

**Comparative Study of  
Feedforward and Feedback  
Process Control**

**Garbis Palandjian**

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COMPARATIVE STUDY OF  
FEEDFORWARD AND FEEDBACK  
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ABSTRACT

COMPARATIVE STUDY OF FEEDFORWARD AND  
FEEDBACK PROCESS CONTROL

Garbis Palandjian

In this report, the performance of feedforward and feedback process control systems are studied. The general concepts of process control and its types are presented. The feedback control system is described and the transfer function of each of its components are derived. The advantages and the disadvantages of the feedback control system are listed. Feedforward control system is presented and its transfer functions, both steady-state and dynamic are derived. The combination feedforward-feedback control system is also described.

Using digital computer simulation a heat exchanger is controlled by each of the control systems. The results of the simulation are shown graphically and the performance of each control system is evaluated.

### ACKNOWLEDGEMENTS

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CHAPTER 1

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INTRODUCTION

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In the last few decades, many new technologies have been applied to process control hardware as the industrial use of automation techniques has developed and matured.

Historically, the first stages in the development of modern controllers consisted of the introduction of indicating and recording instruments in 1920's. Control was accomplished at this point by manual means. Automatic proportional control was next introduced by using the motion of the pen on the recorder to adjust the position of the control valve through the use of pneumatic transducers and transmission lines. The first general theoretical treatment of automatic control was published in 1932.

During the middle 1930's the idea of using an additional integration in a control loop was proposed, the objective being to reduce the steady state errors to zero. In the late 1940's and early 1950's derivative action was proposed in order to speed up the action of the control loop and to provide "anticipatory" behavior in the face of sudden disturbances.

In the mid 1950's electronic controllers began to appear and had supplanted the pneumatic controllers because

of their increased reliability, flexibility, versatility and ease of maintenance. The greater flexibility of electronic devices promoted the development of more exotic control actions.

In early 1960's, it was felt that the limit of what can be done by conventional feedback control was fast-approaching [1], therefore the feedforward control was introduced.

Although it is believed that feedforward control was combined with feedback control loop and has been used in the early 1930's to control boiler drum levels, yet the theoretical treatment was only published in 1963 [1]. Through out 1960's studies were carried out and various applications of feedforward control were proposed [2, 3, 4, 5, 6, 7].

With the increased use of digital computers in process control, new control methods like adaptive control were introduced in the first half of 1970's. In late 1970's microprocessor based controllers were introduced and they began replacing the electronic controllers at an unbelievable rate due to their reliability, speed and extreme versatility.

Where it once was essential to know all the details of the process (especially for feedforward control loops)

before ordering the proper controller for the control loop, today with programming capabilities of the microprocessor based controllers, the characteristics of the controller are programmed with the actual process conditions.

It is the purpose of this paper to discuss in detail the feedforward control and to demonstrate its advantages and disadvantages. Using practical process control applications and digital computer simulations feedforward control will be compared with feedback control. The steady-state and dynamic components of feedforward control will be discussed and the influence of each of these components on the control of the process will be demonstrated. The combination of feedback-feedforward control will also be discussed and its response will be simulated.

CHAPTER 2

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PROCESS CONTROL

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2.1 General Concepts of Process Control

=====

The role of a closed-loop control system is to enable the automatic maintenance of balanced conditions within a process, in order to achieve the desired output. A system is said to be controlled if the quality of its performance is within certain limits. If these limits are not exceeded, a well controlled system exists. The end result of a controlled process is to obtain a quantity of a product that has a given property, but the method of achieving that end result is immaterial.

For this reason, indirect or secondary variables are often controlled in a process rather than the physical and chemical properties which are considered the primary variables. The major secondary variables are level, flow, pressure and temperature. All these variables are easily measured and transmitted without any long time lags. On the other hand, the measurement of the primary variables such as heat content, composition or reaction rate is more difficult due to the lack of suitable economical instruments or due to the long response time of these instruments.

Control system efficiency is measured by the effectiveness of the control loop in recovering from load disturbances. However, this does not mean that the controlled variable must be held to an exact value at all times. The process variable can fall within a wide band and still be adequate as long as the material balance of the system remains constant. For example, the level of a tank under control can vary if the more desirable feature is to have the flow to the next vessel fairly constant.

The important thing to determine in every control system is the correct method to control the balance of materials and energy in the process. Once this is done, the next step is to select the appropriate form of control whether it be feedback, feedforward, cascade or any other form or combination of these forms that can best do the job.

In the analysis of control systems it is quite common to use the "lumped-parameter" approach rather than the "distributed-parameter" one. This is done to simplify the mathematics of the models used to represent the control systems. By the lumped parameter approach, the elements of the control systems are considered as being point masses, where all the frictional losses are grouped, etc. The use of lumped parameters allows the mathematical models of the systems to consist of ordinary differential equations, while if distributed parameters were used, the models would be in

partial differential form. Hence, throughout this report we will use the lumped parameter approach in our analysis and design of the control system.

## 2.2 Types of Control Systems =====

The objective of an automatic control system is to maintain the controlled variable or the output of the system equal to the desired value (set point) or to the input of the system. There are two different types of automatic control systems, namely "servomechanism" and "regulator", which are defined as follows:

### a. Servomechanism

A control system is said to be servomechanism type if the purpose of that system is to follow the changes of the set point as closely as possible. Typical applications of this type of control systems are seen in electrical and mechanical systems such as position control systems and valve positioners.

### b. Regulator

A control system is said to be regulator type, if the purpose of that system is to maintain the controlled variable or the output of the system, steady at the value set by the setpoint despite any disturbances imposed externally. Process control



systems are usually regarded as regulator type control systems.

A servomechanism type control system will generally not be well suited for a regulator type control system applications, therefore one must be well aware of the purpose of the control system beforehand.

In process control much more emphasis is placed on minimizing the variations of the controlled variable due to the disturbances, because a typical continuous process will operate with a constant set point for days at a time, and even if the set point is changed, the change is generally a minor adjustment. On the other hand, disturbances in the process such as uncontrolled flow rates, temperatures and pressures are more frequent and cause larger errors than the set point changes. Therefore, throughout this report, the control systems discussed will be the regulator type.

### 2.3 Dynamic and Transient Response =====

Regardless of how we classify a control system, the key to its performance is the manner in which it responds to the various kinds of disturbances imposed on it. Indeed, for all dynamic systems, the basis of analysis, is the behavior in time, of the principal time varying properties of the system following some manipulation of the system. This behavior is the "dynamic response" of the system. The

manipulation that causes the response is an input signal called the forcing variable.

For servomechanism, the forcing variable is the reference variable or the set point, and for the regulator it is the disturbance. The forcing variable and the controlled variable are functions of time which are uniquely related to each other by the characteristics of the control system.

The analysis problem for dynamic systems is concerned with determining the characteristics of the system from observed responses to particular forcing variables. On the other hand, the design problem involves choosing the characteristics of the system in such a manner that economically desirable responses are obtained for normal and typical forcing variables.

The dynamic response of a system to any forcing variable is made up of a steady-state part and a transient part. The initial and final (i.e. after a forcing variable has acted on the control system) steady-states are easily calculated by the algebraic equations of mass and energy balance of the control system. The transient part of the response is the dynamic behavior of the system between the initial and final steady states. The transient response provides a convenient and readily recognizable measure of the dynamic performance of the control system.

The transient response analysis of a control system must consider the dynamic behavior of the process and the control components in terms of their differential equations, and the overall behavior of a system that is described by a set of these equations and the relationship between them. The transient response will also depend on the type of forcing variable. Although in real life the forcing variable could be any type of time varying function, such as a step function, a ramp function, a pulse function, a steady-state sinusoid or any random function, but in process control system analysis and design only two of these types are more frequently used. The step function is used because the solutions for this type of forcing variables are easier to obtain than an other type, also because a step change in the forcing variable is the most severe type of disturbance. The second of forcing function most commonly used is the steady-state sinusoid because it is the basis of frequency response.

In this report, unless otherwise stated, all the forcing variables will be step functions.

CHAPTER 3  
=====

FEEDBACK CONTROL  
=====

3.1 The Conventional Regulating Loop  
=====

The basic control loop for regulating process disturbances is shown in Fig. 3.1.

The system shown consists of four major components:

1. The process to be controlled
2. The transducer which measures the controlled variable
3. The controller
4. The final control element, i.e. control valve or variable speed pump

All of the above mentioned components are non linear elements which are subject to many types of disturbances such as power supply disturbances, abrupt ambient condition changes, etc. The most critical disturbance that could upset the control system is the "process disturbance" which occurs near the output of the

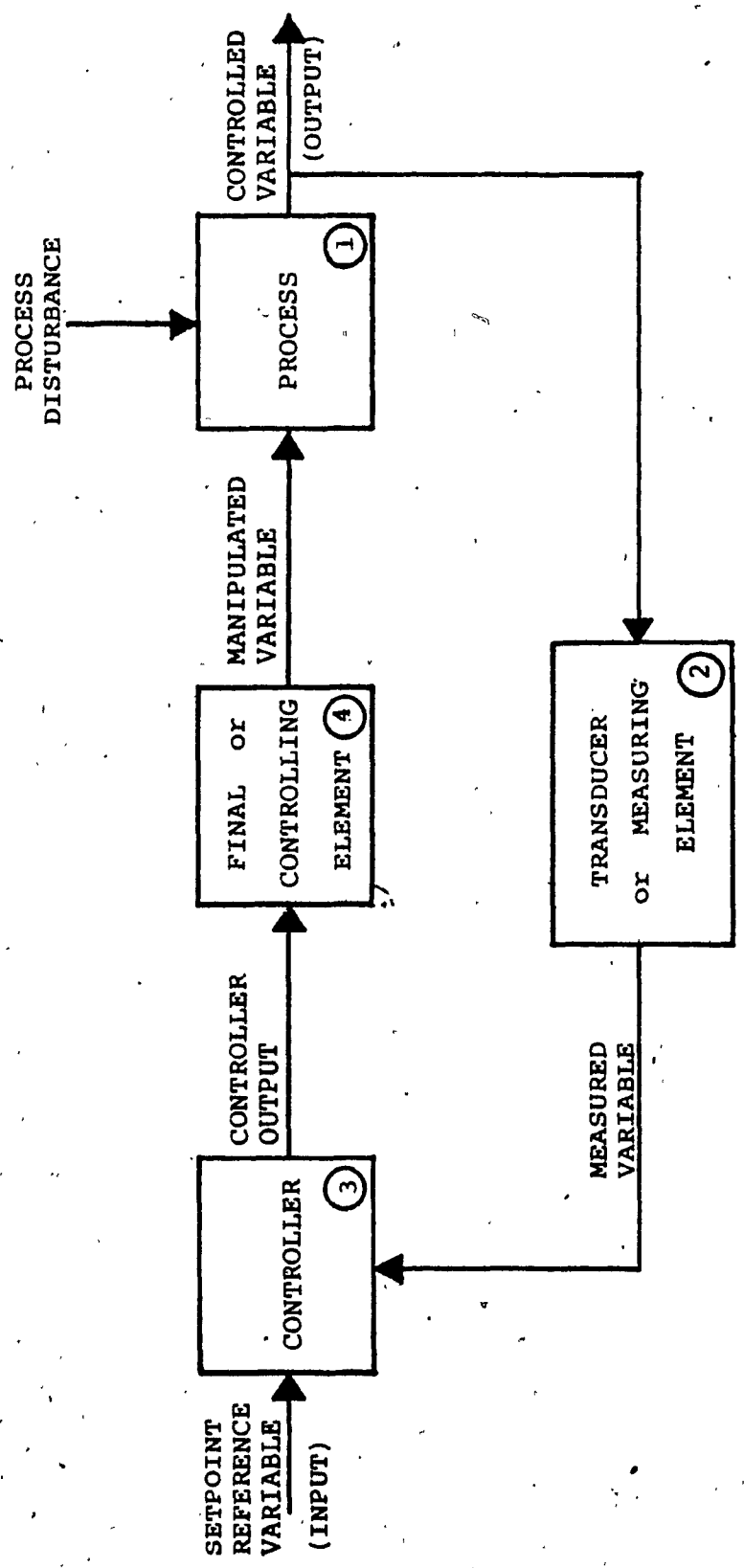


Figure 3.1.- The basic regulating loop

loop and is considered as a fluctuating random process.

Consideration of the nature of the behavior of the conventional loop indicates that a useful view point is to treat the regulation problem as a filtering problem [8]. Then depending on the spectrum of the disturbance, the regulating loop should be designed such that it could filter out the disturbance. Typically, if the disturbance is a step-like transient then the behavior of the controlled variable that is desired, is a rapid return to the setpoint with minimal overshoot. The key feature here is that the error should decay below a predetermined value very rapidly even though it does not tend to zero rapidly. On the other hand, if the disturbance spectrum is wide-band, the best that can be done is to make the process control loop behave like a low-pass filter. If the disturbance spectrum is limited to a narrow band around zero frequency, designing the loop to have high-pass characteristics will be successful. In practice, both approaches are used depending not only on the disturbance spectrum but also on the particular process being controlled.

It is clear from Fig. 3.1 that the basic regulating loop is a feedback control loop. It is called a feedback control loop since the controlled variable (output) is

measured and fed back to the controller where it is compared with the setpoint (input). If an error exists, the controller amplifies it with its control modes. The amplified signal then manipulates the final control element which in turn causes the process to be corrected. The error is reduced each time the signal makes the circuit of the complete control loop until it is either within prescribed limits or appreciably zero.

The above paragraph states the concept of feedback as it applies to the control of a process. But a more formal definition of feedback states that: feedback exists when an output variable depends on a variable that is itself a function of output and input.

If in Fig. 3.1 the feedback path is removed and the controlled variable (output) is not compared with setpoint (input) the result is an "open-loop", and if the disturbance was applied and the response of the control system was monitored, the result would have been the "open-loop response" of the system. The open-loop response is used for the design and transient response of the control system.

3.2      The Feedback Control Loop  
=====

The essential features of the elements of the feedback control loop can best be shown if the linearized (1) model of the basic control loop shown in Fig. 3.2 is examined.

In the diagram of Fig. 3.2

$r^{(2)}$  = the reference variable or the setpoint

$e$  = the error between the measured variable and setpoint ( $e = r - c_m$ )

---

(1) Although by nature, most systems are non linear, but the linearized and time invariant models are used so that we may be able to apply Laplace transforms to the differential equations by which the elements of the control loop will be represented.

(2) Throughout this report, the lower case letters designate the functions of time such as  $r(t), e(t)$ , etc. The upper case letters designate transformed variables such as  $G_c(s), G_v(s)$ , etc..., which are algebraic functions of  $s$ ,  $s$  being the Laplace operator. The reference to related functions will be dropped for simplicity. Upper case letters will also be used to represent constant values.



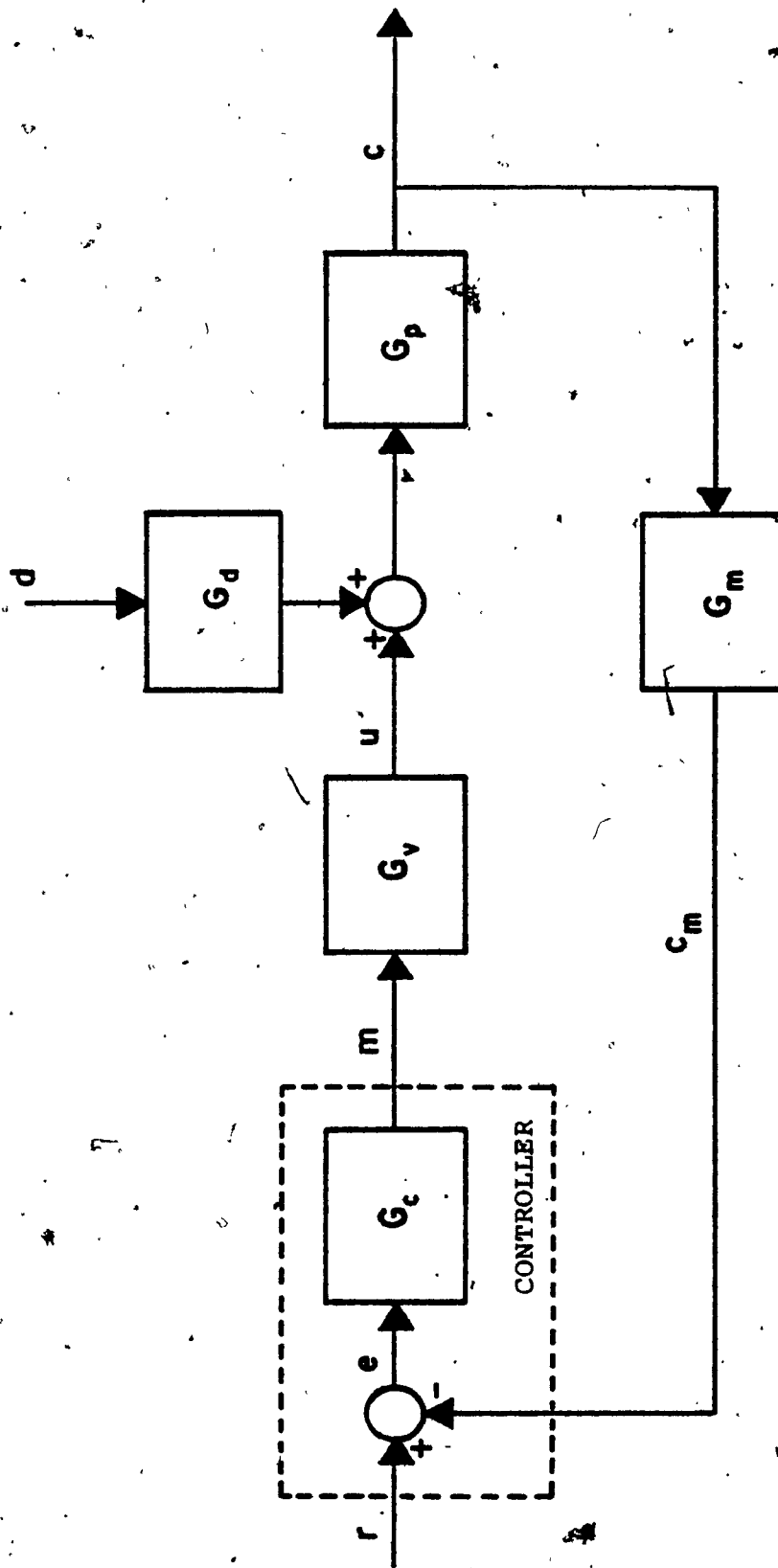


Figure 3.2.- Linearized model of basic control loop

- m = the controller output  
u = the manipulated variable  
d = the disturbance (all the disturbances are combined into an equivalent disturbance. This is possible in the linear systems)  
c = the controlled variable  
c<sub>m</sub> = the measurement variable  
G<sub>c</sub> = the controller transfer functions  
G<sub>v</sub> = the final control element transfer function  
G<sub>d</sub> = the disturbance transfer function  
G<sub>p</sub> = the process transfer function  
G<sub>m</sub> = the measuring element transfer function

The general equation for the response of closed-loop control is obtained by algebraic manipulation of the signals and the transfer functions of the block diagram representing that control loop.

Hence, for the block diagram of Fig. 3.2, we have:

$$c = (u + dG_d) G_p$$

$$\text{but since } u = mG_v$$

$$m = eG_c$$

$$e = r - c_m$$

$$c_m = cG_m$$

then  $e = r - cG_m$

$$m = (r - cG_m)G_c = rG_c - cG_mG_c$$

$$u = G_v(rG_c - cG_mG_c)$$

$$u = rG_cG_v - cG_mG_cG_v$$

$$c = rG_vG_cG_p - cG_mG_cG_vG_p + dG_dG_p$$

$$c(1 + G_mG_cG_vG_p) = rG_vG_cG_p + dG_dG_p$$

$$c = r(G_vG_cG_p)/(1 + G_mG_cG_vG_p) +$$

$$d(G_dG_p)/(1 + G_mG_cG_vG_p)$$

(3.1)

As defined above, the variables  $c$ ,  $r$  and  $d$  are time dependent variables of the output, the setpoint and the disturbance respectively. The response of the control loop for setpoint changes (servo-control) is obtained by letting  $d = 0$ . The transfer function of the control loop for setpoint change will then be:

$$c/r = (G_v G_c G_p) / (1 + G_m G_c G_v G_p) \quad (3.2)$$

The response for the disturbances (regulating) is obtained by letting  $r = 0$ . The transfer function of the control loop for the disturbances will then be:

$$c/d = (G_d G_p) / (1 + G_m G_c G_v G_p) \quad (3.3)$$

In order to evaluate the above two transfer functions we have to derive the transfer function of each elements.

### 3.3 Development of Transfer Functions =====

#### a. Process transfer function ( $G_p$ )

##### - Pure Capacitive process

Let us consider the storage tank of Fig. 3.3. Liquid enters the tank at a variable rate,  $f_i$  ( $\text{ft}^3/\text{s}$ ), but it is removed at a constant rate  $F_o$  ( $\text{ft}^3/\text{sec}$ ) by a constant displacement pump. The liquid level in the tank is  $h$  (ft). For the purpose of this discussion we assume the tank level,

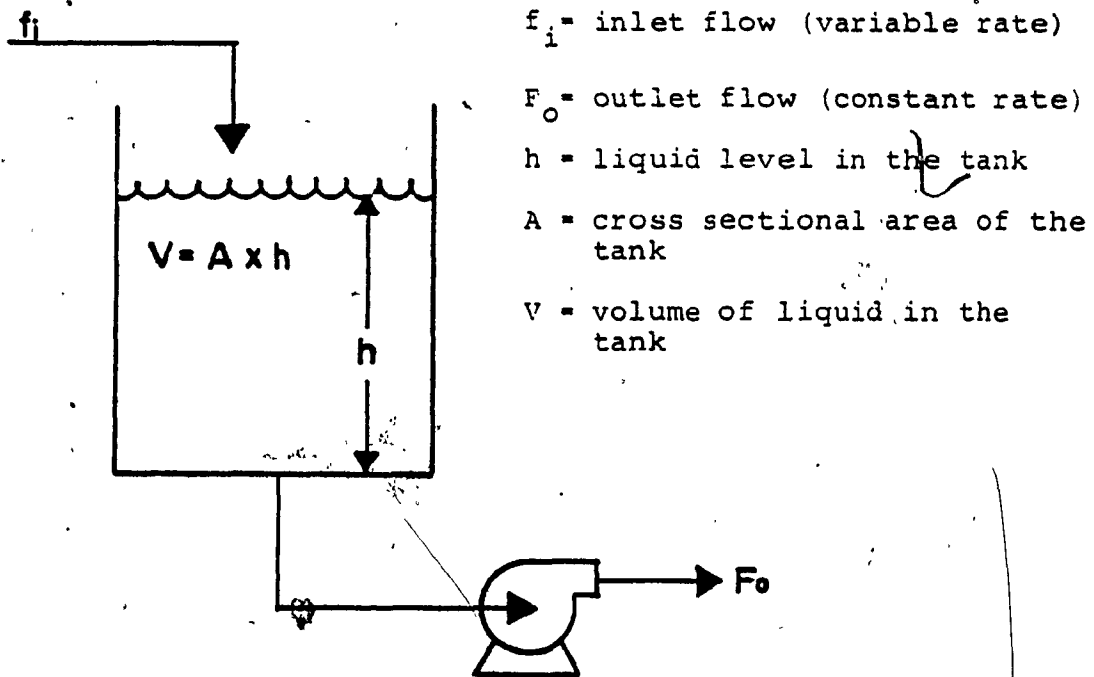


Figure 3.3.- Purely capacitive storage tank

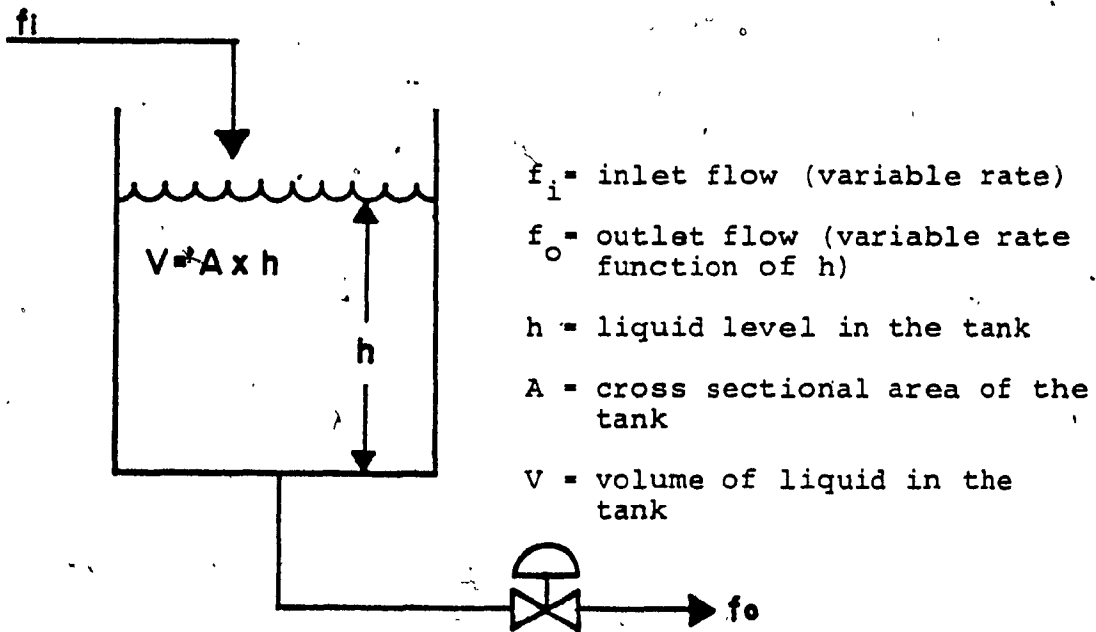


Figure 3.4.- First-order storage tank

$h$ , is measured and since the output is constant flow,  $F_o$ , then the problem is, to determine the response of liquid level,  $h$ , to changes in the inlet flow,  $f_i$ .

The transient response material balance gives:

$$f_i - F_o = dV/dt = A(dh/dt) \quad (3.4)$$

where  $V$  = Volume of the liquid in the tank ( $\text{ft}^3$ )

$A$  = Cross sectional area of the tank ( $\text{ft}^2$ )

Applying the Laplace transformation (and assuming the initial conditions to be equal to zero) Eq. 3.4 becomes:

$$F_i(s) = AsH(s) \quad (3.5)$$

Rearranging Eq. 3.5 (and dropping the reference to  $s$ ) gives:

$$H/F_i = 1/As \quad (3.6)$$

#### - First Order Process

A first order process is one that is satisfactorily modeled by a linear, first order differential equation. The general form of a first order differential equation is given by:

$$\tau(dy/dt) + y = Kx$$

where  $y$  = output or response variable  
 $x$  = input or forcing function  
 $\tau$  = time constant  
 $t$  = time  
 $k$  = gain factor

The transfer functions obtained by Laplace transformation with a zero initial condition is

$$\tau s Y(s) + Y(s) = KX(s)$$

$$Y(s) (\tau s + 1) = KX(s)$$

$$Y/X = K/(\tau s + 1) \quad (3.7)$$

Examining the dynamic behavior of the storage tank of Fig. 3.4 we see that unlike the purely capacitive storage tank discussed above the outlet flow rate,  $f_o$ , depends on the level,  $h$ , which is the driving force for flow through the exit line and the valve. Again the problem is to determine the response of level,  $h$ , to the changes in the inlet flow,  $f_i$ .

The transient response mass balance for the tank is given by:

$$f_i - f_o = A(dh/dt) \quad (3.8)$$

Since the outlet flow,  $f_o$ , is a function of level,  $h$ , it can be shown that:

$$f_o = h (\delta f_o / \delta h) \quad (3.9)$$

Substitution of Eq. 3.9 into Eq. 3.8 yields:

$$f_i - h (\delta f_o / \delta h) = A (dh/dt) \quad (3.10)$$

Equation 3.10 could be rearranged into the form:

$$[A / (\delta f_o / \delta h)] dh/dt + h = f_i (\delta h / \delta f_o) \quad (3.11)$$

Comparing equations 3.7 and 3.11, we find:

$$\tau = A / (\delta f_o / \delta h) = \text{Time constant}$$

$$K = \delta h / \delta f_o = \text{Gain factor}$$

Substitution of these factors and transformation of Eq. 3.11 gives:

$$(\tau s + 1)H(s) = K F_i(s) \quad \text{or}$$

$$H/F_i = K / (\tau s + 1) \quad (3.12)$$

Equation 3.12 indicates that the storage tank of Fig. 3.4 is a first order process.



Few, if any, real processes are truly first order, especially over wide ranges of operating conditions. However, for purposes of control system analysis and design, first order models may be perfectly satisfactory. Furthermore, they are the logical starting point for the development and understanding of more complex models.

In the development of a transfer function, a transient response balance is required - either a mass, an energy or a momentum balance. Only few problems in control involve momentum balances. The bulk of the problems involves mass and energy balances. The purpose of the control system will dictate whether the energy entering and leaving a system should be balanced or its mass.

#### - Second-order Process

A second order process is one that is described by a second-order differential equation. As it was true for first order process, second-order processes arise from particular combinations of passive elements.

The second-order differential equation is:

$$A (d^2y/dt^2) + B(dy/dt) + y = Kx$$

where  $y$  = output or response variable

$x$  = input or forcing function

$t$  = time

k = gain factor

A, B = coefficients (for this report they will be considered to be real constants only)

The transfer function is obtained by Laplace transformation with zero initial conditions:

$$As^2Y(s) + BsY(s) + Y(s) = KX(s)$$

$$Y(s) (As^2 + Bs + 1) = KX(s)$$

$$Y/X = K/(As^2 + Bs + 1)$$

There are three categories of second-order processes:

- i. inherently second-order
- ii. interacting second-order
- iii. noninteracting second-order

The derivation of the transfer functions for second-order systems are quite involved and tedious and since their derivation is not essential to the subject matter of this report they will be left out. An example of each category will be given with its transfer function. The derivation of these transfer functions could be found in [9].

### i. Inherently Second-Order Processes

Inherently second-order processes frequently arise in situations involving mechanical translation. The electrical analogy for this type of process is a circuit containing a capacitor, an inductor and some resistors. The mechanical parts of a pneumatic controller and those of a pneumatic control valve are examples of this kind of a process. The derivation of the transfer function of the pneumatic control valve will be shown later in this report.

### ii. Interacting Second-Order Processes

Referring to the two storage tanks shown Fig. 3.5 we see that the flow rate,  $f_2$ , depends on the difference in level between the two tanks, so the behavior of the first tank depends on the behavior of the second tank. And if we intend to find the relationship between inlet flowrate,  $f_1$ , and the level of the second tank,  $h_2$ , the transfer function is given by:

$$H_2/F_1 = R_2 / [\tau_1 \tau_2 s^2 + (\tau_1 + \tau_2 + R_2 C_1) s + 1] \quad (3.13)$$

where  $\tau_1 = R_1 C_1 =$  time constant of the first tank  
 $\tau_2 = R_2 C_2 =$  time constant of the second tank  
 $R_2 C_1 =$  interaction factor

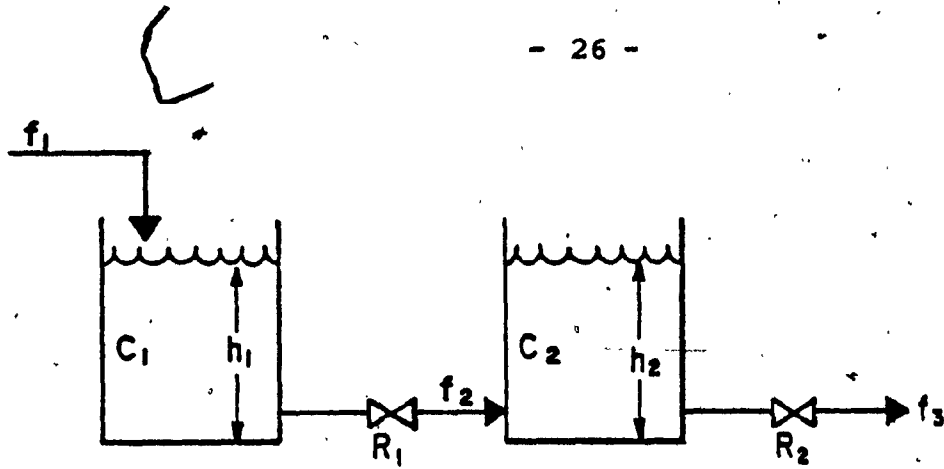


Figure 3.5.- Interacting storage tanks

$f_1$  = inlet flow rate

$C_1$  = capacity of first tank

$h_1$  = liquid level in first tank

$R_1$  = resistance at the outlet of first tank

$f_2$  = outlet flow rate for first tank

$C_2$  = capacity of second tank

$h_2$  = liquid level in second tank

$R_2$  = resistance at the outlet of second tank

$f_3$  = outlet flow rate

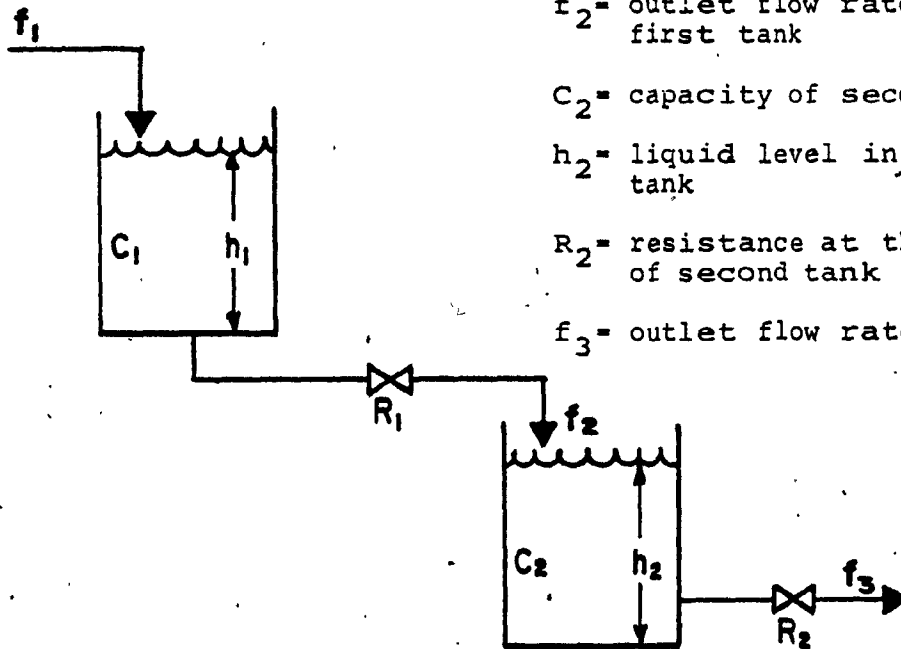


Figure 3.6.- Noninteracting storage tanks

iii. Non interacting Second-Order Processes

Referring to the two storage tanks of Fig 3.6 it is clear that the two storage tanks are not interacting, that is, the behavior of the first tank is completely independent of the behavior of the second. Again, if we intend to find the relationship between the inlet flow rate to the first tank,  $f_1$ , and the level of the second tank,  $h_2$ , the transfer function is given by:

$$\begin{aligned} H_2/F_1 &= R_2 / [(\tau_1 s + 1)(\tau_2 s + 1)] \\ &= R_2 / [\tau_1 \tau_2 s^2 + (\tau_1 + \tau_2) s + 1] \end{aligned} \quad (3.14)$$

where  $\tau_1$  and  $\tau_2$  are the time constant of the first and second tanks respectively.

b. Control Valve Transfer Function ( $G_v$ )

A typical single-seat, air-to-close type control valve is shown in Fig. 3.7 [9]. Since the mechanical part of the valve, involve a mass attached to a spring, second-order behavior is to be expected.

The analysis of the dynamic behavior of the valve centers around the application of Newton's Law to the stem position of the valve. There are five forces to consider.

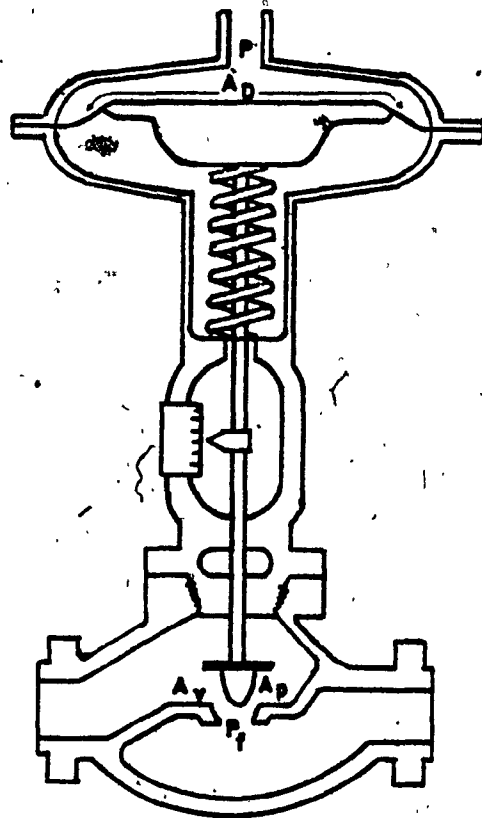


Figure 3.7.- Pneumatic control valve

Referring to the Fig. 3.7, the first downward force is exerted by the diaphragm on the stem. The air supplied by the controller output (assuming we were using a pneumatic controller) acts against this diaphragm. The second downward acting force is that of gravity, if the valve is mounted vertically.

The third force is that of the spring which acts upward and is proportional to the displacement,  $x$ . The fourth force, acting upward, is the so called "thrust force" provided by the pressure of the fluid acting against the area of the plug,  $A_p$ . The fifth force is frictional and arises mainly from the close contact between the stem and the valve packing. The frictional force is roughly proportional to the velocity of the stem,  $dx/dt$ .

In accordance with the Newton's Law, the equation for the stem is given by [9] (where downward direction is taken as positive):

$$pA_d - Kx - p_f A_p + Mg/g_c - R(dx/dt) = (M/g_c)(d^2x/dt^2) \quad (3.15)$$

where  $p$  = pressure into the valve's actuator, ( $lb_f/ft^2$ )

$p_f$  = fluid pressure at valve seat, ( $lb_f/ft^2$ )

$A_d$  = area of diaphragm, (ft<sup>2</sup>)

$K$  = spring constant, (lb<sub>f</sub>/ft)

$R$  = coefficient of friction between stem and  
packing, (lb<sub>f</sub> sec/eq)

$M$  = mass of the stem, (lb<sub>m</sub>)

$g$  = acceleration of gravity, (ft/sec<sup>2</sup>)

$g_c$  = conversion constant, (32.17 lb<sub>m</sub> ft/lb<sub>f</sub>sec<sup>2</sup>)

$x$  = stem position, (ft)

Possible input variables in Eq. 3.15 are the pressure in the valves actuator,  $p$ , and the pressure in the fluid at the valve seat,  $p_f$ . The equation is linear in these variables as well as in the dependent variable,  $x$ . Our interest is mainly in the transfer function,  $x/p$ , rather than  $x/p_f$ . Therefore, taking the term related to  $p_f$  to zero, and dropping the gravitational force term since it is constant, Eq. 3.15 is reduced to:

$$pA_d - Kx - R(dx/dt) = (M/g_c)(d^2 x/dt^2) \quad (3.16)$$

Rearranging Eq. 3.16 and applying Laplace



transformation with zero initial condition, the transfer function is obtained:

$$(M/g_c) s^2 X(s) + R s X(s) + K X(s) = A_d P(s)$$

$$X/P = (AD/K) / [(M/KG_c) s^2 + (R/K) s + 1] \quad (3.17)$$

From Eq. 3.17 it is clear that the mechanical behavior of the valve is second-order with the following natural frequency and damping factor:

$$\omega_n = \sqrt{Kg_c/M}$$
$$\zeta = \sqrt{(R/K)^2 / (4 (M/kg_c))}$$

In the above analysis the static frictional forces which cause hysteresis were neglected.

For small changes in the stem position, the change in area for flow,  $a_v$ , is linearly related to the change in stem position:

$$a_v = K_s x \quad (3.18)$$

Combining Eqs. 3.17 and 3.18, we get the transfer

function relating the change in valve flow area to the change in pressure to the actuator of the valve, which gives:

$$A_v/P = (KsA_d/K)/[(M/Kg_c)s^2 + (R/K)s + 1] \quad (3.19)$$

In derivation of the transfer function above, the dynamic behavior of the valve and that of the actuator were considered. In practice, a control valve includes other hardware as well, such as a positioner which is used to overcome the hysteresis effects of the valve, and a current to pneumatic (I/P) convertor which converts the current signal sent by electronic controllers, to the pneumatic signal required to activate the valves actuator.

Although the dynamic behavior of these elements could influence the behavior of the valve and the actuator, for the design and analysis of control systems, they are ignored and their behavior is lumped in the second-order representation of Eqs. 3.17 and 3.19.

Also, it is worth mentioning that with the recent energy conservation drive, alternative control elements such as variable speed pumps are being widely used. However for the purpose of this report energy conservation not being an issue, control valves will be considered as the only control elements.

c. The Measuring Element Transfer Function ( $G_m$ )

Although for each type of control variable there is a specific type of measuring and transmitting element, it will suffice to derive the transfer function of one of these types and use it as a model for the others.

Before the transfer function of the measuring element is derived, a rather special element associated with the measuring element will be introduced. This element is the "time delay", sometimes also referred to as "transport lag" or "dead time".

As an example to demonstrate the importance of time delay, we refer to inline blending system as shown in Fig. 3.8. Stream "A" and Stream "B" are combined in a mixing T at x and the composition is analyzed at y. The transportation time between x and y is  $\tau_d$ .

The relationship between x and y is:

$$y(t) = x(t - \tau_d)$$

Applying the Laplace transformation with zero initial condition, the transfer function of the time delay is given by:

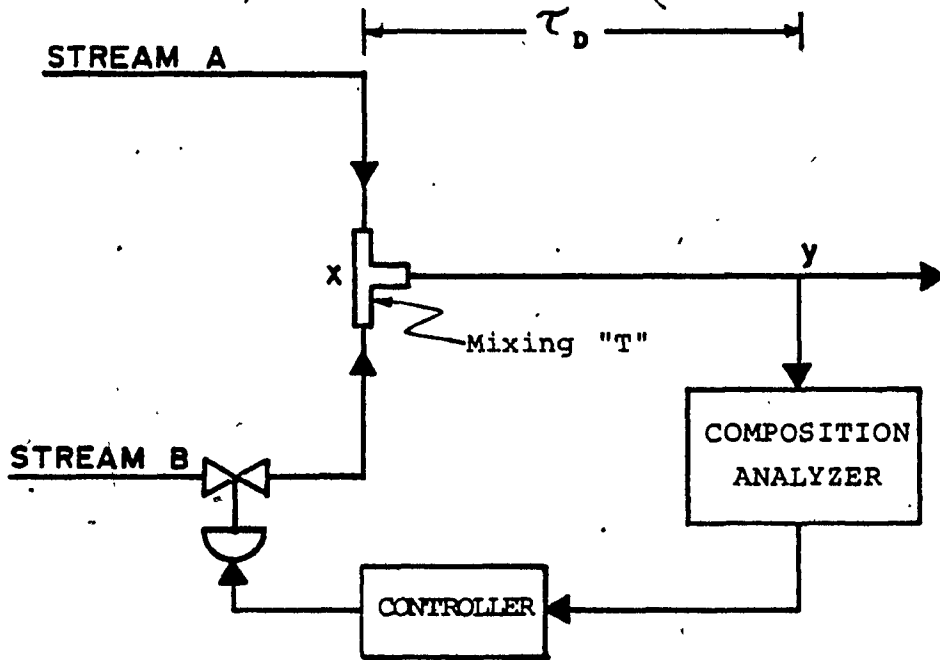


Figure 3.8.- Illustration of time delay

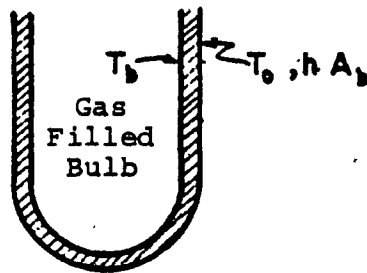


Figure 3.9.- Gas-filled temperature bulb

$$Y/X = e^{-\tau_d s} \quad (3.20)$$

Now the transfer function of a temperature measuring element will be developed.

Referring to Fig. 3.9, the energy balance of the temperature bulb is given by:

$$h A_v (T_o - T_b) = C_v (dt_b/dt)$$

where

$h$  = coefficient of the heat transfer,  
(Btu/hr, ft<sup>2</sup>, °F)

$A_b$  = surface area of the bulb, (ft<sup>2</sup>)

$C_b$  = heat capacitance of the bulb, (Btu/°F)

$T_o$  = outside temperature normally controlled  
variable temperature, (°F)

$T_b$  = bulb temperature, (°F)

Applying the Laplace transformation and rearranging the transfer function of the temperature measuring bulb is

obtained, that is:

$$T_b / T_o = 1 / (C_b / hA_b s + 1) \quad (3.21)$$

It is clear from Eq.3.21 that the measuring element could be represented by a first-order model. Although only the bulb was considered for the derivation of the transfer function, in general it also represents the transmitter, (especially if electronic transmitters are used) as well. If the measuring point is far from the actual process or if pneumatic type transmitters are used, then a time delay is added to the transfer function, giving:

$$T_b / T_o = (e^{-\tau_D s}) / (C_b / hA_b (s + 1)) \quad (3.22)$$

d. The Disturbance Transfer Function ( $G_d$ )

A storage tank with two outlets is shown in Fig. 3.10, where Valve No 1 is a pneumatically operated control valve and Valve No 2 is a hand operated valve which is kept normally closed. With Valve No 2 closed, the storage tank of Fig. 3.10 is the same as the storage tank shown in Fig. 3.4 with a transfer function given by Eq. 3.12.

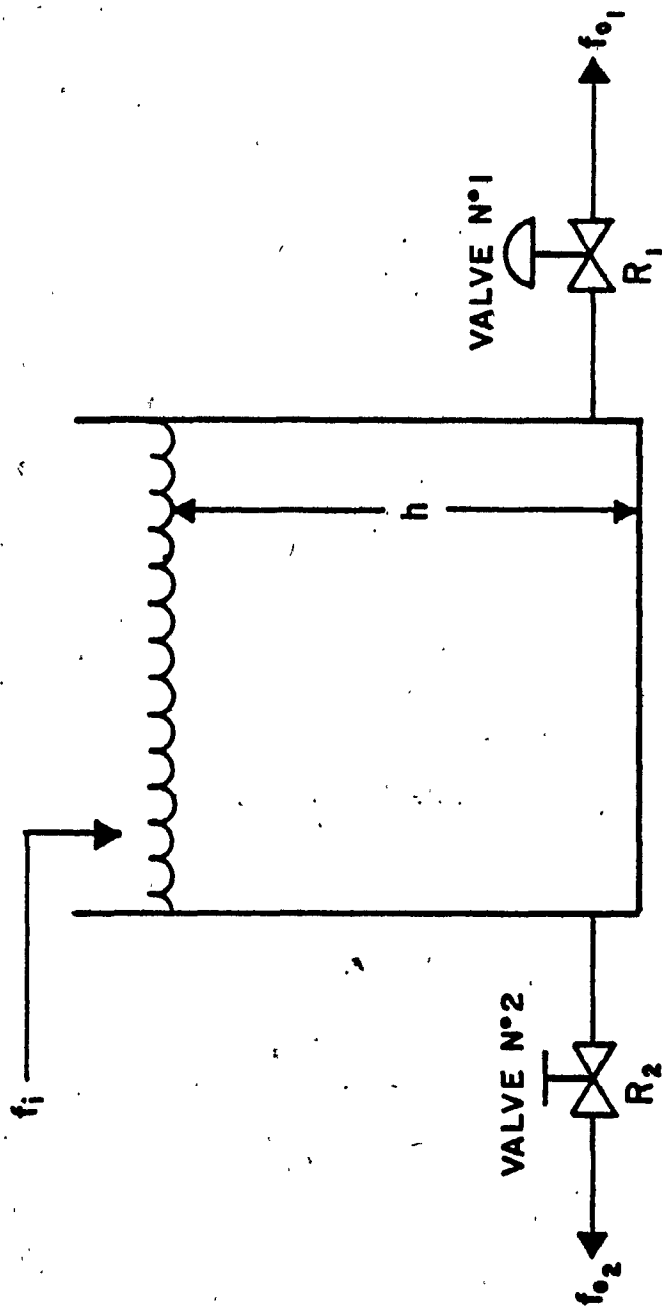


Figure 3.10.- Storage tank with two outlets

If at a given instant Valve No 2 is opened, and as long as the inflow rate  $f_i$  is not increased, the liquid level,  $h$ , will be upset and so will the outflow rate,  $f_{o1}$ .

The transient response mass balance will be:

$$f_i - f_{o1} - f_{o2} = A \, dh/dt \quad (3.23)$$

But from Eq. 3.9, we have:

$$f_{o1} = h \, \delta f_{o1} / \delta h \quad \text{and} \quad f_{o2} = h \, \delta f_{o2} / \delta h$$

Substituting the above equalities in Eq. 3.23, we get:

$$f_i - h(\delta f_{o1} / \delta h) - h(\delta f_{o2} / \delta h) = A(dh/dt) \quad (3.24)$$

To find the transfer function of the disturbance, the term  $f_{o2}/h$  is equated to zero. Eq. 3.24 is reduced to

$$f_i - h(\delta f_{o1} / \delta h) = A(dh/dt)$$

Rearranging the above equation and applying Laplace transformation with zero initial conditions, gives:



$$H/F_i = 1/(\tau s + 1) \quad (3.25)$$

where  $\tau$  = time constant =  $f_{O_2}/h$

Therefore, the transfer function of a disturbance has a first-order form also. Depending on the process conditions, this transfer function could be a constant or it could require a second-order form to satisfy the process requirements. Some process might have several sources of disturbances, each affecting the process in its own way. But for the design and analysis of a process, each disturbance and its effects are analyzed individually and are usually represented by a constant or in a first-order form.

e. The controller Transfer Function ( $G_c$ )

A controller consists of two parts: the comparator and the control card. The comparator takes the difference between the setpoint ( $r$ ) and the input signal (measured variable -  $c_m$ ) and generates the "error" signal ( $e$ ). This error signal is then acted upon by the control card (which contains the controller modes) and the appropriate controller output ( $m$ ) is produced. The equation for the comparator is given by:

$$e = r - c_m$$

There are three modes of continuous control, proportional, integral and derivative. These modes, or some combinations of them, are used in the process control. The choice of which mode or which combination of modes to be used in the controller of a given control loop is based on the characteristic or the requirements of that loop.

