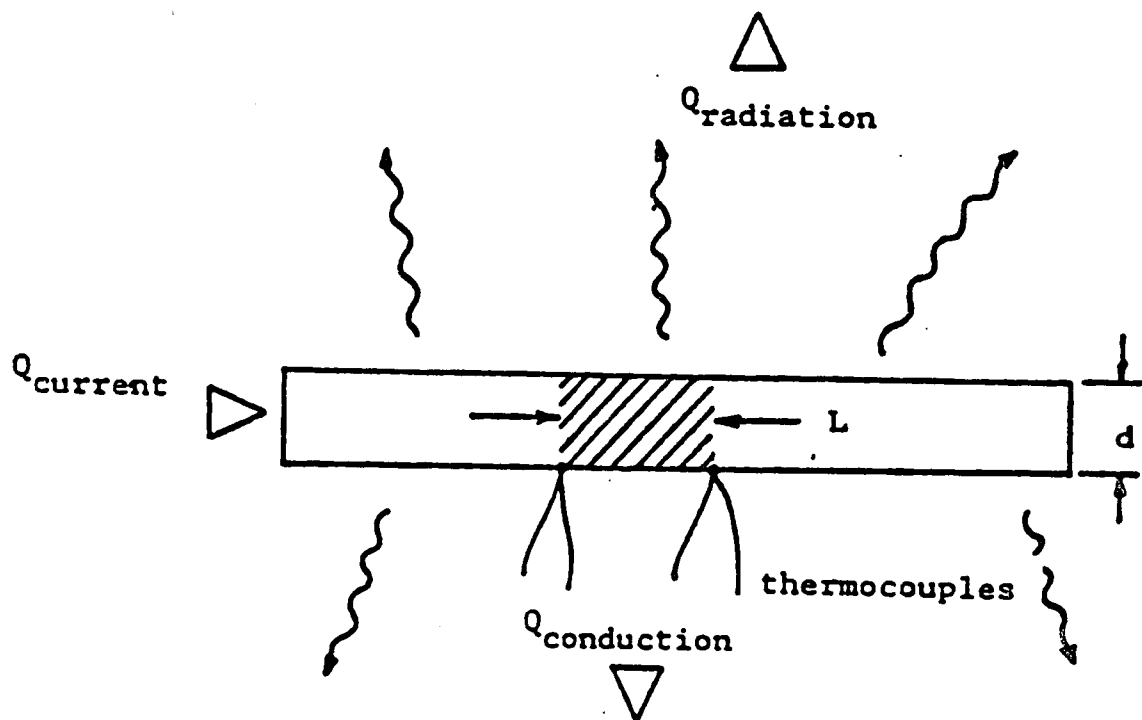


Figure III-1. Schematic diagram of the sample with modes of heat transfer.

$$Q_{\text{current}} + Q_{\text{radiation}} + Q_{\text{conduction}} + Q_{\text{convection}} = \frac{dQ}{dt} - \lambda \quad (\text{III-2})$$

where λ is the latent heat of phase change.

The current term is the well known power law for electrical resistance (35),

$$Q_{\text{current}} = I^2 R = \frac{I^2 \rho L}{A_{\text{xs}}} = \frac{I^2 \rho L}{\pi d^2} \quad (\text{III-3})$$

where I is the current, R is the resistance, ρ is the resistivity, L is the length of the sample, A_{xs} is the cross-sectional area, and d is the diameter.

The radiation term is from the Stephan-Boltzmann law for a grey body (36,37),

$$Q_{\text{radiation}} = \sigma \phi (T_a^4 - T^4) \quad (\text{III-4})$$

where T_a denotes the ambient temperature and T is the absolute temperature of the sample. The factor ϕ is both an area term and a view factor. For concentric cylinders, it is

$$\phi = \left[\frac{1}{A_s \epsilon_s} + \frac{1}{A_o} \left(\frac{1}{\epsilon_o} - 1 \right) \right]^{-1} \quad (\text{III-5})$$

where the subscripts s and o are for the sample and outer cylinder, respectively. Also, ϵ is the emissivity of the material, and σ is the Stephan-Boltzmann constant.

The general form for conduction (36,37) is

$$Q_{\text{conduction}} = A_{\text{xs}} k (T_2 - T_1 / L_{1-2}) \quad (\text{III-6})$$

where k is the thermal conductivity. In the system, there are two possible conduction routes. One is through the current wires, and the other is via the thermocouples. Since the thermocouples are welded close together (~ 0.03 m), the sample is heated almost uniformly, and the cross sectional area is small, the conduction from the sample to the current wires is small. As an estimate,

$$A_{xs} = 5 \times 10^{-6} \text{ m}^2$$

$$k = 20 \text{ J/(s-m-K)}$$

$$L = 0.03 \text{ m}$$

Using a high value of ΔT (10°C), $Q \sim 0.1 \text{ J/s}$, which, as shall be shown later, is much smaller than both current and the radiation heat transfer.

As for the mechanism of conduction through the four thermocouple wires, the heat transfer equation is

$$Q_{\text{conduction}} = 4A_{tc} k_{tc} (T_a - T)/L_{tc} \quad (\text{III-7})$$

where the subscript tc is for the thermocouples. The mechanism turns out to be a very small fraction of the heat loss, except at low temperatures.

The general form of forced convection (36,37) is

$$Q_{\text{convection}} = h_{fc} A_s (T_2 - T_1) \quad (\text{III-8})$$

where h_{fc} is a forced convection coefficient and A_s is the surface area. However, since the sample is in a vacuum, convection is not a heat loss mechanism in the resistometer. If an inert gas purge were to be used in the future for faster cooling, this term would be required in the heat balance.

The accumulation of heat in the sample is given by

$$\frac{dQ}{dt} = \frac{Vd(C_v T)}{v dt} \quad (\text{III-9})$$

where V is the volume of the sample, v is the specific volume, and C_v is the heat capacity. Note that C_v assumed to be a function of temperature and is left inside the derivative.

Given that the fraction of LRO is f , the latent heat of phase change is

$$\lambda = \frac{d(1-f)\Delta H}{dt} \quad (\text{III-10})$$

where ΔH is the latent heat if all material were transformed and if f is the fraction of LRO material. Note that the phase change kinetics are contained in f .

The individual terms thus combine to give the total heat balance equation

$$\frac{I_{\rho L}^2}{A_{xs}} + \sigma\phi(T_a^4 - T^4) + \frac{4A_{tc}k_{tc}(T_a - T)}{L_{tc}} = \frac{Vd(C_v T)}{v dt} - \frac{d[(1-f)\Delta H]}{dt} \quad (\text{III-11})$$

Equation III-11 can be simplified by the following assumptions:

- (1) $T < T_c$ (no phase change)
- (2) conduction heat transfer is negligible
- (3) C_v is constant
- (4) $\rho = a + bT$

Equation III-11 then becomes

$$\frac{I_{aL}^2}{A_{xs}} + \frac{I_{bLT}^2}{A_{xs}} = \sigma\phi T_a^4 - \sigma\phi T^4 = \frac{VC_v dt}{v dt}$$

Using deviation parameters from the steady state conditions and the Euler relationships,

$$\frac{d\Delta T}{dt} + \Delta T \left[\frac{4C_3 T_{ss}^3 - C_2 I_{ss}^2}{C_4} \right] - \Delta I^2 \left[\frac{C_1 + C_2 T_{ss}}{C_4} \right] = 0 \quad (\text{III-12})$$

where $C_1 = aL/A_{xs}$, $C_2 = bL/A_{xs}$, $C_3 = \sigma\phi$, $C_4 = VC_v/v$.

The above ODE has the solution

$$\Delta T = K \Delta I^2 [1 - \exp(-t/\tau)] \quad (\text{III-13})$$

where

$$K = \frac{aL + bLT_{ss}}{4A_{xs} \sigma\phi T_{ss}^3 - bLI_{ss}^2}, \quad \tau = \frac{A_{xs} VC_v}{4A_{xs} \sigma\phi T_{ss}^3 - bLI_{ss}^2}$$

with

$$I_{ss} = \frac{A_{xs} \sigma\phi (T_{ss}^4 - T_a^4)^{1/2}}{\rho L}$$

Thus, Equation III-13 is a method of determining approximate steady state temperatures given the steady state current or the approximate dynamics given either the steady-state temperature or current. Since controller gains tend to vary as the inverse of process gains (31), one might expect

$$\frac{K}{C} = \frac{K_1 T^3 + K_2 I^2}{K_3 + K_4 T} \quad (\text{III-14})$$

Similarly, since τ_I and τ_D are related to the system time constant, one might expect

$$\tau_I = \frac{K_5}{K_6 T^3 + K_7 I^2} \quad (\text{III-15})$$

and

$$\tau_D = \frac{K_8}{K_6 T^3 + K_7 I^2} \quad (\text{III-16})$$

The above could be used as an adaptive tuning technique as discussed in Chapter I.

Phase Change Kinetics

The model used for the nucleation and growth during a phase change was developed by Johnson and Mehl (38) and is based upon the following assumptions:

- (1) "Nuclei tend to form at a constant rate throughout the reaction...."
- (2) "The nuclei grow as interpenetrating spheres."
- (3) "The rate of reaction is derived from the increase in the volume of a sphere which does not include any other sphere."

Bever (39) noted that the general form is applicable to growth other than spherical. The model was incorporated for the SRO to SRO transformation only. The LRO to SRO transformation was assumed to be instantaneous for modeling purposes.

The integrated equation for isothermal conditions is given by

$$f = 1 - \exp(-kt^n) \quad (\text{III-17})$$

where

$$k = \pi N G^3 / 3$$

n = exponential constant ($n=4$ for spherical growth)

N = nucleation rate

G = growth rate

Frye, Stansbury, and McElroy (40) discussed the growth rate and noted that, for pearlite to austenite,

$$G \propto \Delta T \exp(-\Delta F^*/RT) \quad (\text{III-18})$$

where ΔF^* is the change in the free energy of the activated complex and ΔT is the amount of subcooling. The above exponential is of the Arrhenius type. The nucleation rate was also assumed to be of the Arrhenius type. The k term may then be written

$$\begin{aligned} k &= \frac{\pi}{3} N_o \exp(-C_N/T) G_o^3 \Delta T^3 \exp(-3C_G/T) \\ &= \frac{\pi}{3} N_o G_o^3 \Delta T^3 \exp(-3C_G/T - C_N/T) \\ &= A \Delta T^3 \exp(B/T) \end{aligned} \quad (\text{III-19})$$

where $A = \pi N_o G_o^3 / 3$ and $B = -3C_G - C_N/T$. Note that B is of the order of magnitude of the nucleation and/or growth activation energies times $R/4$ based upon the SRO. Thus,

$$f = 1 - \exp(A \Delta T^3 \exp(B/T) t^n) \quad (\text{III-20})$$

For purposes of developing the form of k in Equation III-17, the integrated equation was given first. Recall that Equation III-15 is for the isothermal case, assuming k to be independent of time. The resistometer, however, is not always used isothermally. For the general case, the differential equation is used. Thus,

$$\frac{df}{dt} = -nk(1-f)t^{n-1} \quad (\text{III-21})$$

or

$$\frac{df}{dt} = -An\Delta T^3 \exp(B/T)(1-f)t^{n-1} \quad (\text{III-22})$$

It should be noted that Equation III-22 is coupled with Equation III-11. The modeling problem thus becomes the solving (numerically) of these two differential equations.

There were two methods used to obtain the constants A, B, and n of Equations III-20 and III-22. One was to use isothermal f versus t data to evaluate the constants of Equation III-20. The equation was first linearized in terms of A, B, and n and then regressed using multiple linear regression. Using data from Figure III-2, the following parameters were obtained:

$$A = -3.22 \times 10^{21}$$

$$B = -76,250$$

$$n = 1.686$$

with a coefficient of determination of 0.93. Figure III-3 shows both experimental and calculated f's using the above constants. The major concern with this method was twofold:

- (1) The f of Figure III-2 was based upon isothermal data, which does not directly apply to heating and cooling (41).
- (2) The above parameters did not give good results for resistivity measurements at known cooling rates. This can be seen in Figure III-4.

The method finally chosen was based on the equation

$$\rho = \rho_{\text{SRO}}(1-f) + \rho_{\text{LRO}}(f) \quad (\text{III-23})$$

Since ρ versus T data for 3 different cooling rates were known (1), the above expression and the kinetic model were used to compare various A, B,

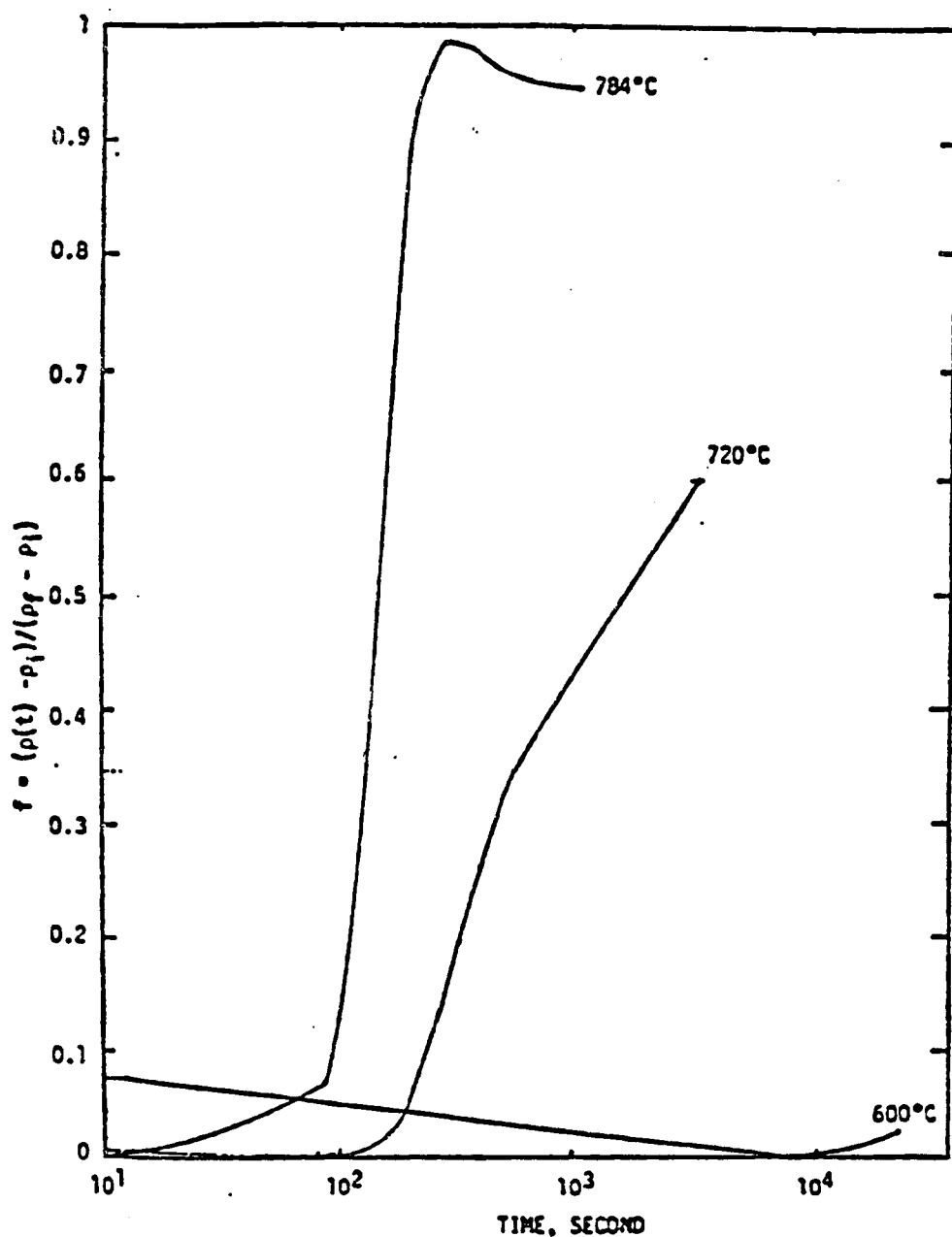


Figure III-2. Experimental data of fraction of LRO in the SRO to LRO isothermal transformation.

Source: Lei, T. S., The Effect of 0-8 Wt. % Iron on Transformations of Alpha Phase Ni-Mo-Fe Alloys with Ni:Mo Ratio Equal to 4:1, Ph. D. Dissertation, The University of Tennessee, Knoxville, (1979).

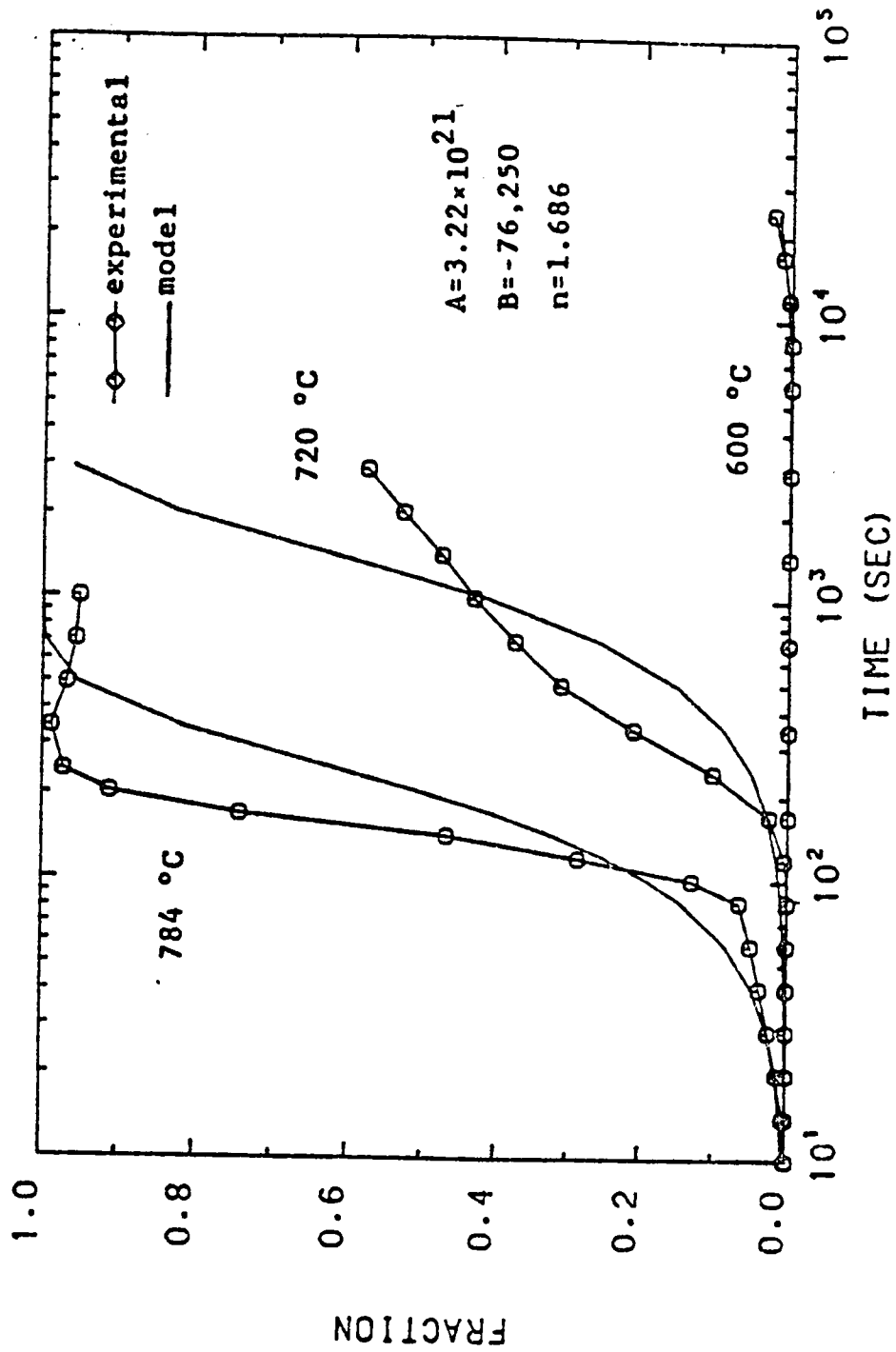


Figure III-3. Fitted isothermal curves of fraction of LRO in the SRO to LRO transformation using multiple linear regression.

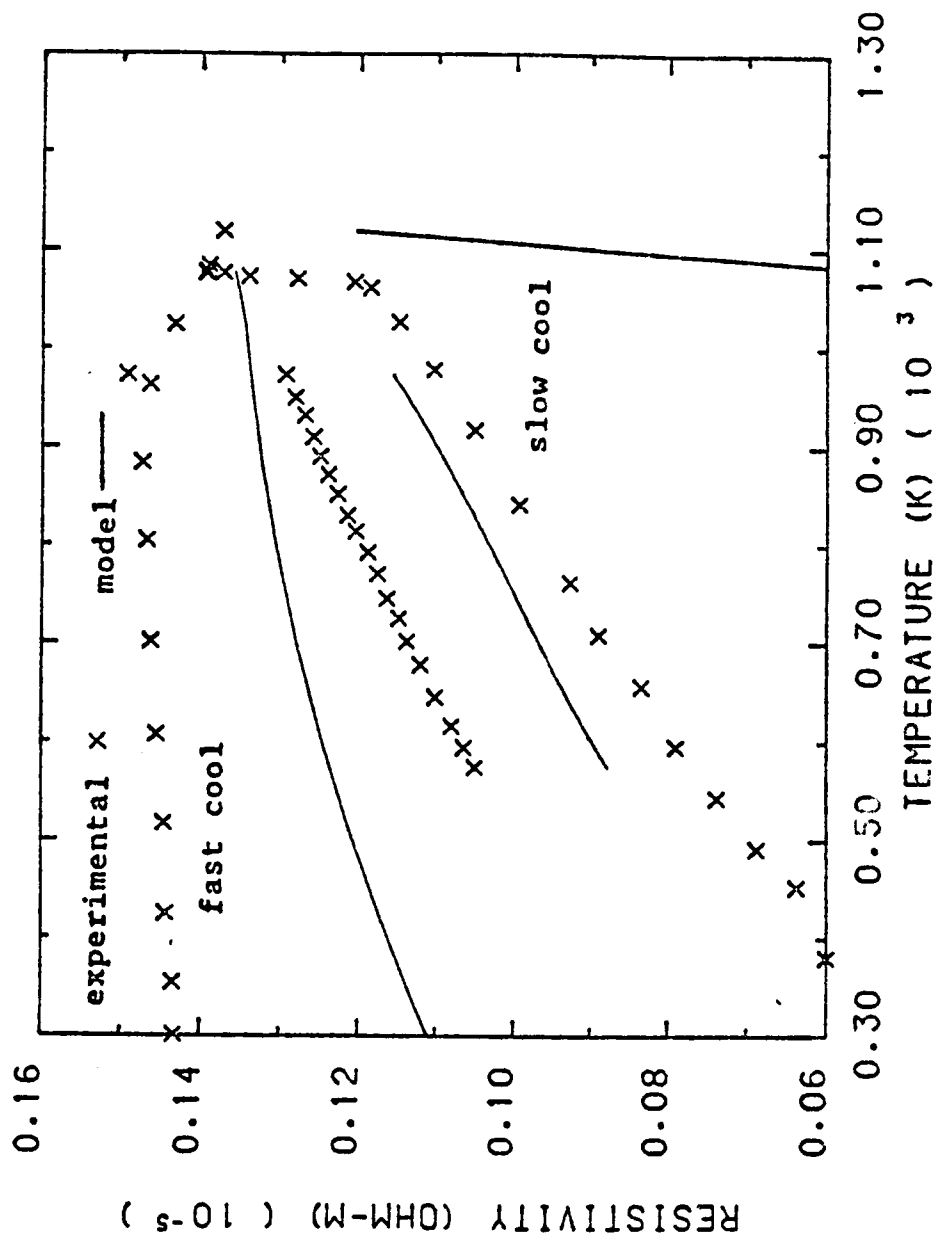


Figure III-4. Resistivity plot for multiple linear regression of the SRO to LRO transformation.

and n values until a minimum in the sum of the squares of the errors between the experimental values of Figure III-4 and the simulation could be found. The ρ_{SRO} was taken to be the fastest cooling rate and ρ_{LRO} to be the slowest. A multiparameter search subroutine called PATTERN (42) was used to estimate the parameters.

The PATTERN subroutine is called by a main program which sets up initial conditions, reads in data, etc. PATTERN calls two subroutines: PROC and BOUNDS. PROC is the subroutine wherein the error (called COST) is calculated from some function, in this case the sum of the squares of the error between the model and the experimental resistivities. BOUNDS is a subroutine to check that the trial values of the searched parameters are reasonable. The main program and the subroutines PROC and BOUNDS are given in Appendix A.

The following parameters from PATTERN were obtained:

$$A = -8.84 \times 10^{13}$$

$$B = -61,330$$

$$n = 1.835$$

Figure III-5 graphically shows these results. The main problem with this method was the assumption that the resistivity can be assumed to be a linear combination of the LRO and SRO phases. Figure III-6 shows the results on a fraction transformed curve, as in Figure III-3. It appears that the "experimental" f and the calculated f significantly differ. The calculations predict slower transformations.

Two significant results can be seen from the parameter values: (1) $n < 2$, i.e., the growth is not spherical ($n=4$) and (2) the activation energies are of the order of $6 \times 10^4 \text{ R/4 J/gmol} \sim 1 \times 10^5 \text{ J/gmol}$.

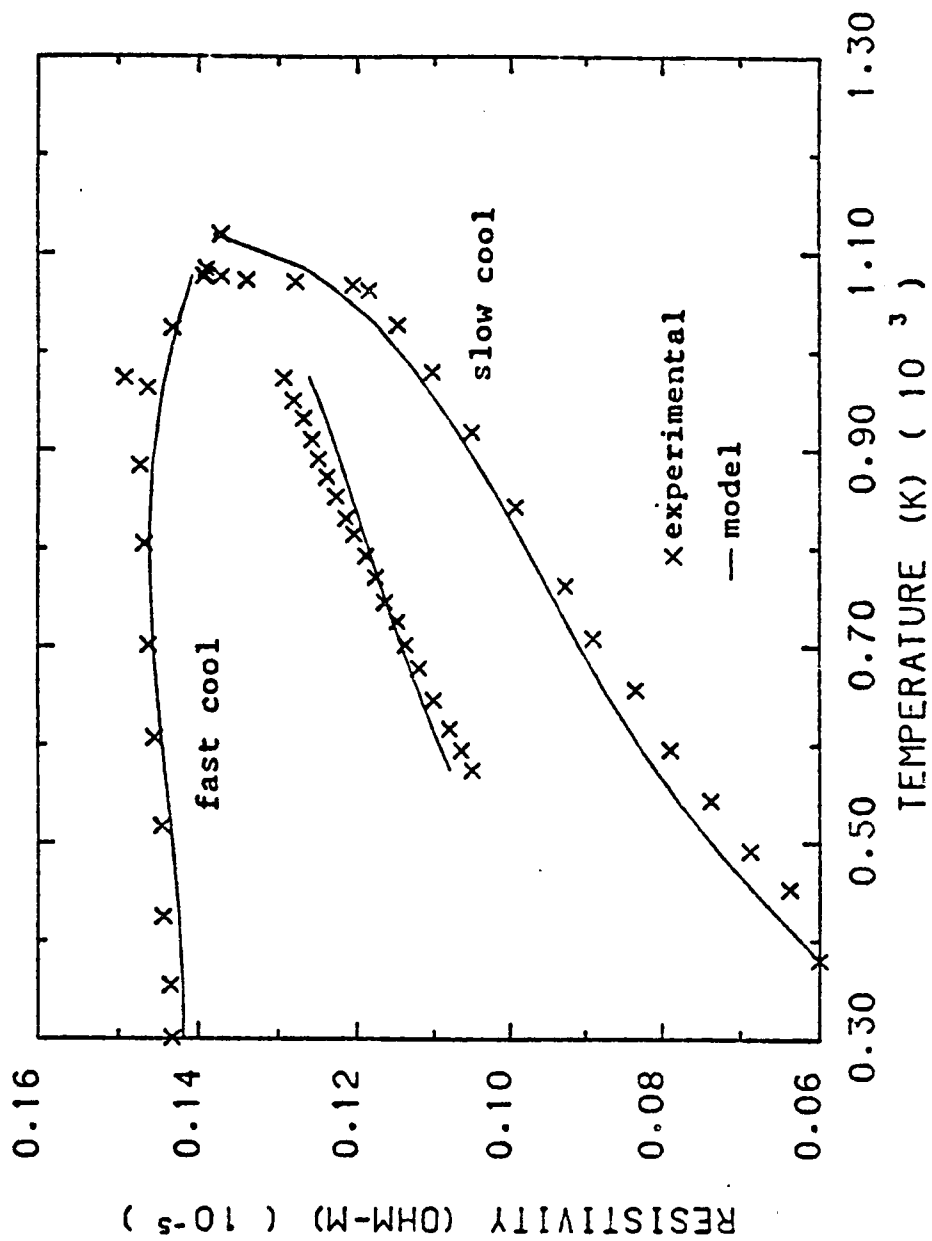


Figure III-5. Resistivity plot for nonisothermal PATTERN fit of the SRO to LRO transformation.

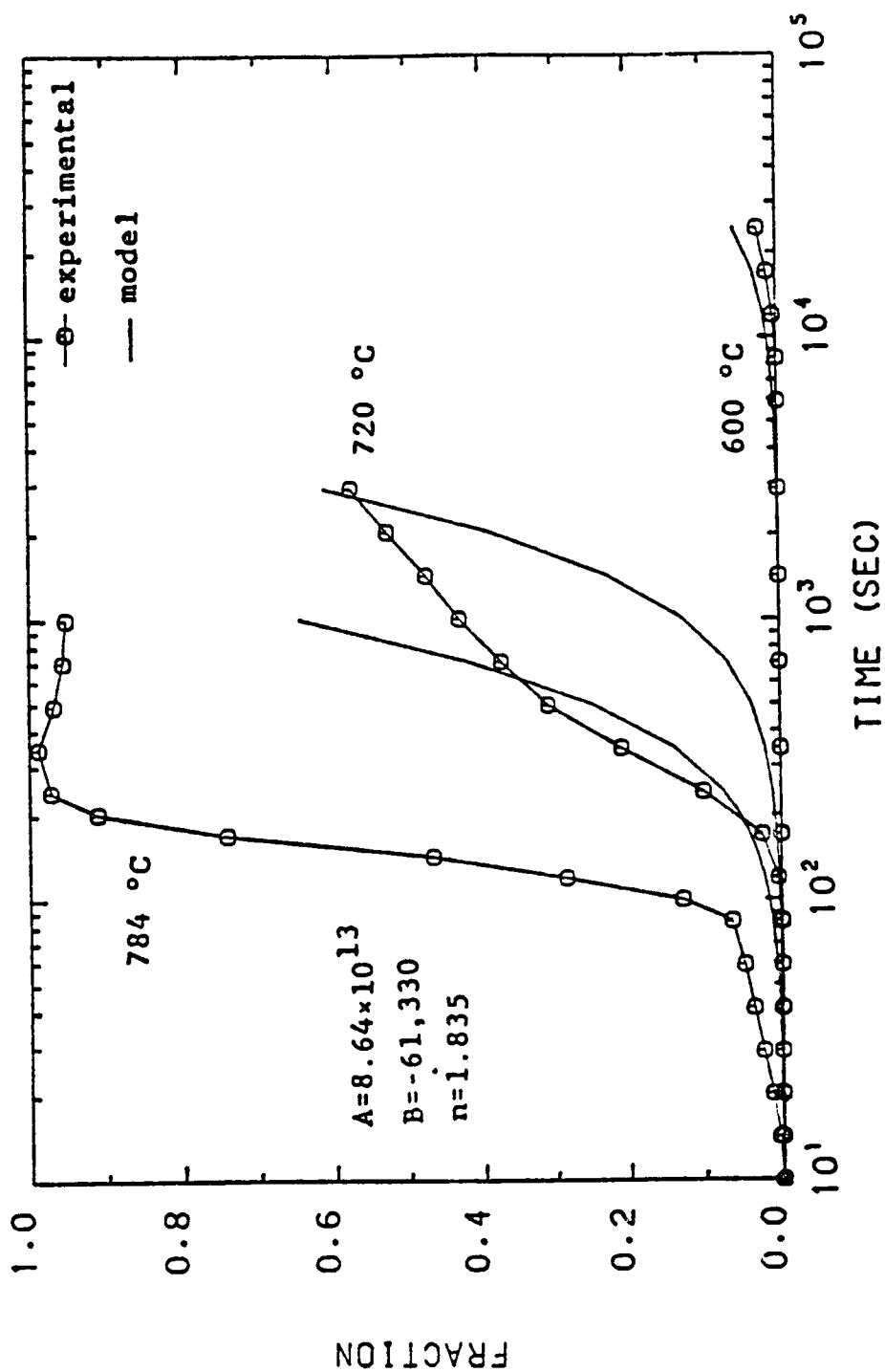


Figure III-6. Fitted isothermal curves of fraction of LRO to SRO transformation using PATERN.

An interesting property of Equations III-20 and III-21 is their ability to predict the "C" curve of the time-temperature-transformation (TTT) curve. This results mainly from the ΔT^3 factor which is related to the thermodynamic driving force (40). Figure III-7 shows the model's TTT curve along with some experimental isothermal data (1). Another way of looking at the TTT curve is by plotting f versus both time and temperature. Such an f -T-T plot is shown in Figure III-8. The TTT curve can be visualized as a slice of the surface at constant f .

Computer Simulation

The model according to Equations III-11 and III-22 was simulated using a FORTRAN program. The model was designed to run as a subroutine for use in not only testing control algorithms, but also possibly as part of a control algorithm.

