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I am submitting herewith a thesis written by William Merle Cash entitled "The Data Acquisition from and the Theoretical Modeling of a Dynamic Adiabatic Calorimeter." I 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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THE DATA ACQUISITION FROM AND THE THEORETICAL MODELING OF A DYNAMIC ADIABATIC CALORIMETER

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

William Merle Cash

December 1976

1304432

ACKNOWLEDGEMENTS

I am deeply indebted to all of those who assisted me during the writing of this thesis and more particularly:

My parents, George and Georgie Cash, without whose encouragement and love I would never have been able to achieve such goals as this degree.

My advisor, Charlie Moore, who has not only guided my engineering education but also my social and intellectual educations as well.

The University of Tennessee Fellowship Committee for selecting me as the recipient of a University of Tennessee Fellowship during the academic years 1973-1974, 1974-1975, 1975-1976, and 1976-1977, greatly assisting me in furthering my education.

Ted Long, Ray Gaddis, Arnold Beal, and Mike Keck of the Chemical and Metallurgical Engineering Department, who have greatly assisted in solving the problems relating to the data acquisition system.

My wife, Miriam, whose love, understanding, patience and typing made this thesis possible.

ABSTRACT

The design and implementation of a data acquisition system (objective 1), capable of collecting data from the calorimeter with sufficient accuracy for modeling, control and specific heat measurements, were successfully accomplished. This system contains a fixed suppression-variable suppression-high gain amplification scheme which allows the sensing elements (thermocouples) to be sampled with an accuracy of $\pm$0.125 microvolts ($\pm$0.0125°C).

A theoretical process model (objective 2) based upon time domain energy balance equations was also successfully developed which possesses the general dynamic process behavior. It also demonstrates the major control problems, namely:

- Multivariable interactions
- Non-linearities
- Process dead-time
- Different mechanisms for heat addition and removal.

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INTRODUCTION

In the last ten to fifteen years, digital computers have greatly enhanced the field of automatic control. This is mainly due to three major aspects of digital computers: (1) extreme flexibility, (2) ease of data storage, and (3) capability of handling more sophisticated control strategies previously deemed very difficult or impossible with analog equipment.

Although the initial investment in a digital computer for control purposes seems astronomical when compared to an analog controller, consideration must be given to the fact that one digital computer is capable of assuming the control of a vast number of analog loops. Also, changes in control strategy involve only software changes in digital systems rather than expensive hardware changes in analog systems.

Initially, digital computers were used only as sophisticated calculators to determine plant operating conditions, such as flow rates, necessary to produce a predetermined product. As increased storage devices became available, computers became the "bookkeepers" of the plant by storing price and inventory information for quick and easy access.

Gradually, as analog-digital interface systems were developed, digital computers were substituted directly into the control loop, replacing standard analog controllers.

This process of direct digital control (DDC) is where the greatest potential for the computer lies. By permitting the use of more sophisticated techniques (other than the mere discrete version of analog equations), better quality products could be produced with less "down time" (the time necessary for the process to reach steady state after set point changes). This means a substantial increase in the amount of dollars to be earned.

In order to assist in the advancement of DDC in industry, the University of Tennessee's Department of Chemical and Metallurgical Engineering has undertaken a program which involves the theoretical investigation and practical application of DDC to control problems of industrial importance (1, 2, 3, 4, 5, 6).

It is the intent of the present author to further this study by the practical application of an advanced control strategy to a process which is inherently non-linear and multivariable.

CHAPTER I

BACKGROUND

The current project under study involves the modeling and control of a dynamic adiabatic calorimeter. This calorimeter was part of an intensive program undertaken in Metallurgical Engineering at the University of Tennessee in 1950. Its objective was to determine the specific heat of metals as a function of temperature from 300^{o} to 1300^{o} K.

Many researchers (7, 8, 9, 10, 11, 12, 13) have been involved in the basic design and use of the calorimeter depicted in Figure 1. It basically consists of a sample (of which the specific heat is to be determined) and surrounding adiabatic shields, designated as G1, G2, G3, cylinder and lower platinum shield. (The lower platinum shield is the only shield which is not controlled to a specified temperature.) Detailed specifications of dimensions and materials of construction are given by Peng (12) and Stout (13).

Operation of the calorimeter is accomplished by continuously supplying a known DC voltage to the sample. By measuring the power (EI) supplied to the sample and the sample temperature rise (ΔT) over a given time period ($\Delta\theta$),

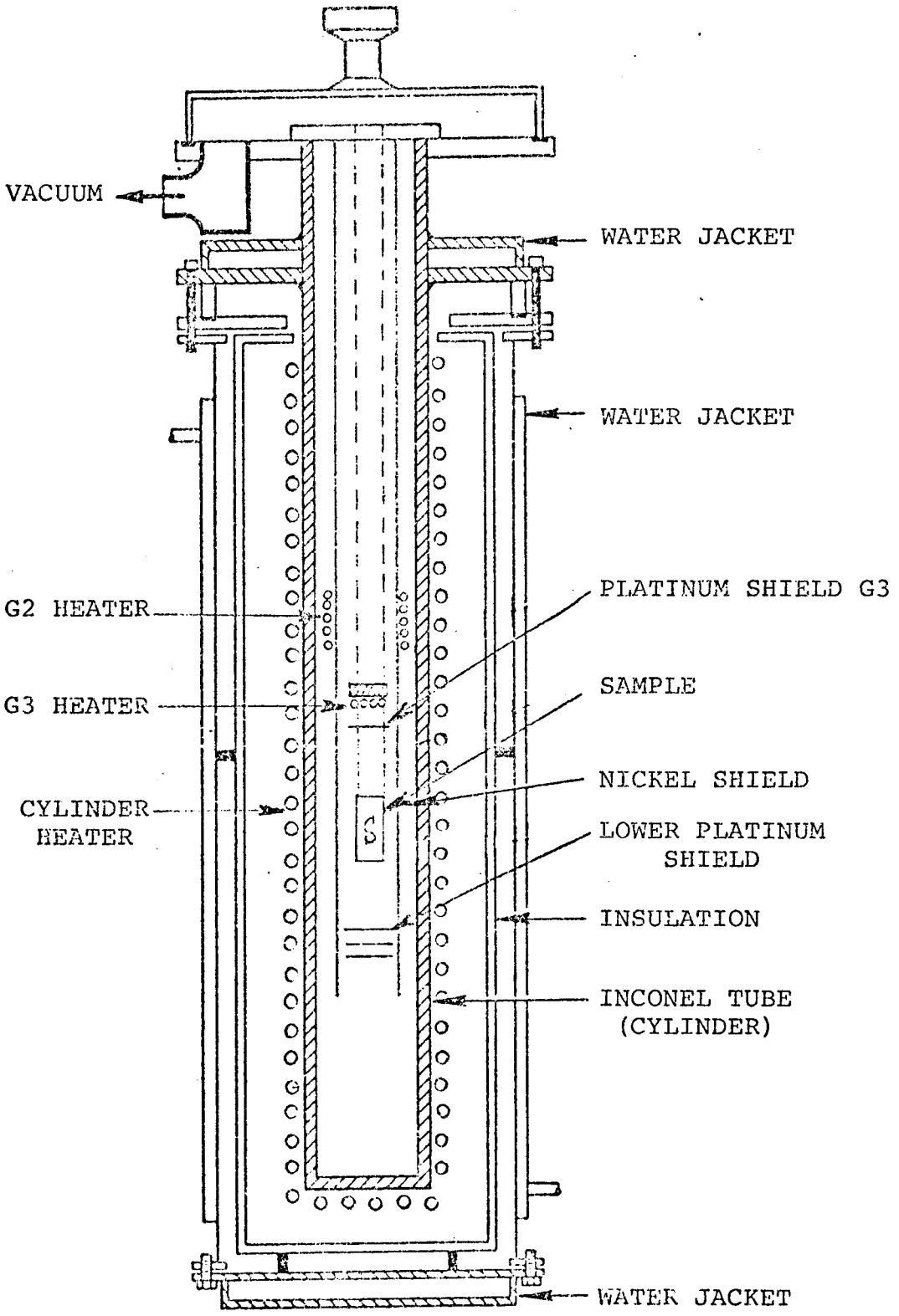


Figure 1. Schematic Diagram of the Calorimeter.

the average specific heat can be calculated from

$$\overline{Cp} = \frac{EI\ \Delta\Theta}{M\,\Delta\,T}$$

where

M = total sample mass (including heater and specimen)

$\overline{Cp}$ = average specific heat over the temperature range ΔT

By correcting for the sample heater mass, the specific heat of the sample can be obtained (10, 12, 13).

In order for the above equation to be valid, the sample heat loss (or gain) must be equal to zero. If this assumption breaks down, then errors in the specific heat will result and other corrections must be made. In order to minimize these approximate corrections, adiabatic conditions around the sample must be approached. In order to accomplish this, the shield temperatures of G1, G2, G3 and the cylinder must be controlled to the sample temperature under dynamic conditions. In an attempt to solve this problem, three mode (PID) analog controllers were installed. At this point "adequate" control was achieved, but numerous problems remained which could not be solved by standard analog methods.

The control problems can be qualitatively analyzed in the following manners:

1. The process is by nature non-linear. This is due to the fact that the specific heat of the sample is measured under an absolute pressure of approximately 10^{-4} torrs; therefore, all heat transfer inside the cylinder (which contains the vacuum) is by radiation and is proportional to differences in temperatures raised to the fourth power (14, 15, 16, 17, 18, 19). This forces the system gains and time constants in the LaPlace domain transfer functions to be strong functions of temperature. Therefore, a controller which is "well-tuned" at $300^{o}K$ may produce a complete unstable response at $1300^{o}K$.

2. The process is multivariable. This can easily be seen by the following example. If all the power to heat the shields were to be suddenly shut off while continuing to heat the sample, an eventual steady state condition would prevail. The relative temperatures of the shields would be:

- Sample at highest temperature
- G1 and G3 shields approximately 20^{o} C less than sample temperature
- Cylinder and upper G2 at the lowest temperature.

If at this point a limited amount of power were to be supplied to the cylinder, all temperatures in the calorimeter would increase. The same would be true for a pulse in

power to any of the other shields but with different relative and absolute increases in individual shield temperatures.

3. Some components exhibit large dead times (approximately 10 to 60 seconds) in their response. This is true of the adiabatic shield G2 and the cylinder, as well as a large sample with thick walls and low thermal conductivity. This phenomena is due to the fact that a finite time is required for the conduction of heat throughout any material. The length of time required is a function of the thermal diffusivity of the material and the distance between the point of heat generation and the heat sensor. This process is mathematically described by Fourier's Second Law of Conduction (20). The current analog control system, even when well-tuned, produces an oscillatory response (due to the dynamic conditions) with limits of up to $\pm$ 10°C and $\pm$ 3°C respectively for the cylinder and G2 temperatures. At a steady state sample temperature, a typical slow approach to steady state for a large dead time system using PID controllers is experienced (1, 2).

Although these deviations are large, the sample is semi-isolated by G1 and G3 from these gross temperature changes; therefore, these oscillations are "acceptable" in the loose sense of not producing large errors in the specific heat.

Therefore, these three areas are of utmost importance in designing a digital compensator for the calorimeter.

Having related the problems of control, the steps to their correction are:

1. Development of a data acquisition system for the calorimeter.

2. Determination of a model which demonstrates the non-linear, multivariable nature of the process based upon theoretical derivations and experimental data.

3. Development of a control strategy which will produce an enhancement of the approach to adiabatic conditions.

Data Acquisition

The design of a data acquisition system depends mainly on the interfacing of an analog hardware device, such as a thermocouple, with a digital computer. This is usually done using an Analog/Digital (A/D) converter which converts a voltage signal to a number based upon a linear scale. The task at hand is to devise a scheme of hardware which will:

1. Produce a signal compatable with the A/D converter input from the output of the analog measuring device.

2. Produce a signal with a comparable sampling

accuracy as that of the analog device. For example, if a thermocouple can be read with analog equipment within $\pm 0.1^{\circ}C$, then this should be approached by the sampling accuracy of the digital computer.

3. Introduce a minimum of sampling noise.

Normally, step 3 is the most difficult to achieve since it involves careful analysis of ground-loop problems (21) and sometimes the addition of analog and/or digital filters.

Modeling

The major objective desired from this procedure is a mathematical description of the process which relates the major input (independent) variables to the major output (dependent) variables. It permits the detailed examination of the system by repetitive calculations off-line. This reduces the amount of process down time for extensive experimentation which minimizes costs. It also leads to quick identification of certain process characteristics, such as non-linearities, variable interactions, etc. However, the ultimate purpose of the model is to aid in the development of new and improved control strategies.

Although modeling is an everyday part of the chemical engineer's life, some authors (22, 23, 24) have devoted time to this subject exclusively. They have

presented the steps necessary in developing a good model. Basically, these steps are:

1. Problem definition;

2. Statement of the mathematical theory governing the process phenomena;

3. Combination of this theory into a governing process equation; and

4. Solution to the process equation.

Lee, Adams and Gaines (22) present many types of models other than physical which can be developed while Luyben (23) focuses his work on standard chemical engineering type models relating to kinetics, transport phenomena, etc. Franks (24) looks at these same type processes but also develops computer programs to simulate some of the simpler examples.

The development of any mathematical model representative of a given process arises from the basic laws of conservation of mass, momentum, energy or charge. The conservation equation can be stated in the following form:

(Rate of Input) - (Rate of Output) =

(Rate of Accumulation)

This convenient form can be applied to all four of the "dynamic analogs" listed above. (Such terms as rate of generation due to chemical reaction, etc. can be considered

as "specialized" forms of input or output.) This form results in dynamic partial or ordinary differential equations in the time domain. These equations can also be "dynamic" in the space domain by considering a "distributed" parameter system rather than a "lumped" parameter system. The "lumped" parameter system, such as a CSTR, assumes uniformity of the measured variable throughout the component under study while the "distributed" parameter system, such as a tubular flow reactor, considers the measured variable to the a function of position inside the component.

In regard to the final form of the model, two major forms are prevalent in the process control area:

1. LaPlace Domain formulations (25, 26, 27, 28, 29). This uses transfer functions arranged into an overall "block diagram" which depicts the interactions between all the variables (both dependent and independent). The key disadvantage here is that the differential equations must be linear. When non-linearities arise, linear approximations, such as a Taylor Series expansion, about some steady state condition must be made. This causes the model parameters to be "load" sensitive. In other words, their values change with the absolute magnitude of the process variables.

2. Simulation equation. This form involves the linear approximation:

$$\frac{d}{d\theta} = \frac{\Delta}{\Delta\theta}$$

where Δ indicates a discrete difference and $\Delta\theta$ is the sampling interval. The advantage here is that dynamic process data can be used to determine the model parameters by use of multiple regression or other optimization techniques (30, 31, 32). It also permits direct calculation of the true constants in the model even though non-linearities may exist. Therefore, the value of these true constants are not as "load" sensitive as in the LaPlace method. This method of formulating real time equations by using discrete approximations is often referred to as state variable theory. This theory has been well defined for linear systems (29, 33).

Control Strategy

Once a working model has been developed which demonstrates accurately the performance of the process, then, and only then, can a meaningful control strategy be developed. This strategy should strive to eliminate as many of the non-linearities and variable interactions as possible in order to enhance the overall performance of the process.

Due to the nature of digital control, caution must be used in haphazard application. Replacement of an

analog controller by its digital counterpart may severely alter the response characteristics of the closed loop system. This is due mainly to the discrete nature of the control action. The theory behind this phenomena has been studied in great depth (34, 35, 36, 37) as well as the application of this simplified theory assuming a linear non-interacting process (38, 39).

As a direct result of this basic theory, more sophisticated control strategies have been investigated by various authors in order to enhance control with a particular type of control problem. Such problems as the control of large dead time processes (40, 41) and multivariable processes (42, 43, 44, 45, 46) fall into this category.

The major effort lies in the development of a control strategy which draws upon a combination of these strategies to accomplish the goal of "improved" control.

CHAPTER II

DEVELOPMENT OF THE THEORETICAL PROCESS MODEL

Before attempting to collect data from any process, it is first necessary to thoroughly understand that process. This necessitates the development of some preliminary model which depicts the major input variables, the major output variables, and their relationships to one another. After this has been accomplished, it is readily apparent which variables should be monitored. Also, an approximate rate of data sampling can be selected if the process data is to be acquired using some type of digital device. This model will also provide certain other process characteristics which are necessary to the development of a good data-acquisition and control strategy.

Description of the Physical Process

The process under study in this work is a dynamic adiabatic calorimeter which is shown schematically in Figure 1. The components considered to be the most important in the model are the sample and the four adiabatic shields which surround it. The nickel shield (G1) also has an auxiliary heater (designated as G2) approximately 10 cm. above the sample.

The sample consists of the material of which the specific heat is to be determined. The weight is between

20 and 200 grams including an internal heater which is powered by a constant DC voltage power supply. The sample temperature is allowed to vary freely due to naturally occurring phenomena. Unless unusually large amounts of heat are liberated or absorbed (as in phase transformations, magnetic transformations, etc.), the sample temperature varies linearly with time over small temperature intervals of 20° to 30°C.

The nickel tube (G1) is directly heated by passing a low DC voltage (0-2 volts), high current (0-80 amps) power along its length. It is 85 cm. in length, 4 cm. in diameter and 0.025 cm. in thickness.

The lower platinum shield consists of three disks which fit snugly inside the bottom portion of G1. They are approximately 1.5 cm. apart and 10 cm. below the sample. This shield is not controlled but acts as a shield by re-radiating any heat lost from the sample back to the sample. This prevents large amounts of heat loss to the water-cooled bottom of the calorimeter.

Above the sample is another platinum shield (G3) which is indirectly heated by a nichrome heater located approximately 1 cm. above the shield G3. This heater is mounted on the surface of a fired lava disk 3.2 cm. in diameter and 0.32 cm. thick.

The auxiliary heater G2 was installed in order to

reduce heat loss from G1 to the top of the calorimeter which is water cooled. Since G1 is maintained at the sample temperature in the area of the sample and is attached to the top of the calorimeter, a tremendous temperature gradient will exist along its length. This leads to large heat losses due to conduction along the length of G1. By installing an auxiliary heater between G1 in the area of the sample and the top of the calorimeter, this heat loss can be prevented. This also minimizes the temperature gradient along G1 in the area of the sample. This renders the location of G1 thermocouple less critical than before G2 was installed.

All these shields are contained inside a thickwalled inconel tube. It is 99 cm. in length, 9.8 cm. in diameter, and 1 cm. in thickness. This tube (designated as the cylinder) is also indirectly heated in the same fashion as G2 (nichrome wire encased in ceramic beads for electrical insulation wound around the outside of the shield). The cylinder serves two major purposes: (1) a secondary adiabatic shield, and (2) a container for the vacuum inside the calorimeter (absolute pressure approximately 10^{-4} torrs).

This is a brief description of the components in the calorimeter. Peng (12) presents a more detailed analysis.

Since the goal of "good" control is to eliminate heat losses from the sample in order to maintain adiabatic

conditions, precise control of the four main heated shields is sought. The following model will aid in this goal.

Dynamic Model Development in the Time Domain

In order to aid in the development of a model, it is necessary to make certain simplifying assumptions based upon a lumped parameter system.

1. All the power supplied to the sample heater is transferred to the sample as heat.

2. The sample is at a uniform temperature throughout.

3. All the heat transferred between non-contacting components inside the cylinder is by radiation. (This is due to the vacuum which exists in this compartment.)

4. The zone of the nickel shield G1 between the platinum shield G3 and the lower platinum shield is at a uniform temperature.

5. The temperature of the nickel shield in zone G2 is uniform circumferentially but not necessarily equal to the temperature of G1 and heat transfer here is due to conduction along the tube wall.

6. All the power supplied to G3 heater is transferred by radiation only to the platinum shield G3.

7. A fraction of the power supplied to the cylinder heater is transferred to the cylinder. This fraction is

constant over a small temperature range.

8. The temperature of the cylinder between G3 and the lower platinum shield is at a uniform surface temperature along its length. Also, another uniform region exists between G2 and G3, but not necessarily at the same temperature as the other region.

Once these assumptions have been stated, ground work for the model development can begin. The basic steps leading to the time domain model as stated by Franks (24) are: (1) definition of problem, (2) definition of theory that governs the phenomena, and (3) equations using the theory which are written in mathematical symbology.

For modeling from a chemical engineer's standpoint, step (3) has its basis in the conservation equations of mass, energy, charge, and momentum. Simply stated it says that:

$$\begin{pmatrix}\text{Rate of}\\ \text{Accumulation}\end{pmatrix} = \begin{pmatrix}\text{Rate of}\\ \text{Input}\end{pmatrix} - \begin{pmatrix}\text{Rate of}\\ \text{Output}\end{pmatrix} \qquad 1$$

Since the main variable in the calorimeter is the temperature of the various components, an energy balance for each of the appropriate components is needed. Due to the large number of components in the calorimeter and to the fact that they have alphanumeric names, the subscript notations listed in Table I will be followed. An enlarged drawing of their location inside the calorimeter appears in Figure 2.

TABLE I

LIST OF COMPONENT SUBSCRIPTS

Subscript	Component
1	Sample Heater
2	Sample
3	Nickel Shield G1
4	G3 Heater
5	Platinum Shield G3
6	Lower Platinum Shield
7	G2 Heater
8	Nickel Shield G2
9	Cylinder Heater
10	Cylinder in area of G1
11	Nitrogen Blanket around Cylinder
12	Water
13	G3 Heater Mount
14	Cylinder in area of G2

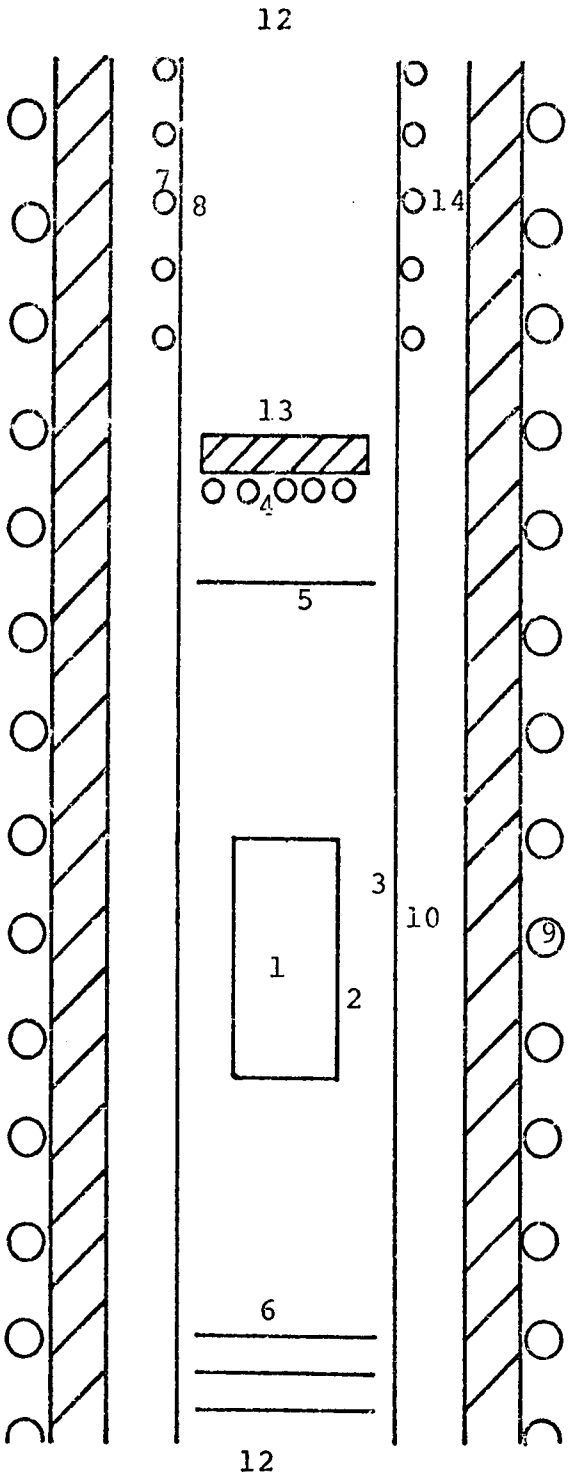


Figure 2. Enlarged Calorimeter Schematic with T/C (Thermocouple) Subscript Notations from Table I.

The theory that governs the heat transfer inside the calorimeter is the basic theory of radiation (inside the cylinder between non-contacting components), conduction (along the metal walls), and convection (outside the cylinder in the nitrogen blanket). For heat loss due to radiation, the following basic law (14, 15, 16, 17, 18, 19) exists for heat transfer between the components i and j:

$$Q_{ij} = \sigma A_i F_{ij} (T_i^4 - T_j^4) = K_{ij} (T_i^4 - T_j^4) \qquad 2$$

where

Q_{ij} = heat transferred (joules/sec)

σ = Stefan-Boltzmann constant (5.71×10^{-12} joules/cm^2-sec-$^oK^4$)

A_i = area of radiating component i (cm^2)

F_{ij} = factor based on component geometry and emissivity ($0 \leq F \leq 1$)

T = absolute temperature (^oK)

K_{ij} = overall constant coefficient ($\sigma A_i F_{ij}$)

For heat loss due to conduction, the following basic law (14, 16, 20) exists for heat transfer between components i and j:

$$Q_{ij} = k A \frac{dT}{dx} = K_{ij} (T_i - T_j) \qquad 3$$

where

Q_{ij} = heat transferred (joules/sec)

k = thermal conductivity (joules/sec-cm-^oC)

A = area normal to direction of heat transfer (cm^2)

dT/dx = temperature gradient ($^{o}C/cm$)

K_{ij} = overall coefficient ($kA/\Delta x$) assuming a linear temperature gradient

For heat loss due to convection, the following basic law (14, 16) applies for transfer between components i and j:

$$Q_{ij} = h\ A\ (T_i - T_j) = K_{ij}\ (T_i - T_j) \qquad 4$$

where

Q_{ij} = heat transferred (joules/sec)

h = convective film coefficient (joules/sec-cm^2-^{o}C)

A = area normal to direction of heat transfer (cm^2)

T = temperature (^{o}C)

K_{ij} = overall coefficient (hA)

Note that the form of the convective and conductive heat transfer equations have identical forms assuming linear temperature profiles for conduction.

Based on equation 1, along with the stated assumptions, derivation of the differential equations in the time domain which govern the process can begin. The general form of the energy conservation equations about each component i is:

$$M_i\ C_{Pi}\ \frac{dTi}{d\theta} = P_i - Q_{ij} \qquad 5$$

where

M = mass (grams)

C_p = specific heat (joules/gm-^oK)

$dT/d\theta$ = rate of change of temperature with respect to time (^oK/sec)

P_i = power supplied to component i (watts)

Q_{ij} = heat loss to component j (joules/sec)

With equations 2 through 5 and Figure 2, the following component balances can be made:

SAMPLE HEATER

$$M_1 C_{P1} \frac{d T_1}{d\theta} = P_1 - Q_1 \quad (6)$$

where

$$Q_1 = K_{12} (T_1 - T_2) \quad (7)$$

or

$$M_1 C_{P1} \frac{d T_1}{d\theta} = P_1 - K_{12} (T_1 - T_2) \quad (8)$$

SAMPLE

$$M_2 C_{P2} \frac{d T_2}{d\theta} = K_{12} (T_1 - T_2) - [K_{23} (T_2^4 - T_3^4) + K_{25} (T_2^4 - T_5^4) + K_{26} (T_2^4 - T_6^4)] \quad (9)$$

NICKEL SHIELD G1

$$M_3 C_{P3} \frac{d T_3}{d\theta} = P_3 - [K_{32} (T_3^4 - T_2^4) + K_{35} (T_3^4 - T_5^4) + K_{36} (T_3^4 - T_6^4) + K_{3,10} (T_3^4 - T_{10}^4) + K_{38} (T_3 - T_8)] \quad (10)$$

G3 HEATER

$$M_4 C_{P4} \frac{d T_4}{d\theta} = P_4 - [K_{4,13} (T_4 - T_{13}) + K_{45} (T_4^4 - T_5^4)] \quad (11)$$

UPPER PLATINUM SHIELD G3

$$M_5 C_{P5} \frac{d T_5}{d \theta} = K_{45} (T_4^4 - T_5^4) - [K_{52} (T_5^4 - T_2^4) + K_{53} (T_5^4 - T_3^4)] \quad 12$$

G2 HEATER

$$M_7 C_{P7} \frac{d T_7}{d \theta} = P_7 - [K_{78} (T_7 - T_8) + K_{7,14} (T_7^4 - T_{14}^4)] \quad 13$$

NICKEL SHIELD G2

$$M_8 C_{P8} \frac{d T_8}{d \theta} = P_3 + K_{78} (T_7 - T_8) - [K_{8,12} (T_8 - T_{12}) + K_{83} (T_8 - T_3) + K_{8,14} (T_8^4 - T_{14}^4)] \quad 14$$

CYLINDER HEATER

$$M_9 C_{P9} \frac{d T_9}{d \theta} = P_9 - [K_{9,10} (T_9 - T_{10}) + K_{9,11} (T_9 - T_{11})] \quad 15$$

CYLINDER

$$M_{10} C_{P10} \frac{d T_{10}}{d \theta} = K_{9,10} (T_9 - T_{10}) - [K_{10,3} (T_{10}^4 - T_3^4) + K_{10,14} (T_{10} - T_{14})] \quad 16$$

These nine equations (8 through 16) are the basic differential equations which govern the dynamic behavior of the individual component temperatures inside the calorimeter. Notice that not all components were treated in the model in differential equations. These components are considered to be "disturbances" since they are not controlled; therefore, it is not necessary to make balances around these components. Once the final model has been developed, an indepth study

can be made of these disturbance variables to determine to what extent their effect is on the overall approach to adiabatic conditions. In other words, they can be characterized as to their effect on heat loss from the sample.

Conversion of the Time Domain Model to the LaPlace Domain

Once the time domain differential equations which govern the process have been developed, one common procedure for further analysis is to convert these equations to the LaPlace domain. In essence, this allows the process to be described by transfer functions which have characteristic responses. The response depends not only on the values of the parameters of the transfer function but also on the form of the transfer function.

The steps necessary to accomplish this transformation from the time domain to the LaPlace Domain are (25):

1. Linearize any non-linear terms in the differential equations using a Taylor Series expansion.

2. Convert the linearized time domain differential equations to the LaPlace domain using LaPlace Transform Tables.

3. Solve for the dependent variables in these LaPlace domain equations.

4. Apply standard block diagram algebra to the LaPlace domain equations.

5. Arrange the individual blocks into an overall diagram relating the independent and dependent variables. (Appendix A demonstrates this procedure for a sample equation.)

Using this procedure on equations 8 through 16, the following LaPlace domain relationships result.

SAMPLE HEATER

$$t_1 = (K_1 P_1 + t_2) \cdot \left(\frac{1}{1+\tau_1 S} \right) \qquad 17$$

SAMPLE

$$t_2 = (K_{12} t_1 + C_{23} t_3 + C_{25} t_5 + C_{26} t_6) \cdot \left(\frac{K_2}{1+ \tau_2 S} \right) \qquad 18$$

NICKEL SHIELD G1

$$t_3 = (P_3 + C_{32} t_2 + C_{35} t_5 + C_{36} t_6 + C_{3,10} t_{10} + K_{38} t_8) \cdot \left(\frac{K_3}{1+\tau_3 S} \right) \qquad 19$$

G3 HEATER

$$t_4 = (P_4 + K_{4,13} t_{13} + C_{45} t_5) \cdot \left(\frac{K_4}{1+\tau_4 S} \right) \qquad 20$$

UPPER PLATINUM SHIELD G3

$$t_5 = (C_{44} t_4 + C_{52} t_2 + C_{53} t_3) \cdot \left(\frac{K_5}{1+\tau_5 S} \right) \qquad 21$$

G2 HEATER

$$t_7 = (P_7 + K_{78} t_8 + C_{7,14} t_{14}) \cdot \left(\frac{K_7}{1+ \tau_7 S} \right) \qquad 22$$

NICKEL SHIELD G2

$$t_8 = (P_3 + K_{78}\, t_7 + K_{8,12}\, t_{12} + K_{83}\, t_3 + C_{8,14}\, t_{14}) \cdot \left(\frac{K_8}{1+\tau_8 S} \right) \quad 23$$

CYLINDER HEATER

$$t_9 = (P_9 + K_{9,10}\, t_{10} + K_{9,11}\, t_{11}) \cdot \left(\frac{K_9}{1+\tau_9 S} \right) \quad 24$$

CYLINDER

$$t_{10} = (K_{9,10}\, t_9 + C_{10,3}\, t_3 + K_{10,14}\, t_{14}) \cdot \left(\frac{K_{10}}{1+\tau_{10} S} \right) \quad 25$$

These equations contain reduced constants which are given in Table II. Once these equations have been developed, steps (4) and (5) can be applied to yield the necessary block diagram (Figure 3). This diagram is the pictorial representation which directly shows the relationships between the major input and output variables. It also shows the type of transfer functions which govern the process.

Conversion of the Time Domain Model to the Discrete Domain

Another useful approach to modeling is by the use of the Discrete domain analysis of the time domain equations. This consists of transforming the differential equations into state variable equations and then the differential term into a discrete difference.

