Final Report *October 1982*

DEVELOPMENT OF A PROTOTYPE AUTOMATIC CONTROLLER FOR LIQUID COOLING GARMENT INLET TEMPERATURE

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CONTRACT NAS 9-16487

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ABSTRACT

The development and limited testing of a computer control of a liquid cooled garment (LCG) inlet temperature is described. An adaptive (computer) model of the LCG is used to predict the heat-removal rates for various inlet temperatures. The predictions can be used to choose an inlet temperature that falls into a comfort-zone of the type that was derived by Kuznetz in earlier studies at NASA.

An experimental system that contains a microcomputer has been constructed. LCG inlet and outlet temperatures and the heat-exchanger outlet temperature form the inputs to the computer. The computer commands a valve to control the LCG inlet temperature. The adaptive-model-prediction method of control has proved successful during tests on a number of subjects where the inlet temperature was automatically chosen by the computer. The program can be implemented in a microprocessor of a size that is practical for a life-support back-pack.

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I INTRODUCTION

A number of techniques have been evaluated for providing a control algorithm for automatic control of the inlet temperature to a liquid cooling garment (LCG).[2,5,8] The closed loop control system will require monitoring of appropriate system (physiological and/or LCG) parameters, processing of these parameters in some manner to generate a control signal, adjustment of the LCG heat removal rate in response to the control signal, and subsequent monitoring and adjustment to insure that the desired response is obtained.

The heat removal requirement for a given LCG is a function of the metabolic rate, the desired thermal comfort conditions, and the heat exhange with the environment. However, since it is relatively easy to minimize heat exchange with the environment, the metabolic heat is the primary concern for a practical system.

The following physiological or system parameters could be monitored and used, with appropriate control algorithms, to provide automatic control of thermal comfort while using an LCG. Each will be briefly discussed to provide the rationale leading to the selection of the parameters and control model developed during the present research.

A. Body Temperature Monitoring

The body temperatures most suitable for providing an input signal to a controller are the core temperature as indicated by a rectal or ear canal probe and/or various skin temperature. However, there are problems associated with these for use in an actual operational EVA system in addition to some physiological drawbacks.

Monitoring of body temperatures requires the attachment of temperature sensors to the subject. This is undesirable for a system which will be used for hundreds of manhours on each mission. In addition, the time constant for the core temperature to respond to a sudden change in metabolic rate is on the order of 10 minutes[3,6,8] so that the control algorithm must anticipate the body's response to changes in inlet temperature. Skin temperature(s) is not a simple function of metabolic rate[7] and thus would be difficult to use by itself as the only input to an LCG controller. A combination of core and surface (skin) temperature could probably be made to work well,[8] but would be difficult to use for a practical system.[1]

B. Direct Metabolic Rate Monitoring

If the metabolic rate could be directly determined, it would provide an excellent input for an automatic controller. Once the characteristics of a particular LCG have been determined, the quantity of heat which must be removed by the LCG to maintain thermal equilibrium at any metabolic rate would be precisely known and the time constant for response is quite small (approximately 30 s)[8]. However, the precise determination of metabolic rate using equipment suitable for integration into a Portable Life Support System (PLSS) is very difficult.

A controller using the oxygen consumption rate as a measure of metabolism was investigated[8] and the performance was satisfactory, but the equipment required to implement this approach for a practical system is still unavailable. This is also true of systems that measure the CO_2 production rate.

The rate of decay of pressure in the PLSS O_2 supply could also be used to indicate metabolic rate.[4] However, this is also considered impractical since the rate of decay is not very sensitive to relatively small changes in metabolic rate and factors such as suit leakage cannot be easily accounted for.

C. Sweat Rate Monitoring

If the instantaneous sweat rate could be reliably determined, it would provide an excellent control signal. The sweat rate responds quickly to changes in metabolic rate and it provides a d'-ect indication of the subject's thermal state. That is, ' n sw ' rates are a clear indication of a need for cooling. A swe.. rate (including respiratory evaporation) of about 50-100 ml/h has been suggested as appropriate for thermal comfort,[4,8] while sweat rates as high as 4 l/h have been reported[7] during severe thermal stress.

There are two basic ways of determining the sweat rate of a subject who is exercising in an impermeable suit. The local sweat rate from small skin segments can be measured and used with appropriate weighting functions to calculate the whole body sweat rate, or the total moisture evaporated into the ventilating air stream can be determined by measuring the air flow rate and the change in specific humidity.

The first method suffers from the requirement for instrumentation of the subject and the lack of reliable humidity cells for use in an operational system. The second method, as explored by Chambers,[2] would be well-suited for an operational system if a reliable, compact humidity measurement system was available. Currently available systems are not sufficiently developed for use in an operational EVA system.[9]

D. <u>LCG Heat Transfer Rate Monitoring</u>

The actual quantity of heat removed bv the LCG can be easily determined by measuring the water flow rate and the difference between the inlet and outlet temperature (ΔT). Since the relationship between heat removal at equilibrium and the total metabolic rate can be determined experimentally, the LCG heat transfer rate can be used to indicate the total metabolic rate. Similarly, the time rate of change (time derivatives) of the LCG heat transfer indicates the future trends in metabolic rate. Since the water flow rate will be constant in an actual EVA system, information on the LCG ΔT can be used as a controller input. Reliable temperature transducers are readily available and no subject instrumentation is required to implement such a control system.

Control stability can be further improved if an additional temperature measurement, such as heat sink outlet temperature, or some subject temperature is added.

The LCG ΔT concept investigated by Kuznetz[5] has been selected for further development since it requires no subject instrumentation and is therefore well-suited for use in an operational EVA system.

Although the instrumentation required to provide the controller inputs is very simple, a serious obstacle related to the long time constant of the LCG/subject system must be overcome. The delay between changes in metabolic heat production and the establishment of a new equilibrium LCG ΔT can be as much as 1 h,[4,5] this requires the use of a sophisticated controller transfer function that essentially predicts the future LCG heat transfer needed for comfort based on trends in the current data.

This control scheme has been tested by Kuznetz[5] both analytically and experimentally using human subjects. However, the human tests, which were intended only to demonstrate system feasibility, were done in an open loop, semi-manual mode. That is the instantaneous controller input temperatures were determined and manually entered into a computer which then calculated the new LCG inlet temperature set point and displayed it to the experimenter. A manual valve was then adjusted to obtain the desired water temperature.

A variety of metabolic rate profiles, including some based on actual EVA experience, were then performed. The experimental results showed that this control scheme was able to maintain the subjects in thermal equilibrium for the full range of expected metabolic rates. Body heat storage and sweat rates were commensurate with comfort, and the subjective reports also indicated thermal comfort.

The program discussed in this report combined the results of this exploratory work by Kuznetz[5] with modern adaptive control techniques that can be implemented on a microprocessor. A closed loop LCG controller was successfully developed and tested. The present program uses the water temperatures previously discussed as the input parameters. However, the adaptive control logic that has been developed could be altered to use inputs from humidity or CO_2 sensors if suitable transducers are developed in the future.

Adaptive techniques to estimate the transfer function between the LCG inlet temperature, T_i, and the difference, ΔT, between T_i and outlet temperature, T_o, were investigated. This transfer function can change with time; therefore, the controller must be able to track the changes and make appropriate adjustments to the control based on the changed transfer function. A brief technical description of Kuznetz's previous work in this area and how it relates to the present project follows.

Figure 1 is reproduced from Kuznetz. The data that are plotted were obtained from empirical measurements and from a highly regarded computer model[3] that is in use at the NASA Johnson Space Center (JSC). The horizontal axis gives the metabolic rate in watts. The left-hand vertical axis gives the LCG heat removal rate in watts when 109 l/h are flowing through the LCG; the right-hand vertical axis gives ΔT. The five curves are plots of ΔT as a function of the metabolic rate for a constant T_i. The numbers near points on the curves indicate the stored body heat in kilojoules (Watthours) for the indicated metabolic rates. There is a well-established comfort zone that relates a comfortable body heat storage with a given metabolic rate. This comfort zone is superimposed upon the five curves. All curves are for steady-state conditions.

It is possible to go from a ΔT on the right-hand axis across to a point on the curve at the center of the comfort zone to determine an inlet temperature that will keep the subject within the zone. The T_i that is necessary to stay at the center of the comfort zone can be plotted against ΔT, as shown in Figure 2 (also reproduced from Kuznetz). This curve is very nearly a straight line.

During steady-state conditions, ΔT will be proportional to the metabolic rate because the heat that is removed is proportional to

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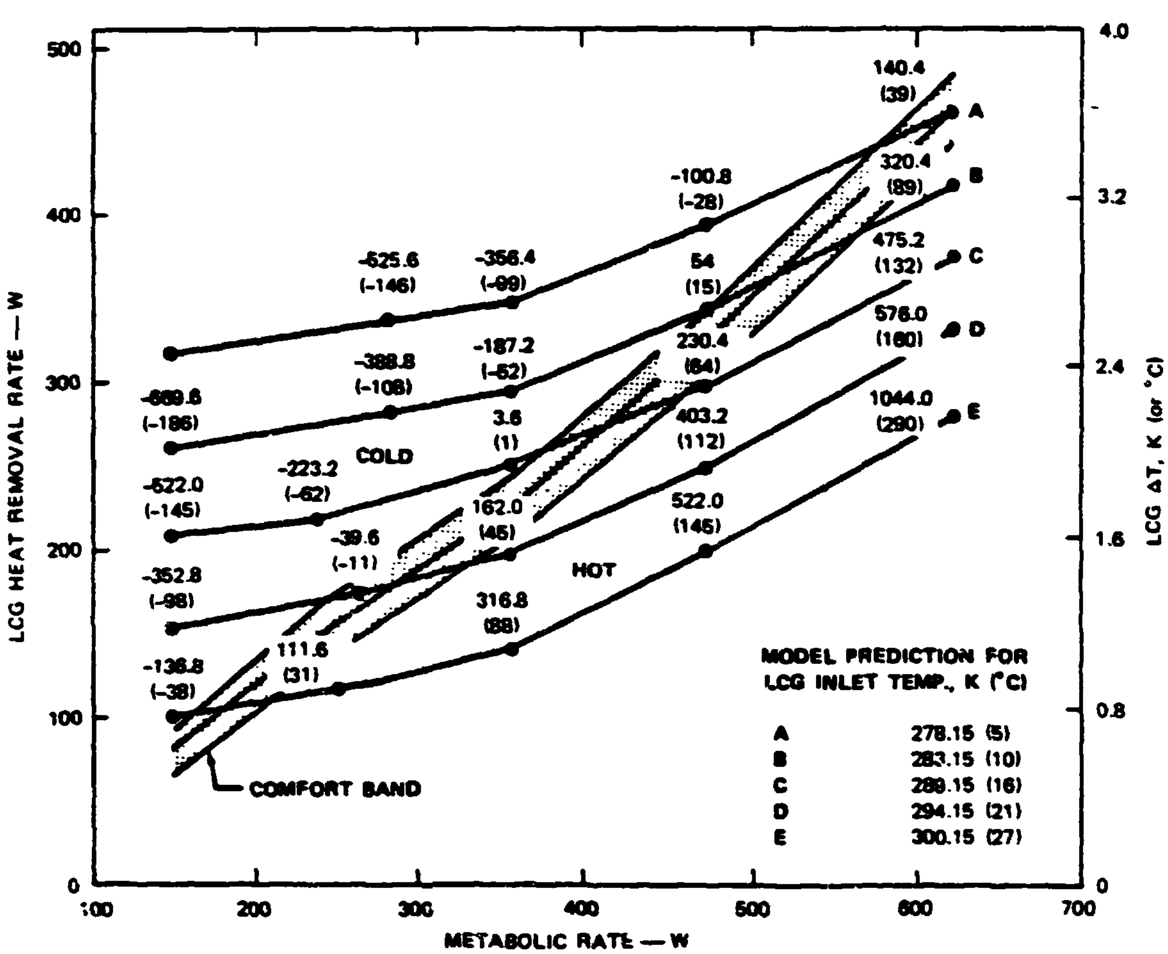


FIGURE 1 PREDICTION OF LCG HEAT REMOVAL (or LCG ΔT) AS A FUNCTION OF METABOLIC RATE. The numbers adjacent to the lines of constant LCG inlet temperature represent total body heat storage predictions in kilojoules (Watt hours) at metabolic rates of 146, 234, 352, 469, and 586 W. Comfort zone -- body heat storage vs metabolic rate.

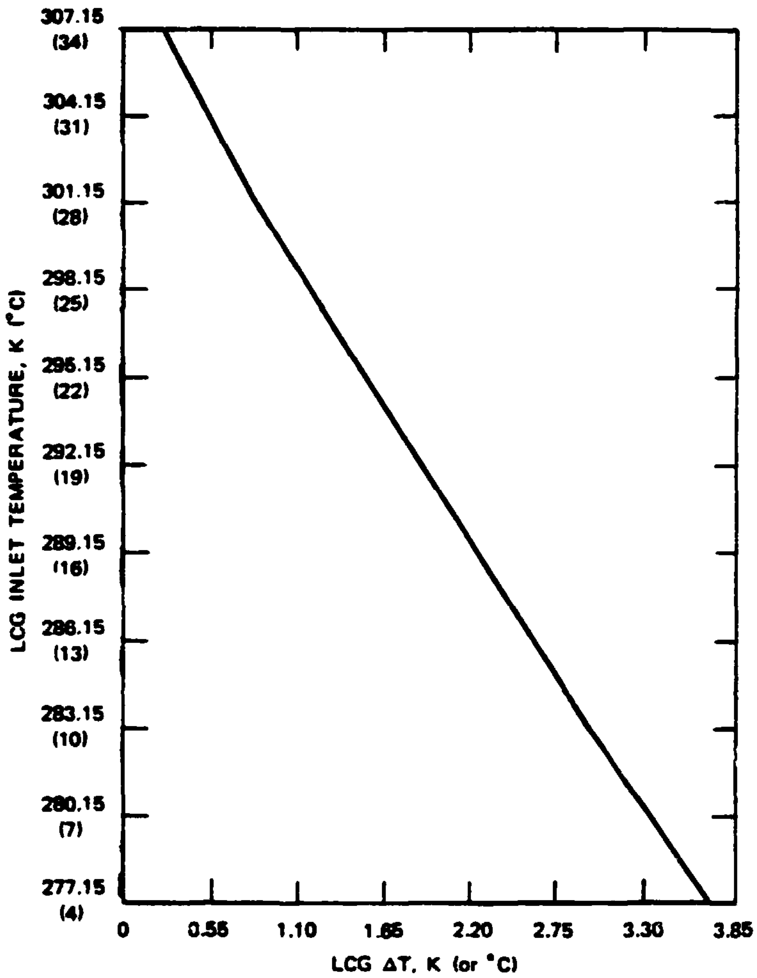


FIGURE 2 LCG INLET TEMPERATURE IN RELATIONSHIP TO LCG ΔT AT THE COMFORT LEVEL

the difference between the inlet and outlet water temperatures. If there were no dynamics involved, T_i could be adjusted for a given ΔT (or a given metabolic rate) to fall on the curve. In reality, the dynamics are highly complex so that a simple change in T_i produces complex variations of ΔT even at a constant metabolic rate. Computer experiments with the NASA JSC model were performed to begin to quantify these effects. When T_i was moved to fall on the curve of Figure 2, the ΔT moved away from the curve with a new ΔT. When successive new values of T_i were chosen to move back on the curve, the system appeared unstable.

By similar procedures Kuznetz has attempted to derive the change in ΔT versus the size of a step change in T_i. This allows the construction of a first-order model. He used the same technique to derive coefficients for a smaller second-order model. A second-order differential equation was programmed and tested with a subject in a LCG. In these experiments, T_i and $\dot{\Delta T}$ were measured. A new T_i was entered into the differential equation and a new ΔT was obtained. This process was iterated until a ΔT and a T_i were obtained that fell on the curve in Figure 2. The T_i that was indicated to be correct by the solution to the differential equation was set by hand into the LCG.

We also used a modeling technique in the SRI study; however, our technique is more general and more rigorous and will converge to the comfort zone more quickly. In addition, we developed a system to control a differential valve that shunts water past the heat exchanger (to control the inlet temperature) with the computer for a fully automatic temperature control.

In this project, we use well-known adaptive control techniques. Figure 3 is a block diagram that illustrates the concept. We assume that the LCG (the garment and the enclosed subject) can be modeled as a linear system, and that the model can be implemented as a computer subroutine. The model input is T_i and the model estimates ΔT based only on the past values of T_i. A subroutine or algorithm adjusts the model's parameters to minimize the average of the square of the

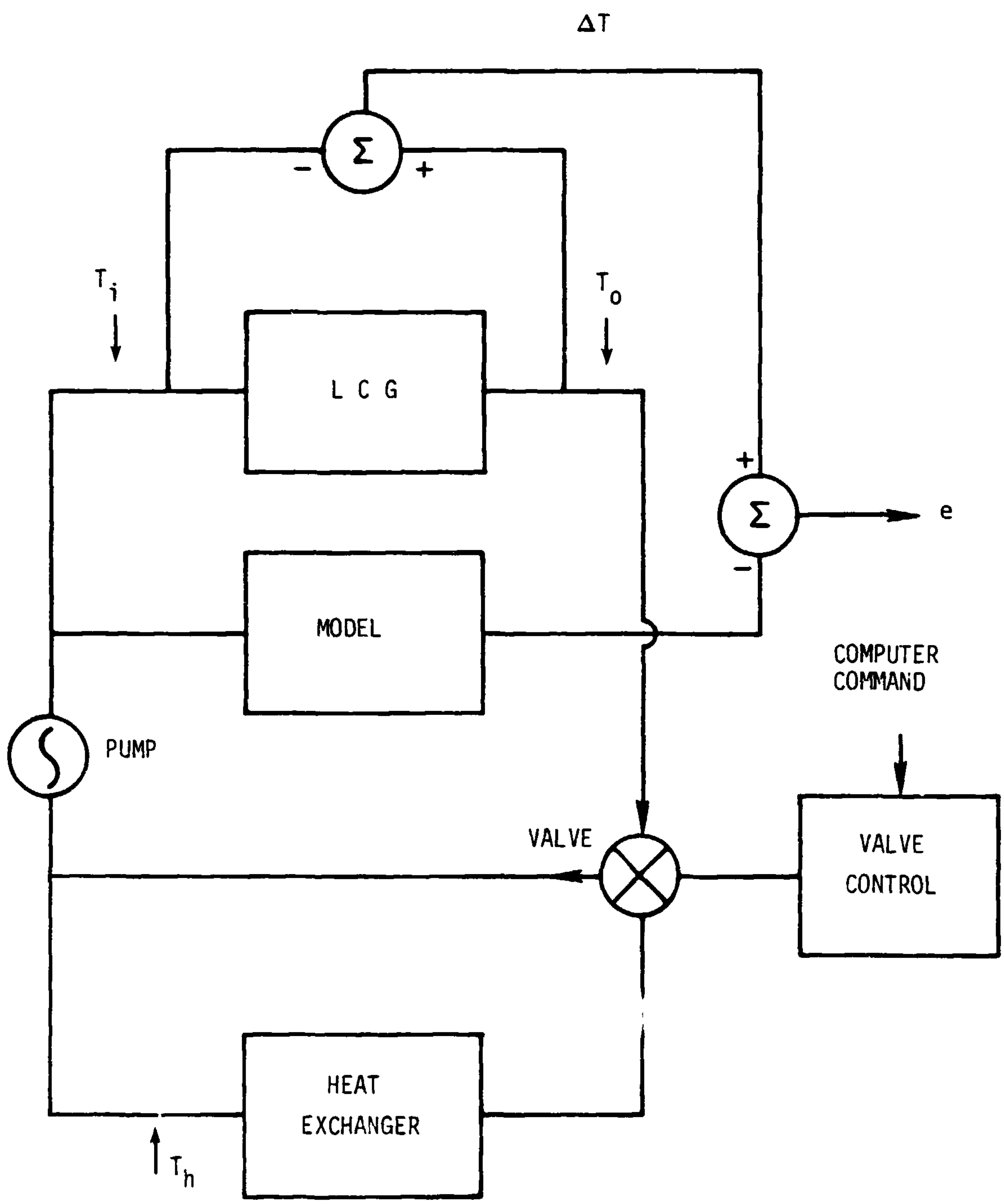


FIGURE 3 BLOCK DIAGRAM SHOWING THE COMPUTER MODEL

difference between the estimated ΔT and the actual ΔT. If the model were perfect, a test T_i could be entered into the model by the computer and the model could be run ahead in time to determine what the ΔT would be for that T_i. If the combination did not fall into the comfort zone, other values of T_i could be chosen until a combination was found that did fall into the zone. The LCG inlet temperature would then be adjusted to equal the successful test T_i.

In practice, of course, it is not possible to make a perfect model, but we show in later sections that it is possible to implement one that has sufficient accuracy. The iterations to pick a new T_i can be done in several seconds so that this type of control can be done in "real time."

The following were the objectives for a first year of the study:

- The hardware for a computer driven LCG temperature control was to be designed and constructed.
- There was to be the preliminary development of a computer algorithm to control the LCG temperature.
- There was to be limited testing on human subjects.

These objectives have been met, and the developments will be described in the remaining sections. Section II contains a description of the experimental system including the computer control. Section III contains an overview of the computer program that will explain the program's organization and design philosophy. Sections IV and V explain in detail the valve control algorithm, the adaptive model, and the algorithm that determines T_i with reference to the model. Sections VI-VIII describe the experimental results, recommendations for further work, and the Appendix contains a listing of the program.

II EXPERIMENTAL SYSTEM DESCRIPTION

Figure 4 is a schematic of the experimental LCG temperature control system. There is a constant flow through the LCG (nominally 109 l/h), and water is shunted around the heat exchanger by the differential valve; if T_i is to be lowered, less water is shunted. Three water temperatures (T_i, T_o, and the heat exchanger output, T_h) are A/D converted and entered into the computer.

An output from the computer is D/A converted to form the analog input to an analog servocontrol for the valve position. The three temperatures are processed by the computer to calculate a "command inlet temperature", T_c, which the computer has determined to be the appropriate temperature for subject comfort. The computer adjusts T_i toward T_c with a control algorithm that includes a closed loop control through the computer. (The analog valve servo is in this loop.)

The computer is a Radio Shack TRS-80 Model I. It was chosen for the following reasons. We wished to demonstrate the concept with the microprocessor-based computer (preferrably a Z-80 microprocessor) to show that a microprocessor has sufficient speed (a flight system would use a microprocessor), and that memory requirements would be reasonable. Commercial multichannel A/D and D/A converters that plug into the TRS-80 are available, and there are commercial temperature probes that are compatable with the A/D converter.

A BASIC compiler for the TRS-80 Model I which compiles programs that also run in the interpretive mode is available from Microsoft. Debugging is greatly facilitated when the program can be run in the interpretive mode prior to compiling. The compiled program runs an estimated five to ten times faster than the interpreter program. Our direct experience when comparing the two versions of the same program showed that the interpreter version is too slow by a factor of four.