The following is a brief description of each mode and some of the most commonly used combinations. Their transfer function will be shown and some comments on their applications will be made.

i. Proportional (P)

The basic continuous control mode is proportional control in which the controller output is algebraically proportional to the error. The controller output is calculated as:

$$m = K_C e \quad (3.26)$$

where  $K_C$  = controller gain or also known as proportional sensitivity

On most industrial controllers, the gain  $K_C$  is not

adjusted directly. The adjustment is done in terms of "proportional band" (PB) which is defined as:

$$PB = 100(1/K_C)$$

The simple block diagram model of the controller is shown in Table 3.1.

Proportional control provides stability, very rapid response, and dynamically is relatively stable. The only disadvantage that the proportional control has, is the fact that at steady state, it produces an "offset", i.e. there is a difference at steady state between the setpoint and the controlled valve.

ii. Integral (I)

With integral control the controller output (m) is proportional to the integral of the error (e). That is:

$$m = (1/T_I) \int edt$$

or  $M/E = 1/(T_I s)$  (3.27)

where  $T_I$  = integral time (sec.)

In effect, this means that in integral control, the value of the controller output (m) is changed at a rate

CONTROL MODE	OUTPUT EQUATION	TRANSFER FUNCTION	TYPICAL RESPONSE TO CHANGES IN ERROR
Proportional (P)	$m = K_C e$	$M = K_C \frac{E}{E}$	<p>Slope = <math>E_r</math></p> <p>← slope = <math>K_C E_r</math></p>
Integral (I)	$m = \frac{1}{T_I} \int e dt$	$M = \frac{1}{T_I} \frac{E}{E}$	<p>Slope = <math>E_r</math></p> <p>← Eq. = <math>E_r t^2 / T_I</math></p>
Derivative (D)	$m = T_D \frac{de}{dt}$	$M = T_D \frac{E}{E}$	<p>Slope = <math>E_r</math></p> <p>← <math>T_D E_r</math></p>
Proportional-Integral (P+I)	$m = K_C (e + \frac{1}{T_I} \int e dt)$	$M = K_C \left[ 1 + \frac{1}{T_I s} \right] \frac{E}{E}$	<p>Slope = <math>K_C E_r t / T_I</math></p> <p>← <math>K_C E_r</math></p>
Proportional-Plus-Derivative (P+D)	$m = K_C (e + T_D \frac{de}{dt})$	$M = K_C [1 + T_D s] \frac{E}{E}$	<p>Slope = <math>K_C E_r</math></p> <p>← <math>K_C E_r t + K_C T_D E_r</math></p>
Proportional-Integral-Plus-Derivative (P+I+D)	$m = K_C (e + \frac{1}{T_I} \int e dt + T_D \frac{de}{dt})$	$M = K_C \left[ 1 + \frac{1}{T_I s} + T_D s \right] \frac{E}{E}$	<p>Slope = <math>E_r</math></p> <p>← Eq. = <math>K_C E_r t^2 / T_I + E_r t</math></p> <p>← <math>K_C E_r t + K_C T_D E_r</math></p>

TABLE 3.1 - Typical Response of Controller Modes

proportional to the error (e). The simple block diagram model of the controller is shown in Table 3.1.

There is no offset with integral control since the controller output keeps changing until the error is reduced to zero. This is a very important aspect of integral control, but its inclusion in a control loop reduces the stability of the loop. One exception to this is the liquid flow control loops. Since liquid flow loops are extremely fast and quite often tend to be noisy, integral control is often added to these control loops to provide filtering action for the loop.

It is possible to use integral control by itself but this is not a common practice. It is combined with proportional control to incorporate the advantage of both modes.

iii. Derivative (D)

With derivative control, the controller output (m) is proportional to the rate of change of the error signal (e). That is:

$$M = T_D (de/dt)$$

or  $M/E = T_D s$  (3.28)

where  $T_D$  = derivative time (sec.).

The simple block diagram model of the controller is shown in Table 3.1.

Although it is theoretically possible to have a control system based solely on the derivative control, it is not practical because, while the error might be huge, if it was not changing, the controller output (m) will be equal to zero. Thus derivative control is usually found in combination with proportional control.

By adding derivative control to the controller, lead is added in the controller to compensate for lag around the loop. Almost any process has lag around the loop, but since derivative control is difficult to implement and adjust, its usage is limited to cases in which there is an extensive amount of lag in the process, such as large temperature control systems.

iv. Proportional-Plus-Integral (P+I)

The output of a proportional-plus-integral (P+I) is given by:

$$M = K_C [e + (1/T_I) \int edt ]$$

or  $M/E = K_C [1 + (1/(T_I s))]$  (3.29)

The simple block diagram model of the controller is shown in Table 3.1.

The advantage of combining proportional and integral controls is that the integral control eliminates the offset created by proportional control, but on the other hand it reduces the stability of the total control loop.

v. Proportional-Plus-Derivative (P+D)

The output of a proportional-plus-derivative (PD) is given by:

$$M = K_C [e + T_D (de/dt)]$$

or  $M / E = K_C (1 + T_D s)$  (3.30)

Refer to Table 3.1 for the block diagram model of the proportional-plus-derivative control.

As discussed in section (iii) above, the combination of proportional-plus-derivative controls reduce the lag time around the control loop. The other advantage of this combination is that it increases the stability of the loop. And since the loop is more stable, the proportional gain may be increased and thus decreasing the offset generated by the proportional control.

vi. Proportional-Plus-Integral-Plus-Derivative (P+I+D)

Proportional-plus-integral-plus-derivative control, (P+I+D) or sometimes referred to as the three mode control is

the most sophisticated control mode available in feedback loops. Its output is given by:

$$M = K_C [e + (1/T_I) \int e dt + T_D (de/dt)]$$

or  $M/E = K_C [ 1 + (1/T_I s) + T_D s ] \quad (3.31)$

The response of the three mode control is very rapid and exhibits no offsets, but it is very difficult to tune.

As a result, it is used only in a very small number of applications, but once it is properly tuned it offers a very good control.

Refer to Table 3.1 for the block diagram model of the three mode control.

### 3.4 Advantages and Disadvantages of Feedback Control

The concept of feedback control and its application are relatively simple. Most problems that arise in feedback control applications are problems associated with the tuning of the controller and the compatibility of various measured or generated signals.

A big advantage of feedback control is that there is little need to know much about the internal workings of



the process beyond that of the proper variable to accomplish the end result. An error takes place due to unknown or unmeasurable factors in the process, and the correction is made externally to the process. For this reason, feedback control finds wide application in process control, especially where process dynamics are not completely known. Also, the end result is achieved economically without elaborate equipment.

The other advantage of feedback control is that it continually updates the control signal as the process changes not only due to major disturbances but also to long range changes such as variations in ambient conditions, deviations from set conditions, or the wear of equipment.

Accuracy of the feedback control system is not of prime importance as long as the controlled variable is repeatable in the same magnitude each time an error occurs. The only time that accuracy is important would be if safety considerations require a careful setting of the limits of control, or if the process data are collected to calculate the efficiency of a given process.

There are two main disadvantages to feedback control systems, and in some systems these disadvantages are serious enough that feedback control may not be satisfactory. One of these disadvantages is obvious, the control system does not and cannot take corrective action to

a system upset until after it has caused the control variable to deviate from its desired value. That is to say, the control system does not act until after the input disturbance has caused an error to exist within the control loop.

The second disadvantage is really a result of the first - any corrective action that the system takes is not felt until after the changing conditions have been propagated around the entire loop, i.e. through each time lag in the loop. This means that not only must the controlled variable deviate from its desired value, but also, corrective action will lag in its effect because of signal propagation around the control loop. In most process control applications these two disadvantages are acceptable, but there are situations in which they are not acceptable - either from a practical or an economical view point.

Because of its characteristics, feedback control is often referred to as compensatory control.

An alternate approach to feedback control problem is not to feed back any value of the controlled variable, but instead, to regulate all inputs into the system. Since there are no feedback paths, this style of control is referred to as feedforward control. In the following section, feedforward control will be studied in detail.

CHAPTER 4  
=====

FEEDFORWARD CONTROL  
=====

4.1 Justification Of Feedforward Control  
=====

The nature of the process largely determines how well it can be controlled. Processes which cannot be controlled well because of their difficult nature are very susceptible to disturbances from load or setpoint changes. When a difficult process is expected to respond well to either of these disturbances, feedback control may no longer be satisfactory for the following reasons:

- a. The nature of feedback implies that there must be a measurable error to generate a restoring force, hence perfect control is unobtainable. In steady state, the controller output will be proportional to the disturbance. When the disturbance occurs, the controller output must change. In going from one steady state output to another, proportional and derivative modes of the controller offer no contribution. Consequently, the net change in output has been shown to be a function of the integrated error.

Any combination of wide band and long reset time (characteristic of difficult processes) results in a severe integrated error per unit disturbance.

b. The feedback controller does not know what its output should be for any given set of conditions, so it changes its output until the measured variable and the setpoint are in agreement.

c. Any feedback loop has a characteristic natural period. Should disturbances occur at intervals less than certain number of periods (some say less than 3 periods) [10], it is evident that no steady state will ever be reached.

There is a way of solving the control problem directly and this is called "feedforward control". The principal factors affecting the process are measured and, along with the setpoint, are used in computing the correct output to meet current conditions. Whenever a disturbance occurs, corrective action starts immediately, to cancel the disturbance before it affects the controlled variable. Feedforward is theoretically capable of perfect control, notwithstanding the difficulty of the process, its performance only being limited by the accuracy of the measurements and computations.

4.2 The Basic Feedforward Control Loop  
=====

A simplified diagram illustrating the arrangement of the feedforward control system is shown in Fig. 4.1. Its essential feature is the forward flow of information. The controlled variable is not used by the control system, because this would constitute feedback; this point is important since it shows how it is possible to control a variable without having a continuous measurement of it available. The setpoint, however, is essential because any control needs a command to give it direction.

Although a single controlled variable is shown in Fig. 4.1, any number may be accommodated in one feedforward control system. Similarly, although only one disturbance is shown, but usually any number of disturbances significantly affecting the process may be used in solving for the controller output and eventually the manipulated variable.

In practice, the feedforward control system directly balances the material or energy delivered to the process against the demands of the load. Consequently, the computations made by the control system are material and energy balances of the process, and manipulated variables must therefore be accurately regulated flow rates.

The control system should be programmed to maintain

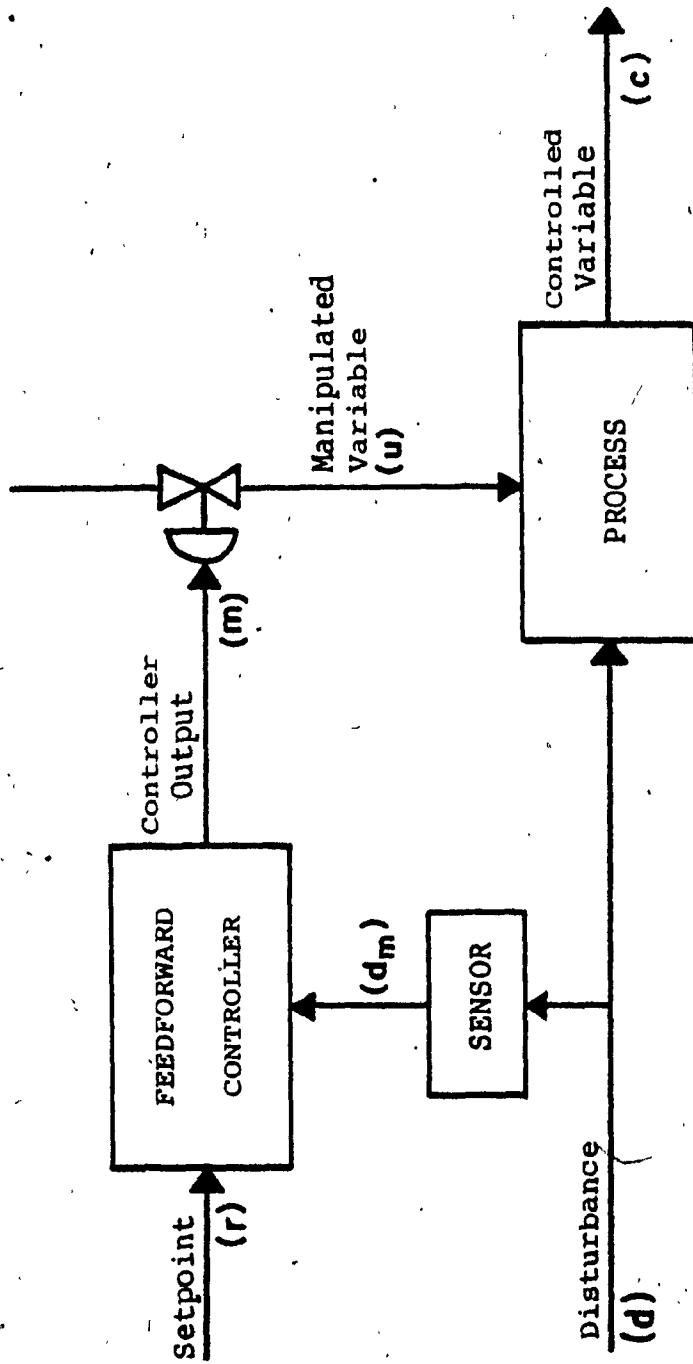


Figure 4.1.- Feedforward control system

the process balance in the steady state and also in transient intervals between steady states. It must consist of both steady state and dynamic components, like the process.

If the steady state calculations are correct, the controlled variable will be at the setpoint as long as the load is steady. If the calculations are in error, an offset will result, which may change with the load. If no dynamic calculations are made, or if they are incorrect, the measurement will deviate from the setpoint while the load is changing, and for some time thereafter, while new material or energy levels are being established in the process. If both the steady state and dynamic calculations are perfect, the process will be continually in balance, and no deviation will be measurable at any time.

In design of the feedforward control system the process model is reversed, that is, the manipulated variables are solved in terms of load components and controlled variables. In the system equations the setpoint should be inserted in the place of controlled variables since the intent of a feedforward control system is to force the process to respond as it was designed, i.e. to follow the setpoints as directed without regard to load upsets.

### 4.3 Theory of Feedforward Control

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Since the purpose of feedforward control is to move the manipulated variable to cancel out the effects of a disturbance before it can upset the process, then feedforward control is really an inverse model of the process. It is possible, however, to structure feedforward control in a more general sense. A generalized feedforward control loop is shown in Fig. 4.2, where:

$r$  = the setpoint

$m$  = the controller output

$u$  = the manipulated variable

$d$  = the disturbance or the load

$d_m$  = the measured variable

$c$  = the controlled variable

$G_{cf}$  = the feedforward controller transfer function

$G_v$  = the final control element transfer function

$G_m$  = the measuring element transfer function

$G_u$  and  $G_d$  = the process transfer function

From Fig. 4.2 we have:

$$c = uG_u - dG_d \quad (4.1)$$



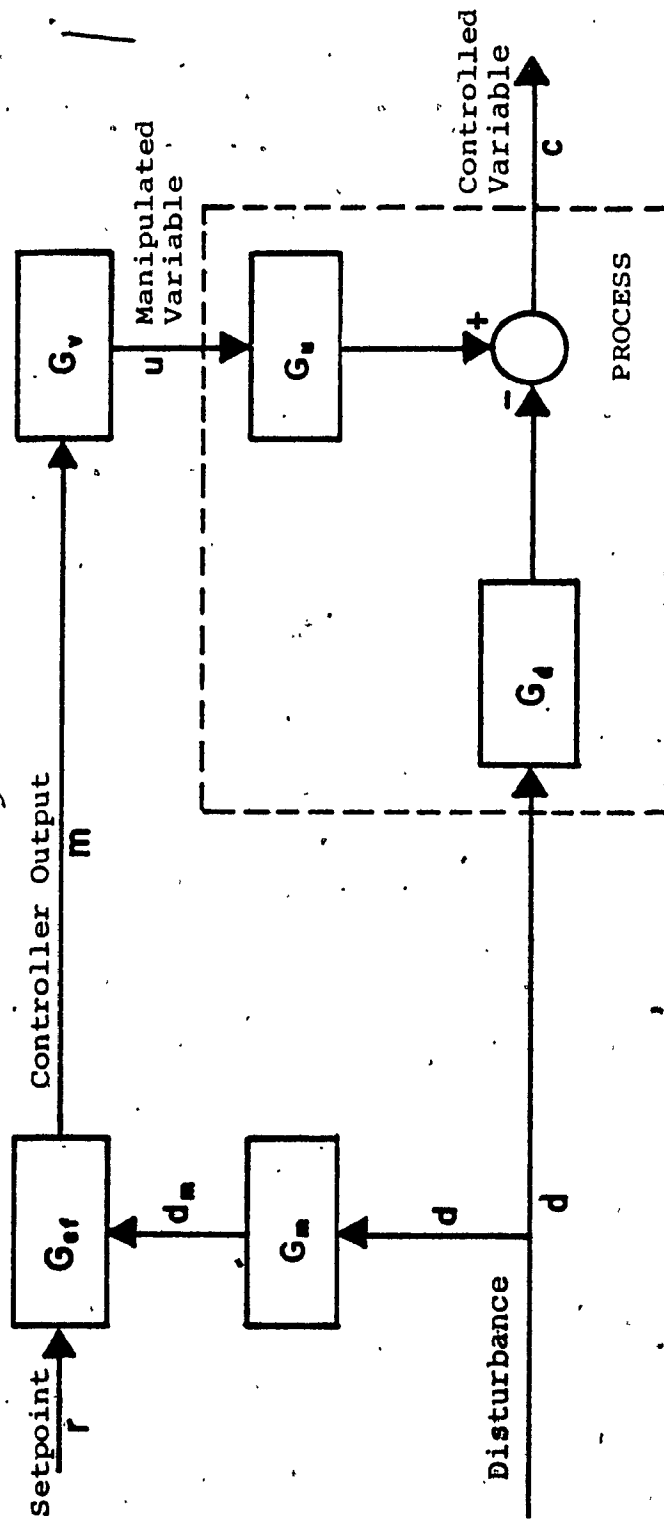


Figure 4.2.- Generalized feedforward control block diagram

In the above relationship,  $G_u$  and  $G_d$  are process transfer functions and are defined as follows:

$$C/U = G_u \quad \text{and} \quad C/D = G_d$$

Each of the above transfer functions has a steady state component  $z$ , and a dynamic component  $w$ , that is:

$$G_u = z_u \cdot w_u \quad \text{and} \quad G_d = z_d \cdot w_d \quad (4.2)$$

Purpose of the feedforward controller is to maintain the controlled variable  $c$  equal to setpoint  $r$ , i.e.,  $c = r$ . Then Eq. 4.1 becomes:

$$r = uG_u - dG_d \quad (4.3)$$

From the diagram of Fig. 4.2, we know that:

$$u = mG_v$$

But for the purpose of the present discussion, the transfer function of the final control element,  $G_v$ , could be equated to unity,  $G_v = 1$ , consequently  $u = m$ . Then Eq. 4.3 becomes:

$$r = mG_u - dG_d \quad (4.4)$$

Rearranging Eq. 4.4 we get:

$$m = (r + dG_d) / G_u \quad (4.5)$$

Equation 4.5 represents the output of the feedforward controller for any disturbance or setpoint.

As previously mentioned, if the feedforward controller is a model of the process, this model should be as perfect as possible to minimize drift or long term deviation. The model should also be able to achieve the desired response,  $c = r$ , even in the transient state.

In the Eq. 4.5 if the transfer functions,  $G_u$  and  $G_d$  are replaced with their steady-state components only, then Eq. 4.5 becomes:

$$m = (r + dz_d) / z_u \quad (4.6)$$

Substituting Eqs. 4.6 and 4.2 into Eq. 4.1,

$$c = [(r + dz_d) / z_u] z_u w_u - dz_d w_d$$

$$c = r w_u + dz_d w_u - dz_d w_d$$

$$c = r w_u + dz_d (w_u - w_d) \quad (4.7)$$

The Eq. 4.7 gives the controlled variable,  $c$ , in terms of upsets in the setpoint,  $r$ , and the disturbance,  $d$ . This is a type of "steady-state" feedforward control. The reaction of the controlled variable,  $c$ , to variations in the setpoint,  $r$ , is derived by letting  $d = 0$  in Eq. 4.7, which reduces to:

$$c = rw_u$$

or in Laplace transform form:

$$C(s)/R(s) = W_u(s) \quad (4.8)$$

The Eq. 4.8 above indicates that the reaction of the controlled variable to the setpoint change is limited to the dynamic component,  $W_u(s)$ , which is characteristic of open loop response.

The reaction of the controlled variable to a disturbance,  $d$ , is given by letting  $r = 0$  in Eq. 4.7, which reduces to:

$$c = dz_d (w_u - w_d)$$

or in the Laplace transform form:

$$C(s)/D(s) = z_d (W_u(s) - W_d(s)) \quad (4.9)$$

It is evident from Eq. 4.9 that a disturbance,  $d$ , produces transient deviation represented by the difference between the dynamic components,  $W_u(s)$  and  $W_d(s)$ . This difference approaches zero as time approaches zero (initial steady-state) or infinity (final steady-state). Often this transient deviation is not zero but small enough that it is neglected or it is reduced to zero by a simple correction known as dynamic compensation.

#### 4.4 The Dynamic Compensation

The ideal model of feedforward control system requires that dynamic compensation be applied to both input and output of the feedforward controller.

Substituting Eq. 4.2 into Eq. 4.5 gives

$$m = (r + dz_d w_d) / (z_u w_u) \quad (4.10)$$

The use of a model such as Eq. 4.10 is troublesome, however, it necessitates two dynamic elements in the hardware of the feedforward controller (this problem is somewhat less critical in present day microprocessor based controllers). A more practical version of Eq. 4.10 can be obtained by considering an approximation in which the

dynamic elements are grouped together. This approximation is given by:

$$m = [(r + dz_d)/z_u](w_d/w_u) \quad (4.11)$$

which is the practical dynamic model of the feedforward controller.

Substituting Eq. 4.11 into Eq. 4.1, the output of the control system is obtained:

$$c = [(r + dz_d)/z_u][w_d/w_u] z_u w_u - dz_d w_d$$

$$\dot{c} = r w_d + d z_d w_d - dz_d w_d$$

$$c = r w_d \quad (4.12)$$

The relationship in Eq. 4.12 indicates that the transient response is due only to setpoint changes.

Having grouped the dynamic function, further simplifications could be made. The dynamic elements extracted in Eq. 4.11 are correct dynamic elements for the system transfer functions  $G_u(s)$  and  $G_d(s)$ . Instead of using these exact dynamic components, it is possible to use approximations of them and still obtain very good results.

Even though these are approximations, they can be expected to give better results than the steady state feedforward control model. If first order lags are used for these dynamic approximations, the dynamic components would take the lead/lag form.

$$\begin{aligned} W_D(s)/W_U(s) &= [1/(1 + \tau_2 s)]/[1/(1 + \tau_1 s)] \\ &= (1 + \tau_1 s)/(1 + \tau_2 s) \end{aligned} \quad (4.13)$$

where  $\tau_1$  is the lead time and  $\tau_2$  is the lag time. If  $\tau_1$  is greater than  $\tau_2$  the response of the lead/lag unit will have an overshoot to a step response, while if  $\tau_2$  is greater than  $\tau_1$  its response will have an undershoot.

It is also worth mentioning that, because the feedforward loop exhibits no oscillatory tendencies, sinusoidal response of the feedforward control loop has no meaning but a step response is quite significant, since it constitutes the most severe test of system performance. Also the response of systems under feedforward control, both with and without dynamic compensation, differs markedly from that experienced with feedback control as will be evident in the next chapter.

#### 4.5 Combined Feedforward and Feedback Control

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One of the disadvantages of the feedforward control is its dependency on accuracy. To provide perfect control, a system must model the plant exactly; otherwise whatever error may exist in positioning the manipulated variable causes offset. Sources of this error are many. The most important of them are:

- i. Inaccuracies in the computing components of the feedforward controller
- ii. Inaccuracies in the measurement of the disturbance and the manipulated variable
- iii. Failure of the feedforward control system to adequately represent the characteristics of the process
- iv. Exclusion of significant disturbance components from the feedforward system

The first two items above limit the accuracy of practical systems to the vicinity of 1 to 2 percent [1].

Some processes are easy to model, but others, particularly those where mass and energy transfer coefficients must be used over a wide range of operating conditions, are not so simple. Therefore item (iii) may be



of considerable importance in the more complicated processes.

The feedforward system cannot be all-inclusive. Some disturbances, such as heat losses and ambient temperature effects are so slight, invariant, or not well defined that their inclusion in the control loop will only complicate the control system with no measurable improvements.

If the offset is intolerable, some means must be provided for adjustments while the system is still operating. The direct way of adjusting is by changing the setpoint, which is already scaled in terms of the controlled variable. Other adjustments could also be made but with less predictable results.

Regardless which parameter is trimmed to remove the offset, the procedure amounts to manual feedback. Automatic feedback is perfectly capable of effecting the same result.

Because the prime purpose of feedback is to eliminate offset, a proportional control will not suffice. Integral mode is obviously necessary. Whether proportional and derivative modes are useful or not depends on the nature of the process. If the disturbance variations are rapid, proportional and derivative actions could be advantageous. If the process is fundamentally non-self-regulating, as in the level control, proportional control is essential.

Finally, if the process is fairly easy to control because of the absence of dead time, derivation may be useful in improving the dynamic response. It is also worth mentioning, that the inclusion of feedback can be detrimental by promoting oscillation in an otherwise stable system. To this extent, the settings of the feedback controller, regardless of what modes have been selected, ought to be relaxed.

The proper application of feedback control is very important. The feedback controller may be asked to perform a number of different services, such as adjusting the zero, or the span or the linearity of the control loop. But a single feedback controller can hardly be called upon to do all these things.

When no one source of offset is outstanding, the argument for readjusting the setpoint of the feedforward controller is irresistible. This arrangement is shown in the block diagram form in Fig. 4.3.

The interesting feature of this configuration is that it displays the inherent inaccuracies of the feedforward loop. The difference between the setpoint and the output of the feedback controller is the offset which would have appeared if feedback had not been used.

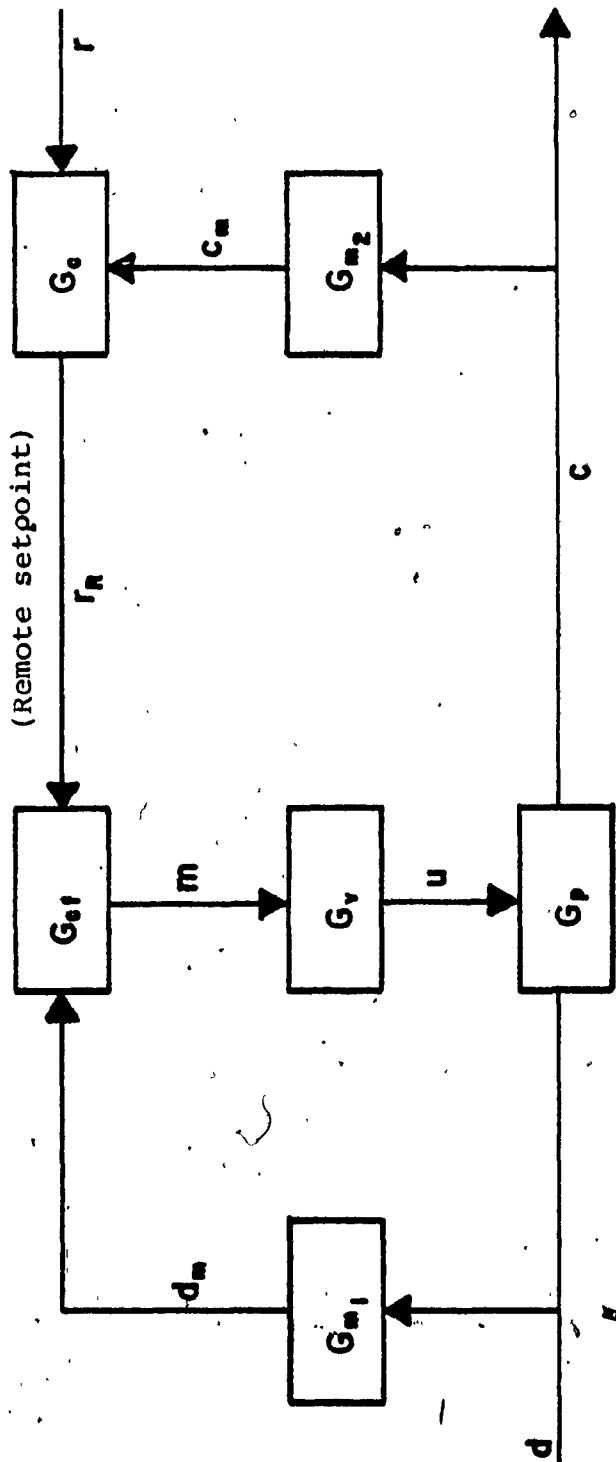


Figure 4.3.- Block diagram of feedforward-feedback combination

CHAPTER 5

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REAL PROCESS APPLICATIONS

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5.1 Choice of the Process

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To evaluate the actual performance of a control system, it has to be applied to control an actual process. For the purpose of this report, the selected process should be the type that could be controlled as well, by a feedback or a feedforward control system. One such process, which could react satisfactorily to feedback control as well as to feedforward control, is the heat exchanger. Heat exchangers are simple and fast, yet sufficiently difficult process to control, therefore they are ideal to demonstrate the performance of feedback and feedforward control systems.

Heat exchanger parameters are distributed and interacting. The exact dynamic equations for an ordinary heat exchanger are quite complex and their derivation require lengthy calculations. But in general, simplified methods of dynamic analysis give results that are fairly accurate except where a very close control is needed. For example, in a counter current heat exchanger the temperature on both sides of the tube varies with length, but when the flow rate of one of the fluids is much higher than that of the other, an approximate behavior can be predicted by

assuming the temperature on one side of the tube to be constant.

The most common type of heat exchangers used in the process industry is the tubular type. This type includes double-pipe exchangers, shell-and-tube exchangers, condensers, kettles with cooling coils and tubular furnaces. The characteristic feature of these exchangers is that the capacities on one or both sides are distributed along the length of the exchanger.

Being interested in its overall behavior only, the heat exchanger could be considered as being a lumped heat balance process. Further simplifications could be achieved by making certain assumptions such as, no tube wall resistance, no capacity in the condensate film, no backmixing, no axial mixing and constant fluid properties. After applying all the above simplifications, a simple model for the heat exchanger could be found.

## 5.2 Modelling the Heat Exchanger =====

Consider the shell-and-tube type steam-water heat exchanger shown in Fig. 5.1. Here the object is to regulate the process fluid (water) outlet temperature,  $\theta_o$ , by manipulating the flow rate of steam,  $f_s$ . Typical

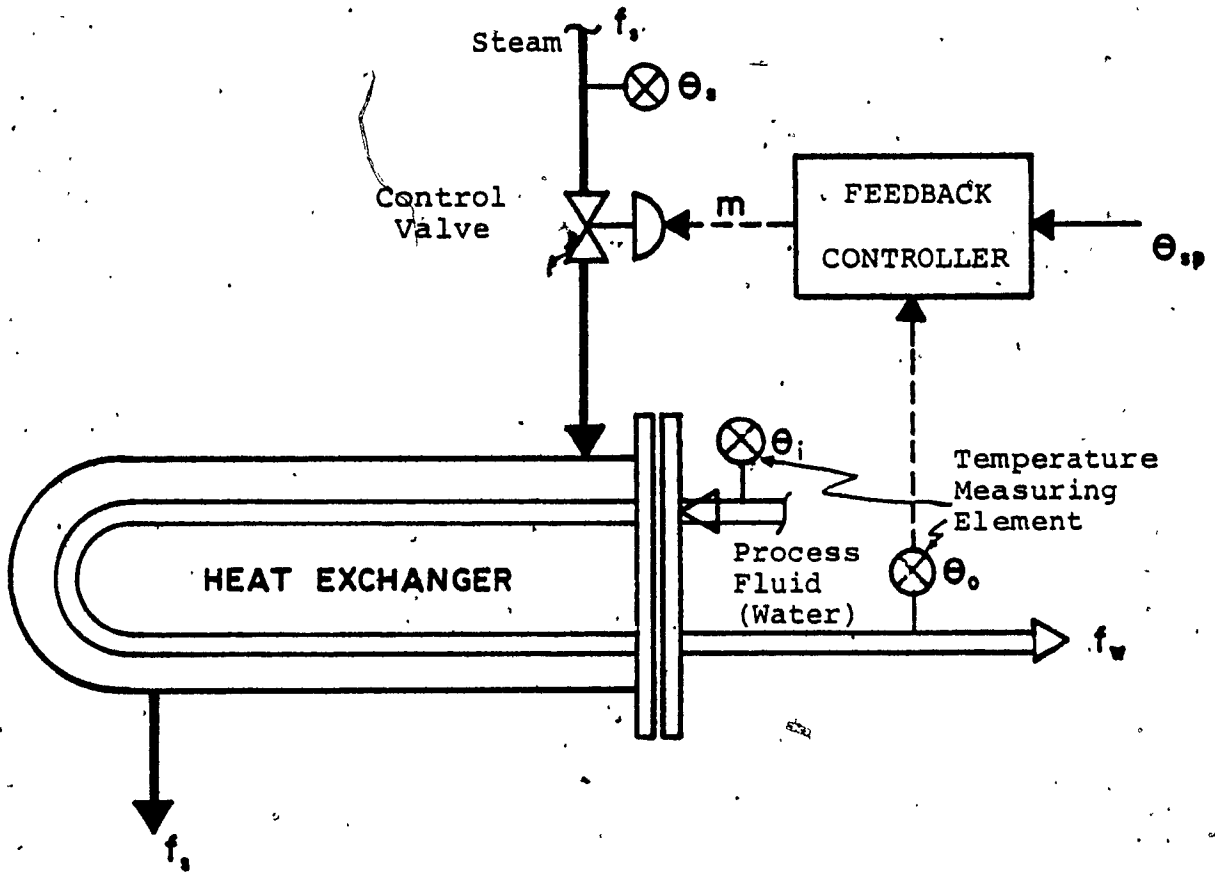


Figure 5.1.- Shell-and-tube heat exchanger

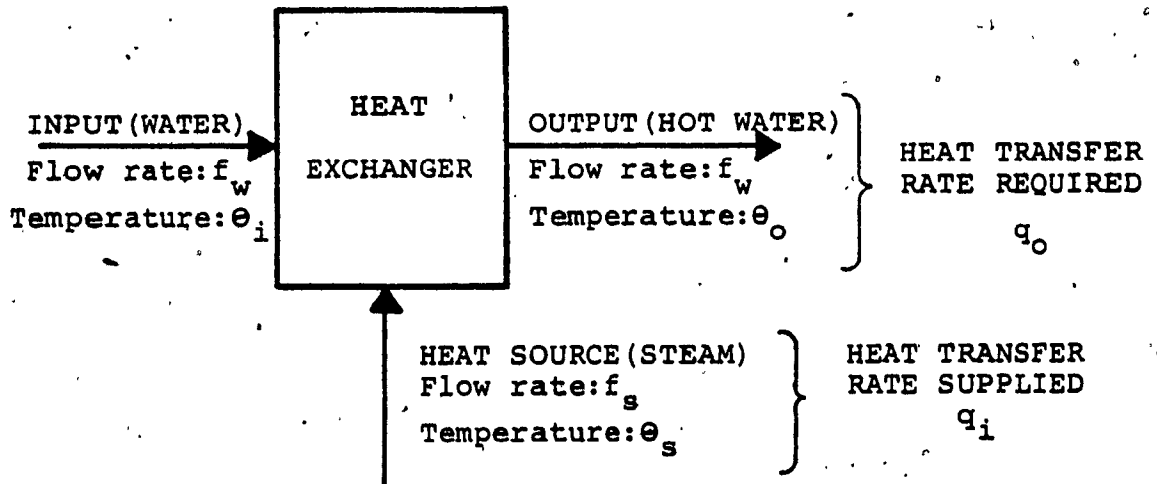


Figure 5.2.- Heat balance of exchanger

disturbances are the process fluid inlet temperature,  $\theta_i$ , the steam temperature,  $\theta_s$ , and the water flow rate,  $f_w$ . The first two of these disturbances, namely  $\theta_i$  and  $\theta_s$  vary slowly and present no difficulty to the control system. Therefore, the major disturbance is the fluctuations in the flow rate of water,  $f_w$ .

a. Steady-state equations

Figure 5.2 shows in block diagram form the heat balance of the heat exchanger.

From Figure 5.2 required heat transfer rate is given by:

$$q_o = f_w C_p (\theta_o - \theta_i) \quad (5.1)$$

where  $f_w$  = process fluid (water) flow rate (ft<sup>3</sup>/sec.)

$C_p$  = heat capacity of the process liquid (Btu/lb°F)

$q_o$  = required heat transfer rate (Btu/sec)

$\theta_o$  = outlet process fluid temperature (°F)

$\theta_i$  = inlet process fluid temperature (°F)

also from Fig. 5.2 supplied heat transfer rate is given by:

$$q_i = H_s f_s \quad (5.2)$$

where  $q_i$  = supplied heat transfer rate (Btu/sec)

$H_s$  = latent heat of the steam (Btu/lb)

$f_s$  = flow rate of steam (lb/sec)

At steady state both of these heat transfer rates,  $q_i$  and  $q_o$ , should be equal (neglecting all losses), that is:

$$q_i = q_o$$

or

$$H_s f_s = f_w C_p (\theta_o - \theta_i) \quad (5.3)$$

Rearranging Eq. 5.3 gives:

$$f_s = f_w (C_p / H_s) (\theta_o - \theta_i) \quad (5.4)$$

Assuming that  $\theta_i$  remains constant, and differentiating (partial differentiation) Eq. 5.4 with respect to  $\theta_o$  gives:



$$\Delta f_s / \Delta \theta_o = f_w (C_p / H_s) \quad (5.5)$$

Putting Eq. 5.5 in the difference form, and inverting

$$\theta_o / f_s = (H_s / C_p) / f_w \quad (5.6)$$

b. Dynamic Equations

The transient response energy balance is given by:

$$H_s f_s + f_w C_p (\theta_i - \theta_o) = M_w C_p (d\theta_o / dt) \quad (5.7)$$

where  $M_w$  = mass of fluid (lb)

Rearranging Eq. 5.7 and assuming  $f_w$  to be constant =  $F_w$  gives:

$$(M_w / F_w) (d\theta_o / dt) + \theta_o = (H_s / f_w C_p) f_s + \theta_i \quad (5.8)$$

Applying the Laplace transform with zero initial condition gives:

$$(M_w / F_w) s \theta_o(s) + \theta_o(s) = (H_s / f_w C_p) F_s(s) + \theta_i(s) \quad (5.9)$$

The pertinent transfer functions are:

$$\theta_o(s)/\theta_s(s) = K_p/(\tau_p s + 1) \quad (5.10)$$

$$\theta_o(s)/\theta_i(s) = 1/(\tau_p s + 1) \quad (5.11)$$

where  $\tau_p = M_w/F_w$  and

$$K_p = H_s/(f_w C_p)$$

### 5.3. Feedback Control of the Heat Exchanger

A block diagram of the feedback control system of a heat exchanger is shown in Fig. 5.3, where

$G_c$  = controller transfer function.

$G_v$  = valve transfer function

$G_p$  = process transfer function

$G_d$  = disturbance transfer function

$G_m$  = measuring element transfer function

To analyze the performance of this feedback control system one merely has to derive the above transfer functions.

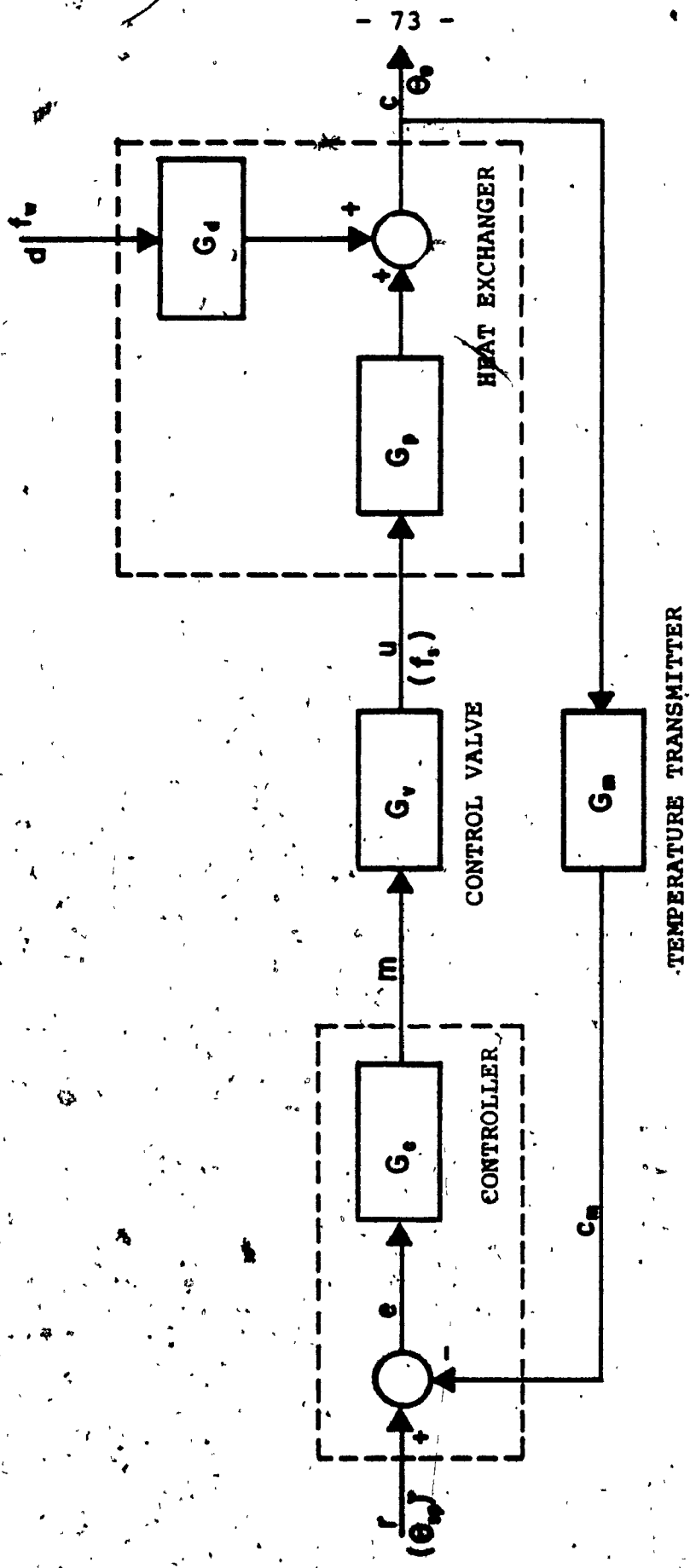


Figure 5.3.- Block diagram of feedback control of heat exchanger

Assuming that the valve and measuring element transfer functions are first-order lag and first-order lag with a time delay respectively, that is:

$$G_v = U(s)/M(s) = K_v / (\tau_v s + 1) \quad (5.12)$$

and

$$G_m = C_m(s)/C(s) = (K_m e^{-\tau_d s}) (\tau_m s + 1) \quad (5.13)$$

The controller is assumed to be equipped with P+I+D control modes whose transfer functions is given by:

$$G_c = M(s)/E(s) = K_C [1 + 1/T_I s + T_D s] \quad (5.14)$$

The process transfer function is given by Eq. 5.10:

$$G_p = \theta_o(s)/F_s(s) = K_p / (\tau_p s + 1) \quad (5.15)$$

The disturbance transfer function is given by:

$$G_d = \theta_o(s)/F_w(s) \quad (5.16)$$

The derivation of these transfer functions is quite complex and requires lengthy calculations, but for the present analysis of the control system, it could be

approximated by first-order lag with a time delay (time delay is added to take into consideration the time it takes for the disturbance to affect the output temperature), that is:

$$G_d = \theta_o(s)/F_w(s) = (K_d e^{-\tau_b s}) / (\tau_d s + 1) \quad (5.17)$$

where

$K_d = \delta \theta_o / \delta F_w$  of the steady-state equation (Eq. 5.3) at steady-state operating  $F_s$  and  $F_w$

$$K_d = (H_s F_s) / (F_w^2 C_p)$$

$\tau_d =$  time delay

$\tau_d \ll \tau_p$  (disturbance being flow loop its dynamics are very fast)

From the block diagram of Fig. 5.3 the overall transfer function for servo-control (setpoint changes) is given by:

$$C(s)/R(s) = (G_c G_v G_p) / (1 + G_m G_c G_v G_p) \quad (5.18)$$

and the overall transfer function of regulator (load

changes or disturbances) is given by:

$$C(s)/D(s) = G_d / (1 + G_m G_c G_v G_p) \quad (5.19)$$

#### 5.4 Feedforward Control of the Heat Exchanger \*\*\*\*\*

If the feedback control of the heat exchanger of Fig. 5.1 is replaced by a feedforward control system, the Fig. 5.1 should be modified slightly to the one shown in Fig. 5.4.

The block diagram of the feedforward control is shown in Fig. 5.5. The transfer functions  $G_v$ ,  $G_p$  and  $G_d$  are given by Eqs. 5.12, 5.16 and 5.17 respectively. The measuring element transfer function  $G_m$  could be assumed to be a first-order lag, that is:

$$G_m = K_m / (\tau_m s + 1) \quad (5.20)$$

where  $\tau_m \ll \tau_p$  (since the measurement taken is that of a flow rate)

The transfer function of the feedforward controller  $G_{cf}$  depends on the type of control applied.

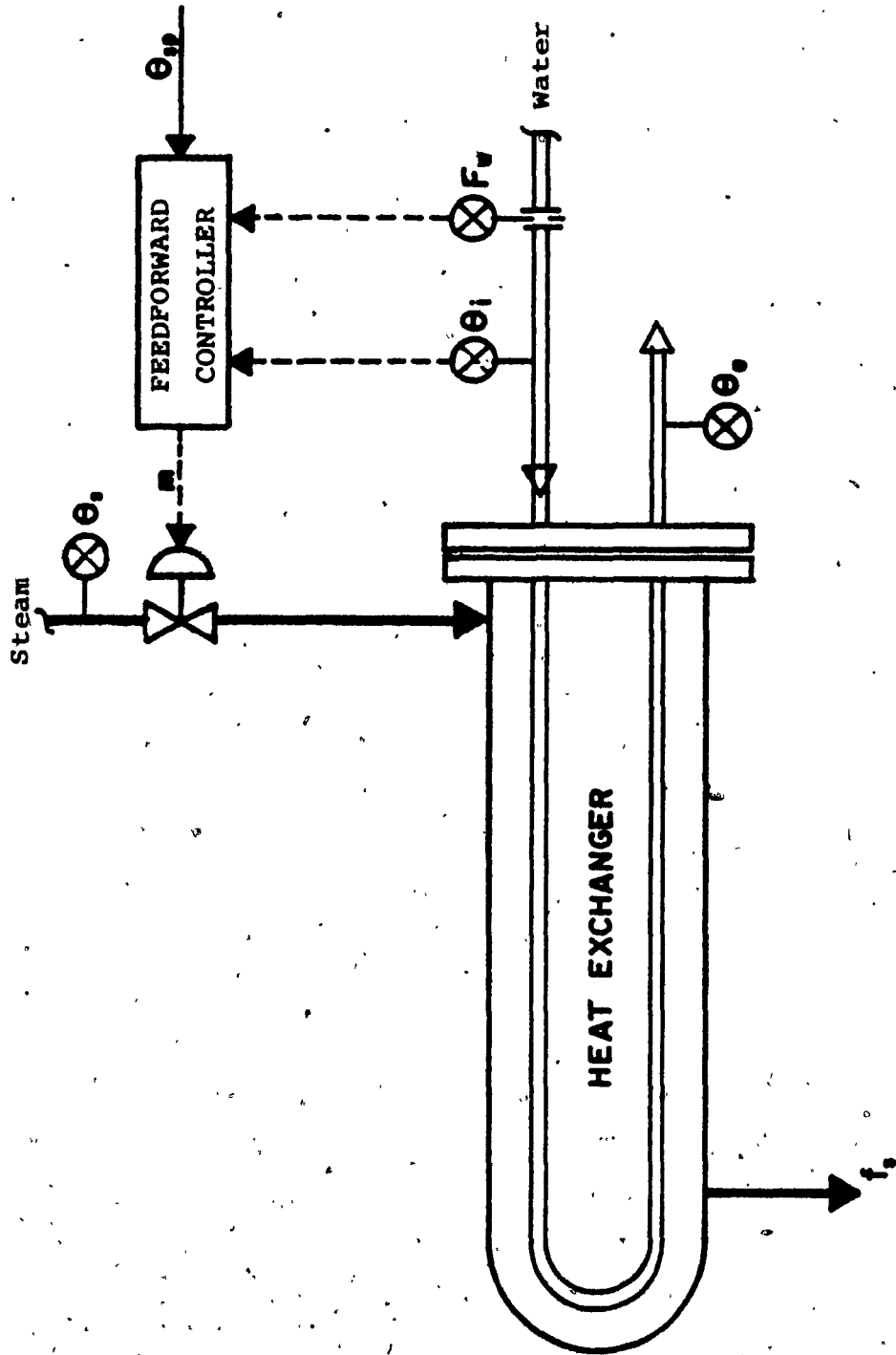


Figure 5.4.- Feedforward control of heat exchanger

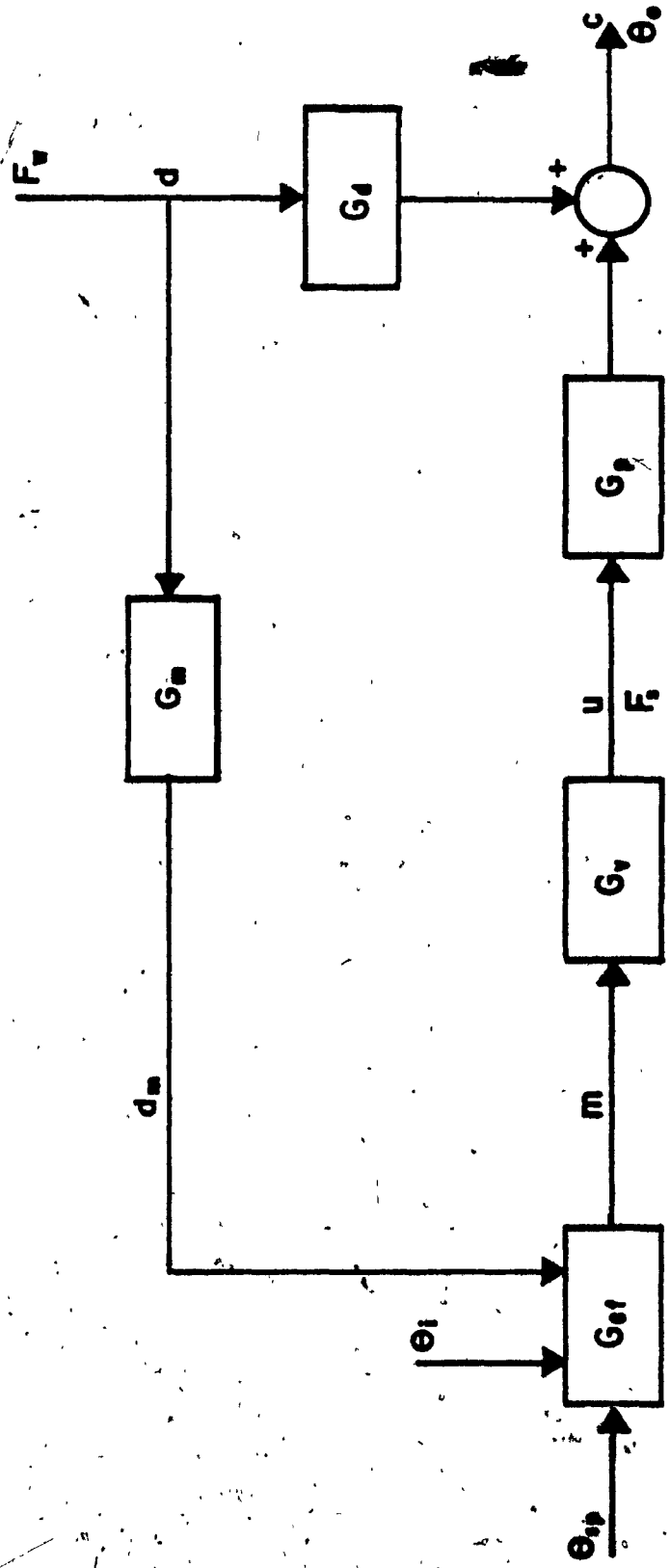


Figure 5.5.- Block diagram of feedforward control of heat exchanger.



a. Steady-state feedforward control

The steady-state equation of the heat exchanger is given by Eq. 5.3 which was rearranged in Eq. 5.4 to give

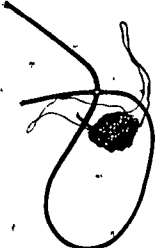
$$f_s = f_w (C_p/H_s) (\theta_i - \theta_o)$$

Since the output temperature,  $\theta_o$  should be equal to setpoint temperature,  $\theta_{sp}$ , and since the feedforward controller should be a model of the process it controls, then the transfer function of the steady-state feedforward controller is given by

$$G_{cf} = f_s (C_p/H_s) (\theta_i - \theta_{sp}) \quad (5.21)$$

b. Dynamic feedforward control

The transfer function of the dynamic feedforward controller is given by:


$$G_{cf} = [f_w (C_p/H_s) (\theta_i - \theta_{sp}) (\tau_1 s + 1)] / (\tau_2 s + 1) \quad (5.22)$$

where the term  $(\tau_1 s + 1) / (\tau_2 s + 1)$  is the lead-lag component for the dynamic feedforward control.