TABLE II

CONSTANTS IN LaPLACE DOMAIN EQUATIONS

$$K_1 = (K_{12})^{-1}$$

$$K_2 = [K_{12} + 4\ (K_{23} + K_{25} + K_{26})\ T_{2_a}{}^3]^{-1}$$

$$K_3 = [K_{38} + 4\ (K_{32} + K_{35} + K_{36} + K_{3,10})\ T_{3_a}{}^3]^{-1}$$

$$K_4 = [K_{4,13} + 4\ K_{45}\ T_{4_a}{}^3]^{-1}$$

$$K_5 = [4\ (K_{45} + K_{52} + K_{53})\ T_{5_a}{}^3]^{-1}$$

$$K_7 = [K_{78} + 4\ K_{7,14}\ T_{7_a}{}^3]^{-1}$$

$$K_8 = [K_{78} + K_{8,12} + K_{83}]^{-1}$$

$$K_9 = [K_{9,10} + K_{9,11}]^{-1}$$

$$K_{10} = [K_{9,10} + 4\ K_{10,3}\ T_{10_a}{}^3 + K_{10,14}]^{-1}$$

$$\gamma_i = M_i\ C_{P_i}\ K_i \quad \text{for } i = 1, 2, 3, 4, 5, 7, 8, 9, \text{ and } 10$$

$$C_{ij} = 4\ K_{ij}\ T_{ja}{}^3 \quad \text{for all 13 } C_{ij}\text{'s}$$

$$C_{44} = 4\ K_{45}\ T_{4_a}{}^3$$

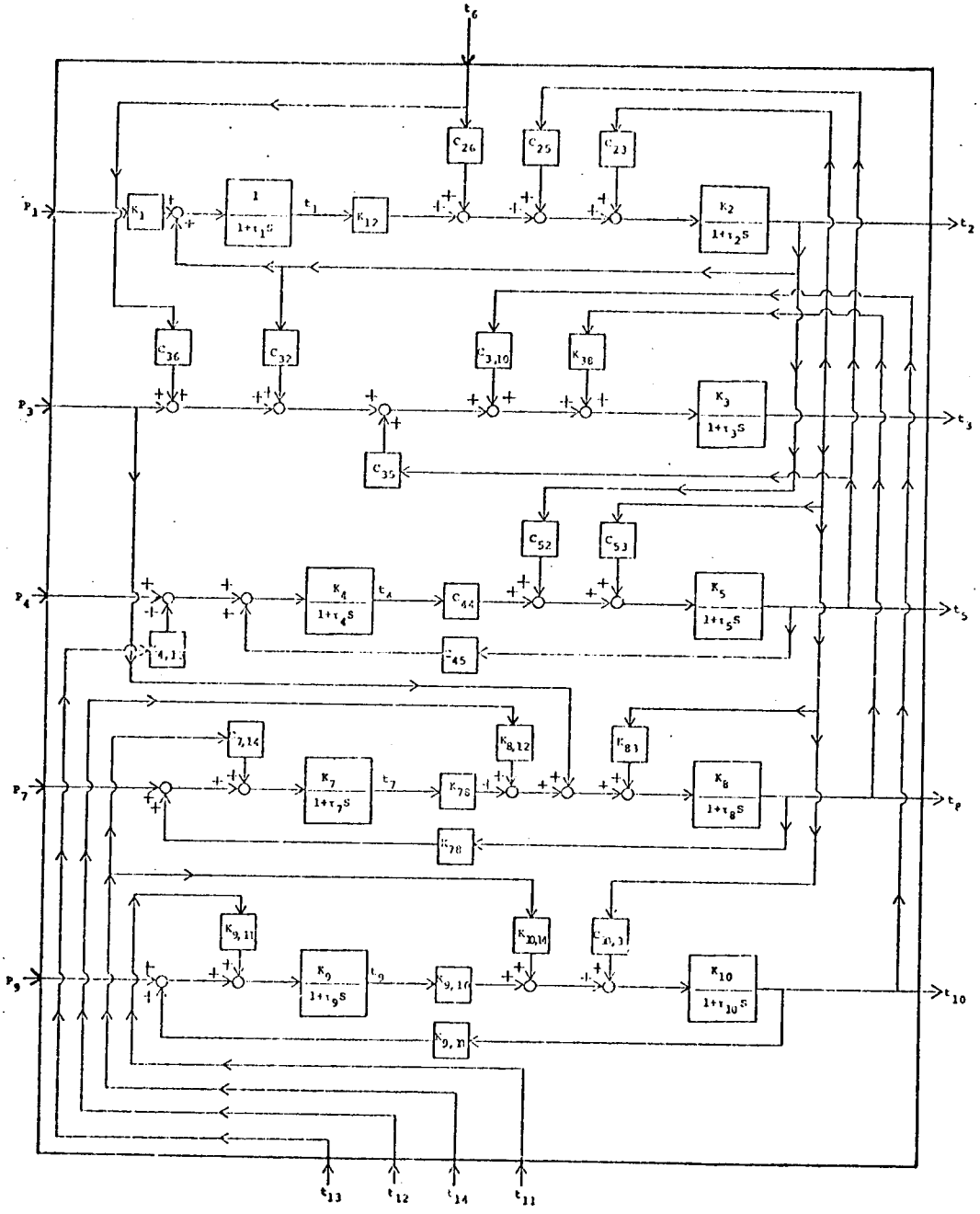


Figure 3. LaPlace Domain Block Diagram for the Calorimeter.

If the right side of equations 8 through 16 are examined, then the only process variables appearing are the powers, P; temperature, T; and the fourth power of the temperature, T^4. If at this point each equation is divided by the constants appearing in the accumulation term, then the rate of change of temperature with respect to time ($dT/d\theta$) is a function of P, T, T^4, and several constants. By making a vector out of these nine temperature rates, equations 8 through 16 can be written as non-linear state variable equations (30, 33):

$$\dot{T} = [A]\, T^4 + [B]\, T + [C]\, P \qquad 26$$

where

$\dot{T} = dT/d\theta$

$\dot{T}$ = a nine element vector

T and T^4 = fourteen element vectors

P = a five element vector

[A] and [B] = 14 x 9 matricies containing only constants

[C] = 5 x 9 matrix containing only constants

At this point, the linear approximation

$$\dot{T} = \frac{dT}{d\theta} = \frac{T_{i+1} - T_i}{\Delta\theta} \qquad 27$$

where

T_{i+1} = temperature at next sampling interval

T_i = temperature at current sampling interval

$\Delta\theta$ = sampling interval

can be made. This allows the state variable equations above to be transformed to the Discrete domain. This also allows a recursive digital relationship to be set up for each predicted temperature. When the above approximation is applied to the state equations, then the following recursive digital model results.

$$T_{i+1} = [A]^1 \; T_i^4 + [B]^1 \; T_i + [C]^1 \; P_i \qquad 28$$

where

$[A]^1 = [A] \cdot \Delta\theta$

$[B]^1 = ([I] + [B]) \cdot \Delta\theta$

$[C]^1 = [C] \cdot \Delta\theta$

$[I]$ = identity matrix

These vectors of variables and matricies of constants constitute the Discrete domain model which can be easily programmed digitally. The verification of this model consists of feeding in the temperature-power data and determining the values of the constants in the matricies by some optimization technique (30, 31, 32).

Analysis of Process

In measuring the specific heat of a material in the calorimeter, equations 8 and 9 are of major interest since they provide the basis for the specific heat calculation. These equations can be rewritten, assuming that the heater and sample are changing at an equal steady state rate.

Therefore:

$$\frac{d\,T_1}{d\theta} = \frac{d\,T_2}{d\theta} = \frac{d\,T_s}{d\theta} \qquad 29$$

By addition of equations 8 and 9, then substituting 29 into this result, the following equation is obtained:

$$(M_1\,C_{P1} + M_2\,C_{P2})\,\frac{d\,T_s}{d\theta} = P_1 - Q_1 \qquad 30$$

or

$$M_s\,C_{Ps}\,\frac{d\,T_s}{d\theta} = P_1 - Q_1 \qquad 31$$

where

M_s = total mass of sample and its heater

C_{Ps} = weighed average specific heat of the sample and its heater

$\frac{d\,T_s}{d\theta}$ = rate of change of temperature with respect to time for the sample and its heater

If we examine the Q_1 term which arises from equation 9, it is a function of the temperature difference between the sample and its surrounding shields. By controlling these shield temperatures exactly to the sample temperature, then Q_1 becomes zero. Therefore, equation 31 becomes:

$$M_s\,C_{Ps}\,\frac{d\,T_s}{d\theta} = P_1 = EI \qquad 32$$

where EI is the DC power input to the sample heater, E being the voltage drop measured at the sample, and I being the

current flowing in the circuit (measured as the voltage drop across a standard 1 ohm. resistor). Since the mass of the sample and heater is constant over all temperature ranges and the sample voltage, current and specific heat are constant over small temperature ranges, then the rate of change of temperature with respect to time will be constant over small temperature ranges. Therefore, $(dT/d\theta)$ can be written as $(\Delta T/\Delta\theta)$. Using this approximation, equation 32 can be solved to yield:

$$C_{Ps} = \frac{EI\ \Delta\theta}{M_s\ \Delta T_s} \qquad 33$$

Therefore, by measuring the sample parameters (voltage, current, and temperature) at a given sampling rate, the specific heat of the sample can be determined by having previously weighed the sample.

The one assumption in this linear approximation is that no heat is transferred to or from the sample. This now becomes the goal of the control strategy since a breakdown in this assumption can lead to gross errors in the specific heat (as much as 100% in the extreme case of total heat loss from the sample to its surrounding shields).

In order to approach this goal of zero heat loss, the time domain equations and the LaPlace domain block diagram are of great assistance. From equation 9, it is obvious that the bracketed heat loss term will be identical-

ly equal to zero if T_3, T_5, and T_6 are equal to T_2. From Table I, these represent the temperatures of G1, G3, the lower platinum shield, and the sample respectively. Since the lower platinum shield is not controlled (due to physical inaccessibility inside the calorimeter), it is of utmost importance to control G1 and G3 to the sample temperature.

Although this may seem simple in theory, it is very difficult due to several characteristics of the process. First of all, analysis of the time domain equations shows that the process is non-linear. This results in model parameters which vary with load conditions (here temperature is the load). The non-linearity arises from the heat transfer being proportional to the fourth power of the absolute temperature. In linearizing this term, it forces the process gains and time constants to be a function of temperature. This is evident by examining the constants in Table II, many of which contain denominator terms involving the cube of the absolute temperature. As this absolute temperature varies from 300° to 1300°K, these process gains and time constants decrease in value. By realizing that the time constant is related to the speed of response, it is obvious that temperature responses occur more quickly at 1300° than 300°K. Also, at higher temperatures the rate of heat loss occurs much more rapidly. This effect can also be borne out by plotting the rate of heat transfer as

a heat flux (heat transferred per unit time and area) vs. absolute temperature at various temperature differences. This plot is shown in Figure 4 and demonstrates that the rate of radiative heat transfer increases with both absolute temperature and temperature difference between the two radiating media. This is also demonstrated by considering the Taylor Series expansion of the non-linear function T^4. It is linearized into $4T^3 \Delta T$. Hence the heat transferred should be proportional to the cube of the absolute temperature and the temperature difference which has been shown to be the case.

When these features due to the non-linearity are related to the actual problem of control, the following observations are made. First of all, any controller must be tuned to the process for which it was intended to control. This tuning is done based upon the physical process parameters such as the process gains, time constants, and dead times. When these change, so must the controller tuning parameters. In the present calorimeter, the PID controllers have three tuning parameters: (1) the proportional band, (2) the reset rate, and (3) the rate time. Since it has been shown above that the process parameters change inversely with the cube of the absolute temperature, then these controller tuning parameters should also change. This would have to be done manually by adjusting knobs on the outside

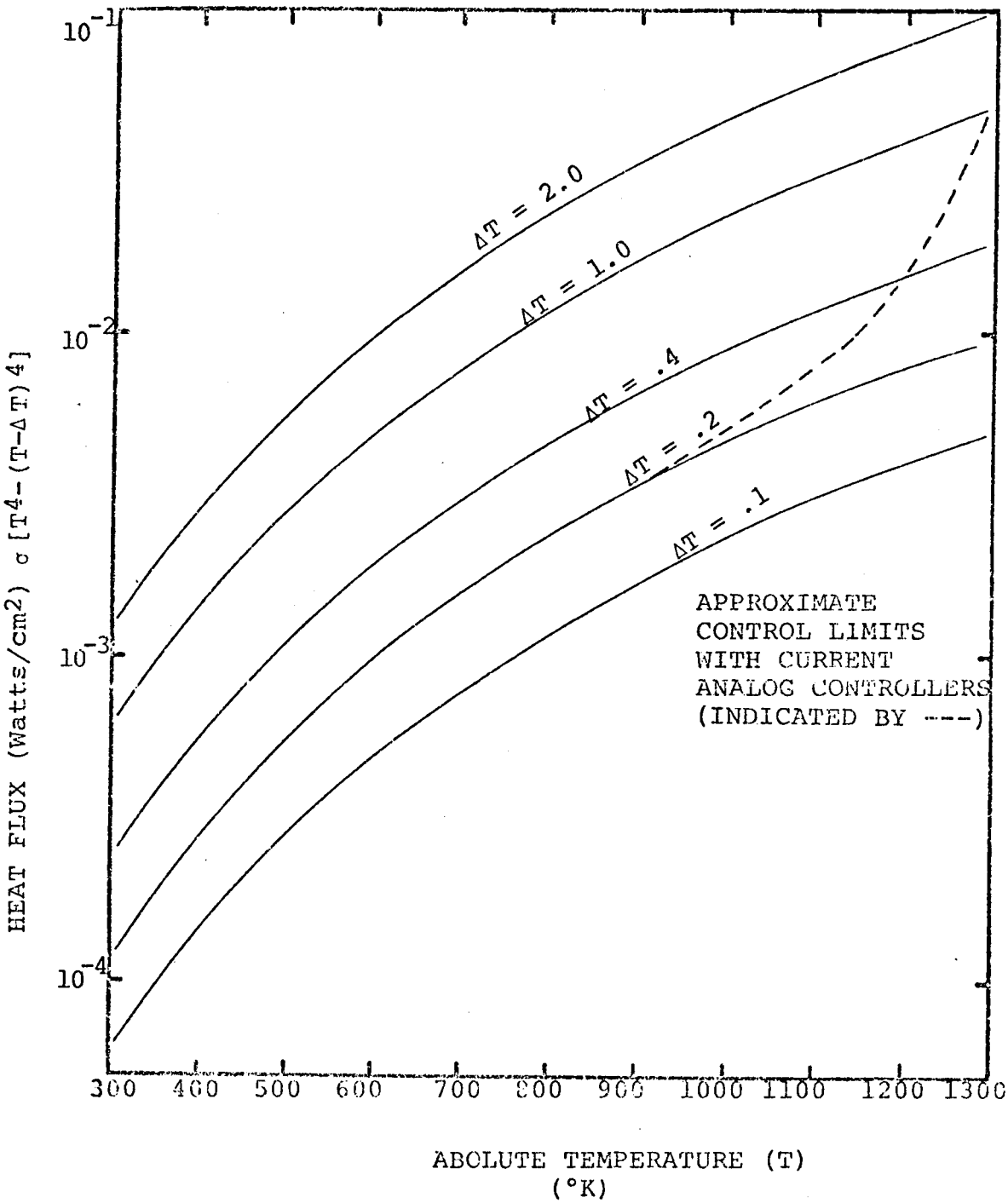


Figure 4. Heat Flux for Radiative Heat Transfer as a Function of Absolute Temperature and the Temperature Difference.

of the actual controller. This can be circumvented by better control strategies which take this non-linear aspect into account. Typically, controllers are tuned under one set of load conditions and are allowed to remain there for all conditions, but a controller which is well tuned for one set of load conditions may exhibit a completely unstable response for another set of load conditions. This process does not present this drastic case, but control limits do increase from 300° to $1300^{\circ}K$ (observed by experience). The approximate limit of controllability is depicted as the dashed line on Figure 4.

In summary, the temperature non-linearity results in a process which is more difficult to control at higher temperatures due to higher rates of heat transfer and changing process parameters not adjusted for by the current control strategy.

The second process characteristic is that it is multivariable. The block diagram (Figure 3) is a graphical depiction of this. Here the major input variables appear on the left, the major output variables on the right, and the disturbance variables at the top and bottom. The complicated pattern inside the dark boundary line represents the direction of the interaction and the transfer function relating the variables. To demonstrate this multivariable nature from the diagram, the effects of issuing a step in-

put *via* P_1 will be traced. First of all, it will affect t_2 which is the major temperature controlled by P_1. But this increase in t_2 will also be transferred down into the loops for t_3 and t_5. A change in t_3 will affect t_2, t_5, t_8, and t_{10}. By continuing this tracing, it would be found that all the output temperatures in the calorimeter would be changed. This is also the case by physical analysis. When the power to the sample (P_1) is turned on, the sample heats the most, but all the shields also heat up due to internal heat transfer.

The effect of this multivariable nature of the process on control can be small or catastrophic. Conventionally, each loop is tuned independently of the others. (A loop consists of an input variable and its major output variable, such as the sample power and the sample.) Then all the loops are placed into automatic control based upon this tuning procedure. However, due to the complicated interactions between the variables, the overall system response may be unstable with none of the variables being controlled to their set points.

The third process characteristic which presents control difficulties is dead time. In this case, the dead time is due to the transport lag of heat between the heat source and thermocouple. This characteristic is evident in the sample, the cylinder, and the nickel shield G2. These

dead times are all due to the finite thickness of the wall between the heater and the thermocouple and is analogous to the transient slab problem. This problem considers an infinite slab with finite thickness at a uniform temperature initially. One side is suddenly raised to some other temperature and the profiles inside the slab are plotted as a function of time. This plot in non-dimensional form appears in standard texts (20) and has been reconstructed here in Figure 5. From this, a plot of the temperature of the left face vs. time in non-dimensional form was made (Figure 6). (This simulates the temperature monitored by a thermocouple placed at this location.) This form clearly represents the response of a first order lag plus dead time system to a step input, or in equation form (LaPlace Domain):

$$\frac{T(s)}{U(s)} = \frac{K\, e^{-\theta s}}{1 + \tau s} \qquad 34$$

When the data in Figure 6 was modeled using this form, the parameters are:

$$K = 1.0$$

$$\tau = 0.427\ \ell^2/\kappa$$

$$\theta = 0.079\ \ell^2/\kappa$$

This presence of dead time severely degrades the controllability of the process. It requires lower controller gains which considerably slows the closed loop response. A detailed study of dead time, its effect on the control of

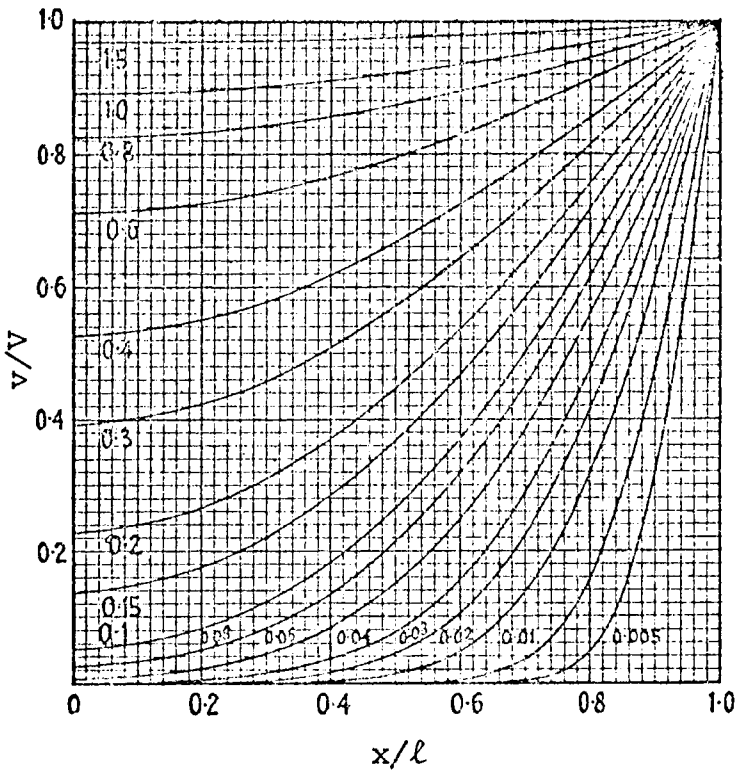


Figure 5. Temperature Distribution at Various Times in the Slab $-\ell<x<\ell$ with Zero Initial Temperature and Surface Temperature V. The Numbers on the Curves are the Values of $\kappa t/\ell^2$.

Source: H. S. Carslaw and J. C. Jaeger, Conduction of Heat in Solids, 2nd Edition, Oxford University Press, London, 1959, p. 101.

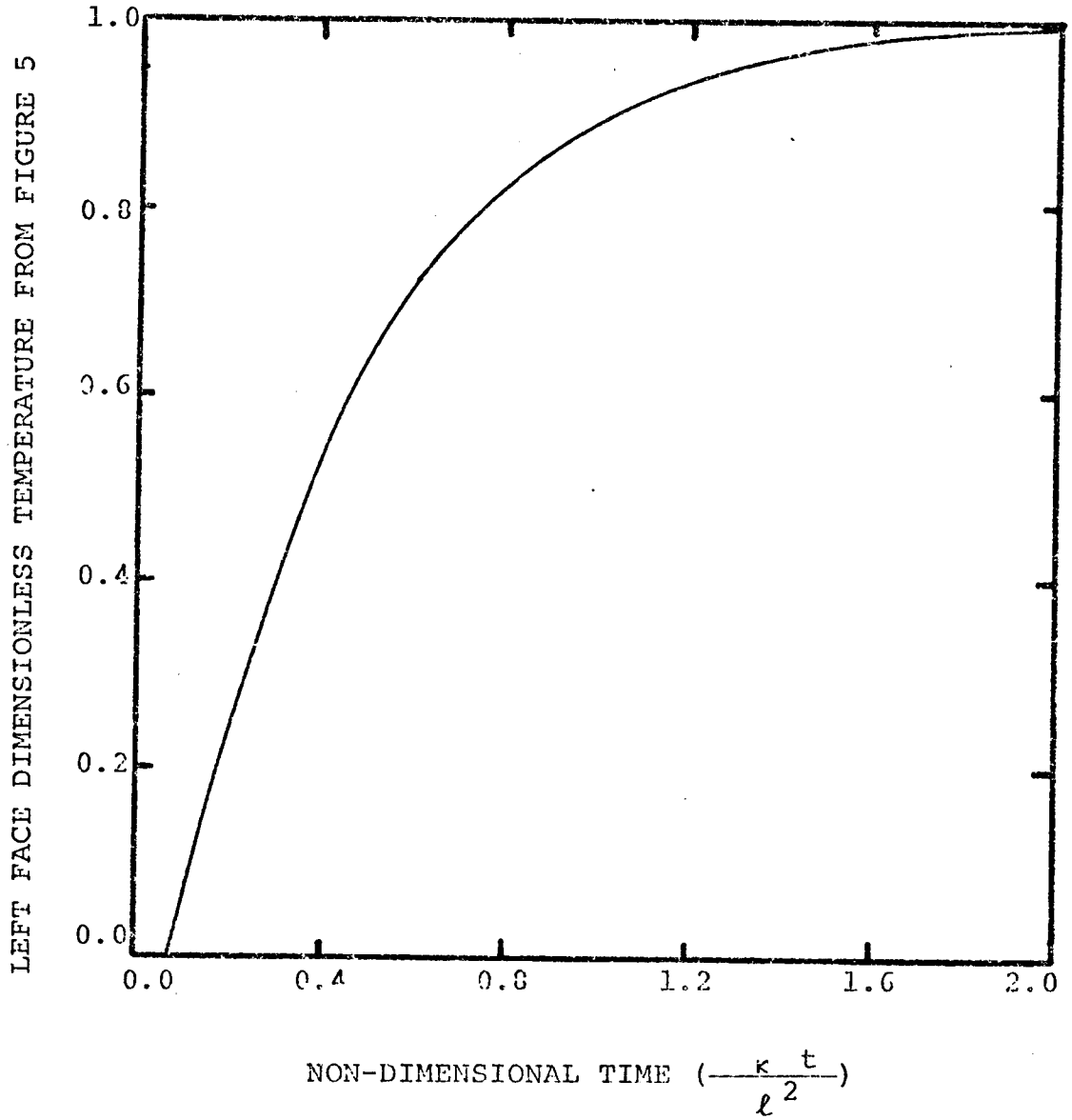


Figure 6. Temperature of the Free Face of a Slab with Zero Initial Temperature and Surface Temperature V.

the process, and digital methods of improving the control have been studied by Doss (2).

The last characteristic prevalent in this process is different dynamics with regard to heating and cooling. Heating can be accomplished quickly by increasing the power input, but cooling can only be accomplished by heat loss to other shields. This causes much care to be exerted to avoid overshoot in the closed loop response. This is also accomplished by lowering the controller gain which once again slows the response of the closed loop system.

In order to fully develop this process from a control standpoint, a control strategy which aids in the solution to each one of these characteristics which is difficult to handle using standard analog (PID) controllers must be developed. This can be done by determining the values of the unknown constant in either the LaPlace or Discrete domain models (one can be calculated from the other). This model can then be used to develop the required control strategy.

CHAPTER III

THE DESIGN, OPERATION, AND APPLICATION OF THE DATA ACQUISITION SYSTEM

In order to develop a meaningful system for data acquisition, consideration must be given to the type of sensing devices to be used, the range of signal produced, the desired accuracy with which this signal is to be measured, and the necessary number of sensing elements. In the case of the calorimeter, thermocouples were selected as the appropriate sensing devices (8, 9, 10) since temperature is the major variable to be measured. To this date, all investigators using the calorimeter have used an "operator" type method for data collection.

This method involves a person who must take data in the following brief steps (a more detailed account can be found in Peng (12)).

1. The operator sets a microvolt reading on a high precision Dauphinee potentiometer (accurate to within $\pm$0.1 microvolt).

2. When the monitored thermocouple signal reaches this preset voltage, a null meter reads 0.0.

3. At this time, the operator quickly flips a switch which simultaneously stops one timer (accurate to within $\pm$0.01 seconds) and starts another timer preset to

zero. This yields the time interval ($\Delta\theta$) required for the thermocouple signal to change from one preset voltage to another. These thermocouple voltages at the beginning and end of the time interval can now be converted to temperatures and the sample temperature rise (ΔT) over this time range calculated using a voltage/temperature conversion chart for that given thermocouple (here a Pt; Pt - 13% Rh thermocouple is used).

4. The operator then reads the voltage (E) supplied to the sample using a voltmeter (accurate to within $\pm$0.001 volts) and the current (I) through the sample heater (measured as the voltage drop across a standard 1.0000 ohm resistor) using the same voltmeter.

5. Having preweighed the sample, the operator can calculate the average specific heat of the sample over this temperature range using equation 33.

In order to transfer the mode of data collection from the "operator" type to digital data acquisition, the range and accuracy of the signal to be sampled must be considered. With the analog equipment, this does not present a problem since the Dauphinee potentiometer can measure voltages between 0 and 1.5 volts with an accuracy of 0.1 microvolt. Since the desired temperature range of the specific heat measurements is between 0^{o} and $1000^{o}C$, the thermocouple output (using a standard Pt/Pt - 13% Rh

thermocouple) is between 0 and 10500 microvolts. This is well within the range of the Dauphinee potentiometer. Also, the accuracy in temperature measurement can be directly related to the voltage accuracy of the Dauphinee. Since the temperature range is 1000°C and the microvolt range is 10500 microvolts, then there is approximately 0.1°C per microvolt. With a voltage capability of 0.1 microvolt, the absolute temperature accuracy is approximately 0.01°C. This accuracy should be approached by the digital system.

The digital system to be used employs a 12 bit analog-to-digital (A/D) converter with a maximum input of $\pm$10.0 volts (DC). Therefore, any voltage input between $\pm$10.0 volts will be scaled linearly to an output of $\pm$2047 counts (0.005 volts/count) which is equivalent to an absolute sampling accuracy of $\pm$0.0025 volts. With unity gain between the thermocouple and the A/D converter, the absolute temperature accuracy would be equal to $\pm$250°C ($\pm$0.0025 volts x 0.1°C/ μV. x 10^6 μ VS./volt). Since the maximum thermocouple output is approximately 10000 μ VS., then a gain of 1000 can be used to boost the thermocouple signal to $^+$10.0 volts. This would correspond to a temperature accuracy of $\pm$0.25°C, still 25 times poorer than the analog system. By using a fixed 5000 μV. suppression and a gain of 2000, the thermocouple signal can then be

altered to $\pm$10.0 volts which yields a temperature accuracy of $\pm$0.125^{o}C. This accuracy is still 12.5 times poorer than the analog circuit which is unacceptable. The only solution is a combination fixed suppression-variable suppression-high gain amplification system. This network was initially conceived and analyzed by E. E. Stansbury and W. P. Murray (47). Credit must be given to them for this network and the Department of Chemical and Metallurgical Engineering Electronics Shop for the actual hardware design and actual construction of the suppression units.

The network consists of a fixed 500 μV. suppression unit, a variable suppression unit (units of suppression in integer multiples of 1000 μVS.), a high gain (5000 x) Astrodata Model 120 amplifier, and a low gain ($\sim$ 4 x) Astrodata Model 885 amplifier. The suppression network alters the input to the amplifiers to $\pm$500 μVS. This is then amplified by the total gain ($\sim$20000 x) to $\pm$10.0 volts which is then converted using the A/D converter to $\pm$2047 counts. This corresponds to a sampling accuracy of $\pm$0.125 μV. which is equivalent to $\pm$0.0125^{o}C. This accuracy is a factor of 1.25 times poorer than the analog system but deemed acceptable. (The schematics for the suppression unit appear in Appendix B.)

The major goals of the data acquisition system are:

1. Collect data suitable for the experimental

verification of the theoretical model.

2. Collect data suitable for use in digital control.

3. Collect data for determination of the specific heat of a metal from 300^{o} to 1300^{o}K with comparable accuracy of that determined using the "operator" type method.

The most logical proving ground for the data acquisition system would be in the specific heat determination since this is a concrete basis for comparison. This can be done by examining the accuracy of the contributing variables used in calculating the specific heat for the digital vs. analog system.

The average specific heat is calculated from

$$C_P = \frac{E\ I\ \Delta\theta}{M\ \Delta\ T} \qquad 35$$

By expanding this equation into a total differential

$$d\ C_P = \left(\frac{\partial\ C_P}{\partial\ E}\right) dE + \left(\frac{\partial\ C_P}{\partial\ I}\right) dI + \frac{\partial C_P}{\partial(\Delta\theta)}\ d(\Delta\theta) + \left(\frac{\partial\ C_P}{\partial\ M}\right) dM + \frac{\partial\ C_P}{\partial\ (\Delta\ T)}\ d(\Delta\ T) \qquad 36$$

which becomes

$$d\ C_P = \left|\frac{C_P}{E}\right|\ d\ E + \left|\frac{C_P}{I}\right|\ dI + \left|\frac{C_P}{\Delta\theta}\right| d\ (\Delta\theta) + \left|\frac{C_P}{M}\right| dM + \left|\frac{C_P}{\Delta\ T}\right| d\ (\Delta\ T) \qquad 37$$

using for the error

$$\% \text{ Error} = \frac{d\,C_P}{C_P} \times 100\% \qquad 38$$

the error as related to the component measurements is

$$\% \text{ Error} = \left(\frac{d\,E}{E} + \frac{d\,I}{I} + \frac{d\,(\Delta\Theta)}{\Delta\Theta} + \frac{d\,M}{M} + \frac{d\,(\Delta T)}{\Delta T} \right) \times 100\% \qquad 39$$

Table III presents the uncertainty values for these variables and the % Error in the specific heat due to these uncertainties for the analog vs. digital system. The digital system was broken down into the minimum theoretical values using the A/D converter and the observed values (discussed in the next chapter) commonly encountered. It is obvious that the digital system is not as accurate as the analog counterpart. Digital data possesses two times the error as the analog data on a theoretical basis and seven times the error on an observed basis. Although this may seem high, methods of reducing this error will be discussed later.

It is also important to note here that the % Error due to uncertainties in the temperature measurement accounts for a large portion of the total error. Table III shows that roughly 70% of the total error in the analog data is due to this variable, while 90% of the total error in the observed digital data is due to this variable. Therefore,

TABLE III

PERCENT ERROR IN SPECIFIC HEAT BASED UPON THE UNCERTAINTY IN CONTRIBUTING VARIABLES

UNCERTAINTY VALUES

		Uncertainty		
			Digital	
Variable	Mean Value	Analog	Theoretical	Observed
E (volts)	5.0	0.001	0.0025	→
I (amps)	0.5	0.0001	0.00025	→
θ (sec)	300	0.02	0.01	→
m (gms)	150	0.01	0.01	→
ΔT (°C)	10.5	0.01	0.0125	0.10

PERCENT ERROR

	Percent Error		
		Digital	
Variable	Analog	Theoretical	Observed
E	0.020	0.050	→
I	0.020	0.050	→
θ	0.007	0.003	→
M	0.007	0.007	→
ΔT	0.10	0.125	1.00
	0.15	0.24	1.11

the most critical variable for which sampling errors should be minimized is temperature.

In the area of modeling and control this effect will be even more pronounced since these depend exclusively on temperature measurements. In controlling the process, sampling errors will severely degrade the control as demonstrated by Figure 4. Since the analog controllers maintain control limits of $\pm 0.2^{\circ}C$, then this should be the goal of the digital system; but the observed digital uncertainty is $0.1^{\circ}C$ which is very adequate for control purposes.

In order to control the process, several thermocouple signals must be monitored. This can be done in one of two ways:

1. Have individual circuits of the aforementioned suppression-amplification scheme for each thermocouple.

2. Design a system whereby many thermocouples share the same suppression-amplification scheme.

By examining these two alternatives, it becomes obvious that method 1 is impractical. This method would require several identically matched suppression-amplification units. The calibration procedure alone would become formidable. This method would also be very costly; therefore, method 2 was chosen as the only practical route.

