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Comparative analysis of two self-tuning controllers

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COMPARATIVE ANALYSIS OF TWO SELF-TUNING CONTROLLERS

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ABSTRACT

The Honeywell UDC 6000 Process Controller and the Fischer and Porter Micro-DCI Modular Controller both have self-tuning control capabilities. The Honeywell Adaptive Control Method and the Fischer and Porter Easy-Tune Method use two different algorithms to model a plant and to designate an appropriate control action. The Honeywell controller is an adaptive controller, and can, therefore, retune itself for process changes. It can also adjust itself for set point changes. The controller can correctly model systems of up to two lags and dead time. The Fischer and Porter controller, on the other hand, having no adaptive capabilities, can not adjust for system changes. It uses the Minimum Integral of Absolute Error Multiplied by Time Criterion, (ITAE) for setting control parameters and can correctly model systems of up to one lag and dead time. With systems of orders higher than the controller's capability, both controllers will yield reasonable approximations.

In this document, the self-tuning algorithms of the two controllers are compared on the basis of tests performed on three controlled systems. Set point and process change tests are performed with the goal of examining how well both controllers calculate or approximate the model of a given system, and how well they maintain the process variable at the set point. The adaptive capabilities of the Honeywell controller are tested under three test conditions of a one lag, a two lag, and a three lag system, all without dead time.

The results of the study show that both the UDC 6000 and the Micro-DCI controllers model and approximate systems of first order well. However, the Honeywell controller has

difficulties modeling higher order systems. On the other hand, the Fischer and Porter controller approximates these systems well.

The Fischer and Porter control tuning is typical of most feedback systems. Variations in process parameters can cause instability. As a result, the Easy-Tune sequence must be run for different process variable settings in order to obtain controller transfer functions with optimal stability for the closed-loop responses. Along with this, tuning parameter modifications are also needed. Even then, the system could be stabilized for only two out of the three controlled systems.

The Honeywell controller, on the other hand, requires no such adjustments for successful closed-loop control. It performs well in both set point and process change tests.

It is concluded that the Fischer and Porter controllers models systems better than the Honeywell controller. However, the Honeywell controller is preferable for general use. It readily adapts to system changes. It is also much easier to master its operation. The Fischer and Porter controller, on the other hand, needs to be configured for each different system condition. This means that the operator must have a reasonable understanding of control theory and some familiarity with the control system.

In addition, this thesis describes an undergraduate laboratory experiment comparing the self-tuning method of the Honeywell controller with the Ziegler-Nichols method of tuning. Using data obtained by the students, the results of the tests are compared. In light of undergraduate laboratory experience, a new experiment is proposed. This experiment is expected to be easier to understand and perform. An instruction manual for undergraduate students is also made available.

CHAPTER ONE

INTRODUCTION

It has been said that control theory is an imperfect science. Furthermore, professionals in the area of automatic and adaptive controls claim that most industries do not even use the automatic mode of control; most control systems in plants are manual. It is therefore safe to assume that automatic control studies, let alone self-tuning control studies, are not common and especially so outside academia. It is with this background that this thesis has been done.

The purpose of the thesis is to investigate self-tuning control theory and its applications to actual systems. More specifically, two controllers, the Honeywell UDC 6000 Process Controller and the Fischer and Porter Micro-DCI Modular Controller, are to be studied with respect to their different self-tuning algorithms. In addition, the UDC 6000 adaptive tuning capabilities are studied. This document also describes an undergraduate controls laboratory experiment using the Honeywell controller. A pressure system is used as the test system for the study.

1.1 Problem Statement

A series of air pressure tanks or a single air pressure tank is used as a plant. Three different test conditions are set up with a combination of one, two, and three tanks connected in series. The Honeywell controller or the Fischer Porter controller actuate a control valve which in turn controls the amount of air flow through a system of tanks.

By a series of set point change and process variable change tests for the different con figurations, the controller and resulting system behavior are evaluated. In this way, a comparative study of the two different self-tuning control algorithms can be made. This also makes possible a study of the Honeywell adaptive control.

1.2 Organization of Thesis

This document is divided into six sections. Chapter Two describes both self-tuning algorithms, the Honeywell Adaptive Control Method and the Fischer and Porter Easy-Tune Method. It describes the detailed steps of each method of system identification and the derivations for the controller tuning parameters. Chapter Three discusses the experimental apparatus and the three different test configurations by which the controllers are examined. In Chapter Four, detailed descriptions of the testing and the data acquisition are given. This includes the tests that are performed, the data to be recorded, and the methods of test analysis. Discussion and analysis of obtained data are the topics of Chapter Five. Finally, general observations and conclusions are offered in Chapter Six, including evaluations and recommendations for further undergraduate and graduate studies and industrial applications. Appendix I describes an undergraduate laboratory experiment with the Honeywell controller. From it, a new experiment is proposed that should be much easier for students to understand.

CHAPTER TWO

CONTROLLER ALGORITHMS

In this chapter, the self-tuning algorithms for the Honeywell UDC 6000 Process Controller and the Fischer and Porter Micro-DCI Modular Controller are discussed. This discussion will include system identification processes, process change compensation, and controller tuning.

2.1 Adaptive Tune: Honeywell Adaptive Control Method

The self-tuning algorithm for the Honeywell UDC 6000 Process Controller is called Adaptive Tune. All calculations and derivations are based upon the "Honeywell Adaptive Control Method", written by Morton Sklarnoff of Industrial Automation and Control Division of Honeywell, Incorporated. This method, in general, fits a transfer function to the process under control, selects the best available tuning algorithm, and tunes the Honeywell controller appropriately. During initialization of Adaptive Tune (or whenever the set point changes), time domain analysis is used to accelerate process variable line out. This is accomplished without any prior knowledge of the system. This mode of Adaptive Tune is called SP Adapt. When process changes occur after line out, the PV Adapt mode of Adaptive Tune is activated. Here, the controller uses frequency analysis to return the process to line out.

Adaptive Tune does not introduce any process disturbances. The method also allows the controller to make the necessary retuning adjustments whenever there is a deviation of five percent from set point. It continues to retune until the disturbance decreases to 0.3%. It should be noted that this method is not applicable to processes that are not type zero.

2.1.1 Set Point Adapt Mode

2.1.1.1 System Identification

The Honeywell Adaptive Control Method assumes a process of up to two lags with or without dead time. If the process is not of the above types, the Adaptive Tune chooses the best combination of lags and dead time to approximate a transfer function for the system. This identification process takes place under Set Point (SP) Adapt within a time period less than one-third of the sum of the system time constants.

The Adaptive Tune procedure begins when the operator manually adjusts the control variable (CV) so that the process variable, PV, is about ten percent of its available range. After the set point is set by the operator, he or she switches the controller to automatic after PV has lined out. The controller is now in SP Adapt mode. The controller uses data, which is explained later, from the previous adjustment to calculate the necessary output value to bring the process variable, PV, to the set point. At that point, the controller begins collecting data as its output steps to the appropriate value.

Note that when a set point change occurs, the controller automatically begins SP Adapt. It then changes to manual control to effect a CO step increase. Once PV approaches line out, the controller switches back to automatic control and continues its calculations.

What follows is an explanation of the SP Adapt algorithm. The time it takes for the process variable to start changing after the output step change is referred to as the "dead time." The controller measures this reaction time. If there is an immediate increase or decrease in PV, the controller sets the dead time to zero. If there is no immediate change, the controller determines the dead time by measuring the time it takes for PV to change by a small increment after the step change takes place. (This increment is chosen by the controller.)

The controller measures the rate of increase of PV after the beginning of its rise. If this slope is continuously decreasing from the start, the controller assumes the plant is a single-lag process. The controller also takes measurements, PV_1 and PV_2, during the rise along with the slopes, $PV_{1'}$ and $PV_{2'}$, at the respective points. The process time constant T_1 and the steady state gain, K, can be calculated. They are

$$T_1 = \frac{(PV_2 - PV_1)}{(PV_{1'} - PV_{2'})} \tag{1}$$

$$K = \frac{(PV_2 + PV_{2'}\, T_1)}{CO} \tag{2}$$

where CO is the output step size of the controller.

If the controller measurements indicate an inflection point in the PV-time curve (Figure 2.1), the controller assumes a two-lag process. Denoting by t_1 the time from the beginning of the rise in PV to the inflection point, one can determine the process time constants, T_1 and T_2, and the steady state gain, K, by measuring PV_1, $PV_{1'}$, and t_1. Note that T_1 and T_2 are such that $T_1 > T_2$. PV_1 and $PV_{1'}$ are the process variable and the slope of the process variable at t_1, respectively. The relevant equations are

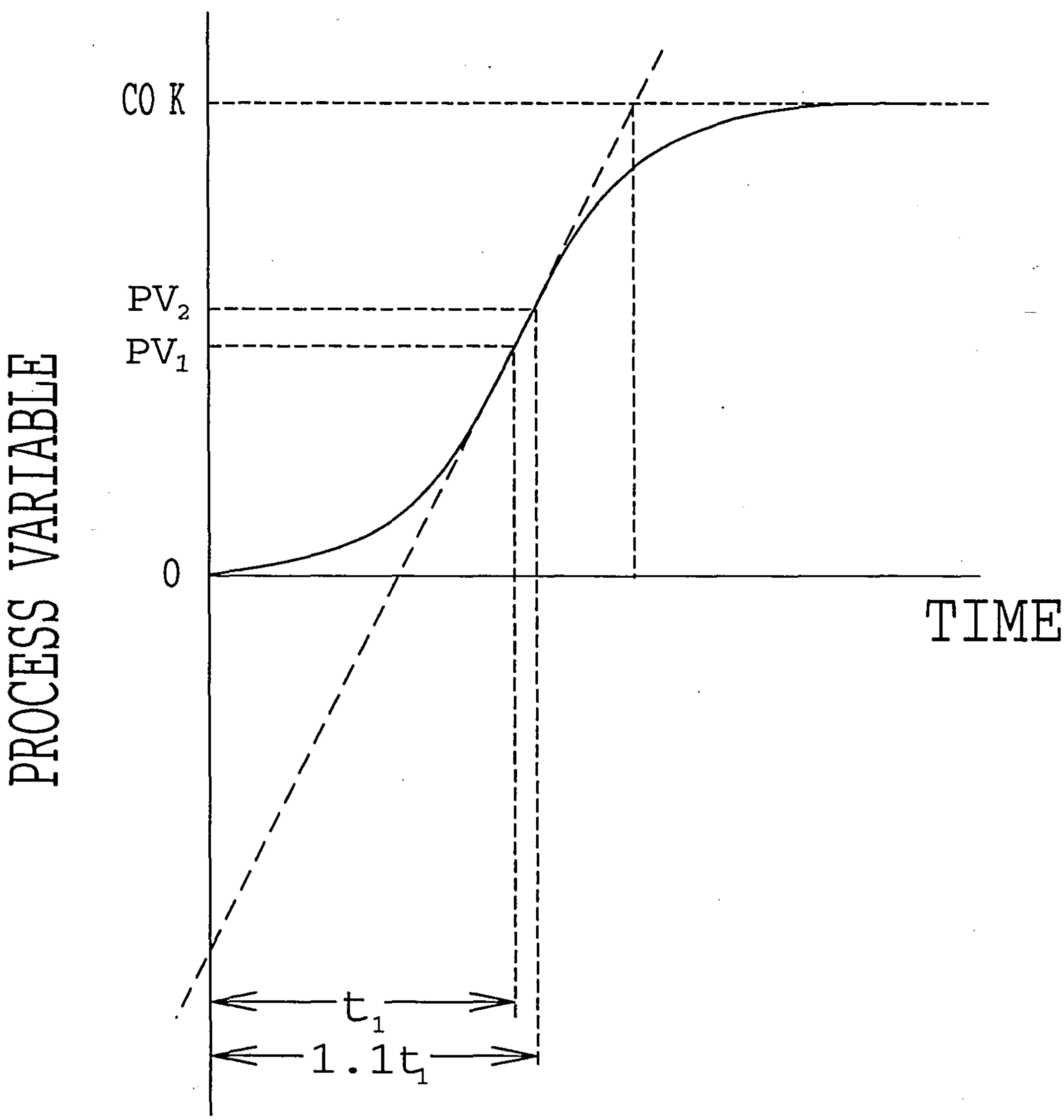
$$CO\ K = (PV_{1'})(F_n) + PV_1 \tag{3}$$

$$N = \frac{T_1}{T_2} \tag{4}$$

FIGURE 2.1

HONEYWELL TWO LAG IDENTIFICATION

PROCESS VARIABLE vs. TIME



$$F_n = \frac{(T_1 + T_2)}{t_1} = \frac{(N^2 - 1)}{\left(N \ln(N)\right)} \tag{5}$$

Initial tuning takes place at $t \simeq t_1$ and, for minimum initial error, one uses a starting value of $N = 6$ and $F_n = 3.3$. With these choices the initial values of K, T_1, and T_2 are approximated and are used for initial tuning.

After the process variable has lined out to the desired value, an accurate measurement of K is obtained and a new value of F_N is calculated. In turn, more accurate values of T_1 and T_2 are calculated. These values are used to retune the controller for consistently better results.

There will be cases where the inflection point at t_1 lies outside of the possible set point range due to a large process gain. For such cases, an additional algorithm is used to determine the approximate value of t_1. The relevant equation is

$$t_1 \simeq t_n + \frac{-a_n}{c_n} \tag{6}$$

where t_n denotes the time when PV = .45 CO K and

$$a_n = PV_{n'} - PV_{n-1'} \tag{7}$$

$$c_n = PV_{n'} + PV_{n-1'} \tag{8}$$

Only the part of the PV response which occurs within forty-five percent of the step change is considered by this numerical algorithm.

Other processes which do not fit under any of the above categories are approximated as a system of up to a two lag system with or without dead time. The Honeywell controller then tunes itself accordingly.

2.1.1.2 Controller Tuning

Controller tuning takes place by either one of two methods, depending upon whether the process has any dead time.

The controller transfer function C(s) obtained is of the form of a PID controller with real zeros

$$C(s) = G_c \frac{(sT_i + 1)(sT_d + 1)}{sT_i(0.25sT_d + 1)} \tag{9}$$

where G_c is the controller gain.

The controller tuning algorithm uses pole cancellation in processes without dead time. The Honeywell controller models a process without dead time in accordance with the relation

$$P(s) = \frac{K}{(sT_1 + 1)(sT_2 + 1)} \tag{10}$$

with $T_1 > T_2$. The poles in this process equation are canceled by the zeros of the PID transfer function. For a one lag process $T_2 = 0.0$ and the variables in Eq (9) take on the following values:

$$T_i = 0.16\ T_1 \tag{11}$$

$$T_d = 0.0 \tag{12}$$

$$G_c = \frac{24}{K} \tag{13}$$

For a two lag process, the variables in Eq (9) become

$$T_i = T_1 \tag{14}$$

$$T_d = T_2 \tag{15}$$

$$G_c = \frac{6}{K} \tag{16}$$

The controller algorithm uses the E. B. Dahlin method for processes with dead time. The controller models the identified process by the following equation

$$P(s) = \frac{K\,e^{-Ts}}{(sT_1 + 1)\,(sT_2 + 1)} \tag{17}$$

For a one lag process T_d is again zero and

$$T_i = T_1 \tag{18}$$

$$G_C = \frac{3}{K\left(1 + \frac{3T}{T_i}\right)} \tag{19}$$

For a two lag process, Eq (16) is still valid, the new values being

$$T_i = T_1 + T_2 \tag{20}$$

$$T_d = \frac{T_1 T_2}{T_1 + T_2} \tag{21}$$

2.1.2 PV Adapt Mode:

In many instances, after the process identification and initial self tuning, a process change may alter the system, i.e., change in dead time, process gain or time constants. Using frequency response analysis, the Honeywell Adaptive Control Method can compensate for these changes under PV Adapt. The controller analyzes a frequency notch which is determined under SP Adapt mode (Figure 2.2). Denote T_i as the reset time with $\omega_i = \frac{1}{T_i}$. Also let T_d denote the derivative time constant with $\omega_d = \frac{1}{T_d}$.

If the system changes so that PV oscillates at a frequency, ω_0, two possibilities arise. One case is when $\omega_0 \leq \omega_i$, in which case the controller shifts its frequency notch so that

$$\omega_i = \frac{1}{T_i} = \frac{\omega_0}{2} \tag{22}$$

The second case is when $\omega_o > \omega_i$. The controller will, then, shift its frequency notch so that

$$\omega_d = \frac{1}{T_d} = \omega_o \tag{23}$$

If oscillation continues, the controller will divide the process gain by two. For the oscillation compensation method, the controller notch stays at the same width as that determined during the SP Adapt.

If the system changes so that PV undergoes a damped oscillation at a frequency, ω_o, the controller notch is shifted so that

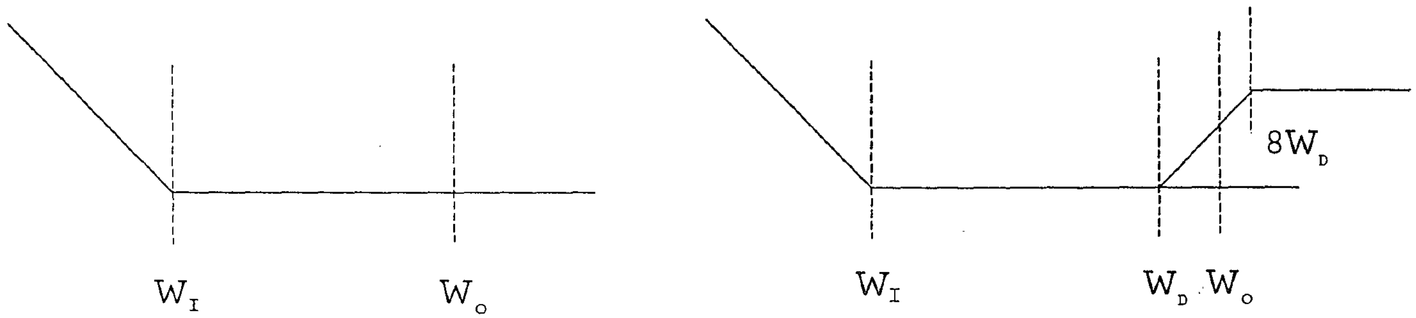
$$\omega_d = \frac{1}{T_d} = \omega_o \tag{24}$$

Again, the same controller frequency notch as that determined during the Set Point adapt mode is maintained.

As mentioned before, the expected time to line is less than time t, where

FIGURE 2.2

CONTROLLER BODE PLOTS



SINGLE LAG

TWO LAGS

$$t < \frac{(T + T_1 + T_2)}{3} \tag{25}$$

where T is dead time. If, however, the event occurs so that

$$t > (T + T_1 + T_2) \tag{26}$$

the controller shifts the notch to a higher frequency, multiplying both ω_i and ω_d by a factor of 1.3.

Another scenario is when the process gain changes but PV must be maintained at the same set point. The new process gain is given by

$$K_n = K_o \frac{CO_o}{CO_n} \tag{27}$$

where K_n is the new process gain, K_o is the old process gain, CO_o is the old controller output step size, and CO_n is the new controller output step size.

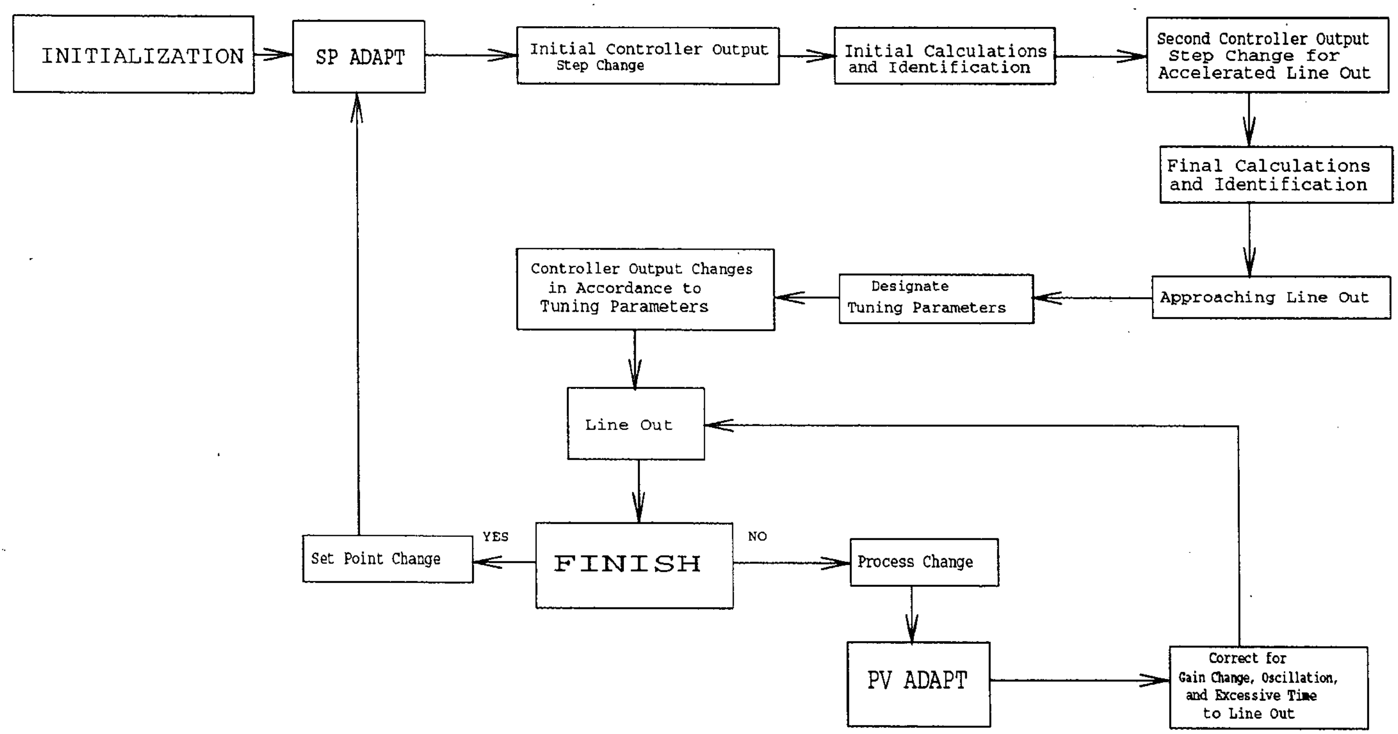
Figure 2.3 shows a flow chart of the Honeywell Adaptive Tune process.

2.2 Easy-Tune: Fischer Porter Control Method

The self-tuning algorithm for the Fischer and Porter Micro-DCI Modular Controller is set for "ideal" tuning parameters based upon the Minimum Integral of Absolute Error Multiplied by Time Criterion (ITAE). The algorithm is the counterpart of the Honeywell SP Adapt algorithm. It is described in the Fischer and Porter Micro-DCI Modular Controller

FIGURE 2.3

HONEYWELL ADAPTIVE TUNE ALGORITHM
FLOW CHART



Customization Bulletin. The controller can be either a Proportional (P), Proportional + Integral (PI), Proportional + Integral + Derivative (PID), Proportional + Derivative (PD), or an Integral (I) type of controller. This choice is left to the operator. Processes which act as pure integrators (systems not of type zero) cannot be tuned with this method. In addition, feed forward control is not possible and process disturbances during the tuning sequence could possibly result in incorrect process characterization.

2.2.1 Process Characterization

The Easy-Tune process, using the ITAE criterion as its basis, models a process as one lag with or without dead time. For a higher order system, Easy-Tune approximates the system as a first order (one lag) transfer function with or without dead time.

The factors which control the amount of time used for the identification process are: (1) the operator-controlled settling time limit, (2) the calculated lag, and (3) the calculated dead time. If the identification process needs more time than the time allowed by these factors, the process is aborted. Specifically, this occurs when

$$t \geq 22\, t_s + 50\, T_p + 2\, W_p \tag{28}$$

where t is the process time, t_s is the operator-controlled initial settling time limit, T_p is the time constant (or lag), and W_p is the dead time. In most cases, however, the process are aborted even before then, as will be described below. Once the process is terminated, all controller settings return back to their original values.

Easy-Tune identifies three system parameters: T_p, W_p, and gain K_p. Given a control output step size, the controller estimates and later calculates the value of PV and the time at which PV reaches 0.2835 and 0.6321 of the total PV increase, t_a and t_b, respectively (Figure 2.4). It calculates the system parameters using the following equations

$$T_p = 1.5\left(t_b - t_a\right) \tag{29}$$

$$W_p = t_a - \frac{T_p}{3} \tag{30}$$

$$K_p = \frac{\text{total PV increase}}{\text{total output increase}} \tag{31}$$

2.2.2 Easy-Tune Sequence

The Easy-Tune Sequence is a five-step sequence. Each sequence has a specific time limit. Before initializing the sequence, the system must be stable, especially if the system is slow. The operator enters the desired PV excursion limit, t_s, the preliminary PV step response limit, and the control output step size. At the first step, the controller waits for PV to settle at its initial testing condition. Here, no change in CO (control output) takes place. The maximum time allowed for this step is t_s.

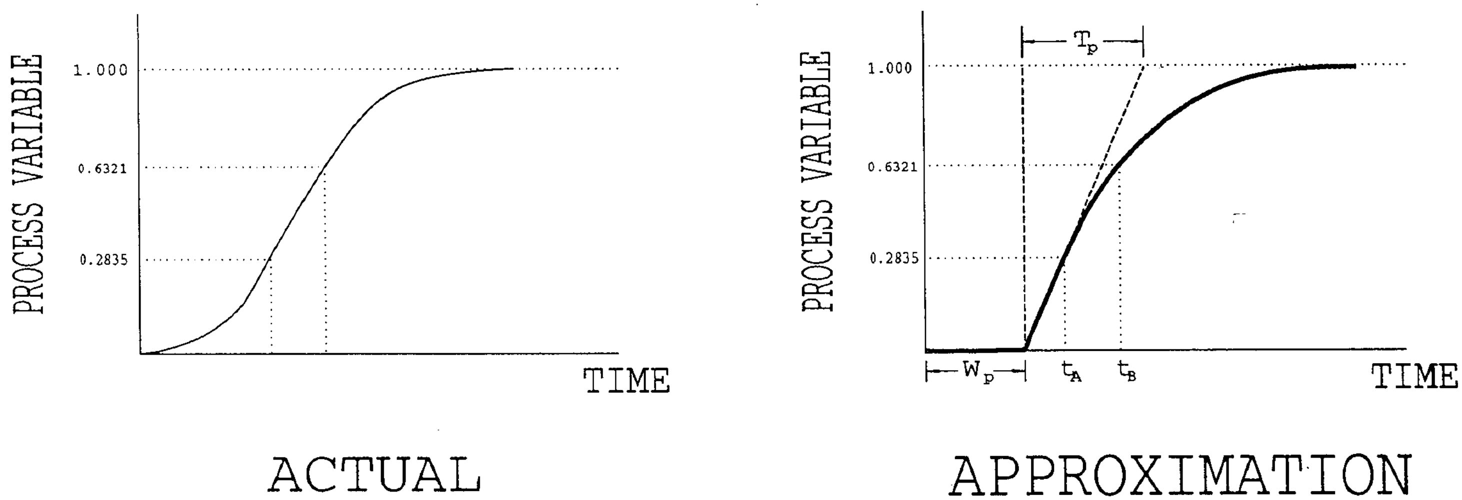
At the second step, CO jumps immediately to the previously determined step size value until PV reaches the preliminary step response limit. If the PV excursion limit is reached before this occurs, however, the process is aborted. It has to be assumed here that the PV excursion limit will always be greater than that of the preliminary step response. If the time for this step exceeds t_s, the process is terminated.

The third step occurs immediately after PV reaches the preliminary step response limit in step two. Here, CO jumps back to its original value (the value before the Easy-Tune Process was initiated). As PV returns to its original value, the controller obtains a preliminary

FIGURE 2.4

FISCHER AND PORTER IDENTIFICATION

PROCESS VARIABLE vs. TIME



estimate of T_p and W_p, denoted by T_e and W_e, respectively. If PV is not approaching its original value in a period of twenty times the duration of step two, the process is aborted.

The CO, at the fourth step, jumps by the same CO step size and remains there until PV has lined out. The value of K_P is calculated. The limiting time, t_4, is set by the following equation

$$t_4 = 10\,(\,2.5\,T_e + W_e\,) \tag{32}$$

Again, if the time for this step exceeds t_4 or if PV has exceeded the excursion limit, the Easy-Tune sequence is stopped.

Once PV has lined out and K_p has been obtained, CO steps back to its original value. In this fifth and final step, PV begins returning to its original value. Final values of T_p and W_p are measured. Once these values are obtained, all controller settings return to their initial settings. The time limit for this step is also determined by Equation (32).

2.2.3 Calculated Tuning Parameters: ITAE Method

The tuning parameters are determined by the type of controller chosen by the operator and by the ideal settings set by the ITAE criterion. The controller transfer function, C(s), takes the form

$$C(s) = G_c\left(1 + \frac{1}{T_i\,s} + T_d\,s\right) \tag{33}$$

For P control, $T_i = 0$ and $T_d = 0$ and

$$G_c = \frac{1}{2.04\,K_p}\left(\frac{T_p}{W_p}\right)^{1.084} \tag{34}$$

For PI control, $T_d = 0$

$$G_c = \frac{1}{1.164\,K_p}\left(\frac{T_p}{W_p}\right)^{0.977} \tag{35}$$

$$T_i = \frac{T_p}{40.44}\left(\frac{W_p}{T_p}\right)^{0.738} \tag{36}$$

For PID control

$$G_c = \frac{1}{0.7369\,K_p}\left(\frac{T_p}{W_p}\right)^{0.947} \tag{37}$$

$$T_i = \frac{T_p}{51.02}\left(\frac{W_p}{T_p}\right)^{0.738} \tag{38}$$

$$T_d = \frac{T_p}{157.5}\left(\frac{W_p}{T_p}\right)^{0.995} \tag{39}$$

Considering now PD control, T_i is no longer relevant. The empirically based equations for PD control are

$$G_c = \frac{1}{0.5402\,K_p}\left(\frac{T_p}{W_p}\right)^{0.947} \tag{40}$$

$$T_d = \frac{T_p}{157.5}\left(\frac{W_p}{T_p}\right)^{0.995} \tag{41}$$

For Integral control, G_c and T_d are no longer relevant. The empirically based equation for Integral control is

$$T_i = \frac{T_p K_p}{25} \left(\frac{W_p}{T_p} \right)^{0.15} \tag{42}$$

Note that if

$$T_d \leq \frac{\text{controller scan file index}}{50} \tag{43}$$

T_d will automatically be set to zero. (The controller scan file index is the repetition period in milliseconds for any task in the Easy-Tune algorithm.) This applies for all types of control modes.

2.3 General Comparisons

The Honeywell controller appears to have an advantage in modeling and tuning. For one, the UDC 6000 can model a second order system. The Fischer and Porter controller can only model a first order system. The Honeywell controller constantly re-tunes using PV Adapt. The Micro-DCI does not have any adaptive capability. It assigns one transfer function to the system. This means that the Easy-Tune sequence must be manually run again for any process changes.

CHAPTER THREE

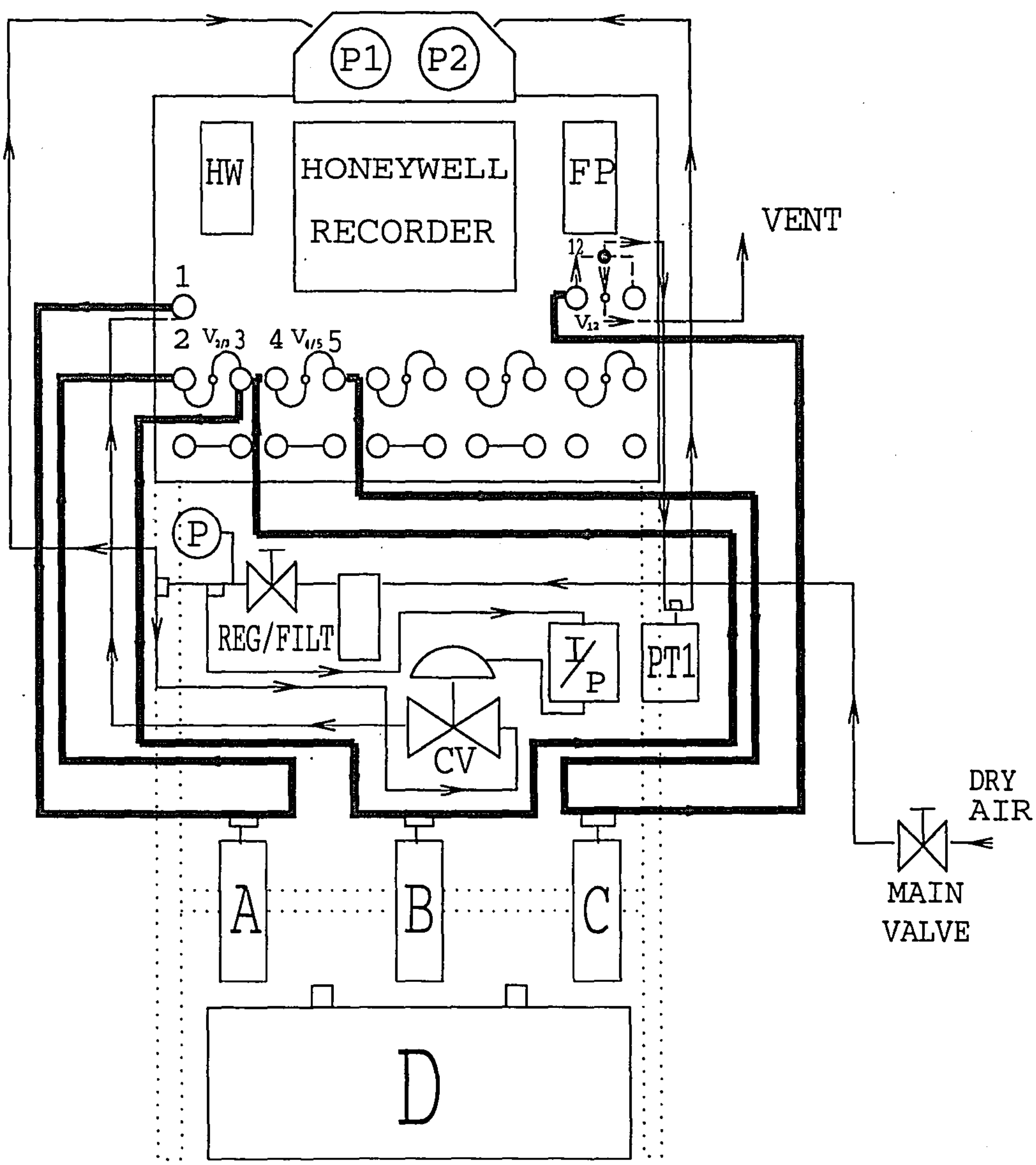
SYSTEM CHARACTERISTICS

This chapter deals with the test system and its characteristics. In addition, both the Honeywell UDC Process Controller and the Fischer and Porter Micro-DCI Modular Controller are examined in terms of features and capabilities regarding self-tuning.

The actual system used to test the self-tuning algorithms of the controllers is a pressure system (Figure 3.1). It consists of one, two, or three tanks connected in series. A needle valve is located after each tank with a control valve, CV, located before the first (or only) tank for the purpose of regulating the amount of air through the system. The process variable is the pressure exiting the last, or only, tank. The system allows only one of the controllers, either the Honeywell or the Fischer and Porter controller, to work at a time. The engaged controller manipulates the system pressure via the control valve (CV). A Rosemount Alphaline Model 1151AP Gage Pressure Transmitter (PT1) transmits the pressure of the air at the system exit (that is, the air pressure preceding the last needle valve).

The source of pressure is dry air supplied by an Ingersoll Rand 689.5 kPa compressor and dried by a separate air dryer. A regulator and pressure gage (P) combination is positioned at the inlet to the overall system and maintains a source pressure of 103.4 kPa. A filter with a trap, immediately following the regulator, prevents any foreign particles from entering the system. A Honeywell DPR 3000 250 mm Strip Chart Recorder constantly records the exiting pressure and also the control valve position signal as read from the engaged controller. A Rosemount Current-to-Pressure Transducer Model 3311 receives a 4 to 20 ma electrical input

FIGURE 3.1
EXPERIMENTAL APPARATUS



from the working controller and sends a proportional 20.7 to 82.7 kPa pneumatic output to actuate the control valve. Pressure gages P1 and P2 are positioned to monitor, as a check, the system inlet and exit air pressures.

Finally, a 6.35 mm outer diameter tubing with a 0.889 mm wall is used to connect the tanks. The tubing is connected to fittings via Swagelok Quick Connects. The recorder and the controllers are mounted on a 0.80 m x 0.584 m vertical panel. The rest of the system (minus the compressor, the air dryer and the largest pressure vessel) is mounted on a separate support, which also supports the vertical panel. The system altogether is 0.80 m wide and stands 1.83 m tall.

3.1 The Needle Valves and Tubing

The identical needle valves each have a range of about -0.37 to 2.37 units. A reading of -0.37 units indicates that the valve is entirely closed, and a reading of 2.37 units indicate that the valve constricts air flow as little as possible. Although the resistance of the valve cannot be determined at a reading of 2.37 units, it is observed that a setting of -0.37 does not allow any air flow. The needle valves between the first two tanks and also between the last two tanks are kept at a constant setting of 1.00 units, whether or not the valves are contributing resistance to the system i.e. whether or not any tanks are connected to the valve. Only the last needle valve changes settings to effect process changes.

The tubing, too, contributes a modeling problem, in that the tubing resistance cannot be determined. For practical purposes, any restrictions are modeled as originating from a combination of the needle valve and tubing resistance.

3.2 The Tanks

There are a total of four tanks of two different sizes which can be connected to the system. Three of the tanks (labeled Tank A, Tank B, and Tank C in Figure 3.1), originally propane tanks, are each approximately 1 liter in volume. The fourth tank, Tank D, can hold approximately 11 liters. The inlets and outlets for all of the tanks are located at the top of each tank.

Since Tanks A, B, and C are identical, Tank A is used as the model tank to determine the parameters of all three tanks. The transfer function for a single tank system is

$$S_s(s) = \frac{K_s}{\tau_s s + 1} \tag{44}$$

In agreement with above, Tank A, as the only tank connected to the apparatus, shows little to no variation in system lag with varying needle valve positions. Therefore, the system is assigned a constant lag. This average lag value, τ_s, is 0.06 minutes. At a valve reading of 0.00, K_s is 1.18. This value increases to a maximum of 1.80 at a valve reading of 0.50 and decreases to a minimum of 0.73 at valve reading of 2.37.

The system lag with Tank D, denoted by τ_l, varies with different valve settings. At a valve reading of 0.25, τ_l is 2.70 minutes. This value decreases with increasing valve reading. The minimum value is 1.17 at 2.25. (Note that calculations of τ_l at valve readings less than 0.25 and greater than 2.25 are not obtained because the tests were configured within this range of valve settings.) The system gain, denoted by K_l, changes with both valve settings and PV values. Maximum gains occur at the lowest needle valve settings and CV values ranging from 20% to 25% open, this maximum being 2.84. The lowest values of K_s come from low needle valve settings and high PV values, the minimum K_s being 0.04.

3.3 Testing Conditions

There are three different testing conditions. One involves the three propane tanks connected in series. The second has two propane tanks in series, with the third and final testing condition involving the 11 liter tank alone. As indicated, each tank in all testing conditions has a needle valve located at its exit.

3.3.1 Test Condition One

Test Condition One (Figure 3.2) is comprised of only Tank D. The inlet and outlet tubing is plugged into Connection 1 and Connection 12, respectively. The last needle valve, V_{12}, is located after Connection 12. Except for extreme V_{12} values, the relationship between maximum PV and V_{12} is mostly linear (Figure 3.3). A V_{12} value of 1.75 is chosen with a maximum PV of 82.74 kPa for the first set of tests in this test condition. The second part of this test condition involves changing V_{12}.

3.3.2 Test Condition Two

Test Condition Two (Figure 3.4) is similar to that of Test Condition One except that Tank A and B are used instead and connected in series. The tubing for the inlet and outlet of Tank A are connected to the system at Connection 1 and Connection 2, respectively. The tubing for the inlet and outlet of Tank B are connected to the system at Connection 3 and Connection 12, respectively. A needle valve, $V_{2/3}$, is inserted between Connection 2 and

FIGURE 3.2
TEST CONDITION ONE

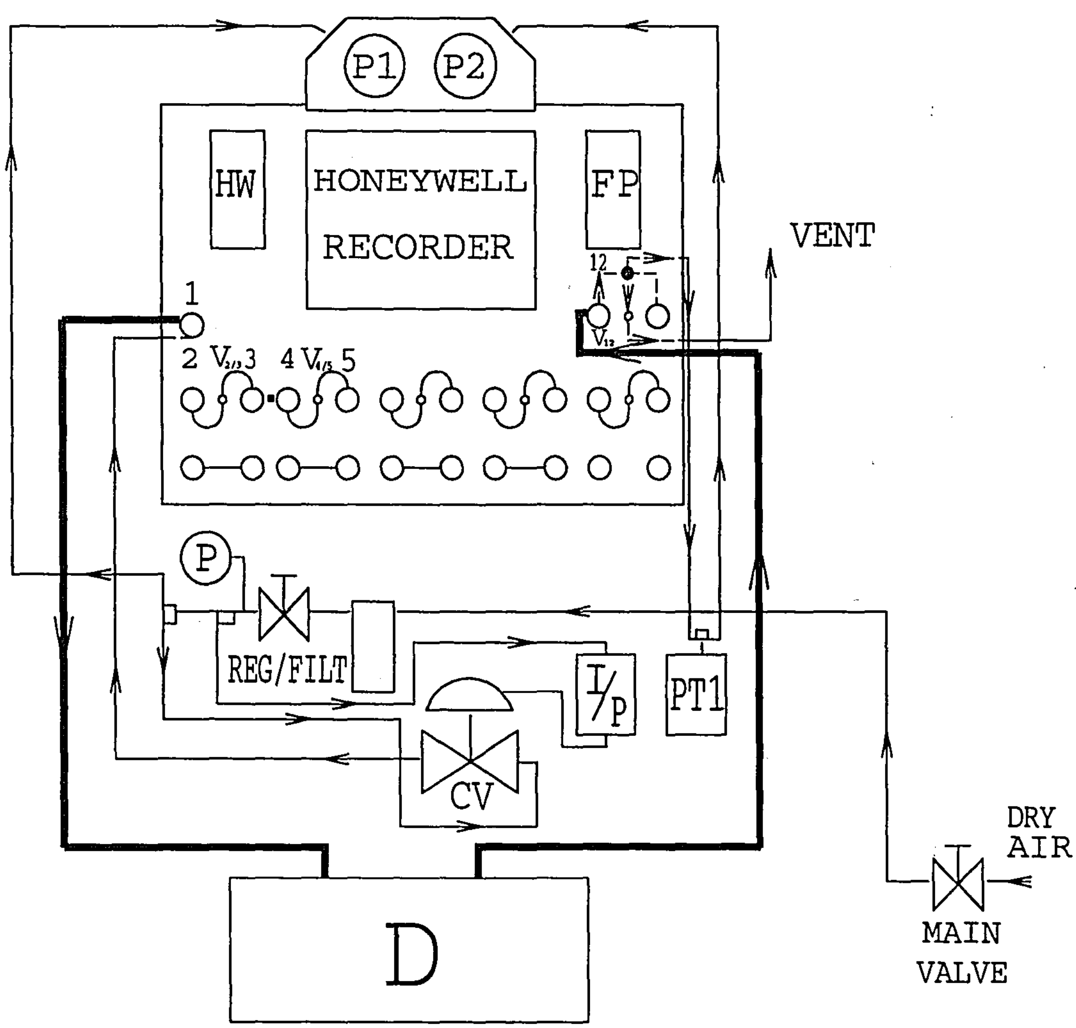


FIGURE 3.3

MAXIMUM PV vs VALVE
ONE TANK

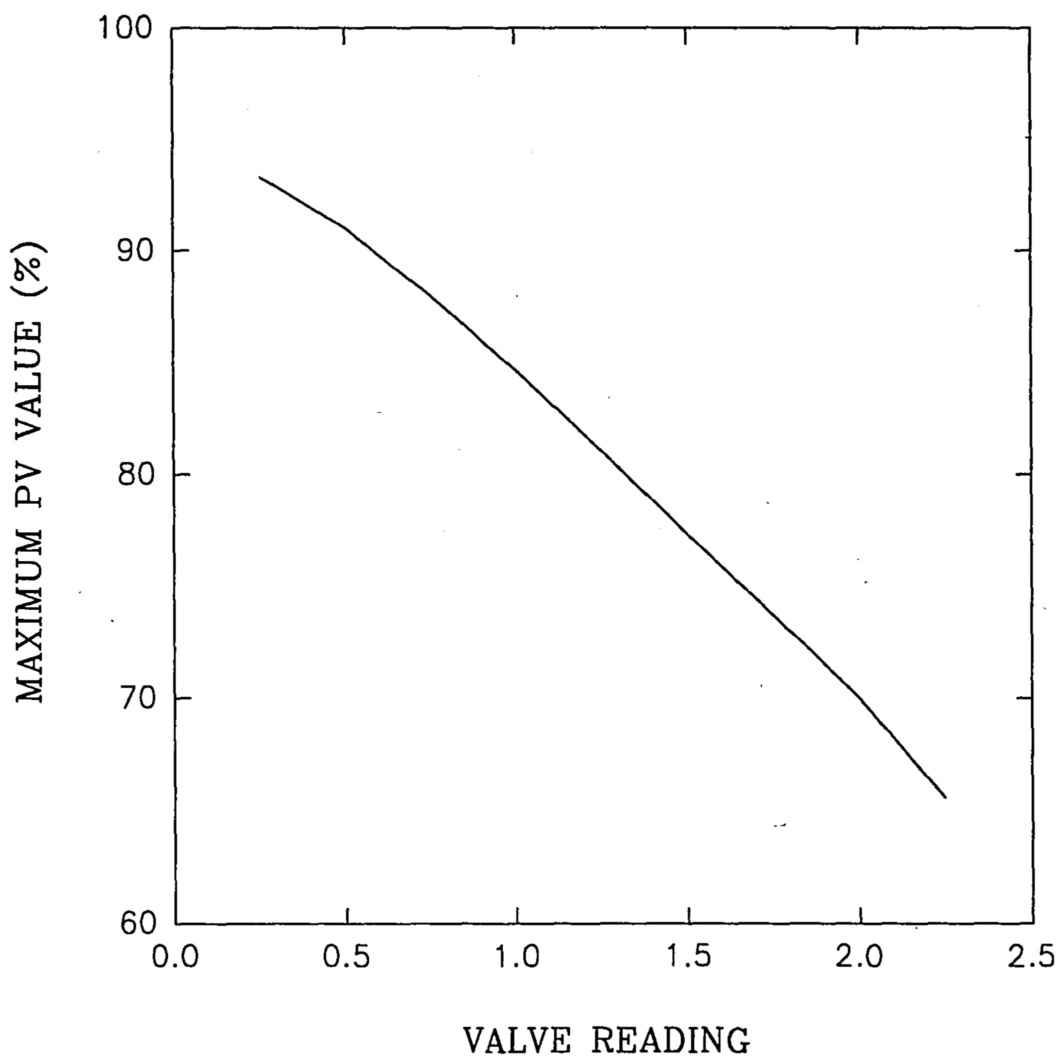
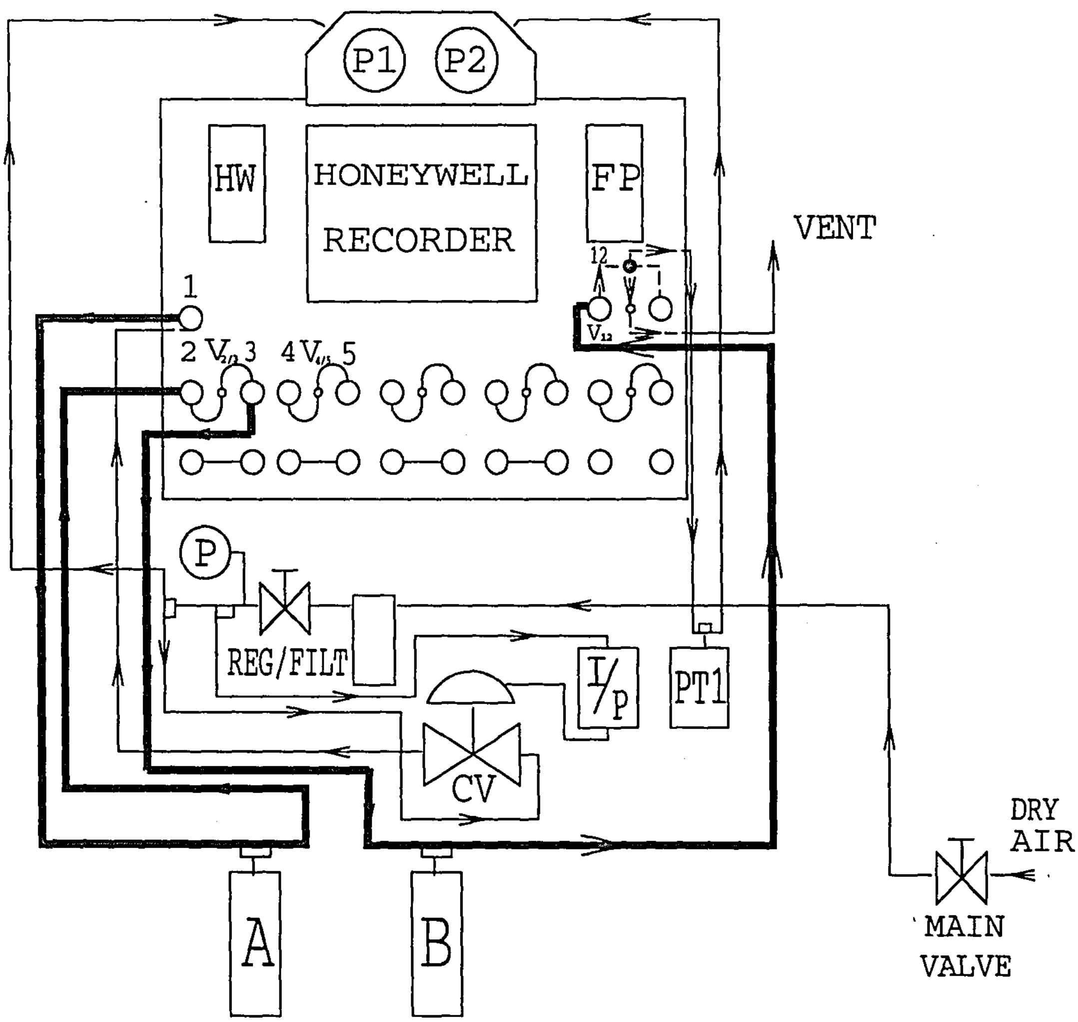


FIGURE 3.4
TEST CONDITION TWO



Connection 3. The reading of $V_{2/3}$ is 1.00 units with V_{12} fixed at 0.75 units. The maximum obtainable exit pressure for this setting is 62.06 kPa.

3.3.3 Test Condition Three

Test Condition Three (Figure 3.5) involves Tanks A, B, and C connected in series. It is almost the same as Test Condition Two except that the outlet tube of Tank B is placed in Connection 4, and the inlet and outlet tubing of Tank C is placed in Connection 5 and Connection 12, respectively. Another needle valve, $V_{4/5}$, is placed between Connection 4 and Connection 5. Both $V_{2/3}$ and $V_{4/5}$ are set at 1.00, with V_{12} set at 0.75.

Under these conditions, the relationship between maximum pressure and V_{12} is mostly linear within two ranges: at $0.00 < V_{12} < 1.00$ and $V_{12} > 1.50$ (Figure 3.6). The maximum obtainable exit pressure is 99.18 kPa at a V_{12} reading of -0.35 and the minimum is 13.24 kPa at $V_{12} = 2.37$. A V_{12} value of 0.75 is chosen with a maximum PV value of 54.30 kPa.

3.4 The Controllers

This section deals with both the Honeywell UDC 6000 Process Controller and the Fischer and Porter Micro-DCI Modular Controller. More specifically, their features and capabilities are described, especially in regard to self-tuning.

FIGURE 3.5

TEST CONDITION THREE

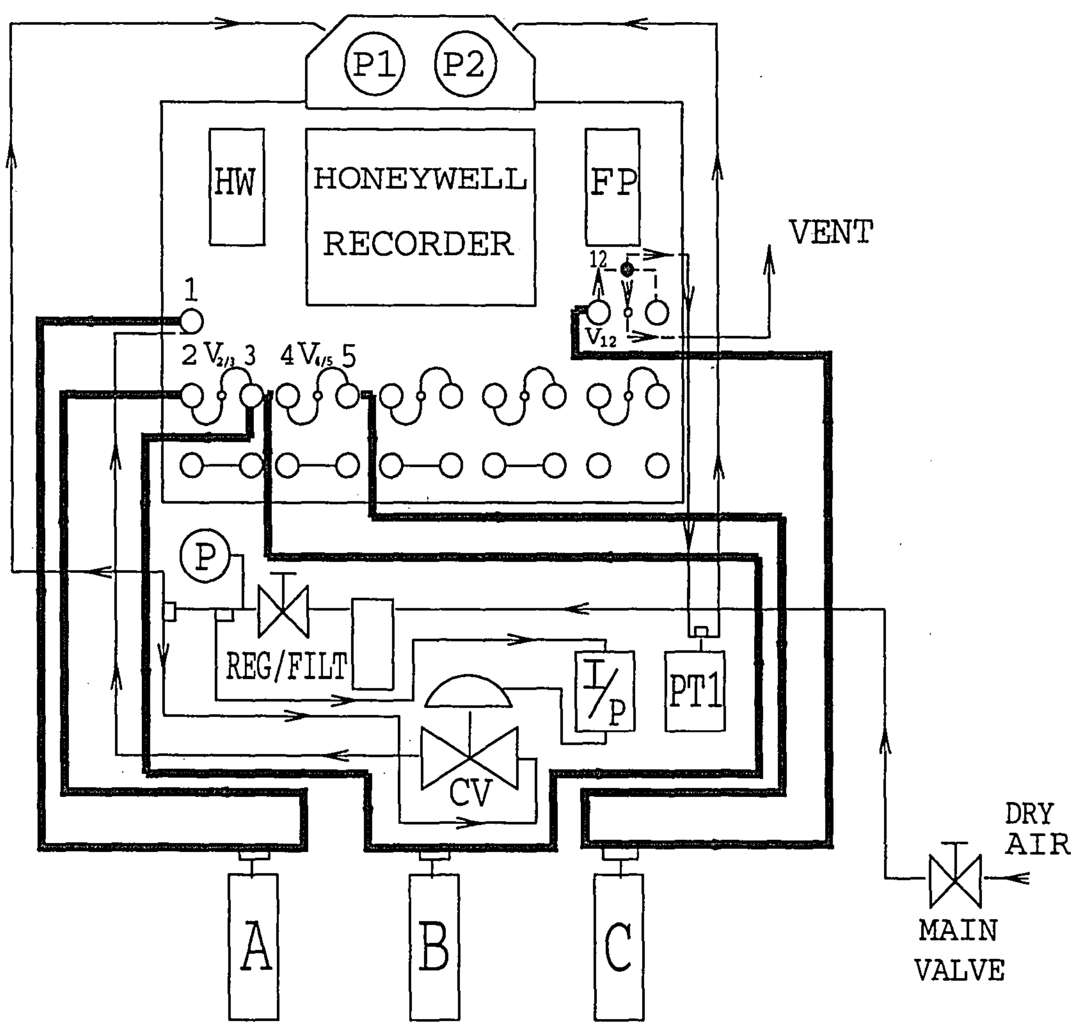
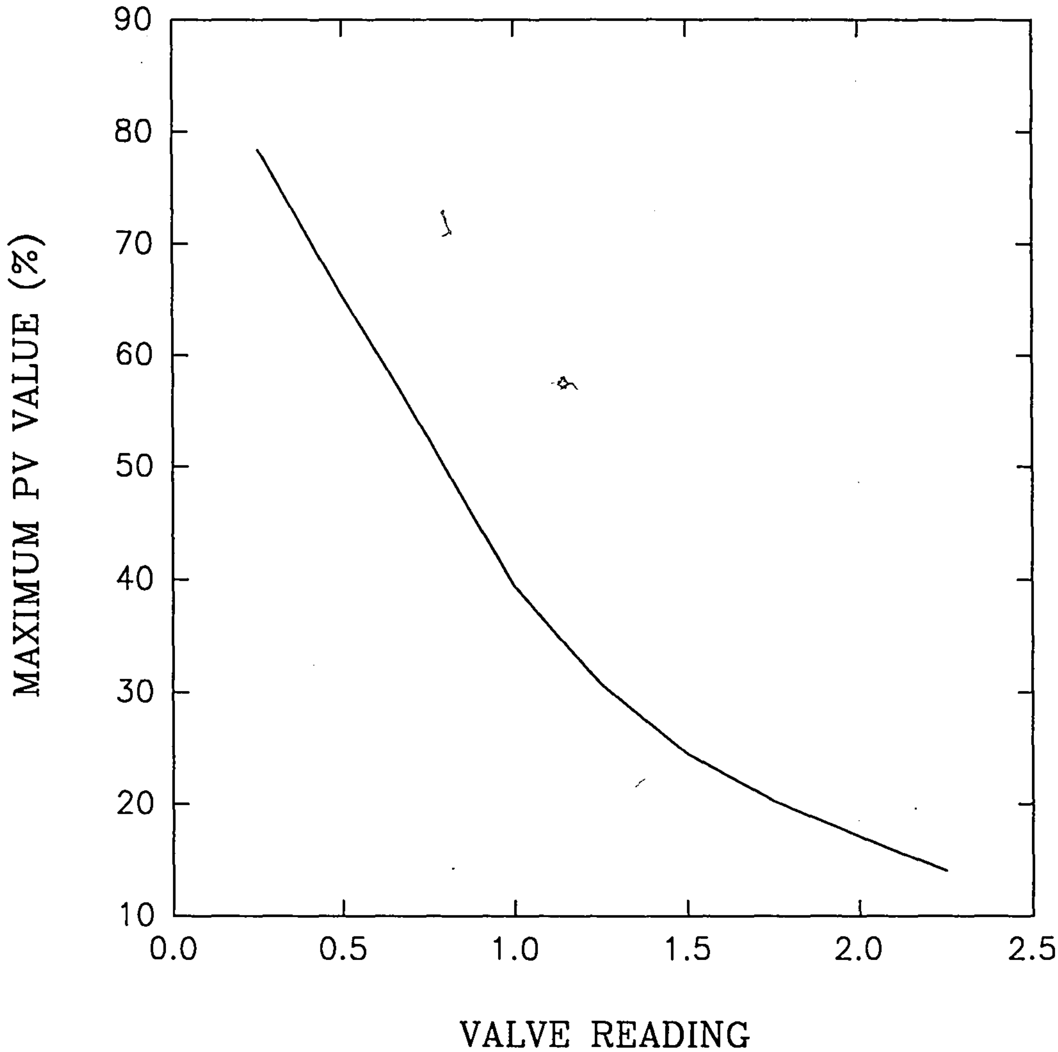


FIGURE 3.6

MAXIMUM PV vs VALVE
THREE TANKS



3.4.1 Honeywell DPR 6000 Process Controller

The UDC 6000 is a process controller that is microprocessor-based and is capable of cascade, feedforward, or two loop control. It is suited for continuous applications. The UDC 6000 has a sample rate of three to twelve times per second. Up to three local set points, one computer set point and one remote set point can be accepted.