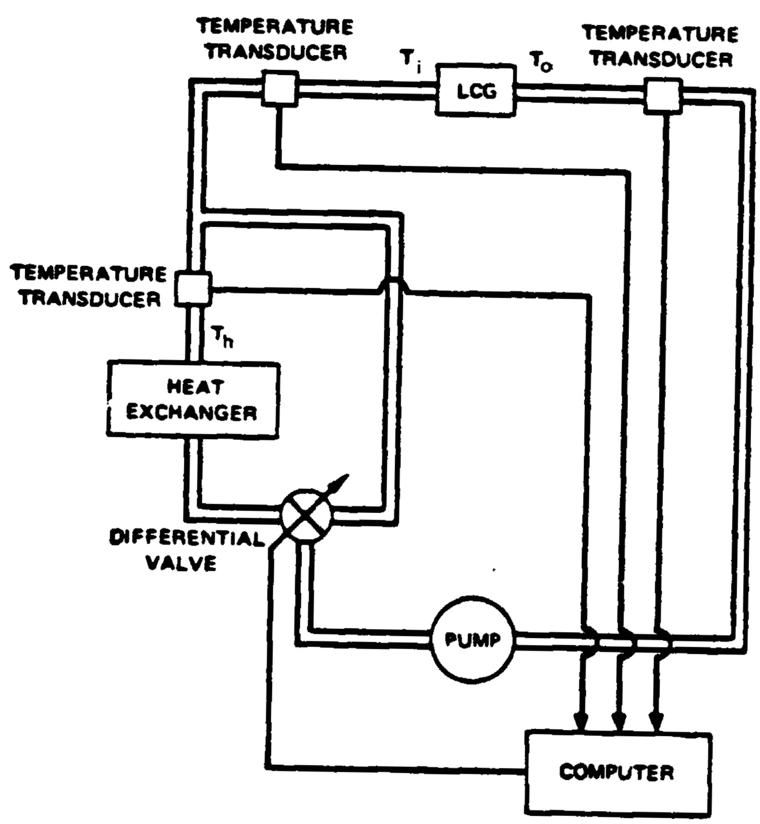


FIGURE 4 SYSTEM SCHEMATIC

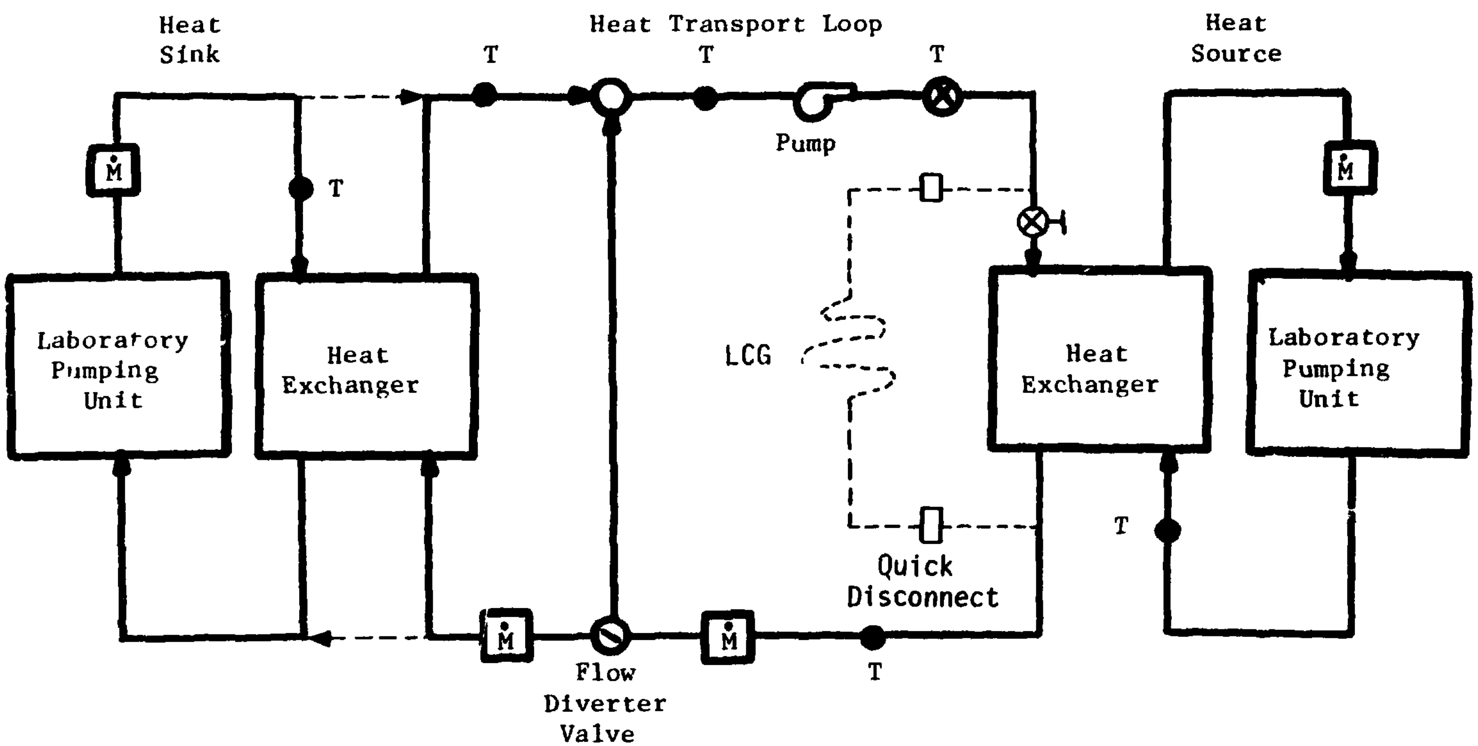
A. <u>The Mechanical Subsystem</u>

The breadboard system schematic is shown on Figure 5. The laboratory pumping units are each capable of supplying up to 3.8 l/min at any temperature from 5°C to 40°C. The heat exchangers are brass, tube-in-shell, commercial units puchased from Exergy Incorporated, (Part No. 012-122). Standard 3/8 in aluminum tubing, Swage fittings, and connectors were used for all plumbing connections. A variable speed Micropump was used to set the LCG flow rate at 1.9 l/min. (240 lb/hr). Rotameters were used to measure the flow rate. The flow diverter valve is the same one used by Chambers (Ref. 2).

This system, including both heat exchangers, was used for the initial checkout tests described elsewhere. It was then modified for use with an actual LCG, as shown by the dashed lines. The LCG replaces the right heat exchanger and pumping unit.

The initial human tests were performed using the left pumping unit and heat exchanger as shown. However, it was found that, due to the approximately 5°C temperature drop across the heat exchanger, it was not possible to reduce the minimum LCG inlet temperature to the desired 5 to 7°C. This heat exchanger was then bypassed as shown by the dotted lines on the left side of the schematic. The circulation pump in the laboratory pumping unit was disconnected and the Micropump was used to pump through the system.

In general this system worked satisfactorily. The primary problems encountered were leakage and slow response of the diverter valve. The effect of this on the test results is discussed elsewhere. The large mass of water in the pumping unit's reservoir, about 8 l, must change temperature when the diverter valve position is changed. This introduces a thermal time constant into dynamic performance of the system that is quite different from an actual PLSS. It would be highly desireable to go back to the original system configuration with the addition of a more effective, aerospace-type compact heat exchanger for any further work. This



• T = Temperature Transducer

M = Flow Transducer

FIGURE 5 BREADBOARD SYSTEM SCHEMATIC

would more accurately simulate the transient thermal response of an actual PLSS heat sink.

B. The Control Electronics

Figure 6 is a block diagram of the control system electronics. The water temperatures are measured by silicon diode temperature probes that are inserted into the water circuit. A 16-channel, 8-bit A/D converter is connected to the TRS-80 to sample T_i, T_o, T_h and ΔT. A measurement resolution of $0.2^{\circ}C$ is sufficient for the first three temperatures, however, the resolution of ΔT should be better than $0.05^{\circ}C$.

Eight-bit conversion allows a resolution of $0.16^{\circ}C$ over a $40^{\circ}C$ range for T_i, T_o and T_h. To increase the resolution for ΔT, the difference between the analog outputs of the T_o and T_i probes, is developed with an operational amplifier. The amplifier output is A/D converted to 8 bits. The resolution is $0.04^{\circ}C$ over a $10^{\circ}C$ range.

An analog servo controls the position of the differential valve. The input to the analog servo is from a 12-bit D/A converter, and the input to the converter is the valve position command from the computer. Figure 7 is the schematic of the analog control. Valve shaft position as sensed by a potentiometer is fed back through an active equalizing network. The 12-bit digital word is output from the computer as a sequence of three 4-bit words (most significant bits first) that are sequentially stored in a 12-bit latch (see Figure 8), prior to the D/A conversion. The servo system can drive the valve over the complete range in 5 s.

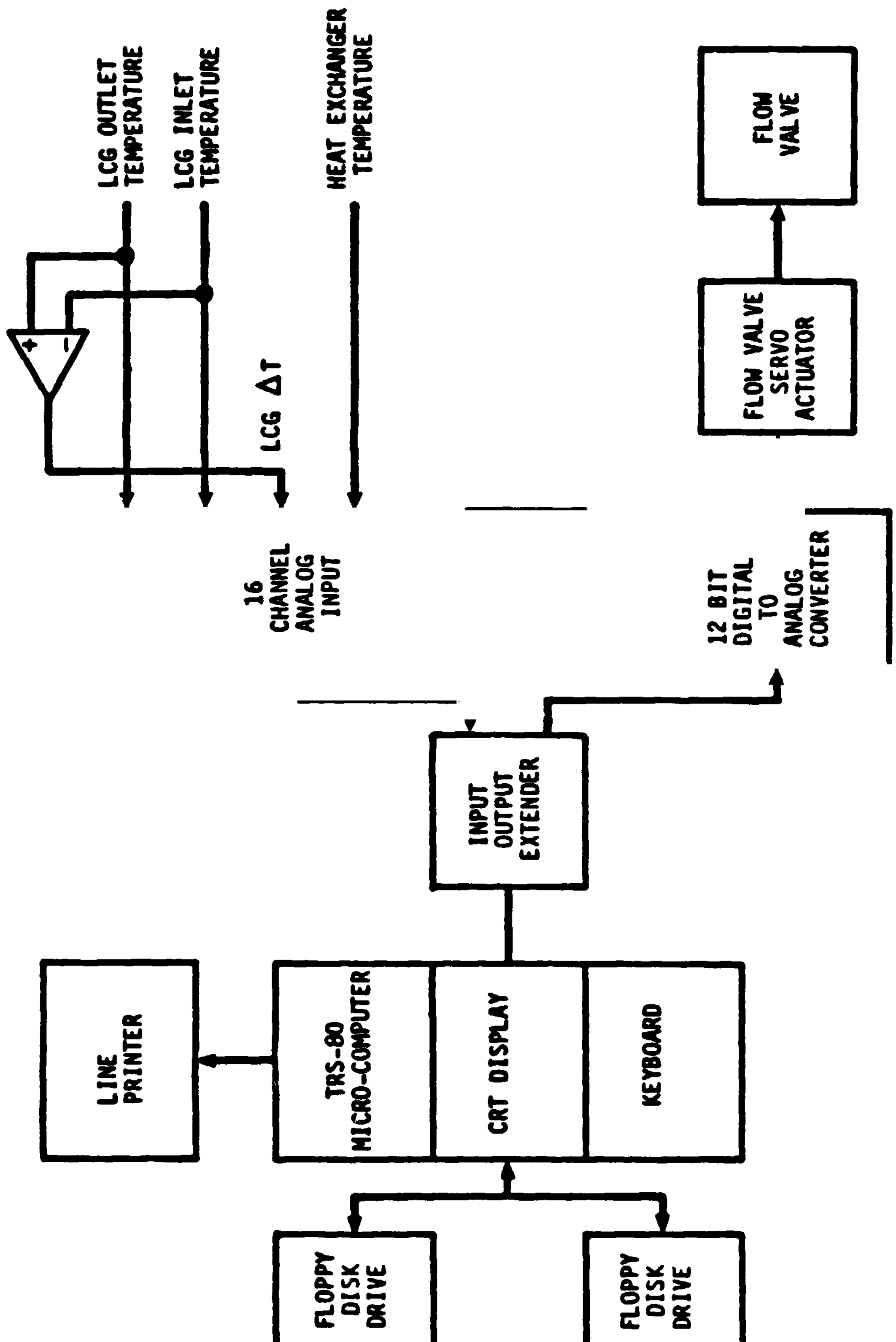


FIGURE 6 ELECTRONIC SYSTEM BLOCK DIAGRAM

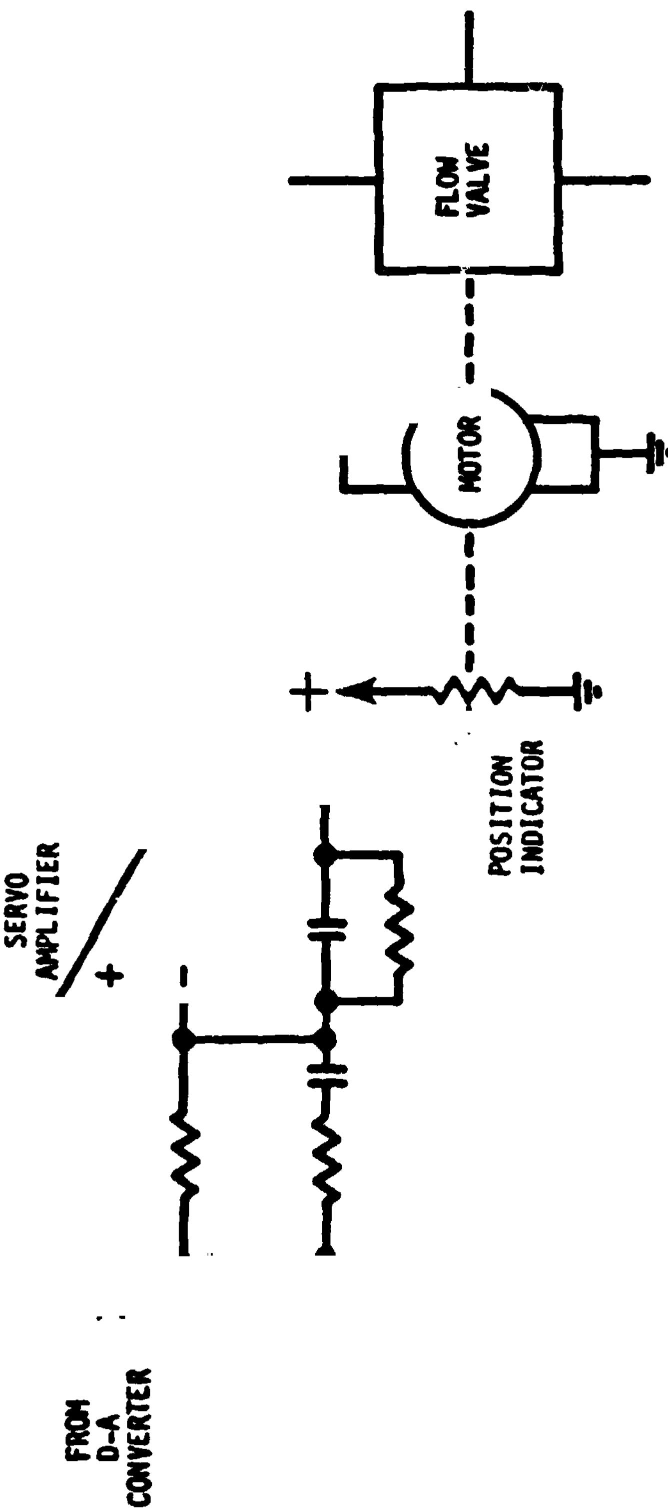


FIGURE 7 ANALOG SERVO SCHEMATIC

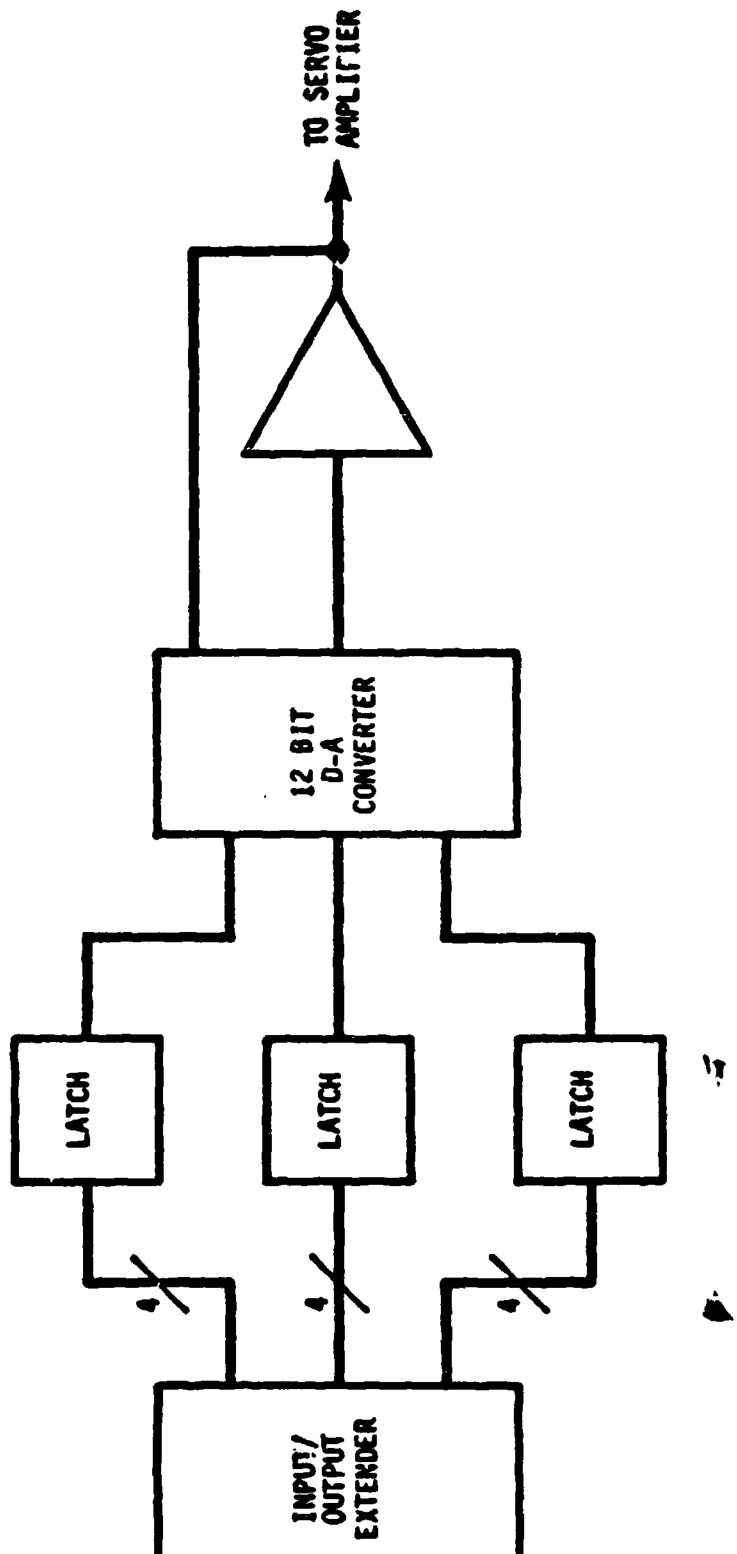


FIGURE 8 D/A CONVERTER BLOCK DIAGRAM

III COMPUTER PROGRA ERVIEW

Figure 9 is a simplified flow diagram of the system computer program. The following major functions are performed:

- Temperatures T_i, T_o, and T_h are measured once a second.
- New valve positions are calculated (usually once every second) and the position commands are transmitted to the analog servo.
- Model coefficients are up-dated (usually there is a model adaption every 20 s).
- When the operation is out of the comfort zone new T_c values are picked to move back into the zone.

After this overview, separate sections will be devoted to these last three functions.

Refer to Figure 9 and assume that the program is in the "has clock changed" block at the top of the diagram. The program will loop back through the block every few milliseconds until the program clock changes (it changes once a second).

At the change the program proceeds down the chart and first adds a random step or "dither" to the commanded inlet temperature This dither, which will be discussed in detail later, is necessary for correct model adaption. One degree C is added to or subtracted from T_c; whether it is added or subtracted is changed randomly every minute. The LCG subject usually will not notice the resulting change in T_i.

Next the three temperatures, T_i, T_o, and T_h, are read. The program loops through this box once a second, which is the period between rea..ngs. A known and constant period between samples is required for the control of T_i and for the adaptve model.

Next the valve position is calculated based on the current values of T_c, T_i, T_o, and T_h. During this calculation the fraction, F, of the water that is shunted around the heat exchanger is

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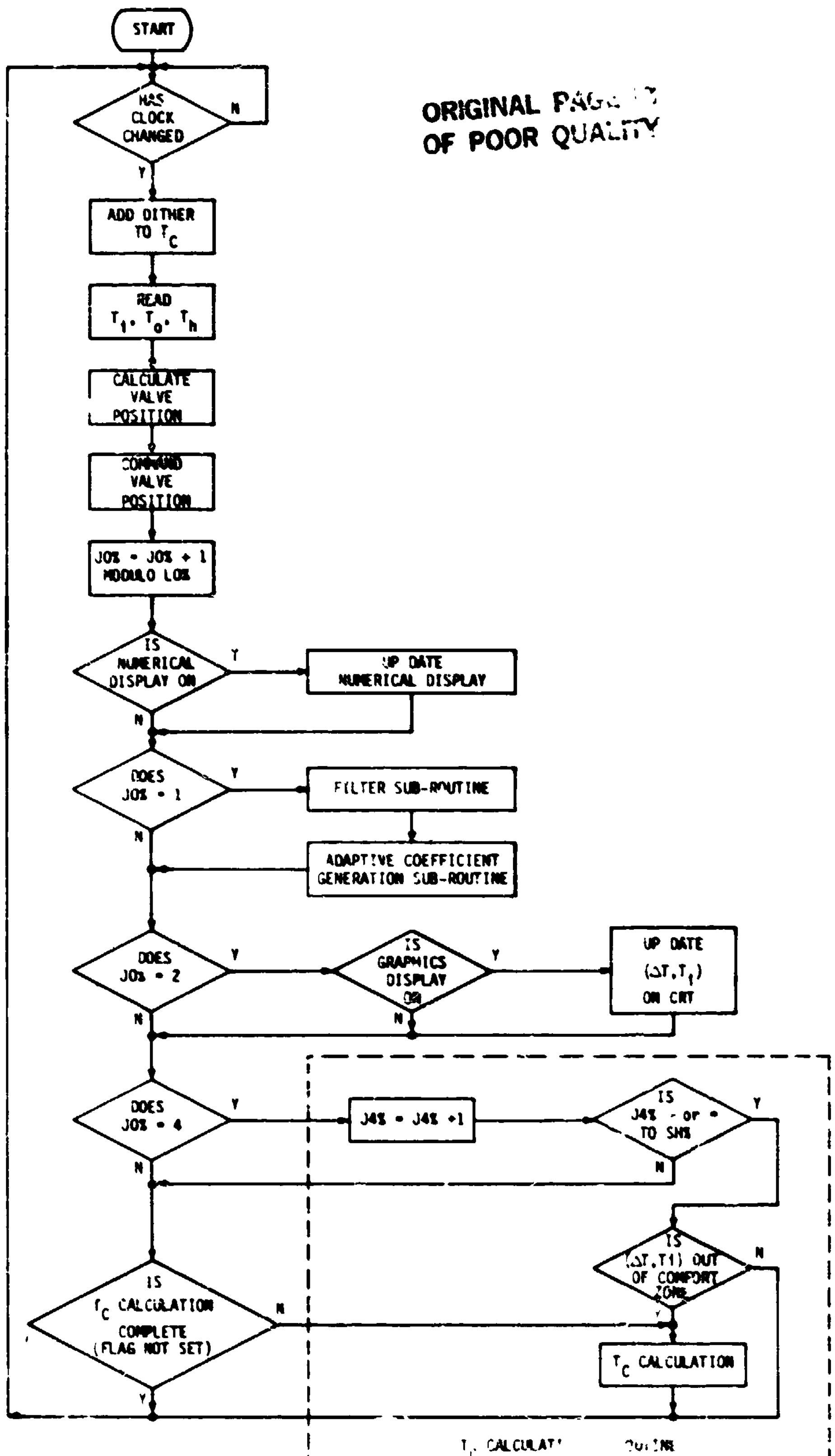

FIGURE 9 SIMPLI... M

calculated. The motor-driven valve requires approximately 5 s to travel from full-shunt to no-shunt, so after a new T_c is calculated by the T_c calculation subroutine, F is held constant for 5 s. Then feedback through the computer is used to adjust F to drive T_i as close as pssible to T_c. The F for different valve positions has been measured and a non-linear regression curve that is fitted to the experimental data is used to determine the valve position. The computer commands this position through the interface.