Method 2 can be accomplished by designing a multiplexer which has the capabilities of selecting any

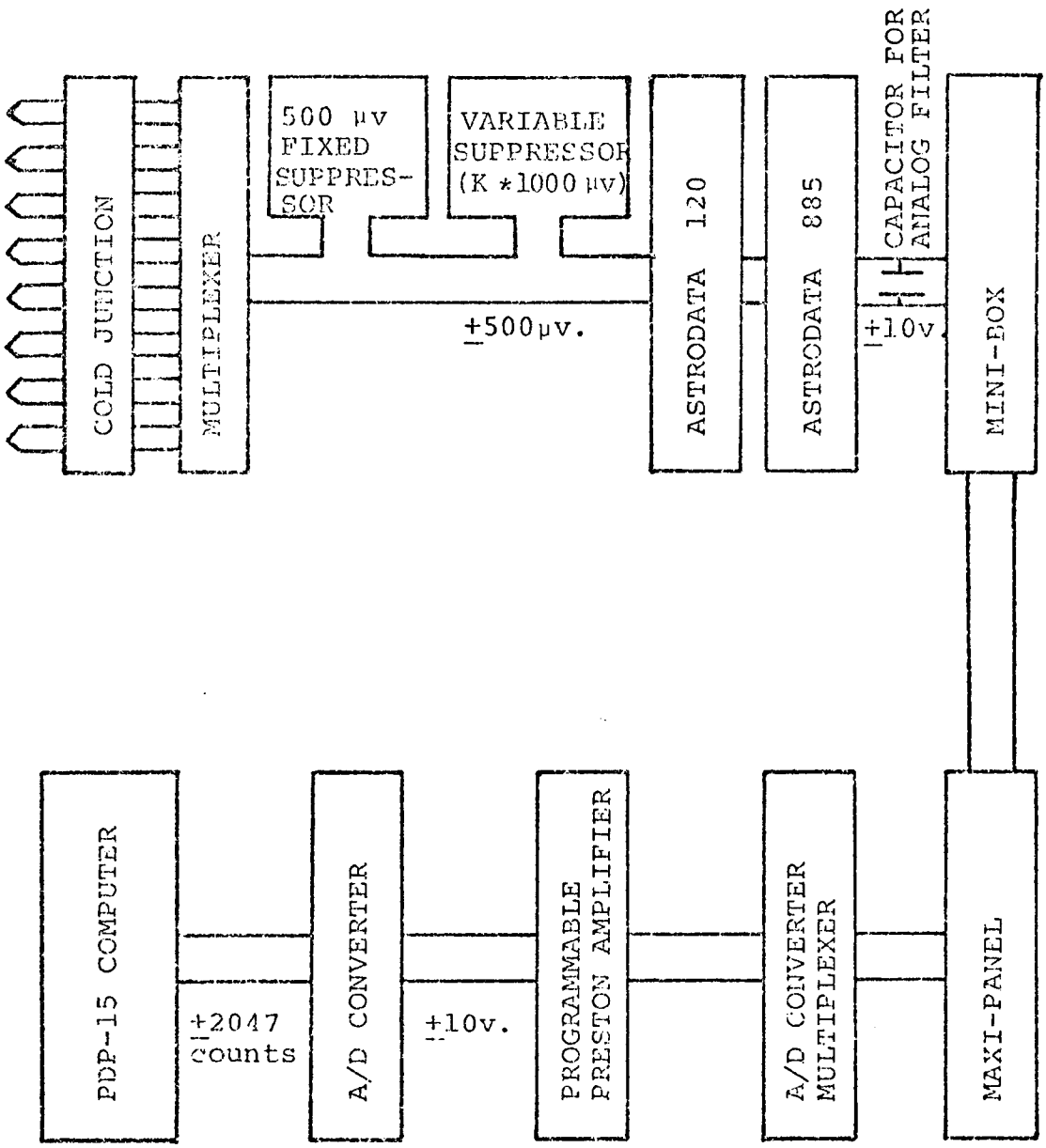
given thermocouple inside the calorimeter. (This can be done by use of the computer operated DR-90 relays which are software controlled.) Each thermocouple signal will then experience the same degree of suppression and amplification; therefore, any small deviations in calibration will be nullified.

The multiplexer (shown schematically in Appendix C) basically consists of eight microswitches which can be opened or closed. When one microswitch is closed, the thermocouple connected to this switch can be sampled by the computer.

At this point, care must be taken when moving from one thermocouple to another. A finite time is required for the switch to close and the output to reach steady state. Also, this system was found to introduce small amounts of noise into the circuit since voltages in the range of microvolts must be passed through its circuitry. For these reasons a capacitor was placed in parallel with the output of the suppressed-amplified thermocouple signal. This capacitor acts as an analog filter and will be characterized in a later chapter.

Figure 7 depicts the overall thermocouple data acquisition loop described above.

The only remaining equipment necessary to complete the data acquisition loop is two A/D converter channels for



1 T/C µv. = 0.1°C = 0.020 volts A/DC input = 4 counts

Figure 7. Data Acquisition Flow Diagram

reading the sample voltage and current and four D/A channels for sending controller signals to the power supplies connected to shields G1, G2, G3 and the cylinder. No additional equipment is required for the reading of the sample voltage and current (read as the voltage drop across a standard one ohm resistor) since they are voltages between 0-10 volts. The only interface necessary for the D/A outputs are resistors. This is due to the fact that the D/A output is between 0-10 volts and the input to the power amplifiers is between 0-5 milliamps. Therefore, by adjusting the circuit resistance between the D/A converter and the input to the power amplifier to 2000 ohms, the necessary scaling is accomplished.

Equipment Operation

After developing the necessary equipment to collect data using the computer, it is now necessary to describe the computer hardware and software used to interface the computer and equipment.

The computer used in this study is a Digital Equipment Corporation PDP-15 with 32K of core storage and a real time clock. The communication devices associated with this computer are two dectape drives, four teletypes, a high speed paper tape punch, and a high speed paper tape reader. The hardware used in data acquisition is a 32 channel-12 bit

A/D converter with $\pm$10 volts input, a 6 channel-10 bit D/A converter with $\pm$10 volts output, and 18 DR-90 relays. This hardware can be operated by using the MCR (Monitor Console Routine) command for random access or from inside a Fortran program using the standard "CALL" statement. (This software was developed by R. L. Stoots (6) for use with this machine.) The overall system for the computer is the DEC RSX-Phase II, a real time executive system controlled by a real time clock. This system can be used for on-line programming as well as data acquisition.

The computer hardware (such as A/D converter, D/A converter, and DR-90 relays) terminates in a panel board located in the room containing the computer itself. Beside this panel board is a "maxi" panel which is the termination point for lines from individual laboratories. These laboratory lines originate in their respective labs from a "mini" box. In order to connect some device to be sampled to the computer, it is a simple matter of using patch cords to connect the device with the mini-box and the proper line in the maxi panel to the desired computer hardware. (A representative sketch is shown by Sayers (3).)

In order to use the suppression-amplification scheme described previously, a rather simple network of computer activated hardware is necessary. It basically consists of

12 DR-90 relays and one A/D converter channel. First, a thermocouple (hereinafter T/C) is selected by closing one of eight DR-90 relays which closes one of the multiplexer microswitches in the lab and opening the other seven DR-90 relays connected to the multiplexer. (This prevents a ground loop since all T/C's are grounded and closing two at the same time would constitute a closed electrical loop.) At this point the T/C value can be sampled by the computer using a single A/D converter channel. In order to read all eight T/C's consecutively, it is a simple matter of alternately opening and closing relays. (Figure 8 is a Fortran routine used to read all eight T/C's consecutively and store their values in a vector ITSIG.) Lastly, the value of the T/C must be checked in order to prevent overloading the A/D converter and the calculation of an erroneous temperature. If this happens, the correct suppression must be set and the value reread. This can also be accomplished by use of the DR-90 relays. In order to attain increments of integer multiples of 1000 microvolts, a suppression unit with values of 1K, 2K, 4K, and 8K microvolts of suppression is all that is necessary. By closing one of the four necessary DR-90 relays, any one of these amounts of suppression can be selected; likewise, the closure of two relays will connect the two proper amounts in series. This allows the selection of integer multiples of suppression between 0K and 15K

```
C       READ ALL THERMOCOUPLES
        DO 300 J=1,8
        CALL RLYON(L(J+4),1,IEV)
        DO 100 I=1,8
        IF (I.EQ.J) GO TO 100
        CALL RLYOF(L(I+4),1,IST)
100     CONTINUE
        CALL RST(5)
        JTO=0
        DO 200 I=1,3
        CALL ADCIN(L(13),ITC,IEV)
        CALL RST(1)
200     JTO=JTO+ITC
300     ITSIG(J)=JTO/3
```

NOTES: RLYON turns on DR-90 relay.
RLYOF turns off DR-90 relay.
RST(N) sets relay to proper position, then waits N ticks before resuming task execution.
ADCIN stores A/D converter value under variable name ITC.
1 tick = 0.01 second

Figure 8. Program Segment for Reading the Eight Multiplexer Channels Successively.

microvolts from this unit, e.g., a value of 7K is accomplished by closing the DR-90 relays connected to the 1K, 2K, and 4K units and leaving the relay connected to the 8K unit open. The Fortran program (SUPRS) used to set the suppression is listed in Appendix D.

The final step in determining a temperature in the calorimeter is to decode value logged in the computer which represents the T/C value. This is a simple matter of back-calculating using the values of the suppression-amplification system. In equation form

$$EMF = \frac{(ITSIG)(10^7)}{(2047)(GAIN)} + 1000K + SUP \qquad 40$$

where

EMF = actual T/C emf in microvolts

ITSIG = value read by computer ($-2047 \leq ITSIG \leq 2047$)

GAIN = total gain in amplification network

K = integer multiple of 1000 microvolts of suppression in use at that time

SUP = fixed suppression of 500 microvolts

In order to convert to temperature, it is a simple matter of linear interpolation over small microvolt ranges (usually 100) to convert the T/C emf to temperature. This is accomplished by using stored temperature vs. T/C emf data at 100 microvolt intervals.

Application of Data Acquisition System to Modeling

Data acquisition for modeling is accomplished by sampling the following variables at a given rate:

- All eight T/C values (sample T/C, five major shield T/C's and two T/C's assigned to various disturbances)

- Four major controller outputs (G1, G2, G3 and the cylinder)

- Sample voltage and current.

All this data can be stored and later used for off-line calculations to determine the constants in Table II, p. 28.

The collecting of T/C data and the sample voltage and current have previously been discussed. The only new area is the acquisition of the controller outputs. This can be done in one of two methods.

1. Sample the analog (PID) controller outputs and assume constant over the sampling interval.

2. Use a preliminary digital controller which will set a controller output and maintain this value until the next sampling interval.

Method 2 was chosen for the following reasons:

- The PID output, being continuous, sometimes varies very rapidly with time within limits of full off and full on. This could produce major errors in the model which could be prevented by using a constant output over the sampling interval.

- The sampling of a thermocouple produces a closed circuit between it and the A/D converter. If this thermocouple were also used for the analog control, parallel circuits would result which destroys the accuracy of the digital value as well as upsetting the analog controllers. Separate T/C's located closely together could also be used, but this is expensive and small differences between the T/C for digital use and the T/C for analog control could also introduce significant modeling errors.

The preliminary controller chosen was the digital equivalent of the analog (PID) controllers now in use. The PID controller is based on the following time domain equation:

$$m(t) = K_c \left[e(t) + \frac{1}{T_i} \int e(t)\, dt + T_d \frac{d\, e(t)}{dt} \right] \qquad 41$$

where

$m(t)$ = controller output

$e(t)$ = error between set point and process signal

K_c, T_i, and T_d = controller tuning parameters

The discrete version of this equation is:

$$m_i = K_c \left[e_i + \frac{T}{T_i} \Sigma e_i + T_d \left(\frac{e_i - e_{i-1}}{T} \right) \right] \qquad 42$$

where

m_i = current controller output

e_i = current error

T = sampling time

In order to implement this equation, it is often useful to employ a recursive type form which is based on the current error and the past controller input. By evaluating equation 42 at the previous sampling period, one obtains:

$$m_{i-1} = K_c \left[e_{i-1} + \frac{T}{T_i} \Sigma\ e_{i-1} + T_d \left(\frac{e_{i-1} - e_{i-2}}{T} \right) \right] \qquad 43$$

Subtracting equations 43 from 42 yields:

$$m_i - m_{i-1} = K_c \left[(e_i - e_{i-1}) + \frac{T}{T_i} e_i + T_d \left(\frac{e_i - 2e_{i-1} + e_{i-2}}{T} \right) \right] \qquad 44$$

or

$$m_i = m_{i-1} + K_c \left[\left(1 + \frac{T}{T_i} + \frac{T_d}{T}\right) e_i - \left(1 + \frac{2\ T_d}{T}\right) e_{i-1} + \frac{T_d}{T}\ e_{i-2} \right] \qquad 45$$

This form prevents gross disturbances from entering the control output due to a change in the overall controller gain, K_c. In the form of equation 42, if K_c is halved, m_i is halved; but, in equation 45 if K_c is halved, m_i will be equal to the last value (m_{i-1}) plus the new control action. Therefore, the steady state value of the controller is much less affected.

The program (called PID) to collect the necessary data for modeling and the program (called STORE) used to

store this data on dectapes appear in Appendix D.

Application of Data Acquisition System to the Determination of the Sample Specific Heat

Data acquisition for the specific heat calculation is accomplished by sampling the following variables at a given time:

- Sample T/C
- Sample voltage and current

The actual sampling of these variables has already been discussed, but certain additional calculations are necessary to complete the actual specific heat calculations.

Since the error in the specific heat decreases as the interval of determination increases (equation 39), it is really only necessary to sample at this temperature interval; but in order to enhance the accuracy of the data, it was decided to take several data points in this interval and determine the slope using a least squares fit. Since the specific heat is assumed to be linear over small temperature intervals, a linear least squares form is all that is necessary. Also, since data points are taken at regular invervals, the normal linear least squares fit can be reduced to a single equation (see Appendix F) by knowing the number of data points included in the fit. In order to speed calculations, this least squares fit can be made directly on the raw sampled data (digital counts). Consider

the following two methods:

1. Convert all N data points of the interval to temperatures, apply least squares to the N temperatures, predict the first and last temperatures of the interval, then subtract these to obtain the temperature rise.

2. Apply least squares to the raw sampled data (digital counts), predict the first and last data points (as digital counts), convert only these two end points to temperatures, then subtract to obtain the temperature rise.

Method 1 requires (N - 2) more temperature conversions; therefore, it is much slower than Method 2.

The programs necessary in the determination of the specific heat are CALØ4 and CALØ6 (see Appendix D).

Summary of Data Acquisition Software

In order to have access to temperatures in the calorimeter, set required variables necessary for data acquisition and display required results of calculations; several programs have been written to complete the data acquisition software. Table IV lists the program names and their function, Appendix D contains the complete program listing for each listing in Table IV, and Appendix E contains the definition of all variables stored in common.

TABLE IV

PROGRAM NAME AND FUNCTIONS

PROGRAM	FUNCTION
	INITILIZATION
STUPP	Start scan of A/D converter channel. Turn on clock.
RSTUP	Initilize variables. Set relays to initial positions. Turn on proper A/D converter channels. Synchronize the execution of CAL Ø4 and PID.
CAL ØØ	Lists current values of variables in common.
CAL Ø1, CAAØ1	Used to change values of variables in common.
	DATA ACQUISITION FOR MODELING
PID	Reads all eight T/C values. Controls shields to specimen temperature using PID algorithm. Requests storage of data using STORE.
STORE	Stores data from controller for future modeling.
	SPECIFIC HEAT DETERMINATION
CAL Ø4	Read 2 sample T/C's, Sample Voltage and Current. Increment T/C table to save last 20 T/C values for each T/C. If required number of data points have been collected since last specific heat measurement: - Read time since last specific heat measurement

TABLE IV (continued)

PROGRAM	FUNCTION
	- Store sample voltage and current - Set up sums for least squares fit - Re-initialize counter - Request CABØ9 and CALØ9 If suppression necessary, request SUPRS.
CALØ6	Calculate specific heat and average temperature over this 20 point period using least squares predicted temperatures. Request CALØ9
CALØ9	List pertinent variables relating to specific heat calculation.
CABØ9	List T/C values (in digital counts) used in least squares fit. Calculate and print standard error of the estimate from least squares fit of T/C data.
	GENERAL
SUPRS	Sets suppression.
CAA1Ø, WRA1Ø	Reads all eight T/C's and prints their value as temperatures. (Used mainly to take drift data.)
CAL1Ø	Reads all eight T/C's and prints their value as emfs. (Used for noise study.)

CHAPTER IV

METHODS OF NOISE ELIMINATION

In Chapter III, Table III, p. 49, it was found that errors in sampling of the temperatures in the calorimeter lead to large percentages of the total error in the specific heat. This sampling error will also present a definite problem in the development of any control strategy since controller outputs are based upon temperature differences between shield temperatures and the sample temperature. For this reason, very accurate temperature measurements must be made. Chapter III describes in depth the hardware necessary to obtain highly accurate measurements, but this system is not without its own problems. Its own complexity tends to destroy the accuracy it seeks to achieve.

There are several possible locations for noise to enter the system. Some of the most important ones are:

- Passage of the T/C signal from the calorimeter to the Astrodata 120 amplifier. The microvolt signal must travel through approximately five feet of wire, encountering a cold junction, multiplexer, fixed suppression unit and a variable suppression unit. This provides a possibly tremendous source for microvolt level noise pick-up due to electrostatic and electromagnetic fields in the

surrounding equipment.

- A/C driven amplifiers. The Astrodata 120 is battery powered but not the Astrodata 885; therefore, 60 Hz line pickup may be superimposed on the amplified T/C signal.

- A/C powered shields. Adiabatic shields G2, G3, and the cylinder are powered by 60 Hz A/C power; therefore, T/C junctions inside the calorimeter are exposed to these high power (0-500 watt) signals. This problem was somewhat aided by converting shield G1 from A/C to D/C power while leaving the three aforementioned shields on A/C power.

In order to aid in noise elimination, the following two methods were implemented.

1. Analog filtering of the amplified T/C signal prior to digital sampling.

2. Digital filtering (off-line) of the stored T/C data for specific heat calculations. (At this point, digital filtering is not necessary for control since the final control strategy has not been implemented.)

Analog Filter Characterization

The analog filter chosen is one commonly used in reduction of high frequency noise superimposed on low frequency signals. It consists of a capacitor placed in parallel with the voltage to be read. This network

(commonly known as a low pass, or RC, filter) is shown in Figure 9. It can be shown using simple electrical theory that the LaPlace domain transfer function for this network is:

$$\frac{E_o}{E_I} = \frac{1}{1+R_L Cs} = \frac{1}{1+\tau_F S} \qquad 46$$

where

E_o = output voltage

E_I = input voltage

R_L = circuit resistance

C = capacitor value

$R_L C$ = network time constant (τ_F)

Selection of the capacitor value for use in the filter is critical since it determines the value of the filter time constant with a fixed line resistance. Its value must be selected so that the true process dynamics are unaffected while producing a maximum reduction in the noise level.

In the introduction to this chapter, three major sources of noise were set forth. Of these three, two have a definite frequency content of 60 Hz (A/C amplifiers and shields), while the other has a random frequency and amplitude. In order to examine the noise in the process signal to be sampled, a photograph (Figure 10) was made of an

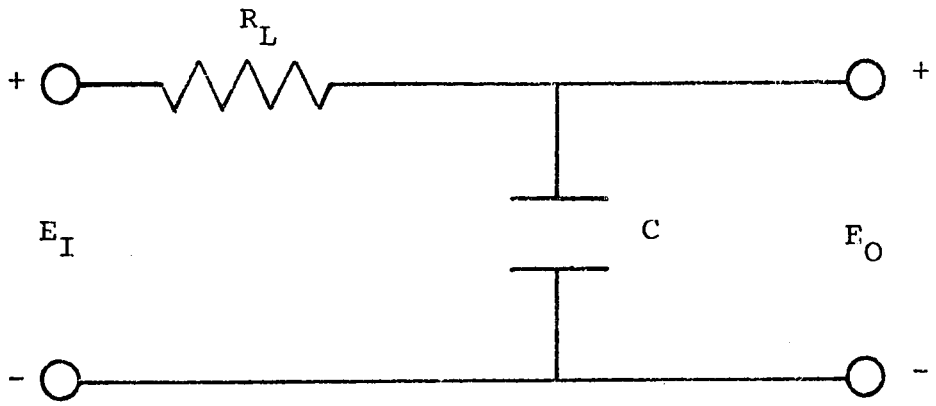


Figure 9. Low Pass Analog Filter Network

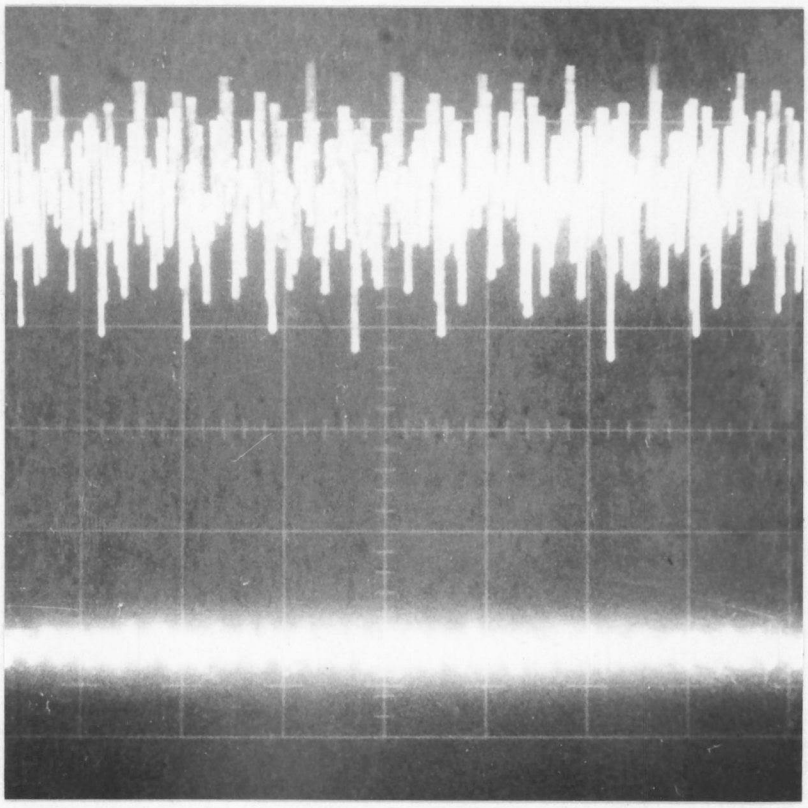


Figure 10. Oscilloscope Trace of the Noise Superimposed on an Amplified (Total Gain = 17500.) Thermocouple Signal.

amplified T/C signal. This amplified signal corresponds to a noise level of 15.7 microvolts in amplitude which is much greater than the desired accuracy of ± 1 microvolt ($\pm 0.1^{o}C$). Also, it is very interesting to note the major peaks along the time axis. These correspond to 16.6 milliseconds in cycle time which corresponds to 60 Hz. This confirms the suspicion that A/C pickup is a major part of the noise. Also, there are several minor random peaks which lie between these major 60 Hz peaks; therefore, noise frequencies of greater than 60 Hz exist. However, it is important to note that no periodic peaks occur with a cycle time greater than 16.6 milliseconds which indicates noise frequencies of less than 60 Hz do not exist. This leads to the conclusion that noise frequencies of 60 Hz should be filtered out. The low pass filter will do this.

In order to tie down the lower frequency boundary of the filter, it is necessary to examine the process. It can be shown (Appendix G) that under normal conditions, the overall transfer function between the temperature of any component and its input power is of the form (less dead time):

$$\frac{T(s)}{P(s)} = \frac{K_p}{S(1+\tau_p S)} \qquad 47$$

The filter to be used should not alter the dynamics of this

process.

A very powerful tool in analyzing processes of this type is that of a straight-line Bode plot (28, 29). Figure 11 is the magnitude plot for the process with (dashed curves) and without (solid curve) a filter. The vertical dashed line represents the 60 Hz frequency location. Figure 12 is the phase plot corresponding to the magnitude plot.

The filter location can be analyzed from these plots by considering each of the three possible locations indicated by Figures 11 and 12. These plots were constructed assuming a process time constant (τ_p) of 1.0 second. Actually, this value varies from 1 to 100 seconds depending on the shield and sample in question, but this value establishes the highest frequency contained within the physical process. The dashed curves in these Figures represent the addition of a filter to the raw process resulting in an overall system transfer function of:

$$\frac{T^1(s)}{P(s)} = \frac{K_P}{S(1+\tau_P S)(1+\tau_F S)} \qquad 48$$

(Note: The time constant is located on the Bode by its reciprocal. This point is called the "break" or "corner" frequency. With this in mind, it is important to note that as the time constant increases, the break frequency

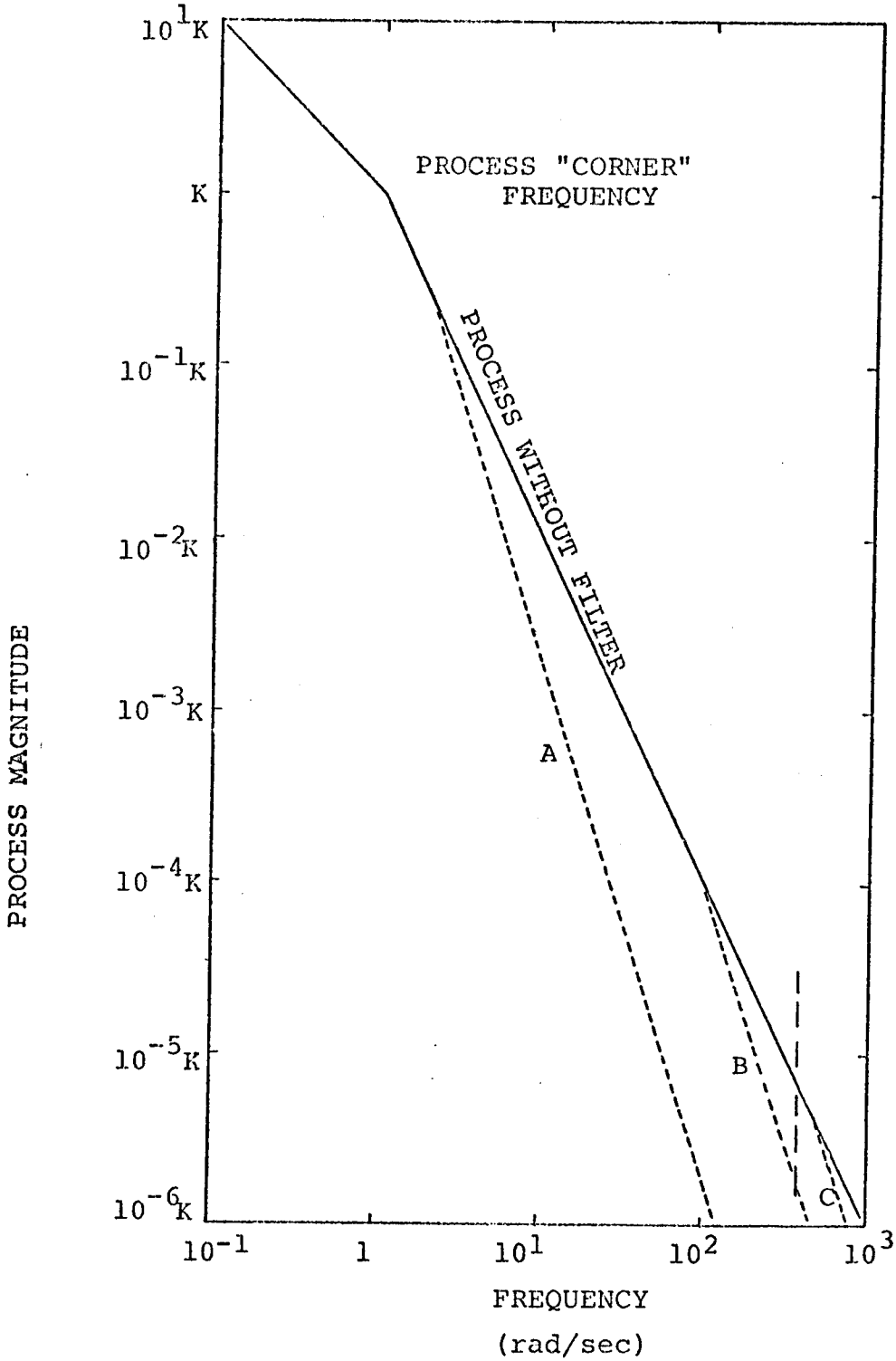


Figure 11. Straight-line Bode Magnitude Plot for Process.

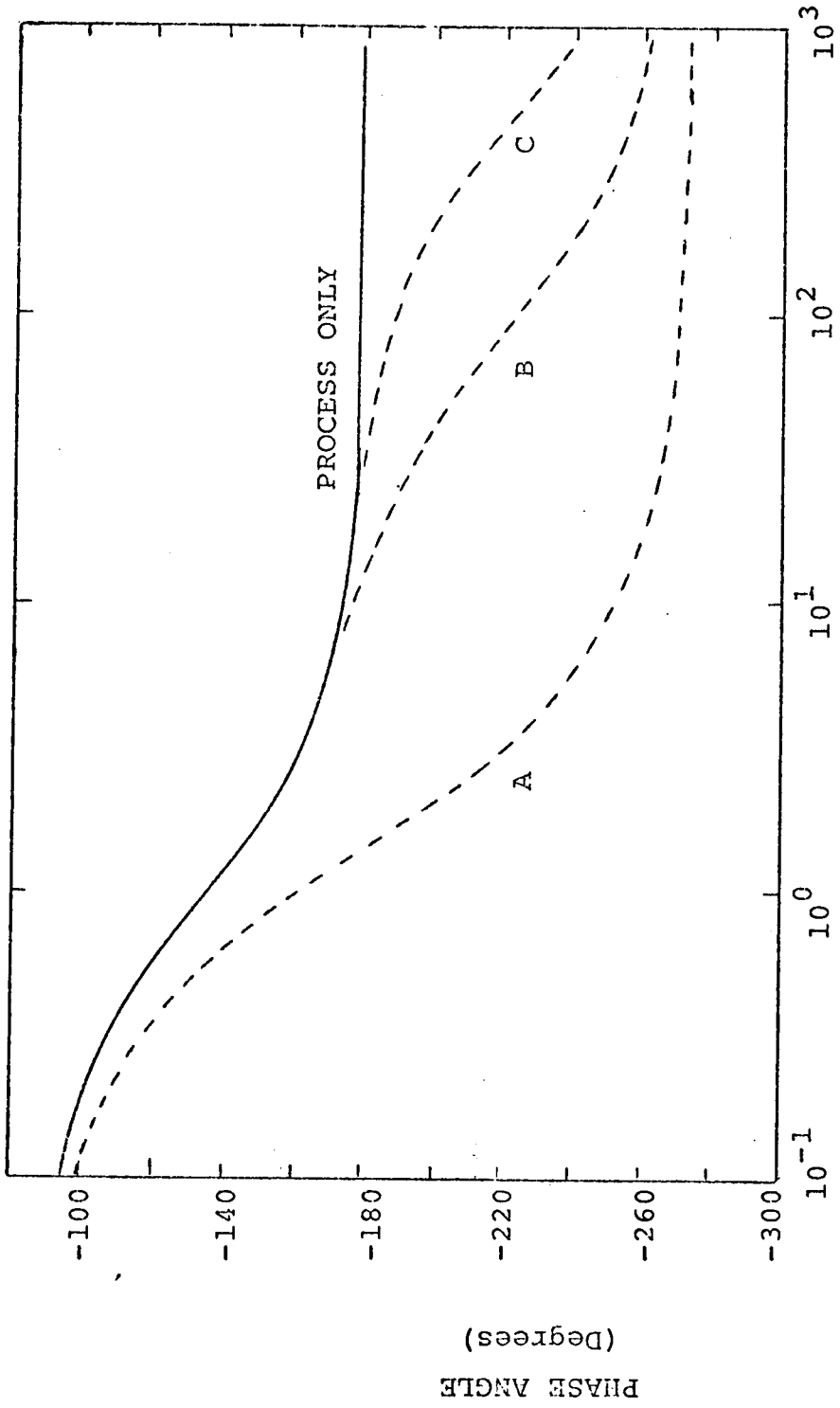


Figure 12. Phase Plot for Figure 11.

decreases or shifts to the left on the Bode plot.)

In order to accomplish the goals of (1) maximum attenuation of the 60 Hz A/C noise and (2) minimum attenuation of the process signal in the region of its break frequency ($1/\tau_P$), the filter time constant must be located on curve B of Figure 11. If it were increased, its break frequency ($1/\tau_F$) would shift to the left (curve A) and attenuate the process signal close to its break frequency. On the other hand, if it were decreased, the filter break frequency would shift to the right and a minimum reduction of the 60 Hz noise (represented by vertical dashed line) results. If τ_F were decreased below 2.65 milliseconds, the filter break frequency would lie to the right of the 60 Hz frequency and no attenuation of this frequency would be realized.

Another consideration is the effect of the filter on the apparent stability of the process. This can be seen by examining the phase plot (Figure 12). When the filter time constant is much less than the process time constant (curve C), the phase is unaffected in the region of the process. As the filter time constant approaches the process time constant (curve A), the phase decreases rapidly. Since the overall stability depends upon the phase remaining above -180° before the magnitude falls below unity, the

situation could arise in which the filtered process would show an apparent instability. This becomes particularly true when dead time is considered in the overall process. Dead time adds negatively to the phase, i.e.,

$$P_D = P_o - \omega\Theta \qquad 49$$

where

P_D = phase with dead time (degrees)

P_o = phase without dead time (degrees)

ω = frequency (radians/sec)

Θ = dead time

In order to demonstrate the attenuating phenomenon of the filter and provide some flexibility in the system, a variable capacitor (adjustable from 0 to 10 microfarads) was installed in parallel with the output of the amplified-suppressed T/C signal. The results of varying the capacitor value, i.e., the filter time constant, are shown in Table V. (This data was taken using a model 4243 digital voltmeter with the average output calibrated in RMS volts from 50 to 1000 Hz.) Table V verifies that as the filter time constant (capacitor value) is increased, the noise level is attenuated.

In order to complete the analog filter characterization, its dynamics must be investigated. This can be accomplished in one of two ways:

TABLE V

NOISE REDUCTION PRODUCED BY ANALOG FILTER

CAPACITOR VALUE (Microfarads)	RMS AMPLIFIED VOLTAGE (Millivolts)	T/C EMF (Microvolts)
0	85.0	4.86
1	36.5	2.09
2	22.8	1.30
3	16.1	0.92
4	13.4	0.77
5	10.4	0.59
6	8.9	0.51
7	7.7	0.44
8	6.6	0.37
9	6.0	0.34
10	5.2	0.30

1. Photographs of an oscilloscope trace of the filter output.

2. Sample filter output using the computer.

The second method seems far more attractive since large amounts of data can be collected, stored, and analyzed at any future time for any specific purpose.