The UDC 6000 can operate as a PID controller for two loops at one time. It has three modes: Manual, Automatic PID (parameters set by operator), and Adaptive Tuning. Within Adaptive Tuning, there are three additional modes: Set Point Adapt (SP Adapt), Process Variable Adapt (PV Adapt), and SP and PV Adapt.

Under SP and PV Adapt, Adaptive Tune continually adjusts the tuning parameters: G_c (Gain), T_i (Reset or Integral Action), and T_d (Rate Action) as necessary. SP Adapt occurs during initialization or_a SP change (whether local, remote, or computer). PV Adapt occurs when a PV change or disturbance causes a 5% error from SP. The controller keeps tuning until PV lines out to within 0.3% error from SP. Before and after PV line out, the Honeywell UDC 6000 can signify when it is tuning or re-tuning its control parameters, and whether it is adapting to PV or SP. Values of G_c, T_i, T_d, and system gain K are displayed.

3.4.2 Fischer and Porter Micro-DCI Modular Controller

The Micro-DCI is a controller capable of a wide range of controls, namely One Loop, Two Loop, Two Loop Cascade, Two Loop Override, Dual Two Loop Cascade, Feed Forward or Four Loop Control. It is suited for a wide range of process applications. The Micro-DCI has a sample rate of twenty times per second, and can accommodate remote, local, ratio, computer, or external/override SP for each active loop. It also has many different screen displays.

The Micro-DCI can perform PID control for all four loops, whether in Cascade or Override and is capable of operating in both Manual and Automatic modes.

Under Easy-Tune, G_c, T_i, and T_d are chosen once. The process must be manually repeated for each different set of process parameters. T_p, K_p, and W_p can be modified for more or less conservative tuning. The controller can inform the operator of the actual stage of the five-stage Easy-Tune process. The operator then has the option of automatic entry of new tuning parameters once G_c, T_i, and T_d are calculated. The operator can choose also one of five PID controllers as well as the maximum and minimum values for G_c, T_i, and T_d. Values of G_c, T_i, T_d, T_p, K_p, and W_p are displayed.

CHAPTER FOUR

EXPERIMENTAL PROCEDURES

Experiments are performed to compare the Honeywell UDC 6000 Process Controller and the Fischer and Porter Micro-DCI Modular Controller. In addition, the Honeywell PV Adapt is evaluated. The ability to model a system of different orders and to choose favorable tuning parameters are examined, and the reactions of the system to the tuning parameters are observed.

Both controllers are configured to try to maintain the PV at a SP between values of 0.00 kPa to 103.43 kPa, where the latter is the maximum input pressure allowed by the system regulator. SP values range from integer values of zero to fifteen. A SP value of zero corresponds to 0.00 kPa and fifteen to 103.43 kPa. In between, each unit SP change corresponds to a change of 6.895 kPa. The main means of comparison between the two controllers is how well each maintains PV at the determined SP. (It is noted that for all Honeywell tests, Adaptive Tune is set for SP and PV Adapt.)

This chapter discusses the experiments for each of the three different test conditions: Test Conditions One, Two, and Three.

4.1 Test Condition One

Test Condition One is a first order system, so that both Honeywell and Fischer and Porter controllers should be able to model the system exactly. Therefore, one of the goals of

Test Condition One is to compare how each controller approximates a system whose order is within controller capability. The models should be similar to the theoretical transfer function

$$S_1(s) = \frac{K_1}{1.5\,s + 1} \tag{45}$$

The experimentally determined values of gain K_1 range from 0.3 to 1.3. The lower K_1 values accompany the higher PV values. The lag of the system is 1.5 minutes.

Two sets of tests are performed for Test Condition One. The tests done for the first part of this test condition are SP change tests, involving SP change combinations from one to ten. Data from the Honeywell controller include the time necessary for retuning (whether in SP Adapt mode or PV Adapt mode), the tuning parameters (G_c, T_i, and T_d), and process gain K; Data from the Fischer and Porter controller include the time necessary for the Easy-Tune sequence, the preliminary output step size, the preliminary step response limit, the initial PV and CV values, the tuning parameters (G_c, T_i, and T_d), and the process parameters (T_p, K_p, and W_p).

The second set of tests involves process changes. The changes will be effected by varying V_{12}. This will cause changes in the system process gain and lag. The goal of this set of tests is to observe the Honeywell's adaptive control abilities to maintain SP and how well Fischer and Porter's Easy-Tune maintains its SP. The set points used are one, five, ten, eleven, twelve, and thirteen. Data obtained for the Honeywell Controller are the same as in the first part of Test Condition One. System response observations are made on the Fischer and Porter controller tests.

4.2 Test Condition Two

Test Condition Two is a second order system with no dead time. Therefore, only the Honeywell controller can accurately model the system. The Fischer and Porter controller can only approximate the system. Therefore, the primary goal of Test Condition Two is to compare Honeywell's ability to model a system that is within its algorithm's capability to Fischer and Porter's ability to approximate a system whose order is higher than its capability. The theoretical transfer function, $S_2(s)$, for Test Condition Two is

$$S_2\,(s) \;=\; \frac{K_2}{0.0036\ s^2 + 0.18\ s + 1} \qquad (46)$$

The system gain K_2 decreases with increasing PV, the gain ranging from 0.3 to 1.6 (Figure 4.1). The complete and reduced block diagrams are shown in Figure 4.2.

The Honeywell controller should model the system as $HW_{s2}(s)$, where

$$HW_{s2}(s) \;=\; \frac{HW_{k2}}{(\ 0.157\ s+\ 1)\ (\ 0.023\ s+\ 1)} \qquad (47)$$

Here, $T_1 = 0.157$ minutes and $T_2 = 0.023$ minutes. The gain HW_{k2} should have the same range as K_2. The Fischer and Porter should model the system as $FP_{s2}(s)$, where

$$FP_{s2}(s) \;=\; \frac{FP_{k2}\ e^{-T_{f2}s}}{(\ 0.24\ s+\ 1\ )} \qquad (48)$$

The system lag should be about 0.24 minutes, the dead time T_{f2} about 0.02 minutes, and the gain FP_{k2} should have the same range as K_1 and HW_{k2}.

FIGURE 4.1

SYSTEM GAIN vs. FINAL PV

TWO TANKS

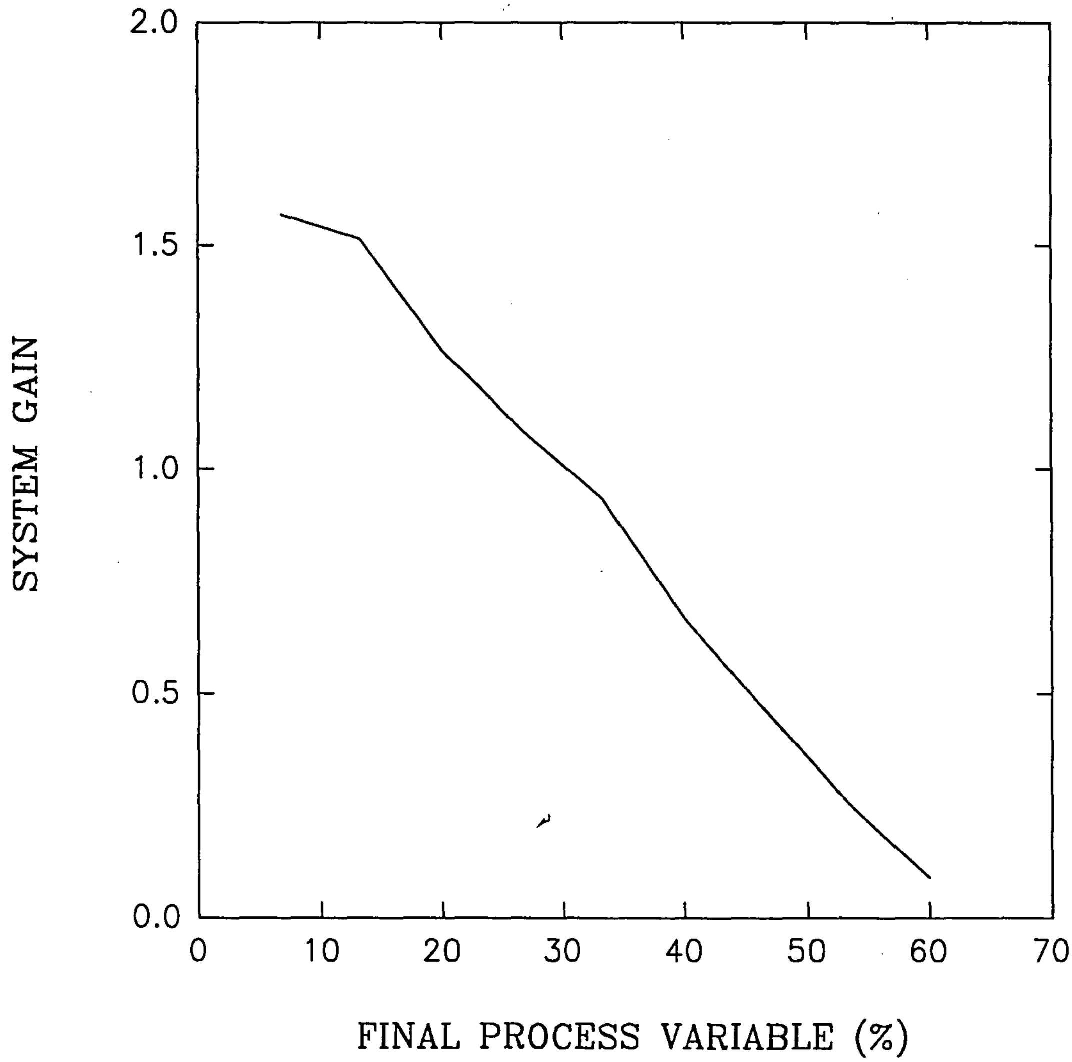
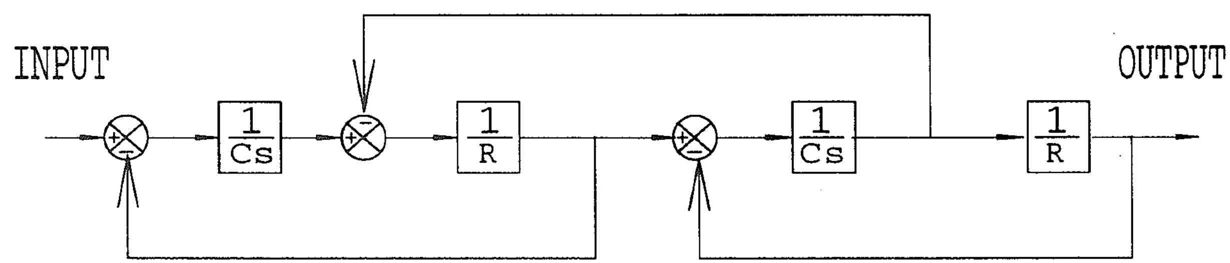
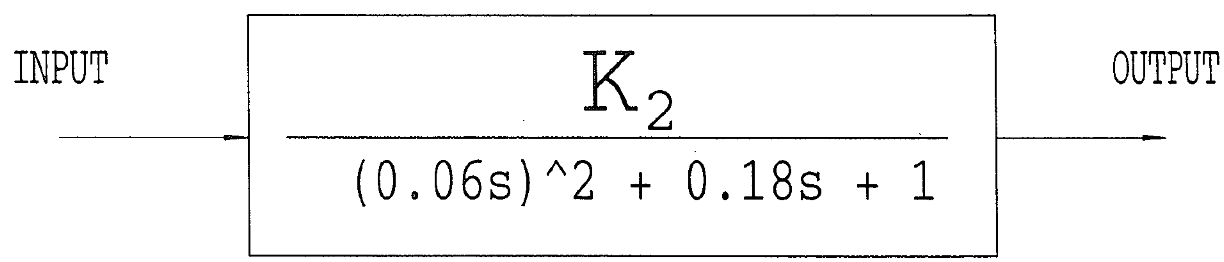


FIGURE 4.2
TEST CONDITION TWO
PLANT BLOCK DIAGRAM





The tests carried out for this test condition are SP change tests, with SP change combinations from one to nine. The same data are recorded for both controllers as was in the first part of Test Condition One.

4.3 Test Condition Three

Test Condition Three is a third order system with no dead time. Therefore, both Honeywell and Fischer and Porter controllers can only approximate this system. The primary goal of Test Condition Three is to compare how each controller approximates a system whose order is higher than its algorithmic capabilities. The theoretical transfer function is given by $S_3(s)$

$$S_3\,(s) \;=\; \frac{K_3}{(0.06\ s)^3 +\ 0.018\ s^2 + 0.36\ s + 1} \tag{49}$$

where the system gain K_3 ranging from 0.6 to 1.4. Figure 4.3 show a complete and reduced block diagram of the plant.

The Fischer and Porter should model the system as $FP_{s3}(s)$, where

$$FP_{s3}(s) \;=\; \frac{FP_{k3}\ e^{-T_{f3}s}}{(0.5\ s+\ 1\ )} \tag{50}$$

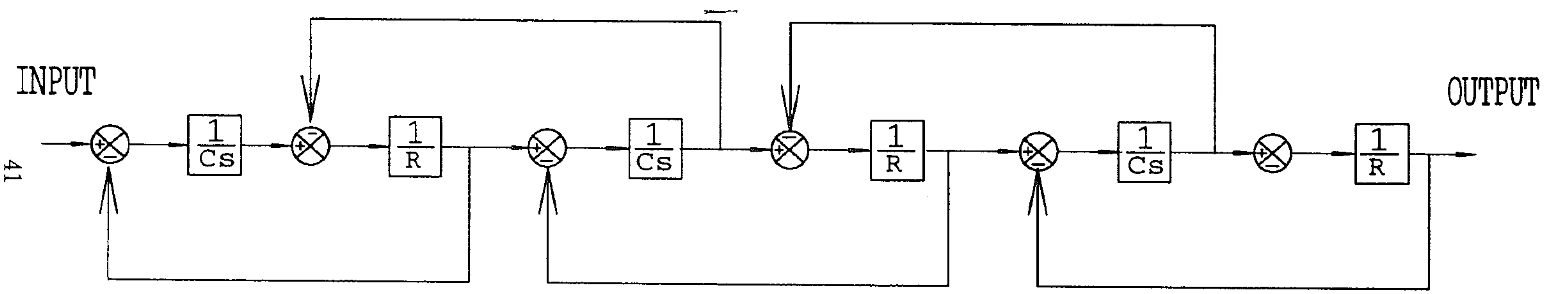
The system lag should be about 0.5 minutes, the dead time T_{f3} about 0.05 minutes, and the gain FP_{k3} should have the same range as K_3 and HW_{k3}.

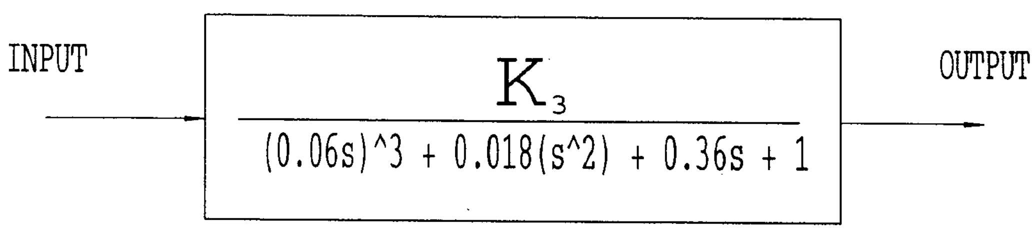
The tests carried out for this test condition are also SP change tests, with SP change

FIGURE 4.3

TEST CONDITION THREE

PLANT BLOCK DIAGRAM





combinations from one to seven. The same data for this test are recorded for both controllers as was in Test Condition One and Two.

4.4 All Test Conditions

For all test conditions, average values calculated for Honeywell (HW) and Fischer Porter (FP) include delay time, rise time, time-to-peak, marginal overshoot, and settling time. There are at most three studied responses. The first set of responses are the system responses from the assigned controller and the control-modeled system. This response is denoted HWC and FPC for the Honeywell and Fischer and Porter controllers, respectively. The second are those of the assigned controller plus the actual system and are denoted HWT and FPT for the Honeywell and Fischer and Porter controllers, respectively. The third and final set consists of the system response actually obtained and recorded on the Honeywell DPR controller. This response is denoted HWA and FPA for the Honeywell and Fischer and Porter controllers, respectively. Note that the HWC and HWT will differ from HWA because the Honeywell controller does not always use the assigned tuning parameters throughout the duration of the tuning process.

4.5 Data Retrieval, Recording, and Review

The main means of recording data is the Honeywell DPR 3000 250 mm Strip Chart Recorder. For all tests, the recorder plots PV and CV values against time for either the

Honeywell controller or the Fischer and Porter controller. P2 is also available to observe PV, and the CV position indicator can serve as a rough check of CV. The DPR 3000 paper is configured to run anywhere between 38.1 and 152.4 cm per minute, depending upon how fast the tested system reacts. For greater accuracy of recording time, a hand-held stop watch is used to time any tuning or retuning sequences.

All system and tuning parameters are obtained from displays from their respective controllers. All displayed information is recorded, excluding stage of tuning. Note that the Honeywell UDC 6000 does not display values for lag or dead time. These values must be inferred from the tuning algorithm equations. Also included are operator settings which affect any tests.

Data analysis is performed with the aid of the program CC (Comprehensive Control) which is used to calculate system time responses for the given system and controller transfer functions. CC is also used to predict theoretical behavior of HWC, FPC, HWT, and FPT. The actual system responses recorded on the Honeywell Recorder (HWA and FPA) can be compared to the theoretical HWC, FPC, HWT, and FPT.

CHAPTER FIVE

DATA ANALYSIS

The following are the parameters and symbols used in this chapter --

controller gain $= G_c$

reset time $= T_i$

rate time $= T_d$

primary system lag $= T_1$

secondary system lag $= T_2$

system gain $= K$

controller-assigned system transfer function $= S(s)$

controller transfer function $= C(s)$

Honeywell = HW

Fischer and Porter = FP

5.1 Test Condition One

5.1.1 Honeywell UDC 6000 Results and Responses: Part One

Figure 5.1 shows a typical SP change test. In general, all SP change tests for the first part of Condition One last from one to four minutes, but usually end between one and two minutes. Table 5.1 shows a summary of average responses of the system. The greater the change in SP, the longer the time to line out. There is no PV overshoot. The CV usually

FIGURE 5.1

SP ADAPT SAMPLE TEST

SP: 8 to 5

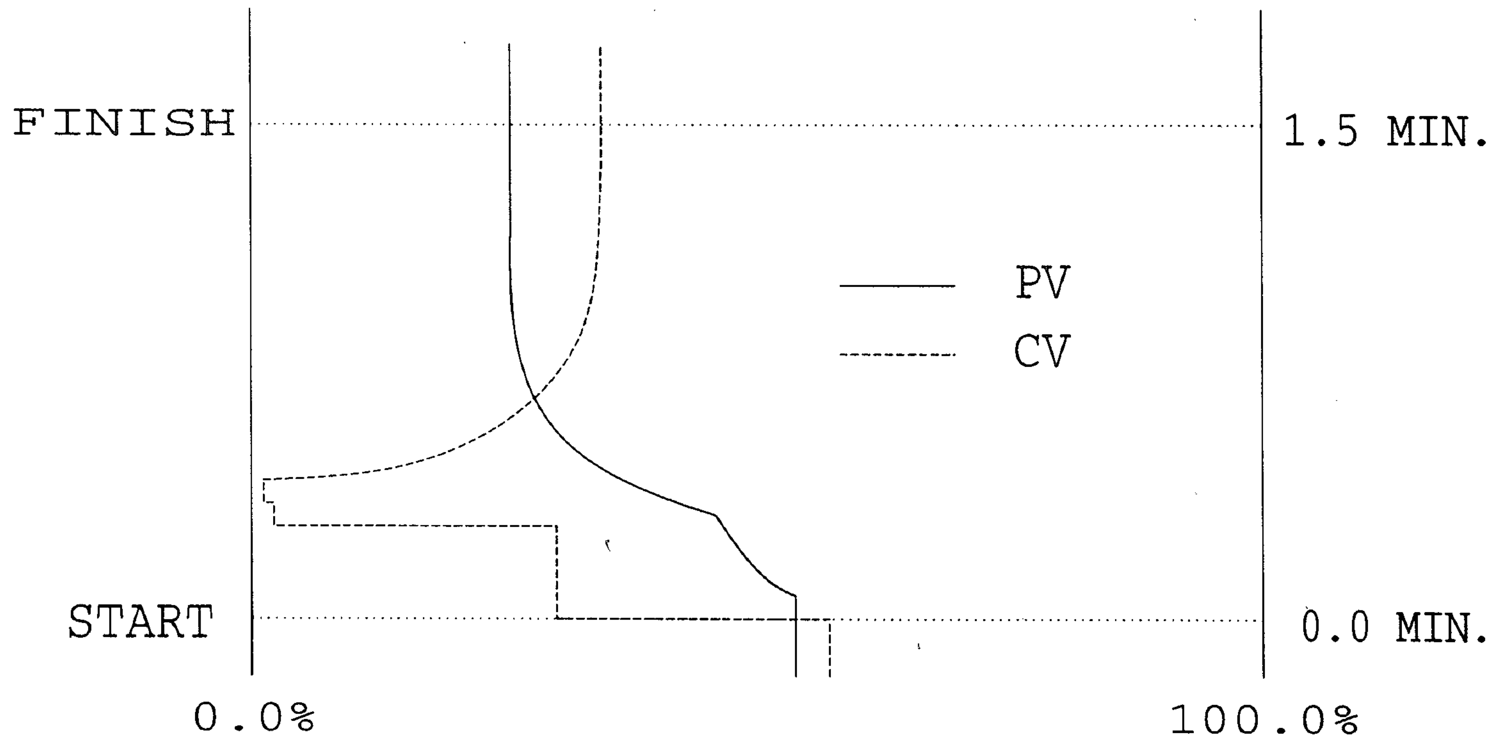


TABLE 5.1

SYSTEM RESPONSE FOR SINGLE TANK
HONEYWELL CONTROLLER

	SYSTEM RESPONSE
DELAY TIME (min.)	0.5
RISE TIME (min.)	1
TIME-TO-PEAK (min.)	1.2
MARGINAL OVERSHOOT (%)	0
SETTLING TIME (min.)	1.2

TABLE 5.2

HWC AND HWT RESPONSE
TEST CONDITION ONE

	HWC RESPONSE	HWT RESPONSE
DELAY TIME (min.)	0.03	0.04
RISE TIME (min.)	0.11	0.2
TIME-TO-PEAK (min.)	0.21	0.2
MARGINAL OVERSHOOT (%)	11	0
SETTLING TIME (min.)	0.7	0.2

makes two equally large step changes. As a result, PV has an almost smooth, double-step transition to the new SP. The UDC 6000 remains in SP Adapt mode practically throughout the entire duration of this testing period.

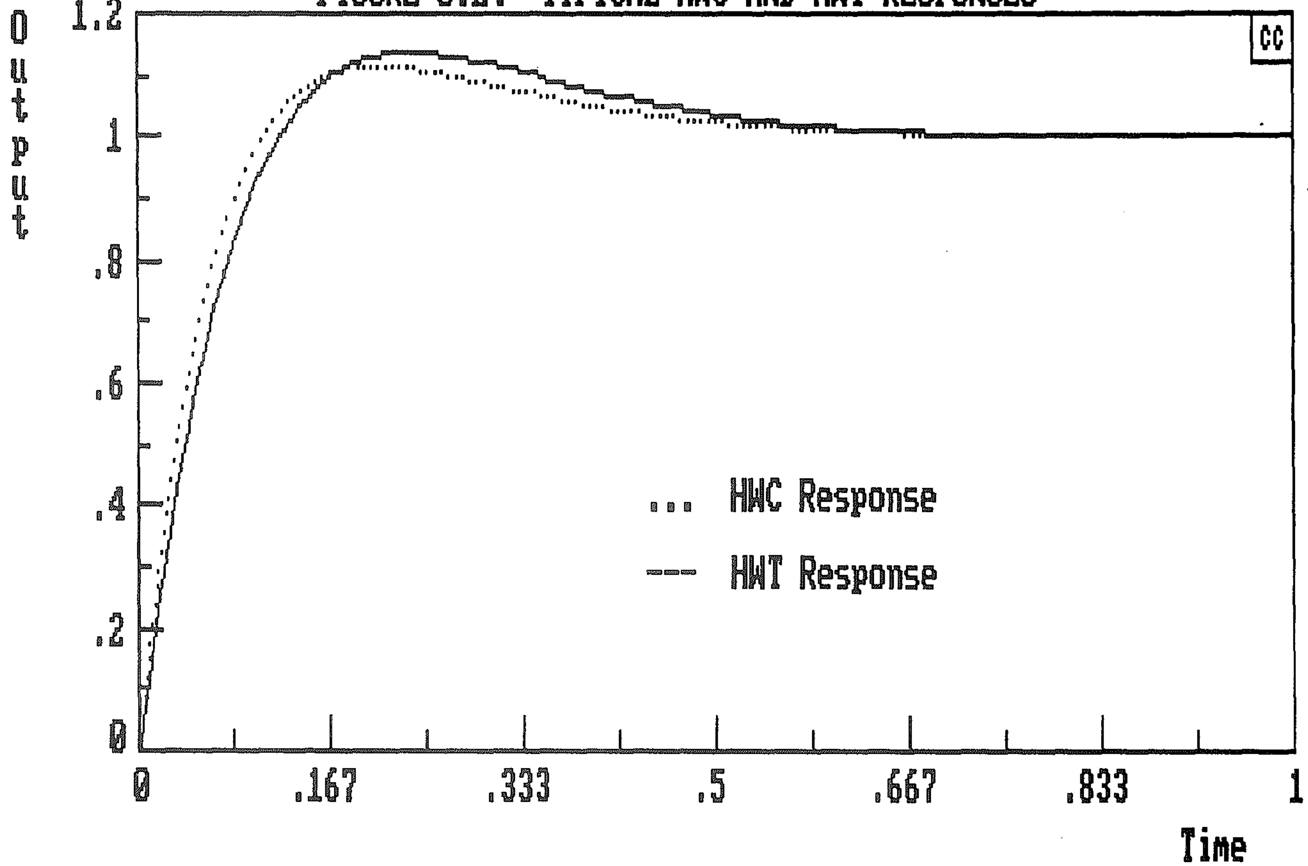
For almost all of the Honeywell Controller SP tests in Test Condition One, the UDC 6000 correctly models Tank D as a first order system without any dead time. Only in very uncommon instances does it model the system with dead time. Therefore, in agreement with the algorithm of the Adaptive Control Method, PI type controller transfer functions are assigned to this system. The control gain G_c is inversely proportional to calculated K, and T_i is directly proportional to the system time constant (the system lag).

Calculated T_i values range from 0.12 minutes to 0.33 minutes, although they usually falls within the range of 0.18 to 0.22. From the given values of T_i, it is inferred from Equation (11) that the controller-obtained time constant values usually fall between 1.13 minutes and 1.38 minutes.

Values for K, according to the UDC 6000 vary with initial and final set points. The values of K generally are between 0.99 and 1.34. K increases to a maximum value then decreases back again for minimum to maximum initial set points and does the same for final set points. The highest system gains occur when starting with a middle initial SP and ending with a middle final SP. Accordingly, the designated controller gain G_c acts inversely, as predicted from Equation (13). G_c values range from 16.1 to 67.6 although they seldom falls below 17.7 or jumps above 23.2.

The Honeywell controller models a first order system well. Figure 5.2 shows typical HWC and HWT responses. Table 5.2 summarizes the results of HWC and HWT responses. Both sets of results are similar, which shows good controller modeling. It can be seen that there is an 11% marginal overshoot and longer settling time with the HWC response. These

FIGURE 5.2: TYPICAL HWC AND HWT RESPONSES



graphs show underdamping and slight overshoot in the controlled system.

Overall, the tests show that the Honeywell controller is successful in modeling and tuning under SP Adapt mode. The tests results show that the UDC 6000 brings PV to line out in an accelerated time through system identification and CV manipulation. Regular controllers do not have this capability because they use the same control parameters throughout.

5.1.2 Honeywell UDC 6000 Results and Responses: Part Two

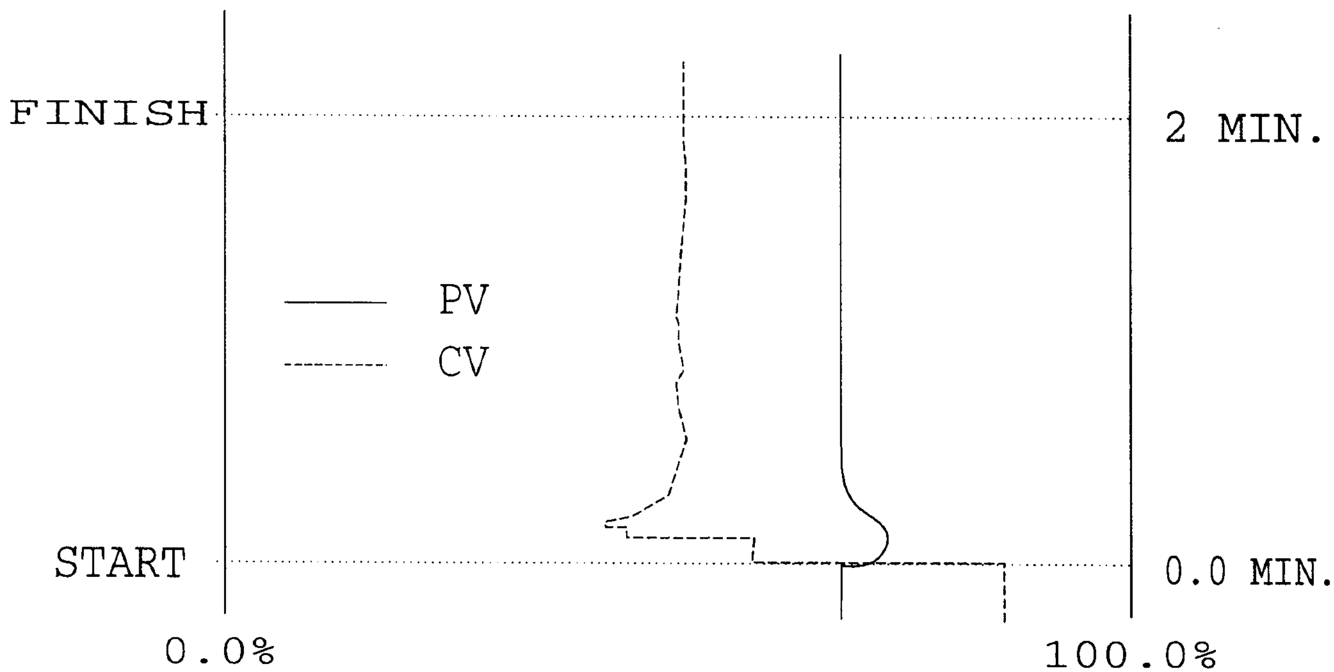
Figure 5.3 shows a typical process change test. The actual system response, as recorded be the DPR 3000, shows amazingly good control. There is always an immediate CV response with each valve change. This results in quick return to set point. In fact, the PV changes are almost always so small that it seems as if no process changes are even taking place. In short, the tuning adjustments are usually just different control gains. This simple adjustment, though, makes CV react quickly and effectively so that any PV changes are minimal.

For all process change tests (set points one, five, ten, eleven, twelve, and thirteen), the Honeywell UDC 6000 controller tunes in PV Adapt mode. In addition, these sets of tests displays a general similarity in results except that for SP 1. Each SP setting results in the same controller-calculated T_i regardless of the initial or final V_{12} setting. All controller gains increase as V_{12} increases. G_c remains constant, regardless of different initial V_{12} settings, as long as the final V_{12} is fixed and the change in V_{12} is greater than 0.25 units. The respective controller obtains values of K change inversely. For all tests, including SP 1, the controller models the system as a first order system with no dead time, meaning only PI controllers are assigned.

FIGURE 5.3

PV ADAPT SAMPLE TEST

VALVE: 2.00 to 1.00



For SP 1 tests, initial and final values of V_{12} are varied from 0.25 to 2.25 in increments of 0.25. Except for V_{12} increases or decreases of one step (a 0.25 increment), the same PI controller is assigned for all individual test settings of V_{12}. This controller transfer function C(s) is

$$C(s) = 75.3\left(1 + \frac{1}{0.44\,s}\right) \tag{51}$$

For the exceptions, the only change is in the P control. This controller gain, G_c, increases from 1.4 to 3.4 with increasing final V_{12} values, which is similar to the tests of other set points. Once the UDC 6000 has chosen the controller in Equation (36), no retuning, thereafter, occurs for the remaining tests in SP 1. The accompanying system gain is 0.31.

For SP 5 tests, initial and final values of V_{12} are the same as for SP 1. The same T_i value of 0.44, which is the same as in SP 1, is used for all initial and final V_{12} readings in this set of tests. The transfer function for SP 5 is

$$C(s) = G_c\left(1 + \frac{1}{0.44\,s}\right) \tag{52}$$

where

$$G_c = 7.2\,V_{12} + 3.6 \tag{53}$$

The control gain G_c ranges linearly from 5.0 to 19.4 (Figure 5.4). Accordingly, the system gain K decreases from 4.64 to 1.18 (Figure 5.5). The controller determines the system to be

FIGURE 5.4

CONTROLLER GAIN vs. VALVE

SP = 5

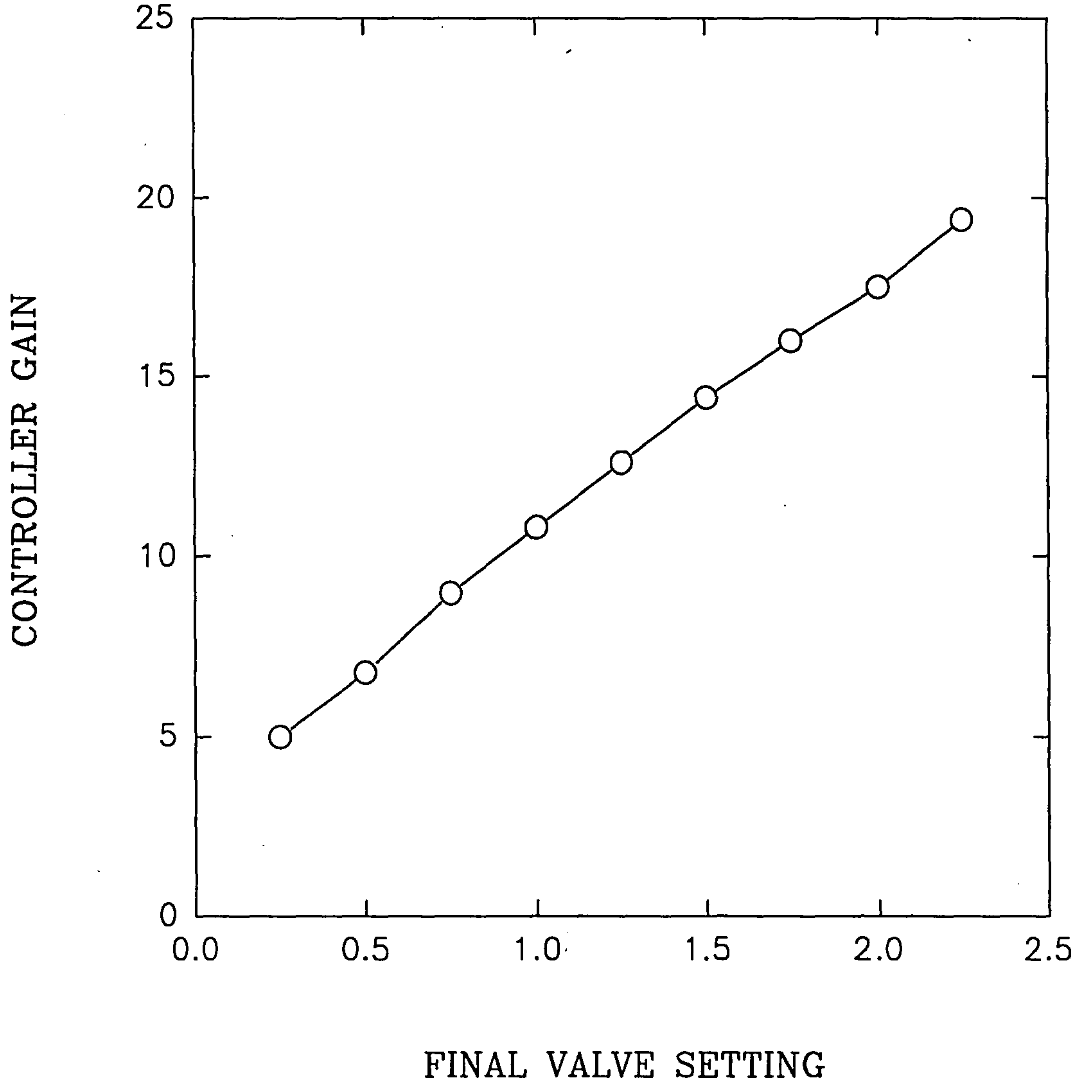
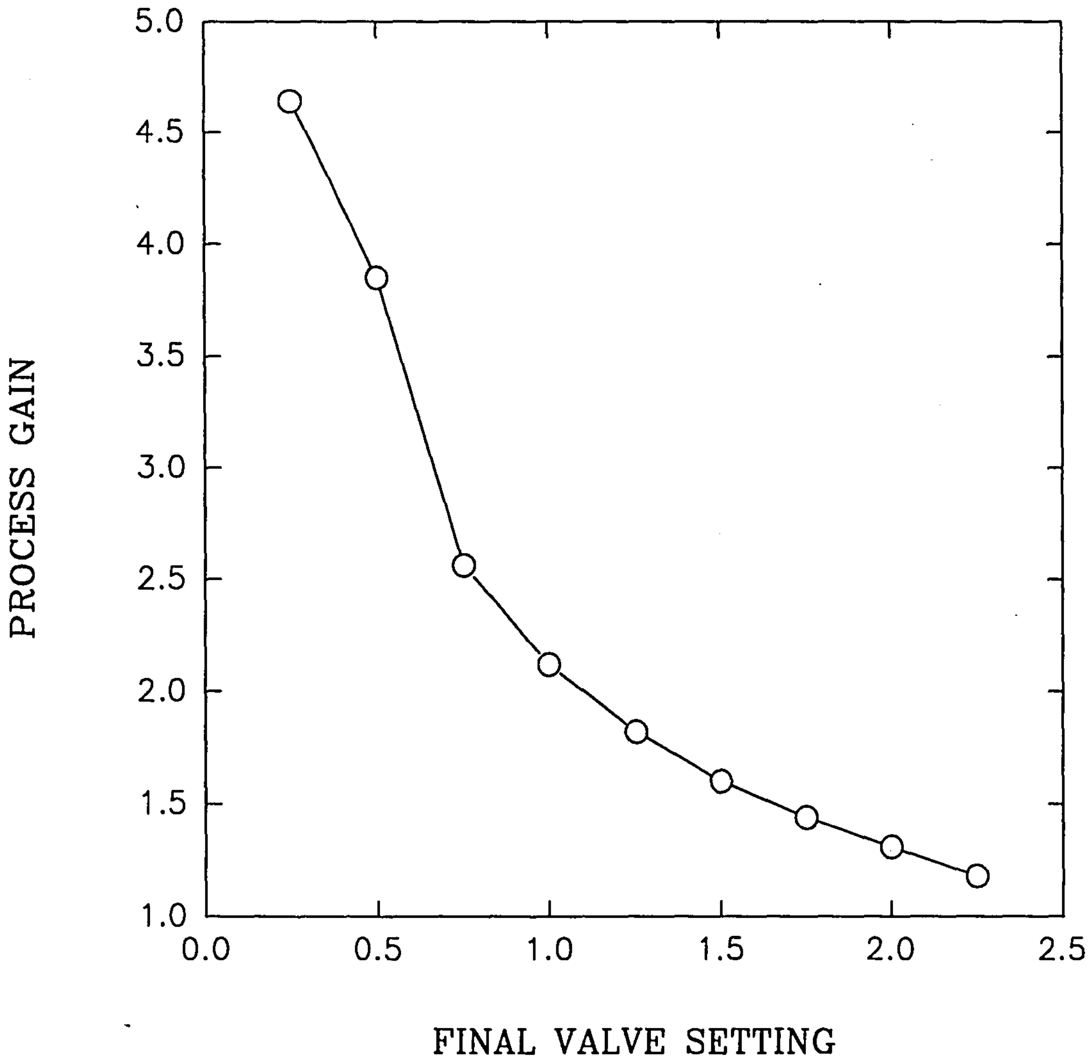


FIGURE 5.5

PROCESS GAIN vs. VALVE
SP = 5



$$S(s) = \frac{K}{2.75\,s + 1} \tag{54}$$

For SP 10 tests, initial and final values of V_{12} are varied from 0.25 to 2.00 in increments of 0.25. Here, the T_i value of 0.26 is used for all initial and final V_{12} readings in this set of tests. The transfer function for SP 10 is

$$C(s) = G_c\left(1 + \frac{1}{0.26\,s}\right) \tag{55}$$

where

$$G_c = 8.8\,V_{12} + 2.7 \tag{56}$$

The control gain G_c ranges from 5.1 to 20.6 (Figure 5.6). Accordingly, the system gain K decreases from 4.52 to 1.12 (Figure 5.7). The controller determines the system to be

$$S(s) = \frac{K}{1.86\,s + 1} \tag{57}$$

For SP 11 tests, initial and final values of V_{12} are varied from 0.25 to 1.75 in the same increments of 0.25. The same T_i value of 0.30 is used for all initial and final V_{12} readings in this set of tests. The transfer function for SP 11 is

$$C(s) = G_c\left(1 + \frac{1}{0.30\,s}\right) \tag{58}$$

FIGURE 5.6

CONTROLLER GAIN vs. VALVE
SP = 10

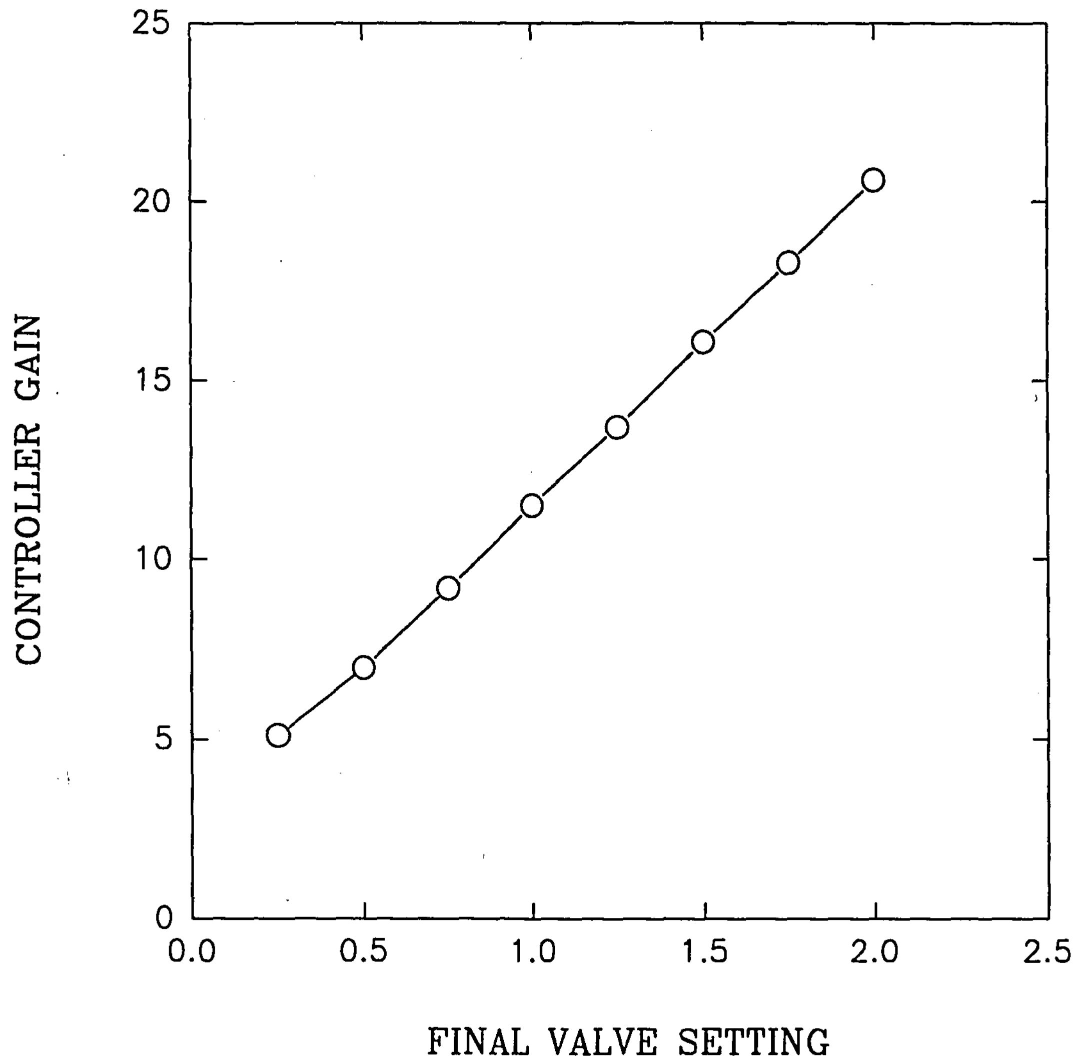
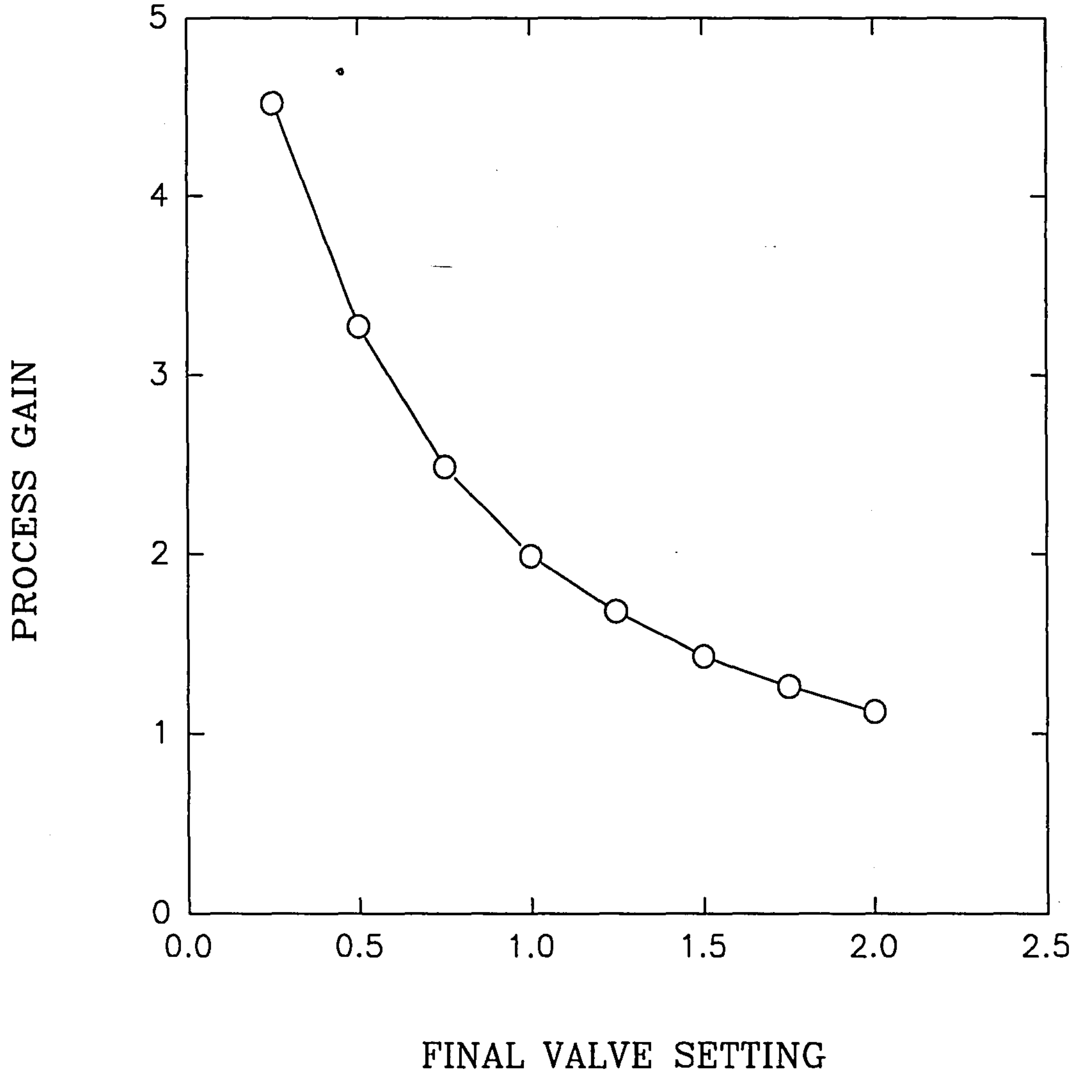


FIGURE 5.7

PROCESS GAIN vs. VALVE
SP = 10



where

$$G_c = 52.8\, V_{12} + 9.3 \tag{59}$$

The control gain G_c ranges from 26.5 to 102.5 (Figure 5.8). Accordingly, the system gain K decreases from 3.83 to 0.99 (Figure 5.9). The controller determines the system to be

$$S(s) = \frac{K}{1.88\, s + 1} \tag{60}$$

For SP 12 tests, initial and final values of V_{12} are varied from 0.25 to 1.25. The same T_i value of 0..11 is used for all initial and final V_{12} readings in this set of tests. The transfer function for SP 12 is

$$C(s) = G_c\left(1 + \frac{1}{0.11\, s}\right) \tag{61}$$

where

$$G_c = 50.4\, V_{12} + 9.6 \tag{62}$$

The control gain G_c ranges from 24.4 to 74.0 (Figure 5.10). The system gain K decreases from 0.94 to 0.31 (Figure 5.11). The controller determines the system to be

$$S(s) = \frac{K}{0.79\, s + 1} \tag{63}$$

FIGURE 5.8

CONTROLLER GAIN vs. VALVE
SP = 11

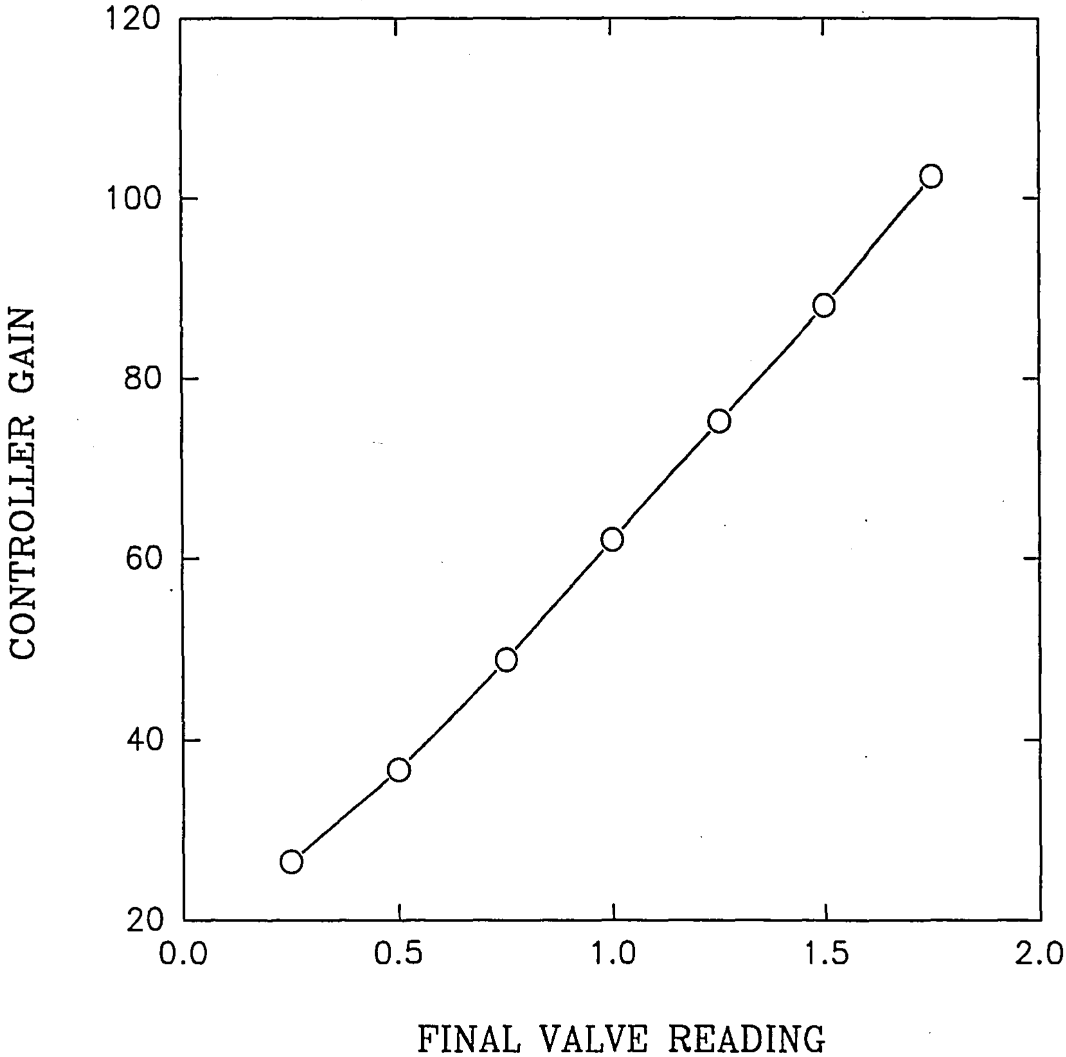


FIGURE 5.9

PROCESS GAIN vs. VALVE
SP = 11

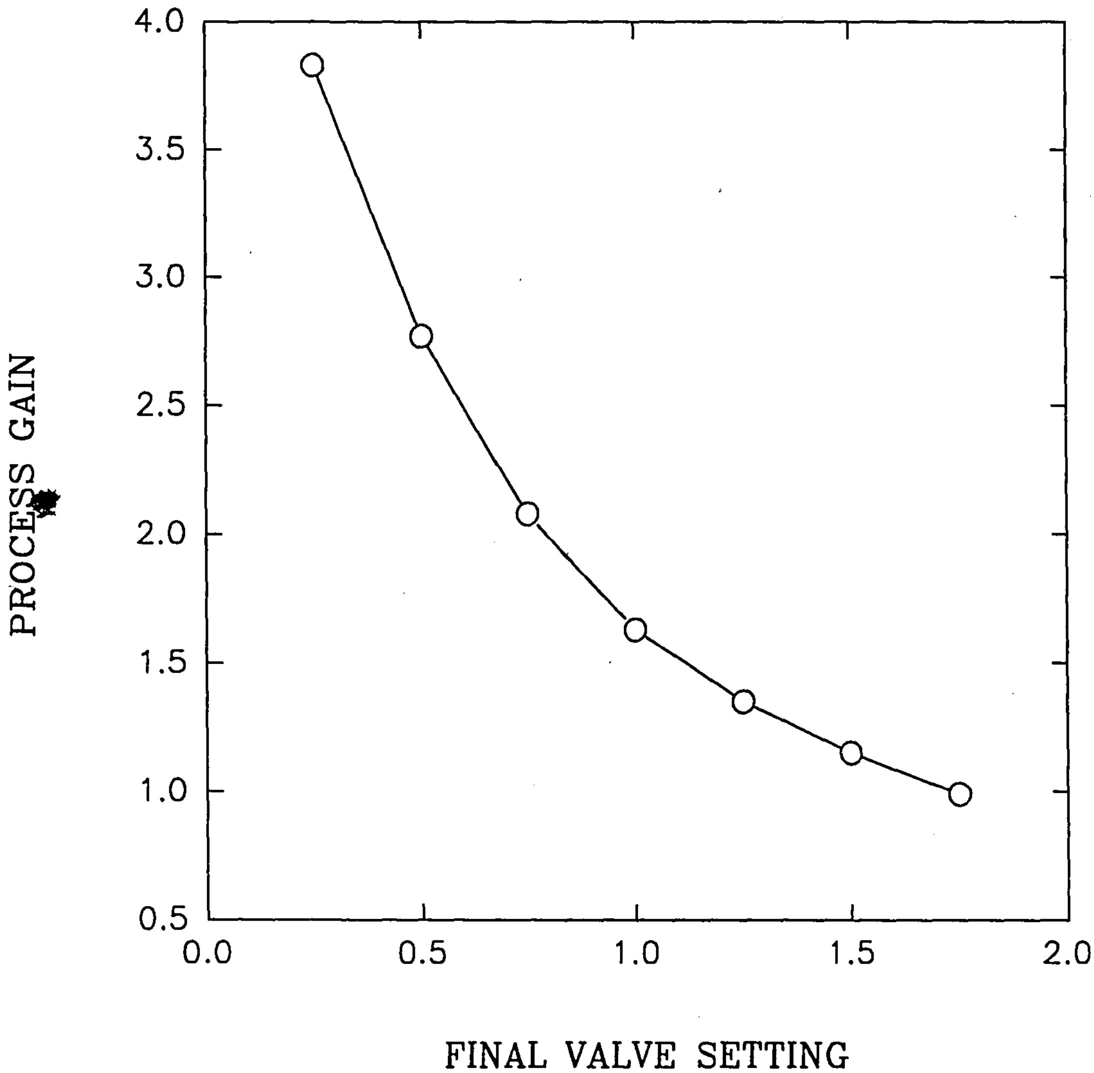


FIGURE 5.10

CONTROLLER GAIN vs. VALVE

SP = 12

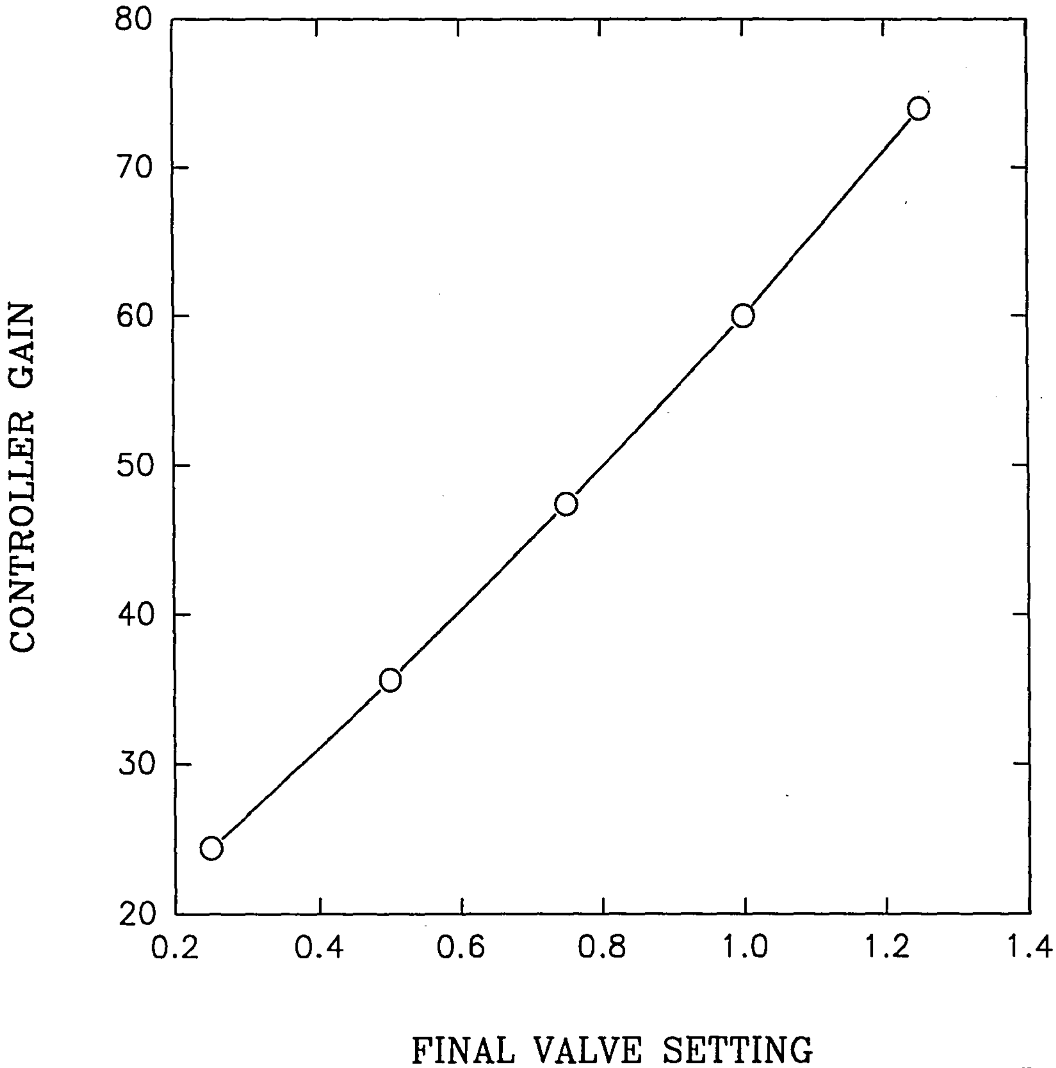
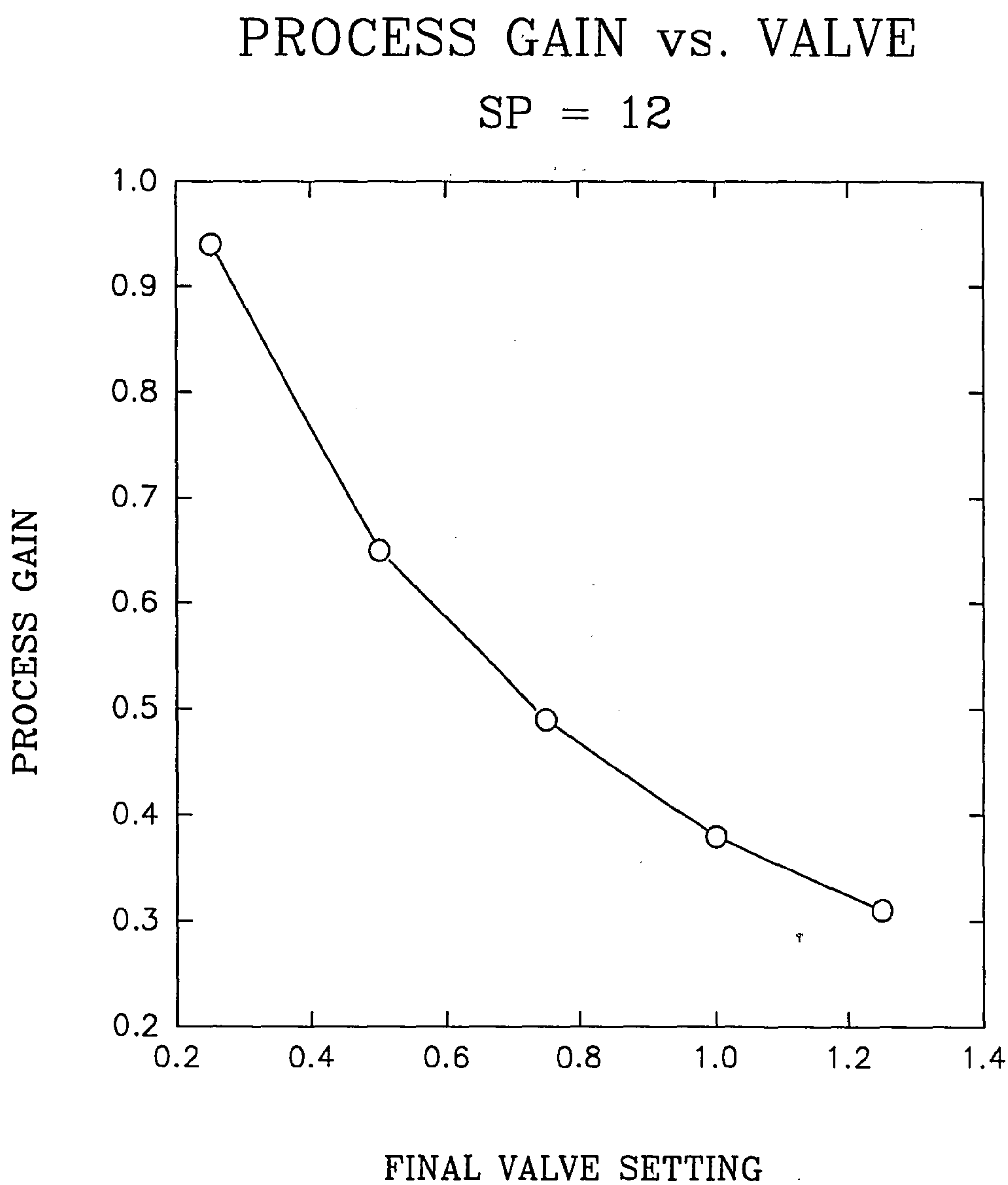


FIGURE 5.11


PROCESS GAIN vs. VALVE
SP = 12
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
PROCESS GAIN
0.2
0.4
0.6
0.8
1.0
1.2
1.4
FINAL VALVE SETTING

For SP 13 tests, initial and final values of V_{12} are varied from 0.25 to 0.75 in increments of 0.25. The same T_i value of 0.14 is used for all initial and final V_{12} readings in this set of tests. The transfer function for SP 13 is

$$C(s) = G_c\left(1 + \frac{1}{0.14\,s}\right) \tag{64}$$

where

$$G_c = 94.4\,V_{12} + 22.7 \tag{65}$$

The control gain G_c ranges from 48.0 to 95.2 (Figure 5.12). Likewise, the system gain K decreases from 0.48 to 0.24 (Figure 5.13). The controller determines the system to be

$$S(s) = \frac{K}{0.89\,s + 1} \tag{66}$$

The Honeywell controller models a first order system well. Appendix A shows HWC and HWT. Table 5.3 summarizes the results of HWC and HWT responses. Both sets of results are similar, which shows good controller modeling. It can be seen that the general trend for the Honeywell controller is that its HWC coincides almost, if not exactly, with its HWT response. These graphs show underdamping and slight overshoot in the controlled system.

