To the Graduate Council:

I am submitting herewith a thesis written by James E. Dunbar, Jr. entitled "Development and Application of a Digital Control System for Chemical Engineering Education." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Chemical Engineering.

Charles F. Moore, Major Professor

We have read this thesis
and recommend its acceptance:

Accepted for the Council:

Associate Vice Chancellor
and Dean of The Graduate School

DEVELOPMENT AND APPLICATION OF A DIGITAL CONTROL SYSTEM FOR CHEMICAL ENGINEERING EDUCATION

A Thesis

Presented for the

Master of Science

Degree

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James E. Dunbar, Jr.

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This work is dedicated to my parents, James and Maryle, for their love, support, and encouragement in all I do.

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ABSTRACT

The purpose of this study was to develop a digital control system for a shell and tube heat exchanger in order to provide a laboratory for students in chemical engineering. An existing heat exchanger was modified to include analog transmitters and connected to a Texas Instruments PM550 programmable controller. The following control strategies were applied to the heat exchanger: temperature feedback, temperature-flow cascade, temperature-pressure cascade, feedforward with temperature feedback, and feedforward with lead lag. Each of these strategies was programmed into the controller, tuned by Ziegler-Nichols, Cohen-Coon, and trial and error methods, and evaluated by response to both set point and load changes. Each strategy was found to be approximately equally efficient in controlling the outlet water temperature for the load applied; however, the feedforward control method was the most effective for the load change used.

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NOMENCLATURE

C_p	=	Heat capacity of water
C_v	=	Valve sizing coefficient
F_S	=	Flow rate of steam
F_W	=	Inlet water flow rate
F_{WSP}	=	Inlet water flow rate set point
H_{fg}	=	Latent heat of vaporization
K_c	=	Controller gain
K_p	=	Process gain
K_u	=	Ultimate gain
$\dot{m}_W$	=	Mass flow rate of water
P_u	=	Ultimate period
ρ	=	Density of water
t_d	=	Process dead time
T_{IN}	=	Temperature of inlet water
T_{OUT}	=	Temperature of outlet water
T_{SP}	=	Outlet water set point
τ	=	Process time constant
τ_D	=	Controller derivative action
τ_I	=	Controller integral time

CHAPTER 1

INTRODUCTION

The primary objective of this project was to develop a digital control system (DCS) for a shell and tube heat exchanger. This DCS was designed to provide a process control laboratory on a common unit operation for both undergraduate and graduate students in chemical engineering. Such a laboratory would allow the student to gain practical experience in the control of an actual physical process before entering the work place. Because digital control is so widely used in industry, students need to become familiar with DCS at the undergraduate level.

An important goal of this work was to create a DCS that employed the common control strategies existing in industry. Five different control strategies were applied to the heat exchanger: temperature feedback, temperature-flow cascade, temperature-pressure cascade, feedforward with temperature feedback, and feedforward with lead-lag. All of these schemes were designed to control the outlet water temperature of the heat exchanger; however, they each utilized different feedback variables to achieve this objective. Because of an increased demand for cold water during certain times of the day, each of these schemes also had in common a flow control loop to control cold water flow. Each strategy was programmed and stored on individual diskettes to be accessed by the user in the laboratory. By retaining each strategy on an individual diskette, the user would require little knowledge of the controller programming. A student would be able to load the actual controller configuration himself, and would then be free to completely concentrate on the effects of each control strategy. Thus, laboratory experiments could be designed for independent study.

The resulting system will allow the student to experiment with loop tuning on an actual process and to evaluate the performance of each control strategy on an individual basis. Comparisons could then be made between the actual response and the proposed theoretical response, consequently emphasizing and reinforcing the theories of process control presented in the lecture material.

CHAPTER 2

BACKGROUND

Development of Process Control Computers. In 1834, the English mathematician, Charles Babbage, conceived the idea of a steam-driven "analytical engine" (1). This concept formed the basis for the first digital computer which was completed in 1946 at the University of Pennsylvania. Subsequently, IBM became the leading manufacturer of large mainframe digital computers. From 1955 to 1973, hardware and software features were developed that made computer use by scientists and engineers both feasible and essential. Some of the advances introduced during this time period include floating-point arithmetic, a FORTRAN compiler, solid-state circuitry, a time-sharing operating system, and virtual memory which allowed large programs to be run with a limited amount of main memory.

Digital Control Systems in Industry. Before automation, process control tasks were performed manually. With progressive instrumentation, control was implemented by analog controllers using electrical, pneumatic, or hydraulic energy (2). By 1959, the first on-line, open-loop process control computers were used for data logging, data reduction, and process monitoring. Because process computers at this time were expensive, difficult to program, and unreliable, direct control of process variables was performed by analog equipment. Since 1962, process computers for direct digital control in an on-line, closed-loop mode have been used in chemical and power plants. In the late 1960s, minicomputers were introduced as a less expensive alternative to mainframes (1). Minicomputers made possible the use of computers in areas where real-time control was essential. Such applications included data acquisition, control of experiments, and interactive computer graphics. In 1975, the microcomputer became available and was "designed for feedforward and feedback control of 8 to 16 variables, and for monitoring (2)." However, extensive recognition of microcomputers did not begin until IBM introduced the PC in 1981 (1). The PC had ten times the internal memory capacity of the first microcomputers, could process 16 bits, and could be modified to increase the speed of scientific and business calculations by the addition of a coprocessor chip.

Today, the objectives of process control are rapidly changing due to energy, economical, and environmental concerns (3). Currently, the operation of most advanced control strategies requires on-line digital computers. As a result of the development of more efficient process computers and appropriate software, the application of computers for process control has increased considerably (2). Computers are now standard components of process automation. Digital control systems are programmable and can perform complex calculations, allowing many new methods to be developed for digital process control. Moreover, inexpensive minicomputers and microprocessors are widely available (3).

Computer Process Control Applications. Digital control systems require two types of software programs for computer process control applications: the computer system programs and the application programs (4). Computer system programs can be supplied by a manufacturer of process control computers or by specialized software manufacturers. They include both operating systems and utility programs.

The operating systems deal with the real-time operation of the computer control system. They oversee the execution of the control programs, organize the operations of the hardware components, and provide efficient use of the central processing unit (CPU), memory, communication peripherals, and input/output (I/O) interface. The utility programs include assemblers, editors, debuggers, and compilers which support the development of the application programs written by the user.

Application programs are written by the user and perform the specific functions required by the control problem. Some examples of these functions are: monitoring the measured process variables at specific time intervals, executing the algorithms of the control laws, correlating the control actions to the final control elements, computing and changing set points, computing and changing values of the adjustable controller parameters, and sounding alarms if process variables exceed preset limits. The application programs may be written in high level languages such as FORTRAN or low-level languages such as machine language.

Control Strategies. The overall objective of a process is to convert raw materials into desired products using available energy sources (4). The operation of a process must function in the presence of changing external disturbances and must satisfy many requirements. These requirements include safety of operation, production of product at a desired quality and quantity, adherence to environmental regulations, operation within constraints imposed by the equipment used, and utilization of raw materials, energy, capital, and labor economically. These conditions demand continuous monitoring of the process operation and external control to guarantee satisfaction of the operational objectives. This is accomplished through the control system.

A general process consists of an output, a potential disturbance, and a variable available for manipulation. The disturbance changes in an unpredictable manner; thus, a control system is needed to meet the objective of maintaining the output at acceptable levels. A feedback control system involves one measurement and one manipulated variable arranged in a single loop. It measures the value of the output, compares the indicated value to the desired value, and supplies the deviation to the main controller. The main controller changes the value of the manipulated variable to reduce the magnitude of the deviation. Feedback control does not require the identification or measurement of a disturbance, and it is insensitive to modeling errors and parameter changes. However, it does not initiate a control action until the effect of the disturbance is felt by the system.

Feedback control systems are unsatisfactory for processes that are slow or have significant dead time and can create instability in the closed-loop response.

A cascade control configuration uses one manipulated variable and more than one measurement with more than one loop. Cascade control initiates a control action based on a disturbance in a variable which is more responsive than the control variable, before that disturbance affects the control variable. The master control loop measures the control variable and uses a set point supplied by the operator. The slave loop measures the other variable and uses the output of the master controller as its set point.

A feedforward control strategy measures the disturbance directly and calculates a control action before the disturbance effects the controlled variable of the process. To perform efficiently, feedforward control requires identification and direct measurement of all possible disturbances. The impact of all changes in the parameters of a process cannot be detected; therefore, these changes cannot be compensated for by feedforward control. To eliminate these problems, a combination of feedforward with feedback control can be implemented. Also, any deviations caused by weaknesses in the feedforward control will be corrected by the feedback controller.

In the application feedforward control, a steady-state equation is formulated which relates the manipulated variable and the process disturbances to the control variable. This equation is used by the feedforward controller to immediately calculate a new value for the manipulated variable which will eliminate the effect of a disturbance on the control variable. A shortcoming of this method is that it does not take into consideration the dynamic response time of the process itself. In some cases, the immediate correction of the steady-state feedforward controller is too fast and results in a disturbance to the process. In other cases, the process responds to the disturbance faster than to the output of the feedforward controller, so that some over-corrective action is required by the feedforward controller. A common method used to compensate for differences in process dynamics is to add a lead-lag element to those disturbances which have significantly different dynamics relative to the control variable. The lead-lag element contains a ratio of the process dynamics and thus introduces an appropriate phase lead or phase lag to compensate for the differences in these dynamics.

Tuning Methods. During the development of control systems, the designer must decide how the best values for the adjustable parameters of a controller can be selected (4). This task is accomplished by tuning the control system through one or more of a variety of tuning methods.

The Ziegler-Nichols tuning technique is based on frequency response analysis and is a closed loop procedure. It requires computation of the ultimate gain and ultimate period. These values are found through the following steps: the control loop tuning is adjusted to proportional only, the proportional gain is increased until the loop cycles with a constant amplitude when a set point change is introduced, the proportional gain is recorded as the ultimate gain, and the period of sustained cycling is recorded as the ultimate period. These values are then used to calculate the final controller tuning.

A process reaction curve tuning method was developed by Cohen and Coon. This method is mainly experimental and uses real process data from the system's response. Cohen and Coon observed that the response of most processing units to an input change has a sigmoidal shape and can be approximated by the response of a first-order system with dead time. The three parameters, process gain, dead time, and time constant, are determined through an open loop disturbance and used to calculate the controller tuning.

Process Control in Education. The basics of process control are taught in the majority of college chemical engineering departments (3,5). Unfortunately, the current curriculum concentrates on very basic facts and tends to use outdated textbooks that fail to properly emphasize computers and digital systems (3,5-7). "The typical B.S. chemical engineering graduate has been exposed to no process control beyond a first course in process dynamics (8)." There is a need in industry for control expertise that is not being met by the established course of study (8-10). To meet this need, some educators propose more training in process control for all undergraduate engineering majors, rather than only those with special interests or career goals in process control (11).

To keep up with the extensive use of DCS in industry, smaller versions of digital computers are being utilized increasingly in undergraduate process control laboratories to educate chemical engineers in the theory and practice of digital control (3,7,12,13). An ideal process control laboratory should allow the student to become familiar with the components of a DCS. It should emphasize the applications of computers for data acquisition, data analysis, and control (14,15). As a direct result of the laboratory, the participant should be able to identify process situations and problems where digital control techniques may be useful, and be able to describe the basic theories underlying these techniques (16).

Simulation is both an economical and a valuable approach to the analysis and design of control systems (17). However, this method of laboratory instruction sometimes fails to impress upon the student the differences between simulated dynamics and those of an actual physical process. For example, a simulation usually assumes a "normal" state for the process, whereas the industrial definition of "normal" is that a process is rarely, if ever, normal (5). Rather than simulation, it is more advantageous to use minicomputers linked directly to the sensors and controllers of laboratory equipment (10). Digitally-based process control computers, like those used in industry, allow the student to focus directly on control theory rather than established problems that can be worked out through textbook or simulation routes.

CHAPTER 3

EQUIPMENT AND METHODS

Experimental Equipment.

Heat exchanger. The experimental system is shown schematically in Figure 1. It consists of a heat exchanger into which saturated steam is piped to the shell side and water is piped to the tube side. Schedule 40 stainless steel pipe is used throughout the system.

The heat exchanger is a one pass countercurrent shell and tube containing several brass tubes. Each tube has an inside diameter of 0.554 inches, an outside diameter of 0.625 inches, and an overall length of 57 inches. The shell is made of brass and has been pressure tested to withstand 175 pounds per square inch (psi) as an added safety precaution.

Steam is supplied through a 1 inch diameter pipe from a nominal 60 psi supply line and is throttled to approximately 15 psi with a variable reducer which is positioned with the aid of a Bourdon pressure gauge. The pipe is expanded to 1 and 1/2 inches in diameter after pressure reduction to accommodate a flowmeter for the steam and to minimize pressure loss through the line. The steam flow rate is controlled by a control valve consisting of a 1 inch body with linear trim and a rated C_v of 10. The valve has a Foxboro series P25 actuator set for air-to-open operation and a model E69F I to P converter. The steam condenses in the exchanger and the condensate passes through an inverted bucket steam trap and is sent to drain.

The water is supplied by a Lawrence centrifugal pump through a 1 and 1/2 inch diameter supply line. The flow is controlled by a Foxboro control valve that is identical to the steam control valve with the exception that the actuator is set for air-to-close operation.

A 1/2 inch diameter pipe was installed from the water discharge line to the water supply line. This pipe was included in the design of the system to allow some recycling of the hot water discharge back to the cold water inlet when used in combination with a pump to overcome the water supply pressure. A pump was not installed during this work; however, the pipe was added with the premise that a pump would be installed in the future. The recycling of the water discharge through the pipe would allow a disturbance to be present in the inlet water temperature which would otherwise remain relatively constant.

Sensors were installed to measure five process variables of the heat exchanger: inlet water temperature, outlet water temperature, water flow rate, steam flow rate, and steam flow pressure. A pressure gauge measures the steam pressure within the shell. Two flowmeters measure the inlet water and steam flow rates, and two temperature detectors measure the temperatures of the inlet and outlet water streams.

Steam pressure within the shell is measured with a Foxboro model 841GM electronic gauge pressure transducer which has a calibrated range of 0 to 20 psi. To prevent damage to the instrument, care was taken during operation so that the pressure did not exceed 25 psi.

The steam flow is measured with a Foxboro series E83L 1 and 1/2 inch vortex flowmeter calibrated to a range of 0 to 1050 pounds per hour (lbs/hr) at 15 pounds per square inch gauge (psig). This meter is well-suited for steam service and has an accuracy within 1.5% of the actual flow.

The inlet water flow rate is measured by an orifice meter. The meter is a 1 inch Foxboro integral orifice assembly with a model 843 differential/pressure (d/p) cell and a plate opening of 0.832 inches. The meter is calibrated to a range of 0 to 50 gallons per minute (gpm).

The temperature of the inlet and outlet water is measured by 100 ohm platinum resistance temperature detectors (RTDs). Both RTDs are connected to Foxboro E94 temperature transmitters. The inlet water transmitter is calibrated to a range of 50 to 100 degrees Fahrenheit (°F) and the outlet water transmitter is calibrated to 50 to 250 °F. Each of the transmitters has a 4-20 milliampere (mA) output signal so that it can be sent to a standard industrial computer for control of the process.

Computer. The computer used in this work is a Texas Instruments PM550. The PM550 system consists of a central control unit (CCU), a power supply, both discrete and analog I/O modules, a loop access module (LAM), a timer/counter access module (TCAM), a read/write programmer, and a video programming unit (VPU).

The PM550 actually has two CCUs - one which processes the control loops and another which processes relay ladder logic and special functions, including mathematical calculations.

Both the LAM and the read/write programmer provide the means for viewing and modifying variables associated with the control loop. Although only the tuning constants, the set point, and the loop mode (manual, automatic, or cascade) may be changed with the LAM, it allows viewing of other loop parameters, such as the process variable and the controller output. These capabilities make the LAM a very valuable tool.

The read/write programmer may be used to program the loops and to change variables within the loops during operation. However, because of the ease of operation and the ability to save programs on a floppy disk drive, the VPU was used almost exclusively in this work.

Experimental Methods. Six control schemes were programmed and stored on floppy disks. The three conventional control methods, feedback, cascade, and feedforward, are represented. Each has the major objective of controlling the water outlet temperature. Since a major disturbance to the heat exchanger is the fluctuation in the water supply pressure, a water flow control loop is common to all schemes.

Temperature feedback control. The temperature feedback control scheme consists of a temperature controller to control the steam flow (Figure 2).

Temperature-flow cascade control. The temperature-flow cascade control system consists of two loops, a temperature loop and a steam flow loop (Figure 3). The master controller is the temperature controller and the slave controller is the steam flow controller, the output of which controls the steam flow rate.

Temperature-pressure cascade control. This control strategy consists of two loops, a temperature loop and a steam pressure loop (Figure 4). The master controller is again the temperature loop, but the slave controller is now the pressure loop. The output of the pressure controller is used to control the steam flow rate.

Feedforward with temperature feedback control. In this control scheme (Figure 5), sensor signals are used to calculate a steam flow which serves as a set point to the steam flow controller. It is necessary to input a numerical value for C_p/H_{fg} into the controller memory based upon the steam and water properties. A temperature feedback loop on the output water temperature corrects for any error in the feedforward calculation.

Feedforward with lead-lag control. The feedforward with lead-lag control strategy is identical to the feedforward with temperature feedback scheme, except for the addition of the lead-lag compensator (Figure 6). In addition to entering a value for C_p/H_{fg}, three constants must also be entered for the lead-lag compensation block.

The loop programs. A loop is programmed into the PM550 by entering the answers in a loop specification sheet (Figure 7) into memory via the VPU or the read/write programmer. For simplicity each loop was given a starting constant (C) and variable (V) starting address in multiples of 100. Thus loop 1 begins at C100 and V100, loop 2 begins at C200 and V200, and etc.. Also, the loops were assigned constant loop numbers (Figure 8). Loop programs are sufficient for most feedback and cascade loops. The loop programs used in this work are shown in Appendix B.

Feedforward control requires the use of two additional types of programs in the PM550 - special functions and relay ladder logic. Special functions, which include the mathematical operations, must be used to calculate the set point of the steam flow controller. Since bumpless transfer between manual and cascade modes is desirable, it is also necessary to use special functions to perform tracking calculations, i.e. - calculate the outlet water temperature set point from the other process variables and assign this value to the output address of the temperature controller while not in the cascade mode. Tracking calculations for the feedforward and feedforward with lead-lag control strategies are shown in

Figures 9 and 10. A loop flag detects what mode the controller is in and a relay ladder logic program switches between the feedforward and tracking calculations when the mode is changed. Figure 11 shows the relay ladder logic used for feedforward control.

In programming the PM550 for feedforward control, an attempt was made to follow the logic given in the "Texas Instrument PM550 Process Applications Manual" to give an additional source of reference. Instructions for loading and viewing programs in the PM550 are given in Figures 12 and 13, respectively.

CHAPTER 4

RESULTS

Five different control strategies were developed for the heat exchanger, each having the primary control objective of controlling the outlet water temperature to some desired set point. These strategies ranged from a simple feedback loop to the more complicated cascade control and feedforward control. Specifically, the five control strategies used in this work were:

1) Temperature feedback to steam flow
2) Temperature-steam flow cascade
3) Temperature-steam pressure cascade
4) Feedforward with temperature feedback
5) Feedforward with lead lag

The main focus of this work was to program different control strategies into a programmable controller, in this case a Texas Instruments model PM550, and to tune the control loops using accepted methods. Three tuning techniques were used in this work:

1) Ziegler-Nichols closed loop method
2) Cohen-Coon method
3) Trial and error method

The Ziegler-Nichols and the trial and error methods were used most extensively, while the Cohen-Coon method was used in one loop (the temperature loop in the temperature feedback strategy) to compare the tuning to that of the Ziegler-Nichols method.

Strip chart recordings of data used to determine the values required for Ziegler-Nichols and Cohen-Coon tuning can be seen in Appendix C. These values were used to determine the tuning constants using the equations which follow. For a Ziegler-Nichols proportional-integral-derivative (PID) controller:

$$K_c = \frac{K_u}{1.7} \qquad [1]$$

$$\tau_I = \frac{P_u}{2} \qquad [2]$$

$$\tau_D = \frac{P_u}{8} \qquad [3]$$

For a Cohen-Coon PID controller:

$$K_c = \frac{1\tau}{Kt_d}\left(\frac{4}{3} + \frac{t_d}{4\tau}\right) \qquad [4]$$

$$\tau_I = t_d \frac{32 + \frac{6t_d}{\tau}}{13 + \frac{8t_d}{\tau}} \qquad [5]$$

$$\tau_D = t_d \frac{4}{11 + \frac{2t_d}{\tau}} \qquad [6]$$

Temperature Feedback. This control strategy consisted of a single feedback loop manipulating the steam flow to the heat exchanger (Figure 2). Ziegler-Nichols tuning was obtained using two methods. One was from an increase step in controller set point and the other was from a decrease step in controller set point. It was initially noted that when the ultimate gain was obtained through the decrease step, the shell steam pressure dropped to zero. This was not the case with the tuning from the increase step. It was of interest to compare the closed loop performance of each sets of tuning. The resulting tuning constants are shown in Table 1.

TABLE 1. Tuning Constants for Temperature Feedback

	K_c	τ_I	τ_D
Ziegler-Nichols (Increase step)	36	0.29	0.07
Ziegler-Nichols (Decrease step)	21	0.28	0.07
Cohen-Coon	12	0.31	0.05

The above tuning constants were evaluated for closed loop performance for set point changes and load changes (Appendix C, pages 76-80).

Temperature-Flow Cascade. This control strategy consisted of two cascade loops. The slave loop was a steam flow feedback loop to compensate for rapid changes in steam flow and the master loop was a temperature feedback loop (Figure 3). Different methods were used for determining the controller tuning constants. The steam flow loop was tuned by the Ziegler-Nichols method, while the temperature loop was tuned by trial and error. The trial and error technique was used to tune the temperature loop because it was found that the tuning constants from Ziegler-Nichols tuning were too aggressive for a master controller. The final tuning constants for the system are shown in Table 2.

TABLE 2. Tuning Constants for Temperature-Flow Cascade

	K_c	τ_I	τ_D
Ziegler-Nichols (Steam Flow)	11	0.34	0.08
Trial and Error (Temperature)	1	0.08	0.00

The closed loop response for the steam flow loop may be seen in Appendix C, page 82. The closed loop responses for the cascade strategy to an outlet temperature set point and to a load change for the above tuning, as well as those from trial and error tuning are shown in Appendix C, pages 83-86.

Temperature-Pressure Cascade. As in the temperature-flow cascade system, the temperature-pressure cascade strategy consisted of two cascade loops. However, in the temperature-pressure cascade system, the slave loop was a pressure feedback loop to compensate for rapid changes in steam pressure. The master loop was a temperature feedback loop (Figure 3). The two tuning techniques used for the temperature-flow cascade were also used for this strategy. The final tuning constants from Ziegler-Nichols and trial and error tuning methods are shown in Table 3.

TABLE 3. Tuning Constants for Temperature-Pressure Cascade

	K_c	τ_I	τ_D
Ziegler-Nichols (Steam Pressure)	17	0.38	0.09
Trial and Error (Temperature)	1.8	0.11	0.00

The closed loop response of the pressure loop is shown in Appendix C, page 88. The closed loop response of the cascade system to a temperature set point and load changes are shown in Appendix C, pages 89-92.

Feedforward with Temperature Feedback. This control strategy consisted of a calculator block to calculate the steam flow set point, which was based upon current values of inputs to the heat exchanger. These input values are based on the following steady state energy balance equation :

$$Steam\ Flow = \frac{C_p\, \dot{m}_W\, (T_{OUT} - T_{IN})}{H_{fg}} \qquad [7]$$

The feedforward with temperature feedback system also incorporated a temperature feedback loop to compensate for errors in the outlet temperature caused by errors in the calculator (Figure 5). The trial and error tuning from the temperature-flow strategy was used for the steam flow loop. The tuning for the temperature feedback loop was determined by the Ziegler-Nichols method and is shown in Table 4.

TABLE 4. Tuning Constants for Feedforward with Temperature Feedback

	K_c	τ_I	τ_D
Ziegler-Nichols (Temperature)	6.6	0.38	0.09
Trial and Error (Steam Flow)	1.1	0.08	0.00

The closed loop performance of this strategy is shown in Appendix C, pages 94-97.