The filter dynamics can be determined by bringing the process thermocouples to steady state, switching from one thermocouple to another at a different temperature, and collecting data as a function of time after switching. This constitutes a step input to a first order lag (filter) whose dynamics can be characterized by three parameters (25, 26, 27, 28): (1) gain, (2) time constant, and (3) dead time.

Physically, this was accomplished using program CAL1Ø (Appendix D) which selects a given T/C, waits a specified length of time (denoted by NTICK), reads the filter output, waits a long time to allow the output to come to steady state, and proceeds to the next T/C. By connecting the sample T/C to multiplexer channels 2, 4, 5, 6, 7 and 8 while grounding channels 1 and 3, step test data can be obtained from the first four channels and steady state noise data from the last four channels. (A step magnitude of 600 microvolts was used to enhance the accuracy of the dynamic data.) Data was taken at various times after relay closure and at various capacitor values.

Figure 13 depicts the step test data in normalized form. These curves should be, and indeed are, the typical response curves of a step input to a first order lag. Note that dead time does exist in this plot due to the finite amount of time required for the relay to close completely. (This phenomenon is more readily apparent in Figure 14, a typical photograph of the filter output after relay closure. Also, note the characteristic first order response.) When the capacitor value is zero, an instantaneous charge does not occur. This indicates capacitance in the system other than the one under study. (After conferring with the electronics shop, it was discovered that a fixed notch filter had been installed in the system to aid in 60 Hz noise elimination. This filter alone was completely inadequate in producing acceptable noise levels.)

In order to characterize the filter dynamics stated previously, it is necessary to examine Figure 13 in detail. First, the filter gain is equal to unity, i.e., the ratio of the filter output to the step input is one. Second, the apparent dead time (induced by relay closure) is approximately 0.017 seconds located by intersection of process curve with the time axis at a percentage response of 0.0. Finally, the last filter parameter is the time constant which should vary linearly with the capacitor value (equation 46). This is determined by locating the time required

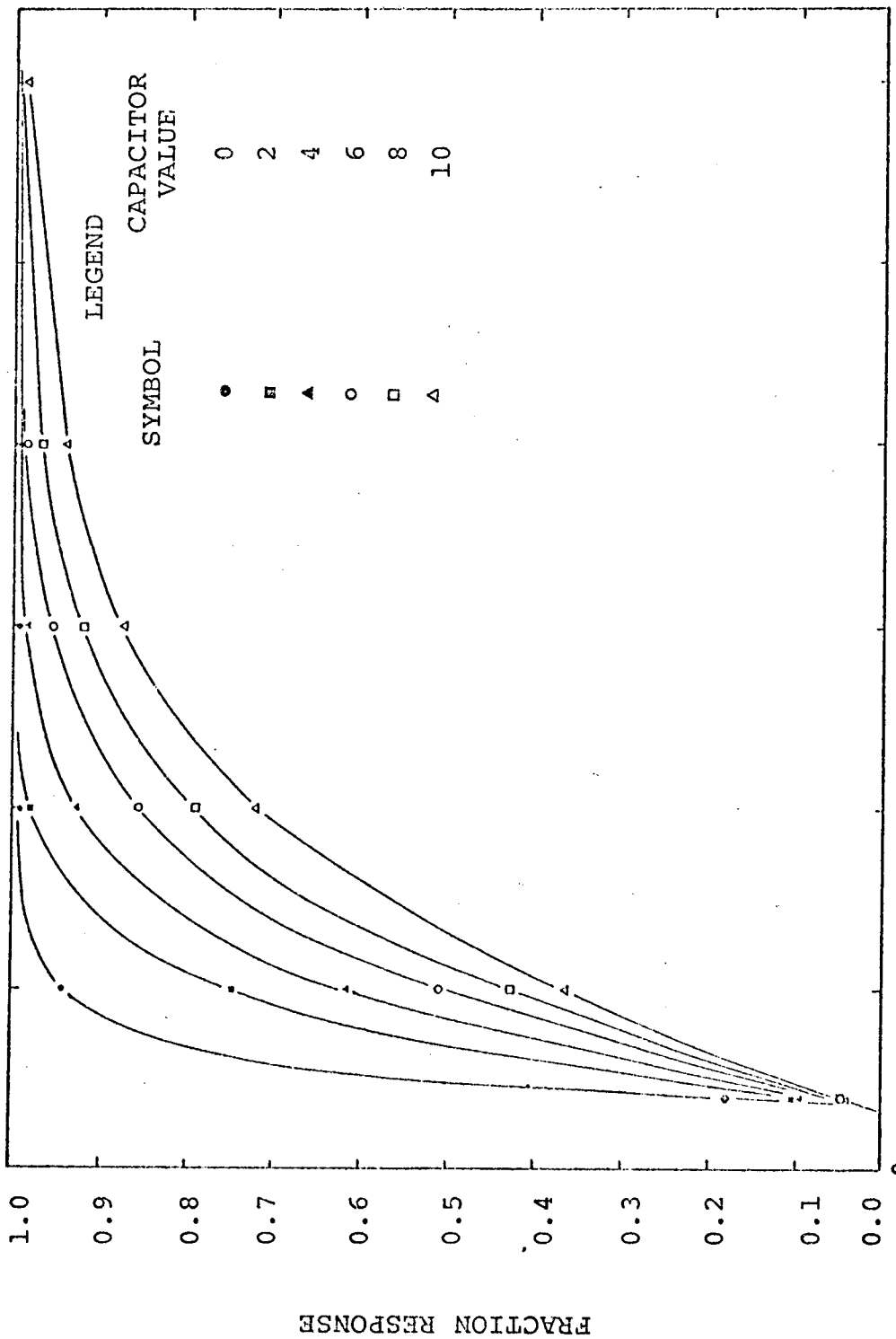
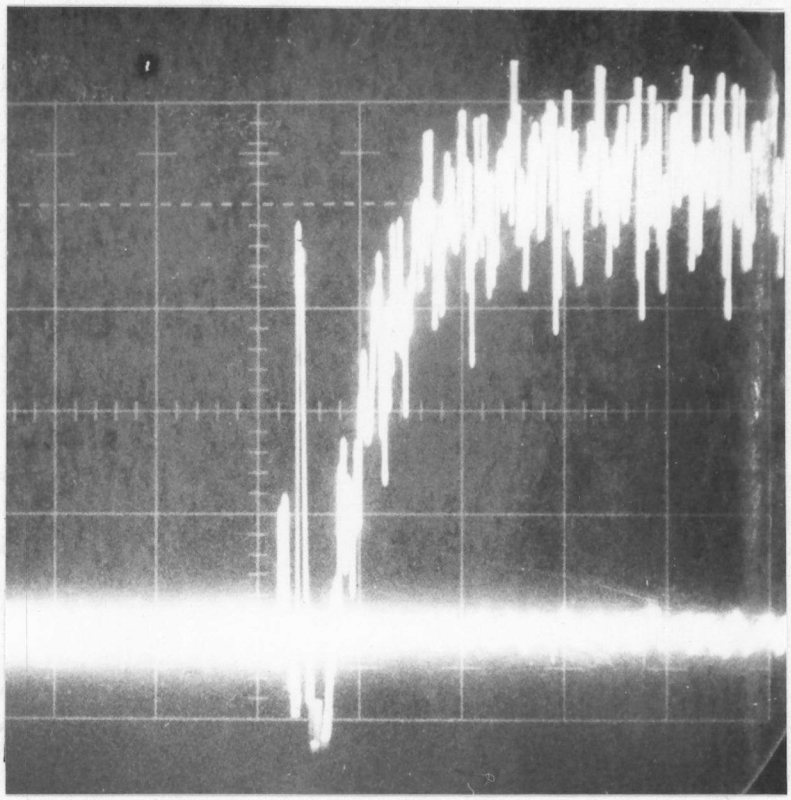


Figure 13. Normalized Step Test Data from Analog Filter.

VOLTAGE

(0.2 volts/division)



TIME

(20 milliseconds/division)

Figure 14. Oscilloscope Trace of a Step Input to the Analog Filter with a Total Amplifier Gain of 17500.

to reach 63.2% of the total response and subtracting the dead time. This was done using Figure 13 for each capacitor value. The result is plotted in Figure 15. Using least squares, a linear fit of

$$\tau_F = 0.005125\ C + 0.01245 \qquad 50$$

was obtained. By adding back in the dead time (θ), the time required to reach 63.2% of the total response is:

$$t_{0.632} = 0.005125\ C + 0.02945 \qquad 51$$

Knowing that the response of a first order lag plus dead time to a step input is governed by

$$\% \text{ Response} = \left(1 - e^{-\frac{t - \theta}{\tau_F}} \right) \times 100\% \qquad 52$$

for

$$\theta \leq t \leq \infty$$

and zero elsewhere, it is possible to calculate the time required to reach a given response level. The total time required to reach the 95% and 99% response levels are 3.0 τ_F and 4.6 τ_F respectively plus the dead time. Thus

$$t_{0.95} = 0.01535\ C + 0.05430 \qquad 53$$

and

$$t_{0.99} = 0.02360\ C + 0.07433 \qquad 54$$

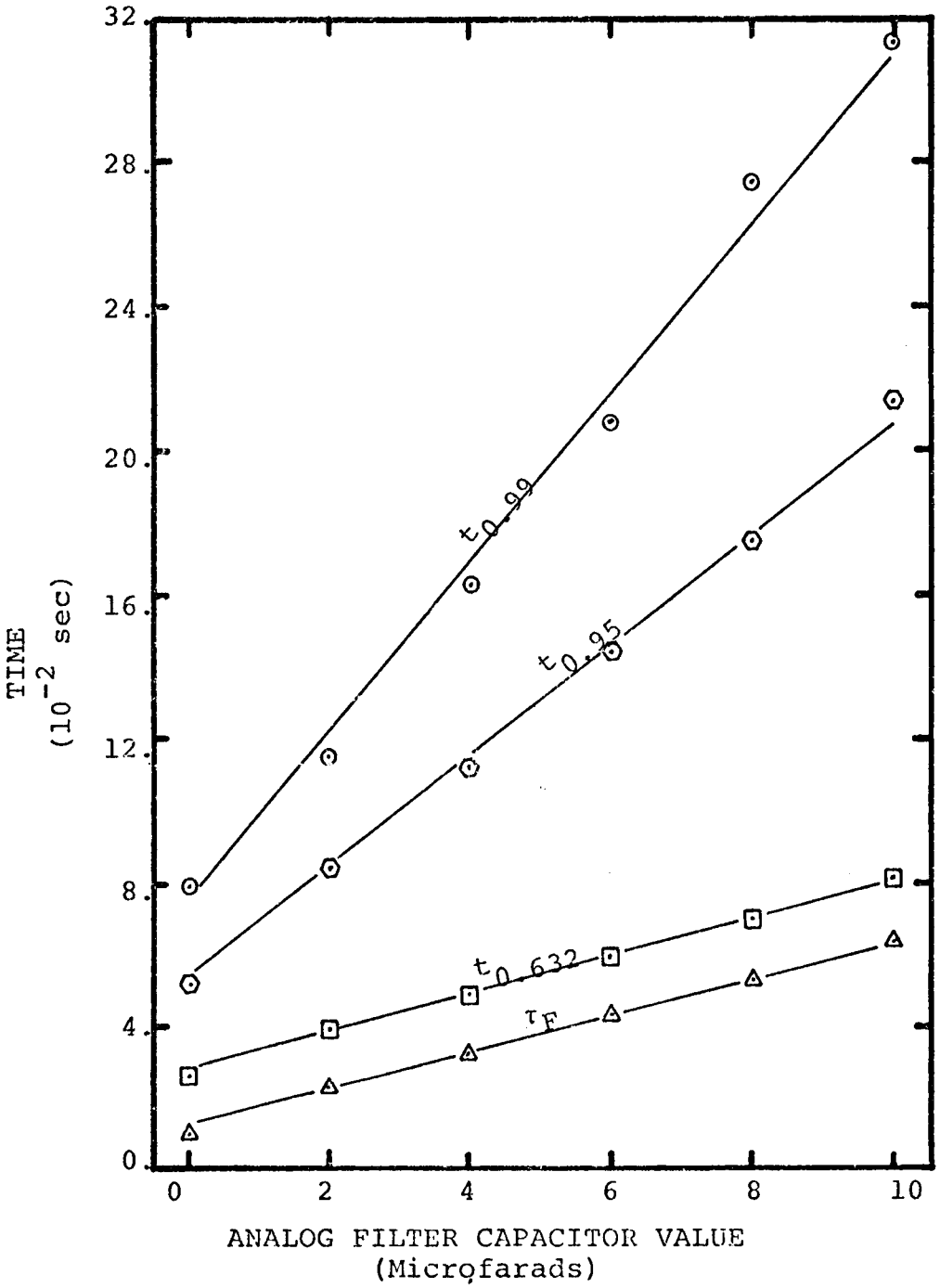


Figure 15. Time Required for the Analog Filter to Reach a Given Fraction of Total Charge as a Function of the Filter Capacitor Value.

These curves along with data points obtained from Figure 13 are also plotted in Figure 15. Disagreement between data and lines for $t_{.95}$ and $t_{.99}$ are mainly due to inability to precisely draw response curve (Figure 13). A change of 1% in response can mean a drastic time change; therefore, the predicted curves of equations 53 and 54 are more accurate than the graphically determined data.

This analysis enables the computer operator to select a desired level of response and know the amount of time necessary to reach that level with a given capacitor setting.

Having characterized the filter dynamics, it is now desirable to examine the noise level of the filter from digitally collected data. This was performed on the previous data set using the last four multiplexer channels which were at a steady state T/C signal. For each data set at a constant capacitor value (independent of time delay since all channels were connected to the same signal; therefore, charging of the filter was not a factor), the standard deviation and 95% probability limit were calculated from

$$95\% \text{ Probability Limit} = \text{Standard Deviation} \times t_{m;\ .025} \qquad 55$$

where

$t_{m;.025}$ = Student t value for 95% probability limit for m+1 data points

This limit yields the boundaries between which 95% of the data will fall centered around the mean. This limit for the digitally collected data is plotted in Figure 16 along with the same limit calculated from the RMS values listed in Table V. (For the analog data, it can be shown (Appendix H) that the RMS value is equal to the standard deviation; therefore, it is only necessary to use the normal distribution $Z_{.025}$ to convert the RMS value to the 95% probability limit.) It is interesting to note in Figure 16 that both the analog and digital noise decrease as the capacitor value is increased (time constant increased) which is the correct result. Also, both are in good agreement except at low noise levels ($\sim$ 1.5 microvolts). This is due to the ability of the voltmeter to continue to accurately read the voltage output, but the digital data becomes limited by the quantization error of the A/D converter. Ideally, this should approach the previously determined value of 0.125 microvolts, but due to inherent transmission line noise, it is only possible to achieve a value of 1.0 microvolts. This corresponds to 0.1^{o}C which is the reason for the observed digital accuracy listed in Table III, p. 49.

In conclusion it has been determined that as the filter time constant (capacitor value) is increased, the

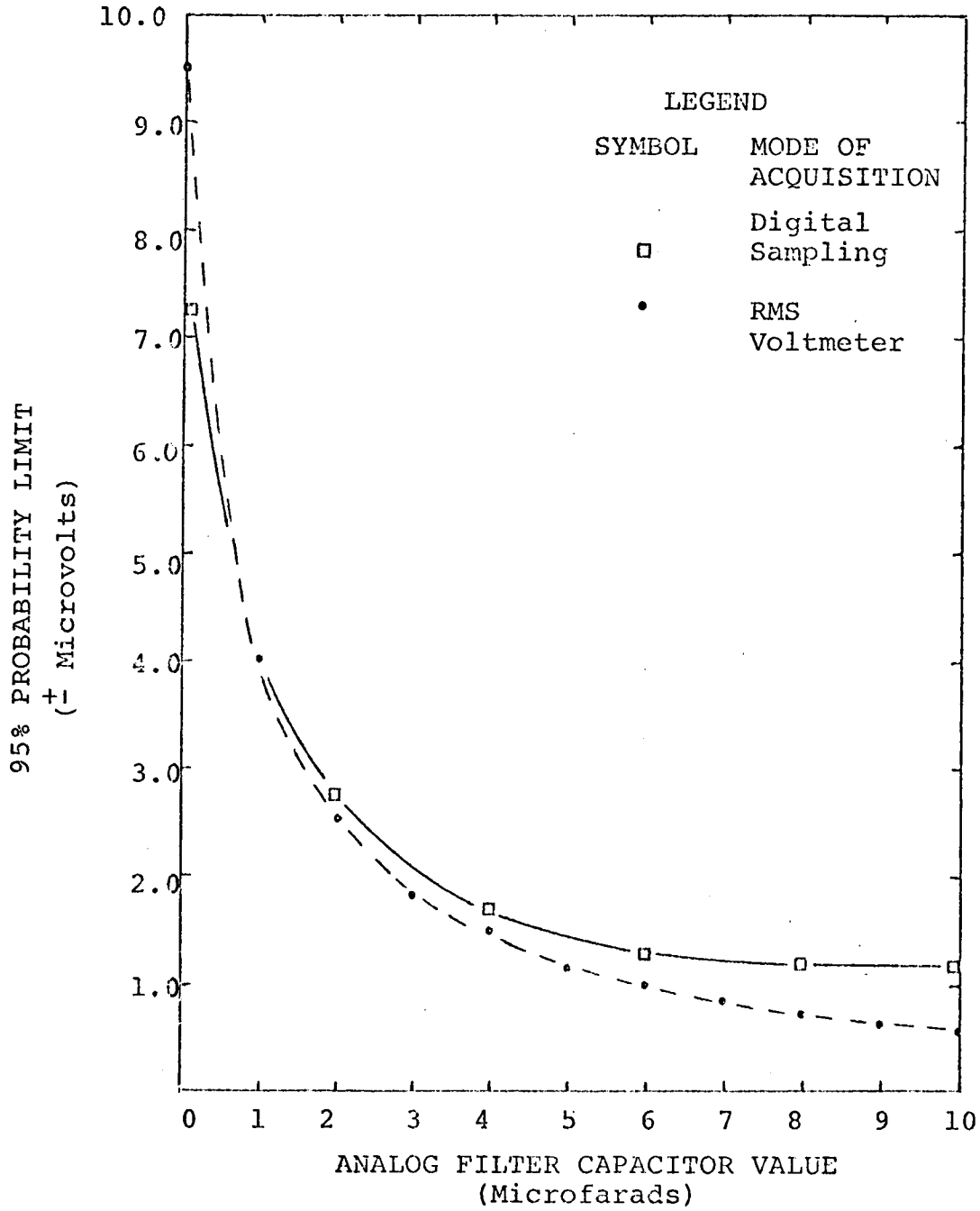


Figure 16. Noise Reduction Produced by Capacitor Used in Analog Filter.

noise level is considerably reduced, but the time required to reach a steady state output drastically increases. This produces a trade-off between computer time and sampling accuracy. In order to aid in this trade-off, a plot of the 95% probability limit for the digital data (from Figure 16) vs. time to a given percentage response (from Figure 15) was constructed (Figure 17). This figure graphically depicts the relationship between charge time and noise level.

Digital Filter Characterization

In order to determine the specific heat as accurately as possible, it is desired to obtain the utmost accuracy in temperature measurements as minimization of the errors in the temperature difference used to calculate the specific heat are critical (see Table III, p. 49). As stated in Chapter III, the method of least squares was employed to enhance the accuracy of the raw data. Although it performs admirably, it is highly susceptible to a large error in single data point. One sampled data point which deviates grossly from the true value can greatly influence the least squares fit (this is especially true of a bad point at the beginning or end of a data set). This error will be directly transmitted to the specific heat.

In order to minimize this effect, it is desired to develop a scheme by which data points with obvious errors

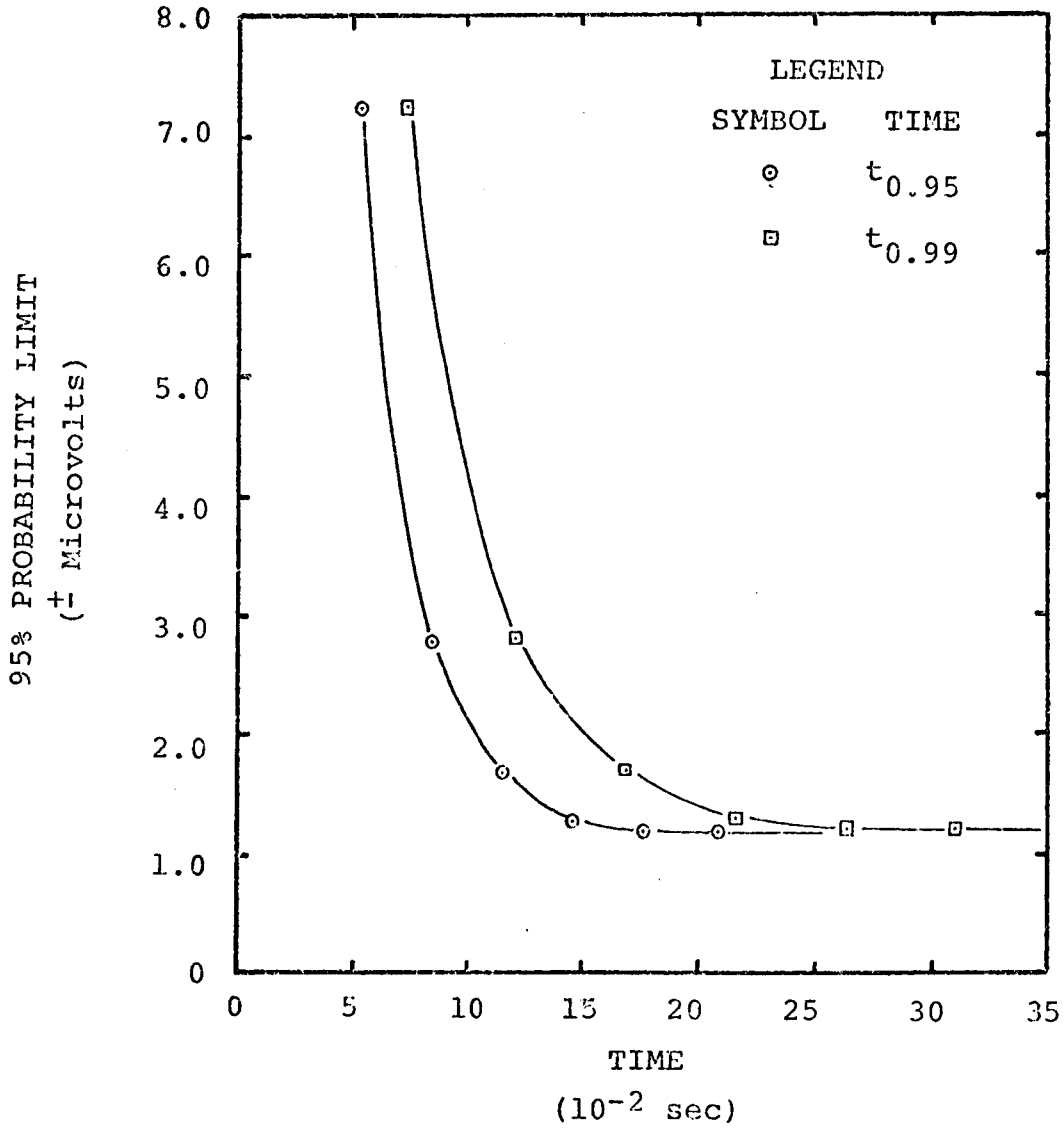


Figure 17. Pictorial Representation of the Trade-off Between Noise Level and Charge Time for the Analog Filter.

can be eliminated and replaced by a more realistic value. One such method would be that of plotting all the T/C data, discarding the bad points, and recalculating the specific heat based upon this "corrected" data set. This would be grossly time consuming. This method could be computerized by comparing the raw data to its least squares value, replacing the worst data points by its least squares value, and refitting the least squares. A more systematic approach (rather than this arbitrary exclusion of data points) is to once again filter the stored data with a discrete digital filter.

As with the analog filter, the digital filter should be a low pass filter. The sampled data is ideally a ramp with random noise. Also, process stability is not affected since all digital filtering will be done off-line on stored data. The filter will have an effect on the specific heat; therefore, this effect must be characterized.

The low pass discrete filter has the same starting point in the LaPlace domain as the analog filter, namely,

$$\frac{Y(s)}{U(s)} = \frac{1}{1+\tau_D S} \qquad 56$$

where

$Y(s)$ = filter output

$U(s)$ = filter input

τ_D = filter time constant

In order to use this filter, a discrete algorithm must be determined based upon standard digital procedures (27, 28, 29, 34, 35, 36, 37). This is accomplished by inserting the dynamics of a sampled data system and converting this to the discrete, commonly known as "Z", domain. Applying this procedure to equation 56 using Z transforms, the following discrete algorithm is obtained:

$$Y_i = \alpha Y_{i-1} + (1 - \alpha) U_{i-1} \qquad 57$$

where

Y_i = filter output at current sampling period

Y_{i-1} = filter output at previous sampling period

U_{i-1} = filter input at previous sampling period

$\alpha = e^{-T/\tau_D}$

T = sampling time

τ_D = filter time constant

In implementing this discrete filter, some interesting results were attained due to the nature of the data. Due to the extreme effect on the accuracy in the specific heat, the major methods of implementation will be discussed here.

The two major methods of implementing the digital filter are by treating the data as a ramp or a step. This is due to the fact that the T/C data increases linearly with time (Figure 18-A) which constitutes a ramp; but, if the

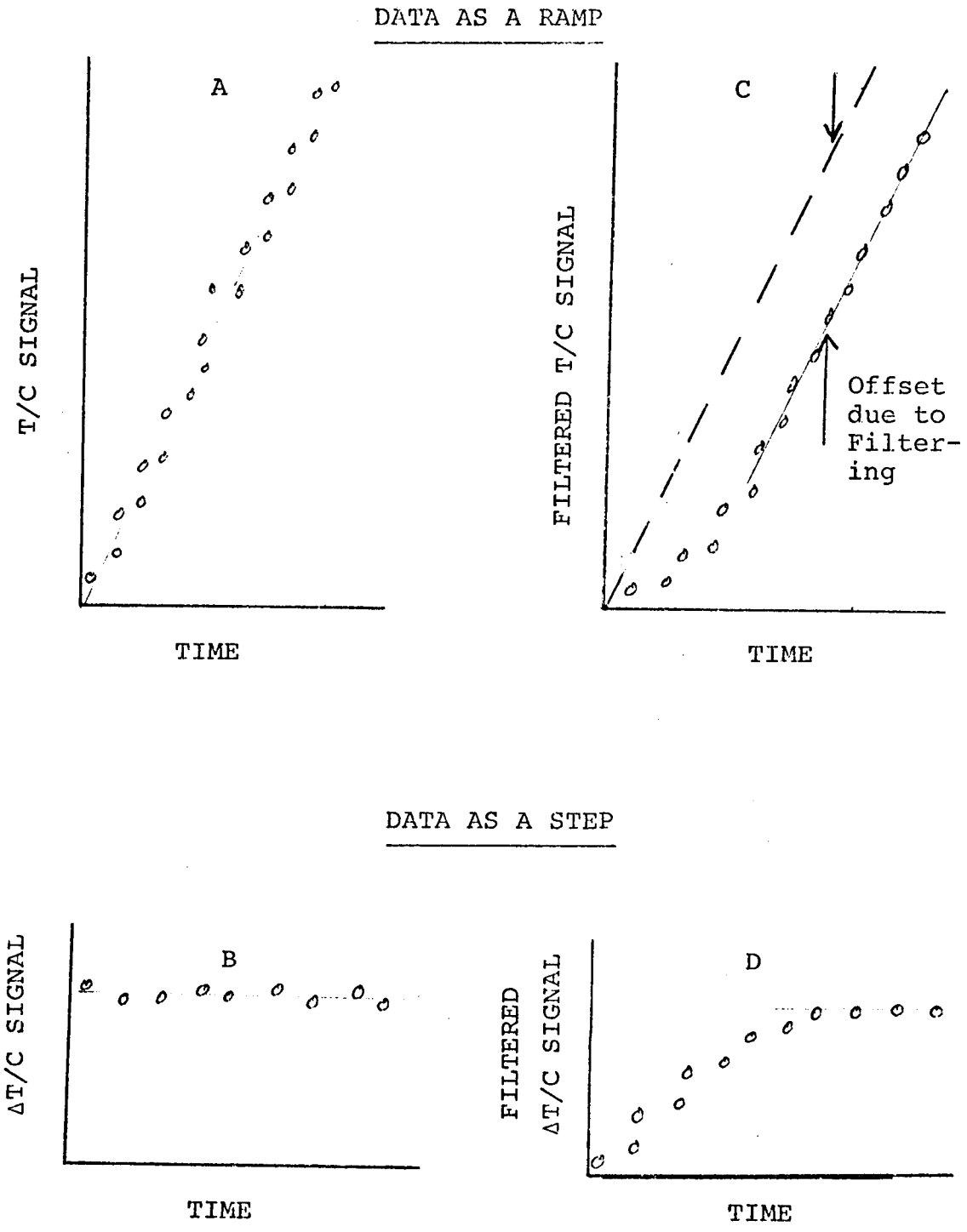


Figure 18. Thermocouple Data Presented as Sampled and as Differences with the Effect of Filtering.

differences between the data points are plotted (Figure 18-B) a step is observed. After filtering, the ramp data appears as depicted in Figure 18-C while the difference data appears as depicted in Figure 18-D. In order to determine the specific heat from the difference data, the filter output must be continually summed (this, in essence, reconstructs the ramp) in order to have the same appearance as Figure 18-C.

After filtering the raw T/C data, it is then necessary to fit this new data using least squares, determine the temperature difference from this fit, and calculate the specific heat. In order to prevent inaccuracies in the determination of the other variables used in the specific heat calculation, the filter study was conducted by using only the temperature differences (ΔT) to be used in the specific heat calculation.

When this procedure (filtering, least squares fitting, and determining temperature difference) was applied to the raw data, the following results were obtained. Figures 19, 20 and 21 display the ΔT as calculated from the raw unfiltered data, data filtered as a ramp, and the data filtered as differences (step) respectively. All have a filter time constant of ten times the sampling time (10T). It is immediately obvious that the filtered data offers no improvement over the raw data. This is contrary to known

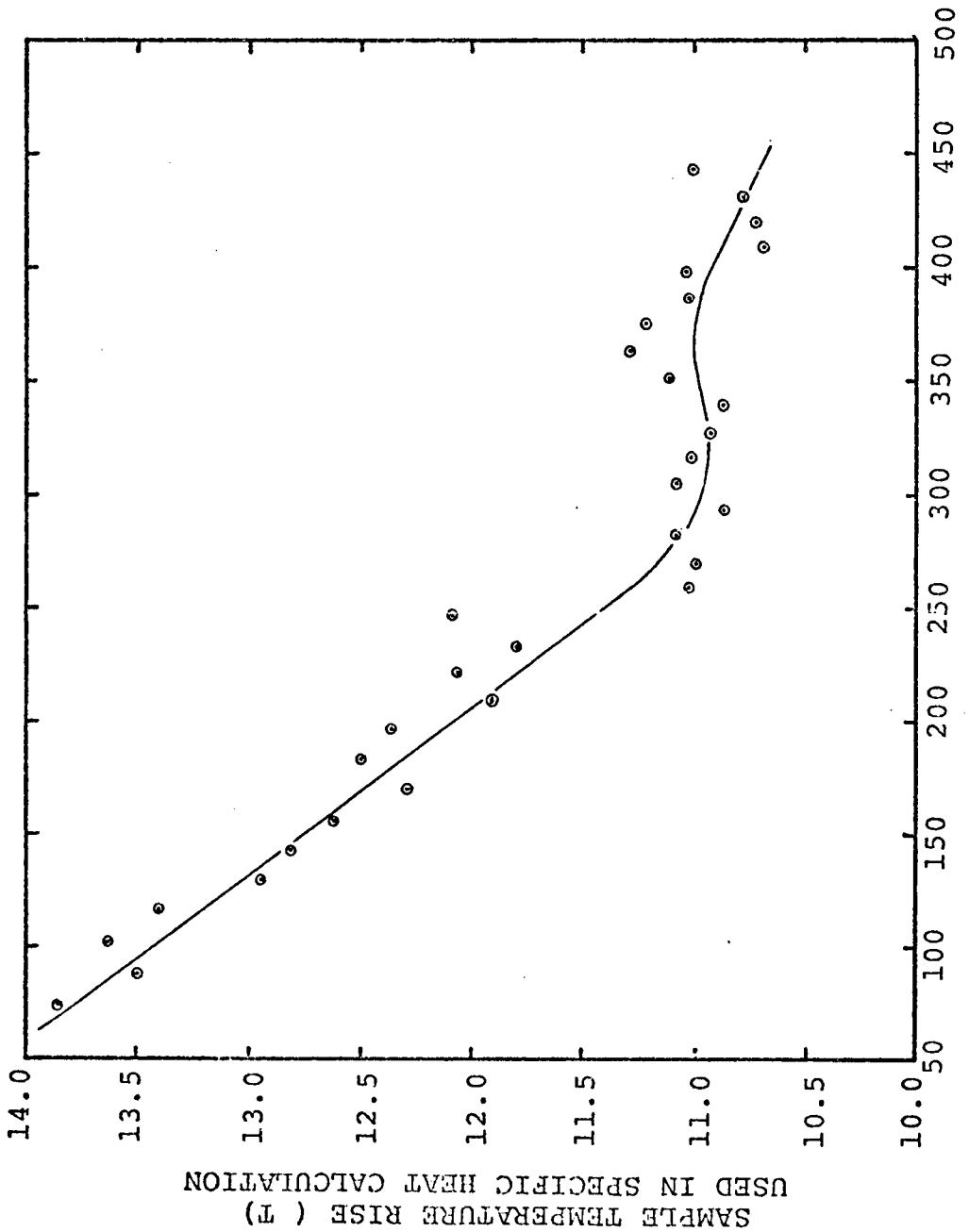


Figure 19. ΔT Data Obtained Using Unfiltered Process Data.