There are two possible CRT displays that can be selected from the computer keyboard. One is a numerical display of the current values of T_c, T_i, T_o, T_h and ΔT, and the other is a graphics display of (ΔT, T_i) and the comfort zone. If the first display is in use it is updated every 1 s immediately after the valve command has been given.

There are four major functions that are performed by the program that is depicted by the remainder of the flow chart. These functions are: model estimate of ΔT, model adaption, CRT display update, and T_c calculation. They are done once each in an interval that usually is 20 s long (the length is set by the parameter L0%). Each time the program loops through the counter J0% is incremented until J0% = L0%. Then J0% is set to 0 (modulo L0%).

The first two functions are done during the same 1 s long interval, and the display and T_c calculations are done during separate subsequent 1 s intervals. Because the total computation time for all four functions is greater than 1 s the program would not always be able to loop through in 1 s if all the calculations were done together.

When J0% = 1, a new filter (model) output, ΔT, is calculated. This need be done no more often than every 20 s because empirical measurements have shown that this period is sufficient for the bandwidth of an actual LCG (the sampling rate should be greater than twice the actual bandwidth). The experiments that determined that L0% = 20 is appropriate are described later. A new update in the estimate of ΔT is necessary for an update in the model adaption, so the adaption must follow the estimate of ΔT. Both functions will be described in detail in a later section on modeling.

When J0% = 2 the graphical display is updated if it is in use. This display is a real-time equivalent of Figure 2 where the latest "target" (ΔT, T_c) is plotted along with the latest actual (ΔT, T_i). These two points are plotted along with the boundaries of the comfort zone, so that system performance can easily be followed.

When J0% = 4 the most complex and time consuming of the computations begins. First there is a test to determine if there have been a sufficient number of 20 s or L0% intervals since the last calculation. The variable J4% is incremented by one; unless it is greater than or equal to parameter SH% the program branches directly back to the main loop so that there is no new calculation of T_c.

There must be this delay in the calculation of the next T_c because the system cannot move into the comfort zone immediately. If a new T_c is chosen before the system has reached steady-state within the zone, the calculated T_c will be pushed farther from the correct T_c by each new calculation (i.e., the system will be unstable). The parameter SH% is chosen so that the "dead-time" is 4-5 min (SH% is 12-15). This range and other techniques that will be discussed result in stable operation.

Next it is determined whether or not (ΔT, T_i) is outside of the comfort zone. If not, the program returns to the top of the flow diagram to await the beginning of the next 1 s interval. If it is outside, the T_c calculation is started. This calculation may last more than 1 s; if it does a flag indicating that the calculation is not complete is set and the program returns to the top of the loop. When the program passes through the "does J0% = 4 test" (J0% now is greater than 4), a flag-set indication will cause a branch to the calculation portion of the subroutine and the T_c calculation will continue. Thus, there will still be a pass-through the main loop once a second. When the calculation is complete the flag is reset so there is no branching on subsequent passes during the 20-s interval.

Figure 10 gives more of the T_c calculation details. On entry to the calculation portion the "is flag set" is tested. The answer "no" means that the calculation has not started, so an initial trial value for T_c is chosen. After a test to check that the 1 s interval has not ended, a model steady-state ΔT (the ΔT that the model predicts will occur in 5-6 min if T_i is set to the value for T_c) is calculated.

A test is made to see if the model (ΔT, T_c) is in the comfort zone. If it is, there is a branch through the reset box and back to the main loop (return). If not a counter (J8%) is incremented to indicate how many trial T_cs have been tested. If the number is less than L8% (usually set to 10 or 12) the program returns to the "next trial T_c" box.

Different procedures for picking the "initial" and "next" values are used when the main loop with the flag set the "next trial T_c" procedure is used.

If a T_c is not chosen that results in (ΔT, T_c) being in the comfort zone by the (L8% + 1) pass, a single pass calculation technique is used. In general, the actual ΔT will not agree with the predicted ΔT as closely when this latter technique is used; however, a solution is guaranteed. After the calculation, the program returns to the main loop. Both the multi- and single-pass techniques calculate ΔT using the adaptive model and the current values of the coefficients.

The next three sections will describe in more detail several of the algorithms that are used in the subroutines.

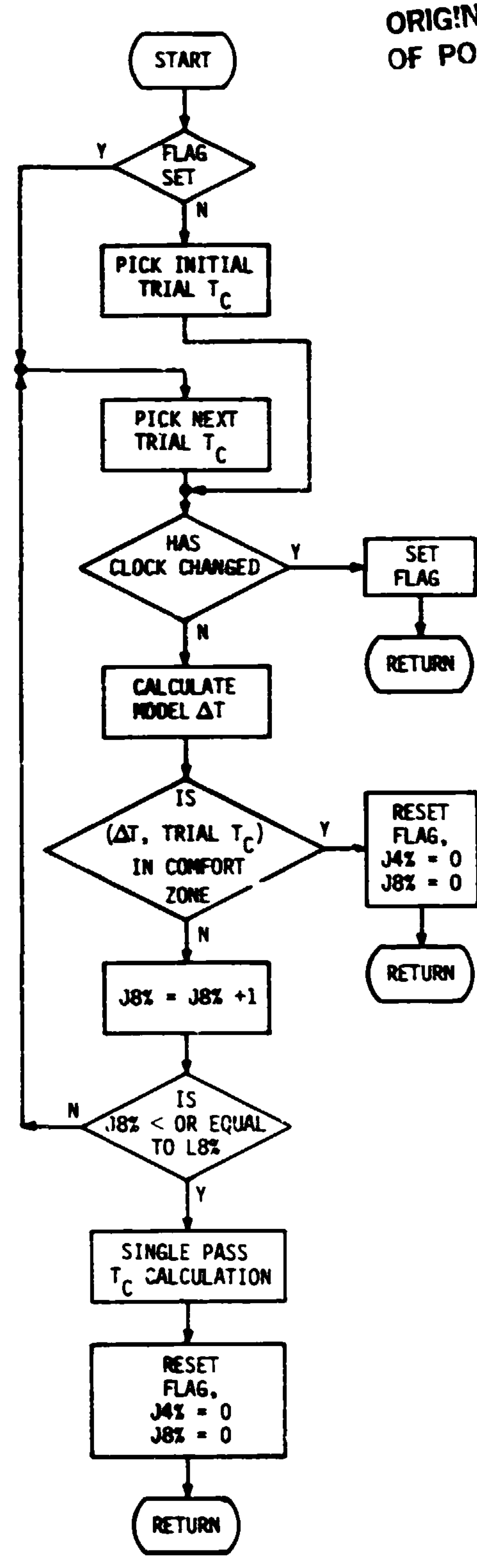

FIGURE 10 SIMPLIFIED FLOW DIAGRAM OF T_C CALCULATION

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IV VALVE CALIBRATION AND SERVOCONTROL

A simple valve calibration technique has been developed. Since the theory of the calibration is related to the servocontrol theory, both are described in this section.

A. Valve Calibration

Assume that there are W grams of water at a temperature of T_h °C. When a fraction, F, of this water is heated to T_o °C the number of calories that is added to the fraction is

$$\Delta C = F \cdot W \cdot (T_o - T_h) \quad . \tag{1}$$

Now mix the water that has been heated to T_o with the remainder of the water (that still is at a temperature T_h). The rise in temperature, ΔT, of the mixture is

$$\Delta T = \frac{\Delta C}{W} \quad . \tag{2}$$

In the LCG system

$$\begin{aligned} T_i &= \Delta T + T_h \\ &= \frac{F \cdot W \cdot (T_o - T_h)}{W} + T_h \\ &= F(T_o - T_h) + T_h \quad , \end{aligned} \tag{3}$$

or

$$F = \frac{T_i - T_h}{T_o - T_h} \quad . \tag{4}$$

Thus it is possible to measure the fraction of water that is shunted around the heat source by measuring T_i, T_o, and T_h. During the calibration the valve position was stepped from full shunt to zero shunt and F was calculated from Eq. 4. A non-linear regression curve of valve position as a function of F was fitted to the data.

The curve and data are shown in Figure 11. The curve is nearly linear and not correct when F is almost 1. This valve did not allow a total shunt; there was always some water going through the heat exchanger due to internal leakage. This annoying feature degraded the still satisfactory servo performance.

The equation of the curve is given in lines 7090 and 7110 in the listing (Appendix) where CP(N%) are the coefficients. The values are given in line 35000.

B. ServoControl of Inlet Temperature

We have designated T_c to be the inlet temperature that is designated by the computer to reach the comfort zone. Let F' be the shunt fraction that gives an inlet temperature of T_c. Let F be the present fraction that resulted in the present temperature, T_i. Then using Eq. 3

$$T_c = F'(T_o - T_h - \Delta T_h) + T_h + \Delta T_h \quad , \tag{5}$$

where the new T_h is $(T_h + \Delta T_h)$,

$$\begin{aligned} T_c - T_i &= [F'(T_o - T_h - \Delta T_h) \\ &\qquad + T_h + \Delta T_h] \\ &\quad -[F'(T_o - T_h) + T_h] \\ &= (F' - F)(T_o - T_h) \\ &\qquad + (1 - F')\,\Delta T_h \end{aligned} \tag{6}$$

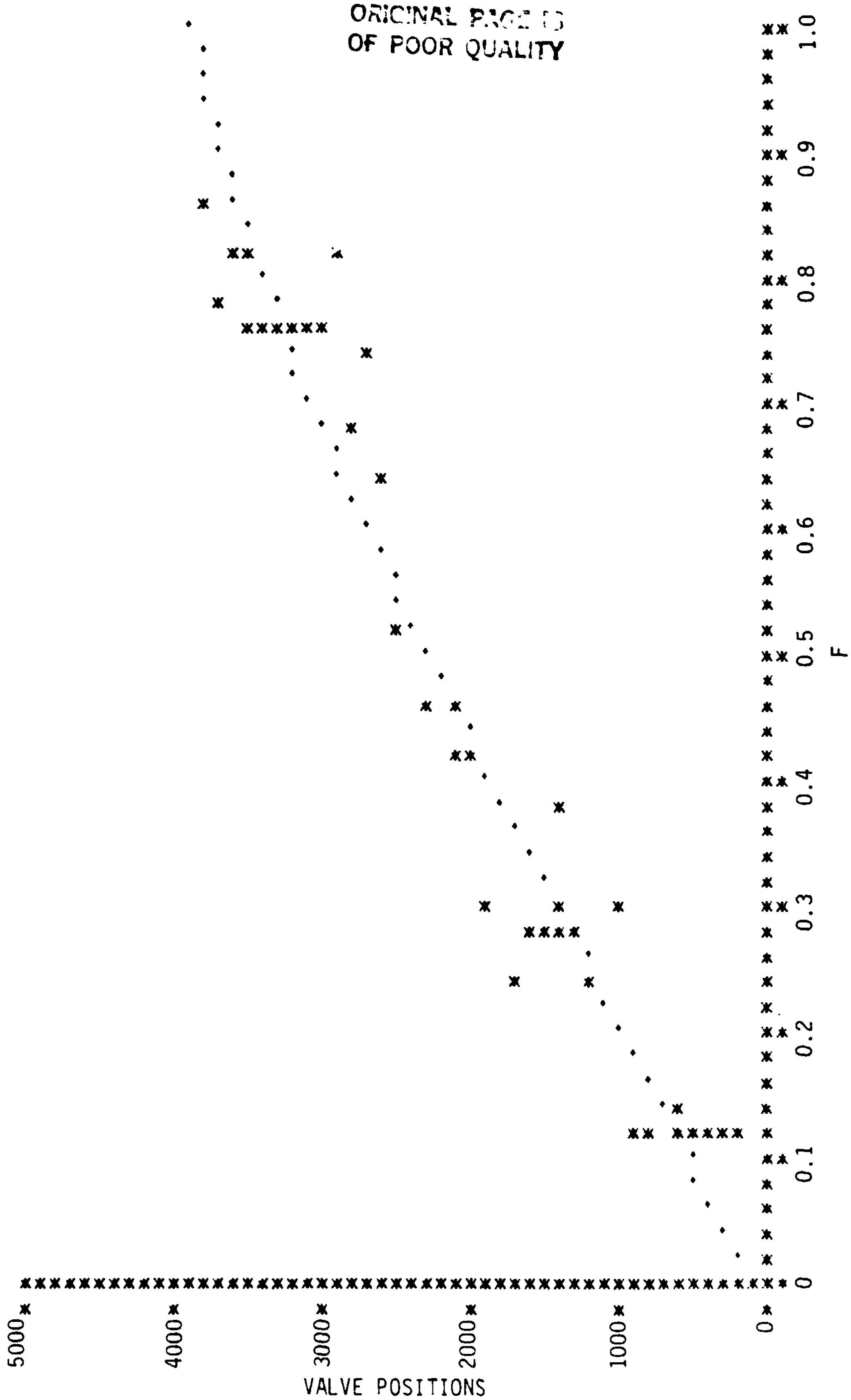

FIGURE 11 VALVE CALIBRATION CURVE

where ΔT_h is the change in T_h with F'.
Neglecting ΔT_h

$$F' = F + \frac{T_c - T_i}{T_c - T_h} \qquad (7)$$

Equation 7 is used to set the initial value of F' whenever there is a change in T_c. This fraction will not be exactly correct so feedback through the computer is used for further adjustment of F' after the initial value is set.

Approximately 5 s (a 5 s dead time) are allowed for the motor to drive the valve to the correct position before feedback through the computer is used to account for $\Delta T_h \neq 0$ and other errors. A first order difference-equation equalization filter was programmed and placed in this loop in an effort to speed the response of the through-the-computer loop. This equalization filter was abandoned because of an increase in loop noise; the difference equation is an imperfect differentiation.

Instead of using equalization filters the following rules are used:

If $T_c - T_i > 0$

$$F(n) = F(n-1) + C_1(T_c - T_i) \qquad (8)$$

If $T_i - T_c > 1$

$$F(n) = F(n-1) - C_2 \qquad (9)$$

If $1 > T_i - T_c > 0$

$$F(n) = F(n-1) + C_2(T_c - T_i) \quad , \qquad (10)$$

where F(n) is the fraction at the n^{th} second after the end of the dead time.

Note T_i is the current value and each second a new F(n) is calculated using one of the three rules. Equation 8 is used when the command temperature is greater than the present inlet temperature. The increase in F is proportional to the difference.

Equation 9 is used if T_c is less than the present value of T_i and the difference is greater than 1^oC. Equation 10 is used when T_i must go lower but the difference is less than 1^oC. Equations 9 and 10 allow a maximum change in F of C_2 each second; but when T_i comes near to T_c the change is proportional to the difference.

The inlet temperature can be changed rapidly in the negative direction because the water is quickly cooled by the heat-exchanger. If Eq. 10 is used over the whole range when T_i is negative-going (i.e., Eq. 9 is not used) either the change in F will be too large and there will be unacceptable overshoots or C_2 must be made small to damp out the overshoots. If a sufficiently small C_2 is used to damp the overshoot the convergence will be too slow when T_i is close to T_c.

Because the only source of heat is from the subject, T_i can be lowered much more quickly than it can be increased. This is why there are two gain constants, C_1 and C_2. Their values were empirically determined to be $C_1 = 0.075$ and $C_2 = 0.02$. They depend on many system parameters such as flow rate, water volume, and LCG heat transfer characteristics. Because of all the unknown or hard-to-measure parameters it probably is best to determine C_1 and C_2 by experiment instead of by engineering design.

The above algorithm may appear to be a "seat-of-the-pants" approach and to a certain extent it is. Unfortunately, classical servo design techniques are far from applicable because of system non-linearities and most importantly because there is no source of hot water. If the servocontrol could rapidly dump a large number of calories into the water loop, then T_i could rapidly be driven in both positive and negative directions. It then would be a nearly classical servo design problem, and equalizing filters (difference equation iterated by the computer) to maximize the rise time and minimize the overshoot and settling time could be used. Optimum control techniques could be used to minimize the time required to return to the comfort zone.

After many months of intense experimentation the algorithm has proven to be satisfactory, and given the system constraints (especially the valve characteristics) we believe that there is little likelihood that the design could be significantly improved.

V THE MODEL

A. Model Description

The model (implemented in a subroutine) inputs are measured values of T_i. Not all T_i are used; only every L0%th (usually every 20th) T_i is input. It was mentioned earlier that this low sampling rate can be used because of the low LCG bandwidth. The model outputs are the predicted values of ΔT, ΔT^* at the times there is an input (i.e., every L0% seconds). Model parameters are adjusted (adapted) in real-time to give the minimum mean-squared difference between ΔT and ΔT^*.

The model has been tested against a number of subjects in an LCG and against data from the 41-node LCG model at the JSC. The model generated ΔT^* closely follows the LCG and the 41 node model calculated ΔT.

The 41-node model is a complex simulation. The parameters in our less complex model do not represent different parts of the anatomy or heat flow from the anatomy to the LCG. Thus our adaptive model cannot be used to directly indicate body heat stored or heat flow from a portion of the thigh. However, it requires little memory and calculation and can be implemented on a microprocessor to run much faster than real-time to predict the important variable, ΔT. The model alone is a definite contribution of the project that may have other applications.

Figure 12 is the model block-diagram. The very-low-frequency components of T_i are passed through a low-pass filter, multiplied by a gain of (C_d-1) and added to the adaptive filter output. The high-frequency components of T_i form the inputs to the adaptive filter. The logic of this high-pass, low-pass scheme is as follows. The waveform of the temperature as a function of time has a large, slowly

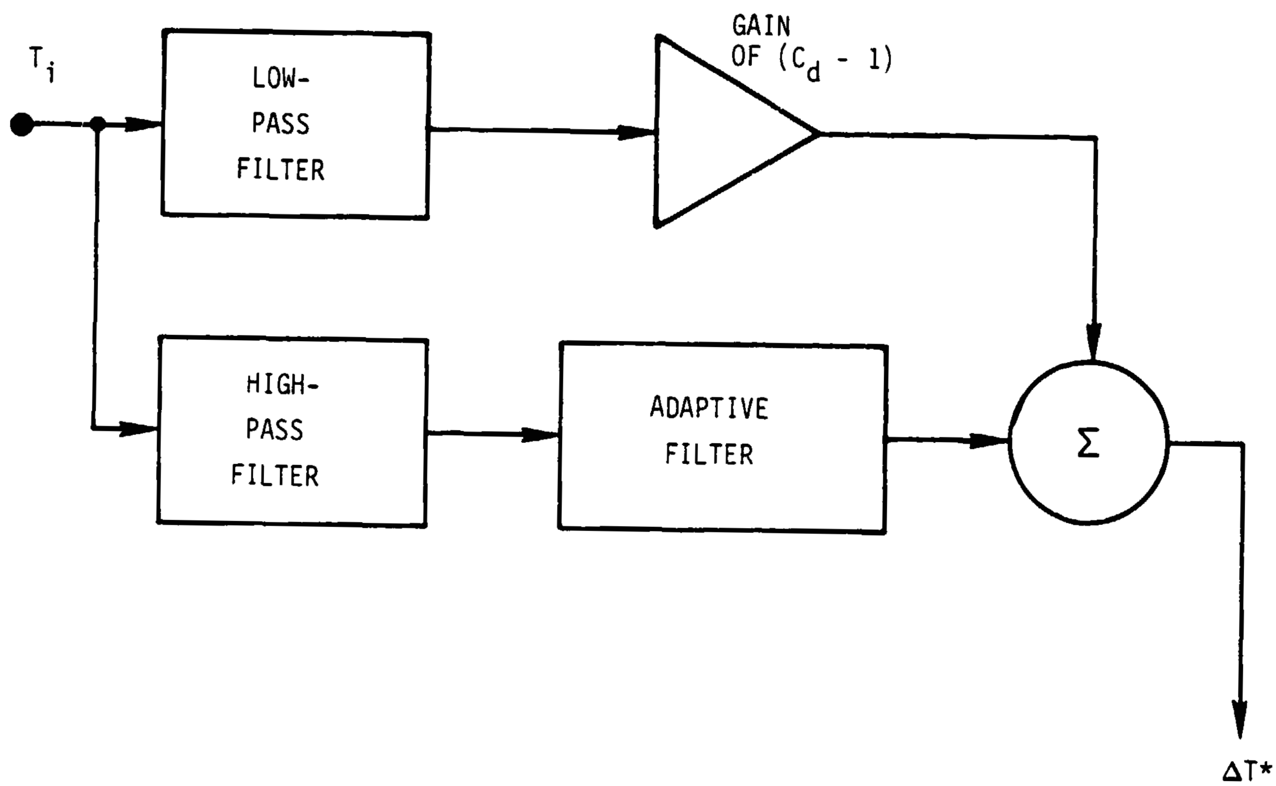

FIGURE 12 MODEL BLOCK DIAGRAM

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varying average (or DC) component and a much smaller and more rapidly varying high-frequency component. During the examination of experimental data it was noted that the average of T_i was almost (but not exactly) proportional to the average of ΔT. The DC value of ΔT*, is inserted through the low-pass gain path. Then the adaptive filter has to adapt only to the much smaller AC component, and the adaption accuracy can be less without degrading the overall performance.

Both the low-pass and high-pass filters are realized with first-order difference equations.* The low-pass equation is (see line 6105 in the listing):

$$I_m(n) = A_m T_i(n) + (1-A_m) I_m(n-1) \quad , \qquad (11)$$

where A_m sets the bandwidth of the filter (usually $A_m = .05$), $T_i(n)$ is the nth input T_i and $I_m(n)$ is the filter output. The high-pass filter is

$$H_i(n) = T_i(n) - T_i(n-1) + (1-B_m) H_i(n-1) \quad , \qquad (12)$$

where $H_i(n)$ is the filter output and B_m sets the low-frequency cut off (usually $B_m = 0.01$). Both A_m and B_m were determined empirically.

The variable C_d (see Figure 6) is approximately equal to the ratio of the average of T_o to the average of T_i. The variable $I_m(n)$ is the average (mean) of $T_i(n)$. An equation of the same form as Eq. 11 [except that $T_o(n)$ is substituted for $T_i(n)$] is used to estimate the mean of T_o, $O_m(n)$ (line 6105). Since

$$\Delta T = T_o - T_i \quad ,$$

the mean of ΔT, D_m, is

*A sometimes awkward variable notation is used in the equations in this report. The notation will be similar to the variables used in the computer program to help with the program documentation.

$$D_m(n) = O_m(n) - I_m(n) = I_m(n)\ (C_d - 1) \quad . \tag{13}$$

A formula for C_d has been found experimentally that is more accurate than the ratio of $I_m(n)$ to $O_m(n)$. It is (line 9115)

$$C_d = \frac{O_m(n)}{I_m(n)} \left[1 + H_c(I_m(n) - T_c)\right] \quad , \tag{14}$$

where H_c is a parameter that is usually set to 0.017. The equation was obtained by fitting a regression curve through points of a plot of C_d verses $(I_m(n)-T_c)$.

Figure 13 is a schematic of the adaptive filter. This form is sometimes called a tapped delay line or finite impulse response filter (FIR). In the computer the output is given by

$$D_1(n) = \sum_{j=1}^{m} H_1(n-j+1)\ C_j \quad , \tag{15}$$

where the C_j are the adapted coefficients.

A discussion of the theory of an FIR is beyond the scope of this report. However, if m is made sufficiently large the FIR can be made to simulate any linear system with one input and one output channel.

Also, there exist well-understood algorithms to adjust the C_j to minimize the mean-squared difference between ΔT and ΔT^*. Ours is a slightly modified version of the Widrow-Hoff algorithm. In our algorithm

$$C_j(n+1) = C_j(n) + k_c A_\ell H_1(n-j+1) \quad , \tag{16}$$

where $C_j(n)$ is the value of C_j at the nth sampling time.