The algorithm chosen is given in Figure III-9. The order of calculating the temperature, resistivity, sensible heat, and accumulated heat was chosen realizing that all of these physically occur simultaneously. The overall technique used was one of simply stepping through time at a constant rate, equal to the experimental sampling rate. Simple Euler relationships were used to estimate the derivatives.

Equation III-11 contains the following parameters which were evaluated:

$$\rho(T)$$

$$C_v(T)$$

$$L = 0.00698 \text{ m}$$

$$D = 0.0032 \text{ m}$$

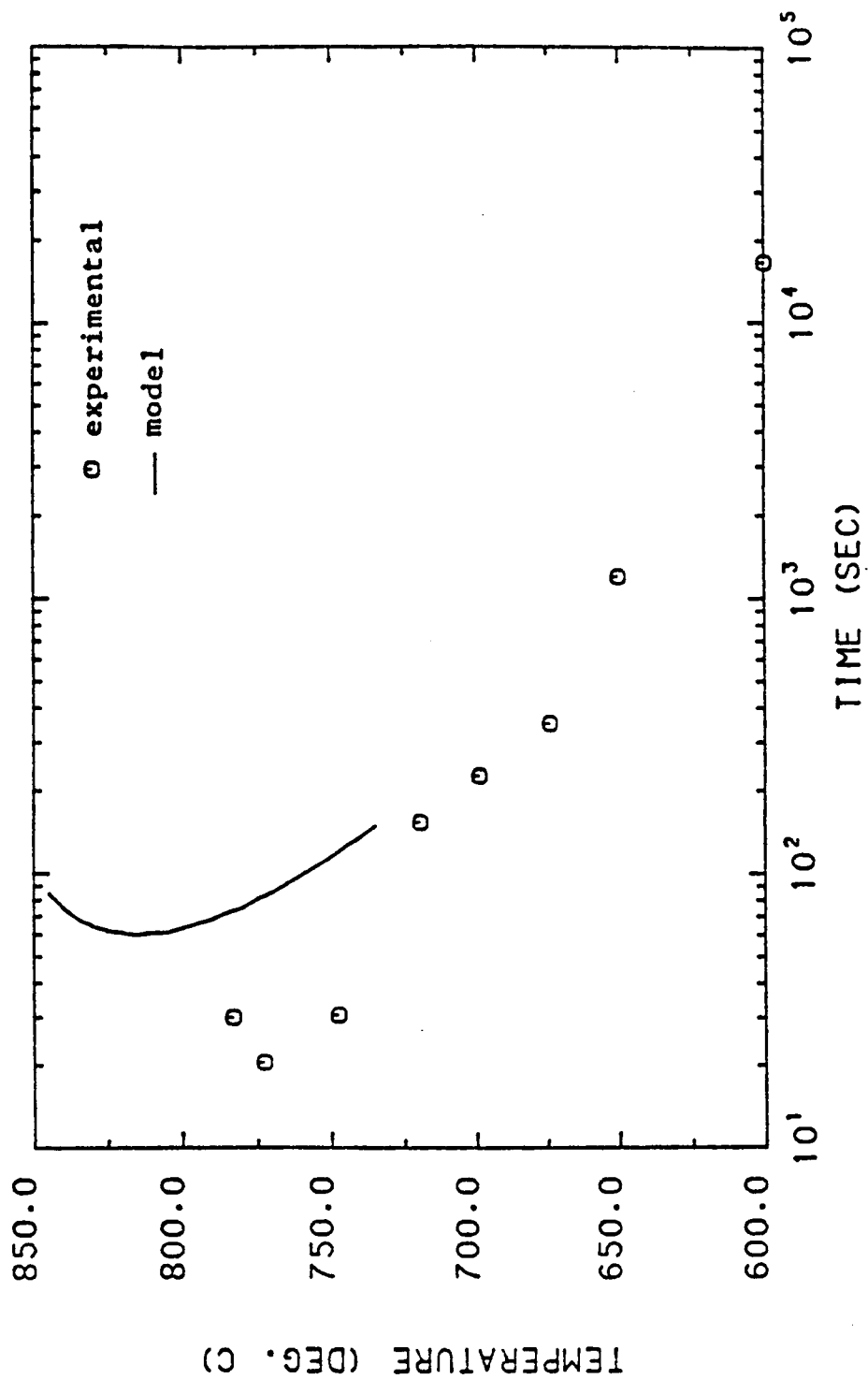


Figure III-7. Model and experimental TTT diagrams for $f=0.01$. The nonisothermal model parameters were used.

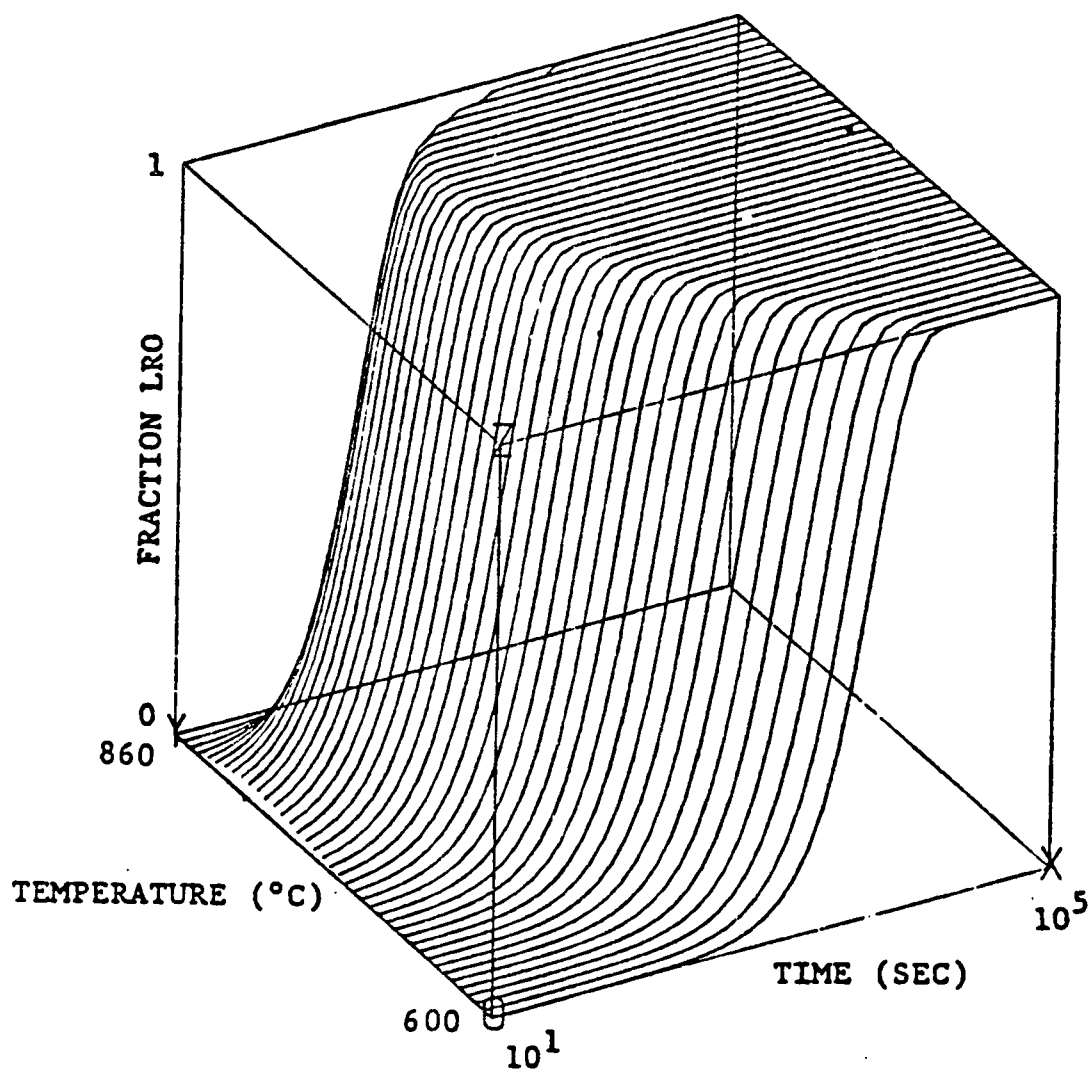


Figure III-8. Fraction of LRO versus time and temperature surface for the PATERN results.

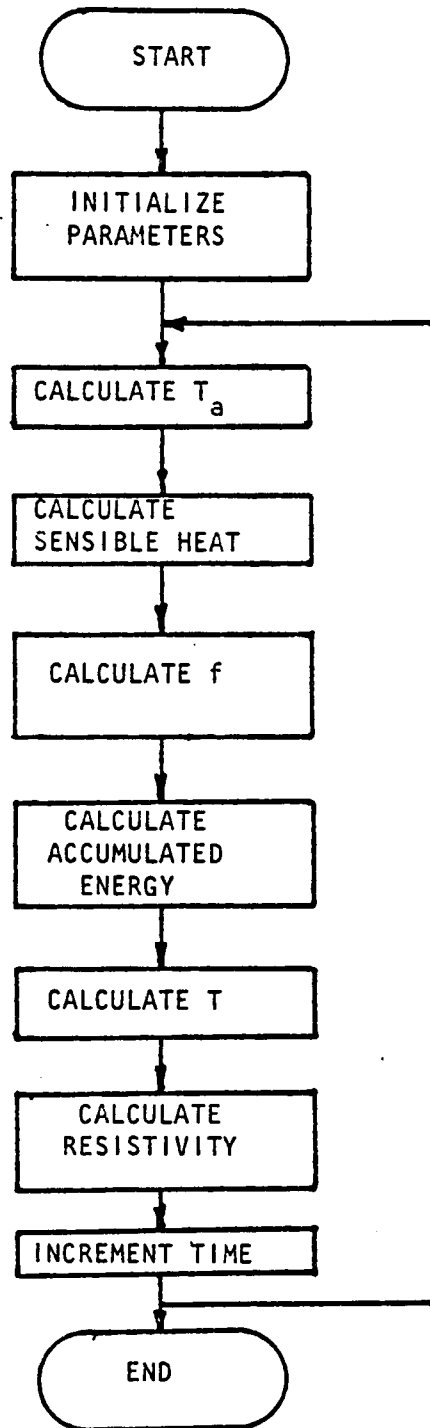


Figure III-9. Computational algorithm for the model.

$$\sigma = 5.677 \times 10^{-8} \text{ J/(s-m}^2\text{-K}^4\text{)}$$

$$\phi(T)$$

$$T_a(T, t)$$

$$k_{tc} = 67.05 \text{ J/(s-m-}^\circ\text{C)}$$

$$L_{tc} = 0.04 \text{ m}$$

$$A_{tc} = 5.067 \times 10^{-8} \text{ m}^2$$

$$v = 0.0001123 \text{ m}^3/\text{kg}$$

$$\Delta H = 51.58 \text{ J}$$

The resistivity versus T was calculated by Equation III-23. Both C_{LRO} and C_{SRO} were fitted by polynomials to experimental data. C_v was calculated by

$$C_v = C_{SRO}(1-f) + C_{LRO} \quad (\text{III-24})$$

C_{LRO} and C_{SRO} data were obtained from Figure III-10. C_{SRO} differs somewhat from the curvy A line of Figure III-10. It was assumed to be a straight line that also incorporated the latent heat. Thus, the model C_{SRO} is higher than the experimental (Figure III-11). ΔH was also obtained from Figure III-10. It was taken to be the area under the phase transition peak. Note that the value of ΔH is specifically for a sample of the dimensions noted above. More generally, for Ni_4Mo , $\Delta H = 30 \text{ kJ/(kg-}^\circ\text{C)}$. The value of ϕ turned out to be approximately the surface area of the sample times the emissivity (due to the dimensions of the outer cylinder with respect to the sample).

The emissivity was obtained by fitting experimental data to a quadratic polynomial in terms of T . Both experimental and fitted data are shown in Figure III-12. The steady-state ambient temperature was also

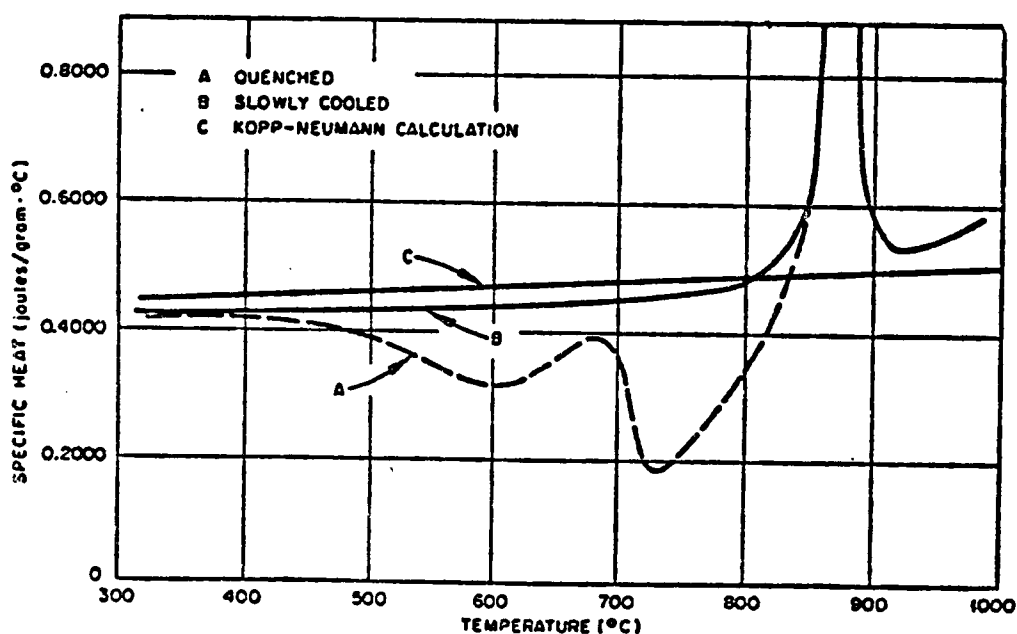
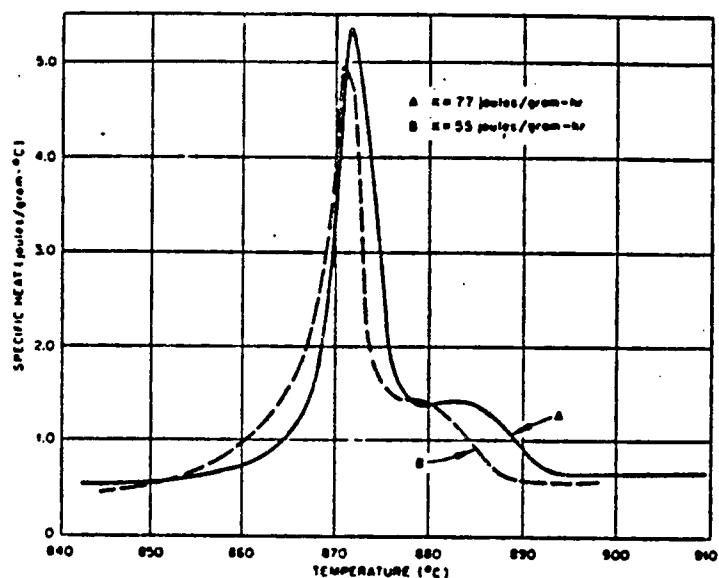


Figure III-10. Heat capacity data for Ni_4Mo .

Source: Noren, W. E., A New Adiabatic Calorimeter for Specific Heat Determination from 250 °C to 1000 °C: Its Use to Study Order-Disorder Reactions in Nickel-Molybdenum Alloys, Ph. D. Dissertation, The University of Tennessee, Knoxville, (1965).

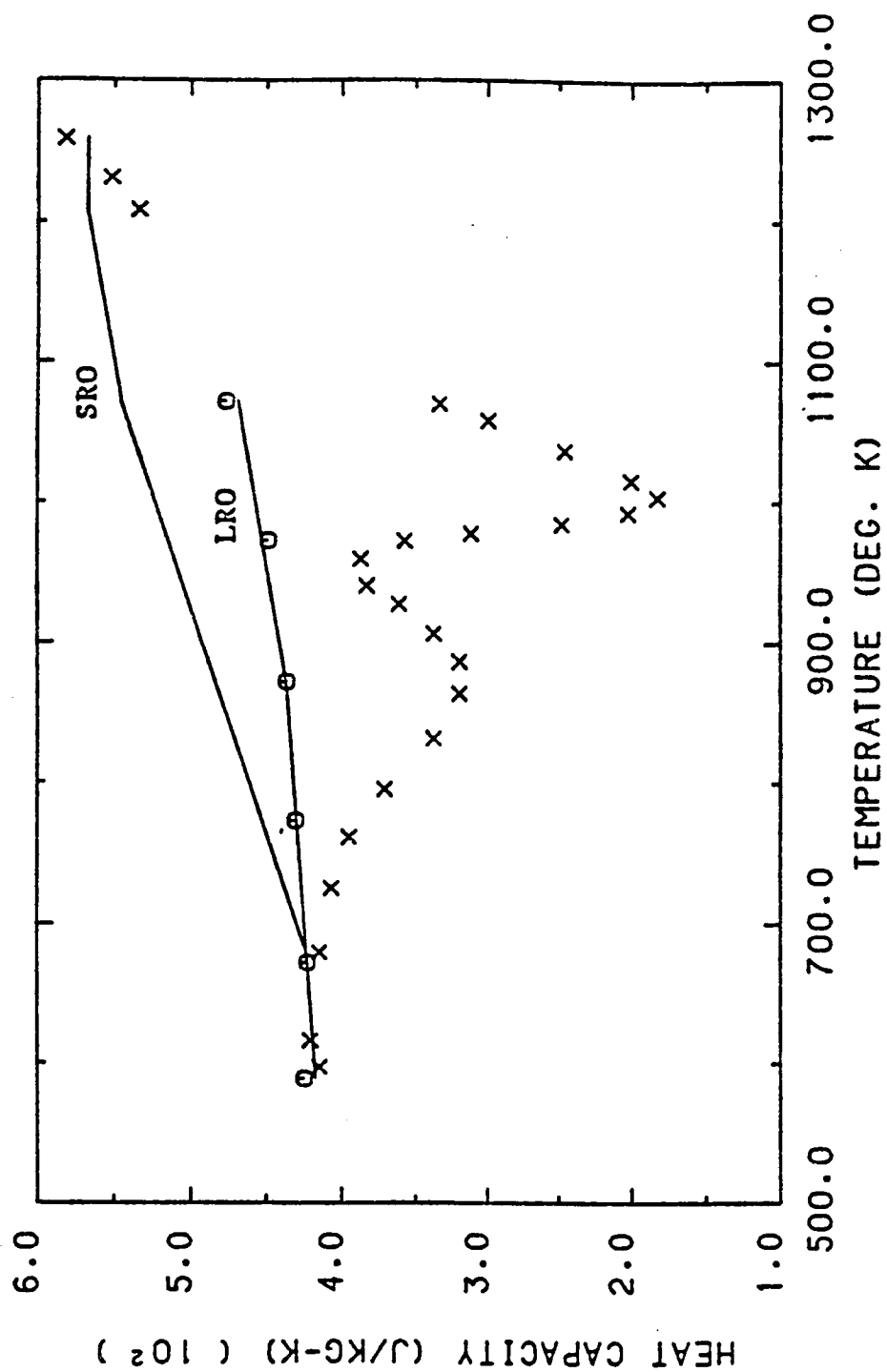


Figure III-11. Fitted heat capacity data for LRO and SRO phases.

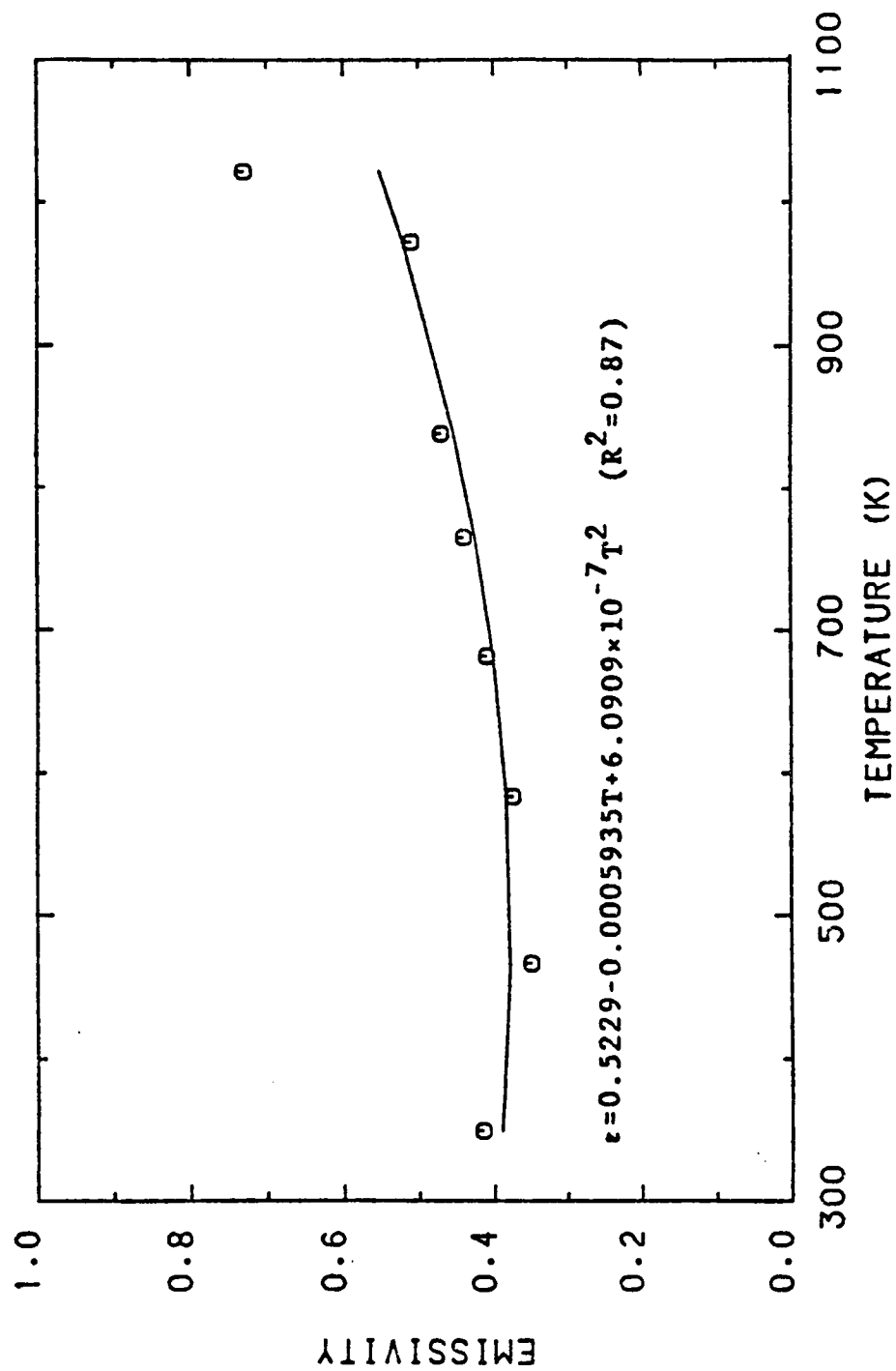


Figure III-12. Experimental emissivity data as a function of the steady-state sample temperature (the highest data point was omitted in the regression).

fitted to experimental data (Figure III-13). T_a was then given first order dynamics and τ_a was found empirically. Thus

$$T_{a,n} = (T_{a,ss} - T_{a,n-1})(1 - \exp(-\Delta t / \tau_a)) + T_{a,n-1} \quad (\text{III-25})$$

The τ_a that best fit a system step test was about 6,000 sec. Thus, the ambient temperature responds rather slowly.

Experimental step tests were done on the equipment, and Figure III-14 shows the results, along with the simulation results. The following should be noted:

- (1) The model predicts the steady-state condition well.
- (2) There is some minor difference in the kinetics near the point where radiation began to become the dominate factor.

Overall, the model reasonably explains the system. Both the heat balance and the phase change kinetics seem to agree, though not perfectly, with the experimental data.

Figure III-15 shows the amount of heat transfer contributing to the steady state temperature, if no phase change takes place. As can be seen, the thermocouple losses are minor, except at low temperatures. The conduction losses through the current wire can now be compared with the other modes of heat transfer. Recall that the current wire losses were about 0.1 J/s, at worst. Compared with the other heat transfer mechanisms of Figure III-15, this is negligible; this model of conduction therefore was not incorporated into the model. Appendix B contains the FORTRAN code for the model of the system.

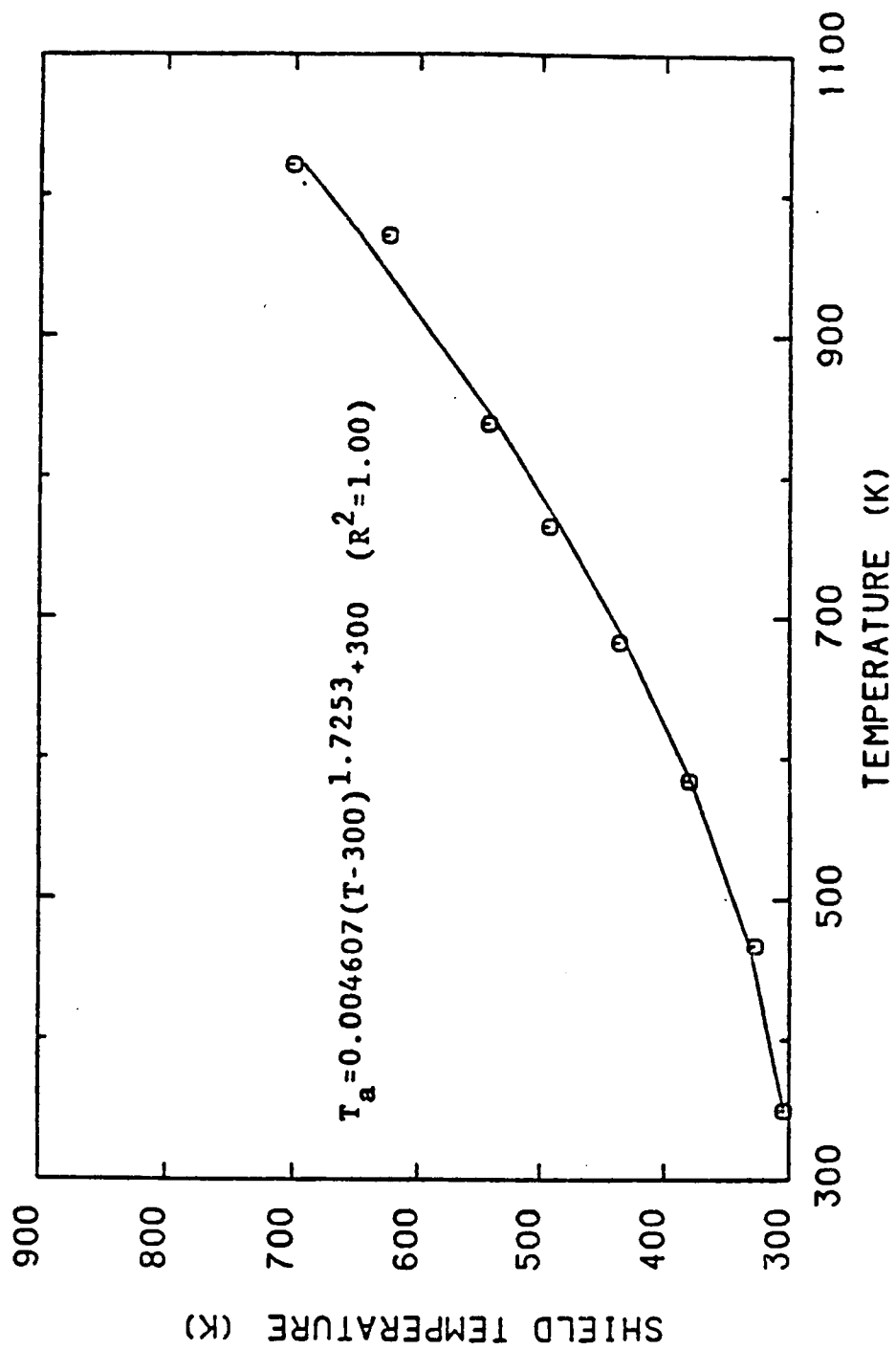


Figure III-13. Steady-state ambient (shield) temperature as a function of the sample temperature.

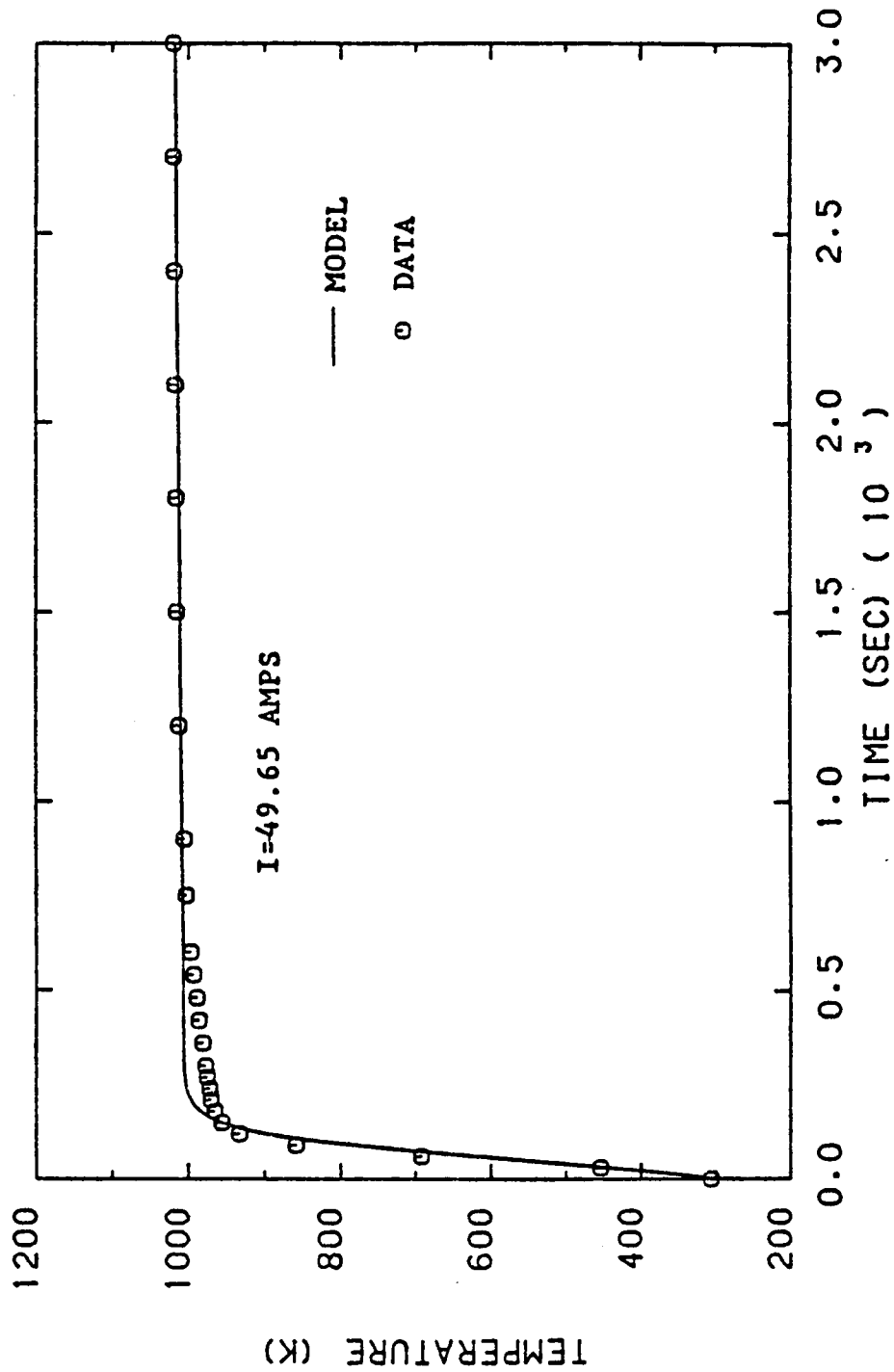


Figure III-14. Model and experimental step test results for a current step of 49.65 amps from 0 amps.