Feedforward with Lead-Lag. This control scheme was identical to the feedforward control strategy with the exception that a lead-lag block was added to compensate for the differences in the dynamics between changes in the water temperature (due to steam flow) and changes in the outlet water flow rate (Figure 6). In order to use a lead-lag compensator in the PM550, it was necessary to represent the compensator with an algebraic equation. A lead-lag compensator can be defined by the following Laplace transfer function:

$$X(s) \longrightarrow \boxed{\frac{\tau_1 s + 1}{\tau_2 s + 1}} \longrightarrow Y(s) \qquad [8]$$

This function can be represented by the differential equation:

$$\tau_2 \frac{dy}{dt} + y = \tau_1 \frac{dx}{dt} + x \qquad [9]$$

Converting the differential equation to a difference equation yields:

$$\tau_2 \frac{y_i - y_{i-1}}{\Delta t} + y_i = \tau_1 \frac{x_i - x_{i-1}}{\Delta t} + x_i \qquad [10]$$

Solving for y_i results in the following:

$$y_i = \left(\frac{\tau_2}{\tau_2 + \Delta t}\right) y_{i-1} + \left(\frac{\tau_1 + \Delta t}{\tau_2 + \Delta t}\right) x_i - \left(\frac{\tau_1}{\tau_2 + \Delta t}\right) x_{i-1} \qquad [11]$$

This equation can be further simplified to:

$$y_i = k_1 y_{i-1} + k_2 x_i + k_3 x_{i-1} \qquad [12]$$

where

$$k_1 = \frac{\tau_2}{\tau_2 + \Delta t}$$

$$k_2 = \frac{\tau_1 + \Delta t}{\tau_2 + \Delta t}$$

$$k_3 = -\frac{\tau_1}{\tau_2 + \Delta t}$$

In order to calculate the lead-lag constants, it was necessary to determine the time constants of the outlet temperature due to both a change in water flow and a change in steam flow. Data for this calculation is in Appendix C, pages 98-99. The closed loop performance of the feedforward with lead-lag control strategy is shown in Appendix C, pages 100-101.

CHAPTER 5

DISCUSSION

In order to control the outlet water temperature of a shell and tube heat exchanger, five different control strategies were developed and tested for closed loop performance. Evaluation of the control strategies consisted of subjecting each scheme to both an outlet temperature set point change and a load change. The response was recorded with a strip chart recorder to allow comparison of each of the control strategies.

The major disturbance to the heat exchanger was determined to be the water flow rate. During periods of high water demand, the uncontrolled flow rate dropped rapidly, by as much as 10 gallons per minute (gpm). For this reason, the load change used in this analysis was a change of water flow rate.

In addition, the water flow rate was very noisy, thus preventing a high controller gain. The best controller was found to be an integral only. In this case the tuning constants were set to obtain the maximum integral reset allowed by the PM550 (gain = 0.0 and reset = 0.01 repeats per minute). These tuning constants were used throughout this work.

Temperature Feedback. Visual inspection of the tuning constants from the temperature feedback control system indicates that while the tuning from each method was similar, the values determined by the Cohen-Coon method were the most conservative (Table 1, page 20). Of the two sets of tuning constants calculated from the Ziegler-Nichols tuning method, those obtained from the decrease step were more conservative than those from the increase step.

The closed-loop responses of these tuning constants show that they all produced stable responses to a change in outlet temperature set point (Appendix C, pages 76-78). The response to a decrease in set point was significantly faster than that of an increase in set point. This is due to the non-linearity of the steam control valve at lower flow rates. In all cases, the steam flow change to an increase in set point was smooth and rapid. However, an oscillation in the temperature was observed for a decrease in set point. The effect of the more sluggish tuning from different tuning methods was a decrease in the amplitude of the oscillation but not elimination of it.

The tuning from the Ziegler-Nichols increase step and the Cohen-Coon methods were tested for a load change (Appendix C, pages 79-80). The difference in the two was small; however, the more aggressive tuning from the Ziegler-Nichols method produced a sharper change in steam flow and was superior in minimization of temperature error.

Temperature-Flow Cascade. The tuning constants for this control strategy are shown in Table 2 on page 21. The tuning constants for the steam flow controller were calculated using the Ziegler-Nichols method, while those for the temperature controller were set by trial and error. The temperature controller was tuned using trial and error because the tuning constants resulting from Ziegler-Nichols tuning were too aggressive for the master controller. The tuning for the temperature loop was a highly integral proportional-integral (PI). The closed-loop response of the steam flow to a set point change is shown in Appendix C on page 82. Despite the sluggish tuning of the temperature loop, the final closed-loop response of the temperature-flow cascade control system compares well with that of the temperature feedback strategy (Appendix C, pages 83 and 85).

When this cascade controller was subjected to a load change, the outlet temperature set point was suitably maintained (Appendix C, pages 84 and 86). The advantage of this controller over the simple temperature feedback was not realized in this test. This was due, in part, to the sluggish tuning of the temperature controller.

Temperature-Pressure Cascade. In this strategy the tuning for the pressure loop was also determined by the Ziegler-Nichols method and the tuning for the temperature loop by trial and error. As shown in Table 3 on page 22, the tuning for the temperature loop of this cascade scheme is also integral. The closed loop response of the pressure loop responded smoothly to a set point change (Appendix C, page 88). The closed-loop cascade response of this strategy is very similar to that of the temperature-flow cascade system. Once again, little advantage was seen with this control strategy over the temperature feedback scheme in terms of the response to a temperature set point change and to a load change (Appendix C, pages 89-92).

Feedforward with Temperature Feedback. During operation of the feedforward with temperature feedback system, it was ascertained that the steam flow meter was not in calibration. This was realized by the fact that initially, the feedforward calculator output was approximately twice the amount of steam that was required to maintain the outlet temperature. To compensate for this error, a calibration factor was employed. The calibration factor was determined by establishing steady state operation and then solving the calculator block for the factor C_p/H_{fg} (equation 7, page 23) with the steady state input values. This method supplied the factor and compensated for the error in the steam flow measurement. The tuning for the steam flow loop was that from the temperature-flow strategy using the trial and error method. The temperature loop tuning was determined using Ziegler-Nichols tuning as shown in Table 4 on page 23.

As shown in Appendix C on pages 94-97, the closed-loop response to a temperature set point does not differ much from the responses of the other strategies. This control system did appear to be slightly superior in response to a load change than the previous systems.

Feedforward with Lead-Lag. This control strategy was identical to the feedforward with temperature feedback scheme with the exception of the addition of a lead-lag block. The lead-lag constants were determined from the following two time constants. The time constant for outlet temperature due to a change in steam flow was determined to be 2.9 minutes. The time constant for the outlet temperature due to a change in water flow rate was 2.6 minutes (Appendix C, pages 98-99). The dynamics of these two loops are essentially equal and thus no lead-lag compensation should be used. For the purpose of this study, however, a lead-lag compensator ($\tau_1 = 4$, $\tau_2 = 2.6$) was added to provided a controller lead since the disturbance was slightly faster than the manipulated variable. With the addition of this lead, the closed loop response would be expected to be more aggressive than that of the feedforward only. The closed loop response was, in fact, found to be more aggressive (Appendix C, pages 100-101). The addition of the lead produced a somewhat better response than that which resulted from the feedforward with temperature feedback strategy. However, since the differences in the time constants for changes in water temperature in this heat exchanger are small, either strategy would be satisfactory.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

Five control strategies were successfully programmed into the PM550. These systems were tuned and tested for closed-loop performance to both a set point change and a load change. Each strategy was then retained on an individual diskette which can be loaded into the PM550 by the user. By maintaining each strategy on a diskette, the laboratory student requires minimal knowledge of the controller programming and can concentrate solely on the effects of each control strategy. Consequently, the operation of the PM550 is uncomplicated and laboratory experiments can be designed for independent study. Thus, a practical process control laboratory was developed for chemical engineering students.

A steady improvement in closed-loop performance was expected as the control strategies progressed from simple feedback to cascade, feedforward, and feedforward with lead-lag. However, there was no noticeable improvement in closed-loop performance with the cascade strategies and only minimal improvement with the feedforward and feedforward with lead-lag strategies. This is primarily due to the sluggish tuning used in many of the control loops.

The load change used in this work was a change in the inlet water flow rate.

It is recognized that this load was probably not the best choice for comparing the control strategies. This is because the cascade control strategies used in this work were designed to compensate for disturbances in the supply steam flow rate and pressure variations within the shell of the heat exchanger. A load change in the water flow rate was chosen because it was found to be the major disturbance in the operation of the heat exchanger and does indirectly affect the steam properties. It is suggested that future work be conducted by performing load changes directly on the steam flow rate and shell pressure, and not through the load change used in this work.

The heat exchanger and associated steam piping were not insulated during this work. Lack of insulation limited the operation to high steam flow rates only. When a low steam rate was attempted, the steam began to condense within the supply pipe causing the pipe to hammer. It is strongly recommended that the equipment be insulated prior to use of this system as a laboratory.

During the operation of this DCS, it was observed that a sufficient water pressure existed to supply more than adequate water flow to the heat exchanger without using the existing water pump. In fact, it is possible to exceed the recommended operating range of both the water and steam flow transmitters, as well as the shell pressure transmitter. Although it was possible to regulate the flows with existing hand valves, it is strongly urged that regulators be installed to better protect these instruments. It is also recommended that the existing water pump be removed.

In addition, the water supply pressure is too great to provide flow through the 1/2 inch diameter pipe which was installed from the water discharge line to provide a load change in inlet water temperature. It is recommended that a pipe be installed to provide this feature.

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APPENDICES

APPENDIX A

FIGURES

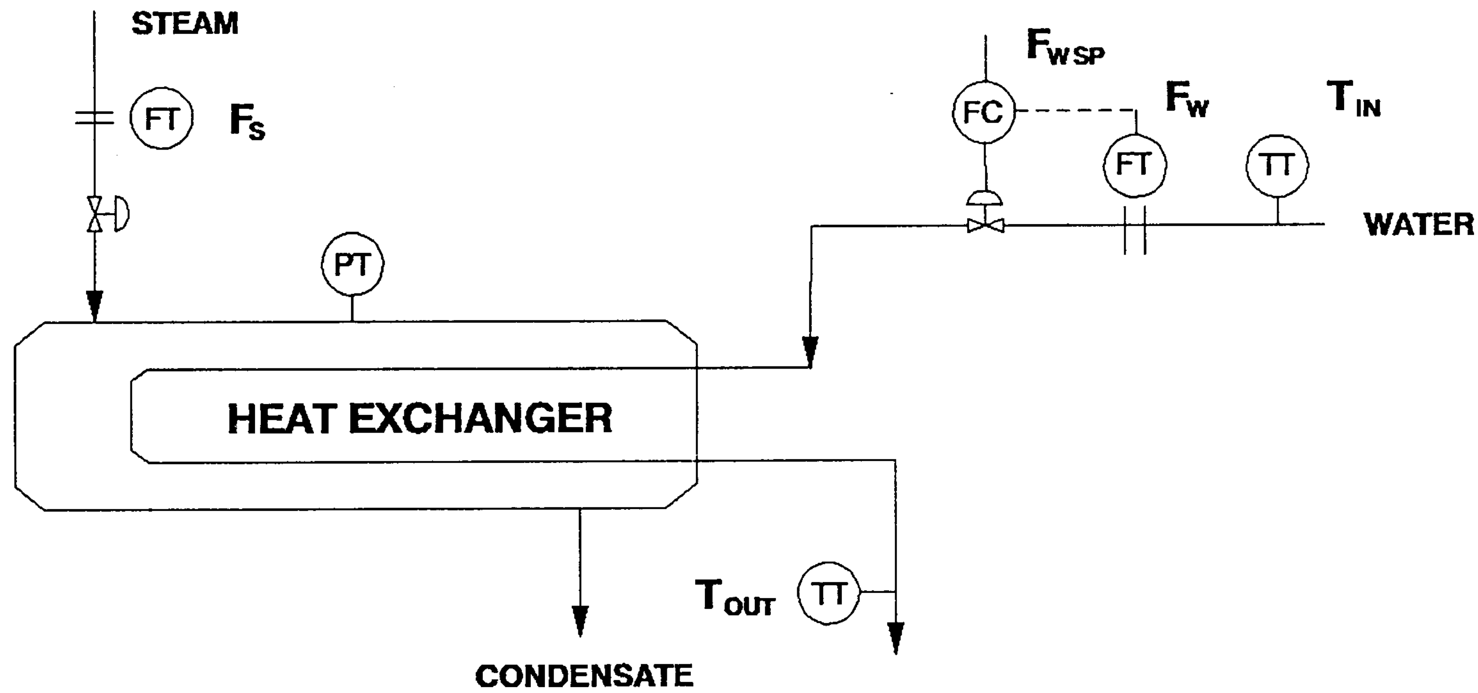


FIGURE 1. Shell and tube heat exchanger.

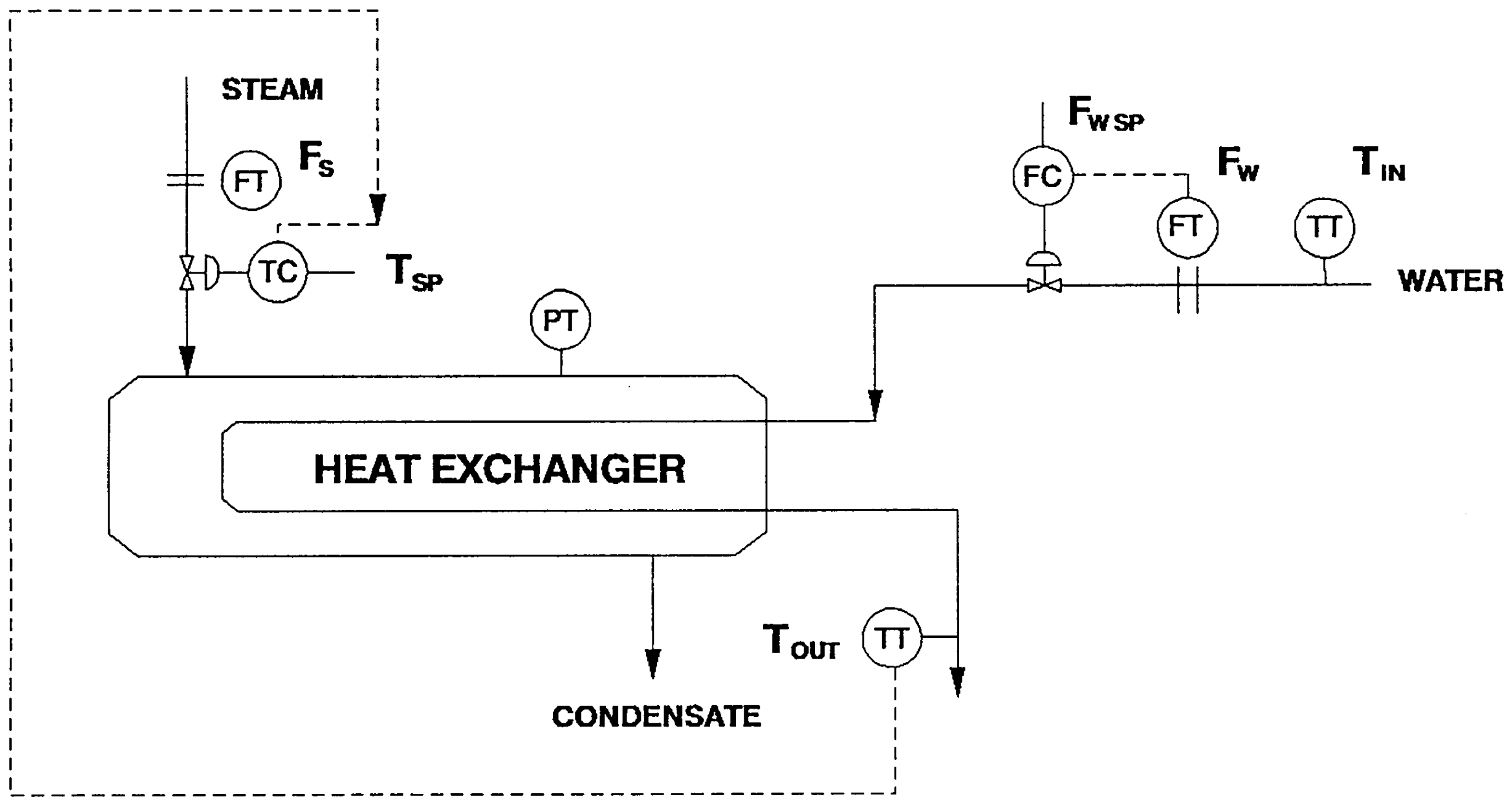


FIGURE 2. Temperature feedback control.

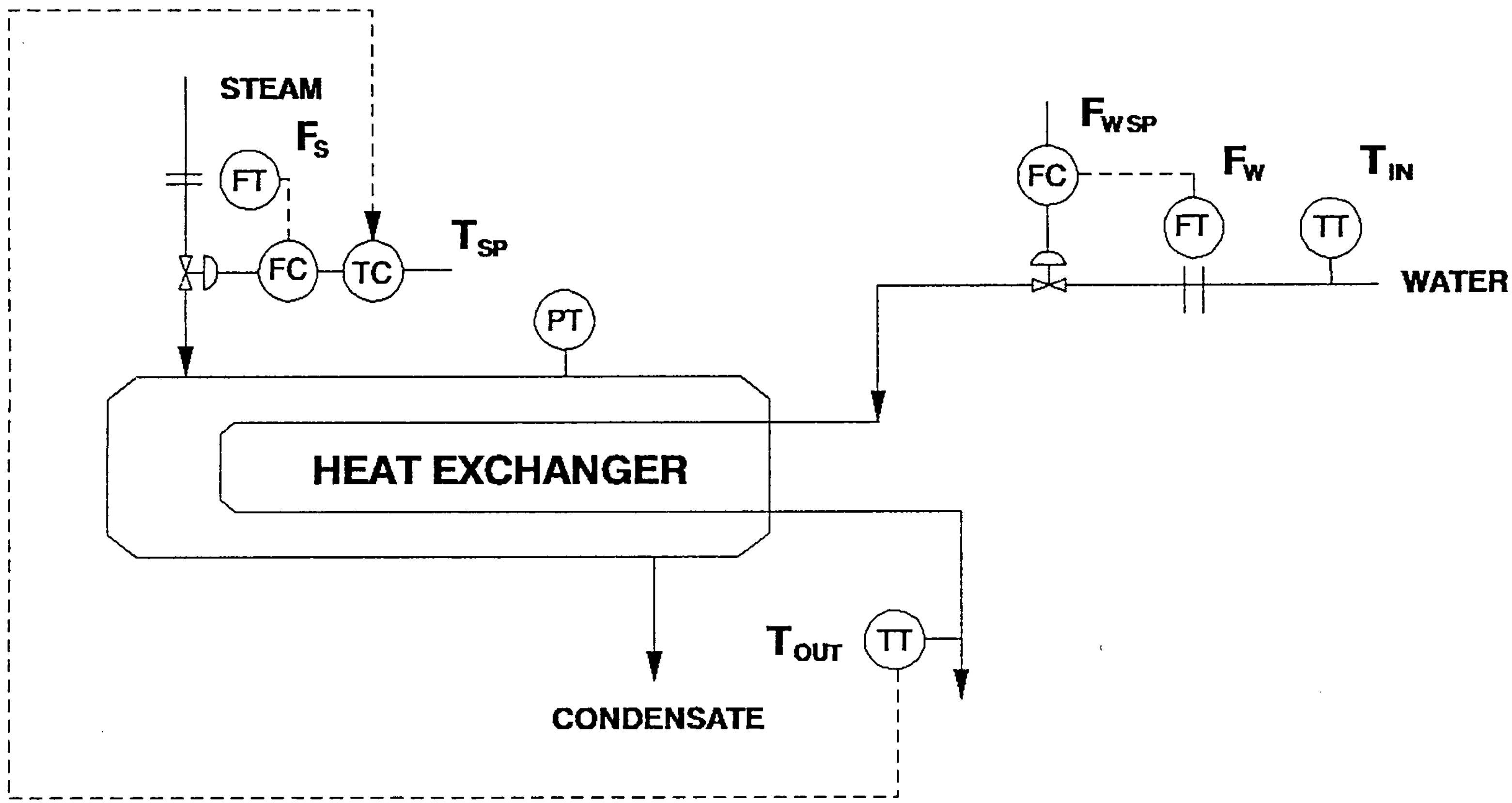


FIGURE 3. Temperature-flow cascade control.

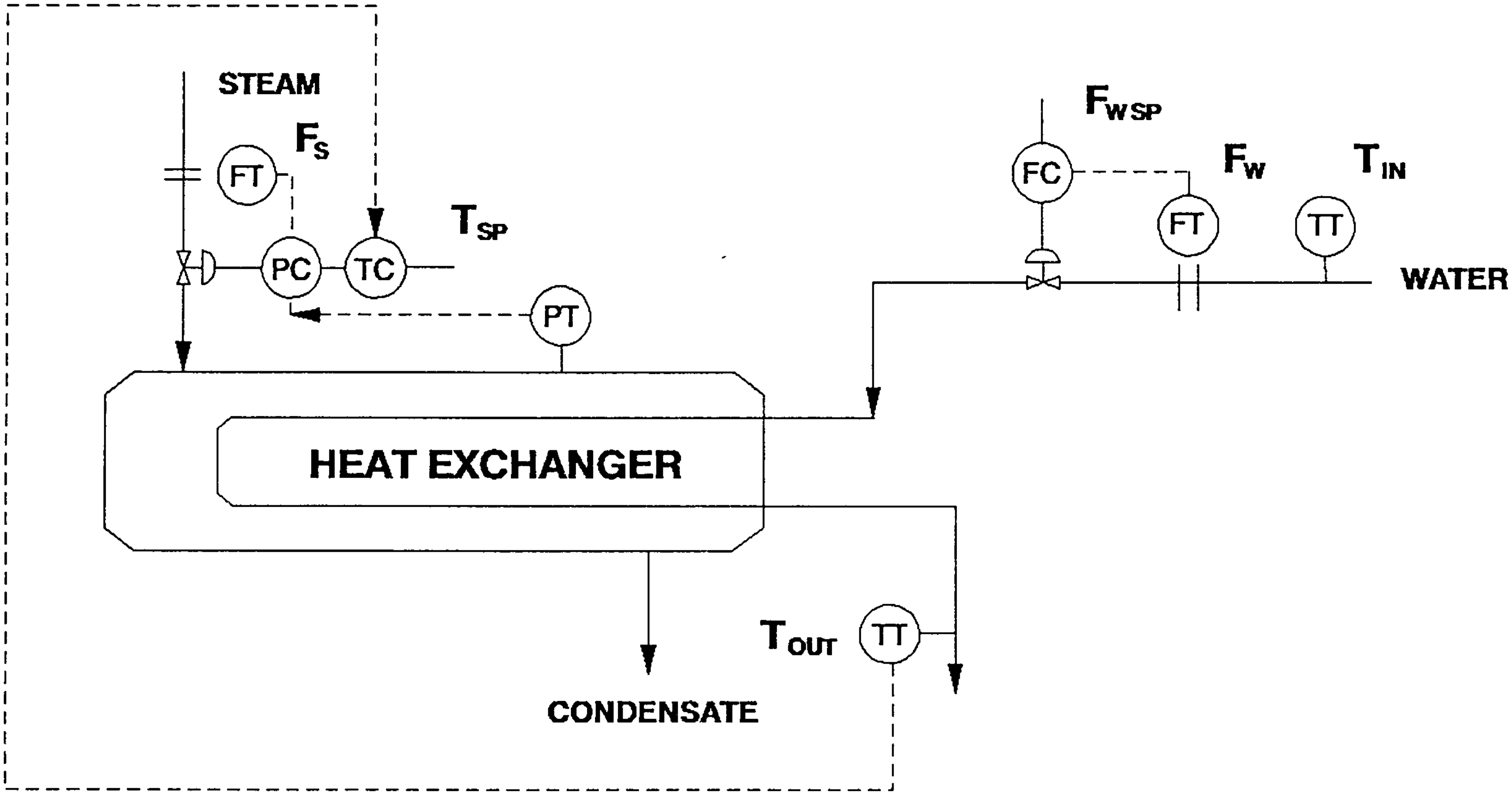


FIGURE 4. Temperature-pressure cascade control.