If $(\Delta T - T^*)^2 > 1$, then

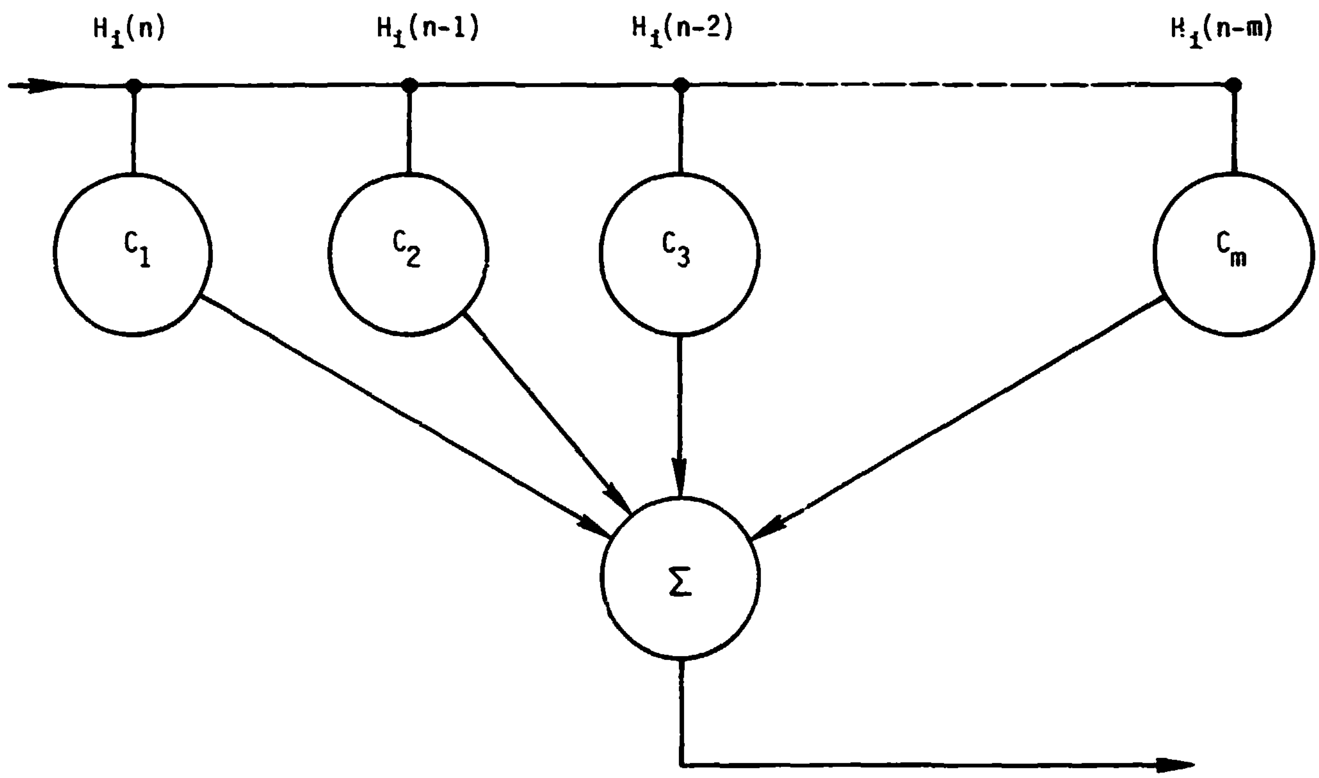

FIGURE 13 SCHEMATIC OF THE ADAPTIVE FILTER

$$k_c = \text{sign of } (\Delta T - \Delta T^*) \quad . \tag{17}$$

If $(\Delta T - \Delta T^*)^2 \leq 1$, then

$$k_c = (\Delta T - \Delta T^*) \quad , \tag{18}$$

where A_ℓ is an adjustable constant; $A_\ell \cong 0.01$.

During each step the change in the weight at the jth tap is proportional to the value of H_i at that tap times the error between ΔT and ΔT^* if the error magnitude is one or less; it is proportional to ± 1 if the magnitude is greater than one.* Notice that only two input variables are required: ΔT and H_i.

Examination of Eq. 16 shows that if T_i is constant (and therefore $H_i = 0$) there will be no adaption. To ensure that adaption is occurring continuously the small random step or dither is added to T_c so that T_i is never constant. The size and frequency of change of the dither depend on the LCG bandwidth and temperature and other system noise. A step size of $1^\circ C$ has proven to be more than adequate (probably a smaller size will do), and choosing a random value of the square-wave once a minute is adequate.

B. Model Experiments

Upon completion of the control program, a series of human subject tests were conducted to refine the LCG predictive model and adaptive subroutine coefficients. As discussed earlier the purpose of these subroutines is to provide a continuously updated predictive model of the LCG transfer function. This allows the LCG performance to be predicted before the valve position is actually changed. Thus, the desired system response can be selected based on the current state of the system.

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*The truncated error function allows stability with a much larger A_ℓ and therefore a much faster adaptation.

A set of five model coefficients must be used to minimize the error between the actual LCG ΔT values and those predicted by the computer control algorithm during a given exercise condition. This set of model coefficients was determined in the following manner:

- The control system was operated without T_c calculation during treadmill exercise tests with specified LCG inlet temperatures. The cooling system's transient response characteristics were obtained by recording the resultant LCG outlet temperatures during these tests.
- A parametric computer study was then performed to determine the set of model coefficients that could best be used to analytically duplicate the above experimental results.

If the calculated LCG outlet temperatures were sufficiently like those that were obtained from the actual tests, the model coefficients could be used to calculate actual LCG outlet temperatures ahead in time with sufficient accuracy for use in the automatic controller.

Four subjects were tested in this series of experiments. In each test sequence, the LCG flow rate was set at 1.9 l/min (240 lb/h). During each test the subject wore insulated clothing, including gloves and hat, over the LCG while he performed the experiment. Each test sequence consisted of a 10-min standing rest period, a walking treadmill exercise period of approximately 20 min, and a standing recovery period of 10 min. An initial treadmill speed of 3 mph (metabolic requirement, $Q_{met} \cong$ 800-900 BTU/h) was used during each exercise period. This speed was held constant during three of the tests. During the fourth test the treadmill speed was later increased to 5 mph ($Q_{met} \cong$ 2400 BTU/h).

The system shown on the schematic in Figure 5 was modified for these human tests. The actual LCG was used in place of the heat exchanger and laboratory pumping unit heat source on the right. It was also found that due to the temperature drop across the left, heat sink, heat exchanger it was not possible to reduce the minimum LCG inlet temperature to the desired 40-46°F range. The system was modified so that the flow diverter valve would send fluid directly through the pumping unit rather than through the heat exchanger. This allowed the heat sink outlet temperature to be brought down to the desired range. The completed system was then ready for the human tests.

The exercise profiles, specified or command LCG inlet temperatures, the actual or measured LCG inlet temperatures and the measured LCG ΔTs for each test sequence are shown in Figures 14, 15, 16, and 17. The actual inlet temperature, shown in the middle of each figure, includes the $\pm 1^{\circ}C$ dither that was superimposed on each commanded inlet temperature. The solid, measured ΔT trace in the top portion of each figure shows the difference between the actual LCG inlet and outlet temperatures for each test.

The inlet temperature profile for each test served as the independent variable during the various parametric calculations. The objective of the parametric study was to determine the set of coefficients that could best duplicate all of the measured ΔT traces shown in Figures 14-17.

Table 1 provides the typical results from one of the analytic calculations. The various parameters listed at the beginning of the printout are discussed in Section V of this report. The variation of the model as the system adapts to different conditions is shown by the changes in the values of the filter coefficients. The actual performance of the model is listed as a function of time. The actual inlet temperature, which included a $\pm 1^{\circ}C$ dither signal in this case, is listed in the third column. The resulting actual LCG ΔT is listed along with the filter output, which is the model's predicted ΔT. The cumulative RMS error between the actual and predicted values is then listed after the first 1000 s of experiment time. This error was used to help to refine the values of various parameters in the model. These parameters were adjusted so as to produce the smallest RMS error. The last two columns listed are not pertinent to this discussion.

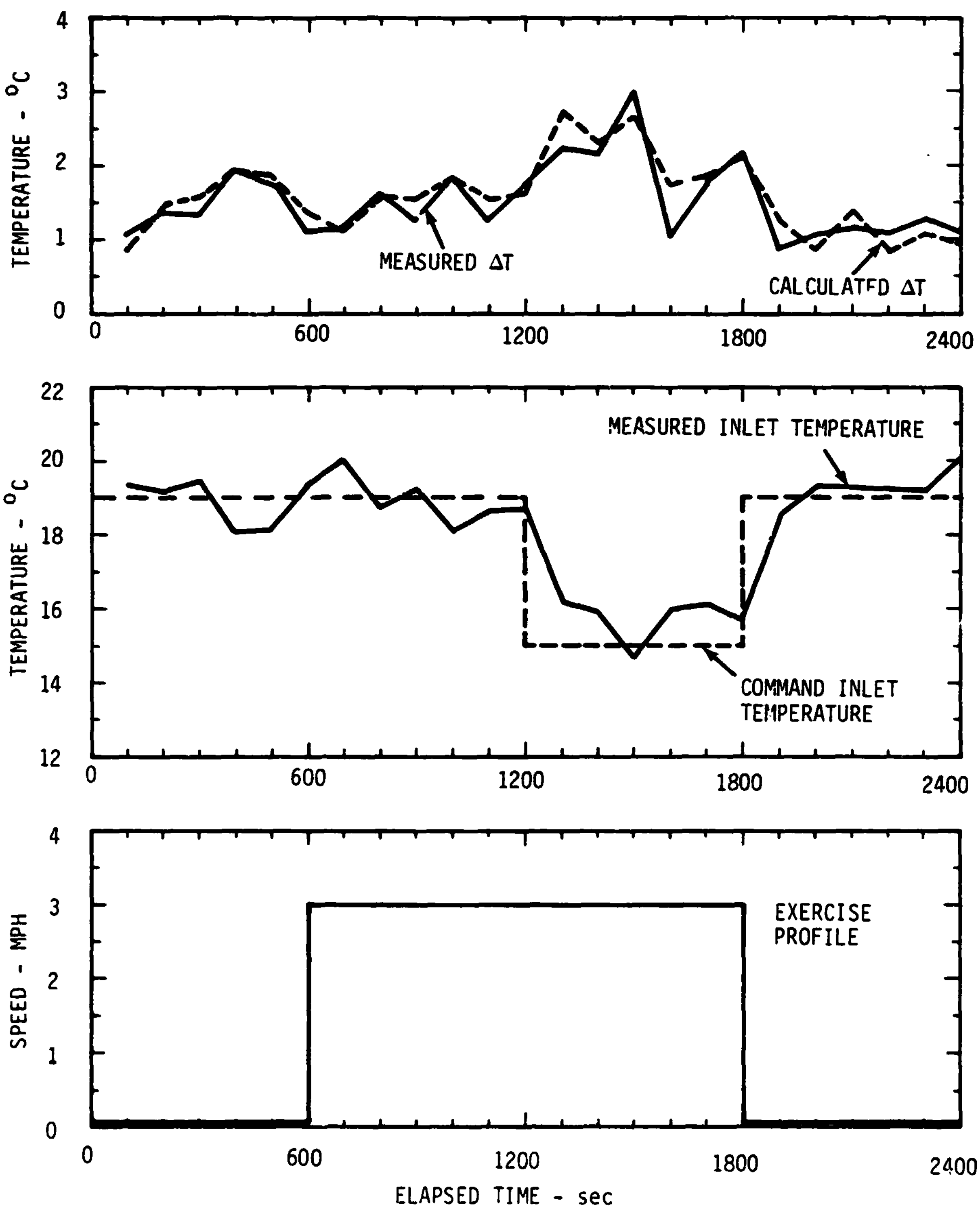

FIGURE 14 LIQUID COOLING GARMENT TEMPERATURE CONTROLLER OPEN LOOP TEST RESULTS--SUBJECT ONE

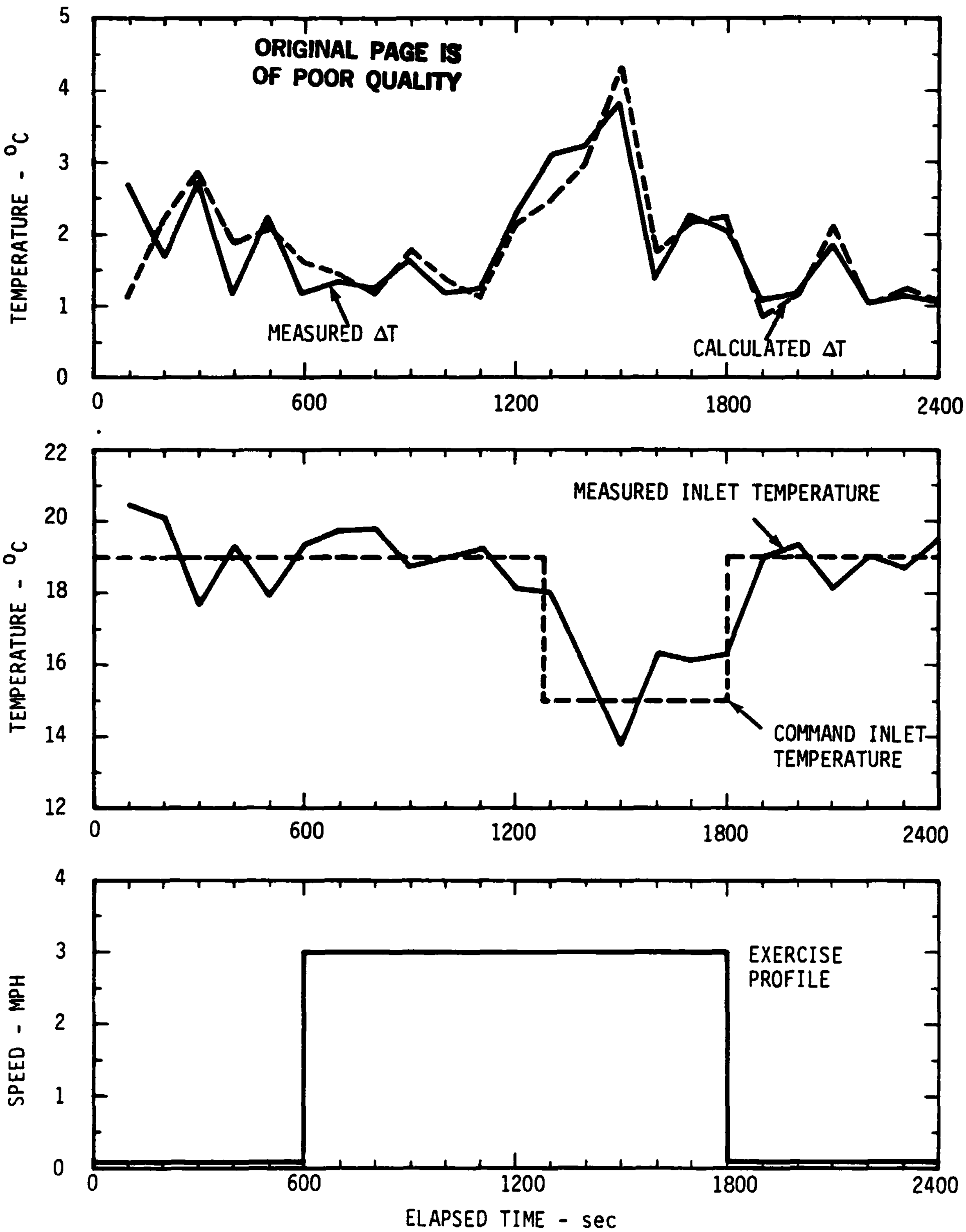

FIGURE 15 LIQUID COOLING GARMENT TEMPERATURE CONTROLLER OPEN LOOP TEST RESULTS--SUBJECT TWO

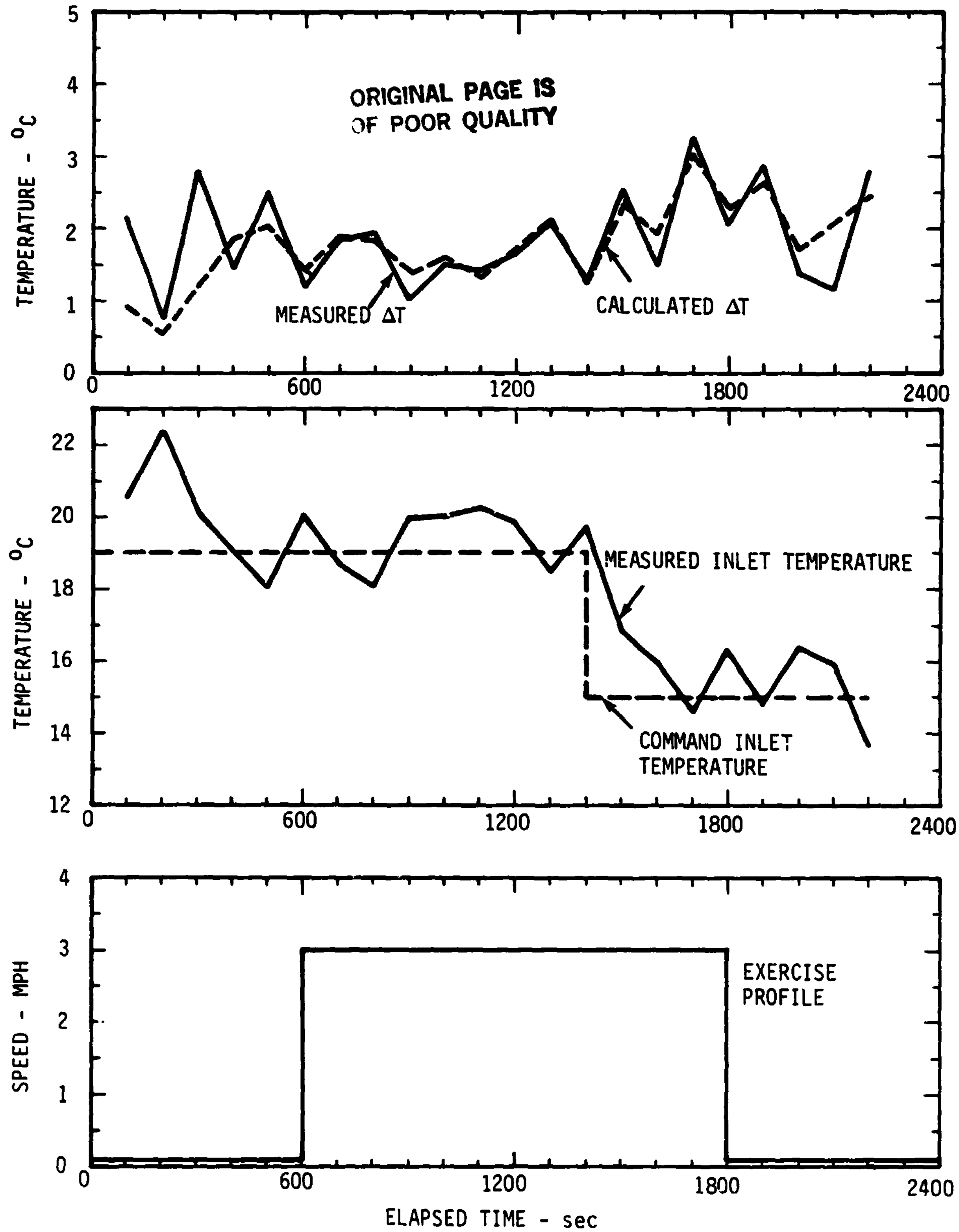

FIGURE 16 LIQUID COOLING GARMENT TEMPERATURE CONTROLLER OPEN LOOP TEST RESULTS--SUBJECT THREE

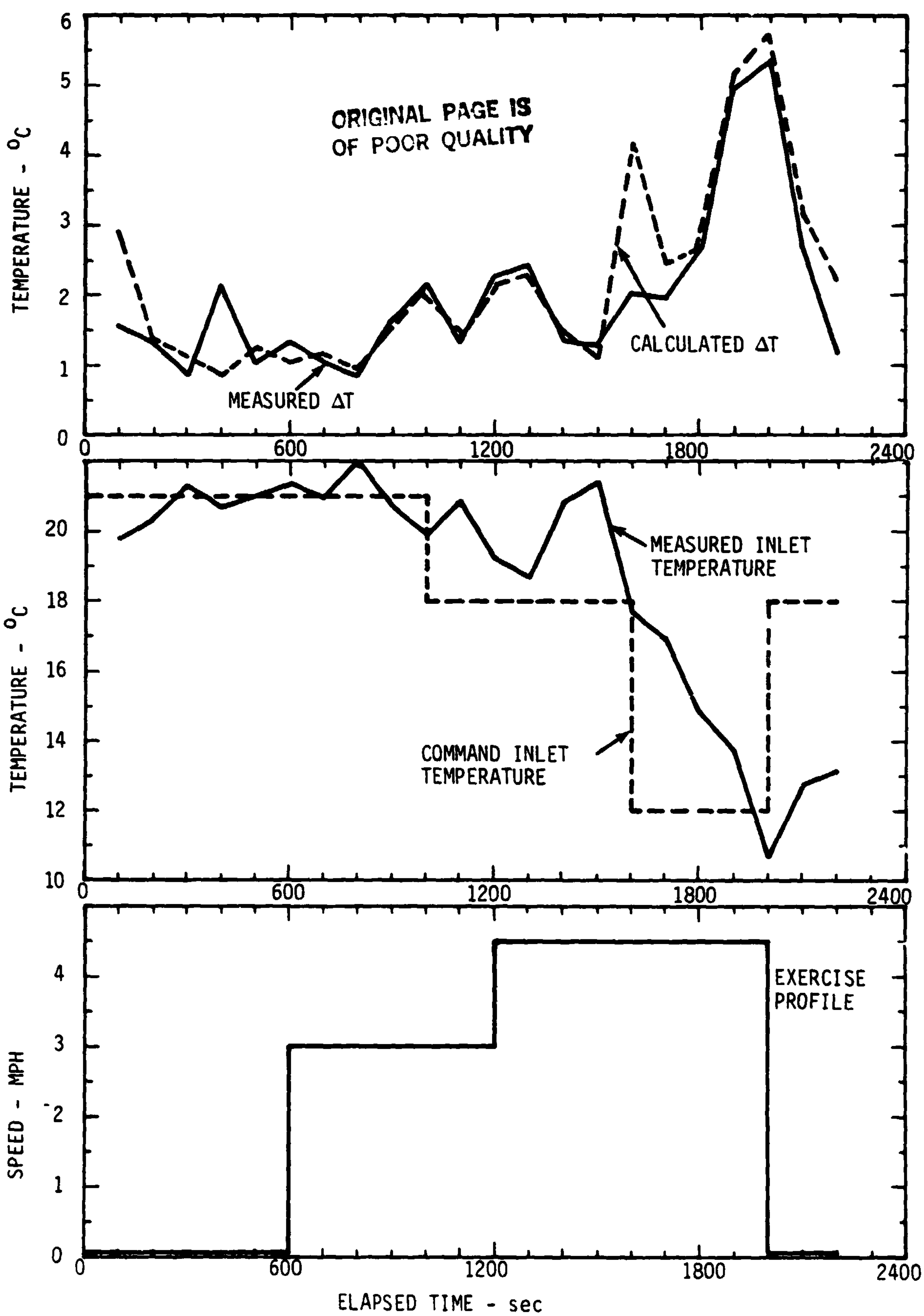

FIGURE 17 LIQUID COOLING GARMENT TEMPERATURE CONTROLLER OPEN LOOP TEST RESULTS--SUBJECT FOUR

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Table 1

SAMPLE ALGORITHM PROGRAM OUTPUT

THE NUMBER OF TAPS IS 4 . THE SIZE OF THE DITHER IS 2 DEG. C.
THE NUMBER OF TEN SECOND INTERVALS BETWEEN CALCULATIONS IS 2 .
THE ADAPTION IS NOT HELD. THE FILE NAME IS DAVE.