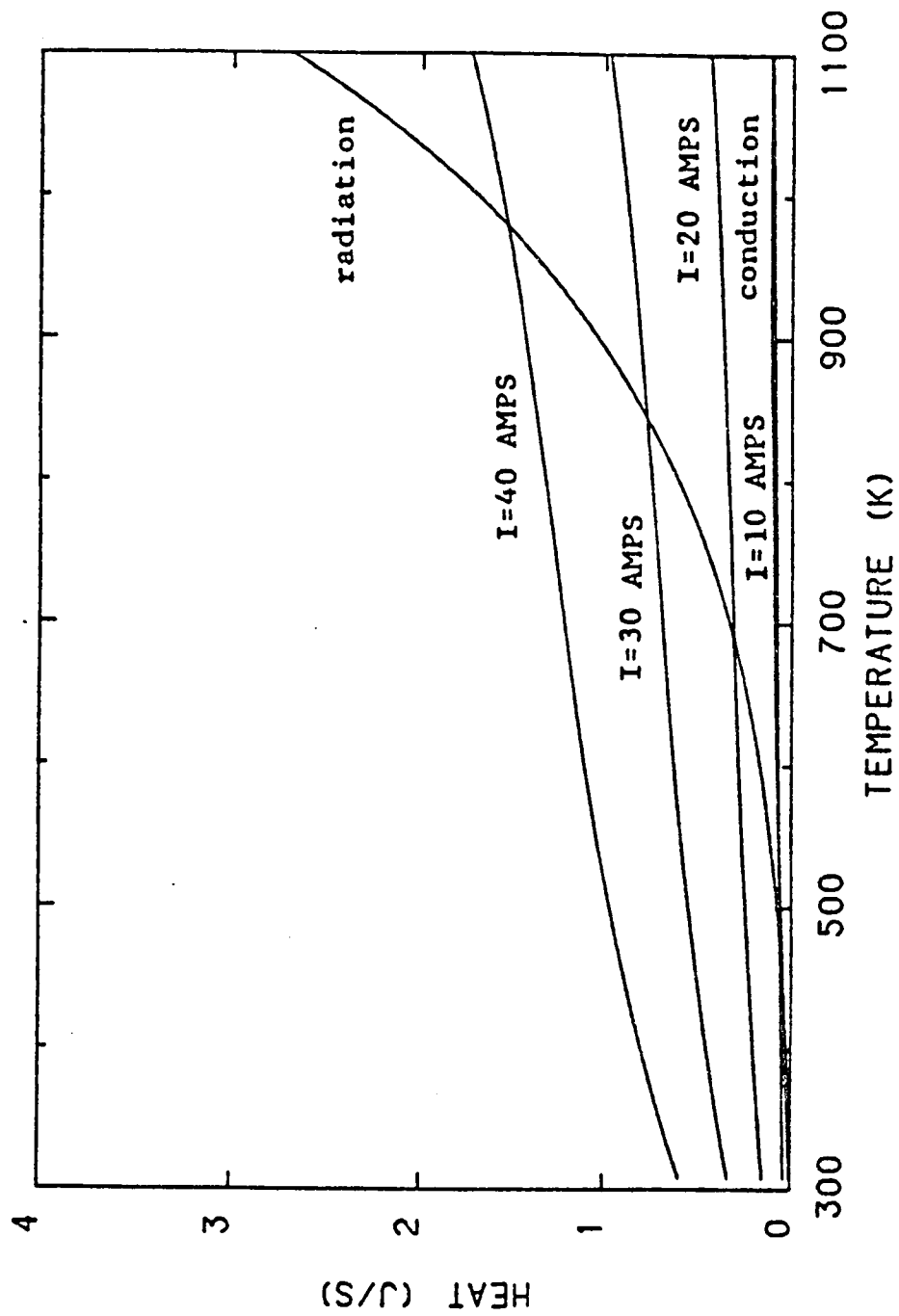


Figure III-15. Magnitudes of various heat transfer mechanisms.

Conclusions

The following may be concluded about the modeling studies.

- (1) Step test results are in good agreement with experimental values. The model is almost totally mechanistic.
- (2) The growth of LRO regions from SRO is probably not spherical, as $n < 2$ would indicate.
- (3) The activation energies of the SRO to LRO transformation are probably on the order of 10^5 J/gmol.

CHAPTER IV

CONTROL

Present Control

The need for reliable temperature control for the resistometer was known during the time of connecting the device to the PDP-15. The computer gave the opportunity for not only control, but data acquisition and programmed heating, cooling, and isothermal experiments as well. Thus, after a run began, no operator convergence was needed. One could start the program, enter a number of different operating regimes, and return a few hours later with the data taken and stored. Obviously, the controller must be reliable for such an operation. The discrete approximation to the PID controller, as discussed in Chapter I, was used (Figure IV-1). The results were somewhat satisfactory. Programmed heating rates ranged from $-1^{\circ}\text{C}/\text{sec}$ (cooling) to $+20^{\circ}\text{C}/\text{sec}$.

For a first order linear process, the PID controller is very capable of achieving the desired control. Step test were performed, and the tuning parameters were calculated from one of these steps for the original PID control settings. The control achieved was within 3°C . Since the process is nonlinear, as discussed in Chapter III, it was soon realized that the optimum control parameters depended upon the process conditions. However, there was no real impetus for another control study until the purchase of the PDP-11 microcomputer.

That the process is significantly nonlinear can be seen in Figure IV-2 where successive step tests were performed a few years ago. The process gain obviously changes with temperature and/or current. An

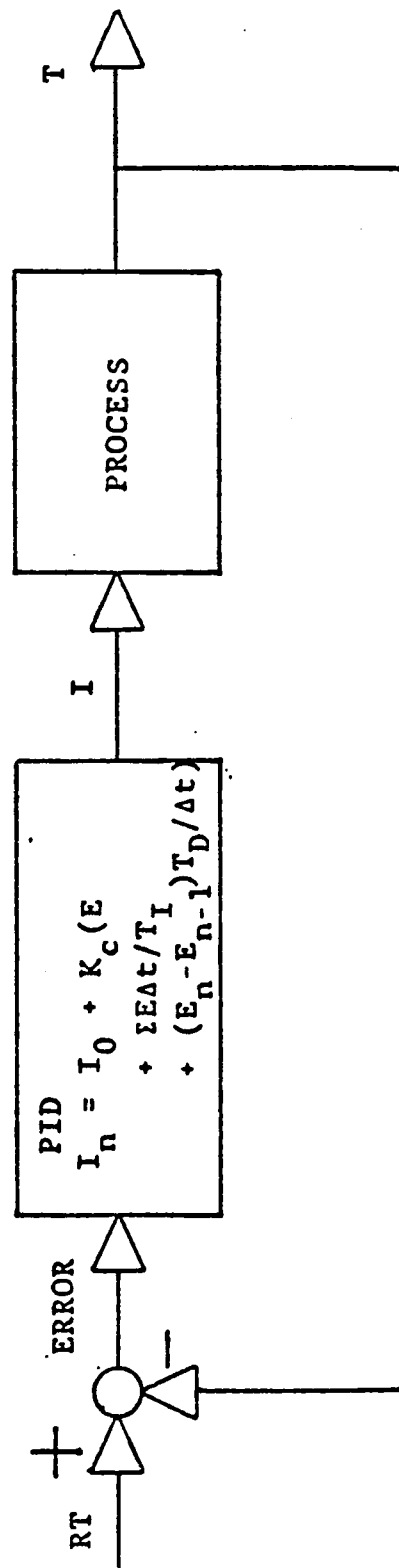


Figure IV-1. Existing control block diagram indicating the discrete PID approximation.

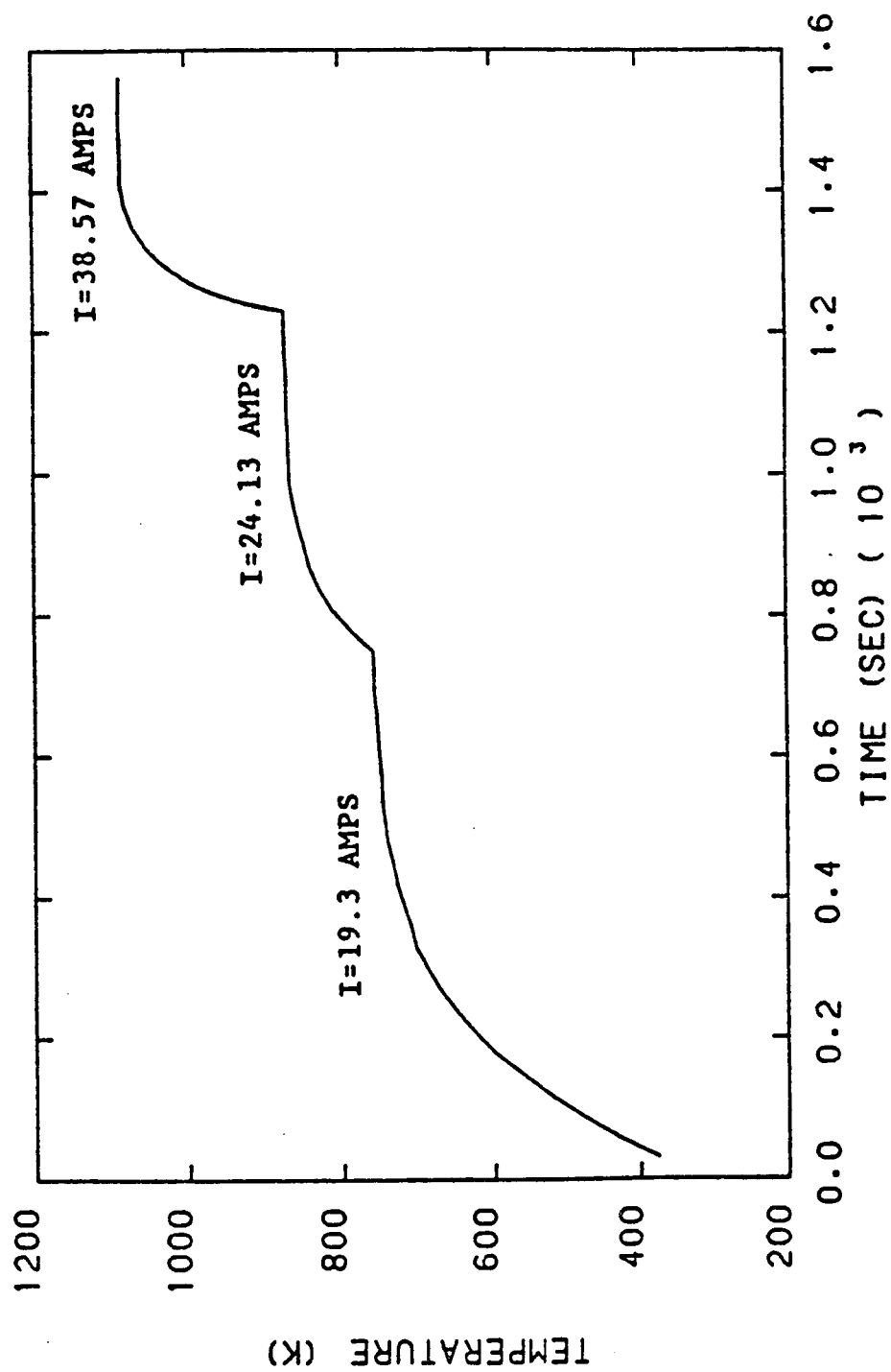


Figure IV-2. Successive step test results illustrating the nonlinearity of the system with respect to temperature.

interesting aspect of the nonlinearity is that the steady-state value of temperature is achieved rather quickly for large current steps and more slowly for smaller steps. This can also be seen from the linearized model in that the process time constant varies as the inverse of the square of the current (Equation III-13). For a set point change to heat the sample, therefore, one can intuitively see that the current should be high initially and taper off to the steady-state value for quick responses.

The present control is adequate in most situations; yet, this project attempts an even tighter control (within 1 °C as opposed to 3 °C) to insure reliable resistivity data acquisition.

Proposed Control Strategy

In previous chapters, it was noted that there are really two regimes where control is needed: (1) heating or cooling and (2) isothermal studies. For heating or cooling at a constant rate, one might use a temperature controller and change the temperature set point at each sampling time by a constant. This was the approach used by the original PID controller. Figure IV-3 illustrates this method and also exhibits one of the problems associated with such control. In (b), one can see that if initially the temperature set point is not reached, the controller will increase the rate of heating until the controller is caught up with the temperature set point. Thus, after the initial error, the rate is still in error in that it is greater than the set point rate in order to catch up ($HR > RHR$). The desired correction is shown in Figure IV-4. In (a), initially there is an error in the heating rate, $RHR > HR$. The controller does not attempt to reach a next temperature set point, but rather tries

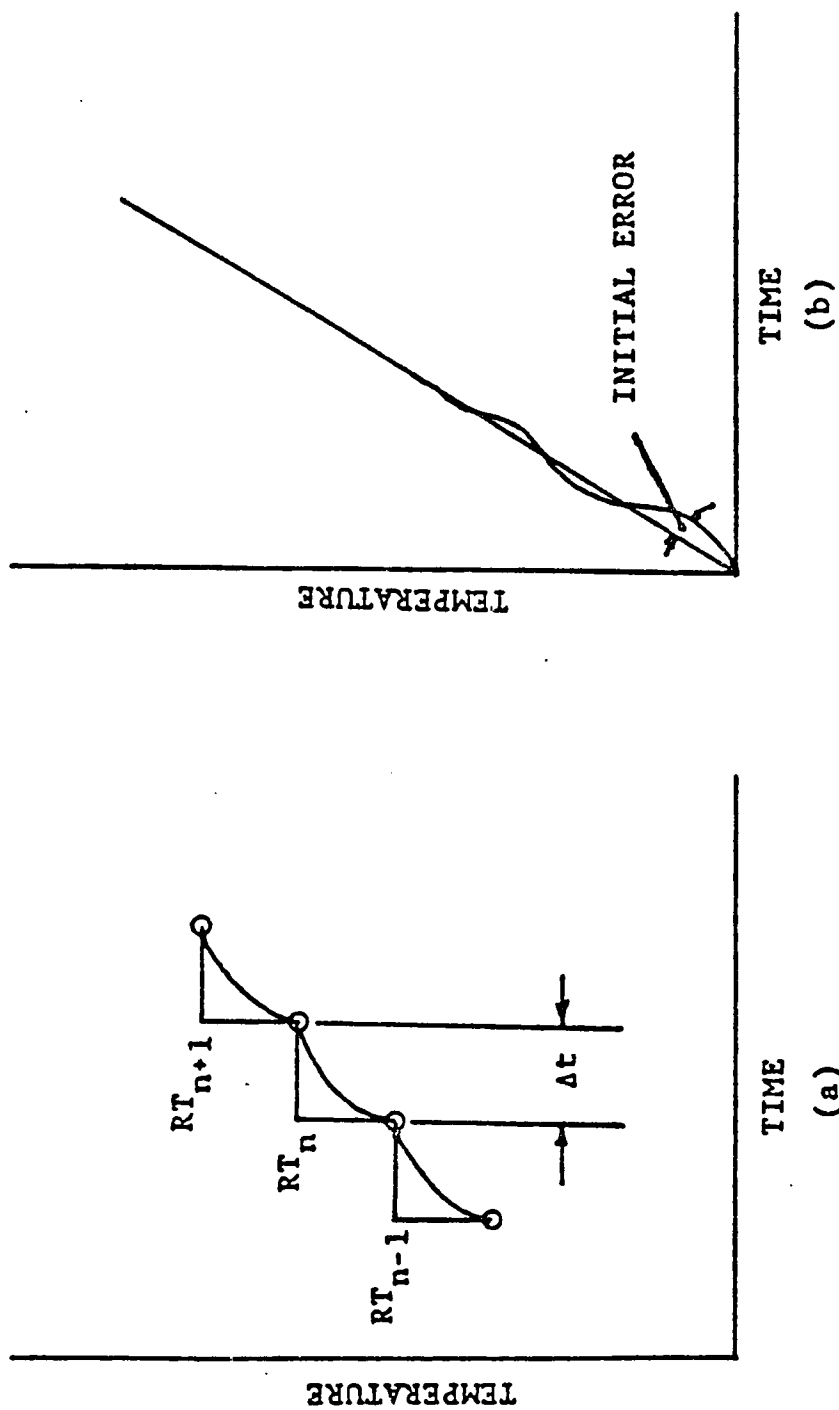


Figure IV-3. Schematic diagram of the process response to temperature control in the heating regime.

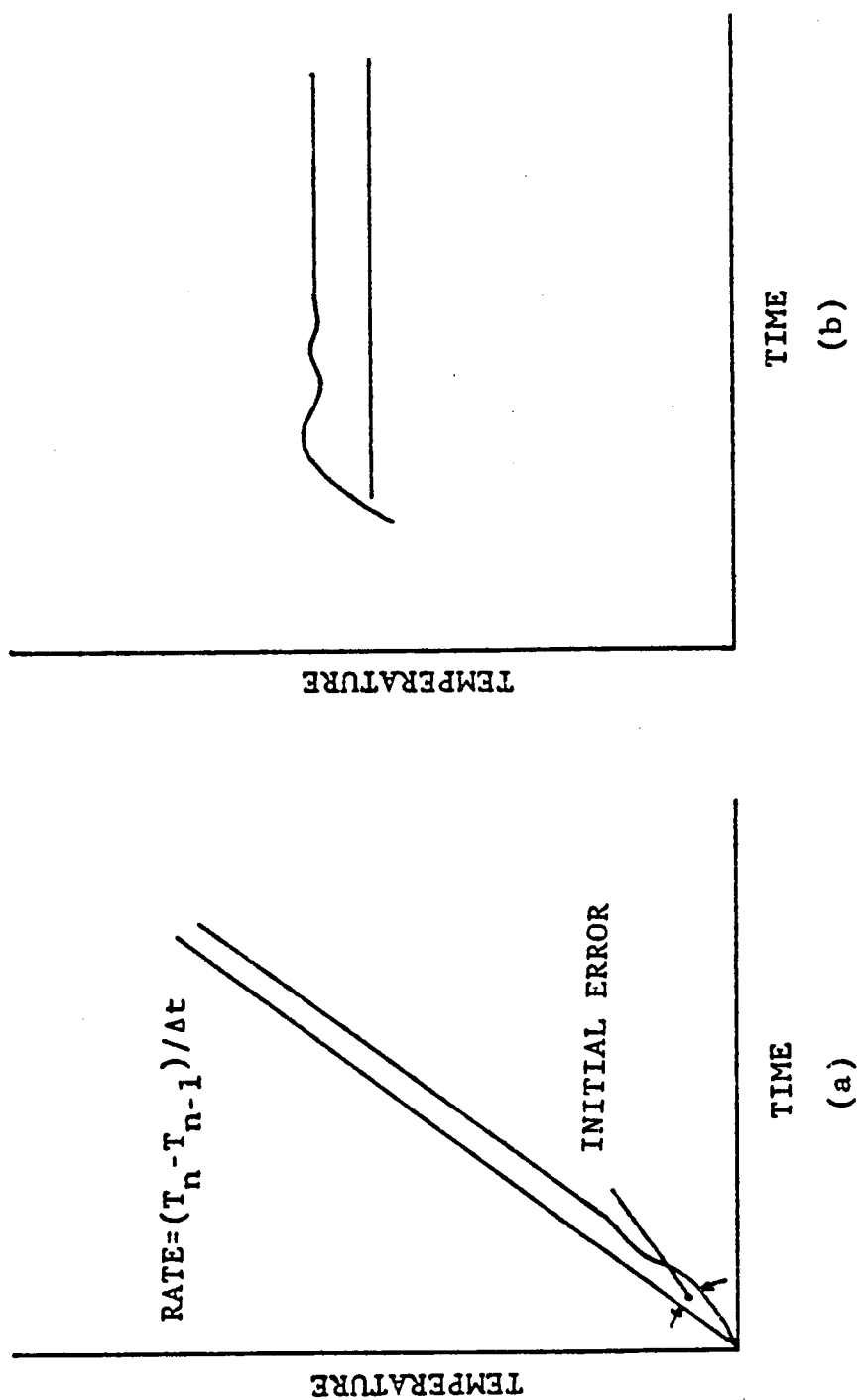


Figure IV-4. Schematic diagram of the process response to rate control in the heating (a) and the isothermal (b) regimes.

to match the slope of the response curve with the set point heating rate. It is thus a rate controller. In this manner, initial errors in rate do not cause such temperature-correcting rate errors as in Figure IV-3 (b).

When the desired rate is zero (isothermal regime), however, the rate controller does not give the desired response. Consider initial conditions of rate error equaling zero and the temperature equaling the set point. If for some reason the temperature is perturbed, then a purely rate controller will only attempt to reset the rate to zero without regard for the need for the temperature to be reset to the set point. This can be corrected somewhat by integral action in a PI rate controller. This, however, is equivalent to a PD controller in temperature. A simple solution with DDC is to use two controllers: a rate controller and a temperature controller. To avoid competition, they can be designed so that one is always turned off when the other is functioning.

Since for one regime a temperature controller is needed and for the other a rate controller is needed, the control strategy will depend upon the heating rate set point. Another control consideration is that a fairly accurate model of the system exists (Chapter III). It would seem somewhat wasteful if the information to be gained by such a model were only used for simulation purposes. The information can be used in terms of a feedforward-feedback control scheme. Recall that the model of the system is given by

$$\frac{I_{ps}^2}{A_{xs}} + \sigma \phi (T_a^4 - T^4) + \frac{4A_{tc} k_{tc}}{L_{tc}} (T_a - T) = \frac{Vd(C_v T)}{vdt} - \frac{d[(1-f)\Delta H]}{dt} \quad (IV-1)$$

The information available to the controller are the temperature, time, and resistivity at the previous measurement. For the resistivity, this information can be 30 seconds old. By possessing information concerning the resistivity versus temperature curve, one can estimate the fraction of LRO. If the actual resistivity is denoted ρ and the estimate of ρ for the LRO and SRO as ρ_{LRO}^* and ρ_{SRO}^* , respectively, then from the relationship $\rho = \rho_{SRO}(1-f) + \rho_{LRO}(f)$,

$$f = (\rho - \rho_{SRO}^*) / (\rho_{LRO}^* - \rho_{SRO}^*) \quad (IV-2)$$

Knowing what the next temperature should be from the desired rate and the sampling period, and denoting it T^* , then

$$\rho(T^*) = \rho_{SRO}^*(T^*) \times (1-f) + \rho_{LRO}^*(T^*) \times f \quad (IV-3)$$

Since the model also contains C_v versus T data, the heat capacity can be estimated. By saving previously calculated parameters, the model current necessary to reach T^* is given by

$$\begin{aligned} I_n^* = & \frac{A_{xs}}{\rho_n^* L} \frac{(1-f_n)\Delta H - (1-f_{n-1})\Delta H}{\Delta t} \\ & + \frac{V}{v} \frac{C_{v,n}^* T_n^* - C_{v,n-1}^* T_{n-1}^*}{\Delta t} \\ & + 4A_{tc} k_{tc} / L_{tc} (T_n^* - T_{a,n}^*)^{1/2} \end{aligned} \quad (IV-4)$$

Equation IV-4 was thus used as the model for the feedforward controller.

A few comments about Equation IV-4 should be made. First, the expression in terms of current is in closed form. Thus, no iterative techniques are necessary. Secondly, the main errors associated with the

equation are probably C_v , T_a , and ϕ . Thirdly, the heat transfer mechanisms in the equation contain all of those that were deemed important in Chapter III.

Figures IV-5 and IV-6 show block diagrams for the proposed control strategies for both heating/cooling and isothermal regimes, respectively. In Figure IV-5, the set point (heating rate) is compared with the actual heating rate to give an error MR. The set point is also sent to the model to calculate T^* and I_n^* (I_n^* equals FFC in the diagram). Since the model will have errors in it, a correction is necessary, ΔR . The correction is calculated with a PI controller, as discussed in Chapter I. The combined current is then output to the process and the temperature and resistivity fed back.

For the temperature controller, the process is generally the same. The set point rate is zero and T^* becomes RT (set point temperature). The control action is PI, as with the rate controller. Figure IV-7 shows the flowchart of the controller calculations and indicates the method of separation of the regimes of temperature and rate control. It is interesting that in general, the controller output M represents the error due to the model, which is independent of the specific controller used. Thus, both the temperature and the rate controller utilize the same M. As for windup in M (controller saturation), after the control action is calculated, including correcting for possible physical limitations, the value of M is recalculated by $M=I-FCC$.

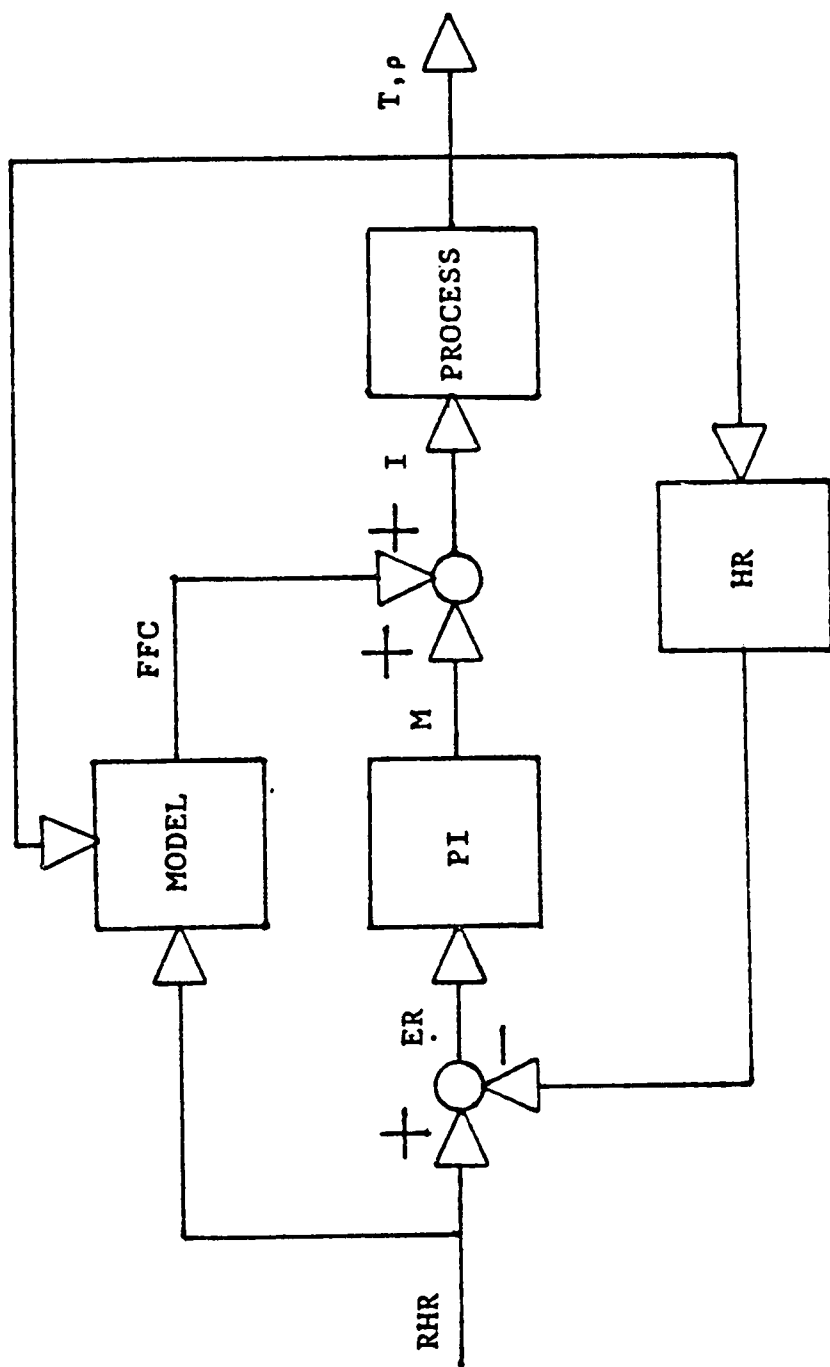


Figure IV-5. Schematic block diagram of the rate control system.

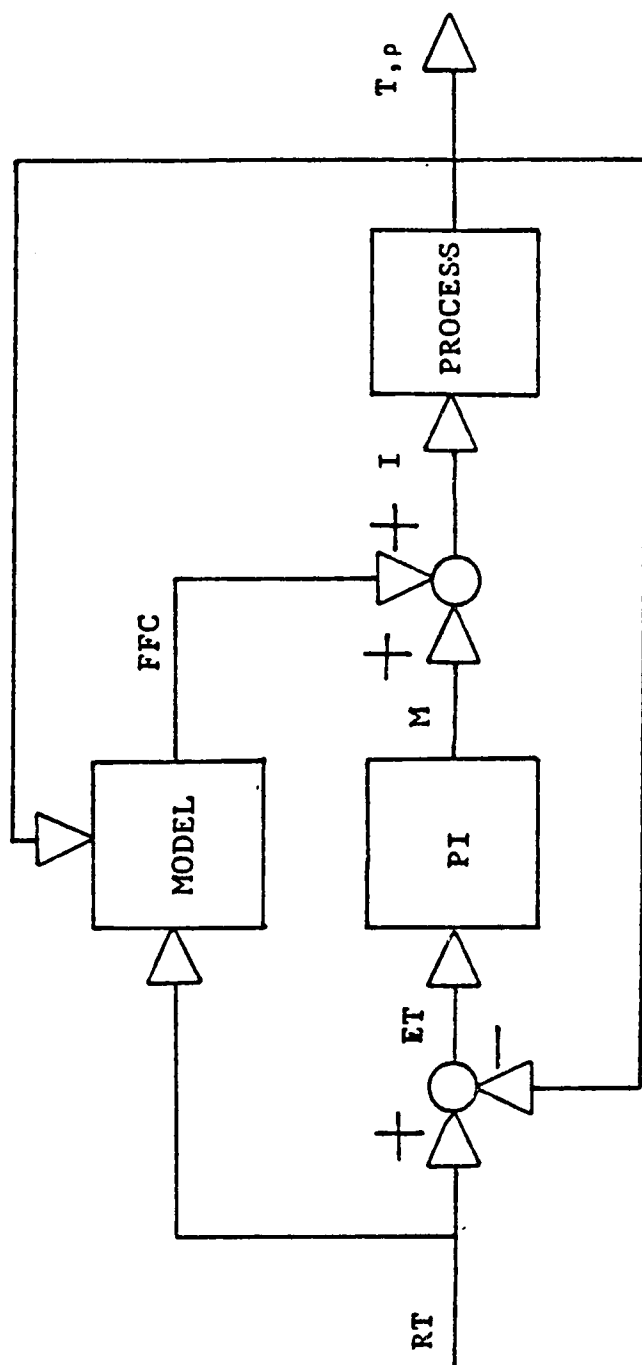


Figure IV-6. Schematic block diagram of the temperature control system.

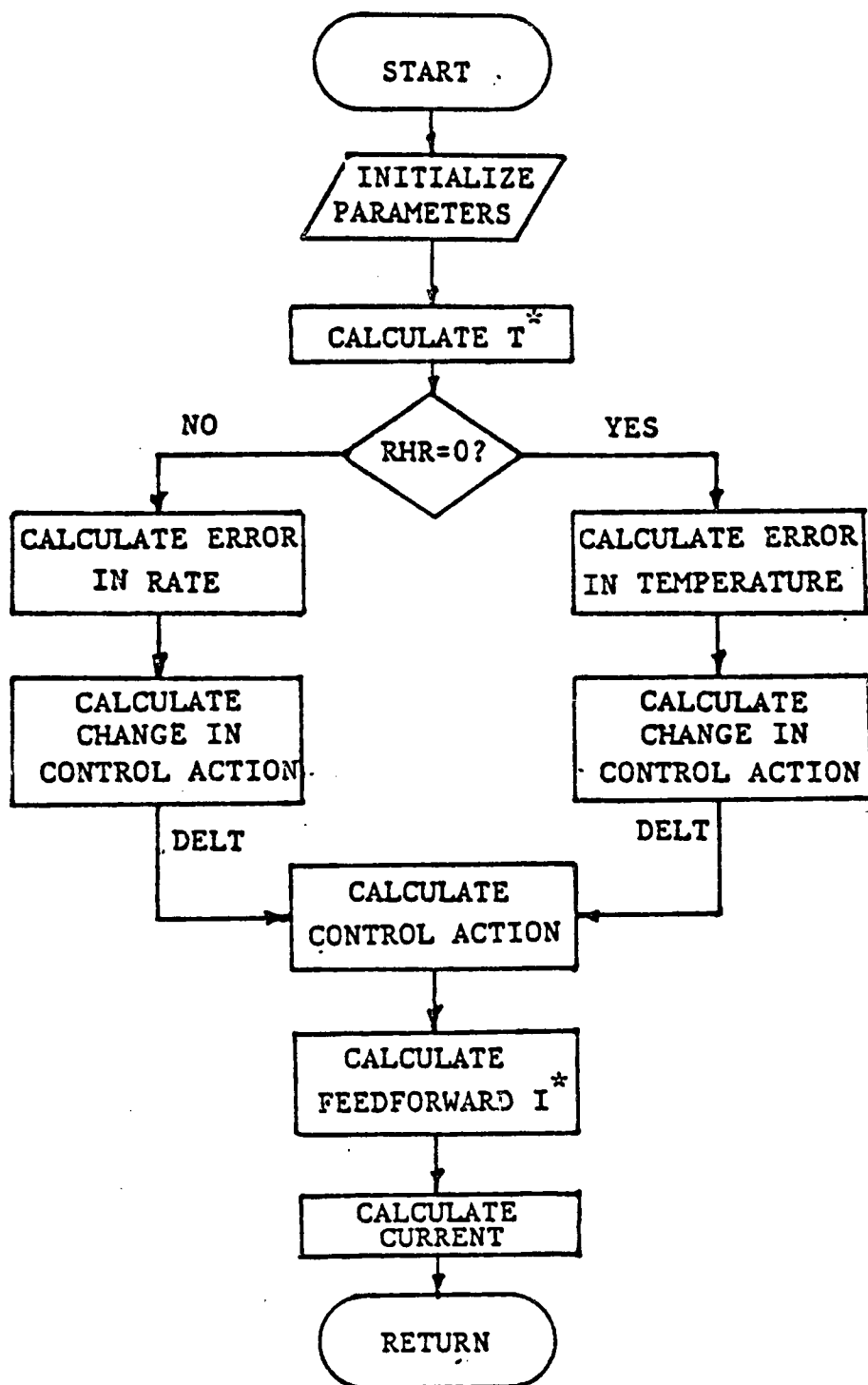


Figure IV-7. Flowchart of the control algorithm indicating the separation of the temperature and rate control regimes.

Controller Tuning

Once the control strategy was chosen, the controllers needed to be tuned. The subroutine PATTERN was also used for this purpose. The method used for tuning was the integral of the absolute error (IAE). The model in the feedforward control algorithm should compensate for much of the nonlinearities of the system. Thus, adaptive control is not as necessary when a mechanistic (and accurate) model is available and used in a feedforward predictive scheme.

Upon calculating the tuning parameters of the temperature controller with the feedforward controller in place, it was found that the controller gain and integral time do vary a little with respect to temperature. However, it was also found that these parameters are more sensitive to the history of the heating of the sample, which affects the amount of SRO in the sample. A controller gain of $K_C=1.0$ was used for LRO regions and $K_C=0.5$ for the regions that contained 10% or more SRO. The integral time used was $T_I=3.5$.

