DIGITAL CONTROL STUDIES OF A LIQUID-LIQUID EXTRACTION COLUMN USING A MINICOMPUTER

by

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SCOPE AND CONTENTS:

This report covers two topics. First is the development of computer programs to carry out the calculations needed to determine the control policy to bring a process from one set of steady state conditions to another. Examples of the implementation of control policies for a liquid-liquid extraction column are included. Suggestions have been made for means of decreasing the calculation time and for means of increasing the size of problem that may be solved.

The second part discusses an initial project of using a Supernova computer as a direct control computer. Characteristics of direct digital control are illustrated using an analog simulation of the extraction unit as the controlled process.

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INTRODUCTION

Chemical processing plants that produce a variety of products from an assortment of feedstocks may suffer significant losses in time and material when changing from one product to another. If a means were available for predicting how best to make the changeover from one product to another, lost time and waste material could be reduced.

Pollock (4, 5) experimented with a Scheibel liquid-liquid extraction column. He obtained frequency response data using pulse disturbance techniques. Pang (3) did a theoretical study of the same extraction column. He made comparisons of his models with Pollock's data.

Pang then used his most realistic model to do control studies on the column. He arrived at various optimal controller configurations.

Pang also studied techniques for determining the changeover policy that is needed to change from one steady state operating condition to another. He assumed fixed flow rates and holdups, and concentrations to the column then became his controls. Putting bounds on the controls and using discrete control with a fixed control time interval, he solved the system equations in terms of the controls using linear programming.

The application of Pang's work to a dynamic system is the topic of this thesis. Included are evaluations of the linear programming changeover calculation and its implementation. Also included is an example of direct digital control of that same dynamic system (an analog model of a liquid-liquid extraction column). Pang's optimal controller configurations were evaluated and some of the problems faced in digital control applications were noted and commented upon.

As a part of this project, the same extraction column used by Pollock and Pang was connected to a distillation column which can be used to recover the solvent from the extraction column. It is now possible to recycle the solvent back to the extraction unit. New feed lines, pumps, surge tanks and a new reboiler on the distillation column were installed to make operation of the two units as flexible as possible.

Plans have now been made to control these units by means of a process control computer. In preparation for that project, the extraction unit has been simulated on TR10 analog computers and this simulation has been controlled successfully by the digital machine.

1. HISTORY OF EQUIPMENT AND MODEL DEVELOPMENT

1.1 HISTORY: The details of the liquid-liquid extraction column which will be referred to frequently are presented in Appendix A.

G. G. Pollock (4) built the equipment as a master's degree project at McMaster University and did some preliminary concentration frequency response analysis using pulse input techniques. His results also include steady state data at various flow rates. He later continued his experiments with the column and collected a large amount of data which has been recorded in his Ph.D. thesis (5).

K. H. Pang (3) continued the work of Pollock. He used Pollock's data to develop mathematical models of the column. He developed a suitable model that was capable of simultaneously simulating the concentration in the two outlet streams in good agreement with the data. Pollock's model was not capable of simulation of both streams simultaneously. The model suggested by Pang was wired up on TR10 analog computers to simulate the extraction unit in doing the study of this report.

1.2 LINEAR EXTRACTION MODEL AND PARAMETERS: The mathematical model of the extraction column chosen by Pang is outlined below. It was decided to use this model as recommended by

Pang because of its close agreement with existing data for the column. It also is easier then to make comparisons of column response obtained by the author with the results obtained by Pang.

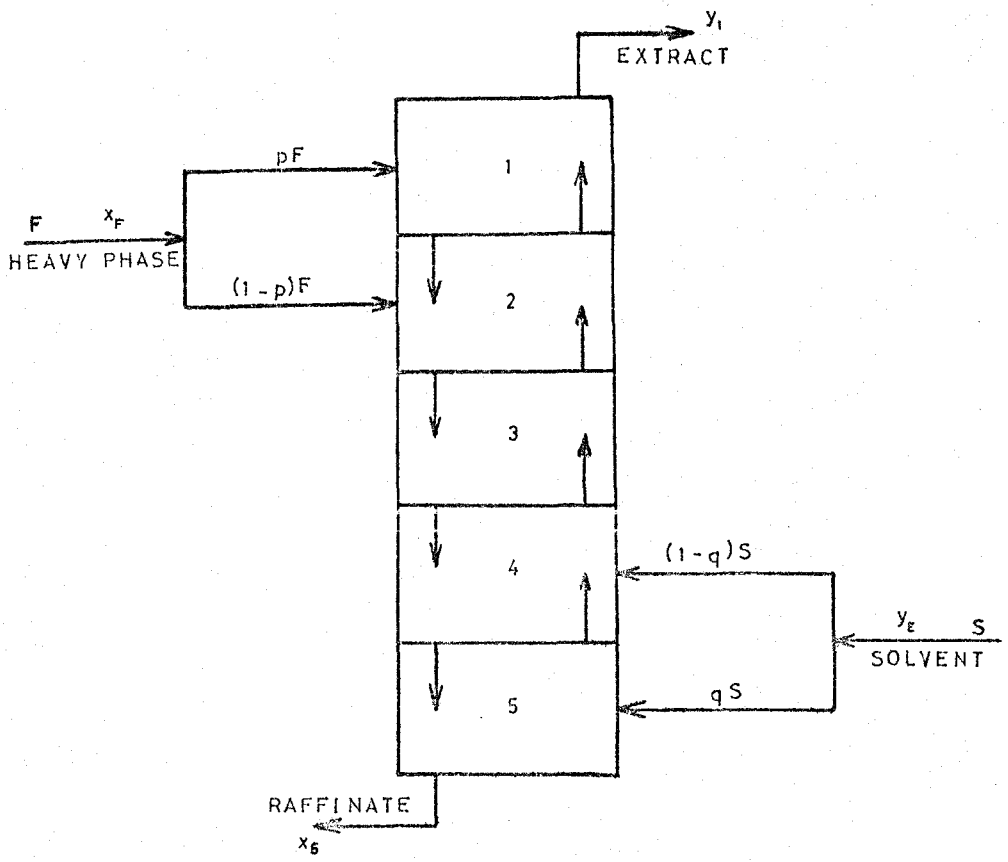


FIGURE 1.1 PANG'S MODEL OF EXTRACTION COLUMN

The model consists of five non-equilibrium transfer stages with two liquid phases in each stage. The equations will be presented in section 1.3. The inlet flows to the column can be assumed to be split upon reaching the first stages. This assumption comes from observation of the flow inside the column. If no splitting of the flow takes place, p and q are unity and the flows enter the top and bottom stages of the column respectively.

Pang carried out a variable search for the best values of the parameters of the column. These variables are outlined below with the corresponding numerical values attached to them by Pang for one particular set of flow rates and mixer shaft speed. These are the data and parameters that will be used later in this report.

p = 1.0

q = 1.0

mass transfer coefficients: .5897, .8410, .4024,
gm/(ml.min) .1028, .1611

solvent rate: 321 gm/min

feed rate: 234 gm/min

	EXTRACT	RAFFINATE
hold up of feed stage:	36.4 gm	142. gm
hold up of each middle stage:	76.7 gm	303. gm
hold up of solvent stage:	14.5 gm	58. gm
hold up of mixing stage:	126.0 gm	248. gm

units of grams refer to a solute free basis

The equilibrium expression used was as follows:

$$y = .783\ x$$

Pang used the selected model to do a study on choice of controller configuration. He then used linear programming techniques to find the optimal values of control variables to be used in changing from one steady state operation to a different set of steady state conditions. In addition to that "minimum time" changeover policy, he developed a

"minimum off-grade" policy for the extraction column in which the move from one steady state to another would have minimum waste or off-grade product.

It should be pointed out that Pollock and Pang used the chemical system methyl-isobutyl ketone (MIBK)-water-acetic acid. No reference to the commercial application of the extraction of acetic acid from water by MIBK could be found in the literature. Further investigation (Struck (6)) revealed that MIBK and acetic acid could not be separated by distillation which is a consideration for our future work in the pilot plant. Di-isobutyl ketone (DIBK) will be substituted for the MIBK because of DIBK's higher boiling point and low solubility in water. This will make it possible to recover the solvent from the extraction process by distillation and then to recycle the solvent back to the extraction unit. For this report, however, the MIBK system was retained since solvent recovery was not dealt with. Retaining the MIBK also allowed comparison of results obtained using a small control computer with the results obtained by Pang on a large scientific computer.

Experimental data to date for the extraction column includes steady state conditions for various flow rates and the dynamic response to disturbances in the concentration of the aqueous phase. No data has been obtained for changes in the flow rate of either phase. Individual phase holdups and mass transfer coefficients may vary with flow rates.

The following statements are assumed to hold:

1. The mass transfer coefficients are fixed for each stage because of fixed flow rates and constant stirring.
2. Phase hold-up is independent of concentration as only low solute concentrations were used in the experiments done by Pollock.
3. The model is linear with respect to concentration. This assumption results from the first two assumptions (fixed flow rates and constant hold-ups).
4. A linear liquid-liquid distribution relationship exists. This is true for the MIBK-water-acetic acid system up to 15 % acid in water.
5. Perfect mixing occurs in each phase. Agitation within each stage was sufficient to eliminate any significant concentration gradient across each stage.
6. Only solute is transferred from one phase to another. This assumes that no backmixing of solvents occurs between stages.

Solubilities and equilibrium distributions have been recorded by Othmer, White and Truegar (2) for various chemical systems including MIBK-acetic acid-water and DIBK-acetic acid-water.

Othmer (1) has tabulated vapour-liquid equilibrium data for DIBK and acetic acid.

1.3 MATHEMATICAL REPRESENTATION OF COLUMN DYNAMICS: The model of the extraction used was the one suggested by Pang. The flow diagram of the model is illustrated in Figure 1.1. The system equations may be written as follows:

$$W_{R_1} \cdot \frac{dx_1}{dt} = F(x_F - x_1) + K_{EA_1} \cdot V_1 (y_1^* - y_1) \qquad (1.1)$$

$$W_{E_5} \cdot \frac{dy_5}{dt} = S(y_E - y_5) - K_{EA_5} \cdot V_5 (y_5^* - y_5) \qquad (1.2)$$

$$W_{R_i} \cdot \frac{dx_i}{dt} = F(x_{i-1} - x_i) + K_{EA_i} \cdot V_i (y_i^* - y_i) \quad i = 2\text{-}5 \qquad (1.3)$$

$$W_{E_i} \cdot \frac{dy_i}{dt} = S(y_{i+1} - y_i) - K_{EA_i} \cdot V_i (y_i^* - y_i) \quad i = 1\text{-}4 \qquad (1.4)$$

where $y_i^* = mx_i \quad i = 1,2,3,4,5$

x_F and y_E are the inlet concentrations

K_{EA_i} is the mass transfer coefficient of stage i

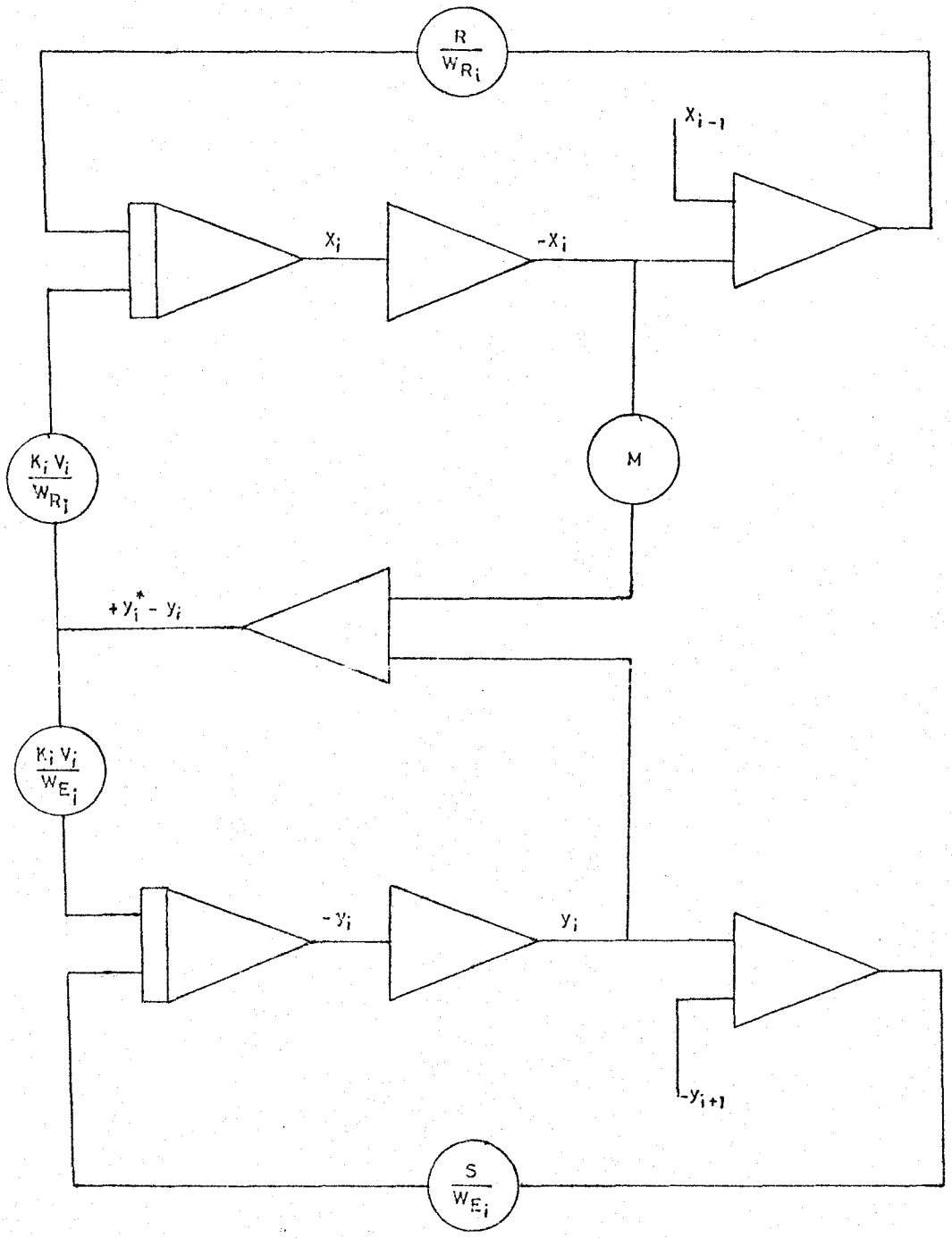
V_i is the total volume of stage i

W_{R_i} and W_{E_i} are the mass holdups of heavy phase and light phase respectively in stage i

Refer to the previous section for units and numerical values of these parameters.