These sets of tests show that the Honeywell Controller is successful in PV Adapt tuning. For each process change the controller automatically tunes parameters appropriately. A regular controller cannot make these adjustments unless manually changed to do so.

FIGURE 5.12

CONTROLLER GAIN vs. VALVE
SP = 13

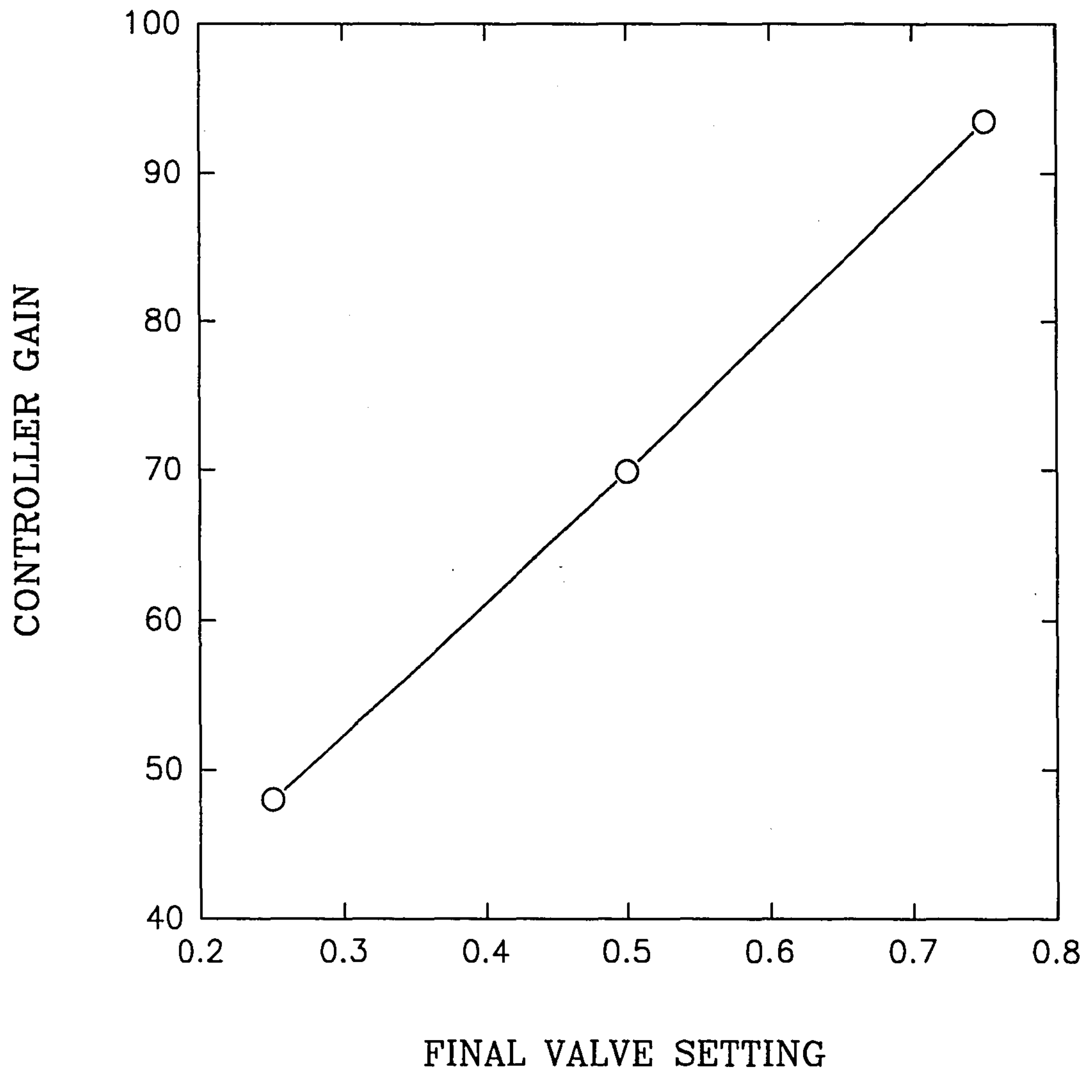


FIGURE 5.13

PROCESS GAIN vs. VALVE

SP = 13

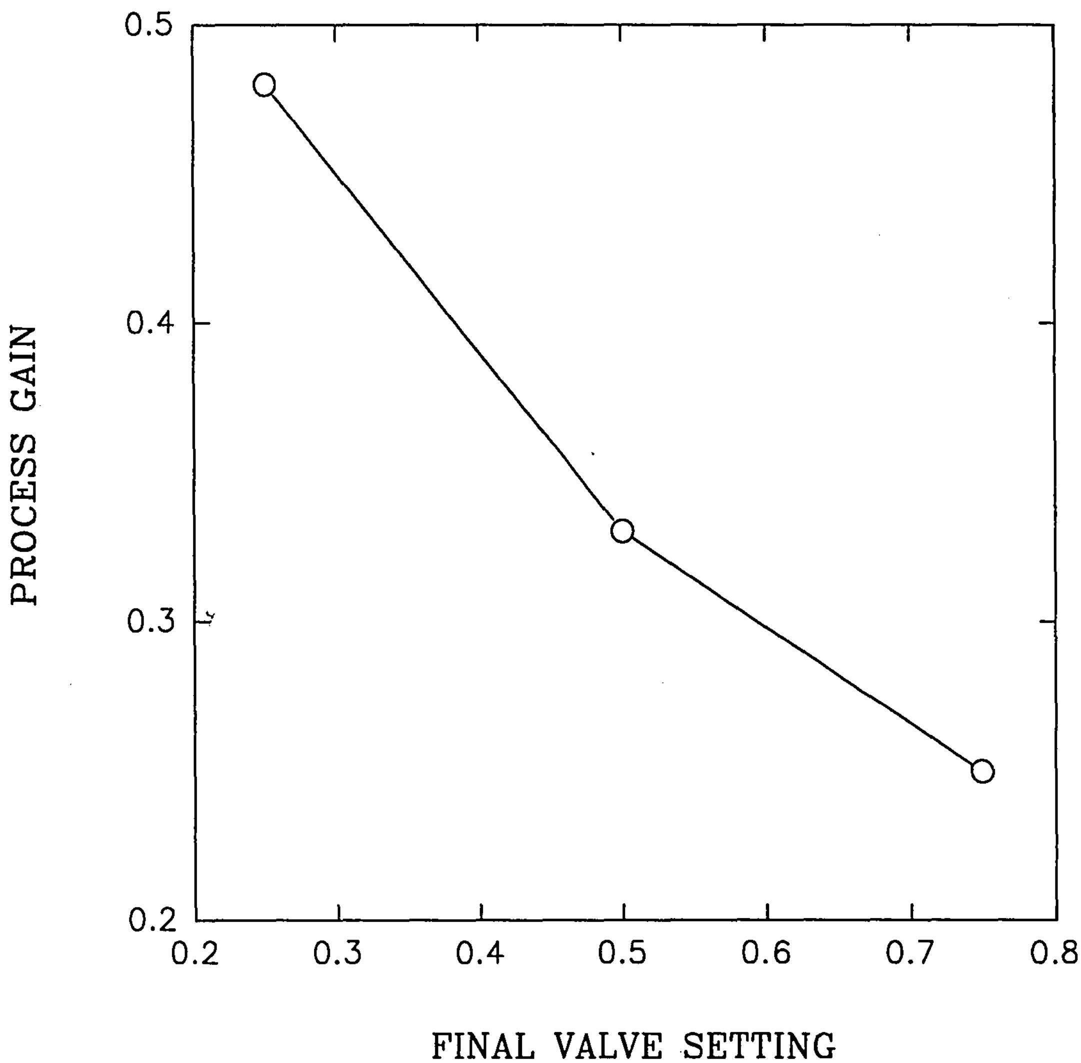


TABLE 5.3

SYSTEM RESPONSE FOR SINGLE TANK
HONEYWELL CONTROLLER
SP CHANGE TESTS

	HWC RESPONSE	HWT RESPONSE
DELAY TIME (min.)	0.15	0.15
RISE TIME (min.)	0.25	0.25
TIME-TO-PEAK (min.)	0.4	0.35
MARGINAL OVERSHOOT (%)	12	8
SETTLING TIME (min.)	1.2	1.2

TABLE 5.4

FPC/FPT RESPONSES
TEST CONDITION ONE

	FPC=FPT RESPONSE
DELAY TIME (min.)	0.005
RISE TIME (min.)	0.01
TIME-TO-PEAK (min.)	0.02
MARGINAL OVERSHOOT (%)	12
SETTLING TIME (min.)	0.06

5.1.3 Fischer and Porter Micro-DCI Results and Responses: Part One and Part Two

The first part of this section of Test Condition One involves performing the Easy-Tune sequence for different V_{12} settings and PV values. The controller mode setting is chosen to be a PID controller. The preliminary CO step size is configured to a 15% step increase for all tests. (Note that 0.0% CO and 100.0% CO are equivalent to the control valve being 0.0% and 100.0% open, respectively. A linear relationship exists between these values.) In addition, the preliminary PV step response limit ranges from 1% to 15% increase in PV but almost always is between 5% and 15%. (Note here that a PV value of 0.0% and 100.0% is equivalent to PV being 0.000 kPa and 103.425 kPa, respectively. A linear relationship exists between these values.) The preliminary PV step response limit changes due to the fact that τ is fixed at 5.00 minutes, and depending upon the system response and step response time, it must be changed to avoid a termination of the tuning sequence, which was described in Section 2.2.2 of this document. All Easy-Tune sequences finished under thirty-five minutes but usually only needed about ten minutes.

In general, both sets of tests show that the Fischer and Porter controller is successful in modeling the system correctly. Appendix B shows FPC responses. Note that FPC and FPT are identical, so only FPC is labeled. This shows extremely accurate modeling. It can be seen that the general trend for time parameters for the Fischer and Porter controller is that its FPC responses are similar to those of the Honeywell controller, sometimes better.

Table 5.4 summarizes the FPC responses. The results show that the system should stabilize quickly to set point. There is slight underdamping and minimal marginal overshoot. The rise, delay, and settling times are also small. For a fixed V_{12} setting and increasing set points, both oscillation and settling times increase and both rise and delay times decrease. Especially for low V_{12} settings, amplitudes of oscillation increase.

After the completion of the tuning sequences, the Fischer and Porter controller correctly models the system as a one lag system. It does, however, incorrectly assign a dead time of 0.005 minutes. The assigned dead time, however, can be attributed to the capacitances such as tubing or the control valve air chamber. As with the Honeywell controller, the Micro-DCI assigns varying process gain values according to different system settings and PV values. There seems to be no trend in its values except that for each V_{12} setting, K_p increases to maximum and then decreases again with minimum to maximum obtainable PV values. The system time lag, as determined by the controller, appears constant for each V_{12} valve setting, regardless of the resulting PV. Furthermore, the time lag generally increases with increasing V_{12} settings. The range of the system time lag, denoted by T_p, for Test Condition One is from 1.17 minutes to 2.74 minutes.

Because of the small W_p values obtained, the Micro-DCI calculates the derivative control parameter, T_d to be zero. In effect, PI controllers are assigned for all system and parameter settings, even though PID control mode is originally chosen. The controller gain, G_c, and the reset time, T_i, are determined by the aforementioned system parameters and are calculated using Equations (37) and (38), respectively. The results from the Fischer and Porter controller shows that G_c varies from 79.7 to 1790 but generally ranges from 209 to 613, which still seems exceedingly high. The resulting T_i values range from 0.018 minutes to 0.055 minutes, but generally fall between 0.020 and 0.030.

For picking appropriate tuning parameters, the Fischer and Porter controller is deemed unsuccessful. The FPC responses in Appendix B shows no similarity to its FPA response. Instead, the actual system shows high amplitude oscillation, as will be explained below.

5.1.3.1 Set Point Tests

None of the system responses to the chosen PI controllers are stable for the SP tests. The PV oscillates with high amplitude in comparison to previous tests with the Honeywell controller. The CV, control valve, also continuously oscillates from 0.0% to 100% with a frequency of about three seconds.

The tests are repeated. This time, after the completion of each individual Easy-Tune sequence, SP change tests are performed in the realization that the system itself sometimes has inconsistent results. Still, when the tests are performed again, the system remains unstable, even for SP changes as small as 0.01 unit in magnitude.

All previous Easy-Tune tests were performed with tuning modification values of 0.0, meaning that the obtained system parameters were not modified before the calculation of the PID parameters. In an attempt to achieve a stable system response, the tuning modification value was changed. At the first attempt, all modification factors (M_t, M_k, and M_w) are set to the factory default value of 0.1 in the "safe" direction. This means:

$$T_p \text{ modified } = T_p (1 - M_t) \tag{67}$$

$$K_p \text{ modified } = K_p (1 + M_p) \tag{68}$$

$$W_p \text{ modified } = W_p (1 + M_w) \tag{69}$$

These values enter Equations (37) and (38) for the modified tuning parameters. The new PI control settings are automatically implemented, but the system is still unstable. Next, higher modification factors are used but the system remains unstable for any SP change tests. Not even the maximum recommended modification factors of 0.5 improve the system stability. Thereafter, different combinations of M_t, M_k, and M_w are entered resulting in no change in improvement.

5.1.3.2 Process Change Tests

None of the system responses to the chosen PI controllers for the process change tests are stable. Again, PV oscillates with significant amplitude, and CO also continuously oscillates from 0.0% to 100% with a frequency of about three seconds. None of the above modification variations result in a stable closed-loop response.

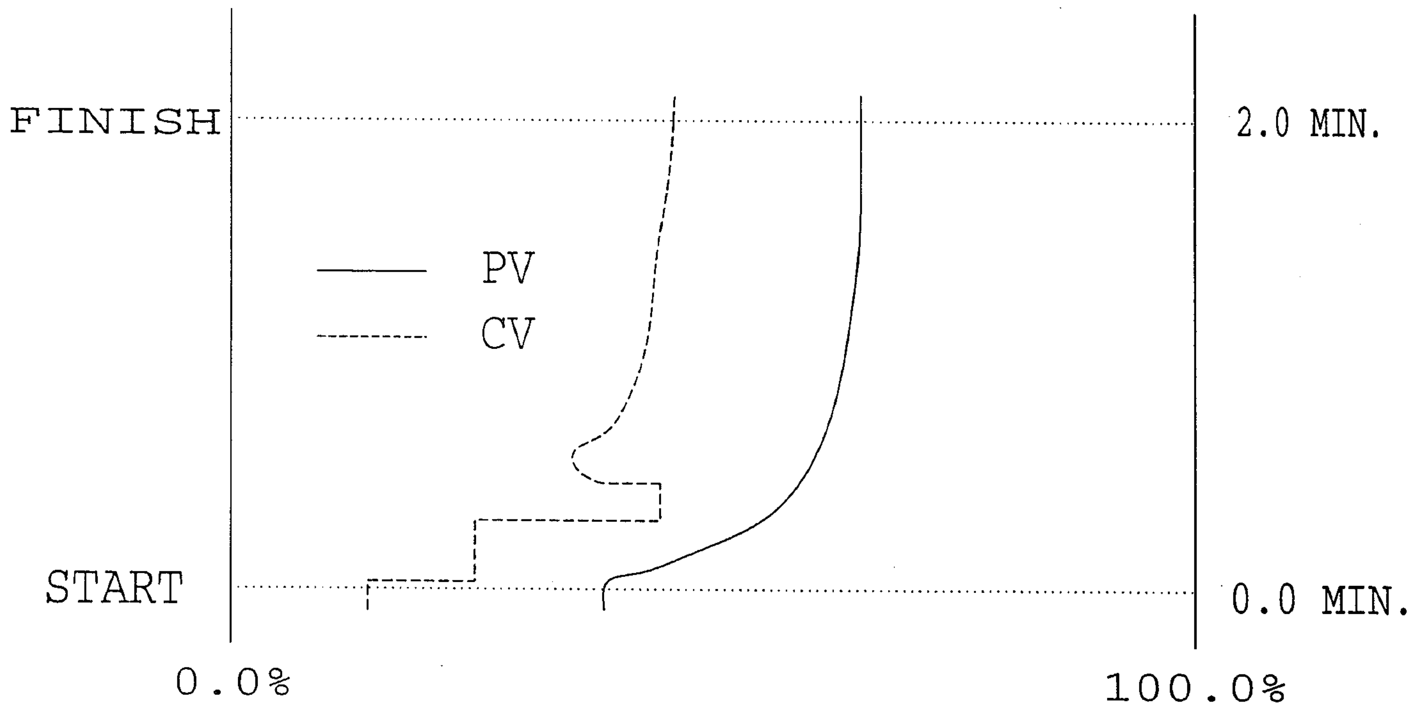
5.2 Test Condition Two

5.2.1 Honeywell UDC 6000 Results and Response

Figure 5.14 shows a typical HWA response. Overall, all SP change tests last from just under one minute to just under two minutes. There is no PV overshoot and the transition to the new SP is always smooth. The resulting tuning is good.

For about half of the SP tests in Test Condition Two, the UDC 6000 models the two tank system, which is of second order, as a two lag system without dead time. The other half of the tests result in a one or two lag process with dead time. The T_2 values are just barely detectable. (For derivative values below 0.02, the controller will display a T_d of zero.). This occurs with large SP change tests. Only in rare cases does a model of a one lag system without dead time appear. Therefore, in accordance with the Adaptive Control Method algorithm, all controller-assigned control transfer equations are of the form of a PI controller, where T_i is designated the value of the calculated first order time constant and G_c is designated values according to controller calculated values of T_1, K, and T.

FIGURE 5.14
HWA SAMPLE TEST
TWO TANKS
SP: 5 to 8



Calculated T values range from 0.001 minutes to 0.107 minutes but usually stay within 0.001 minutes to 0.03 minutes. Calculated K values range from 0.29 to 4.07 but usually stay within 1.00 to 3.00. The calculated K values vary with starting and ending SP values. The peak values occur when one starts at an initial SP of two or three and ends at a final SP of four or five. The calculated gain then decreases with increasing or decreasing initial and final SP values. The lowest gains occur when one starts at high initial set points and ends at high final set points.

T_i ranges from 0.02 minutes to 0.53 minutes but usually stays within 0.02 minutes to 0.28 minutes. Because of the calculated values of T_1, T, and K, G_c ranges from 0.3 to 7.8 but usually is within 1.1 to 2.9.

From the above data and equations of Section 2.1.1.2, it is inferred that the controller models the system in one of three different ways, $S_{21}(s)$, $S_{22}(s)$, or $S_{23}(s)$ For a second order lag without dead time

$$S_{21}(s) = \frac{1.33}{(0.02\,s + 1)(T_2\,s + 1)} \tag{70}$$

where $T_2 < 0.02$ minutes. For a first order lag with dead time

$$S_{22}(s) = \frac{1.28\,e^{-0.026s}}{0.26\,s + 1} \tag{71}$$

and 0.026 minutes is its corresponding dead time. For a second order lag with dead time

$$S_{23}(s) = \frac{1.45\,e^{-0.009s}}{(0.05\,s + 1)(T_2\,s + 1)} \tag{72}$$

and $T_2 < 0.033$ minutes and the dead time is 0.009 minutes. The controller assigned to each system is, respectively

$$C_{21}(s) = \frac{4.5\ (\ 0.02\ s + 1)}{0.02\ s} \qquad (73)$$

$$C_{22}(s) = \frac{1.8\ (\ 0.26\ s + 1)}{0.26\ s} \qquad (74)$$

$$C_{23}(s) = \frac{1.35\ (\ 0.05\ s + 1)}{0.05\ s} \qquad (75)$$

Figure 5.15 shows typical HWC and HWT responses and Table 5.5 summarizes their results. The HWC and HWT responses are similar. There is no marginal overshoot. The HWC responses are about 33% faster than that of the HWT responses.

5.2.2 Fischer and Porter Micro-DCI Results and Response

The mode chosen for the Easy-Tune sequence in Test Condition Two is the same as in Test Condition One. The preliminary CO step size is configured to a 20% step increase for all tests. In addition, the preliminary PV step response limit ranges from 1% to 10% increase in PV but almost always is 10%. This PV step response limit, again, must be changed to avoid a termination of the tuning sequence by matching it to the fixed t_s value of 5.00 minutes. In general, at the first attempt, all Easy-Tune sequences for Test Condition Two last four minutes but usually are completed within two and one-half minutes. Here, with configuration modifications, the Fischer and Porter controller is successful at tuning the system.

After the completion of the tuning sequences, the Micro-DCI models the system as a one lag and dead time system. The assigned dead time is fixed at 0.032 minutes for all values

FIGURE 5.15: TYPICAL HWC AND HWT RESPONSES

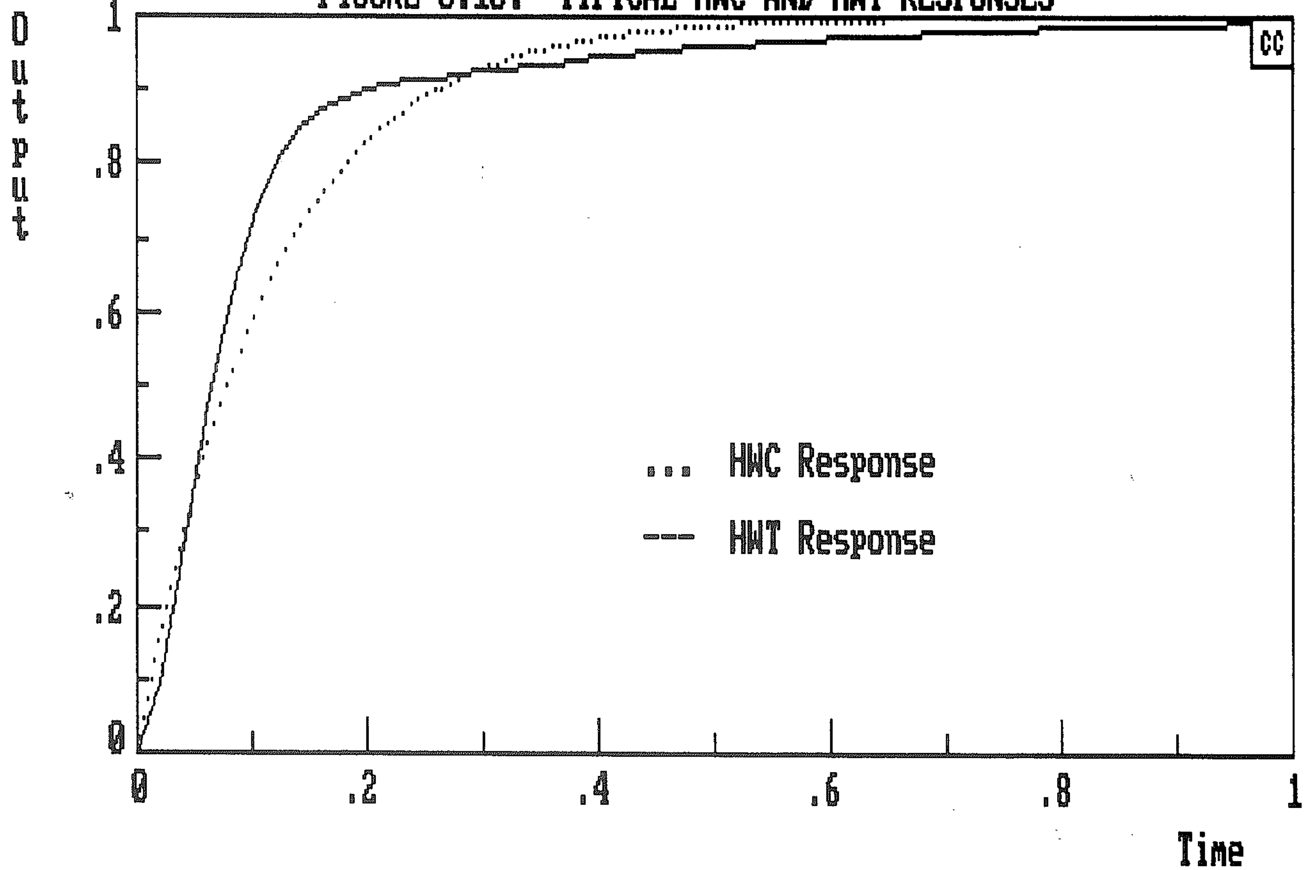


TABLE 5.5

HWC AND HWT RESPONSES
TEST CONDITION TWO

	HWC RESPONSE	HWT RESPONSE
DELAY TIME (min.)	0.06	0.06
RISE TIME (min.)	0.44	0.66
TIME-TO-PEAK (min.)	0.44	0.66
MARGINAL OVERSHOOT (%)	0	0
SETTLING TIME (min.)	0.44	0.66

TABLE 5.6

FPC AND FPT RESPONSES
TEST CONDITION TWO

	FPC RESPONSE	FPT RESPONSE
DELAY TIME (min.)	0.02	0.025
RISE TIME (min.)	0.04	0.03
TIME-TO-PEAK (min.)	0.07	0.06
MARGINAL OVERSHOOT (%)	13	45
SETTLING TIME (min.)	0.3	0.4

of PV. The process gain, K_p, tends to decrease steadily with increasing PV. Its range is 1.57 to 0.09. The T_p value stays constant at 0.238 minutes.

Because of the small W_p values obtained, as in Test Condition One, the Micro-DCI calculates the derivative control parameter, T_d to be zero. In effect, PI controllers are assigned to all values of PV, even though PID controller mode was originally chosen. The results from the Fischer and Porter controller shows that G_c varies from 4.72 to 38.05. The increase accompanies decreasing values of PV. The resulting T_i values range from 0.052 minutes to 0.076 minutes.

Appendix C1 shows the FPC and FPT results of Test Condition Two where all modification factors were changed to 0.10 and 0.30. Table 5.6 summarizes the results of Appendix C1. The FPT response shows significantly more oscillation, although the response times are small compared to those of the HWT responses. The FPC curve shows less damping and more maximum overshoot with greater delay time and rise time. The peak time is less, however, and the settling times are very comparable. The FPT response is, overall, slower and has minute oscillations. As SP increases, furthermore, the response slows even more but the oscillation also decrease or disappear entirely.

The same problem arises in Test Condition Two when SP change tests are performed as in Test Condition One Part 1. Again, modifications of the process parameters are implemented. All modification factors M_t, M_k, and M_w are changed to 0.1. This is not enough to stabilize the system for changing SP tests for tests with the higher initial and final SP values, even for small SP changes. It is found, however, that the PI controller chosen by the Micro-DCI for the tests with lower PV values is adequate to stabilize the system for all PV settings during these SP change tests. Stability is achieved for all tests, even those with extreme SP changes. The transfer function, $C_2(s)$, is

$$C_2(s) = 2.67\left(1 + \frac{1}{0.080\ s}\right) \qquad (76)$$

The setting for this test is at PV of 19.6% and a CV at 14% open. Appendix C2 shows the average FPC response using Equation (77). Figure 5.16 shows a typical FPA response for Test Condition Two. PV line out with the above controller occurs within three minutes. Although oscillation for both PV and CV occur, the oscillations fade to negligible amplitude.

5.3 Test Condition Three

5.3.1 Honeywell UDC 6000 Results and Responses

Figure 5.17 shows a typical HWA response. Table 5.7 summarizes data for this test section. Overall, all SP change tests last from just under one minute to less than ten minutes. In general, the Honeywell controller is successful in tuning to SP changes using SP and PV Adapt. There is no marginal overshoot and the settling times are relatively small.

For about one-half of the Honeywell controller SP tests in Test Condition Three, the UDC 6000 models the three tank system as a two lag (second order) system without dead time. Again, T_2 is barely detectable. For the other half, it is modeled as a one or two lag system with dead time. This tends to happen with large SP change tests. Therefore, in accordance with the Adaptive Control Method algorithm, all controller-assigned control transfer equations are of the form of a PI controller, where T_i is assigned the value of the calculated first order time constant and G_c is assigned values according to controller calculated values of T_1, K, and T.

FIGURE 5.16

FPA SAMPLE TEST

TWO TANKS

SP: 7 to 3

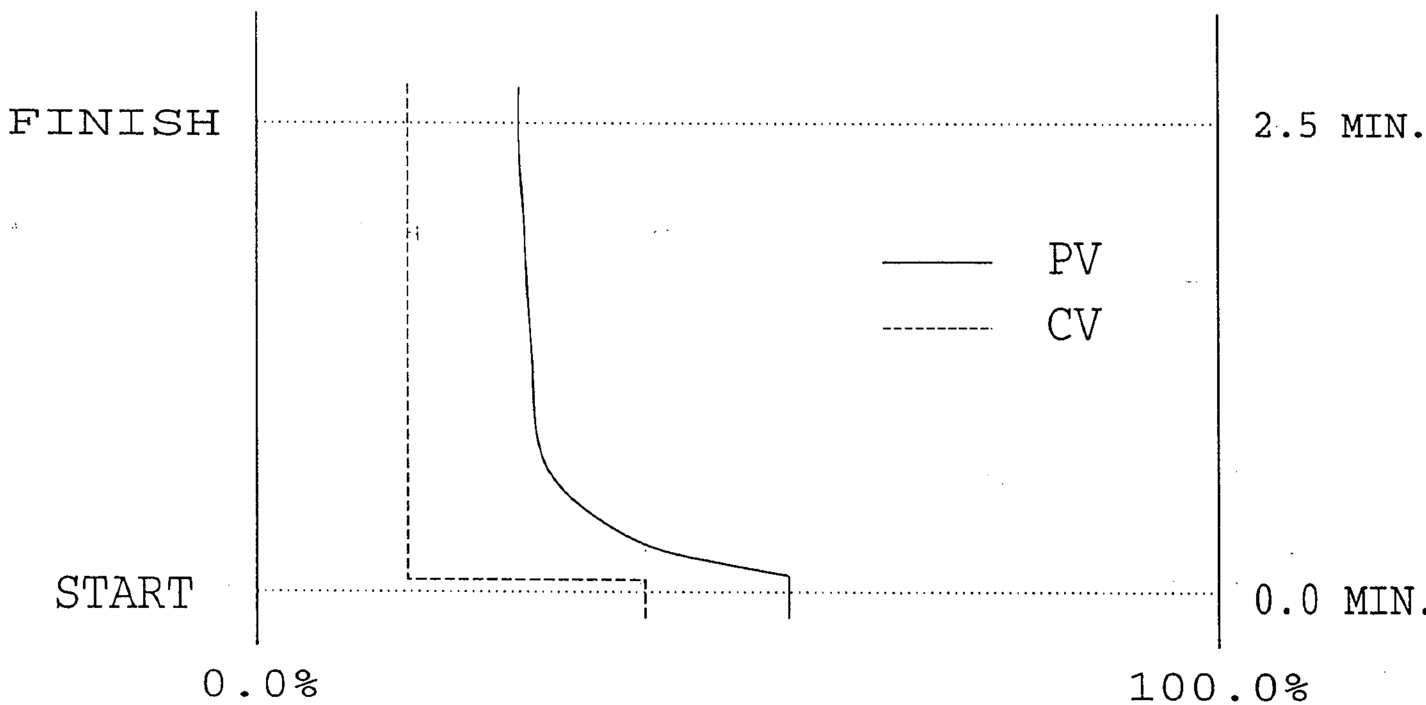


FIGURE 5.17
HWA SAMPLE TEST
THREE TANKS
SP: 3 to 1

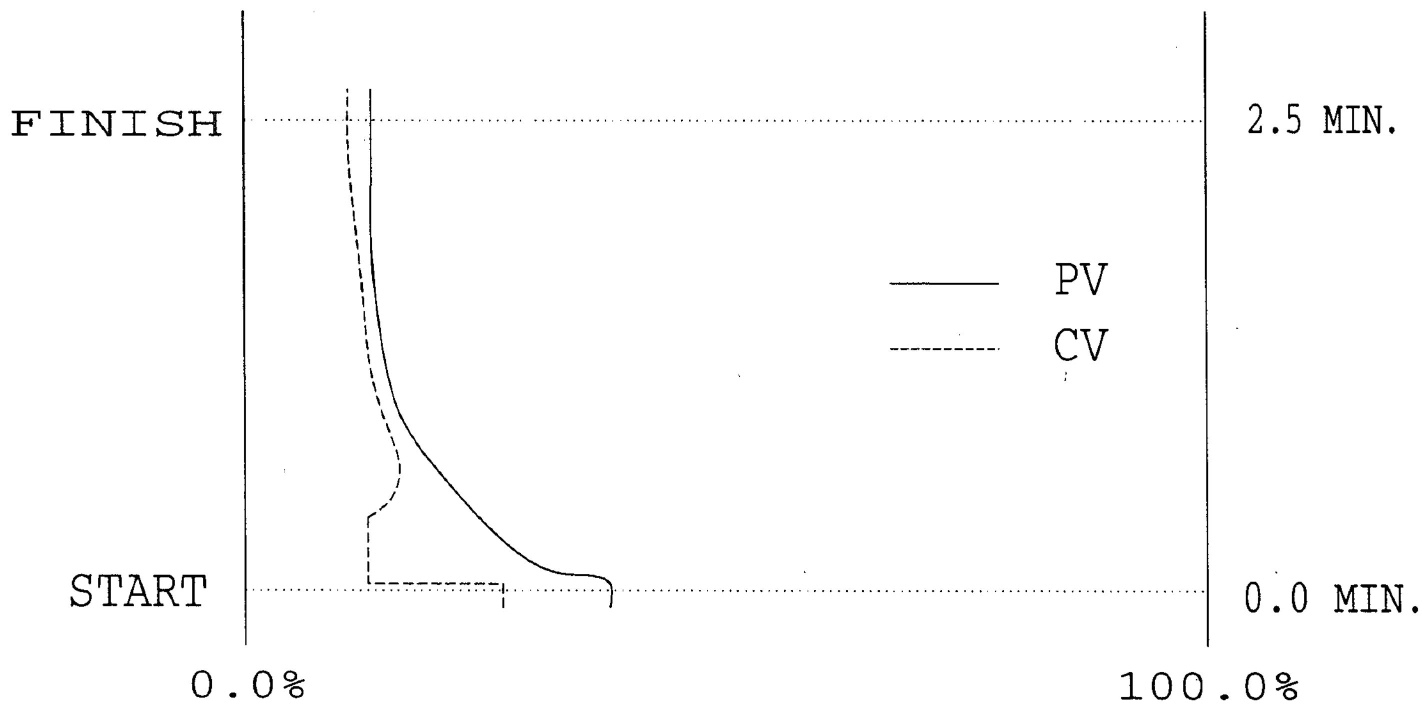


TABLE 5.7

HWA RESPONSE
TEST CONDITION THREE

	HWA RESPONSE
DELAY TIME (min.)	0.4
RISE TIME (min.)	1.8
TIME-TO-PEAK (min.)	1.8
MARGINAL OVERSHOOT (%)	0
SETTLING TIME (min.)	1.8

TABLE 5.8

HWC AND HWT RESPONSES
TEST CONDITION THREE

	HWC RESPONSE	HWT RESPONSE
DELAY TIME (min.)	0.08	0.1
RISE TIME (min.)	0.3	0.2
TIME-TO-PEAK (min.)	0.3	0.3
MARGINAL OVERSHOOT (%)	0	36
SETTLING TIME (min.)	0.3	0.5

Calculated T values, when applicable, range from 0.001 minutes to 0.058 minutes but usually stay within 0.010 minutes to 0.038 minutes. Calculated K values range from 0.47 to 2.13 but usually stay within 0.80 to 2.40. The calculated K values vary with starting and ending SP values. The peak values occur when one starts at an initial SP of two or three and ends at a final SP of three or four. The calculated gain then decreases with increasing or decreasing initial and final SP values. The lowest gains occur when one starts at the high initial set points and end at the high final set points.

T_i ranges from 0.06 minutes to 0.62 minutes but usually stays within 0.08 minutes to 0.42 minutes. Because of the calculated values of T_1, T, and K, G_c ranges from 0.8 to 7.4. From the above data and the equations of Section 2.1.1.2, it is inferred that the controller models the system in one of three different ways, $S_{31}(s)$, $S_{32}(s)$, or $S_{33}(s)$ For a first order lag without dead time

$$S_{31}(s) = \frac{0.83}{(0.89\,s + 1)(T_2\,s + 1)} \tag{77}$$

where $T_2 < 0.02$ minutes. For a first order lag with dead time

$$S_{32}(s) = \frac{1.15\,e^{-0.024s}}{0.39\,s + 1} \tag{78}$$

For a second order lag with dead time

$$S_{33}(s) = \frac{1.35\,e^{-0.011s}}{(0.11\,s + 1)(T_2\,s + 1)} \tag{79}$$

where $T_2 < 0.024$ minutes. The controller assigned to each system is, respectively

$$C_{31}(s) = \frac{7.2\,(0.02\,s + 1)}{0.02\,s} \tag{80}$$

$$C_{32}(s) = \frac{2.2\,(0.39\,s + 1)}{0.39\,s} \tag{81}$$

$$C_{33}(s) = \frac{1.7\,(0.11\,s + 1\,)}{0.11\,s} \tag{82}$$

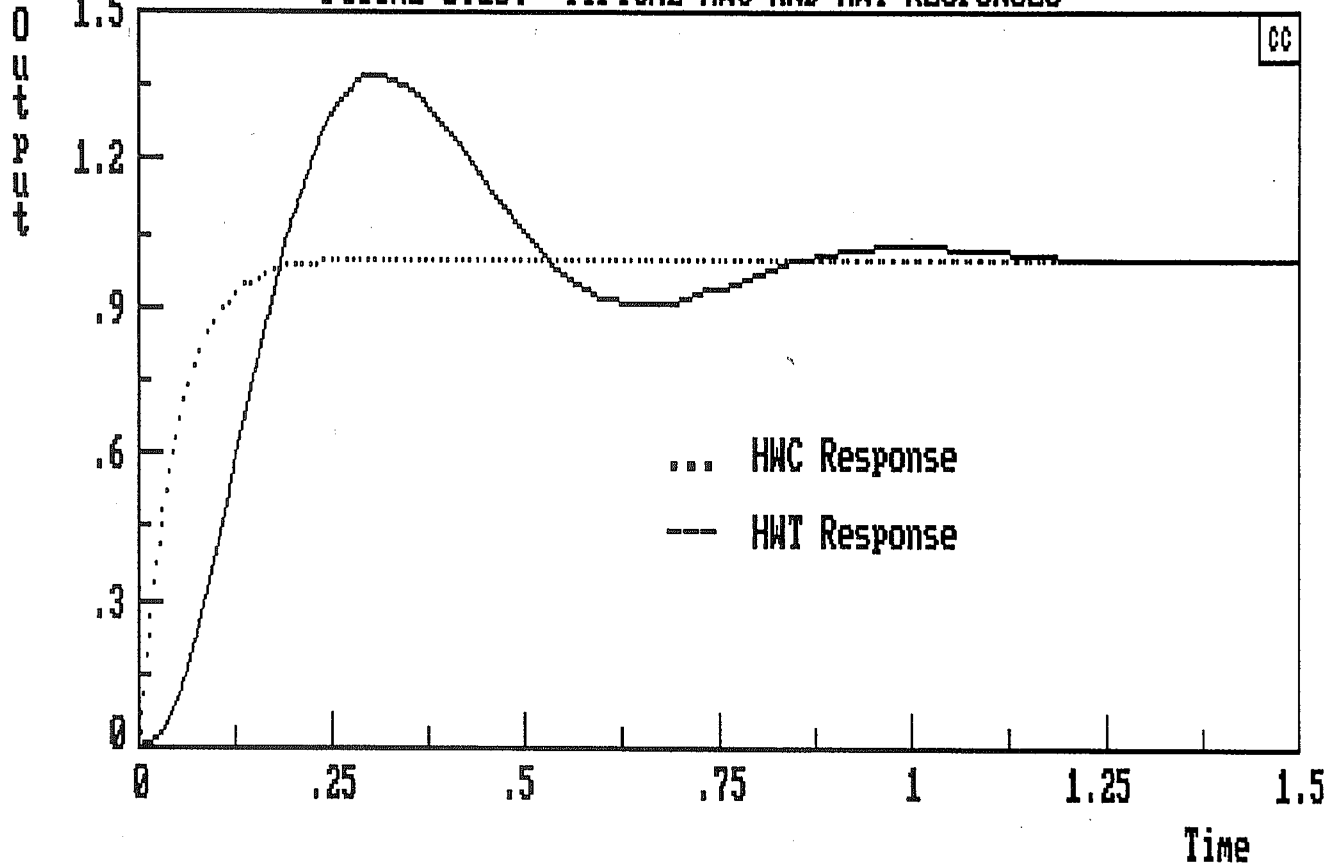
Figure 5.18 shows typical HWC and HWT responses and Table 5.8 summarizes the responses. On the average, the two sets of responses are not similar. This shows poor modeling. The HWC responses have no marginal overshoot. On the other hand, the HWT responses have an average of 36% marginal overshoot and a comparatively slow settling time.

5.3.2 Fischer and Porter Micro-DCI Results and Responses

The mode chosen for the Easy-Tune sequence in Test Condition Three is the same as in Test Condition One and Test Condition Two. The preliminary CO step size is configured to a 20% step increase for all tests. In addition, the preliminary PV step response limit is a 10% increase in PV, and t_1, is still fixed at a value of 5.00 minutes. In general, at the first attempt, all Easy-Tune sequences for Test Condition Three finish within three and one-half minutes. After the completion of the tuning sequences, the Micro-DCI models the system as a one lag and dead time system. The assigned dead time is fixed at 0.30 seconds. Tuning modifications are again necessary for successful test results.

The same problem arises in Test Condition Three as in Test Condition One Part 1 and Test Condition Two when SP change tests are performed. Again, modifications of the process parameters are implemented. All modification factors M_t, M_k, and M_w are changed to 0.1. As

FIGURE 5.18: TYPICAL HWC AND HWT RESPONSES



in Test Condition Two, this is not enough to stabilize the system for changing SP tests for tests with the high initial and final SP values, even for small SP changes. It is found, again, that the controllers chosen by the Micro-DCI for the tests with lower PV values are adequate to stabilize the system for all PV settings during these SP change tests. Stability using the controller is achieved for all tests, even those with extreme SP changes. The transfer function, $C_3(s)$, is

$$C_3(s) = 3.24\left(1 + \frac{1}{0.142\ s} + 0.036\ s\right) \tag{83}$$

The transfer function is obtained from a PV setting of 10.4% and CV at 10% open. Notice that $C_3(s)$ is a PID controller. In this case, the Micro-DCI considered W_p significant enough to add derivative control. PV line out with the above controller occurs within three minutes.

A typical FPA response is shown in Figure 5.19. Table 5.9 summarizes the average FPA results. The responses are slow in comparison to the HWA responses. In addition, there is a 6% overshoot and a slow settling time.

Figure 5.20 shows the FPC and FPT responses to Test Condition Three. The results are very similar to that of Test Condition Two in that the FPA response shows significantly more oscillation although the FPC response times are almost as small. Like Test Condition Three, a modification of 0.10 in the modification parameters results in slower delay time, but the rest of the time parameters are very similar. The real time response of the system with the Fischer and Porter controller shows more oscillation and maximum overshoot. The oscillations do fade away, though.

FIGURE 5.19

FPA SAMPLE TEST

THREE TANKS

SP: 2 to 7

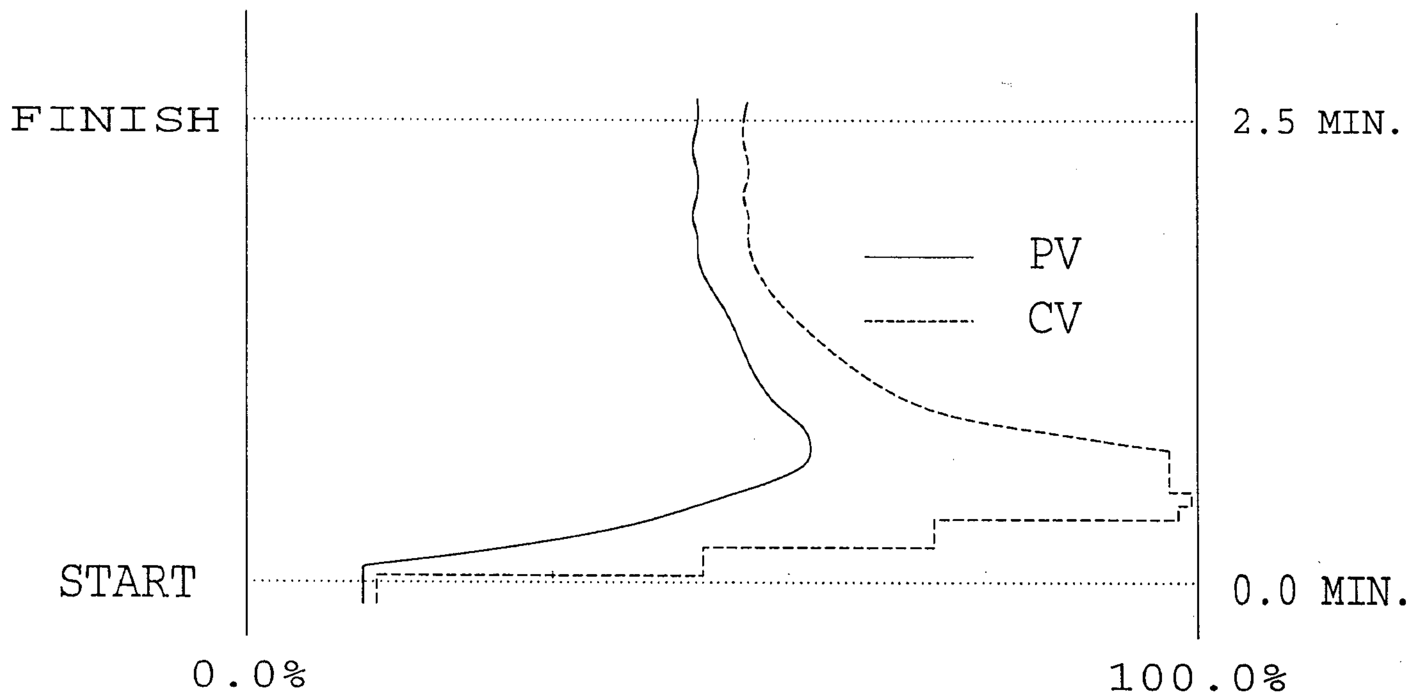


TABLE 5.9

FPA RESPONSE
TEST CONDITION THREE

	FPA RESPONSE
DELAY TIME (min.)	0.3
RISE TIME (min.)	0.8
TIME-TO-PEAK (min.)	2
MARGINAL OVERSHOOT (%)	6
SETTLING TIME (min.)	2

CHAPTER SIX

DISCUSSION AND CONCLUSIONS

This is the final chapter. It includes a discussion of the actual system It also includes observations and conclusions about the performance of the Honeywell UDC 6000 Modular Controller and the Fischer and Porter Micro-DCI Modular Controller. In addition, capabilities of the controllers regarding their performance in factory or academic conditions are briefly discussed. This also includes remarks about both their operational uses and performances. Lastly, comments are made as far as recommendations and predictions in hopes of improvement and effective implementation of these controllers for future use.

6.1 The General Testing System

A few comments are necessary regarding the general system. First of all, there were inconsistencies in all three test conditions. For example, results tests performed only to determine system parameters and characteristics without the aid of the controllers were sometimes not repetitive. For instance, the same CV values would yield different PV values at different times. Second, Tanks A, B, and C may have been too small for the particular system. The tube resistances seemed to have a greater limiting effect than the needle valves themselves.

Whereas the needle valves used were assumed to be identical, this assumption cannot be validated. The only certainty was that any one valve could block all air to the rest of the system when this was required. In other words, turning the needle valve completely to the right signified that the valve was completely closed. Turning the valve completely to the left, however, did not guarantee that it was completely open, or even to be as open as the other needle valves were with the same setting. In short, there may have been inconsistencies in the operation of the needle valves.

6.2 The Honeywell UDC 6000 Process Controller

The Honeywell UDC 6000 Process Controller is capable of identifying systems with two lags and dead time. It was demonstrated that the Honeywell controller was reliable in modeling the system in Test Condition One. The results of SP change tests for this test condition, though, were not repeatable. Different values of system lag and gain were obtained for repeated tests. On the average, however, the controller determined the system lag to within 15% error, and the system gain to within 20% error. On the other hand, the PV change tests were consistent but, on the average, the controller had 20% and 25% error when determining the system lag and gain, respectively.

The tests from Test Condition Two showed that the Honeywell controller modeled a second order system without dead time correctly for only half the tests. For these tests, only the secondary lag was determined correctly. The controller did not recognize the primary lag. However, it was recognized when the system was modeled as first order with dead time. Here, though, the sum of the determined time constants exceeded that of the actual value by double the amount.

It is believed that the approximations of third order system modeling is somewhat weak. The Honeywell controller modeled a third order system as either a two lag system without dead time or even a one or two lag process with dead time. The closed-loop HWC responses of all three models show little similarity to those of the HWT responses.

Whatever inadequacies the Honeywell controller has in modeling, it certainly compensates with control tuning. For all tests, the Honeywell controller brings PV to the desired SP quickly with little or no overshoot. In addition, the PV Adapt responds immediately to any process changes so that any deviation from SP is always negligible.

According to Equation (19), for first order systems without dead time, the product of the controller gain and the system gain is supposed to be 24. In almost all Honeywell tests, however, it is found that the product is 23. On one set of tests, it was found to be 101.

Sometime the controller is halted at a certain CV value and the PV value no longer moves toward SP. When this lock occurs, the Automatic/ Manual button can be pressed, and one of two things happens: (1) PV Adapt takes over and CV starts to move again; or (2) CV jumps an increment according to the G_c assigned at the moment. Here, the operator has a choice of pressing the A/M button until PV Adapt resumes tuning or pressing the A/M button until CV is at the level at which SP can eventually be reached (if PV Adapt has not occurred first).

6.3 The Fischer and Porter Micro-DCI Modular Controller

The ability to model first order system and determine the system's parameters are within the capability of the Fischer and Porter Micro-DCI Controller. This conclusion is drawn from the small differences in gain and capacitance calculated by the controller and that by hand calculations. In fact, the modeling appears almost perfect. The second and third order system approximation were almost as good. However, as noted in Chapter 6, no PID controller was found to stabilize the system in Test Condition Three for applied SP or PV change tests. Changes in modification tuning did not improve the situation for this test condition.

It is conjectured that the characteristics of the applied ITAE Method for tuning might have contributed to the problem. ITAE, by nature, weighs large initial errors in a step response very lightly but weighs errors occurring later in the transient response very heavily. In the extreme, it would mean that the chosen PID (or PI in this case) controller did not compensate enough for the difference in SP in the beginning of the test. Because of this, errors in the step response down the line are magnified. Such errors thus become heavily weighted, and overcompensation takes place to try to remedy the situation. This overcompensation is what causes CV to oscillate with large amplitude and later even increase these factors until the whole system becomes entirely unstable, even for the smallest changes in SP. To add to this, the Fischer and Porter tries to match PV to SP up to 4 significant digits, meaning up to 0.01% of the total PV span.

For Test Conditions Two and Three, it is noted that, with specific tuning modifications, the system reacts fast enough for the initial undercompensation to bring PV closer to SP. The remaining errors that come about later in the transient response are no longer as great. Even though such later errors are weighed much more heavily, they are of much lesser magnitude so the system becomes stable.

One drawback to the Easy-Tune process is that the system characteristics must be known ahead of time for the tuning to be effective. For example, the CO step size must be set large enough so that PV will be able to rise to the preliminary PV step response limit within time t_s. Otherwise the process will be aborted. Also, the preliminary PV step response limit must be set high enough so that the system will be able to return to (or close to) its original PV value within a time period that is twenty times that of the previous step. However, if it is set too high, PV will not be able to reach the preliminary PV step response limit. Furthermore, if the CO step size is too large, PV in step four of the sequence will not line out in acceptable time and the Easy-Tune Sequence will be aborted. Even if the sequence is complete, it does not guarantee that the resulting controller transfer function will result in a stable system. If, however, the system has not been stabilized, additional manipulation of tuning will be necessary. One can see that much initial trial and error is needed for a successful tuning sequence.

It is observed that most tuning sequences should be performed at a system setting whose PV value is in the lower 20% of its total span. The resulting controller transfer function is adequate enough to tune the system for all system settings, although the further away the settings are from the original settings, the longer the time to line out and the greater the oscillation in between.