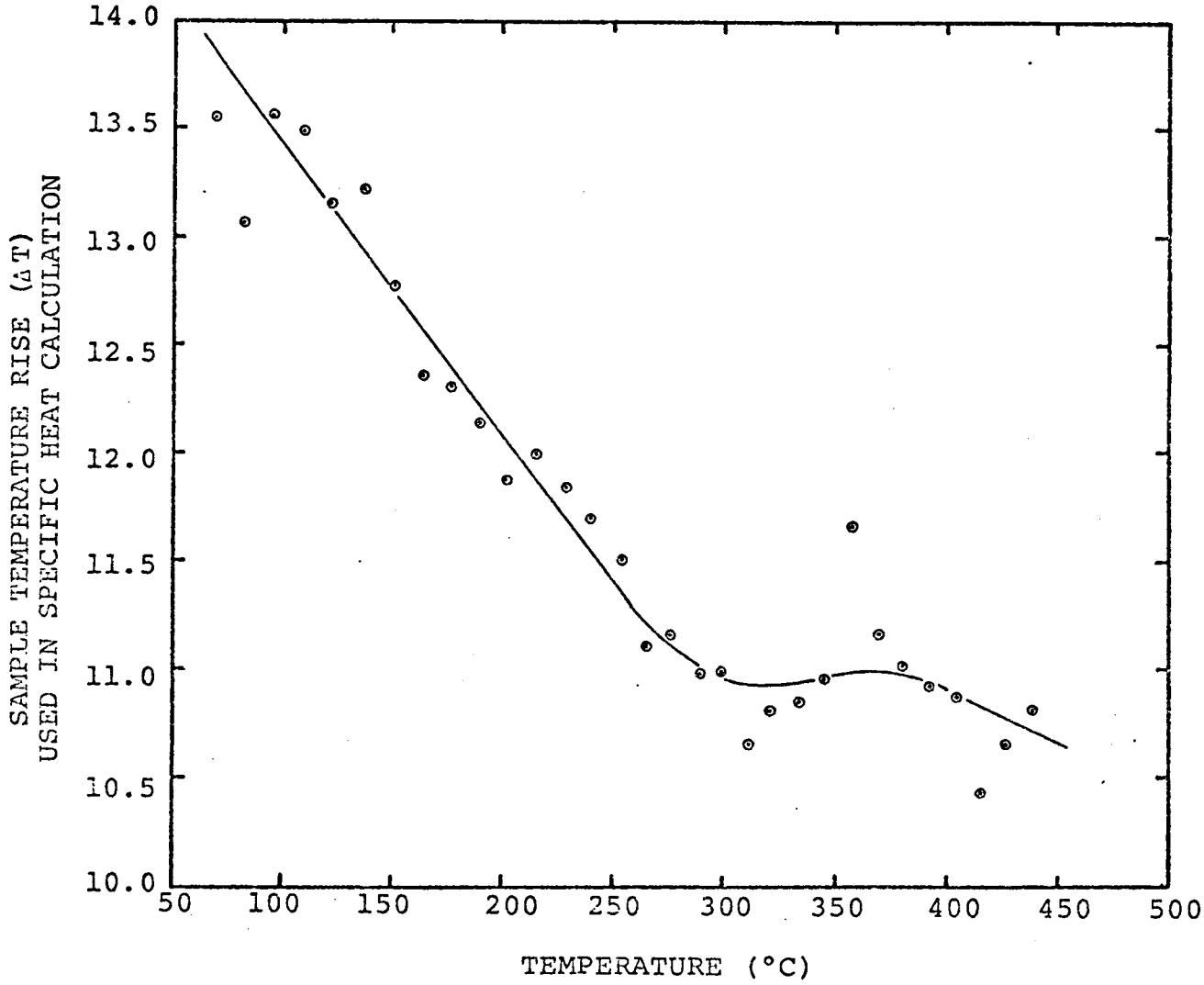


Figure 20. ΔT Data Obtained by Filtering T/C Data as a Ramp with τ_D=10T and Integer Filter Output.

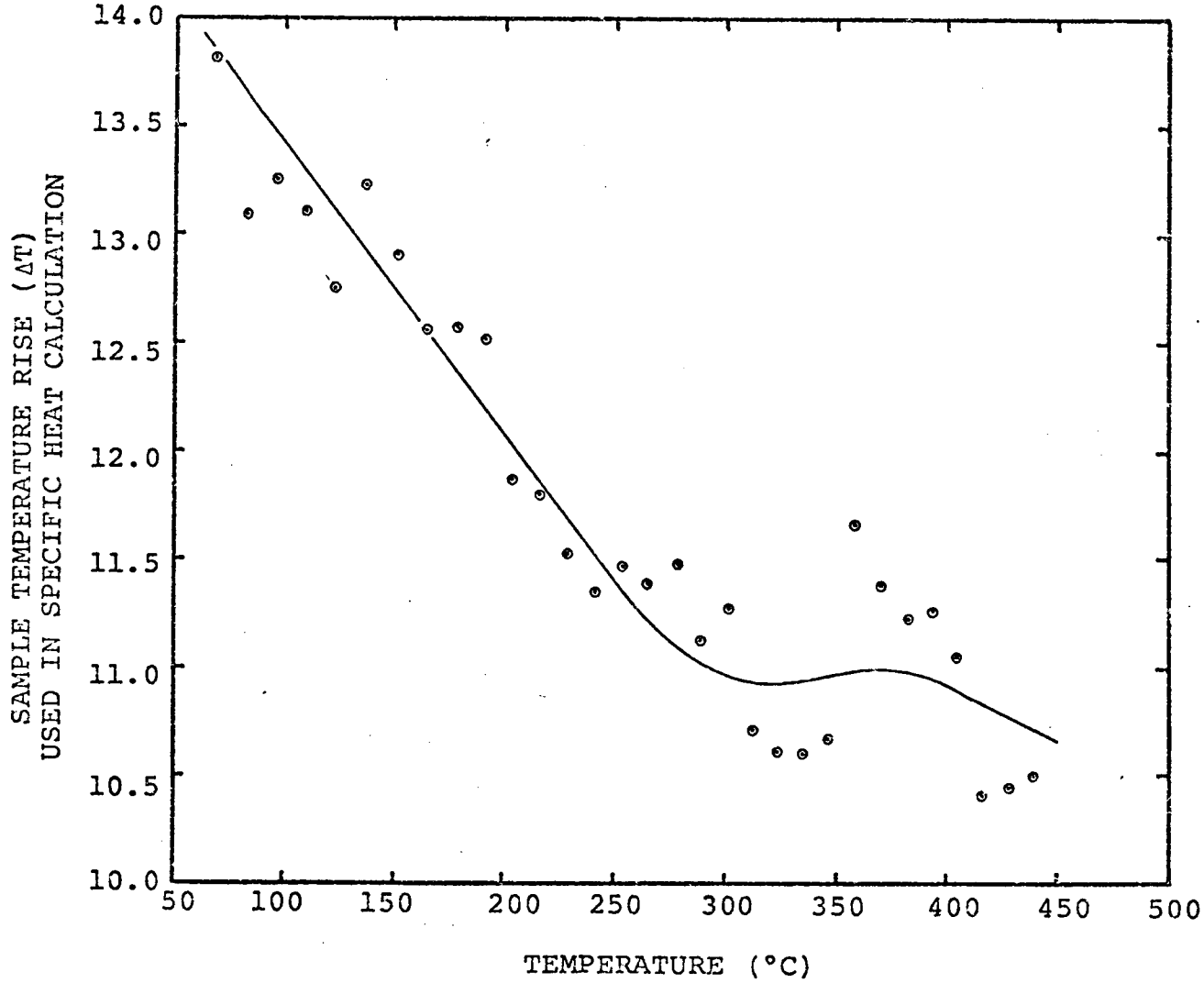


Figure 21. ΔT Data Obtained by Filtering T/C Data as Differences (Step) with τ_D=10T, Integer Filter Output and Zero Initial Condition.

theoretical results.

Upon a detailed examination of the filtered data, the reason for this apparent dilemma became obvious. In order to maintain compatability with the sampled data which are integer values, the filter output was also treated as an integer. This severely degraded its performance. The filter program was changed so that the filter output was real and this real output data was truncated in order to regain program compatability. The results of this procedure appear in Figure 22. This plot is indeed smoother (less noisy) than the ΔT's as determined from the raw data (Figure 19). It is also important to note that filtering of the data as a ramp or as a step produced identical results.

One outstanding disadvantage of this filtering method is the amount of shift in absolute temperature that occurs due to the nature of the filter. It can be shown (Appendix I) that the steady state error between the actual ramp data and the filtered ramp data using a first order filter (depicted in Figure 18-C) is equal to $K\tau$ (product of the slope of the ramp and the filter time constant. This effect can be greatly minimized by filtering the difference data and specifying a non-zero initial condition for the filter output. The result of this procedure appears in Figure 23. By examining the last data point in Figure 19,

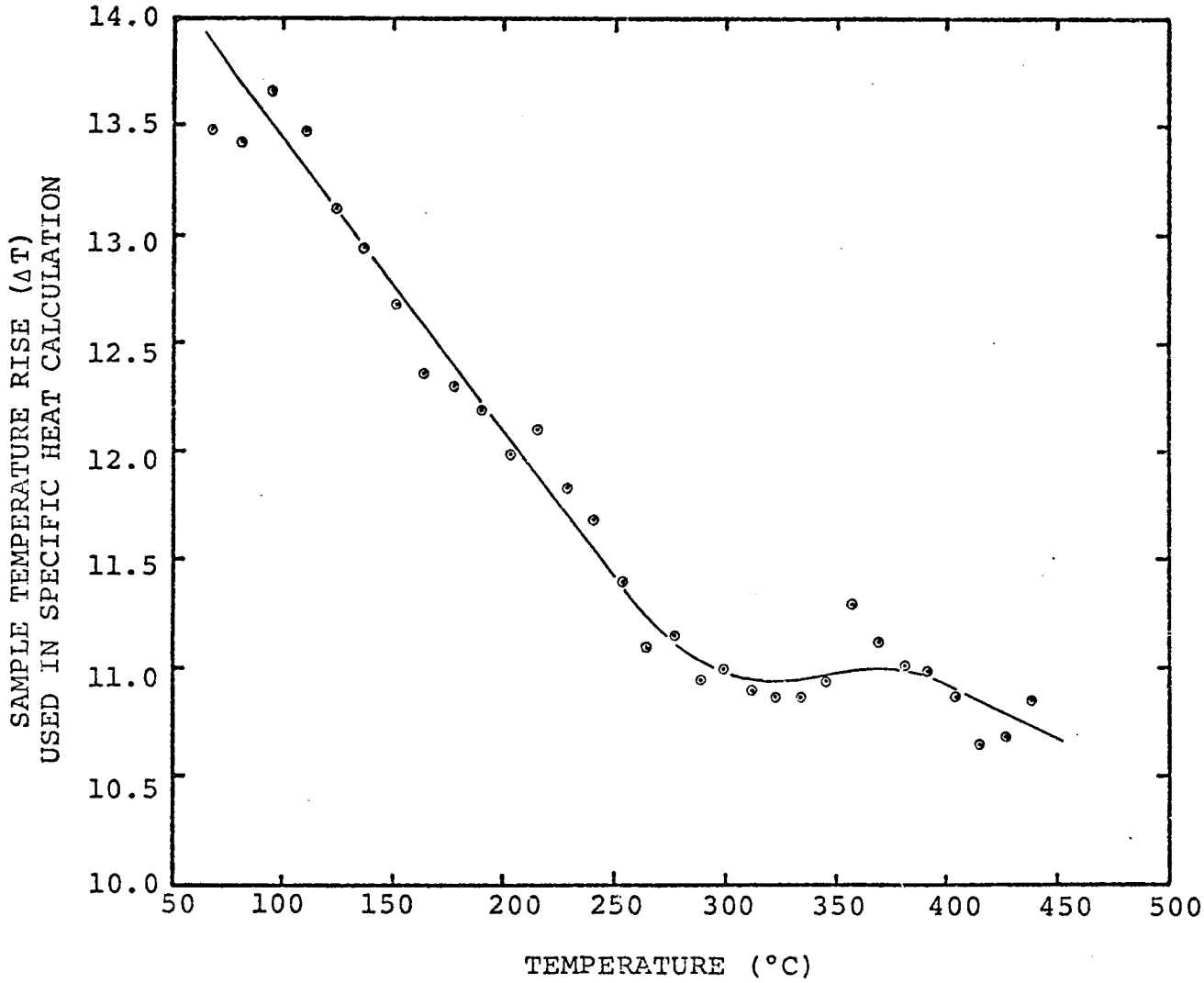


Figure 22. ΔT Data Obtained by Filtering T/C Data as a Ramp or Step with τ_D=10T, Floating Point Filter Output, and Zero Initial Condition for Step.

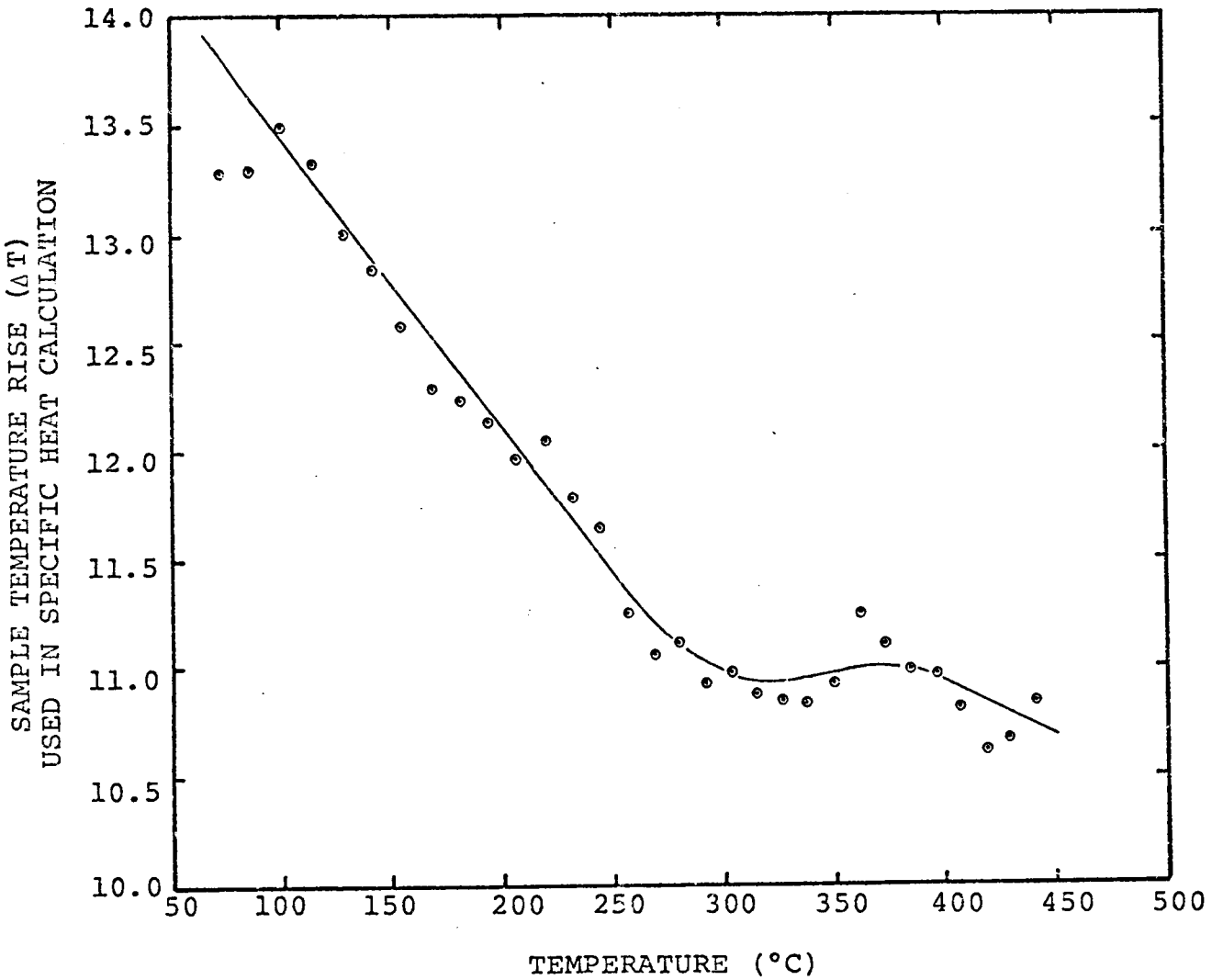


Figure 23. ΔT Data Obtained by Filtering T/C Data as a Step with τ_D=10T and Non-zero Initial Condition.

22 and 23 for the raw data, filtered data with zero initial condition, and filtered data with a non-zero initial condition, it is obvious that the shifting in Figure 22 ($\sim$5°C) has been greatly reduced in Figure 23 ($\sim$0.5°C) for the last data point.

The one remaining variable necessary to complete the digital filter characterization is the proper time constant. This variable will affect the smoothness and shift in the data. For this purpose the data was filtered as a step using zero initial condition (to dramatize the shifting effect) with filter time constants of 4, 10, 20 and 40 times the sampling period (T). The results of this test appear in Figures 24, 21, 25 and 26 respectively. As expected the data becomes increasingly smoother with greater leftward shift as the time constant increases. This increasing smoothness also presents a problem since inaccuracies in the specific heat can actually be introduced. For example, if the time constant were infinite, α in equation 57 would become unity, and all the output data from the filter would be equal to the initial filter value and independent of the sampled data.

In conclusion, the digital filter shall be a first order low pass filter given by equation 56 in the LaPlace Domain and equation 57 in the discrete domain. In order to minimize shifting in absolute temperature, the filter will

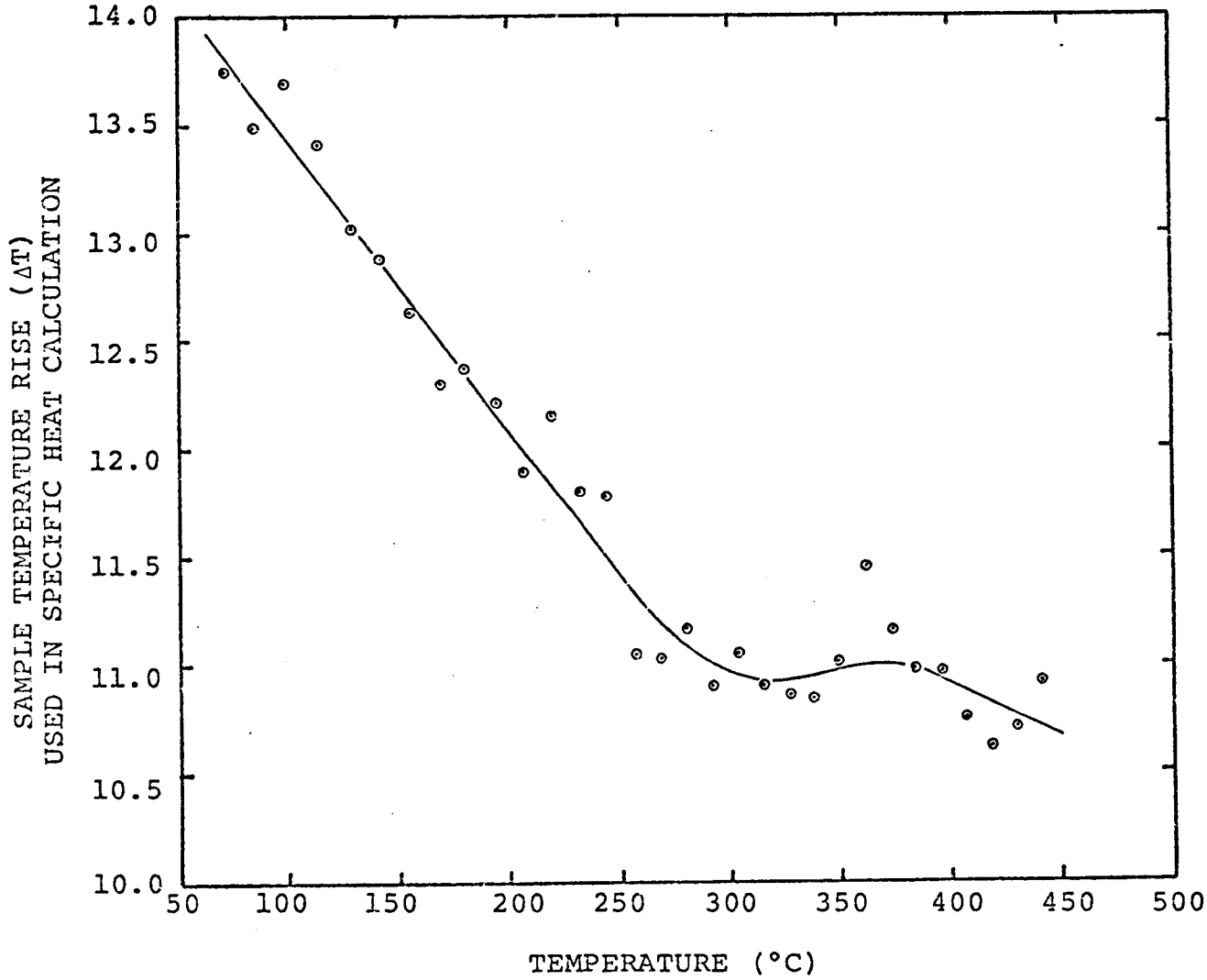


Figure 24. ΔT Data Obtained by Filtering T/C Data as a Step with $\tau_D=4T$ and Zero Initial Condition.

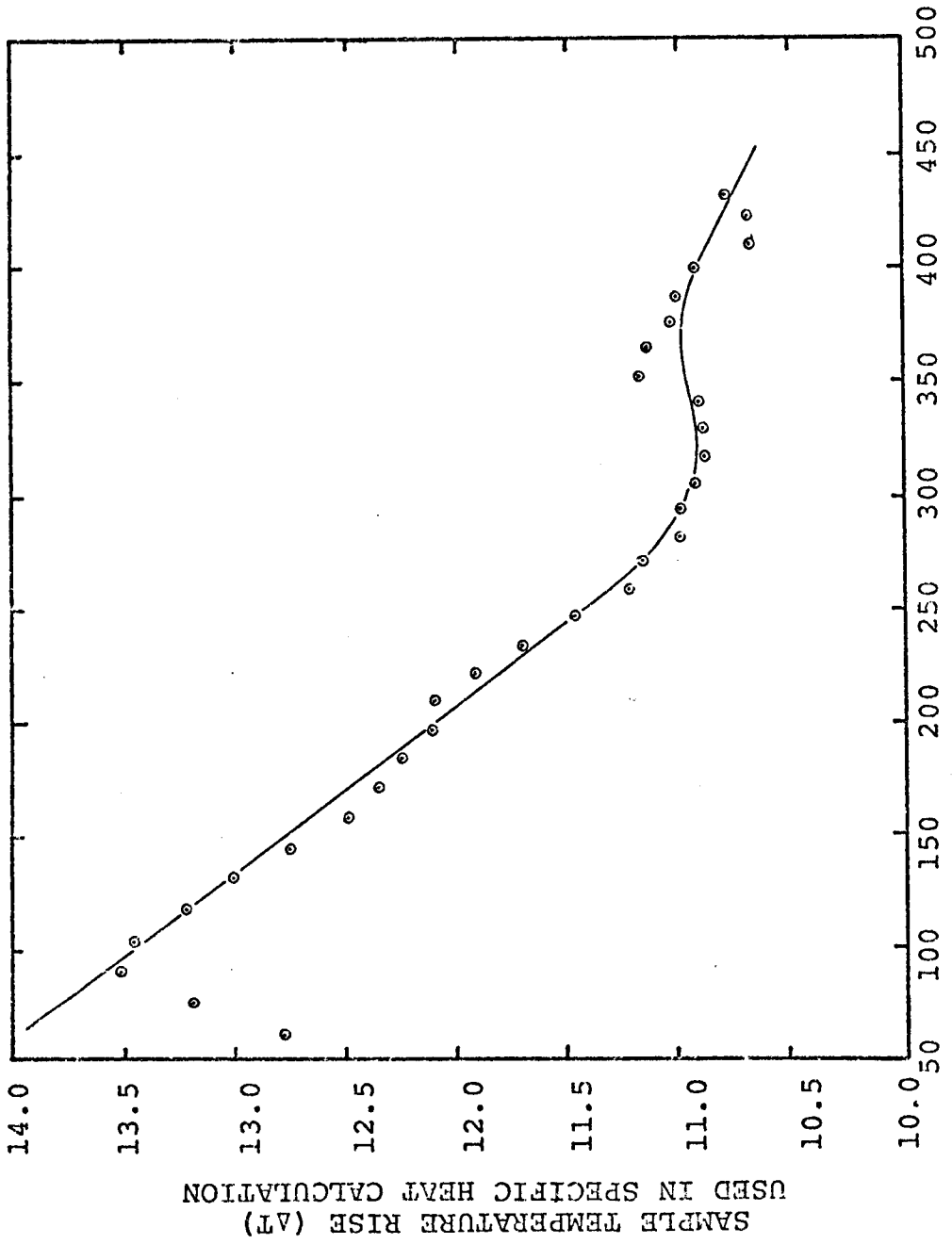


Figure 25. ΔT Data Obtained by Filtering T/C Data as a Step with τ_D=20T and Zero Initial Condition.

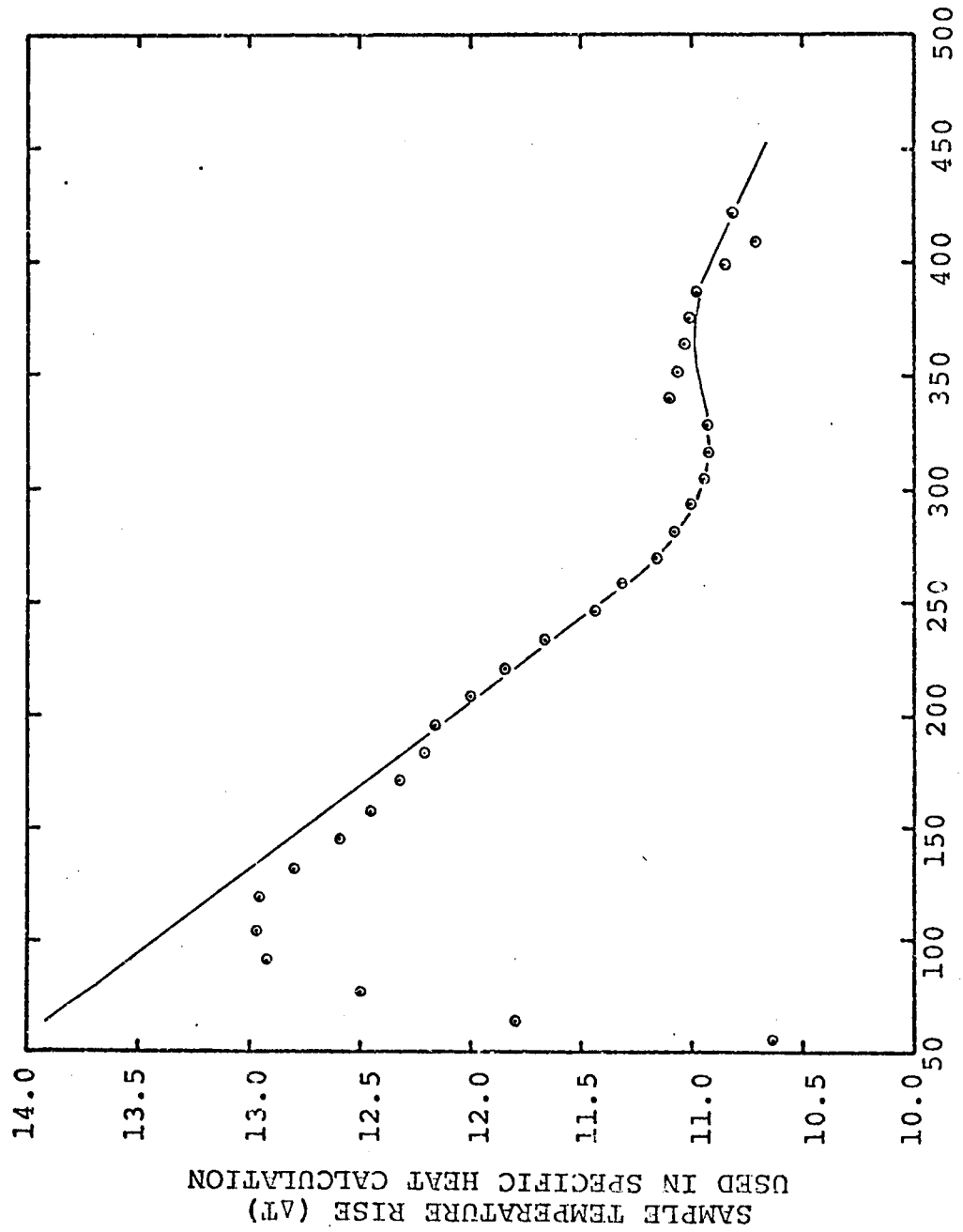


Figure 26. ΔT Data Obtained by Filtering T/C Data as a Step with τ_D=40T and Zero Initial Condition.

be applied to the differences between successive sampled data points with a non-zero initial condition for the filter. The filter time constant should be less than or equal to ten times the sampling period in order to prevent altering the actual specific heat values. The program necessary to accomplish this appears in Appendix D as RADFR.

CHAPTER V

DETERMINATION OF THE SPECIFIC HEAT OF TITANIUM

In order to demonstrate the practicality of the data acquisition system developed in Chapter III and the filtering techniques developed in Chapter IV, this system was used to determine the specific heat of titanium over a moderate temperature range (350^{o} to 850^{o}K). (This temperature region has adequate control using analog equipment. At higher temperatures, this control deteriorates and affects the accuracy in the specific heat; therefore, temperatures of up to 1300^{o}K were not attempted since control inaccuracies would have produced apparent data acquisition inaccuracies at this elevated temperature.)

The data was obtained using a total sample mass of 144.1702 grams (titanium sample, 139.8466 grams; heater, 4.3236 grams). An average power supply of 6.0 watts was supplied which yielded an average sample heating rate of 4.0^{o}K/minute. A T/C data point was taken every 7.00 seconds and the specific heat was calculated after 20 point intervals. This corresponds to a specific heat calculation every 140.00 seconds or approximately every 9.2^{o}K. The analog filter capacitor was set at 6 microfarads; therefore, a pause of 0.25 seconds was used to allow

attainment of a steady state output (see Figure 15).

Figure 27 is the specific heat of the total sample (titanium and heater) as determined from the raw digitally collected data (filter constant = 0). Visual observation indicates this is an extremely good data set with an apparent accuracy of $\pm$0.25 joules/gm-mole-^{o}K. This data was fitted using the method of least squares according to the functional equation

$$C_p = a + bT + cT^{-2} \qquad 58$$

where

a, b and c = constants

C_p = specific heat (joules/gm-mole-^{o}K)

T = temperature (^{o}K)

(The program to accomplish this appears as LSTSQ in Appendix D.)

The result is:

a = 24.275

b = 0.00881

c = -204376.

with a sum of squares of deviations (difference between actual value and least squares predicted value) for the 52 points equal to 0.8989. This corresponds to a 95% probability limit of $\pm$0.2695 joules/gm-mole-^{o}K, or approximately $\pm$1.0% based upon the average specific heat value

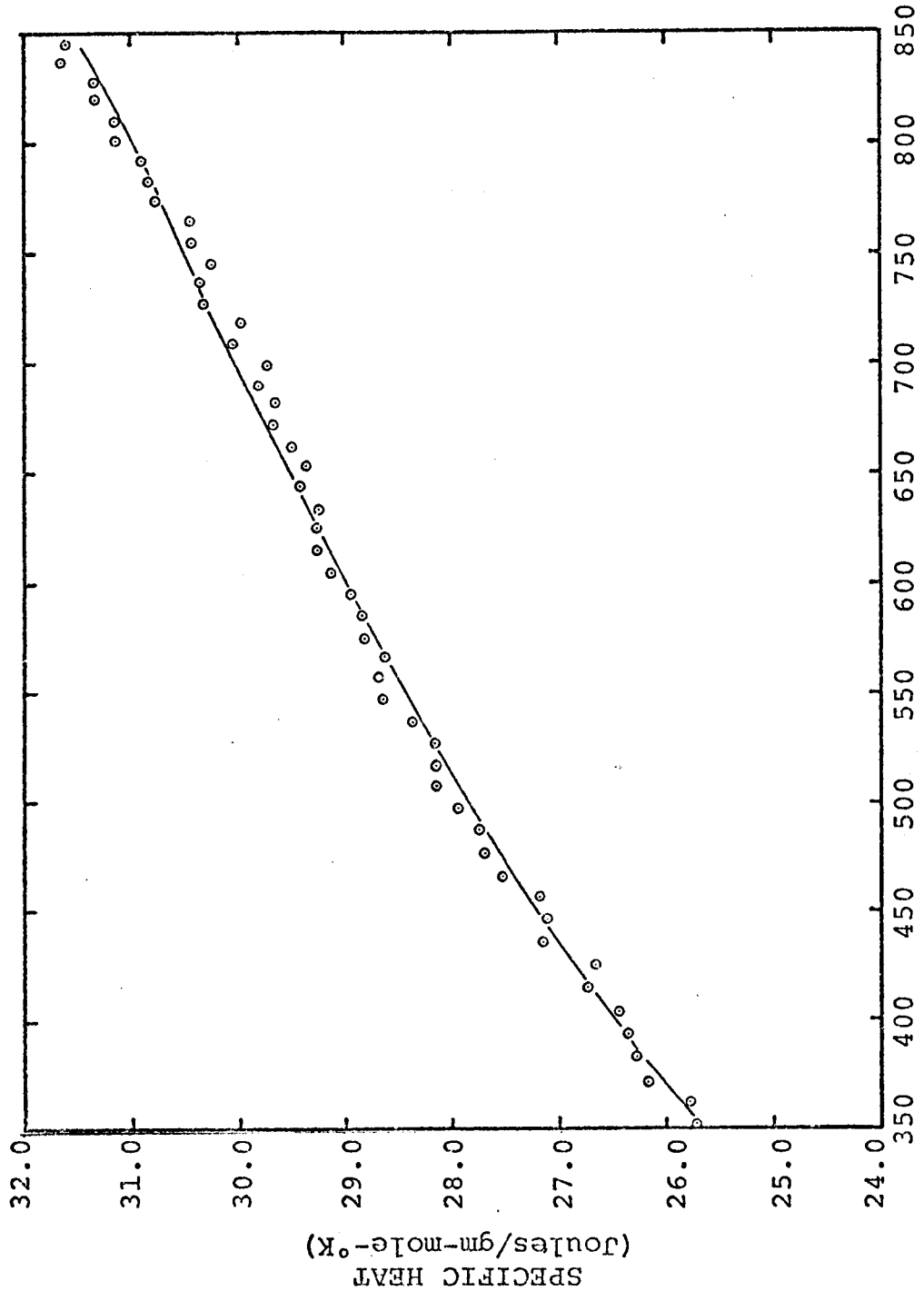


Figure 27. Specific Heat Data for Titanium Sample Obtained Using Unfiltered Data with Its Least Squares "Best Fit" Curve.

of 28. joules/gm-mole-^{o}K. This value in accuracy is comparable to that predicted in Table III, p. 49, and certainly within the desired goal of 1-2%.