The five-stage model was patched on three TR10 analog computers, slaved together. The wiring diagram of a single stage is shown in Figure 1.2. The wiring of all five stages was identical with the input to each stage coming from the appropriate variable location of the adjacent stage.

Pang monitored the outlet concentrations (x_5 and y_1) in his work. The inlet concentrations were his control variables. For calculating changeover policies, he used all ten state variables, i.e., the concentrations in each phase at each stage, in calculating the values of the controls for each control time interval. In doing his classical control studies for the extraction column, Pang used concentration of the solute in the water feed as input or control variable and the extract concentration (organic output phase) as the controlled variable. The extract concentration was assumed to be continuously measurable.



F I G U R E 1.2

ANALOG WIRING DIAGRAM OF AN EXTRACTION STAGE

2. DEVELOPMENT OF THE OPTIMAL CHANGEOVER POLICY

The general state space control equation (2.1) for a linear system of equations is the starting point for the theory of this section.

$$\dot{X} = AX + BU \tag{2.1}$$

Let us define

$$D = \int e^{AS} B ds$$

and $E = e^{AT}$

Also it will be possible to apply discrete control action to the system for N control time intervals, the time duration of one such interval being T.

Pang (3) developed equation 2.2 to calculate the final states of the system after the control scheme had been applied.

$$X(N) = E^N X(0) + GU \tag{2.2}$$

The derivation has been repeated in detail in Appendix B and should be referred to for familiarization with the nomenclature, and for details of dimensions.

Knowing the initial states X(0) and the final states X(N), then the unbounded controls U may be determined from equation 2.2 after calculation of E^N and G^{-1}.

For the bounded case Pang used linear programming to find the fastest changeover time in going from one steady state to another. He introduced an artificial variable, g,

which was a measure of how close he was to the correct choice of controls. The method, described in detail by Pang (3), introduced a large number of constraints and hence a large number of variables for the linear programming matrix.

It is necessary to re-apply the linear program each time the number of sample points is changed. Since the number of sample times is proportional to the time taken for the changeover, it is only necessary to find the minimum number of sample times for which a solution exists. By repeatedly applying the linear program for various values of N, one is able then to find the minimum time for which any feasible solution exists. If several solutions exist, other criteria may be used to choose the "best solution" from amongst them. For this investigation we are only interested in finding any solution.

The following method of finding a feasible solution was proposed by Torng (7). The development of the equations for linear programming is given here.

If the controls are bounded by α as a lower bound and by β as an upper bound i.e. $\alpha \leq U \leq \beta$. Then we need the constraint equations (where every element of C_1 and C_2 are ≥ 0)

$$U - C_1 = \alpha \tag{2.3}$$

$$U + C_2 = \beta \tag{2.4}$$

In our case U will be a concentration so that the lower limit will be $\alpha = 0$ and the first constraint equation may be dropped since the variables will always be greater than or

equal to zero in linear programming.

The problem is now to find a feasible solution for

$$GU = X(N) - E^{N}X(0) \tag{2.2}$$

with

$$U + C = \beta \tag{2.4}$$

A solution exists for

$$GU + W = X(N) - E^{N}X(0) \tag{2.5}$$

$$U + C = \beta \tag{2.4}$$

if we let U = 0 and let W and C be equal to the corresponding values on the right hand side of the equations.

We introduce a new objective function

$$P = \Sigma W_i \tag{2.6}$$

A basic feasible solution to the problem exists then when P = 0.

It is now necessary to minimize P while maintaining the restrictions imposed by equations 2.4 and 2.5.

The number of variables and the number of equations are now reduced sufficiently that the problem at hand may be solved on the control computer with 12K memory. The reduction was necessary in the 12K machine because of the large storage requirements of the linear programming calculation. The entire program plus data was core resident. Overlays from disk were not attempted. Core requirements will be discussed further in the next chapter.

3. RESULTS OF THE CHANGEOVER

3.1 INPUT DATA TO DIGITAL PROGRAM: In the control equation

$$\frac{dX}{dt} = AX + BU \qquad (3.1)$$

the elements of the A and B matrices were calculated from the parameters obtained by Pang (3) for the extraction column from his "model No. 2". The matrices are found in Figures 3.1 and 3.2. Initial conditions were chosen as zero. Final conditions are found in Figure 3.3.

The case studied here is the same as that used by Pang; however, Pang did a transformation of variables so that his final conditions were zero. This was possible because of the linearity of the system equations. He did it so that the difference of the states from the desired value could become the linear programming objective function in one of his methods for finding the minimum time changeover control policy. By minimizing the objective function he was at the same time minimizing the deviation of the system from the desired final state. The second method used by Pang (and proposed by Torng (7)) and described earlier in this report was used here because it used less computer core space.

The Supernova program to calculate a changeover policy is listed in Appendix C. Most of the calculations

	x_1	y_1	x_2	y_2	x_3	y_3	x_4	y_4	x_5	y_5
x_1	-2.27	.797								
y_1	2.43	-11.93		8.82						
x_2	.772		-1.66	1.14						
y_2			3.52	-8.68		4.19				
x_3			.772		-1.20	.545				
y_3					1.68	-6.34		4.19		
x_4					.772		-1.86	1.39		
y_4							4.30	-9.68		4.19
x_5							3.00		-3.17	.218
y_5									.672	-22.9

FIGURE 3.1

A MATRIX

Blank implies 0.0

Units are min^{-1}

	x_F	y_E
x_1	1.65	
y_1		
x_2		
y_2		
x_3		
y_3		
x_4		
y_4		
x_5		
y_5		22.2

FIGURE 3.2

B MATRIX

Blank implies 0.0

Units are min^{-1}

x_1	5.440
y_1	3.080
x_2	4.354
y_2	2.677
x_3	3.658
y_3	1.875
x_4	2.542
y_4	1.368
x_5	2.468
y_5	0.5539

FIGURE 3.3

FINAL CONDITIONS

Units are

concentration

were done by matrix handling subroutines. A manual for the use of these subroutines is on file in McMaster University's Chemical Engineering Department.

Input to the program was through a teletype reader. Data was prepared in advance on paper tape which was fed to the computer through the teletype at execution time. This procedure was used to reduce typing errors.

Data to the program included:

1. control time interval
2. number of state variables
3. number of control variables
4. characteristic matrix of the system
5. control matrix
6. initial state conditions
7. number of time intervals for the control policy
8. upper limit of control
9. final state conditions

The program assumed that the lower control bound was zero. This step was taken to make programming more efficient with respect to computer time and space. It is convenient to have the lower bound be zero since concentrations can never be negative and the variables of linear programming must be non-negative.

The ten state variables were the solute concentrations in each stage. The manipulated variables were solute concentrations in the two inlet streams.

3.2 IMPLEMENTATION OF CONTROL POLICY AND PLOTTING OF RESULTS: To implement the results from the linear programming calculation, the following steps have to be taken:

1. obtain the vector of controls from the linear programming matrix.
2. assign the control elements to the correct output vector.
3. transform the controls from floating point to 10-bit signed integer numbers and scale if necessary to be compatable with the digital to analog converters which have 10-bit registers.
4. output the controls at the correct control time intervals.

Steps 1 and 2 were done as part of the control policy calculation program (Appendix C). Steps 3 and 4 were carried out by a generalized subroutine that accepts up to four control vectors and outputs the control through the analog to digital converters at specified time intervals.

To obtain plots of the response of the state variables as the control was carried out, an x-y recorder was used. The x-input was the variable being plotted. The y-input came from a time base generator whose input was turned on and off by the control computer. Figure 3.4 illustrates the wiring of the y-input.

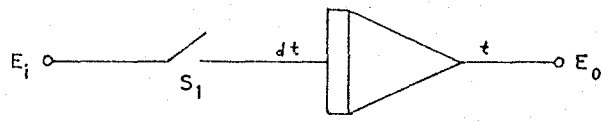


FIGURE 3.4. TIME BASE GENERATOR FOR x-y RECORDER

The source of E_1 was a potentiometer whose setting controlled the scaling of the arm (y-variable). That procedure is standard practice in analog computation. In addition, however, S_1 was a relay that was closed at the time the changeover control was started and then was opened when the changeover control had been completed.

To get the response of a second state variable, the x-input was changed to this second variable, the analog computers were reset to the initial condition (zero in this case), and the output of the control policy was repeated. Because the digital computer controlled the timing for closure of the relay, the plots of different variables superimposed one another on the plotter output.

3.3 ACCURACY OF RESULTS: The calculation of the transition and delta matrices (E and D respectively) on the Supernova gave essentially the same results as those calculated on the CDC 6400 by Pang (Appendix D). However, differences appear in the third and fourth significant figures of all numbers, with differences as large as 1% in some of the larger numbers (ref. Appendix D). This was caused by the fewer number of significant figures carried by the Supernova's

floating point arithmetic. It may also have been caused in part by different input data, as some errors existed in the data Pang claimed to have used. The data used for this study was calculated directly from Pang's results of his modelling study. Pang claimed to have used 16.5 as one element of his control matrix, B. From his modelling studies the element should have been 1.65 and this is what he used, for the 1.65 value is the one that yields the delta matrix published in his thesis. For this reason, when two other small differences occurred in his numbers, those calculated from the modelling studies were used. These latter discrepancies occurred in the less significant terms of the A matrix and had a relative error of 25% in those elements. In fact, when this was tested by using both sets of data, there was practically no difference in the E and D matrices. This means that the floating point arithmetic accounts for most of the differences between Pang's results and those that are found here.

To calculate the G matrix, the delta matrix (with relative differences from Pang's values of 1% in some of the larger elements) is multiplied by increasing powers of the transition matrix which further increases the relative error. Using ten control intervals requires the calculation of the tenth power of the transition matrix, leading to a difference of 10% when there is an error of 1% in the transition matrix. When this result is multiplied by delta and then the inverse

of A, the relative error becomes even larger. This discrepancy is then carried forward from the G matrix to the linear programming section of the calculation.

The large size of the linear programming matrix (31 x 51) amplifies the differences that already exist because of the large number of times rows are multiplied by constants and then subtracted from other rows. The smaller elements in the linear programming matrix will be largely made up of (1) truncation errors and (2) errors already existing before the linear programming calculation began.

3.4 PROGRAM EXECUTION TIME: Calculation of the transition and delta matrices (E and D) for ten state variables and ten control time intervals takes approximately three minutes on the Supernova. At present to calculate a new changeover policy these matrices are recalculated. The recalculation is unnecessary if the same system is used since the transition and delta matrices are constant and could be stored after the first calculation.

The calculation of the transition matrix requires the calling of a subroutine to do a matrix exponentiation. The exponential calculation for this study was done by infinite series with truncation of the series after forty terms to allow time intervals of 0.5 minutes to be used.

The time taken to do that calculation is a large part of the three minutes taken in doing the initial calculations. Pang did his exponentiation computation by using

only sixteen terms in the series calculation and a time interval of 0.1 minutes. He then used multiples of this to obtain the transition matrix, E, for other time intervals. That is, to calculate the transition matrix, for a time interval 0.1N minutes, he used

$$E(T) = e^{AT} = e^{A(0.1N)} = [E(0.1)]^N \qquad (3.2)$$

That procedure is more efficient as the calculation can be cut by two-thirds and machine truncation error will be reduced as a result of the fewer calculations.

Additional time saving could be achieved for a given system if the linear programming matrix were pre-calculated. To do this the linear programming matrices for all cases with a different number of control intervals would be calculated in advance and stored (possibly on disk). The only additional information needed are the initial and final states which are used to calculate the last column of the linear programming matrix. Computation of a single control policy then requires only the time to set up the last column and the time taken to do the linear programming calculation.

3.5 PROBLEM SIZE: The program to calculate the optimal changeover policy will handle a problem with ten state variables and two control variables for up to ten control time intervals. If eleven control intervals are used, memory overflow occurs and the results are lost with 12,000 words

of memory on the Supernova. Reprogramming could possibly bring the number of control intervals up to fourteen by working with only the needed portion of the linear programming result. For this study the final linear programming result was transposed in core memory in such a way that at least twice the linear programming storage area is needed for data storage. If the transposition were done so that the transposed result overwrote the original matrix, then a problem approximately 40% larger could be handled.