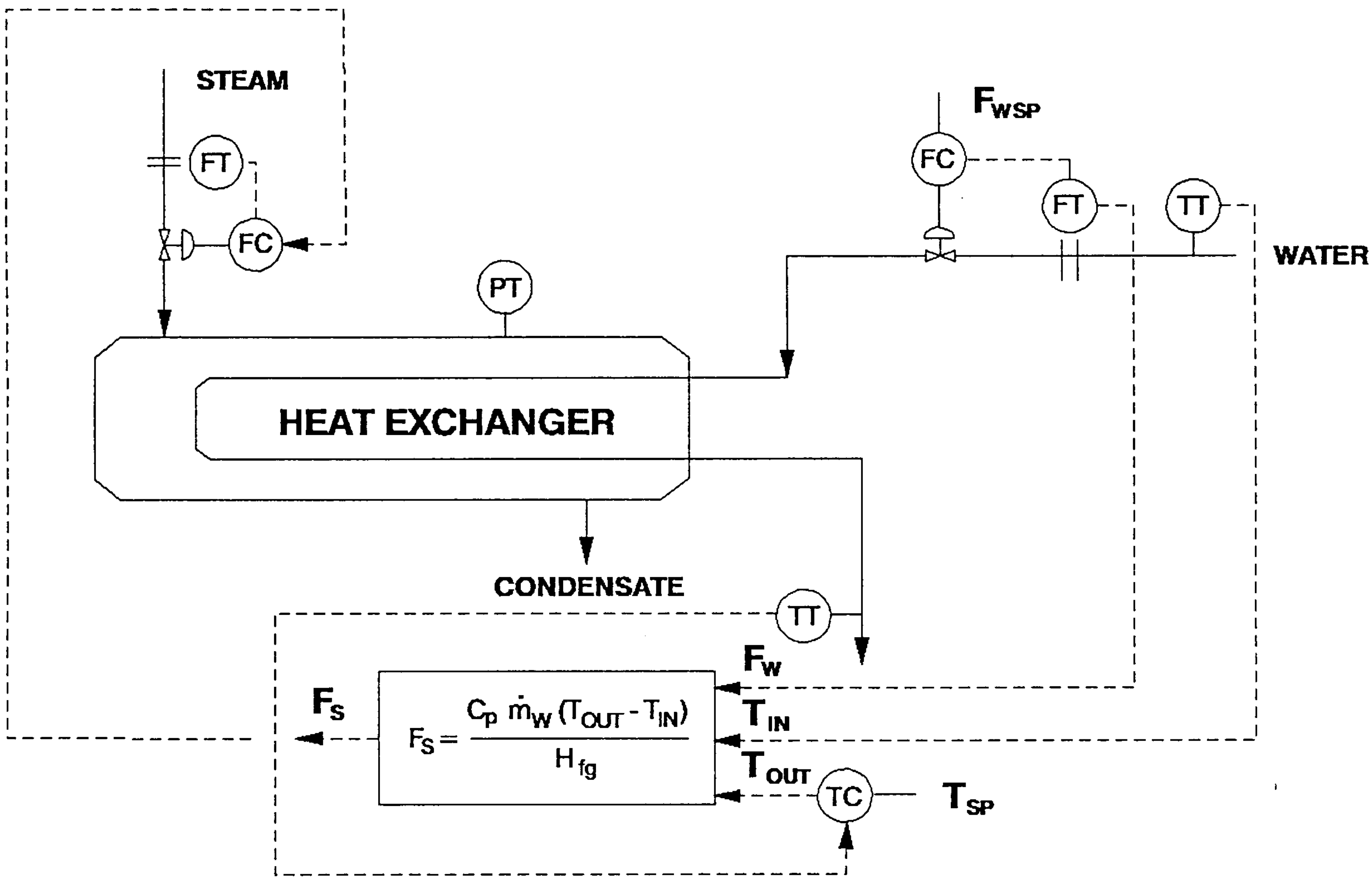


FIGURE 5. Feedforward with temperature feedback control.

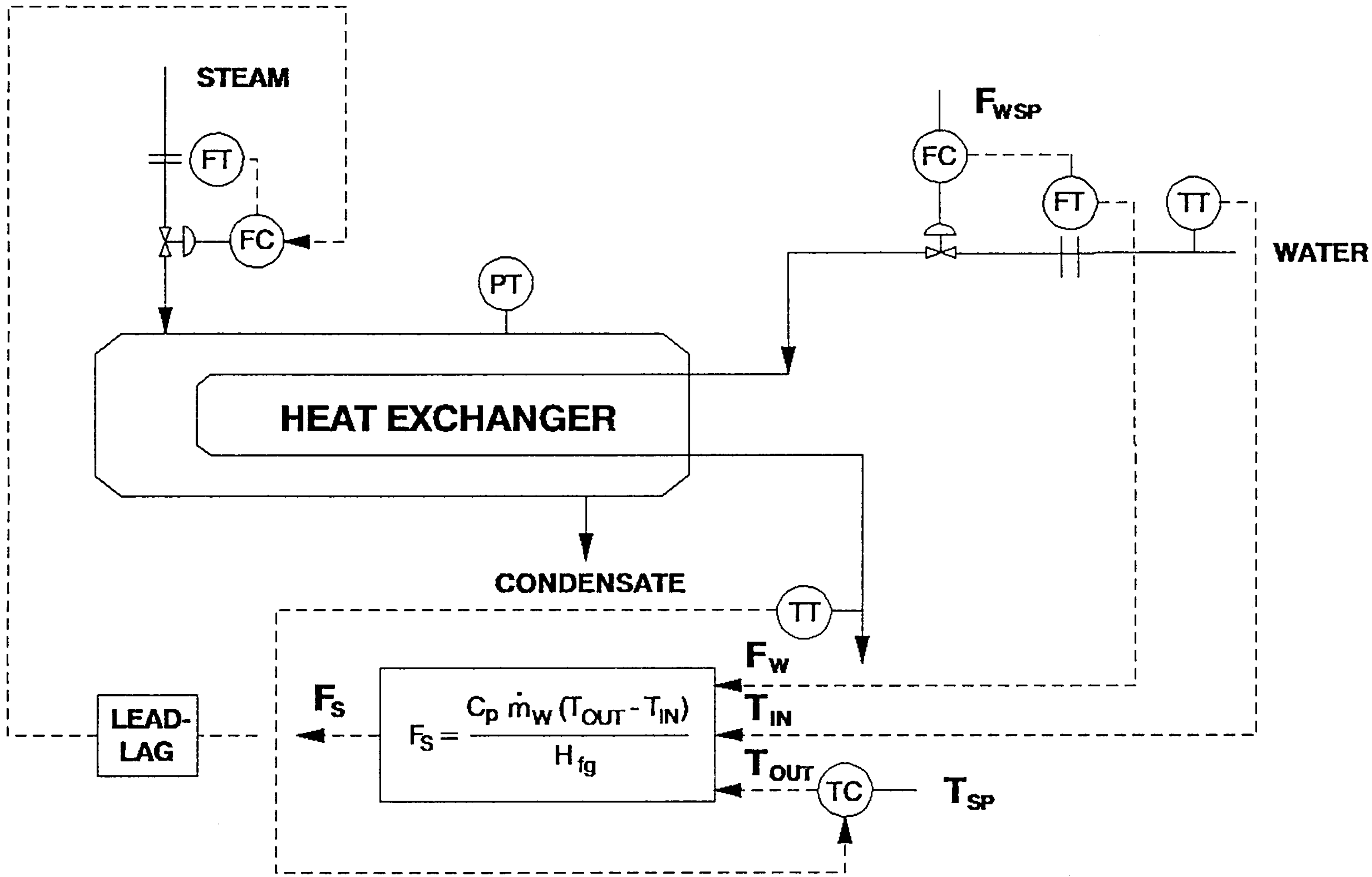


FIGURE 6. Feedforward with lead-lag control.

LOOP SPECIFICATION SHEET

Loop Description:
Tag # ______ PM550 Loop Number ____

MEMORY ALLOCATION
Tuning Constants in___(C or V)

	Beginning Address	Tune C	Tune V	Ending Address
Constant Table	_____	____	____	_____
Variable Table	_____	____	____	_____

Are loop flags for alarms and mode switching allocated in the image register? ____ If yes, give beginning address: ____

PROCESS VARIABLE
20% Offset? _____
Special calculation? _____
Low Range= _____
Engr. Units ______

Address: ____
Square root? ____
If yes, give address: _
High Range= ____
Transmitter ____

CONTROL CALCULATIONS
Remote Setpoint? _____
Special Calculation? _____
LOCKS - Setpoint?
Error Squared? _____
Gain= _____
Rate= _____
Output Address: ______

Sample Time= ____
If yes, give address: _
If yes, give address: _
Auto/Manual?__Cascade?__
Error Deadband? ____
Reset Time= ____
Reverse Acting? ____
20% Offset? ____

ALARMS
Process Variable
Low= _____ High= ____
Deviation
Yellow= ____ Orange= ____

FIGURE 7. Loop specification sheet.

LOOP I/O ASSIGNMENTS

LOOP	PROCESS VARIABLE	PV ADDRESS
1	WATER FLOW	A2
2	OUTLET WATER TEMPERATURE	A3
3	STEAM FLOW	A200
4	STEAM PRESSURE	A201
5	INLET WATER TEMPERATURE	A202

FIGURE 8. Loop I/O assignments.

FEEDFORWARD CALCULATIONS

A2 - C50 / C52. = V50.

SQRT(V50.) = V52.

V52. * C106. = V54.

A5 - C50 / C52. * C506. + C508. = V56.

V208. * C206. + C208. = V58.

V58. - V56. * V54. * C48. = V60.

V60. / C306. * C54. = V49

TRACKING CALCULATIONS

A1 - C50 / C52. = V50.

SQRT(V50.) = V52.

V52. * C106. = V54.

A5 - C50 / C52. * C506. + C508. = V56.

V304. * C306. * C48. / V54. + V56. = V58.

V58. - C208. / C206. = V208.

FIGURE 9. Feedforward and set point tracking calculations.

FEEDFORWARD CALCULATIONS

A2 - C50 / C52. = V50.

SQRT(V50.) = V52.

V52. * C106. = V54.

A5 - C50 / C52. * C506. + C508. = V56.

V208. * C206. + C208. = V58.

V62. = V72.

V58. - V56. * V54. * C48. = V62.

V60. * C36. = V60.

V62. * C38. + V60. = V60.

V72. * C40. + V60. = V60.

V60. / C306. * C54. = V49

TRACKING CALCULATIONS

A2 - C50 / C52. = V50.

SQRT(V50.) = V52.

V52. * C106. = V54.

A5 - C50 / C52. * C506. + C508. = V56.

V304. * C306. = V60.

V60. = V62.

V60. * C48. / V54. + V56. = V58.

V58. - C208. / C206. = V208.

FIGURE 10. Feedforward with lead-lag and set point tracking calculations.

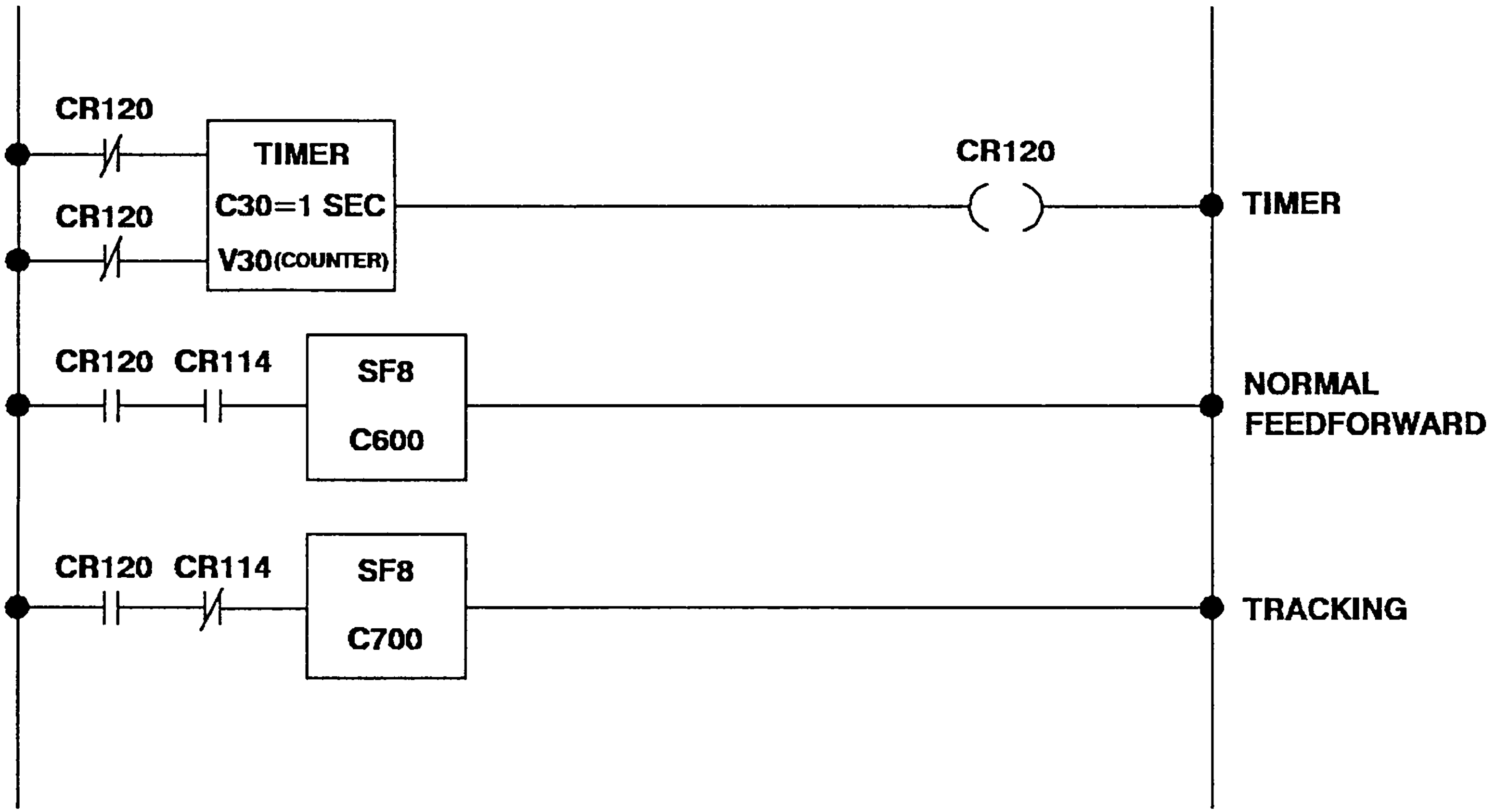


FIGURE 11. Relay ladder logic program for feedforward control.

LOADING A PROGRAM INTO THE PM550 FROM A DISK

The steps to load a program into the PM550 from a disk are as follows:

(1) Turn on the main power switch to the PM550.

(2) Open the front cover to VPU200 and turn on the power switch; the VPU should begin to beep.

(3) Wait for the message "**PRESS SPACE BAR TO BEGIN**" to appear at the bottom of the screen. Press the space bar and the "**POWER-UP MENU**" will be displayed.

(4) Open the door to disk drive, insert the Operating System Disk, and close door. Press "**1**", "**RETURN**", and then "**F5**" to load the operating system. The VPU will beep and "**SYSTEM INITIALIZED: PRESS SPACE BAR TO START**" will be displayed on the screen.

(5) Press "**SPACE BAR**" then "**F4**". The system will prompt for answers to several questions:

   (a) "**TITLE/DATE:**" - Press "**RETURN**" (no title or date is specified)

   (b) "**PRODUCT FAMILY REQUESTED**" - Press "**2**" (to specify the PM550), then "**RETURN**"

   (c) "**LOGIC MEMORY SIZE OPERATIONS:**" - press "**4**" (to specify 4K), then "**RETURN**"

   (d) "**MODE OPTION REQUESTED:**" - Press "**2**" (to specify the controller mode), then "**RETURN**"

   (e) "**PRINTER CONNECTED TO VPU:**" - (No) Press "**RETURN**"

   (f) "**BAUD RATES AVAILABLE**" - Press "**2**" (for 1200), then "**RETURN**"

(6) The "**SYSTEM MENU**" will appear. Press "**3**" (input request), then "**RETURN**", and the "**PROGRAM INPUT REQUEST MENU**" will appear.

(7) Open the disk door, insert a disk containing a controller program, and close the door.

(8) Press "**5**" (read disk to programmer and controller memory), then "**RETURN**", and then "**F1**".

(9) Wait for the title of the disk to be displayed. Press "**F5**" and the program will be loaded into the controller memory.

FIGURE 12. Loading a program into the PM550 from a disk.

VIEWING A PROGRAM IN THE PM550

The steps to view a program that is in the PM550 with the VPU200 are:

(1) From the system menu press "**2**" (format selection), then "**RETURN**". The "**FORMAT SELECTION MENU**" will be displayed.

(2) Select an option depending on which program is to be viewed.

(a) **Ladder diagrams:** Press "**1**", then "**RETURN**". Press "**3**", "**RETURN**" (start address default is 0), then "**F1**" to display the ladder diagram.

(b) **Loop programs:** Press "**3**", then "**RETURN**". Select start address as 1-5, depending on which loop program is to be viewed and press "**RETURN**", then "**F1**". The first page of the loop program will be displayed. Press "**ROLL UP**" to view page 2 and "**ROLL DOWN**" to return to page 1. Press "**HELP**" to return to the system menu.

(c) **Special functions:** Press "**4**", then "**RETURN**". The starting address is either C600 or C700, depending on whether it is feedforward or feedback calculations that will be viewed. Press "**RETURN**", then "**F2**" (read). The first equation of the special functions will be displayed. To continue, press "**F2**" (menu), then "**F5**" (continue). The next starting address is displayed. Press "**RETURN**", then "**F2**" (read). Continue if desired or press "HELP" to return to the system menu.

FIGURE 13. Viewing a program in the PM550.

APPENDIX B

LOOP PROGRAMS

MEMORY ALLOCATION FOR LOOP PROGRAMS

A2.	ANALOG INPUT WATER
A5.	ANALOG INPUT - INLET WATER TEMPERATURE
C30.	TIMER STEP TIME
C36.	CONSTANT FOR LEAD-LAG COMPENSATOR (k_1)
C38.	CONSTANT FOR LEAD-LAG COMPENSATOR (k_2)
C40.	CONSTANT FOR LEAD-LAG COMPENSATOR (k_3)
C48.	C_p/H_{fg}
C50.	20% OFFSET AS AN INTEGER COUNT (6400)
C52.	SPAN OF INPUT WITH 20% OFFSET (25600.)
C54.	SPAN OF INPUT WITHOUT 20% OFFSET (32000.)
C106.	SPAN FOR WATER FLOW RATE (SPECIFIED BY LOOP)
C206.	SPAN FOR WATER OUTLET TEMPERATURE (SPECIFIED BY LOOP)
C208.	LOW TEMPERATURE FOR OUTLET WATER TEMPERATURE (SPECIFIED BY LOOP)
C306.	SPAN FOR STEAM FLOW RATE (SPECIFIED BY LOOP)
C506.	SPAN FOR INLET WATER TEMPERATURE (SPECIFIED BY LOOP)
C508.	LOW WATER OUTLET TEMPERATURE (FROM LOOP TABLE)
C600.	START ADDRESS FOR FEEDFORWARD CALCULATIONS
C700.	START ADDRESS FOR FEEDFORWARD TRACKING CALCULATIONS
V49.	CALCULATED STEAM FLOW SET POINT IN CONTROLLER UNITS
V50.	dP FOR WATER FLOW AS A NORMALIZED FLOATING POINT
V52.	SQRT(dP) FOR WATER FLOW AS A NORMALIZED FLOATING POINT
V54.	WATER FLOW RATE ($\dot{m}_W$) IN ENGINEERING UNITS
V56.	INLET WATER TEMPERATURE (T_{IN}) IN ENGINEERING UNITS
V58.	CALCULATED OUTLET TEMPERATURE SET POINT ($T_{OUT,SP}$) IN ENGINEERING UNITS
V60.	CALCULATED STEAM FLOW SET POINT (F) FROM STEADY STATE EQUATION
V62.	CALCULATED STEAM FLOW ($F_{x,n}$)
V72.	STEAM FLOW RATE IN ENGINEERING UNITS ($F_{x,n-1}$)
V208.	OUTPUT OF OUTLET WATER CONTROLLER (SPECIFIED BY LOOP)

LOOP SPECIFICATION SHEET

Loop Description: **WATER FLOW LOOP - ALL SCHEMES**

Tag # ______   PM550 Loop Number __1__

MEMORY ALLOCATION
Tuning Constants in V (C or V)

	Beginning Address	Tune C	Tune V	Ending Address
Constant Table	C100	21	15	C114
Variable Table	V100	12	18	V117

Are loop flags for alarms and mode switching allocated in the image register? NO
If yes, give beginning address:_______

PROCESS VARIABLE   Address: A2
20% Offset? YES   Square root? YES
Special calculation? NO   If yes, give address: ____
Low Range= 0   High Range= 50
Engr. Units gpm   Transmitter ____

CONTROL CALCULATIONS   Sample Time= 1 SEC
Remote Setpoint? NO   If yes, give address: ____
Special Calculation? NO   If yes, give address: ____
LOCKS - Setpoint? NO   Auto/Manual? NO Cascade? NO
Error Squared? NO   Error Deadband? NO
Gain= 0   Reset Time= 0.11
Rate= 0   Reverse Acting? YES
Output Address: A103   20% Offset? YES

ALARMS
Process Variable
Low= 0   High= 50
Deviation
Yellow= 2   Orange= 5

LOOP SPECIFICATION SHEET

Loop Description: **INLET WATER TEMPERATURE - ALL SCHEMES**

Tag # ______ PM550 Loop Number __5__

MEMORY ALLOCATION
Tuning Constants in V (C or V)

	Beginning Address	Tune C	Tune V	Ending Address
Constant Table	C500	21	15	C514
Variable Table	V500	12	18	V517

Are loop flags for alarms and mode switching allocated in the image register? NO
If yes, give beginning address: _______

PROCESS VARIABLE
20% Offset? YES
Special calculation? NO
Low Range= 50
Engr. Units °F

Address: A202
Square root? NO
If yes, give address: ____
High Range= 100
Transmitter ____

CONTROL CALCULATIONS
Remote Setpoint? NO
Special Calculation? NO
LOCKS - Setpoint? NO
Error Squared? NO
Gain= 0
Rate= 0
Output Address: A300

Sample Time= 1 SEC
If yes, give address: ____
If yes, give address: ____
Auto/Manual? NO Cascade? NO
Error Deadband? NO
Reset Time= 999.99
Reverse Acting? NO
20% Offset? YES

ALARMS
Process Variable
Low= 50 High= 100
Deviation
Yellow= 2 Orange= 5

LOOP SPECIFICATION SHEET

Loop Description: **OUTLET WATER TEMPERATURE - TEMPERATURE FEEDBACK**

Tag # ______ PM550 Loop Number __2__

MEMORY ALLOCATION

Tuning Constants in V (C or V)

	Beginning Address	Tune C	Tune V	Ending Address
Constant Table	C200	21	15	C214
Variable Table	V200	12	18	V217

Are loop flags for alarms and mode switching allocated in the image register? NO
If yes, give beginning address:_______

PROCESS VARIABLE

20% Offset? YES
Special calculation? NO
Low Range= 50
Engr. Units °F

Address: A3
Square root? NO
If yes, give address: ____
High Range= 250
Transmitter ____

CONTROL CALCULATIONS

Remote Setpoint? NO
Special Calculation? NO
LOCKS - Setpoint? NO
Error Squared? NO
Gain= 21
Rate= 0.07
Output Address: A301

Sample Time= 1 SEC
If yes, give address: ____
If yes, give address: ____
Auto/Manual? NO Cascade? NO
Error Deadband? NO
Reset Time= 0.28
Reverse Acting? NO
20% Offset? YES

ALARMS

Process Variable
Low= 50
High= 250

Deviation
Yellow= 2
Orange= 5

LOOP SPECIFICATION SHEET

Loop Description: **STEAM FLOW LOOP - TEMPERATURE FEEDBACK**

Tag # ______ PM550 Loop Number __3__

MEMORY ALLOCATION

Tuning Constants in V (C or V)

	Beginning Address	Tune C	Tune V	Ending Address
Constant Table	C300	21	15	C314
Variable Table	V300	12	18	V317

Are loop flags for alarms and mode switching allocated in the image register? NO

If yes, give beginning address:_______

PROCESS VARIABLE

20% Offset? YES

Special calculation? NO

Low Range= 0

Engr. Units LBS/HR @15PSIG

Address: A200

Square root? NO

If yes, give address: ____

High Range= 1050

Transmitter ____

CONTROL CALCULATIONS

Remote Setpoint? NO

Special Calculation? NO

LOCKS - Setpoint? NO

Error Squared? NO

Gain= 0

Rate= 0

Output Address: A300

Sample Time= 1 SEC

If yes, give address: ____

If yes, give address: ____

Auto/Manual? NO Cascade? NO

Error Deadband? NO

Reset Time= 999.99

Reverse Acting? NO

20% Offset? YES

ALARMS

Process Variable

Low= 0

High= 250

Deviation

Yellow= 2

Orange= 5

LOOP SPECIFICATION SHEET

Loop Description: **STEAM PRESSURE LOOP - TEMPERATURE FEEDBACK**

Tag # ______ PM550 Loop Number **4**

MEMORY ALLOCATION

Tuning Constants in **V** (C or V)

	Beginning Address	Tune C	Tune V	Ending Address
Constant Table	C400	21	15	C414
Variable Table	V400	12	18	V417

Are loop flags for alarms and mode switching allocated in the image register? **NO**