In an attempt to enhance this accuracy, the methods of filtering characterized in Chapter IV were employed, but it was immediately obvious that digital filtering introduced errors into the specific heat data. This effect was demonstrated by plotting (Figure 28) the specific heat as determined using a digital filter time constant of 20 times the sampling period along with the least squares fit equation for the unfiltered data. A noticeable upward shift of the specific heat values (approximately 2%) occurs in the range of 375^{o} to 425^{o}K. This much induced error is entirely unacceptable; therefore, further characterization of the digital filter is required.

Supplemental Characterization of the Digital Filter

Due to the dramatic error produced by the digital filter, specific heat plots using numerous filter time constants were made and compared to that obtained using unfiltered data (Figure 27). As the digital filter time constant was increased, two predominant effects were noted:

1. The specific heat data became increasingly smoother.

2. The upward shift of the specific heat in the

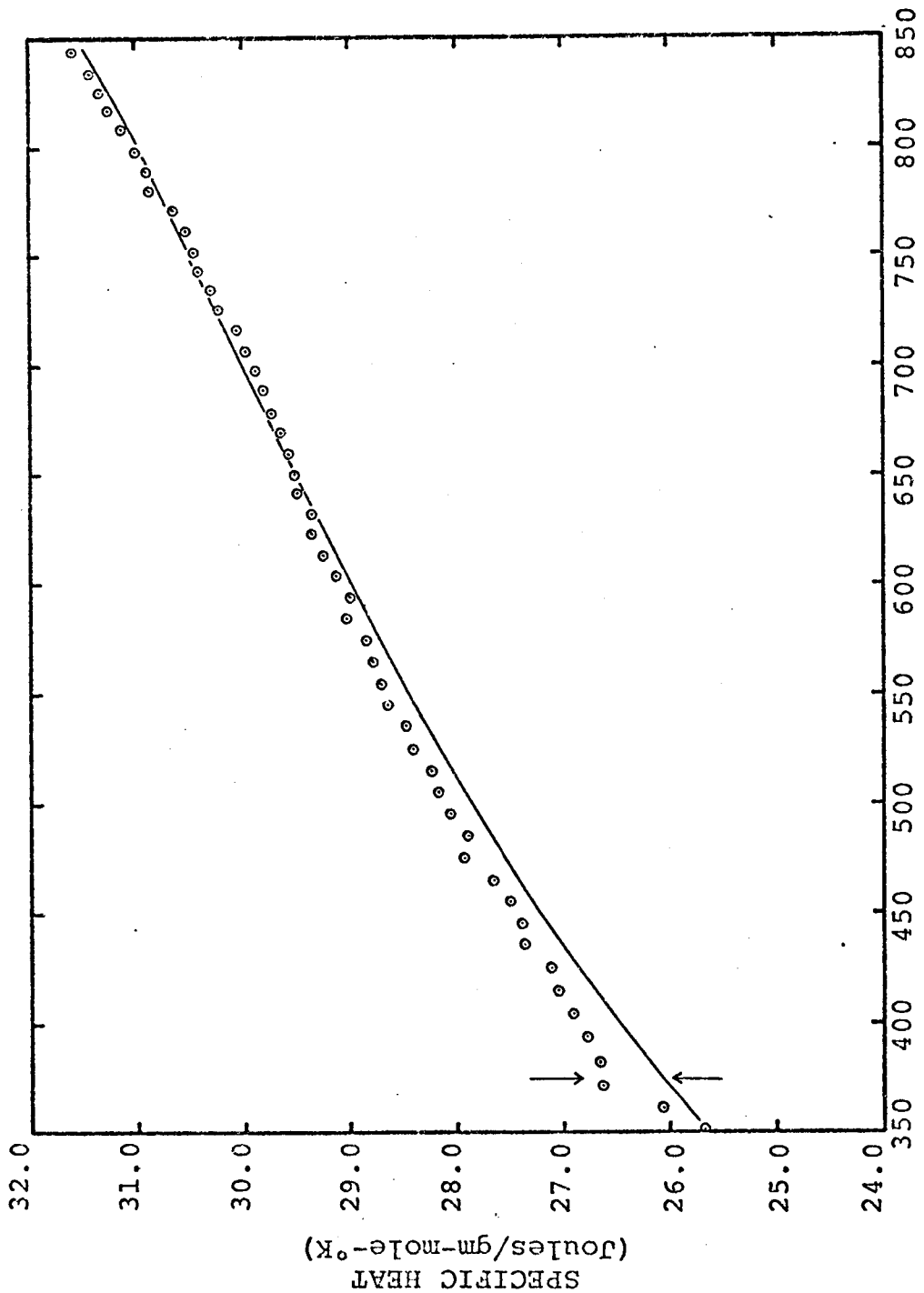


Figure 28. Specific Heat Data for Titanium Sample Obtained Using $\tau_D=20T$ with the Least Squares Curve for $\tau_D=0$.

region of 375° to 425°K became increasingly larger. This observation suggests that a trade-off between data smoothness and filter-induced error exists.

In order to quantify this trade-off, each specific heat data set (determined from various digital filter constants) was fitted to the form of equation 57 and the sum of the squares of deviations between the actual data point and least squares predicted point was calculated. This result appears in Table VI with the sum of the squares of deviations also appearing as curve A in Figure 29. It is very important to note here that the sum of the squares of deviations was calculated using:

$$SSD_{LS} = \sum_{i=1}^{N} (C_{P\,\tau_D} - \hat{C}_{P\,\tau_D})^2 \qquad 59$$

where

SSD_{LS} = sum of the square of deviations

$C_{P\,\tau_D}$ = actual specific heat calculated using a digital filter constant equal to τ_D

$\hat{C}_{P\,\tau_D}$ = specific heat value predicted from equation 58 using the constants in Table VI for a digital filter constant of τ_D

N = number data points (here N=52)

As expected, the data does become increasingly smoother (SSD decreases) as τ_D is increased. Next the upward shift in the specific heat was characterized by comparing the specific heat predicted from equation 58 for $\tau_D = 0$

TABLE VI

LEAST SQUARES FIT OF SPECIFIC HEAT DATA
OBTAINED USING VARIOUS DIGITAL
FILTER TIME CONSTANTS

Digital Filter Time Constant *	Least Squares Predicted Constants **			SSD_{LS} ***
τ_D	a	b	c	
0	24.275	0.00881	-204376.	0.8989
3T	24.165	0.00891	-180800.	0.7757
4T	24.079	0.00902	-172044.	0.7303
5T+	24.154	0.00891	-174844.	0.6840
7T	24.312	0.00872	-183996.	0.6713
10T	24.217	0.00880	-166316.	0.6512

* Integer number of sampling periods

** From equation 58

*** From equation 59

\+ Optimum filter time constant

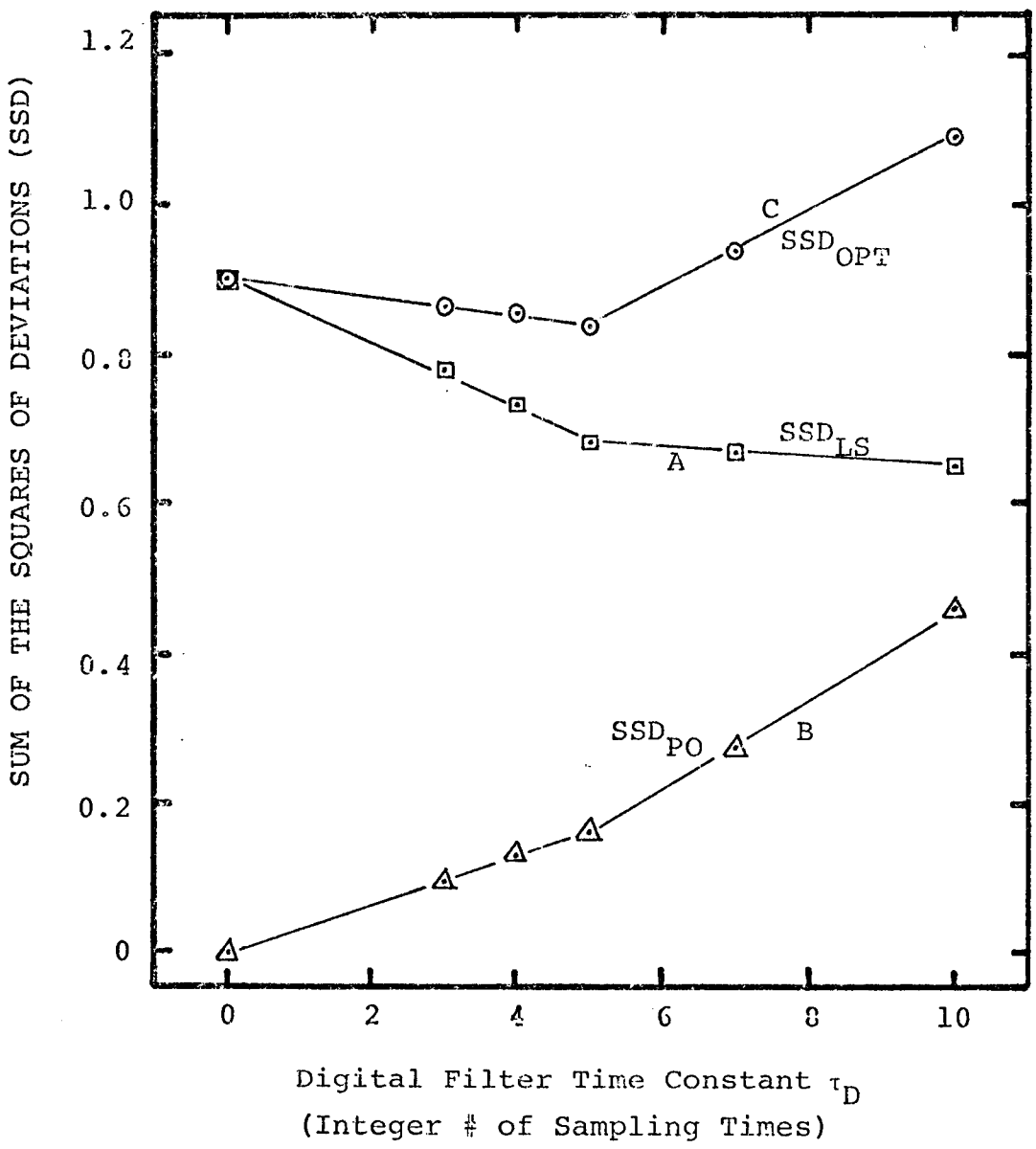


Figure 29. Determination of Optimum Digital Filter Based on Various Types of Prediction Errors.

(denoted by $\hat{C}_{P_o}$) and the specific heat predicted from equation 58 for various values of τ_D (denoted by $\hat{C}_{P\,\tau_D}$). Mathematically, this is represented by

$$SSD_{PO} = \sum_{i=1}^{52} (\hat{C}_{P\,\tau_D} - \hat{C}_{P_o})^2 \qquad 60$$

This result appears as curve B in Figure 29 and demonstrates that as τ_D is increased the filtered data shifts more and more away from the raw unfiltered data, i.e., SSD_{PO} increases. These two plots (curves A and B of Figure 29) lead to the calculation of one more error. This plot (curve C of Figure 29) was calculated using the sum of the squares of deviations between the actual specific heat data for a given filter time constant (denoted by $C_{P\,\tau_D}$, the same as in equation 59) and the least squares predicted value from equation 58 for τ_D equal to zero (denoted by $\hat{C}_{P_o}$, the same as in equation 60). Mathematically, this is represented by:

$$SSD_{OPT} = \sum_{i=1}^{52} (C_{P\,\tau_D} - \hat{C}_{P_o})^2 \qquad 61$$

This curve passes through a minimum, thereby quantitatively establishing the digital filter time constant necessary to maximize smoothness in the specific heat data while minimizing filter-induced error.

The optimum digital filter time constant is equal to five times the sampling time. It is interesting to note

here that not only does a sharp break occur in curve C (SSD_{OPT}) to establish this minimum, but also definite break points occur in SSD_{LS} and SSD_{PO} at this same value (break determined by the intersection of two linear lines). In the case of SSD_{LS}, the data smoothness increases rapidly up to the optimum filter value and then more slowly thereafter. In the case of SSD_{PO}, the diversion of the filtered data away from the raw data occurs gradually up to the optimum filter value and then much more rapidly thereafter. Also, it should be noted that this value of the filter time constant (5T) is such that the filter settling time (20T, or four times the time constant) is exactly equal to the number of data points used in the linear regression for calculation of the specific heat (see Chapter III, page 61). This could be either coincidental or blatantly obvious as the optimum filter value.

The Specific Heat of the Titanium Sample Using Digitally Filtered Data

The specific heat as determined from data obtained from the digital filter using the optimum digital filter time constant of five times the sampling time is presented in Figure 30 along with the least squares "best fit" curve. (The constants used in this curve are found in Table VI.) The sum of the squares of deviations (also in Table VI) was 0.6840 which is equivalent to a 95% probability limit of

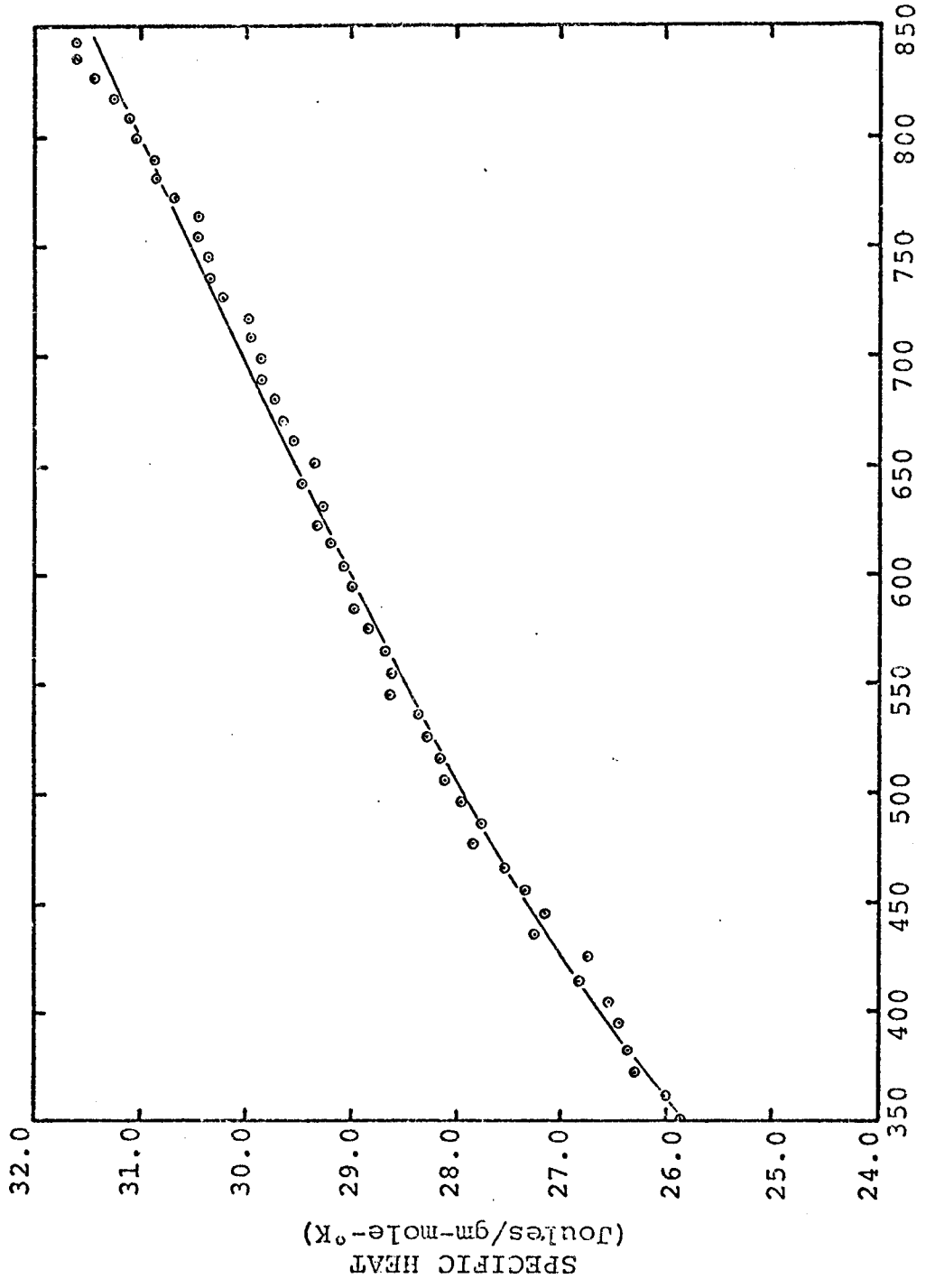


Figure 30. Specific Heat Data for Titanium Sample Obtained Using $\tau_D=5T$ with Its Least Squares "Best Fit" Curve.

$\pm$0.2351 joules/gm-mole-^{o}K. This value corresponds approximately $\pm$0.84% based on a mean specific heat value of 28. joules/gm-mole-^{o}K.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

In this work the task of the design of a data acquisition system adequate for modeling and control purposes was completed. The collection of data for specific heat calculations was used as a proving ground for the system which demonstrated that equivalent accuracy in the specific heat could be obtained by the digital system as compared to the current system. Also, a preliminary theoretical model was developed which possessed the general response dynamics of the physical system.

The recommendations which follow from this work are:

1. Complete the characterization of the physical process model by determination of the constants appearing in Table II.

2. Use the model to determine the relative importance of limits of control for the various process temperatures.

3. Use the model to design an appropriate controller (such as a decoupler) to aid in the minimization of the nonlinear, multivariable nature of the process.

4. Evaluate the improvement of degradation in control afforded by the digital control strategy using

specific heat data as a guideline. (Direct methods of evaluation are not possible due to the destruction of shield temperature readings when under analog control. This simultaneous sampling results in parallel circuits.)

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APPENDICES

APPENDIX A

CONVERSION OF A TYPICAL TIME DOMAIN EQUATION TO THE LAPLACE DOMAIN

The method listed here will follow the procedure set forth in Chapter II using the following sample equation:

$$M_1 C_{P_1} \frac{dT_1}{d\theta} = P_1 - [K_{12}(T_1 - T_2) + K_{13}(T_1^4 - T_3^4)] \qquad A\text{-}1$$

1. Linearize any non-linear terms using a Taylor Series expansion truncated after the first differential term.

The definition of the truncated Taylor Series is:

$$F(X_i) = F(a) + \sum_{i=1}^{N} \frac{\partial F(X_i)}{\partial X_i} (X_i - a) \qquad A\text{-}2$$

where

$F(X_i)$ = a function F which depends on independent variables X_i

X_i = independent variable

N = total number of independent variables on which F depends

a = point of evaluation

By examining equation A-1, it is seen that the only non-linear term is T^4; therefore:

$$F(X_i) = T^4 \qquad A\text{-}3$$

and

$$X_i = T \qquad A\text{-}4$$

Applying equation A-2 to A-3, the following is obtained:

$$T^4 = T_a^4 + 4\,T_a^3\,(T - T_a) \qquad \text{A-5}$$

where

T_a = T evaluated at point a

Rearranging A-5, one obtains:

$$T^4 - T_a^4 = 4\,T_a^3\,(T - T_a) = 4\,T_a^3\,t \qquad \text{A-6}$$

where

t = deviation of T from T_a

In order to use this equation, it is advantageous to evaluate equation A-1 at some steady state condition a and subtract this from equation A-1. The result of this procedure is:

$$M_1 C_{P_1} \frac{d(T_1 - T_{1a})}{d\,\theta} = (P_1 - P_{1a}) - \{K_{12}\,[(T_1 - T_{1a}) - (T_2 - T_{2a})] + K_{13}\,[(T_1^4 - T_{1a}^4) - (T_3^4 - T_{3a}^4)]\} \qquad \text{A-7}$$

Using A-6 in A-7, the linearized equation is:

$$M_1 C_{P_1} \frac{d\,t_1}{d\,\theta} = P_1 - [K_{12}\,(t_1 - t_2) + K_{13}\,(4\,T_{1a}^3\,t_1 - 4\,T_{3a}^3\,t_3)] \qquad \text{A-8}$$

or

$$M_1 C_{P_1} \frac{d\, t_1}{d\, \theta_1} = P_1 - (K_{12} + 4\, K_{13}\, T_{1a}^{\,3}) t_1 + K_{12} t_2 + 4\, K_{13} T_{3a}^{\,3} t_3 \qquad \text{A-9}$$

2. Convert linear time domain equation to LaPlace domain.

The only LaPlace domain conversions (27, 28) necessary are:

$$L[\, a\, f\,(t) + b\, g\,(t)\,] = a\, F(s) + b\, G\,(s) \qquad \text{A-10}$$

and

$$L\left[\frac{d\, f\,(t)}{d\, \theta}\right] = s\, F\,(s) - f\,(o) \qquad \text{A-11}$$

Applying the procedures of A-10 and A-11 to A-9 (with zero initial condition since process can be considered to be at steady state initially), the LaPlace domain equation is:

$$M_1 C_{P_1} (s t_1(s)) = P_1(s) - (K_{12} + 4 K_{13} T_{1a}^{\,3}) t_1(s) + K_{12} t_2(s) + 4\, K_1\, T_{3a}^{\,3} t_3(s) \qquad \text{A-12}$$

3. Solve for major dependent variable.

In this case the major dependent variable is $t_1(s)$; therefore:

$$t_1(s) = \frac{P_1(s) + K_{12} t_2(s) + C_{13} t_3(s)}{M_1 C_{P_1} S + K_{12} + 4 K_{13} T_{1a}^{\,3}} \qquad \text{A-13}$$

where

$$C_{13} = 4\, K_{13}\, T_{3a}^{\,3}$$

likewise

$$t_1(s) = (P_1(s) + K_{12}t_2(s) + C_{13}t_3(s)) \cdot \left(\frac{K_1}{1 + \tau_1 s}\right) \qquad \text{A-14}$$

where

$$K_1 = \frac{1}{K_{12} + 4\,K_{13}T_{1a}}\,3$$

$$\tau_1 = M_1 C_{P_1} K_1$$

4. Apply block diagram algebra (25, 26, 28) to LaPlace domain equation.

By knowing that addition (or subtraction) is denoted by a summing junction and multiplication by a box, equation A-14 is depicted diagrammatically in Figure A-1.

5. Arrange individual blocks to form overall block diagram.

This is accomplished by fitting the separate blocks from each equation into the overall block diagram (Figure 3, p. 29).

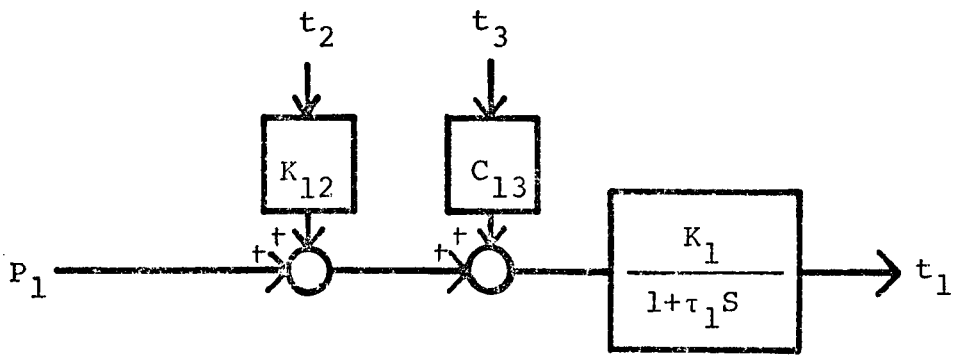
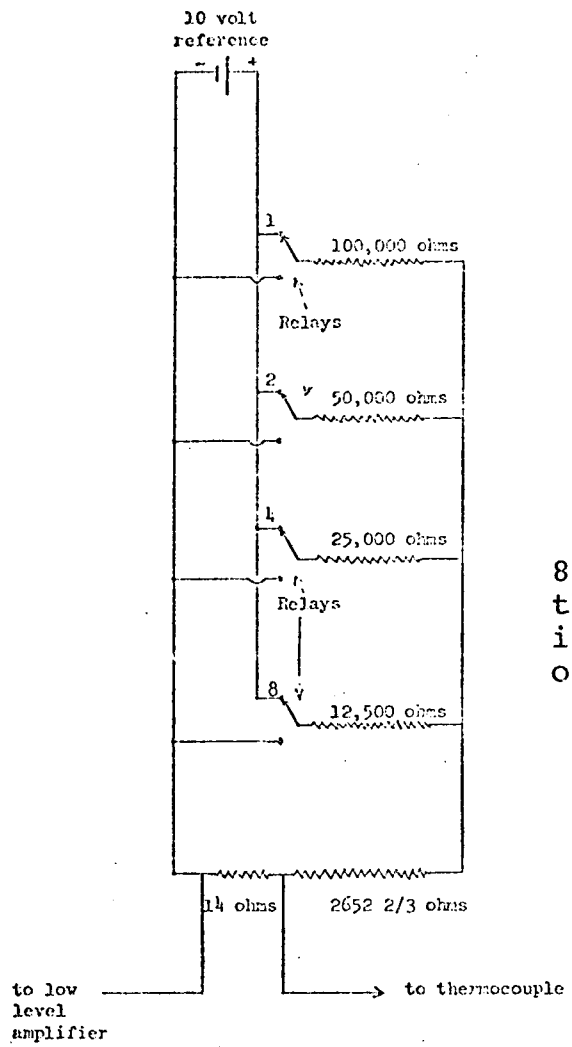


Figure A-1. LaPlace Domain Block Diagram for a Representative Time Domain Equation.

APPENDIX B

SCHEMATIC OF THE VARIABLE SUPPRESSION UNIT



The numbers 1, 2, 4 and 8 mean that the part of the circuit they identify is repeated that number of times.

Figure B-1. Schematic Diagram of the High Accuracy Variable Suppression Unit.

Source: W. P. Murray, Master's Thesis, University of Tennessee, 1970, p. 61.

APPENDIX C

SCHEMATIC OF EIGHT CHANNEL MULTIPLEXER UNIT

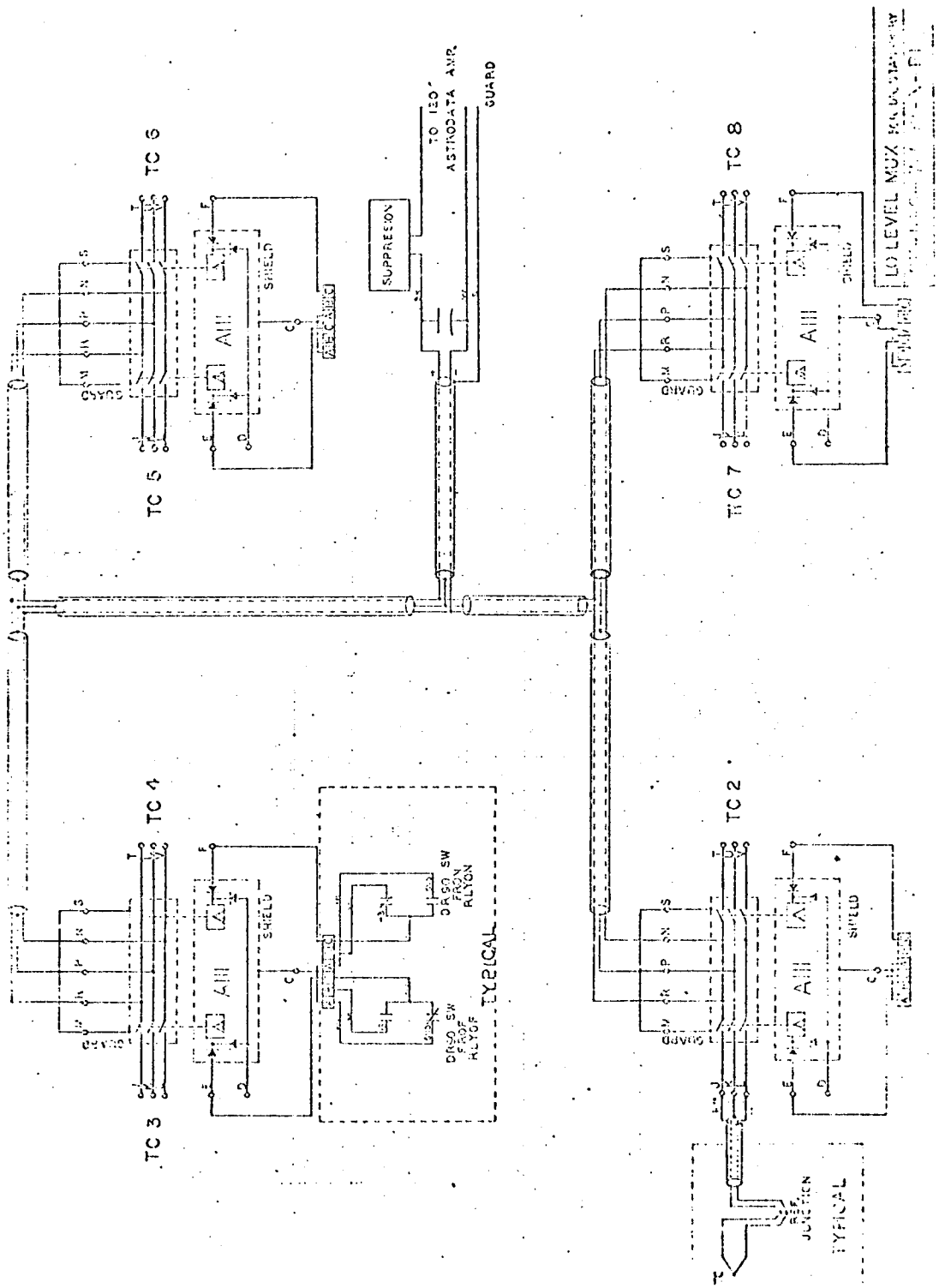


Figure C-1. Schematic Diagram of the 8-Channel Multiplexer Unit.