As for the rate controller, the results of PATTERN's IAE tuning showed that there was not much difference in the values of the controller gain and integral time as a function of set point rate and temperature. The values thus used for the rate controller were $K_C=0.23$, $T_I=0.35$.

Before the control strategy could be tested on the simulation, the controller and the model had to differ for any meaningful tuning and comparison. Otherwise, the only correction that the PID controllers would have to make on the feedforward controller would possibly be some lagging behind of the controller by one sampling period. This would make tuning impracticable. Thus, the model (process simulation) was perturbed by

changing the emissivity model of the sample. This was preferred to changing the resistivity model since the controller uses the actual resistivity measurements for calculations. Thus, at steady state, the feedforward control would be the same as the simulation. However, in terms of an actual Ni_4Mo sample, this allows some model flexibility in the controller (also inputted to the controller are the sample dimensions). Thus, the model was perturbed by setting the emissivity to a constant (0.6).

Control Simulation Results

Figures IV-8-12 show the results of testing the controller for heating. Figures IV-8 and IV-9 are for low heating rates, and Figures IV-10 and IV-11 for high heating rates. There is some offset in temperature in the rate controller, which is more noticeable at lower temperatures due to the different scaling in the diagrams. There is a small overshoot ($<4^\circ\text{C}$) for one sampling time (2 sec.) at higher temperatures when heating very rapidly. The time period of recovery is so short as to not appreciably affect the phase transformation.

Test results for various heating and cooling rates can be seen in Figure IV-12. The control is generally the same as for the heating-only curves: tight with little or no overshoot. Some offset in temperature during rate control does exist (though small) due to the nature of the rate controller as discussed earlier (see Figure IV-4). Note that the testing was not just for the system below T_C ; the testing encompassed the entire range of operating conditions and utilized the phase change

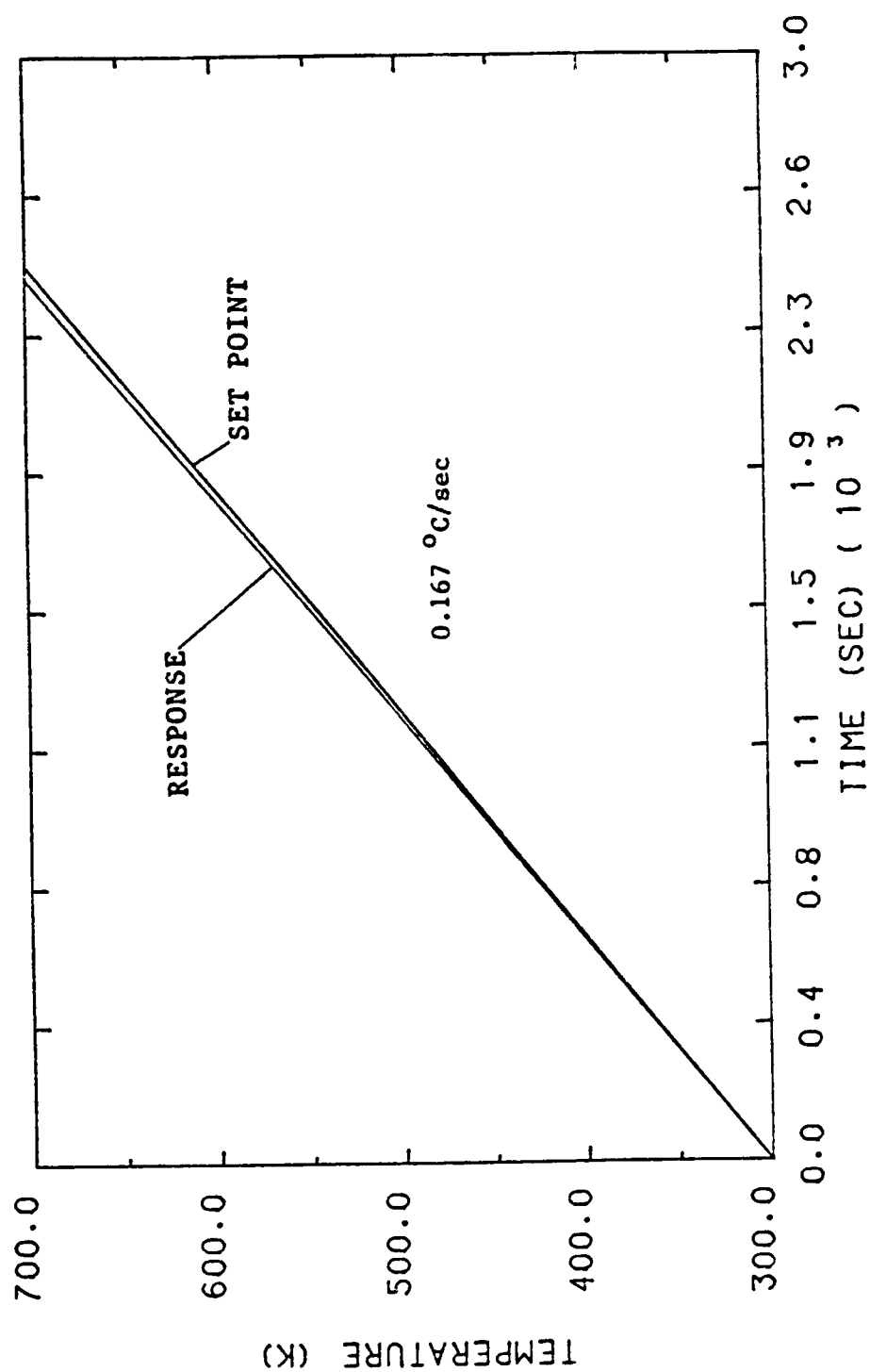


Figure IV-8. Response for a low heating rate set point and a low temperature set point.

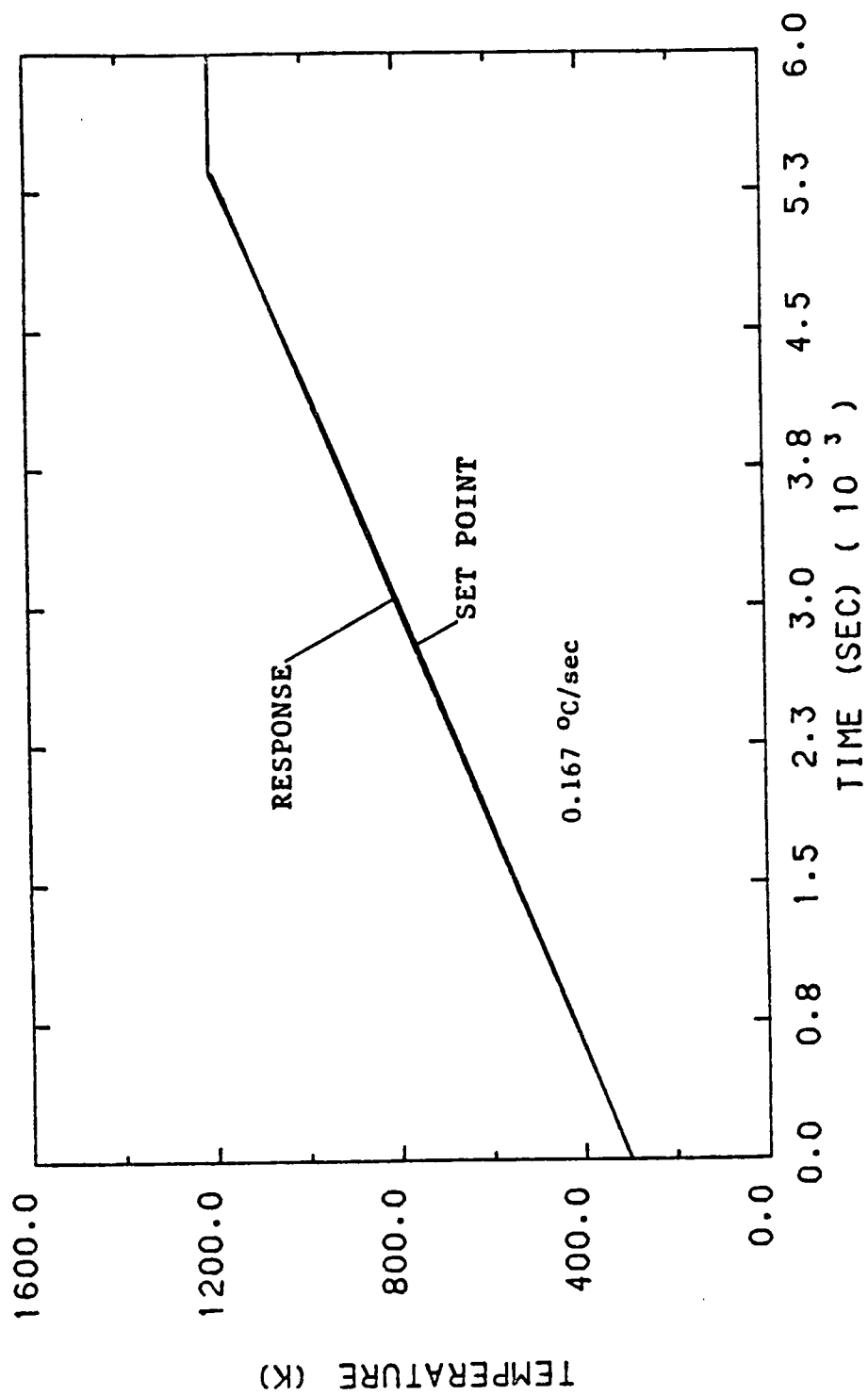


Figure IV-9. Response for a low heating rate set point and a high temperature set point.

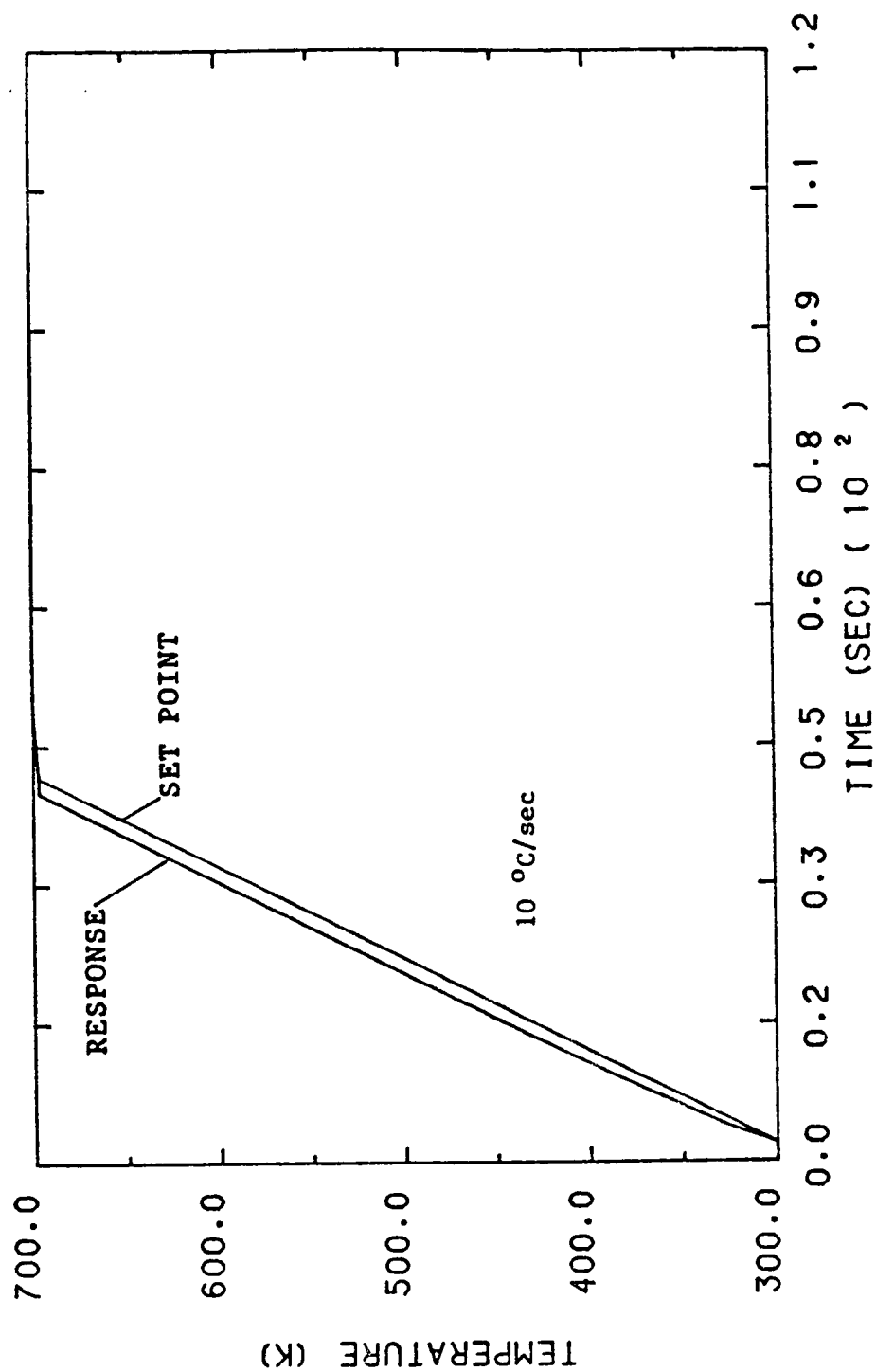


Figure IV-10. Response for a high heating rate set point and a low temperature set point.

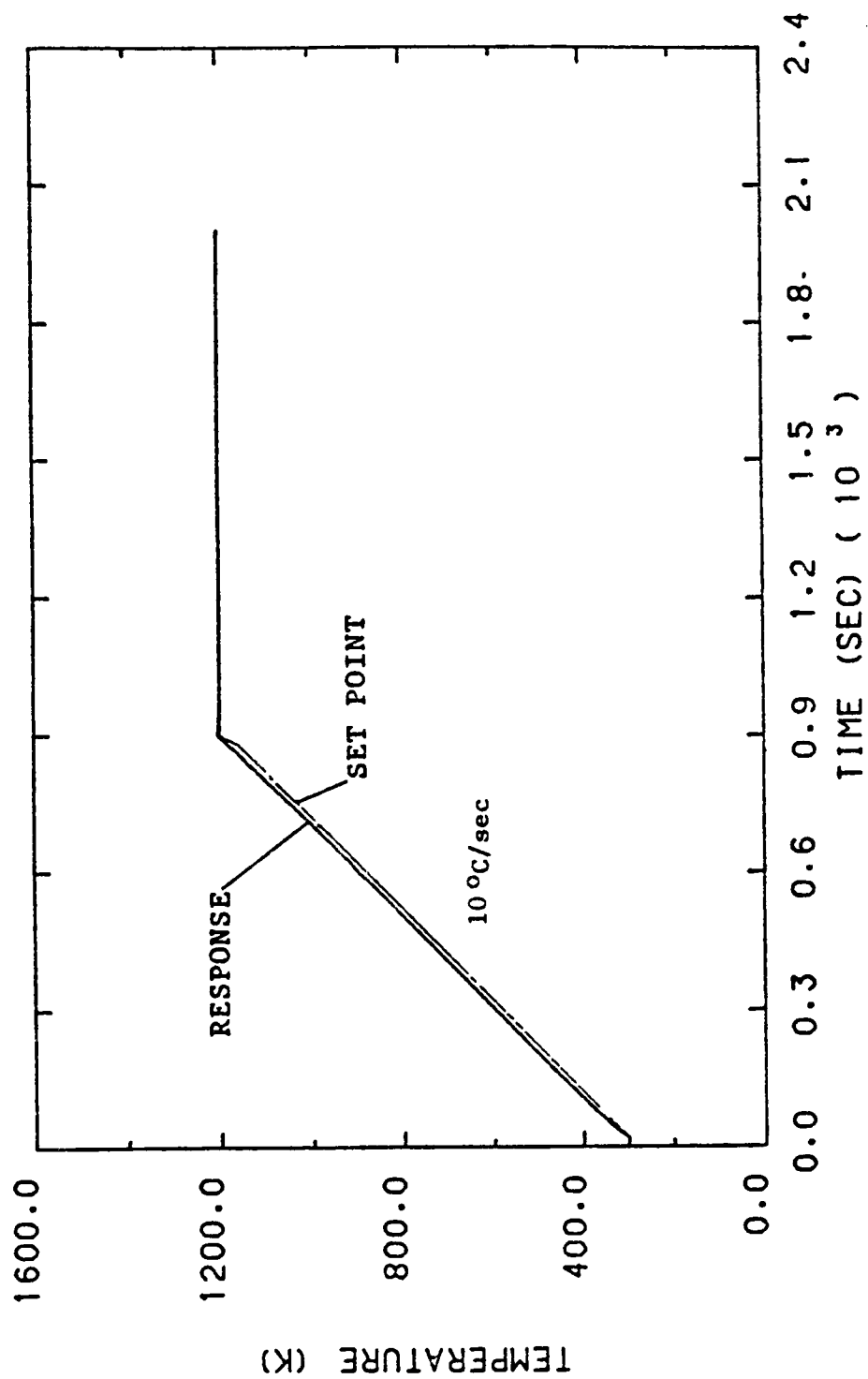


Figure IV-11. Response for a high heating rate set point and a high temperature set point.

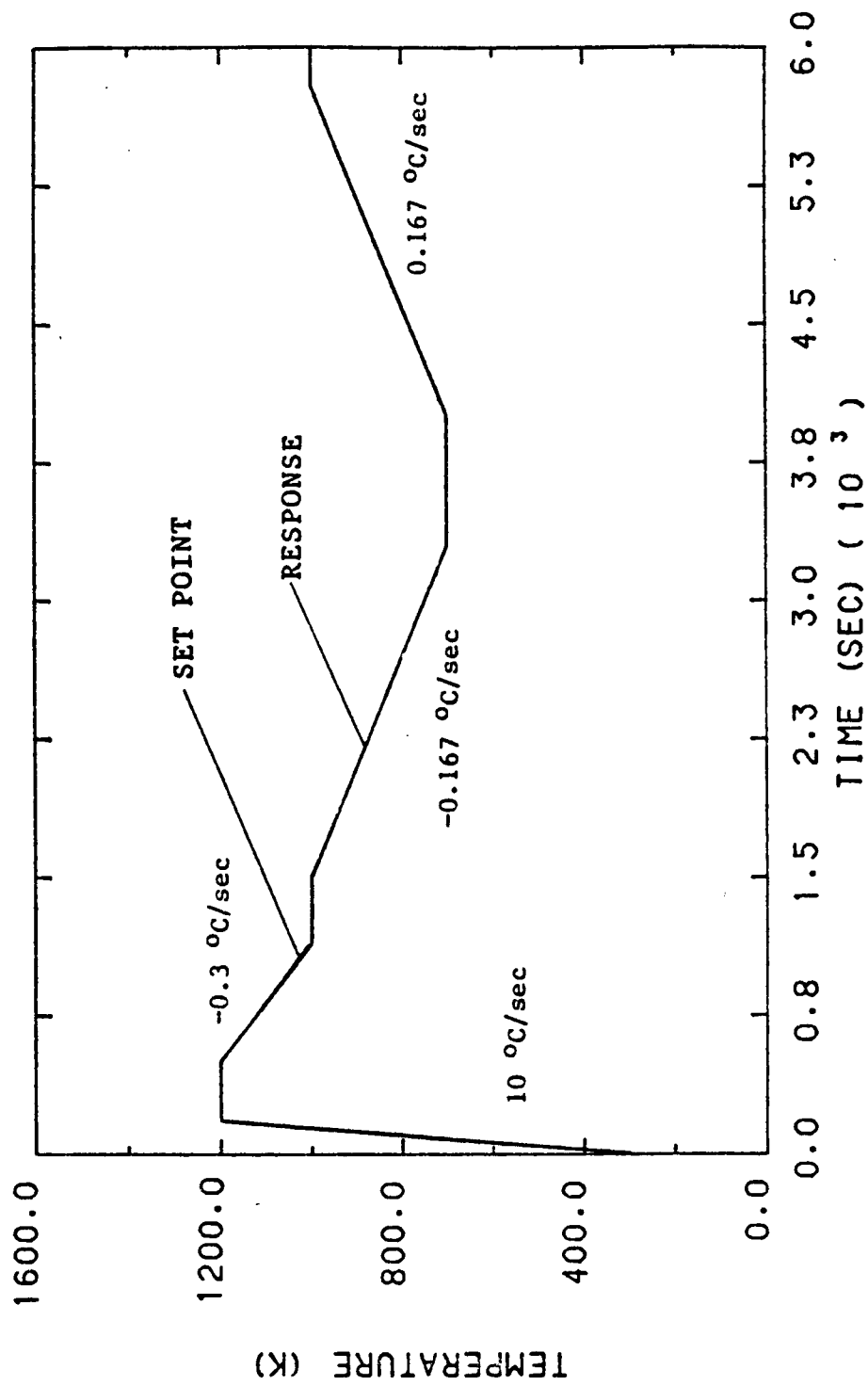


Figure IV-12. Response for a variety of heating, cooling, and temperature set points.

kinetics of the system model. Additional test results can be seen in Appendix C and the controller simulation program listing in Appendix D.

It should be noted that the controller is just as effective in terms of the range of heating and cooling rates as the previous controller. This study indicates that rates of about $-10\text{ }^{\circ}\text{C/min}$ ($-20\text{ }^{\circ}\text{C/min}$ at the higher temperatures) to $+600\text{ }^{\circ}\text{C/min}$ can be used. It should also be noted that step changes in temperature can effectively be made by using a very large rate, whether positive or negative. For instance, to achieve a step to 800 K from 1200 K, one might input a rate of -5 K/s and a set point of 800 K. Thus, the proposed controller has all the capabilities of the previous one.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

The following may be concluded about this study:

1. The model of the resistometer with a Ni_4Mo sample, based upon the heat balance is in good agreement with experimental data. The only significant deviations are dynamic inaccuracies in the radiative breaking of the heating near the steady-state temperature.
2. The growth of LRO regions from SRO is probably not spherical.
3. The activation energy of the SRO to LRO transformation was determined empirically to be on the order of 10^5 J/gmole, based upon the SRO.
4. The feedforward predictor based upon the developed mechanistic model effectively eliminates much (but not all) of the nonlinearities of the system.
5. The feedforward-feedback control scheme was successful in controlling the temperature to within 1 °C. It was also successful in controlling the changeover from a rate set point (even high ones) to an isothermal set point with no appreciable overshoot.
6. The dual controller scheme used in this study (a temperature controller for the isothermal regimes and a rate controller for the heating/cooling regimes) worked well for the entire range of operating conditions.
7. Control parameters were estimated to be $K_C=1.0$ ($K_C=0.5$ for $f<0.9$) and $T_I=0.35$ for the temperature controller and $K_C=0.23$ and $T_I=0.35$ for the rate controller.

In addition, the following recommendations are made:

1. The controller should be implemented into the resistometer system (this is planned for January 1985). The implementation should include the use of digital counts in the controller as much as possible.

2. The D/A converter signal path should be updated so as to utilize a wider range of the digital counts.

3. Further studies in the SRO to LRO phase transitions might be made with other kinetic phase transition models. Such studies might yield important information concerning the mechanisms that are important.

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APPENDIXES

APPENDIX A

PATERN PROGRAMS

```

C
C
C
C
C
C
C
C
C--- PROGRAM NAME:  FRAC.FOR
C--- PURPOSE:  USES PATTERN TO ESTIMATE THE PHASE CHANGE KINETICS
C--- PARAMETERS.
C
C
C
C
C
C
C--- MAIN PROGRAM
C--- PURPOSE:  INITIALIZE PARAMTERS AND READ IN EXPERIMENTAL DATA
C
C--- DEFINITIONS:
C      NO1,2,3      = NUMBER OF DATA SETS IN CURVE 1
C      NP           = NUMBER OF PARAMETERS TO BE SEARCHED (FOR
C                   PATTERN)
C      NPASS        = NUMBER OF TIMES PATTERN WILL REDUCE THE STEP
C                   SIZE
C      RATE1,2,3    = COOLING RATES (K/SEC) FOR CURVES 1,2,3
C      P            = ARRAY OF LENGTH NP CONTAINING THE VALUE
C                   OF THE PARAMETERS
C      STEP         = ARRAY OF LENGTH NP CONTAINING THE STEP SIZE
C      IO           = PATTERN PARAMETER FOR CHOOSING AMOUNT OF
C                   OUTPUT
C      RHO1,2,3     = ARRAY OF EXPERIMENTAL RESISTIVITIES FOR
C                   CURVES 1,2,3
C      T1,2,3       = ARRAY OF EXPERIMENTAL TEMPERATURES FOR
C                   CURVES 1,2,3
C      COST         = FUNCTION TO BE MINIMIZED (SQUARE OF THE
C                   DIFFERENCE BETWEEN EXPERIMENTAL AND
C                   CALCULATED RESISTIVITIES)
C
C--- SUBROUTINES CALLED:
C      PATTERN      = DETERMINES MINIMUM PARAMETERS BASED UPON
C                   COST FUNCTION
C
C--- NOTE:  CURVE 1 IS FOR ALL SRO (F=0.0), CURVE 2 IS FOR ALL LRO
C           (F=1.0), AND CURVE 3 IS FOR A MEDIUM COOLING RATE
C           (1.0>F>0.0)
C
C*****C
C
      DIMENSION P(3),STEP(3)
      COMMON RHO1(1000),RHO2(1000),RHO3(1000),T1(1000),T2(1000),
      1 T3(1000),RATE1,RATE2,RATE3,NO1,NO2,NO3

```

```

      OPEN (UNIT=30,FILE='FASTCO.DAT',ACCESS='SEQIN')
      OPEN (UNIT=31,FILE='SLOWCO.DAT',ACCESS='SEQIN')
      OPEN (UNIT=32,FILE='RESULT.DAT',ACCESS='SEQOUT')
      OPEN (UNIT=33,FILE='MEDCO.DAT',ACCESS='SEQIN')
      NO1      = 0
      NO2      = 0
      NO3      = 0
C--- READ IN DATA FOR CURVE 1 (TEMPERATURE, RESISTIVITY)
      DO 10 I=1,1000
          READ (30,*,END=11) T1(I),RHO1(I)
          NO1      = NO1+1
10      CONTINUE
11      CONTINUE
C--- READ IN DATA FOR CURVE 2 (TEMPERATURE, RESISTIVITY)
      DO 20 I=1,1000
          READ (31,*,END=21) T2(I),RHO2(I)
          NO2      = NO2+1
20      CONTINUE
21      CONTINUE
C--- READ IN DATA FOR CURVE 3 (TEMPERATURE, RESISTIVITY)
      DO 30 I=1,1000
          READ (33,*,END=31) T3(I),RHO3(I)
          NO3      = NO3+1
30      CONTINUE
31      CONTINUE
C--- INITIALIZE PATTERN PARAMETERS AND RATES
      NP      = 3
      NPASS   = 4
      IO      = 1
      RATE1   = 1.0
      RATE2   = 0.08333
      RATE3   = -0.166667
C--- INITIAL PARAMETER GUESSES
C--- P(2) = LN(-A)
      P(2)    = 49.523758
C--- P(1) = N
      P(1)    = 1.685631
C--- P(3) = B
      P(3)    = -76252.91
C--- INITIAL STEP SIZES
      STEP(1) = 1.0
      STEP(2) = 10.0
      STEP(3) = 10000.0
C--- CALL PATTERN SUBROUTINE
      CALL PATTERN(NP,P,STEP,NPASS,IO,COST)
C--- WRITE RESULTS TO RESULT.DAT FILE
      WRITE(32,1000) P(1),P(2),P(3),COST
1000  FORMAT(//,1X,'RESULTS:  P(1) = ',G15.7,/,11X,'P(2) = ',G15.7,
1 /,11X,'P(3) = ',G15.7,/,11X,'COST = ',G15.7)
      WRITE(32,1010) COST1, COST2
1010  FORMAT(//,1X,' COST1 = ',G15.7,';  COST2 = ',G15.7)
      STOP

```

```

      END
C
C
C
C
C
C
C
C
C--- SUBROUTINE PROC
C--- PURPOSE:  CALLED BY PATTERN TO CALCULATE THE COST (SQUARE OF
C              THE DIFFERENCE BETWEEN EXPERIMENTAL AND CALCULATED
C              DATA.
C
C--- DEFINITIONS:
C      P              = SEE MAIN PROGRAM
C      COST           = SEE MAIN PROGRAM
C      RATE1,2,3      = SEE MAIN PROGRAM
C      RHO1,2,3       = SEE MAIN PROGRAM
C      T1,2,3         = SEE MAIN PROGRAM
C      TIME           = TIME (SEC)
C      TIME0          = PREVIOUS TIME
C      TC             = PHASE TRANSITION TEMPERATURE (K)
C      T              = TEMPERATURE (K)
C      FINTIM         = LENGTH OF ISOTHERMAL REGION IN CURVE 3
C      DTIME          = TIME INCREMENT (SEC)
C      TOLD           = PREVIOUS TEMPERATURE
C      CRHO           = CALCULATED RHO (OHM-METERS)
C      NOI            = NUMBER OF ISOTHERMAL ITERATIONS FOR CURVE 3
C      F              = FRACTION OF LRO
C
C--- SUBROUTINES CALLED:
C      FRAC           = CALCULATES THE FRACTION OF THE LRO
C      RHOS           = CALCULATES THE RESISTIVITY AS A FUNCTION
C                      OF TEMPERATURE
C
C*****C
C
      SUBROUTINE PROC(P,COST)
      COMMON RHO1(1000),RHO2(1000),RHO3(1000),T1(1000),T2(1000),
      1 T3(1000),RATE1,RATE2,RATE3,NO1,NO2,NO3
      DIMENSION P(3)
C--- INITIALIZE PARAMTERS
      F      = 0.0
      COST   = 0.0
      TIME0  = 0.0
      TC     = 1141.0
      T      = T3(1)
      FINTIM = 70.0*60.0
      NOI    = 100
      DTIME  = (FINTIM-TIME0)/NOI
      T      = T3(2)
C--- CALCULATE F FOR ISOTHERMAL REGION OF CURVE 3

```

```

DO 10 I=1,NOI
    TIME      = TIME0+DTIME
    CALL FRAC (T,TIME,F,DTIME,P)
    TIME0     = TIME
10  CONTINUE
C--- CALCULATE COST FOR CURVE 3
    CALL RHOS (T,F,CRHO)
    COST      = COST+(CRHO-RHO3(2))**2
    DO 20 I=3,NO3
        RHO    = RHO3(I)
        TOLD   = T3(I-1)
        T      = T3(I)
        TIME    = TIME0+(T-TOLD)/RATE3
        DTIME   = TIME-TIME0
        CALL FRAC (T,TIME,F,DTIME,P)
        CALL RHOS (T,F,CRHO)
        COST    = COST+(CRHO-RHO)**2
        TIME0   = TIME
20  CONTINUE
C--- CALCULATE COST FOR CURVE 1
    F         = 0.0
    TIME0     = 0.0
    DO 30 I=1,NO1
        RHO    = RHO1(I)
        T      = T1(I)
        TIME    = (TC-T)/RATE1
        DTIME   = TIME-TIME0
        CALL FRAC (T,TIME,F,DTIME,P)
        CALL RHOS (T,F,CRHO)
        COST    = COST+(CRHO-RHO)**2
        TIME0   = TIME
30  CONTINUE
C--- CALCULATE COST FOR CURVE 2
    F         = 0.0
    TIME0     = 0.0
    DO 40 I=1,NO2
        RHO    = RHO2(I)
        T      = T2(I)
        TIME    = (TC-T)/RATE2
        DTIME   = TIME-TIME0
        CALL FRAC (T,TIME,F,DTIME,P)
        CALL RHOS (T,F,CRHO)
        COST    = COST+(CRHO-RHO)**2
        TIME0   = TIME
40  CONTINUE
    RETURN
    END

```

C
C
C
C
C

```

C
C
C--- SUBROUTINE FRAC
C--- PURPOSE:  TO CALCULATE THE FRACTION OF LRO
C
C--- DEFINITIONS:
C      T              = TEMPERATURE (K)
C      TIME           = TIME (SEC)
C      F              = FRACTION OF LRO
C      DTIME          = TIME INCREMENT (SEC)
C      TC             = PHASE TRANSITION TEMPERATURE
C      P              = SEE MAIN PROGRAM
C
C*****C
C
C      SUBROUTINE FRAC(T,TIME,F,DTIME,P)
C
C--- SET UP CONSTANTS
C
C      DIMENSION P(3)
C      TC      = 868.0+273
C
C--- CALCULATE F
C
C      SUM      = P(2)+P(3)/T+ALOG(1.0-F)+(P(1)-1.0)*ALOG(TIME)
C      1        +3*ALOG(TC-T)+ALOG(P(1))
C      F        = F+DTIME*EXP(SUM)
C      RETURN
C      END
C
C
C
C
C
C
C--- SUBROUTINE RHOS
C--- PURPOSE:  TO CALCULATE THE RESISTIVITY AS A FUNCTION OF
C              TEMPERATURE AND THE FRACTION OF LRO
C
C--- DEFINITIONS:
C      T              = TEMPERATURE (K)
C      F              = FRACTION OF LRO
C      RHO            = RESISTIVITY (OHM-METERS)
C      TC             = PHASE CHANGE TRANSITION TEMPERATURE
C      A1,2; B1,2;
C      C1,2; D1,2     = CONSTANTS IN RHO VS. T CURVES FOR (1) ALL
C                      LRO AND (2) ALL SRO
C      RHO1,2         = RHO(T) FOR (1) LRO AND (2) SRO
C
C*****C
C