5.5 **Feedforward-feedback Control of Heat Exchanger**  
=====

A feedforward-feedback control system of the heat exchanger is shown in Fig. 5.6 where a feedback loop is added to the basic feedforward control loop to continuously adjust or finetune the setpoint of the feedforward controller.

The block diagram of the feedforward-feedback control is shown in Fig. 5.7. The transfer functions  $G_{cf}$ ,  $G_{m1}$ ,  $G_v$ , and  $G_p$ , are given by Eqs. 5.21 or 5.22, 5.12, 5.16, 5.17 and 5.20 respectively. The transfer functions of feedback loop, namely  $G_c$  and  $G_{m2}$  are given by Eqs. 5.14 and 5.13 respectively.

5.6 **The Numerical Example**  
=====

a. Physical aspects and operating conditions

The shell-and-tube heat exchanger considered has the following characteristics:

- Shell

Outside diameter = 1.5 feet = 18 inches

Inside diameter = 1.42 feet = 17 inches

Overall length = 4 feet = 48 inches

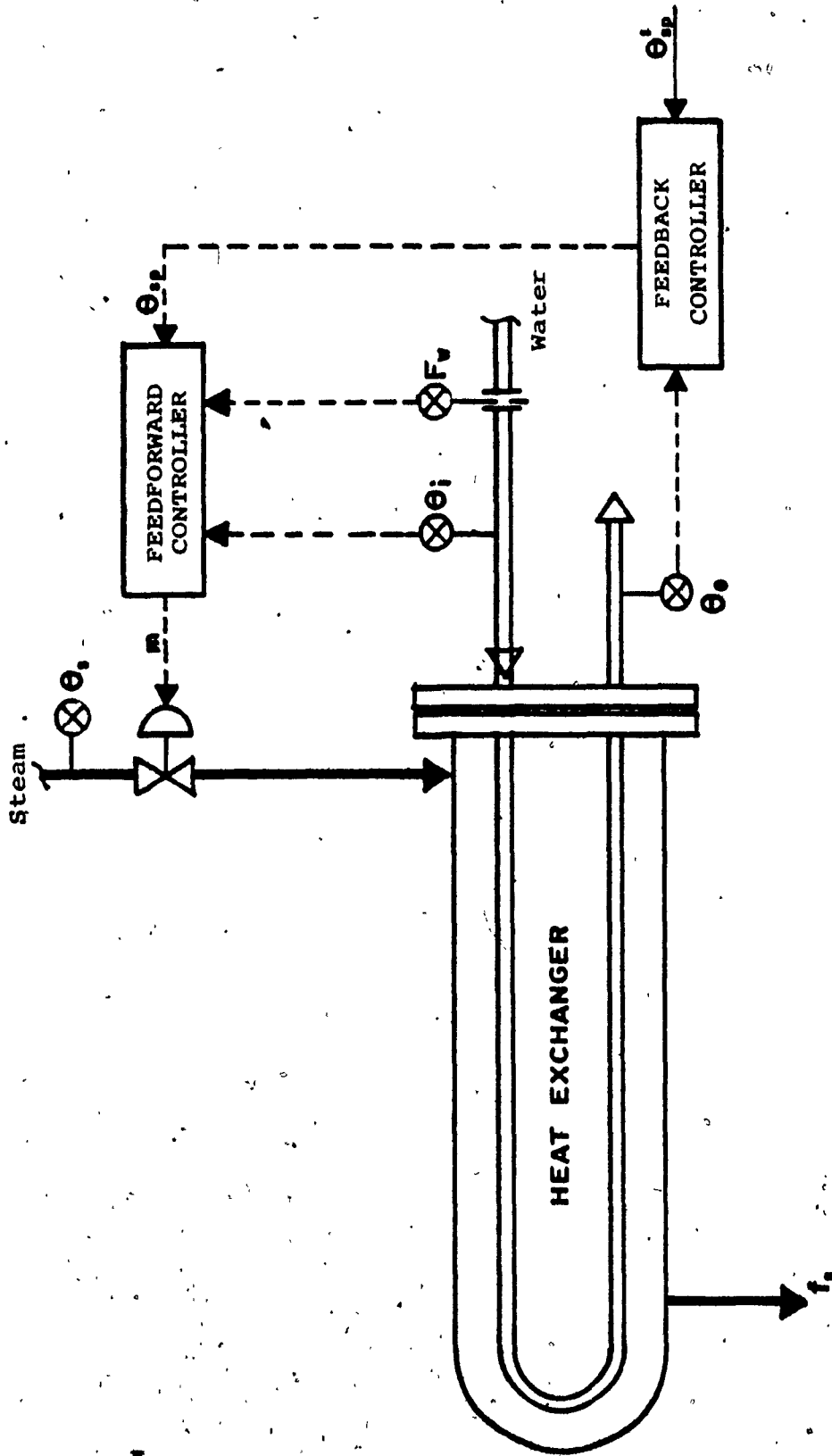


Figure 5.6.—Feedforward-feedback control of the heat exchanger

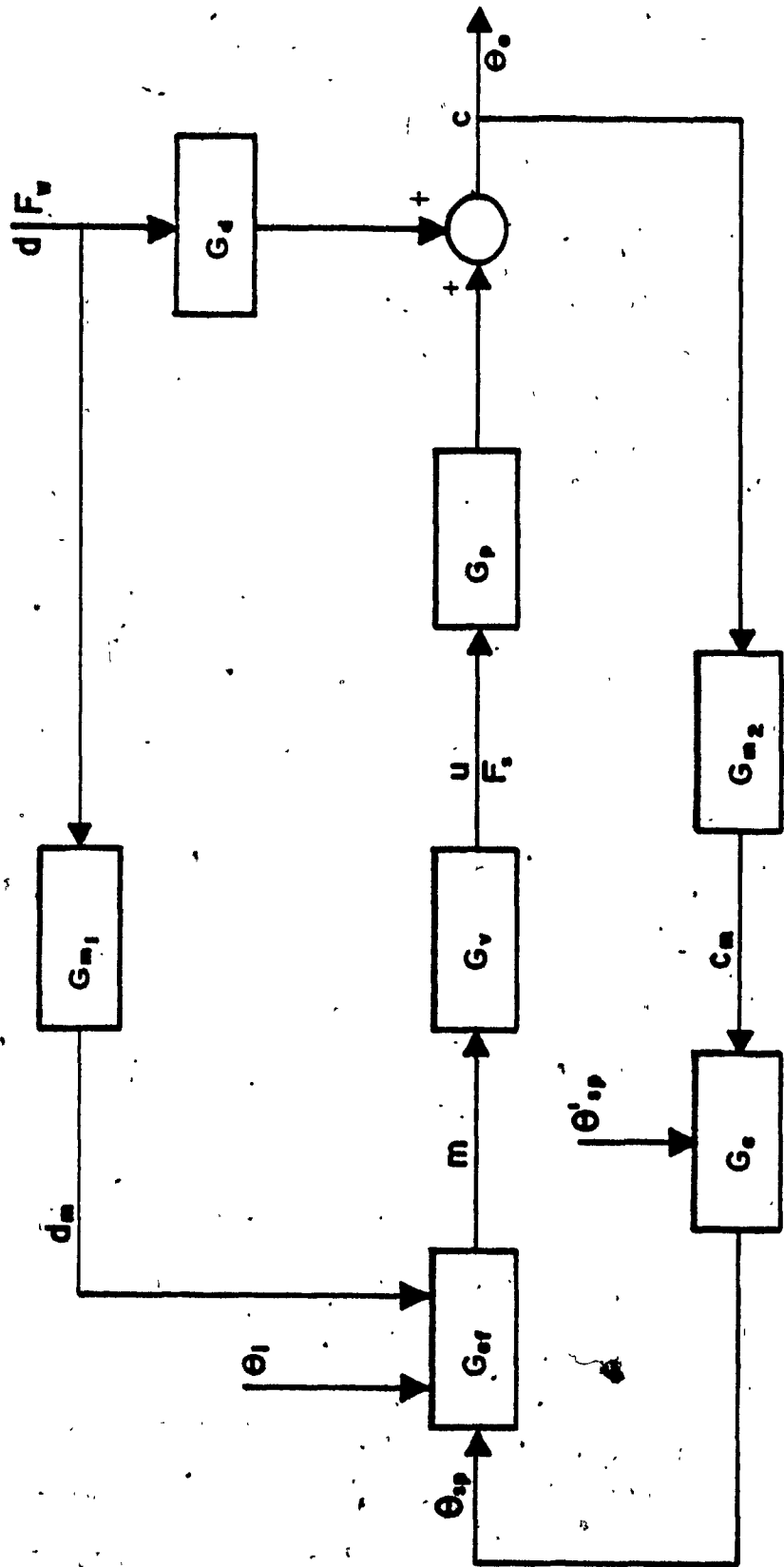


Figure 5.7.- Block diagram of feedforward-feedback control of heat exchanger

- Tubes

Material = copper

Outside diameter = 0.0625 feet = 0.750 inches

Inside diameter = 0.0555 feet = 0.666 inches

Overall length

per pass = 3.75 feet = 45 inches

N° of passes = 20

Total length of

tube = 3.75 X 20 = 75 feet

- Process fluid (water)

Average water temperature (inlet) =  $\theta_i$  = 90°F

Water velocity = 5 ft/sec

Water flow rate =  $f_w$  = 10,000 lb/hr = 20 GPM

Weight of water at 90°F = 62.1 lb/ft<sup>3</sup> = 8.303 lb/Gal.

Desired outlet temperature =  $\theta_o$  = 200°F

Heat capacity of water =  $C_p$  = 1.0 Btu/lb, °F

- Steam

Latent heat of steam =  $H_s$  = 970 Btu/lb

Steam flow rate =  $f_s$  = 1,135 lb/hr

b. Calculation of parameters

i. process transfer function

$$\begin{aligned} \text{Mass of fluid} &= \text{surface of tube} \times \text{weight of water} \\ &= (0.666 \times 12 / 2)^2 (\text{ft}^2) \times 62.1 (\text{lb}/\text{ft}^3) \\ &= 0.00242 \times 62.1 \\ &= 0.150 \text{ lb}/\text{ft} \end{aligned}$$

$$\begin{aligned} \text{Total mass of fluid} &= M_w = 0.150 \text{ lb}/\text{ft} \times 75 \text{ ft} \\ &= 11.25 \text{ lb} \end{aligned}$$

From Eq. 5.16

$$\begin{aligned} \tau_p &= M_w / f_w = 11.25 (\text{lb}) / 10000 (\text{lb}/\text{hr}) \\ &= 0.001125 (\text{hr}) \\ &= 4.05 (\text{sec}) \end{aligned}$$

$$\begin{aligned} K_p &= H_s / (f_w C_p) = 970 (\text{Btu}/\text{lb}) / (10000 (\text{lb}/\text{hr}) \times 1 (\text{Btu}/\text{lb}^\circ\text{F})) \\ &= 0.097 (^\circ\text{F}/(\text{lb}/\text{hr})) \end{aligned}$$

ii. Control valve transfer function

Assuming a critical flow through the valve then the steam flow rate is only a function of the valve opening.

From Eq. 5.4

$$f_s = f_w (C_p / H_s) (\theta_o - \theta_i)$$

$$\begin{aligned} &= 10000(\text{lb/hr}) \times (1/970(\text{Btu hr}/^\circ\text{F})) \times (200:90) \\ &= 1135 \text{ lb/hr} \end{aligned}$$

Therefore, for 110°F increase in the water temperature, 1135 lb/hr of steam is required. Let the 1135 lb/hr flow rate correspond to 75% of the valve opening, and let the valve have a linear characteristic. Then

$$\begin{aligned} 1\% &\longrightarrow 15.13 \text{ lb/hr} \\ 100\% &\longrightarrow 1513 \text{ lb/hr} \end{aligned}$$

Let the controller output be 0-10V which will cause the valve to travel from 0% (fully closed) to 100% (fully opened).

Then the control valve gain  $K_v$  is equal to

$$K_v = 1513/10 (\text{lb/hr})/(\text{V}) = 151.3 ((\text{lb/hr})/(\text{V}))$$

The time constant of the valve with the positioner could be assumed to be 2 seconds. That is

$$\tau_v = 2 \text{ sec.}$$

### .iii. Measuring element transfer function

With the control valve fully opened, steam flow rate is 1513 lb/hr. Rearranging Eq. 5.4 gives:

$$\theta_o = (f_s H_s) / (C_p f_w) + \theta_i$$

$$\begin{aligned} &= (1513 \times 970)/(10000) + 90^\circ \\ &= 146.76^\circ + 90^\circ = 236.76^\circ \end{aligned}$$

which is the maximum temperature that the fluid could obtain.

Then let the temperature transmitter range be 0 to 250°F and its output be 0 to 10V, which gives

$$1^\circ\text{F} \longrightarrow (10/250)\text{V} = 0.04$$

Therefore, the measuring element gain,  $K_m$ , is equal to:

$$K_m = 0.04 \text{ (V/}^\circ\text{F)}$$

The time constant of the measuring element could be assumed to be 3 seconds. The time delay associated with this measuring element could also be assumed to be 3 seconds. Then

$$\begin{aligned} \tau_m &= 3 \text{ sec.} \\ \tau_a &= 3 \text{ sec.} \end{aligned}$$

In the feedforward-feedback control system there is also a flow measuring element. To calculate the gain of this measuring element, assume its range to be 0 to 12000 lb/hr and its output to be 0 to 10V. Then

$$1 \text{ (lb/hr)} \longrightarrow (10/12000) = 0.0008333 \text{ V}$$



Hence the flow measuring element gain,  $K_m$ , is

$$K_m = 0.0008333 \text{ (V/(lb/hr))}$$

Being a flow measuring element and flow loops being extremely fast, the time constant,  $\tau_m$ , could be assumed to be 0.5 seconds. That is

$$\tau_m = 0.5 \text{ sec.}$$

For the flow measuring element there are no time delays involved. Therefore, the transfer function is reduced to first order lag only.

#### iv. Disturbance transfer function

From Eq. 5.17 the gain of disturbance transfer function is given by:

$$\begin{aligned} K_d &= (H_s F_s) / (F_w^2 C_p) \\ &= (970 \text{ (Btu/lb)} \times 1135 \text{ (lb/hr)}) / (10000^2 \text{ (lb}^2/\text{hr}^2) \\ &\quad \times 1.0 \text{ (Btu/lb}^\circ\text{F)}) \\ &= 0.011^\circ\text{F} / (\text{lb/hr}) \end{aligned}$$

and the time constant  $\tau_d$  could be assumed to be equal to 0.5 seconds (same as  $\tau_m$ ).

From the characteristic of the heat exchanger, it is given that the total length of the tube equals to 75 feet and the velocity of the water through the pipes equals 5 ft/sec, which gives a time delay of 15 seconds. Therefore

$$\tau_b = 15 \text{ sec.}$$

### 5.7 Simulation Results

A digital computer simulation is used to demonstrate the performance of feedback, feedforward and feedforward-feedback control systems and their application to controlling the heat exchanger. The computer programs were written in FORTRAN and they were executed on the VAX 11/780 system.

The listings of the programs and their outputs are included in the APPENDIX.

The simulation is divided into two groups for each type of control system. The first group is aimed to simulate the ideal process with ideal measuring elements. The second group is aimed to simulate the real process with real measuring elements. The difference between the ideal process and measuring elements and the real ones being that the latter incorporates the time delays associated with the

process and elements. These grouping was done to demonstrate the effect of the time delays.

The following is a brief description of the programs:

a.- Feedback Control System

To tune the P+I+D controller used for this control system the ultimate method of Ziegler and Nichols [11] was used. Applying the ultimate method, the ultimate sensitivity,  $S_u$ , and the ultimate period,  $P_u$ , were found to be 12 and 16 respectively. Using the  $S_u$  and  $P_u$  the P+I+D controller was tuned by letting.

$$K_C = 0.6 S_u = 0.6 \times 12 = 7.6$$

$$K_I = 0.5 P_u = 0.5 \times 16 = 8.0$$

$$K_D = P_u / 8.0 = 16 / 8.0 = 2.0$$

The values of controller parameters were used in the simulation of the control loop but the results were not found to be satisfactory, i.e. the decay ratio was not one-quarter (the ratio of the overshoot of the first peak to the overshoot of the second peak). By trial and error the optimum values of these parameters were found to be:

- 90 -

$$K_C = 4.0$$

$$K_I = 6.0$$

$$K_D = 2.5$$

The performances of the feedback control system to a setpoint change (a step increase) and a load change (step decrease) are shown in Figures 5.8 and 5.9 respectively.

To simulate the real process and real measuring elements time delays were added to the disturbance and temperature measuring element transfer functions. The controller tuned for the previous run made the system unstable for this case, therefore the parameters were changed to the following:

$$K_C = 3.0$$

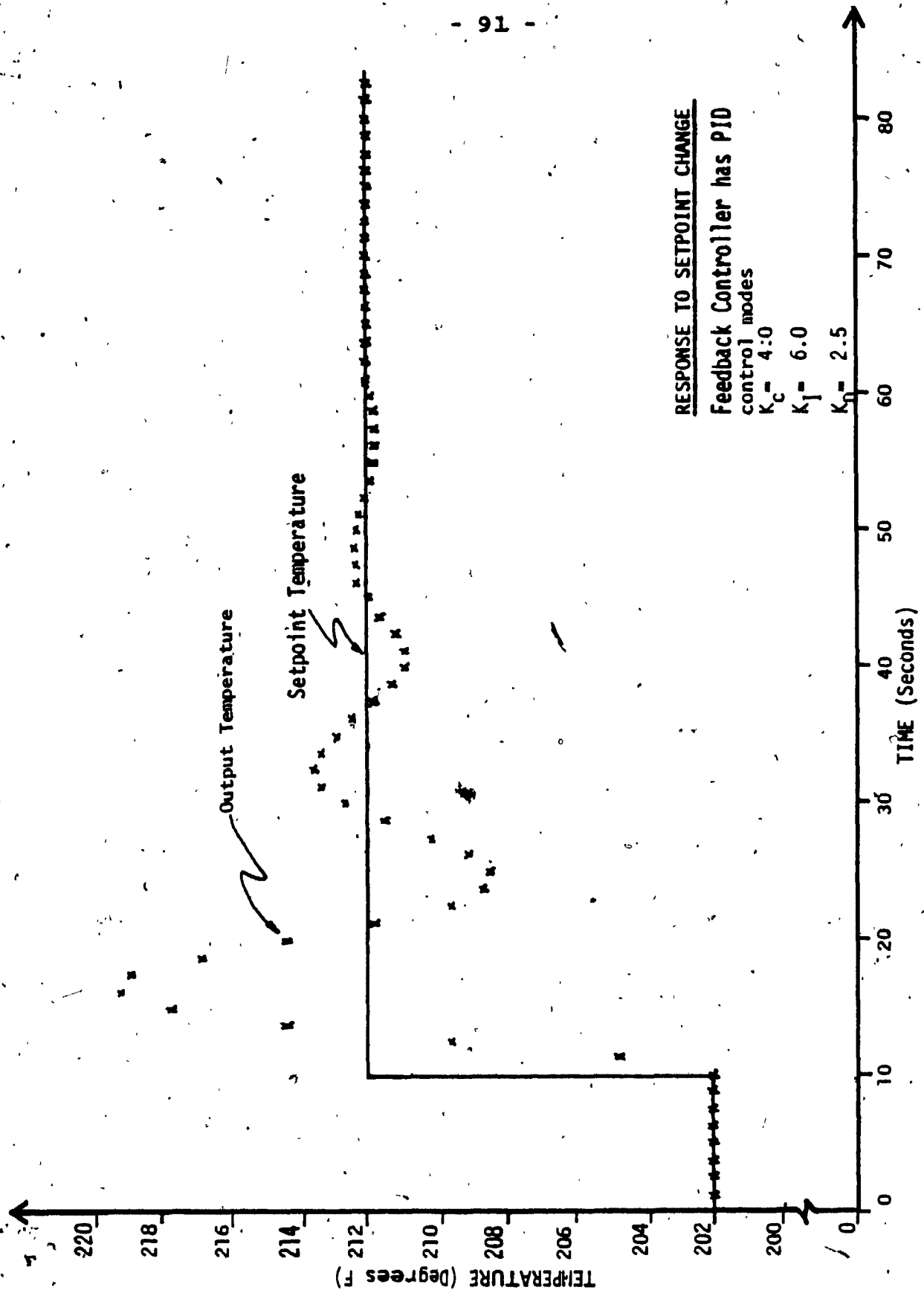
$$K_I = 6.5$$

$$K_D = 9.5$$

The performances to a setpoint change and a load change is given in Figures 5.10 and 5.11

#### b.- Feedforward Control System

Using the equations derived at section 5.4 of this



**RESPONSE TO SETPOINT CHANGE**  
**Feedback Controller has PID**  
control modes  
 $K_C = 4:0$   
 $K_I = 6.0$   
 $K_D = 2.5$

Figure 5.8.- Performance of servo-mechanism feedback control of Heat Exchanger

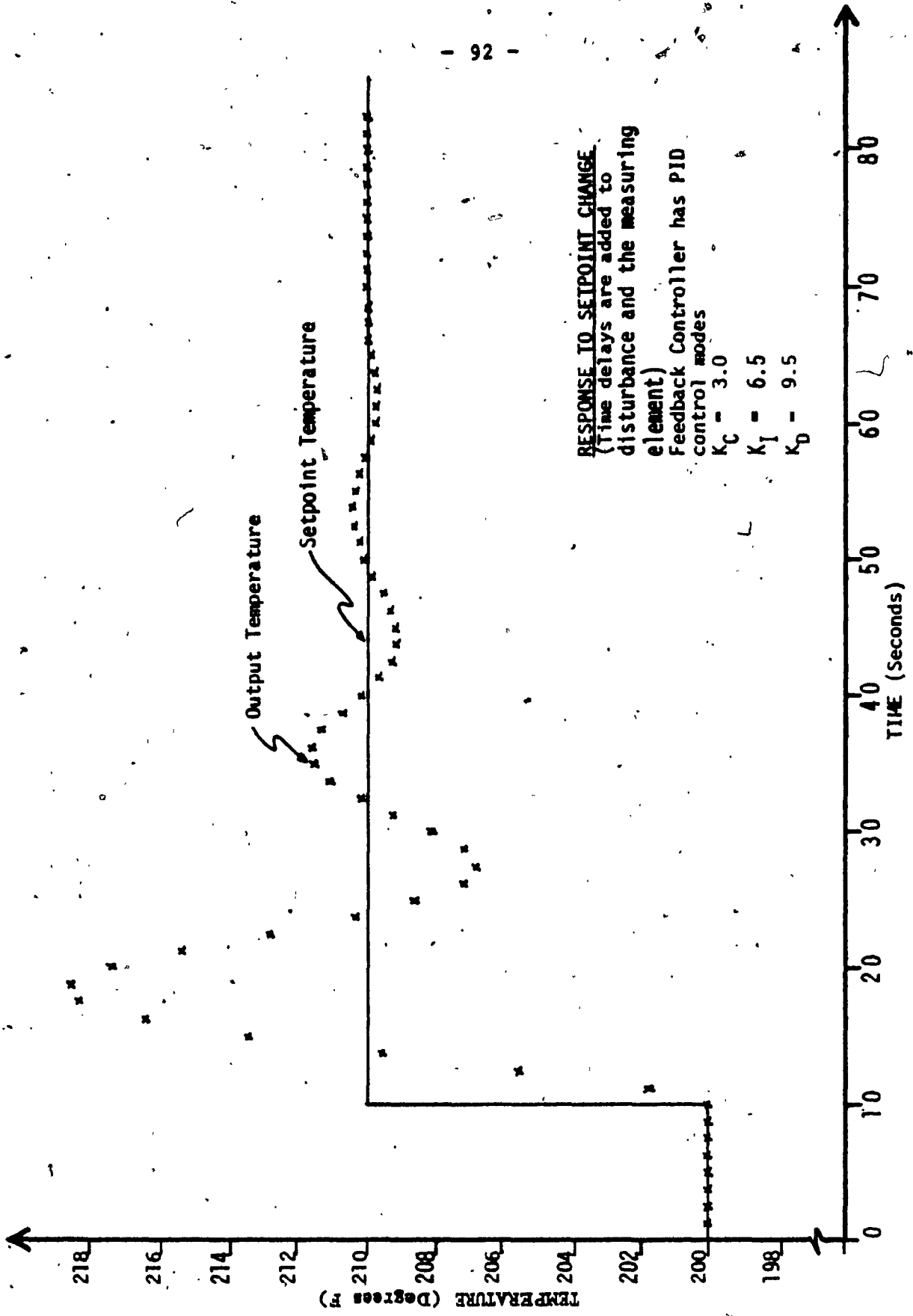


Figure 5.9.- Performance of servo-mechanism feedback control of Heat Exchanger (Time delays added)

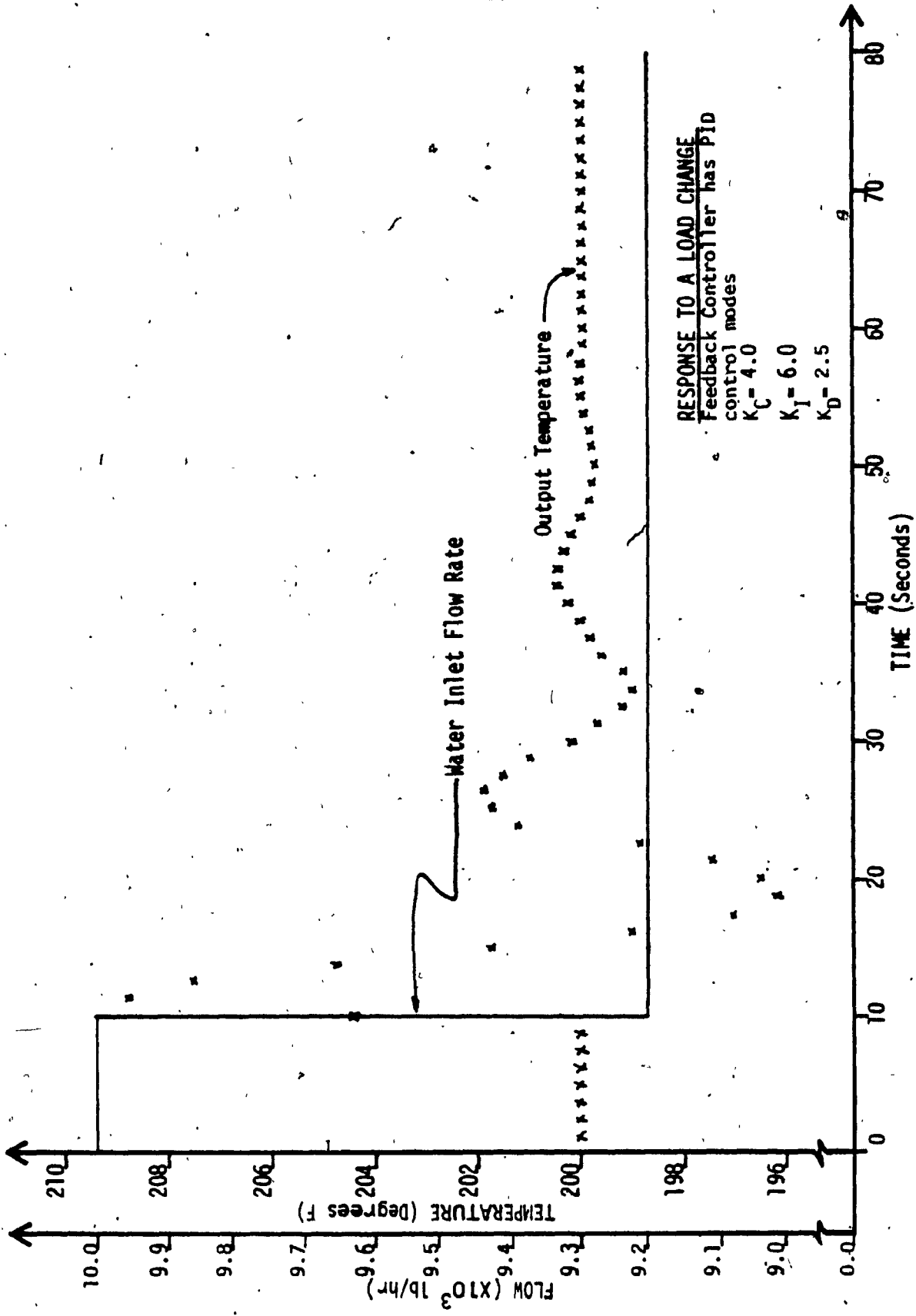


Figure 5.10.- Performance of regulating feedback control of Heat Exchanger

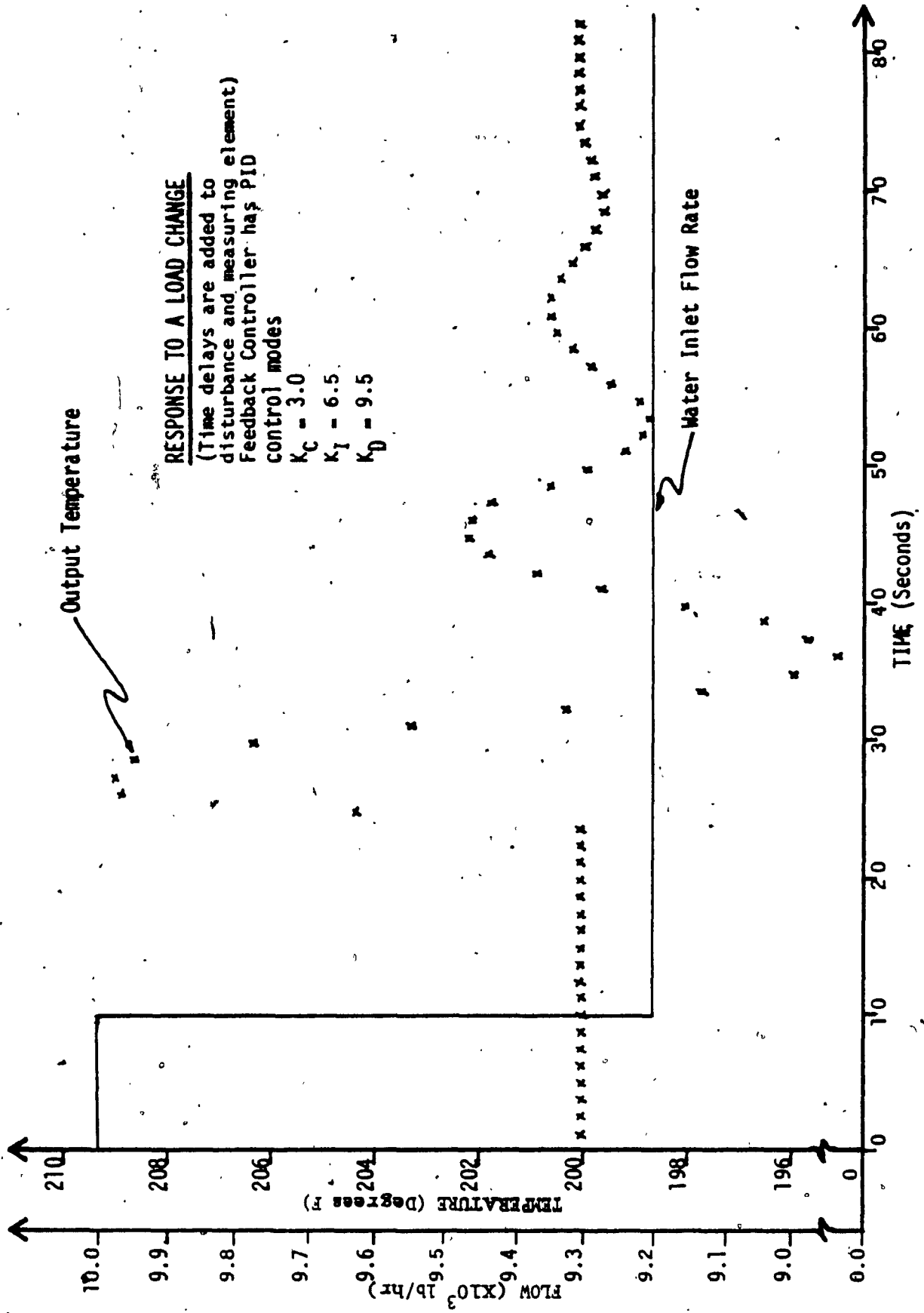


Figure 5.11.- Performance of regulating feedback control of Heat Exchanger (Time delays added)



report steady-state and dynamic feedforward control was simulated.

Fig. 5.12 shows the identical performances of steady-state and dynamic feedforward control in response to a setpoint change. To simulate the real process a time delay was added to the disturbance transfer function. Again the identical performances of steady-state and dynamic feedforward control in response to a setpoint change are shown in Fig. 5.13.

The performances of steady-state and dynamic feedforward control system in response to a load change are shown in Fig. 5.14. Again for the real process a time delay was added to disturbance transfer function and the performances of the feedforward control systems are shown in 5.15.

#### c.- Feedforward-feedback Control System

For this control system feedback controllers with two different control modes were used.

First, to simulate the ideal process and elements, a feedback controller with proportional control mode was used where  $K_C$  was set to be equal to be 1.0.

The identical performances of feedforward-feedback control system - with steady-state and dynamic feedforward

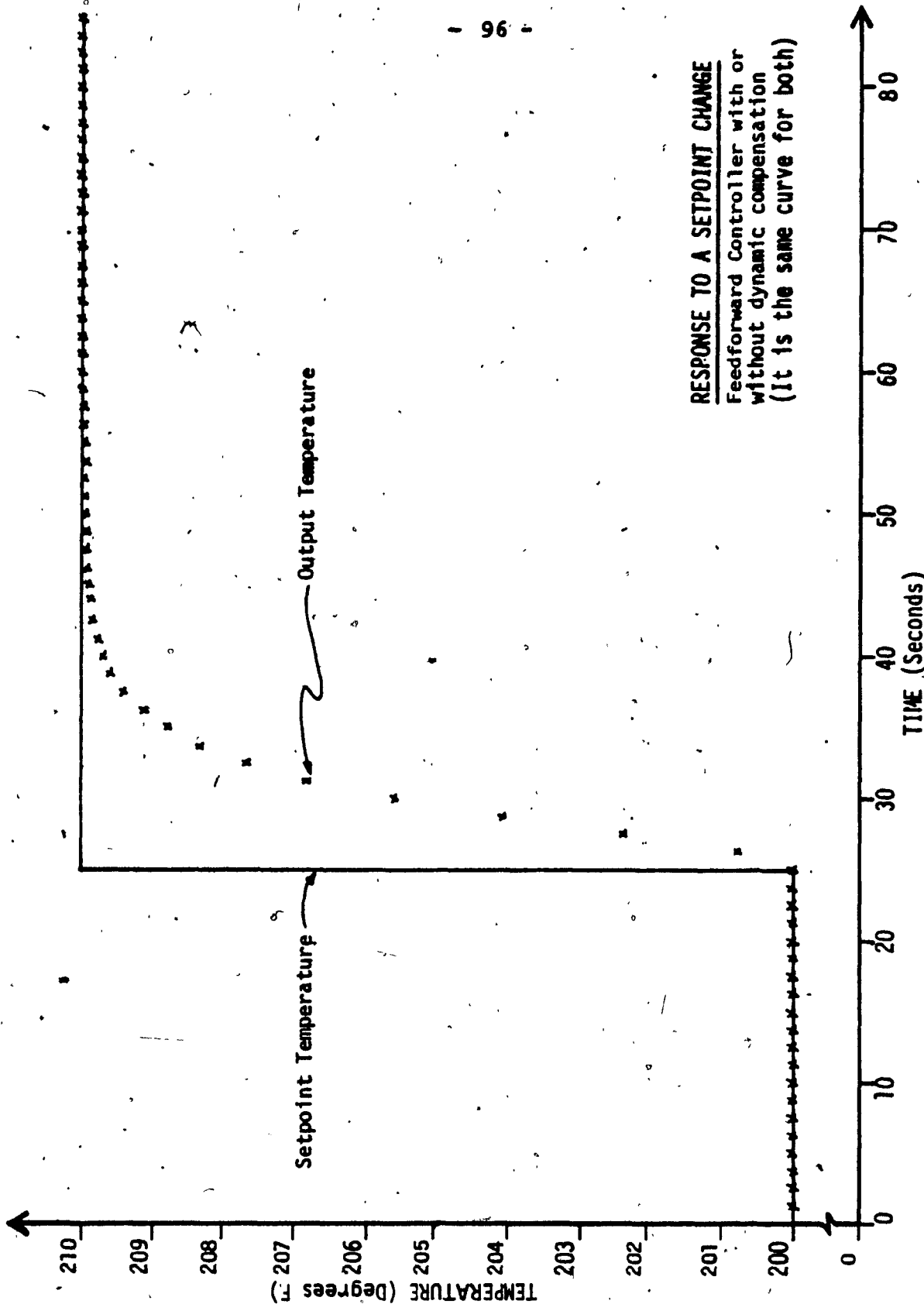


Figure 5.12.- Performance of feedforward control of Heat Exchanger

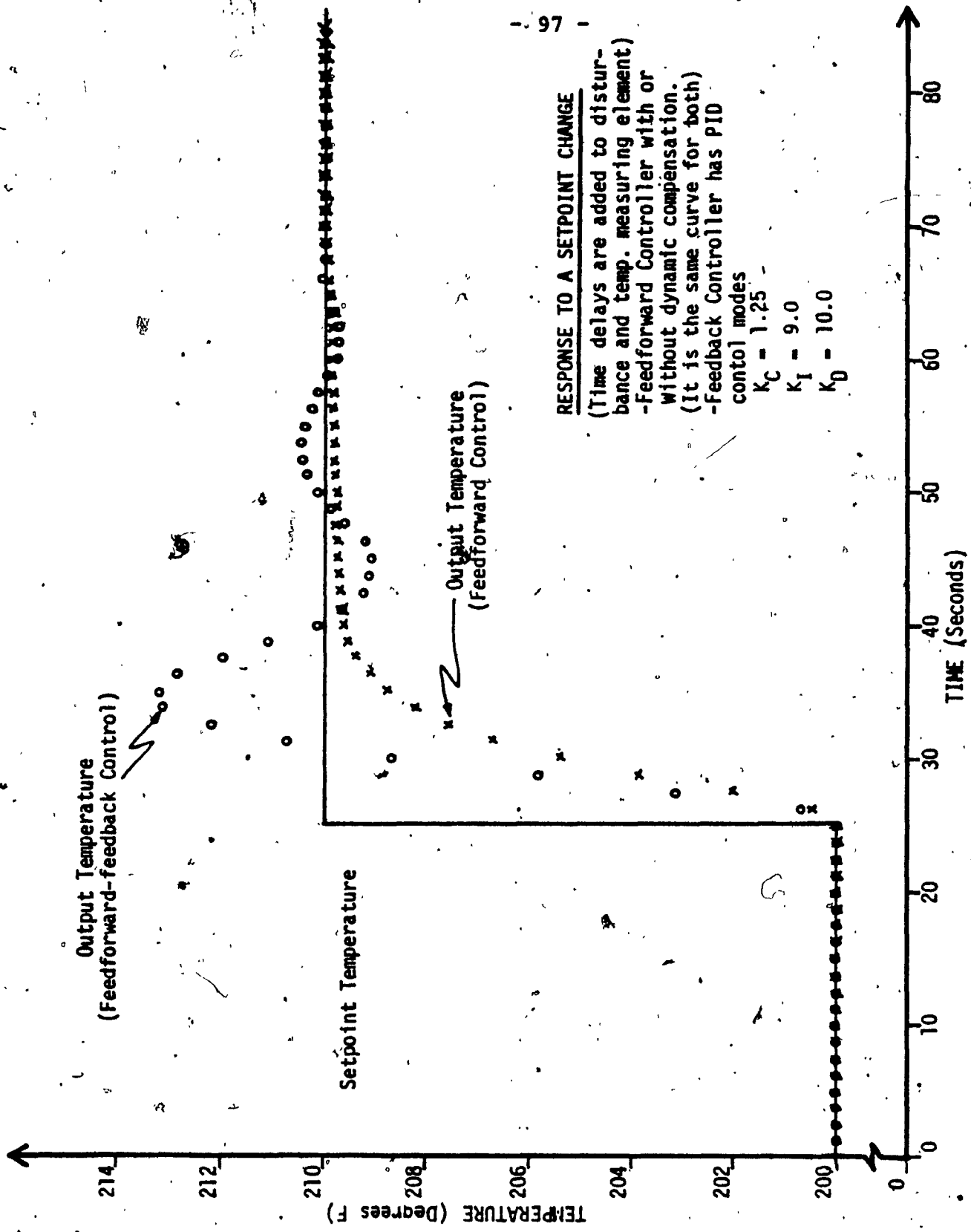


Figure 5.13.- Performances of feedforward & feedback-control of Heat Exchanger.

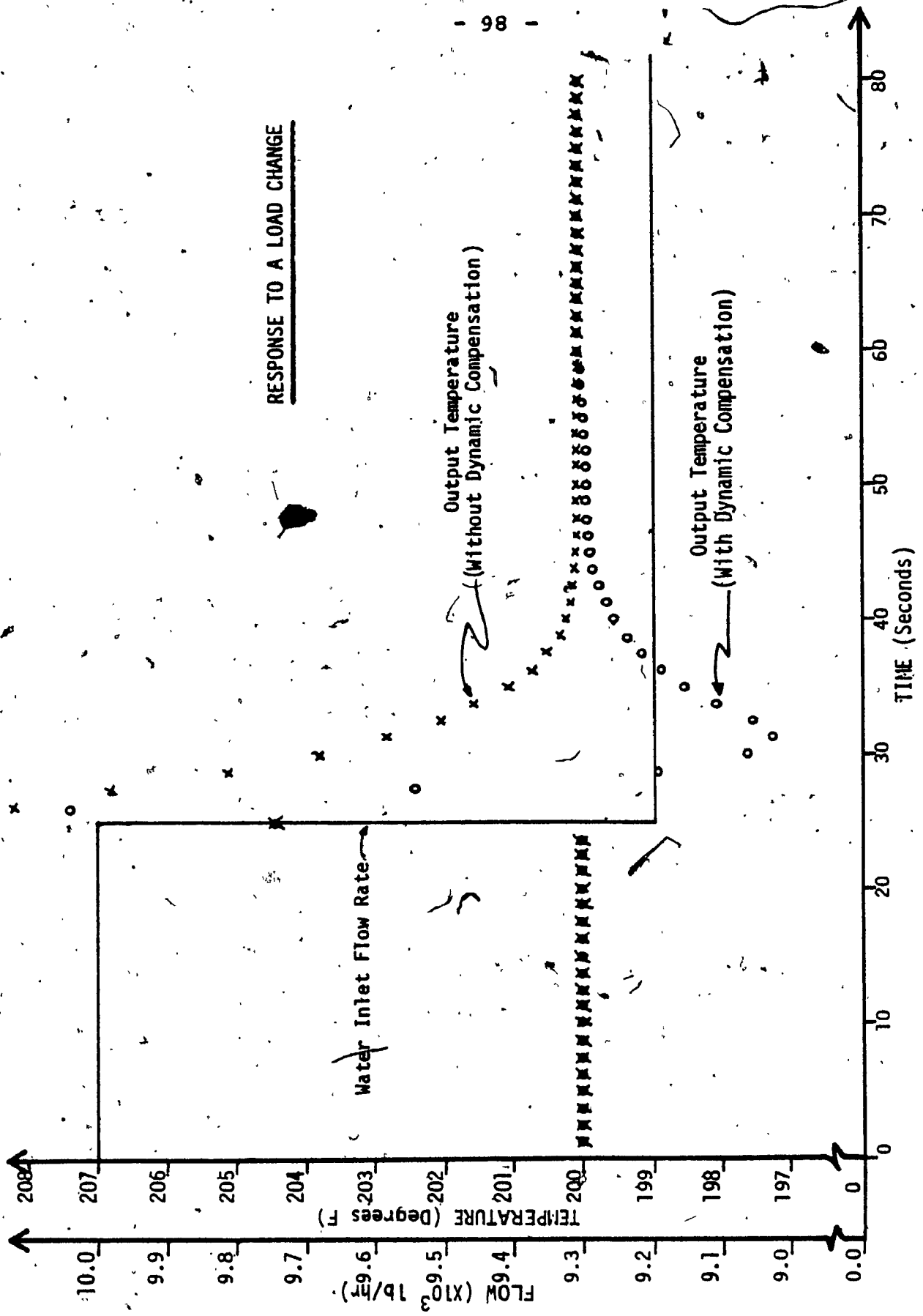


Figure 5.14.- Performance of feedforward control of Heat Exchanger (Load change)

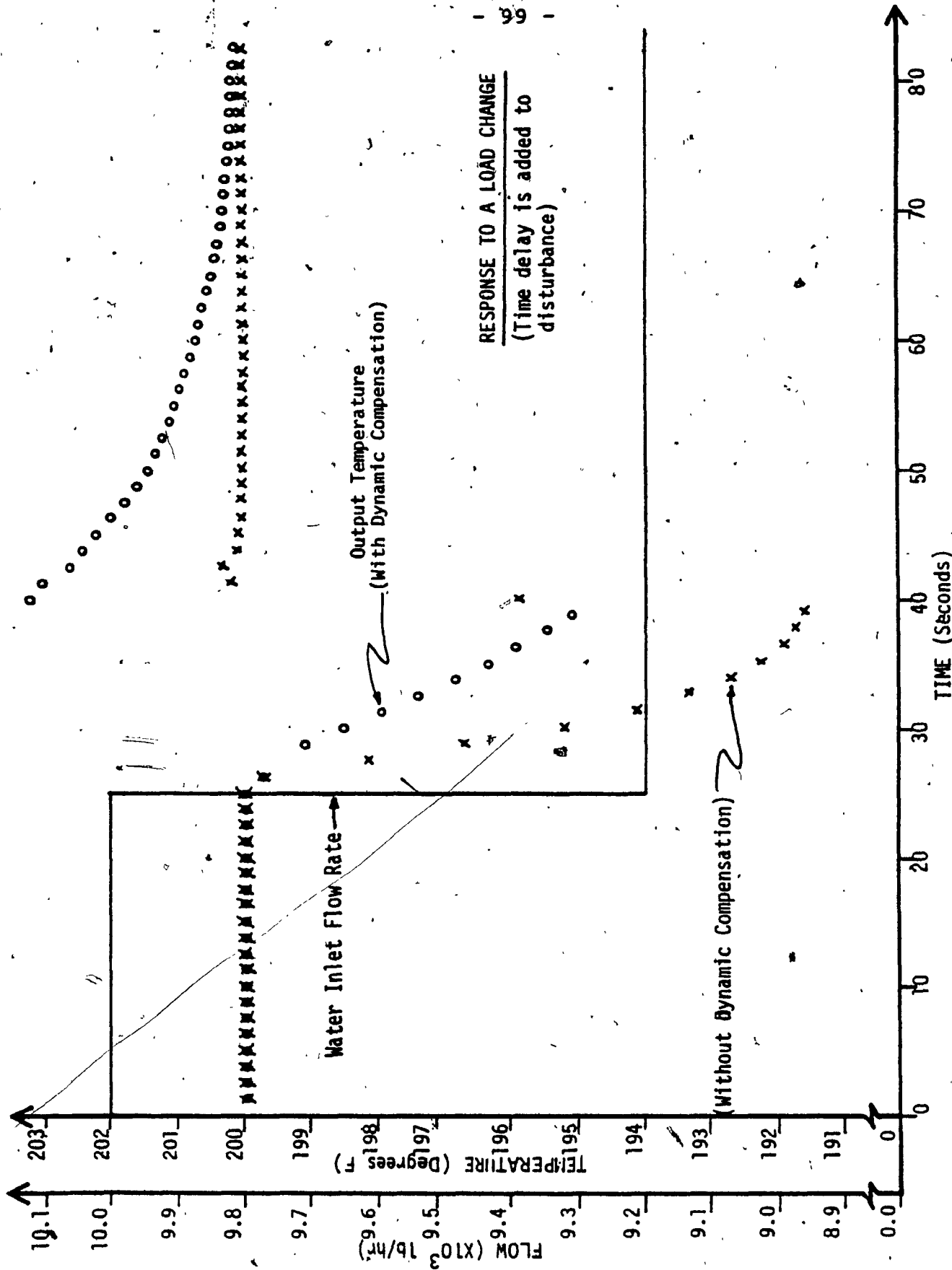


Figure 5.15.- Performance of feedforward control of Heat Exchanger (Load change - delay added)

control - in response to a setpoint change (feedback controller setpoint is changed since the setpoint of feedforward controller is continuously varied by the feedback controller output) are shown in Fig. 5.16.