6.4 Controller Operational Performance

In a comparison of their operation, the two controllers have their respective advantages and disadvantages. The Honeywell UDC 6000 Process Controller is excellent in that all one has to do is activate it. From then on, self-tuning is a continuous process and line out occurs quickly compared to the Fischer and Porter controller. The Fischer and Porter Micro-DCI

Modular Controller has no such capability.

The major disadvantage of the Honeywell controller is that it does not model systems as well as the Fischer and Porter controller. Also, the Honeywell controller does not display all calculated tuning parameters, which makes it difficult to analyze. The Fischer and Porter controller is capable of displaying all calculated and operator set values, although it is cumbersome and inconvenient to read these values unless the compatible Fischer and Porter Hand-Held Configurer is also used. As far as display capabilities are concerned, the Honeywell controller has one display screen which shows PV, CV, and SP. The Fischer and Porter has several display screens, including a screen which monitors PV against time.

Another point worth notice is the relative ease of becoming acquainted with and operating the controllers. The Honeywell controller was much easier to learn how to use. Its manual was much more understandable. The Fischer and Porter, on the other hand, was less well organized and edited. It was more difficult to learn to use its controller. However, after mastering their use, both controllers were easy to use.

The Micro-DCI had many more operator-controlled options. This was both a blessing and a curse, depending upon the operator's knowledge of the working system and of the controller. Although the UDC 6000 had fewer operator-controlled options, everything appeared simple and straightforward.

It can be said that the Honeywell UDC 6000 Process Controller can be used by novices in controller use and also by non-experts in control theory. But for the Fischer and Porter Micro-DCI Modular Controller, it is recommended that only those acquainted with the controllers and familiar with control theory attempt to use it. For systems with process changes and whose PV must stay near SP, UDC 6000 is highly recommended.

6.5 Recommendations for the Future

For undergraduate studies of controllers, it is recommended that the Honeywell Controller be given first priority. Then, if time permits, experiments using the Fischer and Porter Controller can be carried out.

A recommendation for both studies is to use a first order system. The tank should be of a size between that of the smallest and largest tanks. Because of the complexity of the experiment, it is highly recommended that students be closely supervised. Ideally, student background ought to include some theoretical knowledge of modeling of a system with given system parameters. Also a carefully organized operation manual will be very helpful.

For more advanced laboratory work, a system of different size tanks is recommended. They should be connected together to create a system whose lags can be readily differentiated from each other. With this, a detailed investigation of the controller capabilities and responses can be performed. All tanks should be larger than each of Tanks A, B, and C, but none larger than Tank D. A combination of tank sizes and numbers would definitely enhance the study.

After the completion of the suggested experiments and the acquisition of expertise, it is possible to design additional experiments where regulated PV is used as a source of steady air pressure.

A recommendation for both undergraduate and graduate study is that a computer should be connected to the system for easy, quick and more precise analysis. Use of Program CC on site could be very beneficial.

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6. Rosemount Model 3311 Current-to-Pressure Transducer. Rosemount, Inc., Eden Prairie, MN., 1990.

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APPENDIX I

UNDERGRADUATE STUDY

This appendix is divided into three sections. The first section describes a laboratory experiment for the cross-listed course ME/EE/ChE 389, carried out in the Interdisciplinary Controls Laboratory. Purpose, results, and conclusions of the experiment are discussed. The second section proposes an experiment for further undergraduate studies in the same course. This section deals with the general test set up, the set of tests to be performed, and required data. The third and final section is a tutorial designed for students who will be working with the proposed experiment of section two. All necessary information of how to operate the control system is provided.

I.1 ME 3: ME/EE/ChE 389 Experiment

I.1.1 Purpose

The purpose of the undergraduate experiment, as performed in the controls laboratory in Spring 1992, was to compare the tuning capabilities of the Honeywell UDC 6000 Process Controller to that of the Ziegler-Nichols tuning method. (The Fischer and Porter Micro-DCI Modular Controller was not used because it was not operational at the time.) The comparison was based upon a series of set point change tests. In these tests, the Honeywell controller was supposed to have shown that its automatic self-tuning capabilities were equal to, or better than that of a manually calculated tuning procedure. The closed-loop responses of the controller transfer functions of both Honeywell and Ziegler-Nichols tests were evaluated by program CC.

I.1.2 Experimental Apparatus and Procedure

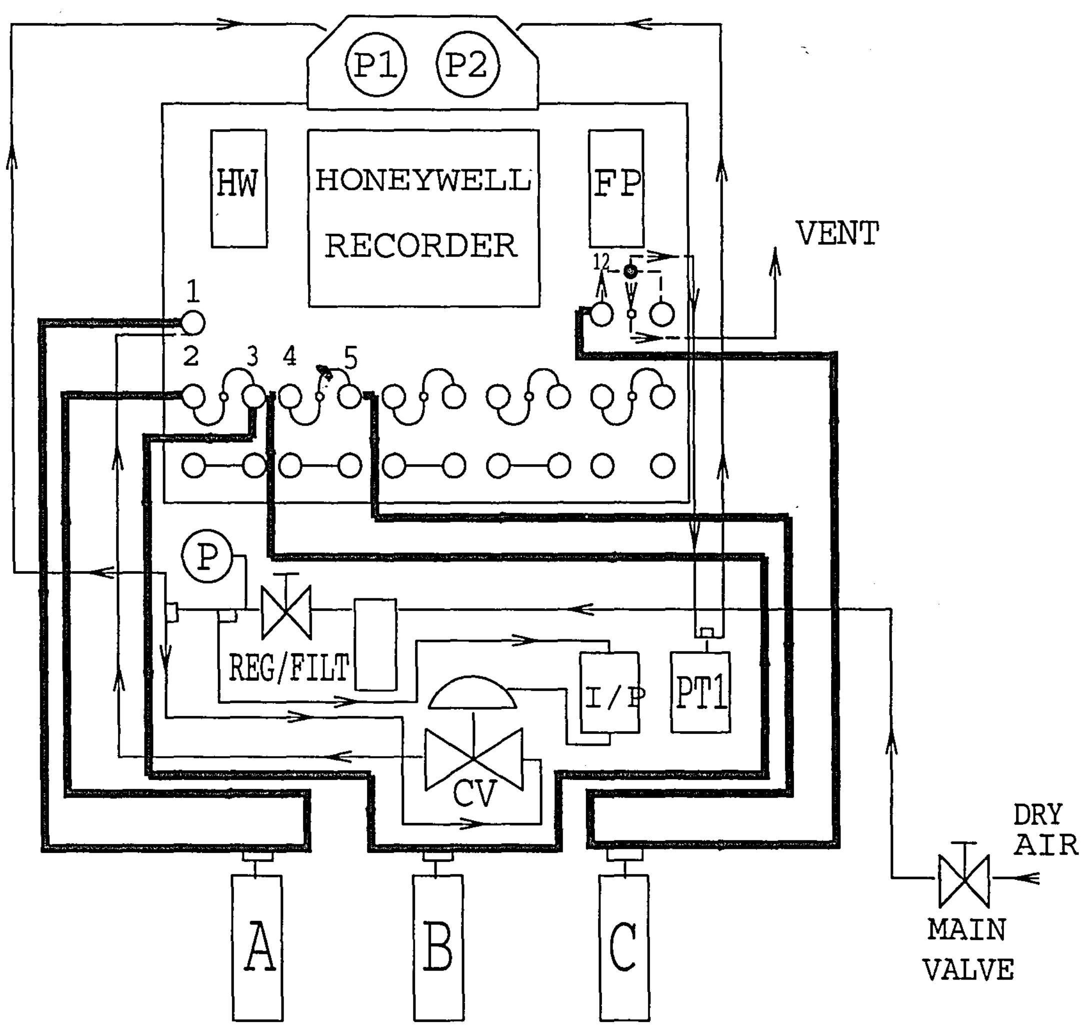
The lab set up was that of Test Condition Three (Figure I.1) where the three 1 l air tanks are connected in series. Here, no needle valves settings are changed throughout the duration of the experiment, their settings being chosen by the students.

The students were told to model the system and find the system parameters, given that each tank was a first order system without dead time. They could assume that all three tanks were identical, and had identical process characteristics. One tank was connected to the control system. Using the Honeywell controller in the manual control, the control output (the control valve) was varied by students upward or downward via this control valve. The one tank system responded in accordance with the step input. The system response was recorded by the Honeywell DPR 3000 Strip Chart Recorder. After line out, the students calculated the gain and time lag of the system. Some students determined the gain and lag for all three tanks.

After mathematically modeling the original three tank system, the experimental gains and lags were incorporated into the derived system transfer function. The theoretical system response was obtained by using program CC. The overall delay and time constant were approximated from plots generated from CC. From these process parameters, a controller was chosen for the system using the Ziegler-Nichols method of tuning. Note that CC was used partly because there was some difficulty in obtaining Honeywell recorder readings. However, some students chose not to use CC and obtained data directly from the strip chart recorder to ensure accuracy.

The calculated tuning parameters were put into the controller. Set point change tests

FIGURE I.1
EXPERIMENTAL APPARATUS



were run using the Ziegler-Nichols parameters. The resulting system responses were recorded. Next, The Honeywell Adaptive Tune process was activated, and the same set point change tests were run. The tuning parameters assigned by the Honeywell controller were recorded along with the system response. Using program CC, the results were analyzed.

I.1.3 Results

There were five student groups. For three of them, it was discovered after the completion of the experiments that the Honeywell Controller was dysfunctional.

For the two groups with a working controller, all Adaptive Tune SP change tests were successfully completed. Only one lab group understood the purpose and basics of the experiment, and the conclusions drawn from the available data from this group showed that the Adaptive Tune, when working properly, performed as well as or better than the Ziegler-Nichols tuning.

Overall, the students did not realize or understand that the Honeywell SP Adapt algorithm identifies the system while it brings the process variable to line out. They did not understand that the controller only assigns tuning parameters at the time of line out. They thought that the controller used these tuning parameters to tune the system from the beginning of SP Adapt.

Student Groups D and E were working with a functioning controller. The average gain was 1.0 and the average time constant was 0.18 minutes for a single tank. For the approximation of the three tank system as a first order system, the average time delay was 0.10 minute and the average lag 1.23 minutes. The assigned control parameters are shown in Table I.1. On the average, the Honeywell controller had a controller gain of 2.1, a reset time of 0.14 minutes, no rate time, and a calculated system gain of 1.52. These values are in

TABLE I.1

AVERAGE TUNING PARAMETERS

	HWT PID	Z-N PI	Z-N PID
P CONTROL	2.1	12.3	14.8
I CONTROL (min.)	0.14	0.33	0.2
D CONTROL (min.)	0	0	0.05

TABLE I.2

HWT AND Z-N RESPONSES

	HWT RESPONSE	Z-N RESPONSE
DELAY TIME (min.)	0.1	0.05
RISE TIME (min.)	0.18	0.07
TIME-TO-PEAK (min.)	0.29	0.11
MARGINAL OVERSHOOT (%)	30	68
SETTLING TIME (min.)	0.84	1.3

reasonable agreement with both sets of equations (23), (24), and (25) and equations (25), (26), and (27). This shows that the Honeywell controller did model the system with one or two lags and dead time.

Neither of the two lab groups with working controllers submitted reliable results of the system responses for the Honeywell controller's Set Point Adapt and the Ziegler-Nichols tuning. The theoretical system responses of both methods of tuning are shown in Figure I.2. Here, one can see that, although the Honeywell system reacts slowly at first, the Adaptive Tune method provides a quicker overall response with half the marginal overshoot of the Ziegler-Nichols method of tuning.

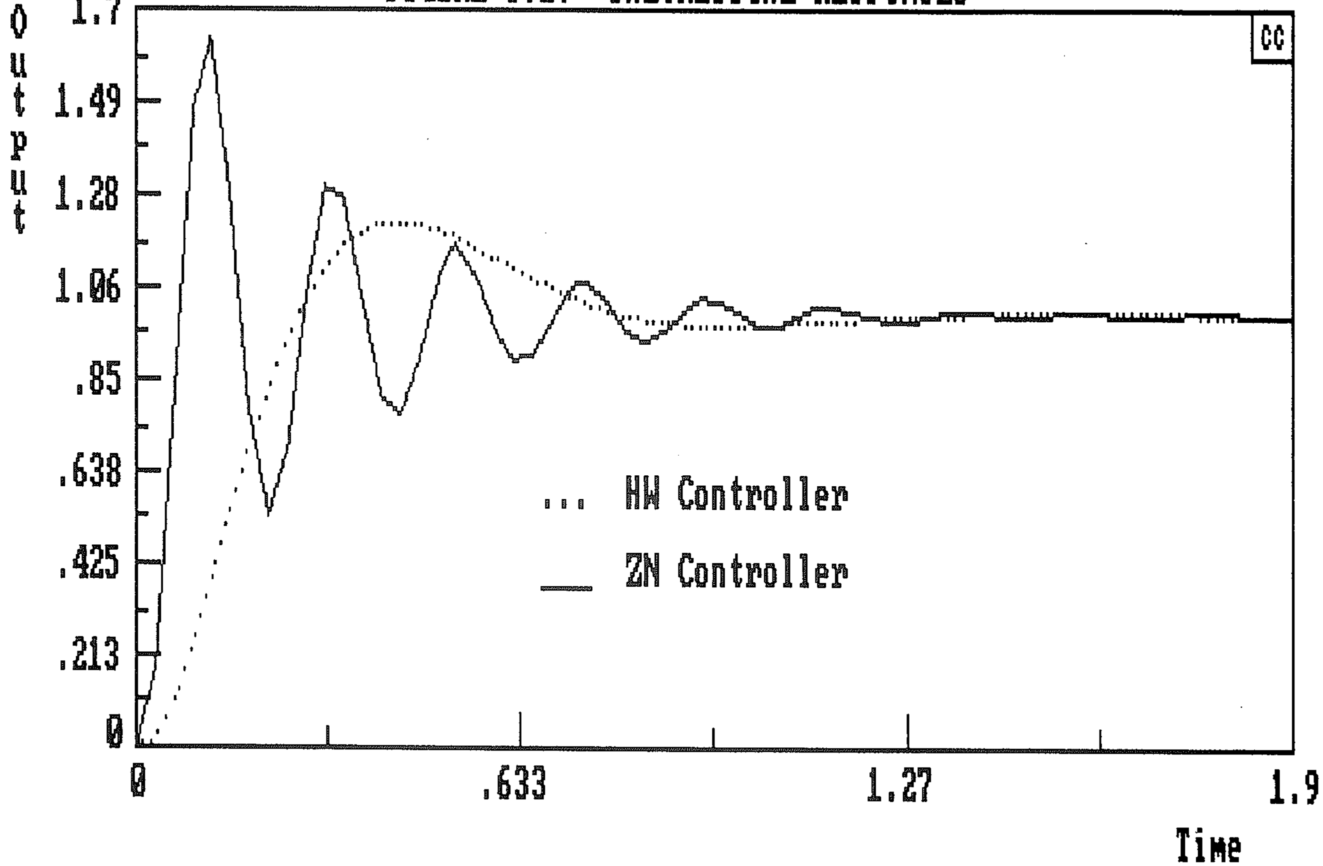
I.1.4 Conclusions

With a functioning controller, the UDC 6000 proved to be a better controller than Ziegler-Nichols, at least in its theoretical time response. This means that the SP Adapt modeled the system more accurately, as it should. We note here that the Ziegler-Nichols method can only model a system as a one lag and dead time plant, while the Honeywell controller is capable of two lags and dead time.

I.2 Proposed Experiment

The students who were assigned the laboratory experiment had difficulty understanding it and completing it within the given time. Another difficulty was determining the process parameters. In light of this, a new experiment is proposed that will be easier for the students to understand and perform. The experiment can be performed easily in six hours.

FIGURE 1.2: THEORETICAL RESPONSES



I.2.1 Purpose

The purpose of the proposed experiment is to become acquainted with and investigate the operation of an adaptive self-tuning controller - the Honeywell UDC 6000 Process Controller. Both Set Point Adapt and Process Variable Adapt modes of the Honeywell's Adaptive Tune are to be examined. This will be done by comparing the SP and PV adapt capabilities with that of a controller chosen by the students. The basis for the comparison will be SP and PV tests performed on controllers. The system includes an 11 liter tank, a first order system with no dead time.

I.2.2 Theory

The self-tuning algorithm for the Honeywell UDC 6000 Process Controller is called Adaptive Tune. It is based upon the Honeywell Adaptive Control Method. In general, this method fits a transfer function to the process under control and selects the best available tuning algorithm on the basis of that transfer function and tunes the Honeywell controller appropriately. During initialization of Adaptive Tune (or whenever the set point changes), time domain analysis is used to accelerate process variable line out. It does this by adjusting the control output to a step value that will cause a quick change in the process variable. The change results from initial controller-approximated process characteristics, and is not large enough to cause overshoot. As the process variable approaches set point, the controller decreases the control output change and accurately calculates the process parameters. It also assigns appropriate tuning parameters. All this is accomplished by the controller automatically without any prior knowledge of the system. This mode of Adaptive Tune is called SP Adapt. When process changes occur after line out, the PV Adapt mode of Adaptive Tune is activated. Here, the controller uses frequency analysis to return the process variable to line out.

Adaptive Tune does not introduce process disturbances. Also, the method allows the controller to make any necessary retuning adjustments for process disturbances which cause a deviation of at least 5% from set point. It continues tuning until the deviation reduced to 0.3%. It should be noted that this method is not applicable to processes that are not type zero.

The Honeywell Adaptive Control Method assumes a process of up to two lags with or without dead time. If the process is not of the above types, the Adaptive Tune chooses the best combination of lags and dead time to approximate a transfer function for the system. In this experiment, the controller should identify the process as a first order system with small or no dead time. This process of identifying and assigning of tuning parameters is called Set Point (SP) Adapt. System identification should take place within a time period less than one-third of the sum of its time constants. Following this process, the resulting controller is then assigned to the system.

The Adaptive Tune procedure begins when the operator manually adjusts the process variable, PV, to a value about ten percent of its range or the next closest allowable value. After the set point is chosen by the operator, he or she activates the automatic control. As will be explained below, the controller uses data from the previous adjustment to calculate the necessary output value to bring the process variable, PV, to the set point. The controller then begins collecting data as the controller output steps to the appropriate value.

Note that when a set point (SP) change greater than 5% of the process variable (PV) range occurs, the controller automatically begins SP Adapt (assuming, of course, that Adaptive Tune is engaged. The controller, then, changes to manual control to effect a CO step increase. Once PV approaches line out, the controller switches back to automatic control and continues its calculations.

The time it takes for the process variable to start changing after the output step change is referred to as the "dead time." The controller measures this reaction time. If there is an immediate increase in PV, the controller sets the dead time to zero. If there is no immediate increase, the controller determines the dead time by measuring the time it takes for PV to increase by a small increment after the step change takes place. (This increment is chosen by the controller.)

The controller measures the rate of increase of PV after the beginning of its rise. If this slope is continuously decreasing from the start, the controller assumes the plant is a single-lag process. The controller also takes measurements, PV_1 and PV_2, during the rise along with the slopes, PV_1' and PV_2', at the respective points. The process time constant, T_1, and the steady state gain, K, are given by

$$T_1 = \frac{(PV_2 - PV_1)}{(PV_1' - PV_2')} \qquad \text{-1-}$$

$$K = \frac{(PV_2 + PV_2' T_1)}{CO} \qquad \text{-2-}$$

where CO is the output step size of the controller.

The determined controller transfer function C(s) is of that form of a PID controller with real zeros

$$C(s) = G_c \frac{(sT_i + 1)(sT_d + 1)}{sT_i(0.25sT_d + 1)} \qquad \text{-3-}$$

where G_c is the controller gain.

The controller tuning algorithm uses pole cancellation in processes without dead time. The Honeywell controller models a process without dead time in accordance with the following relation

$$P(s) = \frac{K}{(sT_1 + 1)(sT_2 + 1)} \qquad \text{-4-}$$

with $T_1 > T_2$. The poles in the process equation are canceled by the zeros of the PID transfer function. The controller P(s) is assigned only at the end of the SP Adapt process.

For a one lag process, $T_2 = 0$ and the variables in Equation (-3-) take on the values

$$T_i = 0.16\ T_1 \qquad \text{-5-}$$

$$T_d = 0.0 \qquad \text{-6-}$$

$$G_c = \frac{23}{K} \qquad \text{-7-}$$

Note that these tuning parameters are assigned only as line out occurs during SP Adapt. After the process parameters have been identified, the controller goes through a series of control operations that are supposed to bring PV to line out as quickly as possible without any overshoot.

In many instances, after the process identification and initial self tuning, a process change may alter the system, i.e. change in dead time, process gain or time constants. Using frequency response analysis, the Honeywell Adaptive Control Method can compensate for such changes. Under SP and PV Adapt, the controller analyzes a frequency notch which is determined under SP Adapt mode.

Let

$$T_i = \text{reset time}$$

$$\omega_i = \frac{1}{T_i}$$

$$T_d = \text{derivative time}$$

$$\omega_i = \frac{1}{T_d}$$

If the system changes so that PV oscillates at a frequency, ω_O, two possibilities arise. One case is when $\omega_O \leq \omega_i$. In this case, the controller shifts its frequency notch so that

$$\omega_i = \frac{1}{T_i} = \frac{\omega_O}{2} \qquad \text{-8-}$$

In the other case, when $\omega_o > \omega_i$, the controller will shift its frequency notch so that

$$\omega_d = \frac{1}{T_d} = \omega_o \qquad \text{-9-}$$

If oscillation continues, the controller will divide the gain by two. For the oscillation compensation method, the controller notch stays within the same width as that determined during the SP Adapt.

If the system changes so that PV undergoes a damped oscillation at a frequency ω_o the controller notch is shifted so that

$$\omega_d = \frac{1}{T_d} = \omega_o \qquad \text{-10-}$$

Again, the same controller range as that determined during the set point adapt mode is maintained.

As mentioned before, the expected time to line out takes place in less than time t, where

$$t < \frac{T + T_1 + T_2}{3} \qquad \text{-11-}$$

where T is dead time. If, however, the event occurs at

$$t > (T + T_1 + T_2) \qquad \text{-12-}$$

the controller will shift to a higher frequency notch. It will multiply both ω_i and ω_d by a factor of 1.3.

Another scenario is when the process gain changes but PV must be maintained at the same set point. The new process gain then becomes

$$K_n = K_o \frac{CO_o}{CO_n} \qquad \text{-13-}$$

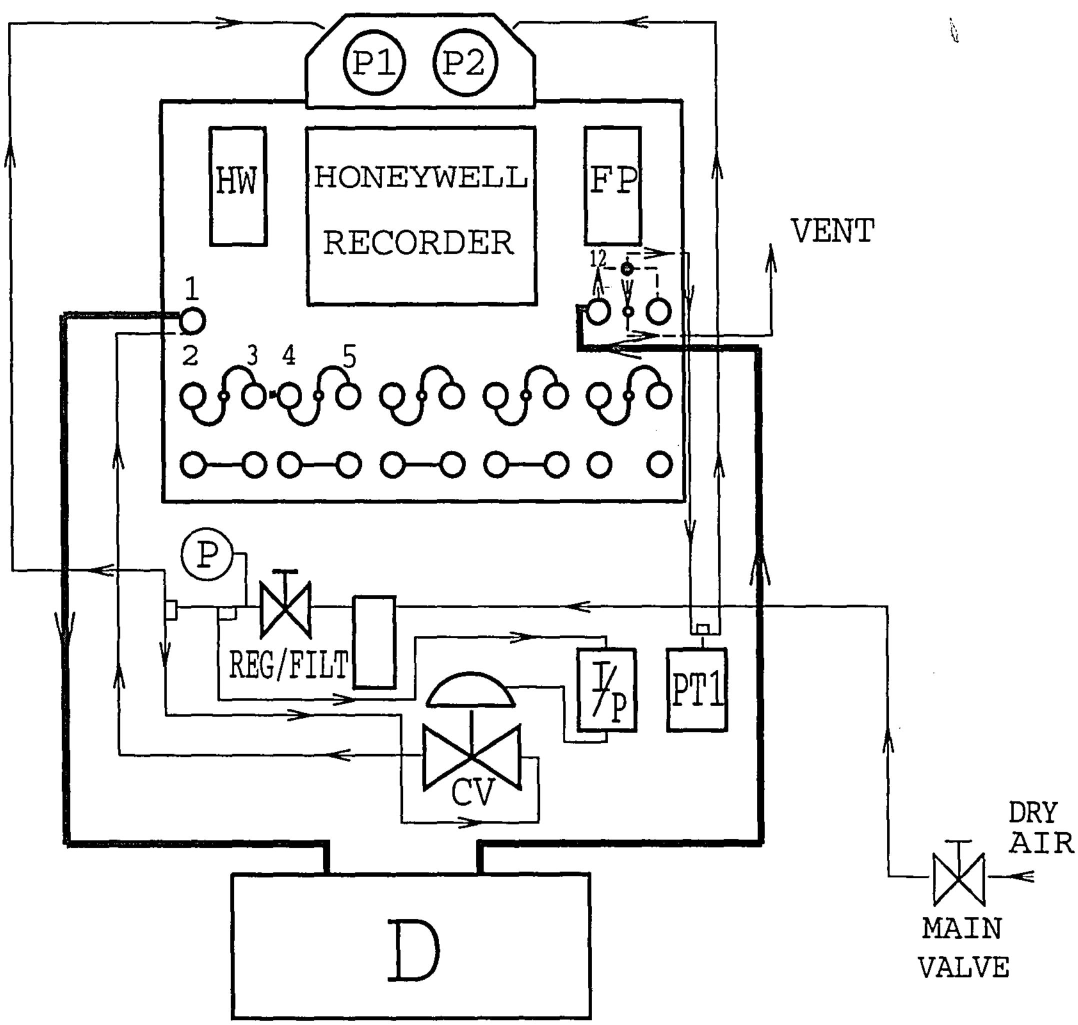
where K_n is the new process gain, K_o is the old process gain, CO_o is the old controller output step size and CO_n is the new controller output step size.

I.2.3 Experimental Apparatus

The experimental apparatus of the proposed experiment is that of Test Condition One where one tank is connected to the system, Figure I.3. The plant is a pressurized air system in which the pneumatic control valve modulates the process fluid directly. A needle valve is located after the tank and is to be fixed for SP change tests at a reading of 1.75 units. A

FIGURE I.3

PROPOSED EXPERIMENTAL APPARATUS



control valve CV located before the tank regulates the amount of air through the system. The controller manipulates the system pressure via the control valve. A Rosemount Alphaline Model 1151AP Gage Pressure Transmitter transmits the reading of the exit air pressure (that is, the air pressure preceding the last needle valve) to the controller.

The source of pressure is dry air supplied by an Ingersoll Rand 689.5 kPa compressor and dried by a separate air dryer. A regulator and pressure gage combination is positioned at the inlet to the overall system and maintains the pressure source of 103.4 kPa. ***The regulator is not to be touched for fear of overloading the Rosemount pressure transducer!*** A filter and trap, immediately following the regulator, keep out particles and prevent any moisture from entering the system. A Honeywell DPR 3000 250 mm Strip Chart Recorder continuously records the pressure exiting the tank and also the control valve position signal. A Rosemount Current-to-Pressure Transducer Model 3311 receives a 4 to 20 ma electrical input from the working controller and sends a 20.685 to 82.740 kPa pneumatic output to actuate the control valve. As a check, the pressure gages P1 and P2 are positioned to monitor the inlet and exit air pressures. Finally, tubing with a 6.35 mm outer diameter tubing with a 0.889 mm wall is used to connect the tanks.

The tubing is connected to fittings via Swagelok Quick Connects. The recorder and the controllers are mounted on a 0.80 m x 0.584 m vertical panel. The rest of the system (minus the compressor, the air dryer and the largest pressure vessel) is mounted on a separate support, which also supports the vertical panel. The system altogether is 0.80 m wide and stands 1.83 m tall (Figure I.4).

The block diagram of the control system of the proposed experiment is shown in Figure I.5. The plant is a single tank that should be modeled, for simplicity, with a lag of 1.45 minutes. The gain of the system should be modeled to vary with the needle valve settings

FIGURE I.4

EXPERIMENTAL APPARATUS

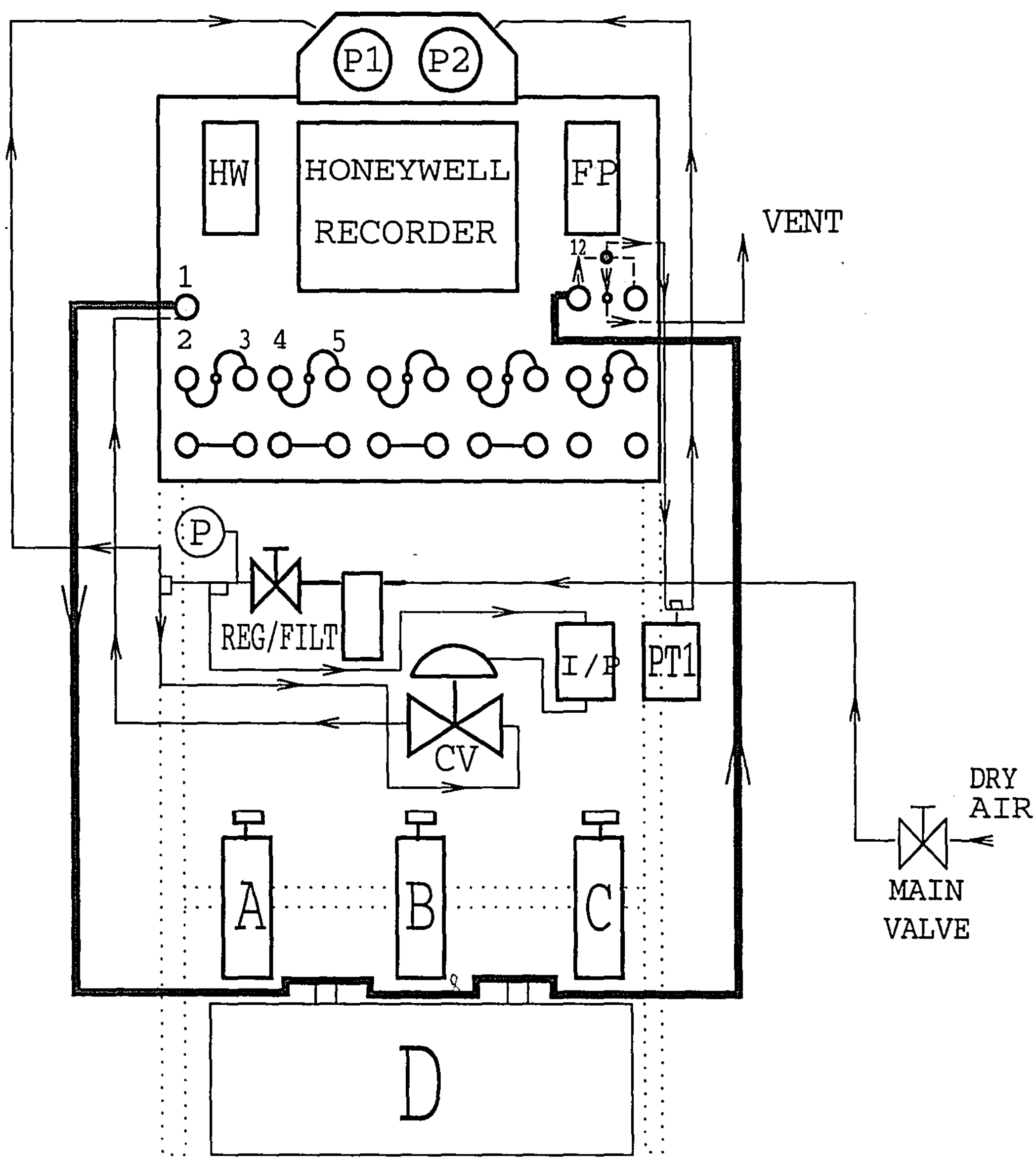
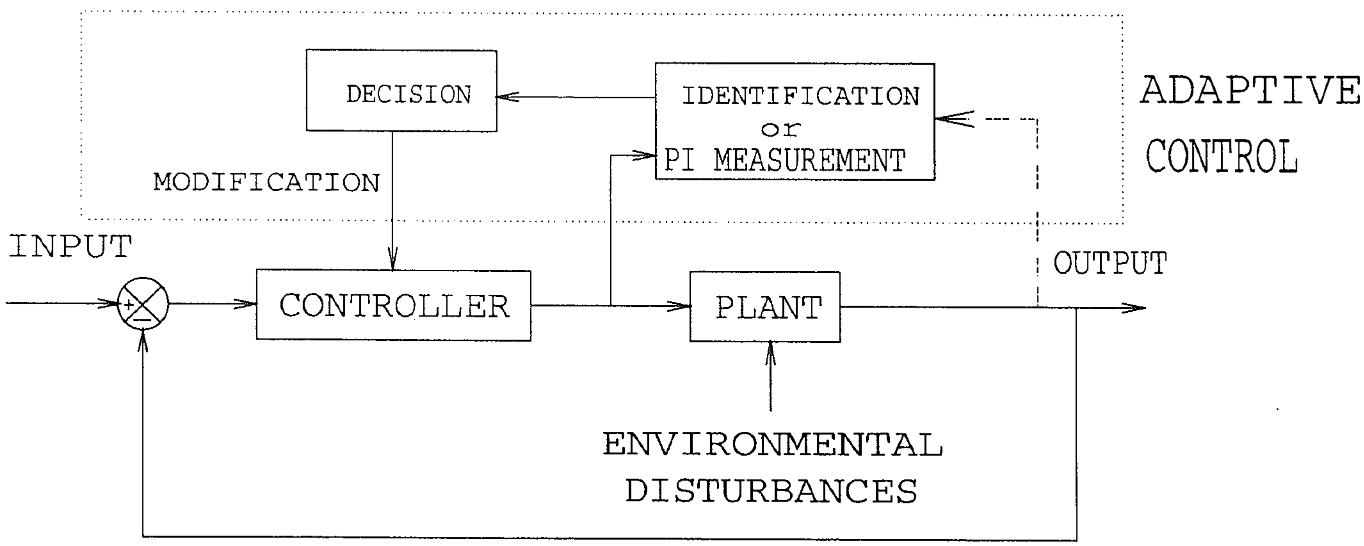


FIGURE I.5

CONTROL SYSTEM

BLOCK DIAGRAM



(Figure I.6). The tuning parameters are those determined by either the Honeywell controller or chosen by the students. A step input from the control valve (CV) activates the system. The controlled or process variable (PV) is the air pressure at the tank exit or that upstream of the needle valve. The Rosemount pressure transducer provides the feedback signal.

I.2.4 Experimental Procedure

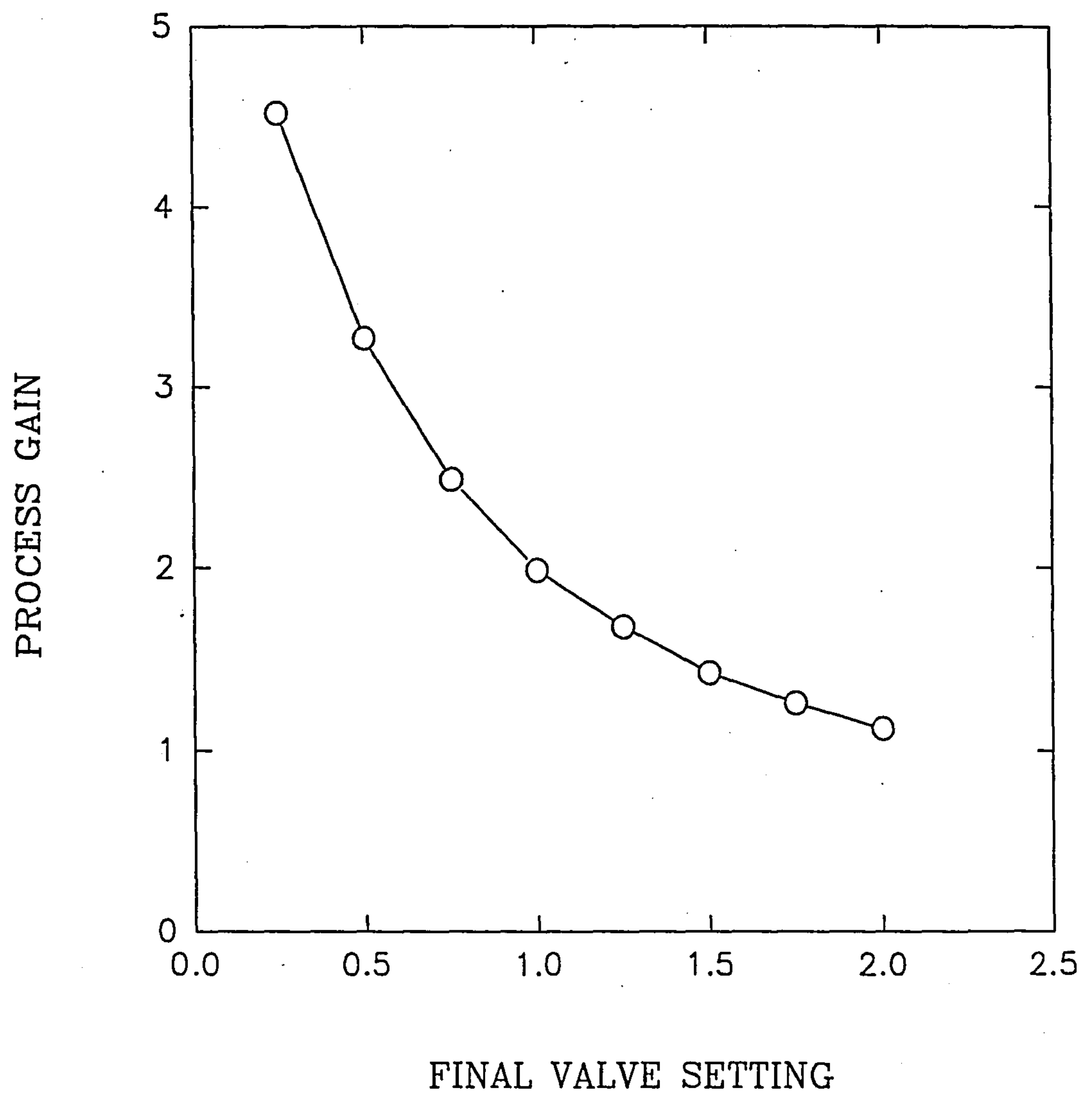
It is recommended that the students become familiar with this chapter prior to the first lab session. They should have also obtained a system transfer function from the above parameters and their knowledge of system modeling. They should have also chosen an appropriate controller transfer function for the system. It is imperative that an understanding of the system is achieved prior to the experiment to avert difficulties.

To start the experiment the compressor and the air dryer are turned on and the air supply valve ***external to the experimental apparatus (not the regulator valve)*** must be open. ***Note that if the regulator valve is not properly adjusted, the pressure transducers will be damaged!!*** When starting the experiment, the students should first acquaint themselves with the system by manually controlling control valve CV and observing the system response via the Honeywell recorder. (Refer to the student operations manual in Section I.3.2.)

The students should then decide upon the specific SP change tests to be performed. The SP can be varied from 1 to 11. Individual changes of at least two units are highly recommended. Following the decision, they should then choose both SP and PV Adapt options on the Honeywell controller and initialize the Adaptive Tune sequence, as described in Section I.3. Following this, the students should proceed with the SP change tests. The controller tuning parameters and the process gain calculated by the controller are to be recorded manually, as the recorder does not record these values. (Refer to Section I.3.3) At the

FIGURE I.6

PROCESS GAIN vs. VALVE
SP = 10



conclusion of the tests, Adaptive Tune is to be deactivated (Section I.3.4).

The next set of tests are to be performed in Automatic Mode. The students enter the tuning parameters of their chosen controller in the Honeywell controller. Next, the same SP change tests as were performed for Adaptive Tune are to be performed for H(s), the chosen controller. Note that the end of a test is signified by PV line out.

All the above tests should be finished by the end of the first lab session.

At the second lab session the students begin their work by choosing the V_{12} settings for the process change tests. The range of these settings is from 0.25 to 2.00 units. The individual changes should be greater than 0.50 units. With the SP for this lab session set at 10, the students will activate Adaptive Tune. After line out has occurred the process change tests can be performed. At the completion of the tests, Adaptive Tune is to be deactivated so that the H(s) tuning parameters can be entered into the controller. The same process change tests are now performed for H(s), and the same data is recorded as was the case in the first lab session.

At this point a comparative analysis can be carried out. From the data obtained from the recorder, rise time, settling time, and marginal overshoot responses can be compared. In addition, a theoretical time response of the system should be performed using the tuning parameters obtained from the SP change tests for the Honeywell controller. (This is done with CC.) In addition to the aforementioned control parameters, the students should compare delay time and time-to-peak of the theoretical time responses.

I.2.5 Expected Results

The students will have obtained the plant transfer function

$$S(s) = \frac{1.2}{1.45\ s + 1} \qquad \text{-14-}$$

The expected control transfer functions obtained from the Honeywell SP Adapt and PV Adapt are denoted by SP(s) and PV(s) respectively. They are

$$SP(s) = \frac{21.0\ (0.19\ s + 1)}{0.19\ s} \qquad \text{-15-}$$

$$PV(s) = \frac{G_c\ (0.26\ s + 1)}{0.26\ s} \qquad \text{-16-}$$

where G_c is the controller gain is given by

$$G_c = 9.2\ V_{12} + 2.3 \qquad \text{-17-}$$

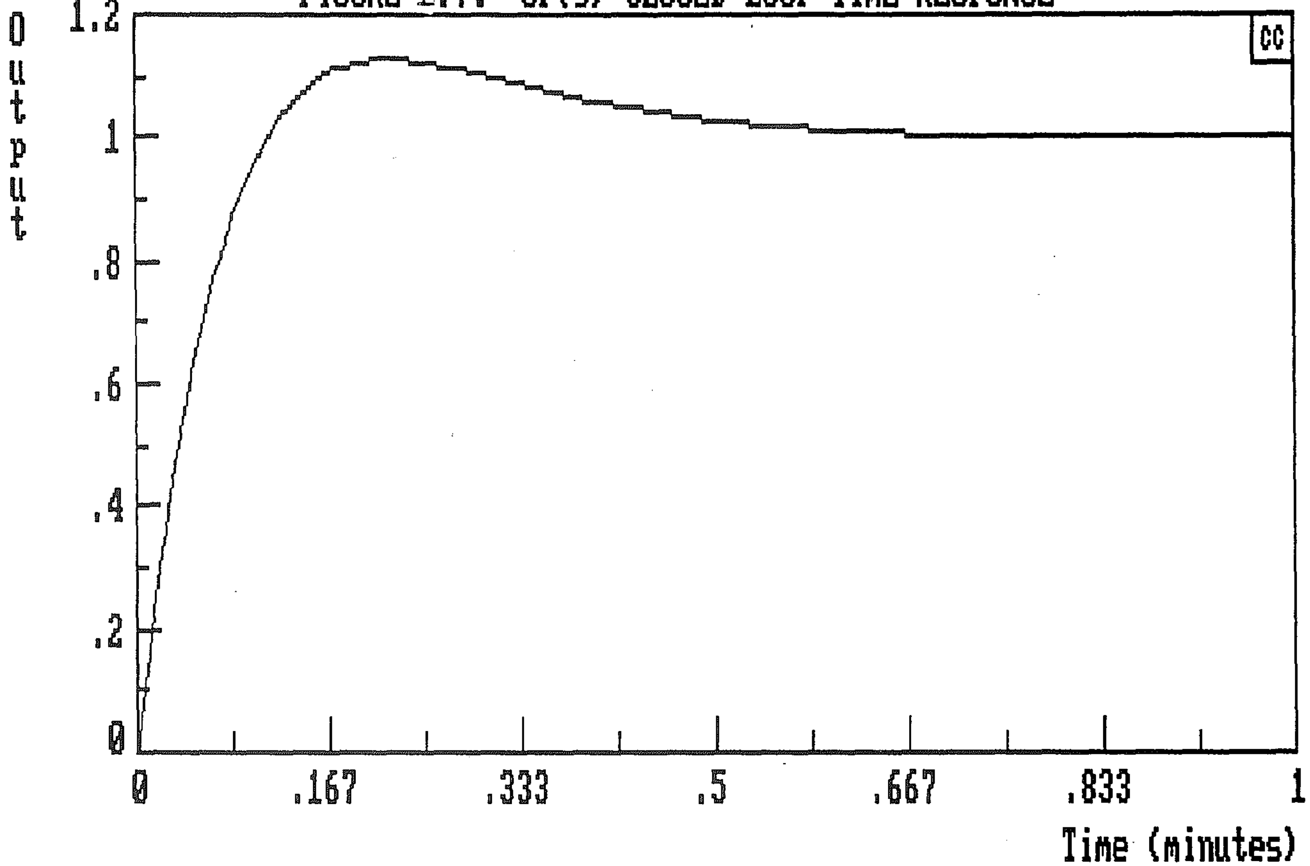
The resulting system gain K is given approximately by

$$K = \frac{23}{9.2\ V_{12} + 2.3} \qquad \text{-18-}$$

The theoretical system responses with SP(s) and PV(s) are shown in Figures I.7 and I.8, respectively. For the PV(s) system response, an average value for the controller is chosen at G_c=11.5.

A summary of results for the system response as determined by CC is shown in Table I.2. An example of an actual system response for the Honeywell's SP and PV adapt is shown

FIGURE I.7: SP(s) CLOSED-LOOP TIME RESPONSE



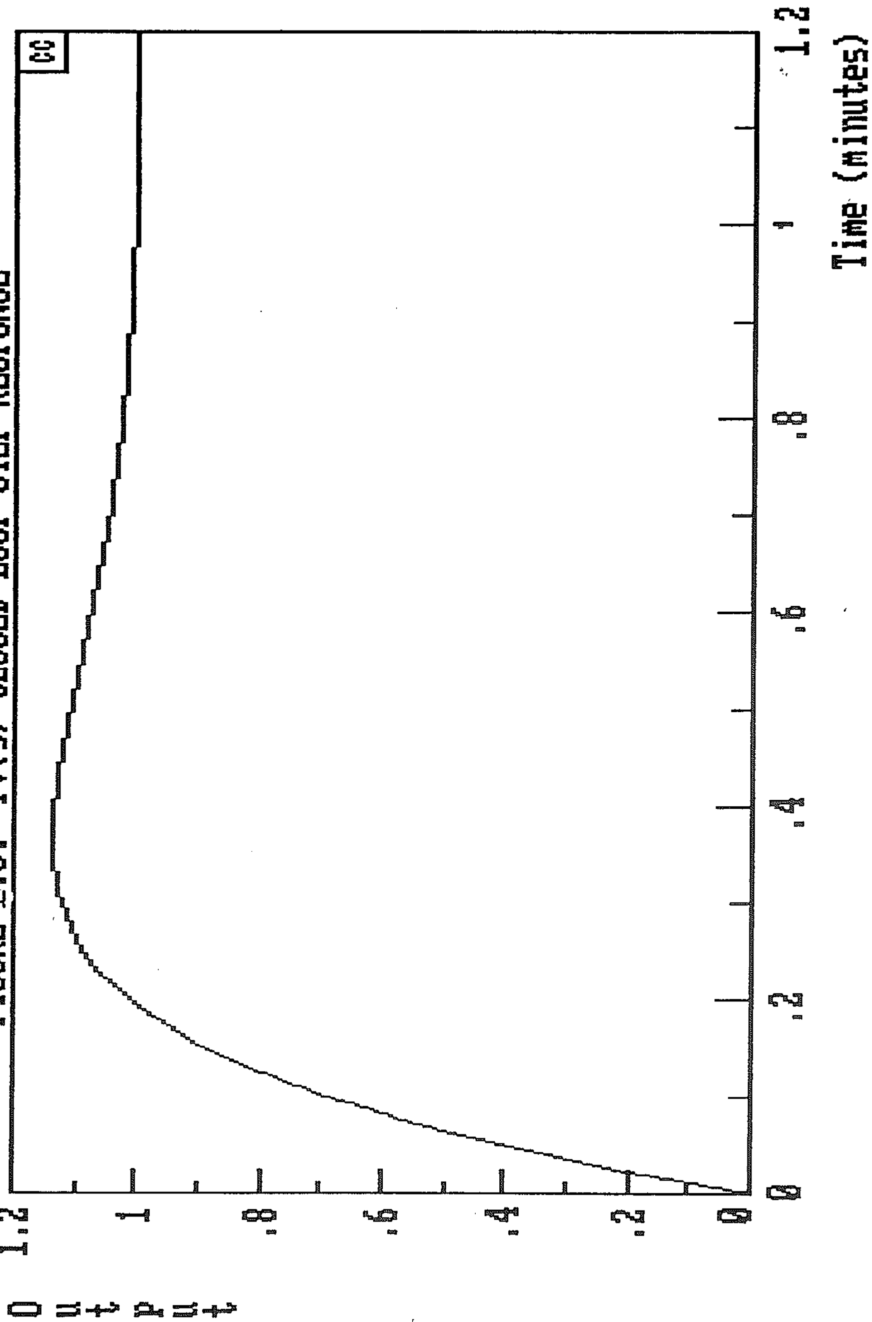


FIGURE I.8: PV(s) CLOSED-LOOP STEP RESPONSE in Figures I.9 and I.10, respectively.

I.2.6 Discussion

From the data anticipated from the proposed experiment, it can be seen that both the PV and SP Adapt involve controllers that give quick responses with relatively low marginal overshoot. For the actual system response, minimal overshoot, if any, is expected. In addition, the settling time for SP Adapt process should be smaller than PV Adapt or the theoretical time responses. The reason is that the Honeywell controller is designed to manipulate the control output to achieve the quickest time to line out during SP Adapt mode. This usually means that the assigned PI controller is not active during the SP Adapt process but, instead, uses controller-determined step outputs. This phenomenon is seen in the example of the actual system SP Adapt response.

Furthermore, it is expected that the Honeywell tests will result in a quicker PV line out than most, if not all, other chosen methods of control. The reason is, especially for SP Adapt, that the Honeywell Controller uses the determined process characteristics to its full advantage. In other words, this controller does not always follow its assigned tuning parameters to bring PV to SP. Instead, it actuates the control output to accelerate line out. As line out is approaching, the tuning parameters are assigned and implemented.

I.3 How to Use the Honeywell UDC 6000 Process Controller

This section is a tutorial explicitly written for undergraduates who will be working with the Honeywell controller. It is hoped that that this material will help undergraduates in

FIGURE I.9

SP ADAPT SAMPLE TEST

SP: 8 to 5

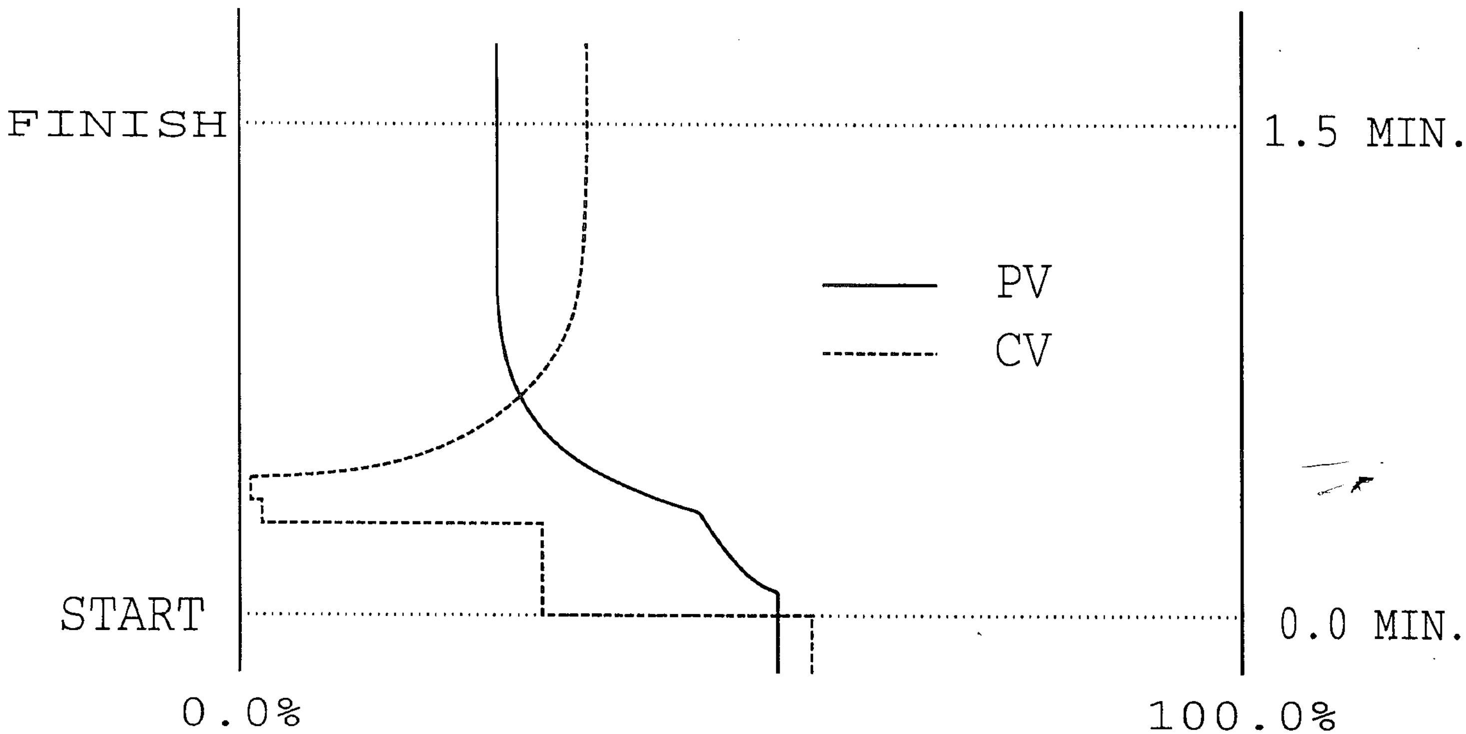
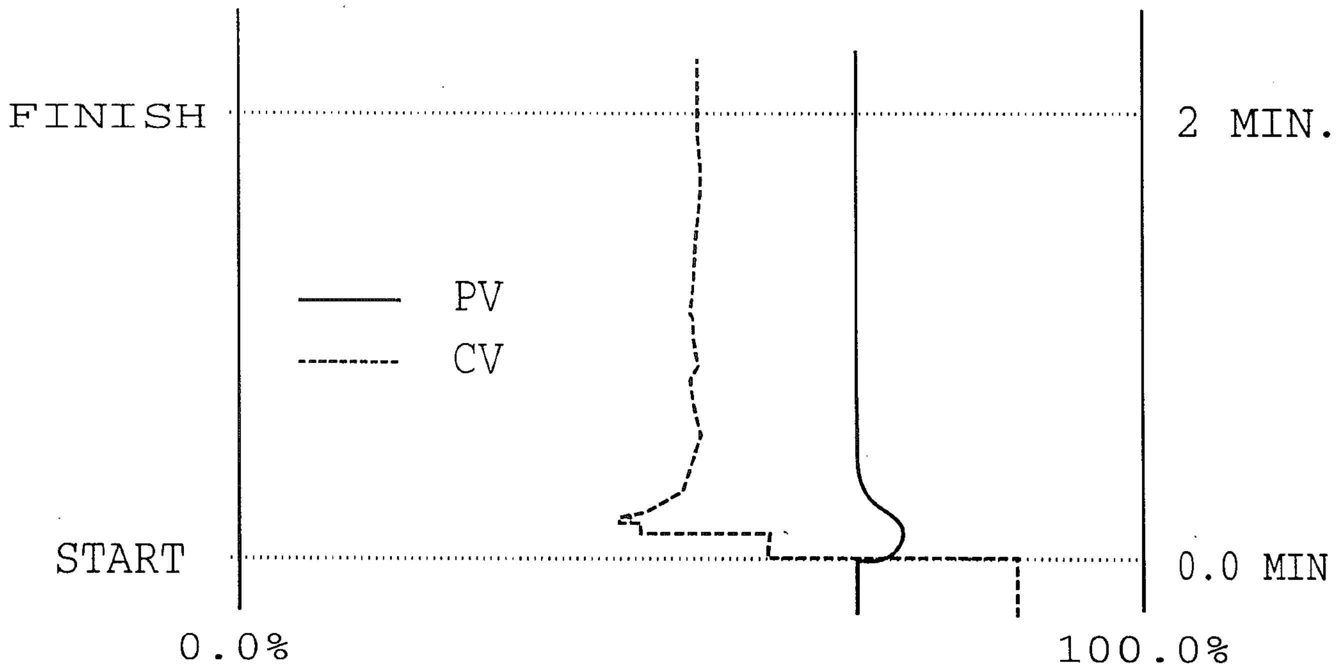


FIGURE I.10

PV ADAPT SAMPLE TEST

VALVE: 2.00 to 1.00



course ME/EE/ChE 389, especially those who will be performing the experiment proposed in Section I.2.

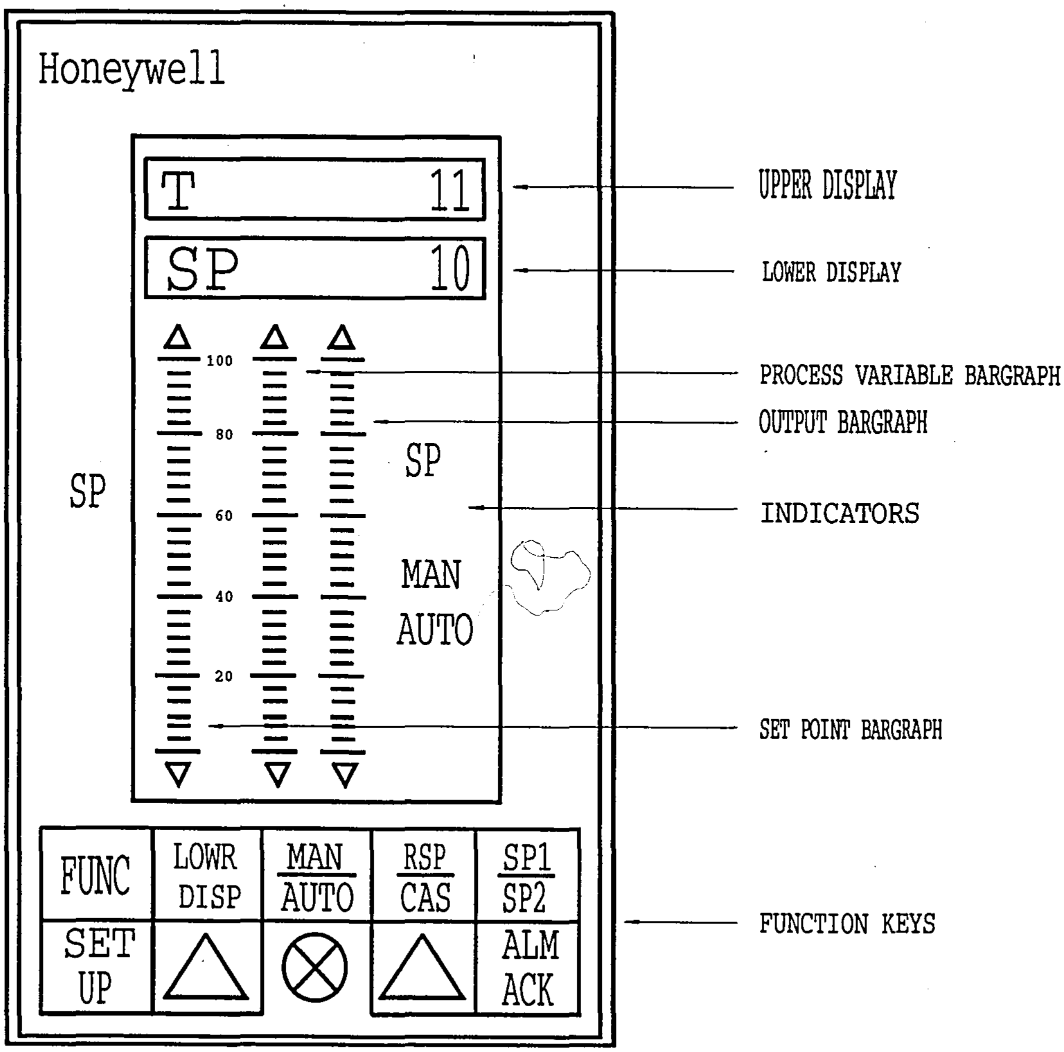
I.3.1 The Display Panel

The display panel is shown in Figure I.11. There are three main features to the display. The primary part is a display of three bar graphs, each ranging from 0% to 100%. The first bar graph shows the set point at which the controller tries to line out the process variable. A reading of 0% signifies 0.000 kPa and 100% signifies 103.425 kPa (or 15 pig). The second bar graph monitors the process variable PV (the exit pressure). A reading of 0% signifies an exit pressure of 0.000 kPa and 100% signifies and exit pressure of 103.425 kPa, the same as the SP bar graph. The last bar graph shows the control output which in this case is the control valve CV. A reading of 0% corresponds to a CV completely closed, and 100% to a CV completely open.