The size of the problem that could be solved would be much larger if the matrix handling subroutines were written to do augmented matrix calculations from a disk with high access speed. Disk storage space would then be the limiting factor instead of core storage.

3.6 RESULTS OF PANG'S CASE STUDY: To test the author's changeover calculation, the case studied by Pang was used here also. Tables 3.1 and 3.2 show the steady values of the final values of the state variables after applying the calculated control policy to the analog models. Figures 3.6 to 3.10 are the corresponding plotted results.

The same parameters that Pang derived from his model studies were used in making the analog computer settings. The steady state values from the analog computers agree to within three percent of those calculated by Pang. The agreement was considered acceptable to test the changeover policy calculations.

TABLE 3.1

FINAL STATE CONDITIONS OF PANG'S CASE STUDY

Stage	By Pang ½ Scale	On Analog Computers	N=10 T=.4	N=8 T=.5	N=7 T=.6	N=7 T=.5	N=6 T=.5	Step Input
x_1	2.72	2.75	2.52	2.71	2.65	2.72	2.70	
y_1	1.54	1.58	1.55	1.51	1.39	1.55	1.50	1.30
x_2	2.177	2.20	2.18	2.15	2.02	2.15	2.15	
y_2	1.338	1.38	1.38	1.32	1.18	1.38	1.31	
x_3	1.826	1.80	1.90	1.79	1.68	1.90	1.78	
y_3	.938	.92	.98	.91	.68	.98	.87	
x_4	1.271	1.26	1.32	1.24	1.22	1.32	1.18	
y_4	.684	.69	.70	.69	.68	.71	.61	
x_5	1.234	1.25	1.25	1.24	1.18	1.27	1.05	0.72
y_5	.277	.28	.15	.28	.25	.29	.28	
[Objective Function]				-.036	-.106	-.141	-.825	

Final States (all cases): Feed = 3.00; Solvent = 0.25

Upper Limits (all cases): Feed = 6.00; Solvent = 0.75

T = control time interval in minutes

N = number of control intervals

It had been hoped to make a direct comparison of Pang's work with the results of the changeover achieved on the analog models. Such a comparison is to be questioned as the calculated values of the E and D matrices are not in exact agreement with those calculated by Pang, as has already been pointed out. Also, Pang (using high digital accuracy) specified a much lower value to the objective function of the linear programming problem. This required at least 18 control time intervals to find a solution. The maximum number of intervals used here was 10 as determined by the available core storage.

The effect of different control time intervals can be seen in Table 3.1. Control interval times of 0.4, 0.5, and 0.6 minutes were used with 10, 8 and 7 control intervals respectively. The total time needed for the changeover is practically the same in all three cases, 4.0, 4.0 and 4.2 minutes. The final objective function of the corresponding linear programming problem is seen to increase with fewer control intervals which was expected with fewer degrees of freedom. Note that the aim is to drive the objective function to zero in order to arrive at final conditions which will be nearer to the desired state.

Also from Table 3.1 one can observe the results of maintaining the control time interval at 0.5 minutes and specifying 8, 7 and 6 control intervals. The linear programming objective function is seen to increase with a

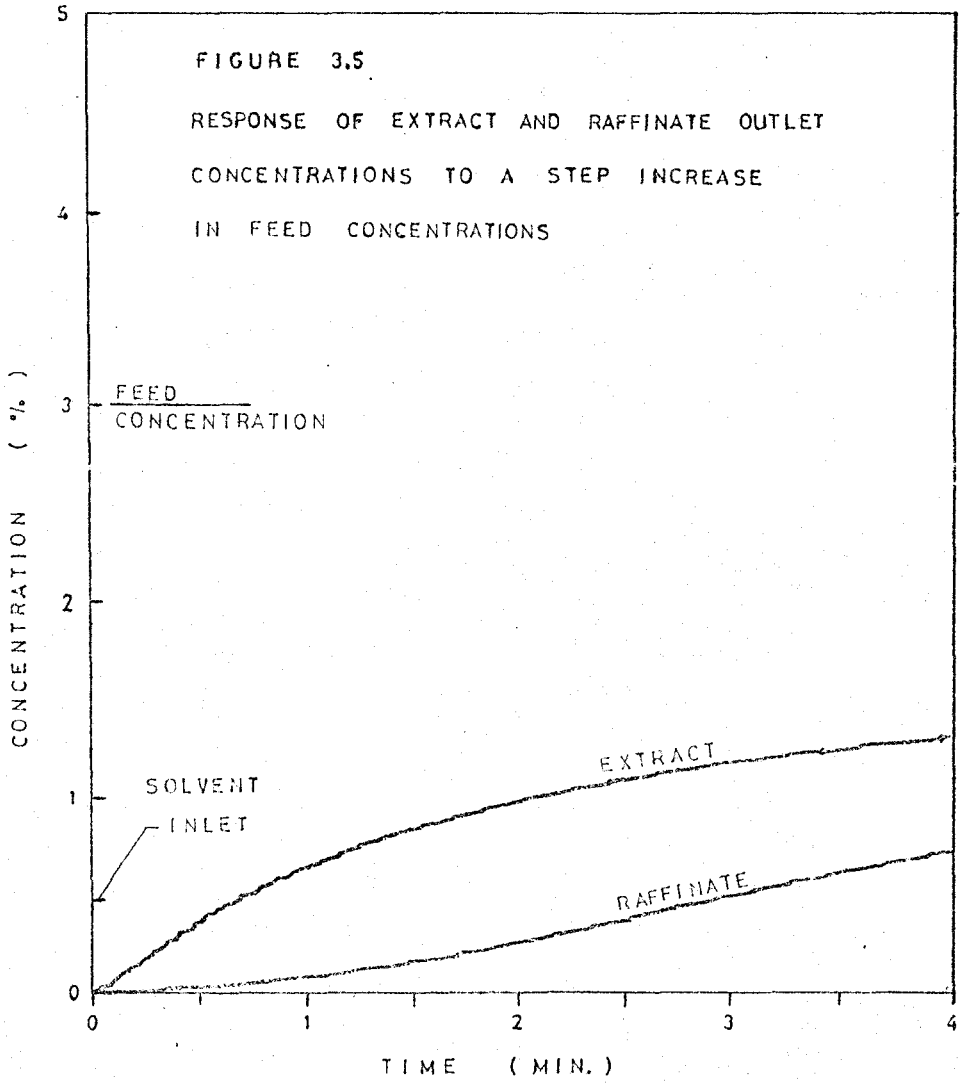
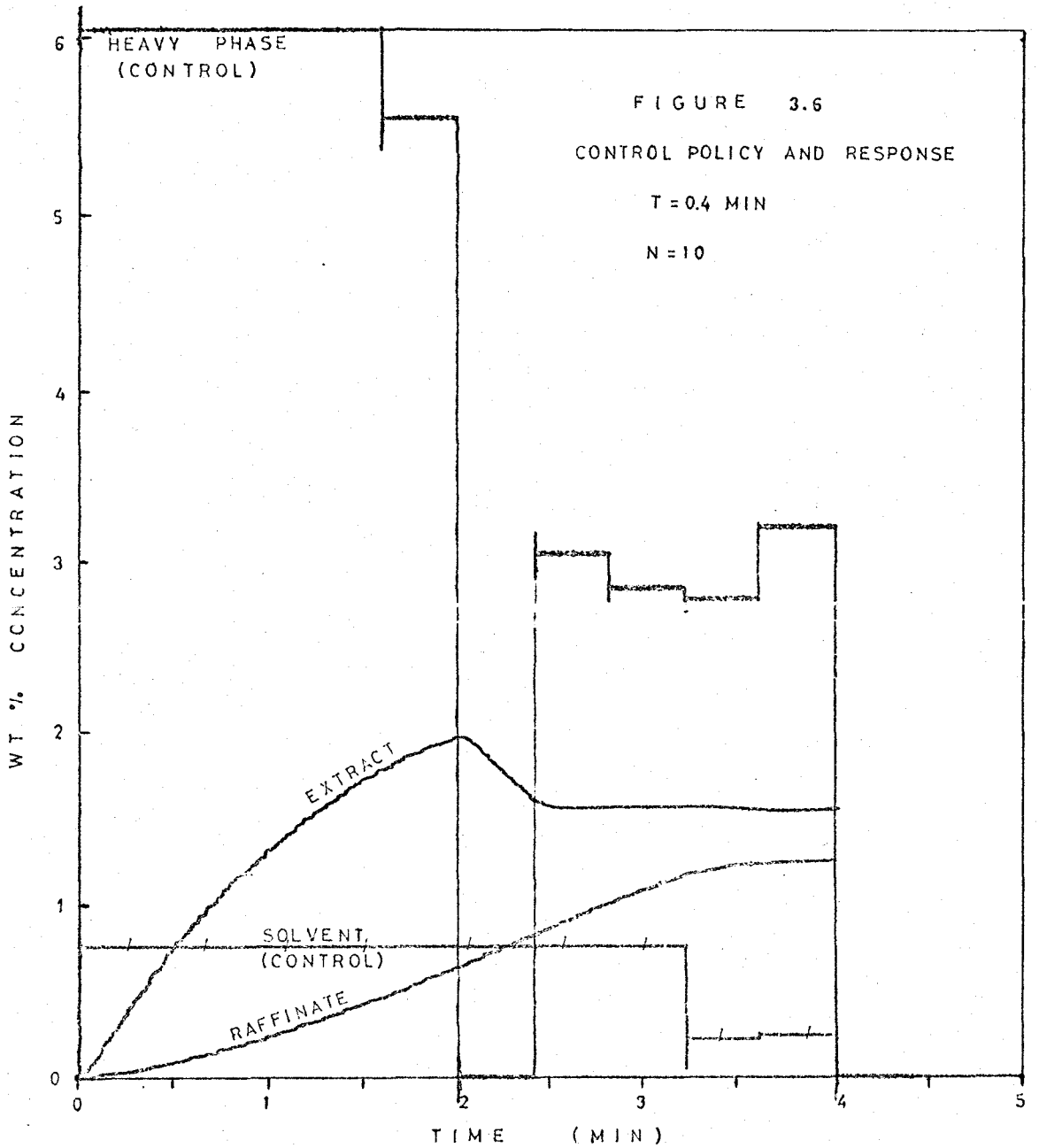
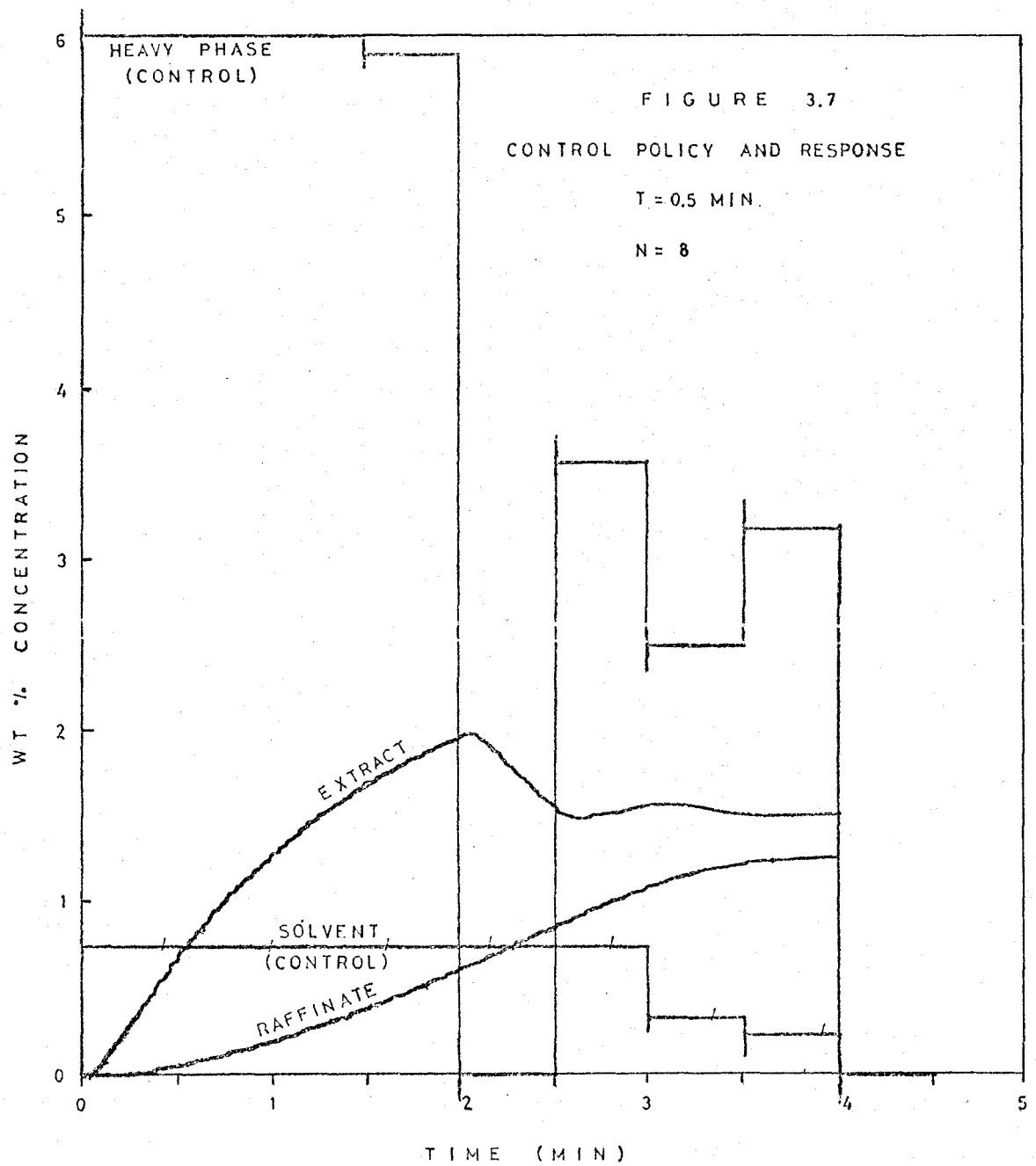
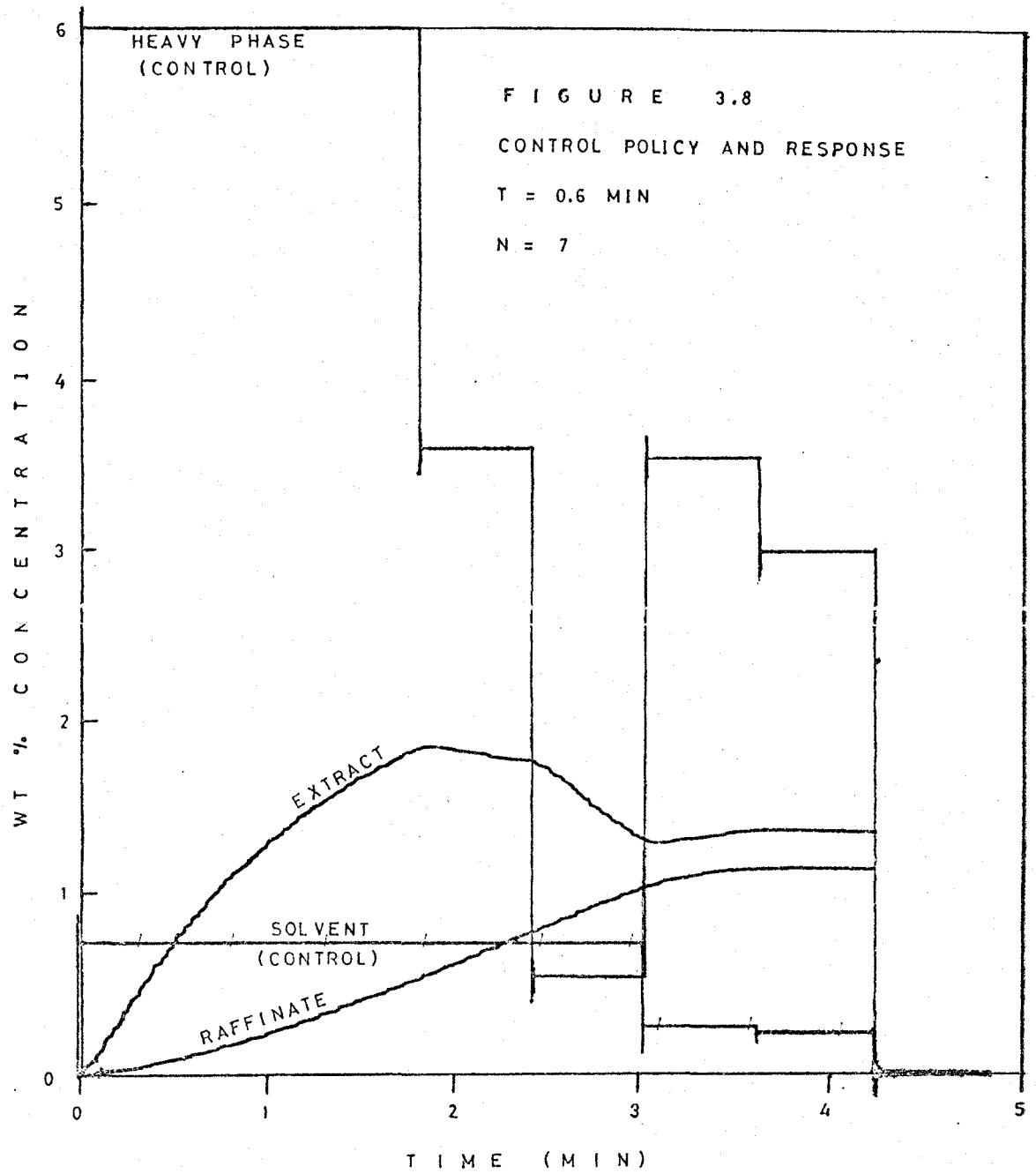
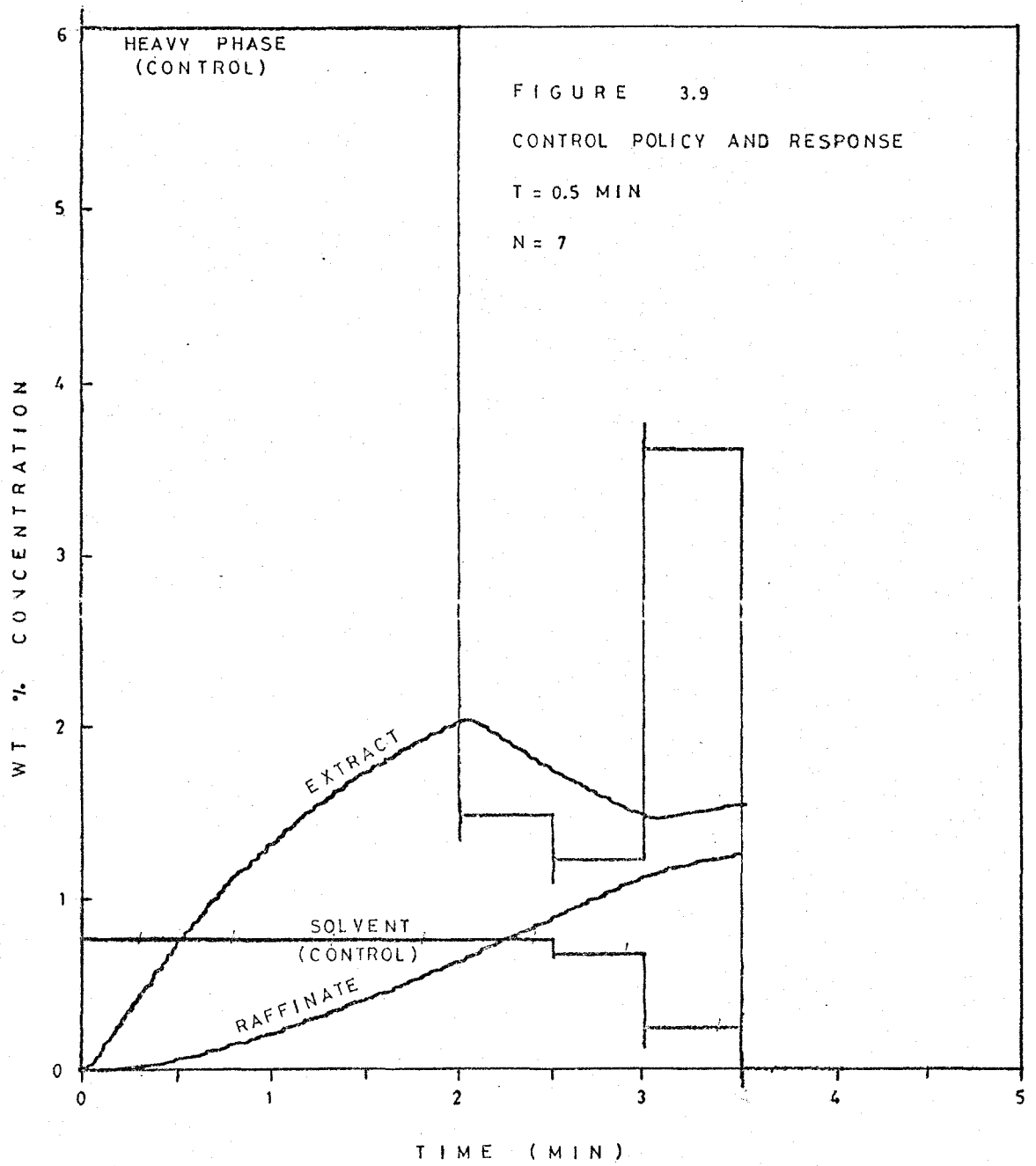