Figure 5.17 shows the performance of the above mentioned control system in response to a load change.

The second feedback controller used was a three mode controller (P+I+D) to simulate the real process and elements. Time delays were added to the disturbance and temperature measuring elements. The feedback controller parameters were set to  $K_C = 1.25$ ,  $K_I = 9.0$  and  $K_D = 10.0$ , and the feedforward controller was used with dynamic compensation or without it. The performances of the feedforward-feedback control system - with the above mentioned characteristic - in response to a load change are shown in Fig. 5.18, and in response to a setpoint change are shown in Fig. 5.13.

5.8.- General Comments on the Simulation Results  
=====

For better understanding of the results of the previous section and to point out few facts some general comments on the simulation results are in order.

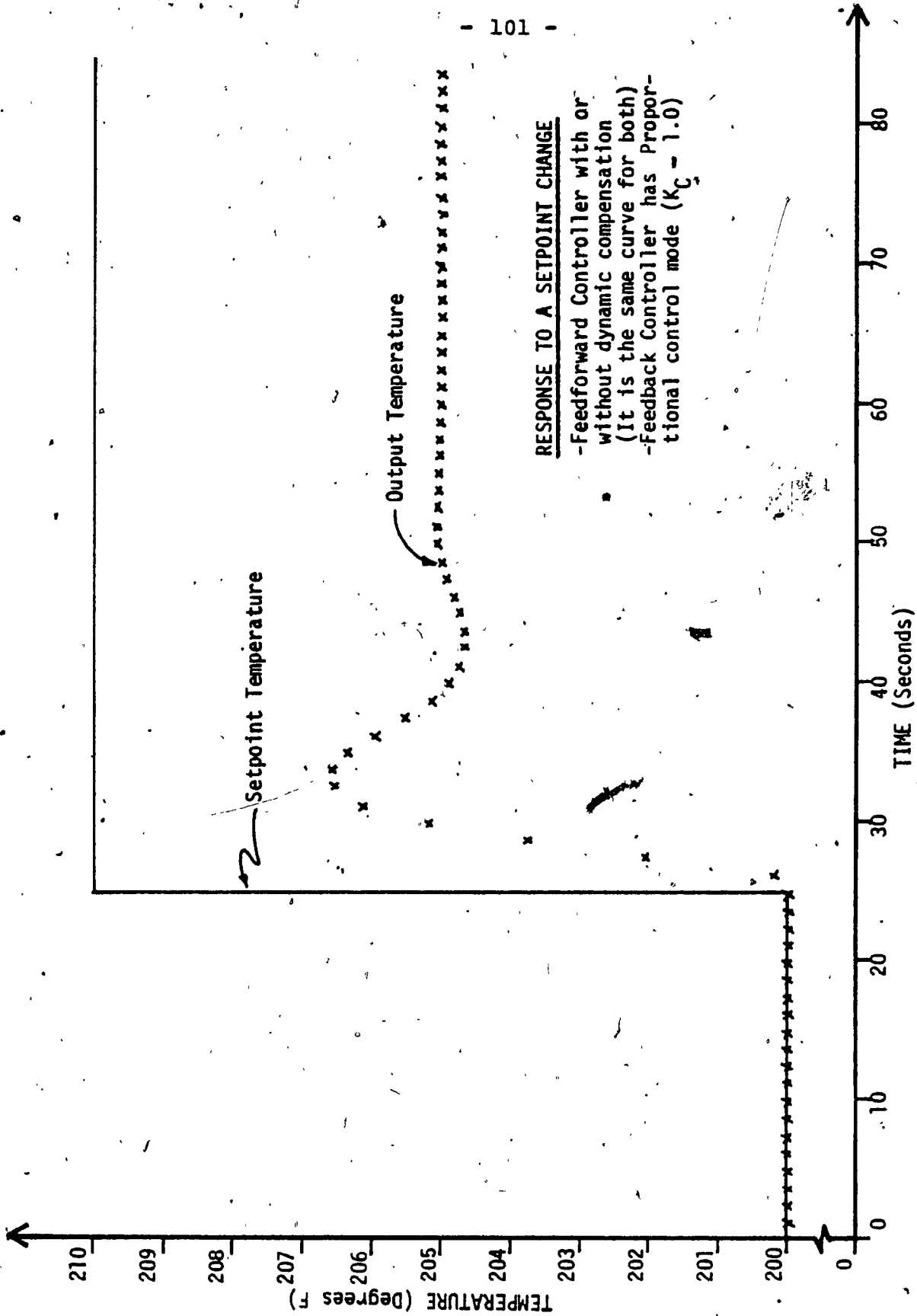
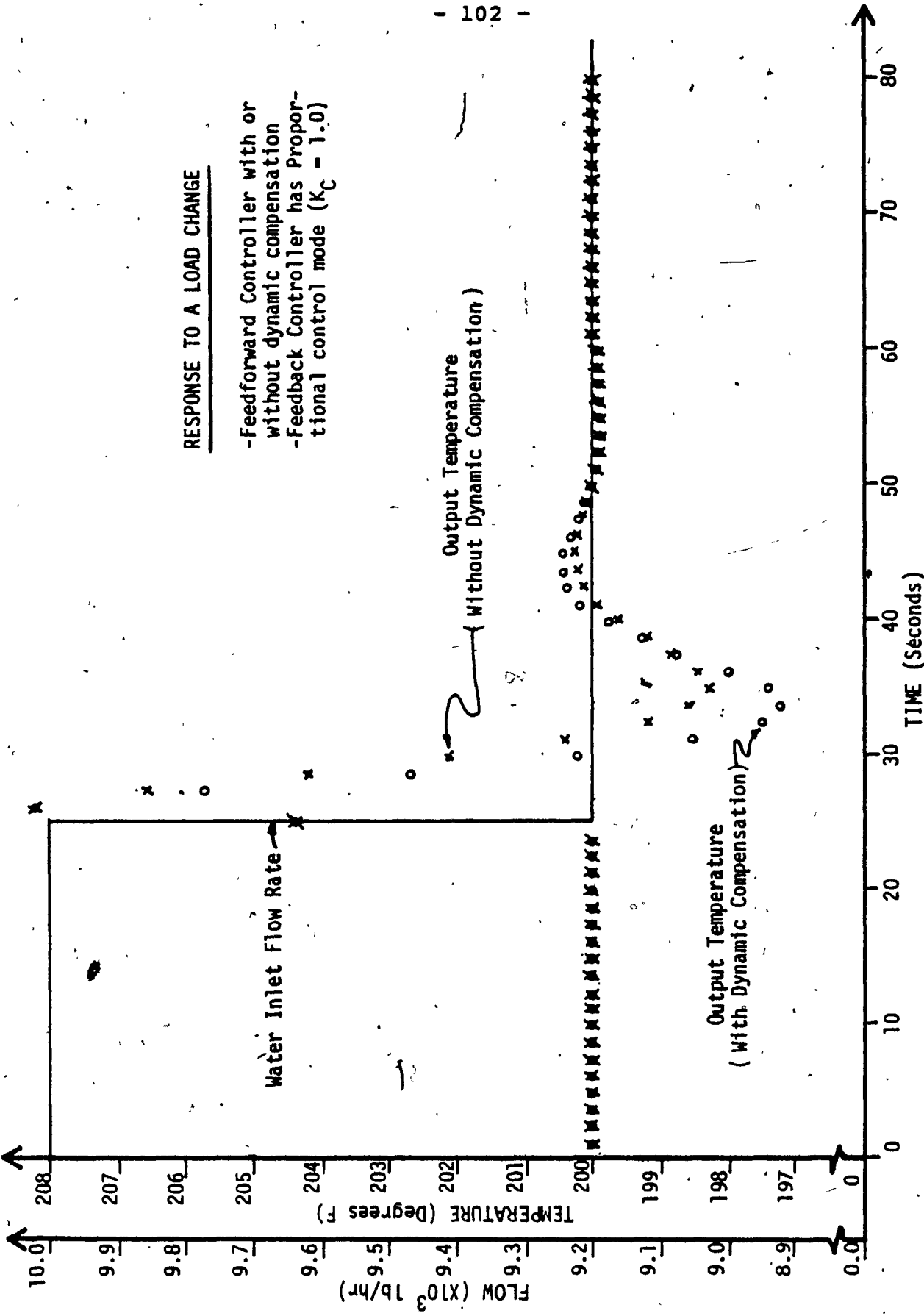


Figure 5.16.- Performance of feedforward-feedback control of Heat Exchanger (Setpoint change)



RESPONSE TO A LOAD CHANGE

- Feedforward Controller with or without dynamic compensation
- Feedback Controller has Proportional control mode ( $K_C = 1.0$ )

Figure 5.17.- Performance of feedforward-feedback control of Heat Exchanger (Load change)



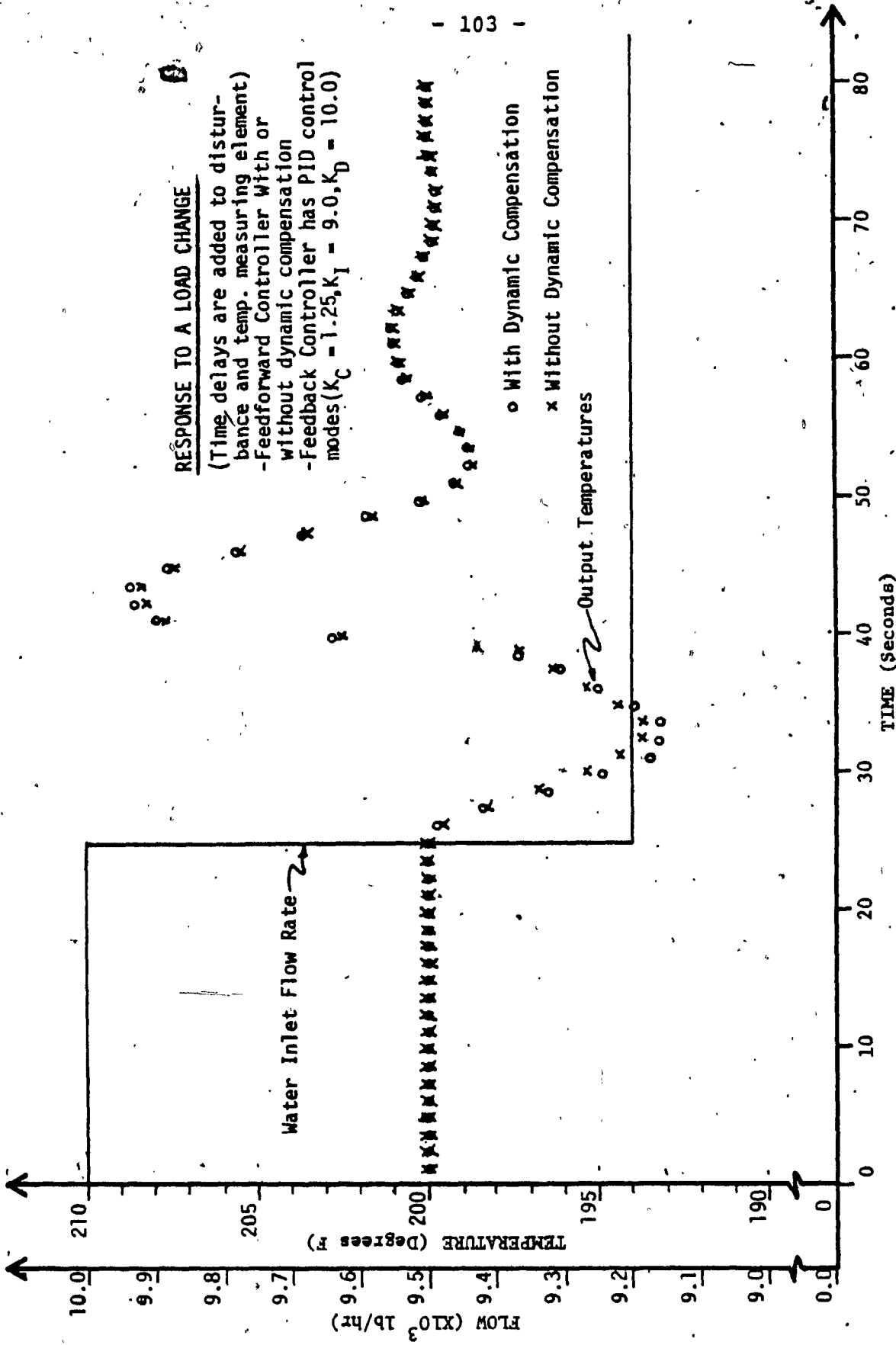


Figure 5.18.- Performance of feedforward-feedback control of Heat Exchanger (Load change - delays added)

- To highlight the variations of the output temperature of the heat exchanger due to changes, only variation zones are shown on Figures 5.8 through 5.18.

- The abrupt changes in the output temperature of the heat exchanger of Figures 5.11, 5.14, 5.15, 5.17 and 5.18 are unrealistic. In real process applications an increase of  $10^{\circ}$  F for systems with the capacity of the heat exchanger will certainly take more than the few seconds that it took in the simulation. Also the output temperature would hardly peak to the levels shown in the figures. The combination of these two will produce a much smoother response.

- The models picked for the elements of the control loops were all first order lags some with time delays associated with them. The values for the time constants of the various elements of the control loop were those suggested in the literature listed in the References. More precise models and more realistic time delays could have influenced the output.

CHAPTER 6

\*\*\*\*\*

CONCLUSION

\*\*\*\*\*

The performance of the feedback, feedforward and feedforward-feedback process control systems were studied. The characteristic of each control system was discussed in detail. The advantages and the disadvantages of each control system was presented.

These control systems were used in a typical process control application, namely, the control of a heat exchanger. With the aid of a digital computer this process control application was simulated.

From the performance curves obtained from the simulation the following conclusions could be drawn:

- i - A properly tuned three mode (P+I+D) controller will respond satisfactorily to a setpoint change or a load change with its characteristic oscillatory type response.
  
- ii - The response of the feedforward control to a setpoint change is exponential, appearing as if the

loop was open. The inclusion or the exclusion of the dynamic compensation term in the feedforward controller did not have any effect on the response.

iii - The response of the feedforward control to a load change was smoother than the feedback one (refer to the comment in Section 5.8 of this report), and not oscillatory. The overshoot was much less than that of feedback control. The inclusion of the dynamic compensation term in the feedforward controller made the response swifter.

iv - The response of feedforward-feedback control system with a Proportional (P) only feedback control to a load change was not significantly different from that of feedforward control system. But the response of this control system to a setpoint change produced an offset (characteristic of Proportional only control).

v - The response of the feedforward-feedback control system with a three mode (P+I+D) feedback control also was not significantly different from that of feedforward control system. But as previously stated the "raison d'etre" of the feedback loop is to fine tune the feedforward control system for

unexpected upsets other than the load which were not considered in this simulations.

The effects of the dynamic compensation of the feedforward loop were not as pronounced as they were in the previous cases.

The response of this control system to a setpoint change was satisfactory with a small overshoot but, no offset.

From the simulation results it could be concluded that for non-critical process applications where wide variations in the controlled variable could be tolerated (e.g. level control of a tank), the feedback control system could provide the necessary control with satisfactory results. For more critical process applications where large variations could not be tolerated (e.g. chemical composition or level control of a boiler), feedforward control should be used. The feedforward-feedback control system combines the advantages of both feedforward and feedback control systems. With present day microprocessor based controllers the feedforward-feedback combination control system could be incorporated in the same controller, thus eliminating the additional hardware required for implementing a superior control system.

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=====

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APPENDIX



• PART A

FEEDBACK CONTROL

30-AUG-1983 17:00:19  
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```
0001 PROGRAM HEATEX
0002 DIMENSION T(400), CM(400), TM(400), TO1(400), TO(400), TS(400), TT(5,400)
0003 DIMENSION TO2(400), U(400), KC(1), KI(1), KD(1), DEL(1), ER(400), Fw(400)
0004 DIMENSION T1(400)
0005 REAL INTER, INTUD, INTOD1, INTOD2, INTMD, KC, KP, KD, KV, KP, KDIS, KM, KS
0006 DATA KC/4./, KI/6./, KD/2.5/, DEL/0.25/
0007 C PARAMETERS AND VARIABLES
0008 C CONTROLLER: KC=PROPORTIONAL GAIN
0009 C KI=INTEGRAL TIME (SEC.)
0010 C KD=DERIVATIVE TIME (SEC.)
0011 C CM=CONTROLLER OUTPUT (VOLTS-RANGE 0-10V)
0012 C CBAIS= CONTROLLER BIAS
0013 C VP, VI, VD=PROPORTIONAL, INTEGRAL, DERIVATIVE PARTS OF
0014 C CONTROLLER OUTPUT
0015 C
0016 C VALVE : THV= VALVE TIME CONSTANT (SEC.)
0017 C KV=VALVE GAIN ((LB./HR)/VOLTS)
0018 C
0019 C EXCHANGER : THP=PROCESS TIME CONSTANT (SEC.)
0020 C KP=PROCESS GAIN (DEG. F/(LB./HR))
0021 C
0022 C DISTURBANCE: THD=DISTURBANCE TIME CONSTANT (SEC.)
0023 C KDIS=DISTURBANCE GAIN (DEG. F/(LB./HR))
0024 C
0025 C MEASURING THM=MEASURING ELEMENT TIME CONSTANT (SEC.)
0026 C ELEMENT : KM=MEASURING ELEMENT GAIN (VOLTS/DEG.F)
0027 C
0028 C OTHERS : TS=SETPOINT TEMPERATURE (DEG. F)
0029 C KS=SETPOINT GAIN (DEG. F/VOLTS)
0030 C IIN=INPUT TEMPERATURE (DEG. F)
0031 C TO=OVERALL OUTPUT TEMPERATURE (DEG. F)
0032 C TO1=OUTPUT TEMPERATURE DUE TO PROCESS (DEG. F)
0033 C TO2=OUTPUT TEMPERATURE DUE TO DISTURBANCE (DEG. F)
0034 C FW=WATER INFLOW RATE (LB./HR)
0035 C
0036 TYPE 13
0037 13 FORMAT(1H1,30X,'SIMULATION OF A HEAT EXCHANGER CONTROL SYSTEM'
0038 + /,31X,45('='),/,10X,'A.- FEEDBACK CONTROL',/,10X,20('='),/)
0039 C CONSTANTS & PARAMETERS
0040 IIN=90.
0041 THV=2.
0042 KV=151.3334
0043 THP=4.05
0044 KP=0.09691
0045 THD=0.5
0046 KDIS=0.011
0047 THM=3.
0048 KM=0.04
0049 KS=0.04
0050 CBAIS=7.5
0051 TYPE 12, KC(1), KI(1), KD(1)
0052 12 FORMAT(10X,'PROPORTIONAL GAIN OF CONTROLLER IS SET =',F10.3,/,
0053 + 10X,'INTEGRAL TIME OF THE CONTROLLER IS SET =',F10.3,/,10X,
0054 + 'DERIVATIVE TIME OF THE CONTROLLER IS SET =',F10.3,/)
0055 DU 99 JK=1,2
0056 IF(JK.EQ.2)GO TO 14
0057 TYPE 15
```

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```

0058      GO TO 16
0059      14  TYPE 17
0060      17  FORMAT(1H1,/,/,9X,'REGULATOR (LOAD CHANGES)',/,/,10X,24('-'))
0061      15  FORMAT(/,10X,'SERVO-MECHANISM (SETPOINT CHANGES)',/,/,10X,34('-'))
0062      C   INITIAL CONDITIONS
0063      16  ER(1)=0.
0064      U(1)=1135.
0065      FW(1)=10000.
0066      INTER=0.
0067      TU(1)=200.
0068      TO1(1)=200.
0069      TU2(1)=0.
0070      TM(1)=TU(1)*KM
0071      TS(1)=200.
0072      CM(1)=7.5
0073      INTUD=1135.
0074      INTMD=8.
0075      INTOD1=200.
0076      INTOD2=110.
0077      T(1)=0.0
0078      DO 2 I=2,400
0079      II=I-1
0080      C
0081      C   SETPOINT CHANGE
0082      FW(I)=FW(II)
0083      TS(I)=TS(II)
0084      IF(JK.EQ.2)GO TO 23
0085      IF(I.EQ.40)TS(I)=TS(II)+10.
0086      C   THE THREE MODE CONTROLLER
0087      23  ER(I)=TS(I)*KS-TM(II)
0088      C   PROPORTIONAL
0089      VP=KC(1)*ER(I)
0090      C   INTEGRAL
0091      VI=INTER*(KC(1)/KI(1))
0092      C   DERIVATIVE
0093      VD=(KC(1)*KD(1))*(ER(I)-ER(II))
0094      C   P+I+D
0095      CM(I)=VP+VI+VD+CBAS
0096      IF(CM(I).GT.10.000)CM(I)=10.0
0097      C   VALVE
0098      UD=(KV*CM(I)-U(II))/THV
0099      U(I)=INTUD
0100      C   HEAT EXCHANGER
0101      PU=KP*U(I)+TIN
0102      TOD1=(PU-TO1(II))/THP
0103      TU1(I)=INTOD1
0104      IF(JK.EQ.2)GO TO 20
0105      TU(I)=TU1(I)
0106      C   MEASURING ELEMENT
0107      22  TMD=(KM*U(I)-TM(II))/THM
0108      Th(I)=INTMD
0109      GO TO 21
0110      C   DISTURBANCE OR LOAD CHANGE
0111      20  TO2(1)=110.
0112      TS(I)=TS(1)
0113      IF(I.EQ.40)FW(I)=FW(II)-800.
0114      TOD2=(KDIS*FW(I)-TO2(II))/THD

```

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```
0115      TU2(I)=INTUD2
0116      TO(I)=TO1(I)+(T02(1)-T02(I))
0117      GO TO 22

0118      C
0119      C  EULER INTEGRATION
0120      21  T(I)=T(II)+DEL(1)
0121      INTER=INTER+ER(I)*DEL(1)
0122      INTUD=INTUD+UD*DEL(1)
0123      INTUD1=INTUD1+TUD1*DEL(1)
0124      INTUD2=INTUD2+TUD2*DEL(1)
0125      INTMD=INTMD+TMD*DEL(1)
0126      C

0127      2   CONTINUE
0128      TYPE 18
0129      18  FORMAT(15X,'T',11X,'FW',10X,'CM',10X,'U',10X,'TO',10X,'TS',
0130      + 11X,'TM',/,10X,83('-'),/)
0131      IK=1
0132      DO 5 I=1,80
0133      T1(I)=T(IK)
0134      TT(1,I)=TO(IK)/10.-19.5
0135      TT(2,I)=TS(IK)/10.-19.5
0136      IF(JK.EQ.2)TT(2,I)=FW(IK)/10000.
0137      TYPE 11,T(IK),FW(IK),CM(IK),U(IK),TO(IK),TS(IK),TM(IK)
0138      11  FORMAT(7X,F12.3)
0139      IK=IK+5
0140      5   CONTINUE
0141      IF(JK.EQ.2)GO TO 98
0142      TYPE 24
0143      24  FORMAT(1H1)
0144      TYPE 15
0145      TYPE 96
0146      96  FORMAT(10X,'THE ACTUAL VALUES OF (TO) & (TS) ARE GIVEN BY:'
0147      + /,20X,'((TU) OR (TS) + 19.5) X 10.0',/)
0148      GO TO 97
0149      98  TYPE 17
0150      TYPE 95
0151      95  FORMAT(10X,'THE ACTUAL VALUES OF (TO) & (FW) ARE GIVEN BY:'
0152      + /,20X,'((TO) + 19.5 ) X 10.0      AND      (FW) X 10000.0',/)
0153      97  CALL PLOT1(T1,TT,80,2,JK)
0154      99  CONTINUE
0155      END
```

```

0001
0002      SUBROUTINE PLOT1(T,F,N,M,K1)
0003      DIMENSION PLINE(400,61),IX(10),FMX(5),FMN(5),PLUS(5)
0004      DIMENSION T(400),F(5,400),DISP(3),DY(11),SCALE(3),SFRCT(5)
0005      DIMENSION ASTRX(1),AXIS(1),BLANK(1),VDASH(1)
0006      DATA SFRCT/1.0,2.5,5.,7.5,10./,DISP/1.5,61.5,31.5/
0007      DATA ASTRX/' ',AXIS/'I',BLANK/' ',VDASH/'!'/
0008      DATA SCALE/2*60.,30./,PLUS/'+','.','*','@','X'/
0009      C
0010      DO 1 J=1,M
0011          FMX(J)=F(J,1)
0012          FMN(J)=F(J,1)
0013      DO 2 I=1,N
0014          IF(F(J,I)-FMX(J))3,3,4
0015      4      FMAX(J)=F(J,I)
0016      3      IF(F(J,I)-FMN(J))5,2,2
0017      5      FMN(J)=F(J,I)
0018      2      CONTINUE
0019      1      CONTINUE
0020      FMAX=FMX(1)
0021      FMIN=FMN(1)
0022      DO 6 I=1,M
0023          IF(FMX(I)-FMAX)7,7,8
0024      8      FMAX=FMX(I)
0025      7      IF(FMN(I)-FMIN)9,6,6
0026      9      FMIN=FMN(I)
0027      6      CONTINUE
0028      IF(ABS(FMAX)-ABS(FMIN))10,11,11
0029      11     DIV=ABS(FMAX)
0030          GO TO 12
0031      10     DIV=ABS(FMIN)
0032      12     NEXP=IFIX(ALOG(DIV)/ALOG(10.))
0033          IF(DIV.LT.1)NEXP=NEXP-1
0034          PP=10.**NEXP
0035          P=10.**(-NEXP)
0036          FRACT=DIV*P
0037          DO 13 I=1,5
0038              DIV=SFRCT(I)*PP
0039              IF(FRACT-SFRCT(I))14,14,13
0040          13     CONTINUE
0041      C 14     TYPE 15,(J,FMX(J),J,FMN(J),J=1,M)
0042      C 15     FORMAT(/,15X,'MAXIMUM #'I2,'=',E13.6,10X,'MINIMUM #'I2,
0043      C 1      ' ',E13.6)
0044      C      TYPE 16,FMAX,FMIN
0045      C 16     FORMAT(/,15X,'OVERALL MAXIMUM ='E13.6,10X,'OVERALL MINIMUM ='
0046      C 1      E13.6,/)
0047      14     TYPE 17,PP
0048      17     FORMAT(T54,'(OUTPUTS SCALED BY 'E8.3,')',/,I40,
0049      +      '(X INDICATES MORE THAN ONE VARIABLE HAS THE GIVEN VALUE)')
0050          IF(FMIN)18,19,19
0051      18     IF(FMAX)20,20,21
0052      19     INDEX=1
0053          DY(1)=0.
0054          YINC=DIV/10.
0055          TYPE 22
0056      22     FORMAT(T38,'0 + =====>')
0057          GO TO 30

```

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```
0058      20  INDEX=2
0059      DY(1)=-DIV*P
0060      YINC=DIV/10.
0061      TYPE 23
0062      23  FORMAT(T89,'<===== - 0')
0063      GO TO 30
0064      21  INDEX=3
0065      DY(1)=-DIV*P
0066      YINC=DIV/5.
0067      TYPE 24
0068      24  FORMAT(T59,'<===== - 0 + =====>')
0069      C
0070      30  DO 31 I=2,11
0071      31  DY(I)=DY(I-1)+YINC*P
0072      TYPE 32,(DY(I),I=1,11)
0073      32  FORMAT(34X,11F6.2)
0074      C
0075      DO 35 K=1,N
0076      DO 36 L=1,60,6
0077      DO 37 J=1,5
0078      37  PLINE(K,L+J)=BLANK(1)
0079      36  PLINE(K,L)=VDASH(1)
0080      35  PLINE(K,61)=VDASH(1)
0081      C
0082      DO 40 K=1,N
0083      C
0084      DO 41 J=1,M
0085      I=IFIX((F(J,K)/DIV)*SCALE(INDEX)+DISP(INDEX))
0086      IF(INDEX.EQ.2)GO TO 50
0087      IF(INDEX.EQ.3)GO TO 51
0088      DO 52 L=1,I
0089      52  PLINE(K,L)=ASTRX(1)
0090      PLINE(K,1)=AXIS(1)
0091      GO TO 55
0092      50  DO 53 L=1,60
0093      53  PLINE(K,L)=ASTRX(1)
0094      PLINE(K,61)=AXIS(1)
0095      GO TO 55
0096      51  IF(I-31)56,57,58
0097      56  DO 54 L=1,30
0098      54  PLINE(K,L)=ASTRX(1)
0099      GO TO 57
0100      58  DO 59 L=32,I
0101      59  PLINE(K,L)=ASTRX(1)
0102      57  PLINE(K,31)=AXIS(1)
0103      55  IX(J)=I
0104      41  CONTINUE
0105      DO 99 L1=1,M
0106      L2=IX(L1)
0107      99  PLINE(K,L2)=PLUS(L1)
0108      DO 98 L3=1,M
0109      L5=IX(L3)
0110      DO 97 L4=1,M
0111      IF(L3.EQ.L4) GO TO 97
0112      IF(IX(L3)-IX(L4))97,96,97
0113      96  PLINE(K,L5)=PLUS(5)
0114      97  CONTINUE
```

PLOT1

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```
0115 98 CONTINUE
0116 40 CUNTINUE
0117 C
0118 IF(M.EQ.2)GO TO 60
0119 IF(M.EQ.3)GO TO 61
0120 TYPE 62
0121 62 FURMAT(12X,' T F(+) ',T38,'+'10('-----+'))
0122 GO TO 63
0123 60 IF(K1.EQ.2)GO TO 199
0124 TYPE 64
0125 64 FURMAT(8X,' T TO(+) TS(.) 'T38,'+'10('-----+'))
0126 GO TO 65
0127 199 TYPE 198
0128 198 FURMAT(8X,' T TO(+) FW(.) 'T38,'+'10('-----+'))
0129 GO TO 65
0130 61 TYPE 66
0131 66 FURMAT(2X,' T F1(+) F2(.) F3(*) ',T38,'+',
0132 1 10('-----+'))
0133 DO 67 J=1,N
0134 67 TYPE 69,T(J),(F(K,J),K=1,M),(PLINE(J,I), I=1,61)
0135 69 FURMAT(1X,F6.3,3(2X,F7.3),3X,61A1)
0136 GO TO 80
0137 63 DO 70 J=1,N
0138 70 TYPE 71,T(J),F(1,J),(PLINE(J,I),I=1,61)
0139 71 FURMAT(12X,F7.3,2X,F8.4,8X,61A1)
0140 GO TO 80
0141 65 DO 72 J=1,N
0142 72 TYPE 74,T(J),(F(K,J),K=1,M),(PLINE(J,I),I=1,61)
0143 74 FURMAT(8X,F6.3,2(2X,F8.4),3X,61A1)
0144 C
0145 80 TYPE 81
0146 81 FURMAT(37X,' I',10('-----+'))
0147 RETURN
0148 END
```

SIMULATION OF A HEAT EXCHANGER CONTROL SYSTEM

A.- FEEDBACK CONTROL

PROPORTIONAL GAIN OF CONTROLLER IS SET = 4.000  
 INTEGRAL TIME OF THE CONTROLLER IS SET = 6.000  
 DERIVATIVE TIME OF THE CONTROLLER IS SET = 2.500

SERVO-MECHANISM (SETPPOINT CHANGES)

T	FW	CM	U	TO	TS	TM
0.000	10000.000	7.500	1135.000	200.000	200.000	8.000
1.250	10000.000	7.500	1135.001	199.998	200.000	8.000
2.500	10000.000	7.500	1135.010	199.997	200.000	8.000
3.750	10000.000	7.500	1135.030	199.996	200.000	8.000
5.000	10000.000	7.501	1135.055	199.996	200.000	8.000
6.250	10000.000	7.501	1135.078	199.997	200.000	8.000
7.500	10000.000	7.501	1135.095	199.998	200.000	8.000
8.750	10000.000	7.501	1135.104	200.000	200.000	8.000
10.000	10000.000	9.167	1182.383	200.001	210.000	8.000
11.250	10000.000	9.423	1308.429	202.924	210.000	8.015
12.500	10000.000	9.387	1372.473	207.768	210.000	8.084
13.750	10000.000	9.103	1390.043	212.485	210.000	8.202
15.000	10000.000	8.675	1368.578	215.849	210.000	8.339
16.250	10000.000	8.225	1321.889	217.310	210.000	8.463
17.500	10000.000	7.856	1265.797	218.893	210.000	8.550
18.750	10000.000	7.634	1214.765	215.053	210.000	8.588
20.000	10000.000	7.578	1179.147	212.474	210.000	8.577
21.250	10000.000	7.667	1163.781	209.874	210.000	8.530
22.500	10000.000	7.853	1168.034	207.830	210.000	8.465
23.750	10000.000	8.075	1187.046	206.682	210.000	8.398
25.000	10000.000	8.277	1213.648	206.506	210.000	8.346
26.250	10000.000	8.417	1240.420	207.145	210.000	8.316
27.500	10000.000	8.478	1261.384	208.293	210.000	8.312
28.750	10000.000	8.461	1273.045	209.594	210.000	8.328
30.000	10000.000	8.385	1274.669	210.728	210.000	8.357
31.250	10000.000	8.280	1267.896	211.476	210.000	8.390
32.500	10000.000	8.174	1255.904	211.749	210.000	8.419
33.750	10000.000	8.091	1242.394	211.580	210.000	8.438
35.000	10000.000	8.045	1230.665	211.095	210.000	8.445
36.250	10000.000	8.039	1222.964	210.465	210.000	8.440
37.500	10000.000	8.065	1210.197	209.858	210.000	8.428
38.750	10000.000	8.113	1221.991	209.404	210.000	8.412
40.000	10000.000	8.166	1227.039	209.173	210.000	8.397
41.250	10000.000	8.213	1233.571	209.172	210.000	8.385
42.500	10000.000	8.243	1239.843	209.355	210.000	8.379
43.750	10000.000	8.254	1244.513	209.645	210.000	8.379
45.000	10000.000	8.247	1246.884	209.956	210.000	8.384
46.250	10000.000	8.227	1246.838	210.215	210.000	8.391
47.500	10000.000	8.201	1244.915	210.374	210.000	8.399
48.750	10000.000	8.176	1241.899	210.419	210.000	8.405
50.000	10000.000	8.158	1238.678	210.362	210.000	8.410
51.250	10000.000	8.148	1236.008	210.236	210.000	8.411
52.500	10000.000	8.148	1234.371	210.083	210.000	8.409
53.750	10000.000	8.156	1233.924	209.942	210.000	8.406
55.000	10000.000	8.168	1234.529	209.842	210.000	8.402
56.250	10000.000	8.181	1235.842	209.797	210.000	8.399
57.500	10000.000	8.191	1237.429	209.806	210.000	8.396
58.750	10000.000	8.198	1238.885	209.856	210.000	8.395
60.000	10000.000	8.200	1239.912	209.929	210.000	8.395
61.250	10000.000	8.197	1240.388	210.002	210.000	8.396
62.500	10000.000	8.192	1240.267	210.061	210.000	8.396
63.750	10000.000	8.186	1239.741	210.094	210.000	8.400
65.000	10000.000	8.180	1238.991	210.100	210.000	8.402
66.250	10000.000	8.176	1238.230	210.082	210.000	8.402
67.500	10000.000	8.174	1237.628	210.050	210.000	8.403
68.750	10000.000	8.174	1237.286	210.013	210.000	8.402
70.000	10000.000	8.177	1237.230	209.981	210.000	8.401
71.250	10000.000	8.179	1237.413	209.959	210.000	8.400
72.500	10000.000	8.182	1237.749	209.951	210.000	8.400
73.750	10000.000	8.185	1238.131	209.955	210.000	8.399
75.000	10000.000	8.186	1238.466	209.968	210.000	8.399
76.250	10000.000	8.186	1238.689	209.986	210.000	8.399
77.500	10000.000	8.186	1238.773	210.003	210.000	8.399
78.750	10000.000	8.184	1238.727	210.016	210.000	8.400
80.000	10000.000	8.183	1238.587	210.023	210.000	8.400
81.250	10000.000	8.182	1238.403	210.024	210.000	8.400
82.500	10000.000	8.181	1238.224	210.019	210.000	8.401
83.750	10000.000	8.180	1238.090	210.010	210.000	8.401
85.000	10000.000	8.181	1238.021	210.002	210.000	8.400
86.250	10000.000	8.181	1238.019	209.994	210.000	8.400
87.500	10000.000	8.182	1238.072	209.990	210.000	8.400
88.750	10000.000	8.182	1238.156	209.988	210.000	8.400
90.000	10000.000	8.183	1238.246	209.990	210.000	8.400
91.250	10000.000	8.183	1238.323	209.993	210.000	8.400
92.500	10000.000	8.183	1238.371	209.997	210.000	8.400
93.750	10000.000	8.183	1238.385	210.001	210.000	8.400
95.000	10000.000	8.183	1238.369	210.004	210.000	8.400
96.250	10000.000	8.182	1238.333	210.006	210.000	8.400
97.500	10000.000	8.182	1238.288	210.006	210.000	8.400
98.750	10000.000	8.182	1238.247	210.004	210.000	8.400



SERVO-MECHANISM (SETPOINT CHANGES)

THE ACTUAL VALUES OF (TO) & (TS) ARE GIVEN BY:  
 ((TO) OR (TS) + 19.5) x 10.0

(OUTPUTS SCALED BY .100E+01)  
 (X INDICATES MORE THAN ONE VARIABLE HAS THE GIVEN VALUE)

T	TO(+)	TS(-)	0 + =====>																	
			0.00	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50							
0.000	0.5000	0.5000	I		X															
1.250	0.4998	0.5000	I		X															
2.500	0.4997	0.5000	I		X															
3.750	0.4996	0.5000	I		X															
5.000	0.4996	0.5000	I		X															
6.250	0.4997	0.5000	I		X															
7.500	0.4998	0.5000	I		X															
8.750	0.5000	0.5000	I		X															
10.000	0.5001	1.5000	I			X														
11.250	0.7524	1.5000	I				X													
12.500	1.2768	1.5000	I					X												
13.750	1.7485	1.5000	I						X											
15.000	2.0849	1.5000	I							X										
16.250	2.2310	1.5000	I								X									
17.500	2.1893	1.5000	I									X								
18.750	2.0053	1.5000	I										X							
20.000	1.7474	1.5000	I											X						
21.250	1.4874	1.5000	I												X					
22.500	1.2830	1.5000	I													X				
23.750	1.1882	1.5000	I														X			
25.000	1.1506	1.5000	I															X		
26.250	1.2145	1.5000	I																X	
27.500	1.3293	1.5000	I																	X
28.750	1.4594	1.5000	I																	X
30.000	1.5728	1.5000	I																	X
31.250	1.6476	1.5000	I																	X
32.500	1.6749	1.5000	I																	X
33.750	1.6580	1.5000	I																	X
35.000	1.6095	1.5000	I																	X
36.250	1.5485	1.5000	I																	X
37.500	1.4858	1.5000	I																	X
38.750	1.4404	1.5000	I																	X
40.000	1.4173	1.5000	I																	X
41.250	1.4172	1.5000	I																	X
42.500	1.4355	1.5000	I																	X
43.750	1.4645	1.5000	I																	X
45.000	1.4950	1.5000	I																	X
46.250	1.5215	1.5000	I																	X
47.500	1.5374	1.5000	I																	X
48.750	1.5419	1.5000	I																	X
50.000	1.5302	1.5000	I																	X
51.250	1.5230	1.5000	I																	X
52.500	1.5083	1.5000	I																	X
53.750	1.4942	1.5000	I																	X
55.000	1.4842	1.5000	I																	X
56.250	1.4797	1.5000	I																	X
57.500	1.4808	1.5000	I																	X
58.750	1.4856	1.5000	I																	X
60.000	1.4929	1.5000	I																	X
61.250	1.5002	1.5000	I																	X
62.500	1.5061	1.5000	I																	X
63.750	1.5094	1.5000	I																	X
65.000	1.5100	1.5000	I																	X
66.250	1.5082	1.5000	I																	X
67.500	1.5050	1.5000	I																	X
68.750	1.5013	1.5000	I																	X
70.000	1.4981	1.5000	I																	X
71.250	1.4959	1.5000	I																	X
72.500	1.4951	1.5000	I																	X
73.750	1.4955	1.5000	I																	X
75.000	1.4968	1.5000	I																	X
76.250	1.4986	1.5000	I																	X
77.500	1.5003	1.5000	I																	X
78.750	1.5016	1.5000	I																	X
80.000	1.5023	1.5000	I																	X
81.250	1.5024	1.5000	I																	X
82.500	1.5019	1.5000	I																	X
83.750	1.5010	1.5000	I																	X
85.000	1.5002	1.5000	I																	X
86.250	1.4994	1.5000	I																	X
87.500	1.4990	1.5000	I																	X
88.750	1.4988	1.5000	I																	X
90.000	1.4990	1.5000	I																	X
91.250	1.4993	1.5000	I																	X
92.500	1.4997	1.5000	I																	X
93.750	1.5001	1.5000	I																	X
95.000	1.5004	1.5000	I																	X
96.250	1.5006	1.5000	I																	X
97.500	1.5008	1.5000	I																	X
98.750	1.5004	1.5000	I																	X

REGULATOR (LOAD CHANGES)

T	FW	CM	U	TO	TS	TA
0.000	10000.000	7.500	1135.000	200.000	200.000	8.000
1.250	10000.000	7.500	1135.001	199.998	200.000	8.000
2.500	10000.000	7.500	1135.010	199.997	200.000	8.000
3.750	10000.000	7.500	1135.030	199.996	200.000	8.000
5.000	10000.000	7.501	1135.055	199.996	200.000	8.000
6.250	10000.000	7.501	1135.078	199.997	200.000	8.000
7.500	10000.000	7.501	1135.095	199.998	200.000	8.000
8.750	10000.000	7.501	1135.104	200.000	200.000	8.000
10.000	9200.000	7.501	1135.103	204.401	200.000	8.000
11.250	9200.000	6.698	1109.872	208.701	200.000	8.139
12.500	9200.000	6.445	1049.101	207.412	200.000	8.208
13.750	9200.000	6.257	1000.250	204.675	200.000	8.225
15.000	9200.000	6.265	970.362	201.719	200.000	8.192
16.250	9200.000	6.413	962.703	199.006	200.000	8.127
17.500	9200.000	6.640	974.748	197.106	200.000	8.050
18.750	9200.000	6.881	999.899	196.265	200.000	7.980
20.000	9200.000	7.078	1029.959	196.448	200.000	7.931
21.250	9200.000	7.197	1057.267	197.405	200.000	7.908
22.500	9200.000	7.226	1076.298	198.765	200.000	7.912
23.750	9200.000	7.178	1084.471	200.141	200.000	7.936
25.000	9200.000	7.078	1082.130	201.223	200.000	7.970
26.250	9200.000	6.958	1071.883	201.826	200.000	8.005
27.500	9200.000	6.850	1057.575	201.911	200.000	8.032
28.750	9200.000	6.775	1043.186	201.568	200.000	8.047
30.000	9200.000	6.742	1031.925	200.938	200.000	8.049
31.250	9200.000	6.751	1025.660	200.235	200.000	8.040
32.500	9200.000	6.792	1024.782	199.623	200.000	8.024
33.750	9200.000	6.848	1028.411	199.219	200.000	8.006
35.000	9200.000	6.905	1034.840	199.071	200.000	7.991
36.250	9200.000	6.950	1042.083	199.160	200.000	7.980
37.500	9200.000	6.974	1048.370	199.418	200.000	7.977
38.750	9200.000	6.978	1052.495	199.755	200.000	7.979
40.000	9200.000	6.983	1053.974	200.080	200.000	7.985
41.250	9200.000	6.938	1053.006	200.323	200.000	7.994
42.500	9200.000	6.909	1050.294	200.446	200.000	8.002
43.750	9200.000	6.884	1046.787	200.446	200.000	8.008
45.000	9200.000	6.868	1043.421	200.347	200.000	8.011
46.250	9200.000	6.862	1040.916	200.191	200.000	8.011
47.500	9200.000	6.866	1039.655	200.024	200.000	8.009
48.750	9200.000	6.877	1039.669	199.885	200.000	8.005
50.000	9200.000	6.891	1040.701	199.800	200.000	8.001
51.250	9200.000	6.904	1042.319	199.776	200.000	7.997
52.500	9200.000	6.914	1044.047	199.806	200.000	7.995
53.750	9200.000	6.919	1045.480	199.874	200.000	7.994
55.000	9200.000	6.919	1046.358	199.956	200.000	7.995
56.250	9200.000	6.915	1046.597	200.031	200.000	7.997
57.500	9200.000	6.908	1046.272	200.085	200.000	7.999
58.750	9200.000	6.901	1045.567	200.109	200.000	8.001
60.000	9200.000	6.896	1044.715	200.104	200.000	8.002
61.250	9200.000	6.892	1043.933	200.077	200.000	8.003
62.500	9200.000	6.891	1043.382	200.038	200.000	8.003
63.750	9200.000	6.893	1043.137	199.999	200.000	8.002
65.000	9200.000	6.895	1043.192	199.967	200.000	8.001
66.250	9200.000	6.899	1043.475	199.950	200.000	8.000
67.500	9200.000	6.902	1043.877	199.946	200.000	7.999
68.750	9200.000	6.904	1044.286	199.956	200.000	7.999
70.000	9200.000	6.905	1044.609	199.973	200.000	7.999
71.250	9200.000	6.905	1044.792	199.993	200.000	7.999
72.500	9200.000	6.904	1044.822	200.010	200.000	7.999
73.750	9200.000	6.902	1044.723	200.022	200.000	8.000
75.000	9200.000	6.900	1044.543	200.016	200.000	8.000
76.250	9200.000	6.899	1044.337	200.024	200.000	8.001
77.500	9200.000	6.898	1044.157	200.017	200.000	8.001
78.750	9200.000	6.898	1044.038	200.007	200.000	8.001
80.000	9200.000	6.899	1043.993	199.998	200.000	8.000
81.250	9200.000	6.899	1044.019	199.991	200.000	8.000
82.500	9200.000	6.900	1044.094	199.987	200.000	8.000
83.750	9200.000	6.901	1044.193	199.987	200.000	8.000
85.000	9200.000	6.901	1044.289	199.990	200.000	8.000
86.250	9200.000	6.902	1044.361	199.994	200.000	8.000
87.500	9200.000	6.901	1044.397	199.999	200.000	8.000
88.750	9200.000	6.901	1044.398	200.003	200.000	8.000
90.000	9200.000	6.901	1044.370	200.006	200.000	8.000
91.250	9200.000	6.900	1044.324	200.006	200.000	8.000
92.500	9200.000	6.900	1044.276	200.006	200.000	8.000
93.750	9200.000	6.900	1044.235	200.004	200.000	8.000
95.000	9200.000	6.900	1044.209	200.001	200.000	8.000
96.250	9200.000	6.900	1044.202	199.999	200.000	8.000
97.500	9200.000	6.900	1044.210	199.998	200.000	8.000
98.750	9200.000	6.900	1044.230	199.997	200.000	8.000

REGULATOR (LOAD CHANGES)

THE ACTUAL VALUES OF (T0) & (Fw) ARE GIVEN BY:  
 ((T0) + 19.5) X 10.0 AND (Fw) X 10000.0

(OUTPUTS SCALED BY .100E+01)  
 (X INDICATES MORE THAN ONE VARIABLE HAS THE GIVEN VALUE)

T	T0(+)	FW(%)	0 + =====>																			
			0.00	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50									
0.000	0.5000	1.0000	I																			
1.250	0.4998	1.0000	I																			
2.500	0.4997	1.0000	I																			
3.750	0.4996	1.0000	I																			
5.000	0.4996	1.0000	I																			
6.250	0.4997	1.0000	I																			
7.500	0.4998	1.0000	I																			
8.750	0.5000	1.0000	I																			
10.000	0.9401	0.9200	I																			
11.250	1.3701	0.9200	I																			
12.500	1.2412	0.9200	I																			
13.750	0.9675	0.9200	I																			
15.000	0.6719	0.9200	I																			
16.250	0.4006	0.9200	I																			
17.500	0.2106	0.9200	I																			
18.750	0.1265	0.9200	I																			
20.000	0.1448	0.9200	I																			
21.250	0.2405	0.9200	I																			
22.500	0.3765	0.9200	I																			
23.750	0.5141	0.9200	I																			
25.000	0.6223	0.9200	I																			
26.250	0.6826	0.9200	I																			
27.500	0.6911	0.9200	I																			
28.750	0.6560	0.9200	I																			
30.000	0.5938	0.9200	I																			
31.250	0.5235	0.9200	I																			
32.500	0.4623	0.9200	I																			
33.750	0.4219	0.9200	I																			
35.000	0.4071	0.9200	I																			
36.250	0.4160	0.9200	I																			
37.500	0.4418	0.9200	I																			
38.750	0.4755	0.9200	I																			
40.000	0.5080	0.9200	I																			
41.250	0.5323	0.9200	I																			
42.500	0.5446	0.9200	I																			
43.750	0.5446	0.9200	I																			
45.000	0.5347	0.9200	I																			
46.250	0.5191	0.9200	I																			
47.500	0.5024	0.9200	I																			
48.750	0.4885	0.9200	I																			
50.000	0.4800	0.9200	I																			
51.250	0.4776	0.9200	I																			
52.500	0.4806	0.9200	I																			
53.750	0.4874	0.9200	I																			
55.000	0.4956	0.9200	I																			
56.250	0.5031	0.9200	I																			
57.500	0.5085	0.9200	I																			
58.750	0.5109	0.9200	I																			
60.000	0.5104	0.9200	I																			
61.250	0.5077	0.9200	I																			
62.500	0.5038	0.9200	I																			
63.750	0.4999	0.9200	I																			
65.000	0.4967	0.9200	I																			
66.250	0.4950	0.9200	I																			
67.500	0.4946	0.9200	I																			
68.750	0.4956	0.9200	I																			
70.000	0.4973	0.9200	I																			
71.250	0.4993	0.9200	I																			
72.500	0.5010	0.9200	I																			
73.750	0.5022	0.9200	I																			
75.000	0.5026	0.9200	I																			
76.250	0.5024	0.9200	I																			
77.500	0.5017	0.9200	I																			
78.750	0.5007	0.9200	I																			
80.000	0.4998	0.9200	I																			
81.250	0.4991	0.9200	I																			
82.500	0.4987	0.9200	I																			
83.750	0.4987	0.9200	I																			
85.000	0.4990	0.9200	I																			
86.250	0.4994	0.9200	I																			
87.500	0.4999	0.9200	I																			
88.750	0.5003	0.9200	I																			
90.000	0.5006	0.9200	I																			
91.250	0.5006	0.9200	I																			
92.500	0.5006	0.9200	I																			
93.750	0.5004	0.9200	I																			
95.000	0.5001	0.9200	I																			
96.250	0.4999	0.9200	I																			
97.500	0.4998	0.9200	I																			
98.750	0.4997	0.9200	I																			

PART B

FEEDBACK CONTROL

(With time delays added to disturbance  
and measuring element)

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0001 PROGRAM HEATEX
0002 DIMENSION T(470), CM(470), TM(470), TO1(470), TO(470), TS(470), TT(5,400)
0003 DIMENSION TO2(470), U(470), KC(1), KI(1), KD(1), DEL(1), ER(470), FW(470)
0004 DIMENSION T1(470), X(470), X1(470), Y(470), Y1(470)
0005 REAL INTER, INTUD, INTUD1, INTOD2, INTMD, KC, KI, KD, KV, KP, KDIS, KM, KS
0006 DATA KC/3./, KI/6.5/, KD/9.5/, DEL/0.25/
0007 C PARAMETERS AND VARIABLES
0008 C CONTROLLER: KC=PROPORTIONAL GAIN
0009 C KI=INTEGRAL TIME (SEC.)
0010 C KD=DERIVATIVE TIME (SEC.)
0011 C CM=CONTROLLER OUTPUT (VOLTS-RANGE 0-10V)
0012 C CBAIS= CONTROLLER BIAS
0013 C VP, VI, VD=PROPORTIONAL, INTEGRAL, DERIVATIVE PARTS OF
0014 C CONTROLLER OUTPUT
0015 C
0016 C VALVE : THV= VALVE TIME CONSTANT (SEC.)
0017 C KV=VALVE GAIN ((LB./HR)/VOLTS)
0018 C
0019 C EXCHANGER : THP=PROCESS TIME CONSTANT (SEC.)
0020 C KP=PROCESS GAIN (DEG. F/(LB./HR))
0021 C
0022 C DISTURBANCE: THD=DISTURBANCE TIME CONSTANT (SEC.)
0023 C KDIS=DISTURBANCE GAIN (DEG. F/(LB./HR))
0024 C
0025 C MEASURING THM=MEASURING ELEMENT TIME CONSTANT (SEC.)
0026 C ELEMENT : KM=MEASURING ELEMENT GAIN (VOLTS/DEG.F)
0027 C
0028 C OTHERS : TS=SETPOINT TEMPERATURE (DEG. F)
0029 C KS=SETPOINT GAIN (DEG. F/VOLTS)
0030 C TIN=INPUT TEMPERATURE (DEG. F)
0031 C TO=OVERALL OUTPUT TEMPERATURE (DEG. F)
0032 C TO1=OUTPUT TEMPERATURE DUE TO PROCESS (DEG. F)
0033 C TO2=OUTPUT TEMPERATURE DUE TO DISTURBANCE (DEG. F)
0034 C FW=WATER INFLOW RATE (LB./HR)
0035 C
0036 TYPE 13
0037 13 FORMAT(1H1,10X,'B.- FEEDBACK CONTROL',/,10X,20('='),/,10X,
0038 + '(WITH TIME DELAYS ADDED TO DISTURBANCE & MEASURING ELEMENT)',
0039 + '/')
0040 C CONSTANTS & PARAMETERS
0041 TIN=90.
0042 THV=2.
0043 KV=151.3334
0044 THP=4.05
0045 KP=0.09691
0046 THD=0.5
0047 KDIS=0.011
0048 THM=3.
0049 KM=0.04
0050 KS=0.04
0051 CBAIS=7.5
0052 TYPE 12, KC(1), KI(1), KD(1)
0053 12 FORMAT(10X, 'PROPORTIONAL GAIN OF CONTROLLER IS SET =', F10.3,/,
0054 + 10X, 'INTEGRAL TIME OF THE CONTROLLER IS SET =', F10.3,/, 10X,
0055 + 'DERIVATIVE TIME OF THE CONTROLLER IS SET =', F10.3,/)
0056 DO 99 JK=1,2
0057 IF(JK.EQ.2)GO TO 14
  
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0058      TYPE 15
0059      GO TO 16
0060      14  TYPE 17
0061      17  FORMAT(1H1,/,9X,'REGULATOR (LOAD CHANGES)',/,10X,24(' '),/)
0062      15  FORMAT(/,10X'SERVO-MECHANISM (SETPOINT CHANGES)',/,10X,34(' '),/)
0063      C  INITIAL CONDITIONS
0064      16  ER(59)=0.
0065      U(59)=1135.
0066      FW(59)=10000.
0067      INTER=0.
0068      TU(59)=200.
0069      TO1(59)=200.
0070      TO2(59)=110.
0071      TM(59)=TO(59)*KM
0072      TS(59)=200.
0073      CM(59)=7.5
0074      INTUD=1135.
0075      INTMD=8.
0076      INTUD1=200.
0077      INTOD2=110.
0078      T(59)=0.0
0079      DO 98 JJ=49,59
0080      98  X1(JJ)=TM(59)
0081      DO 97 JI=1,59
0082      97  X(JI)=110.
0083      DO 2 I=60,461
0084      I I=I-1
0085      I1=I-59
0086      I2=I-11
0087      C  SETPOINT CHANGE
0088      FW(I)=FW(I1)
0089      TS(I)=TS(I1)
0090      IF(JK.EQ.2)GO TO 23
0091      IF(I.EQ.99)TS(I)=TS(I1)+10.
0092      23  Y1(I)=X1(I2)
0093      C  THE THREE MODE CONTROLLER
0094      ER(I)=TS(I)*KS-Y1(I)
0095      C  PROPORTIONAL
0096      VP=KC(1)*ER(I)
0097      C  INTEGRAL
0098      VI=INTER*(KQ(1)/KI(1))
0099      C  DERIVATIVE
0100      VD=(KC(1)*KD(1))*(ER(I)-ER(I1))
0101      C  P+I+D
0102      CM(I)=VP+VI+VD+CBAIS
0103      IF(CM(I).GT.10.000)CM(I)=10.0
0104      C  VALVE
0105      UD=(KV*CM(I)-U(I1))/THV
0106      U(I)=INTUD
0107      C  HEAT EXCHANGER
0108      PU=KP*U(I)+TIN
0109      TOD1=(PU-TD1(I1))/THP
0110      TUI(I)=INTOD1
0111      IF(JK.EQ.2)GO TO 20
0112      TO(I)=TO1(I)
0113      C  MEASURING ELEMENT
0114      22  TMD=(KM*TO(I)-TM(I1))/THM

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0115      1M(I)=INTMD
0116      X1(I)=TM(I)
0117      GO TO 21
0118      C  DISTURBANCE OR LOAD CHANGE
0119      20  TS(I)=TS(59)
0120      IF(I.EQ.99)FW(I)=FW(I1)-800.
0121      TOD2=(KDIS*FW(I)-TO2(I1))/TMD
0122      TO2(I)=INTOD2
0123      X(I)=TO2(I)
0124      Y(I)=X(I1)
0125      TO(I)=TO1(I)+(TO2(59)-Y(I))
0126      GO TO 22
0127      C
0128      C  EULER INTEGRATION
0129      21  T(I)=T(I1)+DEL(1)
0130      INTER=INTER+ER(I)*DEL(1)
0131      INTUD=INTUD+UD*DEL(1)
0132      INTOD1=INTOD1+TOD1*DEL(1)
0133      INTOD2=INTOD2+TOD2*DEL(1)
0134      INTMD=INTMD+TMD*DEL(1)
0135      C
0136      2   CONTINUE
0137      TYPE 18
0138      18  FORMAT(15X,'T',11X,'FW',10X,'CM',10X,'U',10X,'TO',10X,'TS',
0139      +    11X,'TM',/,10X,83('-',),/)
0140      IK=59
0141      DO 5 I=1,81
0142      T1(I)=T(IK)
0143      TT(1,I)=TO(IK)/10.-19.5
0144      TT(2,I)=TS(IK)/10.-19.5
0145      IF(JK.EQ.2)TT(2,I)=FW(IK)/10000.
0146      TYPE 11,T(IK),FW(IK),CM(IK),U(IK),TO(IK),TS(IK),TM(IK)
0147      11  FORMAT(7X,7F12,3)
0148      IK=IK+5
0149      5   CONTINUE
0150      IF(JK.EQ.2)GO TO 90
0151      TYPE 24
0152      24  FORMAT(1H1)
0153      TYPE 15
0154      TYPE 91
0155      91  FORMAT(10X,'THE ACTUAL VALUES OF (TO) & (TS) ARE GIVEN BY:'
0156      +    /,20X,'((TO) OR (TS) + 19.5) X 10.0',/)
0157      GO TO 92
0158      90  TYPE 17
0159      TYPE 93
0160      93  FORMAT(10X,'THE ACTUAL VALUES OF (TO) & (FW) ARE GIVEN BY:'
0161      +    /,20X,'((TO) + 19.5) X 10.0   AND   (FW) X 10000.0',/)
0162      92  CALL PLOT1(T1,TT,81,2,JK)
0163      99  CONTINUE
0164      END