To the right of the bar graphs is a display of operation codes. The **SP** should be lit, indicating that the local SP is being used. Note that neither the numbers **2** or **3** shown next to the **SP** should be lit. Either **MAN** or **AUTO** should be lit, but not both. **MAN** signifies that the controller is in Manual Mode, and **AUTO** that the controller is in Automatic Mode. If any of the numbers below **AUTO** are lit, this indicates an error -- an alarm condition. This should not occur if incorrect keys are not pressed.

Above the bar graphs are operation displays which show numerical values of operational parameters. Under normal operation the upper display shows the present value of PV. Note that PV is not shown as a percent, as in the bar graph. Instead, it is an integer number from 0 to 15. The number **0** represents 0.000 kPa (or 0 psi) while **15** represents 103.425 kPa (or 15 pig). The upper display also shows whether or not the controller is in the

FIGURE I.11
HONEYWELL UDC 6000



process of tuning, and whether it is tuning under SP Adapt or PV Adapt mode. The lower display shows the operating parameters and values in the same way as the upper display. Under Configuration Mode, the upper display shows either the actual parameter value or that selected by the operator; the lower display shows the corresponding function groups or parameters.

Below the main display panel are the control keys. The **SET UP** key is used in conjunction with the **FUNCT**, or FUNCTION key. It selects and configures selected control parameters. The **LOWR DISP** or LOWER DISPLAY key produces a display of actual operating conditions, i.e. SP, CV, and PV deviance from SP. The **MAN/AUTO** key toggles the controller between Manual and Automatic Modes. The keys with up and down arrows allow the user to increase or decrease parameter values. The **ALM ACK** or ALARM ACKNOWLEDGE key, when pressed, acknowledges an alarm. This button is seldom used.

I.3.2 Displaying and Changing Parameters

Value Changes: Pressing the up and down keys will change a parameter's value in the least significant digit. If the key of opposite direction is pressed momentarily at the same time, the next least significant digit changes. An additional pressing of the opposite key allows one to change the next to least significant digit, and so on. Be careful with this. It is not very easy to control.

Set Point: Press **LOWR DISP** until **SP** appears to the left of the lower display. To change SP, use the up and down arrow keys to enter the desired SP.

Manual or Automatic Mode: Press the **MAN/AUTO** so that **MAN** or **AUTO** appears on the side of the display board.

Control Output (Valve): Press **LOWR DISP** until **OUT** appears to the left of the lower display. To change CV, use the up and down arrow keys to enter the desired CV. Note that CV values can only be changed under Manual Mode.

For the above three functions, the upper display will show the value of PV.

I.3.3 Display of Tuning Parameters and the Process Gain

Tuning Parameters: Press the **SET UP** key once. The upper and lower displays should respectively read **SET UP** and **TUNING**. Pressing the **FUNC** shows the controller gain value on the upper display and reads **GAIN** on the lower display. Pressing the **FUNC** a second time displays the derivative time constant in minutes on the upper display, and reads **RATE MIN** on the lower display. Hitting the **FUNC** a third time displays the integral time constant on the upper display and reads **RESET MIN** on the lower display. To return to normal operating conditions, hit the **LOWR DISP** button.

Process Gain: Press **SET UP** until the lower display reads **ADAPTIVE**. Then press **FUNC** until the upper display reads **PROC GAIN**. The lower display should now show the calculated process gain value.

Once any of the above values are displayed, they can be changed via the up and down arrow keys. Note, however, that the tuning parameters can only be changed when Adaptive Tune is disabled.

I.3.4 The Adaptive Tune Procedure

Step One: Put the controller into Manual Mode.

Step Two: Set CV to about 20%.

Step Three: While waiting for PV to line out, activate Easy-Tune.

1. Press the **SET UP** until **ADAPTIVE** appears on the lower display.

2. Press **FUNC** until **SP + PV** is shown on the upper display.

3. Press **LOWR DISP** to return to normal operation conditions.

Step Four: Once PV has lined out, switch to Automatic control, i.e. press **MAN/AUTO**. At this point, a **T** will appear on the right hand side of the upper display. This signifies SP Adapt. If, however, the symbol T appears, this signifies PV Adapt. This situation will arise only during the second lab session.

Step Five: When each test is finished, record the tuning parameter values and the process gain value.

Step Six: When tests with Adaptive Tune are finished, deactivate Adaptive Tune.

1. Press the **SET UP** until **ADAPTIVE** appears on the lower display.

2. Press **FUNC** until **DISABLE** is shown on the upper display.

3. Press **LOWR DISP** to return to normal operation conditions.

APPENDIX II

SYSTEM RESPONSES

APPENDIX A

TEST CONDITION ONE

HWC AND HWT CLOSED-LOOPED RESPONSES

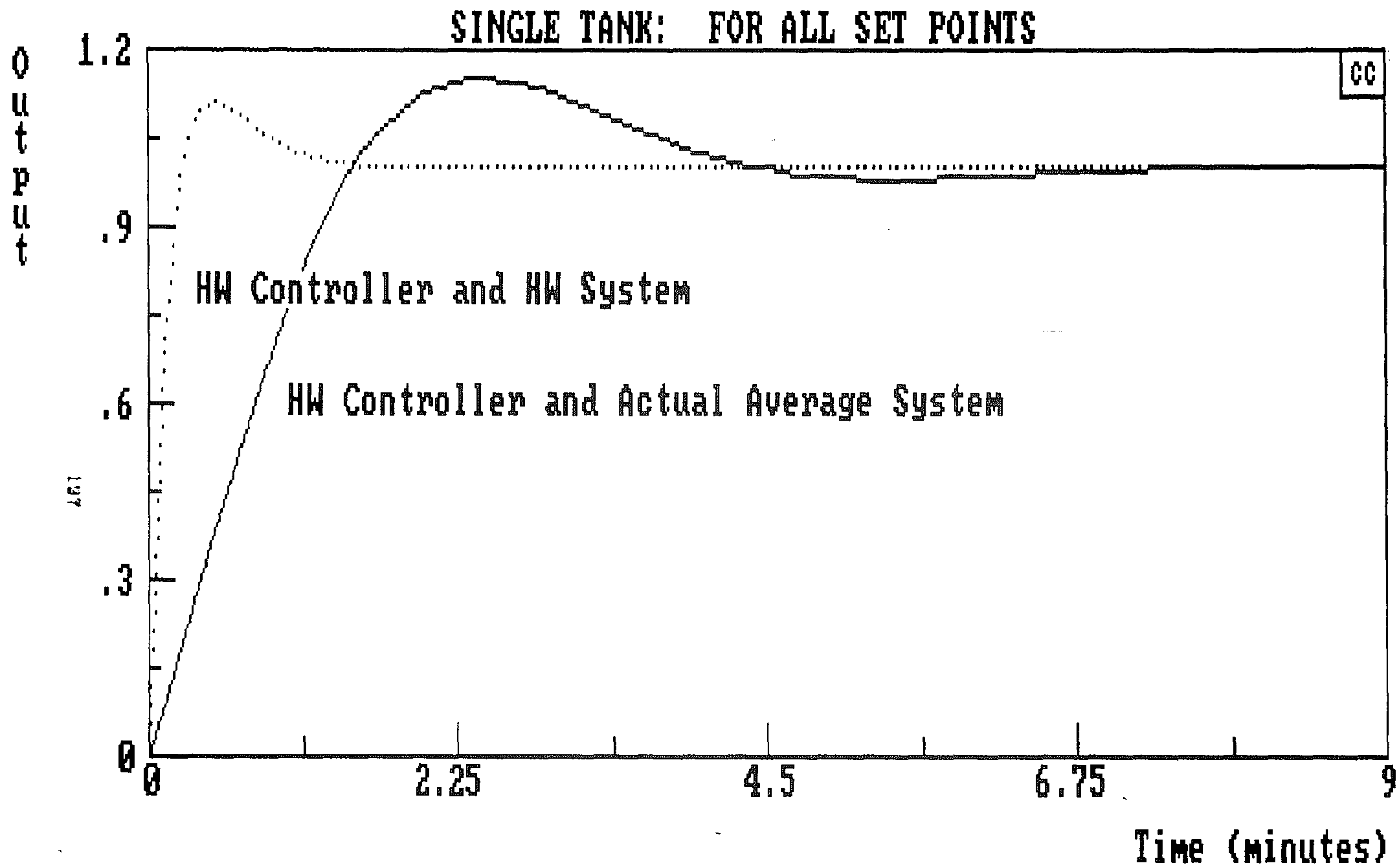
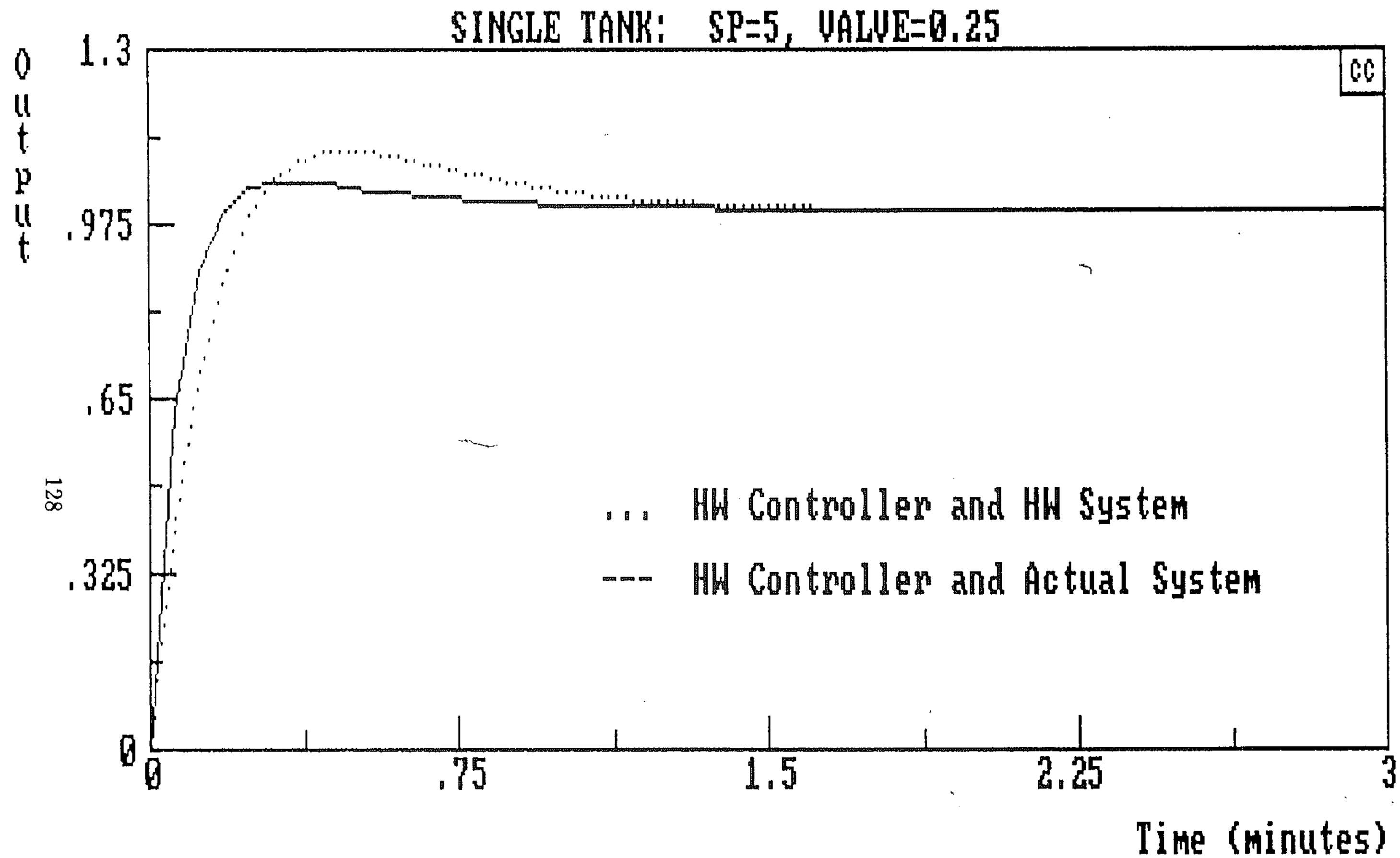

SINGLE TANK: FOR ALL SET POINTS
Output
1.2
.9
.6
.3
0
CC
HW Controller and HW System
HW Controller and Actual Average System
0
2.25
4.5
6.75
9
Time (minutes)

FIGURE A.1



SINGLE TANK: SP=5, VALVE=0.25
Output
1.3
.975
.65
.325
0
0
.75
1.5
2.25
3
Time (minutes)
CC
... HW Controller and HW System
--- HW Controller and Actual System

FIGURE A.2

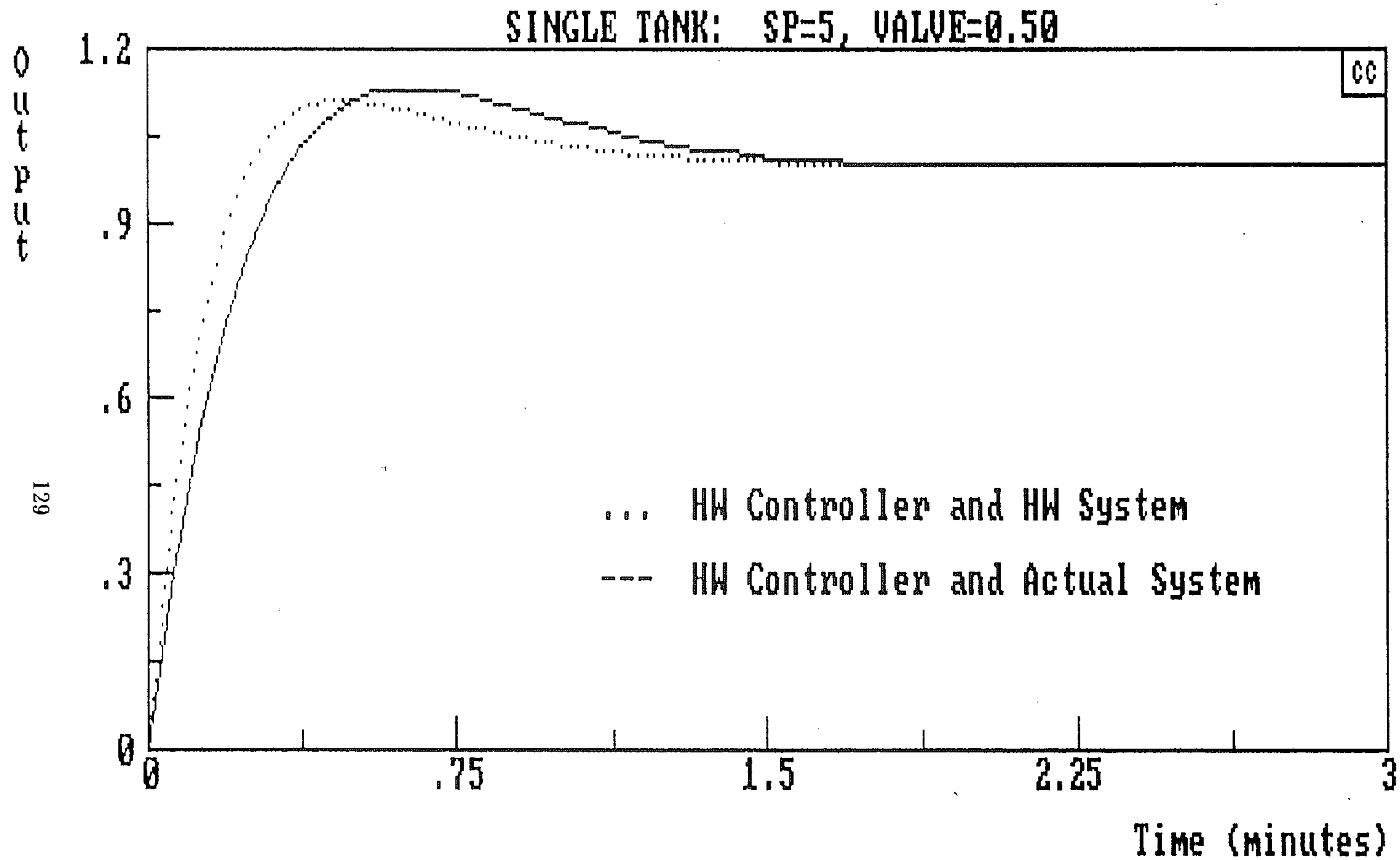

SINGLE TANK: SP=5, VALVE=0.50
CC
Output
1.2
.9
.6
.3
0
0
.75
1.5
2.25
3
Time (minutes)
... HW Controller and HW System
--- HW Controller and Actual System

FIGURE A.3

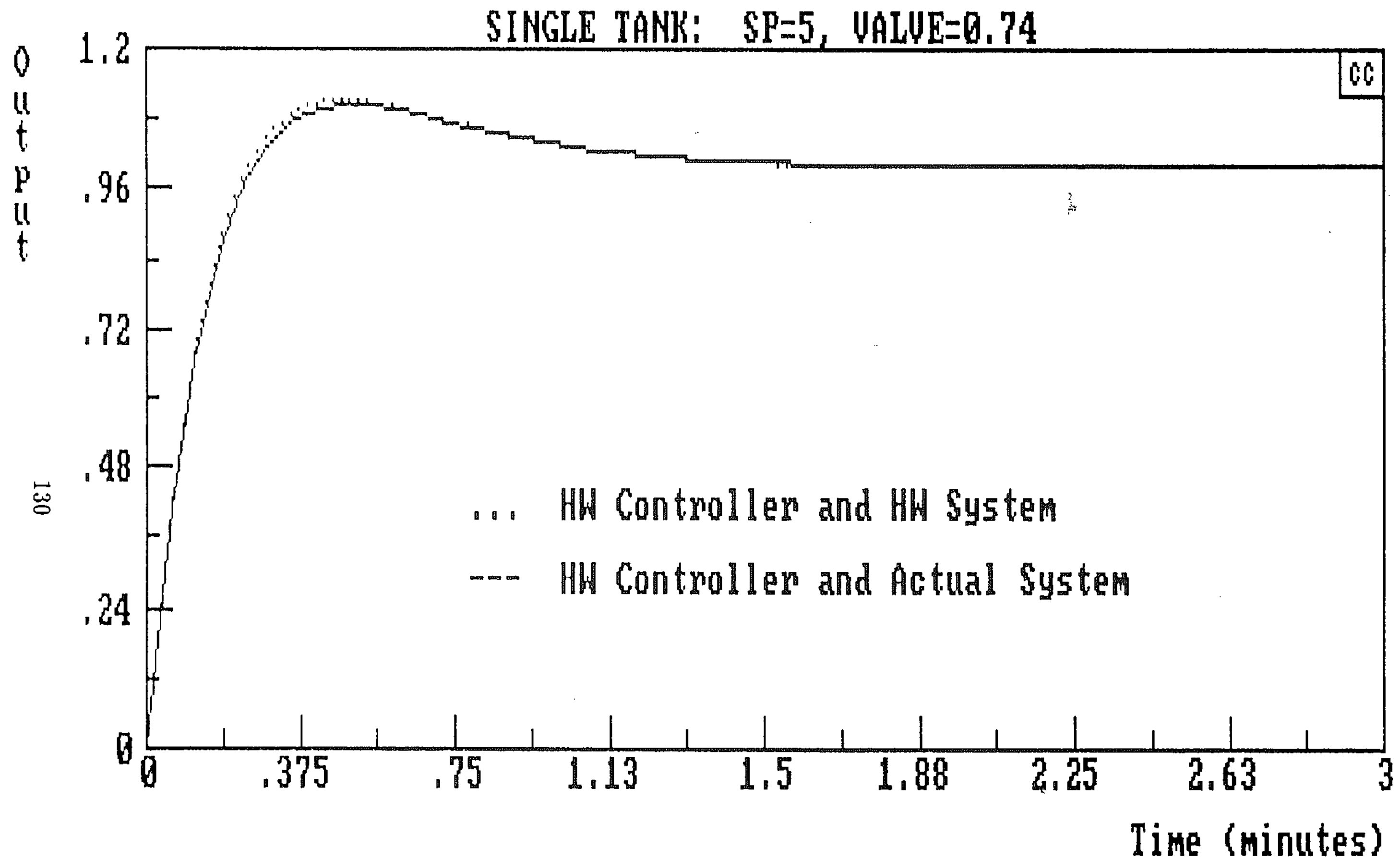

SINGLE TANK: SP=5, VALVE=0.74
Output
1.2
.96
.72
.48
.24
0
CC
... HW Controller and HW System
--- HW Controller and Actual System
0
.375
.75
1.13
1.5
1.88
2.25
2.63
3
Time (minutes)

FIGURE A.4

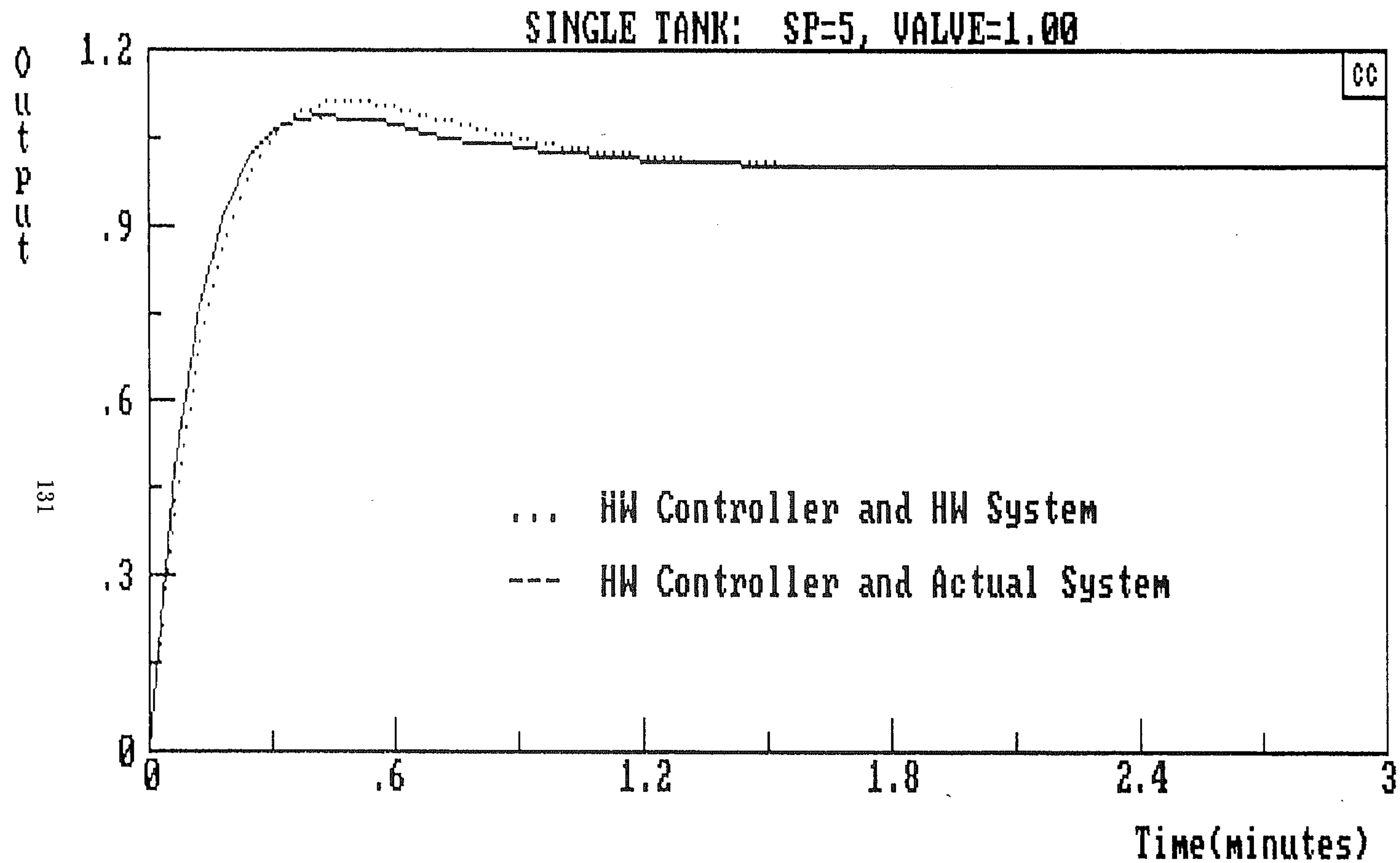

SINGLE TANK: SP=5, VALVE=1.00
Output
1.2
.9
.6
.3
0
0
.6
1.2
1.8
2.4
3
Time(minutes)
CC
... HW Controller and HW System
--- HW Controller and Actual System

FIGURE A.5

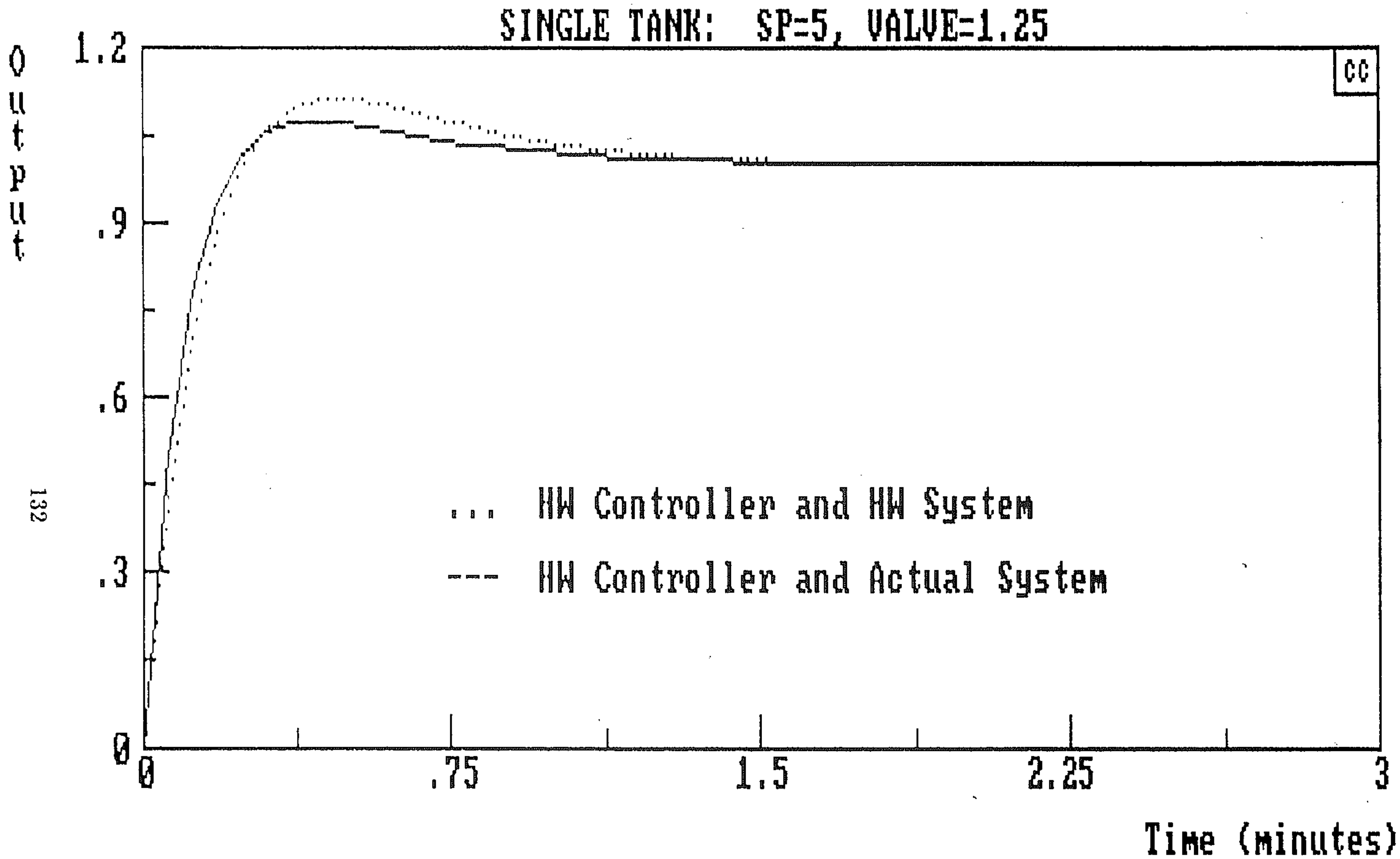

SINGLE TANK: SP=5, VALVE=1.25
Output
1.2
.9
.6
.3
0
0
.75
1.5
2.25
3
Time (minutes)
CC
... HW Controller and HW System
--- HW Controller and Actual System

FIGURE A.6

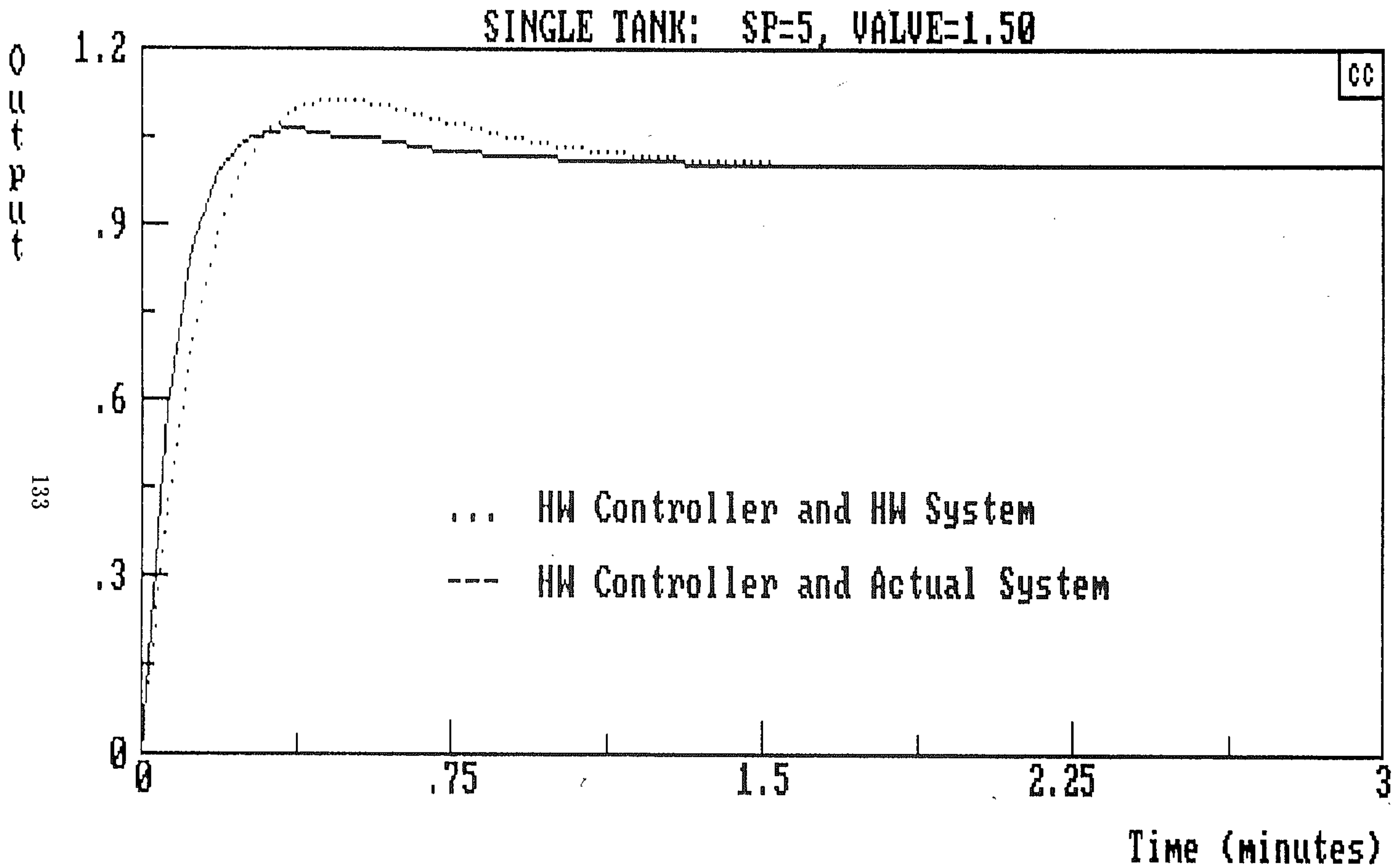

SINGLE TANK: SP=5, VALVE=1.50
Output
1.2
.9
.6
.3
0
0
.75
1.5
2.25
3
Time (minutes)
CC
... HW Controller and HW System
--- HW Controller and Actual System

FIGURE A.7

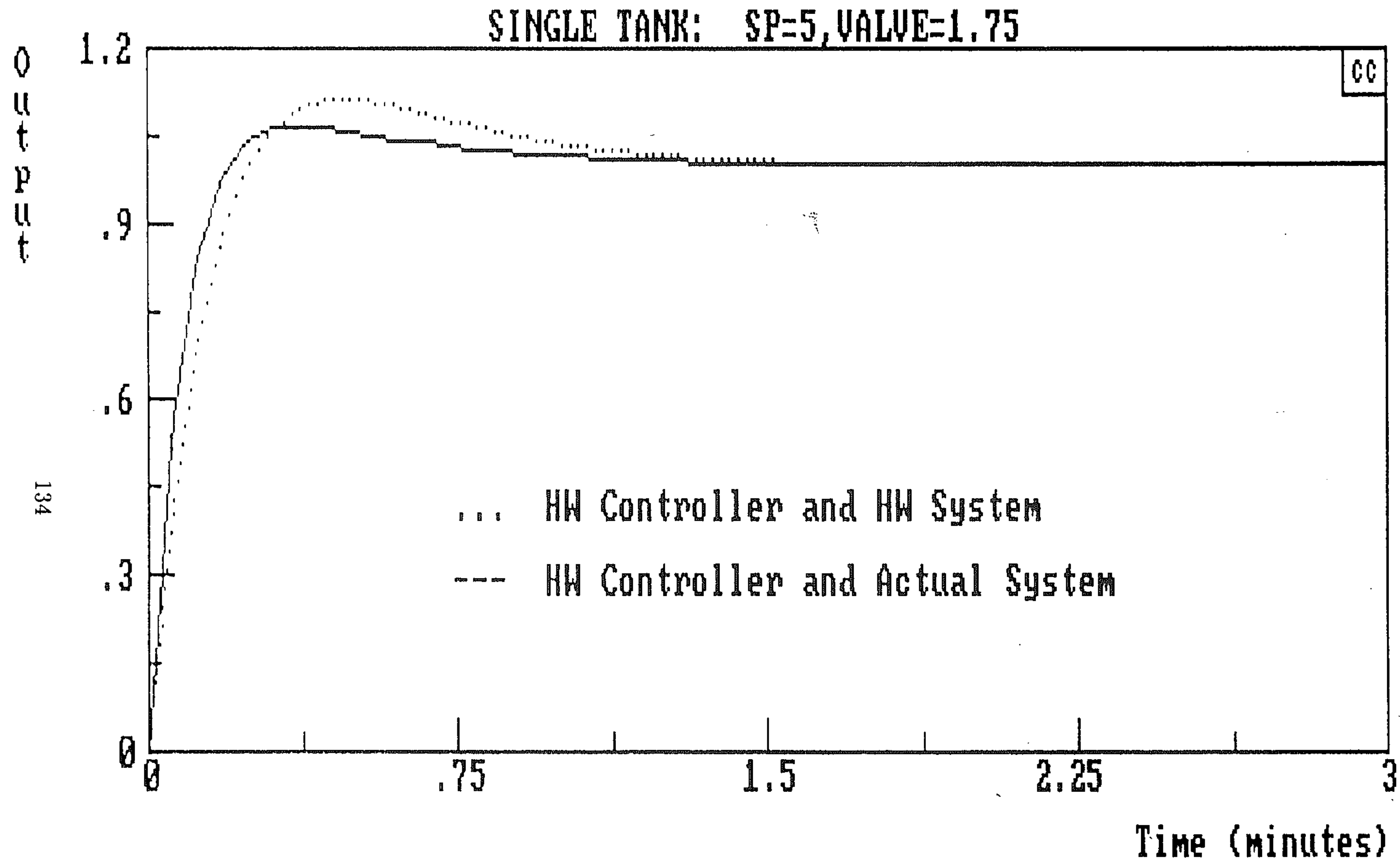

SINGLE TANK: SP=5,VALUE=1.75
Output
1.2
.9
.6
.3
0
CC
... HW Controller and HW System
--- HW Controller and Actual System
0
.75
1.5
2.25
3
Time (minutes)

FIGURE A.8

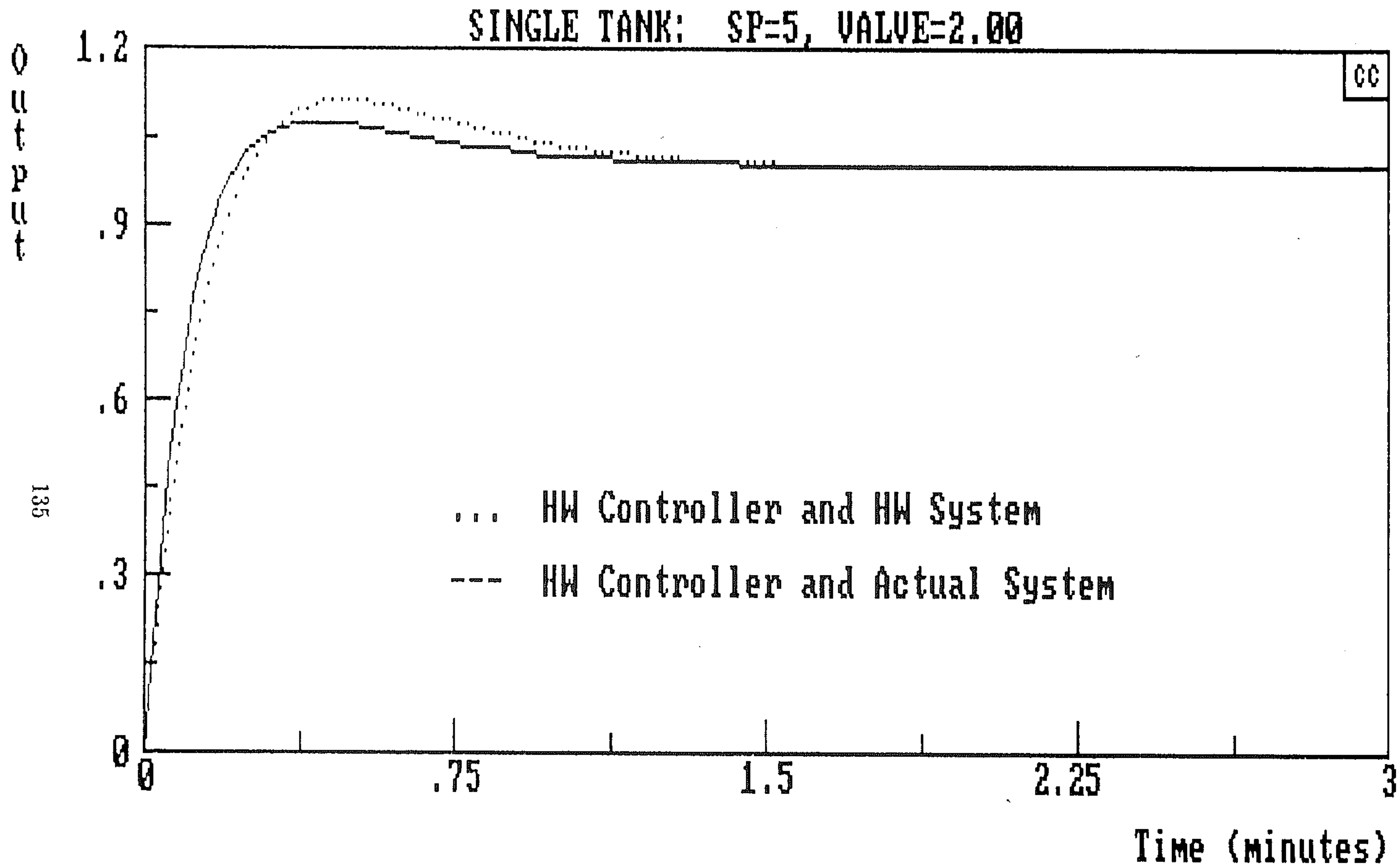
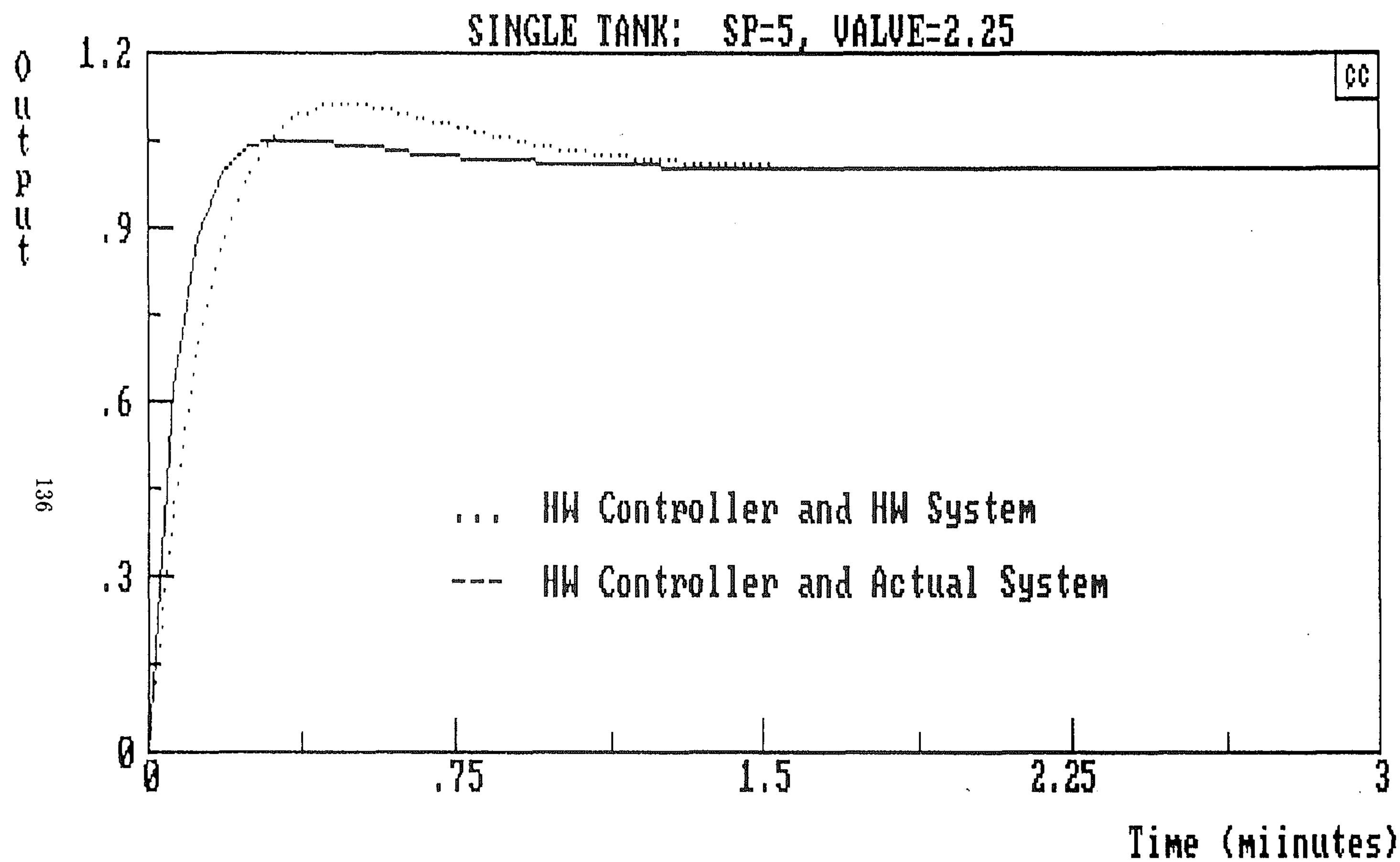

SINGLE TANK: SP=5, VALVE=2.00
Output
1.2
.9
.6
.3
0
0
.75
1.5
2.25
3
Time (minutes)
CC
... HW Controller and HW System
--- HW Controller and Actual System

FIGURE A.9



SINGLE TANK: SP=5, VALVE=2.25
Output
1.2
.9
.6
.3
0
0
.75
1.5
2.25
3
Time (miinutes)
CC
... HW Controller and HW System
--- HW Controller and Actual System

FIGURE A.10

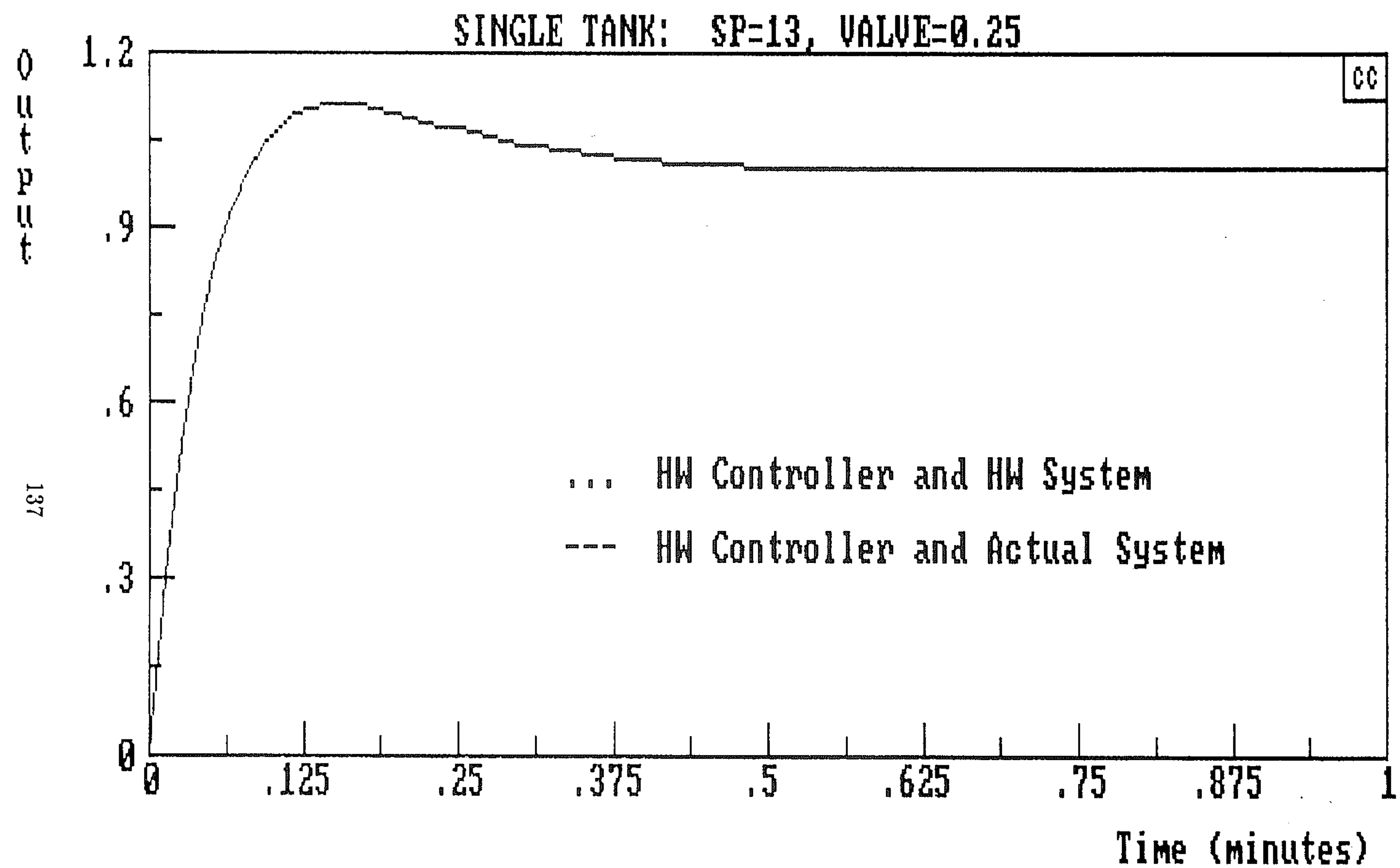

SINGLE TANK: SP=13, VALVE=0.25
Output
1.2
.9
.6
.3
0
CC
0
.125
.25
.375
.5
.625
.75
.875
1
Time (minutes)
... HW Controller and HW System
--- HW Controller and Actual System

FIGURE A.11

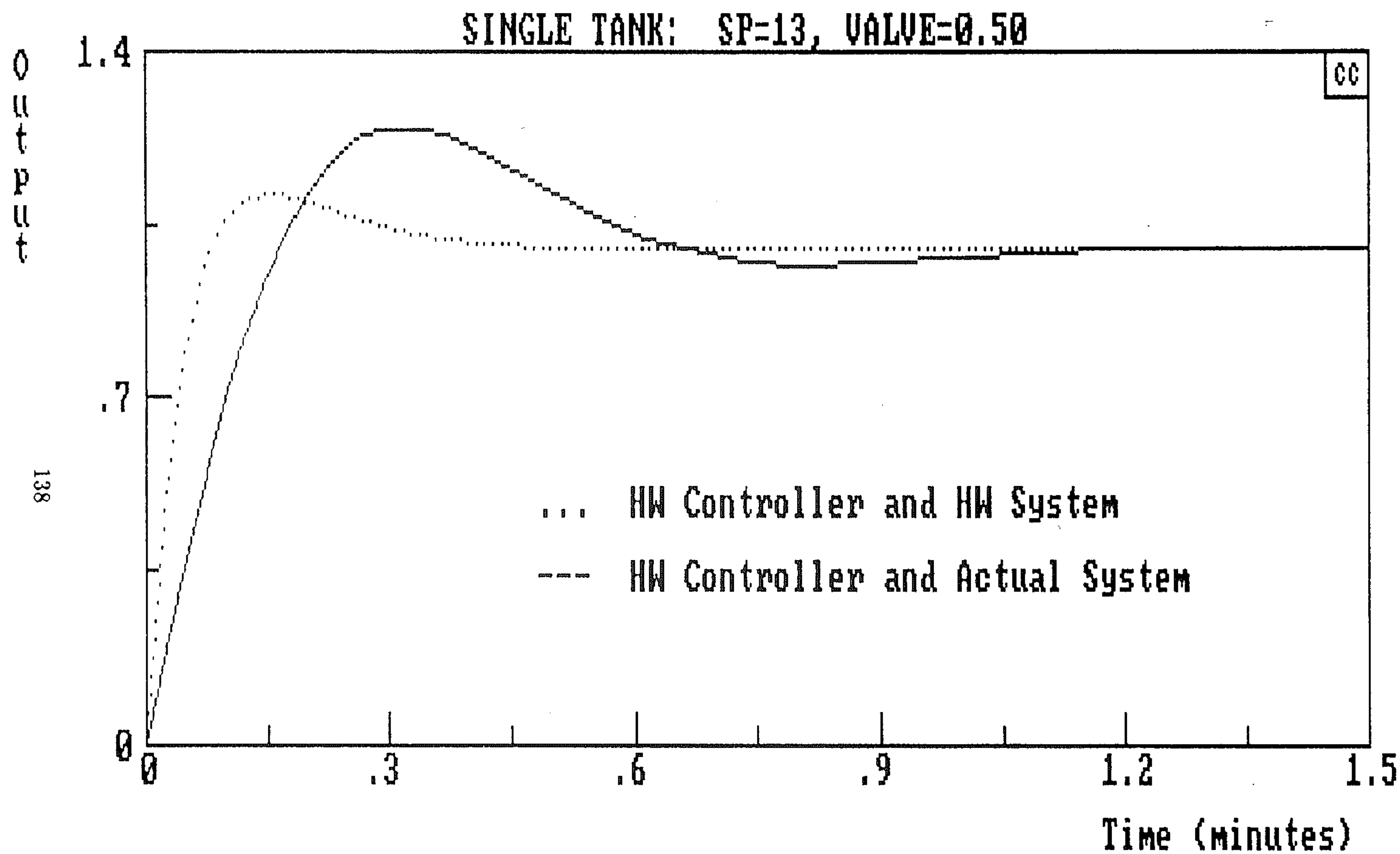

SINGLE TANK: SP=13, VALVE=0.50
Output
1.4
.7
0
CC
0
.3
.6
.9
1.2
1.5
Time (minutes)
... HW Controller and HW System
--- HW Controller and Actual System

FIGURE A.12

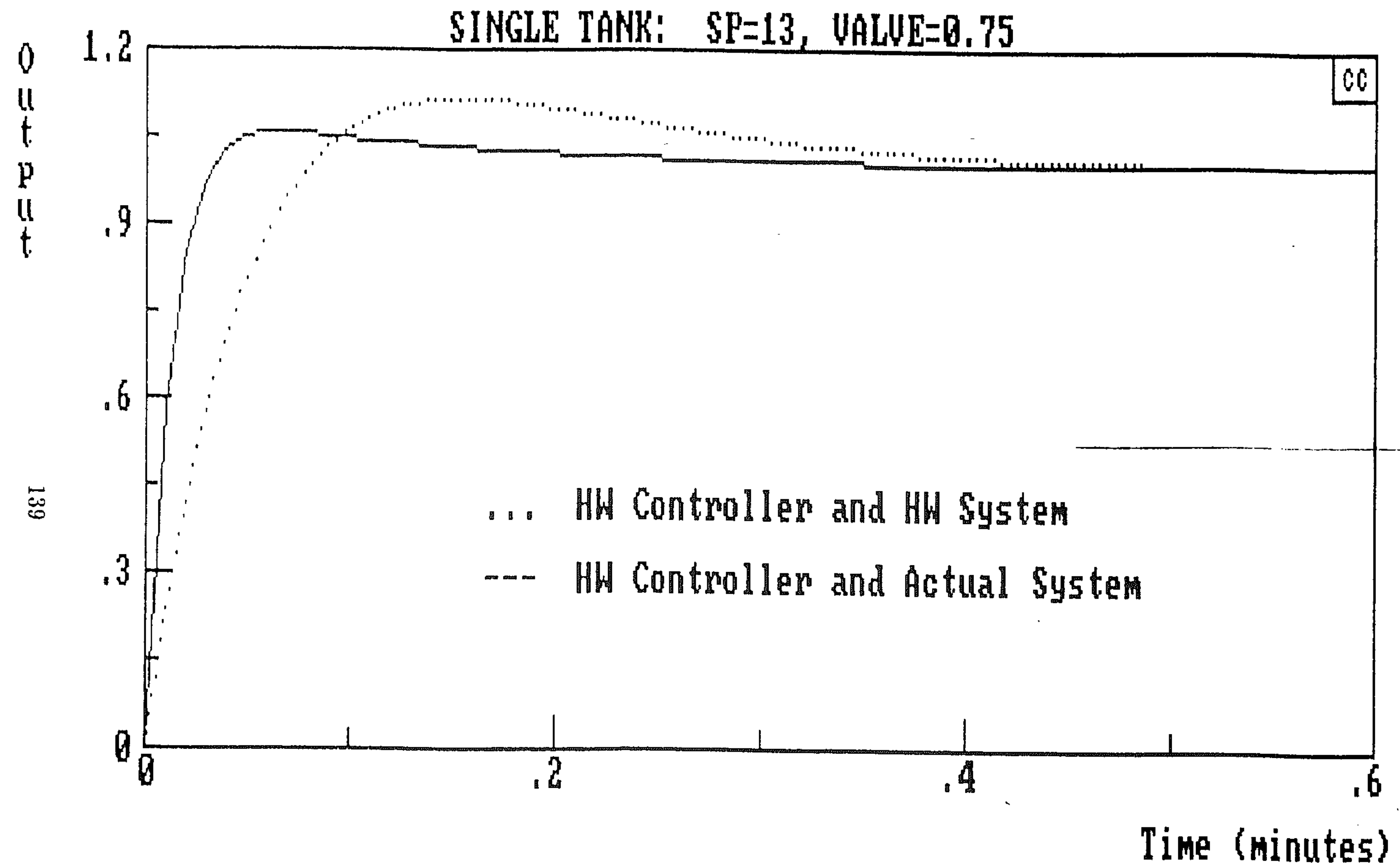

SINGLE TANK: SP=13, VALVE=0.75
Output
1.2
.9
.6
.3
0
0
.2
.4
.6
Time (minutes)
CC
... HW Controller and HW System
--- HW Controller and Actual System