If yes, give beginning address:_______

PROCESS VARIABLE

20% Offset? **YES**

Special calculation? **NO**

Low Range= **0**

Engr. Units **PSIG**

Address: **A201**

Square root? **NO**

If yes, give address: ____

High Range= **20**

Transmitter ____

CONTROL CALCULATIONS

Remote Setpoint? **NO**

Special Calculation? **NO**

LOCKS - Setpoint? **NO**

Error Squared? **NO**

Gain= **0**

Rate= **0**

Output Address: **A300**

Sample Time= **1 SEC**

If yes, give address: ____

If yes, give address: ____

Auto/Manual? **NO** Cascade? **NO**

Error Deadband? **NO**

Reset Time= **999.99**

Reverse Acting? **NO**

20% Offset? **YES**

ALARMS

Process Variable

Low= **0** High= **30**

Deviation

Yellow= **2** Orange= **5**

LOOP SPECIFICATION SHEET

Loop Description: **OUTLET WATER TEMPERATURE - TEMPERATURE-FLOW CASCADE**

Tag # ______ PM550 Loop Number __2__

MEMORY ALLOCATION

Tuning Constants in V (C or V)

	Beginning Address	Tune C	Tune V	Ending Address
Constant Table	C200	21	15	C214
Variable Table	V200	12	18	V217

Are loop flags for alarms and mode switching allocated in the image register? NO

If yes, give beginning address: _______

PROCESS VARIABLE

Address: A3

20% Offset? YES

Square root? NO

Special calculation? NO

If yes, give address: ____

Low Range= 50

High Range= 250

Engr. Units °F

Transmitter ____

CONTROL CALCULATIONS

Sample Time= 1 SEC

Remote Setpoint? NO

If yes, give address: ____

Special Calculation? NO

If yes, give address: ____

LOCKS - Setpoint? NO

Auto/Manual? NO Cascade? NO

Error Squared? NO

Error Deadband? NO

Gain= 11

Reset Time= 0.34

Rate= 0.08

Reverse Acting? NO

Output Address: V218

20% Offset? NO

ALARMS

Process Variable

Low= 50

High= 250

Deviation

Yellow= 2

Orange= 5

LOOP SPECIFICATION SHEET

Loop Description: **STEAM FLOW LOOP - TEMPERATURE-FLOW CASCADE**

Tag # ______ PM550 Loop Number __3__

MEMORY ALLOCATION

Tuning Constants in V (C or V)

	Beginning Address	Tune C	Tune V	Ending Address
Constant Table	C300	21	15	C314
Variable Table	V300	12	18	V317

Are loop flags for alarms and mode switching allocated in the image register? NO

If yes, give beginning address:_______

PROCESS VARIABLE

20% Offset? YES

Special calculation? NO

Low Range= 0

Engr. Units LBS/HR @15PSIG

Address: A200

Square root? NO

If yes, give address: ____

High Range= 1050

Transmitter ____

CONTROL CALCULATIONS

Remote Setpoint? YES

Special Calculation? NO

LOCKS - Setpoint? NO

Error Squared? NO

Gain= 1.1

Rate= 0

Output Address: A301

Sample Time= 1 SEC

If yes, give address: V218

If yes, give address: ____

Auto/Manual? NO Cascade? NO

Error Deadband? NO

Reset Time= 0.08

Reverse Acting? NO

20% Offset? YES

ALARMS

Process Variable

Low= 0

High= 1050

Deviation

Yellow= 2

Orange= 5

LOOP SPECIFICATION SHEET

Loop Description: **STEAM PRESSURE LOOP - TEMPERATURE-FLOW CASCADE**

Tag # ______ PM550 Loop Number __4__

MEMORY ALLOCATION

Tuning Constants in V (C or V)

	Beginning Address	Tune C	Tune V	Ending Address
Constant Table	C400	21	15	C414
Variable Table	V400	12	18	V417

Are loop flags for alarms and mode switching allocated in the image register? NO

If yes, give beginning address:_______

PROCESS VARIABLE

20% Offset? YES

Special calculation? NO

Low Range= 0

Engr. Units PSIG

Address: A201

Square root? NO

If yes, give address: ____

High Range= 20

Transmitter ____

CONTROL CALCULATIONS

Remote Setpoint? NO

Special Calculation? NO

LOCKS - Setpoint? NO

Error Squared? NO

Gain= 0

Rate= 0

Output Address: A300

Sample Time= 1 SEC

If yes, give address: ____

If yes, give address: ____

Auto/Manual? NO Cascade? NO

Error Deadband? NO

Reset Time= 999.99

Reverse Acting? NO

20% Offset? YES

ALARMS

Process Variable

Low= 0 High= 30

Deviation

Yellow= 2 Orange= 5

LOOP SPECIFICATION SHEET

Loop Description: **OUTLET WATER TEMPERATURE - TEMPERATURE-PRESSURE CASCADE**

Tag # ______ PM550 Loop Number __2__

MEMORY ALLOCATION
Tuning Constants in V (C or V)

	Beginning Address	Tune C	Tune V	Ending Address
Constant Table	C200	21	15	C214
Variable Table	V200	12	18	V217

Are loop flags for alarms and mode switching allocated in the image register? NO
If yes, give beginning address: _______

PROCESS VARIABLE
20% Offset? __YES__
Special calculation? __NO__
Low Range= __50__
Engr. Units __°F__

Address: __A3__
Square root? __NO__
If yes, give address: ____
High Range= __250__
Transmitter ____

CONTROL CALCULATIONS
Remote Setpoint? __NO__
Special Calculation? __NO__
LOCKS - Setpoint? __NO__
Error Squared? __NO__
Gain= __16.8__
Rate= __0.09__
Output Address: __V218__

Sample Time= __1 SEC__
If yes, give address: ____
If yes, give address: ____
Auto/Manual? __NO__ Cascade? __NO__
Error Deadband? __NO__
Reset Time= __0.38__
Reverse Acting? __NO__
20% Offset? __NO__

ALARMS
Process Variable
Low= __50__ High= __250__
Deviation
Yellow= __2__ Orange= __5__

LOOP SPECIFICATION SHEET

Loop Description: **STEAM FLOW LOOP - TEMPERATURE-PRESSURE CASCADE**

Tag # ______ PM550 Loop Number __3__

MEMORY ALLOCATION
Tuning Constants in __V__ (C or V)

	Beginning Address	Tune C	Tune V	Ending Address
Constant Table	C300	21	15	C314
Variable Table	V300	12	18	V317

Are loop flags for alarms and mode switching allocated in the image register? __NO__
If yes, give beginning address: _______

PROCESS VARIABLE
20% Offset? __YES__
Special calculation? __NO__
Low Range= __0__
Engr. Units __LBS/HR__

Address: __A200__
Square root? __NO__
If yes, give address: ____
High Range= __1050__
Transmitter ____

CONTROL CALCULATIONS
Remote Setpoint? __NO__
Special Calculation? __NO__
LOCKS - Setpoint? __NO__
Error Squared? __NO__
Gain= __0__
Rate= __0__
Output Address: __A300__

Sample Time= __1 SEC__
If yes, give address: ____
If yes, give address: ____
Auto/Manual? __NO__ Cascade? __NO__
Error Deadband? __NO__
Reset Time= __999.99__
Reverse Acting? __NO__
20% Offset? __YES__

ALARMS
Process Variable
Low= __0__ High= __1050__
Deviation
Yellow= __2__ Orange= __5__

LOOP SPECIFICATION SHEET

Loop Description: **STEAM PRESSURE LOOP - TEMPERATURE-PRESSURE CASCADE**

Tag # ______

PM550 Loop Number __4__

MEMORY ALLOCATION

Tuning Constants in_V_ (C or V)

	Beginning Address	Tune C	Tune V	Ending Address
Constant Table	C400	21	15	C414
Variable Table	V400	12	18	V417

Are loop flags for alarms and mode switching allocated in the image register? NO

If yes, give beginning address:_______

PROCESS VARIABLE

20% Offset? YES

Special calculation? NO

Low Range= 0

Engr. Units PSIG

Address: A201

Square root? NO

If yes, give address: ____

High Range= 20

Transmitter ____

CONTROL CALCULATIONS

Remote Setpoint? YES

Special Calculation? NO

LOCKS - Setpoint? NO

Error Squared? NO

Gain= 0.75

Rate= 0

Output Address: A301

Sample Time= 1 SEC

If yes, give address: V218

If yes, give address: ____

Auto/Manual? NO Cascade? NO

Error Deadband? NO

Reset Time= 0.11

Reverse Acting? NO

20% Offset? YES

ALARMS

Process Variable

Low= 0

High= 30

Deviation

Yellow= 2

Orange= 5

LOOP SPECIFICATION SHEET

Loop Description: **OUTLET WATER TEMPERATURE - FEEDFORWARD CONTROL**

Tag # ______ PM550 Loop Number __2__

MEMORY ALLOCATION

Tuning Constants in __V__ (C or V)

	Beginning Address	Tune C	Tune V	Ending Address
Constant Table	C200	21	15	C214
Variable Table	V200	12	18	V217

Are loop flags for alarms and mode switching allocated in the image register? __NO__

If yes, give beginning address:________

PROCESS VARIABLE

20% Offset? __YES__

Special calculation? __NO__

Low Range= __50__

Engr. Units __°F__

Address: __A3__

Square root? __NO__

If yes, give address: ____

High Range= __250__

Transmitter ____

CONTROL CALCULATIONS

Remote Setpoint? __NO__

Special Calculation? __NO__

LOCKS - Setpoint? __NO__

Error Squared? __NO__

Gain= __6.6__

Rate= __0.09__

Output Address: __A300__

Sample Time= __1 SEC__

If yes, give address: ____

If yes, give address: ____

Auto/Manual? __NO__ Cascade? __NO__

Error Deadband? __NO__

Reset Time= __0.38__

Reverse Acting? __NO__

20% Offset? __YES__

ALARMS

Process Variable

Low= __50__ High= __250__

Deviation

Yellow= __2__ Orange= __5__

LOOP SPECIFICATION SHEET

Loop Description: **STEAM FLOW LOOP - FEEDFORWARD CONTROL**

Tag # ______ PM550 Loop Number __3__

MEMORY ALLOCATION

Tuning Constants in V (C or V)

	Beginning Address	Tune C	Tune V	Ending Address
Constant Table	C300	21	15	C314
Variable Table	V300	12	18	V317

Are loop flags for alarms and mode switching allocated in the image register? YES

If yes, give beginning address: CR110

PROCESS VARIABLE

20% Offset? YES

Special calculation? NO

Low Range= 0

Engr. Units LBS/HR @15PSIG

Address: A200

Square root? NO

If yes, give address: ____

High Range= 1050

Transmitter ____

CONTROL CALCULATIONS

Remote Setpoint? YES

Special Calculation? NO

LOCKS - Setpoint? NO

Error Squared? NO

Gain= 1.1

Rate= 0

Output Address: A301

Sample Time= 1 SEC

If yes, give address: V49

If yes, give address: ____

Auto/Manual? NO Cascade? NO

Error Deadband? NO

Reset Time= 0.08

Reverse Acting? NO

20% Offset? YES

ALARMS

Process Variable

Low= 0

High= 1050

Deviation

Yellow= 2

Orange= 5

LOOP SPECIFICATION SHEET

Loop Description: **STEAM PRESSURE LOOP - FEEDFORWARD CONTROL**

Tag # ______ PM550 Loop Number __4__

MEMORY ALLOCATION
Tuning Constants in V (C or V)

	Beginning Address	Tune C	Tune V	Ending Address
Constant Table	C400	21	15	C414
Variable Table	V400	12	18	V417

Are loop flags for alarms and mode switching allocated in the image register? NO
If yes, give beginning address:_______

PROCESS VARIABLE
20% Offset? YES
Special calculation? NO
Low Range= 0
Engr. Units PSIG

Address: A201
Square root? NO
If yes, give address: ____
High Range= 20
Transmitter ____

CONTROL CALCULATIONS
Remote Setpoint? NO
Special Calculation? NO
LOCKS - Setpoint? NO
Error Squared? NO
Gain= 0
Rate= 0
Output Address: A300

Sample Time= 1 SEC
If yes, give address: ____
If yes, give address: ____
Auto/Manual? NO Cascade? NO
Error Deadband? NO
Reset Time= 999.99
Reverse Acting? NO
20% Offset? YES

ALARMS
Process Variable
Low= 0 High= 30
Deviation
Yellow= 2 Orange= 5

LOOP SPECIFICATION SHEET

Loop Description: **OUTLET WATER TEMPERATURE - FEEDFORWARD WITH LEAD-LAG**

Tag # ______

PM550 Loop Number __2__

MEMORY ALLOCATION

Tuning Constants in V (C or V)

	Beginning Address	Tune C	Tune V	Ending Address
Constant Table	C200	21	15	C214
Variable Table	V200	12	18	V217

Are loop flags for alarms and mode switching allocated in the image register? NO

If yes, give beginning address:_______

PROCESS VARIABLE

20% Offset? YES

Special calculation? NO

Low Range= 50

Engr. Units °F

Address: A3

Square root? NO

If yes, give address: ____

High Range= 250

Transmitter ____

CONTROL CALCULATIONS

Remote Setpoint? NO

Special Calculation? NO

LOCKS - Setpoint? NO

Error Squared? NO

Gain= 6.6

Rate= 0.09

Output Address: A300

Sample Time= 1 SEC

If yes, give address: ____

If yes, give address: ____

Auto/Manual? NO Cascade? NO

Error Deadband? NO

Reset Time= 0.38

Reverse Acting? NO

20% Offset? YES

ALARMS

Process Variable

Low= 50

High= 250

Deviation

Yellow= 2

Orange= 5

LOOP SPECIFICATION SHEET

Loop Description: **STEAM FLOW LOOP - FEEDFORWARD WITH LEAD-LAG**

Tag # ______ PM550 Loop Number __3__

MEMORY ALLOCATION
Tuning Constants in V (C or V)

	Beginning Address	Tune C	Tune V	Ending Address
Constant Table	C300	21	15	C314
Variable Table	V300	12	18	V317

Are loop flags for alarms and mode switching allocated in the image register? **YES**
If yes, give beginning address: **CR110**

PROCESS VARIABLE
20% Offset? **YES**
Special calculation? **NO**
Low Range= **0**
Engr. Units **LBS/HR @15PSIG**

Address: **A200**
Square root? **NO**
If yes, give address: ____
High Range= **1050**
Transmitter ____

CONTROL CALCULATIONS
Remote Setpoint? **YES**
Special Calculation? **NO**
LOCKS - Setpoint? **NO**
Error Squared? **NO**
Gain= **1.1**
Rate= **0**
Output Address: **A301**

Sample Time= **1 SEC**
If yes, give address: **V49**
If yes, give address: ____
Auto/Manual? **NO** Cascade? **NO**
Error Deadband? **NO**
Reset Time= **0.08**
Reverse Acting? **NO**
20% Offset? **YES**

ALARMS
Process Variable
Low= **0** High= **1050**
Deviation
Yellow= **2** Orange= **5**

LOOP SPECIFICATION SHEET

Loop Description: **STEAM PRESSURE LOOP - FEEDFORWARD WITH LEAD-LAG**

Tag # ______ PM550 Loop Number 4

MEMORY ALLOCATION

Tuning Constants in V (C or V)

	Beginning Address	Tune C	Tune V	Ending Address
Constant Table	C400	21	15	C414
Variable Table	V400	12	18	V417

Are loop flags for alarms and mode switching allocated in the image register? NO
If yes, give beginning address: _______

PROCESS VARIABLE Address: A201
20% Offset? YES Square root? NO
Special calculation? NO If yes, give address: ____
Low Range= 0 High Range= 20
Engr. Units PSIG Transmitter ____

CONTROL CALCULATIONS Sample Time= 1 SEC
Remote Setpoint? NO If yes, give address: ____
Special Calculation? NO If yes, give address: ____
LOCKS - Setpoint? NO Auto/Manual? NO Cascade? NO
Error Squared? NO Error Deadband? NO
Gain= 0 Reset Time= 999.99
Rate= 0 Reverse Acting? NO
Output Address: A300 20% Offset? YES

ALARMS

Process Variable
Low= 0 High= 30
Deviation
Yellow= 2 Orange= 5

APPENDIX C

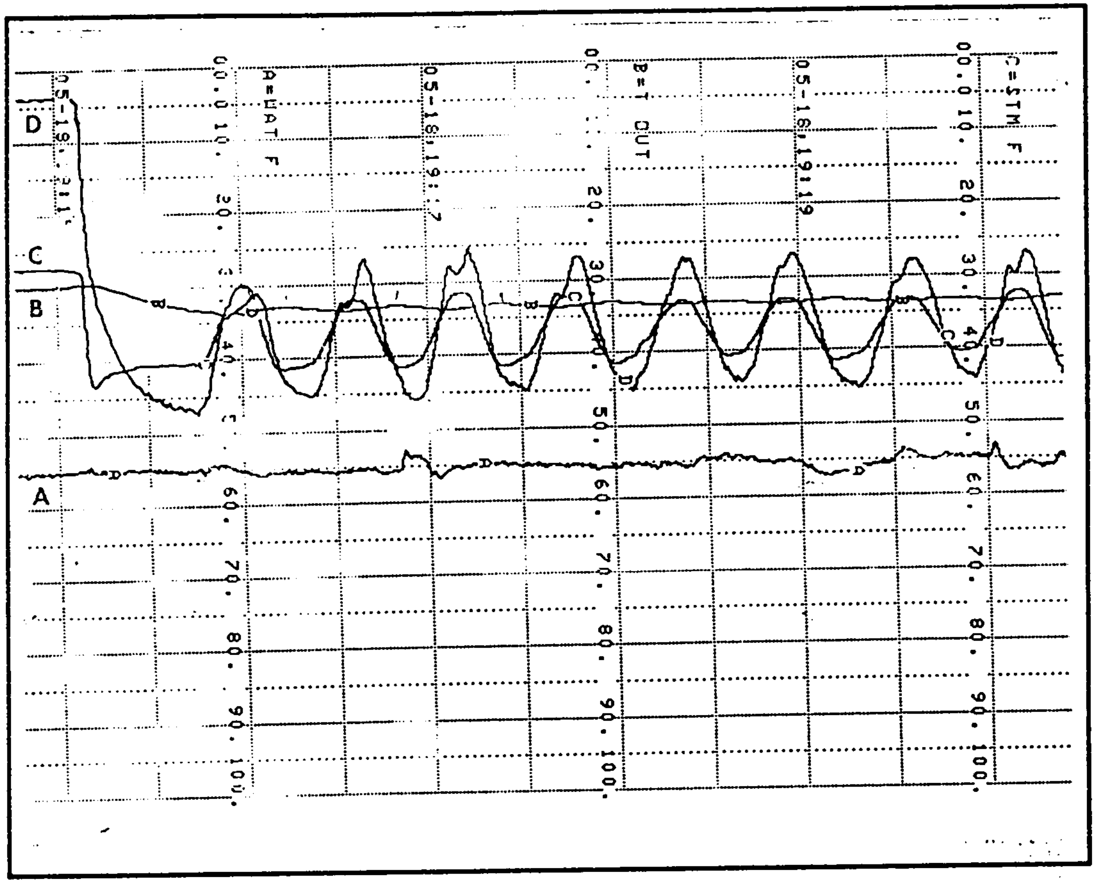
STRIP CHART RECORDINGS

TABLE 5. Relationship of Strip Chart Recordings to Engineering Units

TRANSMITTER	STRIP CHART LABEL	STRIP CHART RANGE	ENGINEERING RANGE
WATER FLOW	A	0 - 100%	0 - 50 gpm *
OUTLET WATER TEMPERATURE	B	0 - 100%	50 - 250 °F
STEAM FLOW	C	0 - 100%	0 - 1050 lbs/hr @ 15 psig
STEAM PRESSURE	D	0 - 100%	0 - 20 psig

* Strip chart reading is actually percent differential pressure across orifice plate. The following equation should be used to obtain gpm:

$$gpm - 5\sqrt{STRIP\ CHART\ READING}$$



TEMPERATURE FEEDBACK

ZIEGLER-NICHOLS TUNING CURVE FOR TEMPERATURE LOOP USING SET POINT INCREASE

CHART SPEED = $\frac{1\ \text{IN}}{\text{MIN}}$

$K_u = 60$

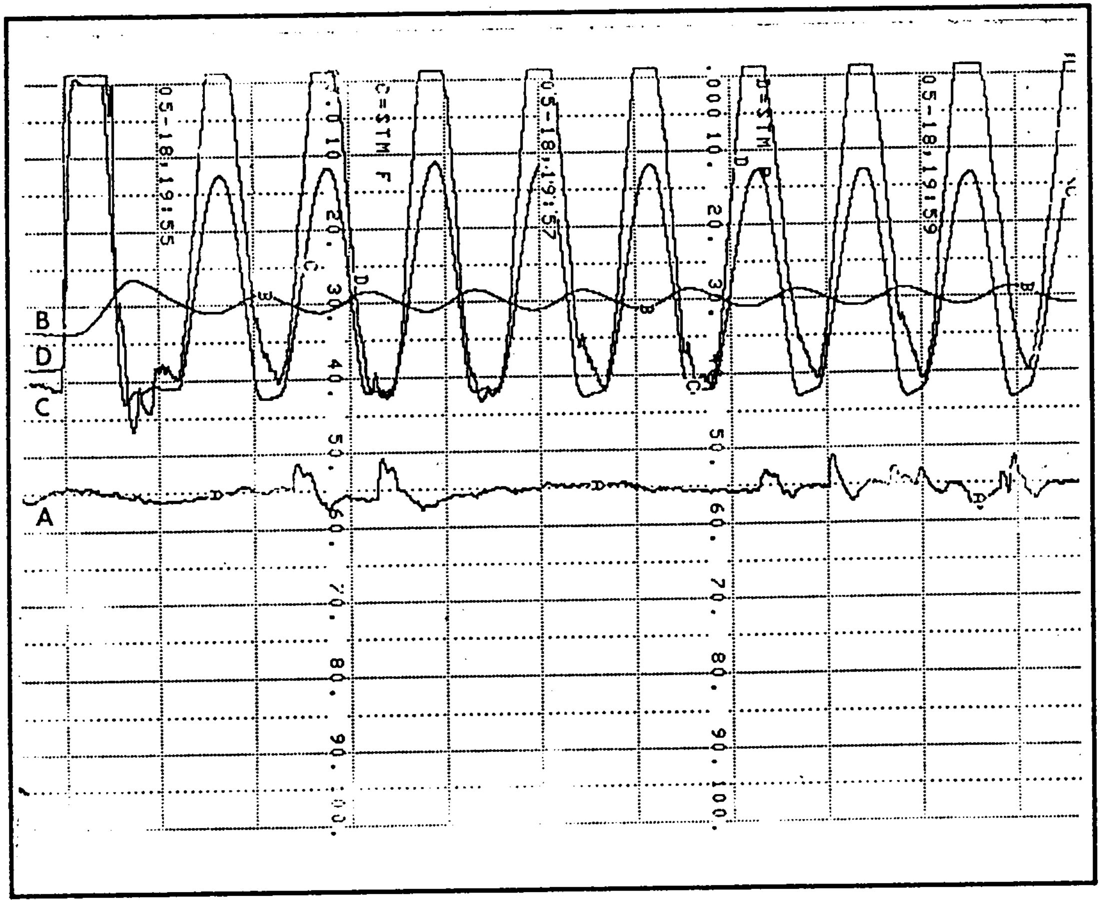
$P_u = 0.59$ MIN

A = WATER FLOW

B = OUTLET WATER TEMPERATURE

C = STEAM FLOW

D = STEAM PRESSURE



TEMPERATURE FEEDBACK

ZIEGLER-NICHOLS TUNING CURVE FOR TEMPERATURE LOOP USING SET POINT DECREASE

CHART SPEED = $\frac{1\ \text{IN}}{\text{MIN}}$

$K_u = 35$

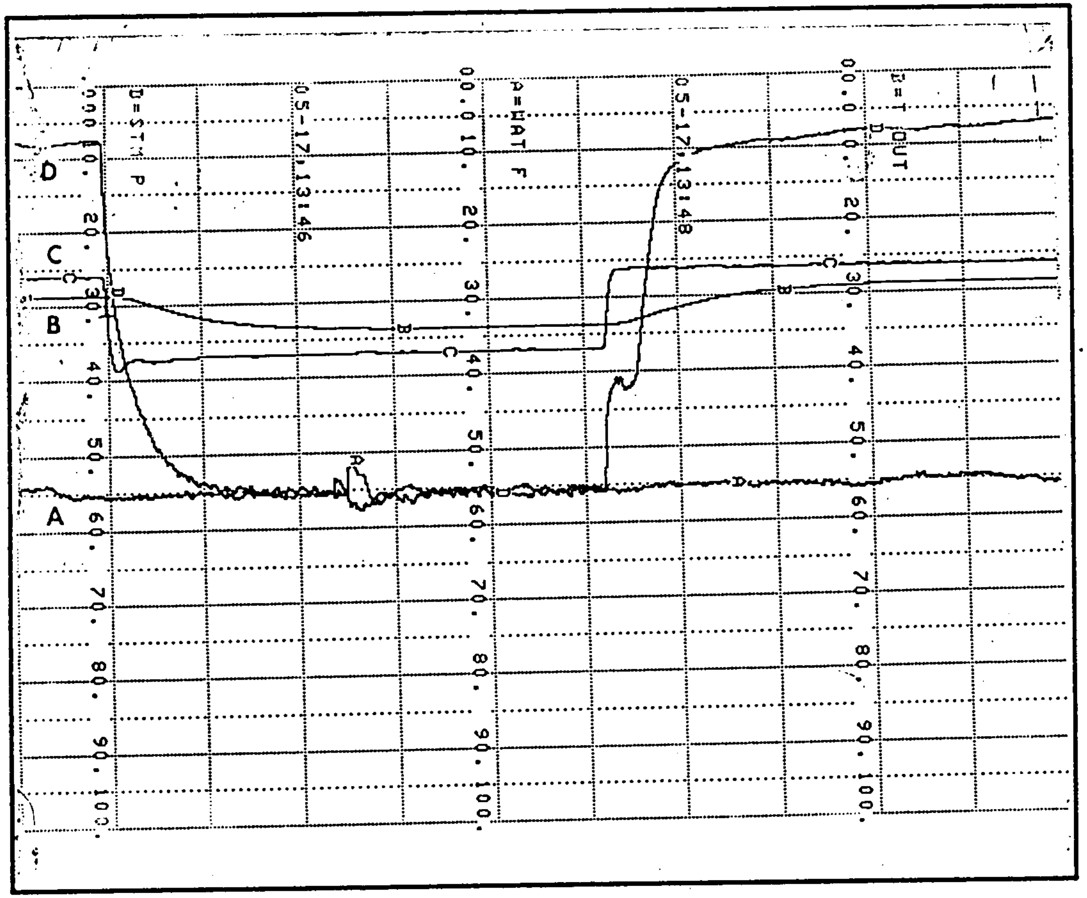
$P_u = 0.58$ MIN

A = WATER FLOW

B = OUTLET WATER TEMPERATURE

C = STEAM FLOW

D = STEAM PRESSURE



TEMPERATURE FEEDBACK

OPEN LOOP CHANGE IN STEAM FLOW TO DETERMINE TEMPERATURE DYNAMICS

DUE TO CHANGE IN STEAM FLOW FOR COHEN-COON TUNING

CHART SPEED = $\frac{0.75\ IN}{MIN}$

$K_p = 0.47$

$\tau = 0.55$ MIN

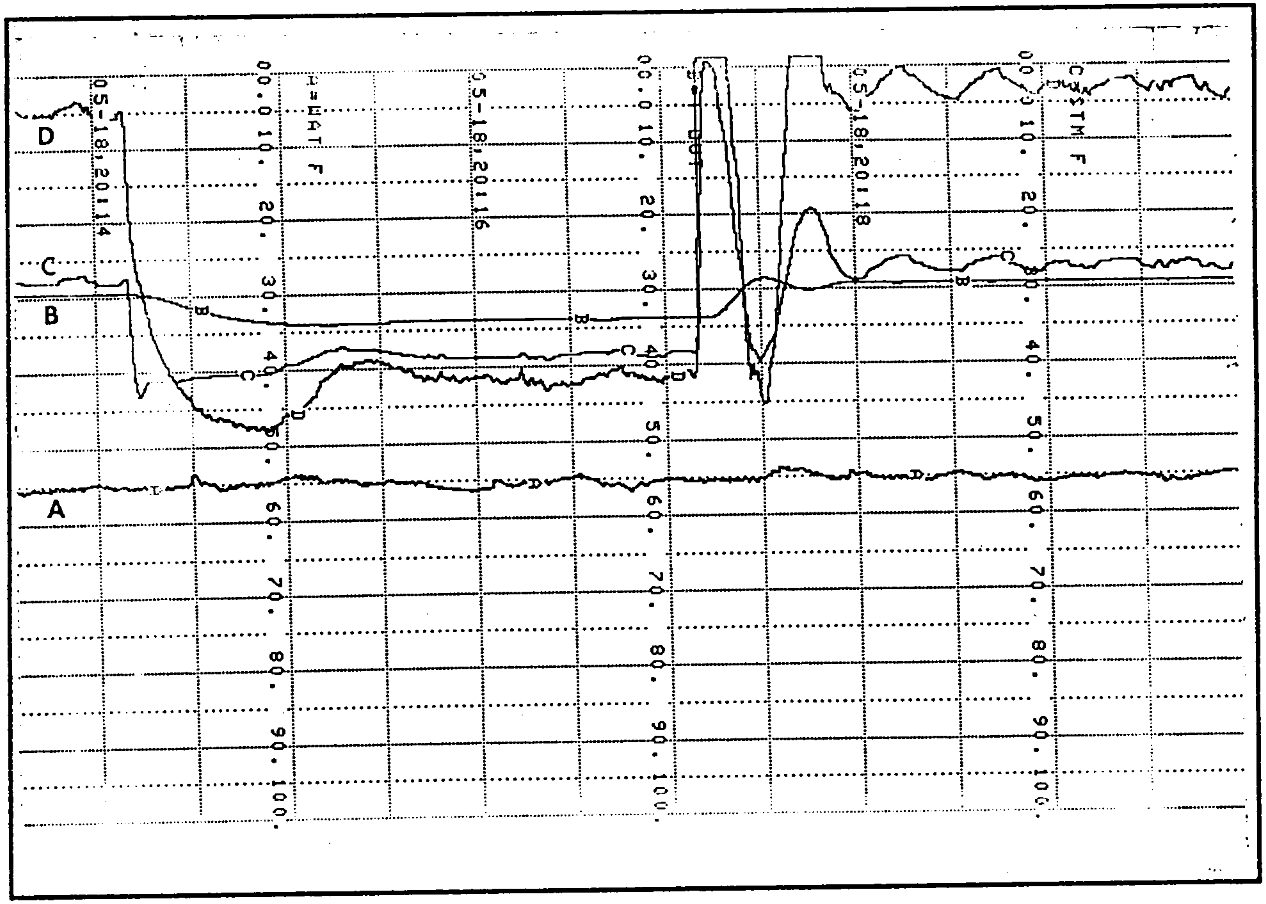
$t_d = 0.14$ MIN

A = WATER FLOW

B = OUTLET WATER TEMPERATURE

C = STEAM FLOW

D = STEAM PRESSURE



TEMPERATURE FEEDBACK

CLOSED LOOP PERFORMANCE TO SET POINT CHANGE

ZIEGLER-NICHOLS TUNING DERIVED FROM SET POINT INCREASE TUNING DATA

CHART SPEED = $\frac{1\ IN}{MIN}$

$K_c = 36$

$\tau_I = 0.29$

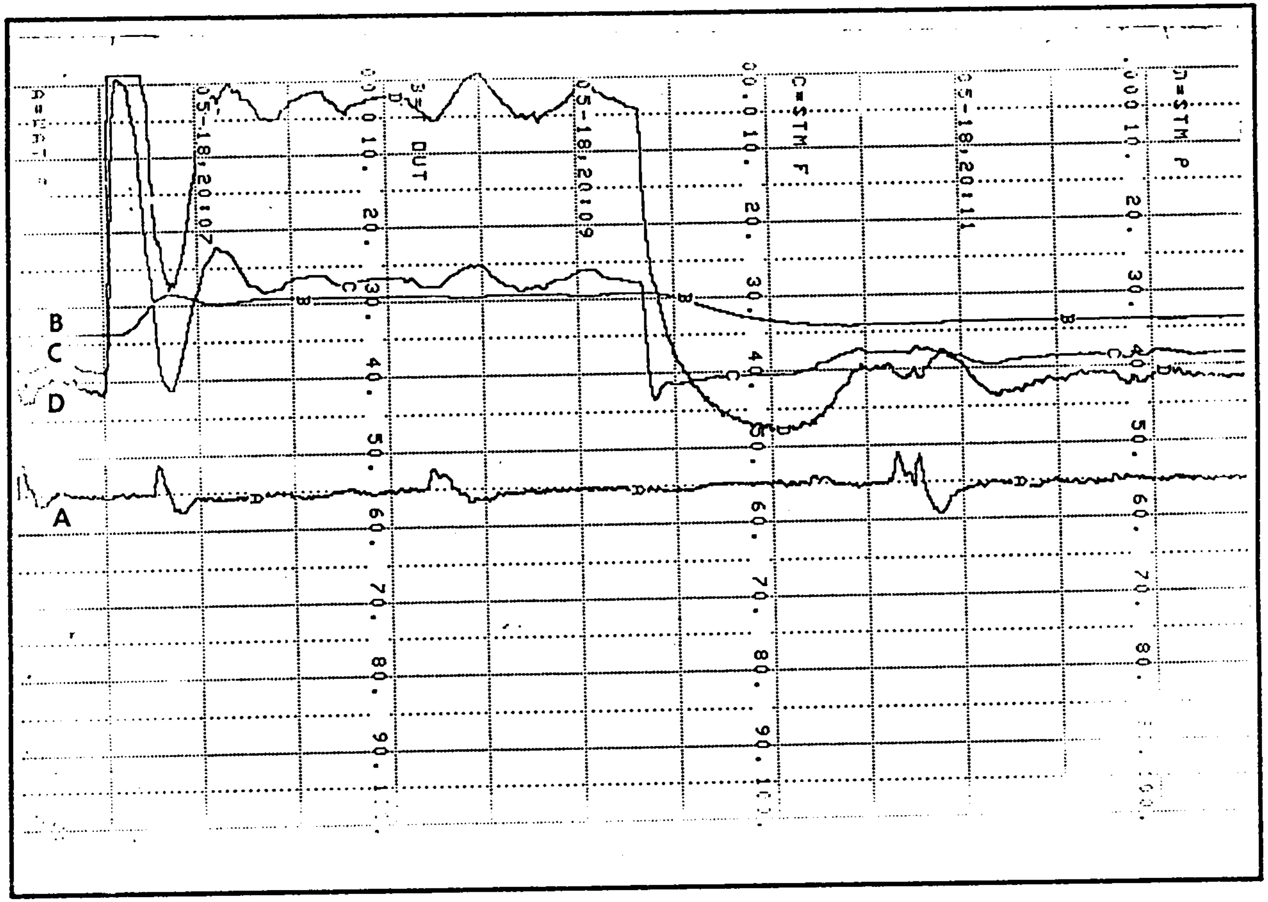
$\tau_D = 0.07$

A = WATER FLOW

B = OUTLET WATER TEMPERATURE

C = STEAM FLOW

D = STEAM PRESSURE



TEMPERATURE FEEDBACK

CLOSED LOOP PERFORMANCE TO SET POINT CHANGE

ZIEGLER-NICHOLS TUNING DERIVED FROM SET POINT DECREASE TUNING DATA

CHART SPEED = $\frac{1\ \text{IN}}{\text{MIN}}$

$K_c = 21$

$\tau_I = 0.28$

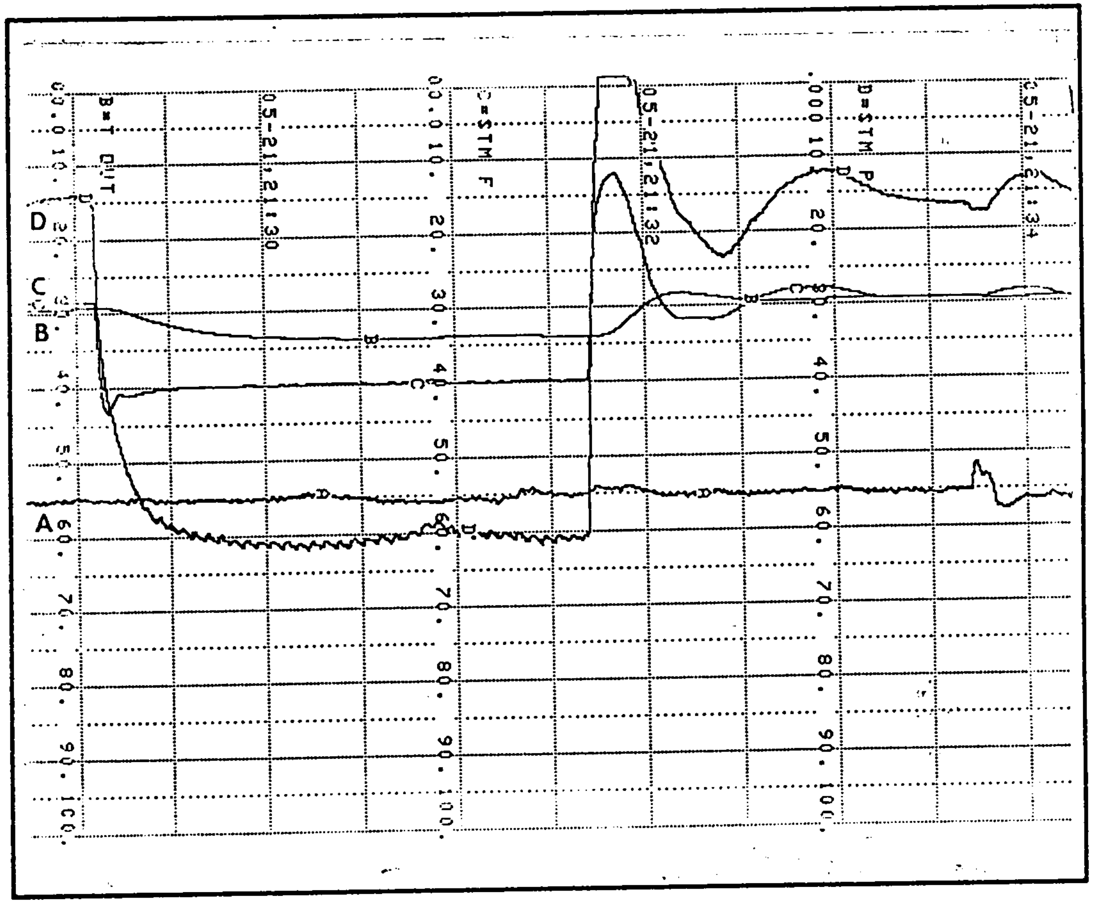
$\tau_D = 0.07$

A = WATER FLOW

B = OUTLET WATER TEMPERATURE

C = STEAM FLOW

D = STEAM PRESSURE



TEMPERATURE FEEDBACK

CLOSED LOOP PERFORMANCE TO SET POINT CHANGE - COHEN-COON TUNING

CHART SPEED = $\frac{1\ IN}{MIN}$

$K_c = 11.6$

$\tau_I = 0.31$

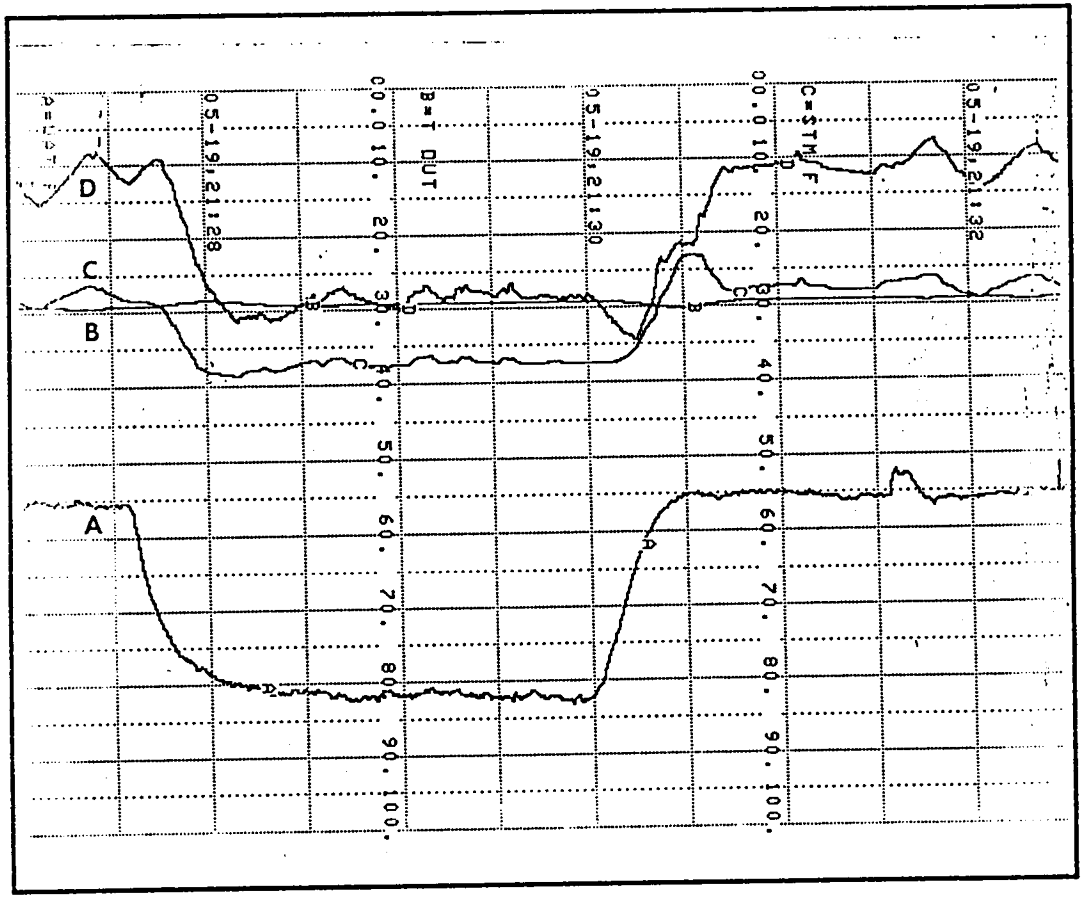
$\tau_D = 0.05$

A = WATER FLOW

B = OUTLET WATER TEMPERATURE

C = STEAM FLOW

D = STEAM PRESSURE



TEMPERATURE FEEDBACK

PERFORMANCE TO A LOAD CHANGE IN WATER FLOW RATE

ZIEGLER-NICHOLS TUNING DERIVED FROM SET POINT INCREASE PARAMETERS

CHART SPEED = $\frac{1\ IN}{MIN}$

$K_c = 36$

$\tau_I = 0.29$

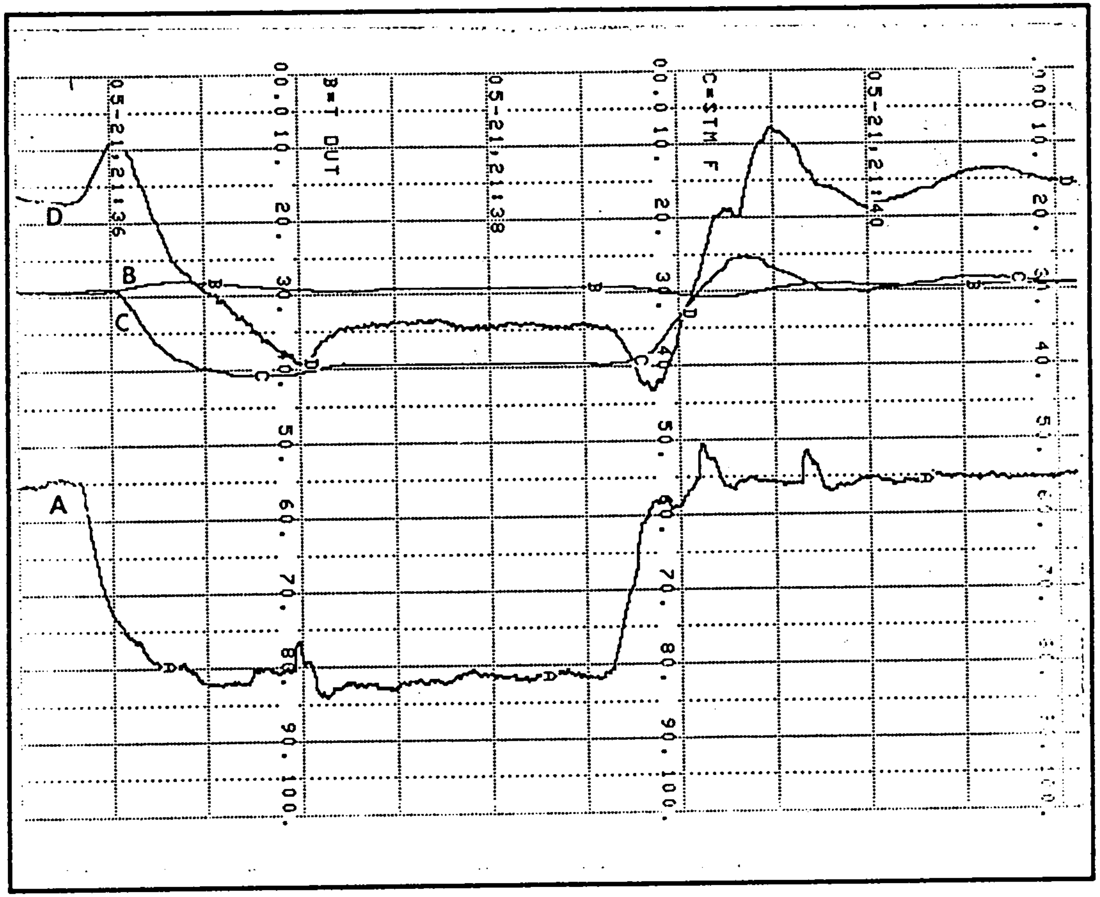
$\tau_D = 0.07$

A = WATER FLOW

B = OUTLET WATER TEMPERATURE

C = STEAM FLOW

D = STEAM PRESSURE