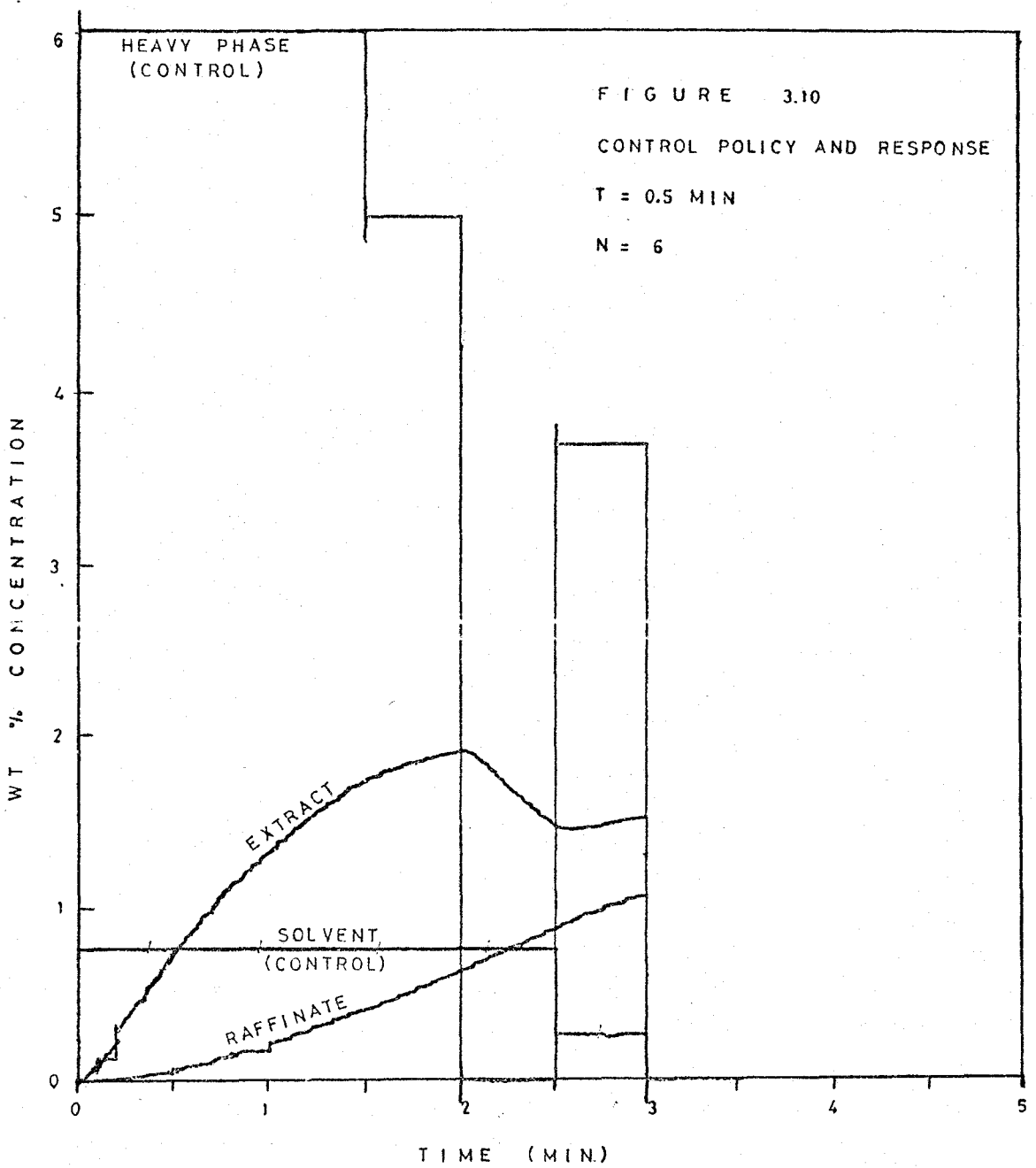
FIGURE 3.5
RESPONSE OF EXTRACT AND RAFFINATE OUTLET
CONCENTRATIONS TO A STEP INCREASE
IN FEED CONCENTRATIONS
CONCENTRATION (%)
TIME (MIN.)
FEED
CONCENTRATION
SOLVENT
INLET
EXTRACT
RAFFINATE
0
1
2
3
4
5


HEAVY PHASE
(CONTROL)
FIGURE 3.6
CONTROL POLICY AND RESPONSE
T = 0.4 MIN
N = 10
WT % CONCENTRATION
EXTRACT
SOLVENT
(CONTROL)
RAFFINATE
TIME (MIN)
0
1
2
3
4
5
6


HEAVY PHASE
(CONTROL)
FIGURE 3.7
CONTROL POLICY AND RESPONSE
T = 0.5 MIN.
N = 8
EXTRACT
SOLVENT
(CONTROL)
RAFFINATE
WT % CONCENTRATION
TIME (MIN)
0
1
2
3
4
5
6


HEAVY PHASE
(CONTROL)
FIGURE 3.8
CONTROL POLICY AND RESPONSE
T = 0.6 MIN
N = 7
WT % CONCENTRATION
TIME (MIN)
EXTRACT
SOLVENT
(CONTROL)
RAFFINATE
0
1
2
3
4
5
6


HEAVY PHASE
(CONTROL)
FIGURE 3.9
CONTROL POLICY AND RESPONSE
T = 0.5 MIN
N = 7
WT % CONCENTRATION
TIME (MIN)
EXTRACT
SOLVENT
(CONTROL)
RAFFINATE
0
1
2
3
4
5
6


HEAVY PHASE
(CONTROL)
FIGURE 3.10
CONTROL POLICY AND RESPONSE
T = 0.5 MIN
N = 6
WT % CONCENTRATION
TIME (MIN.)
EXTRACT
SOLVENT
(CONTROL)
RAFFINATE
0
1
2
3
4
5
6

decreasing number of control intervals. In this case we not only have fewer degrees of freedom, but also less time to carry out the changeover. This results in a much greater effect on the value of final objective function. One should note, however, that even though there is a large increase in the value of the objective function as fewer control intervals are used, there was not as large a change in the deviation of the final states from the desired states.