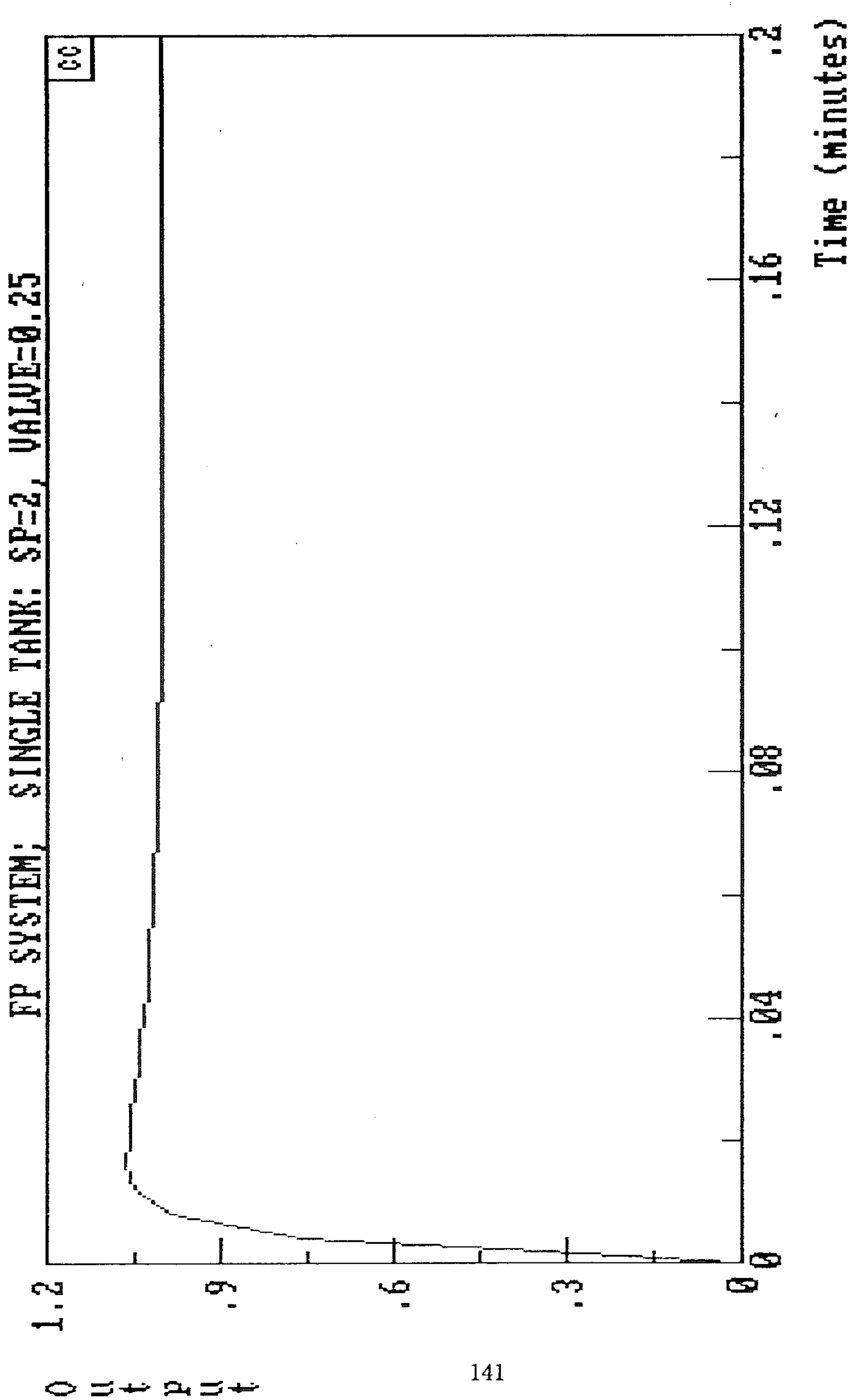
FIGURE A.13

APPENDIX B

TEST CONDITION ONE AND TWO

FPC AND FPT CLOSED-LOOPED RESPONSES

FIGURE B.1


FP SYSTEM; SINGLE TANK; SP=2, VALVE=0.25
GC
Output
1.2
.9
.6
.3
0
.04
.08
.12
.16
.2
Time (minutes)

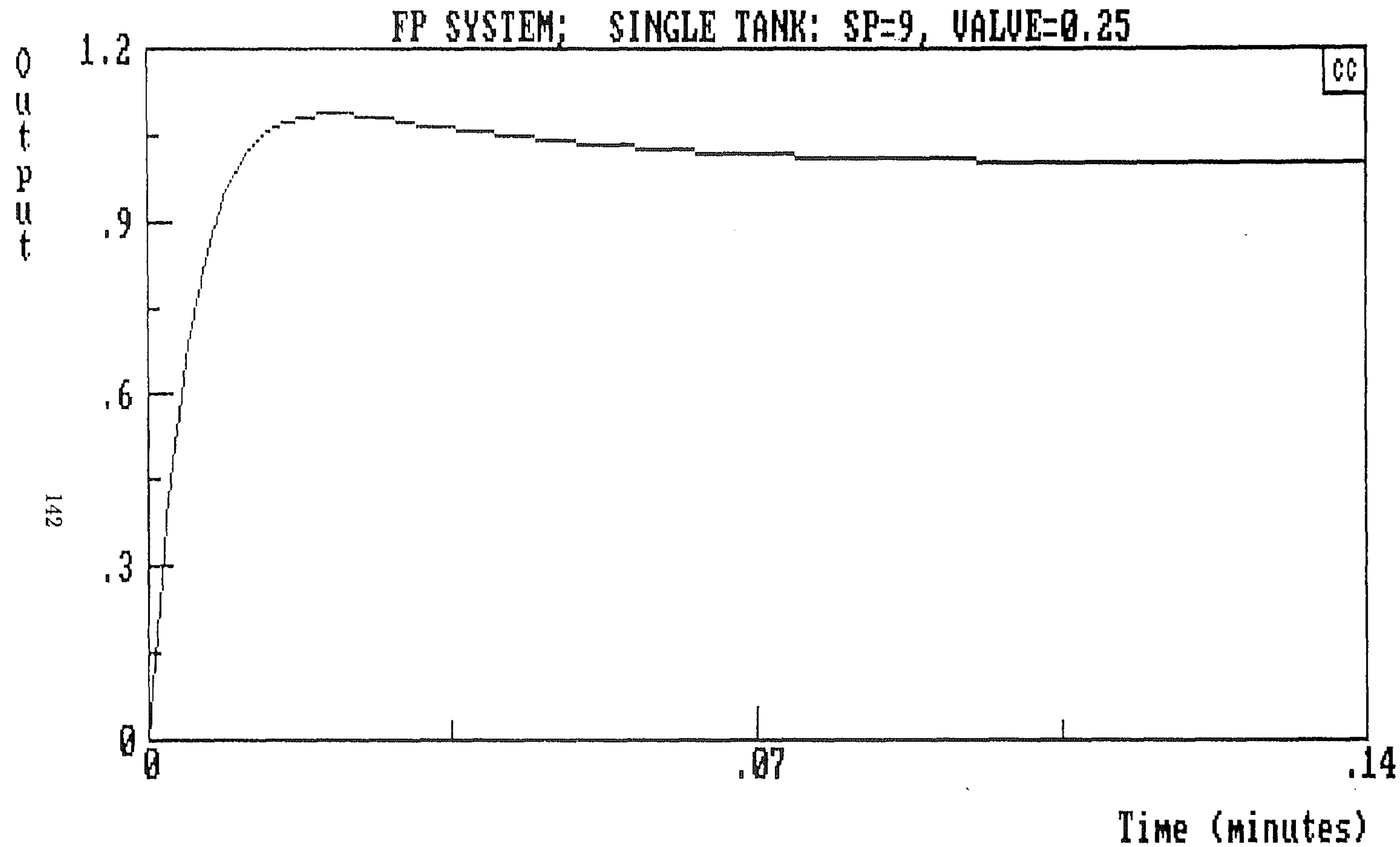

FP SYSTEM; SINGLE TANK: SP=9, VALVE=0.25
Output
1.2
.9
.6
.3
0
CC
0
.07
.14
Time (minutes)

FIGURE B.2

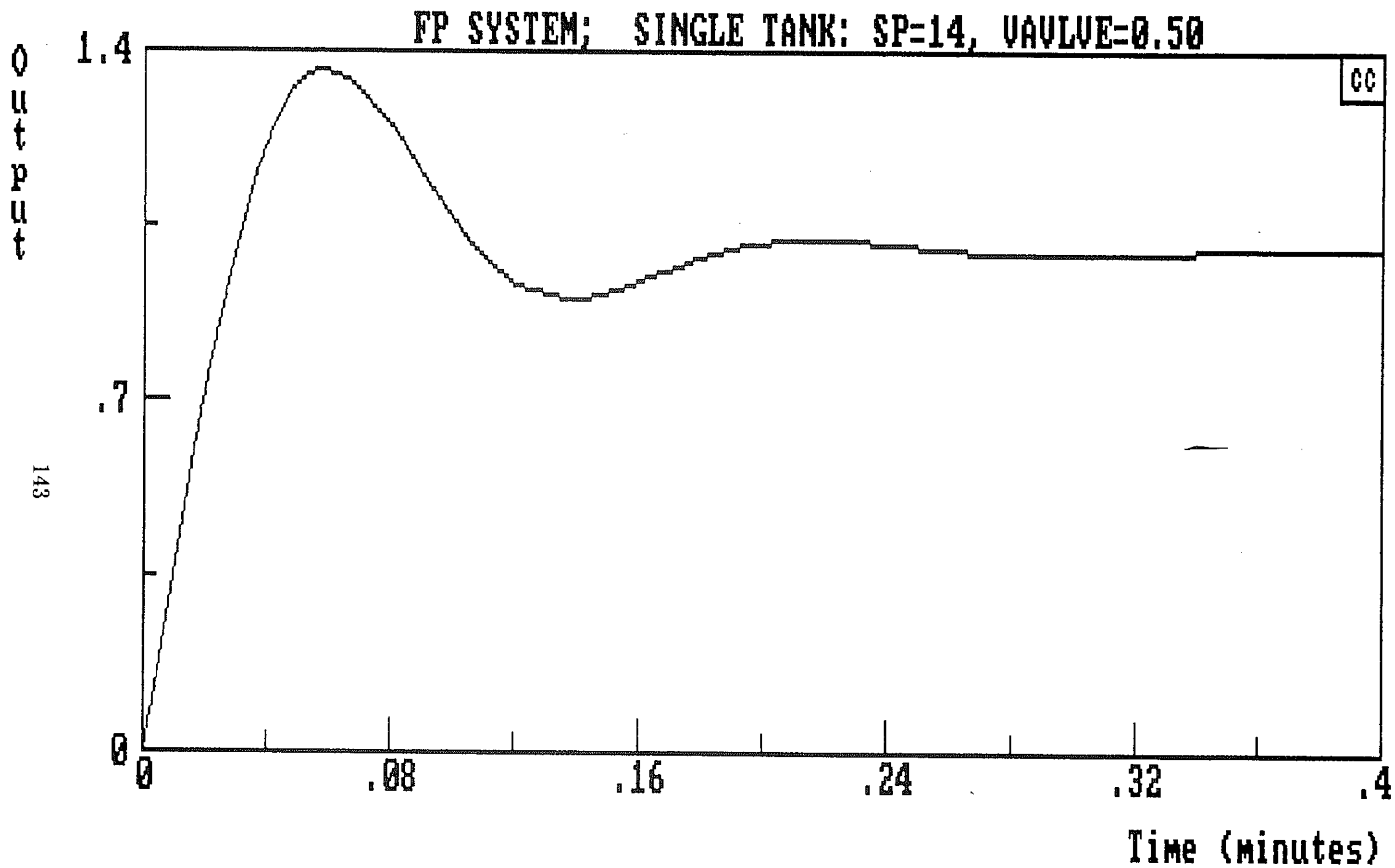

FP SYSTEM; SINGLE TANK: SP=14, VAVLVE=0.50
Output
1.4
.7
0
CC
0
.08
.16
.24
.32
.4
Time (minutes)

FIGURE B.3

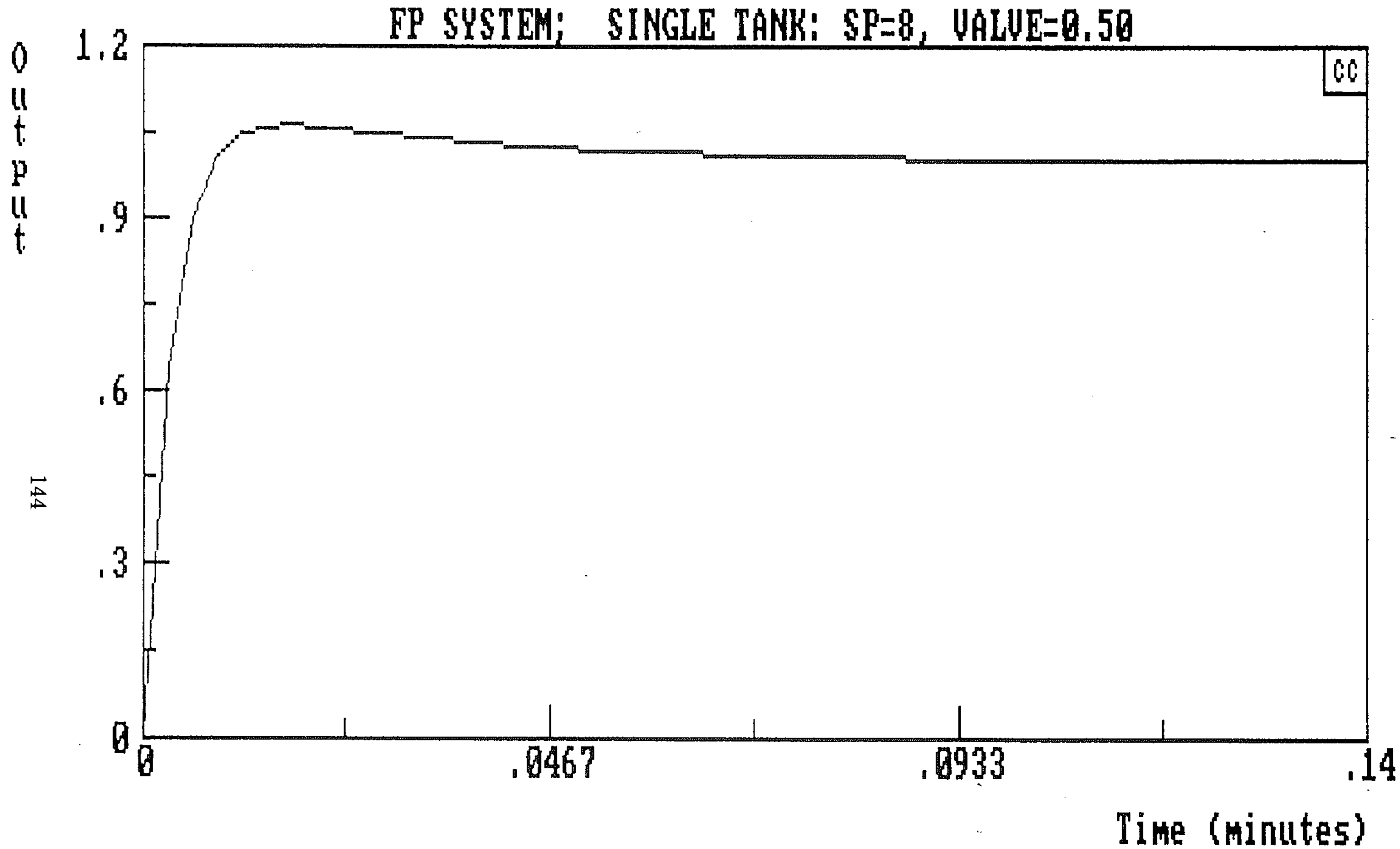
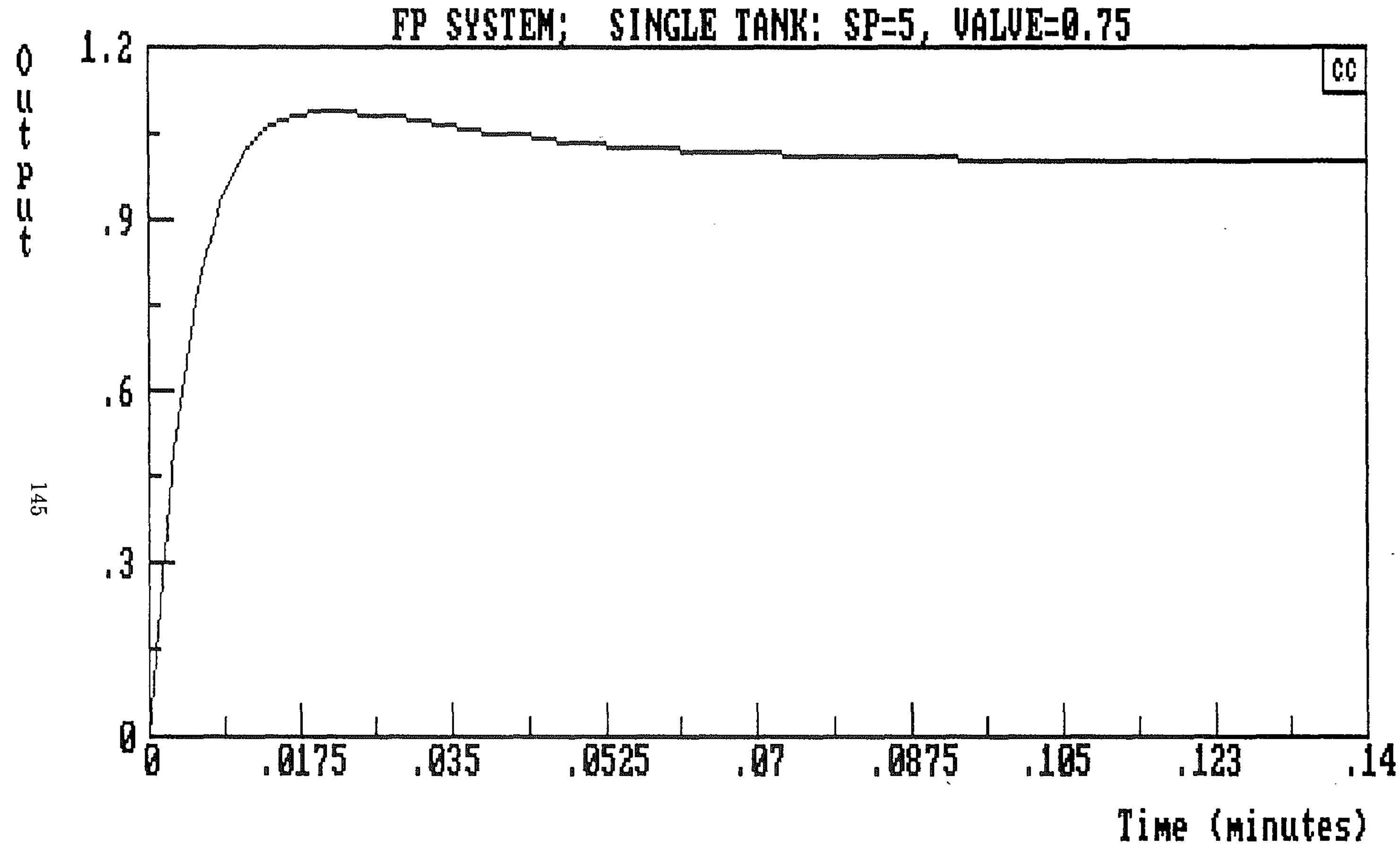

FP SYSTEM; SINGLE TANK: SP=8, VALVE=0.50
Output
1.2
.9
.6
.3
0
CC
0
.0467
.0933
.14
Time (minutes)

FIGURE B.4



FP SYSTEM; SINGLE TANK: SP=5, VALVE=0.75
CC
Output
1.2
.9
.6
.3
0
0
.0175
.035
.0525
.07
.0875
.105
.123
.14
Time (minutes)

FIGURE B.5

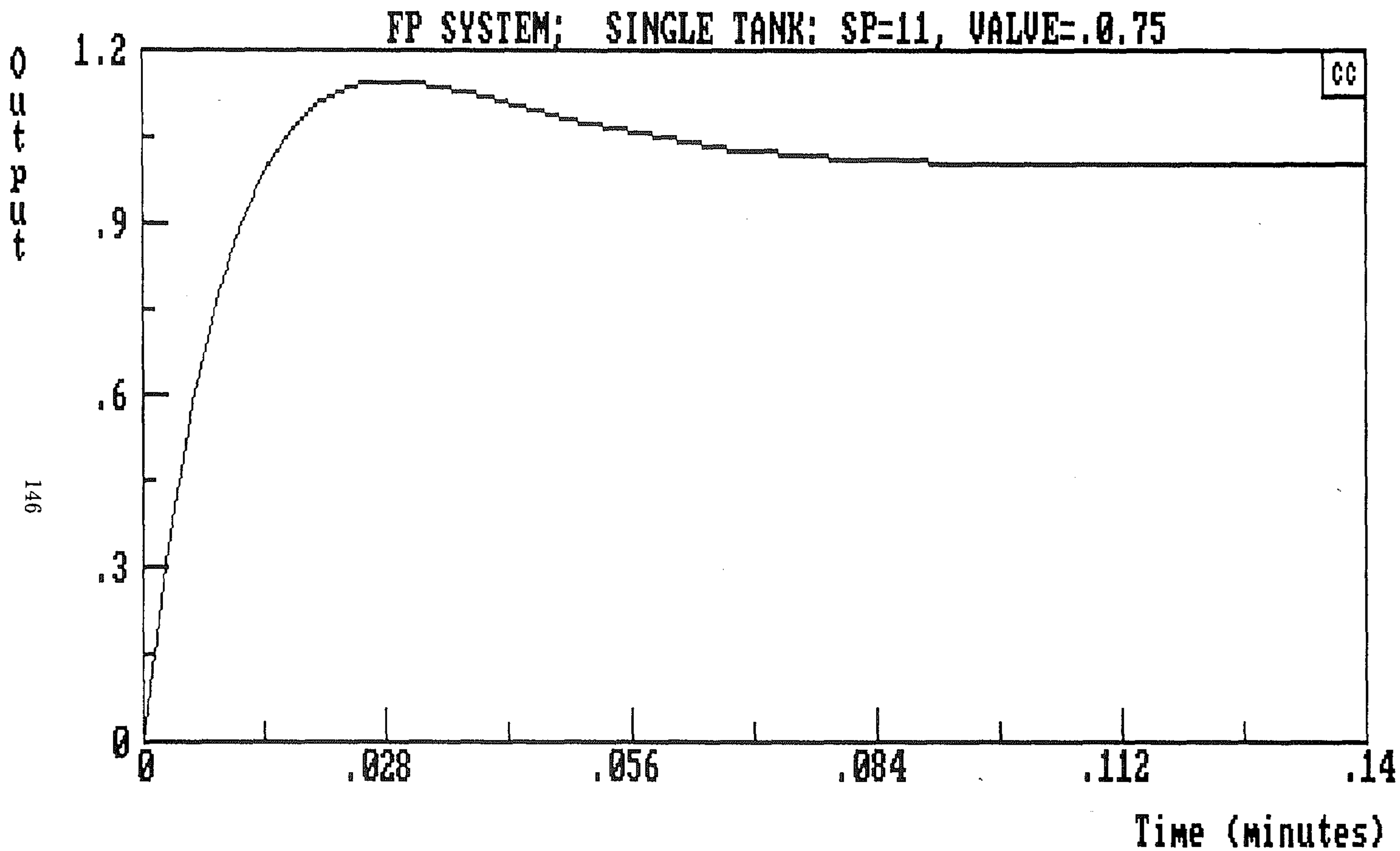

FP SYSTEM; SINGLE TANK: SP=11, VALVE=.0.75
Output
1.2
.9
.6
.3
0
CC
0
.028
.056
.084
.112
.14
Time (minutes)

FIGURE B.6

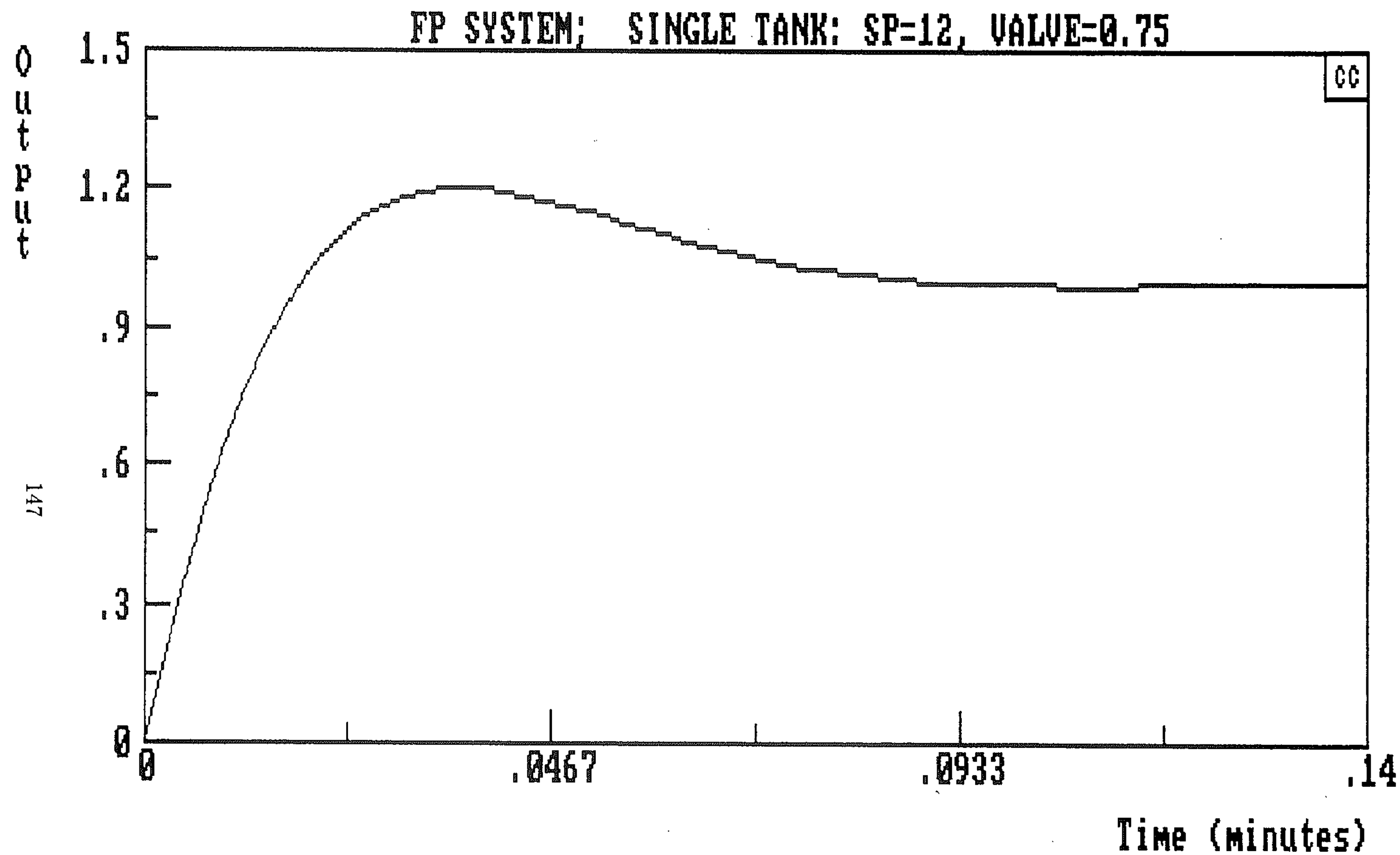

FP SYSTEM; SINGLE TANK: SP=12, VALVE=0.75
Output
1.5
1.2
.9
.6
.3
0
0
.0467
.0933
.14
Time (minutes)
CC

FIGURE B.7

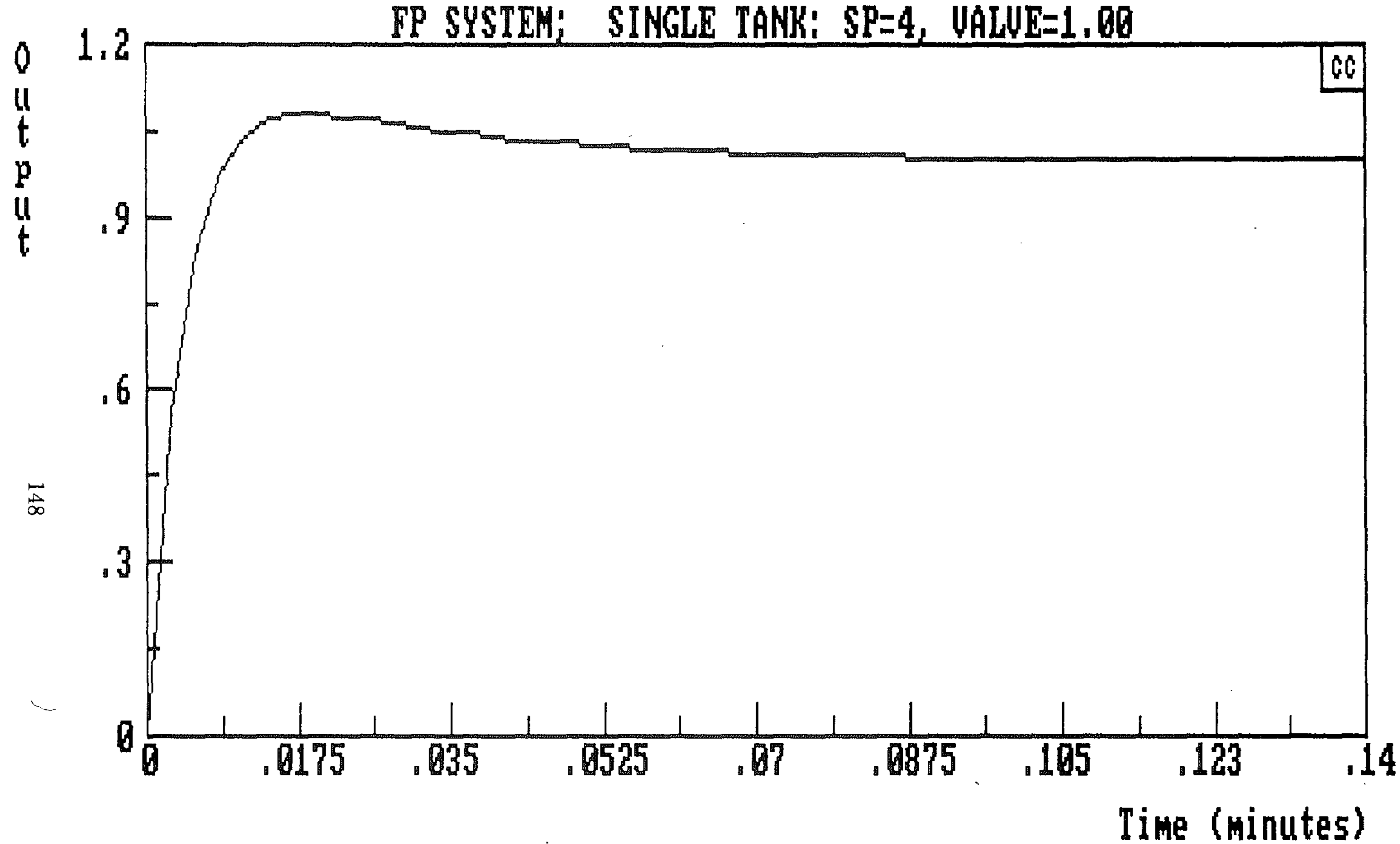
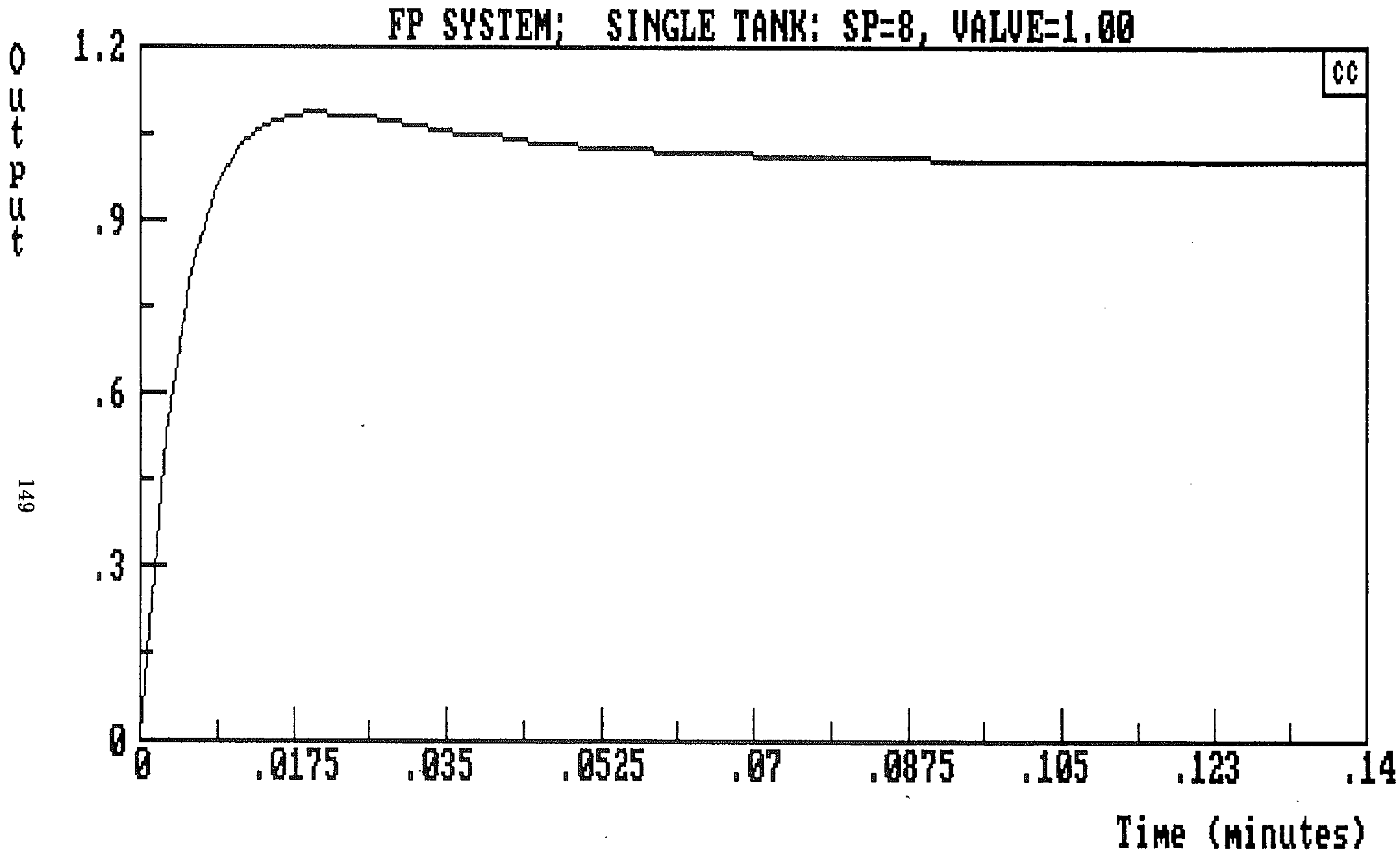

FP SYSTEM; SINGLE TANK: SP=4, VALVE=1.00
CC
Output
1.2
.9
.6
.3
0
0
.0175
.035
.0525
.07
.0875
.105
.123
.14
Time (minutes)

FIGURE B.8



FP SYSTEM; SINGLE TANK: SP=8, VALUE=1.00
CC
Output
1.2
.9
.6
.3
0
0
.0175
.035
.0525
.07
.0875
.105
.123
.14
Time (minutes)

FIGURE B.9

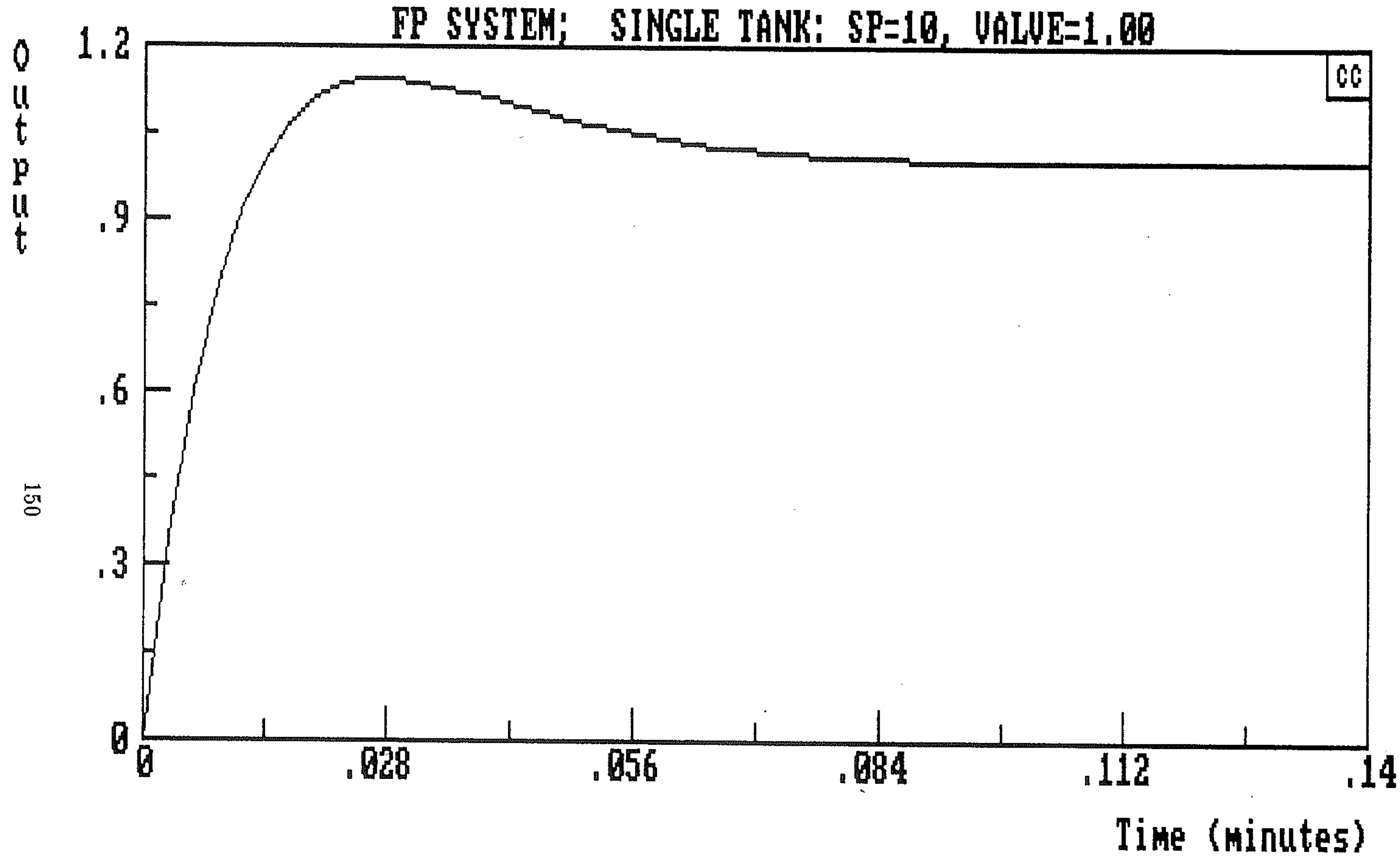

FP SYSTEM; SINGLE TANK: SP=10, VALVE=1.00
CC
Output
1.2
.9
.6
.3
0
0
.028
.056
.084
.112
.14
Time (minutes)

FIGURE B.10

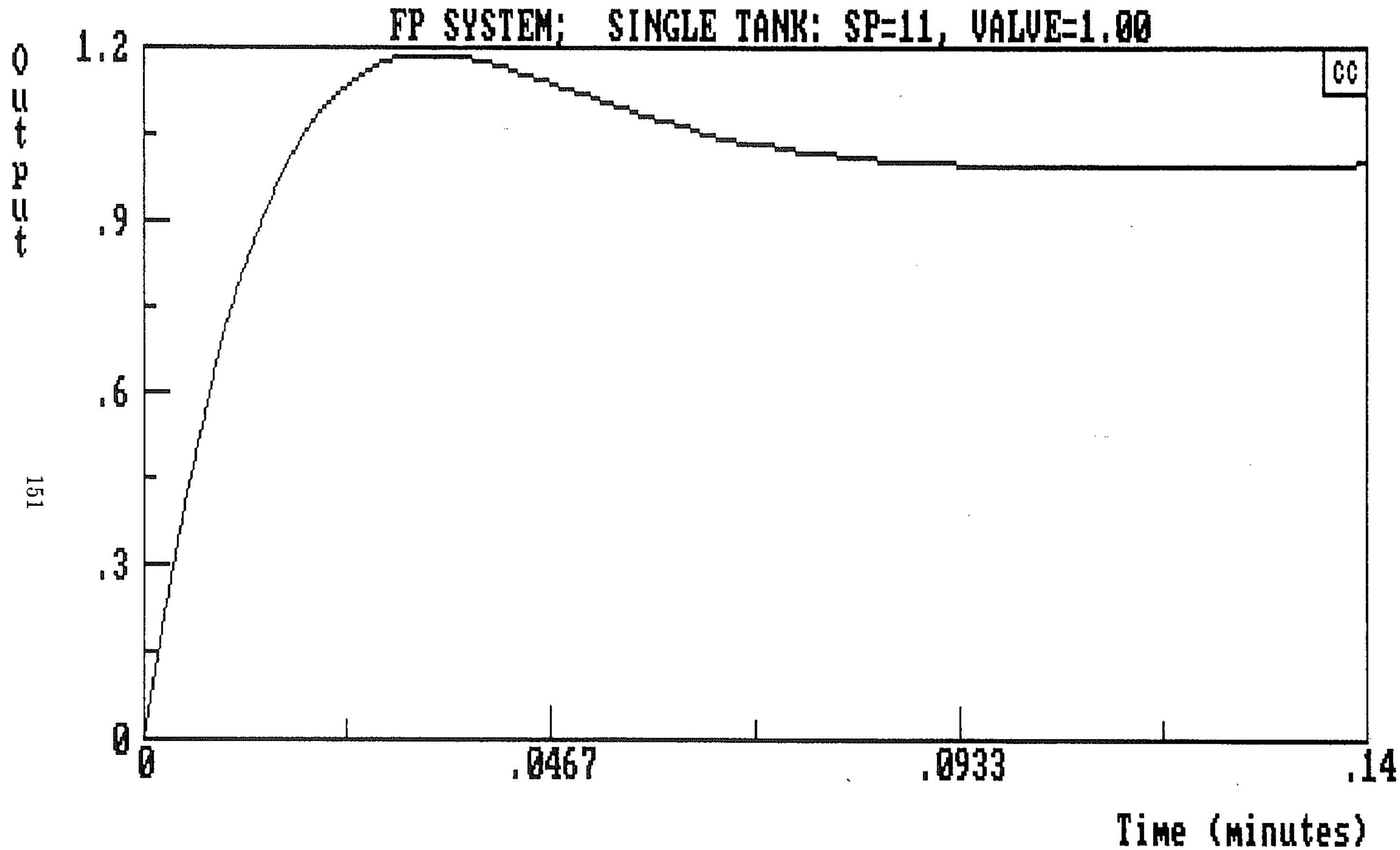

FP SYSTEM; SINGLE TANK: SP=11, VALVE=1.00
Output
1.2
.9
.6
.3
0
CC
0
.0467
.0933
.14
Time (minutes)

FIGURE B.11

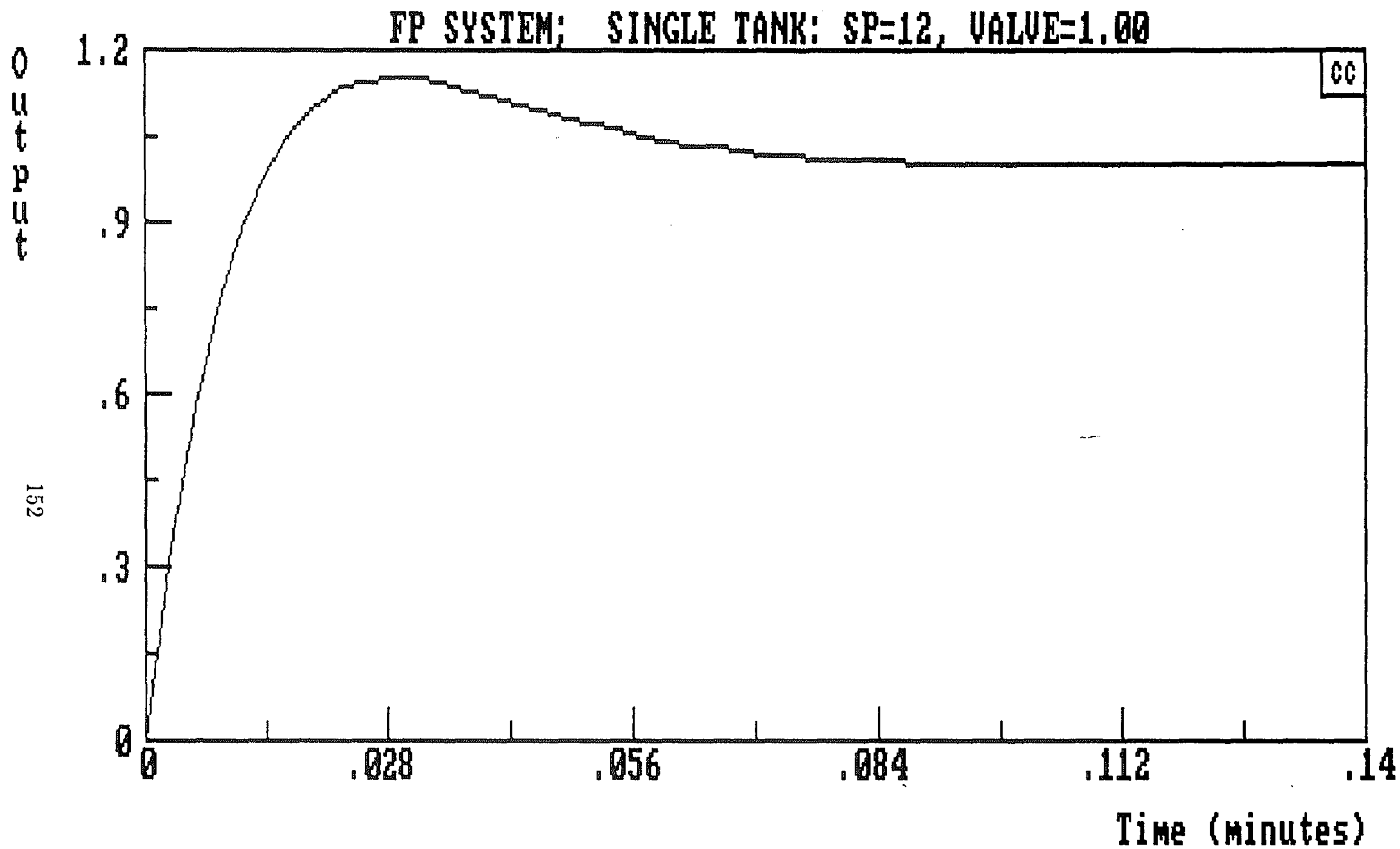

FP SYSTEM; SINGLE TANK: SP=12, VALVE=1.00
CC
Output
1.2
.9
.6
.3
0
0
.028
.056
.084
.112
.14
Time (minutes)

FIGURE B.12

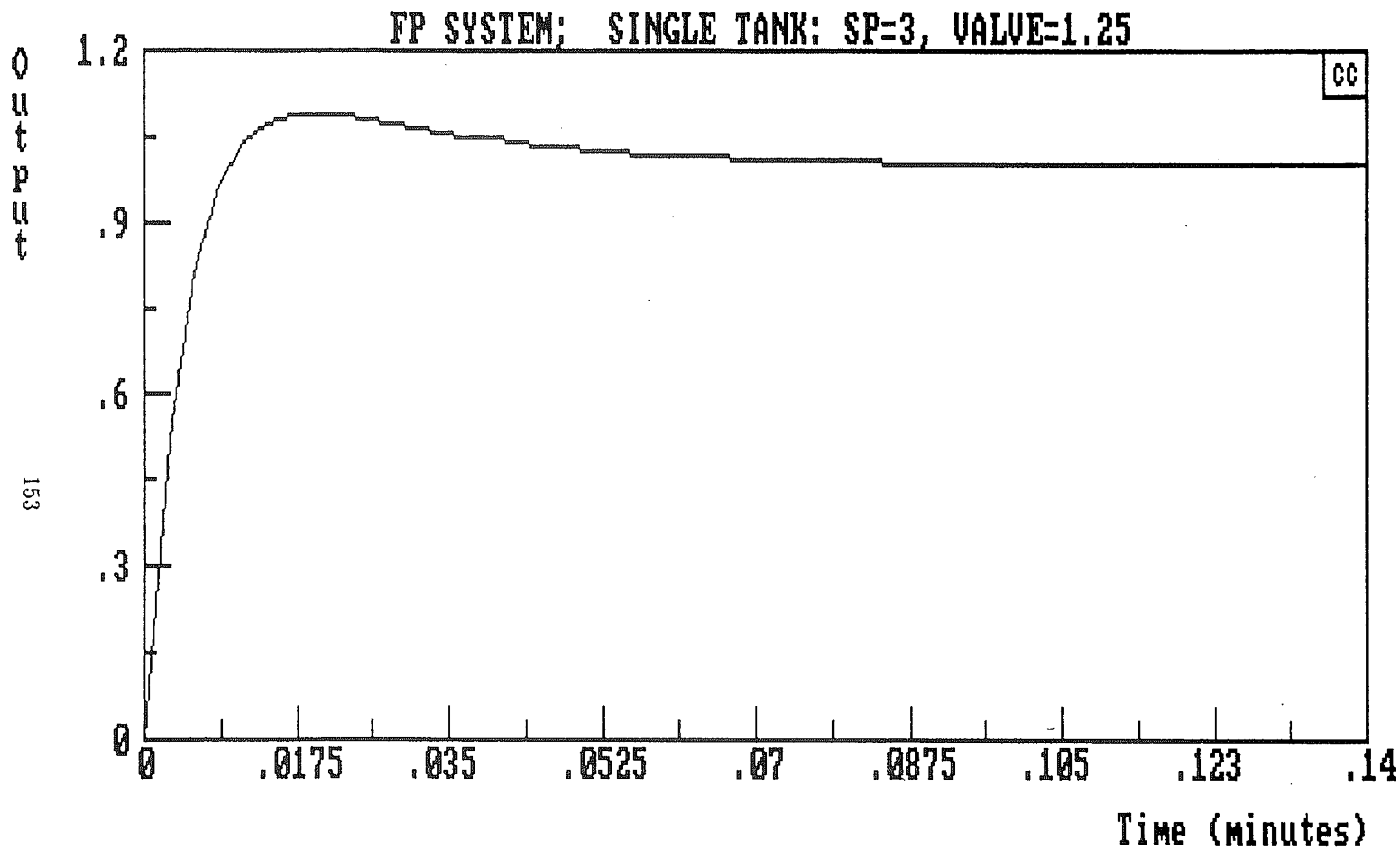

FP SYSTEM; SINGLE TANK: SP=3, VALVE=1.25
CC
Output
1.2
.9
.6
.3
0
0
.0175
.035
.0525
.07
.0875
.105
.123
.14
Time (minutes)

FIGURE B.13

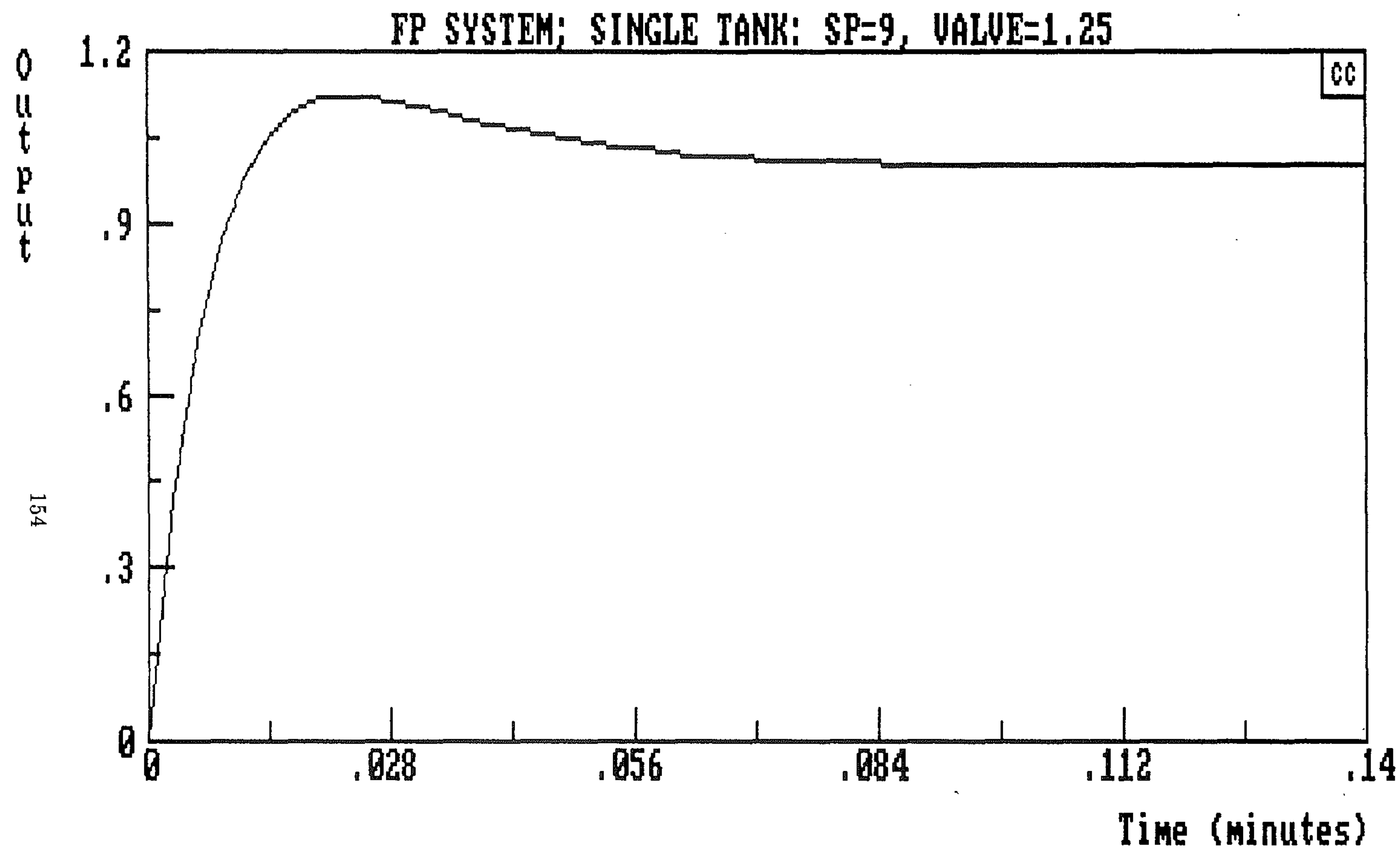

FP SYSTEM; SINGLE TANK: SP=9, VALVE=1.25
Output
1.2
.9
.6
.3
0
CC
0
.028
.056
.084
.112
.14
Time (minutes)