THE ADAPTIVE CONSTANT IS NOW .05 . N IS NOW 0

THE VALUE OF THE MEAN CONSTANT NOW IS .2 . N IS NOW 0

N= 34 . THE FILTER COEFFICENTS ARE AS FOLLOWS:
-.378675 .116319 .115468 .128741

N= 64 . THE FILTER COEFFICENTS ARE AS FOLLOWS:
-.642678 .18342 .121965 .173501

N= 94 . THE FILTER COEFFICENTS ARE AS FOLLOWS:
-.838757 .0988944 .119488 .168583

N	TIME (SEC.)	INLET TEMP.	DELTA TEMP.	FILTER OUTPUT	RMS ERROR	T$	DC
5	100	20.4222	2.7027	-13.6021	0	16:12	1.20935
6	120	20.7735	1.99089	3.13627	0	16:32	1.18011
7	140	19.594	2.69232	2.93115	0	16:52	1.17016
8	160	19.7835	1.75467	2.83041	0	17:12	1.15165
9	180	20.1232	1.62464	2.53514	0	17:32	1.13576
10	200	20.101	1.66913	2.28304	0	17:52	1.12423
11	220	18.5924	3.03786	2.05846	0	18:12	1.13213
12	240	18.7481	2.72648	2.2184	0	18:32	1.13483
13	260	19.0994	2.01468	2.2972	0	18:52	1.12881
14	280	17.5019	3.56135	2.27427	0	19:12	1.14302
15	300	17.6247	2.75716	2.77902	0	19:32	1.14561
16	320	18.0534	2.44919	2.63166	0	19:52	1.14364
17	340	17.9093	2.17881	2.68415	0	20:12	1.1393
18	360	18.065	1.86742	2.4239	0	20:32	1.13214
19	380	18.9669	1.16252	2.14418	0	20:52	1.11745
20	400	19.2667	1.12152	1.98435	0	21:12	1.1051
21	420	19.5397	1.12494	1.92642	0	21:32	1.09517
22	440	17.6799	3.20548	2.28895	0	21:52	1.11164
23	460	19.111	1.4329	2.05032	0	22:12	1.10411
24	480	18.0534	2.44919	2.13096	0	22:32	1.11027
25	500	17.8648	2.26778	2.00955	0	22:52	1.11351
26	520	18.0872	1.82294	2.02911	0	23:12	1.111
27	540	18.065	1.86742	1.85264	0	23:32	1.10949
28	560	18.6938	1.1591	1.68039	0	23:52	1.09982
29	580	19.2444	1.166	1.54285	0	24:12	1.09167
30	600	19.2667	1.12152	1.64972	0	24:32	1.08477
31	620	19.5175	1.16942	1.6273	0	24:52	1.07962
32	640	19.5397	1.12494	1.61709	0	25:12	1.07508
33	660	19.795	1.1729	1.41534	0	25:32	1.07181

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N	TIME (SEC.)	INLET TEMP.	DELTA TEMP.	FILTER OUTPUT	RMS ERROR	T$	DC
34	680	19.795	1.1729	1.40955	0	25:52	1.06923
35	700	19.7283	1.30635	1.39763	0	26:12	1.06862
36	720	20.0458	1.22081	1.27262	0	26:32	1.06703
37	740	17.3907	3.78377	2.32001	0	26:52	1.09447
38	760	19.1555	1.34394	1.62668	0	27:12	1.0896
39	780	19.7506	1.26187	1.24937	0	27:32	1.08431
40	800	19.7728	1.21739	1.17135	0	27:52	1.07966
41	820	19.7061	1.35084	1.53289	0	28:12	1.07741
42	840	19.1217	1.97019	1.85307	0	28:32	1.08247
43	860	19.3886	1.43638	1.64655	0	28:52	1.08079
44	880	17.4468	3.11303	2.54576	0	29:12	1.09874
45	900	18.749	1.60742	1.6391	0	29:32	1.09617
46	920	18.6156	1.87432	1.77264	0	29:52	1.09706
47	940	17.9982	2.00087	1.96617	0	30:12	1.09978
48	960	18.0205	1.95639	2.03261	0	30:32	1.10148
49	980	18.6716	1.20358	1.58136	0	30:52	1.09404
50	1000	18.9669	1.16252	1.35423	.191713	31:12	1.08738
51	1020	19.2444	1.166	1.28136	.158213	31:32	1.08189
52	1040	17.9867	2.58264	2.15126	.280568	31:52	1.09381
53	1060	18.838	1.42948	1.59695	.257003	32:12	1.09019
54	1080	17.6914	2.62371	2.29538	.272765	32:32	1.10133
55	1100	19.2222	1.21048	1.10921	.252408	32:52	1.09341
56	1120	19.2222	1.21048	1.46714	.25302	33:12	1.08716
57	1140	19.5175	1.16942	1.21078	.23713	33:32	1.08153
58	1160	17.469	3.06855	2.74314	.248492	33:52	1.0992
59	1180	19.0888	1.47739	1.45888	.235813	34:12	1.09475
60	1200	18.1424	2.27126	2.18097	.226481	34:32	1.10069
61	1220	19.2	1.25497	1.17564	.218045	34:52	1.09344
62	1240	19.2222	1.21048	1.56782	.231752	35:12	1.08722
63	1260	19.2444	1.166	1.45124	.235975	35:32	1.08179
64	1280	19.795	1.1729	1.21775	.228267	35:52	1.07712
65	1300	18.0196	3.07545	2.45745	.269666	36:14	1.09499
66	1320	17.9199	2.7161	2.41207	.271807	36:34	1.10584
67	1340	17.4806	2.48678	2.63892	.266572	36:54	1.11275
68	1360	16.8632	2.61333	2.56724	.259678	37:14	1.12061
69	1380	16.5457	2.69887	2.59695	.254126	37:34	1.1285
70	1400	15.7505	3.1813	2.96869	.252304	37:54	1.14181
71	1420	14.8486	3.8862	3.4648	.262366	38:14	1.1629
72	1440	14.9598	3.66370	3.49052	.259129	38:34	1.17777
73	1460	14.6822	3.6603	3.70517	.253839	38:54	1.19078
74	1480	13.758	4.40968	4.2529	.250679	39:14	1.21358
75	1500	13.7696	3.82791	4.2967	.262441	39:34	1.22518
76	1520	13.5365	3.73546	3.93005	.260244	39:54	1.23439
77	1540	13.581	3.64649	3.54269	.256306	40:14	1.24071
78	1560	14.1983	3.51994	3.14068	.2615.	40:34	1.24211
79	1580	16.1916	1.1725	1.9029	.289639	40:54	1.20522
80	1600	16.4025	1.30943	1.76362	.296376	41:14	1.17815
81	1620	15.8955	2.33262	2.43935	.292318	41:34	1.17164
82	1640	15.251	2.42159	2.83924	.296895	41:54	1.16776
83	1660	15.7843	2.55504	2.39597	.293493	42:14	1.16656
84	1680	15.8732	2.3771	2.47468	.28974	42:34	1.16314
85	1700	16.1907	2.29156	2.16911	.286415	42:54	1.15869

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N	TIME (SEC.)	INLET TEMP.	DELTA TEMP.	FILTER OUTPUT	RMS ERROR	T$	DC
86	1720	16.213	2.24707	2.20602	.282599	43:14	1.15456
87	1740	16.2574	2.15811	2.22919	.279094	43:34	1.1501
88	1760	16.2574	2.15811	2.27315	.276108	43:54	1.14657
89	1780	16.2797	2.11362	2.23471	.273306	44:14	1.14317
90	1800	16.3019	2.06914	2.19711	.270691	44:34	1.13988
91	1820	17.4814	1.36772	1.14631	.269622	44:59	1.12671
92	1840	17.5926	1.1453	1.22497	.266746	45:19	1.11366
93	1860	18.1655	1.10771	.836209	.266855	45:39	1.10235
94	1880	18.7383	1.07013	.743528	.268327	45:59	1.09254
95	1900	19.011[illegible]	1.07355	.880402	.266918	46:19	1.08476
96	1920	19.0113	1.07355	1.24168	.2652	46:39	1.07875
97	1940	18.4047	1.73739	1.77136	.262468	46:59	1.08195
98	1960	19.2222	1.21048	1.07038	.260546	47:19	1.07795
99	1980	19.2444	1.166	1.13426	.257967	47:39	1.07433
100	2000	19.2444	1.166	1.147[illegible]6	.255438	47:59	1.07149
101	2020	19.1777	1.29945	1.37478	.253186	48:19	1.07072
102	2040	19.1555	1.34394	1.36288	.2508	48:39	1.07061
103	2060	19.1332	1.38842	1.36282	.248491	48:59	1.07101
104	2080	18.1869	2.18229	2.10342	.246451	49:19	1.08052
105	2100	18.065	1.86742	2.08963	.246039	49:39	1.08496
106	2120	18.1317	1.73397	1.82586	.244175	49:59	1.08705
107	2140	18.1762	1.645	1.57651	.242228	50:19	1.08773
108	2160	18.2206	1.55603	1.55099	.240167	50:39	1.08727
109	2180	18.7161	1.11462	1.18577	.238334	50:59	1.08165
110	2200	19.0113	1.07355	1.02055	.23647	51:19	1.07649
111	2220	19.0113	1.07355	1.15344	.234775	51:39	1.07241
112	2240	18.4269	1.69291	1.73555	.232966	51:59	1.07627
113	2260	18.5826	1.38152	1.57915	.232455	52:19	1.07588
114	2280	17.9537	2.08984	1.97452	.231103	52:39	1.08376
115	2300	18.7[illegible]	1.11462	1.21786	.229697	52:59	1.07887
116	2320	19.0336	1.02907	.995254	.228014	53:19	1.0738
117	2340	19.3112	1.03255	.810781	.227924	53:39	1.06961
118	2360	19.3112	1.03255	1.09007	.226372	53:59	1.06631
119	2380	19.5842	1.03597	.956094	.224952	54:19	1.06355
120	2400	19.5842	1.03597	1.06875	.223396	54:39	1.06137
121	2420	17.5135	2.97958	2.72791	.223813	54:59	1.08163

Table 2 shows the results of variations in 3 of the model parameters, with the resulting effects on the cumulative RMS error, for four different subjects. The combination chosen based on this preliminary optimization was number of Taps = 4, adaptive coefficient = 0.05, and mean coefficient = 0.2. This combination produces an average error of about 0.4°C for all of the subjects. This error can be reduced even further by more detailed refinement using additional test data from more subjects. These values were then used to generate the various calculated ΔT results shown as the dashed traces in Figures 14-17. In each case, the adaptive coefficients were set equal to 0 at the start of the run. This produced a relatively large initial error that decreased after 5-10 min as the model adapted. This initial adaptation will eventually be avoided when the optimal starting values for the coefficients have been identified. The figures show that following the initial adaptation, the predicted and actual values are very close, even during large transients. This clearly demonstrates the accuracy of this adaptive technique for predicting LCG performance. The values of the various program parameters derived from this series of calculations were included in the automatic LCG inlet temperature control program.

Table 2

R M S - ERROR MINIMIZATION

# TAPS	ADAPTIVE COEFFICIENT	MEAN COEFFICIENT	SUBJECT 1	2	3	4
2	.15	.1	.5119	.3461	.4916	1.366
2	.15	.2	.4245	.3041	.4278	1.0039
2	.05	.1	.5180	.4213	.4799	.7220
2	.05	.2	.4787	.3991	.4416	.6006
2	.025	.1	.6077	.4899	.5834	.8018
2	.025	.2	.5864	.4695	.5488	.7596
4	.15	.1	.6726	.7606	.6900	2.3674
4	.15	.2	.5657	.2387	.3317	1.6281
4	.05	.1	.4899	.2555	.3466	.7350
4	.05	.2	.4619	.2220	.3051	.6454
4	.025	.1	.5743	.3418	.4428	.7512
4	.025	.2	.5613	.3336	.4206	.7235
6	.15	.1	.8443	1.2502	1.1426	2.9721
6	.15	.2	.7493	.4733	.5519	2.1357
6	.05	.1	.4417	.3991	.4309	.9090
6	.05	.2	.4330	.2251	.3252	.6524
6	.025	.1	.5325	.3430	.4830	.7631
6	.025	.2	.5332	.3274	.4458	.7248
8	.15	.1	1.1326	1.6311	1.5000	4.0165
8	.15	.2	.8105	.7234	.8092	2.7082
8	.05	.1	.4728	.4849	.4957	1.0764
8	.05	.2	.4354	.2515	.3378	.6973
8	.025	.1	.5453	.3633	.4847	.8242
8	.025	.2	.5358	.3440	.4591	.7379

VI CHOOSING THE INLET TEMPERATURE

Assume that the model has adapted and that due to a metabolic transient (T_i) is out of the comfort zone. The computer now picks a new T_c by entering a trial T_c into the model and running the model ahead in time to see if the model (ΔT^*, T_c) falls into the zone. If the first choice is incorrect others are chosen iteratively until (ΔT^*, T_c) falls into the zone. If there is no success after the L8% trial T_cs, a second more direct (but less accurate) method that does not require iteration is used. This section describes both techniques.

Figure 18 shows the comfort zone that was derived by Kuznetz and the zone that usually was used in the experiments at SRI. In the experiments that are described in the next section the subjects universally reported that they were too cold when $T_c \cong 16^{\circ}C$ or less and the Kuznetz zone was used. The width, slope, and intercept of the experimental zone, which can be changed from the keyboard during an experiment, were modified so that the subjects reported comfort over the complete range of T_c that was encountered in the experiments.

A difference in the zones should be expected because of different test conditions during Kuznetz's and SRI's experiments. Kuznetz used a full space-suit where significant heat was removed by airflow and sweat evaporation. At SRI the subjects were enclosed in a down insulated garment and there was no air flow; virtually all the heat removal was via the LCG.

The optimum comfort zone is not required to experimentally verify the method; if the scheme works with one zone, it will work with another. Since our insulated garment did not give the same conditions as a space suit we did not feel that an elaborate set of tests to optimize the zone parameters was justified at this time. We have the impression that there is no zone that is most comfortable

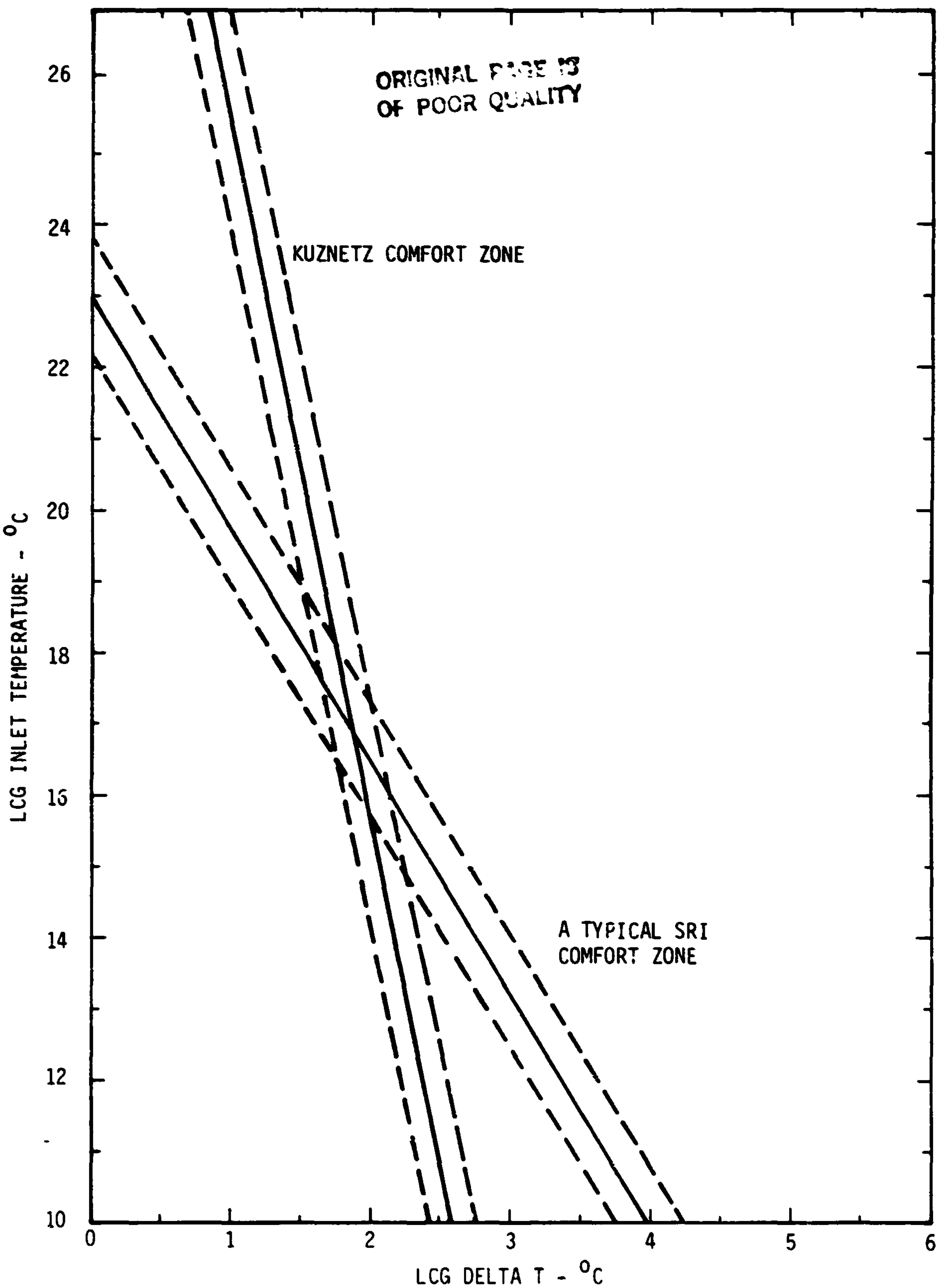

FIGURE 18 COMPARISON OF SRI AND KUZNETZ COMFORT ZONES

for everyone, and it appears simple to experimentally pick the parameters to tailor the zone for an individual. This should be a subject of further study.

A. The Iterative Method

An approximate steady-state ΔT can be obtained by starting with Eq. 13. Assuming that ΔT^* will be near D_m and that the trial T_c will equal I_m,

$$\Delta T^* \cong T_c(C_d - 1) \quad . \tag{19}$$

Substituting in Eq. 14

$$\Delta T^* \cong \left\{ D_c \left[1 + H_c(I_m - T_c) \right] - 1 \right\} \quad , \tag{20}$$

where (line 2080)

$$D_c = \frac{O_m(n)}{I_m(n)} \quad , \tag{21}$$

the center of the comfort zone is the line

$$T_c = A_a - K_4 \, \Delta T^* \quad , \tag{22}$$

where A_a is the intercept on the vertical axis and K_4 is the slope (both are input parameters; see line 9012).*

The initial trial T_c is the T_c that is a solution to both Eqs. 20 and 22. The algebra to derive the solution is straightforward, and the solution is as follows (see lines 9500 through 9550 and line 9030):

---

*In line 9012 and line 9200 $K_4 = A_4 \times 9.389$. The number 9.389 is the slope of Kuznetz's comfort zone and A_4 is an input parameter to adjust to SRI's zone. A_5 is a keyboard input parameter for adjustment during the experiment (normally set to 0).

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OF POOR QUALITY

$$A_q = K_4 D_c \tag{23}$$

$$B_q = K_4 - K_4 D_c - K_4 D_c H_c I_m(n)-1 \tag{24}$$

$$C_q = A_a + A_5 \tag{25}$$

$$T_c = \frac{-B_q - \sqrt{B_q^2 - 4A_q C_q}}{2A_q} \tag{26}$$

The variables I_m and D_c are continuously calculated and Eq. 26 gives the initial trial T_c.

The iteration procedure to choose the remaining trial T_c is illustrated by the ficticious situation that is depicted in Figure 19. Based on the present ΔT and T_i an initial trial T_c, $T_c(1)$ is chosen and the model is used to calculate the first [ΔT^*, $\Delta T^*(1)$]. The point is outside the comfort zone so the next trial [T_c, $T_c(2)$] is picked by dropping a vertical line to the zone center and moving $T_c(2)$ down some fraction, H_d, of the vertical distance.

The point [$\Delta T^*(2)$, $T_c(2)$] is not in the comfort zone, so another vertical distance is measured and $T_c(3)$ is moved down H_f of the vertical distance. After the model run, the point [$\Delta T^*(3)$, $T_c(3)$] is found below the zone. The trial T_c is moved up by half the movement fraction that was used to pick $T_c(3)$ because there has been movement across the zone (each time there is movement across the zone the fraction is half the previous fraction). In our ficticious example the fourth trial T_c results in a point in the comfort zone, [$\Delta T^*(4)$, $T_c(4)$], and this stage of the T_c selection is complete.

More specifically the rule for the variable movement fraction, $H_f(n)$, at the nth iteration is (line 9237)

$$H_f(n) = \begin{cases} 2H_f(n-1) \text{ if the zone is not crossed} \\ \text{and } 2H_f(n-1) < H_d \\ H_d \text{ if } 2H_f(n-1) > \text{or} = H_d \\ .5\, H_f(n-1) \text{ if the zone is crossed} \end{cases} \tag{27}$$

where H_d is some number such that $0 < H_d < 1$.

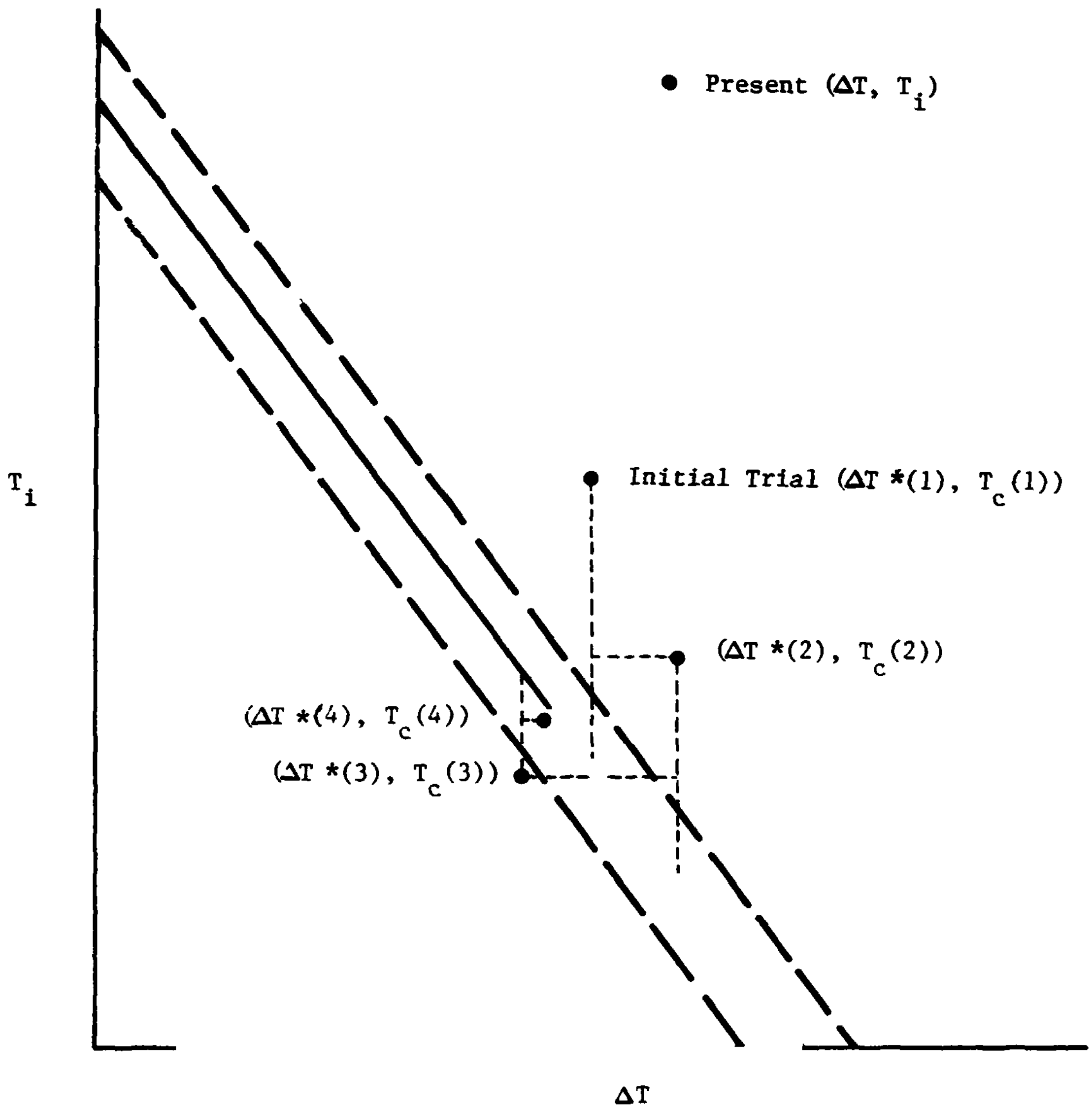

FIGURE 19 A SEQUENCE OF TRIAL POINTS

The rational for the variable movement fraction is as follows: During extensive iterative tests of the scheme it was found that a constant-movement fraction frequently resulted in jumps across the zone on each new trial with no convergence into the zone. If jumps in the trial T_cs are sufficiently small, the movement of the point will not be enough to cross the zone. However, convergence to the zone will be very slow. If the zone is bracketed on each trial and the variable fraction is used, the jump size will be reduced so that the point will eventually fall into the zone. When the point remains on the same side the fraction is doubled to prevent the fraction from being "locked into" a very small value.