3.7 SCALING: The results of Table 3.2 were obtained using an analog scaling factor of 1 volt equal to 2% in concentration. To do this, all the digital computer input data was scaled by one-half as well as the setting on the analog computers. To test if significant differences would result when scaling was done, the first two cases of Table 3.2 were carried out. Steady state input concentrations of 2% for the water feed and 0% for the solvent feed were set on the analog models and allowed to reach steady state. The steady states from the analog computers were recorded and used as the desired state in calculating a changeover policy (case 1). The plotted results are shown in Figure 3.11 with zero initial conditions. The spikes on the corners of the control pulses on the plot are due to recorder overshoot and are not real electrical signals.

The procedure was then repeated with input solute concentrations of 4% in the water feed and 0% in the solvent (Figure 3.12).

TABLE 3.2

TEST OF SCALING - FINAL STATE CONDITIONS

		x1 Scale	x2 Scale	Case 1	Case 2	Case 3	Case 4
Initial Controls	x_F	-	-	0.0	0.0	2.0	4.0
	y_E	-	-	0.0	0.0	0.0	0.0
Final Controls	x_F	2.0	4.0	2.0	4.0	4.0	2.0
	y_E	0.0	0.0	0.0	0.0	0.0	0.0
Maximum Controls	x_F	-	-	5.0	10.0	10.0	10.0
	y_E	-	-	1.0	2.0	2.0	2.0
Final States	x_1	1.75	3.50	1.77	3.56	3.60	1.78
	y_1	0.95	1.88	0.95	1.90	1.90	0.93
	x_2	1.32	2.65	1.28	2.64	2.65	1.29
	y_2	0.78	1.60	0.80	1.60	1.58	0.75
	x_3	1.05	2.10	1.08	2.18	2.10	0.95
	y_3	0.50	1.00	0.52	1.04	1.02	0.45
	x_4	0.72	1.42	0.79	1.54	1.40	0.72
	y_4	0.33	0.64	0.33	0.70	0.65	0.31
	x_5	0.72	1.41	0.72	1.46	1.40	0.72
	y_5	0.026	0,045	0.02	0.06	0.05	0.02

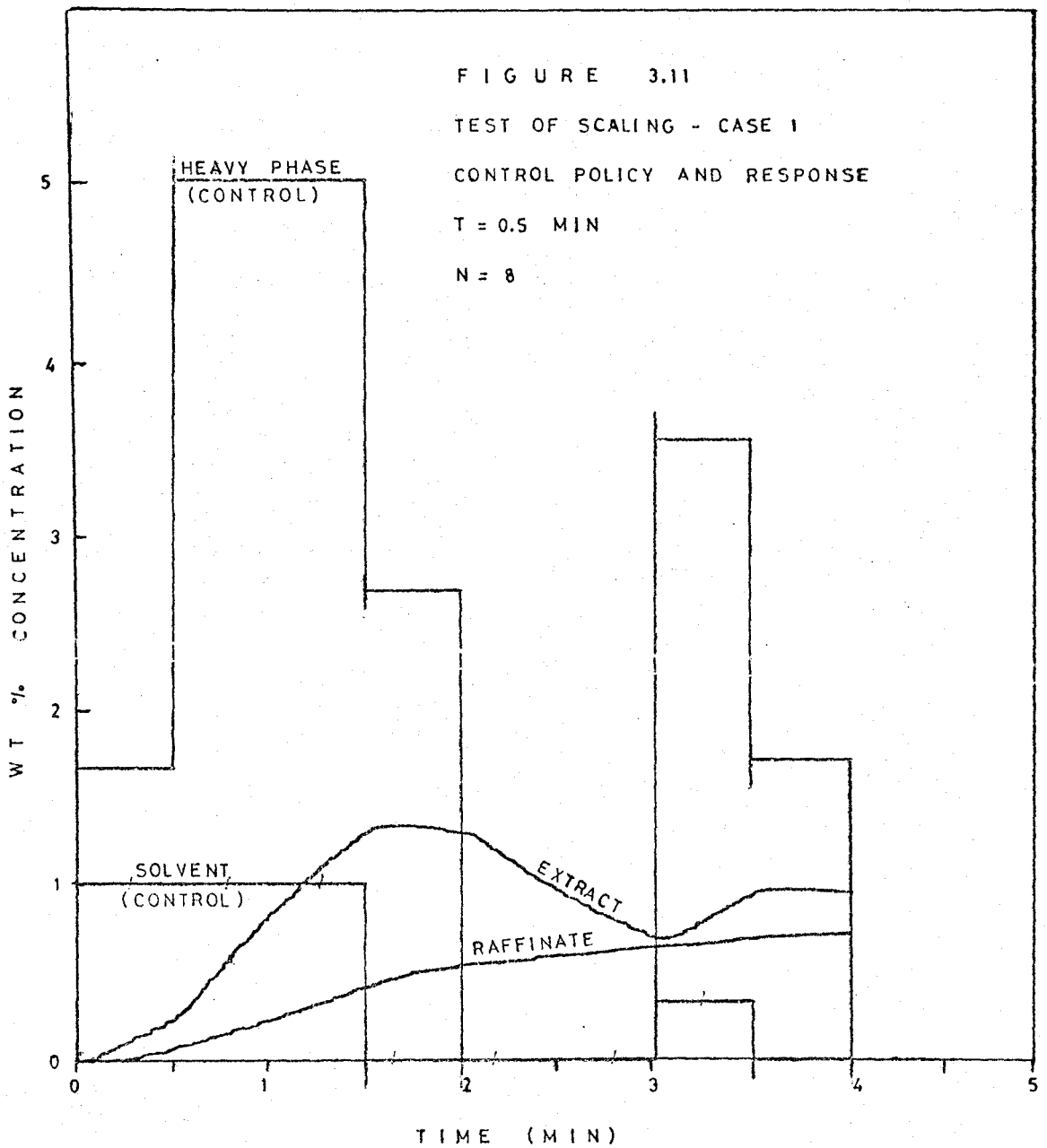


FIGURE 3.11

TEST OF SCALING - CASE 1

CONTROL POLICY AND RESPONSE

T = 0.5 MIN

N = 8

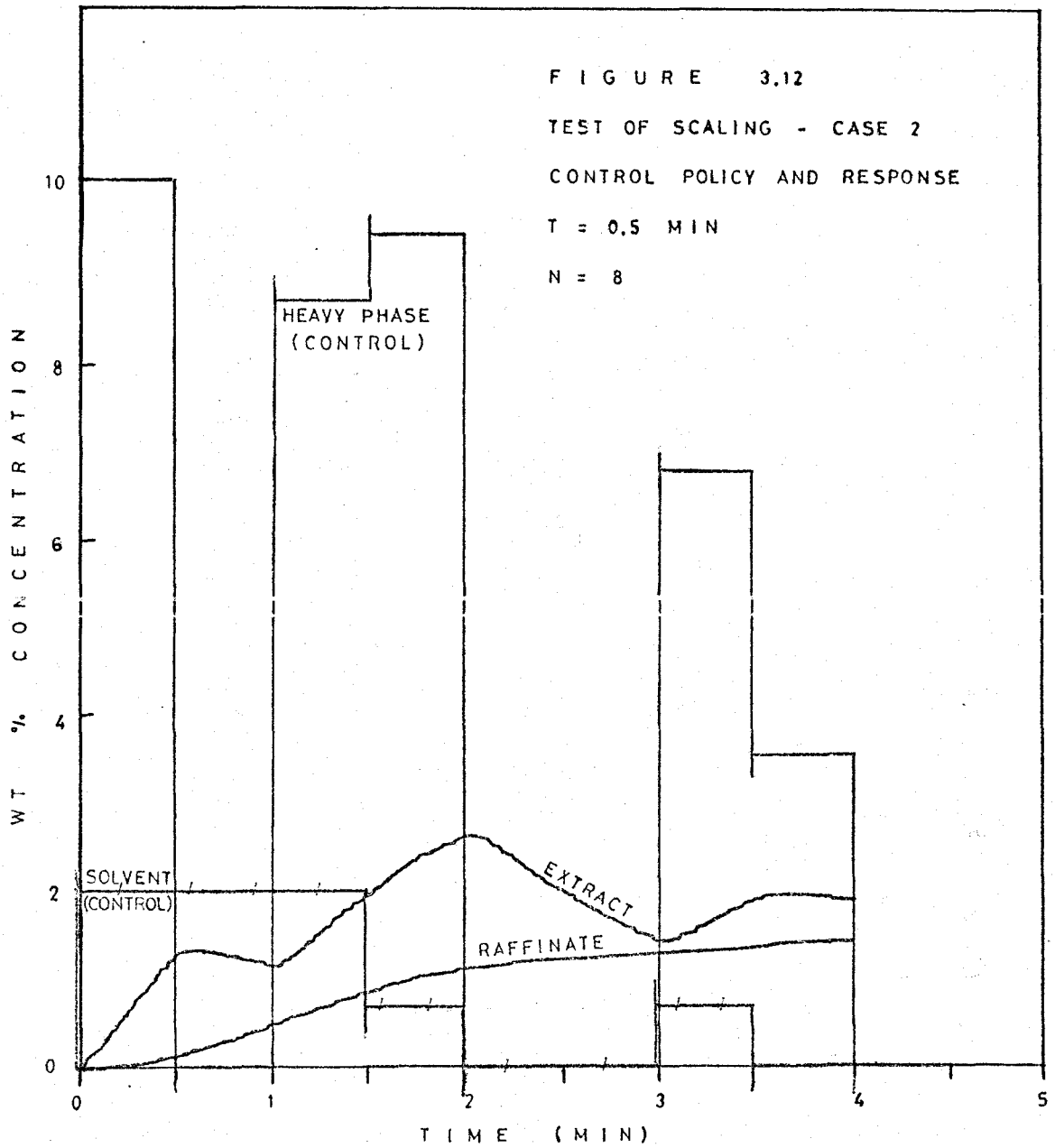


FIGURE 3.12
TEST OF SCALING - CASE 2
CONTROL POLICY AND RESPONSE
T = 0.5 MIN
N = 8
HEAVY PHASE
(CONTROL)
SOLVENT
(CONTROL)
EXTRACT
RAFFINATE
WT % CONCENTRATION
TIME (MIN)
0
2
4
6
8
10
0
1
2
3
4
5

For the first case the upper limits to the control inputs were set at 5% and 1% for the water and solvent phases respectively. For the second case, they were set at 10% and 2%. Because the model is linear with respect to concentration, one would expect the results of the second case (including the control policy output) to be twice those of the first case. The tabulated results show that indeed the steady states for the first case are one-half the steady states of the second case. Also, the final states, after implimentation of the changeover, show this one to two relationship. One can also see that the final states as a result of the changeover are nearly the same as the steady states determined by allowing the system to completely respond to the corresponding fixed control inputs. From these observations, it could be concluded that linearity of the system was exact. However the plotted result of these two cases (Figures 3.11 and 3.12) show a completely different set of controls were applied and the paths taken by the state variables in going from the initial to the final conditions were different in each case. Closer observation of these plots shows that the last half of the control policy was nearly the same for the two cases with a maximum deviation of 5% in the last four of the eight control time intervals.

Referring back to the derivation of the linear programming equations, one is looking for any solution; therefore, it is reasonable to expect two different solutions

to the same problem to exist as found here. However, the reason why they are different has not been identified, especially when it is the same problem in each case only scaled differently. Certainly truncation error may cause differences, but such extreme differences were not anticipated.

The results of this exercise point out one fact which is intuitive anyway. It is this, that the last few control intervals have a greater effect on setting the final states than the earlier time intervals. Common to both cases is a large surge of solute to the extraction column in both phases in the early part of the control. Even though the control pulses of the water phase concentrations vary widely, the amount of solute entering the column in the first half of the control (proportional to the area of the pulses) is nearly the same in each case. In other words, the first half of the control policy gives the system an initial boost towards the final state and the last half of the control brings the states in line with the desired conditions. There appears to be less freedom in the choice of the final controls, whereas much larger freedom of choice of the controls exists for the early part of the control scheme.

Another generalization may be gathered from all the plotted results. The final controls of the control policy tend toward the predicted controls of the final steady state, resulting in a flattening of the curves of the state variables during the final control interval.

Two additional cases were looked at in this series. Test case 3 went from an initial steady state with a water inlet concentration of 2% to the final state which was the same as the steady state of case 2 with an initial solute concentration in the water of 0%. The last case (case 4) started from the 4% feed concentration steady state and moved the system to the 2% feed steady state conditions. The solute concentration in the solvent inlet for each of these steady states was zero. Details of the steady state controls, limits on the controls and the final states are shown in Table 3.2. Plotter output of these changeovers are Figures 3.13 and 3.14.