FIGURE B.14

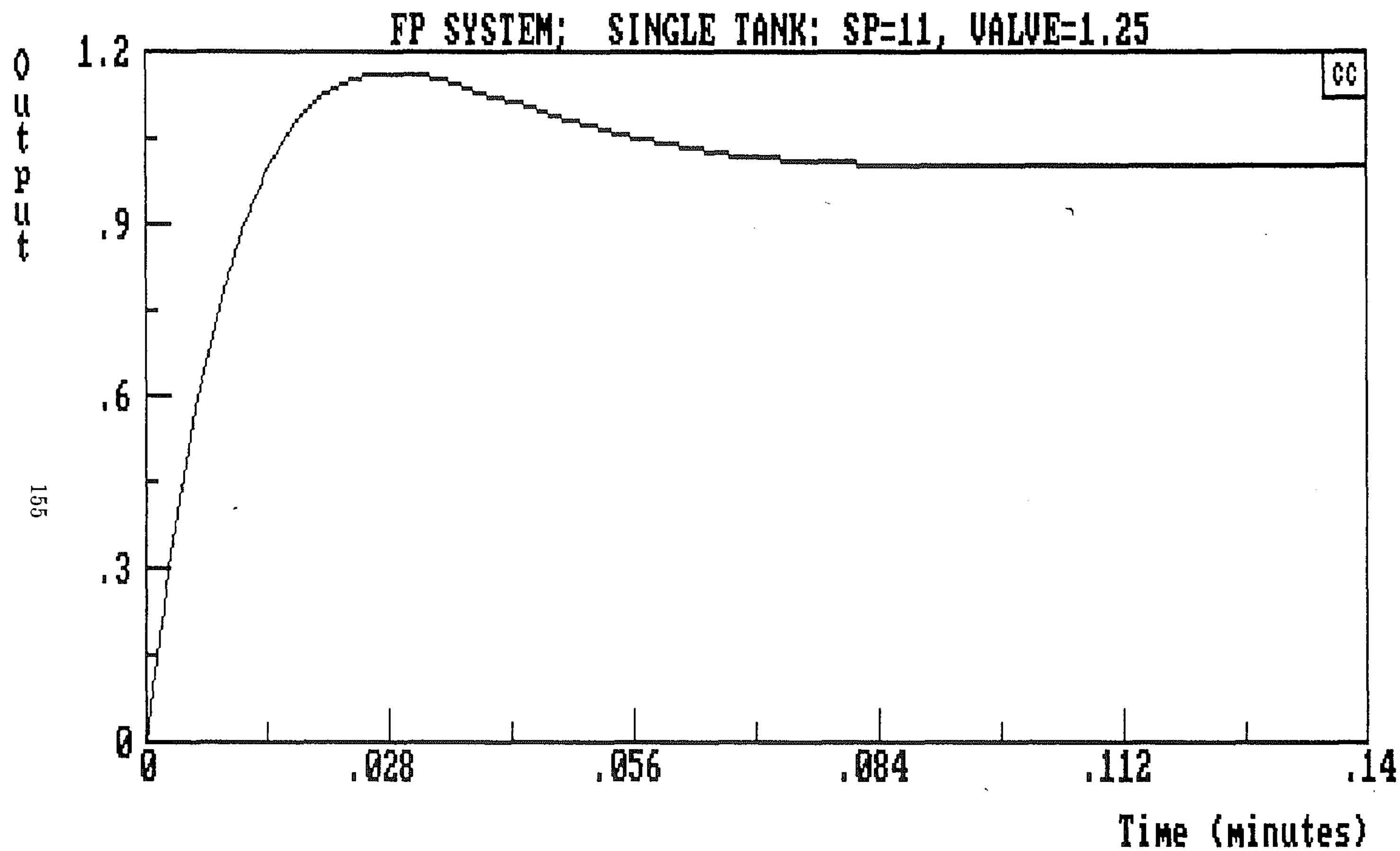
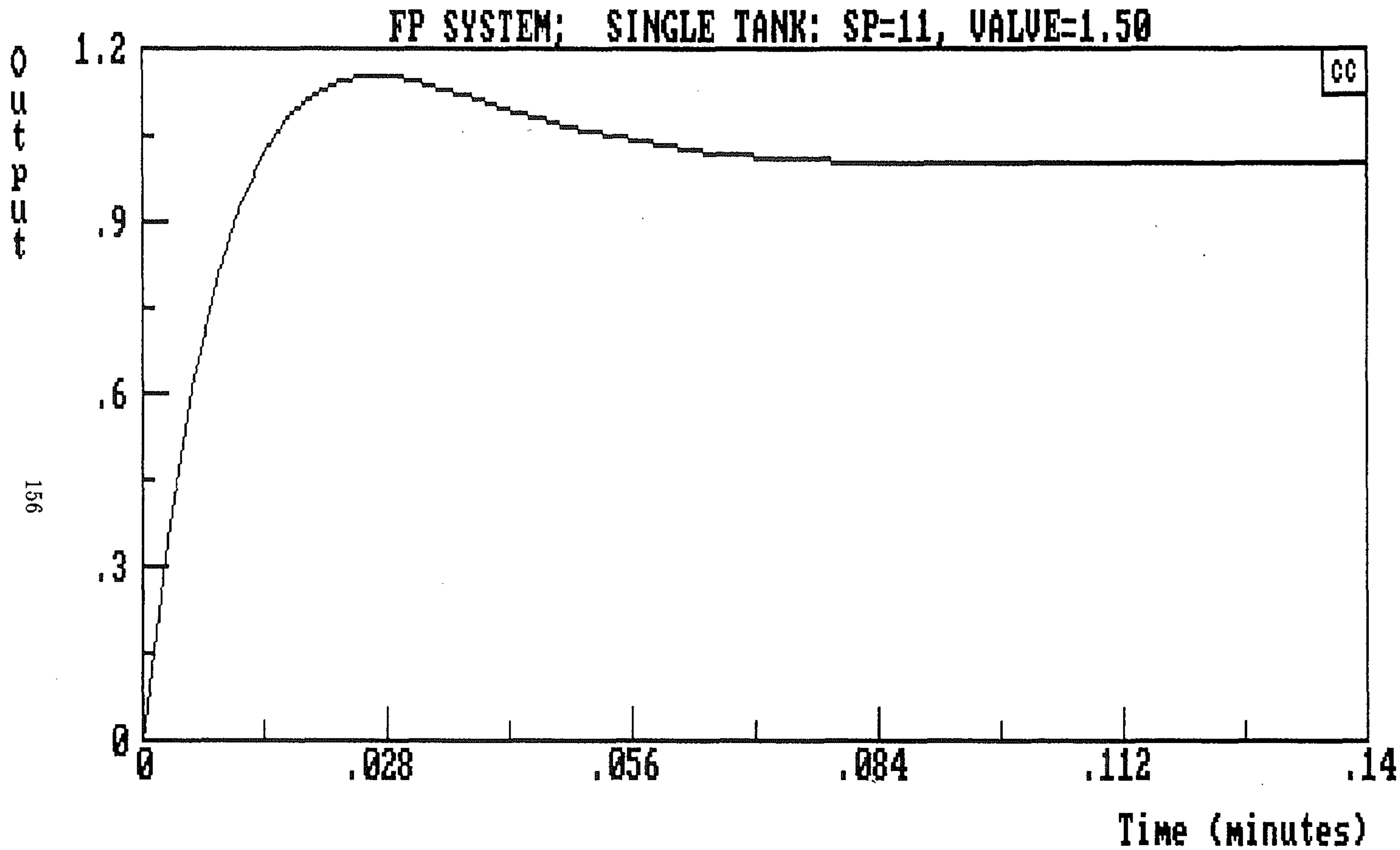
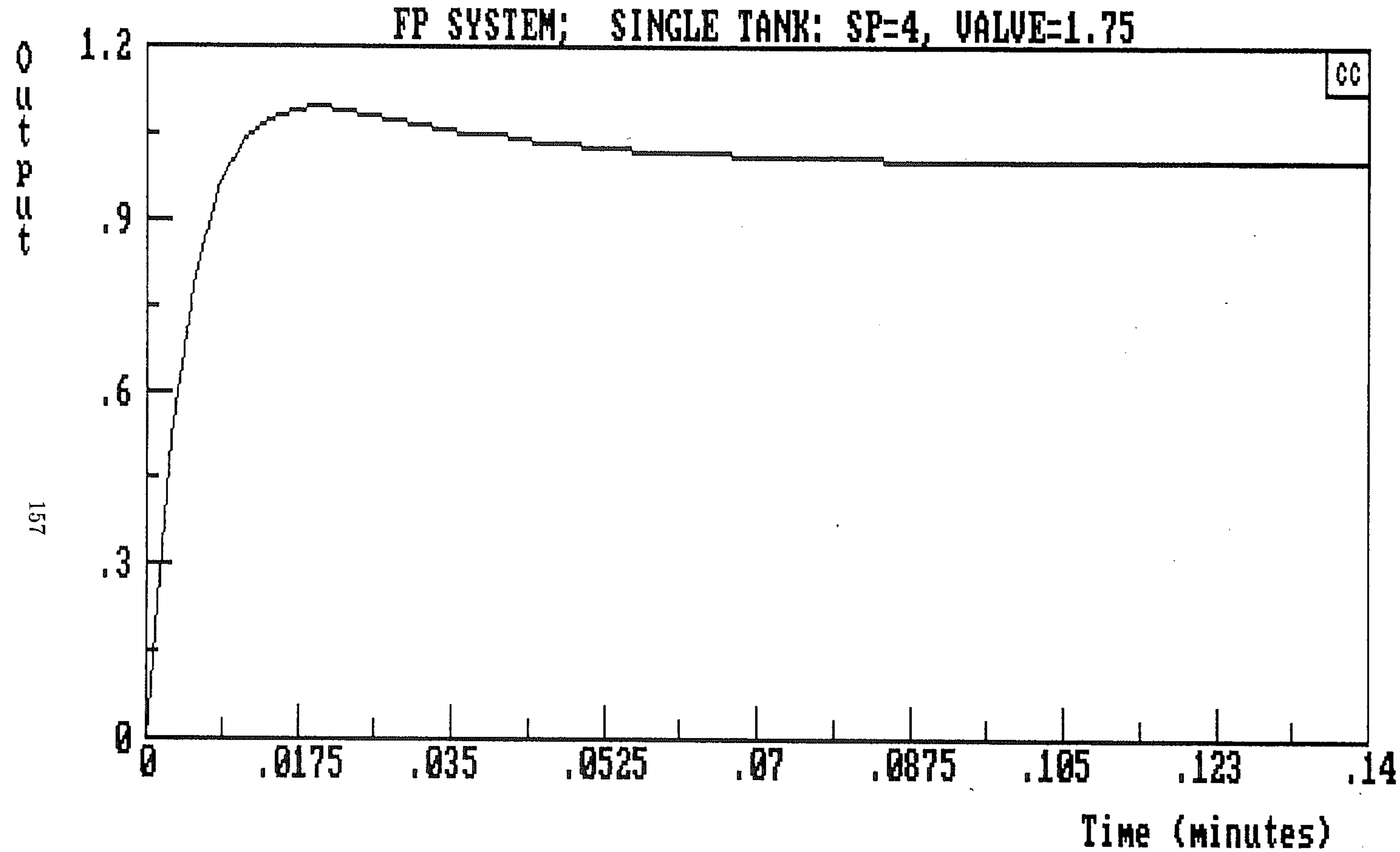

FP SYSTEM; SINGLE TANK: SP=11, VALVE=1.25
Output
1.2
.9
.6
.3
0
CC
0
.028
.056
.084
.112
.14
Time (minutes)

FIGURE B.15



FP SYSTEM; SINGLE TANK: SP=11, VALVE=1.50
Output
1.2
.9
.6
.3
0
CC
0
.028
.056
.084
.112
.14
Time (minutes)

FIGURE B.16



FP SYSTEM; SINGLE TANK: SP=4, VALVE=1.75
Output
1.2
.9
.6
.3
0
CC
0
.0175
.035
.0525
.07
.0875
.105
.123
.14
Time (minutes)

FIGURE B.17

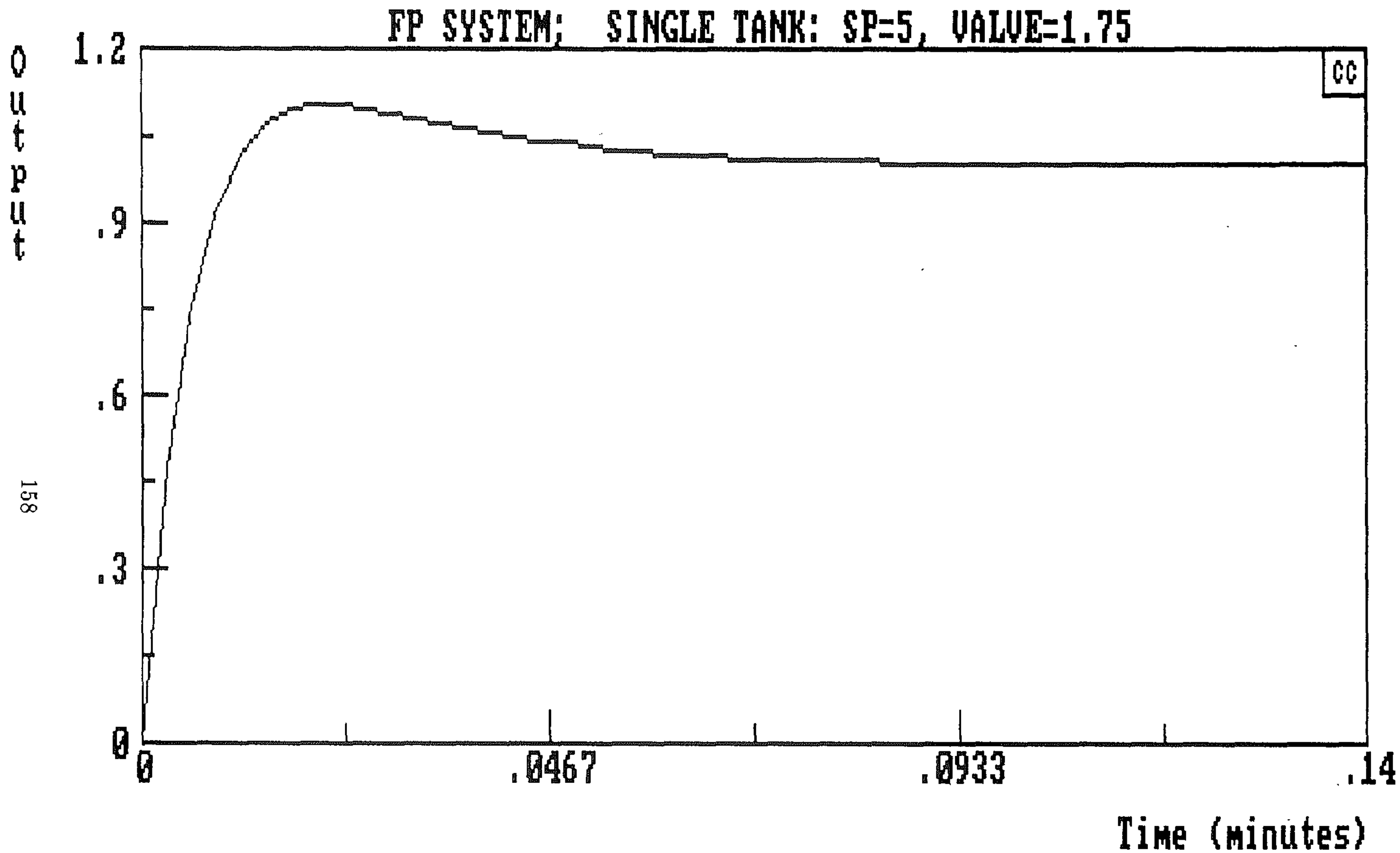

FP SYSTEM; SINGLE TANK: SP=5, VALUE=1.75
Output
1.2
.9
.6
.3
0
CC
0
.0467
.0933
.14
Time (minutes)

FIGURE B.18

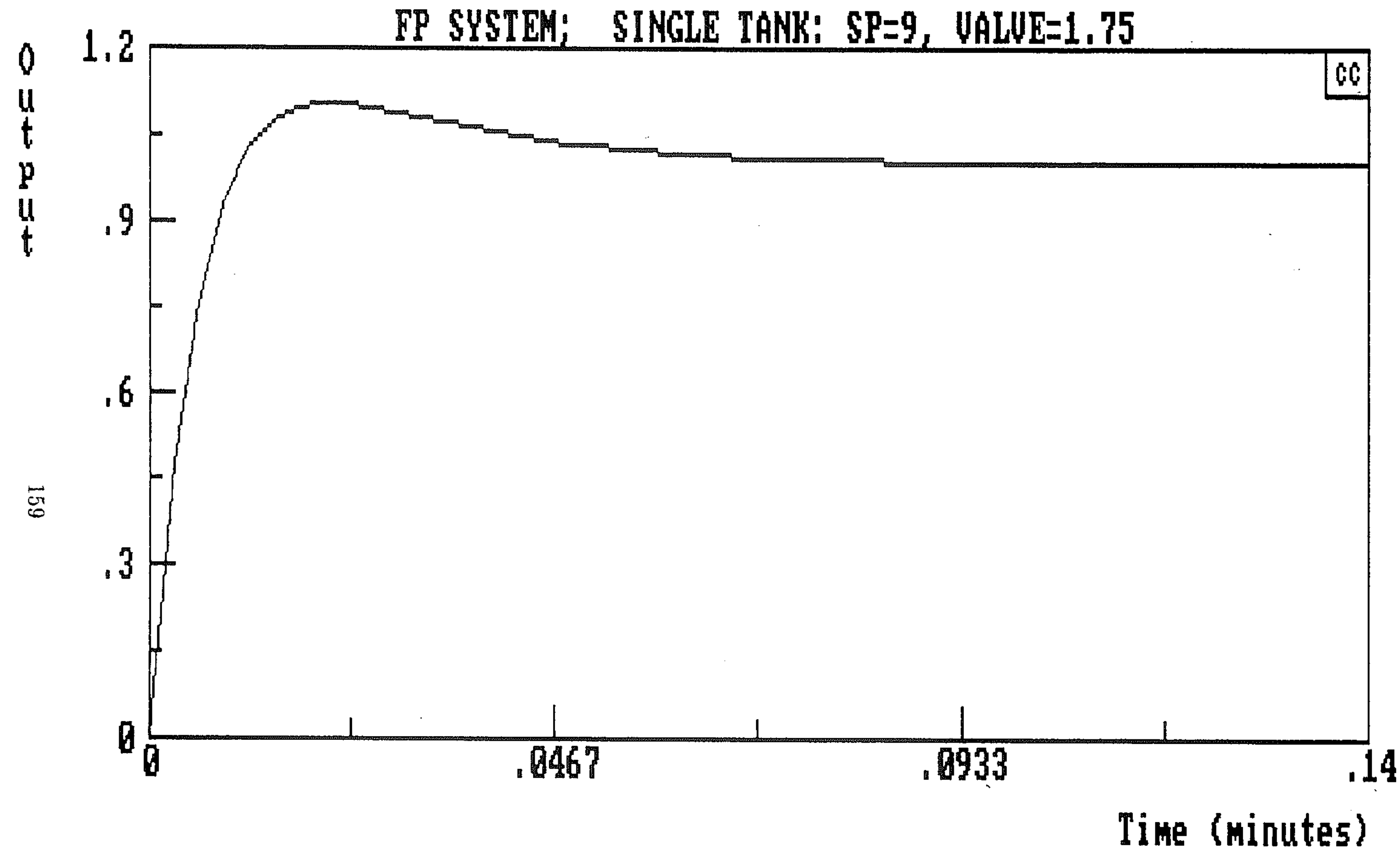

FP SYSTEM; SINGLE TANK: SP=9, VALVE=1.75
Output
1.2
.9
.6
.3
0
CC
0
.0467
.0933
.14
Time (minutes)

FIGURE B.19

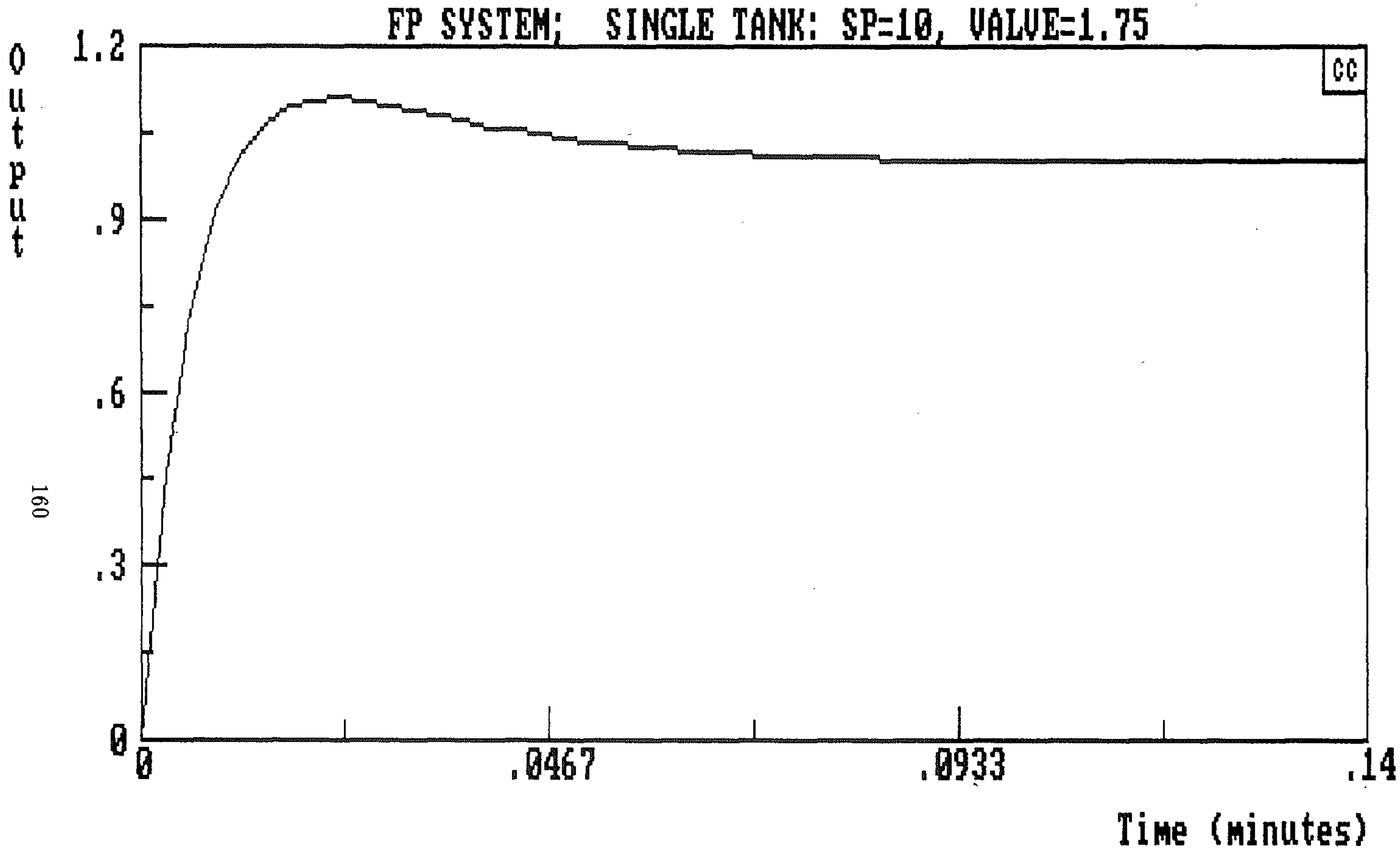

FP SYSTEM; SINGLE TANK: SP=10, VALVE=1.75
Output
1.2
.9
.6
.3
0
CC
0
.0467
.0933
.14
Time (minutes)

FIGURE B.20

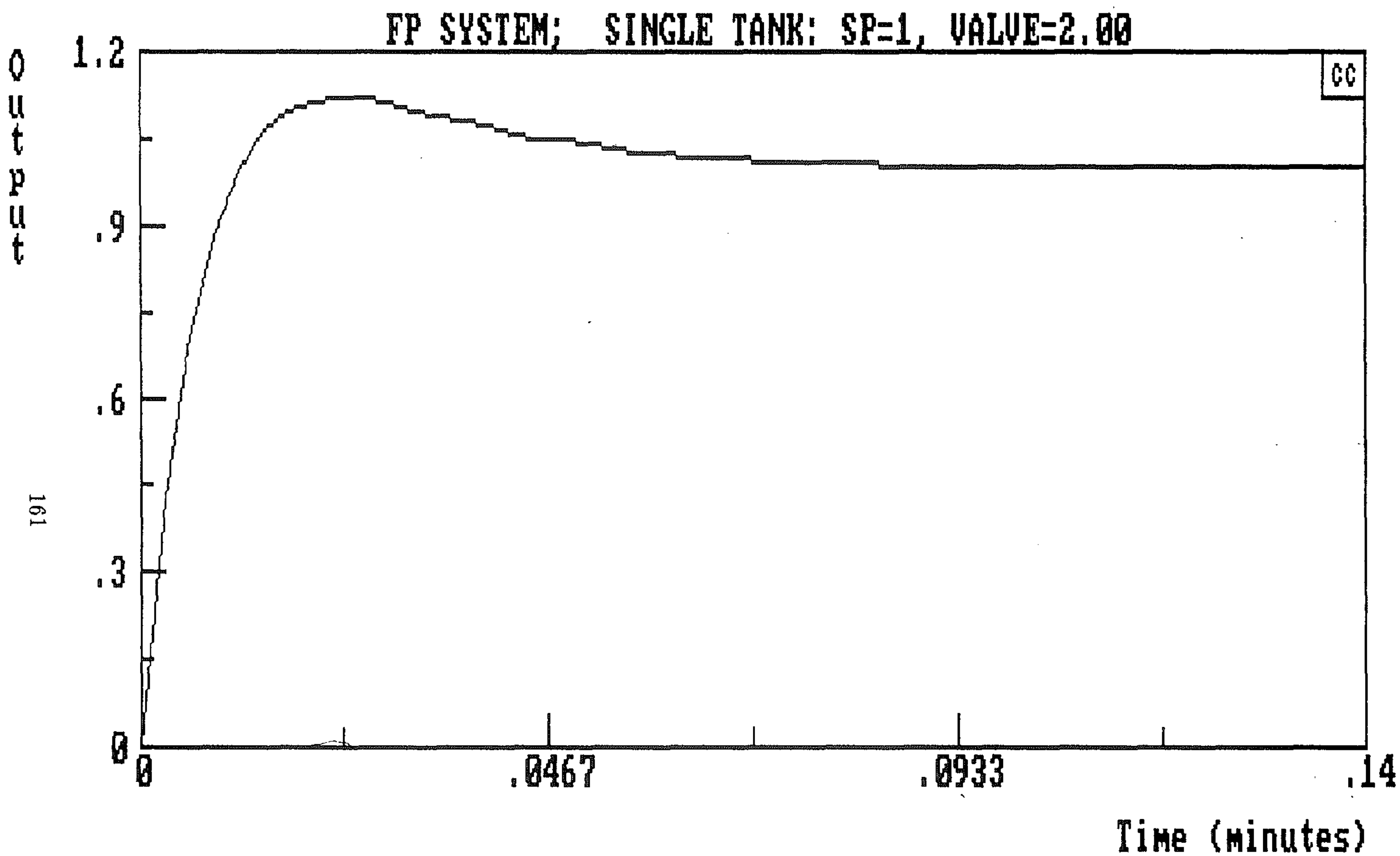

FP SYSTEM; SINGLE TANK: SP=1, VALVE=2.00
Output
1.2
.9
.6
.3
0
CC
0
.0467
.0933
.14
Time (minutes)

FIGURE B.21

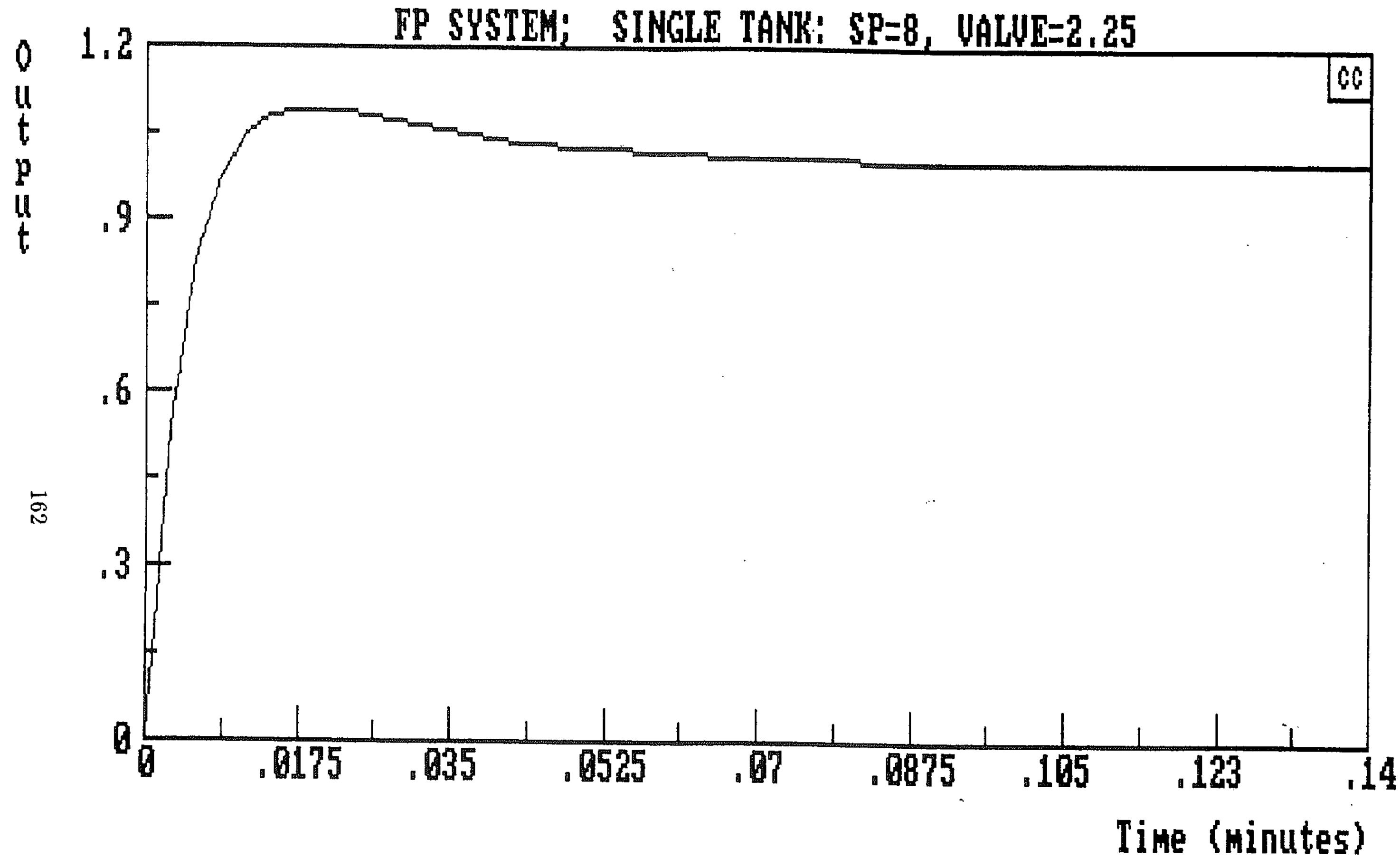

FP SYSTEM; SINGLE TANK: SP=8, VALUE=2.25
Output
1.2
.9
.6
.3
0
CC
0
.0175
.035
.0525
.07
.0875
.105
.123
.14
Time (minutes)

FIGURE B.22

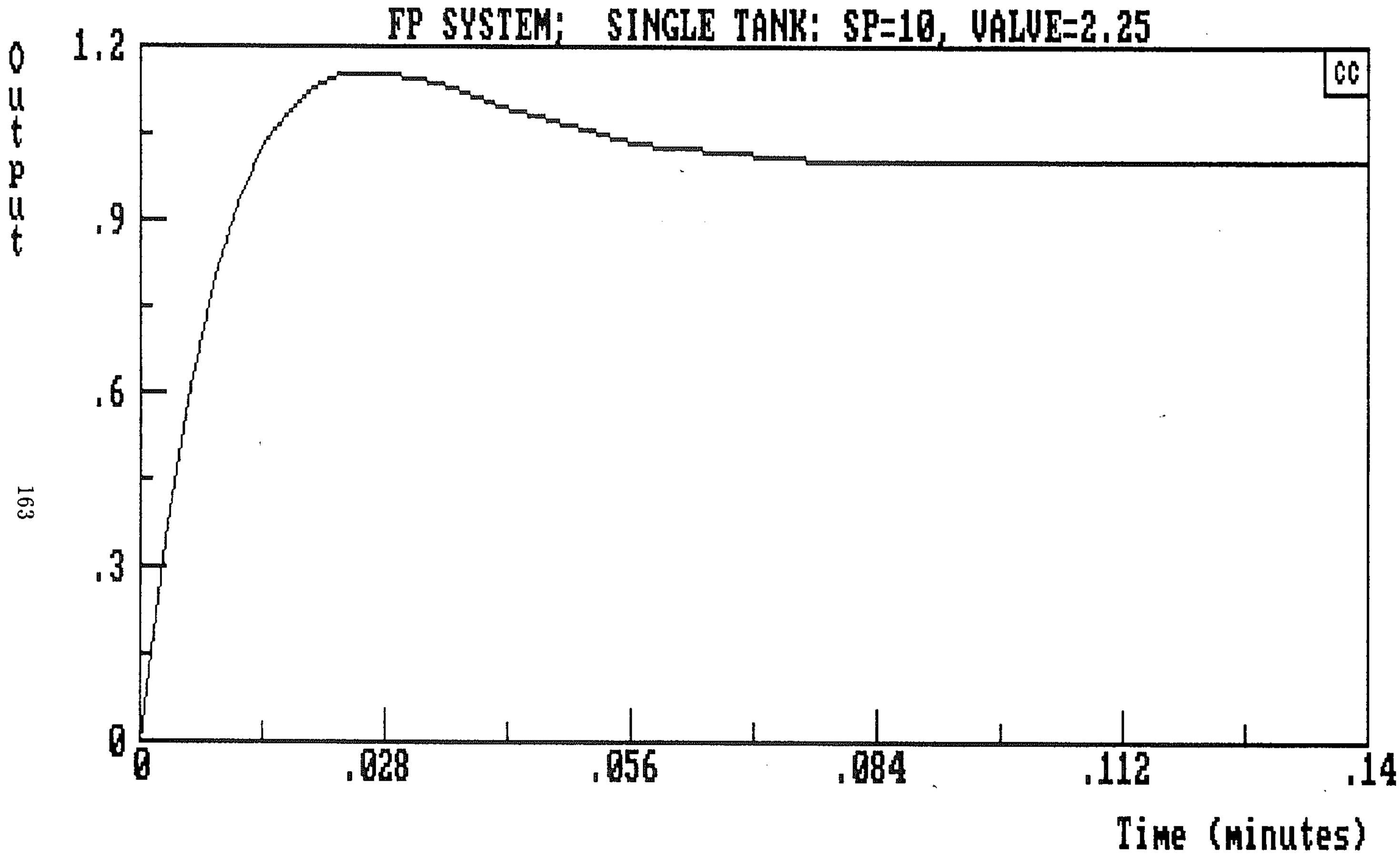

FP SYSTEM; SINGLE TANK: SP=10, VALVE=2.25
CC
Output
1.2
.9
.6
.3
0
0
.028
.056
.084
.112
.14
Time (minutes)

FIGURE B.23

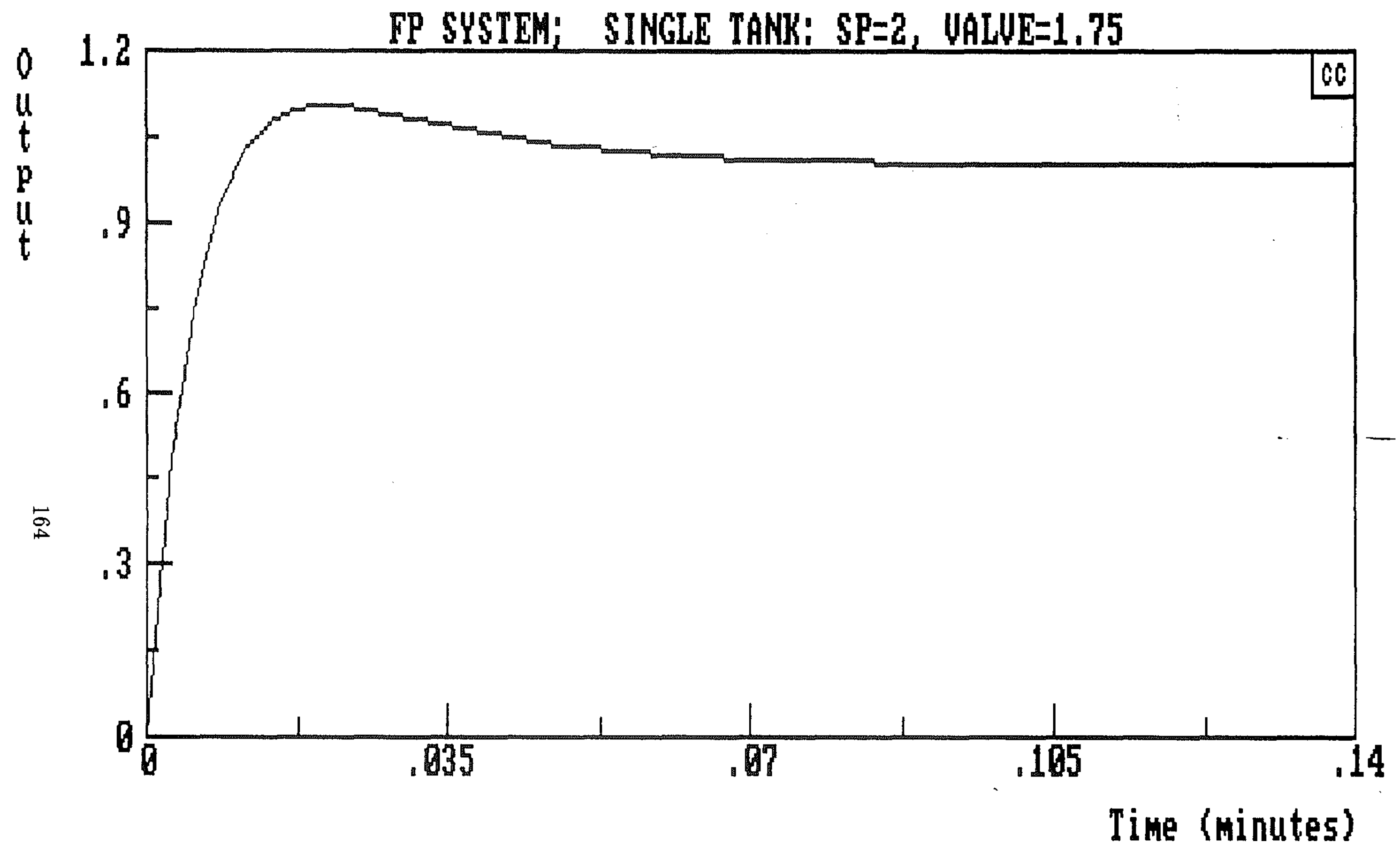

FP SYSTEM; SINGLE TANK: SP=2, VALUE=1.75
CC
Output
1.2
.9
.6
.3
0
0
.035
.07
.105
.14
Time (minutes)

FIGURE B.24

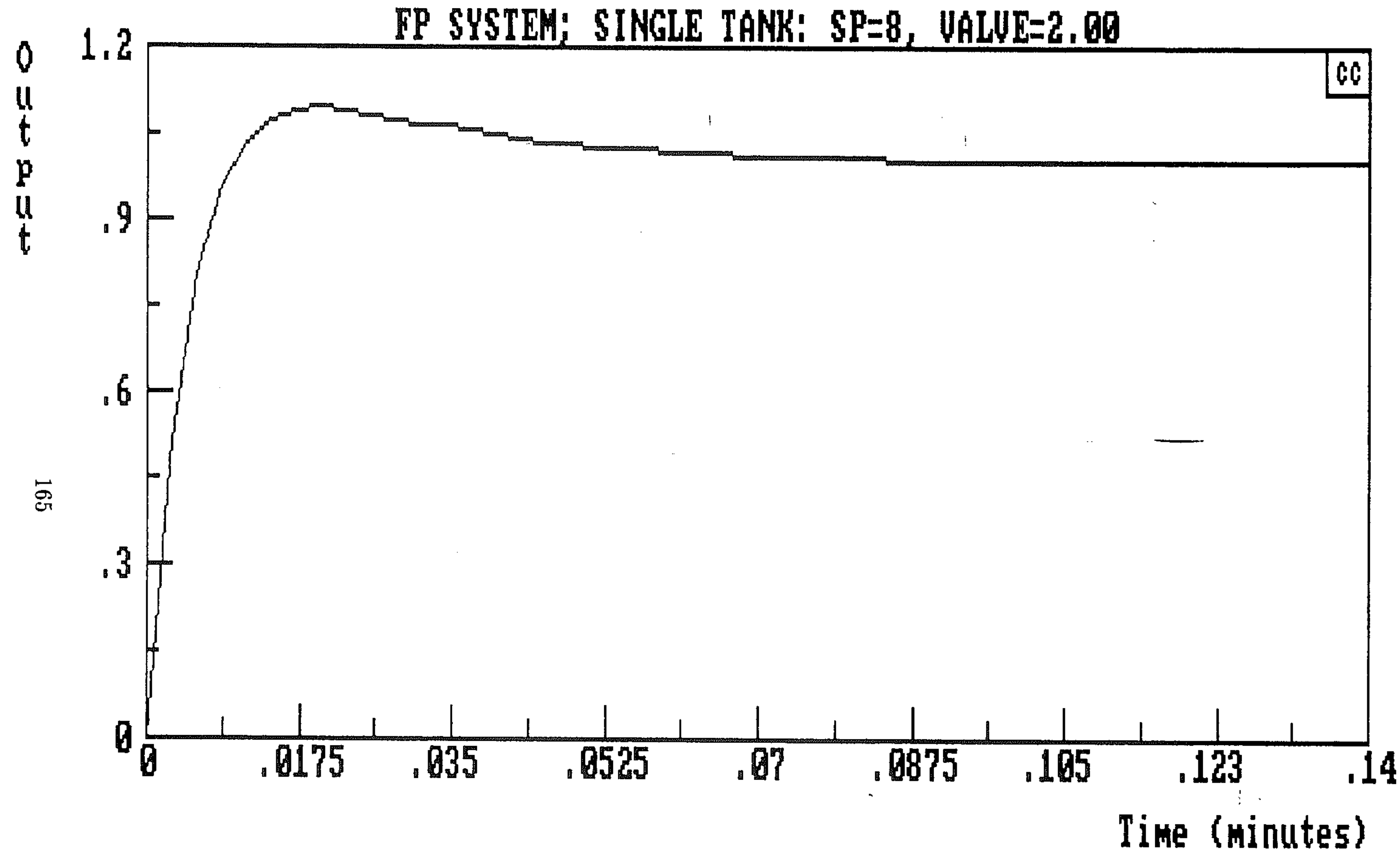

FP SYSTEM; SINGLE TANK: SP=8, VALVE=2.00
CC
Output
1.2
.9
.6
.3
0
0
.0175
.035
.0525
.07
.0875
.105
.123
.14
Time (minutes)

FIGURE B.25

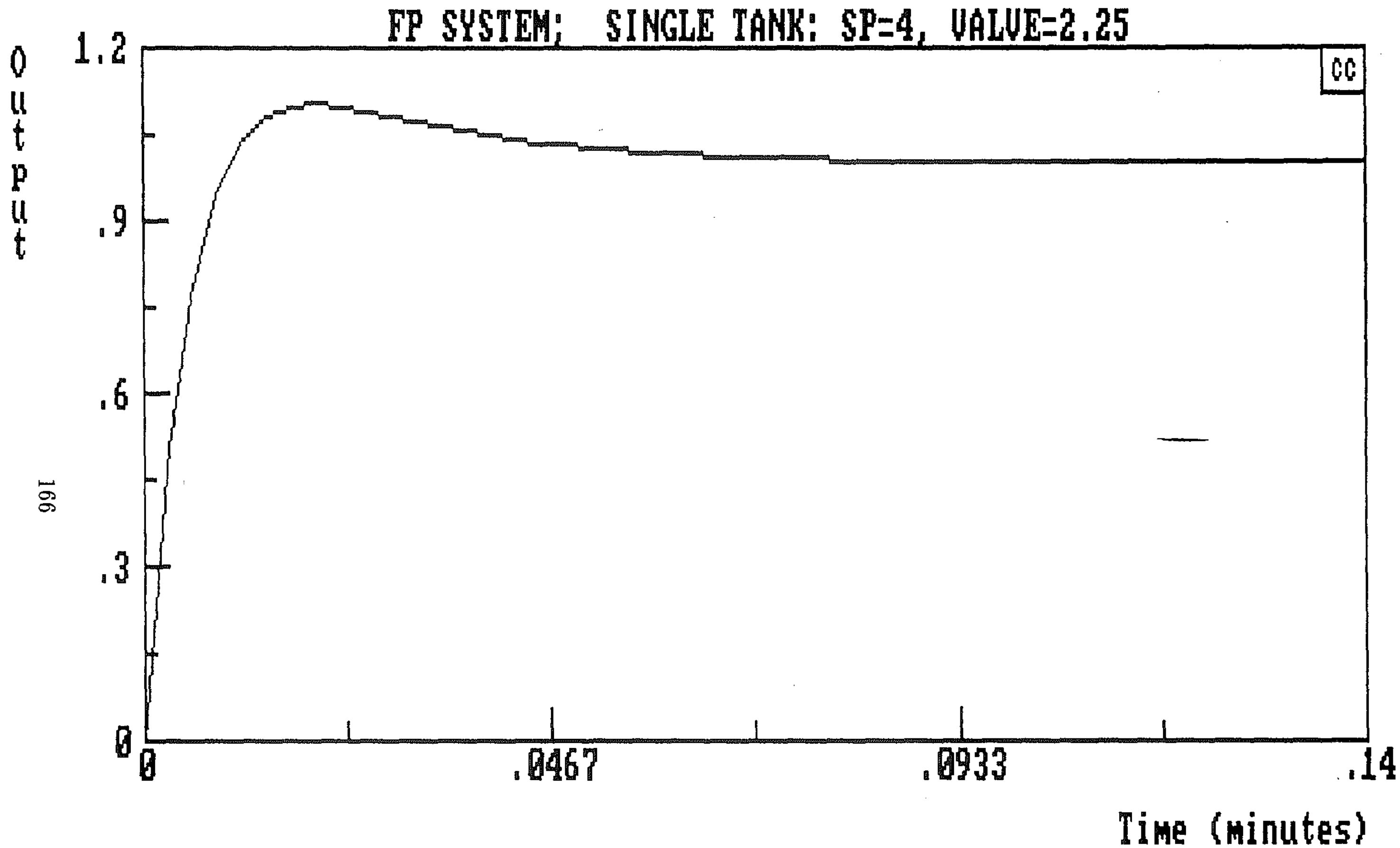

FP SYSTEM; SINGLE TANK: SP=4, VALVE=2.25
Output
1.2
.9
.6
.3
0
CC
0
.0467
.0933
.14
Time (minutes)

FIGURE B.26

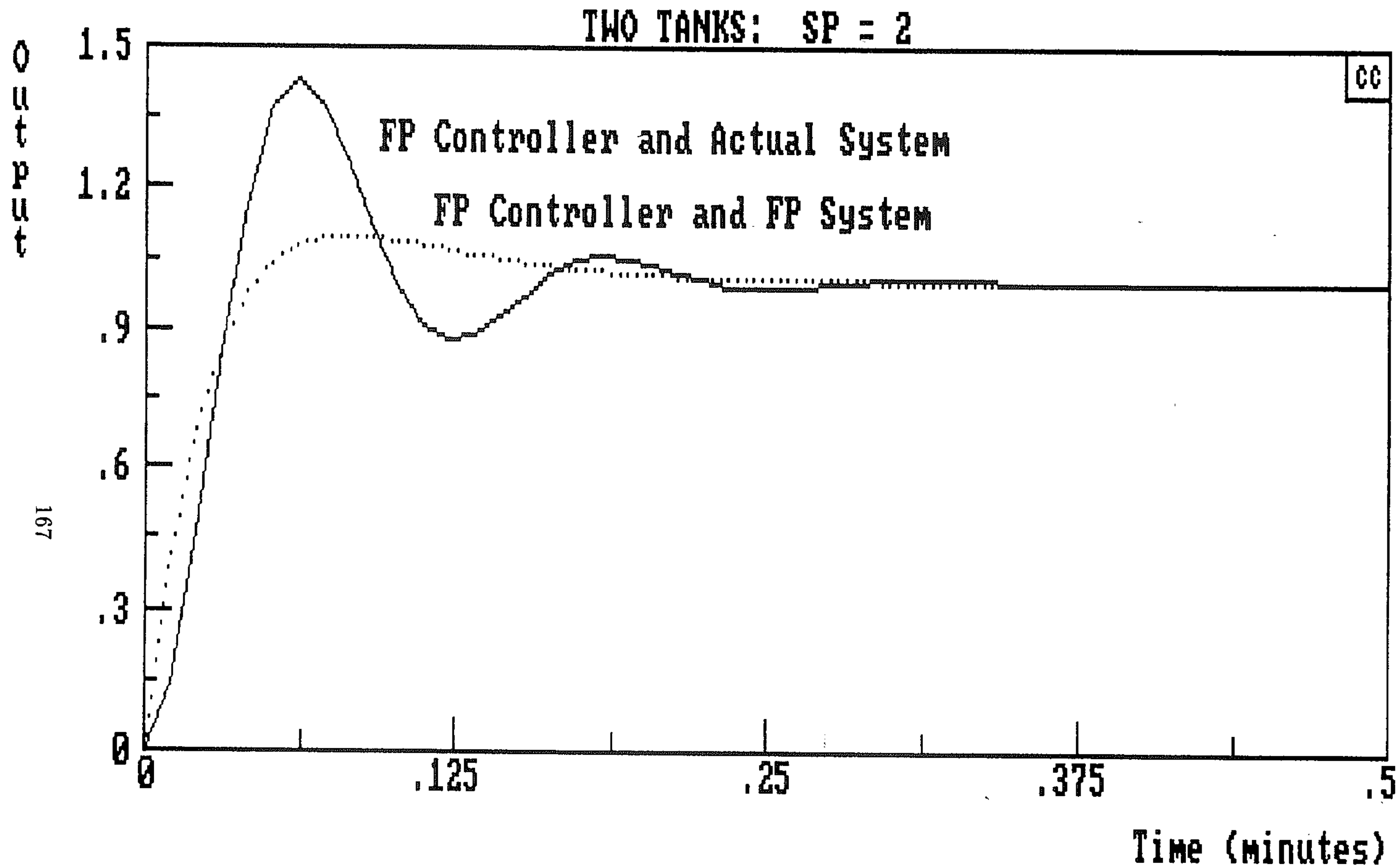

TWO TANKS: SP = 2
Output
1.5
1.2
.9
.6
.3
0
CC
FP Controller and Actual System
FP Controller and FP System
0
.125
.25
.375
.5
Time (minutes)

FIGURE B1.1

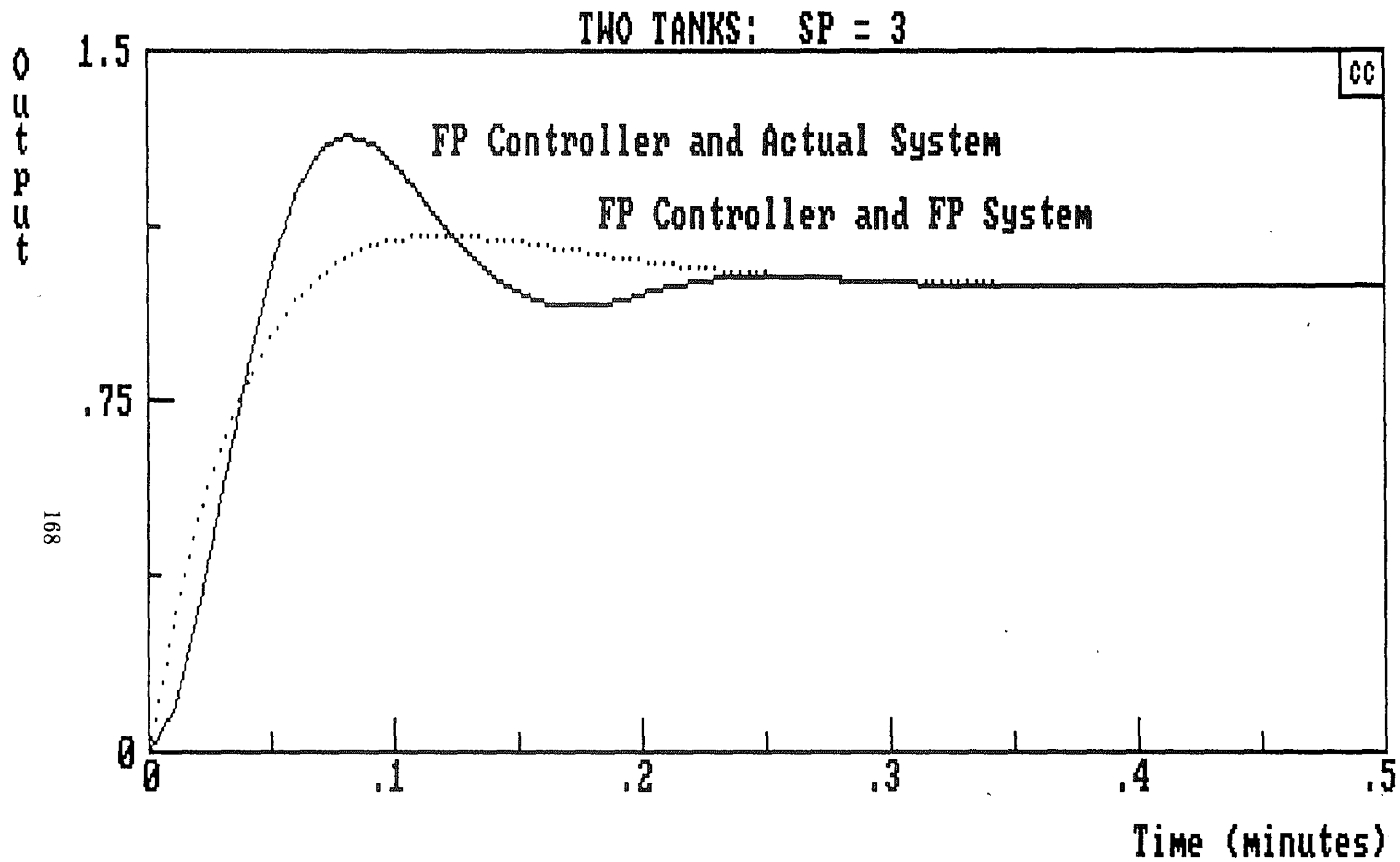
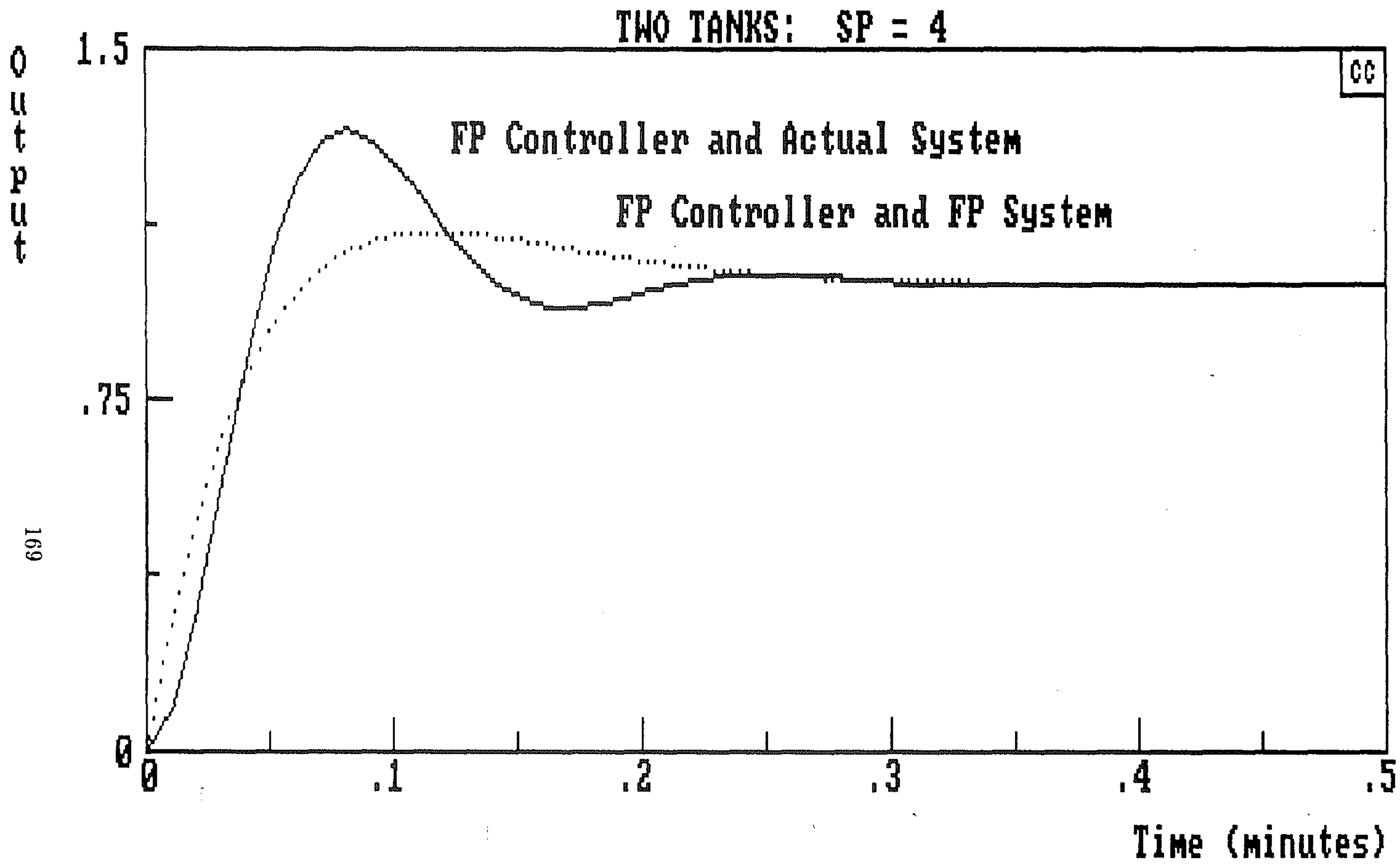

TWO TANKS: SP = 3
Output
1.5
.75
0
CC
FP Controller and Actual System
FP Controller and FP System
0
.1
.2
.3
.4
.5
Time (minutes)

FIGURE B1.2



TWO TANKS: SP = 4
Output
1.5
.75
0
0
.1
.2
.3
.4
.5
Time (minutes)
CC
FP Controller and Actual System
FP Controller and FP System

FIGURE B1.3

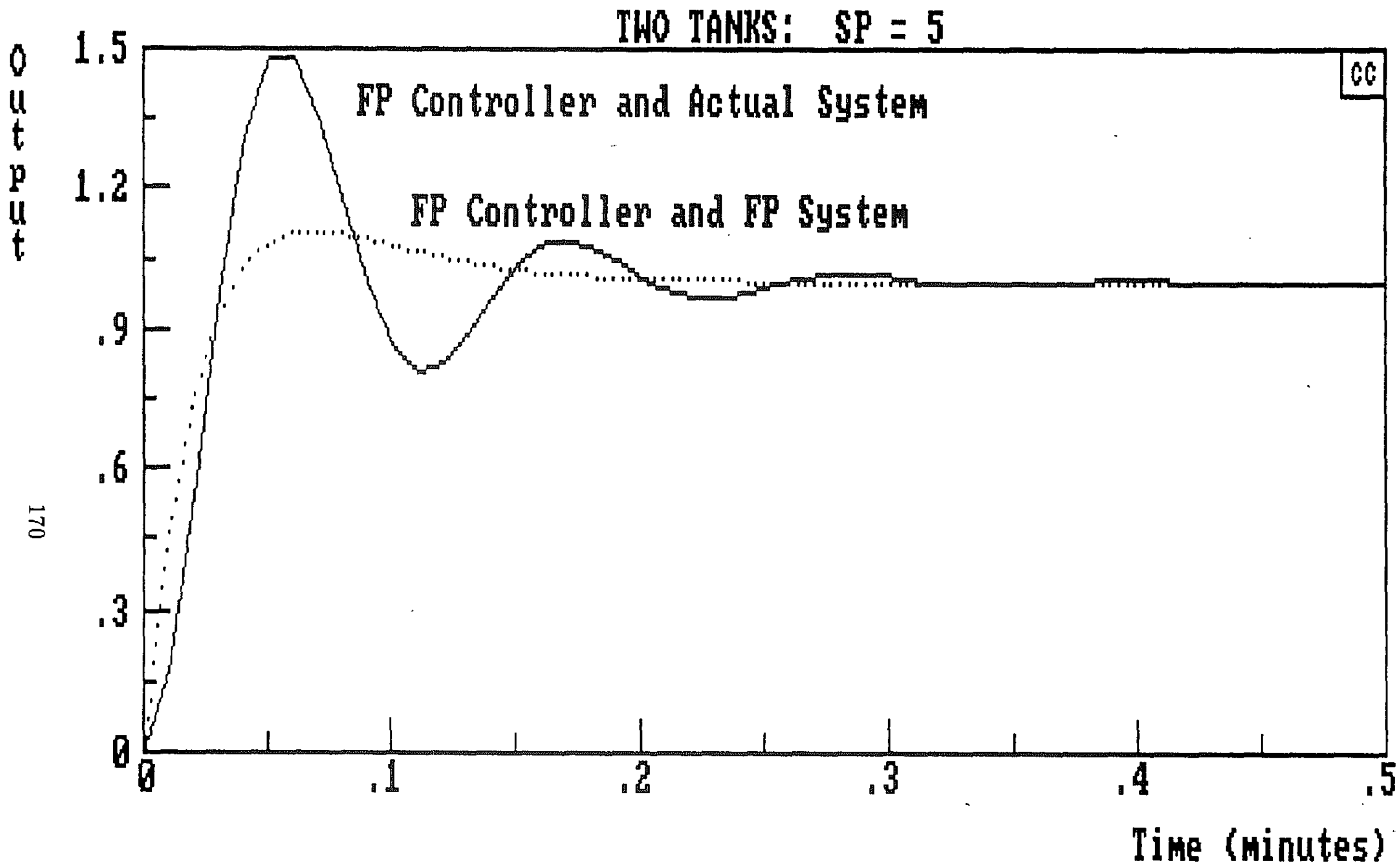

TWO TANKS: SP = 5
FP Controller and Actual System
FP Controller and FP System
CC
Output
1.5
1.2
.9
.6
.3
0
.1
.2
.3
.4
.5
Time (minutes)