```

B.- FEEDBACK CONTROL

(WITH TIME DELAYS ADDED TO DISTURBANCE & MEASURING ELEMENT)

PROPORTIONAL GAIN OF CONTROLLER IS SET = 3.000  
 INTEGRAL TIME OF THE CONTROLLER IS SET = 0.500  
 DERIVATIVE TIME OF THE CONTROLLER IS SET = 9.500

SERVO-MECHANISM (SETPOINT CHANGES)

T	Fw	CM	U	TO	TS	TM
0.000	10000.000	7.500	1135.000	200.000	200.000	8.000
1.250	10000.000	7.500	1135.000	199.998	200.000	8.000
2.500	10000.000	7.500	1135.000	199.997	200.000	8.000
3.750	10000.000	7.500	1135.001	199.996	200.000	8.000
5.000	10000.000	7.500	1135.017	199.995	200.000	8.000
6.250	10000.000	7.501	1135.041	199.995	200.000	8.000
7.500	10000.000	7.501	1135.067	199.996	200.000	8.000
8.750	10000.000	7.501	1135.089	199.997	200.000	8.000
10.000	10000.000	10.000	1135.106	199.999	210.000	8.000
11.250	10000.000	8.932	1255.981	201.814	210.000	8.007
12.500	10000.000	9.162	1316.480	205.428	210.000	8.054
13.750	10000.000	9.316	1362.421	209.506	210.000	8.142
15.000	10000.000	9.171	1384.364	213.459	210.000	8.259
16.250	10000.000	8.895	1377.105	216.531	210.000	8.387
17.500	10000.000	8.546	1348.115	218.240	210.000	8.504
18.750	10000.000	8.192	1305.331	218.461	210.000	8.594
20.000	10000.000	7.904	1258.606	217.349	210.000	8.643
21.250	10000.000	7.724	1217.266	215.291	210.000	8.650
22.500	10000.000	7.666	1187.958	212.798	210.000	8.620
23.750	10000.000	7.720	1174.005	210.378	210.000	8.563
25.000	10000.000	7.855	1175.251	208.448	210.000	8.493
26.250	10000.000	8.029	1188.654	207.262	210.000	8.425
27.500	10000.000	8.202	1209.368	206.893	210.000	8.371
28.750	10000.000	8.339	1231.990	207.246	210.000	8.336
30.000	10000.000	8.420	1251.695	208.107	210.000	8.323
31.250	10000.000	8.439	1265.090	209.204	210.000	8.331
32.500	10000.000	8.401	1270.621	210.270	210.000	8.352
33.750	10000.000	8.326	1268.562	211.091	210.000	8.380
35.000	10000.000	8.234	1260.646	211.544	210.000	8.406
36.250	10000.000	8.146	1249.468	211.600	210.000	8.429
37.500	10000.000	8.080	1237.826	211.314	210.000	8.441
38.750	10000.000	8.045	1228.131	210.802	210.000	8.442
40.000	10000.000	8.042	1221.996	210.205	210.000	8.435
41.250	10000.000	8.068	1220.053	209.657	210.000	8.421
42.500	10000.000	8.111	1221.995	209.260	210.000	8.405
43.750	10000.000	8.162	1226.796	209.069	210.000	8.390
45.000	10000.000	8.207	1233.036	209.087	210.000	8.380
46.250	10000.000	8.241	1239.248	209.279	210.000	8.375
47.500	10000.000	8.257	1244.216	209.577	210.000	8.375
48.750	10000.000	8.255	1247.176	209.906	210.000	8.380
50.000	10000.000	8.240	1247.886	210.196	210.000	8.388
51.250	10000.000	8.216	1246.588	210.398	210.000	8.397
52.500	10000.000	8.189	1243.878	210.488	210.000	8.405
53.750	10000.000	8.166	1240.530	210.466	210.000	8.411
55.000	10000.000	8.150	1237.310	210.356	210.000	8.413
56.250	10000.000	8.143	1234.832	210.195	210.000	8.413
57.500	10000.000	8.145	1233.457	210.024	210.000	8.410
58.750	10000.000	8.154	1233.268	209.877	210.000	8.405
60.000	10000.000	8.167	1234.099	209.780	210.000	8.401
61.250	10000.000	8.181	1235.614	209.744	210.000	8.397
62.500	10000.000	8.193	1237.395	209.764	210.000	8.394
63.750	10000.000	8.201	1239.046	209.828	210.000	8.393
65.000	10000.000	8.203	1240.262	209.915	210.000	8.394
66.250	10000.000	8.202	1240.878	210.004	210.000	8.395
67.500	10000.000	8.196	1240.873	210.078	210.000	8.398
68.750	10000.000	8.189	1240.354	210.123	210.000	8.400
70.000	10000.000	8.182	1239.509	210.137	210.000	8.402
71.250	10000.000	8.176	1238.562	210.121	210.000	8.403
72.500	10000.000	8.172	1237.716	210.084	210.000	8.404
73.750	10000.000	8.171	1237.120	210.037	210.000	8.403
75.000	10000.000	8.172	1236.851	209.990	210.000	8.402
76.250	10000.000	8.176	1236.906	209.954	210.000	8.401
77.500	10000.000	8.179	1237.219	209.932	210.000	8.400
78.750	10000.000	8.183	1237.684	209.928	210.000	8.399
80.000	10000.000	8.186	1238.184	209.938	210.000	8.398
81.250	10000.000	8.188	1238.615	209.959	210.000	8.398
82.500	10000.000	8.188	1238.903	209.985	210.000	8.398
83.750	10000.000	8.187	1239.016	210.009	210.000	8.399
85.000	10000.000	8.186	1238.960	210.027	210.000	8.400
86.250	10000.000	8.184	1238.776	210.037	210.000	8.400
87.500	10000.000	8.182	1238.522	210.038	210.000	8.401
88.750	10000.000	8.180	1238.260	210.031	210.000	8.401
90.000	10000.000	8.179	1238.043	210.019	210.000	8.401
91.250	10000.000	8.179	1237.906	210.006	210.000	8.401
92.500	10000.000	8.180	1237.863	209.993	210.000	8.401
93.750	10000.000	8.181	1237.905	209.984	210.000	8.400
95.000	10000.000	8.182	1238.010	209.980	210.000	8.400
96.250	10000.000	8.183	1238.148	209.980	210.000	8.400
97.500	10000.000	8.184	1238.285	209.984	210.000	8.399
98.750	10000.000	8.184	1238.394	209.991	210.000	8.399



SERVO-MECHANISM (SETPOINT CHANGES)

THE ACTUAL VALUES OF (TO) & (TS) ARE GIVEN BY:  
 ((TO) OR (TS) + 19.5) X 10.0

(OUTPUTS SCALED BY .100E+01)

(X INDICATES MORE THAN ONE VARIABLE HAS THE GIVEN VALUE)

0 + =====>

T	TO(+)	TS(-)	0.00	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50
0.00	0.5000	0.5000	I	X									
1.25	0.4998	0.5000	I	X									
2.50	0.4997	0.5000	I	X									
3.75	0.4996	0.5000	I	X									
5.00	0.4995	0.5000	I	X									
6.25	0.4995	0.5000	I	X									
7.50	0.4996	0.5000	I	X									
8.75	0.4997	0.5000	I	X									
10.00	0.4999	1.5000	I										
11.25	0.6814	1.5000	I										
12.50	1.0428	1.5000	I										
13.75	1.4506	1.5000	I										
15.00	1.8459	1.5000	I										
16.25	2.1531	1.5000	I										
17.50	2.3240	1.5000	I										
18.75	2.3461	1.5000	I										
20.00	2.2349	1.5000	I										
21.25	2.0291	1.5000	I										
22.50	1.7798	1.5000	I										
23.75	1.5378	1.5000	I										
25.00	1.3448	1.5000	I										
26.25	1.2262	1.5000	I										
27.50	1.1893	1.5000	I										
28.75	1.2246	1.5000	I										
30.00	1.3107	1.5000	I										
31.25	1.4204	1.5000	I										
32.50	1.5276	1.5000	I										
33.75	1.6091	1.5000	I										
35.00	1.6544	1.5000	I										
36.25	1.6600	1.5000	I										
37.50	1.6314	1.5000	I										
38.75	1.5802	1.5000	I										
40.00	1.5205	1.5000	I										
41.25	1.4657	1.5000	I										
42.50	1.4260	1.5000	I										
43.75	1.4069	1.5000	I										
45.00	1.4087	1.5000	I										
46.25	1.4279	1.5000	I										
47.50	1.4577	1.5000	I										
48.75	1.4906	1.5000	I										
50.00	1.5196	1.5000	I										
51.25	1.5398	1.5000	I										
52.50	1.5488	1.5000	I										
53.75	1.5466	1.5000	I										
55.00	1.5356	1.5000	I										
56.25	1.5195	1.5000	I										
57.50	1.5024	1.5000	I										
58.75	1.4877	1.5000	I										
60.00	1.4780	1.5000	I										
61.25	1.4744	1.5000	I										
62.50	1.4764	1.5000	I										
63.75	1.4828	1.5000	I										
65.00	1.4915	1.5000	I										
66.25	1.5004	1.5000	I										
67.50	1.5078	1.5000	I										
68.75	1.5123	1.5000	I										
70.00	1.5137	1.5000	I										
71.25	1.5121	1.5000	I										
72.50	1.5084	1.5000	I										
73.75	1.5037	1.5000	I										
75.00	1.4990	1.5000	I										
76.25	1.4954	1.5000	I										
77.50	1.4932	1.5000	I										
78.75	1.4928	1.5000	I										
80.00	1.4938	1.5000	I										
81.25	1.4959	1.5000	I										
82.50	1.4985	1.5000	I										
83.75	1.5009	1.5000	I										
85.00	1.5027	1.5000	I										
86.25	1.5037	1.5000	I										
87.50	1.5038	1.5000	I										
88.75	1.5031	1.5000	I										
90.00	1.5019	1.5000	I										
91.25	1.5006	1.5000	I										
92.50	1.4993	1.5000	I										
93.75	1.4984	1.5000	I										
95.00	1.4980	1.5000	I										
96.25	1.4960	1.5000	I										
97.50	1.4984	1.5000	I										
98.75	1.4991	1.5000	I										
100.00	1.4998	1.5000	I										

REGULATOR (LOAD CHANGES)

T	FW	CM	U	TO	TS	TM
0.000	10000.000	7.500	1135.000	200.000	200.000	8.000
1.250	10000.000	7.500	1135.000	199.998	200.000	8.000
2.500	10000.000	7.500	1135.000	199.997	200.000	8.000
3.750	10000.000	7.500	1135.001	199.996	200.000	8.000
5.000	10000.000	7.500	1135.017	199.995	200.000	8.000
6.250	10000.000	7.501	1135.041	199.995	200.000	8.000
7.500	10000.000	7.501	1135.067	199.996	200.000	8.000
8.750	10000.000	7.501	1135.089	199.997	200.000	8.000
10.000	9200.000	7.501	1135.106	199.999	200.000	8.000
11.250	9200.000	7.501	1135.113	200.000	200.000	8.000
12.500	9200.000	7.501	1135.112	200.001	200.000	8.000
13.750	9200.000	7.501	1135.104	200.002	200.000	8.000
15.000	9200.000	7.500	1135.092	200.002	200.000	8.000
16.250	9200.000	7.500	1135.079	200.002	200.000	8.000
17.500	9200.000	7.500	1135.068	200.001	200.000	8.000
18.750	9200.000	7.500	1135.060	200.001	200.000	8.000
20.000	9200.000	7.500	1135.056	200.000	200.000	8.000
21.250	9200.000	7.500	1135.057	199.999	200.000	8.000
22.500	9200.000	7.500	1135.061	199.999	200.000	8.000
23.750	9200.000	7.501	1135.067	199.999	200.000	8.000
25.000	9200.000	7.501	1135.074	204.399	200.000	8.000
26.250	9200.000	7.501	1135.079	208.800	200.000	8.139
27.500	9200.000	7.501	1135.083	208.937	200.000	8.216
28.750	9200.000	6.207	1085.348	208.552	200.000	8.269
30.000	9200.000	6.392	1019.647	206.301	200.000	8.285
31.250	9200.000	6.218	983.346	203.348	200.000	8.254
32.500	9200.000	6.213	958.142	200.342	200.000	8.188
33.750	9200.000	6.381	953.967	197.728	200.000	8.104
35.000	9200.000	6.597	967.757	195.980	200.000	8.017
36.250	9200.000	6.835	992.961	195.270	200.000	7.943
37.500	9200.000	7.044	1023.388	195.549	200.000	7.893
38.750	9200.000	7.185	1052.175	196.596	200.000	7.872
40.000	9200.000	7.244	1074.030	198.077	200.000	7.878
41.250	9200.000	7.224	1085.976	199.832	200.000	7.905
42.500	9200.000	7.143	1087.421	200.948	200.000	7.945
43.750	9200.000	7.028	1079.962	201.815	200.000	7.986
45.000	9200.000	6.907	1066.635	202.146	200.000	8.022
46.250	9200.000	6.805	1051.117	201.973	200.000	8.046
47.500	9200.000	6.740	1036.876	201.422	200.000	8.055
48.750	9200.000	6.717	1026.530	200.672	200.000	8.051
50.000	9200.000	6.735	1021.473	199.909	200.000	8.037
51.250	9200.000	6.783	1021.813	199.288	200.000	8.017
52.500	9200.000	6.846	1026.568	198.911	200.000	7.997
53.750	9200.000	6.910	1034.052	198.812	200.000	7.981
55.000	9200.000	6.961	1042.319	198.966	200.000	7.971
56.250	9200.000	6.991	1049.602	199.299	200.000	7.968
57.500	9200.000	6.999	1054.625	199.716	200.000	7.972
58.750	9200.000	6.986	1056.775	200.120	200.000	7.981
60.000	9200.000	6.958	1056.111	200.435	200.000	7.992
61.250	9200.000	6.924	1053.236	200.612	200.000	8.003
62.500	9200.000	6.891	1049.089	200.640	200.000	8.012
63.750	9200.000	6.865	1044.701	200.538	200.000	8.016
65.000	9200.000	6.851	1040.975	200.349	200.000	8.017
66.250	9200.000	6.849	1038.534	200.124	200.000	8.015
67.500	9200.000	6.857	1037.638	199.913	200.000	8.010
68.750	9200.000	6.873	1038.203	199.756	200.000	8.003
70.000	9200.000	6.891	1039.867	199.674	200.000	7.996
71.250	9200.000	6.908	1042.115	199.670	200.000	7.994
72.500	9200.000	6.921	1044.406	199.732	200.000	7.991
73.750	9200.000	6.927	1046.278	199.837	200.000	7.991
75.000	9200.000	6.927	1047.435	199.956	200.000	7.993
76.250	9200.000	6.922	1047.770	200.063	200.000	7.996
77.500	9200.000	6.913	1047.356	200.140	200.000	7.999
78.750	9200.000	6.904	1046.402	200.176	200.000	8.002
80.000	9200.000	6.895	1045.188	200.171	200.000	8.004
81.250	9200.000	6.889	1043.998	200.133	200.000	8.005
82.500	9200.000	6.886	1043.063	200.075	200.000	8.005
83.750	9200.000	6.886	1042.524	200.013	200.000	8.004
85.000	9200.000	6.890	1042.419	199.958	200.000	8.002
86.250	9200.000	6.894	1042.698	199.921	200.000	8.000
87.500	9200.000	6.900	1043.239	199.905	200.000	7.999
88.750	9200.000	6.904	1043.891	199.911	200.000	7.998
90.000	9200.000	6.907	1044.507	199.934	200.000	7.997
91.250	9200.000	6.908	1044.971	199.966	200.000	7.998
92.500	9200.000	6.908	1045.218	199.999	200.000	7.998
93.750	9200.000	6.906	1045.235	200.026	200.000	7.999
95.000	9200.000	6.903	1045.059	200.044	200.000	8.000
96.250	9200.000	6.900	1044.756	200.050	200.000	8.001
97.500	9200.000	6.898	1044.408	200.045	200.000	8.001
98.750	9200.000	6.897	1044.092	200.032	200.000	8.001
100.000	9200.000	6.896	1043.665	200.015	200.000	8.001

REGULATOR (LOAD CHANGES)

THE ACTUAL VALUES OF (TO) & (FW) ARE GIVEN BY:  
 ((TO) + 19.5) X 10.0 AND (FW) X 10000.0

(OUTPUTS SCALED BY .100E+01)

(X INDICATES MORE THAN ONE VARIABLE HAS THE GIVEN VALUE)

T	TO(+)	TS(.)	0 + *****																		
			0.00	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50								
0.00	0.5000	1.0000	I																		
1.25	0.4998	1.0000	I																		
2.50	0.4997	1.0000	I																		
3.75	0.4996	1.0000	I																		
5.00	0.4995	1.0000	I																		
6.25	0.4995	1.0000	I																		
7.50	0.4996	1.0000	I																		
8.75	0.4997	1.0000	I																		
10.00	0.4999	0.9200	I																		
11.25	0.5000	0.9200	I																		
12.50	0.5001	0.9200	I																		
13.75	0.5002	0.9200	I																		
15.00	0.5002	0.9200	I																		
16.25	0.5002	0.9200	I																		
17.50	0.5001	0.9200	I																		
18.75	0.5001	0.9200	I																		
20.00	0.5000	0.9200	I																		
21.25	0.4999	0.9200	I																		
22.50	0.4999	0.9200	I																		
23.75	0.4999	0.9200	I																		
25.00	0.9399	0.9200	I																		
26.25	1.3800	0.9200	I																		
27.50	1.3937	0.9200	I																		
28.75	1.3552	0.9200	I																		
30.00	1.1301	0.9200	I																		
31.25	0.8348	0.9200	I																		
32.50	0.5342	0.9200	I																		
33.75	0.2728	0.9200	I																		
35.00	0.0980	0.9200	I +																		
36.25	0.0270	0.9200	I +																		
37.50	0.0549	0.9200	I +																		
38.75	0.1596	0.9200	I																		
40.00	0.3077	0.9200	I																		
41.25	0.4632	0.9200	I																		
42.50	0.5948	0.9200	I																		
43.75	0.6815	0.9200	I																		
45.00	0.7146	0.9200	I																		
46.25	0.6973	0.9200	I																		
47.50	0.6422	0.9200	I																		
48.75	0.5672	0.9200	I																		
50.00	0.4909	0.9200	I																		
51.25	0.4288	0.9200	I																		
52.50	0.3911	0.9200	I																		
53.75	0.3812	0.9200	I																		
55.00	0.3966	0.9200	I																		
56.25	0.4299	0.9200	I																		
57.50	0.4716	0.9200	I																		
58.75	0.5121	0.9200	I																		
60.00	0.5435	0.9200	I																		
61.25	0.5612	0.9200	I																		
62.50	0.5640	0.9200	I																		
63.75	0.5538	0.9200	I																		
65.00	0.5349	0.9200	I																		
66.25	0.5124	0.9200	I																		
67.50	0.4913	0.9200	I																		
68.75	0.4750	0.9200	I																		
70.00	0.4674	0.9200	I																		
71.25	0.4670	0.9200	I																		
72.50	0.4732	0.9200	I																		
73.75	0.4837	0.9200	I																		
75.00	0.4956	0.9200	I																		
76.25	0.5063	0.9200	I																		
77.50	0.5140	0.9200	I																		
78.75	0.5176	0.9200	I																		
80.00	0.5171	0.9200	I																		
81.25	0.5133	0.9200	I																		
82.50	0.5075	0.9200	I																		
83.75	0.5013	0.9200	I																		
85.00	0.4958	0.9200	I																		
86.25	0.4921	0.9200	I																		
87.50	0.4905	0.9200	I																		
88.75	0.4918	0.9200	I																		
90.00	0.4934	0.9200	I																		
91.25	0.4966	0.9200	I																		
92.50	0.4999	0.9200	I																		
93.75	0.5026	0.9200	I																		
95.00	0.5044	0.9200	I																		
96.25	0.5050	0.9200	I																		
97.50	0.5045	0.9200	I																		
98.75	0.5032	0.9200	I																		
100.00	0.5015	0.9200	I																		

PART C

FEEDFORWARD CONTROL

30-AUG-1983 17:52:38  
30-AUG-1983 17:52:25

```
0001 PROGRAM HEATEX
0002 DIMENSION T(410), CM(410), TM(410), TO(410), TS(410), TT(5,400)
0003 DIMENSION U(410), DEL(1), FW(410), ZN(410), CLL(410), T1(410)
0004 DIMENSION TO1(410), TO2(410)
0005 REAL INTUD, INTOD1, INTOD2, INTMD, KV, KP, KM, KS, KFF, KDIS
0006 DATA DEL/0.25/
0007 C PARAMETERS AND VARIABLES
0008 C CONTROLLER: CP=HEAT CAPACITY OF WATER (BTU/(LB.DEG. F))
0009 C HS=LATENT HEAT OF STEAM (BTU/LB.)
0010 C KFF=CONTROLLER GAIN
0011 C CM=CONTROLLER OUTPUT (VOLTS-RANGE 0-10V)
0012 C CLL=DYNAMIC COMPENSATION TERM
0013 C TH1=LEAD TIME CONSTANT (SEC.)
0014 C TH2=LAG TIME CONSTANT (SEC.)
0015 C
0016 C VALVE : PHV= VALVE TIME CONSTANT (SEC.)
0017 C KV=VALVE GAIN ((LB./HR)/VOLTS)
0018 C
0019 C EXCHANGER : THP=PROCESS TIME CONSTANT (SEC.)
0020 C KP=PROCESS GAIN (DEG. F/(LB./HR))
0021 C
0022 C DISTURBANCE: THD=DISTURBANCE TIME CONSTANT (SEC.)
0023 C KDIS=DISTURBANCE GAIN (DEG. F/(LB./HR))
0024 C
0025 C MEASURING THM=MEASURING ELEMENT TIME CONSTANT (SEC.)
0026 C ELEMENT : KM=MEASURING ELEMENT GAIN (VOLTS/DEG.F)
0027 C
0028 C OTHERS : TS=SETPOINT TEMPERATURE (DEG. F)
0029 C KS=SETPOINT GAIN (DEG. F/VOLTS)
0030 C TIN=INPUT TEMPERATURE (DEG. F)
0031 C TO=OVERALL OUTPUT TEMPERATURE (DEG. F)
0032 C TO1=OUTPUT TEMPERATURE DUE TO PROCESS (DEG. F)
0033 C TO2=OUTPUT TEMPERATURE DUE TO DISTURBANCE (DEG. F)
0034 C FW=WATER INFLOW RATE (LB./HR)
0035 C
0036 TYPE 6
0037 6 FORMAT(1H1,/,10X,'C.- FEEDFORWARD CONTROL',/,10X,23('-',),/)
0038 C CONSTANTS & PARAMETERS
0039 HS=970.
0040 CP=1.
0041 TIN=90.
0042 THV=2.
0043 KV=135.9605
0044 THP=4.05
0045 KP=0.09709
0046 THM=0.5
0047 KM=0.00083333
0048 KDIS=0.011
0049 THD=0.5
0050 KS=0.04
0051 TH2=1.5
0052 TH1=7.5
0053 DU 98 JK=1,2
0054 DU 98 JK=1,2
0055 IF (JK.EQ.2) GO TO 7
0056 IF (JK.EQ.2) TYPE 25
0057 25 FORMAT(1H1,//)
```

HEATEX

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30-AUG-1983 17:52:25

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0058      TYPE 8
0059      8   FORMAT(10X,'SERVO-MECHANISM (SETPOINT CHANGES)',/,10X,34('-'))
0060      GO TO 9
0061      7   TYPE 10
0062      10  FORMAT(1H1,/,10X,'REGULATOR (LOAD CHANGES)',/,10X,24('-'))
0063      9   IF(JJ.EQ.2)GO TO 12
0064      TYPE 14
0065      14  FORMAT(10X,'WITHOUT DYNAMIC COMPENSATION',/,10X,28('-'),/)
0066      GO TO 19
0067      12  TYPE 15
0068      15  FORMAT(10X,'WITH DYNAMIC COMPENSATION',/,10X,25('-'),/)
0069      C   INITIAL CONDITIONS
0070      19  U(1)=1133.
0071      FW(1)=10000.
0072      TO(1)=200.
0073      TU1(1)=200.
0074      TO2(1)=0.
0075      TM(1)=FW(1)*KM
0076      TS(1)=200.
0077      CM(1)=8.3333
0078      KFF=HS/(TS(1)-TIN)
0079      ZN(1)=TM(1)
0080      CLL(1)=ZN(1)
0081      INTUD=1133.
0082      INTUD1=200.
0083      INTOD2=110.
0084      INTMD=8.3333
0085      T(1)=0.0
0086      DO 2 I=2,401
0087      II=I-1
0088      TS(I)=TS(II)
0089      IF(JK.EQ.1)GO TO 20
0090      FW(I)=FW(II)
0091      IF(I.EQ.100)FW(I)=FW(II)-800.
0092      GO TO 21
0093      20  IF(I.EQ.100)TS(I)=TS(II)+10.
0094      FW(I)=FW(1)
0095      C   MEASURING ELEMENT
0096      21  TMD=(KM*FW(I)-TM(II))/THM
0097      TM(I)=INIMD
0098      IF(JJ.EQ.2)GO TO 22
0099      C   FEEDFORWAR CONTROLLER WITHOUT DYNAMIC COMPENSATION
0100      CM(I)=TM(I)*KFF*(CP/HS)*(TS(II)-TIN)
0101      GO TO 23
0102      C
0103      22  AA=TM(II)-ZN(II)
0104      ZN(I)=((DEL(1)/TH2)*AA)+ZN(II)
0105      CLL(I)=((TH1/TH2)*AA)+ZN(II)
0106      C   FEEDFORWAR CONTROLLER WITH DYNAMIC COMPENSATION
0107      CM(I)=CLL(I)*KFF*(CP/HS)*(TS(II)-TIN)
0108      C   VALVE
0109      23  UD=(KV*CM(I)-U(II))/THV
0110      U(I)=INTUD
0111      C   HEAT EXCHANGER
0112      PU=KP*U(I)+TIN
0113      TUD1=(PU-TU1(II))/IHP
0114      TU1(I)=INTUD1

```

HEATEX

30-AUG-1983 17:52:38  
30-AUG-1983 17:52:25