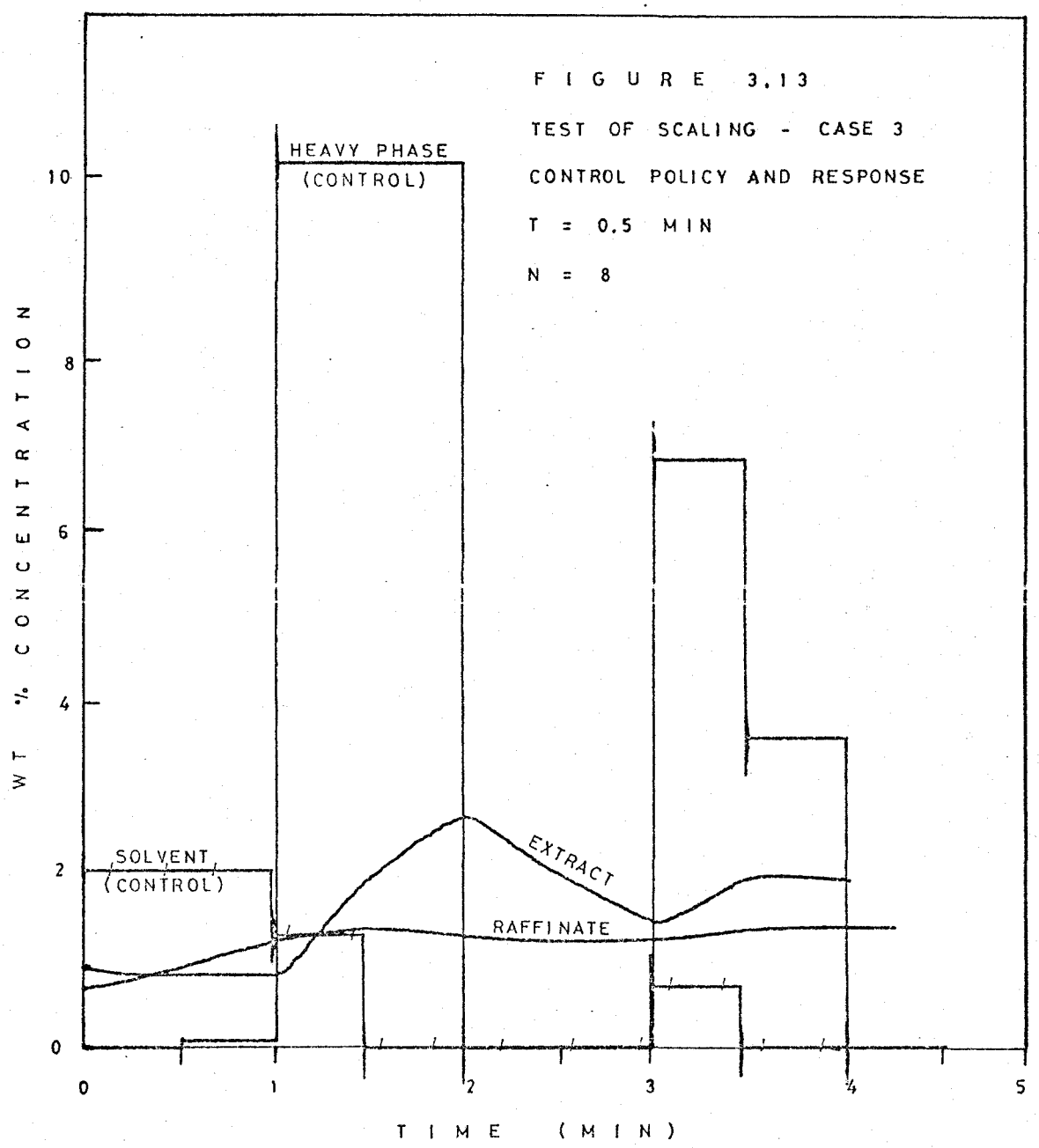


FIGURE 3.13

TEST OF SCALING - CASE 3

CONTROL POLICY AND RESPONSE

T = 0.5 MIN

N = 8

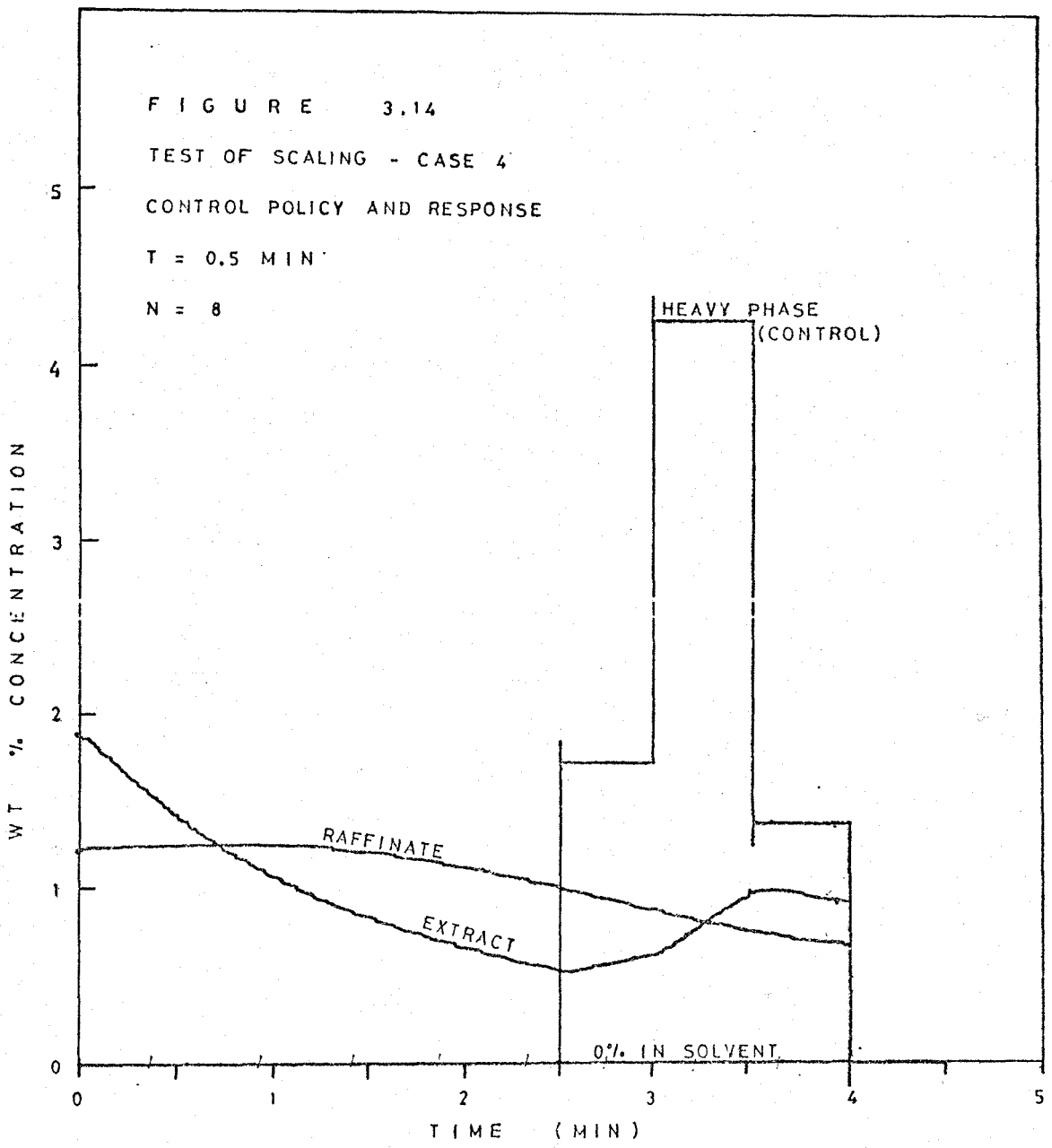


FIGURE 3.14
TEST OF SCALING - CASE 4
CONTROL POLICY AND RESPONSE
T = 0.5 MIN
N = 8
HEAVY PHASE
(CONTROL)
RAFFINATE
EXTRACT
0% IN SOLVENT
WT % CONCENTRATION
TIME (MIN)
0
1
2
3
4
5

4. DIRECT DIGITAL CONTROL OF THE EXTRACTION SIMULATION

This chapter summarizes the initial direct digital control experiences with the Supernova. The analog simulation of the extraction unit as described in Chapter 1 was controlled.

The controlled variable was the extract (light phase) exit concentration. The manipulated variable was the feed concentration (heavy phase inlet). Selection of controller parameters will be presented later.

The open-loop response of the two outlet concentrations to a step change in feed concentration is shown in Figure 3.5.

4.1 SUBROUTINE OF A CONVENTIONAL CONTROLLER: The direct digital control was carried out by using a 3-mode controller* subroutine with floating point arithmetic which was called once every control time interval. Calculation time for one control loop using this subroutine was 12 milliseconds.

The executive program was a simplification of a preliminary version of a real time executive. Real-time clock pulses signified time increments and at preset time intervals the executive transferred control to a subroutine that read in the value of the controlled variable from the A/D converter, then called the controller subroutine to

* see Appendix G for algorithm

calculate the output, scaled it to 10 bits, and transferred this number to the D/A converter. Control was then handed back to the executive which restored the pre-interrupt status of the central processor.

When a teletype interrupt signal was received, control was transferred to a subroutine which received numbers from the teletype. Two letter codes were used to designate sample time (SA), set point (SE), gain (GA), reset rate (RA), and derivative time (DE). When input of new data was completed, central procession control was transferred to the executive which restored the pre-interrupt state of the central processor. See Appendix E for a sample of the teletype commands. Appendix F contains all the programs needed to carry out the control.

The clock was given a higher interrupt priority than the teletype so that DDC could continue as new data was being entered. During a teletype interrupt, values (controller settings) were temporarily stored in a buffer and were then passed to the controller data table just prior to the return to the executive. This allowed the capability of nearly simultaneous entry of new values for the controller constants.

All teletype input to the controller subroutine was in floating point decimal format. No problems arose except when a new sample period was entered. The sample time was multiplied by the real time clock frequency (in floating point) to get the number of clock pulses per sample period.

That number was then converted to an integer number which was used as a counter by the real time clock subroutine. When the floating point to integer conversion was done, truncation occurred. For example, if the clock is running at ten cycles per second and a sample period of 0.4 seconds is to be used, the calculated product of 10 X 0.4 will be fractionally less than 4.0 so that the integer number after truncation will be 3 rather than 4 clock pulses per sample time. This means the controller subroutine will be called every 0.3 seconds but will use a period of 0.4 seconds in its calculation, giving an error of 33% in the terms that use the sample period in their calculation. This problem was avoided by typing times that were fractionally larger than the desired sample period (eg. 1.00001 rather than 1.0). This results in the truncation of a number slightly larger than 4.0 rather than one that is less than 4.0, and hence produces 4 clock pulses per sample period. A better method would have been to use the floating point rounding command. This command rounds a number to the nearest whole number. The subsequent conversion to a fixed point number would then have been correct. In the example the number would have been rounded to 4. When the floating point to fixed point conversion was carried out the correct fixed point integer would have resulted.

4.2 CONTROLLER SELECTION: Pang (3) used a five-stage model of non-equilibrium stages when he did his changeover calculations. That same model was used on the analog computers for this thesis. Satisfactory results were obtained from the changeover studies.

Pang used a slightly different model in doing his classical control studies. All the parameters of the model were the same as before only a mixing stage and a dead time were added to the extract (light phase) outlet. This latter model is the one whose frequency response most closely resembles the frequency response obtained from Pollock's data.

The following is the order in which Pang did his studies. He first wired up a three stage model of the extraction column on analog computers. He adjusted the potentiometer settings of mass transfer coefficients to make the model match Pollock's data. Pang next carried out digital simulations of other models in order to get better agreement with actual column dynamic response. Pang's "best" model is the one referred to in the first paragraph of this section and it was not simulated on the analog computers by Pang.

It is difficult to simulate accurately a dead time on the TR10 analog computers so Pang's controller configurations were not checked on the correct analog model. Figures 4.1, 4.2, and 4.3 illustrate the results of applying Pang's calculated controls to the model he used in his changeover studies.