During some series of trials there is not convergence into the zone within the allotted number of trials. The reason is unknown, but it is suspected that there are situations where the scheme described above results in limit-cycles. There was not sufficient time to investigate this suspicion, and an investigation of and possible improvement in the scheme should be considered for further work.

B. Single-Pass Calculation

When there has been no convergence with the multi-pass scheme, the single-pass technique is used. It is based on the fact that curves of T_i as a function of ΔT at steady-state have a constant slope when the metabolic rate is constant. This can be seen in Figure 20. For example, if T_i is changed from 27°C to 21°C and W = 500, the change in ΔT is 0.8°C. Thus the slope in this region is 6/0.8 = 7.5. Along the vertical line at W = 500 the curves of constant T_i are equal distance apart, so that the slope is constant. The curves when W = 200 are also equal distant but farther apart. When W = 200 the slope is greater than when W = 500.

If T_i is perturbed and the system is allowed to settle (go to steady-state) the point (ΔT, T_i) will move along a straight line if W remains constant. During the calculation, two trial T_cs, one slightly above and one slightly below the present T_i, are entered

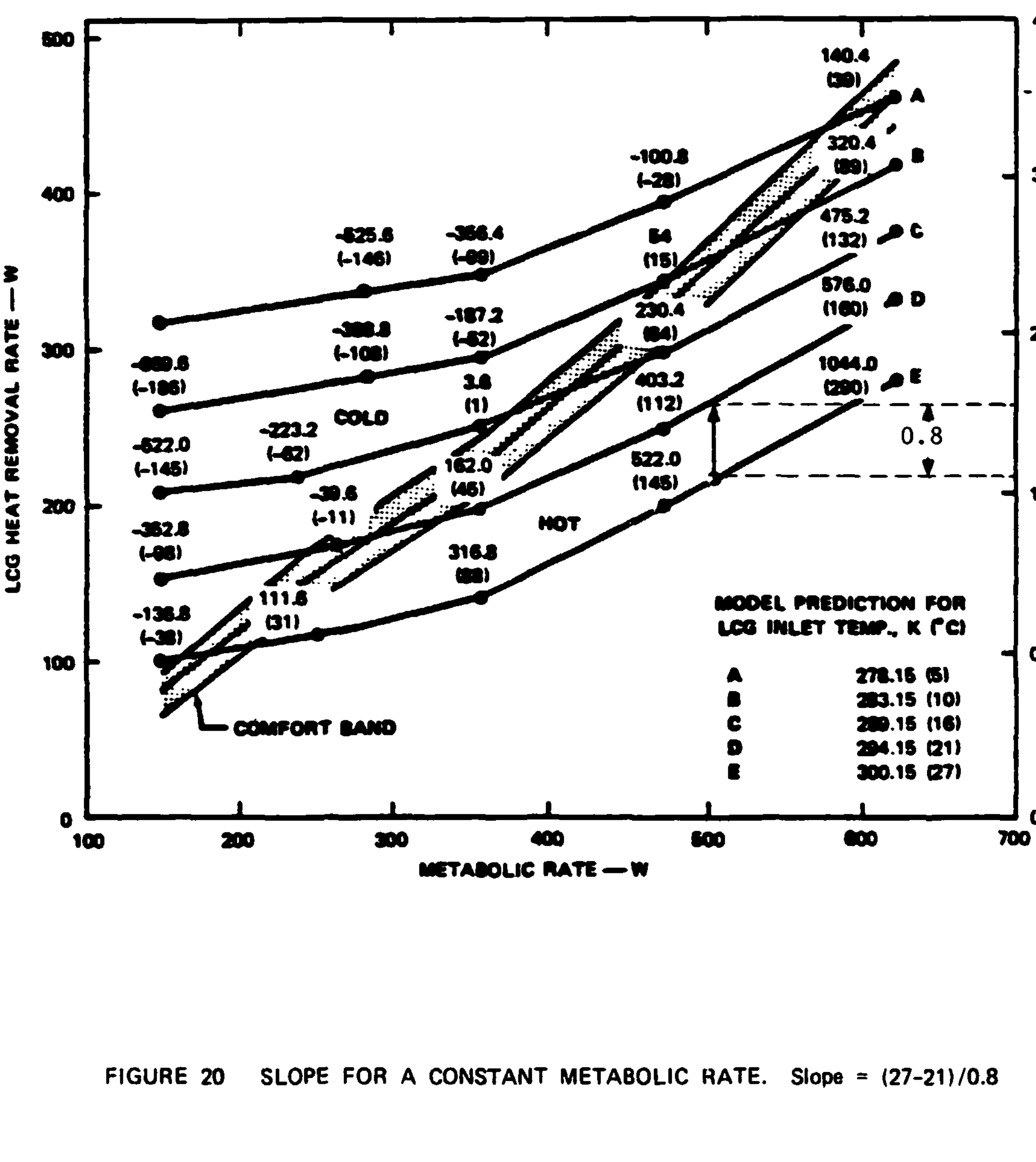

FIGURE 20 SLOPE FOR A CONSTANT METABOLIC RATE. Slope = (27-21)/0.8

into the model to calculate two ΔT's. The slope of the model steady-state trajectory is then calculated. Next a line with this slope is projected from the present (ΔT, T_i) to intersect with the center of the comfort zone. The T_i at the intersection is the new T_c. (The equation for T_c is in line 9760 where CW is the new T_c, SD is the slope, DI is the mean of ΔT and IM is the mean of T_i.)

Several times in this section the phrase "present (ΔT, T_i)" was used. For example, present (ΔT, T_i) is tested against the comfort zone. In this test and in the T_c calculations the running averages of T_i and ΔT (IM and DM in the listing) are used (not the actual present values of T_i and ΔT) to reduce the effects of noise and random variations in these variables. Equation 10 is used to calculate the average of T_i and an identical equation with ΔT as the input is used to calculate the average of ΔT.

Figure 21 is a schematic of two typical trajectories when new T_cs are commanded. When (ΔT, T_i) is above the zone the new T_c will be less than T_i; when the point is below the zone, the new T_c will be greater than T_i. When there is a step change in T_c and the trajectory is above, the trajectory will swing farther away from the zone in the ΔT direction because ΔT rapidly increases with the drop in T_i and without an initial equal drop in skin temperature. As the skin temperature drops, the trajectory will move back toward the zone with a decrease in ΔT. Trajectories below tend to be more parallel to the zone.

Trajectories will remain nearer to the zone (particularly those above the zone) if the T_i is not abruptly changed to the new T_c. There are a number of obvious schemes for changing T_i that do not involve a step. For example, T_c could be moved along a ramp to the new "target" T_c. The method that has proven successful in our experiments moves T_c to the target T_c (the one chosen in the T_c calculations) with the following first order difference equation (see the subroutine starting at line 11000):

$$T_c(n) = (1-A_t)T_c(n-1)+A_tT_t \qquad (28)$$

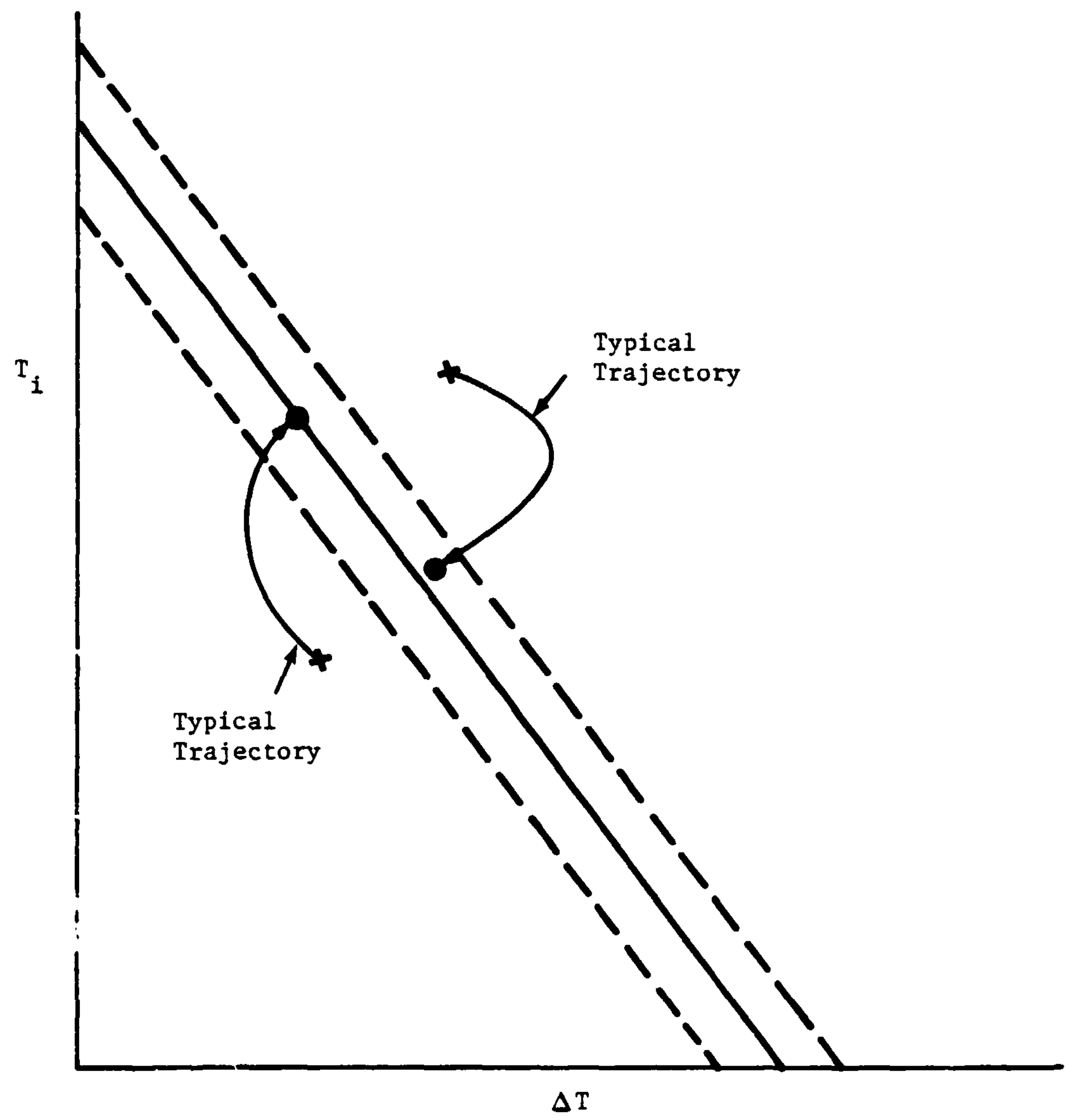

FIGURE 21 TRAJECTORIES OF ΔT vs T_i AFTER STEP CHANGES IN T_c

where T_t is the target T_c and A_t is a constant less than 1 which has one of two values depending on whether the trajectory is above or below the zone. Equation 28 is iterated once a second.

The command temperature will experimentally approach T_t and the time constant of Eq. 28 can be chosen to minimize the distance the trajectory of $(\Delta T, T_i)$ moves away from the zone. It is our subjective opinion that the subjects were more comfortable when this scheme was used, and we frequently observed that the trajectory moved into the zone and then followed the zone down to the target.

The next section describes the "closed-loop" experiments where the LCG temperature was completely controlled by the computer and the subject was exercising on a treadmill.

VII LCG AUTOMATIC CONTROLLER TESTS

A second series of human subject exercise tests was completed during the LCG automatic controller program. The purposes of these tests were to: (1) test the adaptive control program; (2) optimize the thermal comfort subroutine; and (3) demonstrate the use of the LCG inlet temperature automatic controller technique during treadmill exercise. The computer model actively selected the command LCG inlet temperature during all phases of these tests.

As was mentioned in the last section, the thermal comfort zone as defined by Kuznetz has been found to be inapplicable for our experiments. The subjects tested by Kuznetz were enclosed in a sealed suit with ventilation flow that could remove body heat by sweat evaporation and convection. Our subjects had no ventilation and thus essentially all metabolic heat was removed by a combination of respiration and the LCG. Thus, in our case, at any particular metabolic rate the LCG must remove more heat for the subjects to be comfortable. For a given inlet temperature the ΔT will be greater than given by Kuznetz so that our comfort line appears to have a smaller slope. The Kuznetz comfort zone has a Y intercept of ~34.6°C and a comfort band of ±0.15°C (see Figure 18). The initial SRI comfort zone had a Y intercept of 23°C and a comfort band of ±0.25°C. The slope and comfort band of the SRI curve remained constant during the various parametric study exercise tests. However, during the first series of tests the different subjects tested subjectively preferred different Y intercepts when standing at rest. This preference appears to be a function of how well the LCG fits during the tests; when the LCG fit a subject tight he preferred that the comfort zone Y intercept be increased as would be expected since the thermal conductance between the LCG and the skin is increased.

The thermal comfort subroutine was therefore modified to allow the comfort line to be easily varied to accommodate a subject's preference. However, the fact that the comfort line has been found to be a function of personal preference and test conditions indicates the need for further experimental work.

Five subject/exercise tests were completed during the LCG automatic controller tests. The results of these experiments are presented in Figure 22-26. The same presentation format was used in each of these figures. The measured LCG ΔT (^{o}C) is shown on the X axis and the actual LCG inlet temperature (^{o}C) is shown on the Y axis. The comfort zone used during each test is presented as the solid trace dashed lines in each figure. To provide a uniform basis of comparison between these tests and the previously described tests the exercise profile given in Figure 14 was used in each case studied. Each subject stood at rest for 10 min, walked at 3 mph for 20 min, and stood at rest for 10 min following the exercise period. The thermal conditions during each test are plotted every 100 s in Figures 22-26.

The control program's response was similar during each of the five tests conducted. As the subject starts to exercise the LCG inlet temperatures versus LCG ΔT point moves to the right of the comfort zone, showing that the subject needs a lower inlet temperature to remain comfortable. The adaptive subroutine of the control program detects this requirement and alters the control valve position accordingly. As the subject continues to work an optimal equilibrium point on the comfort zone is reached for each test case. The controller automatically adjusts the LCG inlet temperature to maintain the desired conditions. Upon cessation of exercise the subject's response point falls to the left of the comfort zone. This indicates that a higher inlet temperature is needed to maintain thermal comfort. Once again this requirement is detected by the control program which makes the appropriate valve adjustments to move the LCG inlet temperature versus LCG ΔT point back into the comfort zone.

A second exercise period was initiated during the test shown in Figure 24. As shown in Figure 23 the LCG inlet temperature was