APPENDIX D

```
C       TASK NAME STUPP(START UP PROGRAM)
        DIMENSION IT(4)
C       TURN ON DTCLK AND SCAN.
        IT(1)=0
        IT(2)=2
        IT(3)=1
        IT(4)=1
        CALL FIX(5HDTCLK,IEV)
        CALL RUN(5HDTCLK,IT,0)
        CALL REQST(4HSCAN,0)
        CALL EXIT
        STOP
        END
```

```
        SUBROUTINE RST(ITICKS)
C       SUBROUTINE TO SET RELAYS AND WAIT ITICKS
C       BEFORE RESUMING PROGRAM EXECUTION
        DIMENSION IT(2)
        IT(1)=ITICKS
        IT(2)=1
        CALL RLYST
        CALL MARK(IT,IEV)
        CALL WAITFR(IEV)
        RETURN
        END
```

```
C       TASK NAME RSTUP(RE-START UP PROGRAM)
C
        COMMON/COMA/L(23),IPCR,ITSIG(8),FSIG(8),ISPEC,JE(4),
        1 JDE(4),M(6),JOF(4),CKC(4),TI(4),TD(4),NTICK,ITCR,
        1 JTSIG(2,21),IVS,ICS,INEC,ITK,ISEC,IVSA,ICSA,IDTK,
        1 IDSEC,JSUM(2),MSUM(2),NSUM(2),NTCCP,VO,CU,GAIN,K,
        1 SUP,SMASS,CP(2),TEMP(12),MM,ISPAN
        K = 0
        MM = 0
        ITK = 0
        ISEC = 0
        INEC = 0
        IVS = 0
        ICS = 0
C       THIS PORTION SETS RELAYS TO PROPER POSITIONS.
C
        CALL RLYOF(L(1),1,IEV)
        CALL RLYOF(L(2),1,IEV)
        CALL RLYOF(L(3),1,IEV)
        CALL RLYOF(L(4),1,IEV)
        CALL RLYON(L(5),1,IEV)
        CALL RLYOF(L(6),1,IEV)
        CALL RLYOF(L(7),1,IEV)
        CALL RLYOF(L(8),1,IEV)
        CALL RLYOF(L(9),1,IEV)
        CALL RLYOF(L(10),1,IEV)
        CALL RLYOF(L(11),1,IEV)
        CALL RLYOF(L(12),1,IEV)
        CALL RLYST
C
C       THIS PORTION FIXES CAL04 AND PID
C
        CALL FIX(5HCAL04,IEV)
        CALL FIX(3HPID,IEV)
C
C       REQUEST CAL04 AND PID
        CALL REQST(3HPID,0,IEV)
        CALL RST(100)
        CALL REQST(5HCAL04,0,IEV)
C
C       CALLS FOR CHANNELS TO BE SCANNED.
C
        CALL ADCON(L(13),1,1,IX,IST)
        CALL ADCON(L(14),1,1,IX,JST)
        CALL ADCON(L(15),1,10,IX,JST)
        CALL EXIT
        STOP
        END
```

```
C       TASK NAME - CAL00
C       TASK LISTS CURRENT VALUES OF VARIABLES IN COMMON
        COMMON/COMA/L(23),IPCR,ITSIG(8),FSIG(8),ISPEC,JE(4),
        1 JDE(4),M(6),JOF(4),CKC(4),TI(4),TD(4),NTICK,ITCR,
        1 JTSIG(2,21),IVS,ICS,INEC,ITK,ISEC,IVSA,ICSA,IDTK,
        1 IDSEC,JSUM(2),MSUM(2),NSUM(2),NTCCP,VO,CU,GAIN,K,
        1 SUP,SMASS,CP(2),TEMP(12),MM,ISPAN
        WRITE(4,1500)
        WRITE(4,2000)(L(I),  I=1,8)
        WRITE(4,2500)
        WRITE(4,3000)(L(I),  I=9,15)
        WRITE(4,3200)
        WRITE(4,3400)(L(I),  I=16,23)
        WRITE(4,3500)SMASS,NTICK,IPCR
        WRITE(4,5000)ITCR,NTCCP,GAIN,SUP
        WRITE(4,5500)
        WRITE(4,6000)K,MM,ITK,ISEC,INEC,VO,CU
        WRITE(4,7500)
        DO 100 I=1,4
100     WRITE(4,8000) I,CKC(I),TI(I),TD(I),JOF(I)
1500    FORMAT(/1X40H L(1) L(2) L(3) L(4) L(5) L(6) L(7) L(8))
2000    FORMAT(8I5)
2500    FORMAT(/1X42H  L(9) L(10) L(11) L(12) L(13) L(14) L(15))
3000    FORMAT(7I6)
3200    FORMAT(/1X48H L(16) L(17) L(18) L(19) L(20) L(21) L(22) L(23))
3400    FORMAT(8I6)
3500    FORMAT(/1X13HSPEC.  MASS = ,F10.5,5X,7HNTICK= ,I5,5X,6HIPCR =,I5)
5000    FORMAT(/1X7HITCR = ,I5,5X,8HNTCCP = ,I5,3X,6HGAIN= ,F8.0,
        1   2X,6HSUP = ,F6.1)
5500    FORMAT(/1X50H  K        MM     ITK     ISEC     INEC     VO      CU  )
6000    FORMAT(/1X,I3,I8,I7,I9,I8,2X,F8.4,1X,F8.4)
7500    FORMAT(/1X12HCONTROLLER #,5X,2HKC,7X,2HTI,7X,2HTD,5H  JOF)
8000    FORMAT(I7,6X,F9.5,2F9.3,I5)
        CALL EXIT
        STOP
        END
```

```
C       TASK NAME - CAL01
C       TASK SETS OPERATING VARIABLES
        DIMENSION V(7)
        COMMON/COMA/L(23),IPCR,ITSIG(8),FSIG(8),ISPEC,JE(4),
        1 JDE(4),M(6),JOF(4),CKC(4),TI(4),TD(4),NTICK,ITCR,
        1 JTSIG(2,21),IVS,ICS,INEC,ITK,ISEC,IVSR,ICSR,IDTK,
        1 IDSEC,JSUM(2),MSUM(2),NSUM(2),NTCCP,VO,CU,GAIN,K,
        1 SUP,SMASS,CP(2),TEMP(12),MM,ISPAN
        DATA YES/1HY/,V(1),V(2),V(3),V(4),V(5),V(6),V(7)
        1/5HLIOTE,5HLINTF,5HLISTT,5HSMASS,3HSUP,4HGAIN
        1,4HNONE/
10      WRITE(4,500)
        READ(4,1000)VAR
        DO 20 I = 1,7
        J = I
        IF(VAR.EQ.V(I)) GOTO 30
20      CONTINUE
        WRITE(4,1100)
        WRITE(4,1150)
        GOTO 10
30      GOTO(50,70,80,90,100,110,140), J
50      WRITE(4,1500)
        READ(4,2000)(L(I), I = 1,8)
        WRITE(4,2500)(L(I), I = 1,8)
65      READ(4,3000)ANS
        IF(ANS.NE.YES) GOTO(50,70,80,90,100,110), J
        GOTO 10
70      WRITE(4,3500)
        READ(4,4000)(L(I), I =9,15)
        WRITE(4,4500)(L(I), I =9,15)
        GOTO 65
80      WRITE(4,4600)
        READ(4,4700)(L(I), I=16,23)
        WRITE(4,4800)(L(I), I=16,23)
        GOTO 65
90      WRITE(4,5000)
        READ(4,5500)SMASS
        WRITE(4,6000)SMASS
        GOTO 65
100     WRITE(4,190)
        READ(4,200)SUP
        WRITE(4,250)SUP
        GOTO 65
110     WRITE(4,9000)
        READ(4,9500)GAIN
        WRITE(4,9600)GAIN
        ISPAN = (GAIN/10000.)*2047.
        GOTO 65
```

```
500     FORMAT(//1X4HVAR:)
190     FORMAT(/1X11H SUPRESSION)
200     FORMAT(F8.3)
250     FORMAT(/1X8H  SUP = ,F8.3,14H  CHECK Y OR N)
1000    FORMAT(1A5)
1100    FORMAT(/1X23HINCORRECT VARIABLE NAME)
1150    FORMAT(1X40HTRY AGAIN OR TYPE  NONE  TO EXIT PROGRAM)
1500    FORMAT(/1X40H L(1) L(2) L(3) L(4) L(5) L(6) L(7) L(8))
2000    FORMAT(8I5)
2500    FORMAT(1X,8I5,15H   CHECK Y OR N)
3000    FORMAT(1A1)
3500    FORMAT(/1X42H  L(9) L(10) L(11) L(12) L(13) L(14) L(15))
4000    FORMAT(7I6)
4500    FORMAT(1X,7I6,15H   CHECK Y OR N)
4600    FORMAT(/1X48H L(16) L(17) L(18) L(19) L(20) L(21) L(22) L(23))
4700    FORMAT(8I6)
4800    FORMAT(1X,8I6/1X,15H   CHECK Y OR N)
5000    FORMAT(/1X18HSPEC. MASS, GRAMS:)
5500    FORMAT(F10.5)
6000    FORMAT(1X7HMASS = , F10.5, 15H   CHECK Y OR N)
9000    FORMAT(//1X23HCALIBRATED SYSTEM GAIN:)
9500    FORMAT(F8.0)
9600    FORMAT(/1X8H GAIN = ,F8.0,15H   CHECK Y OR N)
140     CALL EXIT
        STOP
```

```
C       CAR01
C       TASK TO SET VARIABLES IN COMMON NOT SET BY CAL01
        DIMENSION V(7)
        COMMON/COMA/L(23),IPCR,ITSIG(8),FSIG(8),ISPEC,JE(4),
        1 JDE(4),M(6),JOF(4),CKC(4),TI(4),TD(4),NTICK,ITCR,
        1 JTSIG(2,21),IVS,ICS,INEC,ITK,ISEC,IVSA,ICSA,IDTK,
        1 IDSEC,JSUM(2),MSUM(2),NSUM(2),NTCCP,VO,CU,GAIN,K,
        1 SUP,SMASS,CP(2),TEMP(12),MM,ISPAN
        DATA YES/1HY/,V(1),V(2),V(3),V(4),V(5),V(6),V(7)
        1 /5HNTICK,1HK,5HNTCCP,4HITCR,4HIPCR,3HPID,4HNONE/
10      WRITE(4,150)
        READ(4,200) VAR
        DO 20 I=1,7
        J=I
        IF(VAR.EQ.V(I)) GO TO 30
20      CONTINUE
        WRITE(4,300)
        WRITE(4,400)
        GO TO 10
30      GO TO (50,60,70,80,90,100,999), J
65      READ(4,800) ANS
        IF(ANS .NE. YES) GO TO (50,60,70,80,90,100), J
        GO TO 10
50      WRITE(4,500)
        READ(4,600)NTICK
        WRITE(4,700) NTICK
        GO TO 65
60      WRITE(4,900)
        READ(4,1000)K
        WRITE(4,1100) K
        GO TO 65
70      WRITE(4,1200)
        READ(4,600) NTCCP
        WRITE(4,1400) NTCCP
        GO TO 65
80      WRITE(4,1500)
        READ(4,600) ITCR
        WRITE(4,1600)ITCR
        GO TO 65
```

```
90      WRITE(4,1700)
        READ(4,600) IPCR
        WRITE(4,1800) IPCR
        GO TO 65
100     WRITE(4,1900)
        READ(4,1000) N
        WRITE(4,2000) N
        READ(4,2100) CKC(N),TI(N),TD(N),JOF(N)
        WRITE(4,2200) CKC(N),TI(N),TD(N),JOF(N)
        GO TO 65
150     FORMAT(//1X4HVAR:)
200     FORMAT(1A5)
300     FORMAT(/1X23HINCORRECT VARIABLE NAME)
400     FORMAT(1X38HTRY AGAIN OR TYPE NONE TO EXIT PROGRAM)
500     FORMAT(/1X19HNO. OF TICKS DELAY:)
600     FORMAT(I5)
700     FORMAT(1X7HNTICK= ,I5,5X,12HCHECK Y OR N)
800     FORMAT(1A1)
900     FORMAT(/1X30HUNITS OF 1000 MICROVOLTS SUPP:)
1000    FORMAT(I3)
1100    FORMAT(1X3HK= ,I3,5X,12HCHECK Y OR N)
1200    FORMAT(/1X47H NO. OF SETS OF TC READINGS BETWEEN SP HT CALC:)
1400    FORMAT(/1X9H NTCCP = ,I5,15H   CHECK Y OR N)
1500    FORMAT(/1X,40H TICKS BETWEEN SETS OF TC READINGS-XX00:)
1600    FORMAT(/1X8H ITCR = ,I5,15H   CHECK Y OR N)
1700    FORMAT(/1X40H NO. TICKS BETWEEN CONTROLLER READINGS :)
1800    FORMAT(/1X8H IPCR = ,I5,15H   CHECK Y OR N)
1900    FORMAT(/1X,15H CONTROLLER # ?)
2000    FORMAT(/1X,13H CONTROLLER #,I2/9X,2HKC,8X,2HTI,8X,2HTD,
        15H  JOF)
2100    FORMAT(3F10.6,I5)
2200    FORMAT(/8X,2HKC,7X,2HTI,7X,2HTD,5H  JOF/1X,F9.5,2F9.3,I5,
        11H  CHECK Y OR N)
999     CALL EXIT
        STOP
        END
```

```
C       PROGRAM NAME--PID
C       THIS PROGRAM IS USED TO TAKE THERMOCOUPLE DATA
C       AND USING THE SPECIMEN AS A SET POINT, CONTROL THE
C       OTHER THERMOCOUPLES USING A STANDARD DISCRETE PID
C       ALGORITHM
        DIMENSION IT(4)
        COMMON/COMA/L(23),IPCR,ITSIG(8),FSIG(8),ISPEC,JE(4),
        1 JDE(4),M(6),JOF(4),CKC(4),TI(4),TD(4)
C
C       CALL PROGRAM BACK IN AT NEXT SAMPLE INTERVAL
        IT(1)=IPCR
        IT(2)=1
        IT(3)=0
        IT(4)=1
        IP=0
        CALL RUN(3HPID,IT,IP,IEV)
C
C       READ ALL THERMOCOUPLES
        DO 300 J=1,8
        CALL RLYON(L(J+4),1,IEV)
        DO 100 I=1,8
        IF (I.EQ.J) GO TO 100
        CALL RLYOF(L(I+4),1,IST)
100     CONTINUE
        CALL RST(5)
        JTO=0
        DO 200 I=1,3
        CALL ADCIN(L(13),ITC,IEV)
        CALL RST(1)
200     JTO=JTO+ITC
300     ITSIG(J)=JTO/3
        CALL RLYON(L(6),1,IST)
        CALL RLYOF(L(12),1,IST)
        CALL RST(1)
C
C       CALCULATE ERRORS,CALCULATE CONTROLLER OUTPUTS, AND OUTPUT
C       THESE VALUES ON APPROPRIATE DACS
        ISPEC=(ITSIG(1)+ITSIG(2))/2
        T=FLOAT(IPCR)/6000.
        DO 400 I=1,4
        IERR=(ISPEC+JOF(I))-ITSIG(I+2)
        IDM=CKC(I)*(FLOAT(IERR-JE(I))+T*FLOAT(IERR)/TI(I))
        1 +(TD(I)*FLOAT(IERR-2*JE(I)+JDE(I))/T))
        M(I)=M(I)+IDM
        IF (M(I).GT.0) GO TO 360
        M(I)=0
        GO TO 370
360     IF (M(I).LT.512) GO TO 370
        M(I)=511
370     CALL DACST(L(I+19),1,M(I),IEV)
        JDE(I)=JE(I)
400     JE(I)=IERR
C
```

```
C       READ SPECIMEN VOLTAGE AND CURRENT
        CALL ADCIN(L(14),M(5),IST)
        CALL ADCIN(L(15),M(6),IST)
C
C       WRITE ALL DATA USING PROGRAM STORE
        CALL RESUME(5HSTORE,IEV)
        CALL EXIT
        STOP
        END



C       PROGRAM NAME-STORE  USED TO STORE DATA ON DECTAPE
        COMMON/COMA/L(23),IPCR,ITSIG(8),FSIG(8),ISPEC,JE(4),
        1 JDE(4),M(6),JOF(4),IBLK(90),K,ICLK(32),MM,ISPAN
C
C       NAME DATA FILE
        WRITE(4,10)
        READ(4,20) FNAM
        WRITE(4,30) FNAM
10      FORMAT(/1X,"ENTER DATA FILE NAME (5 CHARACTERS)")
20      FORMAT(A5)
30      FORMAT(/1X,"DATA FILE NAME =",A6)
C
C       OPEN DATA FILE FOR INPUT
        CALL ENTER(19,FNAM,3HSRC,IEV)
C
C       SET UP TO WRITE DATA EVERY TIME PID EXECUTES
1       CALL SUSPND
        IF (MM.EQ.1) GOTO 1000
C
C       WRITE THERMOCOUPLE DATA
        WRITE(19,300) (ITSIG(I),I=1,8),K,M(5),M(6)
C
C       WRITE CONTROLLER OUTPUT DATA
        DO 250 I=1,3,2
250     WRITE(19,400) JE(I),JDE(I),M(I),JE(I+1),JDE(I+1),M(I+1)
C
300     FORMAT(1X,8I7,I3,2I6)
400     FORMAT(15X,6I7)
        GOTO 1
C
C       IF ALL DATA HAS BEEN TAKEN CLOSE FILE
1000    CALL CLOSE(19,FNAM,3HSRC,JEV)
        CALL EXIT
        STOP
        END
```

```
C       PROGRAM NAME--CAL04--USED TO TAKE THERMOCOUPLE DATA EVERY
C       ITCR TICKS, COLLECT CONTROLLER OUTPUTS FROM CONOP AND
C       WRITE APPROPRIATE DATA
C       THIS PROGRAM USES AN AVERAGE OF THREE READINGS FOR T/C DATA
        DIMENSION IT(4)
        COMMON/COMA/L(23), IBLANK(68), NTICK, ITCR, JTSIG(2,21),
        1 IVS, ICS, INEC, ITK, ISEC, IVSA, ICSA, IDTK, IDSEC, JSUM(2),
        1 MSUM(2), NSUM(2), NTCCP
C
C       SET UP NEXT DATA ACQUISITION
        IT(1)=ITCR
        IT(2)=1
        IT(3)=0
        IT(4)=1
        IP=0
        CALL RUN(5HCAL04, IT, IP, IEV)
C
C       READ NEW SET OF TC EMFS
50      DO 550 J = 1,2
        CALL RLYON(L(J + 4),1,IEV)
        DO 100 IN = 1,8
        IF(IN+4.EQ.J+4) GOTO 100
        CALL RLYOF(L(IN +4),1,IST)
100     CONTINUE
        CALL RST(NTICK)
        JTO=0
        DO 160 N=1,5
        CALL ADCIN(L(13), ITC, IST)
        CALL RST(2)
160     JTO=JTO+ITC
550     JTSIG(J,21) = JTO/5
        CALL ADCIN(L(14), IVO, IEV)
        CALL ADCIN(L(15), ICU, IEV)
        IVS=IVS+IVO
        ICS=ICS+ICU
C
C       READ DELTA TIME IF HAVE COLLECTED NTCCP NEW DATA POINTS
600     INEC=INEC + 1
        IF(INEC .GE. NTCCP) GO TO 625
        GO TO 650
625     CALL DTIM(ITK, ISEC, IDTK, IDSEC)
        CALL DTIMON(ITK, ISEC)
C
C       INCREMENT THERMOCOUPLE AND CONTROLLER TABLES BY 1
650     DO 700 J=1,2
        DO 700 I=1,20
700     JTSIG(J,I)=JTSIG(J,I+1)
C
C       WRITE DATA ON TELETYPE IF HAVE COLLECTED NTCCP NEW POINTS
        IF(INEC.GE.NTCCP) GOTO 850
        GOTO 170
850     IVSA=IVS
        ICSA=ICS
        CALL REQST(5HCAB09, 0, IEV)
```

```
C
C       ALSO SET UP SUMS FOR LEAST SQUARES FIT
        DO 890 J=1,2
        MSUM(J)=0
        NSUM(J)=0
        JSUM(J)=0
        DO 890 I=1,20
        MSUM(J)=MSUM(J)+JTSIG(J,I)
        NSUM(J)=NSUM(J)+I*JTSIG(J,I)
        IF(IABS(NSUM(J)).GE.10000) GOTO 660
        GOTO 890
660     IC=NSUM(J)/10000
        NSUM(J)=NSUM(J)-IC*10000
        JSUM(J)=JSUM(J)+IC
890     CONTINUE
        CALL REQST(5HCAL06,0,IEV)
        IVS=0
        ICS=0
        INEC=0
C
C       SET SUPRESSION IF NECESSARY
170     IF(IABS(JTSIG(2,21)).GE.1850) CALL REQST(5HSUPRS,0,IEV)
        CALL EXIT
        STOP
        END
```

```
C       TASK NAME - CAL66
C       TASK TO CALCULATE SPECIFIC HEAT
        DIMENSION EXVAL(4),EMF(4),JT(121)
        COMMON/COMA/IBLK(140),IVSA,ICSA,IDTK,IDSEC,JSUM(2),MSUM(2),
        1 NSUM(2),NTCCP,VO,CU,GAIN,K,SUP,SMASS,CP(2),TEMP(12)
        DATA JT(1),JT(2),JT(3),JT(4),JT(5),JT(6),JT(7)/
        1 0,1796,3466,5039,6536,7972,9357/
        DATA JT(8),JT(9),JT(10),JT(11),JT(12),JT(13),JT(14)/
        1 10697,12000,13270,14510,15725,16917,18087/
        DATA JT(15),JT(16),JT(17),JT(18),JT(19),JT(20),JT(21)/
        1 19239,20373,21492,22597,23688,24768,25836/
        DATA JT(22),JT(23),JT(24),JT(25),JT(26),JT(27),JT(28),JT(29)/
        1 26894,27943,28982,30014,31038,32054,33064,34067/
        DATA JT(30),JT(31),JT(32),JT(33),JT(34),JT(35),JT(36),JT(37)/
        1 35064,36056,37042,38022,38998,39969,40935,41897/
        DATA JT(38),JT(39),JT(40),JT(41),JT(42),JT(43),JT(44),JT(45)/
        1 42854,43806,44755,45699,46639,47575,48507,49435/
        DATA JT(46),JT(47),JT(48),JT(49),JT(50),JT(51),JT(52),JT(53)/
        1 50359,51279,52195,53107,54016,54920,55821,56718/
        DATA JT(54),JT(55),JT(56),JT(57),JT(58),JT(59),JT(60),JT(61)/
        1 57612,58502,59388,60271,61150,62026,62899,63769/
        DATA JT(62),JT(63),JT(64),JT(65),JT(66),JT(67),JT(68),JT(69)/
        1 64635,65499,66360,67217,68072,68924,69774,70620/
        DATA JT(70),JT(71),JT(72),JT(73),JT(74),JT(75),JT(76),JT(77)/
        1 71464,72305,73144,73980,74813,75644,76473,77298/
        DATA JT(78),JT(79),JT(80),JT(81),JT(82),JT(83),JT(84),JT(85)/
        1 78121,78942,79760,80576,81389,82200,83008,83814/
        DATA JT(86),JT(87),JT(88),JT(89),JT(90),JT(91),JT(92),JT(93)/
        1 84617,85418,86217,87013,87807,88599,89388,90175/
        DATA JT(94),JT(95),JT(96),JT(97),JT(98),JT(99),JT(100)/
        1 90960,91743,92523,93301,94078,94852,95624/
        DATA JT(101),JT(102),JT(103),JT(104),JT(105),JT(106),JT(107)/
        1 96394,97162,97928,98692,99454,100214,100972/
        DATA JT(108),JT(109),JT(110),JT(111),JT(112),JT(113),JT(114)/
        1 101729,102484,103238,103989,104739,105487,106234/
        DATA JT(115),JT(116),JT(117),JT(118),JT(119),JT(120),JT(121)/
        1 106979,107723,108465,109206,109945,110683,111420/
C       SET UP LEAST SQUARES FIT TO CURRENT LAST 10 VALUES
        DO 30 J=1,2
30      EXVAL(J)=-.01428571*(FLOAT(NSUM(J))+10000.*FLOAT(JSUM(J)))
        1 +.2*FLOAT(MSUM(J))
        DO 50 J = 1,2
50      EXVAL(J+2)=.0142857*(FLOAT(NSUM(J))+10000.*FLOAT(JSUM(J)))
        1   -.1*FLOAT(MSUM(J))
        VO=FLOAT(IVSA/(NTCCP))/204.7
        CU=FLOAT(ICSA/(NTCCP))/2047.
        DO 100 I=1,4
        EMF(I) = EXVAL(I)*1.E7/(2047.*GAIN) + FLOAT(K)*1000.  + SUP
        LA=AINT(EMF(I)/100.)+1.
100     TEMP(I)=(FLOAT(JT(LA))+((EMF(I)-FLOAT((LA-1)*100))/100.)
        1 *FLOAT(JT(LA+1)-JT(LA)))/100.
C       CP(1,2) = SPECIFIC HEAT CALCULATED FROM TC 1,2
        CP(1) = .95*VO*CU*(FLOAT(100*IDSEC + IDTK)/100.)/
        1         (SMASS*(TEMP(3) - TEMP(1)))
        CP(2) = .95*VO*CU*(FLOAT(100*IDSEC + IDTK)/100.)/
        1         (SMASS*(TEMP(4) - TEMP(2)))
        CALL REQST(5HCAL69,0,IEV)
        CALL EXIT
        STOP
        END
```

```
C       TASK NAME - CAL09
C       TASK LISTS CURRENT VALUES OF VARIABLES IN COMMON
        COMMON/COMA/L(23),IPCR,ITSIG(8),FSIG(8),ISPEC,JE(4),
       1 JDE(4),M(6),JOF(4),CKC(4),TI(4),TD(4),NTICK,ITCR,
       1 JTSIG(2,21),IVS,ICS,INEC,ITK,ISEC,IVSA,ICSA,IDTK,
       1 IDSEC,JSUM(2),MSUM(2),NSUM(2),NTCCP,VO,CU,GAIN,K,
       1 SUP,SMASS,CP(2),TEMP(12),MM,ISPAN
        T1AVG=(TEMP(1)+TEMP(3))/2.
        T2AVG=(TEMP(2)+TEMP(4))/2.
        DT1=TEMP(3)-TEMP(1)
        DT2=TEMP(4)-TEMP(2)
        WRITE(4,1000)
        WRITE(4,2000)K,MM,ITK,ISEC,INEC,VO,CU
        WRITE(4,3000)
        WRITE(4,4000) (TEMP(I),I=1,4)
        WRITE(4,5000)
        WRITE(4,6000) T1AVG,T2AVG,DT1,DT2
        WRITE(4,7000) (CP(I),I=1,2)
1000    FORMAT(/1X50H  K        MM     ITK      ISEC     INEC     VO      CU  )
2000    FORMAT(/1X,I3,I8,I7,I9,I8,2X,F8.4,1X,F8.4)
3000    FORMAT(/42H TEMP(1,1) TEMP(2,1) TEMP(1,20) TEMP(2,20))
4000    FORMAT(2F16.2,2F11.2)
5000    FORMAT(/36H     T1AVG     T2AVG       DT1       DT2)
6000    FORMAT(4F9.2)
7000    FORMAT(/1X,11HSP.  HT.  1 =,F8.4,5X,11HSP.  HT.  2 =,F8.4///)
        CALL EXIT
        STOP
        END
```

```
C       TASK NAME_CAB69
C       TASK TO WRITE JTSIG(J,I) USED IN EMF CALCULATION.
        DIMENSION KTSIG(2,20),SEE(2)
        COMMON/COMA/L(23),IPCR,ITSIG(8),FSIG(8),ISPEC,JE(4),
       1 JDE(4),M(6),JOF(4),CKC(4),TI(4),TD(4),NTICK,ITCR,
       1 JTSIG(2,21),IVS,ICS,INEC,ITK,ISEC,IVSA,ICSA,IDTK,
       1 IDSEC,JSUM(2),MSUM(2),NSUM(2),NTCCP,VO,CU,GAIN,K,
       1 SUP,SMASS,CP(2),TEMP(12),MM,ISPAN
        DO 100 I = 1,20
        KTSIG(1,I) = JTSIG(1,I)
100     KTSIG(2,I) = JTSIG(2,I)
        DO 200 J=1,2
        DO 200 I=1,20
200     SEE(J)=(FLOAT(KTSIG(J,I))-(FLOAT(I)*.0015038-.0157895)
       1 *(FLOAT(NSUM(J))+10000.*FLOAT(JSUM(J)))
       1 -(.2157895-FLOAT(I)*.0157895)*FLOAT(MSUM(J)))**2+SEE(J)
        WRITE(4,1000) (KTSIG(1,I), I = 1,10)
        WRITE(4,1000) (KTSIG(2,I), I = 1, 10)
        WRITE(4,2000) (KTSIG(1,I),I=11,20)
        WRITE(4,1000) (KTSIG(2,I),I=11,20)
        WRITE(4,3000) (SEE(J),J=1,2)
1000    FORMAT(1X,10(I6))
2000    FORMAT(/1X,10(I6))
3000    FORMAT(/1X,6HSEE1 =,F10.2,3X,6HSEE2 =,F10.2)
        CALL EXIT
        STOP
        END
```

```
C       PROGRAM NAME--SUPRS
C       USED TO SET SUPRESSION ON THERMOCOUPLES
        COMMON/COMA/L(23),IPCR,ITSIG(8),FSIG(8),ISPEC,JE(4),
       1 JDE(4),M(6),JOF(4),CKC(4),TI(4),TD(4),NTICK,ITCR,
       1 JTSIG(2,21),IVS,ICS,INEC,ITK,ISEC,IVSA,ICSA,IDTK,
       1 IDSEC,JSUM(2),MSUM(2),NSUM(2),NTCCP,VO,CU,GAIN,K,
       1 SUP,SMASS,CP(2),TEMP(12),MM,ISPAN
170     IF(JTSIG(2,21) .GT. 1850) GO TO 300
        IF(JTSIG(2,21) .LT. -1850) GO TO 370
        GO TO 900
300     K=K+1
        DO 330 JJ=1,2
        DO 330 II=1,21
330     JTSIG(JJ,II)=JTSIG(JJ,II)-ISPAN
        GO TO 380
370     K=K-1
        DO 375 JJ=1,2
        DO 375 II=1,21
375     JTSIG(JJ,II)=JTSIG(JJ,II)+ISPAN
380     DO 400 N = 1,4
        CALL RLYOF(L(N),1,IST)
400     CONTINUE
        MK=K
        DO 500 N=1,4
        IF(2*(MK/2) .NE. MK) CALL RLYON(L(N),1,IST)
500     MK=MK/2
        CALL RST(30)
        CALL RLYON(L(6),IST,IEV)
        DO 600 N=1,8
        IF(N.EQ.2) GOTO 600
        CALL RLYOF(L(N+4),IST,IEV)
600     CONTINUE
        CALL RST(100)
        JTO=0
        DO 165 N=1,3
        CALL ADCIN(L(13),ITC,IST)
        CALL RST(3)
165     JTO=JTO+ITC
        JTSIG(2,21)=JTO/3
        GO TO 170
900     CALL EXIT
        STOP
        END
```

```
C       PROGRAM--CAR10
C       USED TO TAKE THERMOCOUPLE DATA EVERY SPECIFIED INTERVAL
C       USING RUN COMMAND (MAINLY FOR DRIFT)
        DIMENSION JT(121),EXVAL(12)
        COMMON/COMA/L(23),IPCR,ITSIG(8),FSIG(8),ISPEC,JE(4),
        1 JDE(4),M(6),JOF(4),CKC(4),TI(4),TD(4),NTICK,ITCR,
        1 JTSIG(2,21),IVS,ICS,INEC,ITK,ISEC,IVSA,ICSA,IDTK,
        1 IDSEC,JSUM(2),MSUM(2),NSUM(2),NTCCP,VO,CU,GAIN,K,
        1 SUP,SMASS,CP(2),TEMP(12),MM,ISPAN
        DATA JT(1),JT(2),JT(3),JT(4),JT(5),JT(6),JT(7)/
        1 0,1796,3466,5039,6536,7972,9357/
        DATA JT(8),JT(9),JT(10),JT(11),JT(12),JT(13),JT(14)/
        1 10697,12000,13270,14510,15725,16917,18087/
        DATA JT(15),JT(16),JT(17),JT(18),JT(19),JT(20),JT(21)/
        1 19239,20373,21490,22597,23688,24768,25836/
        DATA JT(22),JT(23),JT(24),JT(25),JT(26),JT(27),JT(28),JT(29)/
        1 26894,27943,28982,30014,31038,32054,33064,34067/
        DATA JT(30),JT(31),JT(32),JT(33),JT(34),JT(35),JT(36),JT(37)/
        1 35064,36056,37042,38022,38998,39969,40935,41897/
        DATA JT(38),JT(39),JT(40),JT(41),JT(42),JT(43),JT(44),JT(45)/
        1 42854,43806,44755,45699,46639,47575,48507,49435/
        DATA JT(46),JT(47),JT(48),JT(49),JT(50),JT(51),JT(52),JT(53)/
        1 50359,51279,52195,53107,54016,54920,55821,56718/
        DATA JT(54),JT(55),JT(56),JT(57),JT(58),JT(59),JT(60),JT(61)/
        1 57612,58502,59388,60271,61150,62026,62899,63769/
        DATA JT(62),JT(63),JT(64),JT(65),JT(66),JT(67),JT(68),JT(69)/
        1 64635,65499,66360,67217,68072,68924,69774,70620/
        DATA JT(70),JT(71),JT(72),JT(73),JT(74),JT(75),JT(76),JT(77)/
        1 71464,72305,73144,73980,74813,75644,76473,77298/
        DATA JT(78),JT(79),JT(80),JT(81),JT(82),JT(83),JT(84),JT(85)/
        1 78121,78942,79760,80576,81389,82200,83008,83814/
        DATA JT(86),JT(87),JT(88),JT(89),JT(90),JT(91),JT(92),JT(93)/
        1 84617,85418,86217,87013,87807,88599,89388,90175/
        DATA JT(94),JT(95),JT(96),JT(97),JT(98),JT(99),JT(100)/
        1 90960,91743,92523,93301,94078,94852,95624/
        DATA JT(101),JT(102),JT(103),JT(104),JT(105),JT(106),JT(107)/
        1 96394,97162,97928,98692,99454,100214,100973/
        DATA JT(108),JT(109),JT(110),JT(111),JT(112),JT(113),JT(114)/
        1 101729,102484,103238,103989,104739,105487,106234/
        DATA JT(115),JT(116),JT(117),JT(118),JT(119),JT(120),JT(121)/
        1 106979,107723,108465,109206,109945,110683,111420/
        DO 200 J=5,12
        CALL RLYON(L(J),1,IST)
        DO 130 N=5,12
        IF (N.EQ.J) GO TO 130
        CALL RLYOF(L(N),1,IST)
130     CONTINUE
        CALL RST(NTICK)
        JTC=0
        DO 150 N=1,3
        CALL ADCIN(L(13),ITC,IST)
        CALL RST(2)
150     JTC=JTC+ITC
200     EXVAL(J)=JTC/3
```

```
      CALL RLYON(L(6),1,IST)
      CALL RLYOF(L(12),1,IST)
      CALL RST(1)
      JTSIG(2,21)=EXVAL(6)
      IF (IABS(JTSIG(2,21)).GE.1856) CALL REQST(5HSUPRS,0,IEV)
      DO 500 J=5,12
      EMF=EXVAL(J)*1.0E7/(2047.0*GAIN)+FLOAT(K)*1000.0+SUP
      LA=AINT(EMF/100.0)+1.0
500   TEMP(J)=(FLOAT(JT(LA))*((EMF-FLOAT((LA-1)*100))/100.0)
      1 *FLOAT(JT(LA+1)-JT(LA)))/100.0
      CALL REQST(5HWRA10,0,IEV)
      CALL EXIT
      STOP
      END
```

```
C     PROGRAM CALLED WRA10 TO BE USED IN JUNCTION WITH
C     PROGRAM CRA10 TO OUTPUT RESULTS.
      COMMON/COMA/L(23),IPCR,ITSIG(8),FSIG(8),ISPEC,JE(4),
      1 JDE(4),M(6),JDF(4),CKC(4),TI(4),TD(4),NTICK,ITCR,
      1 JTSIG(2,21),IVS,ICS,INEC,ITK,ISEC,IVSA,ICSA,IDTK,
      1 IDSEC,JSUM(2),MSUM(2),NSUM(2),NTCCP,VO,CU,GAIN,K,
      1 SUP,SMASS,CP(2),TEMP(12),MM,ISPAN
      WRITE(4,1100)
      WRITE(4,1200) TEMP(5),TEMP(6),TEMP(7),TEMP(8)
      WRITE(4,1300)
      WRITE(4,1200) TEMP(9),TEMP(10),TEMP(11),TEMP(12)
1100  FORMAT(//1X,3X,6H5TEMP ,8X,6H6TEMP ,8X,6H7TEMP ,8X,6H8TEMP )
1200  FORMAT(1X,4(F10.5,4X))
1300  FORMAT(/1X,2X,7H 9TEMP ,7X,7H10TEMP ,7X,7H11TEMP ,7X,7H12TEMP )
      CALL EXIT
      STOP
      END
```

```
C       PROGRAM--CAL10
C       USED TO MEASURE THE TIME REQUIRED FOR THE ANALOG
C       CIRCUIT TO CHARGE--FUNCTION OF CAPACITOR SETTING AND NTICK
        DIMENSION EXVAL(8),EMF(8)
        COMMON/COMA/L(23),IPCR,ITSIG(8),FSIG(8),ISPEC,JE(4),
        1 JDE(4),M(6),JOF(4),CKC(4),TI(4),TD(4),NTICK,ITCR,
        1 JTSIG(2,21),IVS,ICS,INEC,ITK,ISEC,IVSA,ICSA,IDTK,
        1 IDSEC,JSUM(2),MSUM(2),NSUM(2),NTCCP,VO,CU,GAIN,K,
        1 SUP,SMASS,CP(2),TEMP(12),MM,ISPAN
C
C       READ THERMOCOUPLES
C
        DO 200 J=5,12
        CALL RLYON(L(J),1,IST)
        DO 130 N=5,12
        IF (N.EQ.J) GO TO 130
        CALL RLYOF(L(N),1,IST)
130     CONTINUE
        CALL RST(NTICK)
        CALL ADCIN(L(13),ITC,IST)
        CALL RST(25)
200     EXVAL(J-4)=ITC
        CALL RLYON(L(6),1,IST)
        CALL RLYOF(L(12),1,IST)
        CALL RST(1)
C
C       SET SUPRESSION IF NECESSARY
C
        JTSIG(2,21)=EXVAL(2)
        IF (IABS(JTSIG(2,21)).GE.1850) CALL REQST(5HSUPRS,0,IEV)
C
C       CALCULATE EMF VALUES AND WRITE ON TELETYPE
C
        DO 500 J=1,8
500     EMF(J)=EXVAL(J)*1.0E7/(2047.0*GAIN)+FLOAT(K)*1000.0+SUP
        WRITE(4,1100) (EMF(I),I=1,8)
1100    FORMAT(8F9.2)
        CALL EXIT
        STOP
        END
```

```
C       PROGRAM NAME--RPDFR
C       DELTA FILTER--USED TO FILTER THE DIFFERENCES
C       BETWEEN T/C MEASUREMENTS FOR SPECIFIC HEAT CALCULATIONS
        DIMENSION KTSIG(2,21),DY(2),DLY(2),DFY(2),TSIG(2)
        COMMON/COMA/L(23),IPCR,ITSIG(8),FSIG(8),ISPEC,JE(4),
        1 JDE(4),M(6),JOF(4),CKC(4),TI(4),TD(4),NTICK,ITCR,
        1 JTSIG(2,21),IVS,ICS,INEC,ITK,ISEC,IVSA,ICSA,IDTK,
        1 IDSEC,JSUM(2),MSUM(2),NSUM(2),NTCOP,VO,CU,GAIN,K,
        1 SUP,SMASS,CP(2),TEMP(12),MM,ISPAN
C
C       ENTER DATA FILE NAME
        WRITE(4,1000)
        READ(4,1100) FNAM
        WRITE(4,1200) FNAM
        CALL SEEK(19,FNAM,3HSRC,IEV)
C
C       ENTER FILTER CONSTANT
        WRITE(4,1210)
        READ(4,1220) INST
        IF(INST.NE.0) GO TO 10
        ALPHA=0.
        GO TO 20
10      ALPHA=EXP(-1./FLOAT(INST))
20      WRITE(4,1230) ALPHA
C
C       INITIALIZE STARTING POINTS
        WRITE(4,1240)
        READ(4,1220) IFC
        WRITE(4,1250) IFC
        READ(19,1300) K,IVSA,ICSA,IDTK,IDSEC
        WRITE(4,1300) K
        DO 50 I=1,2
        DLY(I)=IFC
        READ(19,1300) (KTSIG(I,J),J=2,11)
        READ(19,1300) (KTSIG(I,J),J=12,21)
        KTSIG(I,1)=KTSIG(I,2)-IFC
50      TSIG(I)=KTSIG(I,2)-IFC
        GO TO 250
C
C       ENTER DATA
1       READ(19,1300) KK,IVSA,ICSA,IDTK,IDSEC
        WRITE(4,1300) KK
        IF(KK.EQ.1000) GO TO 600
        IF(KK.EQ.K) GO TO 100
        KTSIG(1,1)=KTSIG(1,1)-ISPAN
        KTSIG(2,1)=KTSIG(2,1)-ISPAN
        TSIG(1)=TSIG(1)-ISPAN
        TSIG(2)=TSIG(2)-ISPAN
100     K=KK
        DO 200 I=1,2
        READ(19,1300) (KTSIG(I,J),J=2,11)
200     READ(19,1300) (KTSIG(I,J),J=12,21)
250     DO 300 I=1,2
        DO 300 J=1,20
        DY(I)=KTSIG(I,J+1)-KTSIG(I,J)
        DFY(I)=ALPHA*DLY(I)+(1.-ALPHA)*DY(I)
        TSIG(I)=TSIG(I)+DFY(I)
        JTSIG(I,J+1)=TSIG(I)
300     DLY(I)=DFY(I)
C
```

```
C       INCREMENT T/C TABLES BY ONE POSITION FOR COMPATABILITY
        DO 400 I=1,2
        DO 400 J=1,20
400     JTSIG(I,J)=JTSIG(I,J+1)
C
C       SET UP LEAST SQUARE SUMS
        DO 500 I=1,2
        MSUM(I)=0
        NSUM(I)=0
        JSUM(I)=0
        DO 500 J=1,20
        MSUM(I)=MSUM(I)+JTSIG(I,J)
        NSUM(I)=NSUM(I)+J*JTSIG(I,J)
        IF(IABS(NSUM(I)).GE.10000) GO TO 450
        GO TO 500
450     IC=NSUM(I)/10000
        NSUM(I)=NSUM(I)-IC*10000
        JSUM(I)=JSUM(I)+IC
500     CONTINUE
C
C       DEVELOP CONTINUITY WITH CAB09,CAL06,CAL09 AND WAIT FOR
C       THEIR EXECUTION
        CALL REQST(5HCAB09,0,IEV)
        CALL RST(100)
        CALL REQST(5HCAL06,0,IEV)
        CALL RST(NTICK)
C
C       SET UP INITIAL POINT FOR NEXT PASS THROUGH
        KTSIG(1,1)=KTSIG(1,21)
        KTSIG(2,1)=KTSIG(2,21)
        GO TO 1
C
C       CLOSE DATA FILE
600     CALL CLOSE(19,FNAM,3HSRC,IEV)
1000    FORMAT(/1X,21H ENTER DATA FILE NAME)
1100    FORMAT(A5)
1200    FORMAT(/1X,12H FILE NAME =,A6)
1210    FORMAT(//1X,51H ENTER FILTER TIME CONSTANT (INT.  # OF SAMP.
        1 TIMES))
1220    FORMAT(I4)
1230    FORMAT(/1X,8H ALPHA =,F10.5)
1240    FORMAT(/1X,55H INITIAL CONDITION FOR FILTER (DELTA
        1 VALUE--IN COUNTS):)
1250    FORMAT(/1X,8H I. C. =,I6)
1300    FORMAT(10I6)
        CALL EXIT
        STOP
        END
```

```
C       PROGRAM NAME--LSTSQ
C       USED TO FIT SPECIFIC HEAT DATA TO THE FUNCTIONAL
C       EQUATION CP = A + B*T + C/T**2
        DIMENSION X(100,3),XT(3,100),XTX(3,3),XTY(3),Y(100)
        DIMENSION A(3),YY(100),TMP(2,100),C(2,100)
C
C       M=NUMBER OF TERMS IN MODEL
C       N=NUMBER OF DATA POINTS
C
C       READ IN M AND M
C
        READ(6,1000) N,M
C
C       READ IN DATA POINTS INTO MATRIX X (M ROWS;N COLUMNS)
C       ALSO READ IN DATA FOR DEPENDENT VECTOR Y (M ROWS)
        DO 10 J=1,N
10      READ(6,1100) (TMP(I,J),C(I,J),I=1,2)
        DO 900 NTC=1,2
        DO 20 J=1,N
        X(J,1)=1.
        X(J,2)=TMP(NTC,J)
        X(J,3)=1./TMP(NTC,J)**2
20      Y(J)=C(NTC,J)*47.90
C
C       CALCULATE X TRANSPOSE
C
        DO 50 I=1,M
        DO 50 J=1,N
50      XT(I,J)=X(J,I)
C
C       CALCULATE XTX(X-TRANSPOSE TIMES X)
C
        DO 60 I=1,M
        DO 60 J=1,M
        XTX(I,J)=0.
        DO 60 K=1,N
60      XTX(I,J)=XTX(I,J)+XT(I,K)*X(K,J)
C
C       CALCULATE XTY(X-TRANSPOSE TIMES Y)
C
        DO 80 I=1,M
        XTY(I)=0.
        DO 80 J=1,N
80      XTY(I)=XTY(I)+XT(I,J)*Y(J)
C
C       INVERT MATRIX XTX
C
        CALL INVERT(XTX,M,M)
C
C       CALCULATE VECTOR OF CONSTANTS (A) AND WRITE RESULT
C
        DO 90 I=1,M
        A(I)=0.
        DO 90 J=1,M
90      A(I)=A(I)+XTX(I,J)*XTY(J)
        WRITE(4,1200) (A(I),I=1,M)
```

```
C
C       USE CONSTANTS AND INDEPENDENT VARIABLES TO PREDICT VALUE
C       OF DEPENDENT VARIABLE.  WRITE ACTUAL DEPENDENT VARIABLE
C       AND PREDICTED DEP. VAR.  CALCULATE SUM OF SQUARES OF
C       DEVIATIONS AND WRITE RESULT.
C
        COST=0.
        DO 110 I=1,N
        YY(I)=0.
        DO 100 J=1,M
100     YY(I)=YY(I)+A(J)*X(I,J)
        WRITE(4,1300)TMP(NTC,I),Y(I),YY(I)
110     COST=COST+(Y(I)-YY(I))**2
900     WRITE(4,1400) COST
1000    FORMAT(2I5)
1100    FORMAT(4F10.0)
1200    FORMAT(1X,4HA = ,E15.6/1X,4HB = ,E15.6/1X,4HC = ,E15.6)
1300    FORMAT(3F12.3)
1400    FORMAT(//1X,7HCOST = ,F15.5)
        STOP
        END
```

```
        SUBROUTINE INVERT(A,ORDER,NA)
        INTEGER ORDER
        REAL A(3,3),B(20),C(20)
        INTEGER IP(20),IQ(20)
        N=ORDER
        DO 1 K=1,N
        PIVOT=0.
        DO 100 I=K,N
        DO 100 J=K,N
        IF(ABS(A(I,J))-ABS(PIVOT))100,100,101
101     PIVOT=A(I,J)
        IP(K)=I
        IQ(K)=J
100     CONTINUE
        IF(PIVOT)102,900,102
102     IPK=IP(K)
        IQK=IQ(K)
        IF(IPK-K)200,299,200
200     DO 201 J=1,N
        Z=A(IPK,J)
        A(IPK,J)=A(K,J)
201     A(K,J)=Z
299     CONTINUE
```

```
      IF(IQK-K)300,399,300
300   DO 301 I=1,N
      Z=A(I,IQK)
      A(I,IQK)=A(I,K)
301   A(I,K)=Z
399   CONTINUE
      DO 400 J=1,N
      IF(J-K)403,402,403
402   B(J)=1./PIVOT
      C(J)=1.
      GOTO 404
403   B(J)=-A(K,J)/PIVOT
      C(J)=A(J,K)
404   A(K,J)=0.
400   A(J,K)=0.
      DO 405 I=1,N
      DO 405 J=1,N
405   A(I,J)=A(I,J)+C(I)*B(J)
1     CONTINUE
C
C     REORDERING THE MATRIX
      K=N
      DO 500 KOUM=1,N
      IPK=IP(K)
      IQK=IQ(K)
      IF(IPK-K)501,502,501
501   DO 503 I=1,N
      Z=A(I,IPK)
      A(I,IPK)=A(I,K)
503   A(I,K)=Z
502   IF(IQK-K)504,500,504
504   DO 506 J=1,N
      Z=A(IQK,J)
      A(IQK,J)=A(K,J)
506   A(K,J)=Z
500   K=K-1
      RETURN
900   RETURN
      END
```