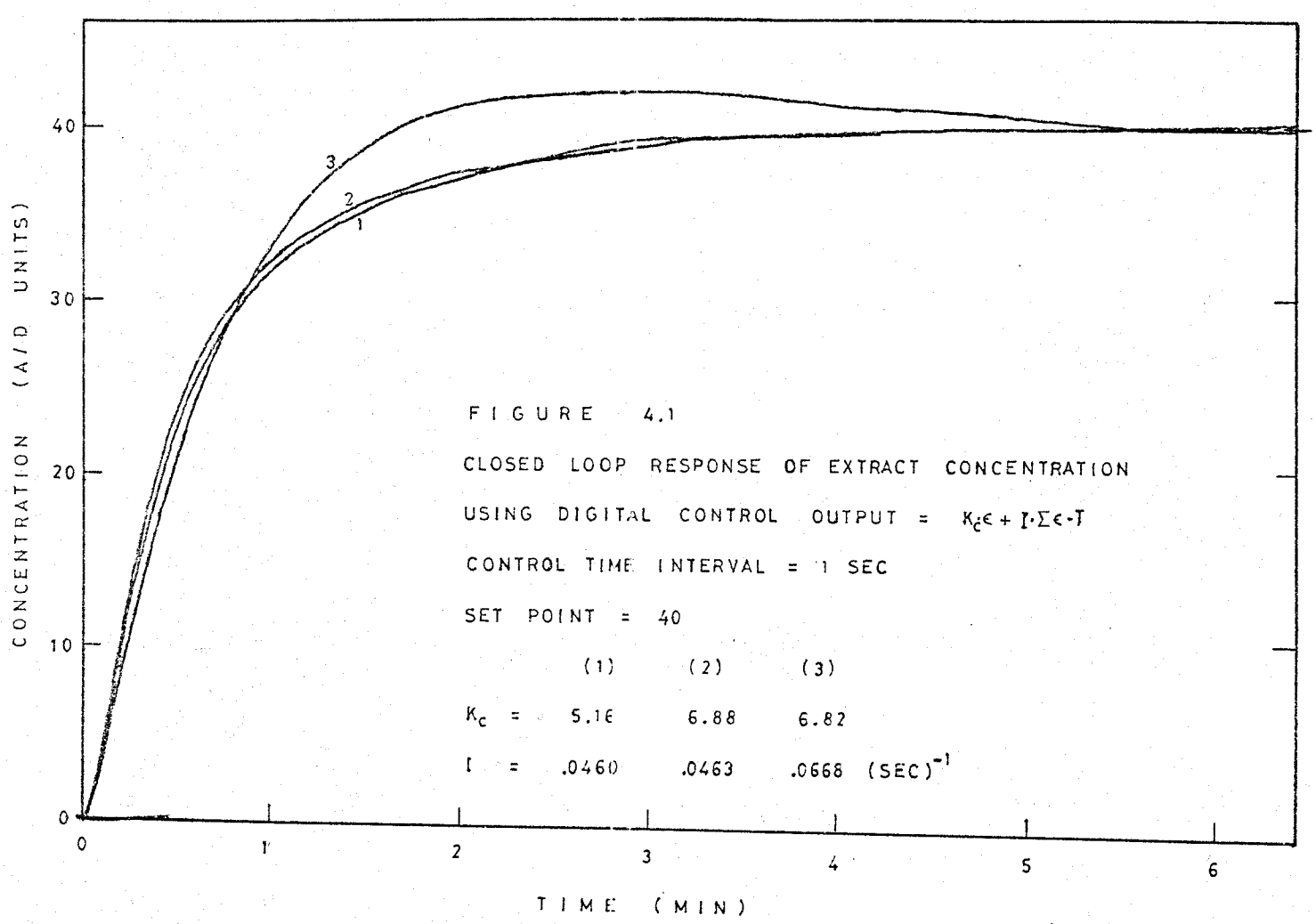


FIGURE 4.1

CLOSED LOOP RESPONSE OF EXTRACT CONCENTRATION

USING DIGITAL CONTROL OUTPUT = $K_c\epsilon + I\cdot\Sigma\epsilon\cdot T$

CONTROL TIME INTERVAL = 1 SEC

SET POINT = 40

	(1)	(2)	(3)
K_c =	5.16	6.88	6.82
I =	.0460	.0463	.0668 $(SEC)^{-1}$

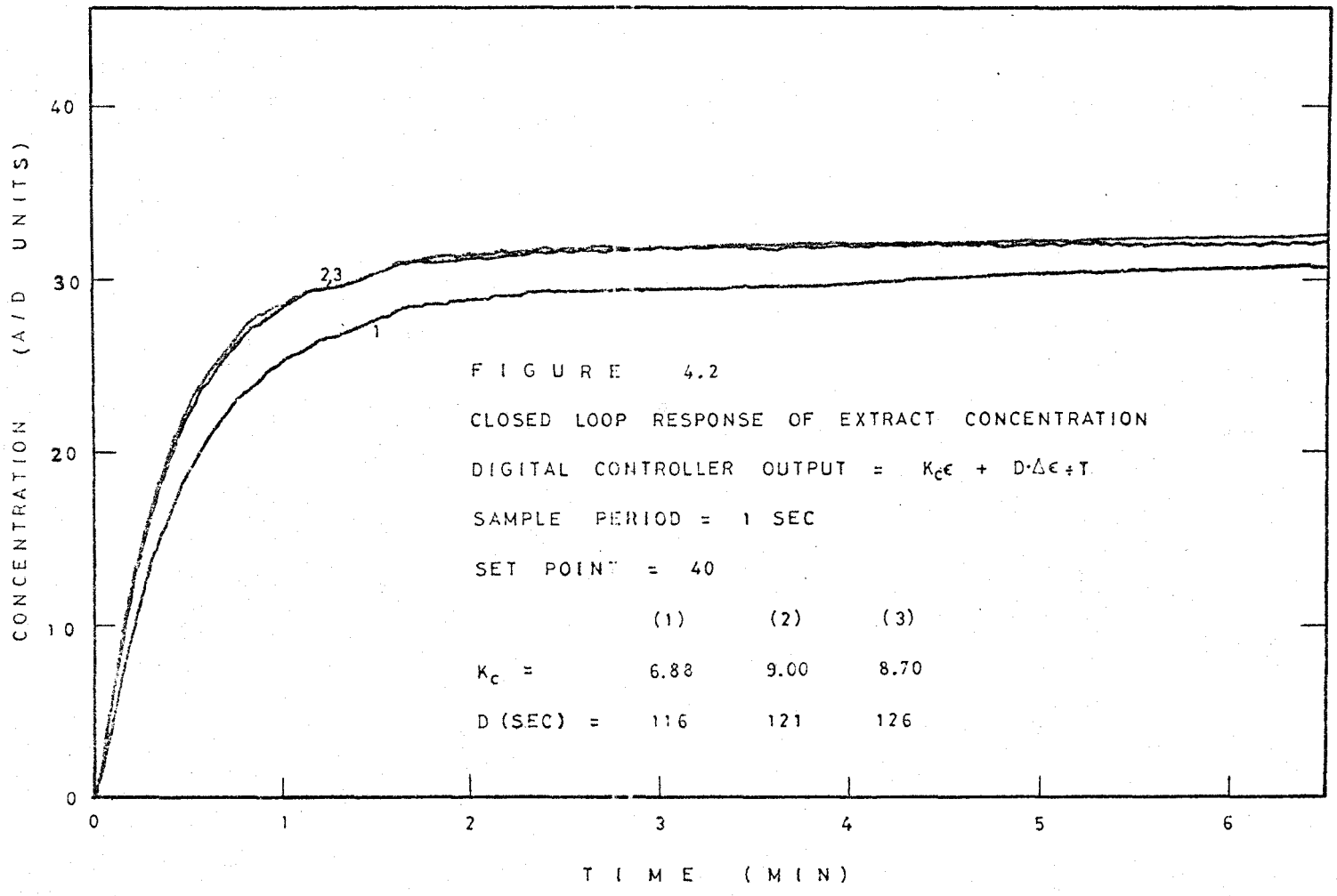


FIGURE 4.2

CLOSED LOOP RESPONSE OF EXTRACT CONCENTRATION

DIGITAL CONTROLLER OUTPUT = $K_c\epsilon + D\cdot\Delta\epsilon + T$

SAMPLE PERIOD = 1 SEC

SET POINT = 40

	(1)	(2)	(3)
K_c =	6.88	9.00	8.70
D (SEC) =	116	121	126

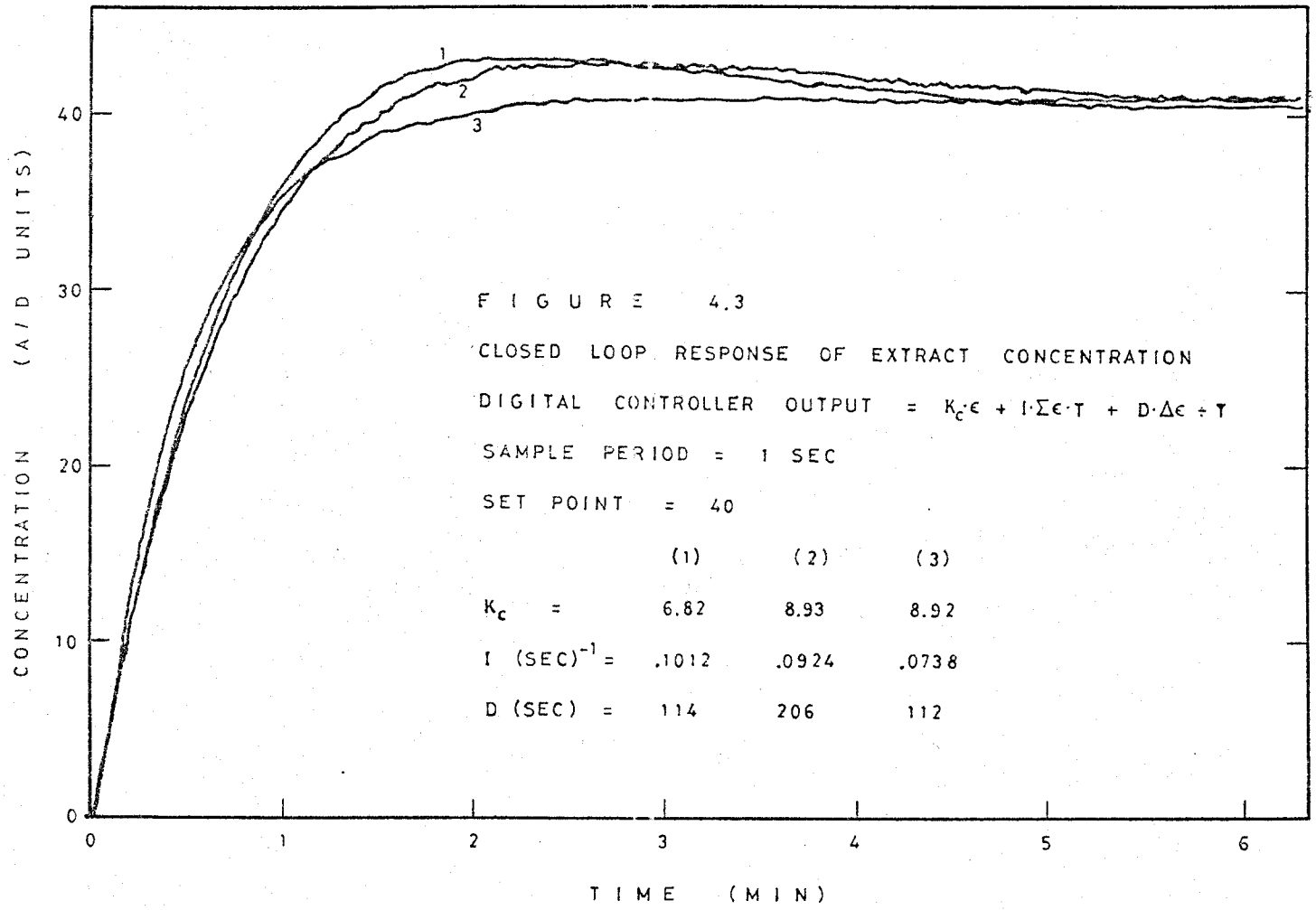


FIGURE 4.3

CLOSED LOOP RESPONSE OF EXTRACT CONCENTRATION

DIGITAL CONTROLLER OUTPUT = $K_c \cdot \epsilon + I \cdot \Sigma\epsilon \cdot T + D \cdot \Delta\epsilon \div T$

SAMPLE PERIOD = 1 SEC

SET POINT = 40

	(1)	(2)	(3)
K_c =	6.82	8.93	8.92
I $(SEC)^{-1}$ =	.1012	.0924	.0738
D (SEC) =	114	206	112

For all the examples in which the controller parameters were chosen from the frequency response of the extraction column (i.e. from Pollock's data (5)), the design can be seen to be strongly conservative. This is the result of applying control for a less stable system (Pang's) to a more stable one (the author's).

In the discussion which follows, the disturbance is always a positive step change in the set point unless designated otherwise for individual diagrams. Concentration units have not been used in this chapter since any units may have been used for the analog models. A single scaling factor is sufficient to convert to any desired concentration units. The numbers that appear on the figures correspond to the digitized converter values of the analog computer voltages. For both the A/D and D/A converters, the range is from -512 to 511 which corresponds to -10 volts to +10 volts on the analog computers, with zero volts normally representing some base case of steady state conditions. The numbers on the digital side of the converters have been used so that one may be aware of any significant discontinuities caused by the input and output of integer values through the converters.