```
0115      IF(JK.EQ.2)GO TO 17
0116      TO(I)=TO1(I)
0117      GO TO 18
0118      17      TU2(1)=110.
0119      TOD2=(KDIS*FW(I)-TO2(I))/THD
0120      TO2(I)=INTOD2
0121      TO(I)=TO1(I)+(TO2(1)-TO2(I))
0122      C
0123      C EULER INTEGRATION
0124      18      T(I)=T(I1)+DEL(1)
0125      INTUD=INTUD+UD*DEL(1)
0126      INTOD1=INTOD1+TOD1*DEL(1)
0127      INTOD2=INTOD2+TOD2*DEL(1)
0128      INTMD=INTMD+TMD*DEL(1)
0129      2      CONTINUE
0130      TYPE 16
0131      16      FORMAT(15X,'T',9X,'FW',12X,'CM',10X,'U',11X,'TO',10X,
0132      + 'TS',/,10X,70(' '),/)
0133      IK=1
0134      DU 5 I=1,81
0135      T1(I)=T(IK)
0136      TT(1,I)=TO(IK)/10.-19.5
0137      TT(2,I)=FW(IK)/10000.
0138      IF(JK.EQ.1)TT(2,I)=TS(IK)/10.-19.5
0139      TYPE 11,T(IK),FW(IK),CM(IK),U(IK),TO(IK),TS(IK)
0140      11      FORMAT(7X,6F12.3)
0141      IK=IK+5
0142      5      CONTINUE
0143      IF(JK.EQ.2)GO TO 90
0144      TYPE 24
0145      24      FORMAT(IH1)
0146      TYPE 8
0147      TYPE 91
0148      91      FORMAT(10X,'THE ACTUAL VALUES OF (TO) & (TS) ARE GIVEN BY:'
0149      + /,20X,'( (TO OR (TS) + 19.5) X 10.0',/)
0150      GO TO 92
0151      90      TYPE 10
0152      TYPE 93
0153      93      FORMAT(10X,'THE ACTUAL VALUES OF (TO) & (FW) ARE GIVEN BY:'
0154      + /,20X,'( (TO + 19.5 ) X 10.0      AND      (FW) X 10000.0',/)
0155      92      CALL PLOT1(T1,TT,81,2,JK)
0156      99      CONTINUE
0157      98      CONTINUE
0158      END
```

C. - FEEDFORWARD CONTROL

SERVO-MECHANISM (SETPOINT CHANGES)

WITHOUT DYNAMIC COMPENSATION

T	Fw	CM	U	TU	TS
0.000	10000.000	8.333	1133.000	200.000	200.000
1.250	10000.000	8.333	1133.000	200.001	200.000
2.500	10000.000	8.333	1133.000	200.001	200.000
3.750	10000.000	8.333	1133.000	200.002	200.000
5.000	10000.000	8.333	1133.000	200.002	200.000
6.250	10000.000	8.333	1133.000	200.002	200.000
7.500	10000.000	8.333	1133.000	200.003	200.000
8.750	10000.000	8.333	1133.000	200.003	200.000
10.000	10000.000	8.333	1133.000	200.003	200.000
11.250	10000.000	8.333	1133.000	200.003	200.000
12.500	10000.000	8.333	1133.000	200.003	200.000
13.750	10000.000	8.333	1133.000	200.003	200.000
15.000	10000.000	8.333	1133.000	200.003	200.000
16.250	10000.000	8.333	1133.000	200.003	200.000
17.500	10000.000	8.333	1133.000	200.003	200.000
18.750	10000.000	8.333	1133.000	200.003	200.000
20.000	10000.000	8.333	1133.000	200.003	200.000
21.250	10000.000	8.333	1133.000	200.003	200.000
22.500	10000.000	8.333	1133.000	200.003	200.000
23.750	10000.000	8.333	1133.000	200.003	200.000
25.000	10000.000	9.091	1133.000	200.003	210.000
26.250	10000.000	9.091	1187.920	200.717	210.000
27.500	10000.000	9.091	1214.217	202.406	210.000
28.750	10000.000	9.091	1226.131	204.153	210.000
30.000	10000.000	9.091	1231.528	205.642	210.000
31.250	10000.000	9.091	1233.974	206.812	210.000
32.500	10000.000	9.091	1235.082	207.694	210.000
33.750	10000.000	9.091	1235.584	208.343	210.000
35.000	10000.000	9.091	1235.811	208.815	210.000
36.250	10000.000	9.091	1235.914	209.156	210.000
37.500	10000.000	9.091	1235.961	209.399	210.000
38.750	10000.000	9.091	1235.982	209.573	210.000
40.000	10000.000	9.091	1235.992	209.697	210.000
41.250	10000.000	9.091	1235.996	209.786	210.000
42.500	10000.000	9.091	1235.998	209.849	210.000
43.750	10000.000	9.091	1235.999	209.893	210.000
45.000	10000.000	9.091	1235.999	209.925	210.000
46.250	10000.000	9.091	1235.999	209.948	210.000
47.500	10000.000	9.091	1235.999	209.964	210.000
48.750	10000.000	9.091	1235.999	209.975	210.000
50.000	10000.000	9.091	1235.999	209.983	210.000
51.250	10000.000	9.091	1235.999	209.989	210.000
52.500	10000.000	9.091	1235.999	209.993	210.000
53.750	10000.000	9.091	1235.999	209.996	210.000
55.000	10000.000	9.091	1235.999	209.998	210.000
56.250	10000.000	9.091	1235.999	210.000	210.000
57.500	10000.000	9.091	1235.999	210.001	210.000
58.750	10000.000	9.091	1235.999	210.001	210.000
60.000	10000.000	9.091	1235.999	210.002	210.000
61.250	10000.000	9.091	1235.999	210.002	210.000
62.500	10000.000	9.091	1235.999	210.003	210.000
63.750	10000.000	9.091	1235.999	210.003	210.000
65.000	10000.000	9.091	1235.999	210.003	210.000
66.250	10000.000	9.091	1235.999	210.003	210.000
67.500	10000.000	9.091	1235.999	210.003	210.000
68.750	10000.000	9.091	1235.999	210.003	210.000
70.000	10000.000	9.091	1235.999	210.003	210.000
71.250	10000.000	9.091	1235.999	210.003	210.000
72.500	10000.000	9.091	1235.999	210.003	210.000
73.750	10000.000	9.091	1235.999	210.003	210.000
75.000	10000.000	9.091	1235.999	210.003	210.000
76.250	10000.000	9.091	1235.999	210.003	210.000
77.500	10000.000	9.091	1235.999	210.003	210.000
78.750	10000.000	9.091	1235.999	210.003	210.000
80.000	10000.000	9.091	1235.999	210.003	210.000
81.250	10000.000	9.091	1235.999	210.003	210.000
82.500	10000.000	9.091	1235.999	210.003	210.000
83.750	10000.000	9.091	1235.999	210.003	210.000
85.000	10000.000	9.091	1235.999	210.003	210.000
86.250	10000.000	9.091	1235.999	210.003	210.000
87.500	10000.000	9.091	1235.999	210.003	210.000
88.750	10000.000	9.091	1235.999	210.003	210.000
90.000	10000.000	9.091	1235.999	210.003	210.000
91.250	10000.000	9.091	1235.999	210.003	210.000
92.500	10000.000	9.091	1235.999	210.003	210.000
93.750	10000.000	9.091	1235.999	210.003	210.000
95.000	10000.000	9.091	1235.999	210.003	210.000
96.250	10000.000	9.091	1235.999	210.003	210.000
97.500	10000.000	9.091	1235.999	210.003	210.000
98.750	10000.000	9.091	1235.999	210.003	210.000
100.000	10000.000	9.091	1235.999	210.003	210.000



SERVO-MECHANISM (SETPOINT CHANGES)

THE ACTUAL VALUES OF (TO) & (TS) ARE GIVEN BY:  
 ((TO OR (TS) + 19.5) X 10.0

(OUTPUTS SCALED BY .100E+01)

(X INDICATES MORE THAN ONE VARIABLE HAVE THE GIVEN VALUE)

0 + >>>>

T	TO(+)	TS(.)	0.00	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50
0.00	0.500	0.500	I		X								
1.25	0.500	0.500	I		X								
2.50	0.500	0.500	I		X								
3.75	0.500	0.500	I		X								
5.00	0.500	0.500	I		X								
6.25	0.500	0.500	I		X								
7.50	0.500	0.500	I		X								
8.75	0.500	0.500	I		X								
10.00	0.500	0.500	I		X								
11.25	0.500	0.500	I		X								
12.50	0.500	0.500	I		X								
13.75	0.500	0.500	I		X								
15.00	0.500	0.500	I		X								
16.25	0.500	0.500	I		X								
17.50	0.500	0.500	I		X								
18.75	0.500	0.500	I		X								
20.00	0.500	0.500	I		X								
21.25	0.500	0.500	I		X								
22.50	0.500	0.500	I		X								
23.75	0.500	0.500	I		X								
25.00	0.500	1.500	I			+							
26.25	0.572	1.500	I										
27.50	0.741	1.500	I			+							
28.75	0.915	1.500	I				+						
30.00	1.064	1.500	I					+					
31.25	1.181	1.500	I						+				
32.50	1.269	1.500	I							+			
33.75	1.334	1.500	I								+		
35.00	1.382	1.500	I									+	
36.25	1.416	1.500	I										+
37.50	1.440	1.500	I										+
38.75	1.457	1.500	I										+
40.00	1.470	1.500	I										+
41.25	1.479	1.500	I										+
42.50	1.485	1.500	I										X
43.75	1.489	1.500	I										X
45.00	1.493	1.500	I										X
46.25	1.495	1.500	I										X
47.50	1.496	1.500	I										X
48.75	1.498	1.500	I										X
50.00	1.498	1.500	I										X
51.25	1.499	1.500	I										X
52.50	1.499	1.500	I										X
53.75	1.500	1.500	I										X
55.00	1.500	1.500	I										X
56.25	1.500	1.500	I										X
57.50	1.500	1.500	I										X
58.75	1.500	1.500	I										X
60.00	1.500	1.500	I										X
61.25	1.500	1.500	I										X
62.50	1.500	1.500	I										X
63.75	1.500	1.500	I										X
65.00	1.500	1.500	I										X
66.25	1.500	1.500	I										X
67.50	1.500	1.500	I										X
68.75	1.500	1.500	I										X
70.00	1.500	1.500	I										X
71.25	1.500	1.500	I										X
72.50	1.500	1.500	I										X
73.75	1.500	1.500	I										X
75.00	1.500	1.500	I										X
76.25	1.500	1.500	I										X
77.50	1.500	1.500	I										X
78.75	1.500	1.500	I										X
80.00	1.500	1.500	I										X
81.25	1.500	1.500	I										X
82.50	1.500	1.500	I										X
83.75	1.500	1.500	I										X
85.00	1.500	1.500	I										X
86.25	1.500	1.500	I										X
87.50	1.500	1.500	I										X
88.75	1.500	1.500	I										X
90.00	1.500	1.500	I										X
91.25	1.500	1.500	I										X
92.50	1.500	1.500	I										X
93.75	1.500	1.500	I										X
95.00	1.500	1.500	I										X
96.25	1.500	1.500	I										X
97.50	1.500	1.500	I										X
98.75	1.500	1.500	I										X
100.00	1.500	1.500	I										X

REGULATOR (LOAD CHANGES)

WITHOUT DYNAMIC COMPENSATION

T	FW	CM	U	TO	TS
0.000	10000.000	8.333	1133.000	200.000	200.000
1.250	10000.000	8.333	1133.000	200.001	200.000
2.500	10000.000	8.333	1133.000	200.001	200.000
3.750	10000.000	8.333	1133.000	200.002	200.000
5.000	10000.000	8.333	1133.000	200.002	200.000
6.250	10000.000	8.333	1133.000	200.002	200.000
7.500	10000.000	8.333	1133.000	200.003	200.000
8.750	10000.000	8.333	1133.000	200.003	200.000
10.000	10000.000	8.333	1133.000	200.003	200.000
11.250	10000.000	8.333	1133.000	200.003	200.000
12.500	10000.000	8.333	1133.000	200.003	200.000
13.750	10000.000	8.333	1133.000	200.003	200.000
15.000	10000.000	8.333	1133.000	200.003	200.000
16.250	10000.000	8.333	1133.000	200.003	200.000
17.500	10000.000	8.333	1133.000	200.003	200.000
18.750	10000.000	8.333	1133.000	200.003	200.000
20.000	10000.000	8.333	1133.000	200.003	200.000
21.250	10000.000	8.333	1133.000	200.003	200.000
22.500	10000.000	8.333	1133.000	200.003	200.000
23.750	10000.000	8.333	1133.000	200.003	200.000
25.000	9200.000	8.000	1133.000	204.403	200.000
26.250	9200.000	7.667	1081.572	208.240	200.000
27.500	9200.000	7.666	1061.453	206.826	200.000
28.750	9200.000	7.669	1050.737	205.108	200.000
30.000	9200.000	7.666	1046.182	203.834	200.000
31.250	9200.000	7.667	1044.093	202.801	200.000
32.500	9200.000	7.667	1043.144	202.026	200.000
33.750	9200.000	7.667	1042.715	201.457	200.000
35.000	9200.000	7.667	1042.521	201.043	200.000
36.250	9200.000	7.667	1042.433	200.745	200.000
37.500	9200.000	7.667	1042.393	200.532	200.000
38.750	9200.000	7.667	1042.375	200.379	200.000
40.000	9200.000	7.667	1042.367	200.270	200.000
41.250	9200.000	7.667	1042.363	200.193	200.000
42.500	9200.000	7.667	1042.361	200.138	200.000
43.750	9200.000	7.667	1042.360	200.099	200.000
45.000	9200.000	7.667	1042.360	200.071	200.000
46.250	9200.000	7.667	1042.360	200.051	200.000
47.500	9200.000	7.667	1042.360	200.037	200.000
48.750	9200.000	7.667	1042.360	200.027	200.000
50.000	9200.000	7.667	1042.360	200.020	200.000
51.250	9200.000	7.667	1042.360	200.015	200.000
52.500	9200.000	7.667	1042.360	200.012	200.000
53.750	9200.000	7.667	1042.360	200.009	200.000
55.000	9200.000	7.667	1042.360	200.007	200.000
56.250	9200.000	7.667	1042.360	200.006	200.000
57.500	9200.000	7.667	1042.360	200.005	200.000
58.750	9200.000	7.667	1042.360	200.004	200.000
60.000	9200.000	7.667	1042.360	200.004	200.000
61.250	9200.000	7.667	1042.360	200.004	200.000
62.500	9200.000	7.667	1042.360	200.003	200.000
63.750	9200.000	7.667	1042.360	200.003	200.000
65.000	9200.000	7.667	1042.360	200.003	200.000
66.250	9200.000	7.667	1042.360	200.003	200.000
67.500	9200.000	7.667	1042.360	200.003	200.000
68.750	9200.000	7.667	1042.360	200.003	200.000
70.000	9200.000	7.667	1042.360	200.003	200.000
71.250	9200.000	7.667	1042.360	200.003	200.000
72.500	9200.000	7.667	1042.360	200.003	200.000
73.750	9200.000	7.667	1042.360	200.003	200.000
75.000	9200.000	7.667	1042.360	200.003	200.000
76.250	9200.000	7.667	1042.360	200.003	200.000
77.500	9200.000	7.667	1042.360	200.003	200.000
78.750	9200.000	7.667	1042.360	200.003	200.000
80.000	9200.000	7.667	1042.360	200.003	200.000
81.250	9200.000	7.667	1042.360	200.003	200.000
82.500	9200.000	7.667	1042.360	200.003	200.000
83.750	9200.000	7.667	1042.360	200.003	200.000
85.000	9200.000	7.667	1042.360	200.003	200.000
86.250	9200.000	7.667	1042.360	200.003	200.000
87.500	9200.000	7.667	1042.360	200.003	200.000
88.750	9200.000	7.667	1042.360	200.003	200.000
90.000	9200.000	7.667	1042.360	200.003	200.000
91.250	9200.000	7.667	1042.360	200.003	200.000
92.500	9200.000	7.667	1042.360	200.003	200.000
93.750	9200.000	7.667	1042.360	200.003	200.000
95.000	9200.000	7.667	1042.360	200.003	200.000
96.250	9200.000	7.667	1042.360	200.003	200.000
97.500	9200.000	7.667	1042.360	200.003	200.000
98.750	9200.000	7.667	1042.360	200.003	200.000
100.000	9200.000	7.667	1042.360	200.003	200.000

REGULATOR (LOAD CHANGES)

THE ACTUAL VALUES OF (TO) & (FW) ARE GIVEN BY:

( (TO) + 19.5 ) X 10.0 AND (FW) X 10000.0

(OUTPUTS SCALED BY .100E+01)

(X INDICATES MORE THAN ONE VARIABLE HAVE THE GIVEN VALUE)

0 + >>>>>

T	TO(+)	FW(.)	0.00	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50
0.00	0.500	1.000	I										
1.25	0.500	1.000	I										
2.50	0.500	1.000	I										
3.75	0.500	1.000	I										
5.00	0.500	1.000	I										
6.25	0.500	1.000	I										
7.50	0.500	1.000	I										
8.75	0.500	1.000	I										
10.00	0.500	1.000	I										
11.25	0.500	1.000	I										
12.50	0.500	1.000	I										
13.75	0.500	1.000	I										
15.00	0.500	1.000	I										
16.25	0.500	1.000	I										
17.50	0.500	1.000	I										
18.75	0.500	1.000	I										
20.00	0.500	1.000	I										
21.25	0.500	1.000	I										
22.50	0.500	1.000	I										
23.75	0.500	1.000	I										
25.00	0.940	0.920	I										
26.25	1.324	0.920	I										
27.50	1.183	0.920	I										
28.75	1.011	0.920	I										
30.00	0.883	0.920	I										
31.25	0.780	0.920	I										
32.50	0.703	0.920	I										
33.75	0.646	0.920	I										
35.00	0.604	0.920	I										
36.25	0.575	0.920	I										
37.50	0.553	0.920	I										
38.75	0.538	0.920	I										
40.00	0.527	0.920	I										
41.25	0.519	0.920	I										
42.50	0.514	0.920	I										
43.75	0.510	0.920	I										
45.00	0.507	0.920	I										
46.25	0.505	0.920	I										
47.50	0.504	0.920	I										
48.75	0.503	0.920	I										
50.00	0.502	0.920	I										
51.25	0.501	0.920	I										
52.50	0.501	0.920	I										
53.75	0.501	0.920	I										
55.00	0.501	0.920	I										
56.25	0.501	0.920	I										
57.50	0.500	0.920	I										
58.75	0.500	0.920	I										
60.00	0.500	0.920	I										
61.25	0.500	0.920	I										
62.50	0.500	0.920	I										
63.75	0.500	0.920	I										
65.00	0.500	0.920	I										
66.25	0.500	0.920	I										
67.50	0.500	0.920	I										
68.75	0.500	0.920	I										
70.00	0.500	0.920	I										
71.25	0.500	0.920	I										
72.50	0.500	0.920	I										
73.75	0.500	0.920	I										
75.00	0.500	0.920	I										
76.25	0.500	0.920	I										
77.50	0.500	0.920	I										
78.75	0.500	0.920	I										
80.00	0.500	0.920	I										
81.25	0.500	0.920	I										
82.50	0.500	0.920	I										
83.75	0.500	0.920	I										
85.00	0.500	0.920	I										
86.25	0.500	0.920	I										
87.50	0.500	0.920	I										
88.75	0.500	0.920	I										
90.00	0.500	0.920	I										
91.25	0.500	0.920	I										
92.50	0.500	0.920	I										
93.75	0.500	0.920	I										
95.00	0.500	0.920	I										
96.25	0.500	0.920	I										
97.50	0.500	0.920	I										
98.75	0.500	0.920	I										
100.00	0.500	0.920	I										

## SERVO-MECHANISM (SETPOINT CHANGES)

## WITH DYNAMIC COMPENSATION

T	Fw <sup>2</sup>	CM	U	TO	IS
0.000	10000.000	8.333	1133.000	200.000	200.000
1.250	10000.000	8.333	1133.000	200.001	200.000
2.500	10000.000	8.333	1133.000	200.001	200.000
3.750	10000.000	8.333	1133.000	200.002	200.000
5.000	10000.000	8.333	1133.000	200.002	200.000
6.250	10000.000	8.333	1133.000	200.002	200.000
7.500	10000.000	8.333	1133.000	200.003	200.000
8.750	10000.000	8.333	1133.000	200.003	200.000
10.000	10000.000	8.333	1133.000	200.003	200.000
11.250	10000.000	8.333	1133.000	200.003	200.000
12.500	10000.000	8.333	1133.000	200.003	200.000
13.750	10000.000	8.333	1133.000	200.003	200.000
15.000	10000.000	8.333	1133.000	200.003	200.000
16.250	10000.000	8.333	1133.000	200.003	200.000
17.500	10000.000	8.333	1133.000	200.003	200.000
18.750	10000.000	8.333	1133.000	200.003	200.000
20.000	10000.000	8.333	1133.000	200.003	200.000
21.250	10000.000	8.333	1133.000	200.003	200.000
22.500	10000.000	8.333	1133.000	200.003	200.000
23.750	10000.000	8.333	1133.000	200.003	200.000
25.000	10000.000	9.091	1133.000	200.003	210.000
26.250	10000.000	9.091	1187.920	200.717	210.000
27.500	10000.000	9.091	1214.217	202.406	210.000
28.750	10000.000	9.091	1226.131	204.153	210.000
30.000	10000.000	9.091	1231.528	205.642	210.000
31.250	10000.000	9.091	1231.974	206.812	210.000
32.500	10000.000	9.091	1235.082	207.694	210.000
33.750	10000.000	9.091	1235.584	208.343	210.000
35.000	10000.000	9.091	1235.811	208.815	210.000
36.250	10000.000	9.091	1235.914	209.156	210.000
37.500	10000.000	9.091	1235.961	209.399	210.000
38.750	10000.000	9.091	1235.982	209.573	210.000
40.000	10000.000	9.091	1235.992	209.697	210.000
41.250	10000.000	9.091	1235.996	209.786	210.000
42.500	10000.000	9.091	1235.998	209.849	210.000
43.750	10000.000	9.091	1235.999	209.893	210.000
45.000	10000.000	9.091	1235.999	209.925	210.000
46.250	10000.000	9.091	1235.999	209.948	210.000
47.500	10000.000	9.091	1235.999	209.964	210.000
48.750	10000.000	9.091	1235.999	209.975	210.000
50.000	10000.000	9.091	1235.999	209.983	210.000
51.250	10000.000	9.091	1235.999	209.989	210.000
52.500	10000.000	9.091	1235.999	209.993	210.000
53.750	10000.000	9.091	1235.999	209.996	210.000
55.000	10000.000	9.091	1235.999	209.996	210.000
56.250	10000.000	9.091	1235.999	210.000	210.000
57.500	10000.000	9.091	1235.999	210.001	210.000
58.750	10000.000	9.091	1235.999	210.001	210.000
60.000	10000.000	9.091	1235.999	210.002	210.000
61.250	10000.000	9.091	1235.999	210.002	210.000
62.500	10000.000	9.091	1235.999	210.003	210.000
63.750	10000.000	9.091	1235.999	210.003	210.000
65.000	10000.000	9.091	1235.999	210.003	210.000
66.250	10000.000	9.091	1235.999	210.003	210.000
67.500	10000.000	9.091	1235.999	210.003	210.000
68.750	10000.000	9.091	1235.999	210.003	210.000
70.000	10000.000	9.091	1235.999	210.003	210.000
71.250	10000.000	9.091	1235.999	210.003	210.000
72.500	10000.000	9.091	1235.999	210.003	210.000
73.750	10000.000	9.091	1235.999	210.003	210.000
75.000	10000.000	9.091	1235.999	210.003	210.000
76.250	10000.000	9.091	1235.999	210.003	210.000
77.500	10000.000	9.091	1235.999	210.003	210.000
78.750	10000.000	9.091	1235.999	210.003	210.000
80.000	10000.000	9.091	1235.999	210.003	210.000
81.250	10000.000	9.091	1235.999	210.003	210.000
82.500	10000.000	9.091	1235.999	210.003	210.000
83.750	10000.000	9.091	1235.999	210.003	210.000
85.000	10000.000	9.091	1235.999	210.003	210.000
86.250	10000.000	9.091	1235.999	210.003	210.000
87.500	10000.000	9.091	1235.999	210.003	210.000
88.750	10000.000	9.091	1235.999	210.003	210.000
90.000	10000.000	9.091	1235.999	210.003	210.000
91.250	10000.000	9.091	1235.999	210.003	210.000
92.500	10000.000	9.091	1235.999	210.003	210.000
93.750	10000.000	9.091	1235.999	210.003	210.000
95.000	10000.000	9.091	1235.999	210.003	210.000
96.250	10000.000	9.091	1235.999	210.003	210.000
97.500	10000.000	9.091	1235.999	210.003	210.000
98.750	10000.000	9.091	1235.999	210.003	210.000
100.000	10000.000	9.091	1235.999	210.003	210.000

SERVO-MECHANISM (SETPOINT CHANGES)

THE ACTUAL VALUES OF (TO) & (TS) ARE GIVEN BY:  
 ((TO OR (TS) + 19.5) X 10.0

(OUTPUTS SCALED BY .100E+01)  
 (X INDICATES MORE THAN ONE VARIABLE HAVE THE GIVEN VALUE)  
 0 + =====>

T	TO(+)	TS(.)	0.00	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50
0.00	0.500	0.500	I		X								
1.25	0.500	0.500	I		X								
2.50	0.500	0.500	I		X								
3.75	0.500	0.500	I		X								
5.00	0.500	0.500	I		X								
6.25	0.500	0.500	I		X								
7.50	0.500	0.500	I		X								
8.75	0.500	0.500	I		X								
10.00	0.500	0.500	I		X								
11.25	0.500	0.500	I		X								
12.50	0.500	0.500	I		X								
13.75	0.500	0.500	I		X								
15.00	0.500	0.500	I		X								
16.25	0.500	0.500	I		X								
17.50	0.500	0.500	I		X								
18.75	0.500	0.500	I		X								
20.00	0.500	0.500	I		X								
21.25	0.500	0.500	I		X								
22.50	0.500	0.500	I		X								
23.75	0.500	0.500	I		X								
25.00	0.500	1.500	I			+							
26.25	0.572	1.500	I										
27.50	0.741	1.500	I				+						
28.75	0.915	1.500	I					+					
30.00	1.064	1.500	I						+				
31.25	1.181	1.500	I							+			
32.50	1.269	1.500	I								+		
33.75	1.334	1.500	I									+	
35.00	1.382	1.500	I										+
36.25	1.416	1.500	I										+
37.50	1.440	1.500	I										+
38.75	1.457	1.500	I										+
40.00	1.470	1.500	I										+
41.25	1.479	1.500	I										+
42.50	1.485	1.500	I										X
43.75	1.489	1.500	I										X
45.00	1.493	1.500	I										X
46.25	1.495	1.500	I										X
47.50	1.496	1.500	I										X
48.75	1.498	1.500	I										X
50.00	1.498	1.500	I										X
51.25	1.499	1.500	I										X
52.50	1.499	1.500	I										X
53.75	1.500	1.500	I										X
55.00	1.500	1.500	I										X
56.25	1.500	1.500	I										X
57.50	1.500	1.500	I										X
58.75	1.500	1.500	I										X
60.00	1.500	1.500	I										X
61.25	1.500	1.500	I										X
62.50	1.500	1.500	I										X
63.75	1.500	1.500	I										X
65.00	1.500	1.500	I										X
66.25	1.500	1.500	I										X
67.50	1.500	1.500	I										X
68.75	1.500	1.500	I										X
70.00	1.500	1.500	I										X
71.25	1.500	1.500	I										X
72.50	1.500	1.500	I										X
73.75	1.500	1.500	I										X
75.00	1.500	1.500	I										X
76.25	1.500	1.500	I										X
77.50	1.500	1.500	I										X
78.75	1.500	1.500	I										X
80.00	1.500	1.500	I										X
81.25	1.500	1.500	I										X
82.50	1.500	1.500	I										X
83.75	1.500	1.500	I										X
85.00	1.500	1.500	I										X
86.25	1.500	1.500	I										X
87.50	1.500	1.500	I										X
88.75	1.500	1.500	I										X
90.00	1.500	1.500	I										X
91.25	1.500	1.500	I										X
92.50	1.500	1.500	I										X
93.75	1.500	1.500	I										X
95.00	1.500	1.500	I										X
96.25	1.500	1.500	I										X
97.50	1.500	1.500	I										X
98.75	1.500	1.500	I										X
100.00	1.500	1.500	I										X

## REGULATOR (LOAD CHANGES)

## WITH DYNAMIC COMPENSATION

ΔT	F <sub>w</sub>	CM	U	T0	T5
0.000	10000.000	8.333	1133.000	200.000	200.000
1.250	10000.000	8.333	1133.000	200.001	200.000
2.500	10000.000	8.333	1133.000	200.001	200.000
3.750	10000.000	8.333	1133.000	200.002	200.000
5.000	10000.000	8.333	1133.000	200.002	200.000
6.250	10000.000	8.333	1133.000	200.002	200.000
7.500	10000.000	8.333	1133.000	200.003	200.000
8.750	10000.000	8.333	1133.000	200.003	200.000
10.000	10000.000	8.333	1133.000	200.003	200.000
11.250	10000.000	8.333	1133.000	200.003	200.000
12.500	10000.000	8.333	1133.000	200.003	200.000
13.750	10000.000	8.333	1133.000	200.003	200.000
15.000	10000.000	8.333	1133.000	200.003	200.000
16.250	10000.000	8.333	1133.000	200.003	200.000
17.500	10000.000	8.333	1133.000	200.003	200.000
18.750	10000.000	8.333	1133.000	200.003	200.000
20.000	10000.000	8.333	1133.000	200.003	200.000
21.250	10000.000	8.333	1133.000	200.003	200.000
22.500	10000.000	8.333	1133.000	200.003	200.000
23.750	10000.000	8.333	1133.000	200.003	200.000
25.000	9200.000	8.333	1133.000	204.403	200.000
26.250	9200.000	6.039	952.927	207.331	200.000
27.500	9200.000	7.150	941.974	202.347	200.000
28.750	9200.000	7.484	968.884	198.989	200.000
30.000	9200.000	7.583	999.018	197.623	200.000
31.250	9200.000	7.635	1018.507	197.337	200.000
32.500	9200.000	7.654	1029.865	197.565	200.000
33.750	9200.000	7.661	1036.024	198.014	200.000
35.000	9200.000	7.665	1039.217	198.454	200.000
36.250	9200.000	7.666	1040.827	198.835	200.000
37.500	9200.000	7.666	1041.621	199.141	200.000
38.750	9200.000	7.666	1042.007	199.375	200.000
40.000	9200.000	7.667	1042.193	199.549	200.000
41.250	9200.000	7.667	1042.281	199.677	200.000
42.500	9200.000	7.667	1042.323	199.770	200.000
43.750	9200.000	7.667	1042.343	199.836	200.000
45.000	9200.000	7.667	1042.352	199.884	200.000
46.250	9200.000	7.667	1042.356	199.918	200.000
47.500	9200.000	7.667	1042.357	199.943	200.000
48.750	9200.000	7.667	1042.358	199.960	200.000
50.000	9200.000	7.667	1042.359	199.972	200.000
51.250	9200.000	7.667	1042.359	199.981	200.000
52.500	9200.000	7.667	1042.359	199.987	200.000
53.750	9200.000	7.667	1042.359	199.992	200.000
55.000	9200.000	7.667	1042.359	199.995	200.000
56.250	9200.000	7.667	1042.359	199.997	200.000
57.500	9200.000	7.667	1042.359	199.999	200.000
58.750	9200.000	7.667	1042.359	200.000	200.000
60.000	9200.000	7.667	1042.359	200.001	200.000
61.250	9200.000	7.667	1042.359	200.001	200.000
62.500	9200.000	7.667	1042.359	200.002	200.000
63.750	9200.000	7.667	1042.359	200.002	200.000
65.000	9200.000	7.667	1042.359	200.002	200.000
66.250	9200.000	7.667	1042.359	200.002	200.000
67.500	9200.000	7.667	1042.359	200.002	200.000
68.750	9200.000	7.667	1042.359	200.002	200.000
70.000	9200.000	7.667	1042.359	200.003	200.000
71.250	9200.000	7.667	1042.359	200.003	200.000
72.500	9200.000	7.667	1042.359	200.003	200.000
73.750	9200.000	7.667	1042.359	200.003	200.000
75.000	9200.000	7.667	1042.359	200.003	200.000
76.250	9200.000	7.667	1042.359	200.003	200.000
77.500	9200.000	7.667	1042.359	200.003	200.000
78.750	9200.000	7.667	1042.359	200.003	200.000
80.000	9200.000	7.667	1042.359	200.003	200.000
81.250	9200.000	7.667	1042.359	200.003	200.000
82.500	9200.000	7.667	1042.359	200.003	200.000
83.750	9200.000	7.667	1042.359	200.003	200.000
85.000	9200.000	7.667	1042.359	200.003	200.000
86.250	9200.000	7.667	1042.359	200.003	200.000
87.500	9200.000	7.667	1042.359	200.003	200.000
88.750	9200.000	7.667	1042.359	200.003	200.000
90.000	9200.000	7.667	1042.359	200.003	200.000
91.250	9200.000	7.667	1042.359	200.003	200.000
92.500	9200.000	7.667	1042.359	200.003	200.000
93.750	9200.000	7.667	1042.359	200.003	200.000
95.000	9200.000	7.667	1042.359	200.003	200.000
96.250	9200.000	7.667	1042.359	200.003	200.000
97.500	9200.000	7.667	1042.359	200.003	200.000
98.750	9200.000	7.667	1042.359	200.003	200.000
100.000	9200.000	7.667	1042.359	200.003	200.000

REGULATOR (LOAD CHANGES)

THE ACTUAL VALUES OF (TO) & (FW) ARE GIVEN BY:  
 ( (TO) + 19.5 ) X 10.0      AND      (FW) X 10000.0

(OUTPUTS SCALED BY .100E+01)  
 (X INDICATES MORE THAN ONE VARIABLE HAVE THE GIVEN VALUE)

T	FO(+)	FW(.)	0 + =====>																		
			0.00	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25									
0.00	0.500	1.000	I																		
1.25	0.500	1.000	I																		
2.50	0.500	1.000	I																		
3.75	0.500	1.000	I																		
5.00	0.500	1.000	I																		
6.25	0.500	1.000	I																		
7.50	0.500	1.000	I																		
8.75	0.500	1.000	I																		
10.00	0.500	1.000	I																		
11.25	0.500	1.000	I																		
12.50	0.500	1.000	I																		
13.75	0.500	1.000	I																		
15.00	0.500	1.000	I																		
16.25	0.500	1.000	I																		
17.50	0.500	1.000	I																		
18.75	0.500	1.000	I																		
20.00	0.500	1.000	I																		
21.25	0.500	1.000	I																		
22.50	0.500	1.000	I																		
23.75	0.500	1.000	I																		
25.00	0.940	0.920	I																		
26.25	1.233	0.920	I																		
27.50	0.735	0.920	I																		
28.75	0.399	0.920	I																		
30.00	0.262	0.920	I																		
31.25	0.234	0.920	I																		
32.50	0.259	0.920	I																		
33.75	0.301	0.920	I																		
35.00	0.345	0.920	I																		
36.25	0.384	0.920	I																		
37.50	0.414	0.920	I																		
38.75	0.437	0.920	I																		
40.00	0.455	0.920	I																		
41.25	0.468	0.920	I																		
42.50	0.477	0.920	I																		
43.75	0.484	0.920	I																		
45.00	0.488	0.920	I																		
46.25	0.492	0.920	I																		
47.50	0.494	0.920	I																		
48.75	0.496	0.920	I																		
50.00	0.497	0.920	I																		
51.25	0.498	0.920	I																		
52.50	0.499	0.920	I																		
53.75	0.499	0.920	I																		
55.00	0.499	0.920	I																		
56.25	0.500	0.920	I																		
57.50	0.500	0.920	I																		
58.75	0.500	0.920	I																		
60.00	0.500	0.920	I																		
61.25	0.500	0.920	I																		
62.50	0.500	0.920	I																		
63.75	0.500	0.920	I																		
65.00	0.500	0.920	I																		
66.25	0.500	0.920	I																		
67.50	0.500	0.920	I																		
68.75	0.500	0.920	I																		
70.00	0.500	0.920	I																		
71.25	0.500	0.920	I																		
72.50	0.500	0.920	I																		
73.75	0.500	0.920	I																		
75.00	0.500	0.920	I																		
76.25	0.500	0.920	I																		
77.50	0.500	0.920	I																		
78.75	0.500	0.920	I																		
80.00	0.500	0.920	I																		
81.25	0.500	0.920	I																		
82.50	0.500	0.920	I																		
83.75	0.500	0.920	I																		
85.00	0.500	0.920	I																		
86.25	0.500	0.920	I																		
87.50	0.500	0.920	I																		
88.75	0.500	0.920	I																		
90.00	0.500	0.920	I																		
91.25	0.500	0.920	I																		
92.50	0.500	0.920	I																		
93.75	0.500	0.920	I																		
95.00	0.500	0.920	I																		
96.25	0.500	0.920	I																		
97.50	0.500	0.920	I																		
98.75	0.500	0.920	I																		
100.00	0.500	0.920	I																		

PART D

FEEDFORWARD CONTROL

(With time delays added to the disturbance).



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0001 PROGRAM HEATEX
0002 DIMENSION T(470), CM(470), TH(470), TO(470), TS(470), TT(5,405)
0003 DIMENSION U(470), DEL(1), FW(470), ZN(470), CLL(470), T1(470)
0004 DIMENSION TO1(470), TO2(470), X(470), Y(470)
0005 REAL INTUD, INTOD1, INTOD2, INTMD, KV, KP, KM, KS, KFF, KDIS
0006 DATA DEL/0.25/

0007 C PARAMETERS AND VARIABLES
0008 C CONTROLLER: CP=HEAT CAPACITY OF WATER (BTU/(LB.DEG. F))
0009 C HS=LATENT HEAT OF STEAM (BTU/LB.)
0010 C KFF=CONTROLLER GAIN
0011 C CM=CONTROLLER OUTPUT (VOLTS=RANGE 0-10V)
0012 C CLL=DYNAMIC COMPENSATION TERM
0013 C TH1=LEAD TIME CONSTANT (SEC.)
0014 C TH2=LAG TIME CONSTANT (SEC.)
0015 C
0016 C VALVE : THV= VALVE TIME CONSTANT (SEC.)
0017 C KV=VALVE GAIN ((LB./HR)/VOLTS)
0018 C
0019 C EXCHANGER : THP=PROCESS TIME CONSTANT (SEC.)
0020 C KP=PROCESS GAIN (DEG. F/(LB./HR))
0021 C
0022 C DISTURBANCE: THD=DISTURBANCE TIME CONSTANT (SEC.)
0023 C KDIS=DISTURBANCE GAIN (DEG. F/(LB./HR))
0024 C
0025 C MEASURING THM=MEASURING ELEMENT TIME CONSTANT (SEC.)
0026 C ELEMENT : KM=MEASURING ELEMENT GAIN (VOLTS/DEG.F)
0027 C
0028 C OTHERS : TS=SEIPOINT TEMPERATURE (DEG. F)
0029 C TIN=INPUT TEMPERATURE (DEG. F)
0030 C TO=OVERALL OUTPUT TEMPERATURE (DEG. F)
0031 C TO1=OUTPUT TEMPERATURE DUE TO PROCESS (DEG. F)
0032 C TO2=OUTPUT TEMPERATURE DUE TO DISTURBANCE (DEG. F)
0033 C FW=WATER INFLOW RATE (LB./HR)
0034 C
0035 TYPE 6
0036 o FORMAT(1H1,/,/,10X,'D.- FEEDFORWARD CONTROL',/,10X,23('-'),/,
0037 + 10X,'(WITH TIME DELAYS ADDED TO THE DISTURBANCE)',/)
0038 C CONSTANTS & PARAMETERS
0039 HS=970.
0040 CP=1.
0041 TIN=90.
0042 THV=2.
0043 KV=135.9605
0044 THP=4.05
0045 KP=0.09709
0046 THM=0.5
0047 KM=0.00083333
0048 KDIS=0.011
0049 THD=0.5
0050 TH2=13.
0051 TH1=3.
0052 DU 97 JI=1,59
0053 97 X(JI)=110.
0054 DU 98 JJ=1,2
0055 DU 99 JK=1,2
0056 IF(JK.EQ.2)GO TO 7
0057 IF(JJ.EQ.2)TYPE 25
  
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0058      25      FORMAT(1H1,/)
0059              TYPE 8
0060      8        FORMAT(10X,'SERVO-MECHANISM (SETPOINT CHANGES)',/,10X,34('-'))
0061              GO TO 9
0062      7        TYPE 10
0063      10       FORMAT(1H1,/,10X,'REGULATOR (LOAD CHANGES)',/,10X,24('-'))
0064      9        IF(JJ.EQ.2)GO TU 12
0065              TYPE 14
0066      14       FORMAT(10X,'WITHOUT DYNAMIC COMPENSATION',/,10X,28('-'),/)
0067              GO TO 19
0068      12       TYPE 15
0069      15       FORMAT(10X,'WITH DYNAMIC COMPENSATION',/,10X,25('-'),/)
0070      C        INITIAL CONDITIONS
0071      19       U(59)=1133.
0072              FW(59)=10000.
0073              TO(59)=200.
0074              TO1(59)=200.
0075              TO2(59)=0.
0076              TM(59)=FW(59)*KM
0077              TS(59)=200.
0078              CM(59)=8.3333
0079              KFF=HS/(TS(59)-TIN)
0080              ZN(59)=TM(59)
0081              CLL(59)=ZN(59)
0082              INTUD=1133.
0083              INTOD1=200.
0084              INTOD2=110.
0085              INTMD=8.3333
0086              T(59)=0.0
0087              DO 2 I=60,461
0088              II=I-1
0089              I1=I-59
0090              TS(I)=TS(II)
0091              IF(JK.EQ.1)GO TO 20
0092              FW(I)=FW(II)
0093              IF(I.EQ.159)FW(I)=FW(II)-800.
0094              GO TU 21
0095      20       IF(I.EQ.159)TS(I)=TS(II)+10.
0096              FW(I)=FW(59)
0097      C        MEASURING ELEMENT
0098      21       TMD=(KM*FW(I)-TM(II))/THM
0099              TM(I)=INTMD
0100              IF(JJ.EQ.2)GO TO 22
0101      C        FEEDFORWAR CONTROLLER, WITHOUT DYNAMIC COMPENSATION
0102              CM(I)=TM(I)*KFF*(CP/HS)*(TS(II)-IIN)
0103              GO TU 23
0104      C        DYNAMIC COMPENSATION(LEAD/LAG)
0105      22       AA=TM(II)-ZN(II)
0106              ZN(I)=((DEL(I)/TH2)*AA)+ZN(II)
0107              CLL(I)=((TH1/TH2)*AA)+ZN(II)
0108      C        FEEDFORWAR CONTROLLER WITH DYNAMIC COMPENSATION
0109              CM(I)=CLL(I)*KFF*(CP/HS)*(TS(II)-TIN)
0110      C        VALVE
0111      23       UD=(KV*CM(I)-U(II))/THV
0112              U(I)=INTUD
0113      C        HEAT EXCHANGER
0114              PU=KP*U(I)+TIN

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HEATEX

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0115      TOD1=(PO-101(II))/THP
0116      TO1(I)=INTOD1
0117      IF(JK.EQ.2)GO TO 17
0118      TO(I)=TO1(I)
0119      GO TO 18
0120      17      TO2(59)=110.
0121      TOD2=(KDIS*FW(I)-TO2(II))/THD
0122      TO2(I)=INTO02
0123      C TIME DELAY ON THE DISTURBANCE
0124      X(I)=TO2(I)
0125      Y(I)=X(I1)
0126      TO(I)=TO1(I)+(TO2(59)-Y(I))
0127      C EULER INTEGRATION
0128      18      T(I)=T(II)+DEL(1)
0129      INTUD=INTUD+UD*DEL(1)
0130      INTOD1=INTOD1+TOD1*DEL(1)
0131      INTOD2=INTOD2+TOD2*DEL(1)
0132      INTMD=INTMD+TMD*DEL(1)
0133      2      CONTINUE
0134      TYPE 16
0135      16      FORMAT(15X,'T',9X,'FW',12X,'CM'10X,'U',11X,'FO',10X,
0136      + 'TS',/,10X,70(' '),/)
0137      IK=59
0138      DO 5 I=1,81
0139      T1(I)=T(IK)
0140      TT(1,I)=TO(IK)/10.-19.5
0141      TT(2,I)=FW(IK)/10000.
0142      IF(JK.EQ.1)TT(2,I)=TS(IK)/10.-19.5
0143      TYPE 11,T(IK),FW(IK),CM(IK),U(IK),TO(IK),TS(IK)
0144      11      FORMAT(7X,6F12.3)
0145      IK=IK+5
0146      5      CONTINUE
0147      IF(JK.EQ.2)GO TO 90
0148      TYPE 24
0149      24      FORMAT(1H1)
0150      TYPE 8
0151      TYPE 91
0152      91      FORMAT(10X,'THE ACTUAL VALUES OF (TO) & (TS) ARE GIVEN BY:'
0153      + /,20X,'((TO) OR (TS) + 19.5) X 10.0',/)
0154      GO TO 92
0155      90      TYPE 10
0156      TYPE 93
0157      93      FORMAT(10X,'THE ACTUAL VALUES OF (TO) & (FW) ARE GIVEN BY:'
0158      + /,20X,'((TO) + 19.5) X 10.0 . AND (FW) X 10000.0',/)
0159      92      CALL PLOT1(T1,TT,81,2,JK)
0160      99      CONTINUE
0161      98      CONTINUE
0162      END

```

D.- FEEDFORWARD CONTROL

(WITH TIME DELAYS ADDED TO THE DISTURBANCE)

SERVO-MECHANISM (SETPOINT CHANGES)

WITHOUT DYNAMIC COMPENSATION

L	FW	CM	U	TU	TS
0.000	10000.000	8.333	1133.000	200.000	200.000
1.250	10000.000	8.333	1133.000	200.001	200.000
2.500	10000.000	8.333	1133.000	200.001	200.000
3.750	10000.000	8.333	1133.000	200.002	200.000
5.000	10000.000	8.333	1133.000	200.002	200.000
6.250	10000.000	8.333	1133.000	200.002	200.000
7.500	10000.000	8.333	1133.000	200.003	200.000
8.750	10000.000	8.333	1133.000	200.003	200.000
10.000	10000.000	8.333	1133.000	200.003	200.000
11.250	10000.000	8.333	1133.000	200.003	200.000
12.500	10000.000	8.333	1133.000	200.003	200.000
13.750	10000.000	8.333	1133.000	200.003	200.000
15.000	10000.000	8.333	1133.000	200.003	200.000
16.250	10000.000	8.333	1133.000	200.003	200.000
17.500	10000.000	8.333	1133.000	200.003	200.000
18.750	10000.000	8.333	1133.000	200.003	200.000
20.000	10000.000	8.333	1133.000	200.003	200.000
21.250	10000.000	8.333	1133.000	200.003	200.000
22.500	10000.000	8.333	1133.000	200.003	200.000
23.750	10000.000	8.333	1133.000	200.003	200.000
25.000	10000.000	8.333	1133.000	200.003	210.000
26.250	10000.000	9.091	1179.672	200.451	210.000
27.500	10000.000	9.091	1210.479	202.046	210.000
28.750	10000.000	9.091	1224.438	204.419	210.000
30.000	10000.000	9.091	1230.761	205.369	210.000
31.250	10000.000	9.091	1233.626	206.602	210.000
32.500	10000.000	9.091	1234.924	207.538	210.000
33.750	10000.000	9.091	1235.512	208.229	210.000
35.000	10000.000	9.091	1235.779	208.733	210.000
36.250	10000.000	9.091	1235.900	209.096	210.000
37.500	10000.000	9.091	1235.954	209.357	210.000
38.750	10000.000	9.091	1235.979	209.543	210.000
40.000	10000.000	9.091	1235.990	209.676	210.000
41.250	10000.000	9.091	1235.995	209.770	210.000
42.500	10000.000	9.091	1235.998	209.838	210.000
43.750	10000.000	9.091	1235.999	209.888	210.000
45.000	10000.000	9.091	1235.999	209.920	210.000
46.250	10000.000	9.091	1235.999	209.944	210.000
47.500	10000.000	9.091	1235.999	209.961	210.000
48.750	10000.000	9.091	1235.999	209.973	210.000
50.000	10000.000	9.091	1235.999	209.982	210.000
51.250	10000.000	9.091	1235.999	209.988	210.000
52.500	10000.000	9.091	1235.999	209.992	210.000
53.750	10000.000	9.091	1235.999	209.996	210.000
55.000	10000.000	9.091	1235.999	209.998	210.000
56.250	10000.000	9.091	1235.999	209.999	210.000
57.500	10000.000	9.091	1235.999	210.000	210.000
58.750	10000.000	9.091	1235.999	210.001	210.000
60.000	10000.000	9.091	1235.999	210.002	210.000
61.250	10000.000	9.091	1235.999	210.002	210.000
62.500	10000.000	9.091	1235.999	210.002	210.000
63.750	10000.000	9.091	1235.999	210.003	210.000
65.000	10000.000	9.091	1235.999	210.003	210.000
66.250	10000.000	9.091	1235.999	210.003	210.000
67.500	10000.000	9.091	1235.999	210.003	210.000
68.750	10000.000	9.091	1235.999	210.003	210.000
70.000	10000.000	9.091	1235.999	210.003	210.000
71.250	10000.000	9.091	1235.999	210.003	210.000
72.500	10000.000	9.091	1235.999	210.003	210.000
73.750	10000.000	9.091	1235.999	210.003	210.000
75.000	10000.000	9.091	1235.999	210.003	210.000
76.250	10000.000	9.091	1235.999	210.003	210.000
77.500	10000.000	9.091	1235.999	210.003	210.000
78.750	10000.000	9.091	1235.999	210.003	210.000
80.000	10000.000	9.091	1235.999	210.003	210.000
81.250	10000.000	9.091	1235.999	210.003	210.000
82.500	10000.000	9.091	1235.999	210.003	210.000
83.750	10000.000	9.091	1235.999	210.003	210.000
85.000	10000.000	9.091	1235.999	210.003	210.000
86.250	10000.000	9.091	1235.999	210.003	210.000
87.500	10000.000	9.091	1235.999	210.003	210.000
88.750	10000.000	9.091	1235.999	210.003	210.000
90.000	10000.000	9.091	1235.999	210.003	210.000
91.250	10000.000	9.091	1235.999	210.003	210.000
92.500	10000.000	9.091	1235.999	210.003	210.000
93.750	10000.000	9.091	1235.999	210.003	210.000
95.000	10000.000	9.091	1235.999	210.003	210.000
96.250	10000.000	9.091	1235.999	210.003	210.000
97.500	10000.000	9.091	1235.999	210.003	210.000
98.750	10000.000	9.091	1235.999	210.003	210.000
100.000	10000.000	9.091	1235.999	210.003	210.000

SERVO-MECHANISM (SETPOINT CHANGES)

THE ACTUAL VALUES OF (TO) & (TS) ARE GIVEN BY:  
 ((TO) OR (TS) + 19.5) X 10.0

(OUTPUTS SCALED BY .100E+01)

(X INDICATES MORE THAN ONE VARIABLE HAVE THE GIVEN VALUE)

0 + =====>

T	TO(+)	TS(.)	0.00	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50
0.00	0.500	0.500	I		X								
1.25	0.500	0.500	I		X								
2.50	0.500	0.500	I		X								
3.75	0.500	0.500	I		X								
5.00	0.500	0.500	I		X								
6.25	0.500	0.500	I		X								
7.50	0.500	0.500	I		X								
8.75	0.500	0.500	I		X								
10.00	0.500	0.500	I		X								
11.25	0.500	0.500	I		X								
12.50	0.500	0.500	I		X								
13.75	0.500	0.500	I		X								
15.00	0.500	0.500	I		X								
16.25	0.500	0.500	I		X								
17.50	0.500	0.500	I		X								
18.75	0.500	0.500	I		X								
20.00	0.500	0.500	I		X								
21.25	0.500	0.500	I		X								
22.50	0.500	0.500	I		X								
23.75	0.500	0.500	I		X								
25.00	0.500	1.500	I										
26.25	0.545	1.500	I										
27.50	0.705	1.500	I										
28.75	0.842	1.500	I										
30.00	1.037	1.500	I										
31.25	1.160	1.500	I										
32.50	1.254	1.500	I										
33.75	1.323	1.500	I										
35.00	1.373	1.500	I										
36.25	1.410	1.500	I										
37.50	1.436	1.500	I										
38.75	1.454	1.500	I										
40.00	1.468	1.500	I										
41.25	1.477	1.500	I										
42.50	1.484	1.500	I										
43.75	1.489	1.500	I										
45.00	1.492	1.500	I										
46.25	1.494	1.500	I										
47.50	1.496	1.500	I										
48.75	1.497	1.500	I										
50.00	1.498	1.500	I										
51.25	1.499	1.500	I										
52.50	1.499	1.500	I										
53.75	1.500	1.500	I										
55.00	1.500	1.500	I										
56.25	1.500	1.500	I										
57.50	1.500	1.500	I										
58.75	1.500	1.500	I										
60.00	1.500	1.500	I										
61.25	1.500	1.500	I										
62.50	1.500	1.500	I										
63.75	1.500	1.500	I										
65.00	1.500	1.500	I										
66.25	1.500	1.500	I										
67.50	1.500	1.500	I										
68.75	1.500	1.500	I										
70.00	1.500	1.500	I										
71.25	1.500	1.500	I										
72.50	1.500	1.500	I										
73.75	1.500	1.500	I										
75.00	1.500	1.500	I										
76.25	1.500	1.500	I										
77.50	1.500	1.500	I										
78.75	1.500	1.500	I										
80.00	1.500	1.500	I										
81.25	1.500	1.500	I										
82.50	1.500	1.500	I										
83.75	1.500	1.500	I										
85.00	1.500	1.500	I										
86.25	1.500	1.500	I										
87.50	1.500	1.500	I										
88.75	1.500	1.500	I										
90.00	1.500	1.500	I										
91.25	1.500	1.500	I										
92.50	1.500	1.500	I										
93.75	1.500	1.500	I										
95.00	1.500	1.500	I										
96.25	1.500	1.500	I										
97.50	1.500	1.500	I										
98.75	1.500	1.500	I										
100.00	1.500	1.500	I										

REGULATOR (LOAD CHANGES)

WITHOUT DYNAMIC COMPENSATION

T	PW	CH	U	FO	TS
0.000	10000.000	8.333	1133.000	200.000	200.000
1.250	10000.000	8.333	1133.000	200.001	200.000
2.500	10000.000	8.333	1133.000	200.001	200.000
3.750	10000.000	8.333	1133.000	200.002	200.000
5.000	10000.000	8.333	1133.000	200.002	200.000
6.250	10000.000	8.333	1133.000	200.002	200.000
7.500	10000.000	8.333	1133.000	200.003	200.000
8.750	10000.000	8.333	1133.000	200.003	200.000
10.000	10000.000	8.333	1133.000	200.003	200.000
11.250	10000.000	8.333	1133.000	200.003	200.000
12.500	10000.000	8.333	1133.000	200.003	200.000
13.750	10000.000	8.333	1133.000	200.003	200.000
15.000	10000.000	8.333	1133.000	200.003	200.000
16.250	10000.000	8.333	1133.000	200.003	200.000
17.500	10000.000	8.333	1133.000	200.003	200.000
18.750	10000.000	8.333	1133.000	200.003	200.000
20.000	10000.000	8.333	1133.000	200.003	200.000
21.250	10000.000	8.333	1133.000	200.003	200.000
22.500	10000.000	8.333	1133.000	200.003	200.000
23.750	10000.000	8.333	1133.000	200.003	200.000
25.000	9200.000	8.333	1133.000	200.003	200.000
26.250	9200.000	7.583	1090.512	199.687	200.000
27.500	9200.000	7.667	1064.648	198.207	200.000
28.750	9200.000	7.669	1052.126	196.638	200.000
30.000	9200.000	7.666	1046.853	195.269	200.000
31.250	9200.000	7.667	1044.389	194.185	200.000
32.500	9200.000	7.667	1043.278	193.363	200.000
33.750	9200.000	7.667	1042.776	192.757	200.000
35.000	9200.000	7.667	1042.548	192.315	200.000
36.250	9200.000	7.667	1042.445	191.997	200.000
37.500	9200.000	7.667	1042.398	191.769	200.000
38.750	9200.000	7.667	1042.377	191.606	200.000
40.000	9200.000	7.667	1042.368	191.589	200.000
41.250	9200.000	7.667	1042.363	200.206	200.000
42.500	9200.000	7.667	1042.361	200.285	200.000
43.750	9200.000	7.667	1042.361	200.071	200.000
45.000	9200.000	7.667	1042.360	200.080	200.000
46.250	9200.000	7.667	1042.360	200.055	200.000
47.500	9200.000	7.667	1042.360	200.040	200.000
48.750	9200.000	7.667	1042.360	200.029	200.000
50.000	9200.000	7.667	1042.360	200.021	200.000
51.250	9200.000	7.667	1042.360	200.016	200.000
52.500	9200.000	7.667	1042.360	200.012	200.000
53.750	9200.000	7.667	1042.360	200.009	200.000
55.000	9200.000	7.667	1042.360	200.007	200.000
56.250	9200.000	7.667	1042.360	200.006	200.000
57.500	9200.000	7.667	1042.360	200.005	200.000
58.750	9200.000	7.667	1042.360	200.004	200.000
60.000	9200.000	7.667	1042.360	200.004	200.000
61.250	9200.000	7.667	1042.360	200.004	200.000
62.500	9200.000	7.667	1042.360	200.003	200.000
63.750	9200.000	7.667	1042.360	200.003	200.000
65.000	9200.000	7.667	1042.360	200.003	200.000
66.250	9200.000	7.667	1042.360	200.003	200.000
67.500	9200.000	7.667	1042.360	200.003	200.000
68.750	9200.000	7.667	1042.360	200.003	200.000
70.000	9200.000	7.667	1042.360	200.003	200.000
71.250	9200.000	7.667	1042.360	200.003	200.000
72.500	9200.000	7.667	1042.360	200.003	200.000
73.750	9200.000	7.667	1042.360	200.003	200.000
75.000	9200.000	7.667	1042.360	200.003	200.000
76.250	9200.000	7.667	1042.360	200.003	200.000
77.500	9200.000	7.667	1042.360	200.003	200.000
78.750	9200.000	7.667	1042.360	200.003	200.000
80.000	9200.000	7.667	1042.360	200.003	200.000
81.250	9200.000	7.667	1042.360	200.003	200.000
82.500	9200.000	7.667	1042.360	200.003	200.000
83.750	9200.000	7.667	1042.360	200.003	200.000
85.000	9200.000	7.667	1042.360	200.003	200.000
86.250	9200.000	7.667	1042.360	200.003	200.000
87.500	9200.000	7.667	1042.360	200.003	200.000
88.750	9200.000	7.667	1042.360	200.003	200.000
90.000	9200.000	7.667	1042.360	200.003	200.000
91.250	9200.000	7.667	1042.360	200.003	200.000
92.500	9200.000	7.667	1042.360	200.003	200.000
93.750	9200.000	7.667	1042.360	200.003	200.000
95.000	9200.000	7.667	1042.360	200.003	200.000
96.250	9200.000	7.667	1042.360	200.003	200.000
97.500	9200.000	7.667	1042.360	200.003	200.000
98.750	9200.000	7.667	1042.360	200.003	200.000
100.000	9200.000	7.667	1042.360	200.003	200.000



SERVO-MECHANISM (SETPOINT CHANGES)  
 WITH DYNAMIC COMPENSATION

T	FM	CM	U	IO	IS
0.000	10000.000	8.333	1133.000	200.000	200.000
1.250	10000.000	8.333	1133.000	200.001	200.000
2.500	10000.000	8.333	1133.000	200.001	200.000
3.750	10000.000	8.333	1133.000	200.002	200.000
5.000	10000.000	8.333	1133.000	200.002	200.000
6.250	10000.000	8.333	1133.000	200.002	200.000
7.500	10000.000	8.333	1133.000	200.003	200.000
8.750	10000.000	8.333	1133.000	200.003	200.000
10.000	10000.000	8.333	1133.000	200.003	200.000
11.250	10000.000	8.333	1133.000	200.003	200.000
12.500	10000.000	8.333	1133.000	200.003	200.000
13.750	10000.000	8.333	1133.000	200.003	200.000
15.000	10000.000	8.333	1133.000	200.003	200.000
16.250	10000.000	8.333	1133.000	200.003	200.000
17.500	10000.000	8.333	1133.000	200.003	200.000
18.750	10000.000	8.333	1133.000	200.003	200.000
20.000	10000.000	8.333	1133.000	200.003	200.000
21.250	10000.000	8.333	1133.000	200.003	200.000
22.500	10000.000	8.333	1133.000	200.003	200.000
23.750	10000.000	8.333	1133.000	200.003	200.000
25.000	10000.000	8.333	1133.000	200.003	210.000
26.250	10000.000	9.091	1179.672	200.451	210.000
27.500	10000.000	9.091	1210.479	202.040	210.000
28.750	10000.000	9.091	1224.438	203.819	210.000
30.000	10000.000	9.091	1230.761	205.369	210.000
31.250	10000.000	9.091	1233.626	206.602	210.000
32.500	10000.000	9.091	1234.924	207.538	210.000
33.750	10000.000	9.091	1235.512	208.229	210.000
35.000	10000.000	9.091	1235.779	208.733	210.000
36.250	10000.000	9.091	1235.900	209.096	210.000
37.500	10000.000	9.091	1235.954	209.357	210.000
38.750	10000.000	9.091	1235.979	209.543	210.000
40.000	10000.000	9.091	1235.990	209.676	210.000
41.250	10000.000	9.091	1235.995	209.770	210.000
42.500	10000.000	9.091	1235.998	209.838	210.000
43.750	10000.000	9.091	1235.999	209.886	210.000
45.000	10000.000	9.091	1235.999	209.920	210.000
46.250	10000.000	9.091	1235.999	209.944	210.000
47.500	10000.000	9.091	1235.999	209.961	210.000
48.750	10000.000	9.091	1235.999	209.973	210.000
50.000	10000.000	9.091	1235.999	209.982	210.000
51.250	10000.000	9.091	1235.999	209.988	210.000
52.500	10000.000	9.091	1235.999	209.992	210.000
53.750	10000.000	9.091	1235.999	209.996	210.000
55.000	10000.000	9.091	1235.999	209.998	210.000
56.250	10000.000	9.091	1235.999	209.999	210.000
57.500	10000.000	9.091	1235.999	210.000	210.000
58.750	10000.000	9.091	1235.999	210.001	210.000
60.000	10000.000	9.091	1235.999	210.002	210.000
61.250	10000.000	9.091	1235.999	210.002	210.000
62.500	10000.000	9.091	1235.999	210.002	210.000
63.750	10000.000	9.091	1235.999	210.003	210.000
65.000	10000.000	9.091	1235.999	210.003	210.000
66.250	10000.000	9.091	1235.999	210.003	210.000
67.500	10000.000	9.091	1235.999	210.003	210.000
68.750	10000.000	9.091	1235.999	210.003	210.000
70.000	10000.000	9.091	1235.999	210.003	210.000
71.250	10000.000	9.091	1235.999	210.003	210.000
72.500	10000.000	9.091	1235.999	210.003	210.000
73.750	10000.000	9.091	1235.999	210.003	210.000
75.000	10000.000	9.091	1235.999	210.003	210.000
76.250	10000.000	9.091	1235.999	210.003	210.000
77.500	10000.000	9.091	1235.999	210.003	210.000
78.750	10000.000	9.091	1235.999	210.003	210.000
80.000	10000.000	9.091	1235.999	210.003	210.000
81.250	10000.000	9.091	1235.999	210.003	210.000
82.500	10000.000	9.091	1235.999	210.003	210.000
83.750	10000.000	9.091	1235.999	210.003	210.000
85.000	10000.000	9.091	1235.999	210.003	210.000
86.250	10000.000	9.091	1235.999	210.003	210.000
87.500	10000.000	9.091	1235.999	210.003	210.000
88.750	10000.000	9.091	1235.999	210.003	210.000
90.000	10000.000	9.091	1235.999	210.003	210.000
91.250	10000.000	9.091	1235.999	210.003	210.000
92.500	10000.000	9.091	1235.999	210.003	210.000
93.750	10000.000	9.091	1235.999	210.003	210.000
95.000	10000.000	9.091	1235.999	210.003	210.000
96.250	10000.000	9.091	1235.999	210.003	210.000
97.500	10000.000	9.091	1235.999	210.003	210.000
98.750	10000.000	9.091	1235.999	210.003	210.000
100.000	10000.000	9.091	1235.999	210.003	210.000



SERVO-MECHANISM (SETPOINT CHANGES)

THE ACTUAL VALUES OF (TO) & (TS) ARE GIVEN BY:  
 ((TO) OR (TS) + 19.5) X 10.0

(OUTPUTS SCALED BY .100E+01)

(X INDICATES MORE THAN ONE VARIABLE HAVE THE GIVEN VALUE)