TEMPERATURE FEEDBACK

PERFORMANCE TO LOAD CHANGE IN WATER FLOW RATE - COHEN-COON TUNING

CHART SPEED = $\frac{1\ IN}{MIN}$

$K_c = 11.6$

$\tau_I = 0.31$

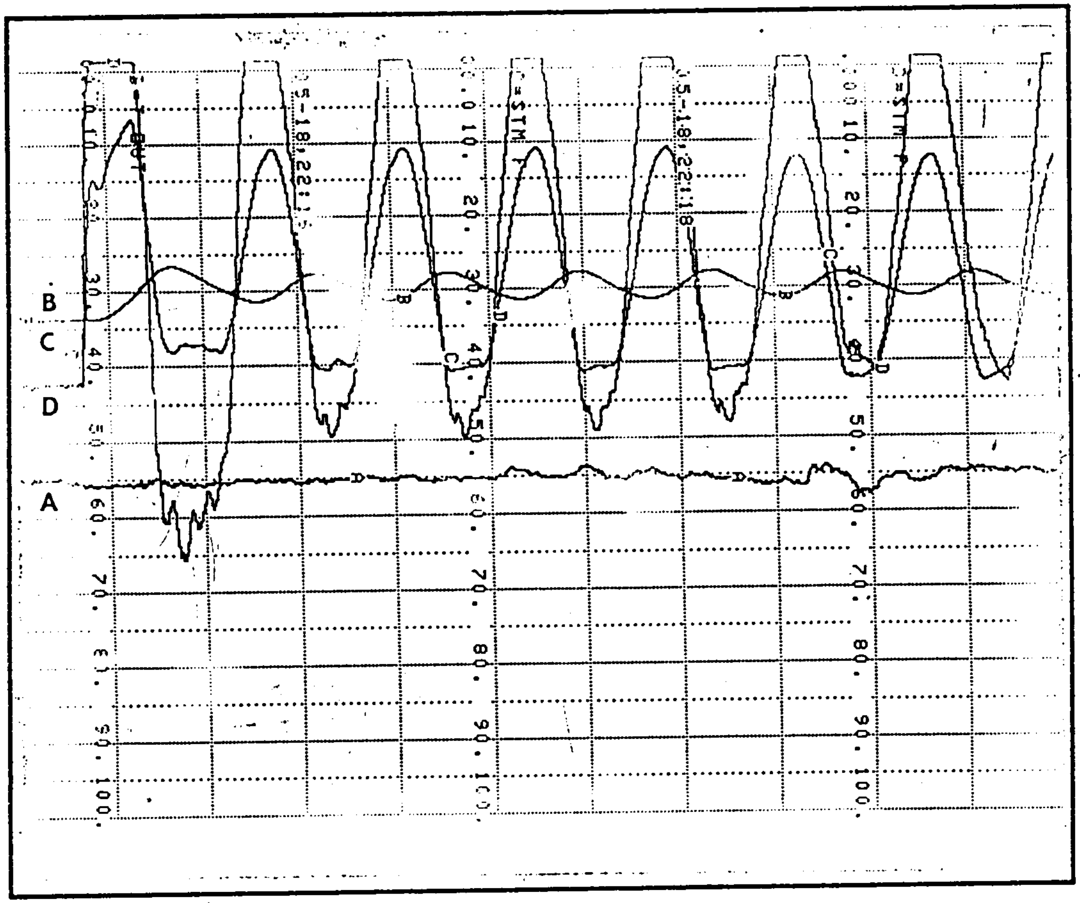
$\tau_D = 0.05$

A = WATER FLOW

B = OUTLET WATER TEMPERATURE

C = STEAM FLOW

D = STEAM PRESSURE



TEMPERATURE-FLOW CASCADE

ZIEGLER-NICHOLS TUNING CURVE FOR STEAM FLOW LOOP

CHART SPEED = $\frac{1\ IN}{MIN}$

K_u = 18.5

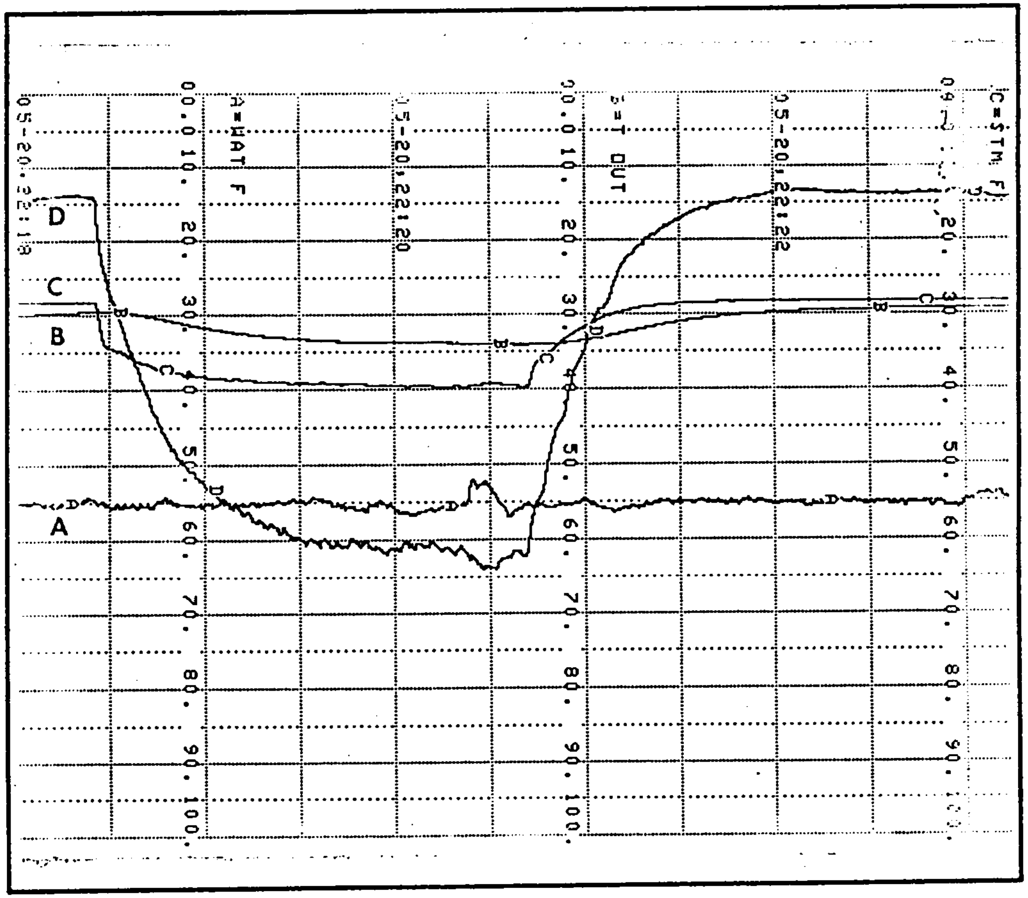
P_u = 0.69 MIN

A = WATER FLOW

B = OUTLET WATER TEMPERATURE

C = STEAM FLOW

D = STEAM PRESSURE



TEMPERATURE-FLOW CASCADE

CLOSED LOOP PERFORMANCE OF STEAM FLOW LOOP TO SET POINT CHANGE

ZIEGLER-NICHOLS TUNING

CHART SPEED = $\frac{1\ \text{IN}}{\text{MIN}}$

$K_c = 11.1$

$\tau_I = 0.34$

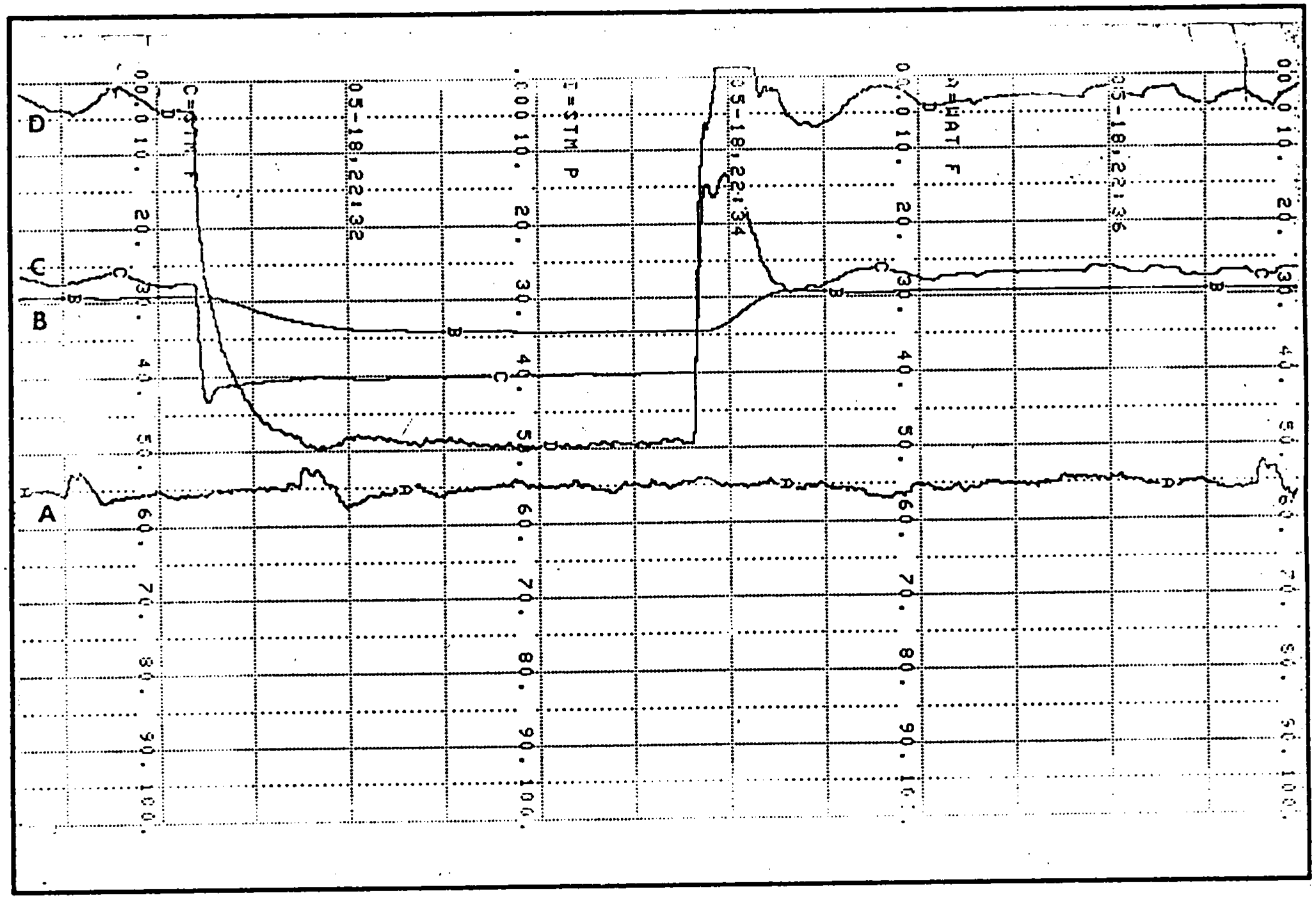
$\tau_D = 0.08$

A = WATER FLOW

B = OUTLET WATER TEMPERATURE

C = STEAM FLOW

D = STEAM PRESSURE

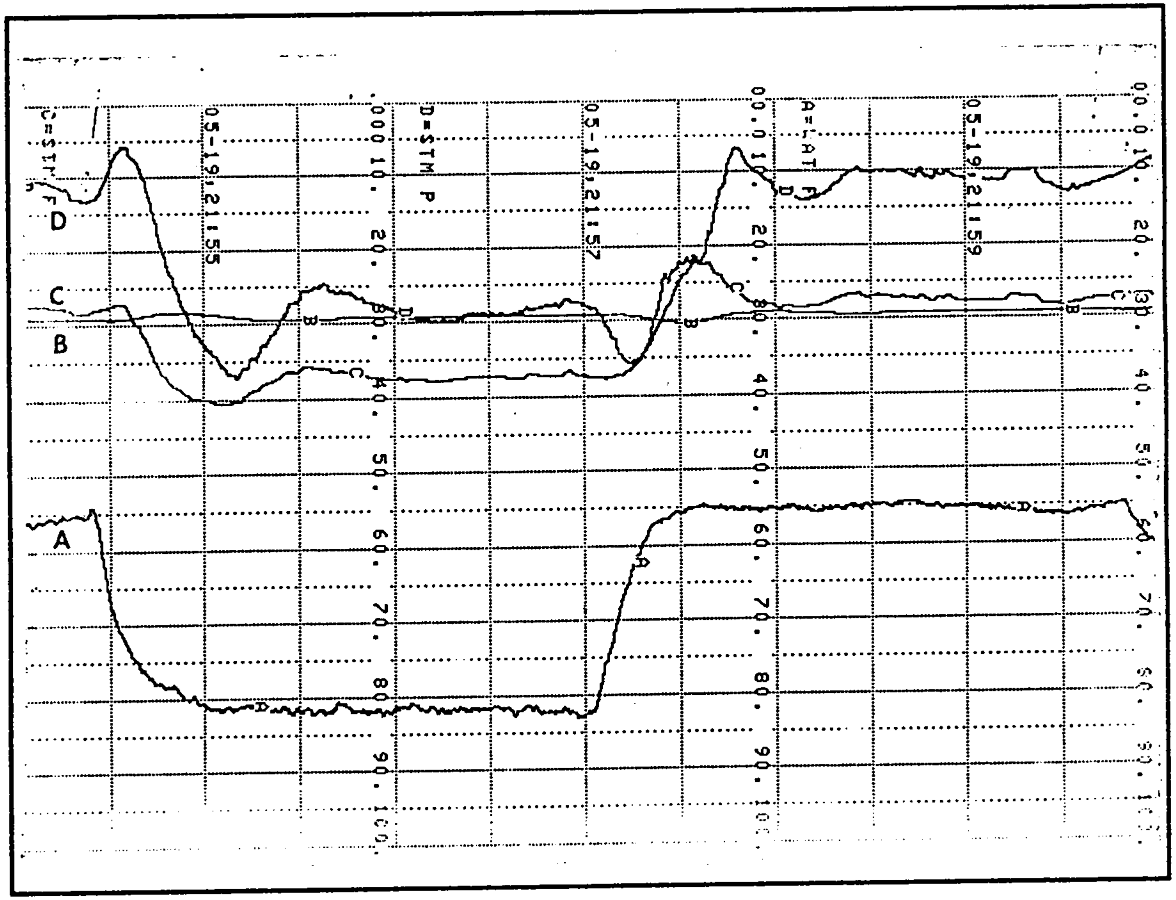


TEMPERATURE-FLOW CASCADE

CLOSED LOOP CASCADE PERFORMANCE TO TEMPERATURE SET POINT CHANGE

CHART SPEED = $\frac{1\ \text{IN}}{\text{MIN}}$

STEAM FLOW	TEMPERATURE	
K_c = 11.1	K_c = 1.1	A = WATER FLOW
τ_I = 0.34	τ_I = 0.08	B = OUTLET WATER TEMPERATURE
τ_D = 0.08		C = STEAM FLOW
		D = STEAM PRESSURE

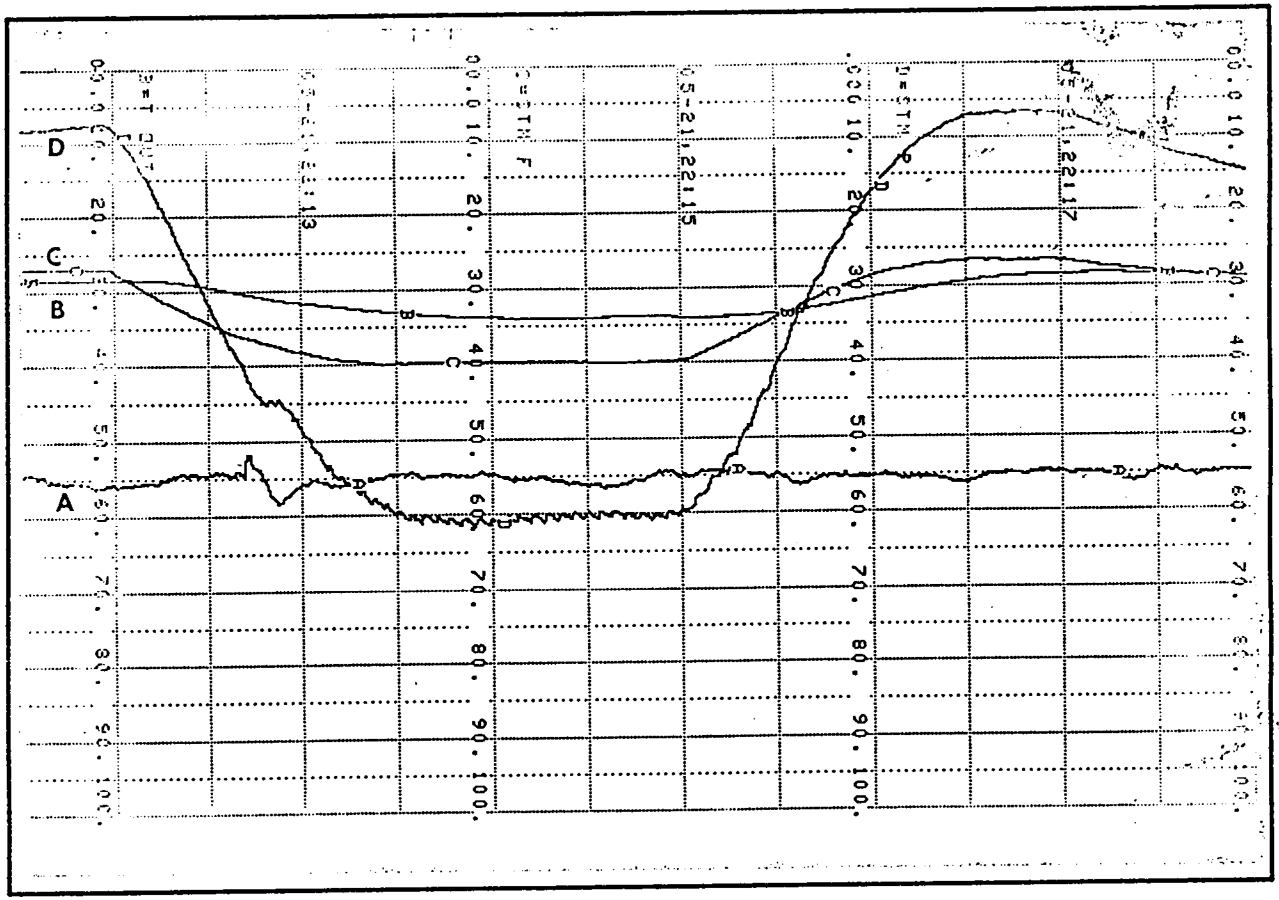


TEMPERATURE-FLOW CASCADE

CLOSED LOOP CASCADE PERFORMANCE TO A CHANGE IN WATER FLOW RATE

CHART SPEED = $\frac{1\ \text{IN}}{\text{MIN}}$

STEAM FLOW	TEMPERATURE	
$K_c = 11.1$	$K_c = 1.1$	A = WATER FLOW
$\tau_I = 0.34$	$\tau_I = 0.08$	B = OUTLET WATER TEMPERATURE
$\tau_D = 0.08$		C = STEAM FLOW
		D = STEAM PRESSURE

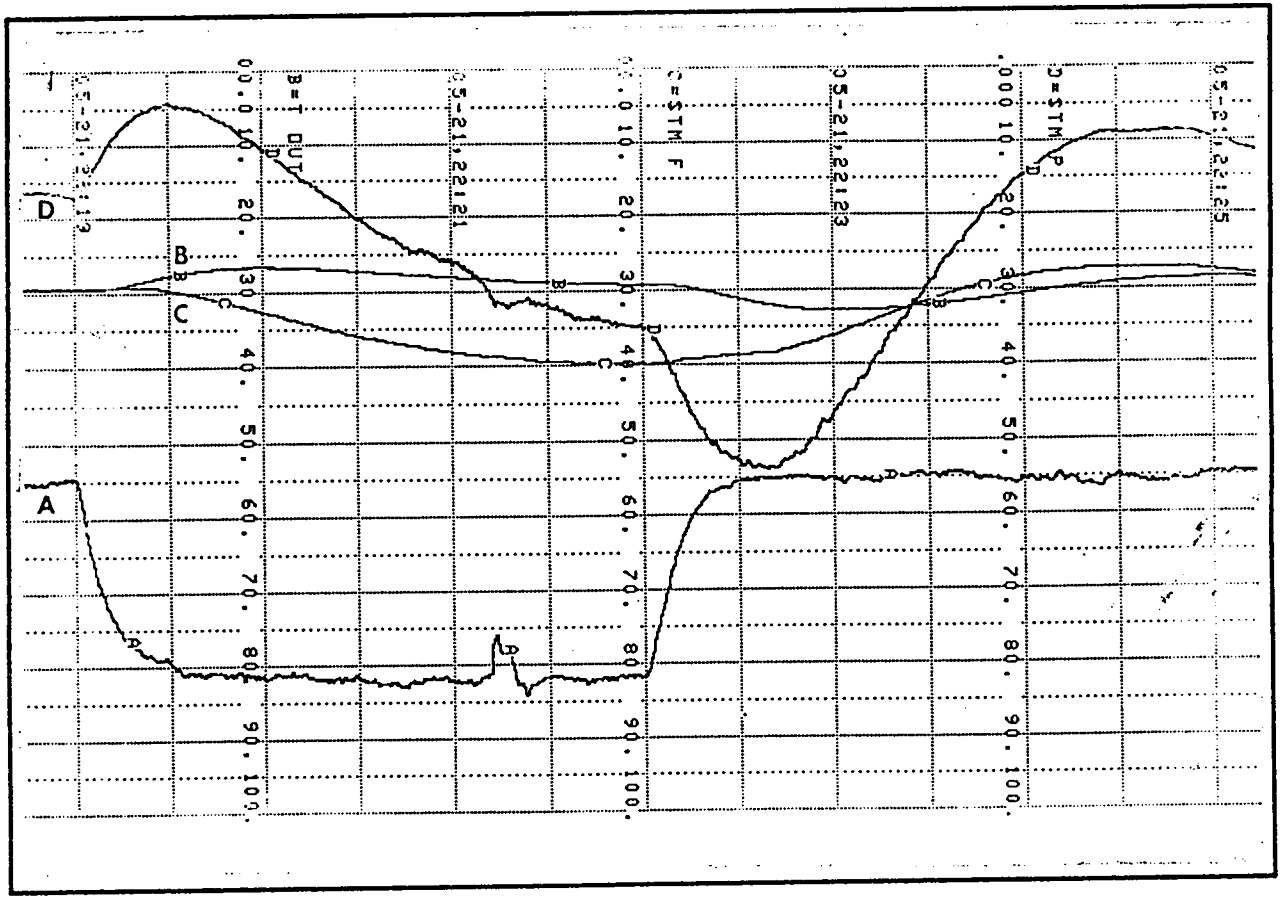


TEMPERATURE-FLOW CASCADE

CLOSED LOOP CASCADE PERFORMANCE TO TEMPERATURE SET POINT CHANGE

TRIAL AND ERROR TUNING

CHART SPEED = $\frac{1\ IN}{MIN}$	STEAM FLOW	TEMPERATURE	A = WATER FLOW
	$K_c = 1.1$	$K_c = 0.3$	B = OUTLET WATER TEMPERATURE
	$\tau_I = 0.08$	$\tau_I = 0.11$	C = STEAM FLOW
		$\tau_D = 0.1$	D = STEAM PRESSURE

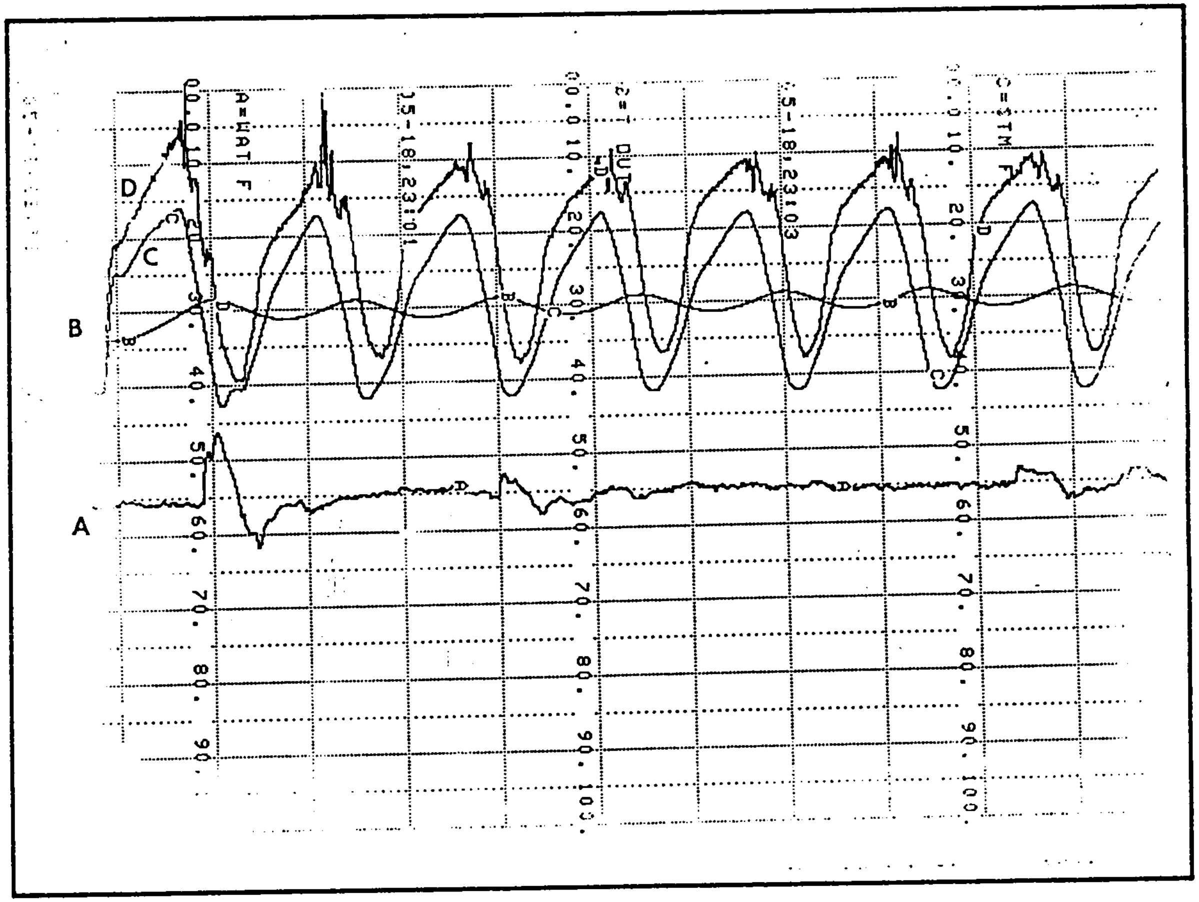


TEMPERATURE-FLOW CASCADE

CLOSED LOOP CASCADE PERFORMANCE TO CHANGE IN WATER FLOW RATE

TRIAL AND ERROR TUNING

CHART SPEED = $\frac{1\ IN}{MIN}$	STEAM FLOW	TEMPERATURE	
	$K_c = 1.1$	$K_c = 0.3$	A = WATER FLOW
	$\tau_I = 0.08$	$\tau_I = 0.11$	B = OUTLET WATER TEMPERATURE
		$\tau_D = 0.1$	C = STEAM FLOW
			D = STEAM PRESSURE