```

```

      SUBROUTINE RHOS (T,F,RHO)
C--- SET UP CONSTANTS
C
      TC      = 868.0+273.0
C
      A1      = -4.0907464E-07
      B1      = 3.775097E-09
      C1      = -4.012551E-12
      D1      = 1.775517E-15
      IF(T.GT.1235.0) A1=0.130E-05
      IF(T.GT.1235.0) B1= 0.0
      IF(T.GT.1235.0) C1= 0.0
      IF(T.GT.1235.0) D1= 0.0
C
      A2      = 1.540493E-06
      B2      = -6.611138E-10
      C2      = 1.363067E-12
      D2      = -7.995826E-16
C
C
C--- CALCULATE RESISTIVITY FOR LRO PHASE
C
      IF((T.LT.TC).OR.(F.GE.0.999999)) GO TO 10
      RHO1     = 0.0
      GO TO 20
10      RHO1     = A1+B1*T+C1*T**2+D1*T**3
C
C--- CALCULATE RESISTIVITY FOR SRO PHASE
C
20      RHO2     = A2+B2*T+C2*T**2+D2*T**3
C
C--- CALCULATE OVERALL RESISITIVITY
C
      RHO      = RHO1*F+RHO2*(1.0-F)
C
C--- RETURN RHO VALUE
C
      RETURN
      END
C
C
C
C
C--- SUBROUTINE BOUNDS
C--- PURPOSE:  TO DETERMINE IF THE PARAMETERS ESTIMATED BY PATERN
C              ARE REASONABLE.
C
C--- DEFINITIONS:
C      IOUT      = PARAMETER INDICATING IF ALL THE PARAMETERS
C                ARE REASONABLE (0=YES, 1=NO)
C      P          = ARRAY OF PARAMETERS

```

C

C*****C

C

```
SUBROUTINE BOUNDS(P,IOUT)
  DIMENSION P(3)
  IOUT      = 0
  IF(P(2).LE.0.0) IOUT=1
  IF(P(3).GE.0.0) IOUT=1
  IF(P(1).LE.0.0) IOUT=1
  RETURN
END
```

```

C
C      PROGRAM NAME:  TUNET.FOR
C      PURPOSE:  TO TUNE THE TEMPERATURE CONTROLLER
C
C      FOR DEFINITIONS, SEE CONTRO.FOR AND FRAC.FOR
C
C      SUBROUTINES CALLED:
C          PROC      : CALCULATES THE COST FUNCTION
C          PATERN     : DETERMINES THE PARAMETERS TO MINIMIZE THE
C                      COST FUNCTION
C          MODEL      : MODEL OF THE RESITOMETER
C          SENSHT     : CALCULATES THE SENSITIVE HEAT
C          FRAC       : CALCULATES THE FRACTION OF LRO
C          RHOS       : CALCULATES THE RESISTIVITY AS A FUNCTION
C                      OF SAMPLE TEMPERATURE
C          TFCNH      : CALCULATES THE TEMPERATURE AS A FUNCTION OF
C                      THE ACCUMULATED HEAT
C          CPS        : CALCULATES THE HEAT CAPACITY AS A FUNCTION
C                      OF TEMPERATURE
C          CONTRL     : CALCULATES THE CONTROL ACTION (CURRENT)
C          FF         : CALCULATES THE FEEDFORWARD CONTROL ACTION
C          CPSCTL     : CALCULATES THE HEAT CAPACITY FOR FF
C          RHOCTL     : CALCULATES THE RESISTIVITY FOR FF
C
C*****C
COMMON/LIST1/TA,TA0,TC,VOL,V,AREA,AS,IFLAG,LAMBDA,SIGMA,PHI
COMMON/LIST2/ L,EPS,LNA,A,N,B,THCL,THCK,THCA
COMMON/LIST3/DTIME,TTIME,SH,SHO,ACC,ACCO,CP,TAU
COMMON/LIST4/IX,RHR,RT,COSTX,IAN,TIMEF,NREG,NP,ENDTIM
REAL LAMBDA,LNA,N,L,MO,LATHTO,KCT,KCR
DIMENSION RHR(10),RT(10),ENDTIM(10)
DIMENSION COSTX(10),P(2),STEP(2)
OPEN (UNIT=30,FILE='RESULT.DAT',ACCESS='SEQOUT')
WRITE (5,1000)
READ(5,*) TIMEF,DTIME
WRITE (5,1020)
READ(5,*) NREG
DO 5 I=1,NREG
    WRITE (5,1030) I
    READ(5,*) RHR(I),RT(I)
    WRITE(5,1040) I
    READ(5,*) ENDTIM(I)
5  CONTINUE
WRITE(5,1050)
1050 FORMAT(1X,'FOR WHICH REGIME DO YOU WISH THE COST? ',$,)
READ(5,*) IX
WRITE(5,1060)
1060 FORMAT(1X,'IS THIS REGIME ISOTHERMAL (Y/N)? ',$,)
READ(5,1070) IANS
1070 FORMAT(1A1)
NP=2
NPASS=3

```

```

      IO=1
C--- P(1)=KCT
      P(1)=0.8
C--- P(2)=TIT
      P(2)=5.0
      STEP(1)=0.1
      STEP(2)=0.1
      CALL PATERN(NP,P,STEP,NPASS,IO,COST)
      WRITE(30,2000)
2000  FORMAT(10X,'RESULTS:',/)
      DO 100 I=1,NP
          WRITE(30,2010) I,P(I)
2010  FORMAT(10X,'P(',I2,')= ',G15.7)
      100  CONTINUE
      WRITE(30,2020) COST
2020  FORMAT(10X,'COST =',G15.7)
1000  FORMAT(1X,'INPUT FINAL TIME AND TIME INCREMENT: ',$,)
1020  FORMAT(1X,'INPUT # OF REGIMES: ',$,)
1030  FORMAT(1X,'INPUT HEATING RATE AND FINAL TEMP. SET POINT
      1 FOR REGIME #',I2,': ',$,)
1040  FORMAT(1X,'INPUT END TIME FOR REGIME #',I2,': ',$,)
      STOP
      END

```

C
C
C
C

```

SUBROUTINE PROC(P,COST)
COMMON/LIST1/TA,TAO,TC,VOL,V,AREA,AS,IFLAG,LAMBDA,SIGMA,PHI
COMMON/LIST2/ L,EPS,LNA,A,N,B,THCL,THCK,THCA
COMMON/LIST3/DTIME,TTIME,SH,SHO,ACC,ACCO,CP,TAU
COMMON/LIST4/IX,RHR,RT,COSTX, IANS,TIMEF,NREG,NP,ENDTIM
REAL LAMBDA,LNA,N,L,MO,LATHTO,KCT,KCR
DIMENSION RHR(10),RT(10),ENDTIM(10),RHR2(10)
DIMENSION COSTX(10),P(2),STEP(2)

```

C
C---
C

INITIALIZE PARAMETERS

C
C
C

```

      SH      = 0.0
      SHO     = 0.0
      TIME    = 0.0
      TTIME   = 0.0
      ACC     = 0.0
      TAO     = 300.0
      TA      = TAO
      TC      = 1141.0
      PI      = 3.14159265
      D       = 0.0032
      L       = 0.00698
      AREA    = PI*D**2/4.0
      VOL     = AREA*L
      V       = 0.0001085

```

```

      AS      = PI*D*L
      THCL    = 0.04
      THCK    = 67.05
      THCA    = 5.0671E-08
      IFLAG   = 0
      ICOUNT  = 0
      LAMBDA  = 51.58
      SIGMA   = 5.677E-8
      TAU     = 6000.0
      EPS     = 1.0-1.0E-8
      LNA     = 32.08977
      A       = -EXP(LNA)
C      A       = 8.637937E+13
      N       = 1.835001
      B       = -61330.0
      F       = 1.0
      T       = TA
      CURREN  = 0.0
      CALL RHOS (T,F,RHO)
      CALL CPS(T,F,CP)
      ACCO    = VOL*CP*T/V
      CP0     = 0.0
      DO 5 I=1,NP
                COSTX(I)=0.0
5      CONTINUE
      DO 7 I=1,NREG
                RHR2(I)=RHR(I)
7      CONTINUE
C
C--- START TIME LOOP
C
      ICOUNT  = 0
      ERROR   = 0.0
      DO 20 J=1,NREG
                IF(J.GE.2) GO TO 100
                NOIT    = INT(ENDTIM(J)/DTIME)
                TIMERT   = (RT(J)-T)/RHR2(J)
                GO TO 200
100             NOIT    = INT((ENDTIM(J)-ENDTIM(J-1))/DTIME)
                TIMERT   = (RT(J)-T)/RHR2(J)+ENDTIM(J-1)
200             CONTINUE
                DO 10 I=1,NOIT
                        TIME    = TIME+DTIME
                IF((RHR2(J).GT.0.0).AND.(T.GE.RT(J)-RHR2(J)*DTIME))
1                 RHR2(J)=0.0
                IF((RHR2(J).LT.0.0).AND.(T.LE.RT(J)-RHR2(J)*DTIME))
1                 RHR2(J)=0.0
                        CALL MODEL(T,TIME,CURREN,F,RHO)
                        CALL CONTRL(T,RHO,L,D,TO,TAM0,LATHT0,
1                                FO,CURREN,CP0,RHR2(J),RT(J),ETO,
2                                ERO,M0,P)
                IF(IANS.EQ.'Y') COSTX(J)=COSTX(J)+ABS(ETO)

```

```

                IF(IANS.NE.'Y') COSTX(J)=COSTX(J)+ABS(ERO)
C--- OUTPUT MODEL
10             CONTINUE
20             CONTINUE
              COST  = COSTX(IX)
              RETURN
1000          FORMAT(1X,'INPUT FINAL TIME AND TIME INCREMENT: ', $)
1010          FORMAT(1X,'INPUT # OF POINTS IN PLOTS: ', $)
1020          FORMAT(1X,'INPUT # OF REGIMES: ', $)
1030          FORMAT(1X,'INPUT HEATING RATE AND FINAL TEMP. SET POINT
1 FOR REGIME #',I2,' ': ', $)
1040          FORMAT(1X,'INPUT END TIME FOR REGIME #',I2,' ': ', $)
2000          FORMAT(1X,'HEAD')
2010          FORMAT(1X,'DATA ', $)
2020          FORMAT(2G15.5)
              END

C
C
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C
C
C
C--- SUBROUTINE MODEL FOR MODELING OF RESISTIVITY DEVICE
              SUBROUTINE MODEL(T,TIME,CURREN,F,RHO)
              COMMON/LIST1/TA,TA0,TC,VOL,V,AREA,AS,IFLAG,LAMBDA,SIGMA,PHI
              COMMON/LIST2/ L,EPS,LNA,A,N,B,THCL,THCK,THCA
              COMMON/LIST3/DTIME,TTIME,SH,SHO,ACC,ACC0,CP,TAU
              REAL LAMBDA,LNA,N,L
C--- CALCULATE PHI(T)
              EMISS  = 0.5229-0.00059335*T+6.0901E-07*T**2
              EMISS  = 0.6
              PHI    = EMISS*AS
C--- CALCULATE TA AS A FUNCTION OF T
              IF(T.LT.300.0) T=300.0
              TASS   = 0.004607*(T-300.0)**1.7253+300.0
              TA     = (TASS-TA0)*(1.0-EXP(-DTIME/TAU))+TA0
              IF(TA.LT.300.0) TA=300.0
              TA0    = TA
C--- CALCULATE THE TOTAL ENERGY OF THE SYSTEM
              CALL SENSHT(T,CURREN,F,RHO)
C--- CALCULATE FRACTION OF LRO
              CALL FRAC(T,F)
C--- CORRECT FOR LATENT HEAT
              ACC    = SH+LAMBDA*(1.0-F)
C--- CALCULATE TEMPERATURE
              CALL TFCNH(T,F)
C--- CALCULATE RESISTIVITY
              CALL RHOS(T,F,RHO)
              RETURN

```



```

IF(IFLAG.EQ.0) WRITE (5,1000)
1000 FORMAT(//,1X,'ERROR: IFLAG ZERO.',/)
RETURN
END

C
C
C
C
C
C
C
C
C

SUBROUTINE FRAC(T,F)

C
C SUBRRoutine NAME: FRAC
C PURPOSE: TO CALCULATE THE FRACTION OF THHE LRO TRANSFORMED
C FROM THE SRO
C VARIABLE DEFINITIONS:
C T = TEMPERATURE (DEG. K)
C TIME = TIME (SEC)
C F = FRACTION OF LRO PHASE
C DTIME = TIME INCREMENT (DELTA- TIME, SEC)
C
C--- SET UP CONSTANTS
C
COMMON/LIST1/TA,TAO,TC,VOL,V,AREA,AS,IFLAG,LAMBDA,SIGMA,PHI
COMMON/LIST2/ L,EPS,LNA,A,N,B,THCL,THCK,THCA
COMMON/LIST3/DTIME,TTIME,SH,SHO,ACC,ACCO,CP,TAU
REAL LAMBDA,LNA,N,L

C
C--- TEST FOR REGIME
C
IF ((IFLAG.EQ.1).OR.(IFLAG.EQ.2)) F=1.0
IF ((IFLAG.EQ.5).OR.(IFLAG.EQ.6)) F=0.0
C--- TTIME=0 IF NO PHASE CHANGE YET
IF ((IFLAG.NE.3).OR.(IFLAG.NE.4)) TTIME = 0.0
IF ((IFLAG.EQ.3).OR.(IFLAG.EQ.4)) GO TO 10
GO TO 30

C
C--- CALCULATE F
C
10 TTIME = TTOLD+DTIME
SUM = LNA+B/T+ALOG(1.0-F)+(N-1.0)*ALOG(TTIME)+4*ALOG(TC-T)
1 +ALOG(N)
IF(SUM.LT.-70.0) SUM=-70.0
IF(SUM.GT.70.0) SUM=70.0
F = F+DTIME*EXP(SUM)

30 RETURN
END

```

```

C
C
C
C
C
C
C
C
SUBROUTINE TFCNH(T,F)
C
C
C
C
C
C
C
C
SUBROUTINE NAME:  TFCNH
C
C
C
C
PURPOSE:  TO CALCULATE THE TEMPERATURE GIVEN A SENSIBLE
C
C
C
C
HEAT VALUE
C
C
C
C
VARIABLE DEFINITIONS:
C
C
C
C
T      = TEMPERATURE (DEG. K)
C
C
C
C
ACC     = TOTAL ACCUMULATED HEAT (J)
C
C
C
C
TA      = AMBIENT TEMPERATURE (DEG. K)
C
C
C
C
COMMON/LIST1/TA,TAO,TC,VOL,V,AREA,AS,IFLAG,LAMBDA,SIGMA,PHI
COMMON/LIST2/ L,EPS,LNA,A,N,B,THCL,THCK,THCA
COMMON/LIST3/DTIME,TTIME,SH,SHO,ACC,ACC0,CP,TAU
REAL LAMBDA,LNA,N,L
C
C
C
C
C--- SET UP CONSTANTS
C
C
C
C
CALL CPS(T,F,CP)
T      = V/VOL/CP*(ACC+ACC0)
RETURN
END
C
C
C
C
C
C
C
C
SUBROUTINE CPS(T,F,CP)
IF(T.GT.873.0) GO TO 10
A1=376.36545
B1=0.06960968
C1=0.0
D1=0.0
GO TO 100
C
10  A1= 296.93
    B1= 0.1604
    C1= 0.0
    D1= 0.0
C
100 IF(T.GT.1141.0) GO TO 20
    IF((T.LE.1141.0).AND.(T.GT.680.0)) GO TO 30
    A2= 376.36545

```

```

        B2= 0.06960968
        C2= 0.0
        D2= 0.0
        GO TO 200
C
20      A2= 567.3736
        B2= 0.0
        C2= 0.0
        D2= 0.0
        GO TO 200
C
30      A2= 211.78
        B2= 0.3117
        C2= 0.0
        D2= 0.0
C
C--- CALCULATE CP(T)
C
200     CONTINUE
        CPLRO  = A1+B1*T+C1*T**2+D1*T**3
        CPSRO  = A2+B2*T+C2*T**2+D2*T**3
        CP     = F*CPLRO+(1.0-F)*CPSRO
        RETURN
        END
C
C
C
C
C
C
C
C
C
        SUBROUTINE CONTRL(T,RHO,L,D,TO,TAMO,LATHTO,FO,CURREN,CPO,
1          RHR,RT,ETO,ERO,MO,P)
        DIMENSION P(2)
        REAL M,MO,KCT,KCR,LATHTO,L
        INDEX  = 1
        IF(CPO.LT.1.0) INDEX=0
        IF(INDEX.EQ.1) GO TO 5
C--- INITIALIZE PARAMETERS
        ETO    = 0.0
        ERO    = 0.0
        MO     = 0.0
        TO     = T
        LATHTO = 0.0
        TAMO   = TO
5        DTIME = 2.0
        KCT    = 0.5
        TIT    = 2.0
        KCR    = 0.23
        TIR    = 0.35
        KCT    = P(1)

```

```

      TIT      = P(2)
C--- CALCULATE TSTAR
      TSTAR   = T+RHR*DTIME
      IF((RHR.GT.0.0).AND.(TSTAR.GT.RT)) TSTAR=RT
      IF((RHR.LT.0.0).AND.(TSTAR.LT.RT)) TSTAR=RT
      IF(RHR.EQ.0.0) TSTAR=RT
C--- DETERMINE WHICH CONTROLLER TO USE
      IF(RHR.EQ.0.0) GO TO 10
C--- RATE CONTROLLER
      HR      = (T-T0)/DTIME
      ET0     = 0.0
      ER      = RHR-HR
      DELT    = KCR*(ER-ER0)+KCR*DTIME/TIR*ER
      ER0     = ER
      GO TO 20
C--- TEMPERATURE CONTROLLER
10    ER0     = 0.0
      ET      = RT-T
      DELT    = KCT*(ET-ET0)+KCT*DTIME/TIT*ET
      ET0     = ET
20    M       = MO+DELT
      MO      = M
C--- CALL FEEDFORWARD CONTROLLER
      CALL FF(FFC,T,TO,TAMO,CPO,LATHTO,RHO,L,D,DTIME,RHR,RT,F0,
1      TSTAR)
      CURREN  = FFC+M
      IF(CURREN.GT.90.0) CURREN=90.0
      IF(CURREN.LT.0.0) CURREN=0.0
      TO      = T
      RETURN
      END
C
C
C
C
C
C
C
C
      SUBROUTINE FF(FFC,T,TO,TAMO,CPO,LATHTO,RHO,L,D,DTIME,RHR,RT,F0,
1      TSTAR)
      REAL LAMBDA,LATHTO,LATHT,L
C--- INITIALIZE PARAMETERS
      PI      = 3.14159265
      TC      = 1141.0
      AREA    = PI*D**2/4.0
      AS      = PI*D*L
      VOL     = AREA*L
      V       = 0.0001085
      LAMBDA  = 51.58
      SIGMA   = 5.677E-8
      TAU     = 6000.0

```

```

      THCL    = 0.04
      THCK    = 67.05
      THCA    = 5.0671E-08
C--- CALCULATE PHI(T)
      EMISS   = 0.5229-0.00059335*TSTAR+6.0901E-07*TSTAR**2
      PHI     = EMISS*AS
C--- CALCULATE TA AS A FUNCTION OF T
      TASS    = 0.004607*(TSTAR-300.0)**1.7253+300.0
      TASTAR  = (TASS-TAMO)*(1.0-EXP(-DTIME/TAU))+TAMO
      IF(TASTAR.LT.300.0) TASTAR=300.0
      TAMO    = TASTAR
C--- DETERMINE F
      CALL RHOCTL(T,1.0,RHOLRO)
      CALL RHOCTL(T,0.0,RHOSRO)
      F= (RHO-RHOSRO)/(RHOLRO-RHOSRO)
      IF(F.LT.0.0) F= 0.0
      IF(F.GT.1.0) F= 1.0
      IF(CP0.LT.1.0) F0=F
      GO TO 20
10    F      = 0.0
C--- CALCULATE THE CURRENT FROM THE HEAT BALANCE
20    LATHT   = LAMBDA*(1.0-F)
      CALL CPSCTL(TSTAR,F,CPSTAR)
      CALL CPSCTL(T,F0,CP0)
      CALL RHOCTL(TSTAR,F,RHOSTR)
      DACC    = CPSTAR*TSTAR-CP0*T
      IF(RHR.EQ.0.0) DACC=0.0
      CRNT2   = AREA/RHOSTR/L*(VOL/V*DACC/DTIME
1      - (LATHT-LATHT0)/DTIME-SIGMA*PHI*(TASTAR**4-TSTAR**4)
2      -4*THCK*THCA/THCL*(TASTAR-TSTAR))
      IF(CRNT2.LT.0.0) CRNT2=0.0
      FFC     = SQRT(CRNT2)
      IF(FFC.GT.90.0) FFC=90.0
C--- RESET PREVIOUS LATENT HEAT AND F
      LATHT0  = LATHT
      F0      = F
      RETURN
      END

```

C
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C
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C

```

SUBROUTINE RHOCTL (T,F,RHO)
C
C SUBROUTINE NAME: RHOCTL
C PURPOSE: TO CALCULATE THE RESISTIVITY AS A FUNCTION OF
C TEMPERATURE AND THE FRACTION OF LRO.
C

```

C
C
C
C

C


```

        B1=0.06960968
        C1=0.0
        D1=0.0
GO TO 100

C
  10    A1= 296.93
        B1= 0.1604
        C1= 0.0
        D1= 0.0

C
  100    IF(T.GT.1141.0) GO TO 20
        IF((T.LE.1141.0).AND.(T.GT.680.0)) GO TO 30
        A2= 376.36545
        B2= 0.06960968
        C2= 0.0
        D2= 0.0
        GO TO 200

C
  20    A2= 567.3736
        B2= 0.0
        C2= 0.0
        D2= 0.0
        GO TO 200

C
  30    A2= 211.78
        B2= 0.3117
        C2= 0.0
        D2= 0.0

C
C--- CALCULATE CP(T)
C
  200    CONTINUE
        CPLRO = A1+B1*T+C1*T**2+D1*T**3
        CPSRO = A2+B2*T+C2*T**2+D2*T**3
        CP     = F*CPLRO+(1.0-F)*CPSRO
        RETURN
        END

```

C
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C

```

C
C      PROGRAM NAME:  TUNER.FOR
C      PURPOSE:  TO TUNE THE RATE CONTROLLER
C
C      FOR DEFINITIONS, SEE CONTRO.FOR AND FRAC.FOR
C
C      SUBROUTINES CALLED:
C          PROC      :  CALCULATES THE COST FUNCTION
C          PATTERN   :  DETERMINES THE PARAMETERS TO MINIMIZE THE
C                      COST FUNCTION
C          MODEL     :  MODEL OF THE RESITOMETER
C          SENSHT    :  CALCULATES THE SENSITIVE HEAT
C          FRAC      :  CALCULATES THE FRACTION OF LRO
C          RHOS      :  CALCULATES THE RESISTIVITY AS A FUNCTION
C                      OF SAMPLE TEMPERATURE
C          TFCNH     :  CALCULATES THE TEMPERATURE AS A FUNCTION OF
C                      THE ACCUMULATED HEAT
C          CPS       :  CALCULATES THE HEAT CAPACITY AS A FUNCTION
C                      OF TEMPERATURE
C          CONTRL    :  CALCULATES THE CONTROL ACTION (CURRENT)
C          FF        :  CALCULATES THE FEEDFORWARD CONTROL ACTION
C          CPSCTL    :  CALCULATES THE HEAT CAPACITY FOR FF
C          RHOCTL    :  CALCULATES THE RESISTIVITY FOR FF
C
C*****C
C
COMMON/LIST1/TA,TA0,TC,VOL,V,AREA,AS,IFLAG,LAMBDA,SIGMA,PHI
COMMON/LIST2/ L,EPS,LNA,A,N,B,THCL,THCK,THCA
COMMON/LIST3/DTIME,TTIME,SH,SH0,ACC,ACC0,CP,TAU
COMMON/LIST4/IX,RHR,RT,COSTX,IAN,S,TIMEF,NREG,NP,ENDTIM
REAL LAMBDA,LNA,N,L,M0,LATHT0,KCT,KCR
DIMENSION RHR(10),RT(10),ENDTIM(10)
DIMENSION COSTX(10),P(2),STEP(2)
OPEN (UNIT=30,FILE='RESULT.DAT',ACCESS='SEQOUT')
WRITE (5,1000)
READ(5,*) TIMEF,DTIME
WRITE (5,1020)
READ(5,*) NREG
DO 5 I=1,NREG
    WRITE (5,1030) I
    READ(5,*) RHR(I),RT(I)
    WRITE(5,1040) I
    READ(5,*) ENDTIM(I)
5  CONTINUE
WRITE(5,1050)
1050 FORMAT(1X,'FOR WHICH REGIME DO YOU WISH THE COST? ',5)
READ(5,*) IX
WRITE(5,1060)
1060 FORMAT(1X,'IS THIS REGIME ISOTHERMAL (Y/N)? ',5)
READ(5,1070) IANS
1070 FORMAT(1A1)
NP=2

```

```

      NPASS=3
      IO=1
C--- P(1)=KCR
      P(1)=0.2
C--- P(2)=TIR
      P(2)=0.4
      STEP(1)=0.1
      STEP(2)=0.1
      CALL PATERN(NP,P,STEP,NPASS,IO,COST)
      WRITE(30,2000)
2000  FORMAT(10X,'RESULTS:',//)
      DO 100 I=1,NP
          WRITE(30,2010) I,P(I)
2010  FORMAT(10X,'P(',I2,')= ',G15.7)
      100  CONTINUE
      WRITE(30,2020) COST
2020  FORMAT(10X,'COST =',G15.7)
1000  FORMAT(1X,'INPUT FINAL TIME AND TIME INCREMENT: ',$,)
1020  FORMAT(1X,'INPUT # OF REGIMES: ',$,)
1030  FORMAT(1X,'INPUT HEATING RATE AND FINAL TEMP. SET POINT
1 FOR REGIME #',I2,': ',$,)
1040  FORMAT(1X,'INPUT END TIME FOR REGIME #',I2,': ',$,)
      STOP
      END

C
C
C
C

      SUBROUTINE PROC(P,COST)
      COMMON/LIST1/TA,TA0,TC,VOL,V,AREA,AS,IFLAG,LAMBDA,SIGMA,PHI
      COMMON/LIST2/ L,EPS,LNA,A,N,B,THCL,THCK,THCA
      COMMON/LIST3/DTIME,TTIME,SH,SH0,ACC,ACC0,CP,TAU
      COMMON/LIST4/IX,RHR,RT,COSTX, IANS,TIMEF,NREG,NP,ENDTIM
      REAL LAMBDA,LNA,N,L,MO,LATHTO,KCT,KCR
      DIMENSION RHR(10),RT(10),ENDTIM(10),RHR2(10)
      DIMENSION COSTX(10),P(2),STEP(2)

C
C--- INITIALIZE PARAMETERS
C
      SH      = 0.0
      SH0     = 0.0
      TIME    = 0.0
      TTIME   = 0.0
      ACC     = 0.0
      TA0     = 300.0
      TA      = TA0
      TC      = 1141.0
      PI      = 3.14159265
      D       = 0.0032
      L       = 0.00698
      AREA    = PI*D**2/4.0
      VOL     = AREA*L

```

```

V      = 0.0001085
AS      = PI*D*L
THCL    = 0.04
THCK    = 67.05
THCA    = 5.0671E-08
IFLAG   = 0
ICOUNT  = 0
LAMBDA  = 51.58
SIGMA   = 5.677E-8
TAU     = 6000.0
EPS     = 1.0-1.0E-8
LNA     = 32.08977
A       = -EXP(LNA)
C       A       = 8.637937E+13
N       = 1.835001
B       = -61330.0
F       = 1.0
T       = TA
CURREN  = 0.0
CALL RHOS (T,F,RHO)
CALL CPS(T,F,CP)
ACCO    = VOL*CP*T/V
CP0     = 0.0
DO 5 I=1,NP
      COSTX(I)=0.0
5  CONTINUE
DO 7 I=1,NREG
      RHR2(I)=RHR(I)
7  CONTINUE
C
C--- START TIME LOOP
C
ICOUNT  = 0
ERROR   = 0.0
DO 20 J=1,NREG
      IF(J.GE.2) GO TO 100
      NOIT   = INT(ENDTIM(J)/DTIME)
      TIMERT = (RT(J)-T)/RHR2(J)
      GO TO 200
100     NOIT   = INT((ENDTIM(J)-ENDTIM(J-1))/DTIME)
      TIMERT = (RT(J)-T)/RHR2(J)+ENDTIM(J-1)
200     CONTINUE
      DO 10 I=1,NOIT
            TIME = TIME+DTIME
            IF((RHR2(J).GT.0.0).AND.(T.GE.RT(J)-RHR2(J)*DTIME))
1             RHR2(J)=0.0
            IF((RHR2(J).LT.0.0).AND.(T.LE.RT(J)-RHR2(J)*DTIME))
1             RHR2(J)=0.0
            CALL MODEL(T,TIME,CURREN,F,RHO)
            CALL CONTRL(T,RHO,L,D,TO,TAM0,LATHT0,
1             F0,CURREN,CP0,RHR2(J),RT(J),ETO,
2             ERO,M0,P)

```

```

                IF(IANS.EQ.'Y') COSTX(J)=COSTX(J)+ABS(ETO)
                IF(IANS.NE.'Y') COSTX(J)=COSTX(J)+ABS(ERO)
C--- OUTPUT MODEL
10      CONTINUE
20      CONTINUE
        COST   = COSTX(IX)
        RETURN
1000    FORMAT(1X,'INPUT FINAL TIME AND TIME INCREMENT: ',,$)
1010    FORMAT(1X,'INPUT # OF POINTS IN PLOTS: ',,$)
1020    FORMAT(1X,'INPUT # OF REGIMES: ',,$)
1030    FORMAT(1X,'INPUT HEATING RATE AND FINAL TEMP. SET POINT
1 FOR REGIME #',I2,' ': ',,$)
1040    FORMAT(1X,'INPUT END TIME FOR REGIME #',I2,' ': ',,$)
2000    FORMAT(1X,'HEAD')
2010    FORMAT(1X,'DATA ',,$)
2020    FORMAT(2G15.5)
        END

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C
C--- SUBROUTINE MODEL FOR MODELING OF RESISTIVITY DEVICE
        SUBROUTINE MODEL(T,TIME,CURREN,F,RHO)
        COMMON/LIST1/TA,TAO,TC,VOL,V,AREA,AS,IFLAG,LAMBDA,SIGMA,PHI
        COMMON/LIST2/ L,EPS,LNA,A,N,B,THCL,THCK,THCA
        COMMON/LIST3/DTIME,TTIME,SH,SHO,ACC,ACCO,CP,TAU
        REAL LAMBDA,LNA,N,L
C--- CALCULATE PHI(T)
        EMISS  = 0.5229-0.00059335*T+6.0901E-07*T**2
        EMISS  = 0.6
        PHI    = EMISS*AS
C--- CALCULATE TA AS A FUNCTION OF T
        IF(T.LT.300.0) T=300.0
        TASS   = 0.004607*(T-300.0)**1.7253+300.0
        TA     = (TASS-TAO)*(1.0-EXP(-DTIME/TAU))+TAO
        IF(TA.LT.300.0) TA=300.0
        TAO    = TA
C--- CALCULATE THE TOTAL ENERGY OF THE SYSTEM
        CALL SENSHT(T,CURREN,F,RHO)
C--- CALCULATE FRACTION OF LRO
        CALL FRAC(T,F)
C--- CORRECT FOR LATENT HEAT
        ACC    = SH+LAMBDA*(1.0-F)
C--- CALCULATE TEMPERATURE
        CALL TFCNH(T,F)
C--- CALCULATE RESISTIVITY
        CALL RHOS(T,F,RHO)

```

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C--- RETURN RHO VALUE
C
C      RETURN
C      END
C
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C
C
C
C      SUBROUTINE SENSHT (T,CURREN,F,RHO)
C
C      SUBROUTINE NAME:  SENSHT
C      PURPOSE:  TO CALCULATE THE TOTAL ENERGY OF THE SYSTEM
C                USING THE (CURRENT-RADIATION) EQUATION
C      VARIABLE DEFINITIONS:
C          T      = TEMPERATURE (DEG. K)
C          RHO     = RESISTIVITY (OHM-METERS)
C          CURREN  = CURRENT (AMPERES)
C          SH      = TOTAL SENSIBLE HEAT OF THE SYSTEM (J)
C          TA      = AMBIENT TEMPERATURE (DEG. K)
C          SH0     = OLD SH VALUE
C
C      COMMON/LIST1/TA,TA0,TC,VOL,V,AREA,AS,IFLAG,LAMBDA,SIGMA,PHI
C      COMMON/LIST2/ L,EPS,LNA,A,N,B,THCL,THCK,THCA
C      COMMON/LIST3/DTIME,TTIME,SH,SH0,ACC,ACCO,CP,TAU
C      REAL LAMBDA,LNA,N,L
C      IFLAG = 0
C
C
C--- CALCULATE SH
C      CURRENT HEATING=CURRENT**2*RHO*L/AREA
C      RADIATION COOLING=SIGMA*PHI*(TA**4-T**4)
C      CONDUCTION (THERMOCOUPLE) COOLING=4*THCK*(TA-T)*THCA/THCL
C      LATENT HEAT OF PHASE CHANGE=LAMBDA*(1.0-F)
C
C      SH      = SH0+DTIME*(CURRENT**2*RHO*L/AREA+SIGMA*PHI*
C      1      (TA**4-T**4)+4*THCK*(TA-T)*THCA/THCL)
C--- IF COOLING BELOW TC W/ SRO, IFLAG=4
C      IF((SH.LT.SH0).AND.(F.LT.EPS).AND.(T.LT.TC)) IFLAG=4
C--- IF COOLING ABOVE TC, IFLAG=6
C      IF((SH.LT.SH0).AND.(T.GE.TC)) IFLAG=6
C--- IF COOLING W/O SRO (BELOW TC) IFLAG=2
C      IF((SH.LT.SH0).AND.(F.GE.EPS)) IFLAG=2
C--- IF HEATING W/O SRO (BELOW TC), IFLAG=1
C      IF((SH.GE.SH0).AND.(F.GE.EPS)) IFLAG=1
C--- IF HEATING BELOW TC W/ SRO, IFLAG=3
C      IF((SH.GE.SH0).AND.(F.LT.EPS).AND.(T.LT.TC)) IFLAG=3
C--- IF HEATING ABOVE TC, IFLAG=5
C      IF((SH.GE.SH0).AND.(T.GE.TC)) IFLAG=5

```