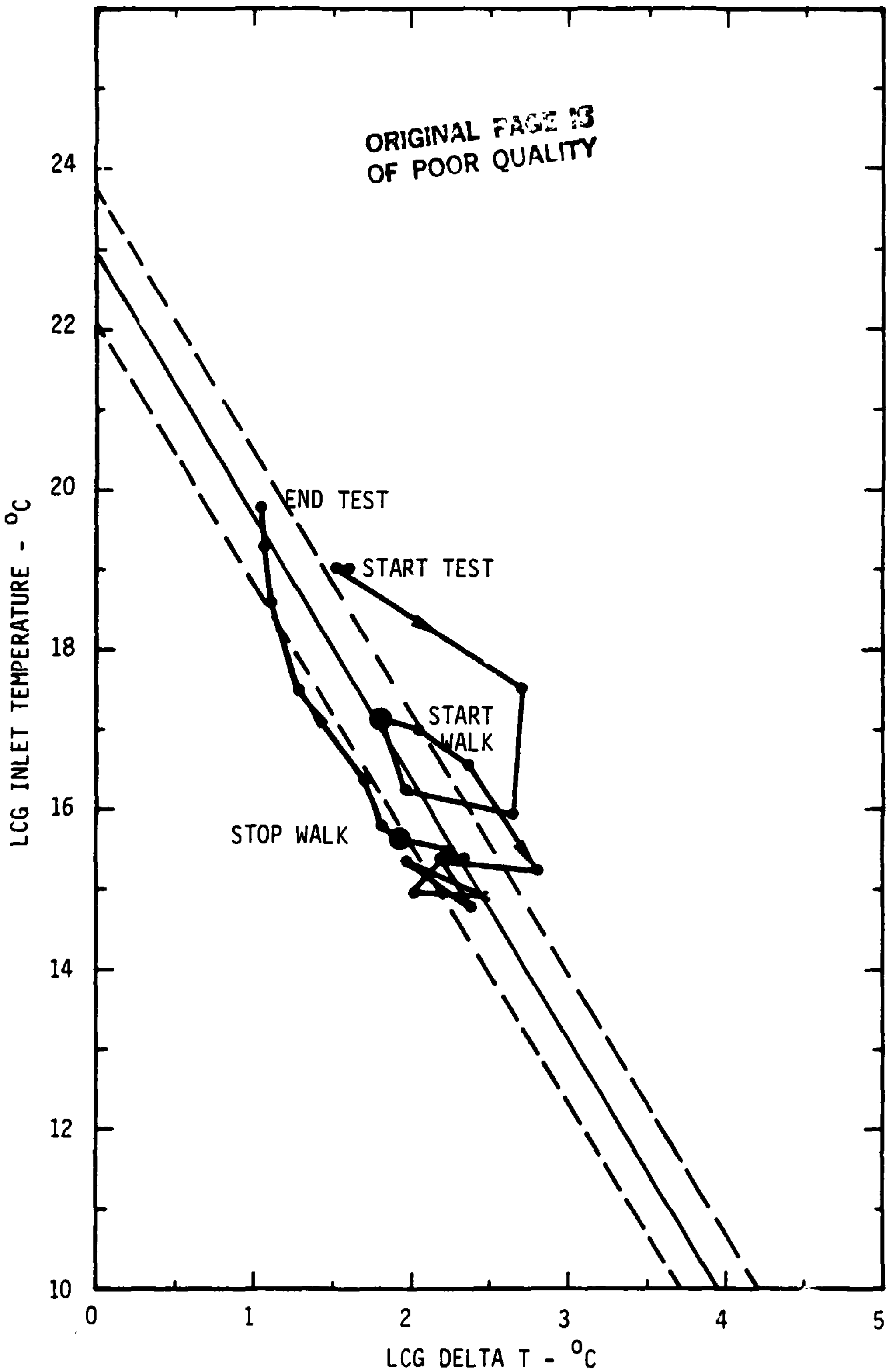

FIGURE 22 LCG INLET TEMPERATURE vs LCG ΔT--SUBJECT SCL/12

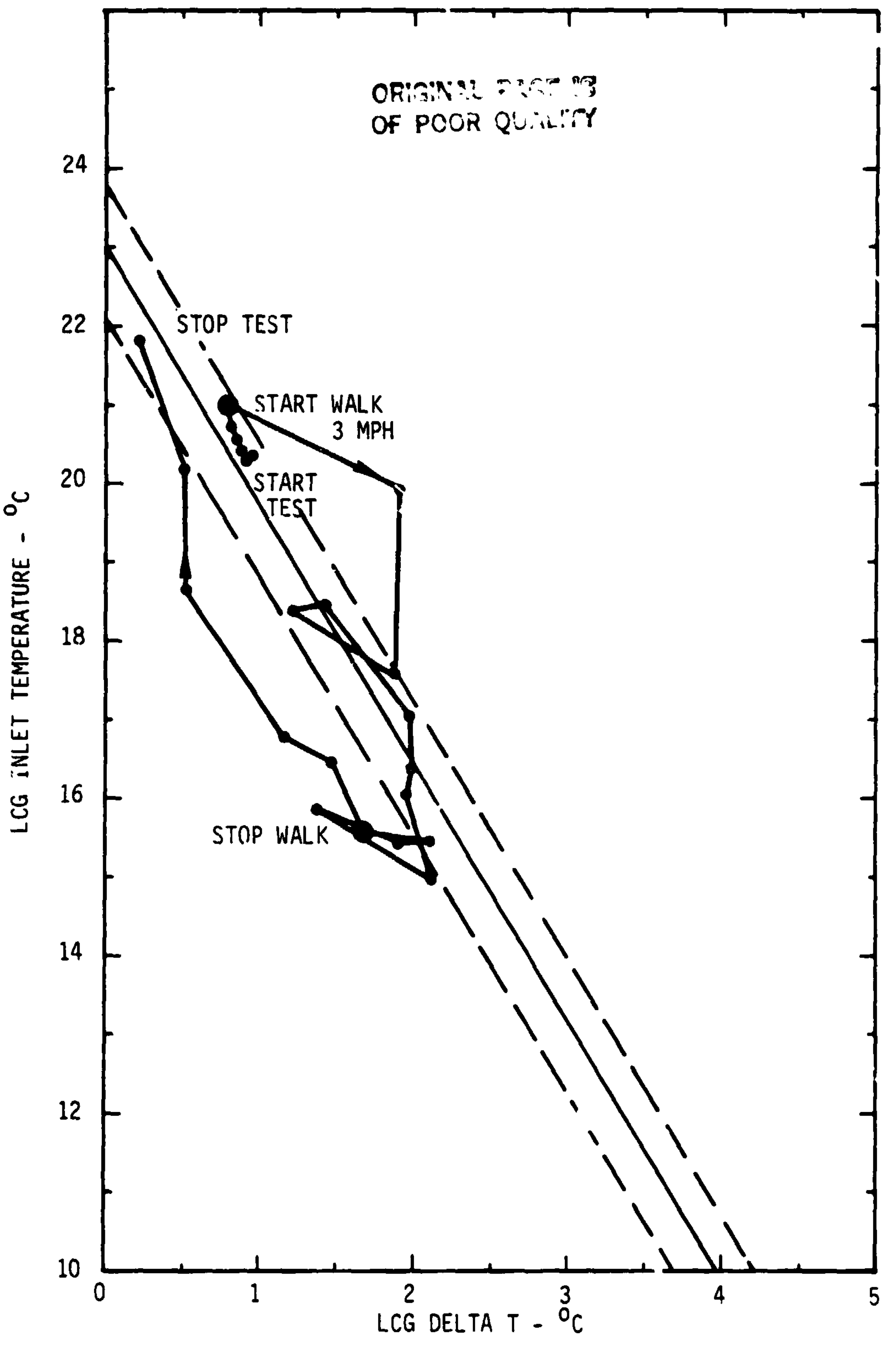

FIGURE 23 LCG INLET TEMPERATURE vs LCG ΔT--SUBJECT PC' /56

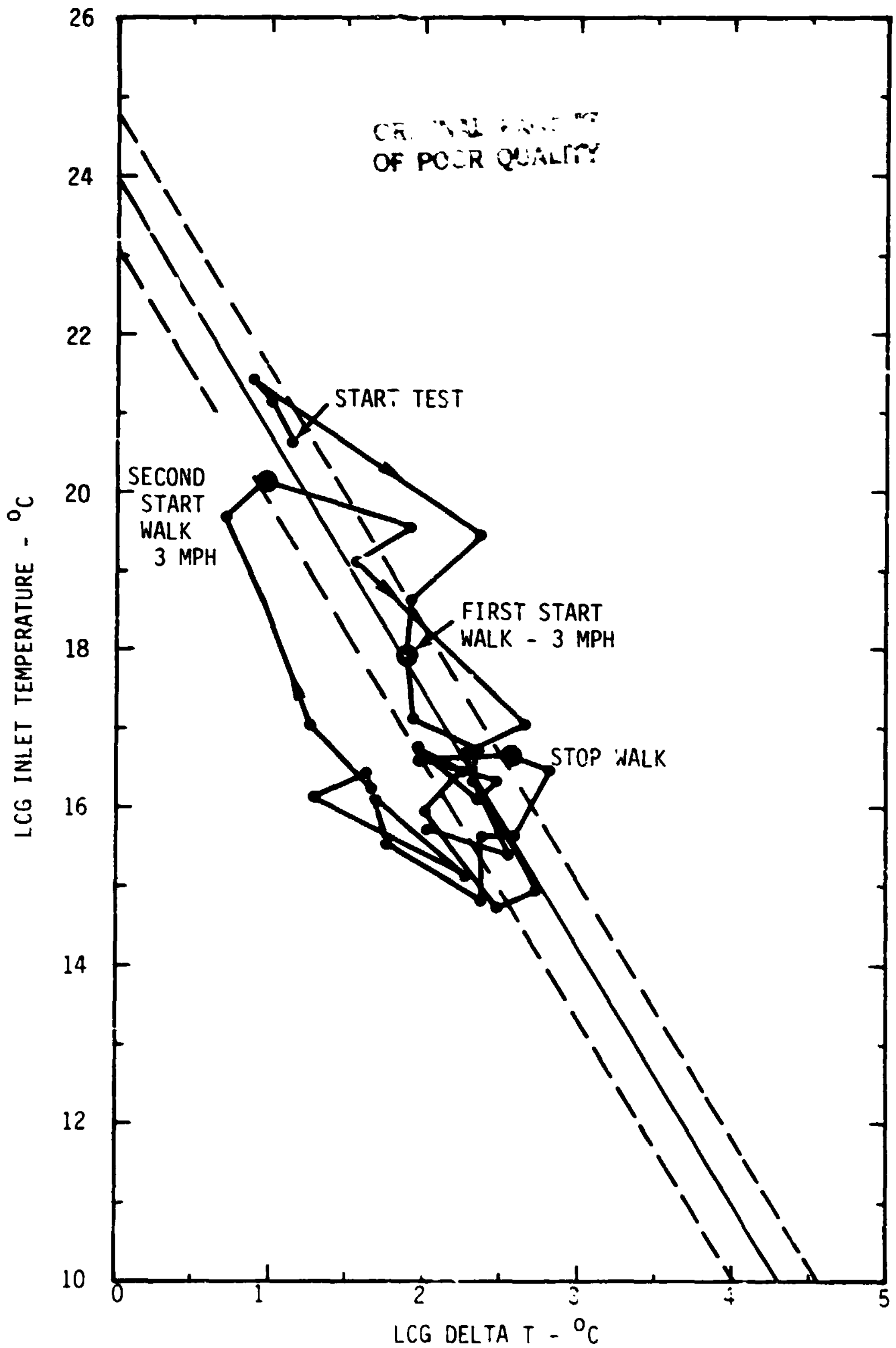

FIGURE 24 LCG INLET TEMPERATURE vs LCG ΔT--SUBJECT PCL/89

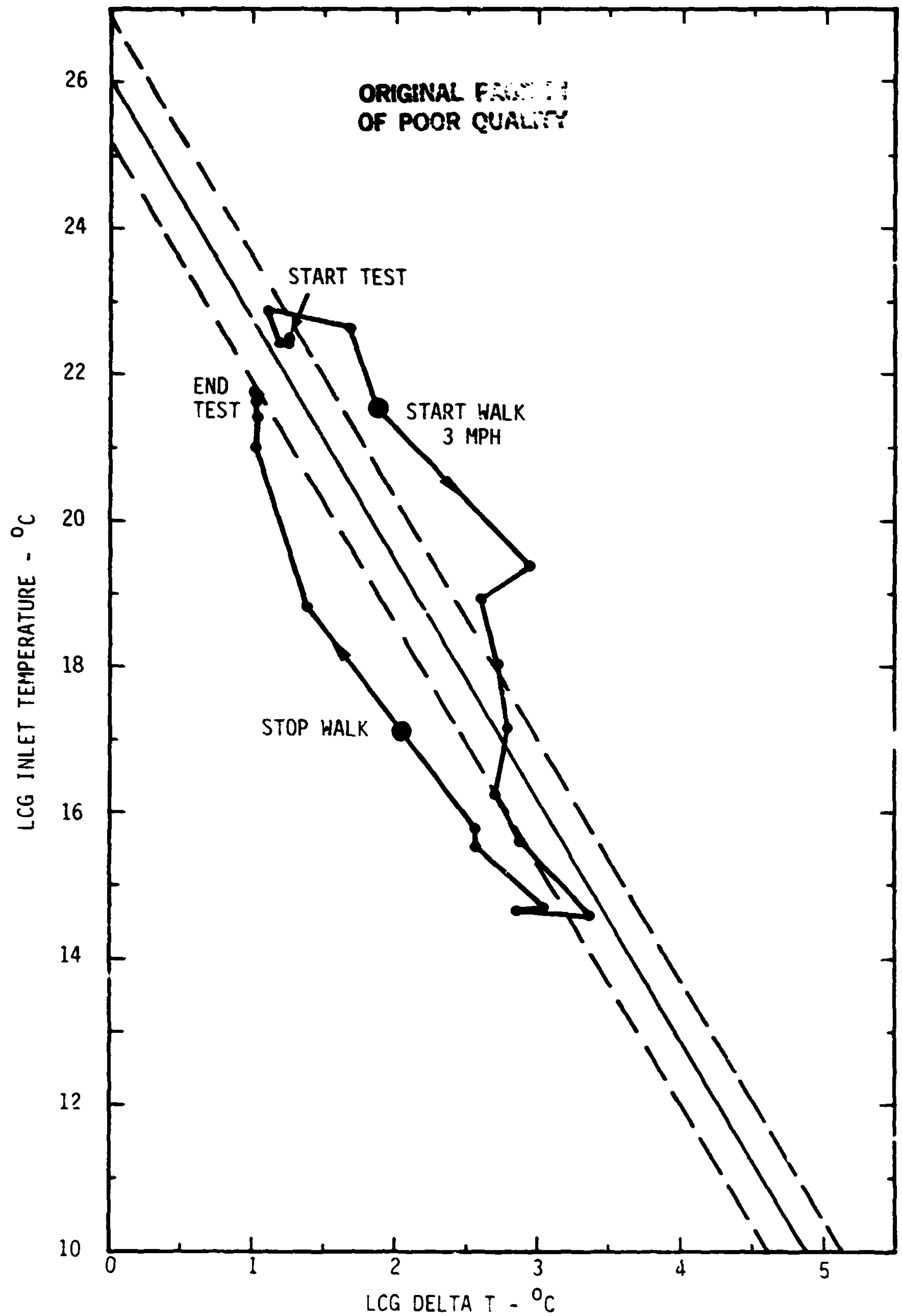

FIGURE 25 LCG INLET TEMPERATURE vs LCG ΔT--SUBJECT LCL/12

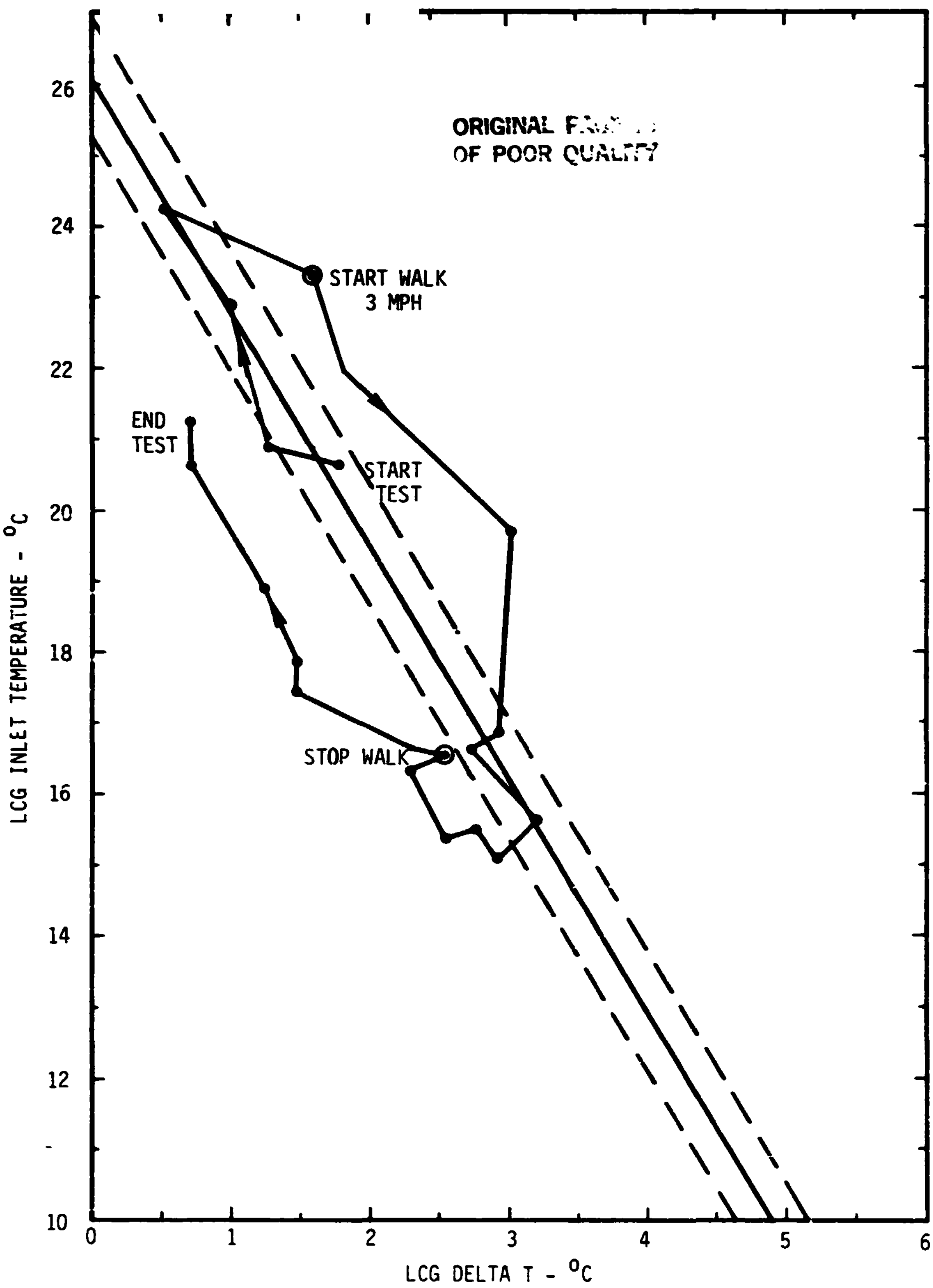

FIGURE 26 LCG INLET TEMPERATURE vs LCG ΔT--SUBJECT GCL/12

automatically readjusted to a valve position similar to that used during the first exercise period.

A Y intercept of 23°C was used during the tests illustrated in Figures 22 and 23. The subject tested in Figure 23 complained of being cold before the start of the exercise. The Y intercept was then raised to 24°C and the test repeated. The repeated test results are given in Figure 24. The subject did not feel cold during the Figure 24 control period.

A Y intercept of 26°C was used during the tests illustrated in Figures 25 and 26. The LCG fit these two subjects tighter than it fit the previous subjects. Initial tests on these two subjects showed that they were uncomfortable at rest with lower Y intercept values.

VIII CONCLUDING REMARKS AND RECOMMENDATIONS FOR FURTHER WORK

A. Concluding Remarks

We have demonstrated that the adaptive-model-reference method is a viable technique for the control of LCG temperature. Although the algorithms are complex, they can be implemented on a reasonably-sized microprocessor of a type that probably would be needed for other life-support, back pack, house keeping chores. Thus there will be little increase in the hardware complexity when compared to temperature controls that are much less sophisticated. Both the house keeping and temperature control should be able to be implemented on a single microprocessor.

We have developed an experimental microcomputer-driven system that can be used to test various algorithms. This system includes a through-the-computer loop for the control of the LCG inlet temperature. The study developed a servo algorithm that performs satisfactorily under the special conditions that are encountered with LCG inlet temperature control. We feel that elements of this algorithm probably will be included in any operational computerized LCG control.

We have developed a simple but accurate adaptive computer model that gives outlet temperature as a function of the inlet temperature waveform. The model can be run much faster than real-time on a microprocessor. It is the heart of the LCG temperature control algorithm, and it also might be of value in general computer simulations of life support systems.

There is evidence that the comfort zone varies among individuals. A simple parameter change allows the LCG temperature algorithm to be adjusted to virtually any comfort zone. If one life-support system were to be worn by more than one subject, a subject identifying number could be entered to automatically select the correct parameters.

The remainder of this section describes additional work that is required or desirable prior to the development of an operational adaptive-model-reference LCG temperature control.

B. Recommendations for Further Development

1. Mechanical Subsystem Improvements

A number of areas were identified during this program where additional work is needed to optimize the controller logic before proceeding to an actual EVA system. The existing breadboard controller can be used for this optimization if several improvements are made.

It was found that the thermal time constant of the system is too long. This is primarily caused by the commercial tube-in-shell heat exchangers that were used (see Figure 5). These heat exchangers were bypassed for the human tests discussed previously. However, this was only marginally effective due to the large mass of water in the system. These heat exchangers should be replaced by aerospace quality compact liquid-to-liquid heat exchangers that are available from a number of sources.

The proportioning valve must also be replaced. The present valve, which was borrowed from NASA, leaks both internally and externally, responds slowly to commands to change position, and has excess mechanical hysteresis.

If the above hardware improvements to the breadboard system are implemented, the following test series, with accompanying analysis and control logic optimization, should be performed.

2. Tests Using an Insulated Overgarment

Both the steady-state and transient controller responses should be investigated further. Limited human evaluations were performed during the current program. In particular, very few repetitive runs of the type needed to develop statistically significant data were performed. It is expected that the controller performance can be improved significantly by these tests.

3. Whole Body Heat and Mass Balance

Following the tests discussed above, a series of human experiments should be performed to completely quantify all aspects of the controller's physiologic performance. These tests would be similar to those performed by Webbon[9] wherein subjects were enclosed in a sealed environment simulating a space suit. The subject's thermal state would be continuously assessed by measuring the suit air and water inlet and outlet conditions, as well as physiological parameters such as heart rate, actual metabolic rate, and various body temperatures. The subject's precise thermal state can be calculated from these data. Repetitive runs would be performed using a variable metabolic rate to completely characterize the controller's performance.

4. Model Coefficient Refinement Tests

A preliminary model coefficient parametric study was performed as part of this investigation to determine the number of taps, the adaptive coefficient, and the mean coefficient values that should be used in the control program. The procedure and the results obtained during this parametric study are described in Section V.B. of this report. As discussed earlier, the parameter values used led to an average error of about 0.4^{o}C between the predicted and measured LCG ΔT values for a series of four exercise tests. It is recommended that additional parametric calculations be made to verify and refine the previous coefficients.

The measured LCG ΔT values obtained during the insulated overgarment tests will then be used in a parametric study to determine the coefficient values that provide the best calculated LCG ΔT values. The following parameter values will be studied during the parametric portion of this test series:

- Number of taps: 2, 4, 6, 8
- Adaptive coefficient: 0.15, 0.10, 0.075, 0.05, 0.025
- Mean coefficient: 0.1, 0.2, 0.3.

The optimal set of these coefficient values will then be incorporated into the automatic controller program.

5. Dither Signal Optimization Tests

An additional exercise test series should be performed to optimize the amplitude and frequency of the dither signal required for the adaptive control model. A random dither signal of ±1°C, with a dither interval greater than 30 s was used in all previous tests. System performance and subject thermal sensitivity will be determined with the following dither signals:

Amplitude(°C)	Interval (s)
0.25	20
0.25	60
0.25	120
0.50	20
0.50	60
0.50	120
1.00	20
1.00	60
1.00	120

Two subjects will perform the metabolic profile shown in Figure 27 during treadmill exercise with the above dither signals. The LCG inlet temperature will be under full automatic control during these tests. Metabolic rate will not be measured directly but will be determined using standard correlations with the known treadmill speed. The LCG will be an Apollo-type garment. The subjects will wear an insulated down suit over the LCG. The subject's thermal state will be determined using the same thermal-comfort index used by Kuznetz. No other physiological data will be measured at this time.

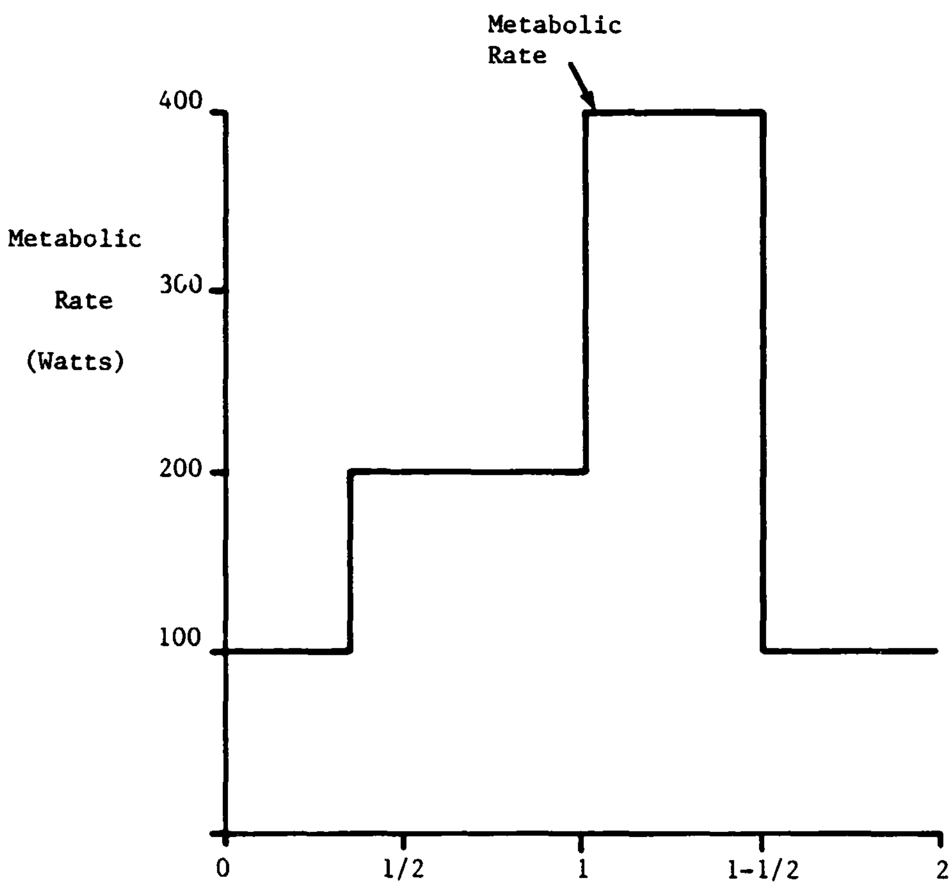

FIGURE 27 DITHER SIGNAL OPTIMIZATION

Control system performance will be assessed using the LCG inlet and outlet temperature profiles during the various tests. A dither amplitude and frequency will be selected which optimizes the system control characteristics and minimizes the subject's sensation of thermal change.

6. Hot-Cold Water Inlet Temperature Control

Use of optimum control techniques and a more rapid return to the comfort zone would be possible if a source of hot water (in addition to the cold water from the heat exchanger) were available. Then T_i could be rapidly driven in either direction and the overshoot could be minimized. Optimum control could minimize the time and distance away from the control zone.

There should be a study of hot water sources using heat from the LCG. For example, water from the LCG when it is operating at the upper range of T_o could be stored in a hot-water reservoir, and water from the heat exchanger could be stored in a cold-water reservoir. Algorithms for deciding when to withdraw, the rates for withdrawal from either reservoir, and the replenishment rates with typical metabolic rate profiles should be developed. Reservoir sizes should be studied along with control algorithms that utilize a hot/cold water control.

7. Algorithm Improvements

The control algorithms that are described in this report are preliminary developments and additional refinement will be required prior to any operational use of these techniques. For example, the convergence in the T_c calculations should be better understood and perhaps a modified technique should be developed. It is important to conduct an extensive set of experiments (similar to the proposed model experiments) to optimize the parameters in the T_c calculation and in the computer servocontrol loop.

There are over 20 input variables for the servo and T_c calculation algorithms. Our data base was too small, and we did not have time for more than cursory optimization.

8. LCG Transient Responses

Kuznetz's work and the T_i control algorithms that were developed during the present study are based on a constant T_i, an LCG at steady-state, and a constant metabolic rate. None of these are strictly true in practice. Kuznetz's curves and comfort zone assume steady-state, and the comfort region when the metabolic rates are changing is not known. What are the most comfortable T_i versus ΔT trajectories? Eventually Kuznetz's work must be extended to include a dynamically changing environment.

Appendix

PROGRAM LISTING

The following is a listing of the Microsoft BASIC version of the program that is used to control the LCG temperature. This program is compiled (Microsoft BASIC compiler) for the experimental studies. The parameter values can be obtained by comparing lines 30 and 34,000.