TEMPERATURE-PRESSURE CASCADE

ZIEGLER-NICHOLS TUNING CURVE FOR STEAM PRESSURE CONTROL LOOP

CHART SPEED = $\frac{1\ IN}{MIN}$

$K_u = 28$

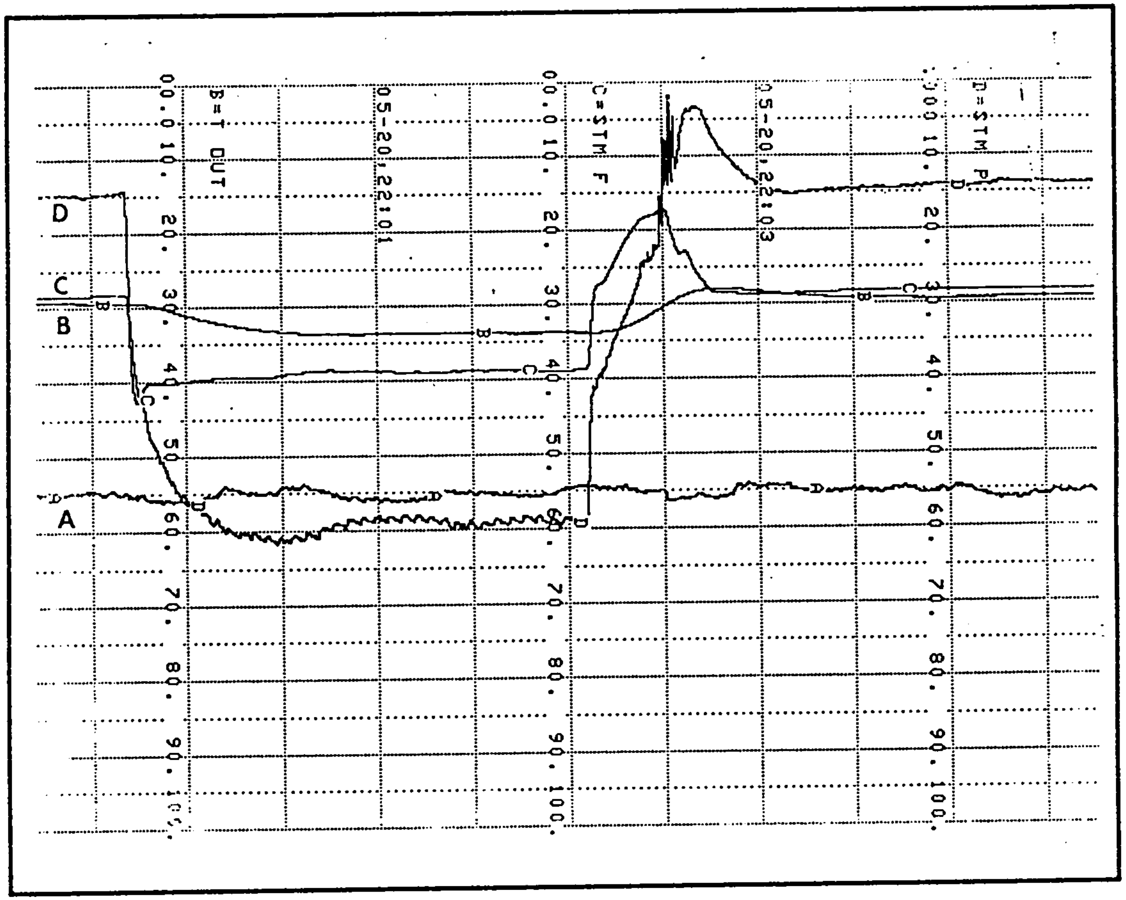
$P_u = 0.75$ MIN

A = WATER FLOW

B = OUTLET WATER TEMPERATURE

C = STEAM FLOW

D = STEAM PRESSURE



TEMPERATURE-PRESSURE CASCADE

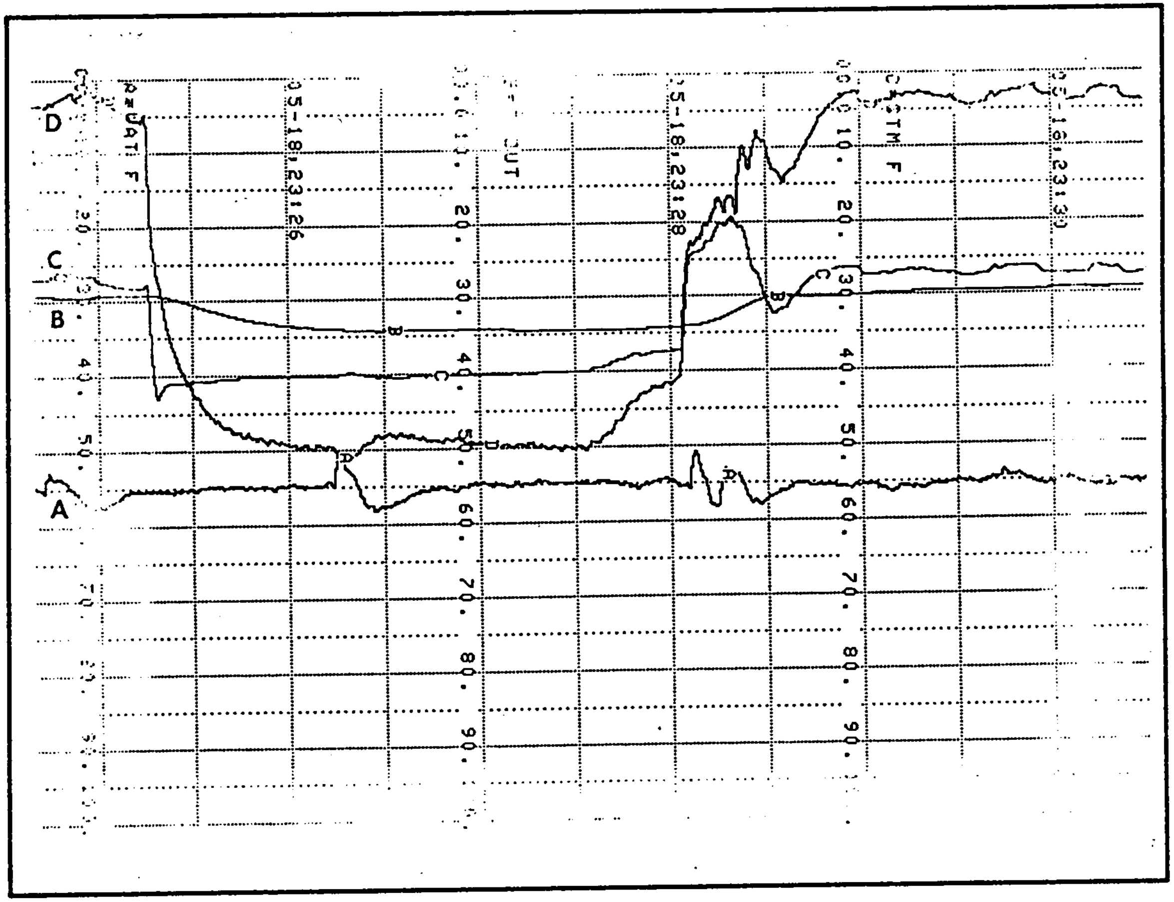
CLOSED LOOP PERFORMANCE OF PRESSURE LOOP TO SET POINT CHANGE

ZIEGLER-NICHOLS TUNING

CHART SPEED = $\frac{1\ IN}{MIN}$

$K_c = 16.8$
$\tau_I = 0.38$
$\tau_D = 0.09$

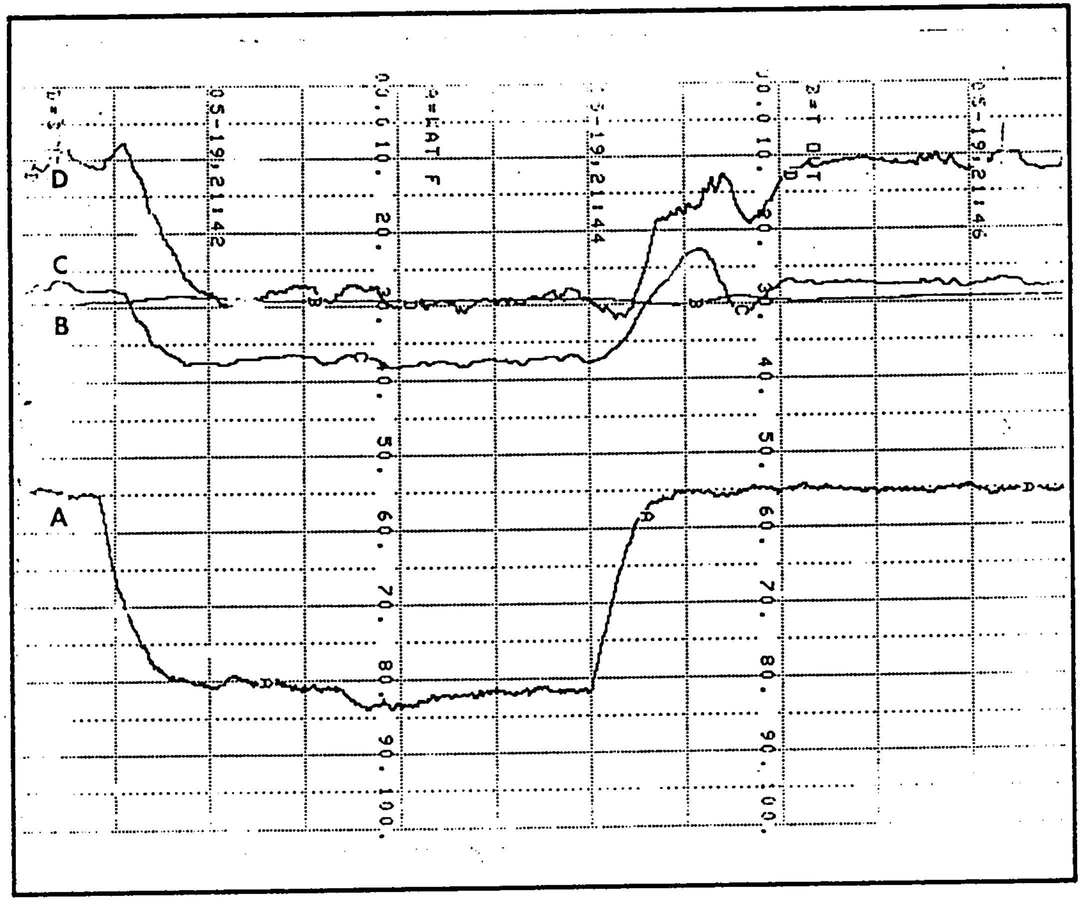
A = WATER FLOW
B = OUTLET WATER TEMPERATURE
C = STEAM FLOW
D = STEAM PRESSURE



TEMPERATURE-PRESSURE CASCADE

CLOSED LOOP CASCADE PERFORMANCE TO TEMPERATURE SET POINT CHANGE

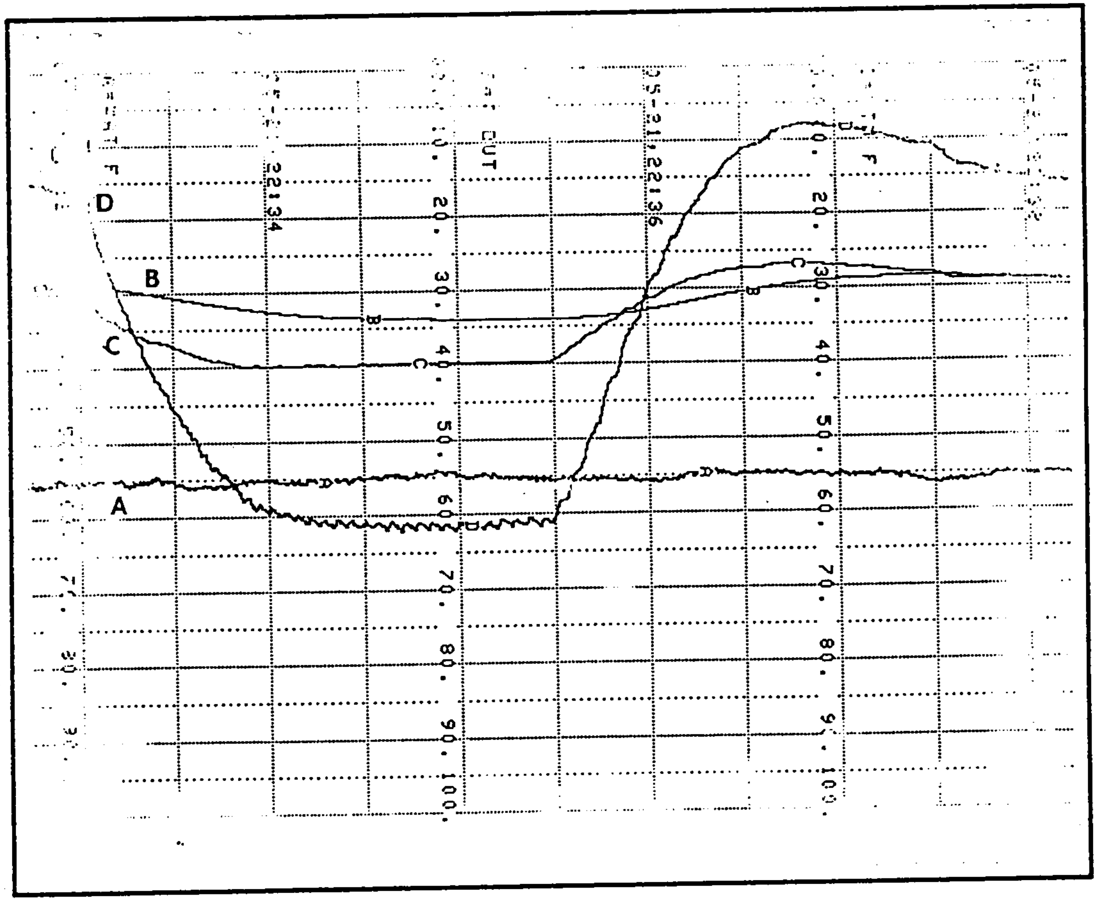
CHART SPEED = $\frac{1\ IN}{MIN}$	STEAM PRESSURE	TEMPERATURE	
	$K_c = 16.8$	$K_c = 1.8$	A = WATER FLOW
	$\tau_I = 0.38$	$\tau_I = 0.11$	B = OUTLET WATER TEMPERATURE
	$\tau_D = 0.09$		C = STEAM FLOW
			D = STEAM PRESSURE



TEMPERATURE-PRESSURE CASCADE

CLOSED LOOP CASCADE PERFORMANCE TO CHANGE IN WATER FLOW RATE

CHART SPEED = $\frac{1\ \text{IN}}{\text{MIN}}$	STEAM PRESSURE	TEMPERATURE	
	$K_c = 16.8$	$K_c = 1.8$	A = WATER FLOW
	$\tau_I = 0.38$	$\tau_I = 0.11$	B = OUTLET WATER TEMPERATURE
	$\tau_D = 0.09$		C = STEAM FLOW
			D = STEAM PRESSURE

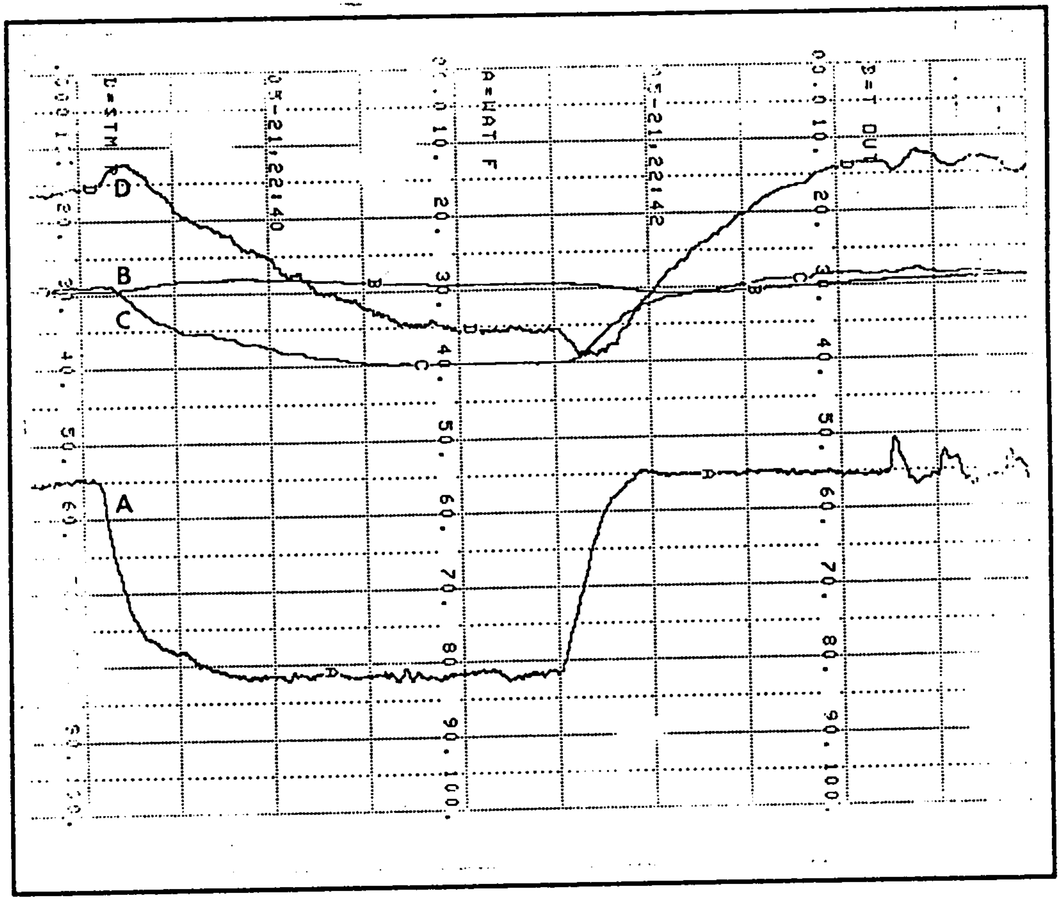


TEMPERATURE-PRESSURE CASCADE

CLOSED LOOP CASCADE PERFORMANCE TO TEMPERATURE SET POINT CHANGE

TRIAL AND ERROR TUNING

CHART SPEED = $\frac{1\ IN}{MIN}$	STEAM PRESSURE	TEMPERATURE	
			A = WATER FLOW
	$K_c = 0.75$	$K_c = 1.8$	B = OUTLET WATER TEMPERATURE
	$\tau_I = 0.11$	$\tau_I = 0.11$	C = STEAM FLOW
		$\tau_D = 0.5$	D = STEAM PRESSURE

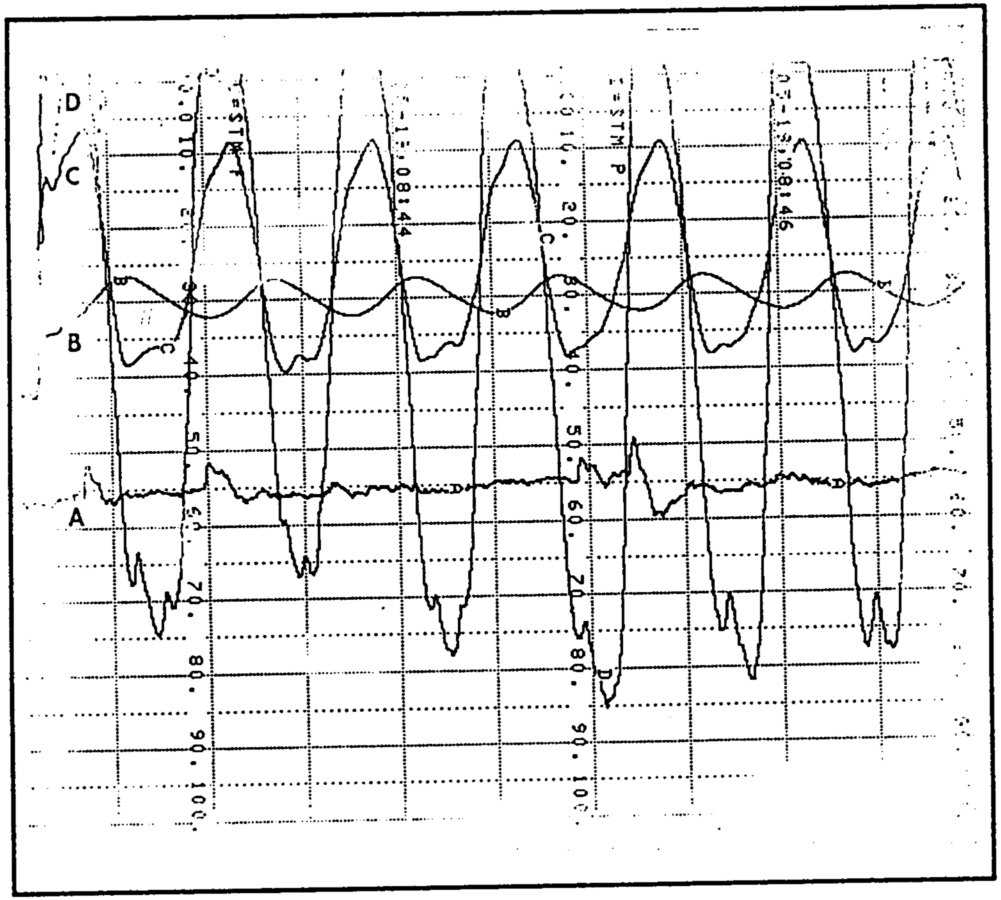


TEMPERATURE-PRESSURE CASCADE

CLOSED LOOP CASCADE PERFORMANCE TO SET POINT CHANGE IN WATER FLOW RATE

TRIAL AND ERROR TUNING

CHART SPEED = $\frac{1\ IN}{MIN}$	STEAM PRESSURE	TEMPERATURE	
	$K_c = 0.75$	$K_c = 1.8$	A = WATER FLOW
	$\tau_I = 0.11$	$\tau_I = 0.11$	B = OUTLET WATER TEMPERATURE
		$\tau_D = 0.5$	C = STEAM FLOW
			D = STEAM PRESSURE



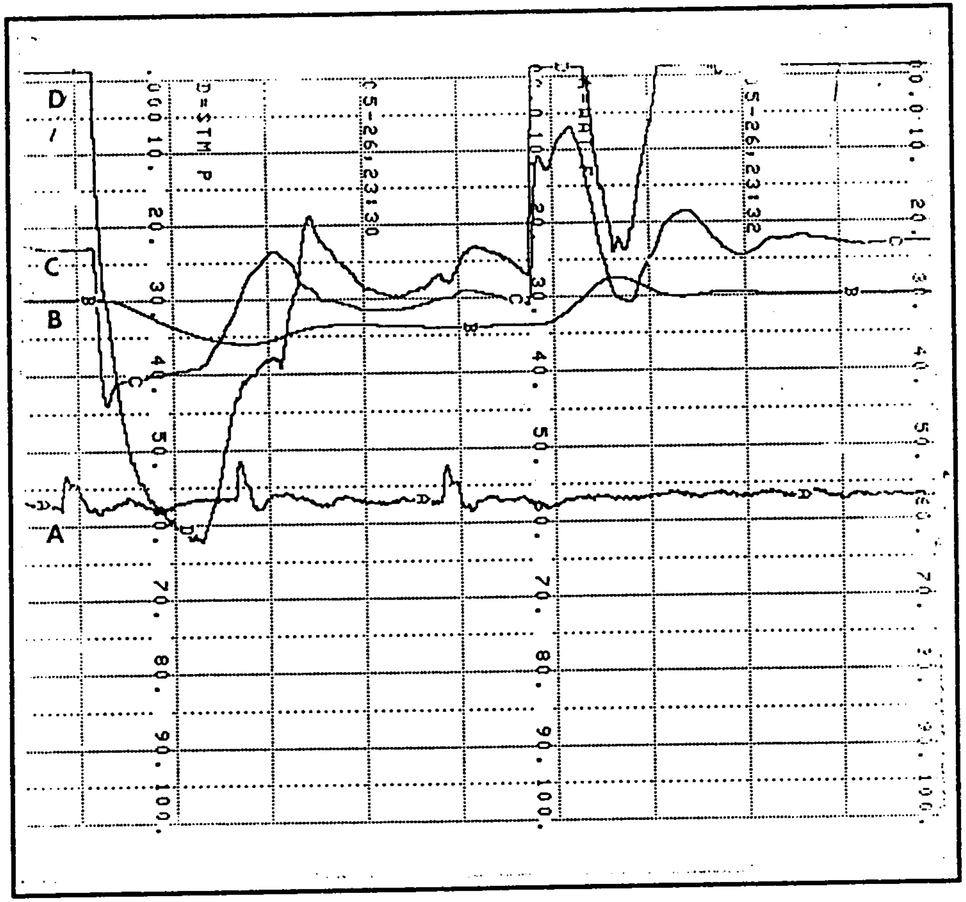
FEEDFORWARD WITH TEMPERATURE FEEDBACK

ZIEGLER-NICHOLS TUNUNG CURVE FOR TEMPERATURE LOOP

CHART SPEED = $\frac{1\ IN}{MIN}$ $K_u = 11$ $P_u = 0.75$ MIN

STEAM FLOW $K_c = 1.1$ $\tau_I = 0.08$

A = WATER FLOW
B = OUTLET WATER TEMPERATURE
C = STEAM FLOW
D = STEAM PRESSURE

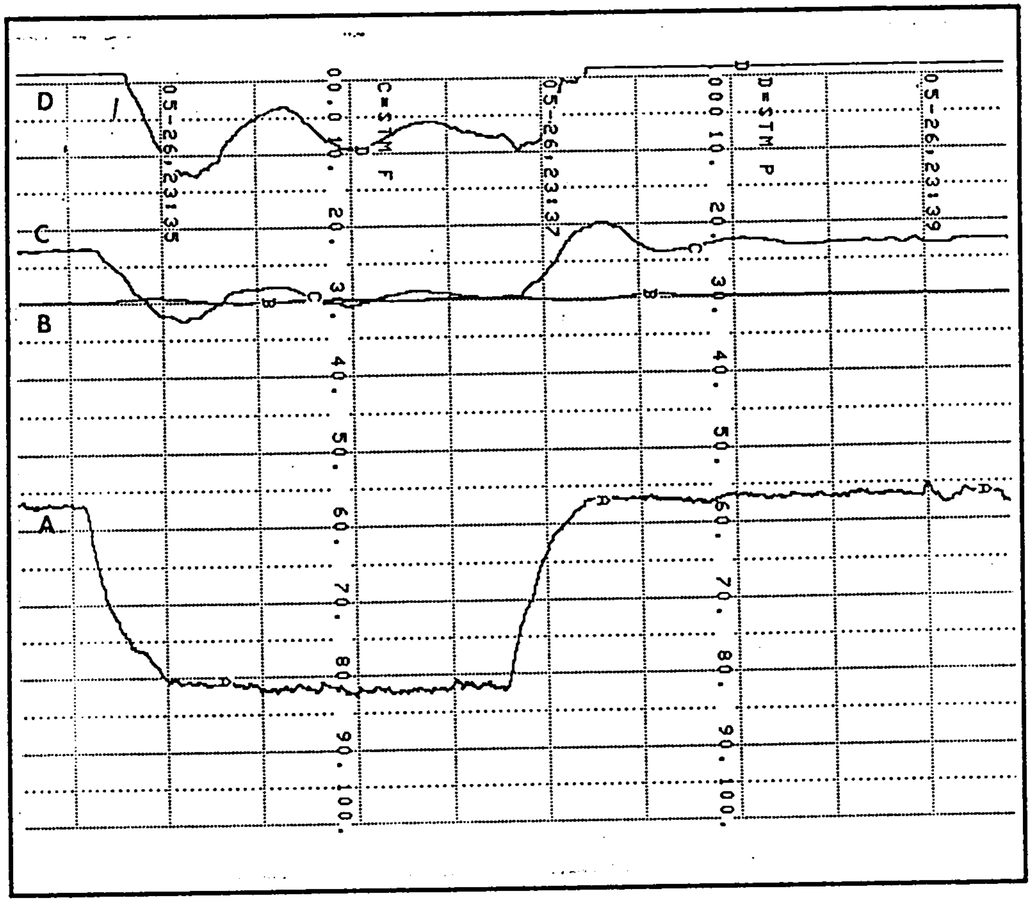


FEEDFORWARD WITH TEMPERATURE FEEDBACK

CLOSED LOOP PERFORMANCE TO TEMPERATURE SET POINT CHANGE

ZIEGLER-NICHOLS TUNUNG

CHART SPEED =	STEAM FLOW	TEMPERATURE	
$\frac{1\ IN}{MIN}$			A = WATER FLOW
	$K_c = 1.1$	$K_c = 6.6$	B = OUTLET WATER TEMPERATURE
	$\tau_I = 0.08$	$\tau_I = 0.38$	C = STEAM FLOW
		$\tau_D = 0.09$	D = STEAM PRESSURE