```
C      = SH
C      IF(IFLAG.EQ.0) WRITE (5,1000)
1000   FORMAT(/,1X,'ERROR: IFLAG ZERO.',/)
       RETURN
       END

C
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C
SUBROUTINE FRAC(T,F)

C
C     SUBRRoutine NAME:  FRAC
C     PURPOSE: TO CALCULATE THE FRACTION OF THHE LRO TRANSFORMED
C              FROM THE SRO
C     VARIABLE DEFINITIONS:
C           T          = TEMPERATURE (DEG. K)
C           TIME        = TIME (SEC)
C           F           = FRACTION OF LRO PHASE
C           DTIME       = TIME INCREMENT (DELTA- TIME, SEC)
C
C--- SET UP CONSTANTS
C
COMMON/LIST1/TA,TAO,TC,VOL,V,AREA,AS,IFLAG,LAMBDA,SIGMA,PHI
COMMON/LIST2/ L,EPS,LNA,A,N,B,THCL,THCK,THCA
COMMON/LIST3/DTIME,TTIME,SH,SHO,ACC,ACCO,CP,TAU
REAL LAMBDA,LNA,N,L

C
C--- TEST FOR REGIME
C
    IF ((IFLAG.EQ.1).OR.(IFLAG.EQ.2)) F=1.0
    IF ((IFLAG.EQ.5).OR.(IFLAG.EQ.6)) F=0.0
C--- TTIME=0 IF NO PHASE CHANGE YET
    IF ((IFLAG.NE.3).OR.(IFLAG.NE.4)) TTIME = 0.0
    IF ((IFLAG.EQ.3).OR.(IFLAG.EQ.4)) GO TO 10
    GO TO 30

C
C--- CALCULATE F
C
10    TTIME  = TTOLD+DTIME
      SUM    = LNA+B/T+ALOG(1.0-F)+(N-1.0)*ALOG(TTIME)+4*ALOG(TC-T)
      1      +ALOG(N)
      IF(SUM.LT.-70.0) SUM=-70.0
      IF(SUM.GT.70.0) SUM=70.0
      F      = F+DTIME*EXP(SUM)

30    RETURN
      END
```

SUBROUTINE TFCNH(T,F)

CCCCCCCC

SUBROUTINE NAME: TFCNH

PURPOSE: TO CALCULATE THE TEMPERATURE GIVEN A SENSIBLE
HEAT VALUE

VARIABLE DEFINITIONS:

T = TEMPERATURE (DEG. K)

$$\text{ACC} = \text{TOTAL ACCUMULATED HEAT (J)}$$

TA = AMBIENT TEMPERATURE (DEG. K)

C
C
C
C
C
C
C
C
C

```
COMMON/LIST1/TA,TAO,TC,VOL,V,AREA,AS,IFLAG,LAMBDA,SIGMA,PHI
COMMON/LIST2/ L,EPS,LNA,A,N,B,THCL,THCK,THCA
COMMON/LIST3/DTIME,TTIME,SH,SHO,ACC,ACCO,CP,TAU
REAL LAMBDA,LNA,N,L
```

C
C-
C

C--- SET UP CONSTANTS

C
C
C

CALL CPS(T,F,CP)

$$T = V/VOL/CP*(ACC+ACC0)$$

RETURN

END

C
C
C
C
C
C
C

SUBROUTINE CPS(T,F,CP)

```
IF(T.GT.873.0) GO TO 10
```

A1=376.36545

$$B1=0.06960968$$

C1=0.0

D1=0.0

GO TO 100

C

10 A1= 296.93

$$B1 = 0.1604$$

C1= 0.0

D1= 0.0

C

```
100      IF(T.GT.1141.0) GO TO 20
```

```
IF((T.LE.1141.0).AND.(T.GT.680.0)) GO TO 30
```

```

      A2= 376.36545
      B2= 0.06960968
      C2= 0.0
      D2= 0.0
      GO TO 200
C
20    A2= 567.3736
      B2= 0.0
      C2= 0.0
      D2= 0.0
      GO TO 200
C
30    A2= 211.78
      B2= 0.3117
      C2= 0.0
      D2= 0.0
C
C--- CALCULATE CP(T)
C
200   CONTINUE
      CPLRO  = A1+B1*T+C1*T**2+D1*T**3
      CPSRO  = A2+B2*T+C2*T**2+D2*T**3
      CP      = F*CPLRO+(1.0-F)*CPSRO
      RETURN
      END
C
C
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C
C
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C
C
      SUBROUTINE CONTRL(T,RHO,L,D,TO,TAMO,LATHTO,FO,CURREN,CPO,
1          RHR,RT,ETO,ERO,MO,P)
      DIMENSION P(2)
      REAL M,MO,KCT,KCR,LATHTO,L
      INDEX  = 1
      IF(CPO.LT.1.0) INDEX=0
      IF(INDEX.EQ.1) GO TO 5
C--- INITIALIZE PARAMETERS
      ETO    = 0.0
      ERO    = 0.0
      MO     = 0.0
      TO     = T
      LATHTO = 0.0
      TAMO   = TO
5      DTIME = 2.0
      KCT    = 0.827
      TIT    = 5.405
      KCR    = 0.05
      TIR    = 0.1

```

```

        KCR      = P(1)
        TIR      = P(2)
C--- CALCULATE TSTAR
        TSTAR    = T+RHR*DTIME
        IF((RHR.GT.0.0).AND.(TSTAR.GT.RT)) TSTAR=RT
        IF((RHR.LT.0.0).AND.(TSTAR.LT.RT)) TSTAR=RT
        IF(RHR.EQ.0.0) TSTAR=RT
C--- DETERMINE WHICH CONTROLLER TO USE
        IF(RHR.EQ.0.0) GO TO 10
C--- RATE CONTROLLER
        HR       = (T-TO)/DTIME
        ETO      = 0.0
        ER       = RHR-HR
        DELT     = KCR*(ER-ERO)+KCR*DTIME/TIR*ER
        ERO      = ER
        GO TO 20
C--- TEMPERATURE CONTROLLER
10      ERO      = 0.0
        ET       = RT-T
        DELT     = KCT*(ET-ETO)+KCT*DTIME/TIT*ET
        ETO      = ET
20      M        = MO+DELT
        MO       = M
C--- CALL FEEDFORWARD CONTROLLER
        CALL FF(FFC,T,TO,TAMO,CPO,LATHTO,RHO,L,D,DTIME,RHR,RT,FO,
1         TSTAR)
        CURREN   = FFC+M
        IF(CURREN.GT.90.0) CURREN=90.0
        IF(CURREN.LT.0.0) CURREN=0.0
        TO       = T
        RETURN
        END

C
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C
        SUBROUTINE FF(FFC,T,TO,TAMO,CPO,LATHTO,RHO,L,D,DTIME,RHR,RT,FO,
1         TSTAR)
        REAL LAMBDA,LATHTO,LATHT,L
C--- INITIALIZE PARAMETERS
        PI       = 3.14159265
        TC       = 1141.0
        AREA     = PI*D**2/4.0
        AS       = PI*D*L
        VOL      = AREA*L
        V        = 0.0001085
        LAMBDA   = 51.58
        SIGMA    = 5.677E-8

```

```

        TAU      = 6000.0
        THCL     = 0.04
        THCK     = 67.05
        THCA     = 5.0671E-08
C--- CALCULATE PHI(T)
        EMISS    = 0.5229-0.00059335*TSTAR+6.0901E-07*TSTAR**2
        PHI      = EMISS*AS
C--- CALCULATE TA AS A FUNCTION OF T
        TASS     = 0.004607*(TSTAR-300.0)**1.7253+300.0
        TASTAR   = (TASS-TAMO)*(1.0-EXP(-DTIME/TAU))+TAMO
        IF(TASTAR.LT.300.0) TASTAR=300.0
        TAMO     = TASTAR
C--- DETERMINE F
        CALL RHOCTL(T,1.0,RHOLRO)
        CALL RHOCTL(T,0.0,RHOSRO)
        F= (RHO-RHOSRO)/(RHOLRO-RHOSRO)
        IF(F.LT.0.0) F= 0.0
        IF(F.GT.1.0) F= 1.0
        IF(CP0.LT.1.0) F0=F
        GO TO 20
10      F        = 0.0
C--- CALCULATE THE CURRENT FROM THE HEAT BALANCE
20      LATHT    = LAMBDA*(1.0-F)
        CALL CPSCTL(TSTAR,F,CPSTAR)
        CALL CPSCTL(T,F0,CP0)
        CALL RHOCTL(TSTAR,F,RHOSTR)
        DACC     = CPSTAR*TSTAR-CP0*T
        IF(RHR.EQ.0.0) DACC=0.0
        CRNT2    = AREA/RHOSTR/L*(VOL/V*DACC/DTIME
1          -(LATHT-LATHTO)/DTIME-SIGMA*PHI*(TASTAR**4-TSTAR**4)
2          -4*THCK*THCA/THCL*(TASTAR-TSTAR))
        IF(CRNT2.LT.0.0) CRNT2=0.0
        FFC      = SQRT(CRNT2)
        IF(FFC.GT.90.0) FFC=90.0
C--- RESET PREVIOUS LATENT HEAT AND F
        LATHTO   = LATHT
        F0       = F
        RETURN
        END

```

C
C
C
C
C
C
C
C
C

SUBROUTINE RHOCTL (T,F,RHO)

C
C
C

SUBROUTINE NAME: RHOCTL

C

PURPOSE: TO CALCULATE THE RESISTIVITY AS A FUNCTION OF

C

C


```

      A1=376.36545
      B1=0.06960968
      C1=0.0
      D1=0.0
      GO TO 100
C
  10    A1= 296.93
        B1= 0.1604
        C1= 0.0
        D1= 0.0
C
  100    IF(T.GT.1141.0) GO TO 20
        IF((T.LE.1141.0).AND.(T.GT.680.0)) GO TO 30
        A2= 376.36545
        B2= 0.06960968
        C2= 0.0
        D2= 0.0
        GO TO 200
C
  20    A2= 567.3736
        B2= 0.0
        C2= 0.0
        D2= 0.0
        GO TO 200
C
  30    A2= 211.78
        B2= 0.3117
        C2= 0.0
        D2= 0.0
C
C--- CALCULATE CP(T)
C
  200    CONTINUE
        CPLRO = A1+B1*T+C1*T**2+D1*T**3
        CPSRO = A2+B2*T+C2*T**2+D2*T**3
        CP     = F*CPLRO+(1.0-F)*CPSRO
        RETURN
        END
C
C
C
C
      SUBROUTINE BOUNDS (P,IOUT)
      DIMENSION P(2)
      IOUT = 0
      IF((P(1).LE.0.0).OR.(P(2).LE.0.0))IOUT=1
      IF((P(1).GT.10.0).OR.(P(2).GT.50.0))IOUT=1
      RETURN
      END

```

C
C
C

APPENDIX B

MODEL PROGRAM


```

C
C      SUBROUTINES CALLED:
C
C      MODEL      : MAIN SUBROUTINE FOR MODELING
C      RHOS       : CALCULATES RHO AS A FUNCTION OF T
C      CPS        : CALCULATES CP AS A FUNCTION OF T
C
C*****C
C
C
COMMON/LIST1/TA,TAO,TC,VOL,V,AREA,AS,IFLAG,LAMBDA,SIGMA,PHI
COMMON/LIST2/ L,EPS,LNA,A,N,B,THCL,THCK,THCA
COMMON/LIST3/DTIME,TTIME,SH,SHO,ACC,ACCO,CP,TAU
REAL LAMBDA,LNA,N,L
DIMENSION CURENT(10),ENDTIM(10)
C--- PREPARE PLOTTING FILES
OPEN (UNIT=30,FILE='PLOT.DAT',ACCESS='SEQOUT')
OPEN (UNIT=31,FILE='PLOT2.DAT',ACCESS='SEQOUT')
OPEN (UNIT=32,FILE='PLOT3.DAT',ACCESS='SEQOUT')
WRITE (30,2000)
WRITE (31,2000)
WRITE (32,2000)
WRITE (30,2010)
WRITE (31,2010)
WRITE (32,2010)
C--- ASK USER FOR RUN INFORMATION
WRITE (5,1000)
READ(5,*) TIMEF,DTIME
WRITE (5,1010)
READ (5,*) NP
NO      = INT(TIMEF/DTIME)
DUM     = NO/NP
NUM     = INT(DUM)
NPP     = NP+1
WRITE (30,*) NPP
WRITE (31,*) NPP
WRITE (32,*) NP
WRITE (5,1020)
READ(5,*) NREG
DO 5 I=1,NREG
      WRITE (5,1030) I
      READ(5,*) CURENT(I),ENDTIM(I)
5      CONTINUE
C
C--- INITIALIZE PARAMETERS
C
      SH      = 0.0
      SHO     = 0.0
      TIME    = 0.0
      TTIME   = 0.0
      ACC     = 0.0

```

```

      TAO      = 300.0
      TA       = TAO
      TC       = 1141.0
      PI       = 3.14159265
      D        = 0.0032
      L        = 0.00698
      AREA     = PI*D**2/4.0
      VOL      = AREA*L
      V        = 0.0001085
      AS       = PI*D*L
      THCL     = 0.04
      THCK     = 67.05
      THCA     = 5.0671E-08
      IFLAG    = 0
      ICOUNT   = 0
      LAMBDA   = 51.58
      SIGMA    = 5.677E-8
      TAU      = 6000.0
      EPS      = 1.0-1.0E-8
      LNA      = 32.08977
      A        = -EXP(LNA)
      N        = 1.835001
      B        = -61330.0
      F        = 1.0
      T        = TA
      CALL RHOS (T,F,RHO)
      CALL CPS(T,F,CP)
      ACCO     = VOL*CP*T/V
      WRITE (30,2020) TIME,T
      WRITE (31,2020) T,RHO
C
C--- START TIME LOOP
C
      J        = 1
      DO 10 I=1,NO
C--- SET CURRENT
          CURREN = CURENT(J)
          FINTIM = ENDTIM(J)
C--- CALCULATE TIME
          TIME    = TIME+DTIME
          ICOUNT  = ICOUNT+1
C--- CALCULATE SYSTEM PARAMETERS
          CALL MODEL(T,TIME,CURREN,F,RHO)
          IF(ICOUNT.NE.NUM) GO TO 10
C--- OUTPUT MODEL
          WRITE (30,2020) TIME,T
          WRITE (31,2020) T,RHO
          WRITE (32,2020) T,CP
          WRITE(33,3000) TIME,T,CURREN
          WRITE(33,3010) F,RHO,CP,SH
          WRITE(33,3020) IFLAG,TTIME,ACC
          WRITE(33,3030)

```



```

C          FRAC      : CALCULATES THE FRACTION OF LRO
C          TFCNH     : CALCULATES T AS A FUNCTION OF ACC
C          RHOS      : CALCULATES THE RESISTIVITY
C
C*****C
C
C          SUBROUTINE MODEL(T,TIME,CURREN,F,RHO)
C          COMMON/LIST1/TA,TA0,TC,VOL,V,AREA,AS,IFLAG,LAMBDA,SIGMA,PHI
C          COMMON/LIST2/ L,EPS,LNA,A,N,B,THCL,THCK,THCA
C          COMMON/LIST3/DTIME,TTIME,SH,SH0,ACC,ACC0,CP,TAU
C          REAL LAMBDA,LNA,N,L
C--- CALCULATE PHI(T)
C          EMISS      = 0.5229-0.00059335*T+6.0901E-07*T**2
C          PHI        = EMISS*AS
C--- CALCULATE TA AS A FUNCTION OF T
C          TASS       = 0.004607*(T-300.0)**1.7253+300.0
C          TA         = (TASS-TA0)*(1.0-EXP(-DTIME/TAU))+TA0
C          IF(TA.LT.300.0) TA=300.0
C          TA0        = TA
C--- CALCULATE THE TOTAL ENERGY OF THE SYSTEM
C          CALL SENSHT(T,CURREN,F,RHO)
C--- CALCULATE FRACTION OF LRO
C          CALL FRAC(T,F)
C--- CORRECT FOR LATENT HEAT
C          ACC        = SH+LAMBDA*(1.0-F)
C--- CALCULATE TEMPERATURE
C          CALL TFCNH(T,F)
C--- CALCULATE RESISTIVITY
C          CALL RHOS(T,F,RHO)
C          RETURN
C          END
C
C
C
C
C
C
C
C
C
C
C          SUBROUTINE NAME: RHOS
C          PURPOSE: TO CACULATE THE RESISTIVITY AS A FUNCTION OF
C                   TEMPERATURE AND THE FRACTION OF LRO.
C          VARIABLE DEFINITIONS:
C                   T      = TEMPERATURE (DEG. K)
C                   F      = FRACTION OF LRO
C                   RHO    = RESISTIVITY (OHM-METERS)
C*****C
C
C          SUBROUTINE RHOS (T,F,RHO)
C

```

C--- SET UP CONSTANTS

C
C

A1 = -4.0907464E-07
B1 = 3.775097E-09
C1 = -4.012551E-12
D1 = 1.775517E-15

C

A2 = 1.540493E-06
B2 = -6.611138E-10
C2 = 1.363067E-12
D2 = -7.995826E-16
IF(T.GT.1235.0) A2=0.130E-05
IF(T.GT.1235.0) B2= 0.0
IF(T.GT.1235.0) C2= 0.0
IF(T.GT.1235.0) D2= 0.0

C
C

C--- CALCULATE RESISTIVITY FOR LRO PHASE

C

10 RHO1 = A1+B1*T+C1*T**2+D1*T**3

C

C--- CALCULATE RESISTIVITY FOR SRO PHASE

C

20 RHO2 = A2+B2*T+C2*T**2+D2*T**3

C

C--- CALCULATE OVERALL RESISITIVITY

C

RHO = RHO1*F+RHO2*(1.0-F)

C

C--- RETURN RHO VALUE

C

RETURN
END

C

C

C

C

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C

SUBROUTINE NAME: SENSHT

PURPOSE: TO CALCULATE THE TOTAL ENERGY OF THE SYSTEM
USING THE (CURRENT-RADIATION) EQUATION

VARIABLE DEFINITIONS:

T = TEMPERATURE (DEG. K)

RHO = RESISTIVITY (OHM-METERS)

CURREN = CURRENT (AMPERES)

SH = TOTAL SENSIBLE HEAT OF THE SYSTEM (J)

```

C          TA      = AMBIENT TEMPERATURE (DEG. K)
C          SHO      = OLD SH VALUE
C          IFLAG    = FLAG TO DETERMINE IF HEATING OR COOLING AND
C                     IF ABOVE OR BELOW TC
C          TC       = SEE MAIN PROGRAM
C          AREA     = SEE MAIN PROGRAM
C          SIGMA    = SEE MAIN PROGRAM
C          PHI      = SEE MAIN PROGRAM
C          THCK     = SEE MAIN PROGRAM
C          THCA     = SEE MAIN PROGRAM
C          THCL     = SEE MAIN PROGRAM
C
C*****C
C
C          SUBROUTINE SENSHT (T,CURREN,F,RHO)
C          COMMON/LIST1/TA,TAO,TC,VOL,V,AREA,AS,IFLAG,LAMBDA,SIGMA,PHI
C          COMMON/LIST2/ L,EPS,LNA,A,N,B,THCL,THCK,THCA
C          COMMON/LIST3/DTIME,TTIME,SH,SHO,ACC,ACCO,CP,TAU
C          REAL LAMBDA,LNA,N,L
C          IFLAG    = 0
C
C          C--- CALCULATE SH
C          CURRENT HEATING=CURRENT**2*RHO*L/AREA
C          RADIATION COOLING=SIGMA*PHI*(TA**4-T**4)
C          CONDUCTION (THERMOCOUPLE) COOLING=4*THCK*(TA-T)*THCA/THCL
C
C          SH      = SHO+DTIME*(CURRENT**2*RHO*L/AREA+SIGMA*PHI*
C          1        (TA**4-T**4)+4*THCK*(TA-T)*THCA/THCL)
C          C--- IF COOLING BELOW TC W/ SRO, IFLAG=4
C          IF((SH.LT.SHO).AND.(F.LT.EPS).AND.(T.LT.TC)) IFLAG=4
C          C--- IF COOLING ABOVE TC, IFLAG=6
C          IF((SH.LT.SHO).AND.(T.GE.TC)) IFLAG=6
C          C--- IF COOLING W/O SRO (BELOW TC) IFLAG=2
C          IF((SH.LT.SHO).AND.(F.GE.EPS)) IFLAG=2
C          C--- IF HEATING W/O SRO (BELOW TC), IFLAG=1
C          IF((SH.GE.SHO).AND.(F.GE.EPS)) IFLAG=1
C          C--- IF HEATING BELOW TC W/ SRO, IFLAG=3
C          IF((SH.GE.SHO).AND.(F.LT.EPS).AND.(T.LT.TC)) IFLAG=3
C          C--- IF HEATING ABOVE TC, IFLAG=5
C          IF((SH.GE.SHO).AND.(T.GE.TC)) IFLAG=5
C          SHO      = SH
C          IF(IFLAG.EQ.0) WRITE (5,1000)
1000    FORMAT(//,1X,'ERROR:  IFLAG ZERO.',//)
C          RETURN
C          END
C
C
C
C
C
C
C

```

```

C
C
C
C
C      SUBROUTINE NAME:  FRAC
C      PURPOSE:  TO CALCULATE THE FRACTION OF THE LRO TRANSFORMED
C               FROM THE SRO
C      VARIABLE DEFINITIONS:
C          T      = TEMPERATURE (DEG. K)
C          TIME    = TIME (SEC)
C          F      = FRACTION OF LRO PHASE
C          DTIME   = TIME INCREMENT (DELTA- TIME, SEC)
C          IFLAG   = FLAG TO SEE IF HEATING OR COOLING, ABOVE
C                   OR BELOW TC
C          LNA     = SEE MAIN PROGRAM
C          B       = SEE MAIN PROGRAM
C          N       = SEE MAIN PROGRAM
C          TTIME   = ELAPSED TIME OF PHASE TRANSFORMATION
C
C*****C
C
C      SUBROUTINE FRAC(T,F)
C      COMMON/LIST1/TA,TAO,TC,VOL,V,AREA,AS,IFLAG,LAMBDA,SIGMA,PHI
C      COMMON/LIST2/ L,EPS,LNA,A,N,B,THCL,THCK,THCA
C      COMMON/LIST3/DTIME,TTIME,SH,SHO,ACC,ACCO,CP,TAU
C      REAL LAMBDA,LNA,N,L
C
C--- TEST FOR REGIME
C
C      IF ((IFLAG.EQ.1).OR.(IFLAG.EQ.2)) F=1.0
C      IF ((IFLAG.EQ.5).OR.(IFLAG.EQ.6)) F=0.0
C--- TTIME=0 IF NO PHASE CHANGE YET
C      IF ((IFLAG.NE.3).OR.(IFLAG.NE.4)) TTIME = 0.0
C      IF ((IFLAG.EQ.3).OR.(IFLAG.EQ.4)) GO TO 10
C      GO TO 30
C
C--- CALCULATE F
C
C      10  TTIME  = TTOLD+DTIME
C          SUM    = LNA+B/T+ALOG(1.0-F)+(N-1.0)*ALOG(TTIME)+4*ALOG(TC-T)
C              1  +ALOG(N)
C          IF(SUM.LT.-70.0) SUM=-70.0
C          IF(SUM.GT.70.0) SUM=70.0
C          F      = F+DTIME*EXP(SUM)
C      30  RETURN
C          END
C
C
C
C
C
C
C
C

```

```

C
C
C
C
C      SUBROUTINE NAME:  TFCNH
C      PURPOSE:  TO CALCULATE THE TEMPERATURE GIVEN A SENSIBLE
C               HEAT VALUE
C      VARIABLE DEFINITIONS:
C          T      = TEMPERATURE (DEG. K)
C          ACC     = TOTAL ACCUMULATED HEAT (J)
C          TA      = AMBIENT TEMPERATURE (DEG. K)
C          F       = FRACTION LRO
C          V       = SEE MAIN PROGRAM
C          VOL     = SEE MAIN PROGRAM
C          CP      = SEE MAIN PROGRAM
C          ACC     = SEE MAIN PROGRAM
C          ACCO    = SEE MAIN PROGRAM
C
C*****C
C
C
C      SUBROUTINE TFCNH(T,F)
C      COMMON/LIST1/TA,TAO,TC,VOL,V,AREA,AS,IFLAG,LAMBDA,SIGMA,PHI
C      COMMON/LIST2/ L,EPS,LNA,A,N,B,THCL,THCK,THCA
C      COMMON/LIST3/DTIME,TTIME,SH,SHO,ACC,ACCO,CP,TAU
C      REAL LAMBDA,LNA,N,L
C
C
C--- SET UP CONSTANTS
C
C      CALL CPS(T,F,CP)
C      T      = V/VOL/CP*(ACC+ACCO)
C      RETURN
C      END
C
C
C
C
C
C
C
C
C      SUBROUTINE NAME:  CPS
C      PURPOSE:  TO CALCULATE THE HEAT CAPACITY AS A FUNCTION OF T
C      VARIABLE DEFINITIONS:
C          T      = TEMPERATURE (K)
C          F      = FRACTION LRO
C          CP     = HEAT CAPACITY (J/(KG-DEG.K))
C          CPLRO  = CP OF LRO PHASE
C          CPSRO  = CP OF SRO PHASE
C
C*****C
C
C      SUBROUTINE CPS(T,F,CP)
C--- SET UP POWER SERIES CONSTANTS

```