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```
5 CLEAR 500:DIM CT(100),IM(100),DM(100)
7 AF=0:AD=1:L3%=0:A3%=0:LT$="O":J0%=0:J4%=0:L7%=0:FM%=0:F5%=0:J8%=0:F9%=0:BX%=0
10 CLS
15 ON ERROR GOTO 900
20 PRINT"THIS PROGRAM DOES THE CLOSED-LOOP CONTROL.":PRINT
25 INPUT"PRESS <ENTER> TO CONTINUE";A:CLS
30 READ CU,BU,BD,C$,C1$,DS,TD%,PH,P,AL,AN,L0%,L3%,BN,BL,A5,HC,SI%,SJ%,HL%,HD,AB$
,CC,A6,BC$,A7,A8,BA$,L8%,A0,A4,AA,BG$,BI,BJ,BH$,AX,AY,AW
35 IC=AA/(9.389*A4):AM=AN*L3%:BM=BN*L3%:A1=A4*9.389*(IC-BL):A2=A4*9.389*(IC+BL):
A9=A0+A5
40 INPUT"ARE ALL THE DEFAULT VALUES TO BE USED (Y/N)";A$:CLS:PRINT:IF A$="N" THE
N AG=0:GOSUB 13000:ELSE AG=1
45 FOR N%=1 TO 4:READ CP(N%):NEXT N%:FOR N=1 TO P:C(N)=0:NEXT N:IF P=4 AND AB$="
Y" THEN FOR N=1 TO 4:READ C(N):CZ(N)=C(N):NEXT N
50 GOSUB 11000:GOSUB 8000:GOSUB 6000:GOSUB 7000:GOSUB 5000
55 J0%=J0%+1:IF J0%>=L0% THEN J0%=0
57 J3%=J3%+1:IF J3%=L3% THEN J3%=0
60 IF AF=0 THEN PRINT @ 321,"CT";:PRINT TAB(12)"IT"; TAB(24)"OT";TAB(36)"HT";TAB
(48)"F"
70 IF AF=0 THEN PRINT @ 385,CT;:PRINT TAB(12)IT; TAB(24)OT;TAB(36)HT;TAB(48)F
80 IF FL%=1 AND AF=0 THEN PRINT"J1=";J1%
100 IF A3%=0 THEN GOSUB 1000
110 IF LT$="O" THEN 500
130 IF J0%=1 THEN GOSUB 3000:GOSUB 2000
140 IF J0%=2 AND AF=1 THEN GOSUB 14000
145 IF J0%=3 AND FL%=1 THEN GOSUB 12000
150 IF (J0%=4) OR (FM%=1 AND J0%<L0%-1) THEN GOSUB 9000
500 A$=""
510 A$=INKEY$
520 IF A$="C" THEN AD=1:GOSUB 13000
530 IF T$=TIME$ THEN 500
540 T.=TIME$:COTO 50
550 POKE 16425,1
560 CLS:INPUT"RECORD THE INLET TEMPERATURES (Y/N)";A$:IF A$="N" THEN 640
570 PRINT:INPUT"ENTER THE FILE NAME";NF$
580 OPEN"O",1,NF$+":1"
590 PRINT#1,J1%
600 FOR N%=1 TO J1%
610 PRINT#1,CT(N%);IM(N%);DM(N%)
620 [illegible]T N%
630 CLOSE:J1%=0
640 PRINT:INPUT"CONTINUE THE RUN (Y/N)";AU$:IF AU$="Y" THEN 50
650 END
900 RESUME 910
910 J1%=J1%-1:IF OT-HT=0 THEN F=F+BS*(CT-IT):FS=F:IF IT-CT<0 THEN FH=1
920 IF IT-CT>0 AND OT-HT=0 THEN FH=2
930 IF OT-HT=0 THEN 7050 ELSE GOTO 550
1000 REM:THIS SUB INIALIZES IM AND OM
1010 L7%=L7%+1:IF L7%=10 THEN A3%=1
1020 IM=IM+IT:OM=OM+OT
1030 IF A3%=0 THEN 1050
1040 IM=IM/10:OM=OM/10
1050 RETURN
```

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```
2000 REM:THIS SUB CALCULATES THE COEFFICENTS
2027 IF (DT-DE)[illegible]1 THEN KC=SGN(DT-DE) ELSE KC=DT-DE
2030 FOR NC=1 TO R
2050 C(NC)=C(NC)+AL*KC*XC(NC)
2070 NEXT NC
2080 DC=OM/IM
2090 RETURN
3000 REM:THIS SUB DOES THE FILTERING
3010 FOR NF=R TO 2 STEP -1
3025 XC(NF)=XC(NF-1)
3030 NEXT NF
3035 XC(1)=H1
3040 DE=0
3050 FOR NF= 1 TO R:DE=DE+XC(NF)*C(NF):NEXT NF
3060 DE=DE+(DC-1)*IM
3070 RETURN
5000 REM: THIS SUB-PROGRAM SETS THE VALVE POSITION
5010 REM:  VARIABLE 'PV' IS THE VALVE POSITION
5012 IP=IP+1:IF IP<PH THEN 5120 ELSE IF CT<>RT THEN IP=0:RT=CT
5020 PA=223
5030 MS=INT(PV/256 + .00
5040 OUT PA,16*1+MS
5050 OUT PA,MS
5060 MI=INT((PV/16)-16*MS+.001)
5070 OUT PA,16*2+MI
5080 OUT PA,MI
5090 LS=INT(PV-256*M[illegible] 16*MI+.001)
5100 OUT PA,16*3+LS
5110 OUT PA,LS
5120 RETURN
6000 REM:THIS SUB READS THE TEMPERATURES
6010 OUT 223,128
6015 FOR MT=0 TO 10:NEXT MT
6020 FOR NT%=0 TO 4
6022 IF FG%=1 AND NT%=4 THEN 6050
6025 FOR MT=1 TO 10:NEXT MT
6030 OUT 223,NT%
6032 FOR MT=1 TO 10:NEXT MT
6035 OUT 223,128
6037 FOR MT=1 TO 10:NEXT MT
6040 TT(NT%+1)=INP(223)
6045 IF NT%<4 AND TT(NT%+1)>115 THEN TT(NT%+1)=VT(NT%+1)
6047 VT(NT%+1)=TT(NT%+1)
6050 NEXT NT%
6055 IF TT(5)>190 THEN FG%=1
6060 HT=(TT(3)-51.49)/1.79
6080 IT=(TT(2)-49.95)/1.82
6090 OT=(TT(1)-51.49)/1.79
6091 IF FG%=1 THEN DT=OT-[illegible]T ELSE DT=(TT(5)-52.1+.28*(((OT+IT)/2)-8))/22.48
6093 IS=IT:OS=OT:IT=(IT+OT-DT)/2:IF IT<0 THEN IT=IS
6096 OT=(IS+DT+OT)/2:IF OT<2 THEN OT=OS
6100 IF FG%=1 AND DT [illegible] THEN FG%=0
6105 IFJ3%=0 THEN DM=[illegible]DT+(1-A[illegible])*D[illegible]:IM=AM*IT+(1-AM)*IM:OM=AM*OT+(1-AM)*OM:H1=IT
-IE+(1-BM)*H1:IE=IT
6110 RETURN
```

```
7000 REM:THIS SUB GENERATES THE VALVE POSITION.
7010 IF CT=ST THEN 7033 ELSE ST=CT
7015 IF C1$="N" AND CT-IT>=0 THEN 7033
7020 F=F+(CT-IT)/(OT-HT):FS=F:IF IT-CT<0 THEN FH=1 ELSE IF IT-CT>0 THEN FH=2
7030 GOTO 7050
7033 IF CT-IT>=0 THEN BS=BU:GOTO 7040
7036 GOTO 7200
7040 F=F+BS*(C  IT)
7050 PV=0
7053 IF FH=1 AND IT-CT>=0 THEN F=FS:FH=0
7056 IF FH=2 AND IT-CT<=0 THEN F=FS:FH=0
7060 IF F>1 THEN F=1
7070 IF F<0 THEN F=0
7080 FOR NS%=1 TO 3
7090 PV=PV+(F[(4-NS%))*CP(NS%)
7100 NEXT NS%
7110 PV=PV+CP(4):PV=INT(PV):IF PV<1 THEN PV=1
7115 IF PV>4095 THEN PV=4095
7120 RETURN
7200 BS=BD
7210 IF C$="N" THEN 7040
7220 IF (IT-CT)<1 THEN 7040
7230 F=F-BS:GOTO 7050
8000 REM:THI SUB PICK THE DITHER
8010 IF DS=0 THEN CT=CU:GOTO 8070
8020 JD%=JD%+1:IF JD%=TD% THEN JD%=0
8030 T1$=MID$(T$,14,1):IF T1$="7" THEN CT=CU+DS/2:GOTO 8070
8040 IF T1$="8" THEN CT=CU:GOTO 8070
8050 IF T1$="9" THEN CT= CU-DS/2:GOTO 8070
8060 IF JD%=1 THEN XD=RND(2):CT=CU+DS*((XD-1)-.5):CW=CU
8065 IF CW<>CU THEN CT=CU+DS*((XD-1)-.5):CW=CU
8070 RETURN
8500 REM:THIS SUB CHANGES THE DITHER SIZE
8510 CLS:INPUT"ENTER THE DITHER SIZE";DS:PRINT
8515 INPUT "ENTER THE TIME IN SECONDS BETWEEN DITHER CHANGES";TD%:CLS
8520 RETURN
```

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```
9000 REM:THIS SUB PICKS THE CT DURING CLOSED-LOOP OPERATION
9005 IF LT$="A" AND FM%=0 THEN 9260
9010 IF FM%=1 THEN 9060
9012 IF IM AA-A4*9.389*DM+A5 THEN SH%=SJ% ELSE SH%=SI%
9015 J4%=J4%+1:IF J4%<= 'H% AND F9%=0 THEN 9260
9020 IF IM>A1-A4*9.389 M+A5 AND IM<A_-A4*9.389*DM+A5 THEN 9260
9025 IF F9%>0 AND J4%<=SH% THEN 9950
9027 IF BG$="Y" THEN 960_
9030 DD=DC:GOSUB 9500:PRINT @ 63,"*"
9040 FOR NH%=1 TO R:XH(NH%)=XC(NH%):CH(NH%)=C(NH%):NEXT NH%:DD=DC:IH=IM:H2=H1:H2
=CV-IT+(1-BM)*H2:DI=DM:HF=HD:CY=CU
9050 FOR NH%=1 TO HL%
9060 IF T$<>TIME$ THEN FM%=1:GOTO 9260
9070 FOR NI%=R TO2 STEP -1
9080 XH(NI%)=XH(NI%-1)
9085 NEXT NI%
9090 XH(1)=H2
9100 DF=0
9110 FOR NI%=1 TO R:DF=DF+XH(NI%)*CH(NH%):NEXT NI%
9112 H2=(1-BM)*H2
9114 NEXT NH%
9115 CD=DD*(1+HC*(IH-CV)):IF CD<1 THEN CD=CC
9120 DF=DF+(CD-1)*CV:IF (DI-DF)[2>2.25 OR DF<0 OR DF>5.5 THEN DF=(CD-1)*CV
9150 IF F5%=1 THEN 9250
9200 IF LC%=0 AND CV>=AA-A4*9.389*DF+A5-A6 AND CV<A2-A4*9.389*DF+A5 THEN IF BC$=
"Y" GOTO 9600 ELSE GOTO 9250
9210 IF LC%=1 AND CV<=AA-A4*9.389*DF+A5+A6 AND CV>A1-A4*9.389*DF+A5 THEN IF BC$=
"Y" GOTO 9600 ELSE GOTO 9250
9215 IF BC$="Y" AND CV>AA-A4*9.839*(DF+A7)+A5 AND CV<AA-A4*9.389*(DF-A7)+A5 AND
IH-CV<A8 THEN 9600
9220 CV=CV+HF*(AA-A4*9.389*DF+A5-CV)
9225 LD%=LC%
9230 IF CV<AA-A4*9.389*DF+A5 THEN LC%=0 ELSE LC%=1
9235 IF LD%<>LC% THEN HF=HF*.5
9237 IF LD%=LC% THEN HF=HF*2:IF HF>HD THEN HF=HD
9238 J8%=J8%+1: IF J8%>=L8% THEN 9600
9240 GOTO 9050
9250 CR=CV:BX%=0:F9%=0:J8%=0:F5%=0:FM%=0:CU=CV:PRINT @ 63," ":X3=DF/.05+1:Y3=46-
(CU-10)*2.4:IF X3<0 THEN X3=0 ELSE IF X3>127 THEN X3=127
9251 IF Y3<0 THEN Y3=0 ELSE IF Y3>46 Y3=46
9252 IF AF=1 AND FR=0 THEN RESET(X4,Y4)
9254 IF AF=1 AND FQ=0 THEN RESET(X4+1,Y4)
9256 IF POINT(X3,Y3) THEN FR=1 ELSE FR=0
9258 IF POINT(X3+1,Y3) THEN FQ=1 ELSE FQ=0
9259 X4=X3:Y4=Y3:IF AF=1 THEN SET(X3,Y3):SET(X3+1,Y3)
9260 RETURN
```

```
9500 AQ=A4*9.389*DD*HC
9510 BQ=A4*9.389*(1-DD-DD*HC*IH)-1
9520 CQ=AA+A5
9530 DQ=BQ*BQ-4*AQ*CQ
9540 IF DQ<0 THEN 9560
9550 CV=(-BQ-SQR(DQ))/(2*AQ):GOTO 9570
9560 CV=HD*(AA-A4*9.389*DM+A5)
9570 IF CV>45 THEN CV=45
9580 J4%=0:IF CV-IH>0 THEN LC%=0 ELSE LC%=1
9590 RETURN
9600 IF BA$="N" THEN CV=CU:F5%=1: GOTO 9040
9605 PRINT @ 63."/":FOR NJ%=1 TO 3 STEP 2
9610 FOR NH%=1 TO R:XH(NH%)=XC(NH%):NEXT NH%
9630 H2=H1:H2=NJ%-2+(1-BM)*H2:DI=DM:HF=HD
9640 FOR NH%=1 TO HL%
9650 FOR NI%=R TO 2 STEP-1
9660 XH(NI%)=XH(NI%-1)
9670 NEXT NI%
9680 XH(1)=H2
9690 DG=0
9700 FOR NI%=1 TO R:DG=DG+XH(NI%)*CH(NH%):NEXT NI%
9710 H2=(1-BM)*H2
9720 NEXT NH%
9730 CG=DC*(1+HC*(2-NJ%)):IF CG<1 THEN CG=CC
9740 DG(NJ%)=DG+(CG-1)*(IH+NJ%-2)
9750 SD=2/(DG(3)-DG(1))
9754 NEXT NJ%
9760 CW=(SD*AA-A4*9.389*(SD*DI-IH)+A5*SD)/(SD+A4*9.389)
9765 IF CV>CU KH=KL ELSE KH=KM
9770 IF (SD<-A4*9.389 AND J8%>=L8%) OR (BG$="Y" AND SD<-A4*9.389) THEN CV=CW:DF=
(AA+A5-CW)/(A4*9.389):ELSE IF SD>=-A4*9.389 AND J8%>=L8% THEN F9%=1:GOTO 9900
9780 IF CV<A9 THEN CV=A9:F5%=1:GOTO 9040
9785 IF CV>AW THEN CV=AW:F5%=1:GOTO 9040
9790 GOTO 9250
9900 IF BA$="N" THEN CV=CU:F5%=1:GOTO 9040
9910 SE=-BI*A4*9.389:CV=(SE*AA-A4*9.389*(SE*DI-IH)+A5*SE)/(SE+A4*9.389):F9%=2
9920 F5%=1:GOTO 9040
9950 IF CU<AA-A4*9.389*DM+A5 THEN CX=-1 ELSE CX=+1
9955 CU=CU+BJ*SE*CX:F9%=1
9960 IF CU<A9 THEN CU=A9
9965 IF CU>AW THEN CU=AW
9970 GOTO 9260
11000 REM:THIS SUB DOES THE CT FILTERING
11010 IF BH$="N" OR F9%=1 OR LT$<>"C" THEN 11040
11020 IF BX%=0 THEN CU=CY:BX%=1
11025 IF CU<CR THEN AT=AX ELSE AT=AY
11030 CU=(1-AT)*CU+AT*CR
11040 RETURN
12000 REM:THIS SUB STORES VARIABLES FOR RECORDING
12010 J1%=J1%+1
12015 IF AF=1 THEN PRINT @101,"J1=";J1%
12020 CT(J1%)=CT:IM(J1%)=IM:DM(J1%)=DM
12030 RETURN
```

```
13000 REM:THIS SUB CHANGES THE VARIABLES
13010 CLS:PRINT @ 62,"**"
13040 A$=""
13050 A$=INKEY$
13052 IF A$="b" THEN INPUT"IS THE SLOPE PREDICTION MODE TO BE USED";BG$:REM-<B>
IS SHIFT <B>
13055 IF A$="0" THEN INPUT"ENTER THE DT INTERCEPT VALUE";IC:A4=AA/(9.389*IC):GOT
O 13500
13060 IF A$="T" THEN INPUT"ENTER THE NEW COMMAND INLET TEMPERATURE";CU
13062 IF A$="r" THEN INPUT"ENTER THE FACTOR THAT INCREASES THE TRAJECTORY SLOPE"
:BI
13065 IF A$="8" THEN PRINT"THE VALUE OF A4 NOW IS";A4:INPUT"ENTER THE NEW SLOPE
CHANGE-FACTOR, A4 (ENTER  0  IF THERE IS TO
BE NO CHANGE)":AZ:IF AZ<>0 THEN A4=AZ:GOSUB 13500:ELSE GOSUB 13500
13070 IF A$="G" THEN FL%=1
13072 IF A$="j" THEN INPUT"ENTER THE SIZE OF THE CT-SERVO STEP";BJ
13075 IF A$="7" THEN INPUT"ENTER THE VERTICAL INTERCEPT, AA";AA:GOSUB 13500
13080 IF A$="D" THEN GOSUB 8500
13082 IF A$="h" THEN INPUT"IS THE CT-FILTER MODE TO BE USED (Y/N)";BH$
13085 IF A$="6" THEN INPUT"ENTER THE LOWEST CT";A9
13090 IF A$="C" THEN INPUT"ENTER THE NEW UP SERVO GAIN CONSTANT";BU:PRINT:INPUT"
ENTER THE NEW DOWN SERVO GAIN CONSTANT";BD
13095 IF A$="5" THEN INPUT"IS CT TO BE ADAPTED WITH OUT THE MODEL BEING ADAPTED
(Y/N)";BA$
13100 IF A$="E" THEN 550
13102 IF A$="a" THEN INPUT"ENTER THE DOWN CT-FILTERING CONSTANT";AX
13105 IF A$="4" THEN INPUT"ARE THE EXTRA LOOK-AHEAD STOPPING CRITERIA TO BE USED
 (Y/N)";BC$
13110 IF A$="F" THEN INPUT"IS THE INITIAL F TO BE USED AFTER A DOWN COMMAND (Y/N
)":C1$
13112 IF A$="k" THEN INPUT"ENTER THE UP CT-FILTERING CONSTANT";AY
13115 IF A$="3" THEN INPUT"ENTER THE VALUE OF <A8> (THE SECOND LIMIT OPERATES WH
EN
IH-CV>A8)";A8
13120 IF A$="H" THEN INPUT"ENTER THE NEW SERVO HOLD TIME";PH
13122 IF A$="i" THEN INPUT"ENTER THE NUMBER OF STEPS TO HOLD CT WHEN (DM,IM) IS
ABOVE THE
COMFORT-ZONE";SJ%
13125 IF A$="2" THEN INPUT"ENTER THE VALUE OF THE CONSTANT FOR THE SECOND LIMIT
(A7)";A7
13130 IF A$="X" THEN INPUT"IS THE STEPPED-DOWN COMMAND TO BE USED(Y/N)";C$
13132 IF A$="q" THEN PRINT"J4%=";J4%:INPUT"ENTER J4%";J4%
13135 IF A$="1" THEN INPUT"ENTER THE NEW VALUE OF THE ADAPTIVE CURVE OFF-SET";A5
13140 IF A$="A" THEN INPUT"ENTER THE VALUE OF THE ADAPTIVE CONSTANT";AL
13142 IF A$="m" THEN INPUT"ENTER THE NUMBER OF STEPS TO HOLD CT WHEN (DM,IM) IS
BELOW THE
COMFORT-ZONE";SI%
13145 IF A$="Q" THEN INPUT"ENTER THE NEW DEAD-ZONE CONSTANT";A6
13150 IF A$="M" THEN INPUT"ENTER THE VALUE OF THE MEAN CONSTANT";AM
13152 IF A$="t" THEN INPUT"ENTER THE UPPER CT-LIMIT";AW
13155 IF A$="O" THEN INPUT"ARE NON-ZERO INITIAL VALUES FOR C(N) TO BE USED (Y/N)
":AB$:IF AB$="Y" AND R=4 THEN FOR NZ=1 TO 4:C(NZ)=CZ(NZ):NEXT NZ:ELSE FOR NZ=1 T
O R:C(NZ)=0:NEXT NZ
```

```
13160 IF A$="P" THEN INPUT"ENTER THE VALUE OF THE DC PROJECTION CONSTANT":HC
13165 IF A$="N" THEN INPUT"ENTER THE NUMBER OF CALCLATIONS FOR LOOK-AHEAD";HL%
13170 IF A$="W" THEN INPUT"ENTER TYPE OF DISPLAY (1 OR 2)";AF:AF=AF-1
13175 IF A$="I" THEN INPUT"ENTER THE  NUMBER OF STEPS TO HOLD A NEW CT WHEN (DM,
IM) IS
BELOW THE COMFORT-ZONE";SI%
13180 IF A$="L" THEN INPUT"ENTER <C> FOR CLOSED-LOOP OR <O> FOR OPEN-LOOP CONTRO
L OR <A>
FOR OPEN-LOOP CONTROL WITH FILTER ADAPTION";LT$
13185 IF A$="V" THEN INPUT"ENTER THE CT ADAPTION CONSTANT";HD
13190 IF A$="B" THEN INPUT"ENTER THE NUMBER OF SECONDS BETWEEN FILTER CALCULATIO
NS";L0%
13195 IF A$="U" THEN INPUT"ENTER THE HI-PASS CONSTANT IN 1/SEC.";BN:BM=BN*L3%
13200 IF A$="R" THEN INPUT"ENTER THE NUMBER OF TAPS";R
13205 IF A$="Z" THEN INPUT"ENTER THE HI-PASS CONSTANT";BM
13210 IF A$="K"THEN INPUT"ENTER THE DELTA T LIMIT";BL:A1=A4*9.389*(IC-BL):A2=A4*
9.389*(IC+BL):IF BL<A7 THEN A7=BL/2
13215 IF A$="Y" THEN INPUT"ENTER THE MEAN CONSTANT IN 1/SEC.";AN:AM=AN*L3%
13220 IF A$="S" THEN FL%=0
13225 IF A$="J" THEN INPUT"ENTER THE SECONDS BETWEEN MEAN CALCULATIONS";L3%:INPU
T"CHANGE AM AND BM (Y/N)";AA$:IF AA$="Y" THEN AM=AN*L3%:BM=BN*L3%
13230 IF AG=0 AND A$<>"@" THEN 13040
13240 IF A$="" THEN 13040
13250 CLS:AG=1:RETURN
13500 IC=AA/(A4*9.389):A1=A4*9.389*(IC-BL):A2=A4*9.389*(IC+BL)
13510 RETURN
```

```
14000 REM:THIS SUB PLOTS THE CRT
14010 IF POINT(120,46) THEN 14250
14020 CLS
14030 FOR MC%=10 TO 34 STEP 12
14040 SET(0,MC%)
14045 NEXT MC%
14050 SET(0,47)
14060 FOR MC%=1 TO 120 STEP 10
14070 SET(MC%,47)
14080 NEXT MC%
14090 FOR MC%=0 TO 46
14100 SET(1,MC%)
14110 NEXT MC%
14120 FOR MC%=0 TO 120
14130 SET(MC%,46)
14140 NEXT MC%
14150 FOR MC%=1 TO 120
14160 MD=(MC%-1)*.05
14170 Y1=46-(A1-A4*9.389*MD+A5-10)*2.4
14180 IF Y1<0 OR Y1>46 THEN 14200
14190 SET(MC%,Y1)
14200 Y2=46-(A2-A4*9.389*MD+A5-10)*2.4
14210 IF Y2<0 OR Y2>46 THEN 14230
14220 SET(MC%,Y2)
14230 NEXT MC%
14240 SET(X4,Y4):SET(X4+1,Y4)
14250 RESET(X5,Y5)
14260 X5=DM/.05+1:Y5=46-(IM-10)*2.4:IF X5<0 THEN X5=0 ELSE IF X5>120 THEN X5=120
14265 IF Y5<0 THEN Y5=0 ELSE IF Y5>46 THEN Y5=46
14270 SET(X5,Y5)
14280 PRINT @37,INT(CU*100)/100;"  ";INT(IM*100)/100;"  ";INT(DM*100)/100
14290 RETURN
34000 DATA 21,.075,.025,"Y","Y",2,60,5,4,.05,.01 20,1,.005,.25,0,.017,15,15,6,.5
,"Y",1.08,.5,"Y",.15,4,"Y",10,12,.35,23,"N",1.5,.6,"N",.004,.02,21
35000 DATA -199.25,-802.063,4912.55,34.6582
35010 DATA -.491,.0089,.115,.187
```

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