T	TO(+)	TS(.)	0 + =====>																		
			0.00	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50								
0.00	0.500	0.500	I																		
1.25	0.500	0.500	I	X																	
2.50	0.500	0.500	I	X																	
3.75	0.500	0.500	I	X																	
5.00	0.500	0.500	I	X																	
6.25	0.500	0.500	I	X																	
7.50	0.500	0.500	I	X																	
8.75	0.500	0.500	I	X																	
10.00	0.500	0.500	I	X																	
11.25	0.500	0.500	I	X																	
12.50	0.500	0.500	I	X																	
13.75	0.500	0.500	I	X																	
15.00	0.500	0.500	I	X																	
16.25	0.500	0.500	I	X																	
17.50	0.500	0.500	I	X																	
18.75	0.500	0.500	I	X																	
20.00	0.500	0.500	I	X																	
21.25	0.500	0.500	I	X																	
22.50	0.500	0.500	I	X																	
23.75	0.500	0.500	I	X																	
25.00	0.500	1.500	I		+																
26.25	0.545	1.500	I			+															
27.50	0.705	1.500	I				+														
28.75	0.882	1.500	I					+													
30.00	1.037	1.500	I						+												
31.25	1.160	1.500	I							+											
32.50	1.254	1.500	I								+										
33.75	1.323	1.500	I									+									
35.00	1.373	1.500	I										+								
36.25	1.410	1.500	I											+							
37.50	1.436	1.500	I												+						
38.75	1.454	1.500	I													+					
40.00	1.468	1.500	I														+				
41.25	1.477	1.500	I															+			
42.50	1.484	1.500	I																+		
43.75	1.489	1.500	I																	+	
45.00	1.492	1.500	I																		+
46.25	1.494	1.500	I																		X
47.50	1.496	1.500	I																		X
48.75	1.497	1.500	I																		X
50.00	1.498	1.500	I																		X
51.25	1.499	1.500	I																		X
52.50	1.499	1.500	I																		X
53.75	1.500	1.500	I																		X
55.00	1.500	1.500	I																		X
56.25	1.500	1.500	I																		X
57.50	1.500	1.500	I																		X
58.75	1.500	1.500	I																		X
60.00	1.500	1.500	I																		X
61.25	1.500	1.500	I																		X
62.50	1.500	1.500	I																		X
63.75	1.500	1.500	I																		X
65.00	1.500	1.500	I																		X
66.25	1.500	1.500	I																		X
67.50	1.500	1.500	I																		X
68.75	1.500	1.500	I																		X
70.00	1.500	1.500	I																		X
71.25	1.500	1.500	I																		X
72.50	1.500	1.500	I																		X
73.75	1.500	1.500	I																		X
75.00	1.500	1.500	I																		X
76.25	1.500	1.500	I																		X
77.50	1.500	1.500	I																		X
78.75	1.500	1.500	I																		X
80.00	1.500	1.500	I																		X
81.25	1.500	1.500	I																		X
82.50	1.500	1.500	I																		X
83.75	1.500	1.500	I																		X
85.00	1.500	1.500	I																		X
86.25	1.500	1.500	I																		X
87.50	1.500	1.500	I																		X
88.75	1.500	1.500	I																		X
90.00	1.500	1.500	I																		X
91.25	1.500	1.500	I																		X
92.50	1.500	1.500	I																		X
93.75	1.500	1.500	I																		X
95.00	1.500	1.500	I																		X
96.25	1.500	1.500	I																		X
97.50	1.500	1.500	I																		X
98.75	1.500	1.500	I																		X
100.00	1.500	1.500	I																		X

REGULATOR (LOAD CHANGES)

WITH DYNAMIC COMPENSATION

T	FW	CM	U	TO	TS
0.000	10000.000	8.333	1133.000	200.000	200.000
1.250	10000.000	8.333	1133.000	200.001	200.000
2.500	10000.000	8.333	1133.000	200.001	200.000
3.750	10000.000	8.333	1133.000	200.002	200.000
5.000	10000.000	8.333	1133.000	200.002	200.000
6.250	10000.000	8.333	1133.000	200.002	200.000
7.500	10000.000	8.333	1133.000	200.003	200.000
8.750	10000.000	8.333	1133.000	200.003	200.000
10.000	10000.000	8.333	1133.000	200.003	200.000
11.250	10000.000	8.333	1133.000	200.003	200.000
12.500	10000.000	8.333	1133.000	200.003	200.000
13.750	10000.000	8.333	1133.000	200.003	200.000
15.000	10000.000	8.333	1133.000	200.003	200.000
16.250	10000.000	8.333	1133.000	200.003	200.000
17.500	10000.000	8.333	1133.000	200.003	200.000
18.750	10000.000	8.333	1133.000	200.003	200.000
20.000	10000.000	8.333	1133.000	200.003	200.000
21.250	10000.000	8.333	1133.000	200.003	200.000
22.500	10000.000	8.333	1133.000	200.003	200.000
23.750	10000.000	8.333	1133.000	200.003	200.000
25.000	9200.000	8.333	1133.000	200.003	200.000
26.250	9200.000	8.114	1125.639	199.971	200.000
27.500	9200.000	8.110	1114.191	199.618	200.000
28.750	9200.000	8.065	1106.205	199.105	200.000
30.000	9200.000	8.028	1099.723	198.534	200.000
31.250	9200.000	7.995	1094.136	197.957	200.000
32.500	9200.000	7.964	1089.222	197.398	200.000
33.750	9200.000	7.937	1084.830	196.870	200.000
35.000	9200.000	7.912	1080.875	196.376	200.000
36.250	9200.000	7.889	1077.300	195.918	200.000
37.500	9200.000	7.868	1074.062	195.497	200.000
38.750	9200.000	7.850	1071.120	195.110	200.000
40.000	9200.000	7.833	1068.463	194.756	200.000
41.250	9200.000	7.817	1066.048	203.232	200.000
42.500	9200.000	7.804	1063.856	203.074	200.000
43.750	9200.000	7.791	1061.867	202.634	200.000
45.000	9200.000	7.779	1060.062	202.428	200.000
46.250	9200.000	7.769	1058.424	202.201	200.000
47.500	9200.000	7.759	1056.938	201.998	200.000
48.750	9200.000	7.751	1055.589	201.814	200.000
50.000	9200.000	7.743	1054.365	201.647	200.000
51.250	9200.000	7.736	1053.254	201.495	200.000
52.500	9200.000	7.730	1052.246	201.357	200.000
53.750	9200.000	7.724	1051.331	201.232	200.000
55.000	9200.000	7.718	1050.501	201.119	200.000
56.250	9200.000	7.714	1049.748	201.015	200.000
57.500	9200.000	7.709	1049.064	200.922	200.000
58.750	9200.000	7.705	1048.444	200.837	200.000
60.000	9200.000	7.702	1047.881	200.760	200.000
61.250	9200.000	7.699	1047.370	200.690	200.000
62.500	9200.000	7.696	1046.907	200.626	200.000
63.750	9200.000	7.693	1046.486	200.568	200.000
65.000	9200.000	7.690	1046.104	200.516	200.000
66.250	9200.000	7.688	1045.757	200.469	200.000
67.500	9200.000	7.686	1045.443	200.426	200.000
68.750	9200.000	7.684	1045.156	200.386	200.000
70.000	9200.000	7.683	1044.899	200.351	200.000
71.250	9200.000	7.681	1044.664	200.319	200.000
72.500	9200.000	7.680	1044.451	200.289	200.000
73.750	9200.000	7.679	1044.257	200.263	200.000
75.000	9200.000	7.678	1044.082	200.239	200.000
76.250	9200.000	7.677	1043.922	200.217	200.000
77.500	9200.000	7.676	1043.778	200.197	200.000
78.750	9200.000	7.675	1043.647	200.179	200.000
80.000	9200.000	7.674	1043.528	200.163	200.000
81.250	9200.000	7.673	1043.420	200.148	200.000
82.500	9200.000	7.673	1043.321	200.135	200.000
83.750	9200.000	7.672	1043.232	200.122	200.000
85.000	9200.000	7.672	1043.152	200.111	200.000
86.250	9200.000	7.671	1043.078	200.101	200.000
87.500	9200.000	7.671	1043.012	200.092	200.000
88.750	9200.000	7.670	1042.952	200.084	200.000
90.000	9200.000	7.670	1042.897	200.076	200.000
91.250	9200.000	7.670	1042.847	200.070	200.000
92.500	9200.000	7.669	1042.802	200.063	200.000
93.750	9200.000	7.669	1042.761	200.058	200.000
95.000	9200.000	7.669	1042.724	200.053	200.000
96.250	9200.000	7.669	1042.690	200.048	200.000
97.500	9200.000	7.669	1042.660	200.044	200.000
98.750	9200.000	7.668	1042.632	200.040	200.000
100.000	9200.000	7.668	1042.607	200.037	200.000



PART E

FEEDFORWARD-FEEDBACK CONTROL.

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0001 PROGRAM HEATEX
0002 DIMENSION T(410), CM(410), TM(410), TO(410), TS(410), TT(5,410)
0003 DIMENSION U(410), DEL(1), FW(410), ZN(410), CLL(410), T1(410)
0004 DIMENSION T01(410), T02(410), TS1(410), CM1(410), TM1(410), X(410), Y(410)
0005 DIMENSION X1(410), Y1(410)
0006 REAL INTOD, INTOD1, INTOD2, INTMD, INTMD1, KV, KP, KM, KS, KFF, KC, KM1, KDIS
0007 DATA DEL/0.25/
0008 C PARAMETERS AND VARIABLES
0009 C FEEDFORWARD CP=HEAT CAPACITY OF WATER (BTU/(LB.DEG. F))
0010 C CONTROLLER: HS=LATENT HEAT OF STEAM (BTU/LB.)
0011 C KFF=CONTROLLER GAIN
0012 C CM=CONTROLLER OUTPUT (VOLTS-RANGE 0-10V)
0013 C CLL=DYNAMIC COMPENSATION TERM
0014 C TH1=LEAD TIME CONSTANT (SEC.)
0015 C TH2=LAG TIME CONSTANT (SEC.)
0016 C
0017 C FEEDBACK KG=PROPORTIONAL GAIN
0018 C CONTROLLER: CM1=CONTROLLER OUTPUT
0019 C CBAIS=CONTROLLER BIAS
0020 C
0021 C VALVE : THV= VALVE TIME CONSTANT (SEC.)
0022 C KV=VALVE GAIN ((LB./HR)/VOLTS)
0023 C
0024 C EXCHANGER : THP=PROCESS TIME CONSTANT (SEC.)
0025 C KP=PROCESS GAIN (DEG. F/(LB./HR))
0026 C
0027 C DISTURBANCE: THD=DISTURBANCE TIME CONSTANT (SEC.)
0028 C KDIS=DISTURBANCE GAIN (DEG. F/(LB./HR))
0029 C
0030 C MEASURING THM=FLOW MEASURING ELEMENT TIME CONSTANT (SEC.)
0031 C ELEMENTS : KM=FLOW MEASURING ELEMENT GAIN (VOLTS/DEG.F)
0032 C THM1=TEMPERATURE MEASURING ELEMENT TIME CONSTANT (SEC.)
0033 C KM1=TEMPERATURE MEASURING ELEMENT GAIN (VOLTS/DEG. F)
0034 C
0035 C OTHERS : TS=SETPOINT TEMPERATURE (FEEDBACK CONTROLLER) (DEG. F)
0036 C TS1=FEEDFORWARD CONTROLLER SETPOINT (DEG. F)
0037 C KS=SETPOINT GAIN (DEG. F/VOLTS)
0038 C TIN=INPUT TEMPERATURE (DEG. F)
0039 C TO=OVERALL OUTPUT TEMPERATURE (DEG. F)
0040 C TD1=OUTPUT TEMPERATURE DUE TO PROCESS (DEG. F)
0041 C TO2=OUTPUT TEMPERATURE DUE TO DISTURBANCE (DEG. F)
0042 C FW=WATER INFLOW RATE (LB./HR)
0043 C
0044 TYPE 6
0045 o FORMAT(1H1, //, 10X, 'E.- FEEDFORWARD-FEEDBACK CONTROL', //, 10X,
0046 + 32(' '), //, 10X, '(NO TIME DELAYS ARE INCLUDED)', //, 10X,
0047 + '(FEEDBACK CONTROLLER HAS PROPORTIONAL CONTROL MODE ONLY)', //)
0048 C CUNSTANTS & PARAMETERS
0049 HS=970.
0050 CP=1.
0051 TIN=90.
0052 THV=2.
0053 KV=135.9605
0054 THP=4.05
0055 KP=0.09709
0056 THM=0.5
0057 KM=0.00083333
  
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0058      THM1=3.
0059      KM1=0.0416665
0060      KDIS=0.011
0061      THD=0.5
0062      KS=0.0416665
0063      CBAIS=8.3333
0064      KC=1.0
0065      TH2=4.
0066      TH1=7.
0067      DU 98 JJ=1,2
0068      DO 99 JK=1,2
0069      IF(JK.EQ.2)GO TO 7
0070      IF(JJ.EQ.2)TYPE 25
0071      25  FORMAT(1H1,/)
0072      TYPE 8
0073      8   FORMAT(10X,'SERVO-MECHANISM (SETPOINT CHANGES)',/,10X,34('-'))
0074      GO TO 9
0075      7   TYPE 10
0076      10  FORMAT(1H1,/,10X,'REGULATOR (LOAD CHANGES)',/,10X,24('-'))
0077      9   IF(JJ.EQ.2)GO TO 12
0078      TYPE 14
0079      14  FORMAT(10X,'WITHOUT DYNAMIC COMPENSATION',/,10X,28('-'),/)
0080      GO TO 19
0081      12  TYPE 15
0082      15  FORMAT(10X,'WITH DYNAMIC COMPENSATION',/,10X,25('-'),/)
0083      C   INITIAL CONDITIONS
0084      19  U(1)=1133.
0085      FW(1)=10000.
0086      TO(1)=200.
0087      TO1(1)=200.
0088      TO2(1)=0.
0089      TM(1)=FW(1)*KM
0090      TS(1)=200.
0091      TS1(1)=200.
0092      CM1(1)=8.3333
0093      CM(1)=8.3333
0094      KFF=HS/(TS(1)-T(N))
0095      TM1(1)=8.3333
0096      ZN(1)=TM(1)
0097      CLL(1)=ZN(1)
0098      Y1(1)=8.3333
0099      INTUD=1133.
0100      INTUD1=200.
0101      INTUD2=110.
0102      INTMD=8.3333
0103      INTMD1=8.3333
0104      T(1)=0.0
0105      DO 2 I=2,401
0106      II=I-1
0107      TS(I)=TS(II)
0108      IF(JK.EQ.1)GO TO 20
0109      FW(I)=FW(II)
0110      IF(I.EQ.100)FW(I)=FW(II)-100.
0111      GO TO 21
0112      20  IF(I.EQ.100)TS(I)=TS(II)+10.
0113      FW(I)=FW(1)
0114      C   FEEDBACK CONTROLLER

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0115      21      ER=TS(II)*KS-TM1(I)
0116      CM1(I)=KC*ER+CBAIS
0117      TS1(I)=CM1(I)/KS
0118      C MEASURING ELEMENT
0119      TMD=(KM*FW(I)-TM(II))/THM
0120      TM(I)=INTMD
0121      IF(JJ.EQ.2)GO TO 22
0122      C FEEDFORWAR CONTROLLER WITHOUT DYNAMIC COMPENSATION
0123      CM(I)=TM(I)*KFF*(CP/HS)*(TS1(II)-TIN)
0124      GO TO 23
0125      C DYNAMIC COMPENSATION (LEAD/LAG)
0126      22      AA=TM(II)-ZN(II)
0127      ZN(I)=$((DEL(1)/TH2)*AA)+ZN(II)
0128      CLL(I)=$((TH1/TH2)*AA)+ZN(II)
0129      C FEEDFORWAR CONTROLLER WITH DYNAMIC COMPENSATION
0130      CM(I)=CLL(I)*KFF*(CP/HS)*(TS1(II)-TIN)
0131      C VALVE
0132      23      UD=(KV*CM(I)-U(II))/THV
0133      U(I)=INTUD
0134      C HEAT EXCHANGER
0135      PU=KP*U(I)+TIN
0136      TUD1=(PO-TO1(II))/THP
0137      TO1(I)=INTOD1
0138      IF(JK.EQ.2)GO TO 17
0139      TO(I)=TO1(I)
0140      GO TO 18
0141      17      TO2(I)=110.
0142      TOD2=(KD1S*FW(I)-TO2(II))/THD
0143      TO2(I)=INTOD2
0144      TO(I)=TO1(I)+(TO2(I)-TO2(I))
0145      C TEMPERATURE MEASURING ELEMENT
0146      18      TMD1=(KM1*TO(I)-TM1(II))/THM1
0147      TM1(I)=INTMD1
0148      C EULER INTEGRATION
0149      T(I)=T(II)+DEL(1)
0150      INTUD=INTUD+UD*DEL(1)
0151      INTOD1=INTOD1+TOD1*DEL(1)
0152      INTOD2=INTOD2+TOD2*DEL(1)
0153      INTMD=INTMD+TMD*DEL(1)
0154      INTMD1=INTMD1+TMD1*DEL(1)
0155      2      CONTINUE
0156      TYPE 16
0157      16      FORMAT(15X,'T',9X,'FW',11X,'CM1',9X,'CM',10X,'U',11X,'TO',10X,
0158      + 'TS',/,10X,84('-',/))
0159      IK=1
0160      DU 5 I=1,81
0161      T1(I)=T(IK)
0162      TT(1,I)=FO(IK)/10.-19.5
0163      TT(2,I)=FW(IK)/10000.
0164      IF(JK.EQ.1)TT(2,I)=TS(IK)/10.-19.5
0165      TYPE 11,T(IK),FW(IK),CM1(IK),CM(IK),U(IK),TO(IK),TS(IK)
0166      11      FORMAT(7X,7F12.3)
0167      IK=IK+5
0168      5      CONTINUE
0169      IF(JK.EQ.2)GO TO 90
0170      TYPE 24
0171      24      FORMAT(1H1)

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0172          TYPE 8
0173          TYPE 91
0174          91  FORMAT(10X,'THE ACTUAL VALUES OF (TO) & (TS) ARE GIVEN BY:')
0175          +  /,20X,'((TO) OR (TS) + 19.5) X 10.0',/)
0176          GO TO 92
0177          90  TYPE 10
0178          TYPE 93
0179          93  FORMAT(10X,'THE ACTUAL VALUES OF (TO) & (TS) ARE GIVEN BY:')
0180          +  /,20X,'((TO) + 19.5) X 10.0      AND      (FW) X 10000.0',/)
0181          92  CALL PLOT1(T1,TT,81,2,JK)
0182          99  CONTINUE
0183          98  CONTINUE
0184          END

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## PROGRAM SECTIONS

NAME	BYTES	ATTRIBUTES
0 SCODE	1437	PIC CUN REL LCL SHR EXE RD NOWI
1 SPDATA	603	PIC CUN REL LCL SHR NOEXE RD NOWI
2 SLOCAL	39536	PIC CUN REL LCL NOSHR NOEXE RD W
TOTAL SPACE ALLOCATED	41576	

## ENTRY POINTS

ADDRESS	TYPE	NAME
0-00000000		HEATEX

## VARIABLES

ADDRESS	TYPE	NAME	ADDRESS	TYPE	NAME	ADDRESS	TYPE
2-00009A3C	R*4	AA	2-00009A18	R*4	CBAS	2-000099FC	R*4
2-000099F8	R*4	HS	2-00009A2C	I*4	I	2-00009A30	I*4
2-000099D0	R*4	INTMD	2-000099D4	R*4	INTMD1	2-000099C8	R*4
2-000099C4	R*4	INTGD	2-00009A24	I*4	JJ	2-00009A28	I*4
2-000099F4	R*4	KDIS	2-000099E8	R*4	KFF	2-000099E0	R*4
2-000099DC	R*4	KP	2-000099E4	R*4	KS	2-000099D8	R*4
2-00009A20	R*4	TH1	2-00009A1C	R*4	TH2	2-00009A14	R*4
2-00009A10	R*4	THM1	2-00009A08	R*4	THP	2-00009A04	R*4
2-00009A38	R*4	TMD	2-00009A50	R*4	TMD1	2-00009A48	R*4
2-00009A40	R*4	UD					



E.- FEEDFORWARD-FEEDBACK CONTROL

(NO TIME DELAYS ARE INCLUDED)  
(FEEDBACK CONTROLLER HAS PROPORTIONAL CONTROL MODE ONLY)

SERVU-MECHANISM (SETPOINT CHANGES)

WITHOUT DYNAMIC COMPENSATION

T	FW	CM1	CM	U	TO	TS
0.000	10000.000	8.333	8.333	1133.000	200.000	200.000
1.250	10000.000	8.333	8.333	1133.000	200.001	200.000
2.500	10000.000	8.333	8.333	1132.999	200.001	200.000
3.750	10000.000	8.333	8.333	1132.997	200.002	200.000
5.000	10000.000	8.333	8.333	1132.993	200.002	200.000
6.250	10000.000	8.333	8.333	1132.990	200.002	200.000
7.500	10000.000	8.333	8.333	1132.986	200.002	200.000
8.750	10000.000	8.333	8.333	1132.984	200.002	200.000
10.000	10000.000	8.333	8.333	1132.982	200.002	200.000
11.250	10000.000	8.333	8.333	1132.981	200.002	200.000
12.500	10000.000	8.333	8.333	1132.982	200.001	200.000
13.750	10000.000	8.333	8.333	1132.982	200.001	200.000
15.000	10000.000	8.333	8.333	1132.983	200.001	200.000
16.250	10000.000	8.333	8.333	1132.984	200.001	200.000
17.500	10000.000	8.333	8.333	1132.984	200.001	200.000
18.750	10000.000	8.333	8.333	1132.984	200.001	200.000
20.000	10000.000	8.333	8.333	1132.984	200.001	200.000
21.250	10000.000	8.333	8.333	1132.984	200.001	200.000
22.500	10000.000	8.333	8.333	1132.984	200.001	200.000
23.750	10000.000	8.333	8.333	1132.984	200.001	200.000
25.000	10000.000	8.750	8.333	1132.984	200.001	210.000
26.250	10000.000	8.750	9.091	1179.656	200.450	210.000
27.500	10000.000	8.737	9.076	1210.193	202.043	210.000
28.750	10000.000	8.703	9.021	1221.670	203.768	210.000
30.000	10000.000	8.656	8.938	1221.784	205.206	210.000
31.250	10000.000	8.605	8.846	1215.233	206.130	210.000
32.500	10000.000	8.581	8.782	1205.604	206.559	210.000
33.750	10000.000	8.529	8.698	1195.617	206.584	210.000
35.000	10000.000	8.509	8.658	1187.092	206.335	210.000
36.250	10000.000	8.502	8.640	1180.977	205.945	210.000
37.500	10000.000	8.503	8.641	1177.497	205.527	210.000
38.750	10000.000	8.511	8.653	1176.355	205.161	210.000
40.000	10000.000	8.521	8.671	1176.962	204.890	210.000
41.250	10000.000	8.531	8.690	1178.630	204.729	210.000
42.500	10000.000	8.540	8.706	1180.724	204.667	210.000
43.750	10000.000	8.546	8.718	1182.750	204.682	210.000
45.000	10000.000	8.549	8.725	1184.389	204.746	210.000
46.250	10000.000	8.550	8.727	1185.496	204.832	210.000
47.500	10000.000	8.549	8.726	1186.063	204.917	210.000
48.750	10000.000	8.547	8.723	1186.174	204.988	210.000
50.000	10000.000	8.545	8.719	1185.965	205.038	210.000
51.250	10000.000	8.543	8.715	1185.576	205.064	210.000
52.500	10000.000	8.541	8.712	1185.134	205.072	210.000
53.750	10000.000	8.540	8.710	1184.730	205.065	210.000
55.000	10000.000	8.540	8.709	1184.420	205.050	210.000
56.250	10000.000	8.540	8.709	1184.224	205.031	210.000
57.500	10000.000	8.540	8.709	1184.138	205.014	210.000
58.750	10000.000	8.540	8.710	1184.139	205.001	210.000
60.000	10000.000	8.541	8.711	1184.197	204.992	210.000
61.250	10000.000	8.541	8.711	1184.284	204.988	210.000
62.500	10000.000	8.542	8.712	1184.376	204.987	210.000
63.750	10000.000	8.542	8.712	1184.455	204.989	210.000
65.000	10000.000	8.542	8.713	1184.512	204.993	210.000
66.250	10000.000	8.542	8.713	1184.546	204.996	210.000
67.500	10000.000	8.542	8.713	1184.558	205.000	210.000
68.750	10000.000	8.542	8.712	1184.553	205.002	210.000
70.000	10000.000	8.542	8.712	1184.539	205.004	210.000
71.250	10000.000	8.542	8.712	1184.520	205.005	210.000
72.500	10000.000	8.542	8.712	1184.501	205.004	210.000
73.750	10000.000	8.541	8.712	1184.485	205.004	210.000
75.000	10000.000	8.541	8.712	1184.475	205.003	210.000
76.250	10000.000	8.541	8.712	1184.469	205.002	210.000
77.500	10000.000	8.542	8.712	1184.466	205.002	210.000
78.750	10000.000	8.542	8.712	1184.470	205.001	210.000
80.000	10000.000	8.542	8.712	1184.473	205.001	210.000
81.250	10000.000	8.542	8.712	1184.477	205.001	210.000
82.500	10000.000	8.542	8.712	1184.481	205.001	210.000
83.750	10000.000	8.542	8.712	1184.484	205.001	210.000
85.000	10000.000	8.542	8.712	1184.486	205.001	210.000
86.250	10000.000	8.542	8.712	1184.487	205.001	210.000
87.500	10000.000	8.542	8.712	1184.487	205.002	210.000
88.750	10000.000	8.542	8.712	1184.486	205.002	210.000
90.000	10000.000	8.542	8.712	1184.486	205.002	210.000
91.250	10000.000	8.542	8.712	1184.484	205.002	210.000
92.500	10000.000	8.542	8.712	1184.484	205.002	210.000
93.750	10000.000	8.542	8.712	1184.484	205.002	210.000
95.000	10000.000	8.542	8.712	1184.484	205.002	210.000
96.250	10000.000	8.542	8.712	1184.484	205.002	210.000
97.500	10000.000	8.542	8.712	1184.484	205.002	210.000
98.750	10000.000	8.542	8.712	1184.484	205.002	210.000
100.000	10000.000	8.542	8.712	1184.484	205.002	210.000

SERVO-MECHANISM (SETPOINT CHANGES)

THE ACTUAL VALUES OF (TO) & (TS) ARE GIVEN BY:  
 ((TO) OR (TS) + 19.5) X 10.0

(OUTPUTS SCALED BY .100E+01)  
 (X INDICATES MORE THAN ONE VARIABLE HAVE THE GIVEN VALUE)

T	TO(+)	TS(.)	0 + ----->																	
			0.00	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50							
0.00	0.500	0.500	I		X															
1.25	0.500	0.500	I		X															
2.50	0.500	0.500	I		X															
3.75	0.500	0.500	I		X															
5.00	0.500	0.500	I		X															
6.25	0.500	0.500	I		X															
7.50	0.500	0.500	I		X															
8.75	0.500	0.500	I		X															
10.00	0.500	0.500	I		X															
11.25	0.500	0.500	I		X															
12.50	0.500	0.500	I		X															
13.75	0.500	0.500	I		X															
15.00	0.500	0.500	I		X															
16.25	0.500	0.500	I		X															
17.50	0.500	0.500	I		X															
18.75	0.500	0.500	I		X															
20.00	0.500	0.500	I		X															
21.25	0.500	0.500	I		X															
22.50	0.500	0.500	I		X															
23.75	0.500	0.500	I		X															
25.00	0.500	1.500	I			+														
26.25	0.545	1.500	I				+													
27.50	0.704	1.500	I					+												
28.75	0.879	1.500	I						+											
30.00	1.021	1.500	I							+										
31.25	1.113	1.500	I								+									
32.50	1.156	1.500	I									+								
33.75	1.179	1.500	I										+							
35.00	1.134	1.500	I											+						
36.25	1.095	1.500	I												+					
37.50	1.053	1.500	I													+				
38.75	1.016	1.500	I														+			
40.00	0.989	1.500	I															+		
41.25	0.973	1.500	I																+	
42.50	0.967	1.500	I																	+
43.75	0.968	1.500	I																	+
45.00	0.975	1.500	I																	+
46.25	0.983	1.500	I																	+
47.50	0.992	1.500	I																	+
48.75	0.999	1.500	I																	+
50.00	1.004	1.500	I																	+
51.25	1.006	1.500	I																	+
52.50	1.007	1.500	I																	+
53.75	1.006	1.500	I																	+
55.00	1.005	1.500	I																	+
56.25	1.003	1.500	I																	+
57.50	1.001	1.500	I																	+
58.75	1.000	1.500	I																	+
60.00	0.999	1.500	I																	+
61.25	0.999	1.500	I																	+
62.50	0.999	1.500	I																	+
63.75	0.999	1.500	I																	+
65.00	0.999	1.500	I																	+
66.25	1.000	1.500	I																	+
67.50	1.000	1.500	I																	+
68.75	1.000	1.500	I																	+
70.00	1.000	1.500	I																	+
71.25	1.000	1.500	I																	+
72.50	1.000	1.500	I																	+
73.75	1.000	1.500	I																	+
75.00	1.000	1.500	I																	+
76.25	1.000	1.500	I																	+
77.50	1.000	1.500	I																	+
78.75	1.000	1.500	I																	+
80.00	1.000	1.500	I																	+
81.25	1.000	1.500	I																	+
82.50	1.000	1.500	I																	+
83.75	1.000	1.500	I																	+
85.00	1.000	1.500	I																	+
86.25	1.000	1.500	I																	+
87.50	1.000	1.500	I																	+
88.75	1.000	1.500	I																	+
90.00	1.000	1.500	I																	+
91.25	1.000	1.500	I																	+
92.50	1.000	1.500	I																	+
93.75	1.000	1.500	I																	+
95.00	1.000	1.500	I																	+
96.25	1.000	1.500	I																	+
97.50	1.000	1.500	I																	+
98.75	1.000	1.500	I																	+
100.00	1.000	1.500	I																	+

REGULATOR (LOAD CHANGES)

WITHOUT DYNAMIC COMPENSATION

T	FW	CM1	CM	U	TO	TS
0.000	10000.000	8.333	8.333	1133.000	200.000	200.000
1.250	10000.000	8.333	8.333	1133.000	200.001	200.000
2.500	10000.000	8.333	8.333	1132.999	200.001	200.000
3.750	10000.000	8.333	8.333	1132.997	200.002	200.000
5.000	10000.000	8.333	8.333	1132.993	200.002	200.000
6.250	10000.000	8.333	8.333	1132.990	200.002	200.000
7.500	10000.000	8.333	8.333	1132.986	200.002	200.000
8.750	10000.000	8.333	8.333	1132.984	200.002	200.000
10.000	10000.000	8.333	8.333	1132.982	200.002	200.000
11.250	10000.000	8.333	8.333	1132.981	200.002	200.000
12.500	10000.000	8.333	8.333	1132.982	200.001	200.000
13.750	10000.000	8.333	8.333	1132.982	200.001	200.000
15.000	10000.000	8.333	8.333	1132.983	200.001	200.000
16.250	10000.000	8.333	8.333	1132.984	200.001	200.000
17.500	10000.000	8.333	8.333	1132.984	200.001	200.000
18.750	10000.000	8.333	8.333	1132.984	200.001	200.000
20.000	10000.000	8.333	8.333	1132.984	200.001	200.000
21.250	10000.000	8.333	8.333	1132.984	200.001	200.000
22.500	10000.000	8.333	8.333	1132.984	200.001	200.000
23.750	10000.000	8.333	8.333	1132.984	200.001	200.000
25.000	9200.000	8.333	8.000	1132.984	204.401	200.000
26.250	9200.000	8.217	7.928	1079.844	208.236	200.000
27.500	9200.000	8.137	7.344	1043.355	206.602	200.000
28.750	9200.000	8.116	7.305	1017.216	204.249	200.000
30.000	9200.000	8.138	7.329	1004.408	202.166	200.000
31.250	9200.000	8.185	7.401	1002.164	200.423	200.000
32.500	9200.000	8.239	7.491	1007.227	199.417	200.000
33.750	9200.000	8.290	7.579	1016.257	198.557	200.000
35.000	9200.000	8.331	7.661	1026.411	198.360	200.000
36.250	9200.000	8.357	7.700	1035.648	198.498	200.000
37.500	9200.000	8.371	7.727	1042.781	198.833	200.000
38.750	9200.000	8.374	7.735	1047.375	199.243	200.000
40.000	9200.000	8.369	7.729	1049.562	199.534	200.000
41.250	9200.000	8.360	7.715	1049.818	199.950	200.000
42.500	9200.000	8.350	7.699	1048.768	200.165	200.000
43.750	9200.000	8.340	7.681	1047.036	200.279	200.000
45.000	9200.000	8.333	7.668	1045.339	200.308	200.000
46.250	9200.000	8.328	7.660	1043.444	200.278	200.000
47.500	9200.000	8.326	7.655	1042.156	200.212	200.000
48.750	9200.000	8.326	7.654	1041.345	200.135	200.000
50.000	9200.000	8.327	7.655	1040.977	200.063	200.000
51.250	9200.000	8.328	7.658	1040.959	200.006	200.000
52.500	9200.000	8.330	7.661	1041.174	199.968	200.000
53.750	9200.000	8.332	7.664	1041.505	199.948	200.000
55.000	9200.000	8.333	7.666	1041.858	199.944	200.000
56.250	9200.000	8.334	7.668	1042.169	199.951	200.000
57.500	9200.000	8.335	7.669	1042.401	199.963	200.000
58.750	9200.000	8.335	7.669	1042.544	199.978	200.000
60.000	9200.000	8.334	7.669	1042.605	199.991	200.000
61.250	9200.000	8.334	7.668	1042.603	200.001	200.000
62.500	9200.000	8.334	7.668	1042.560	200.008	200.000
63.750	9200.000	8.333	7.667	1042.497	200.012	200.000
65.000	9200.000	8.333	7.667	1042.431	200.012	200.000
66.250	9200.000	8.333	7.666	1042.374	200.011	200.000
67.500	9200.000	8.333	7.666	1042.332	200.008	200.000
68.750	9200.000	8.333	7.666	1042.307	200.006	200.000
70.000	9200.000	8.333	7.666	1042.297	200.003	200.000
71.250	9200.000	8.333	7.666	1042.299	200.001	200.000
72.500	9200.000	8.333	7.666	1042.307	200.000	200.000
73.750	9200.000	8.333	7.666	1042.319	199.999	200.000
75.000	9200.000	8.333	7.667	1042.331	199.999	200.000
76.250	9200.000	8.333	7.667	1042.342	200.000	200.000
77.500	9200.000	8.333	7.667	1042.349	200.000	200.000
78.750	9200.000	8.333	7.667	1042.354	200.001	200.000
80.000	9200.000	8.333	7.667	1042.355	200.001	200.000
81.250	9200.000	8.333	7.667	1042.355	200.001	200.000
82.500	9200.000	8.333	7.667	1042.353	200.002	200.000
83.750	9200.000	8.333	7.667	1042.351	200.002	200.000
85.000	9200.000	8.333	7.667	1042.349	200.002	200.000
86.250	9200.000	8.333	7.667	1042.347	200.002	200.000
87.500	9200.000	8.333	7.667	1042.346	200.002	200.000
88.750	9200.000	8.333	7.667	1042.345	200.002	200.000
90.000	9200.000	8.333	7.667	1042.345	200.001	200.000
91.250	9200.000	8.333	7.667	1042.345	200.001	200.000
92.500	9200.000	8.333	7.667	1042.345	200.001	200.000
93.750	9200.000	8.333	7.667	1042.345	200.001	200.000
95.000	9200.000	8.333	7.667	1042.345	200.001	200.000
96.250	9200.000	8.333	7.667	1042.345	200.001	200.000
97.500	9200.000	8.333	7.667	1042.345	200.001	200.000
98.750	9200.000	8.333	7.667	1042.345	200.001	200.000
100.000	9200.000	8.333	7.667	1042.345	200.001	200.000



SERVO-MECHANISM (SETPOINT CHANGES)

WITH DYNAMIC COMPENSATION

T	FM	CM1	CM	U	TO	TS
0.000	10000.000	8.333	8.333	1133.000	200.000	200.000
1.250	10000.000	8.333	8.333	1133.000	200.001	200.000
2.500	10000.000	8.333	8.333	1132.999	200.001	200.000
3.750	10000.000	8.333	8.333	1132.997	200.002	200.000
5.000	10000.000	8.333	8.333	1132.993	200.002	200.000
6.250	10000.000	8.333	8.333	1132.990	200.002	200.000
7.500	10000.000	8.333	8.333	1132.986	200.002	200.000
8.750	10000.000	8.333	8.333	1132.984	200.002	200.000
10.000	10000.000	8.333	8.333	1132.982	200.002	200.000
11.250	10000.000	8.333	8.333	1132.981	200.002	200.000
12.500	10000.000	8.333	8.333	1132.982	200.001	200.000
13.750	10000.000	8.333	8.333	1132.982	200.001	200.000
15.000	10000.000	8.333	8.333	1132.983	200.001	200.000
16.250	10000.000	8.333	8.333	1132.984	200.001	200.000
17.500	10000.000	8.333	8.333	1132.984	200.001	200.000
18.750	10000.000	8.333	8.333	1132.984	200.001	200.000
20.000	10000.000	8.333	8.333	1132.984	200.001	200.000
21.250	10000.000	8.333	8.333	1132.984	200.001	200.000
22.500	10000.000	8.333	8.333	1132.984	200.001	200.000
23.750	10000.000	8.333	8.333	1132.984	200.001	200.000
25.000	10000.000	8.750	8.333	1132.984	200.001	210.000
26.250	10000.000	8.750	9.091	1179.656	200.450	210.000
27.500	10000.000	8.737	9.076	1210.193	202.043	210.000
28.750	10000.000	8.703	9.021	1221.670	203.788	210.000
30.000	10000.000	8.656	8.938	1221.784	205.206	210.000
31.250	10000.000	8.605	8.846	1215.233	206.130	210.000
32.500	10000.000	8.561	8.762	1205.604	206.559	210.000
33.750	10000.000	8.529	8.698	1195.617	206.584	210.000
35.000	10000.000	8.509	8.658	1187.092	206.335	210.000
36.250	10000.000	8.502	8.640	1180.977	205.945	210.000
37.500	10000.000	8.503	8.641	1177.497	205.527	210.000
38.750	10000.000	8.511	8.653	1176.355	205.161	210.000
40.000	10000.000	8.521	8.671	1176.962	204.890	210.000
41.250	10000.000	8.531	8.690	1178.630	204.729	210.000
42.500	10000.000	8.540	8.706	1180.724	204.667	210.000
43.750	10000.000	8.546	8.718	1184.750	204.682	210.000
45.000	10000.000	8.549	8.725	1184.389	204.746	210.000
46.250	10000.000	8.550	8.727	1185.496	204.832	210.000
47.500	10000.000	8.549	8.726	1186.063	204.917	210.000
48.750	10000.000	8.547	8.723	1186.174	204.988	210.000
50.000	10000.000	8.545	8.719	1185.965	205.038	210.000
51.250	10000.000	8.543	8.715	1185.576	205.064	210.000
52.500	10000.000	8.541	8.712	1185.134	205.072	210.000
54.750	10000.000	8.540	8.710	1184.730	205.065	210.000
55.000	10000.000	8.540	8.709	1184.420	205.050	210.000
56.250	10000.000	8.540	8.709	1184.224	205.031	210.000
57.500	10000.000	8.540	8.709	1184.138	205.014	210.000
58.750	10000.000	8.540	8.710	1184.139	205.001	210.000
60.000	10000.000	8.541	8.711	1184.197	204.992	210.000
61.250	10000.000	8.541	8.711	1184.284	204.988	210.000
62.500	10000.000	8.542	8.712	1184.376	204.987	210.000
63.750	10000.000	8.542	8.712	1184.455	204.989	210.000
65.000	10000.000	8.542	8.713	1184.512	204.993	210.000
66.250	10000.000	8.542	8.713	1184.546	204.996	210.000
67.500	10000.000	8.542	8.713	1184.558	205.000	210.000
68.750	10000.000	8.542	8.712	1184.553	205.002	210.000
70.000	10000.000	8.542	8.712	1184.539	205.004	210.000
71.250	10000.000	8.542	8.712	1184.520	205.005	210.000
72.500	10000.000	8.542	8.712	1184.501	205.004	210.000
73.750	10000.000	8.541	8.712	1184.485	205.004	210.000
75.000	10000.000	8.541	8.712	1184.475	205.003	210.000
76.250	10000.000	8.541	8.712	1184.469	205.002	210.000
77.500	10000.000	8.542	8.712	1184.468	205.002	210.000
78.750	10000.000	8.542	8.712	1184.470	205.001	210.000
80.000	10000.000	8.542	8.712	1184.473	205.001	210.000
81.250	10000.000	8.542	8.712	1184.477	205.001	210.000
82.500	10000.000	8.542	8.712	1184.481	205.001	210.000
83.750	10000.000	8.542	8.712	1184.484	205.001	210.000
85.000	10000.000	8.542	8.712	1184.486	205.001	210.000
86.250	10000.000	8.542	8.712	1184.487	205.001	210.000
87.500	10000.000	8.542	8.712	1184.487	205.002	210.000
88.750	10000.000	8.542	8.712	1184.488	205.002	210.000
90.000	10000.000	8.542	8.712	1184.488	205.002	210.000
91.250	10000.000	8.542	8.712	1184.484	205.002	210.000
92.500	10000.000	8.542	8.712	1184.484	205.002	210.000
93.750	10000.000	8.542	8.712	1184.484	205.002	210.000
95.000	10000.000	8.542	8.712	1184.484	205.002	210.000
96.250	10000.000	8.542	8.712	1184.484	205.002	210.000
97.500	10000.000	8.542	8.712	1184.484	205.002	210.000
98.750	10000.000	8.542	8.712	1184.484	205.002	210.000
100.000	10000.000	8.542	8.712	1184.484	205.002	210.000

SERVO-MECHANISM (SETPOINT CHANGES)

THE ACTUAL VALUES OF (TO) & (TS) ARE GIVEN BY:  
 ((TO) ON (TS) + 19.5) X 10.0

(OUTPUTS SCALED BY .100E+01) Δ  
 (X INDICATES MORE THAN ONE VARIABLE HAVE THE GIVEN VALUE)

T	TO(+)	TS(.)	0 + =====>																			
			0.00	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50									
0.00	0.500	0.500	I		X																	
1.25	0.500	0.500	I		X																	
2.50	0.500	0.500	I		X																	
3.75	0.500	0.500	I		X																	
5.00	0.500	0.500	I		X																	
6.25	0.500	0.500	I		X																	
7.50	0.500	0.500	I		X																	
8.75	0.500	0.500	I		X																	
10.00	0.500	0.500	I		X																	
11.25	0.500	0.500	I		X																	
12.50	0.500	0.500	I		X																	
13.75	0.500	0.500	I		X																	
15.00	0.500	0.500	I		X																	
16.25	0.500	0.500	I		X																	
17.50	0.500	0.500	I		X																	
18.75	0.500	0.500	I		X																	
20.00	0.500	0.500	I		X																	
21.25	0.500	0.500	I		X																	
22.50	0.500	0.500	I		X																	
23.75	0.500	0.500	I		X																	
25.00	0.500	1.500	I			+																
26.25	0.545	1.500	I																			
27.50	0.704	1.500	I																			
28.75	0.879	1.500	I																			
30.00	1.021	1.500	I																			
31.25	1.113	1.500	I																			
32.50	1.156	1.500	I																			
33.75	1.158	1.500	I																			
35.00	1.134	1.500	I																			
36.25	1.095	1.500	I																			
37.50	1.053	1.500	I																			
38.75	1.016	1.500	I																			
40.00	0.989	1.500	I																			
41.25	0.973	1.500	I																			
42.50	0.967	1.500	I																			
43.75	0.968	1.500	I																			
45.00	0.975	1.500	I																			
46.25	0.983	1.500	I																			
47.50	0.992	1.500	I																			
48.75	0.999	1.500	I																			
50.00	1.004	1.500	I																			
51.25	1.006	1.500	I																			
52.50	1.007	1.500	I																			
53.75	1.006	1.500	I																			
55.00	1.005	1.500	I																			
56.25	1.003	1.500	I																			
57.50	1.001	1.500	I																			
58.75	1.000	1.500	I																			
60.00	0.999	1.500	I																			
61.25	0.999	1.500	I																			
62.50	0.999	1.500	I																			
63.75	0.999	1.500	I																			
65.00	0.999	1.500	I																			
66.25	1.000	1.500	I																			
67.50	1.000	1.500	I																			
68.75	1.000	1.500	I																			
70.00	1.000	1.500	I																			
71.25	1.000	1.500	I																			
72.50	1.000	1.500	I																			
73.75	1.000	1.500	I																			
75.00	1.000	1.500	I																			
76.25	1.000	1.500	I																			
77.50	1.000	1.500	I																			
78.75	1.000	1.500	I																			
80.00	1.000	1.500	I																			
81.25	1.000	1.500	I																			
82.50	1.000	1.500	I																			
83.75	1.000	1.500	I																			
85.00	1.000	1.500	I																			
86.25	1.000	1.500	I																			
87.50	1.000	1.500	I																			
88.75	1.000	1.500	I																			
90.00	1.000	1.500	I																			
91.25	1.000	1.500	I																			
92.50	1.000	1.500	I																			
93.75	1.000	1.500	I																			
95.00	1.000	1.500	I																			
96.25	1.000	1.500	I																			
97.50	1.000	1.500	I																			
98.75	1.000	1.500	I																			
100.00	1.000	1.500	I																			

REGULATOR (LOAD CHANGES)

WITH DYNAMIC COMPENSATION

T	FW	CM1	CM	U	TU	TS
0.000	10000.000	8.333	8.333	1133.000	200.000	200.000
1.250	10000.000	8.333	8.333	1133.000	200.001	200.000
2.500	10000.000	8.333	8.333	1132.999	200.001	200.000
3.750	10000.000	8.333	8.333	1132.997	200.002	200.000
5.000	10000.000	8.333	8.333	1132.993	200.002	200.000
6.250	10000.000	8.333	8.333	1132.990	200.002	200.000
7.500	10000.000	8.333	8.333	1132.986	200.002	200.000
8.750	10000.000	8.333	8.333	1132.984	200.002	200.000
10.000	10000.000	8.333	8.333	1132.982	200.002	200.000
11.250	10000.000	8.333	8.333	1132.981	200.002	200.000
12.500	10000.000	8.333	8.333	1132.982	200.001	200.000
13.750	10000.000	8.333	8.333	1132.982	200.001	200.000
15.000	10000.000	8.333	8.333	1132.983	200.001	200.000
16.250	10000.000	8.333	8.333	1132.984	200.001	200.000
17.500	10000.000	8.333	8.333	1132.984	200.001	200.000
18.750	10000.000	8.333	8.333	1132.984	200.001	200.000
20.000	10000.000	8.333	8.333	1132.984	200.001	200.000
21.250	10000.000	8.333	8.333	1132.984	200.001	200.000
22.500	10000.000	8.333	8.333	1132.984	200.001	200.000
23.750	10000.000	8.333	8.333	1132.984	200.001	200.000
25.000	9200.000	8.333	8.333	1132.984	204.401	200.000
26.250	9200.000	8.216	7.008	1059.465	208.254	200.000
27.500	9200.000	8.140	7.088	1009.404	205.780	200.000
28.750	9200.000	8.133	7.137	984.457	202.711	200.000
30.000	9200.000	8.175	7.242	979.970	200.250	200.000
31.250	9200.000	8.238	7.384	986.958	198.482	200.000
32.500	9200.000	8.303	7.519	1000.557	197.513	200.000
33.750	9200.000	8.355	7.632	1016.234	197.241	200.000
35.000	9200.000	8.390	7.712	1030.726	197.480	200.000
36.250	9200.000	8.407	7.757	1042.092	198.024	200.000
37.500	9200.000	8.408	7.771	1049.566	198.689	200.000
38.750	9200.000	8.498	7.764	1051.279	199.320	200.000
40.000	9200.000	8.382	7.743	1053.927	199.838	200.000
41.250	9200.000	8.365	7.717	1052.464	200.198	200.000
42.500	9200.000	8.349	7.692	1049.858	200.397	200.000
43.750	9200.000	8.336	7.671	1046.928	200.459	200.000
45.000	9200.000	8.328	7.657	1044.265	200.423	200.000
46.250	9200.000	8.324	7.649	1042.210	200.330	200.000
47.500	9200.000	8.322	7.647	1040.886	200.214	200.000
48.750	9200.000	8.324	7.649	1040.258	200.162	200.000
50.000	9200.000	8.326	7.653	1040.187	200.313	200.000
51.250	9200.000	8.329	7.658	1040.491	199.952	200.000
52.500	9200.000	8.331	7.662	1040.992	199.919	200.000
53.750	9200.000	8.333	7.666	1041.541	199.811	200.000
55.000	9200.000	8.335	7.669	1042.030	199.921	200.000
56.250	9200.000	8.335	7.670	1042.402	199.940	200.000
57.500	9200.000	8.335	7.670	1042.636	199.962	200.000
58.750	9200.000	8.335	7.670	1042.742	199.963	200.000
60.000	9200.000	8.335	7.669	1042.746	200.000	200.000
61.250	9200.000	8.334	7.668	1042.684	200.011	200.000
62.500	9200.000	8.334	7.667	1042.589	200.017	200.000
63.750	9200.000	8.333	7.667	1042.487	200.018	200.000
65.000	9200.000	8.333	7.666	1042.397	200.016	200.000
66.250	9200.000	8.333	7.666	1042.330	200.012	200.000
67.500	9200.000	8.333	7.666	1042.289	200.008	200.000
68.750	9200.000	8.333	7.666	1042.271	200.004	200.000
70.000	9200.000	8.333	7.666	1042.272	200.001	200.000
71.250	9200.000	8.333	7.666	1042.285	199.999	200.000
72.500	9200.000	8.333	7.666	1042.303	199.998	200.000
73.750	9200.000	8.333	7.667	1042.322	199.998	200.000
75.000	9200.000	8.333	7.667	1042.338	199.999	200.000
76.250	9200.000	8.333	7.667	1042.350	199.999	200.000
77.500	9200.000	8.333	7.667	1042.357	200.000	200.000
78.750	9200.000	8.333	7.667	1042.360	200.001	200.000
80.000	9200.000	8.333	7.667	1042.359	200.001	200.000
81.250	9200.000	8.333	7.667	1042.357	200.002	200.000
82.500	9200.000	8.333	7.667	1042.354	200.002	200.000
83.750	9200.000	8.333	7.667	1042.350	200.002	200.000
85.000	9200.000	8.333	7.667	1042.347	200.002	200.000
86.250	9200.000	8.333	7.667	1042.345	200.002	200.000
87.500	9200.000	8.333	7.667	1042.344	200.002	200.000
88.750	9200.000	8.333	7.667	1042.343	200.001	200.000
90.000	9200.000	8.333	7.667	1042.344	200.001	200.000
91.250	9200.000	8.333	7.667	1042.344	200.001	200.000
92.500	9200.000	8.333	7.667	1042.345	200.001	200.000
93.750	9200.000	8.333	7.667	1042.345	200.001	200.000
95.000	9200.000	8.333	7.667	1042.345	200.001	200.000
96.250	9200.000	8.333	7.667	1042.345	200.001	200.000
97.500	9200.000	8.333	7.667	1042.345	200.001	200.000
98.750	9200.000	8.333	7.667	1042.345	200.001	200.000
100.000	9200.000	8.333	7.667	1042.345	200.001	200.000