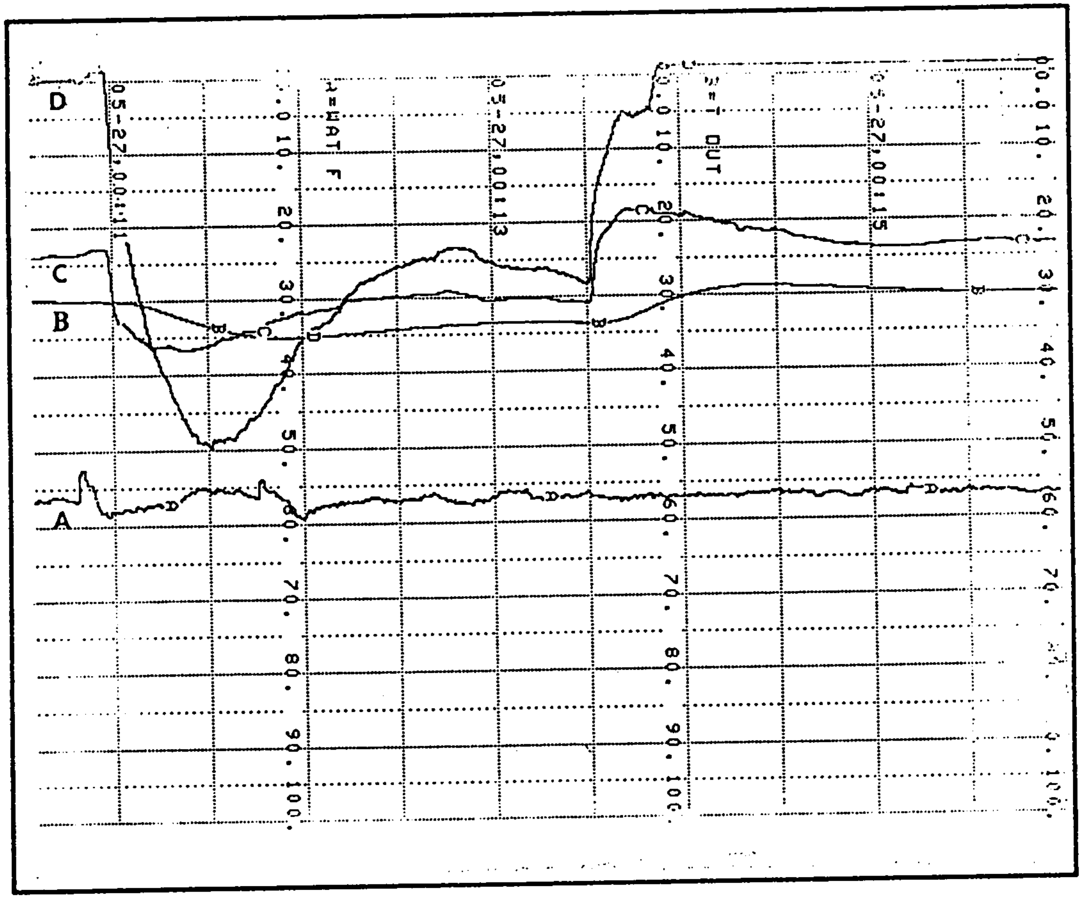


FEEDFORWARD WITH TEMPERATURE FEEDBACK

CLOSED LOOP PERFORMANCE TO CHANGE IN WATER FLOW RATE

ZIEGLER-NICHOLS TUNING

CHART SPEED = $\frac{1\ IN}{MIN}$	STEAM FLOW	TEMPERATURE	
			A = WATRER FLOW
	K_c= 1.1	K_c= 6.6	B = OUTLET WATER TEMPERATURE
	τ_I= 0.08	τ_I= 0.38	C = STEAM FLOW
		τ_D= 0.09	D = STEAM PRESSURE

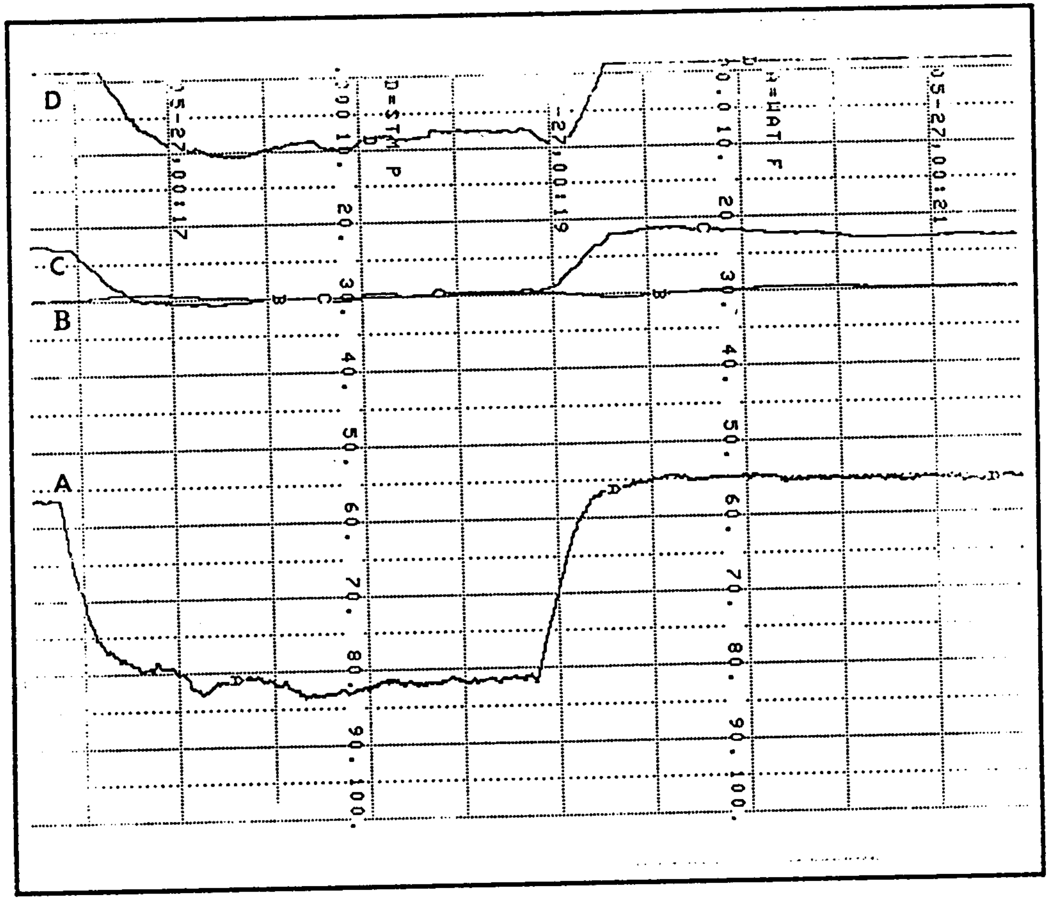


FEEDFORWARD WITH TEMPERATURE FEEDBACK

CLOSED LOOP PERFORMANCE TO TEMPERATURE SET POINT CHANGE

TRIAL AND ERROR TUNING

CHART SPEED = $\frac{1\ IN}{MIN}$	STEAM FLOW	TEMPERATURE	
	K_c= 1.1	K_c= 2.5	A = WATER FLOW
	τ_I= 0.08	τ_I= 0.3	B = OUTLET WATER TEMPERATURE
		τ_D= 0.2	C = STEAM FLOW
			D = STEAM PRESSURE

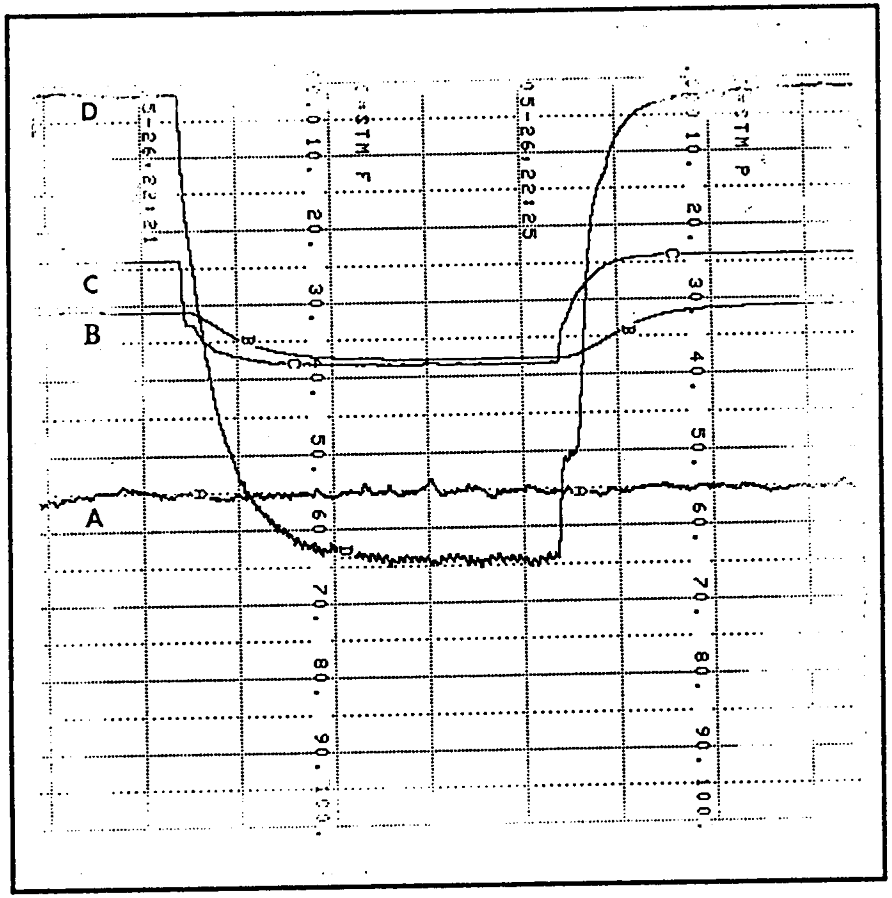


FEEDFORWARD WITH TEMPERATURE FEEDBACK

CLOSED LOOP PERFORMANCE TO CHANGE IN WATER FLOW RATE

TRIAL AND ERROR TUNING

CHART SPEED = $\frac{1\ \text{IN}}{\text{MIN}}$	STEAM FLOW	TEMPERATURE	A = WATER FLOW
	$K_c = 1.1$	$K_c = 2.5$	B = OUTLET WATER TEMPERATURE
	$\tau_I = 0.8$	$\tau_I = 0.3$	C = STEAM FLOW
		$\tau_D = 0.2$	D = STEAM PRESSURE



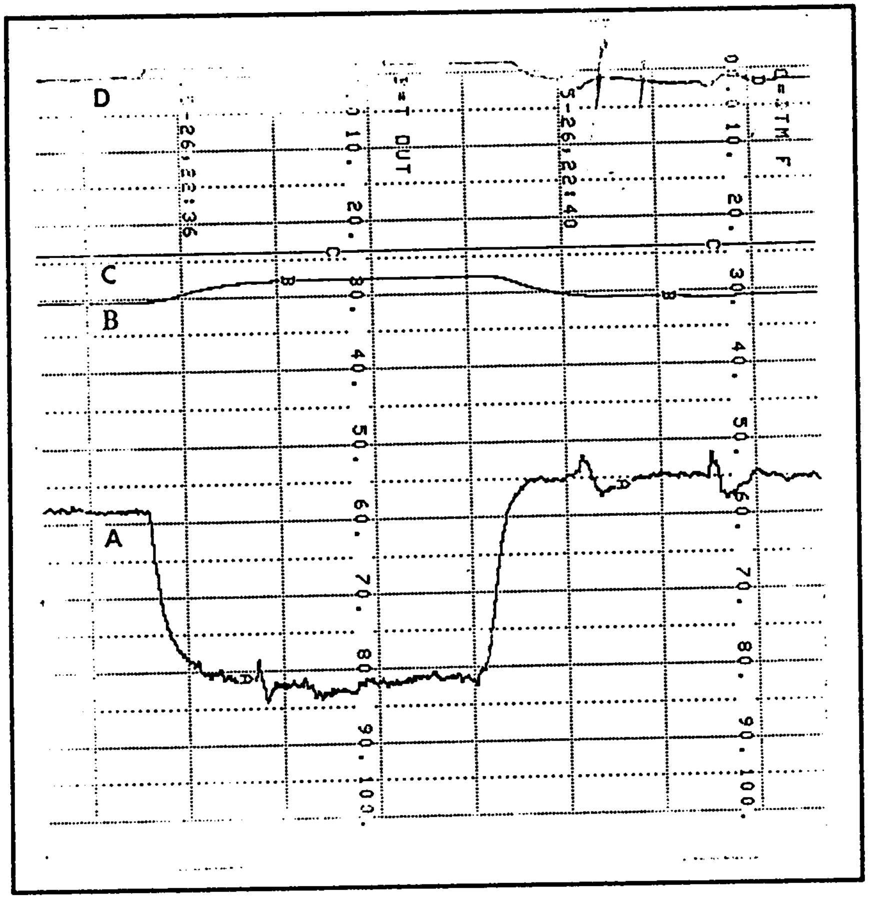
FEEDFORWARD WITH LEAD-LAG

DETERMINATION OF TEMPERATURE TIME CONSTANT DUE TO CHANGE IN STEAM FLOW FOR LEAD-LAG COMPENSATOR

CHART SPEED = $\frac{0.5 \text{ IN}}{\text{MIN}}$

τ = 2.9 MIN

A = WATER FLOW
B = OUTLET WATER TEMPERATURE
C = STEAM FLOW
D = STEAM PRESSURE

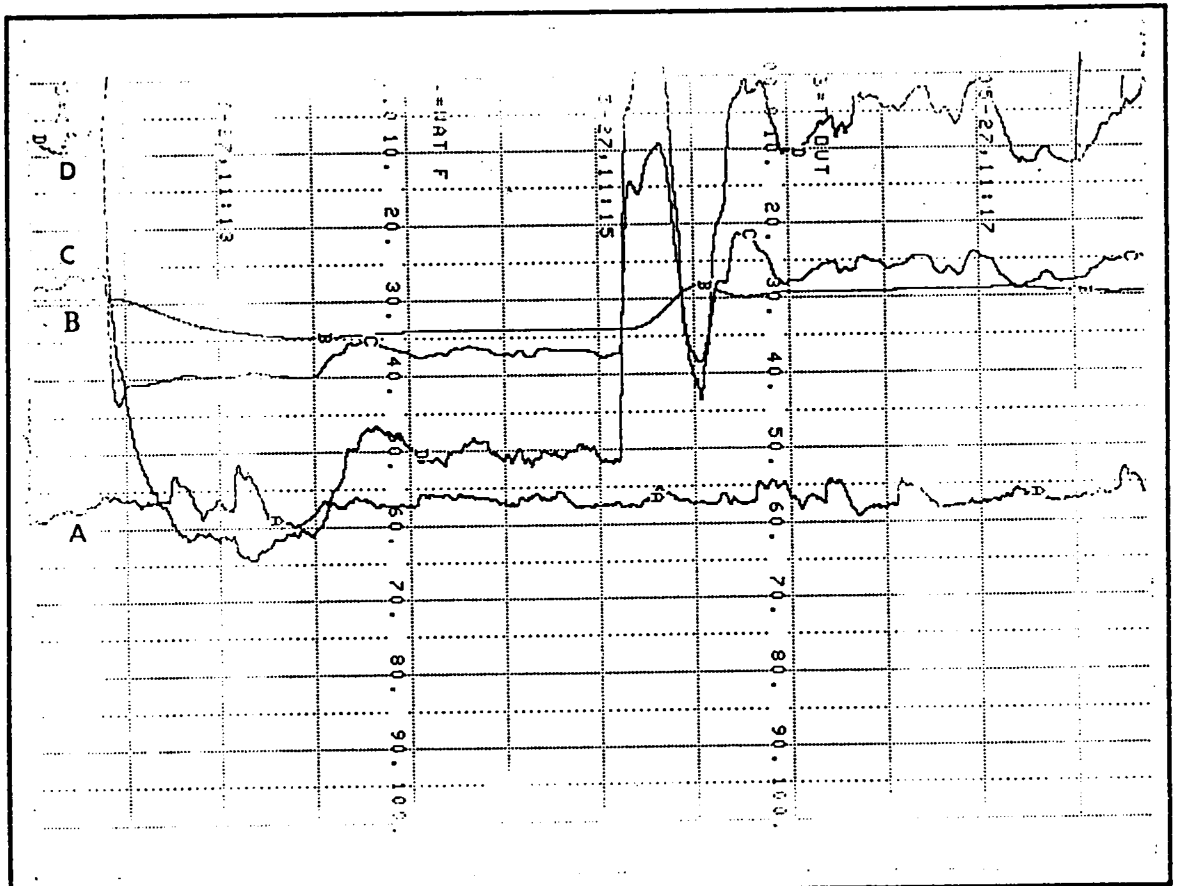


FEEDFORWARD WITH LEAD-LAG

DETERMINATION OF TEMPERATURE TIME CONSTANT DUE TO CHANGE IN OUTLET WATER FLOW FOR LEAD-LAG COMPENSATOR

CHART SPEED = $\frac{0.50\ IN}{MIN}$ τ = 2.6 MIN

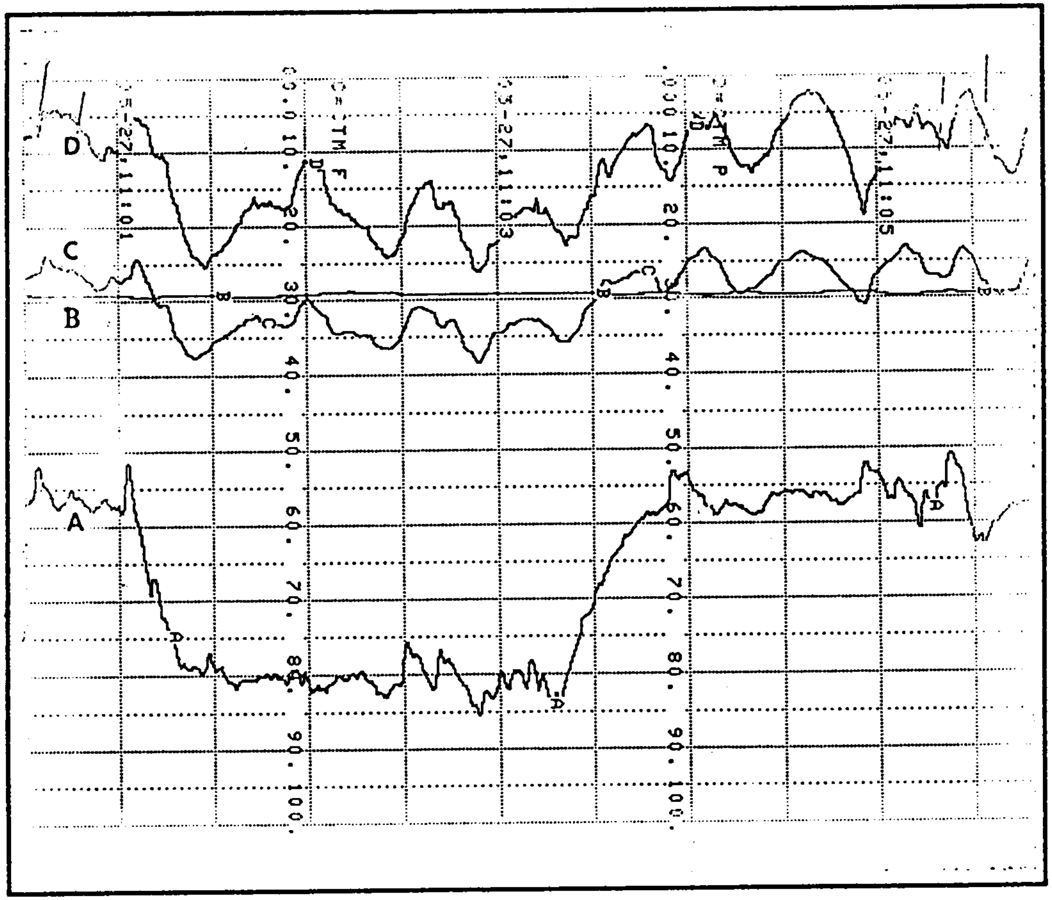
A = WATER FLOW
B = OUTLET WATER TEMPERATURE
C = STEAM FLOW
D = STEAM PRESSURE



FEEDFORWARD WITH LEAD-LAG

CLOSED LOOP PERFORMANCE TO A TEMPERATURE SET POINT CHANGE

CHART SPEED = $\frac{1\ IN}{MIN}$	STEAM FLOW		TEMPERATURE	
	$K_c = 1.1$	$\tau_1 = 4.0$ MIN	$K_c = 6.6$	A = WATER FLOW
	$\tau_I = 0.08$	$\tau_2 = 2.6$ MIN	$\tau_I = 0.38$	B = OUTLET WATER TEMPERATURE
			$\tau_D = 0.09$	C = STEAM FLOW
				D = STEAM PRESSURE



FEEDFORWARD WITH LEAD-LAG

CLOSED LOOP PERFORMANCE TO CHANGE IN WATER FLOW RATE

CHART SPEED =	$\frac{1\ \text{IN}}{\text{MIN}}$	STEAM FLOW	τ_1 = 4.0 MIN	TEMPERATURE	A = WATER FLOW
		K_c = 1.1	τ_2 = 2.6 MIN	K_c = 6.6	B = OUTLET WATER TEMPERATURE
		τ_I = 0.08		τ_I = 0.38	C = STEAM FLOW
				τ_D = 0.09	D = STEAM PRESSURE

VITA

James Edward Dunbar, Jr. was born in Camden, Tennessee on August 26, 1961. He attended public schools in that city and was graduated from Camden Central High School in May, 1979. The following September he entered The University of Tennessee and received a Bachelor of Science degree in Chemical Engineering in June 1984. While an undergraduate, he participated in the Co-operative education program and worked for the DuPont Company in research and development.

He entered the University of Tennessee Graduate School in September, 1984 and received the Master of Science degree in December, 1990. He has been employed by International Paper Company since June, 1987 as a process engineer in the Control Systems Implementation group.