APPENDIX E

MAJOR VARIABLES USED IN PROGRAMS OF APPENDIX D

CKC - PID controller gain (K_c).

CP - Specific heat.

CU - Floating point sample current which is an average of NTCCP readings; calculated from ICSA.

FSIG - Floating point T/C value (in digital counts).

ICS - Integer used to sum sample current (in digital counts) from one specific heat calculation to another. (Reset to zero at each specific heat calculation.)

ICSA - Used to store sample current (in digital counts) after NTCCP additions to ICS.

IDSEC - Integer number of seconds since last specific heat calculation.

IDTK - Integer number of ticks (100 ticks/second) used to complete total time since last specific heat calculation to nearest 0.01 second.

INEC - Number of executions of CAL Ø 6 (program used to take data for specific heat) since last specific heat calculation.

IPCR - Controller sampling interval in ticks.

ISEC - Total number of integer seconds since starting of clock (used in calculation of IDSEC).

ISPAN - Number of digital counts equivalent to one 1000 μV unit of suppression.

ISPEC - Integer value (digital counts) representing sample T/C signal in program PID.

ITCR - Sample T/C sampling rate (in ticks) for specific heat data.

ITK - Number of ticks necessary to complete total time since starting of clock to nearest 0.01 second.

ITSIG - Used to store sampled T/C signals (as digital counts) taken by controller program PID.

IVS - Used to sum sample voltage (in digital counts) from one specific heat calculation to another.

IVSA - Used to store sample current (in digital counts) after NTCCP additions to IVS.

JDE - E_{i-2} in PID algorithm (equation 45).

JE - E_{i-1} in PID algorithm (equation 45).

JOF - Controlled offset of shield temperature from sample temperature (in digital counts).

JSUM - Used in least squares sum for linear fit of T/C data for specific heat calculation.

JTSIG - Integer sample T/C value (in digital counts) used in specific heat calculation.

K - Integer number of 1000 μVS. suppression being used at any given time.

L - Used to assign DR-90 relays, A/D converter channels, or D/A converter channels to a given line from the maxi panel to the lab mini-box.

M - Integer value corresponding to a controller output calculated in PID

MM - Used to close the data file which stores data (using STORE) collected by PID.

MSUM - Used in least squares sum for specific heat calculation.

NSUM - Used in least squares sum for specific heat calculation.

NTCCP - Number of times specific heat data is collected using CAL Ø 6 before a specific heat calculation is made.

NTICK - Number of ticks delay between closure of a multiplexer channel and reading the T/C value.

SMASS - Sample mass.

SUP - Amount of fixed suppression in μVS.

TD - Rate time for controller in PID.

TEMP - Floating point temperature (actual degrees).

TI - Reset rate for controller in PID.

VO - Floating point sample voltage which is an average of NTCCP readings; calculated from IVSA.

APPENDIX F

DERIVATION OF LEAST SQUARES EQUATION FOR CALCULATION OF TEMPERATURES USED IN THE SPECIFIC HEAT CALCULATION

The method of linear regression known as least squares is based upon minimizing the error of the sum of the squares of the deviations between the actual data points and the predicted points. Mathematically, this is given by

$$S = \sum_{i=1}^{N} (Y_i - Y_i')^2 \qquad \text{F-1}$$

where

Y_i = actual data point

Y_i' = predicted data point

N = total number of data points in fit

In calculating the temperatures used in the specific heat calculation, a linear form is assumed:

$$Y_i = a\, x_i + b \qquad \text{F-2}$$

Substituting this into F-1 yields:

$$S = \sum_{i=1}^{N} (Y_i - a\, x_i - b)^2 \qquad \text{F-3}$$

In order to minimize S, two conditions must prevail:

$$1.\ \frac{\partial S}{\partial a} = 0 \qquad \text{F-4}$$

$$2.\ \frac{\partial S}{\partial b} = 0$$

By applying F-4 to F-3, the "normal" equations of least squares are obtained.

$$a \Sigma x^2 + b \Sigma x = \Sigma x y \qquad \text{F-5}$$

$$a \Sigma x + b N = \Sigma y \qquad \text{F-6}$$

Here the subscripts have been dropped as well as limits on summation terms since it is understood that they are performed over all data points (i = 1 to N).

Equations F-5 and F-6 can be set as matrix forms by:

$$\begin{bmatrix} \Sigma x^2 & \Sigma x \\ \Sigma x & N \end{bmatrix} \cdot \begin{bmatrix} a \\ b \end{bmatrix} = \begin{bmatrix} \Sigma x y \\ \Sigma y \end{bmatrix} \qquad \text{F-7}$$

The solution to this is:

$$a = \frac{N \Sigma x y - \Sigma x \Sigma y}{N \Sigma x^2 - (\Sigma x)^2} \qquad \text{F-8}$$

$$b = \frac{\Sigma x^2 \Sigma y - \Sigma x \Sigma xy}{N \Sigma x^2 - (\Sigma x)^2} \qquad \text{F-9}$$

Substituting F-8 and F-9 into F-2, the predicted value of the dependent variable is:

$$Y_i = \frac{N \Sigma x y - \Sigma x \Sigma y}{N \Sigma x^2 - (\Sigma x)^2} X_i + \frac{\Sigma x^2 \Sigma y - \Sigma x \Sigma xy}{N \Sigma x^2 - (\Sigma x)^2} \qquad \text{F-10}$$

In predicting the temperature, data points are taken at regular intervals; therefore, x can be replaced by iT (T equaling sampling time) and y by the T/C emf (E). Substituting these into F-10, the following equation is obtained.

$$E_i = \frac{(N\,T\Sigma i\,E - T\Sigma i\Sigma E)\,i\,T + T^2\Sigma i^2\Sigma E - T^2\Sigma i\Sigma i\,E}{N\,T^2\,\Sigma\,i^2 - T^2\,(\Sigma\,i)^2} \qquad \text{F-11}$$

It can be noted that the sampling time (T) can be factored out of F-11 and disappears from the equation. Then by regrouping, F-11 becomes:

$$E_i = \frac{(i\,N - \Sigma\,i)\,\Sigma\,i\,E + (\Sigma\,i^2 - i\,\Sigma\,i)\,\Sigma\,E}{N\Sigma\,i^2 - (\Sigma\,i)^2} \qquad \text{F-12}$$

This form permits the calculation of any data point from predetermined constants by specifying the number of data points in the fit. For example, the equations for E_1, and E_{20} for a 20 point data set are:

$$E_1 = -0.014286\ \ \Sigma\,i\,E + 0.2\ \ \Sigma\,E \qquad \text{F-13}$$

$$E_{20} = 0.014286\ \ \Sigma\,i\,E - 0.1\ \ \Sigma\,E \qquad \text{F-14}$$

By calculating the sums ΣiE and ΣE and then predicting these values, the average temperature of the range and the temperature rise (E_{20} - E_1) can be calculated for use in the specific heat calculation.

For calculation of the sum of the squares S, it is only necessary to apply F-1 using the following for E_i (assuming a 20 point data set):

$$E_i = (0.0015038 \quad i - 0.015789) \Sigma i E - (0.0157895 \quad i - 0.2157895) \Sigma E \qquad \text{F-15}$$

APPENDIX G

DETERMINATION OF THE OVERALL TRANSFER FUNCTION BETWEEN A COMPONENT TEMPERATURE AND ITS POWER INPUT

For simplicity, consider a component with an internal heater and heat loss to only one other component. The time domain equations for this are:

$$M_1 C_{P_1} \frac{d T_1}{d \theta} = P_1 - K_{12} (T_1 - T_2) \qquad \text{G-1}$$

$$M_2 C_{P_2} \frac{d T_2}{d \theta} = K_{12} (T_1 - T_2) - K_{23} (T_2 - T_3) \qquad \text{G-2}$$

(This is similar to the form of the sample heater and the sample with heat loss to the nickel shield G3 under linearized conditions.)

The LaPlace domain equations for these are:

$$t_1(s) = (K_1 P_1 + t_2) \cdot \left(\frac{1}{1 + \tau_1 s}\right) \qquad \text{G-3}$$

$$t_2(s) = (K_{12} t_1 + K_{23} t_3) \cdot \left(\frac{K_2}{1 + \tau_2 s}\right) \qquad \text{G-4}$$

where

$$K_1 = \frac{1}{K_{12}}$$

$$K_2 = \frac{1}{K_{12} + K_{23}}$$

These equations are represented in block diagram form in Figure G-1. By use of standard block diagram algebra, it can be shown that:

$$t_2(s) = \frac{K_1 K_{12} K_2 P_1 + K_{23} K_2 (1 + \tau_1 S) t_3}{\tau_1 \tau_2 S^2 + (\tau_1 + \tau_2) S + (1 - K_{12} K_2)} \qquad \text{G-5}$$

From G-4:

$$K_2 = \frac{1}{K_{12} + K_{23}} \qquad \text{G-6}$$

then

$$1 - K_{12} K_2 = \frac{K_{23}}{K_{12} + K_{23}} \qquad \text{G-7}$$

This quantity is greater than zero; therefore, equation G-5 will have a stable response.

By considering a step of magnitude P in P_1, it can be shown using the final value theorem (25, 26, 27, 28, 29) that:

$$t_2(\infty) = \frac{K_1 K_{12} K_2 P}{1 - K_{12} K_2} = \frac{P}{K_{23}} \qquad \text{G-8}$$

Also a step in t_3 (of magnitude T) will produce:

$$t_2(\infty) = \frac{K_{23} K_2 T}{1 - K_{12} K_2} = T \qquad \text{G-9}$$

Although the response in a step change in t_3 behaves as experienced, the response produced by a step change in P_1 is contrary to the observed ramp which is produced. The

response of t_2 to P_1 (predicted by G-5 and G-8) is a second order lag with a gain of $1/K_{23}$. By analyzing G-2, this will be the occurrance if T_3 is maintained at some initial value. Eventually, the term $K_{23}(T_2 - T_3)$ will be equal in magnitude to $K_{12}(T_1 - T_2)$ and T_2 will reach a steady state rate $(dT_2/d\theta = 0)$. But under controlled conditions, T_3 is maintained approximately equal to T_2. By placing T_2 and T_3 equal to each other, Figure G-1 becomes as shown in Figure G-2 after resolving the feed back loop. In Figure G-2:

$$K_3 = \frac{K_2}{1-K_{23}K_2} = \frac{1}{K_{12}} \qquad \text{G-10}$$

$$\tau_3 = \frac{\tau_2}{1-K_{23}K_2} = \frac{(K_{12} + K_{23})\ \tau_2}{K_{12}} \qquad \text{G-11}$$

Now the response of t_2 to P_1 is:

$$\frac{t_2}{P_1} = \frac{K_1\ K_{12}\ K_3}{\tau_1\ \tau_3 S^2 + (\tau_1 + \tau_3)S + (1-K_{12}K_3)} \qquad \text{G-12}$$

But from G-10, $K_3 = 1/K_{12}$; therefore, G-12 becomes:

$$\frac{t_2}{P_1} = \frac{K_1}{\tau_1\ \tau_3\ S^2 + (\tau_1 + \tau_3)S} \qquad \text{G-13}$$

which is of the form

$$\frac{t_2}{P_1} = \frac{K}{S\ (1 + \tau_P\ S)} \qquad \text{G-14}$$

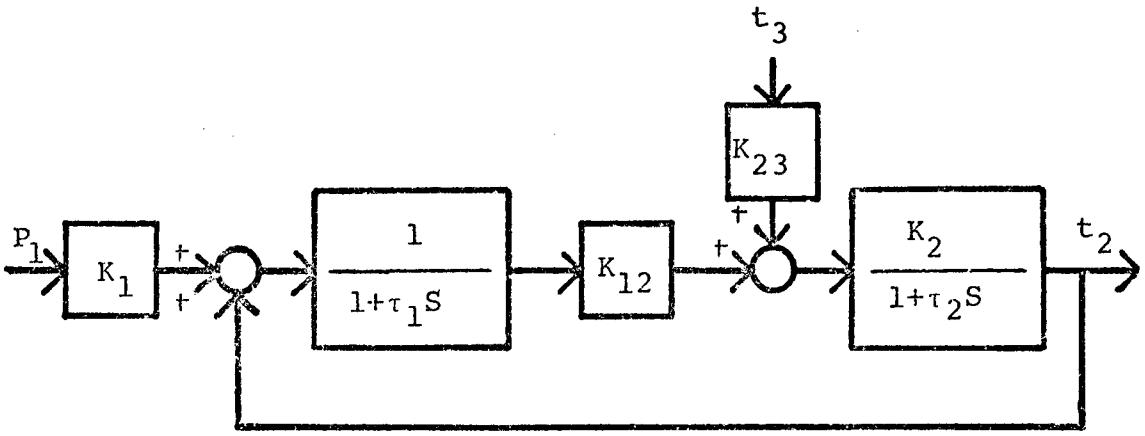


Figure G-1. Block Diagram for Equations G-3 and G-4.

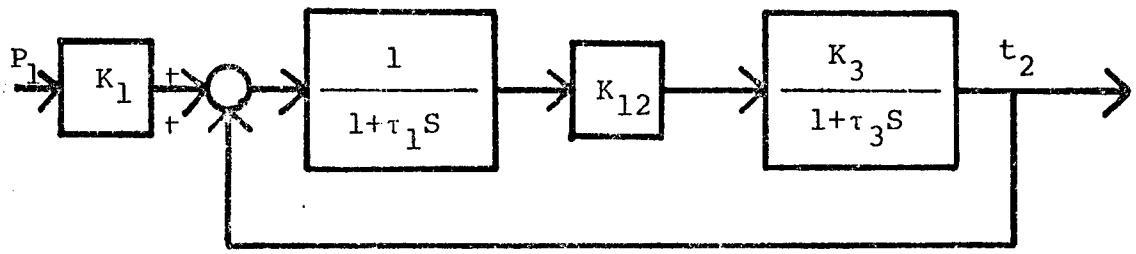


Figure G-2. Block Diagram of Figure G-1 with t_3 Equal to t_2.

APPENDIX H

PROOF OF THE EQUIVALENCY OF THE RMS VALUE OF A WAVE AND ITS STANDARD DEVIATION

The root of the mean of the square (RMS) of a periodic waveform (such as a sine wave) is approached by the standard deviation of that waveform for a large number of sampled points.

By definition the RMS value of a waveform is given by

$$RMS = \frac{1}{T} \int_0^T e^2 \, dt \qquad H\text{-}1$$

where

T = length of the period

The definition of the standard deviation is given by

$$s_X = \frac{\sum_{i=1}^{N} (X_i - \bar{X})^2}{N-1} \qquad H\text{-}2$$

where

N = number of sampled data points

$\bar{X}$ = average value of X

By considering Figure H-1, it can be seen that a new function can be formed by use of:

$$e_i = X_i - \bar{X} \qquad H\text{-}3$$

Taking the expected value of each side of equation H-3, it can be seen that the mean of the function e ($\bar{e}$) will

be equal to zero. By noting that the addition of a constant to a data set does not change its standard deviation, then the standard deviation of data set X (s_X) will be identical to that of data set e (s_e); therefore:

$$s_e = s_X = \frac{\sum_{i=1}^{N} (e_i - \bar{e})^2}{N-1} = \frac{\sum_{i=1}^{N} e_i}{N-1} \qquad \text{H-4}$$

This can also be found by direct substitution of equation H-3 into H-2.

By multiplying both numerator and denominator of equation H-4 by the distance between data points (Δt) of Figure H-1, equation H-4 becomes:

$$s_e = \frac{\sum_{i=1}^{N} e_i^2 \Delta t}{(N-1)\ \Delta t} \qquad \text{H-5}$$

Noting that for N data points there are N-1 line segments between them, then (N-1) Δt is equal to the total period length T; therefore,

$$s_e = \frac{1}{T} \sum_{i=1}^{N} e_i^2 \Delta t \qquad \text{H-6}$$

By letting $N \to \infty$, the summation becomes an integral and $\Delta t \to dt$. This permits equation H-6 to be rewritten as:

$$s_e = \frac{1}{T} \int_o^T e_i^2 dt \qquad \text{H-7}$$

which is exactly equal to the definition of the RMS value .

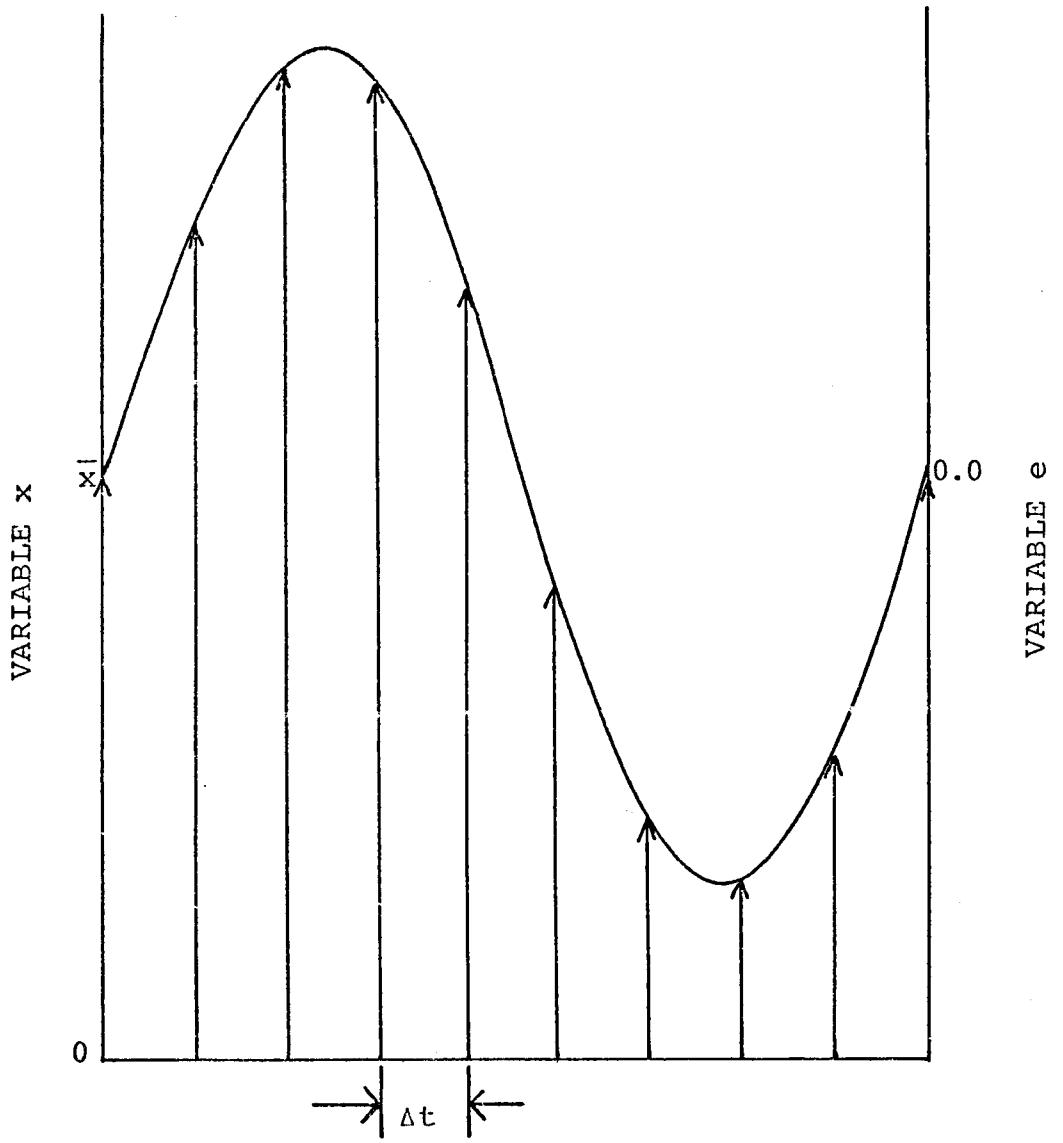


Figure H-1. Diagram Depicting Equivalence Between Variable x with Mean $\bar{x}$ and Variable e (Defined by $e=x-\bar{x}$) with Zero Mean.

APPENDIX I

VELOCITY ERROR COEFFICIENT BETWEEN A RAMP AND ITS FILTERED VALUE

In the LaPlace domain, the process equation is given by:

$$\frac{T(S)}{P(S)} = \frac{K}{S(1 + \tau_P S)} \qquad \text{I-1}$$

Using a set input of power of magnitude P, then:

$$T(S) = \frac{K P}{S^2(1 + \tau_P S)} \qquad \text{I-2}$$

The error between this and its filtered value is given by:

$$E(S) = T(S) - T(S) \cdot \frac{1}{1+ \tau_D S} \qquad \text{I-3}$$

or

$$E(S) = T(S) \left[1 - \frac{1}{1+ \tau_D S}\right] \qquad \text{I-4}$$

which is equal to

$$E(S) = T(S) \cdot \frac{D S}{1+ \tau_D S} \qquad \text{I-5}$$

or

$$E(S) = \frac{K P \tau_D}{S(1+\tau_P S)(1+\tau_D S)} \qquad \text{I-6}$$

The error after a very long time (E (∞)) is given by:

$$E(\infty) = \lim_{S \to 0} S\,E(S) \qquad \text{I-7}$$

which is equal to:

$$E(\infty) = \lim_{S \to 0} \frac{K\,P\,\tau_D}{(1+\tau_P S)(1+\tau_D S)} \qquad \text{I-8}$$

or:

$$E(\infty) = K\,P\,\tau_D \qquad \text{I-9}$$

which varies linearly with the filter time constant τ_D.

VITA

William Merle Cash was born in Milan, Tennessee, on February 3, 1950. He attended elementary schools in that city and was graduated from Milan High School in 1968. The following September he entered the University of Tennessee where he graduated in June of 1973 with a Bachelor of Science in Chemical Engineering.

He is married to the former Miriam Elizabeth Toomey.