REGULATOR (LOAD CHANGES)

THE ACTUAL VALUES OF (TO) & (TS) ARE GIVEN BY:  
 ((IO) + 19.5) X 10.0 AND (FW) X 10000.0

(OUTPUTS SCALED BY .100E+01)  
 (X INDICATES MORE THAN ONE VARIABLE HAVE THE GIVEN VALUE)

T	IO(+)	FW(,)	0 + *****																	
			0.00	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50							
0.00	0.500	1.000	I																	
1.25	0.500	1.000	I																	
2.50	0.500	1.000	I																	
3.75	0.500	1.000	I																	
5.00	0.500	1.000	I																	
6.25	0.500	1.000	I																	
7.50	0.500	1.000	I																	
8.75	0.500	1.000	I																	
10.00	0.500	1.000	I																	
11.25	0.500	1.000	I																	
12.50	0.500	1.000	I																	
13.75	0.500	1.000	I																	
15.00	0.500	1.000	I																	
16.25	0.500	1.000	I																	
17.50	0.500	1.000	I																	
18.75	0.500	1.000	I																	
20.00	0.500	1.000	I																	
21.25	0.500	1.000	I																	
22.50	0.500	1.000	I																	
23.75	0.500	1.000	I																	
25.00	0.940	0.920	I																	
26.25	1.325	0.920	I																	
27.50	1.078	0.920	I																	
28.75	0.771	0.920	I																	
30.00	0.525	0.920	I																	
31.25	0.348	0.920	I																	
32.50	0.451	0.920	I																	
33.75	0.224	0.920	I																	
35.00	0.248	0.920	I																	
36.25	0.307	0.920	I																	
37.50	0.308	0.920	I																	
38.75	0.432	0.920	I																	
40.00	0.484	0.920	I																	
41.25	0.520	0.920	I																	
42.50	0.540	0.920	I																	
44.75	0.540	0.920	I																	
45.00	0.542	0.920	I																	
46.25	0.533	-0.920	I																	
47.50	0.521	0.920	I																	
48.75	0.510	0.920	I																	
50.00	0.501	0.920	I																	
51.25	0.495	0.920	I																	
52.50	0.492	0.920	I																	
53.75	0.491	0.920	I																	
55.00	0.492	0.920	I																	
56.25	0.494	0.920	I																	
57.50	0.496	0.920	I																	
58.75	0.498	0.920	I																	
60.00	0.500	0.920	I																	
61.25	0.501	0.920	I																	
62.50	0.502	0.920	I																	
63.75	0.502	0.920	I																	
65.00	0.502	0.920	I																	
66.25	0.501	0.920	I																	
67.50	0.501	0.920	I																	
68.75	0.500	0.920	I																	
70.00	0.500	0.920	I																	
71.25	0.500	0.920	I																	
72.50	0.500	0.920	I																	
73.75	0.500	0.920	I																	
75.00	0.500	0.920	I																	
76.25	0.500	0.920	I																	
77.50	0.500	0.920	I																	
78.75	0.500	0.920	I																	
80.00	0.500	0.920	I																	
81.25	0.500	0.920	I																	
82.50	0.500	0.920	I																	
83.75	0.500	0.920	I																	
85.00	0.500	0.920	I																	
86.25	0.500	0.920	I																	
87.50	0.500	0.920	I																	
88.75	0.500	0.920	I																	
90.00	0.500	0.920	I																	
91.25	0.500	0.920	I																	
92.50	0.500	0.920	I																	
93.75	0.500	0.920	I																	
95.00	0.500	0.920	I																	
96.25	0.500	0.920	I																	
97.50	0.500	0.920	I																	
98.75	0.500	0.920	I																	
100.00	0.500	0.920	I																	



4

PART F

1

FEEDFORWARD-FEEDBACK CONTROL  
(Time delays added to disturbance and  
temperature measuring element)

30-AUG-1983 18:57:03  
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0001		PROGRAM HEATEX
0002		DIMENSION T(480), CM(480), TM(480), TO(480), TS(480), TT(5,410)
0003		DIMENSION U(480), DEL(1), FW(480), ZN(480), CLL(480), T1(480), ER(480)
0004		DIMENSION T01(480), T02(480), T03(480), CM1(480), TM1(480)
0005		DIMENSION X(480), Y(480), X1(480), Y1(480)
0006		REAL INTUD, INTOD1, INTOD2, INTMD, INTMD1, KV, KP, KM, KS, KFF, KM1, KDIS
0007		REAL INTER, KD, KC, KI
0008		DATA DEL/0.25/
0009	C	PARAMETERS AND VARIABLES
0010	C	FEEDFORWARD CP=HEAT CAPACITY OF WATER (BTU/(LB.DEG. F))
0011	C	CONTROLLER: HS=LATENT HEAT OF STEAM (BTU/LB.)
0012	C	KFF=CONTROLLER GAIN
0013	C	CM=CONTROLLER OUTPUT (VOLTS-RANGE 0-10V)
0014	C	CLL=DYNAMIC COMPENSATION TERM
0015	C	TH1=LEAD TIME CONSTANT (SEC.)
0016	C	TH2=LAG TIME CONSTANT (SEC.)
0017	C	
0018	C	FEEDBACK KC=PROPORTIONAL GAIN
0019	C	CONTROLLER: KI=INTEGRAL TIME (SEC.)
0020	C	KD=DERIVATIVE TIME (SEC.)
0021	C	CM1=CONTROLLER OUTPUT
0022	C	CBAS=CONTROLLER BAS
0023	C	
0024	C	VALVE : THV= VALVE TIME CONSTANT (SEC.)
0025	C	KV=VALVE GAIN ((LB./HR)/VOLTS)
0026	C	
0027	C	EXCHANGER : THP=PROCESS TIME CONSTANT (SEC.)
0028	C	KP=PROCESS GAIN (DEG. F/(LB./HR))
0029	C	
0030	C	DISTURBANCE: THD=DISTURBANCE TIME CONSTANT (SEC.)
0031	C	KDIS=DISTURBANCE GAIN (DEG. F/(LB./HR))
0032	C	
0033	C	MEASURING THM=FLOW MEASURING ELEMENT TIME CONSTANT (SEC.)
0034	C	ELEMENTS : KM=FLOW MEASURING ELEMENT GAIN (VOLTS/DEG.F)
0035	C	THM1=TEMPERATURE MEASURING ELEMENT TIME CONSTANT (SEC.)
0036	C	KM1=TEMPERATURE MEASURING ELEMENT GAIN (VOLTS/DEG. F)
0037	C	
0038	C	OTHERS : TS=SETPOINT TEMPERATURE (FEEDBACK CONTROLLER) (DEG. F)
0039	C	TS1=FEEDFORWARD CONTROLLER SETPOINT (DEG. F)
0040	C	KS=SETPOINT GAIN (DEG. F/VOLTS)
0041	C	TIN=INPUT TEMPERATURE (DEG. F)
0042	C	TO=OVERALL OUTPUT TEMPERATURE (DEG. F)
0043	C	T01=OUTPUT TEMPERATURE DUE TO PROCESS (DEG. F)
0044	C	T02=OUTPUT TEMPERATURE DUE TO DISTURBANCE (DEG. F)
0045	C	FW=WATER INFLOW RATE (LB./HR)
0046	C	
0047		TYPE 6
0048	6	FORMAT(1H1, //, 10X, 'F.- FEEDFORWARD-FEEDBACK CONTROL', //, 10X,
0049	+	32(' '), //, 10X, '(TIME DELAYS ARE ADDED TO DISTURBANCE & TEMP.'
0050	+	' MEASURING ELEMENT)', //, 10X,
0051	+	' (FEEDBACK CONTROLLER HAS P+I+D CONTROL MODES)', //)
0052	C	CONSTANTS & PARAMETERS
0053		HS=970.
0054		CP=1.
0055		TIN=90.
0056		THV=2.
0057		KV=135.9605

HEATEX

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0058      THP=4.05
0059      KP=0.09709
0060      THM=0.5
0061      KM=0.00083333
0062      THM1=3.
0063      KM1=0.0416665
0064      KDIS=0.011
0065      THD=0.5
0066      KS=0.0416665
0067      KC=1.25
0068      KI=9.
0069      KD=10.
0070      CBAIS=8.3333
0071      TH2=5.
0072      TH1=6.
0073      DO 97 JI=49,59
0074      97 X1(JI)=8.3333
0075      DO 96 JI=1,59
0076      96 X(JI)=110.
0077      DO 98 JJ=1,2
0078      DO 99 JK=1,2
0079      IF(JK.EQ.2)GO TO 7
0080      IF(JJ.EQ.2)TYPE 25
0081      25 FORMAT(1H1,/)
0082      TYPE 8
0083      8 FORMAT(10X,'SERVO-MECHANISM (SETPOINT CHANGES)',/,10X,34('-'))
0084      GO TO 9
0085      7 TYPE 10
0086      10 FORMAT(1H1,/,10X,'REGUDATOR (LOAD CHANGES)',/,10X,24('-'))
0087      9 IF(JJ.EQ.2)GO TO 12
0088      TYPE 14
0089      14 FORMAT(10X,'WITHOUT DYNAMIC CUMPENSATION',/,10X,28('-'),/)
0090      GO TO 19
0091      12 TYPE 15
0092      15 FORMAT(10X,'WITH DYNAMIC COMPENSATION',/,10X,25('-'),/)
0093      C INITIAL CONDITIONS
0094      19 U(59)=1133.
0095      ER(59)=0.
0096      Fw(59)=10000.
0097      TU(59)=200.
0098      TU1(59)=200.
0099      TM(59)=Fw(59)*KM
0100      TS(59)=200.
0101      TS1(59)=200.
0102      CM1(59)=8.3333
0103      CM(59)=8.3333
0104      KFF=HS/(TS(59)-TIN)
0105      TM1(59)=8.3333
0106      ZN(59)=TM(59)
0107      CLL(59)=ZN(59)
0108      INTER=0.
0109      INTUD=1133.
0110      INTUD1=200.
0111      INTUD2=110.
0112      INTMD=8.3333
0113      INTMD1=8.3333
0114      T(59)=0.0

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HEATEX

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0115      DO 2 I=60,461
0116      II=I-1
0117      I1=I-59
0118      I2=I-11
0119      Y1(I)=X1(I2)
0120      TS(I)=TS(I1)
0121      IF(JK.EQ.1)GO TO 20
0122      FW(I)=FW(I1)
0123      IF(I.EQ.159)FW(I)=FW(I1)-800.
0124      GO TO 21
0125      20  IF(I.EQ.159)TS(I)=TS(I1)+10.
0126      FW(I)=FW(I1)
0127      C  FEEDBACK CONTROLLER
0128      21  ER(I)=TS(I)*KS-Y1(I)
0129      VP=KC*ER(I)
0130      VI=INTER*(KC/KI)
0131      VD=KC*KD*(ER(I)-ER(I1))
0132      CM1(I)=VP+VI+VD+CBAIS
0133      IF(CM1(I).GT.10.)CM1(I)=10.
0134      TS1(I)=CM1(I)/KS
0135      C  MEASURING ELEMENT
0136      TMD=(KM*FW(I)-TM(I1))/THM
0137      TA(I)=INTMD
0138      IF(JJ.EQ.2)GO TO 22
0139      C  FEEDFORWARD CONTROLLER WITHOUT DYNAMIC COMPENSATION
0140      CM(I)=TA(I)*KFF*(CP/HS)*(TS1(I1)-TIN)
0141      GO TO 23
0142      C  DYNAMIC COMPENSATION (LEAD/LAG)
0143      22  AA=TM(I1)-ZN(I1)
0144      ZN(I)=((DEL(I)/TH2)*AA)+ZN(I1)
0145      CLL(I)=((TH1/TH2)*AA)+ZN(I1)
0146      C  FEEDFORWARD CONTROLLER WITH DYNAMIC COMPENSATION
0147      CM(I)=CLL(I)*KFF*(CP/HS)*(TS1(I1)-TIN)
0148      C  VALVE
0149      23  UD=(KV*CM(I)-U(I1))/THV
0150      U(I)=INTUD
0151      C  HEAT EXCHANGER
0152      PO=KP*U(I)+TIN
0153      TOD1=(PO-TO1(I1))/THP
0154      TO1(I)=INTOD1
0155      IF(JK.EQ.2)GO TO 17
0156      TO(I)=TO1(I)
0157      GO TO 18
0158      17  TO2(59)=110.
0159      TOD2=(KDIS*FW(I)-TO2(I1))/THD
0160      TO2(I)=INTOD2
0161      X(I)=TO2(I)
0162      Y(I)=X(I1)
0163      TG(I)=FO1(I)+(TO2(59)-Y(I))
0164      C  TEMPERATURE MEASURING ELEMENT
0165      18  TMD1=(KM1*TO(I)-TM1(I1))/THM1
0166      TM1(I)=INTMD1
0167      X1(I)=TM1(I)
0168      C  EULER INTEGRATION
0169      T(I)=T(I1)+DEL(I)
0170      INTER=INTER+ER(I)*DEL(I)
0171      INTUD=INTUD+UD*DEL(I)

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HEATEX

30-AUG-1983 18:57:03  
30-AUG-1983 18:56:56

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0172      INTOD1=INTOD1+TOD1*DEL(1)
0173      INTOD2=INTOD2+TOD2*DEL(1)
0174      INTMD=INTMD+TMD*DEL(1)
0175      INTMD1=INTMD1+TMD1*DEL(1)
0176      2      CONTINUE
0177      TYPE 16
0178      16     FORMAT(15X,'T',9X,'FW',11X,'CM1',9X,'CM'10X,'U',11X,'TO',10X,
0179      +      'TS',/,10X,84('-'),/)
0180      IK=59
0181      DO 5 I=1,81
0182      T1(I)=T(1K)
0183      TT(1,I)=TO(IK)/10.-19.5
0184      TT(2,I)=FW(IK)/10000.
0185      IF(JK.EQ.1)TT(2,I)=TS(IK)/10.-19.5
0186      TYPE 11,T(IK),FW(IK),CM1(IK),CM(IK),U(IK),TO(IK),TS(IK)
0187      11     FORMAT(7X,7F12.3)
0188      IK=IK+5
0189      5      CONTINUE
0190      IF(JK.EQ.2)GO TO 90
0191      TYPE 24
0192      24     FORMAT(1H1)
0193      TYPE 8
0194      TYPE 91
0195      91     FORMAT(10X,'THE ACTUAL VALUES OF (TO) & (TS) ARE GIVEN BY:'
0196      +      /,20X,'((TO) OR (TS) + 19.5) X 10.0',/)
0197      GO TO 92
0198      90     TYPE 10
0199      TYPE 93
0200      93     FORMAT(10X,'THE ACTUAL VALUES OF (TO) & (TS) ARE GIVEN BY:'
0201      +      /,20X,'((TO) + 19.5) X 10.0      AND      (FW) X 10000.0',/)
0202      92     CALL PLOT1(T1,TT,81,2,JK)
0203      99     CONTINUE
0204      98     CONTINUE
0205      END
```

F.- FEEDFORWARD-FEEDBACK CONTROL

(TIME DELAYS ARE ADDED TO DISTURBANCE & TEMP. MEASURING ELEMENT)  
 (FEEDBACK CONTROLLER HAS P+I+D CONTROL MODES)

SERVO-MECHANISM (SETPOINT CHANGES)

WITHOUT DYNAMIC COMPENSATION

T	FW	CM1	CM	U	TO	TS
0.000	10000.000	8.333	8.333	1133.000	200.000	200.000
1.250	10000.000	8.333	8.333	1133.000	200.001	200.000
2.500	10000.000	8.333	8.333	1133.000	200.001	200.000
3.750	10000.000	8.333	8.333	1133.000	200.002	200.000
5.000	10000.000	8.333	8.333	1132.997	200.002	200.000
6.250	10000.000	8.333	8.333	1132.990	200.002	200.000
7.500	10000.000	8.333	8.333	1132.982	200.002	200.000
8.750	10000.000	8.333	8.333	1132.976	200.002	200.000
10.000	10000.000	8.333	8.333	1132.970	200.001	200.000
11.250	10000.000	8.333	8.333	1132.966	200.001	200.000
12.500	10000.000	8.333	8.333	1132.964	200.001	200.000
13.750	10000.000	8.333	8.333	1132.964	200.000	200.000
15.000	10000.000	8.333	8.333	1132.965	200.000	200.000
16.250	10000.000	8.333	8.333	1132.968	200.000	200.000
17.500	10000.000	8.333	8.333	1132.970	200.000	200.000
18.750	10000.000	8.333	8.333	1132.971	200.000	200.000
20.000	10000.000	8.333	8.333	1132.973	200.000	200.000
21.250	10000.000	8.333	8.333	1132.973	200.000	200.000
22.500	10000.000	8.333	8.333	1132.973	200.000	200.000
23.750	10000.000	8.333	8.333	1132.972	200.000	200.000
25.000	10000.000	10.000	8.333	1132.971	200.000	210.000
26.250	10000.000	8.926	9.359	1211.566	200.717	210.000
27.500	10000.000	8.999	9.490	1249.121	203.190	210.000
28.750	10000.000	9.071	9.622	1275.850	205.858	210.000
30.000	10000.000	9.032	9.646	1296.185	208.438	210.000
31.250	10000.000	8.960	9.528	1301.041	210.675	210.000
32.500	10000.000	8.877	9.383	1293.473	212.242	210.000
33.750	10000.000	8.791	9.227	1278.843	213.051	210.000
35.000	10000.000	8.719	9.083	1260.753	213.167	210.000
36.250	10000.000	8.672	8.978	1243.009	212.735	210.000
37.500	10000.000	8.652	8.922	1228.726	211.965	210.000
38.750	10000.000	8.655	8.911	1219.546	211.073	210.000
40.000	10000.000	8.676	8.938	1213.853	210.246	210.000
41.250	10000.000	8.707	8.988	1217.015	209.613	210.000
42.500	10000.000	8.739	9.048	1221.673	209.240	210.000
43.750	10000.000	8.768	9.104	1228.165	209.132	210.000
45.000	10000.000	8.787	9.147	1234.887	209.243	210.000
46.250	10000.000	8.797	9.172	1240.556	209.501	210.000
47.500	10000.000	8.797	9.178	1244.370	209.824	210.000
48.750	10000.000	8.789	9.168	1246.041	210.135	210.000
50.000	10000.000	8.776	9.148	1245.723	210.380	210.000
51.250	10000.000	8.762	9.123	1243.894	210.525	210.000
52.500	10000.000	8.750	9.099	1241.192	210.566	210.000
53.750	10000.000	8.740	9.079	1238.271	210.515	210.000
55.000	10000.000	8.735	9.066	1235.678	210.399	210.000
56.250	10000.000	8.733	9.061	1233.784	210.252	210.000
57.500	10000.000	8.735	9.062	1232.753	210.103	210.000
58.750	10000.000	8.740	9.068	1232.564	209.979	210.000
60.000	10000.000	8.745	9.077	1233.053	209.894	210.000
61.250	10000.000	8.750	9.087	1233.975	209.853	210.000
62.500	10000.000	8.754	9.093	1235.085	209.852	210.000
63.750	10000.000	8.756	9.101	1236.089	209.882	210.000
65.000	10000.000	8.757	9.103	1236.877	209.929	210.000
66.250	10000.000	8.756	9.103	1237.339	209.981	210.000
67.500	10000.000	8.755	9.101	1237.466	210.028	210.000
68.750	10000.000	8.753	9.097	1237.308	210.061	210.000
70.000	10000.000	8.751	9.094	1236.956	210.077	210.000
71.250	10000.000	8.749	9.090	1236.513	210.077	210.000
72.500	10000.000	8.748	9.087	1236.077	210.065	210.000
73.750	10000.000	8.747	9.086	1235.722	210.048	210.000
75.000	10000.000	8.747	9.086	1235.493	210.022	210.000
76.250	10000.000	8.748	9.086	1235.400	210.001	210.000
77.500	10000.000	8.749	9.088	1235.429	209.985	210.000
78.750	10000.000	8.749	9.089	1235.547	209.975	210.000
80.000	10000.000	8.750	9.091	1235.714	209.973	210.000
81.250	10000.000	8.751	9.092	1235.888	209.975	210.000
82.500	10000.000	8.751	9.092	1236.037	209.982	210.000
83.750	10000.000	8.751	9.093	1236.141	209.991	210.000
85.000	10000.000	8.751	9.092	1236.191	209.999	210.000
86.250	10000.000	8.750	9.092	1236.190	210.006	210.000
87.500	10000.000	8.750	9.091	1236.151	210.010	210.000
88.750	10000.000	8.750	9.091	1236.087	210.012	210.000
90.000	10000.000	8.750	9.090	1236.017	210.011	210.000
91.250	10000.000	8.749	9.090	1235.953	210.008	210.000
92.500	10000.000	8.749	9.090	1235.906	210.005	210.000
93.750	10000.000	8.749	9.090	1235.880	210.001	210.000
95.000	10000.000	8.750	9.090	1235.875	209.998	210.000
96.250	10000.000	8.750	9.090	1235.888	209.996	210.000
97.500	10000.000	8.750	9.091	1235.911	209.995	210.000
98.750	10000.000	8.750	9.091	1235.939	209.996	210.000
100.000	10000.000	8.750	9.091	1235.965	209.996	210.000

SERVO-MECHANISM (SETPOINT CHANGES)

THE ACTUAL VALUES OF (TO) & (TS) ARE GIVEN BY:  
 ((TO) OR (TS) + 19.5) x 10.0

(OUTPUTS SCALED BY .100E+01)

(X INDICATES MORE THAN ONE VARIABLE HAVE THE GIVEN VALUE)

0 + ----->

T	TO(+)	TS(.)	0.00	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50
0.00	0.500	0.500	I		X								
1.25	0.500	0.500	I		X								
2.50	0.500	0.500	I		X								
3.75	0.500	0.500	I		X								
5.00	0.500	0.500	I		X								
6.25	0.500	0.500	I		X								
7.50	0.500	0.500	I		X								
8.75	0.500	0.500	I		X								
10.00	0.500	0.500	I		X								
11.25	0.500	0.500	I		X								
12.50	0.500	0.500	I		X								
13.75	0.500	0.500	I		X								
15.00	0.500	0.500	I		X								
16.25	0.500	0.500	I		X								
17.50	0.500	0.500	I		X								
18.75	0.500	0.500	I		X								
20.00	0.500	0.500	I		X								
21.25	0.500	0.500	I		X								
22.50	0.500	0.500	I		X								
23.75	0.500	0.500	I		X								
25.00	0.500	1.500	I										
26.25	0.572	1.500	I										
27.50	0.819	1.500	I										
28.75	1.086	1.500	I										
30.00	1.344	1.500	I										
31.25	1.567	1.500	I										
32.50	1.724	1.500	I										
33.75	1.805	1.500	I										
35.00	1.817	1.500	I										
36.25	1.774	1.500	I										
37.50	1.697	1.500	I										
38.75	1.607	1.500	I										
40.00	1.525	1.500	I										
41.25	1.461	1.500	I										
42.50	1.424	1.500	I										
43.75	1.413	1.500	I										
45.00	1.424	1.500	I										
46.25	1.450	1.500	I										
47.50	1.482	1.500	I										
48.75	1.514	1.500	I										
50.00	1.538	1.500	I										
51.25	1.553	1.500	I										
52.50	1.557	1.500	I										
53.75	1.551	1.500	I										
55.00	1.540	1.500	I										
56.25	1.525	1.500	I										
57.50	1.510	1.500	I										
58.75	1.498	1.500	I										
60.00	1.489	1.500	I										
61.25	1.485	1.500	I										
62.50	1.485	1.500	I										
63.75	1.488	1.500	I										
65.00	1.493	1.500	I										
66.25	1.498	1.500	I										
67.50	1.503	1.500	I										
68.75	1.506	1.500	I										
70.00	1.508	1.500	I										
71.25	1.508	1.500	I										
72.50	1.507	1.500	I										
73.75	1.505	1.500	I										
75.00	1.502	1.500	I										
76.25	1.500	1.500	I										
77.50	1.498	1.500	I										
78.75	1.498	1.500	I										
80.00	1.497	1.500	I										
81.25	1.498	1.500	I										
82.50	1.498	1.500	I										
83.75	1.499	1.500	I										
85.00	1.500	1.500	I										
86.25	1.501	1.500	I										
87.50	1.501	1.500	I										
88.75	1.501	1.500	I										
90.00	1.501	1.500	I										
91.25	1.501	1.500	I										
92.50	1.500	1.500	I										
93.75	1.500	1.500	I										
95.00	1.500	1.500	I										
96.25	1.500	1.500	I										
97.50	1.500	1.500	I										
98.75	1.500	1.500	I										
100.00	1.500	1.500	I										

REGULATOR (LOAD CHANGES)

WITHOUT DYNAMIC COMPENSATION

T	FW	CM1	CM	U	TO	IS
0.000	10000.000	8.333	8.333	1133.000	200.000	200.000
1.250	10000.000	8.333	8.333	1133.000	200.001	200.000
2.500	10000.000	8.333	8.333	1133.000	200.001	200.000
3.750	10000.000	8.333	8.333	1133.000	200.002	200.000
5.000	10000.000	8.333	8.333	1132.997	200.002	200.000
6.250	10000.000	8.333	8.333	1132.990	200.002	200.000
7.500	10000.000	8.333	8.333	1132.982	200.002	200.000
8.750	10000.000	8.333	8.333	1132.976	200.002	200.000
10.000	10000.000	8.333	8.333	1132.970	200.001	200.000
11.250	10000.000	8.333	8.333	1132.964	200.001	200.000
12.500	10000.000	8.333	8.333	1132.964	200.001	200.000
13.750	10000.000	8.333	8.333	1132.964	200.000	200.000
15.000	10000.000	8.333	8.333	1132.965	200.000	200.000
16.250	10000.000	8.333	8.333	1132.968	200.000	200.000
17.500	10000.000	8.333	8.333	1132.970	200.000	200.000
18.750	10000.000	8.333	8.333	1132.971	200.000	200.000
20.000	10000.000	8.333	8.333	1132.973	200.000	200.000
21.250	10000.000	8.333	8.333	1132.973	200.000	200.000
22.500	10000.000	8.333	8.333	1132.973	200.000	200.000
23.750	10000.000	8.333	8.333	1132.972	200.000	200.000
25.000	9200.000	8.333	8.333	1132.971	200.000	200.000
26.250	9200.000	8.333	7.583	1090.484	199.684	200.000
27.500	9200.000	8.333	7.666	1064.620	198.204	200.000
28.750	9200.000	8.333	7.669	1052.098	196.635	200.000
30.000	9200.000	8.393	7.713	1047.500	195.268	200.000
31.250	9200.000	8.480	7.853	1052.405	194.269	200.000
32.500	9200.000	8.567	8.000	1065.465	193.804	200.000
33.750	9200.000	8.646	8.139	1082.105	193.890	200.000
35.000	9200.000	8.708	8.256	1099.380	194.431	200.000
36.250	9200.000	8.747	8.337	1114.928	195.285	200.000
37.500	9200.000	8.765	8.381	1126.671	196.288	200.000
38.750	9200.000	8.765	8.392	1134.197	197.283	200.000
40.000	9200.000	8.753	8.378	1137.577	202.552	200.000
41.250	9200.000	8.735	8.351	1137.583	207.623	200.000
42.500	9200.000	8.716	8.319	1135.337	208.209	200.000
43.750	9200.000	8.120	7.555	1126.057	208.277	200.000
45.000	9200.000	8.214	7.510	1062.049	207.433	200.000
46.250	9200.000	8.155	7.387	1035.631	205.511	200.000
47.500	9200.000	8.126	7.328	1016.898	203.489	200.000
48.750	9200.000	8.171	7.359	1005.720	201.611	200.000
50.000	9200.000	8.230	7.453	1005.758	200.093	200.000
51.250	9200.000	8.293	7.557	1013.180	199.112	200.000
52.500	9200.000	8.350	7.659	1024.285	198.674	200.000
53.750	9200.000	8.392	7.741	1036.373	198.692	200.000
55.000	9200.000	8.415	7.792	1047.001	199.032	200.000
56.250	9200.000	8.419	7.811	1054.559	199.539	200.000
57.500	9200.000	8.408	7.802	1058.451	200.070	200.000
58.750	9200.000	8.388	7.773	1058.866	200.515	200.000
60.000	9200.000	8.364	7.734	1056.548	200.809	200.000
61.250	9200.000	8.341	7.695	1052.540	200.930	200.000
62.500	9200.000	8.323	7.661	1047.924	200.894	200.000
63.750	9200.000	8.312	7.637	1043.620	200.741	200.000
65.000	9200.000	8.307	7.625	1040.272	200.521	200.000
66.250	9200.000	8.308	7.623	1038.198	200.285	200.000
67.500	9200.000	8.314	7.630	1037.422	200.075	200.000
68.750	9200.000	8.321	7.641	1037.740	199.917	200.000
70.000	9200.000	8.329	7.655	1038.813	199.823	200.000
71.250	9200.000	8.336	7.667	1040.256	199.792	200.000
72.500	9200.000	8.340	7.676	1041.723	199.811	200.000
73.750	9200.000	8.343	7.681	1042.947	199.864	200.000
75.000	9200.000	8.343	7.683	1043.772	199.931	200.000
76.250	9200.000	8.341	7.681	1044.154	199.997	200.000
77.500	9200.000	8.339	7.677	1044.135	200.050	200.000
78.750	9200.000	8.336	7.673	1043.815	200.083	200.000
80.000	9200.000	8.333	7.668	1043.325	200.095	200.000
81.250	9200.000	8.331	7.665	1042.789	200.089	200.000
82.500	9200.000	8.330	7.662	1042.312	200.070	200.000
83.750	9200.000	8.330	7.661	1041.960	200.045	200.000
85.000	9200.000	8.330	7.661	1041.761	200.019	200.000
86.250	9200.000	8.331	7.662	1041.712	199.996	200.000
87.500	9200.000	8.332	7.664	1041.784	199.981	200.000
88.750	9200.000	8.333	7.665	1041.932	199.972	200.000
90.000	9200.000	8.334	7.667	1042.112	199.971	200.000
91.250	9200.000	8.334	7.668	1042.286	199.975	200.000
92.500	9200.000	8.334	7.668	1042.423	199.983	200.000
93.750	9200.000	8.334	7.668	1042.511	199.992	200.000
95.000	9200.000	8.334	7.668	1042.545	200.000	200.000
96.250	9200.000	8.334	7.668	1042.534	200.006	200.000
97.500	9200.000	8.333	7.667	1042.490	200.009	200.000
98.750	9200.000	8.333	7.667	1042.430	200.010	200.000
100.000	9200.000	8.333	7.666	1042.366	200.009	200.000



REGULATOR (LOAD CHANGES)

THE ACTUAL VALUES OF (TO) & (TS) ARE GIVEN BY:  
 ((TO) + 19.5) X 10.0 AND (FS) X 10000.0

(OUTPUTS SCALED BY .100E+01)  
 (X INDICATES MORE THAN ONE VARIABLE HAVE THE GIVEN VALUE)  
 (ZERO = 0 + ZERO)

T	TO(+)	FS(.)	-----											
			-2.50	-2.00	-1.50	-1.00	-0.50	0.00	0.50	1.00	1.50	2.00	2.50	
0.00	0.500	1.000												
1.25	0.500	1.000	X											
2.50	0.500	1.000												
3.75	0.500	1.000												
5.00	0.500	1.000												
6.25	0.500	1.000												
7.50	0.500	1.000												
8.75	0.500	1.000												
10.00	0.500	1.000												
11.25	0.500	1.000												
12.50	0.500	1.000												
13.75	0.500	1.000												
15.00	0.500	1.000												
16.25	0.500	1.000												
17.50	0.500	1.000												
18.75	0.500	1.000												
20.00	0.500	1.000												
21.25	0.500	1.000												
22.50	0.500	1.000												
23.75	0.500	1.000												
25.00	0.500	0.920												
26.25	0.468	0.920												
27.50	0.320	0.920												
28.75	0.164	0.920												
30.00	0.027	0.920												
31.25	-0.073	0.920												
32.50	-0.120	0.920												
33.75	-0.111	0.920												
35.00	-0.057	0.920												
36.25	0.029	0.920												
37.50	0.129	0.920												
38.75	0.228	0.920												
40.00	0.755	0.920												
41.25	1.262	0.920												
42.50	1.321	0.920												
43.75	1.328	0.920												
45.00	1.243	0.920												
46.25	1.051	0.920												
47.50	0.849	0.920												
48.75	0.661	0.920												
50.00	0.509	0.920												
51.25	0.411	0.920												
52.50	0.367	0.920												
53.75	0.369	0.920												
55.00	0.403	0.920												
56.25	0.454	0.920												
57.50	0.507	0.920												
58.75	0.551	0.920												
60.00	0.581	0.920												
61.25	0.593	0.920												
62.50	0.589	0.920												
63.75	0.574	0.920												
65.00	0.552	0.920												
66.25	0.529	0.920												
67.50	0.507	0.920												
68.75	0.492	0.920												
70.00	0.482	0.920												
71.25	0.479	0.920												
72.50	0.481	0.920												
73.75	0.486	0.920												
75.00	0.493	0.920												
76.25	0.500	0.920												
77.50	0.505	0.920												
78.75	0.508	0.920												
80.00	0.510	0.920												
81.25	0.509	0.920												
82.50	0.507	0.920												
83.75	0.505	0.920												
85.00	0.502	0.920												
86.25	0.500	0.920												
87.50	0.498	0.920												
88.75	0.497	0.920												
90.00	0.497	0.920												
91.25	0.498	0.920												
92.50	0.498	0.920												
93.75	0.499	0.920												
95.00	0.500	0.920												
96.25	0.501	0.920												
97.50	0.501	0.920												
98.75	0.501	0.920												
100.00	0.501	0.920												

SERVO-MECHANISM (SETPPOINT CHANGES)  
 WITH DYNAMIC COMPENSATION

T	FW	CN1	CM	U	TO	TS
0.000	10000.000	8.333	8.333	1133.000	200.000	200.000
1.250	10000.000	8.333	8.333	1133.000	200.001	200.000
2.500	10000.000	8.333	8.333	1133.000	200.001	200.000
3.750	10000.000	8.333	8.333	1133.000	200.002	200.000
5.000	10000.000	8.333	8.333	1132.997	200.002	200.000
6.250	10000.000	8.333	8.333	1132.990	200.002	200.000
7.500	10000.000	8.333	8.333	1132.982	200.002	200.000
8.750	10000.000	8.333	8.333	1132.976	200.002	200.000
10.000	10000.000	8.333	8.333	1132.970	200.001	200.000
11.250	10000.000	8.333	8.333	1132.966	200.001	200.000
12.500	10000.000	8.333	8.333	1132.964	200.001	200.000
13.750	10000.000	8.333	8.333	1132.964	200.000	200.000
15.000	10000.000	8.333	8.333	1132.965	200.000	200.000
16.250	10000.000	8.333	8.333	1132.968	200.000	200.000
17.500	10000.000	8.333	8.333	1132.970	200.000	200.000
18.750	10000.000	8.333	8.333	1132.971	200.000	200.000
20.000	10000.000	8.333	8.333	1132.973	200.000	200.000
21.250	10000.000	8.333	8.333	1132.973	200.000	200.000
22.500	10000.000	8.333	8.333	1132.973	200.000	200.000
23.750	10000.000	8.333	8.333	1132.972	200.000	200.000
25.000	10000.000	10.000	8.333	1132.971	200.000	210.000
26.250	10000.000	8.926	9.359	1211.566	200.717	210.000
27.500	10000.000	8.999	9.490	1249.121	203.190	210.000
28.750	10000.000	9.071	9.622	1275.850	205.858	210.000
30.000	10000.000	9.032	9.646	1296.185	208.438	210.000
31.250	10000.000	8.960	9.528	1301.041	210.675	210.000
32.500	10000.000	8.877	9.383	1293.473	212.242	210.000
33.750	10000.000	8.791	9.227	1278.843	213.051	210.000
35.000	10000.000	8.719	9.083	1260.753	213.167	210.000
36.250	10000.000	8.672	8.978	1243.009	212.735	210.000
37.500	10000.000	8.652	8.922	1228.726	211.965	210.000
38.750	10000.000	8.655	8.911	1219.566	211.073	210.000
40.000	10000.000	8.676	8.938	1215.853	210.246	210.000
41.250	10000.000	8.707	8.988	1217.015	209.613	210.000
42.500	10000.000	8.739	9.048	1221.673	209.240	210.000
43.750	10000.000	8.768	9.104	1228.165	209.132	210.000
45.000	10000.000	8.787	9.147	1234.887	209.243	210.000
46.250	10000.000	8.797	9.172	1240.556	209.501	210.000
47.500	10000.000	8.797	9.178	1244.370	209.824	210.000
48.750	10000.000	8.789	9.168	1246.041	210.135	210.000
50.000	10000.000	8.776	9.148	1245.723	210.380	210.000
51.250	10000.000	8.762	9.123	1243.894	210.525	210.000
52.500	10000.000	8.750	9.099	1241.192	210.566	210.000
53.750	10000.000	8.740	9.079	1238.271	210.515	210.000
55.000	10000.000	8.735	9.066	1235.678	210.399	210.000
56.250	10000.000	8.733	9.061	1233.784	210.252	210.000
57.500	10000.000	8.735	9.062	1232.753	210.103	210.000
58.750	10000.000	8.740	9.068	1232.564	209.979	210.000
60.000	10000.000	8.745	9.077	1233.053	209.894	210.000
61.250	10000.000	8.750	9.087	1233.975	209.853	210.000
62.500	10000.000	8.754	9.095	1235.065	209.852	210.000
63.750	10000.000	8.756	9.101	1236.089	209.882	210.000
65.000	10000.000	8.757	9.103	1236.877	209.929	210.000
66.250	10000.000	8.756	9.103	1237.339	209.981	210.000
67.500	10000.000	8.755	9.101	1237.466	210.028	210.000
68.750	10000.000	8.753	9.097	1237.308	210.061	210.000
70.000	10000.000	8.751	9.094	1236.956	210.077	210.000
71.250	10000.000	8.749	9.090	1236.513	210.077	210.000
72.500	10000.000	8.748	9.087	1236.077	210.065	210.000
73.750	10000.000	8.747	9.086	1235.722	210.045	210.000
75.000	10000.000	8.747	9.086	1235.493	210.022	210.000
76.250	10000.000	8.748	9.086	1235.400	210.001	210.000
77.500	10000.000	8.749	9.088	1235.429	209.985	210.000
78.750	10000.000	8.749	9.089	1235.547	209.975	210.000
80.000	10000.000	8.750	9.091	1235.714	209.973	210.000
81.250	10000.000	8.751	9.092	1235.888	209.975	210.000
82.500	10000.000	8.751	9.092	1236.037	209.982	210.000
83.750	10000.000	8.751	9.093	1236.141	209.991	210.000
85.000	10000.000	8.751	9.092	1236.191	209.999	210.000
86.250	10000.000	8.750	9.092	1236.190	210.000	210.000
87.500	10000.000	8.750	9.091	1236.151	210.010	210.000
88.750	10000.000	8.750	9.091	1236.087	210.012	210.000
90.000	10000.000	8.750	9.090	1236.017	210.011	210.000
91.250	10000.000	8.749	9.090	1235.953	210.008	210.000
92.500	10000.000	8.749	9.090	1235.906	210.005	210.000
93.750	10000.000	8.749	9.090	1235.880	210.001	210.000
95.000	10000.000	8.750	9.090	1235.875	209.998	210.000
96.250	10000.000	8.750	9.090	1235.888	209.998	210.000
97.500	10000.000	8.750	9.091	1235.911	209.995	210.000
98.750	10000.000	8.750	9.091	1235.939	209.996	210.000
100.000	10000.000	8.750	9.091	1235.965	209.996	210.000



REGULATOR (LOAD CHANGES)

WITH DYNAMIC COMPENSATION

T	FW	CM1	CM	U	TO	TS
0.000	10000.000	8.333	8.333	1133.000	200.000	200.000
1.250	10000.000	8.333	8.333	1133.000	200.001	200.000
2.500	10000.000	8.333	8.333	1133.000	200.001	200.000
3.750	10000.000	8.333	8.333	1133.000	200.002	200.000
5.000	10000.000	8.333	8.333	1132.997	200.002	200.000
6.250	10000.000	8.333	8.333	1132.990	200.002	200.000
7.500	10000.000	8.333	8.333	1132.982	200.002	200.000
8.750	10000.000	8.333	8.333	1132.976	200.002	200.000
10.000	10000.000	8.333	8.333	1132.970	200.001	200.000
11.250	10000.000	8.333	8.333	1132.966	200.001	200.000
12.500	10000.000	8.333	8.333	1132.964	200.001	200.000
13.750	10000.000	8.333	8.333	1132.964	200.000	200.000
15.000	10000.000	8.333	8.333	1132.965	200.000	200.000
16.250	10000.000	8.333	8.333	1132.968	200.000	200.000
17.500	10000.000	8.333	8.333	1132.970	200.000	200.000
18.750	10000.000	8.333	8.333	1132.971	200.000	200.000
20.000	10000.000	8.333	8.333	1132.973	200.000	200.000
21.250	10000.000	8.333	8.333	1132.973	200.000	200.000
22.500	10000.000	8.333	8.333	1132.973	200.000	200.000
23.750	10000.000	8.333	8.333	1132.972	200.000	200.000
25.000	9200.000	8.333	8.333	1132.971	200.000	200.000
26.250	9200.000	8.333	7.351	1096.656	199.838	200.000
27.500	9200.000	8.333	7.603	1057.287	198.256	200.000
28.750	9200.000	8.333	7.598	1043.065	196.447	200.000
30.000	9200.000	8.385	7.644	1038.484	194.880	200.000
31.250	9200.000	8.484	7.810	1043.949	193.741	200.000
32.500	9200.000	8.592	7.986	1059.332	193.214	200.000
33.750	9200.000	8.671	8.149	1079.085	193.333	200.000
35.000	9200.000	8.740	8.285	1099.411	193.987	200.000
36.250	9200.000	8.783	8.379	1117.471	195.003	200.000
37.500	9200.000	8.799	8.427	1131.152	196.184	200.000
38.750	9200.000	8.795	8.435	1139.607	197.348	200.000
40.000	9200.000	8.776	8.415	1143.071	202.753	200.000
41.250	9200.000	8.751	8.378	1142.499	207.915	200.000
42.500	9200.000	8.726	8.336	1139.256	208.544	200.000
43.750	9200.000	8.125	7.564	1128.818	208.812	200.000
45.000	9200.000	8.216	7.513	1063.727	207.735	200.000
46.250	9200.000	8.155	7.386	1036.416	205.762	200.000
47.500	9200.000	8.125	7.325	1017.072	203.682	200.000
48.750	9200.000	8.170	7.356	1005.579	201.748	200.000
50.000	9200.000	8.231	7.452	1005.555	200.186	200.000
51.250	9200.000	8.294	7.559	1013.097	199.174	200.000
52.500	9200.000	8.353	7.662	1024.421	198.717	200.000
53.750	9200.000	8.396	7.746	1036.748	198.729	200.000
55.000	9200.000	8.419	7.798	1047.576	199.072	200.000
56.250	9200.000	8.423	7.816	1055.258	199.585	200.000
57.500	9200.000	8.411	7.807	1059.186	200.123	200.000
58.750	9200.000	8.390	7.777	1059.554	200.573	200.000
60.000	9200.000	8.366	7.737	1057.127	200.868	200.000
61.250	9200.000	8.342	7.696	1052.976	200.987	200.000
62.500	9200.000	8.324	7.661	1048.211	200.949	200.000
63.750	9200.000	8.312	7.637	1043.774	200.784	200.000
65.000	9200.000	8.307	7.624	1040.321	200.554	200.000
66.250	9200.000	8.308	7.623	1038.180	200.309	200.000
67.500	9200.000	8.314	7.629	1037.373	200.091	200.000
68.750	9200.000	8.321	7.641	1037.690	199.927	200.000
70.000	9200.000	8.329	7.655	1038.781	199.829	200.000
71.250	9200.000	8.336	7.667	1040.253	199.796	200.000
72.500	9200.000	8.341	7.676	1041.749	199.814	200.000
73.750	9200.000	8.343	7.682	1042.997	199.867	200.000
75.000	9200.000	8.343	7.683	1043.837	199.935	200.000
76.250	9200.000	8.341	7.682	1044.223	200.001	200.000
77.500	9200.000	8.339	7.678	1044.198	200.055	200.000
78.750	9200.000	8.336	7.673	1043.867	200.088	200.000
80.000	9200.000	8.333	7.668	1043.360	200.100	200.000
81.250	9200.000	8.331	7.665	1042.809	200.094	200.000
82.500	9200.000	8.330	7.662	1042.318	200.074	200.000
83.750	9200.000	8.330	7.661	1041.955	200.048	200.000
85.000	9200.000	8.330	7.661	1041.751	200.020	200.000
86.250	9200.000	8.331	7.662	1041.700	199.997	200.000
87.500	9200.000	8.332	7.664	1041.773	199.981	200.000
88.750	9200.000	8.333	7.665	1041.924	199.972	200.000
90.000	9200.000	8.334	7.667	1042.109	199.971	200.000
91.250	9200.000	8.334	7.668	1042.286	199.975	200.000
92.500	9200.000	8.334	7.668	1042.427	199.983	200.000
93.750	9200.000	8.334	7.668	1042.516	199.992	200.000
95.000	9200.000	8.334	7.668	1042.551	200.000	200.000
96.250	9200.000	8.334	7.668	1042.539	200.006	200.000
97.500	9200.000	8.333	7.667	1042.494	200.010	200.000
98.750	9200.000	8.333	7.667	1042.433	200.011	200.000
100.000	9200.000	8.333	7.666	1042.369	200.010	200.000 F-11

REGULATOR (LOAD CHANGES)

THE ACTUAL VALUES OF (TO) & (TS) ARE GIVEN BY:

((TO) + 19.5) X 10.0 AND (FW) X 10000.0

(OUTPUTS SCALED BY .100E+01)

(X INDICATES MORE THAN ONE VARIABLE HAVE THE GIVEN VALUE)

(===== 0 =====)

T	TO(+)	FW(.)	-2.50	-2.00	-1.50	-1.00	-0.50	0.00	0.50	1.00	1.50	2.00	2.50
			-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----										
0.00	0.500	1.000						I	+				
1.25	0.500	1.000						I	+				
2.50	0.500	1.000						I	+				
3.75	0.500	1.000						I	+				
5.00	0.500	1.000						I	+				
6.25	0.500	1.000						I	+				
7.50	0.500	1.000						I	+				
8.75	0.500	1.000						I	+				
10.00	0.500	1.000						I	+				
11.25	0.500	1.000						I	+				
12.50	0.500	1.000						I	+				
13.75	0.500	1.000						I	+				
15.00	0.500	1.000						I	+				
16.25	0.500	1.000						I	+				
17.50	0.500	1.000						I	+				
18.75	0.500	1.000						I	+				
20.00	0.500	1.000						I	+				
21.25	0.500	1.000						I	+				
22.50	0.500	1.000						I	+				
23.75	0.500	1.000						I	+				
25.00	0.500	0.920						I	+				
26.25	0.484	0.920						I	+				
27.50	0.326	0.920						I	+				
28.75	0.145	0.920						I	+				
30.00	-0.012	0.920						I	+				
31.25	-0.126	0.920						I	+				
32.50	-0.179	0.920						I	+				
33.75	-0.167	0.920						I	+				
35.00	-0.101	0.920						I	+				
36.25	0.000	0.920						I	+				
37.50	0.119	0.920						I	+				
38.75	0.235	0.920						I	+				
40.00	0.775	0.920						I	+				
41.25	1.292	0.920						I	+				
42.50	1.354	0.920						I	+				
43.75	1.361	0.920						I	+				
45.00	1.274	0.920						I	+				
46.25	1.076	0.920						I	+				
47.50	0.868	0.920						I	+				
48.75	0.675	0.920						I	+				
50.00	0.519	0.920						I	+				
51.25	0.417	0.920						I	+				
52.50	0.372	0.920						I	+				
53.75	0.373	0.920						I	+				
55.00	0.407	0.920						I	+				
56.25	0.459	0.920						I	+				
57.50	0.512	0.920						I	+				
58.75	0.557	0.920						I	+				
60.00	0.587	0.920						I	+				
61.25	0.599	0.920						I	+				
62.50	0.595	0.920						I	+				
63.75	0.578	0.920						I	+				
65.00	0.555	0.920						I	+				
66.25	0.531	0.920						I	+				
67.50	0.509	0.920						I	+				
68.75	0.493	0.920						I	+				
70.00	0.483	0.920						I	+				
71.25	0.480	0.920						I	+				
72.50	0.481	0.920						I	+				
73.75	0.487	0.920						I	+				
75.00	0.493	0.920						I	+				
76.25	0.500	0.920						I	+				
77.50	0.505	0.920						I	+				
78.75	0.509	0.920						I	+				
80.00	0.510	0.920						I	+				
81.25	0.509	0.920						I	+				
82.50	0.507	0.920						I	+				
83.75	0.505	0.920						I	+				
85.00	0.502	0.920						I	+				
86.25	0.500	0.920						I	+				
87.50	0.498	0.920						I	+				
88.75	0.497	0.920						I	+				
90.00	0.497	0.920						I	+				
91.25	0.498	0.920						I	+				
92.50	0.498	0.920						I	+				
93.75	0.499	0.920						I	+				
95.00	0.500	0.920						I	+				
96.25	0.501	0.920						I	+				
97.50	0.501	0.920						I	+				
98.75	0.501	0.920						I	+				
100.00	0.501	0.920						I	+				