```

      IF(T.GT.873.0) GO TO 10
      A1=376.36545
      B1=0.06960968
      C1=0.0
      D1=0.0
      GO TO 100
C
  10   A1= 296.93
      B1= 0.1604
      C1= 0.0
      D1= 0.0
C
  100  IF(T.GT.1141.0) GO TO 20
      IF((T.LE.1141.0).AND.(T.GT.680.0)) GO TO 30
      A2= 376.36545
      B2= 0.06960968
      C2= 0.0
      D2= 0.0
      GO TO 200
C
  20   A2= 567.3736
      B2= 0.0
      C2= 0.0
      D2= 0.0
      GO TO 200
C
  30   A2= 211.78
      B2= 0.3117
      C2= 0.0
      D2= 0.0
C
C--- CALCULATE CP(T)
C
  200  CONTINUE
      CPLRO = A1+B1*T+C1*T**2+D1*T**3
      CPSRO = A2+B2*T+C2*T**2+D2*T**3
      CP     = F*CPLRO+(1.0-F)*CPSRO
      RETURN
      END

```

APPENDIX C

RESPONSE CURVES

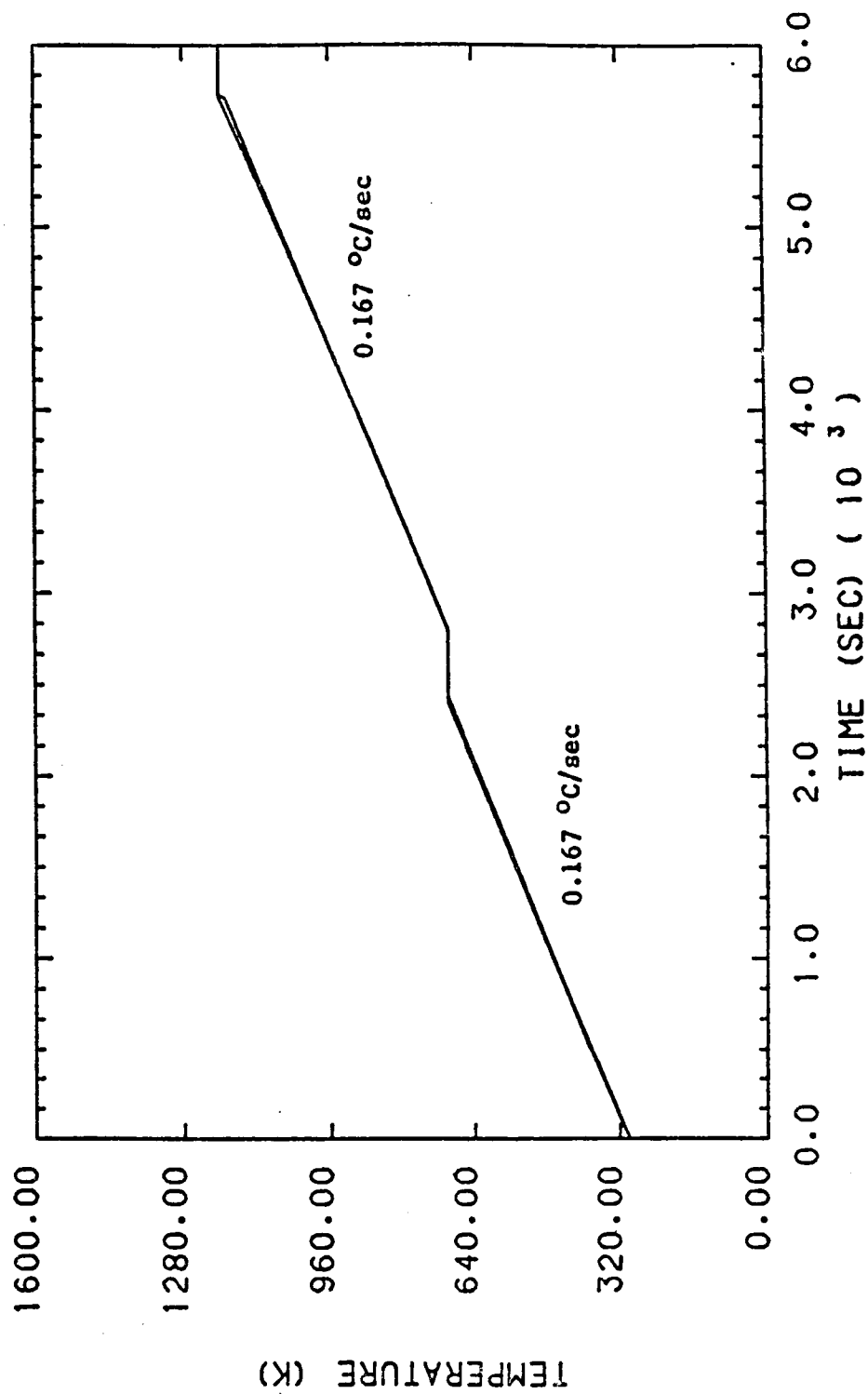


Figure C-1. Temperature response of the feedforward-feedback controller for a rate of 0.167 °C/sec. The temperature set points were 700K and 1200K.

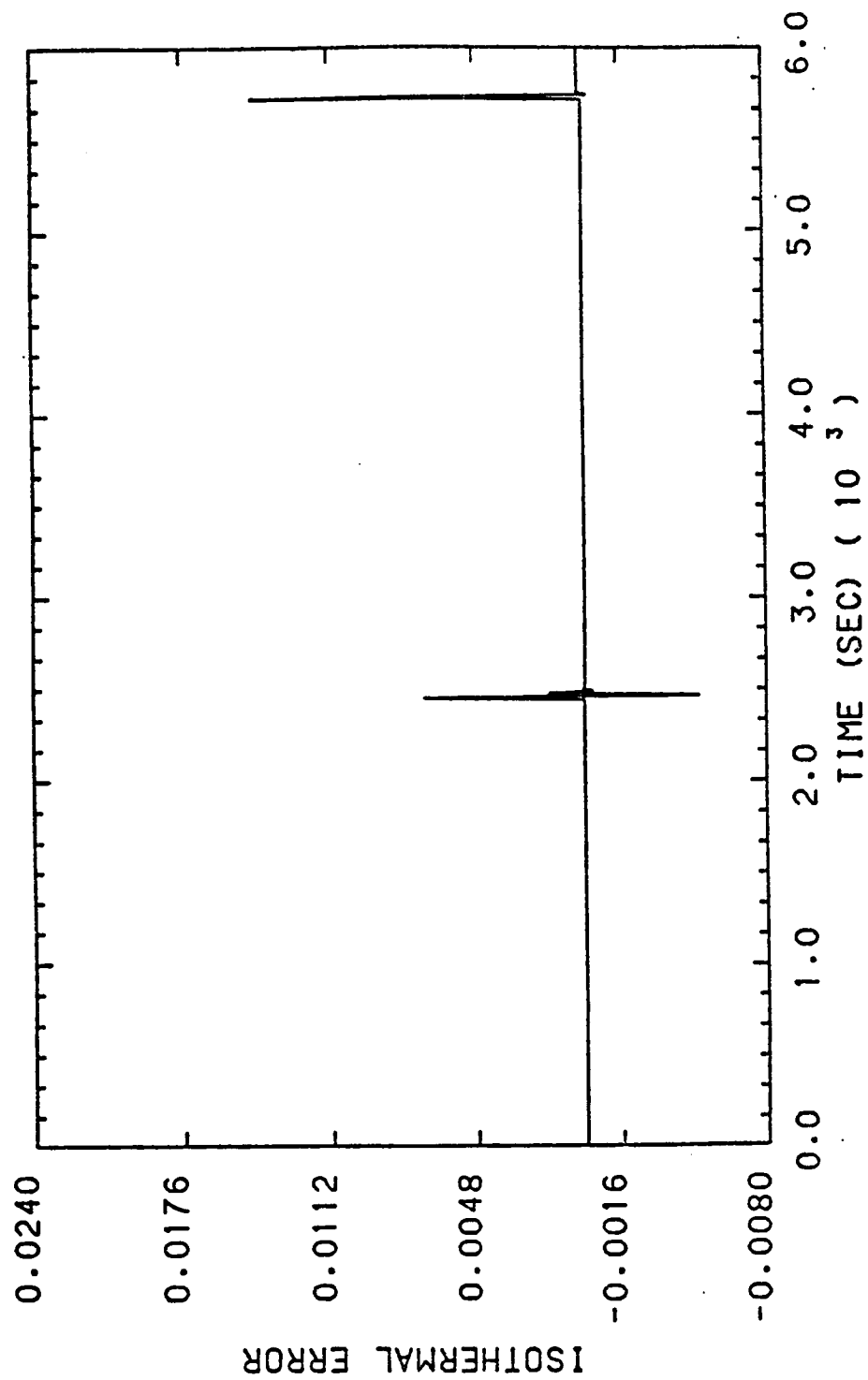


Figure C-2. Error (K) in isothermal regime for the feedforward-feedback controller for a rate of $0.167\text{ }^{\circ}\text{C/sec}$.

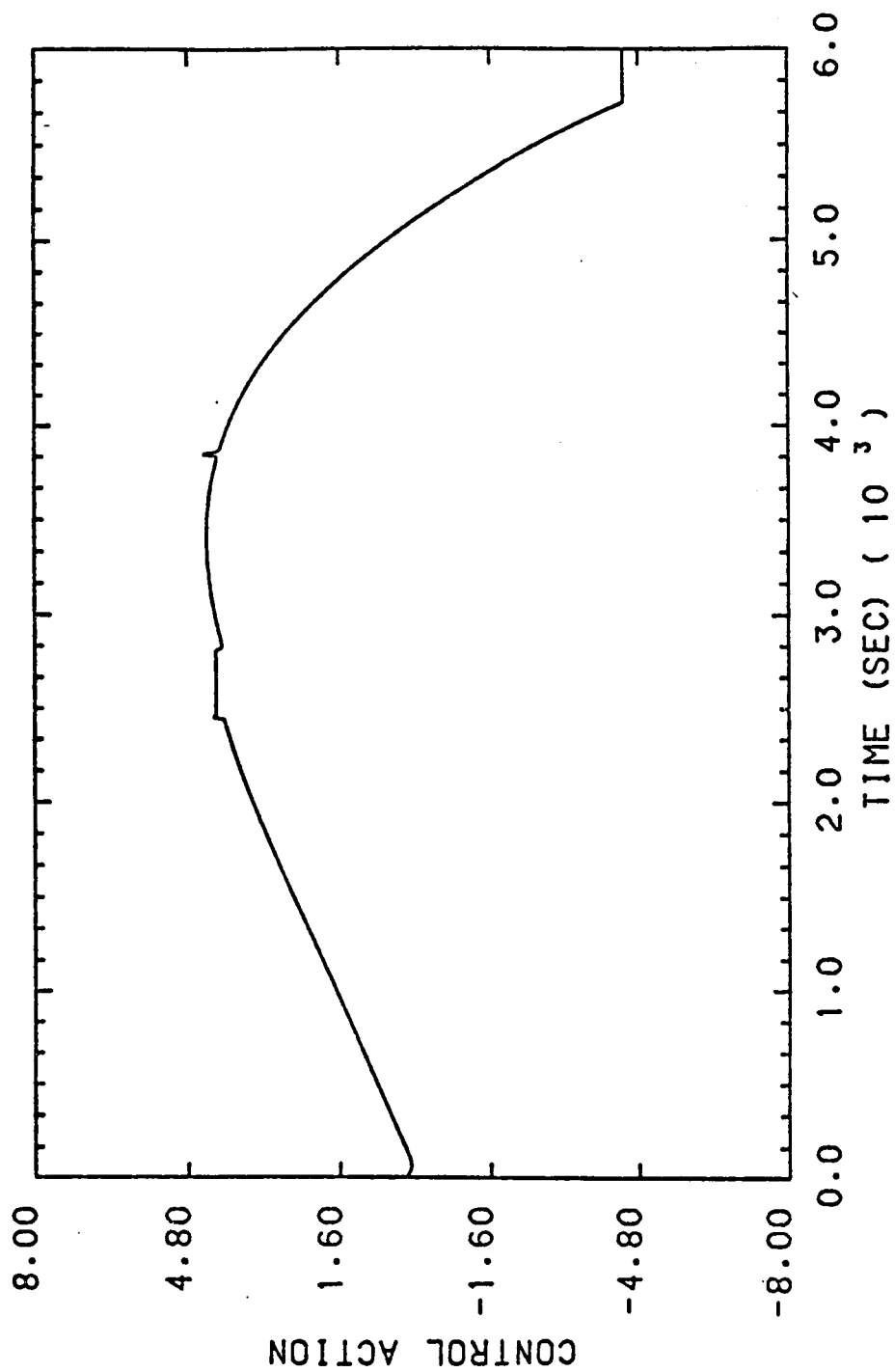


Figure C-3. Control action (M) of the feedforward-feedback controller for a rate of $0.167\text{ }^{\circ}\text{C/sec}$.

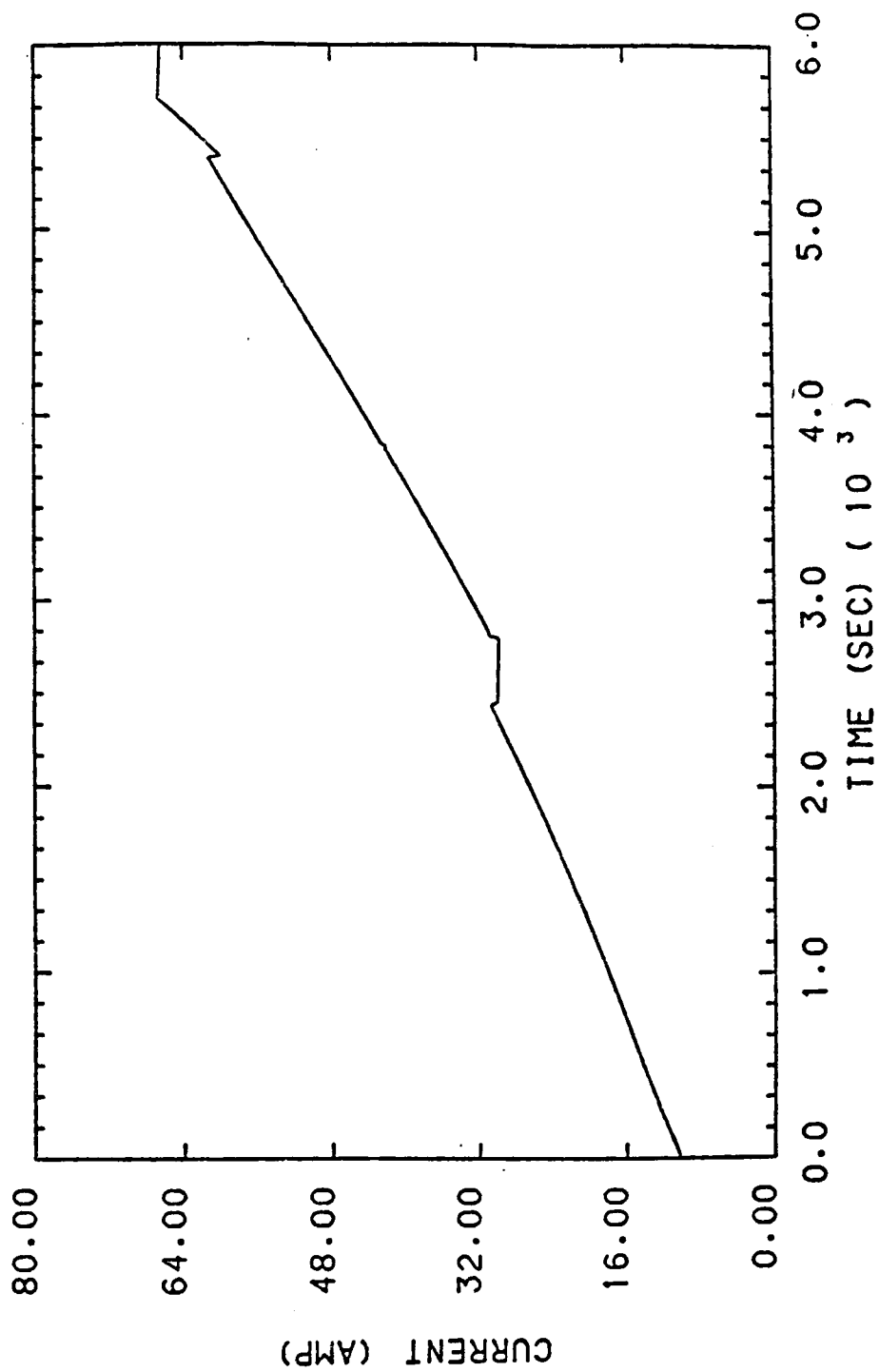


Figure C-4. Current (manipulated variable) from feedforward-feedback controller for a rate of 0.167 °C/sec.

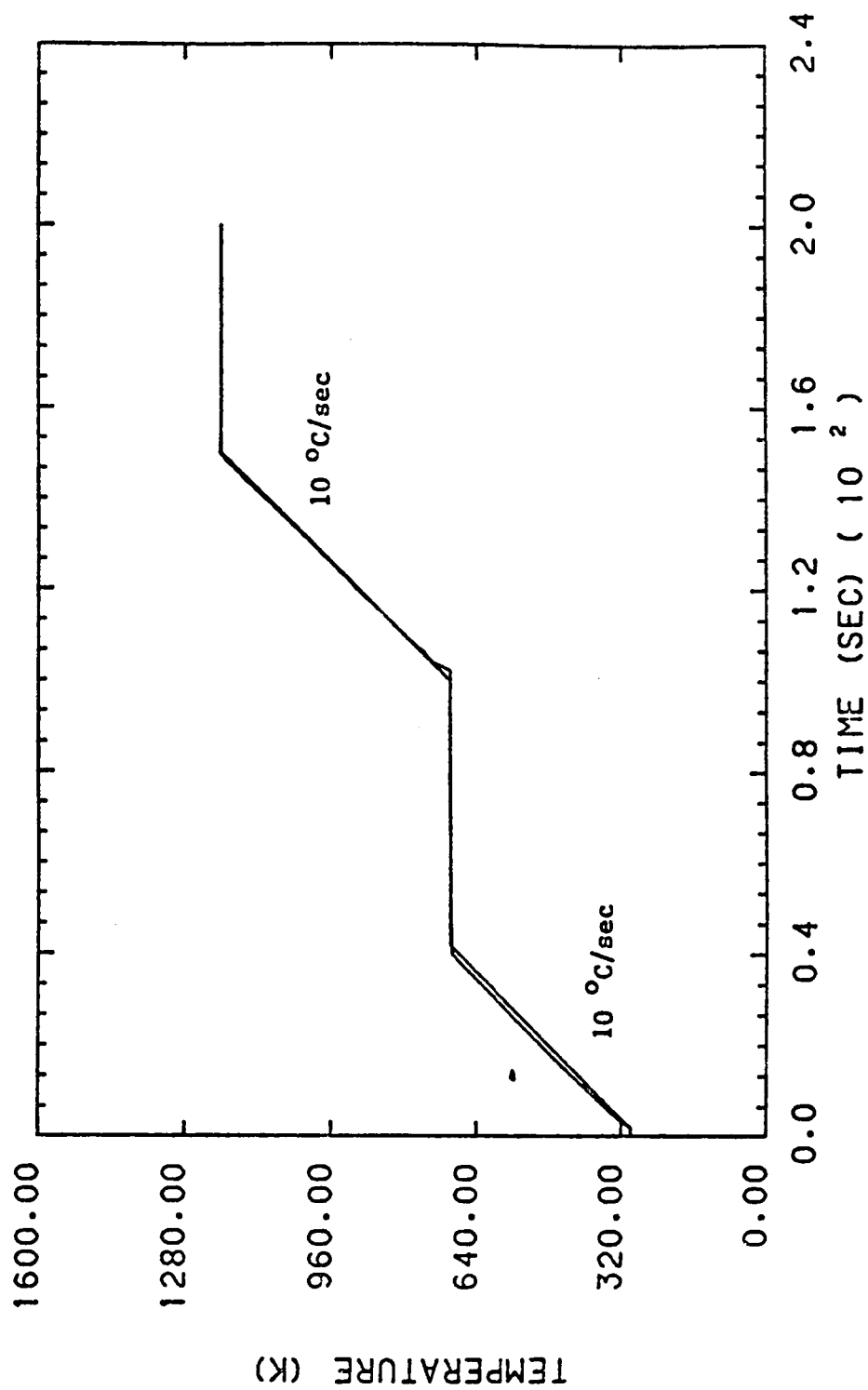


Figure C-5. Temperature response of the feedforward-feedback controller for a rate of 10 °C/sec and temperature set points of 700K and 1200K.

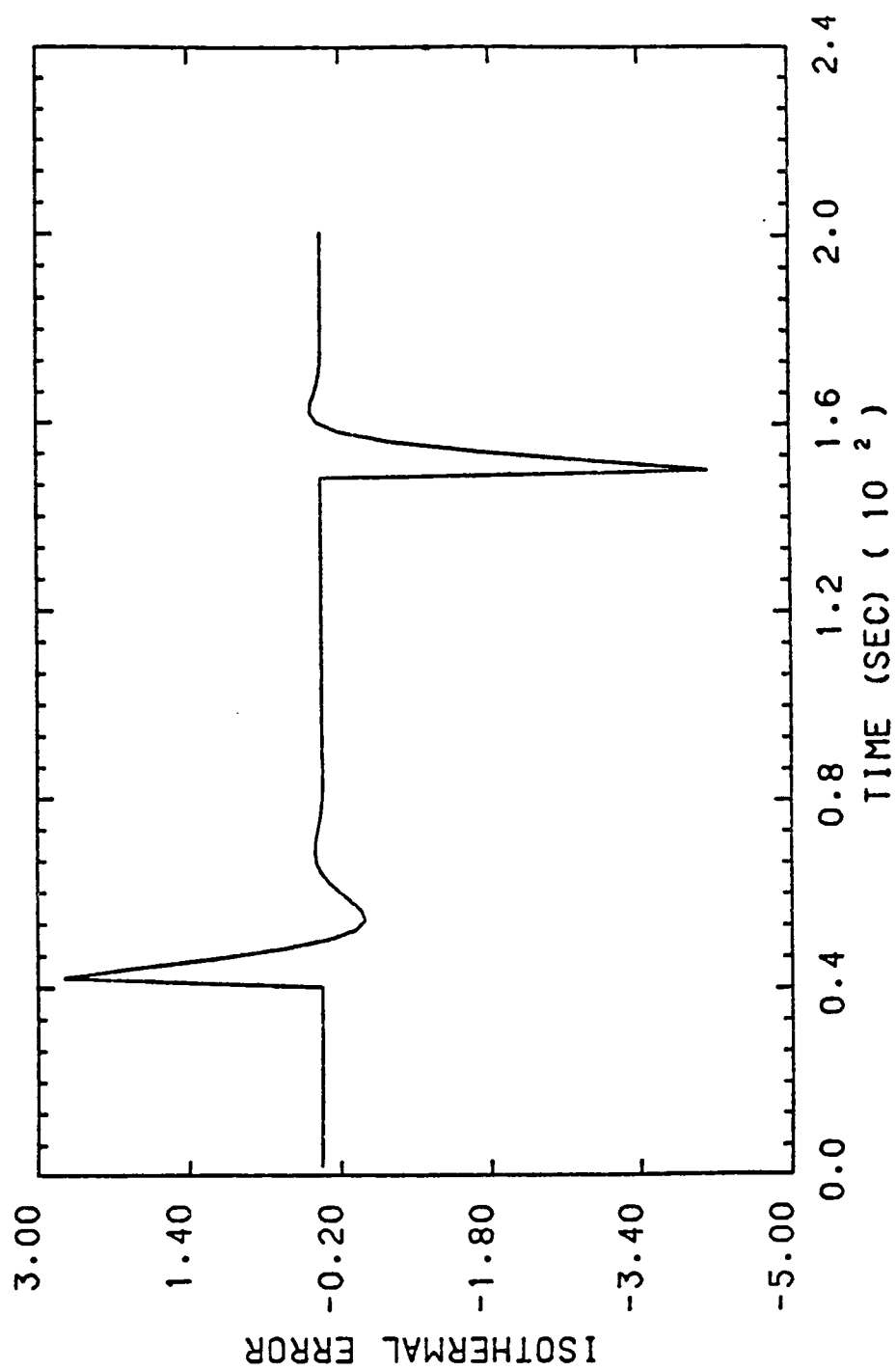


Figure C-6. Isothermal error (K) in temperature for the feedback-feedforward controller for a rate of 10 °C/sec.

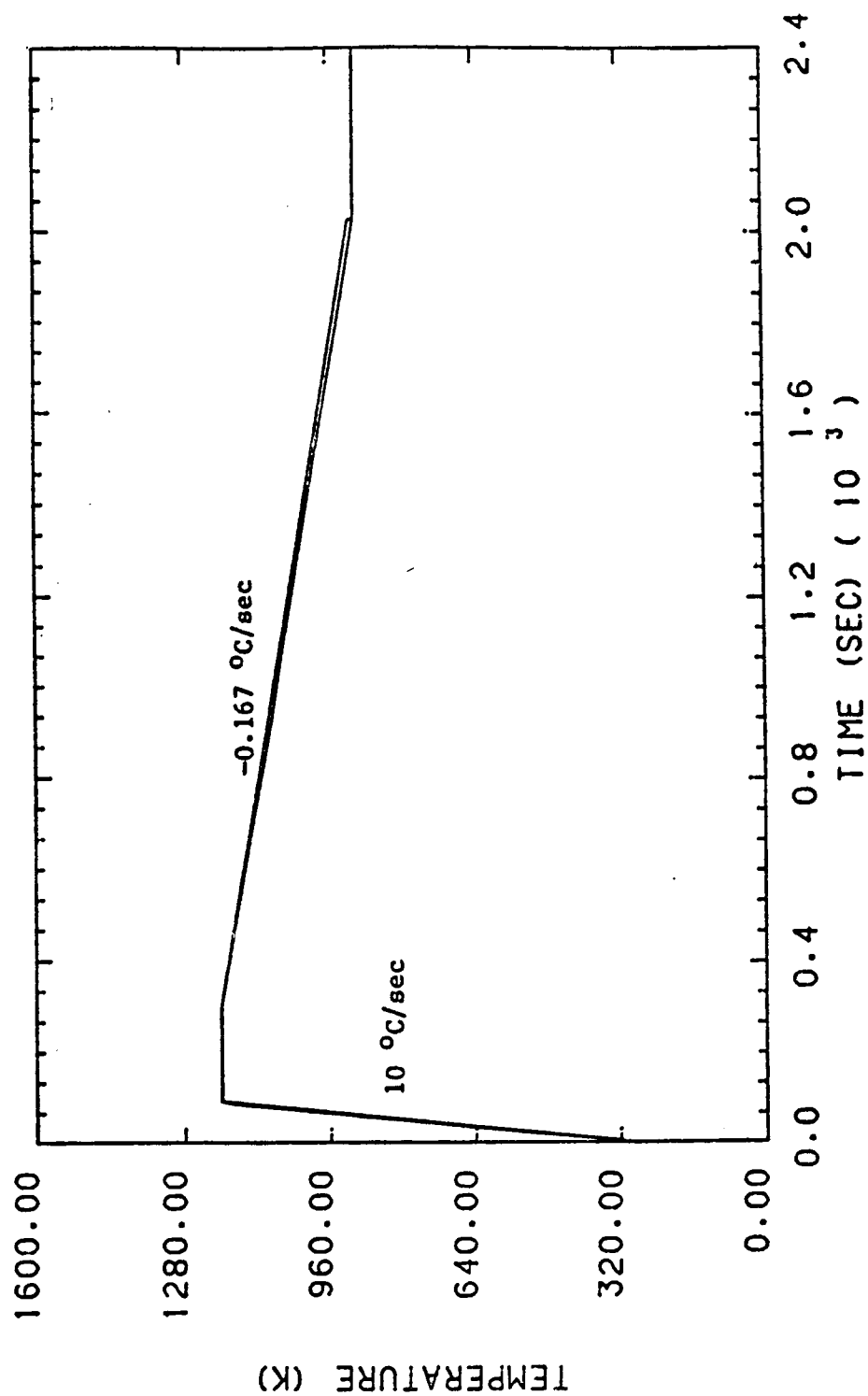


Figure C-7. Temperature response of the feedforward-feedback controller for rates of $10\text{ }^{\circ}\text{C/sec}$ and $-0.167\text{ }^{\circ}\text{C/sec}$.

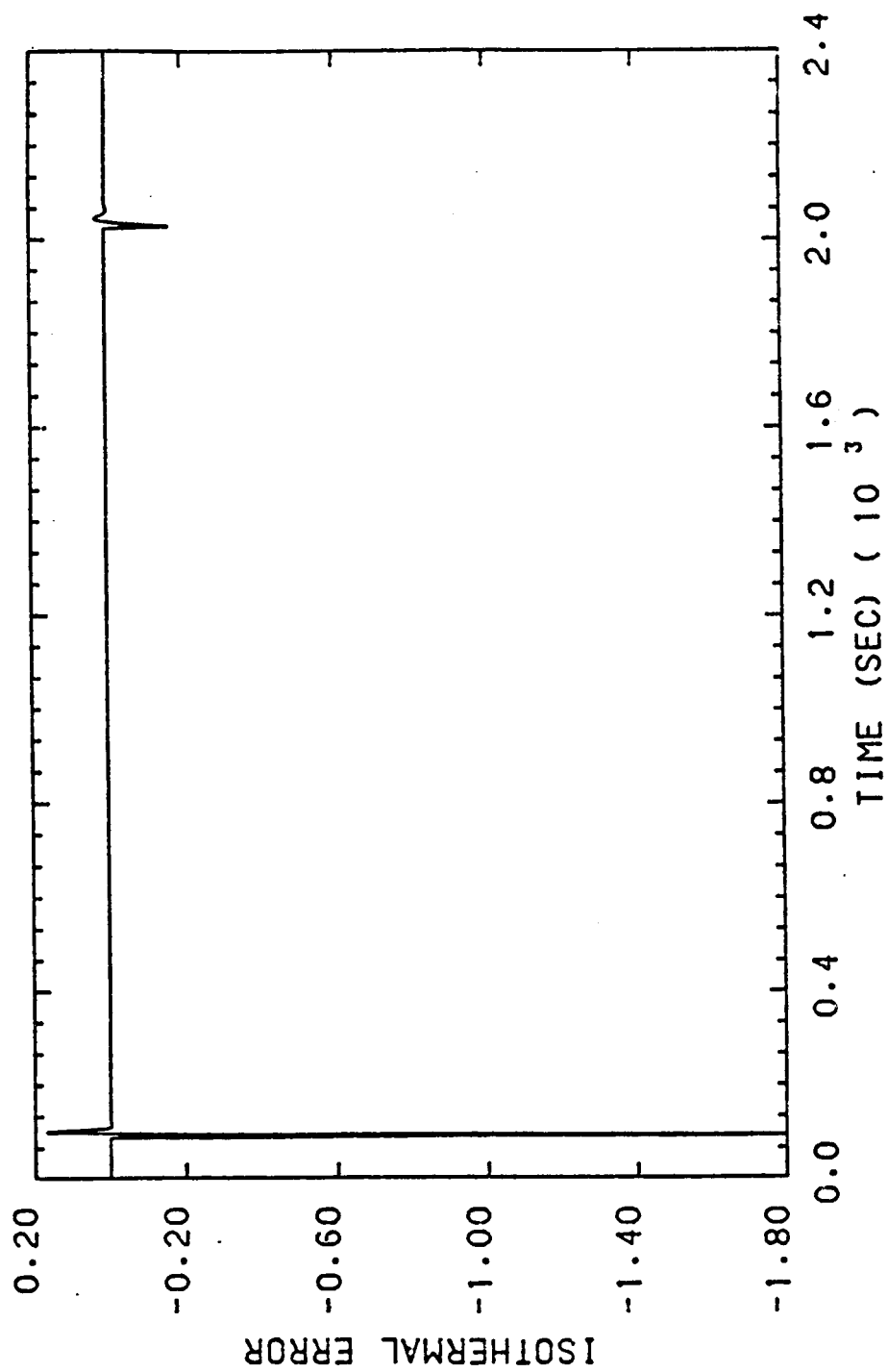


Figure C-8. Isothermal error in temperature (K) for the feedforward-feedback controller and rates of 10 °C/sec and -0.167 °C/sec.

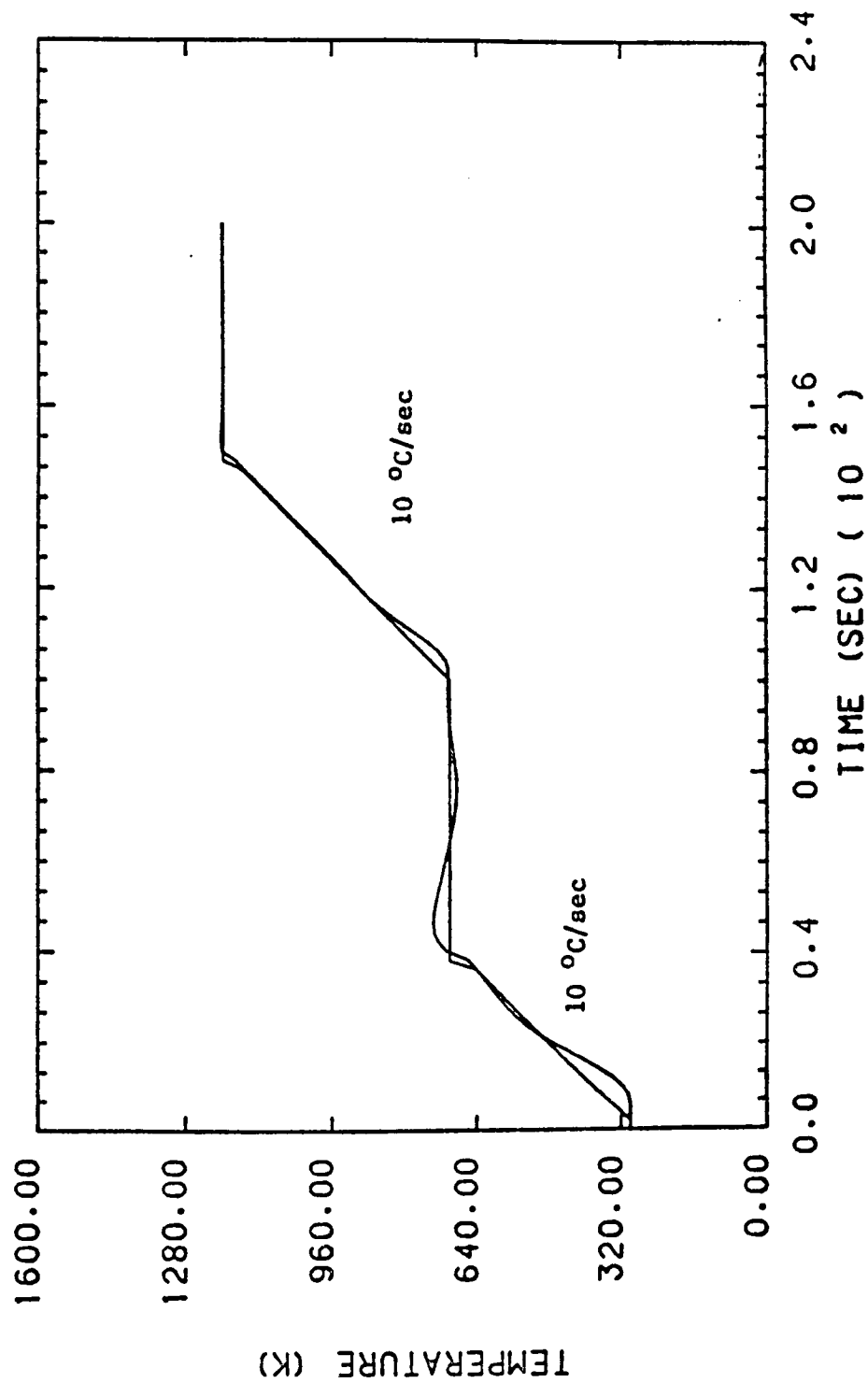


Figure C-9. Temperature response of a feedback temperature controller for a rate of 10 °C/sec ($K_C=0.5$, $T_I=4.0$).

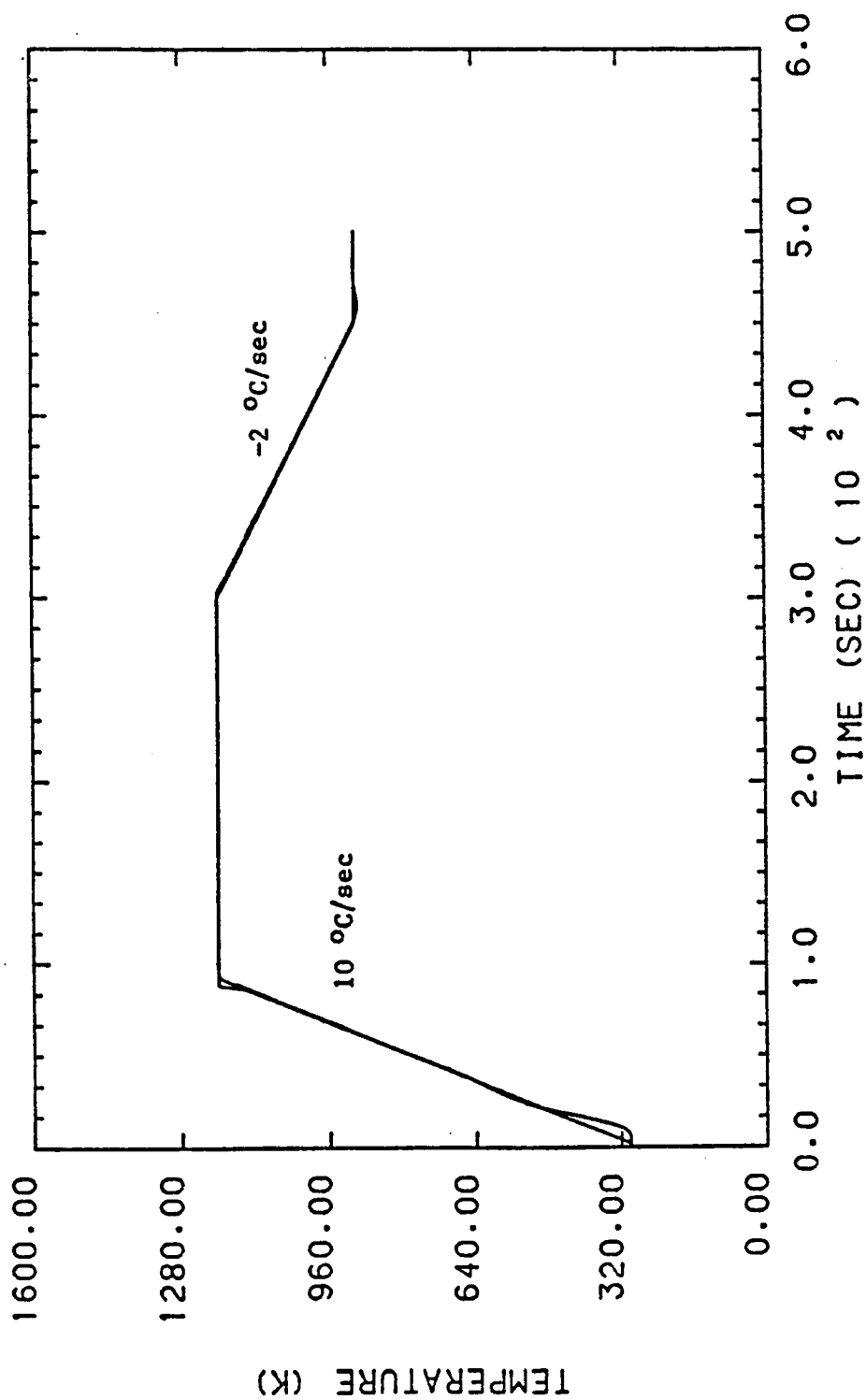


Figure C-10. Temperature response of the feedback controller for rates of 10 °C/sec and -2 °C/sec ($K_C=0.5$, $T_I=4.0$).

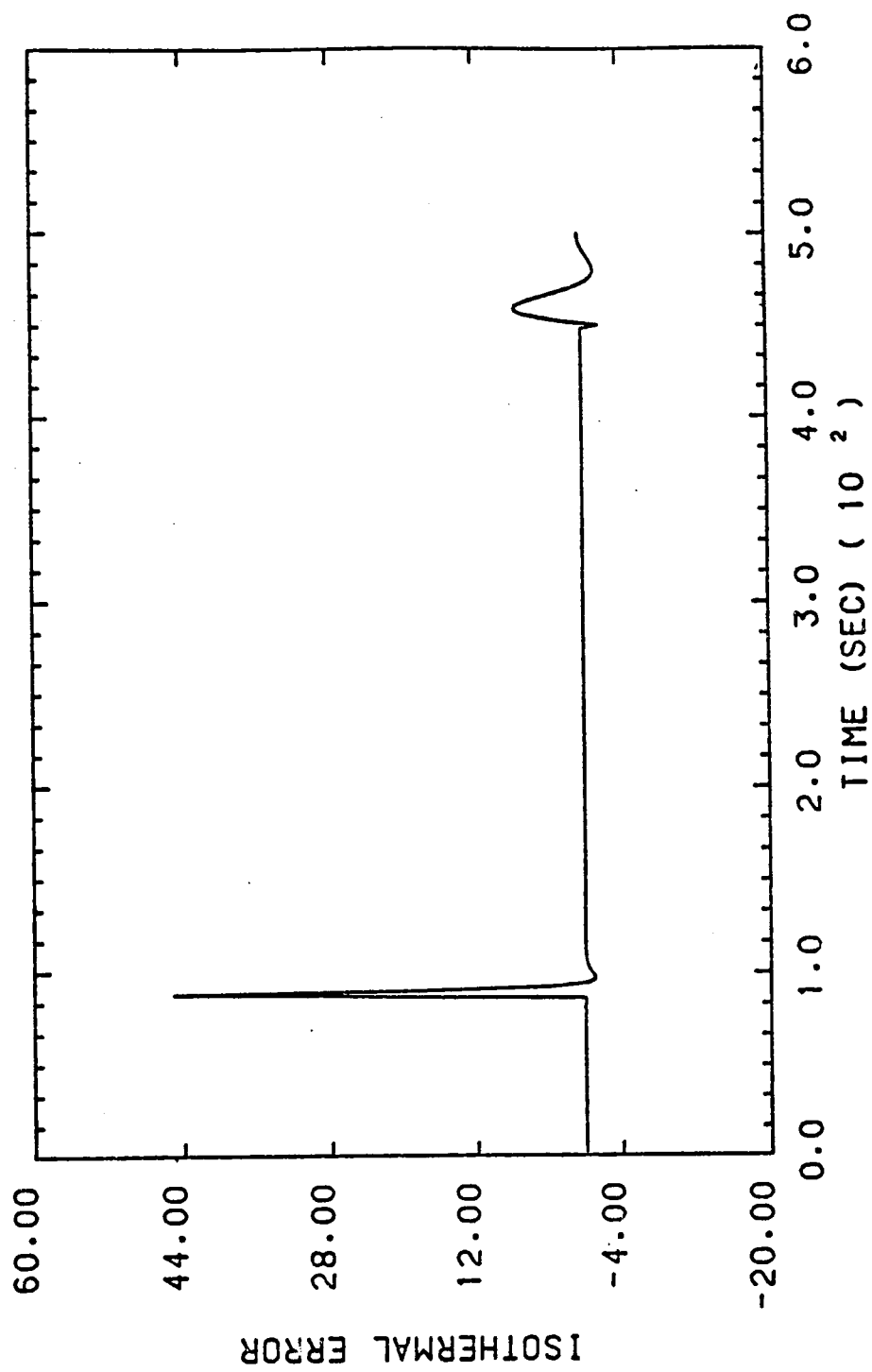


Figure C-11. Isothermal error in temperature (K) for the feedback temperature controller and rates of 10 °C/sec and -2 °C/sec.

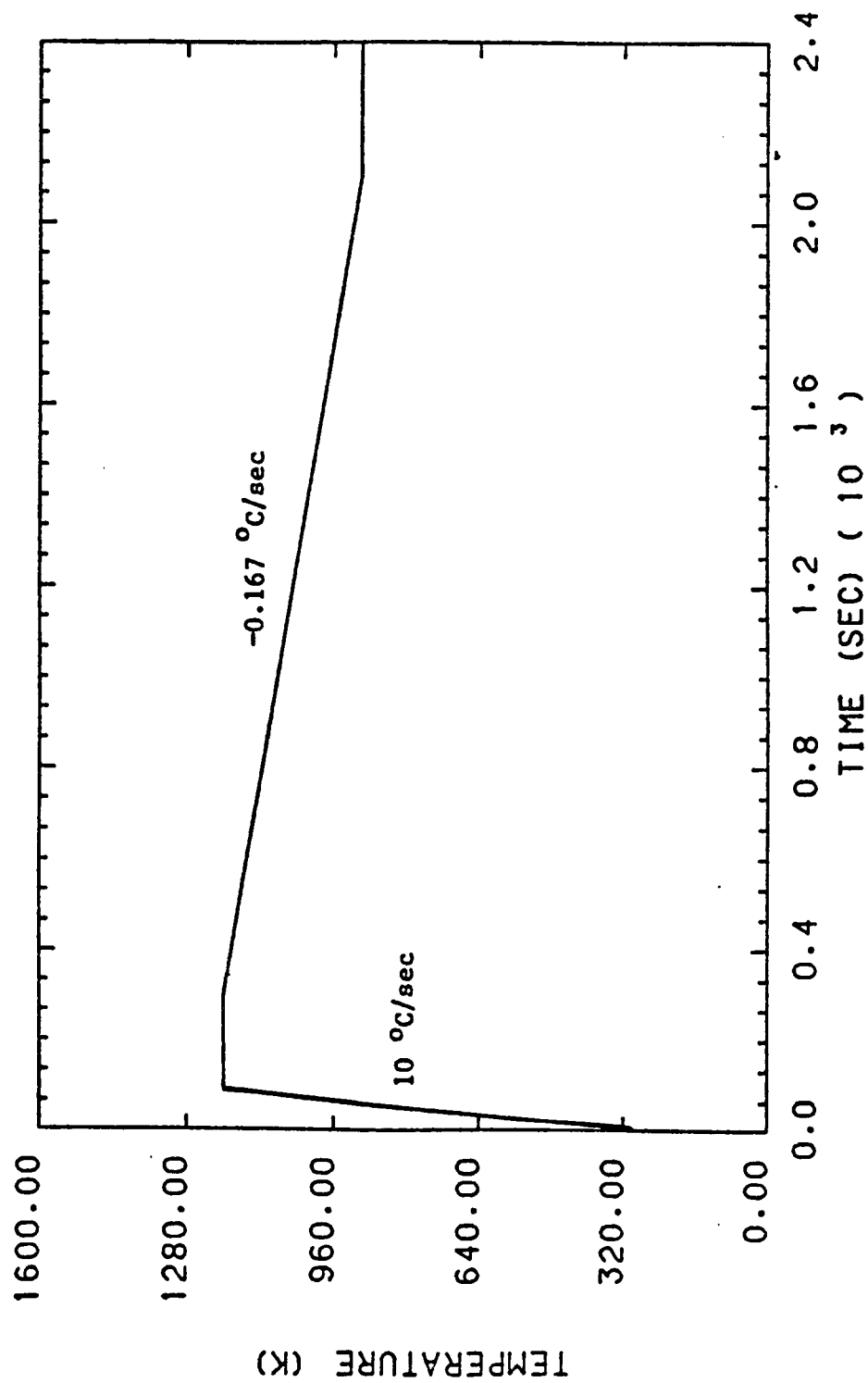


Figure C-12. Temperature response of the feedback temperature controller for rates of $10\text{ }^{\circ}\text{C/sec}$ and $-0.167\text{ }^{\circ}\text{C/sec}$.

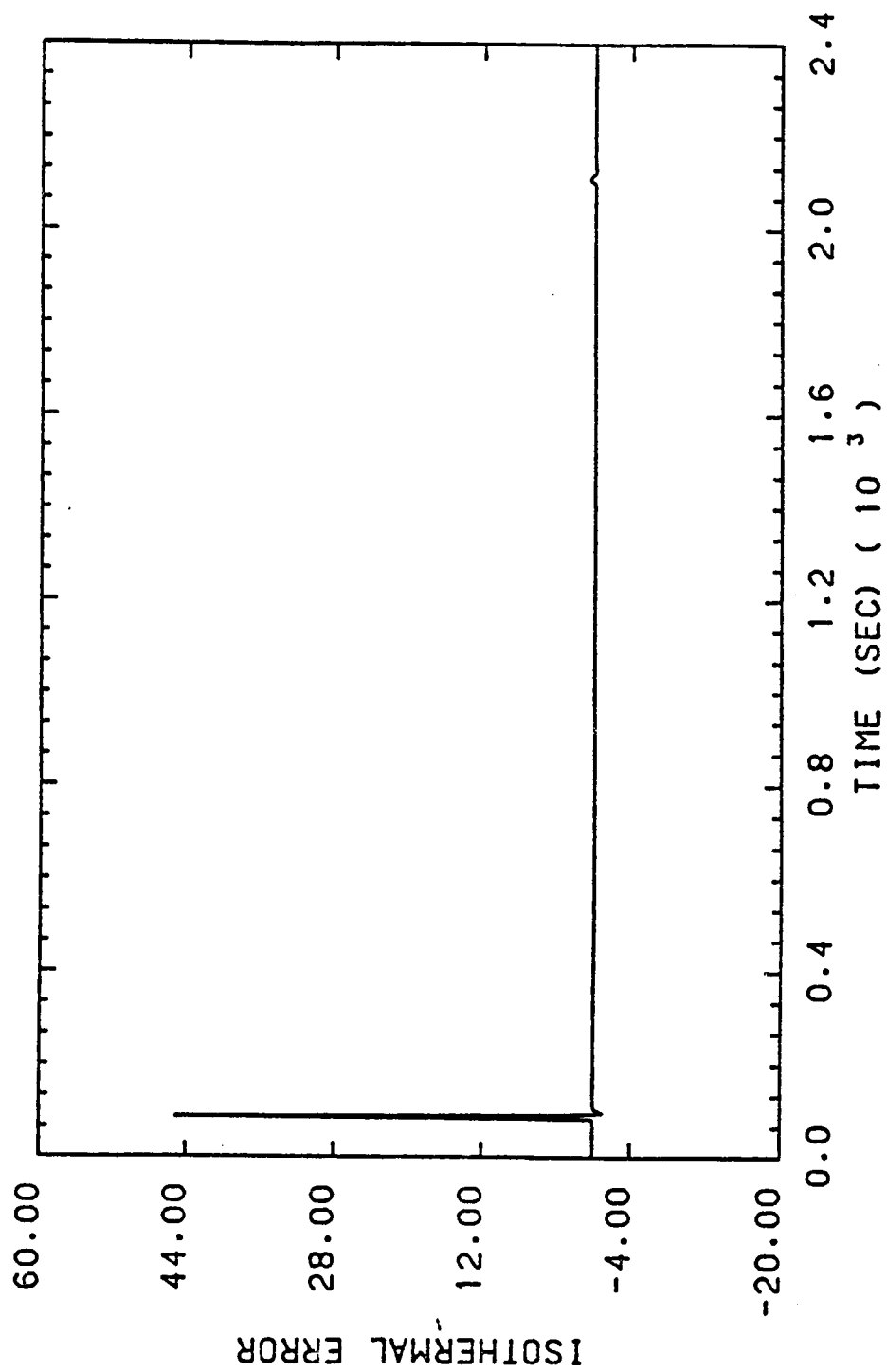


Figure C-13. Isothermal error in temperature (K) for the feedback temperature controller for rates of 10 °C/sec and -0.167 °C/sec.

APPENDIX D

CONTROL PROGRAM

PROGRAM NAME: CONTRO.FOR
 PURPOSE: TO MODEL THE CONTROL OF THE RESISTOMETER DEVICE.

VARIABLE DEFINITIONS:

NO = NUMBER OF ITERATIONS
 NP = NUMBER OF PLOTTING POINTS
 TIMEF = TOTAL RUN TIME (SEC)
 DTIME = TIME INCREMENT (SEC)
 NREG = NUMBER OF REGIMES
 SH = SENSIBLE HEAT (J)
 SHO = PREVIOUS SH
 TIME = TIME (SEC)
 TTIME = PHASE TRANSFORMATION ELAPSED TIME
 ACC = ACCUMULATED HEAT (J)
 TA = AMBIENT TEMPERATURE (K)
 TAO = PREVIOUS TA
 TC = PHASE TRANSITION TEMPERATURE (K)
 D = DIAMETER OF SAMPLE (METERS)
 L = LENGTH OF SAMPLE (METERS)
 AREA = CROSS SECTIONAL AREA OF SAMPLE (SQ. METERS)
 VOL = VOLUME OF SAMPLE (CU. METERS)
 V = SPECIFIC VOLUME OF SAMPLE (CU. METER/KG)
 AS = SURFACE AREA OF SAMPLE (SQ. METERS)
 THCL = THERMOCOUPLE LENGTH (METERS)
 THCK = THERMOCOUPLE WIRE THERMOCONDUCTIVITY
 (J/(SEC-M-DEG.C))
 THCA = THERMOCOUPLE WIRE CROSS SECTIONAL AREA
 (SQ. METERS)
 IFLAG = ERROR FLAG
 LAMBDA = HEAT OF PHASE CHANGE (J)
 SIGMA = STEPHAN'S RADIATION CONSTANT
 (J/(SEC-SQ.METER-K**4))
 TAU = TA TIME CONSTANT (SEC)
 EPS = TOLERANCE (SLIGHTLY<1)
 LNA = PHASE TRANSITION PARAMETER = LN(-A)
 A = PHASE TRANSITION PARAMETER
 N = PHASE TRANSITION PARAMETER
 B = PHASE TRANSITION PARAMETER
 F = FRACTION OF LRO
 T = TEMPERATURE OF SAMPLE (K)
 RHO = RESISTIVITY (OHM-METER)
 CP = HEAT CAPACITY (J/(KG-DEG.K))
 CURREN = CURRENT (AMPS)
 FINTIM = TOTAL ELAPSED TIME OF RUN
 ENDTIM = ARRAY OF FINTIM'S
 CURENT = ARRAY OF CURRENT SET POINTS
 ICOUNT = COUNTER OF NUMBER OF ITERATIONS
 TSET = IDEAL SAMPLE TEMPERATURE