FIGURE B1.4

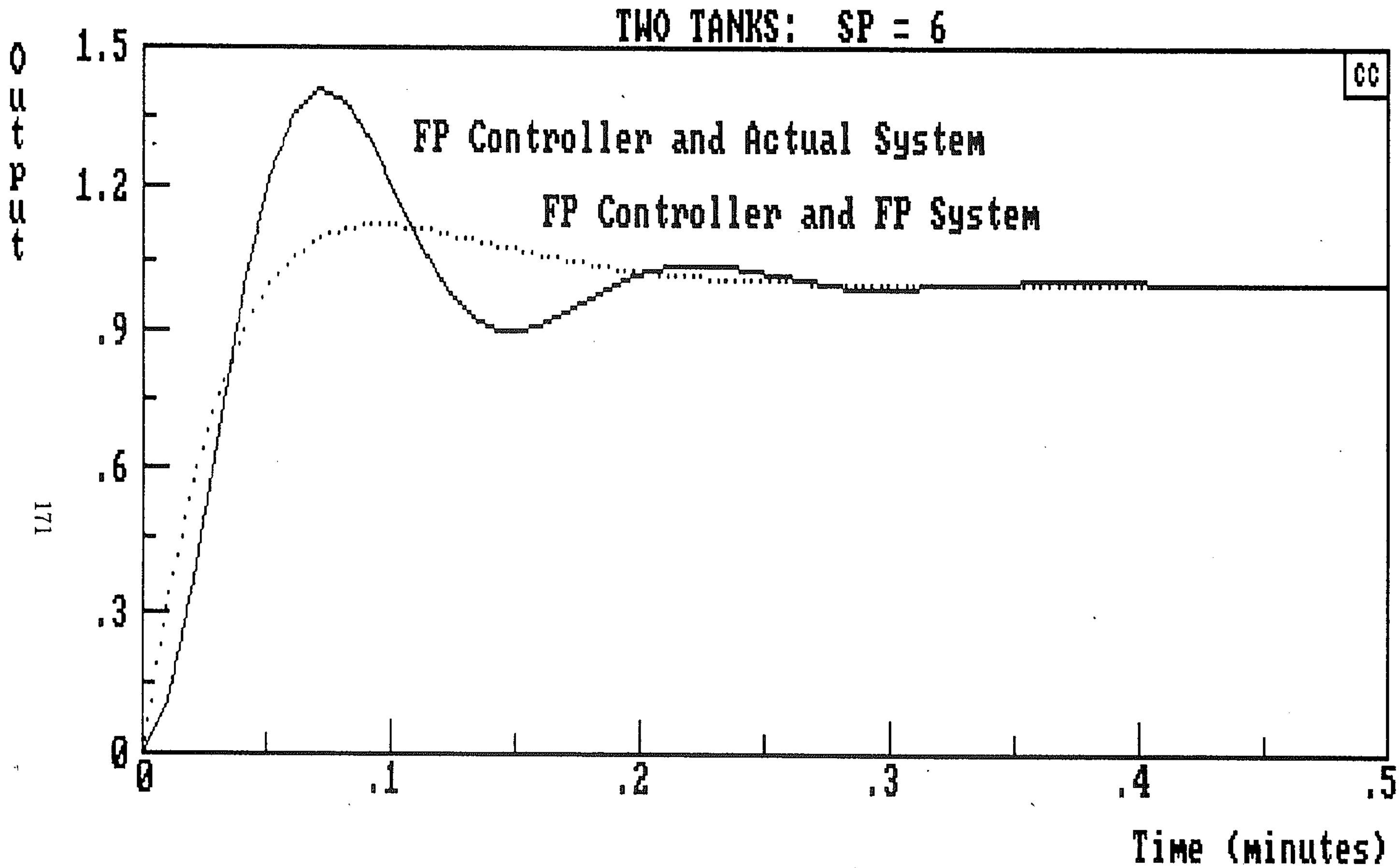

TWO TANKS: SP = 6
Output
1.5
1.2
.9
.6
.3
0
.1
.2
.3
.4
.5
Time (minutes)
CC
FP Controller and Actual System
FP Controller and FP System

FIGURE B1.5

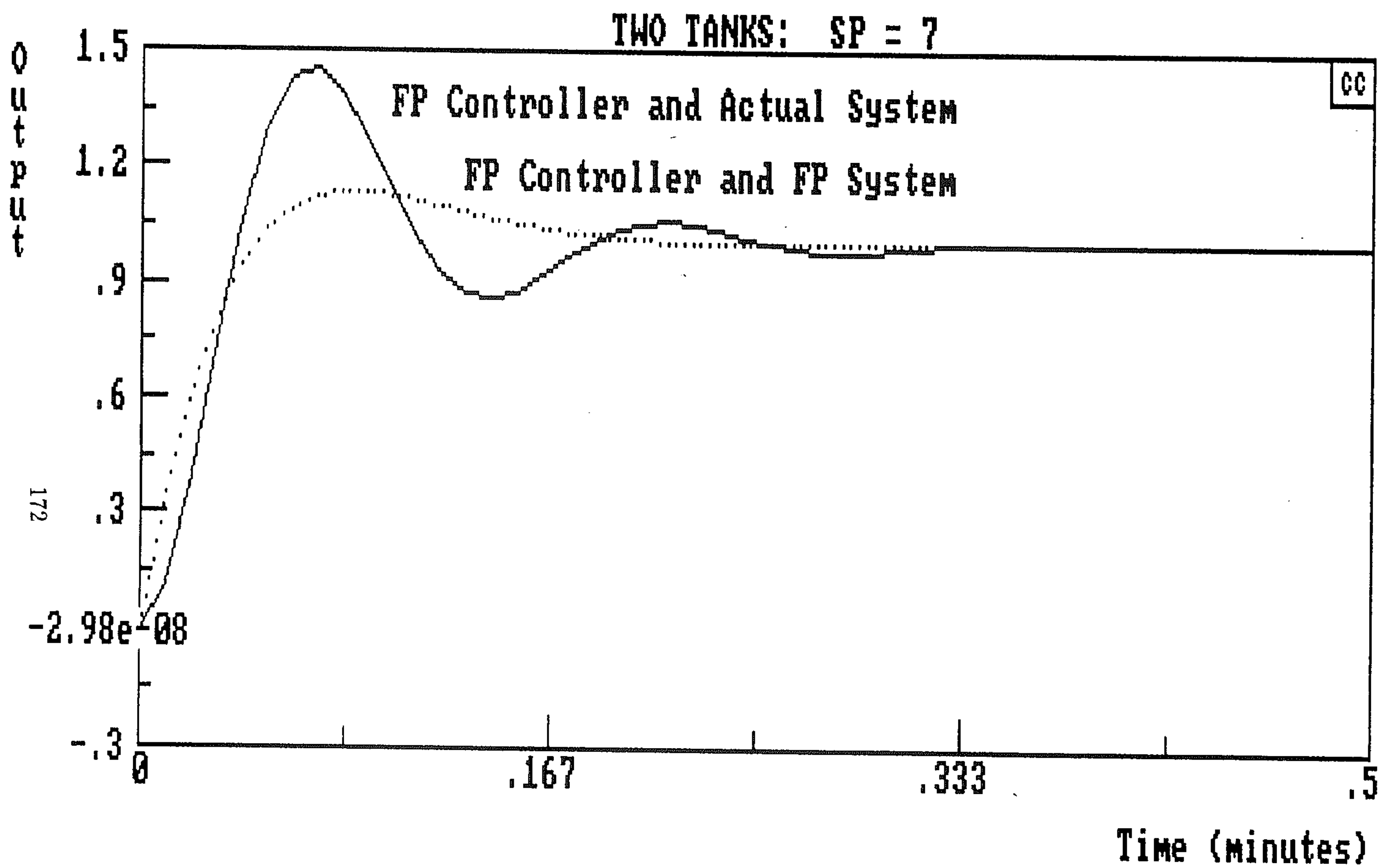

TWO TANKS: SP = 7
CC
FP Controller and Actual System
FP Controller and FP System
Output
1.5
1.2
.9
.6
.3
-2.98e-08
-.3
0
.167
.333
.5
Time (minutes)

FIGURE B1.6

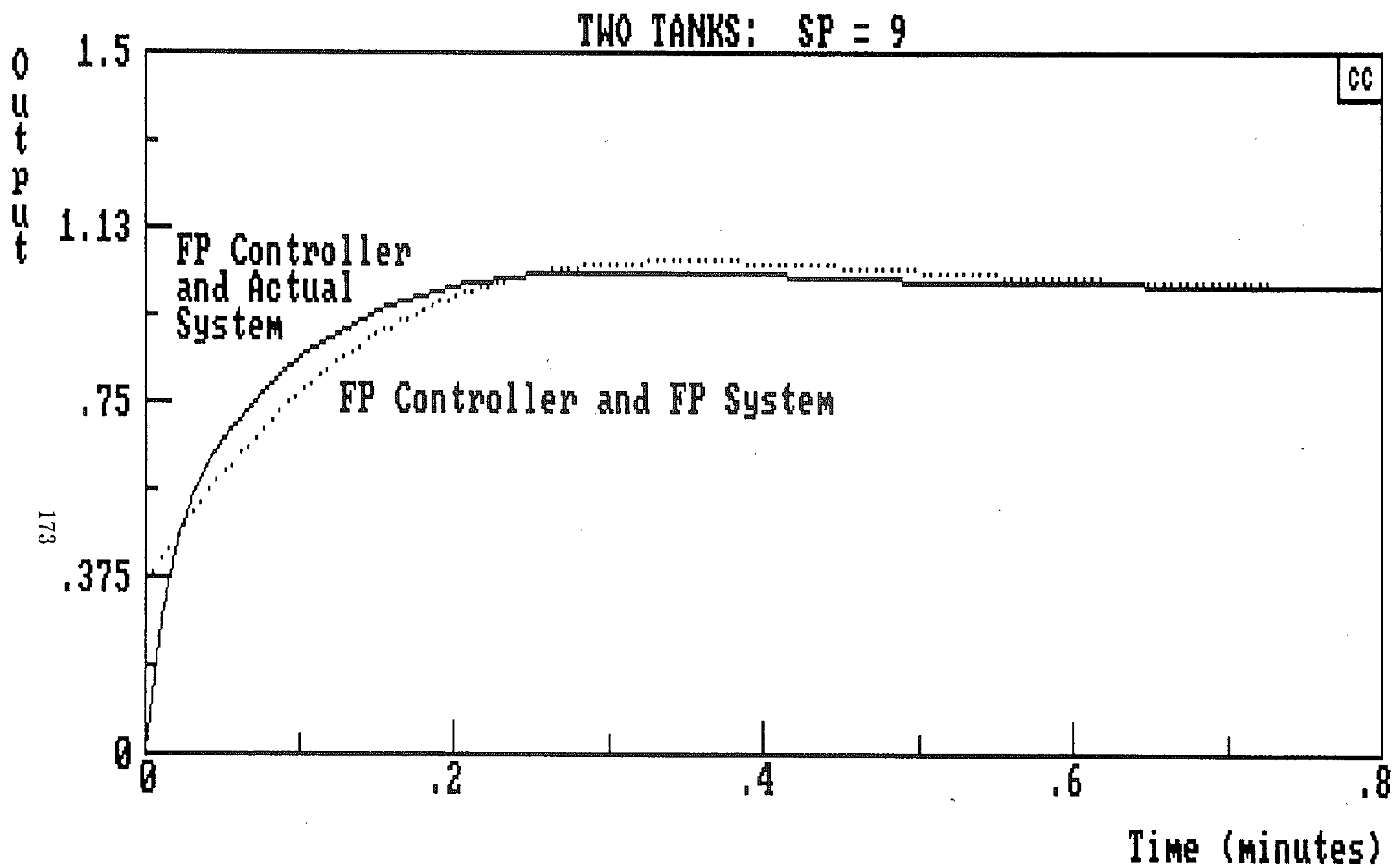

TWO TANKS: SP = 9
Output
1.5
1.13
.75
.375
0
CC
FP Controller and Actual System
FP Controller and FP System
0
.2
.4
.6
.8
Time (minutes)

FIGURE B1.7

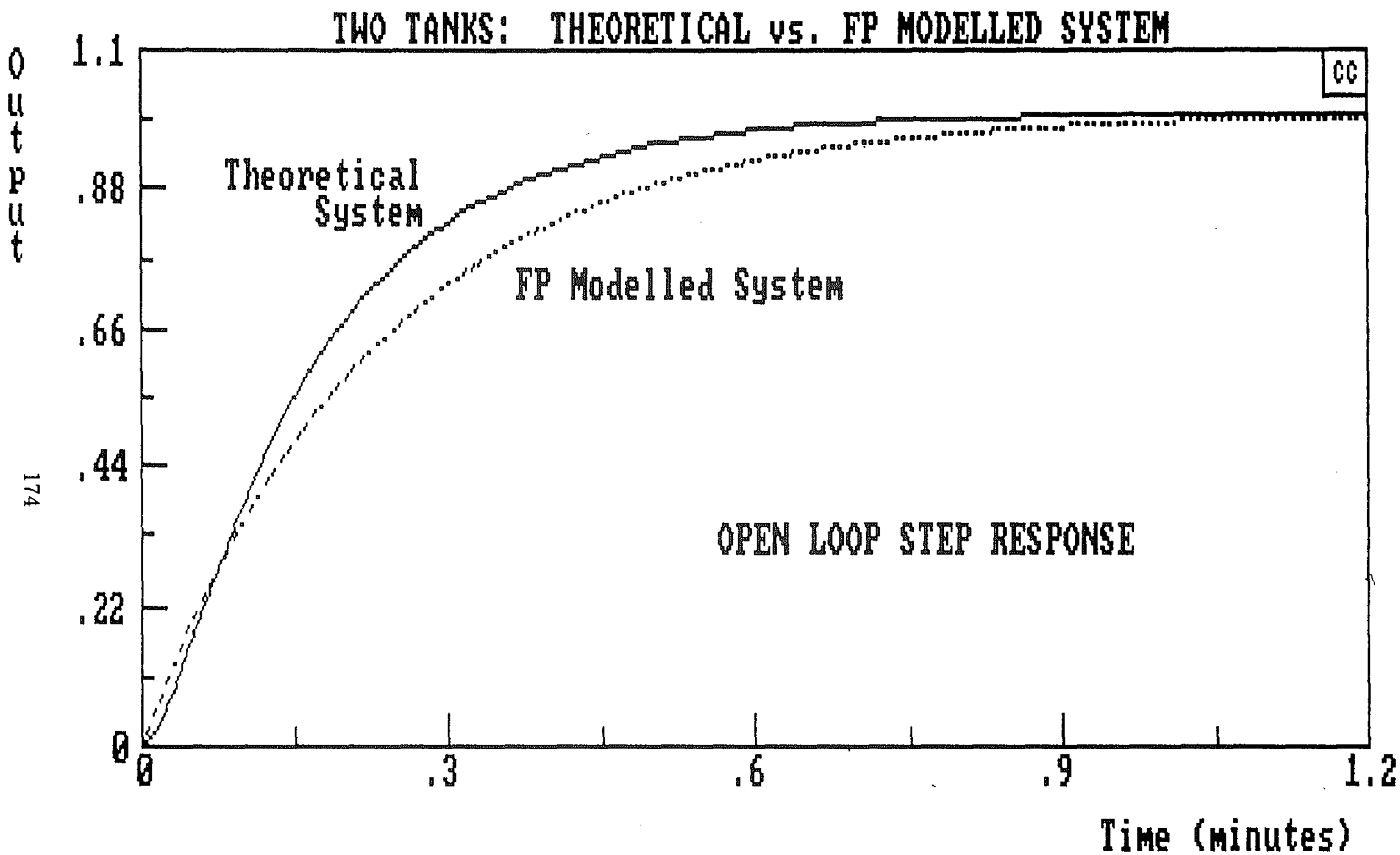

TWO TANKS: THEORETICAL vs. FP MODELLED SYSTEM
Output
1.1
.88
.66
.44
.22
0
.3
.6
.9
1.2
CC
Theoretical System
FP Modelled System
OPEN LOOP STEP RESPONSE
Time (minutes)

FIGURE B1.8

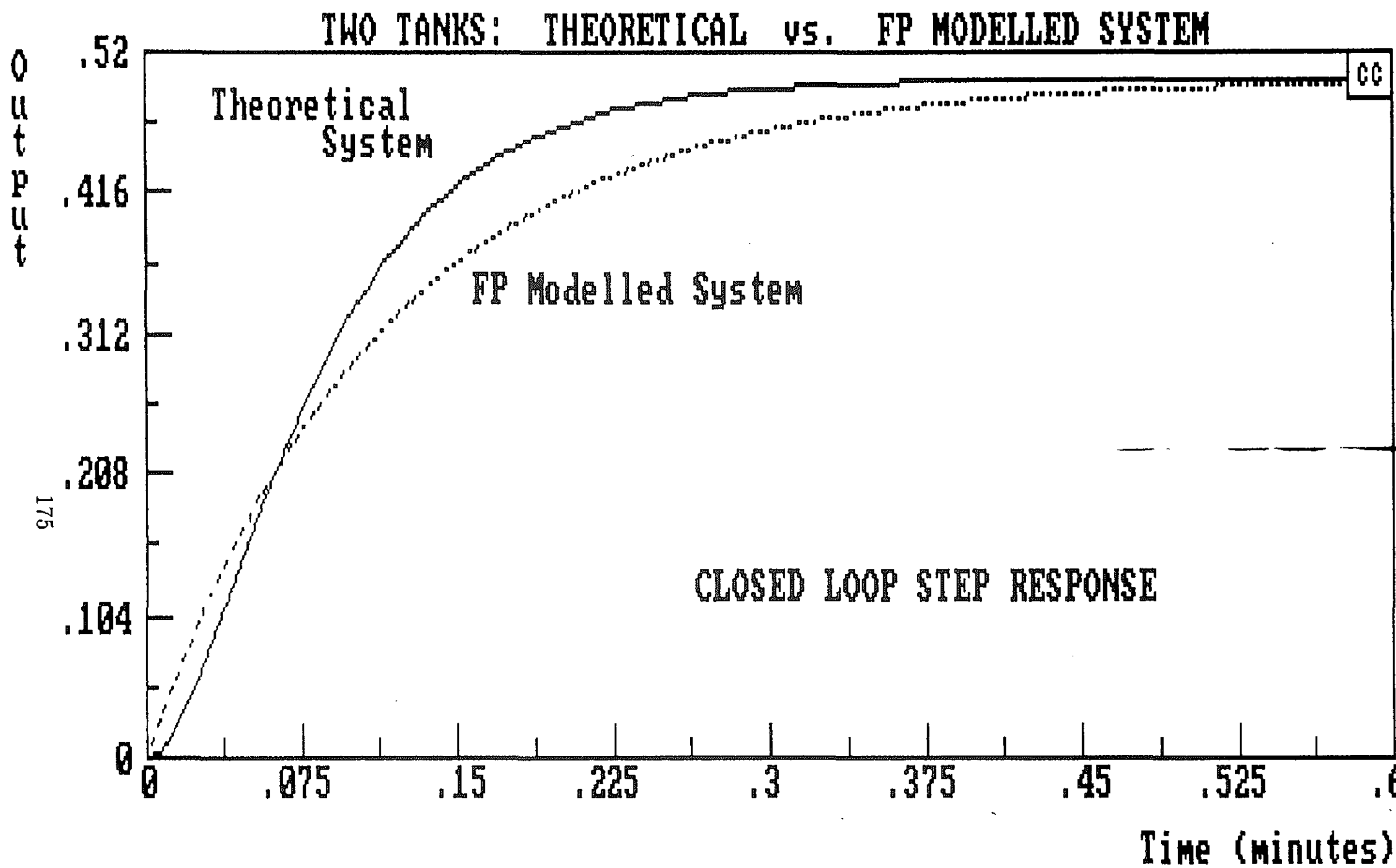

TWO TANKS: THEORETICAL vs. FP MODELLED SYSTEM
Output
.52
.416
.312
.208
.104
0
.075
.15
.225
.3
.375
.45
.525
.6
Time (minutes)
Theoretical System
FP Modelled System
CLOSED LOOP STEP RESPONSE
CC

FIGURE B1.9

APPENDIX C

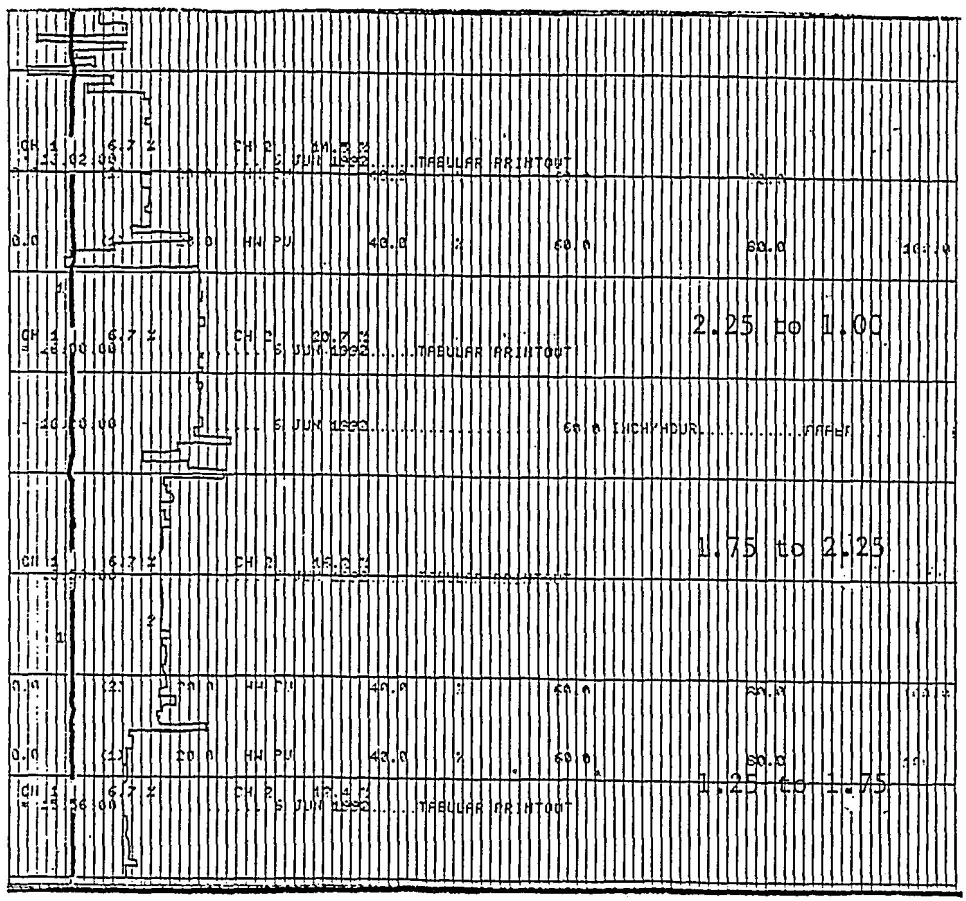
HWA AND FPA RESPONSES

FIGURE C1.1

HWA PROCESS VARIABLE CHANGE TESTS

SP = 1

The following figure, along with the rest of Appendix C, shows sample change tests, where the thicker of the two curves represents PV and the other represents CV.

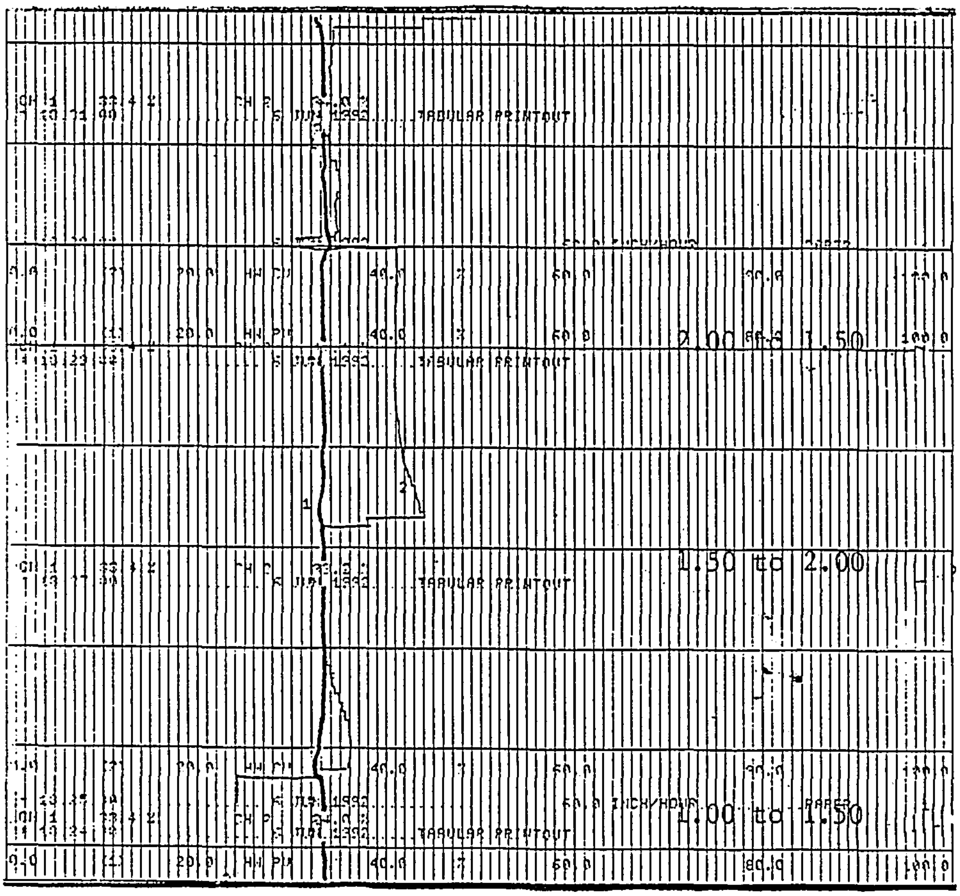


The valve setting changes are shown, signifying the start of each test. The test progresses upwards and a tabular print out displays the resulting PV and CV values at the end of each test. The PV values change very little during all of the above tests.

FIGURE C1.2

HWA PROCESS CHANGE TESTS

SP = 5

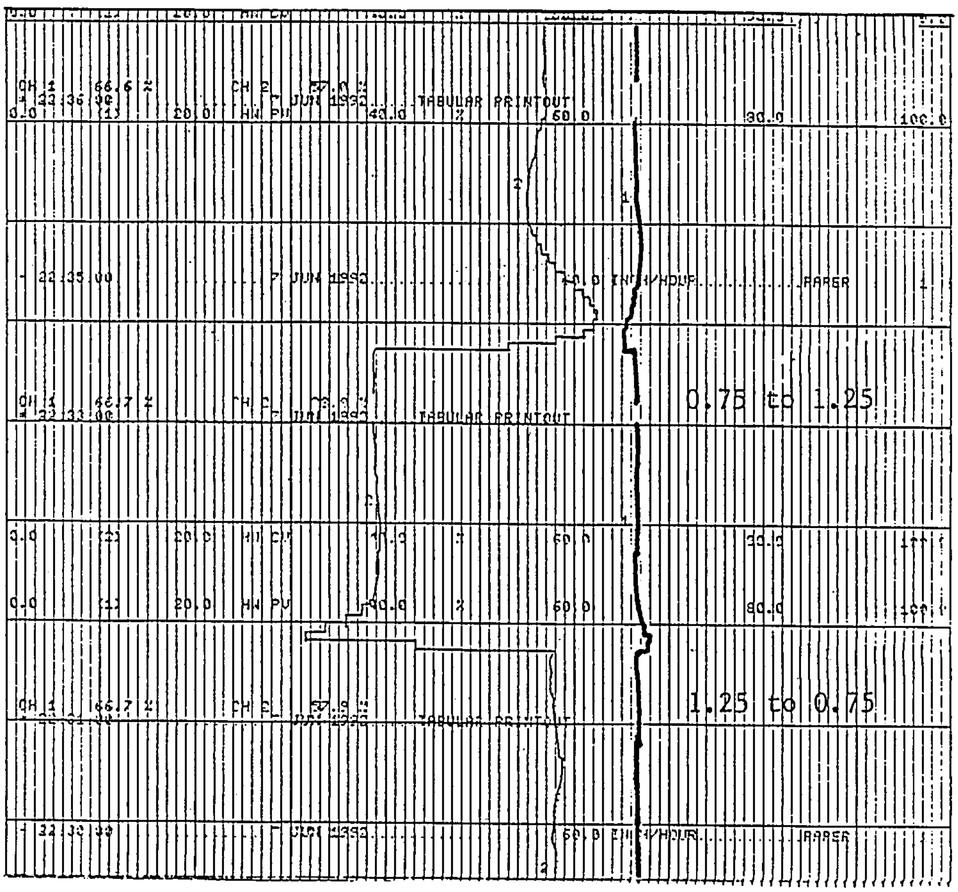


In the three process change tests, PV remains relatively constant throughout the duration of the tests.

FIGURE C1.3

HWA PROCESS CHANGE TESTS

SP = 10

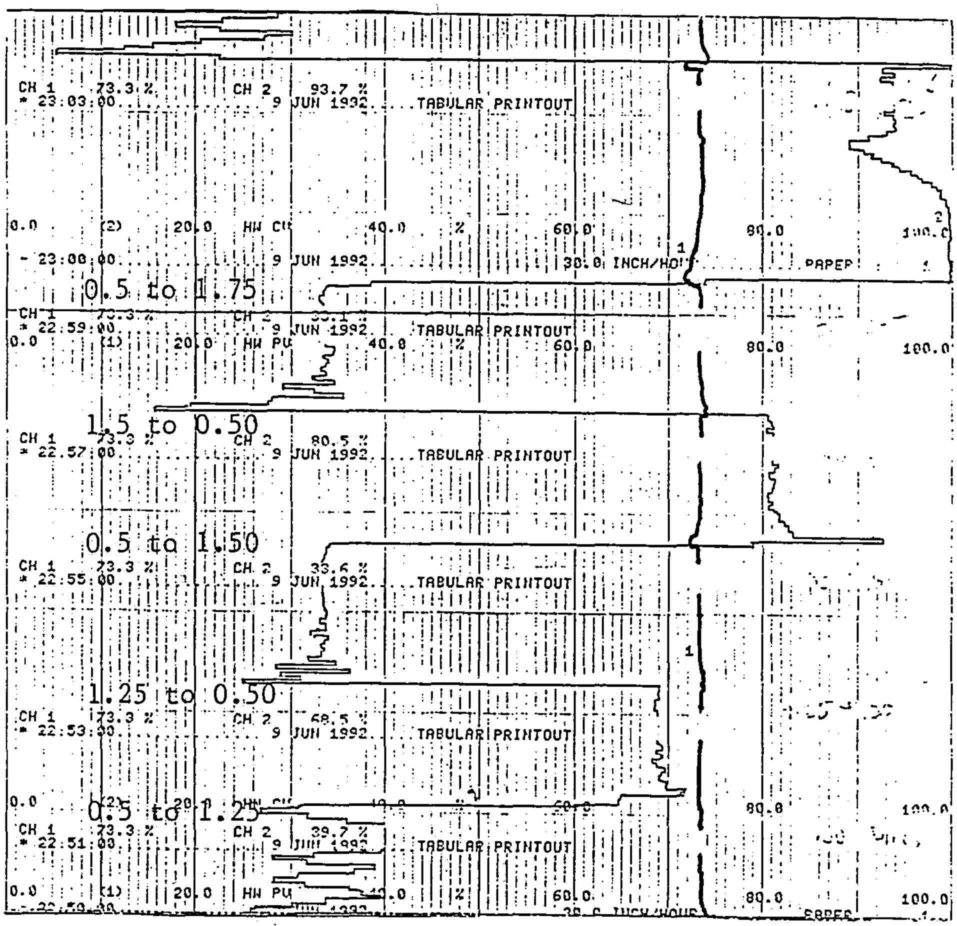


Changes in PV are more evident here, but the changes in valve settings are also significant.

FIGURE C1.4

HWA PROCESS CHANGE TESTS

SP = 11

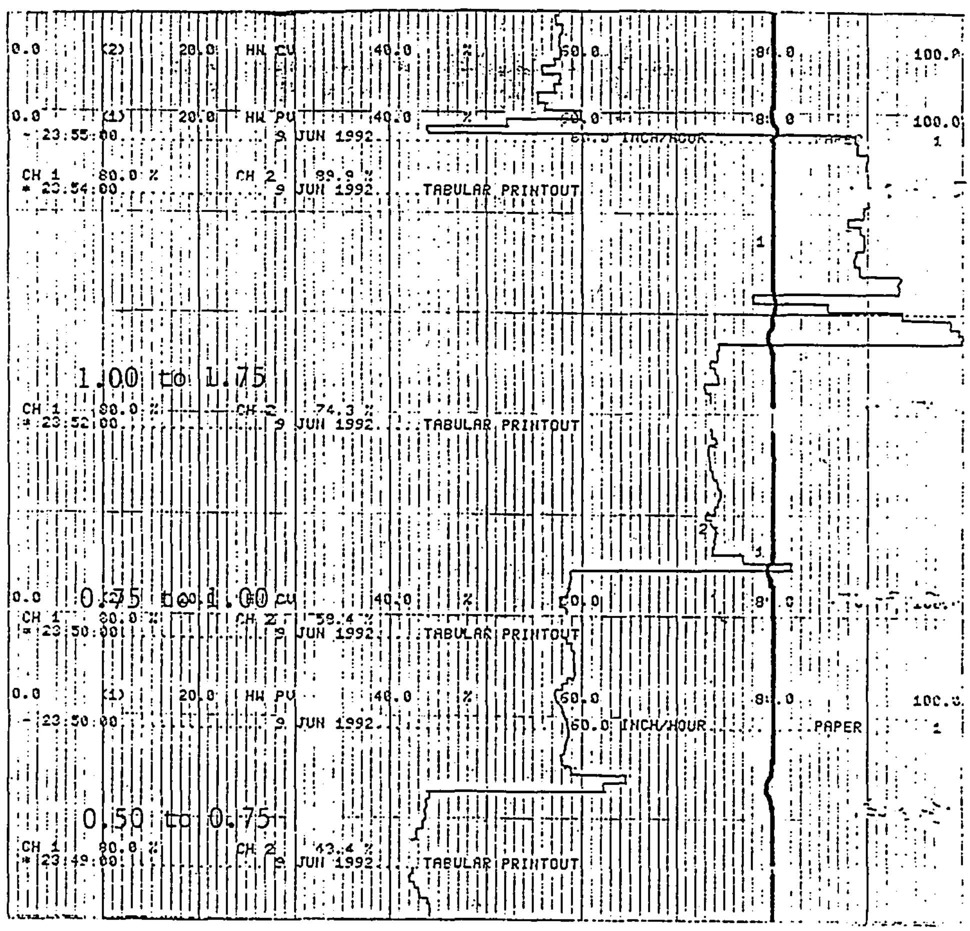


Again, for large changes in valve settings, PV changes are more obvious but return to line out is almost immediate.

FIGURE C1.5

HWA PROCESS CHANGE TESTS

SP = 12

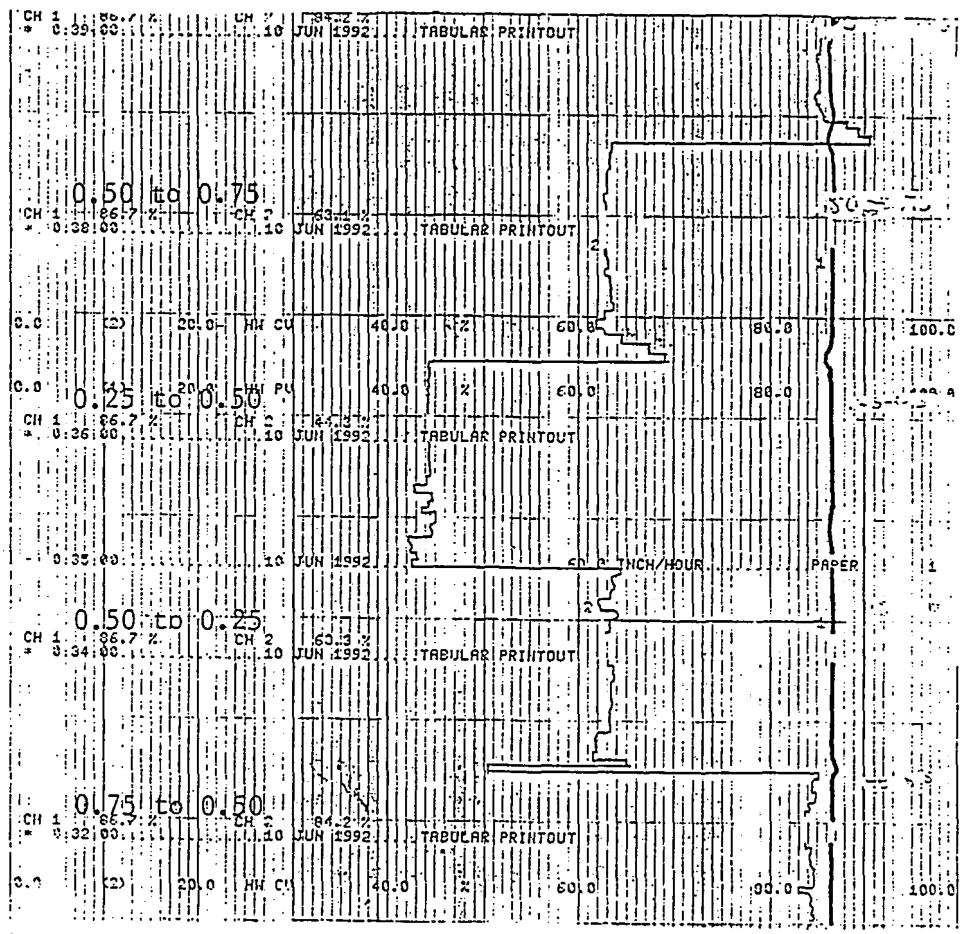


It can be seen here that smaller changes in valve settings are enough to cause noticeable changes in PV and more CV adjustments are necessary.

FIGURE C1.6

HWA PROCESS CHANGE TESTS

SP = 13

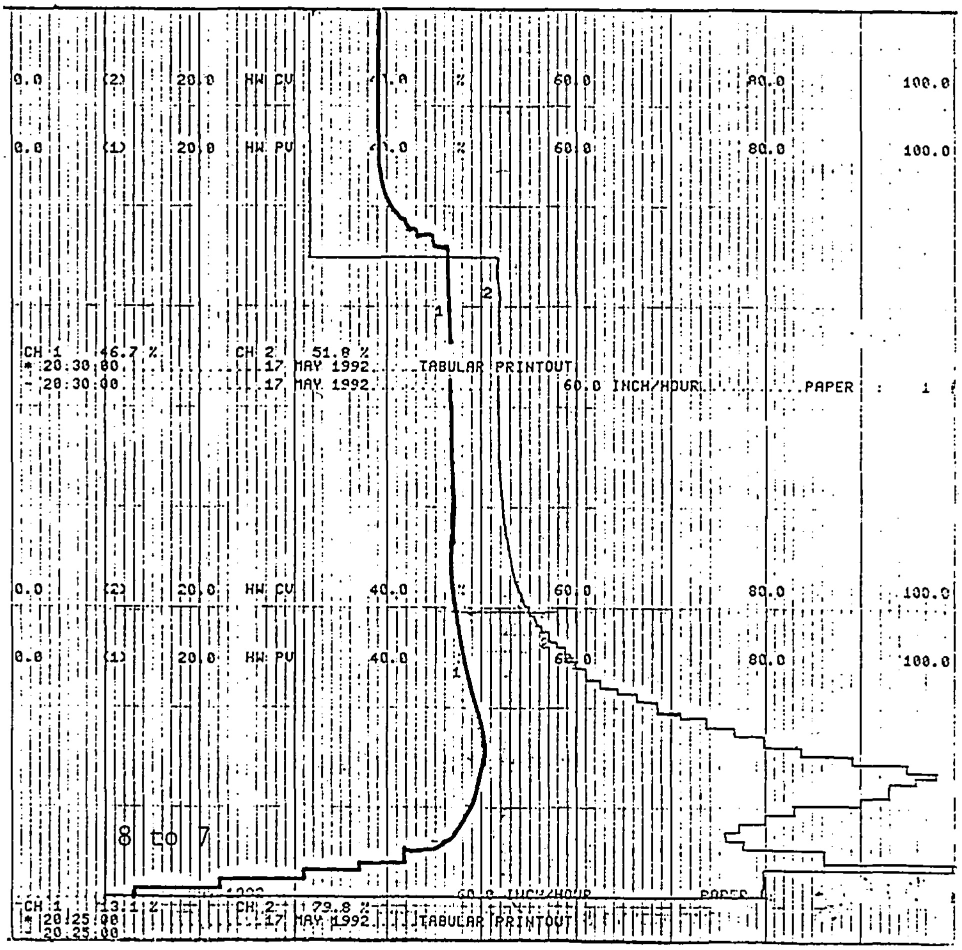


In the above tests, the smallest changes in valve settings result in noticeable changes in PV and large jumps in CV.

FIGURE C2.1

HWA SET POINT CHANGE TESTS

ONE TANK

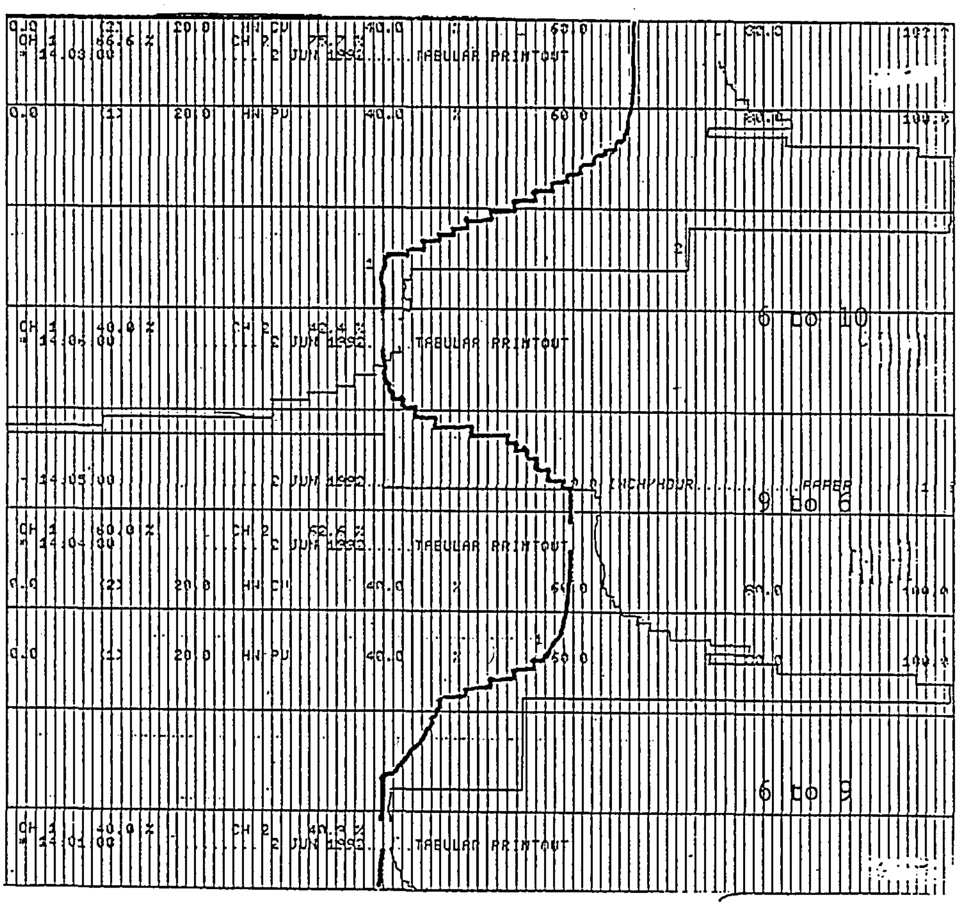


The results of set point change tests for a single tank are similar to theoretical responses. There is a smooth transition to PV line out, and CV changes are large.

FIGURE C2.2

HWA SET POINT CHANGE TESTS

TWO TANKS

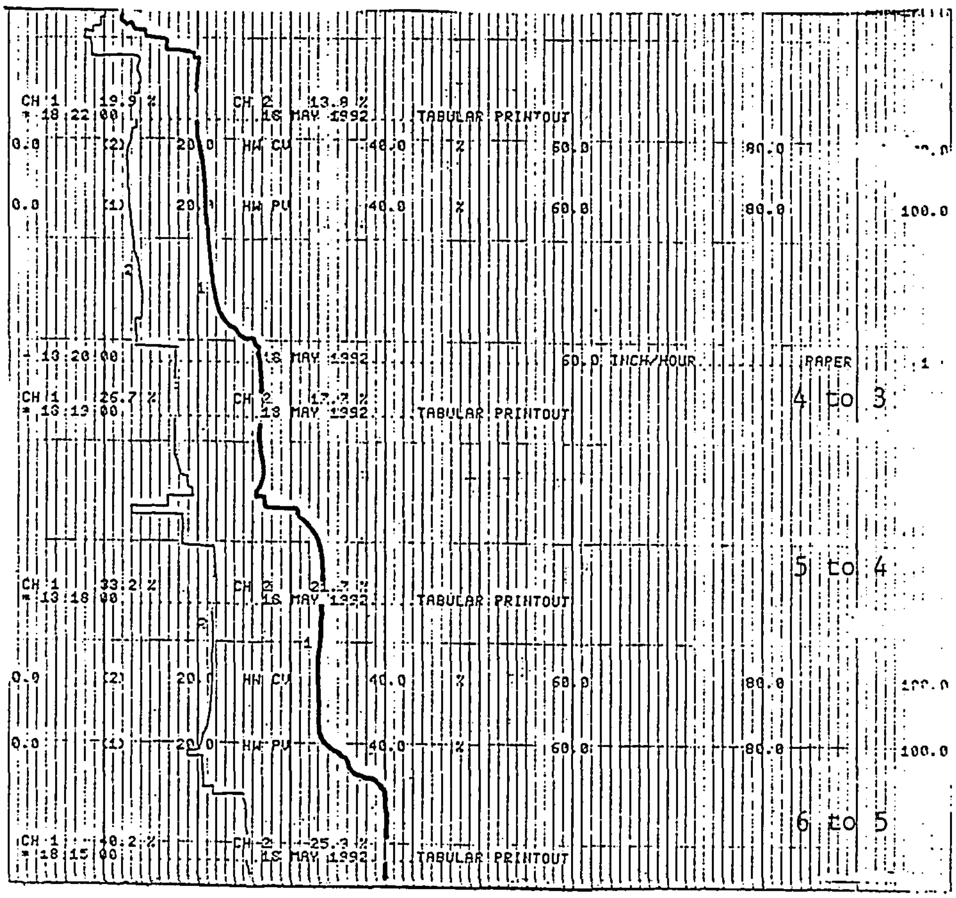


In these set point tests, one can see a smooth double step transition to line out. CV changes consist of basically two large jumps then a gradual change to the final CV value.

FIGURE C2.3

HWA SET POINT CHANGE TESTS

THREE TANKS

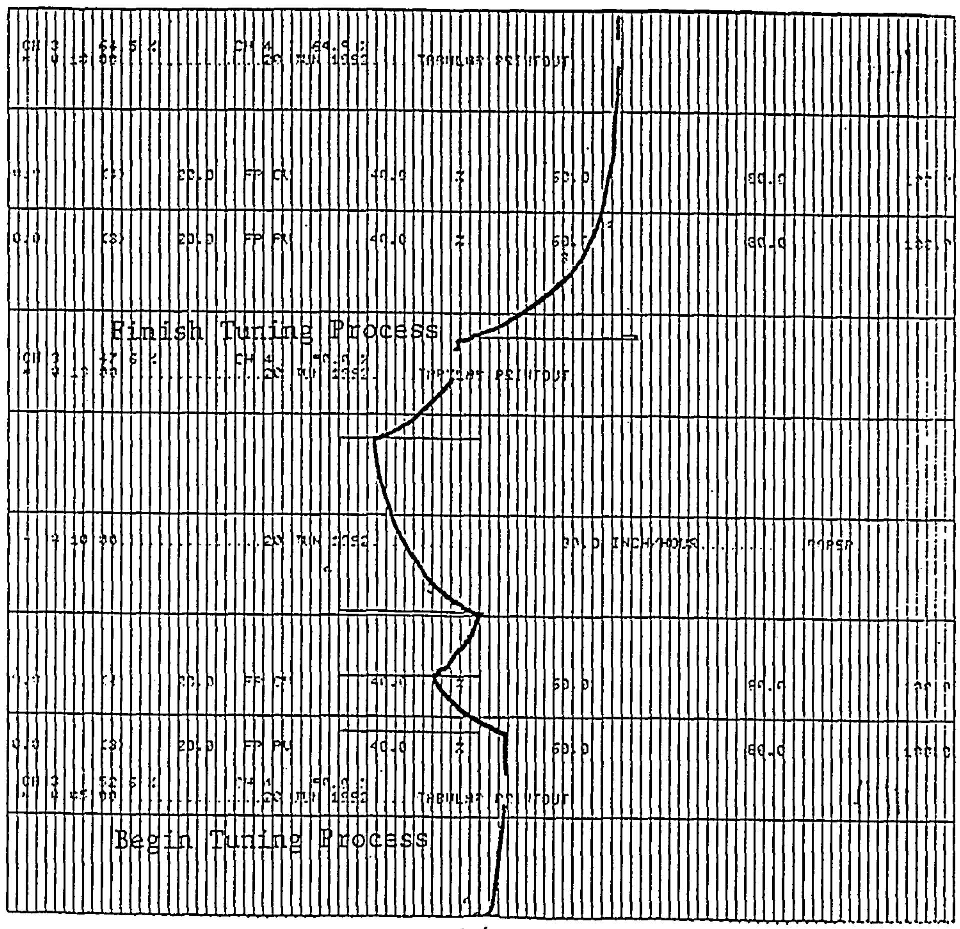


The set point change tests for Test Condition Two are the quickest of all test conditions. However, PV does not line out as smoothly as in other conditions.

FIGURE C3.1

SAMPLE FPA EASY TUNE PROCESS

ONE TANK

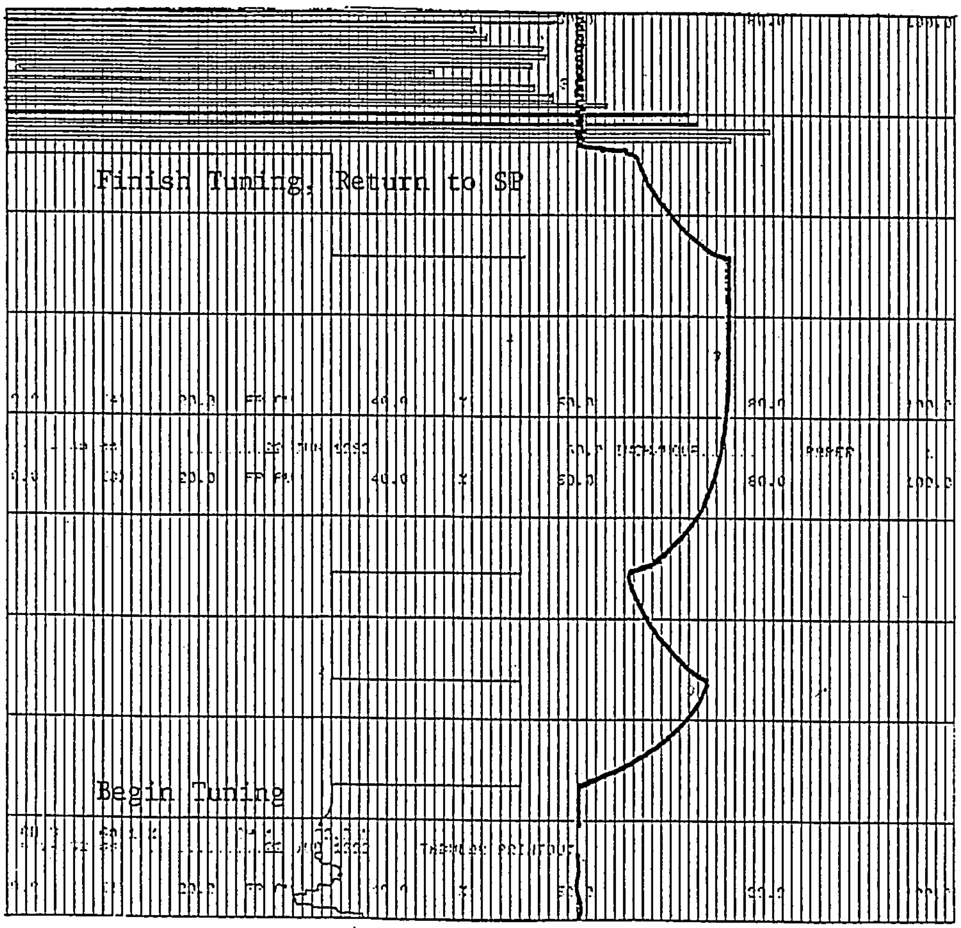


The above figure shows a typical Easy Tune process for Test Condition One. After the completion of the test, the controller is returned to manual control.

FIGURE C3.1

FPA EASY TUNE PROCESS AND SP CHANGE TEST

ONE TANK

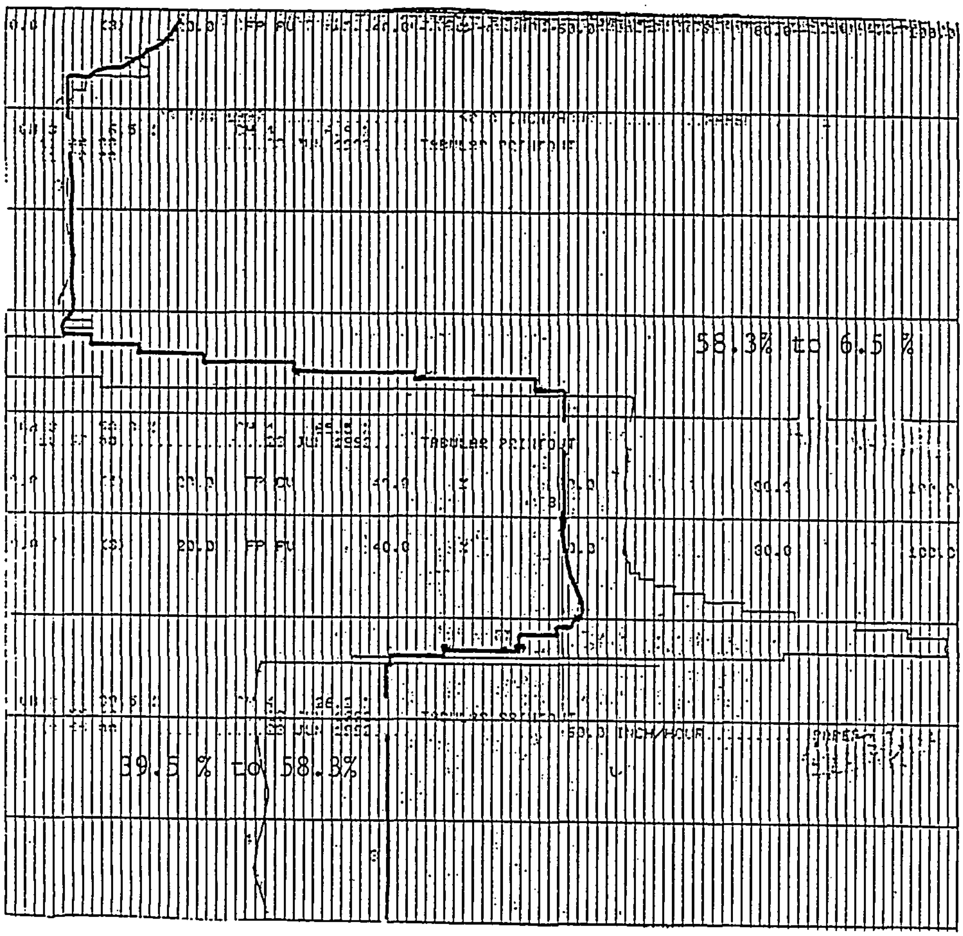


This Easy Tune process is similar to that of the preceding process except that the resulting tuning parameters are implemented and the controller attempts to maintain the original set point. However, there is large CV oscillation and the system is unstable.

FIGURE C3.2

FPA SET POINT CHANGE TEST

TWO TANKS

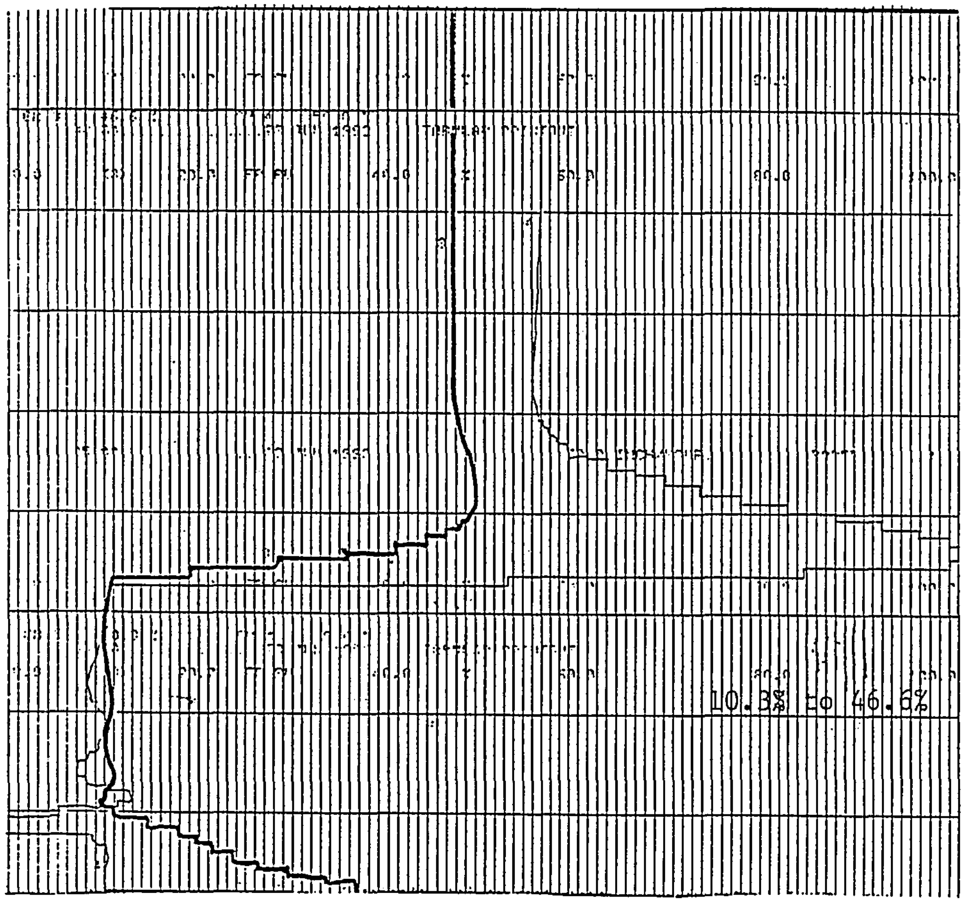


Modification parameters of 0.1 are used to stabilize the system under the set point change tests for Test Condition Two. The tuning parameters designed for a PV value of 6.7% are used for all tests.

FIGURE C3.3

FPA SET POINT CHANGE TEST

THREE TANKS



Modification parameters of 0.1 are used to stabilize the three-tank system. The tuning parameters designed for a PV value of 6.7% are used for all tests.

VITA

May-Win Lwin Thein, daughter of Mr. San and Wendy Thein, was born in Rangoon, Burma, on November 6, 1969. She immigrated to the U.S. in 1971 and became an American citizen.

She graduated with a B.S. in Mechanical Engineering and a minor in Applied Mathematics from Lehigh University in 1991. In August of 1992 she continued her education at Lehigh University in the Mechanical Engineering and Mechanics Department. She worked as a Teaching Assistantship in the Dynamics Laboratory and then for an undergraduate mechanics course.

Miss Thein is a member of Phi Eta Sigma, Pi Tau Sigma, Tau Beta Pi, ASME and SWE. She received the Marcella Geltman Award, the Lehigh University Women's Club Award, and the Elizabeth Major Nevius Award for academic achievement, leadership, and services to Lehigh University and the surrounding community. She was inducted into the Honorary Residential Housing Society Council for contributions to student residential life. She was also recognized in Who's Who Among Students in American Colleges and Universities.

May-Win Thein's summer internships involved mechanical engineering design and research with CertainTeed Corporation in 1988 and 1990 and BF Goodrich Aerospace in 1991. Future plans involve pursuing a Doctorate Degree at Oklahoma State University.

END

OF

TITLE