```

C      SUBROUTINES CALLED:
C
C      MODEL   : MAIN SUBROUTINE FOR MODELING
C      RHOS    : CALCULATES RHO AS A FUNCTION OF T
C      CPS     : CALCULATES CP AS A FUNCTION OF T
C      CONTRL  : CONTROLLER TO CALCULATE CURREN
C
C*****C
C
COMMON/LIST1/TA,TAO,TC,VOL,V,AREA,AS,IFLAG,LAMBDA,SIGMA,PHI
COMMON/LIST2/ L,EPS,LNA,A,N,B,THCL,THCK,THCA
COMMON/LIST3/DTIME,TIME,SH,SHO,ACC,ACCO,CP,TAU
REAL LAMBDA,LNA,N,L,MO,LATHTO,KCT,KCR
DIMENSION RHR(10),RT(10),ENDTIM(10)
C--- 30=T VS. TIME; 31= T SET POINT VS. TIME; 32= ERROR VS. TIME
C--- 33=CURRENT VS. TIME; 34=M VS. TIME
OPEN (UNIT=30,FILE='PLOT.DAT',ACCESS='SEQOUT')
OPEN (UNIT=31,FILE='PLOT2.DAT',ACCESS='SEQOUT')
OPEN (UNIT=32,FILE='PLOT3.DAT',ACCESS='SEQOUT')
C--- INITIALIZE PLOTTING FILES
WRITE (30,2000)
WRITE (32,2000)
WRITE (33,2000)
WRITE (34,2000)
WRITE (30,2010)
WRITE (31,2010)
WRITE (32,2010)
WRITE (33,2010)
WRITE (34,2010)
C--- READ IN FROM USER RUN INFORMATION
WRITE (5,1000)
READ(5,*) TIMEF,DTIME
WRITE (5,1010)
READ (5,*) NP
NO      = INT(TIMEF/DTIME)
DUM     = NO/NP
NUM     = INT(DUM)
NPP     = NP+1
WRITE (30,*) NPP
WRITE (31,*) NP
WRITE (32,*) NP
WRITE (33,*) NP
WRITE (34,*) NP
WRITE (5,1020)
READ(5,*) NREG
DO 5 I=1,NREG
WRITE (5,1030) I
READ(5,*) RHR(I),RT(I)
WRITE(5,1040) I
READ(5,*) ENDTIM(I)

```

```

5    CONTINUE
C
C--- INITIALIZE PARAMETERS
C
      SH      = 0.0
      SHO     = 0.0
      TIME    = 0.0
      TTIME   = 0.0
      ACC     = 0.0
      TAO     = 300.0
      TA      = TAO
      TC      = 1141.0
      PI      = 3.14159265
      D       = 0.0032
      L       = 0.00698
      AREA    = PI*D**2/4.0
      VOL     = AREA*L
      V       = 0.0001085
      AS      = PI*D*L
      THCL    = 0.04
      THCK    = 67.05
      THCA    = 5.0671E-08
      IFLAG   = 0
      ICOUNT  = 0
      LAMBDA  = 51.58
      SIGMA   = 5.677E-8
      TAU     = 6000.0
      EPS     = 1.0-1.0E-8
      LNA     = 32.08977
      A       = -EXP(LNA)
      N       = 1.835001
      B       = -61330.0
      F       = 1.0
      T       = TA
      CURREN  = 0.0
      CALL RHOS (T,F,RHO)
      CALL CPS(T,F,CP)
      ACCO    = VOL*CP*T/V
      WRITE (30,2020) TIME,T
      TSET    = 300.0
C
C--- START TIME LOOP
C
      ICOUNT  = 0
      DPLOT   = TIMEF/NP
      IPLOT   = INT(DPLOT/DTIME)
      ERROR   = 0.0
      DO 20 J=1,NREG
C--- DETERMINE THE NUMBER OF ITERATIONS FOR PRESENT REGIME
          IF(J.GE.2) GO TO 100
          NOIT = INT(ENDTIM(J)/DTIME)
          TIMERT = (RT(J)-T)/RHR(J)

```

```

                GO TO 200
100             NOIT      = INT((ENDTIM(J)-ENDTIM(J-1))/DTIME)
                TIMERT    = (RT(J)-T)/RHR(J)+ENDTIM(J-1)
200             CONTINUE
C--- LOOP FOR REGIME J
                DO 10 I=1,NOIT
                ICOUNT  = ICOUNT+1
                    TIME    = TIME+DTIME
C--- IF ONE STEP FROM SET POINT TEMPERATURE, TURN ON THE TEMPERATURE
C    CONTROLLER
                IF((RHR(J).GT.0.0).AND.(T.GE.RT(J)-RHR(J)*DTIME))
1                   RHR(J)=0.0
                IF((RHR(J).LT.0.0).AND.(T.LE.RT(J)-RHR(J)*DTIME))
1                   RHR(J)=0.0
C--- CALL THE PROCESS MODEL
                    CALL MODEL(T,TIME,CURREN,F,RHO)
C--- CALUCULATE PLOTTING INFORMATION
                IF(TIME.GT.DTIME) TSET = TSET+RHR(J)*DTIME
                IF((RHR(J).GT.0.0).AND.(TSET.GE.RT(J))) TSET=RT(J)
                IF((RHR(J).LT.0.0).AND.(TSET.LE.RT(J))) TSET=RT(J)
                IF(RHR(J).EQ.0.0) TSET=RT(J)
                IF(RHR(J).EQ.0.0) ERROR=RT(J)-T
                IF(ICOUNT.GE.IPLOT) WRITE (31,2020) TIME,TSET
                IF(ICOUNT.GE.IPLOT) WRITE (32,2020) TIME,ERROR
                IF(ICOUNT.GE.IPLOT) WRITE (33,2020) TIME,CURREN
                IF(ICOUNT.GE.IPLOT) WRITE (34,2020) TIME,MO
C--- CALL THE CONTROLLER
                    CALL CONTRL(T,RHO,L,D,TO,TAMO,LATHTO,
1                               FO,CURREN,CPO,RHR(J),RT(J),ETO,
2                               ERO,MO)
C--- OUTPUT MODEL
                IF(ICOUNT.GE.IPLOT) WRITE (30,2020) TIME,T
                IF(ICOUNT.GE.IPLOT) ICOUNT=0
10             CONTINUE
20             CONTINUE
                STOP
1000            FORMAT(1X,'INPUT FINAL TIME AND TIME INCREMENT: ', $)
1010            FORMAT(1X,'INPUT # OF POINTS IN PLOTS: ', $)
1020            FORMAT(1X,'INPUT # OF REGIMES: ', $)
1030            FORMAT(1X,'INPUT HEATING RATE AND FINAL TEMP. SET POINT
1 FOR REGIME #',I2,' : ', $)
1040            FORMAT(1X,'INPUT END TIME FOR REGIME #',I2,' : ', $)
2000            FORMAT(1X,'HEAD')
2010            FORMAT(1X,'DATA ', $)
2020            FORMAT(2G15.5)
                END
C
C
C
C
C
C

```

```

C
C
C
C      SUBROUTINE NAME:  MODEL
C      PURPOSE:  TO CONTROL THE MODELING OF THE RESISTOMETER
C
C      DEFINITIONS:
C
C          EMISS  = EMISSIVITY OF SAMPLE
C          PHI    = RADIATION EQUATION FACTOR (SQ. METERS)
C          TASS   = STEADY-STATE AMBIENT TEMPERATURE
C          TA     = AMBIENT TEMPERATURE (K)
C          TAO    = PREVIOUS TA
C          T      = TEMPERATURE (K)
C          DTIME  = TIME INCREMENT (SEC)
C          TAU    = TA TIME CONSTANT
C          AS     = SEE MAIN PROGRAM
C          CURREN = CURRENT (AMPS)
C          F      = SEE MAIN PROGRAM
C          RHO    = SEE MAIN PROGRAM
C          SH     = SEE MAIN PROGRAM
C          ACC    = SEE MAIN PROGRAM
C          LAMBDA = SEE MAIN PROGRAM
C
C      SUBROUTINES CALLED:
C
C          SENSHT : CALCULATES THE SENSIBLE HEAT
C          FRAC   : CALCULATES THE FRACTION OF LRO
C          TFCNH  : CALCULATES T AS A FUNCTION OF ACC
C          RHOS   : CALCULATES THE RESISTIVITY
C*****C
C
C      SUBROUTINE MODEL(T,TIME,CURREN,F,RHO)
C      COMMON/LIST1/TA,TAO,TC,VOL,V,AREA,AS,IFLAG,LAMBDA,SIGMA,PHI
C      COMMON/LIST2/ L,EPS,LNA,A,N,B,THCL,THCK,THCA
C      COMMON/LIST3/DTIME,TTIME,SH,SH0,ACC,ACC0,CP,TAU
C      REAL LAMBDA,LNA,N,L
C--- CALCULATE PHI(T)
C      EMISS  = 0.5229-0.00059335*T+6.0901E-07*T**2
C      EMISS  = 0.6
C      PHI    = EMISS*AS
C--- CALCULATE TA AS A FUNCTION OF T
C      IF(T.LT.300.0) T=300.0
C      TASS   = 0.004607*(T-300.0)**1.7253+300.0
C      TA     = (TASS-TAO)*(1.0-EXP(-DTIME/TAU))+TAO
C      IF(TA.LT.300.0) TA=300.0
C      TAO    = TA
C--- CALCULATE THE TOTAL ENERGY OF THE SYSTEM
C      CALL SENSHT(T,CURREN,F,RHO)
C--- CALCULATE FRACTION OF LRO

```


[illegible]


```

REAL LAMBDA,LNA,N,L
C
C--- SET UP CONSTANTS
C
      CALL CPS(T,F,CP)
      T      = V/VOL/CP*(ACC+ACCO)
      RETURN
      END
C
C
C
C
C
C
C
C
C
SUBROUTINE NAME:  CPS
PURPOSE:  TO CALCULATE THE HEAT CAPACITY AS A FUNCTION OF T
VARIABLE DEFINITIONS:
          T      = TEMPERATURE (K)
          F      = FRACTION LRO
          CP     = HEAT CAPACITY (J/(KG-DEG.K))
          CPLRO  = CP OF LRO PHASE
          CPSRO  = CP OF SRO PHASE
C*****C
C
      SUBROUTINE CPS(T,F,CP)
C--- SET UP POWER SERIES CONSTANTS
      IF(T.GT.873.0) GO TO 10
        A1=376.36545
        B1=0.06960968
        C1=0.0
        D1=0.0
      GO TO 100
C
10    A1= 296.93
       B1= 0.1604
       C1= 0.0
       D1= 0.0
C
100  IF(T.GT.1141.0) GO TO 20
      IF((T.LE.1141.0).AND.(T.GT.680.0)) GO TO 30
        A2= 376.36545
        B2= 0.06960968
        C2= 0.0
        D2= 0.0
      GO TO 200
C
20    A2= 567.3736
       B2= 0.0
       C2= 0.0

```

```

D2= 0.0
GO TO 200
C
30      A2= 211.78
        B2= 0.3117
        C2= 0.0
        D2= 0.0
C
C--- CALCULATE CP(T)
C
200     CONTINUE
        CPLRO = A1+B1*T+C1*T**2+D1*T**3
        CPSRO = A2+B2*T+C2*T**2+D2*T**3
        CP    = F*CPLRO+(1.0-F)*CPSRO
        RETURN
        END
C
C
C
C
C
C
C
C
SUBROUTINE NAME:  CONTRL
PURPOSE:  TO CALCULATE THE CURRENT GIVEN THE SET POINT
          TEMPERATURE OR HEATING RATE
C
VARIABLE DEFINITIONS:
C
C           T            = SAMPLE TEMPERATURE (K)
C           RHO          = RESISTIVITY (OHM-METERS)
C           L            = SEE MAIN PROGRAM
C           D            = SEE MAIN PROGRAM
C           TO           = PREVIOUS SAMPLE TEMPERATURE
C           TAMO          = PREVIOUS ESTIMATE OF AMBIENT TEMPERATURE
C           LATHTO       = PREVIOUS ESTIMATE OF LATENT HEAT
C           FO           = PREVIOUS ESTIMATE OF FRACTION LRO
C           CURREN       = CURRENT (AMP)
C           CPO          = PREVIOUS ESTIMATE OF HEAT CAPACITY
C           RHR          = HEATING RATE SET POINT
C           RT           = TEMPERATURE SET POINT FOR ISOTHERMAL REGION
C           ETO          = PREVIOUS ERROR IN TEMPERATURE
C           ERO          = PREVIOUS ERROR IN RATE
C           MO           = PREVOUTS CONTROLLER ACTION
C           M            = CONTROLLER ACTION = MO + DELT
C           DELT         = CHANGE IN CONTROLLER ACTION (PI CONTROL)
C           KCT          = TEMPERATURE CONTROLLER GAIN
C           TIT          = TEMPERATURE CONTROLLER INTEGRAL TIME
C           KCR          = RATE CONTROLLER GAIN
C           TIR          = RATE CONTROLLER INTEGRAL TIME
C           TSTAR        = IDEAL NEXT TEMPERATURE
C           DTIME        = TIME INCREMENT

```

```

C          HR      = ACTUAL HEATING RATE (DEG. K/SEC)
C          ET      = ERROR IN ISOTHERMAL TEMPERATURE
C          ER      = ERROR IN RATE
C          FFC     = FEEDFORWARD ESTIMATE OF CURRENT
C
C          SUBROUTINES CALLED:
C
C          FF      : CALCULATES THE FEEDFORWARD CURRENT
C
C*****C
C
C          SUBROUTINE CONTRL(T,RHO,L,D,TO,TAMO,LATHTO,FO,CURREN,CPO,
1              RHR,RT,ETO,ERO,MO)
C          REAL M,MO,KCT,KCR,LATHTO,L
C--- DETERMINE IF THIS IS THE FIRST TIME CALLED (INDEX=0 = Y)
C          INDEX   = 1
C          IF(CPO.LT.1.0) INDEX=0
C          IF(INDEX.EQ.1) GO TO 5
C--- INITIALIZE PARAMETERS
C          ETO     = 0.0
C          ERO     = 0.0
C          MO      = 0.0
C          TO      = T
C          LATHTO  = 0.0
C          TAMO    = TO
C          5      DTIME = 2.0
C          IF(FO.GT.0.9) KCT=1.0
C          IF(FO.LE.0.9) KCT= 0.5
C          TIT     = 3.5
C          KCR     = 0.23
C          TIR     = 0.35
C--- CALCULATE TSTAR
C          TSTAR   = T+RHR*DTIME
C          IF((RHR.GT.0.0).AND.(TSTAR.GT.RT)) TSTAR=RT
C          IF((RHR.LT.0.0).AND.(TSTAR.LT.RT)) TSTAR=RT
C          IF(RHR.EQ.0.0) TSTAR=RT
C--- DETERMINE WHICH CONTROLLER TO USE
C          IF(RHR.EQ.0.0) GO TO 10
C--- RATE CONTROLLER
C          HR      = (T-TO)/DTIME
C          ETO     = 0.0
C          ER      = RHR-HR
C          DELT    = KCR*(ER-ERO)+KCR*DTIME/TIR*ER
C          ERO     = ER
C          GO TO 20
C--- TEMPERATURE CONTROLLER
C          10      ERO   = 0.0
C                  ET    = RT-T
C                  DELT   = KCT*(ET-ETO)+KCT*DTIME/TIT*ET
C                  ETO    = ET
C          20      M     = MO+DELT

```



```

C          THCA    = SEE MAIN PROGRAM
C          EMISS    = EMISSIVITY OF SAMPLE
C          PHI      = RADIATION FACTOR (SEE MAIN PROGRAM)
C          RHOSRO    = RHO OF PURE SRO
C          RHOLRO    = RHO OF PURE LRO
C          LATHT     = LATENT HEAT OF PHASE CHANGE
C          DACC      = CHANGE IN ACCUMULATED HEAT
C          CPSTAR    = HEAT CAPACITY ESTIMATE AT TSTAR
C          RHOSTR     = RHO ESTIMATE AT TSTAR
C          CRNT2     = CURRENT ESTIMATE SQUARED
C
C          SUBROUTINES CALLED:
C          RHOCTL    = SAME AS RHOS BUT FOR THE CONTROLLER
C          CPSCTL    = SAME AS CPS BUT FOR THE CONTROLLER
C
C*****C
C
C          SUBROUTINE FF(FFC,T,TO,TAMO,CPO,LATHTO,RHO,L,D,DTIME,RHR,RT,F0,
1              TSTAR)
C          REAL LAMBDA,LATHTO,LATHT,L
C--- INITIALIZE PARAMETERS
C          PI        = 3.14159265
C          TC        = 1141.0
C          AREA      = PI*D**2/4.0
C          AS        = PI*D*L
C          VOL       = AREA*L
C          V         = 0.0001085
C          LAMBDA    = 51.58
C          SIGMA     = 5.677E-8
C          TAU       = 6000.0
C          THCL      = 0.04
C          THCK      = 67.05
C          THCA      = 5.0671E-08
C--- CALCULATE PHI(T)
C          EMISS     = 0.5229-0.00059335*TSTAR+6.0901E-07*TSTAR**2
C          PHI       = EMISS*AS
C--- CALCULATE TA AS A FUNCTION OF T
C          TASS      = 0.004607*(TSTAR-300.0)**1.7253+300.0
C          TASTAR    = (TASS-TAMO)*(1.0-EXP(-DTIME/TAU))+TAMO
C          IF(TASTAR.LT.300.0) TASTAR=300.0
C          TAMO      = TASTAR
C--- DETERMINE F
C          CALL RHOCTL(T,1.0,RHOLRO)
C          CALL RHOCTL(T,0.0,RHOSRO)
C          F= (RHO-RHOSRO)/(RHOLRO-RHOSRO)
C          IF(F.LT.0.0) F= 0.0
C          IF(F.GT.1.0) F= 1.0
C          IF(CPO.LT.1.0) F0=F
C          GO TO 20
10      F          = 0.0
C--- CALCULATE THE CURRENT FROM THE HEAT BALANCE
20      LATHT      = LAMBDA*(1.0-F)

```

```

CALL CPSCTL(TSTAR,F,CPSTAR)
CALL CPSCTL(T,F0,CP0)
CALL RHOCTL(TSTAR,F,RHOSTR)
DACC      = CPSTAR*TSTAR-CP0*T
IF(RHR.EQ.0.0) DACC=0.0
CRNT2     = AREA/RHOSTR/L*(VOL/V*DACC/DTIME
1          -(LATHT-LATHT0)/DTIME-SIGMA*PHI*(TASTAR**4-TSTAR**4)
2          -4*THCK*THCA/THCL*(TASTAR-TSTAR))
IF(CRNT2.LT.0.0) CRNT2=0.0
FFC       = SQRT(CRNT2)
IF(FFC.GT.90.0) FFC=90.0
C--- RESET PREVIOUS LATENT HEAT AND F
LATHT0    = LATHT
F0         = F
RETURN
END

C
C
C
C
C
C
C
C
C
SUBROUTINE NAME:  RHOCTL
C
PURPOSE:  TO CALCULATE THE RESISTIVITY VERSUS TEMPERATURE
C
FOR THE CONTROLLER
C
C
VARIABLE DEFINITIONS:  (SEE RHOS SUBROUTINE)
C
C*****C
C
SUBROUTINE RHOCTL (T,F,RHO)
C--- SET UP CONSTANTS
C
A1      = -4.0907464E-07
B1      = 3.775097E-09
C1      = -4.012551E-12
D1      = 1.775517E-15
C
A2      = 1.540493E-06
B2      = -6.611138E-10
C2      = 1.363067E-12
D2      = -7.995826E-16
IF(T.GT.1235.0) A2=0.130E-05
IF(T.GT.1235.0) B2= 0.0
IF(T.GT.1235.0) C2= 0.0
IF(T.GT.1235.0) D2= 0.0
C
C
C--- CALCULATE RESISTIVITY FOR LRO PHASE
C

```



```

        C2= 0.0
        D2= 0.0
        GO TO 200
C
    20    A2= 567.3736
        B2= 0.0
        C2= 0.0
        D2= 0.0
        GO TO 200
C
    30    A2= 211.78
        B2= 0.3117
        C2= 0.0
        D2= 0.0
C
C---- CALCULATE CP(T)
C
    200    CONTINUE
        CPLRO = A1+B1*T+C1*T**2+D1*T**3
        CPSRO = A2+B2*T+C2*T**2+D2*T**3
        CP = F*CPLRO+(1.0-F)*CPSRO
        RETURN
        END

```

C
C
C

VITA

James E. Hackney was born January 29, 1960 in Knoxville, Tennessee. He graduated from Rule High School in that city in June 1978. The following September he enrolled in The University of Tennessee, Knoxville, and in June 1982 he received a Bachelor of Science degree with a major in Chemical Engineering. In September 1982 he entered The Graduate School of the same university and received a Master of Science degree with a major in Chemical Engineering in March 1985.