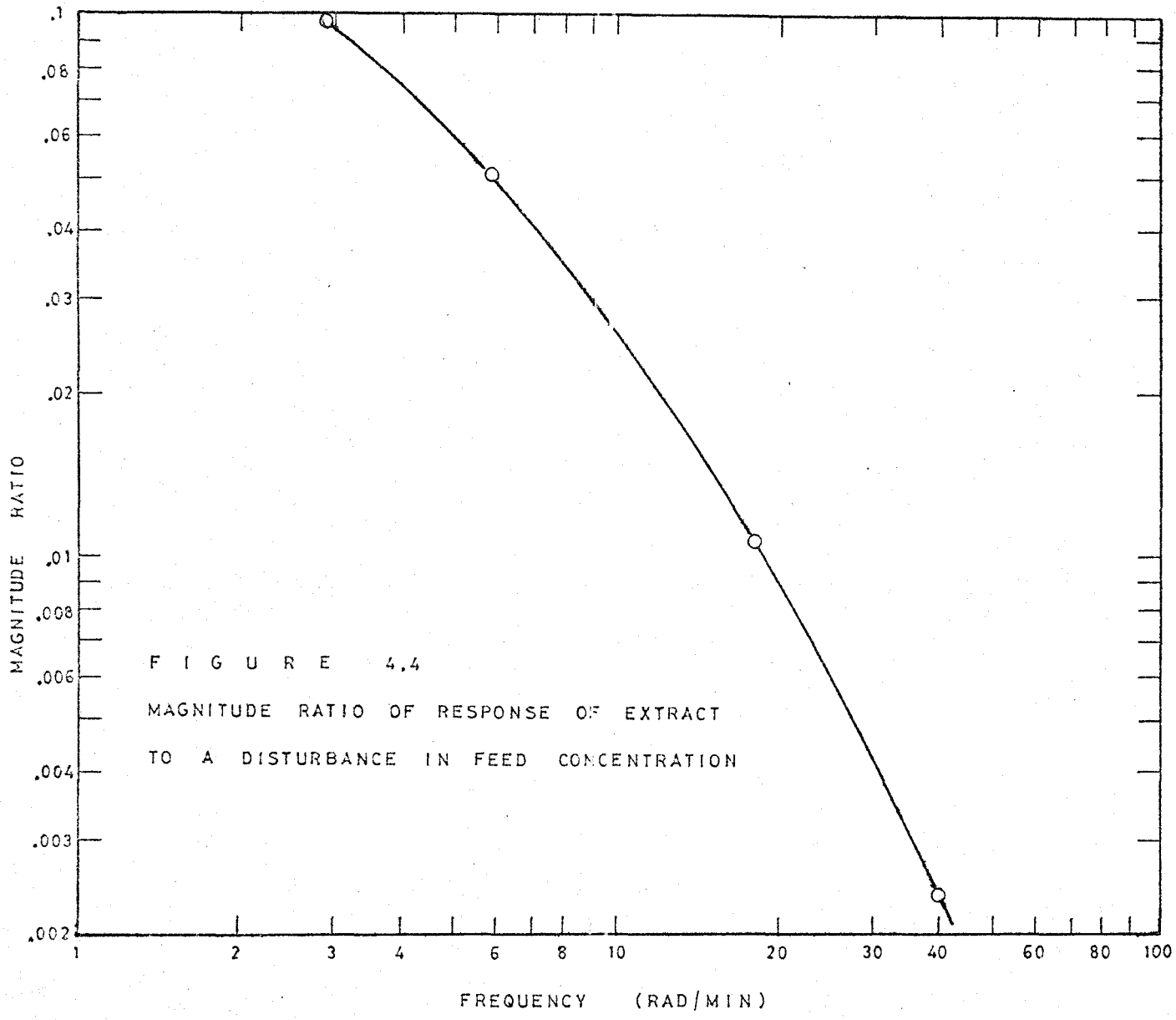
Figure 4.1 is the result of applying proportional reset control to the extraction column simulation. Two of the curves are seen to be closely similar, having had similar controller settings. The third curve had lower gain but larger reset action which resulted in a slight overshoot.

Proportional-derivative response of the extract phase is illustrated in Figure 4.2. As in Figure 4.1, two of the curves are similar because of similar controller settings. Offset from the set point occurred. The third response curve, which resulted from a lower controller gain, has a larger offset which is to be expected. Offset due to proportional control only is illustrated more effectively in Figure 4.7 in which analog and direct digital control were compared.

When three-mode digital control was used (Figure 4.3), one set of controller parameters had less reset action resulting in a lower response curve. The other two curves show a slight overshoot due to the higher reset action.

Figures 4.2 and 4.3 have rippled response curves which is not so for Figure 4.1. The ripples are due to the derivative action. The controller output when derivative action is applied will be discussed later.

A frequency response analysis was done for the five-stage extraction model without the extract mixing stage and time delay to obtain the Bode diagrams. Sinusoidal inputs were applied to the heavy phase inlet concentration and the concentration of the extract outlet was monitored to obtain Figures 4.4 and 4.5. Using these plots, new controller configurations were calculated using the Ziegler-Nichols criterion. Figure 4.6 shows the response of the system to closed loop control using the calculated controller settings.



F I G U R E 4.4

MAGNITUDE RATIO OF RESPONSE OF EXTRACT

TO A DISTURBANCE IN FEED CONCENTRATION

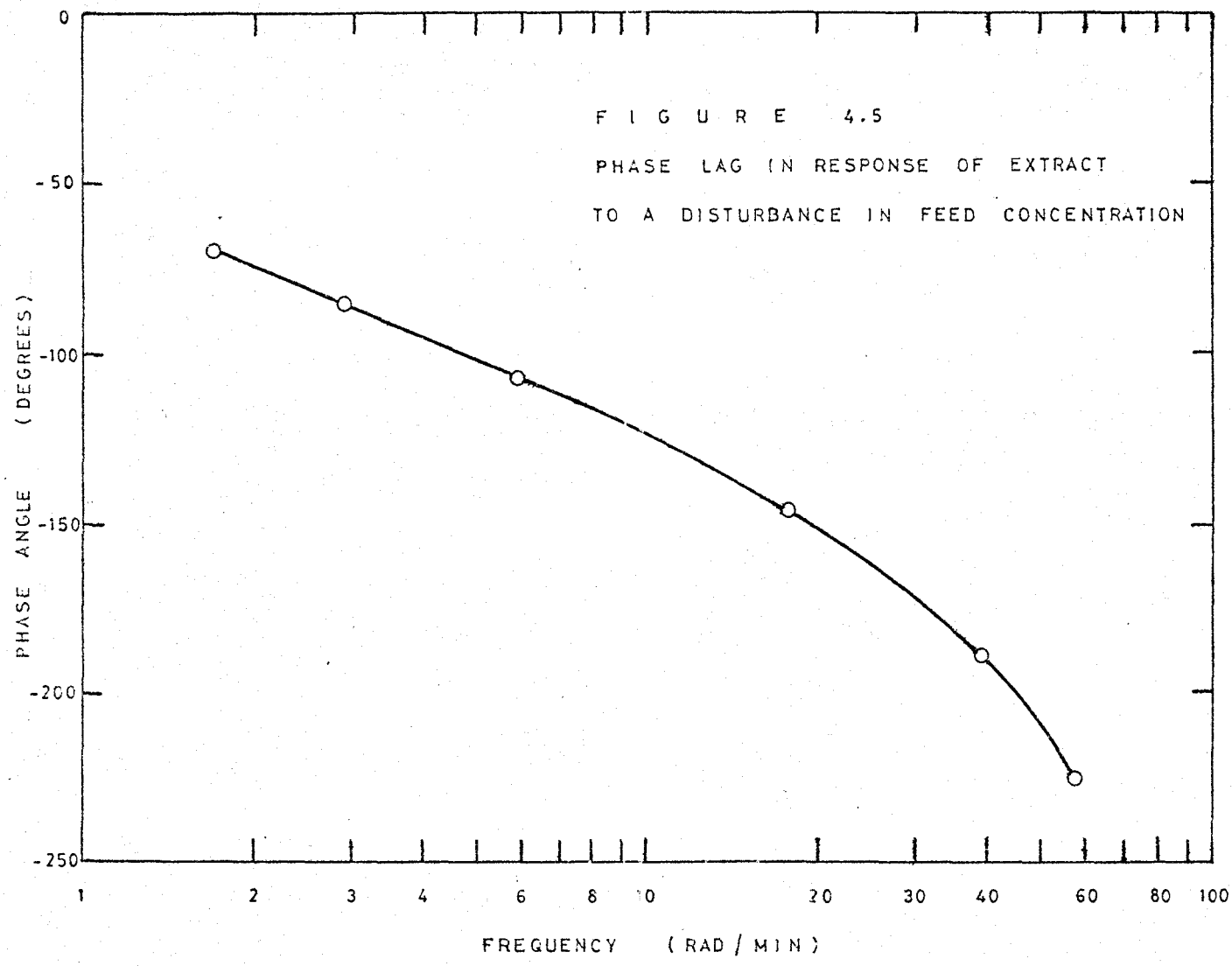


FIGURE 4.5

PHASE LAG IN RESPONSE OF EXTRACT TO A DISTURBANCE IN FEED CONCENTRATION

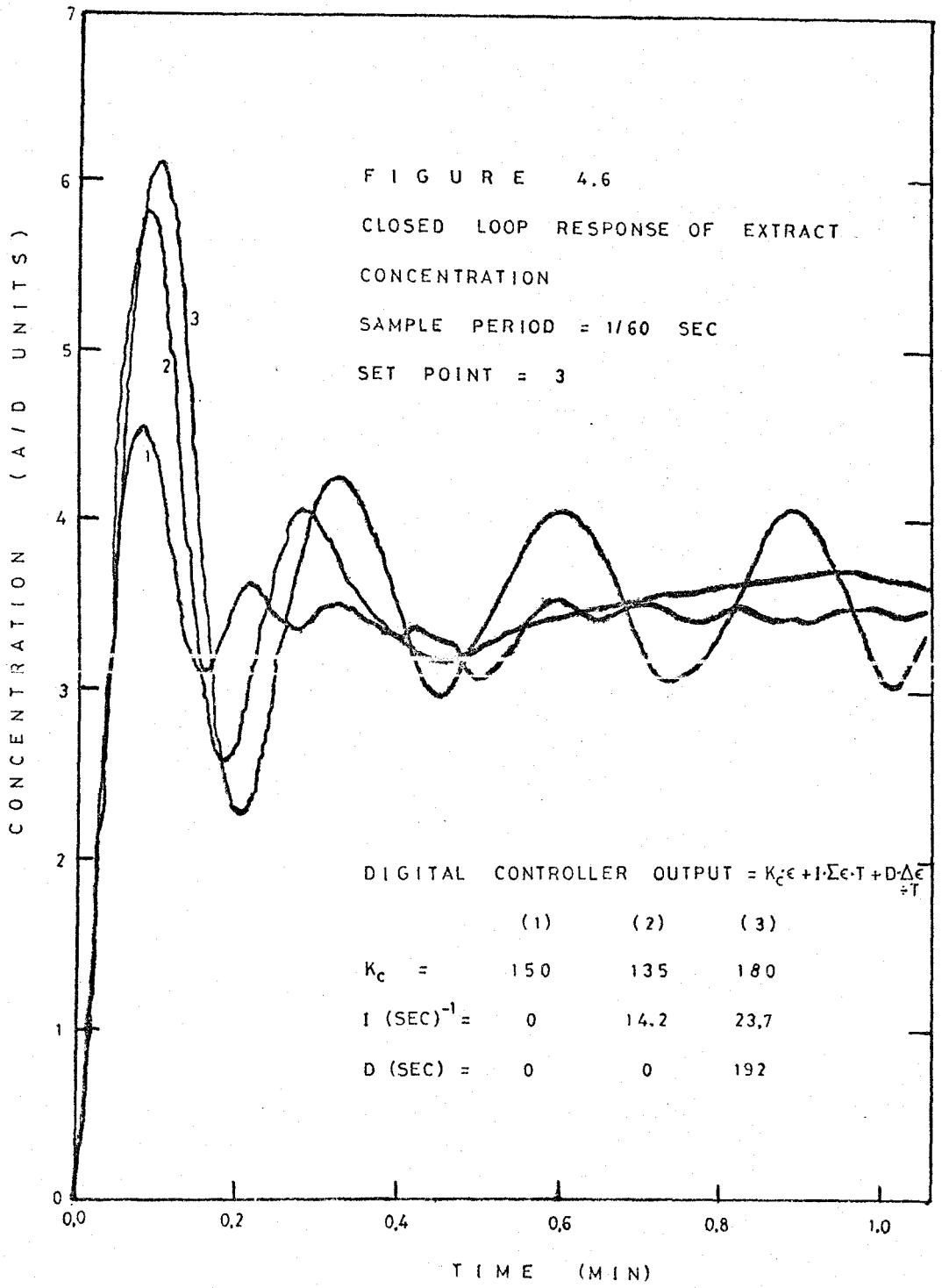


FIGURE 4.6

CLOSED LOOP RESPONSE OF EXTRACT CONCENTRATION

SAMPLE PERIOD = 1/60 SEC

SET POINT = 3

DIGITAL CONTROLLER OUTPUT = $K_c \cdot \epsilon + I \cdot \Sigma \epsilon \cdot T + D \cdot \frac{\Delta \epsilon}{T}$

	(1)	(2)	(3)
K_c =	150	135	180
I $(SEC)^{-1}$ =	0	14.2	23,7
D (SEC) =	0	0	192

In Figure 4.6 there is little difference between the steady state values of the controlled variable for the different controller configurations. This is due to the high gain that has been used. A unit error (one bit error) on input gives an output of 150 using only proportional control. This is 30% of the 512 (10 volt) maximum of the digital to analog converters. That is, an error of 4 in 512 (.008 volts) on input will saturate the output.

4.3 COMPARISON OF ANALOG CONTROL TO DIRECT DIGITAL CONTROL:

Figure 4.7 shows the response of the extract concentration to a load change in the feed concentration to the extraction model using an analog proportional controller. Three controller settings with gains of 4, 10 and 100 were used. The set point in each case was zero. The offset is seen to decrease as the gain increases with a slight oscillation occurring for the case in which high gain was used.

The same controller settings were then used for a proportional digital control. The response curves of the digital control were identical to those of Figure 4.7. Sample rate was 60 times per second. From this we conclude that direct digital control of the extraction simulation is the same as the analog control up to gains of at least 100 when the sampling rate is at least 60 times per second.

For comparison, Figure 3.5 is an example of the uncontrolled response of the extract and raffinate outlet concentrations to a step increase in feed concentration.

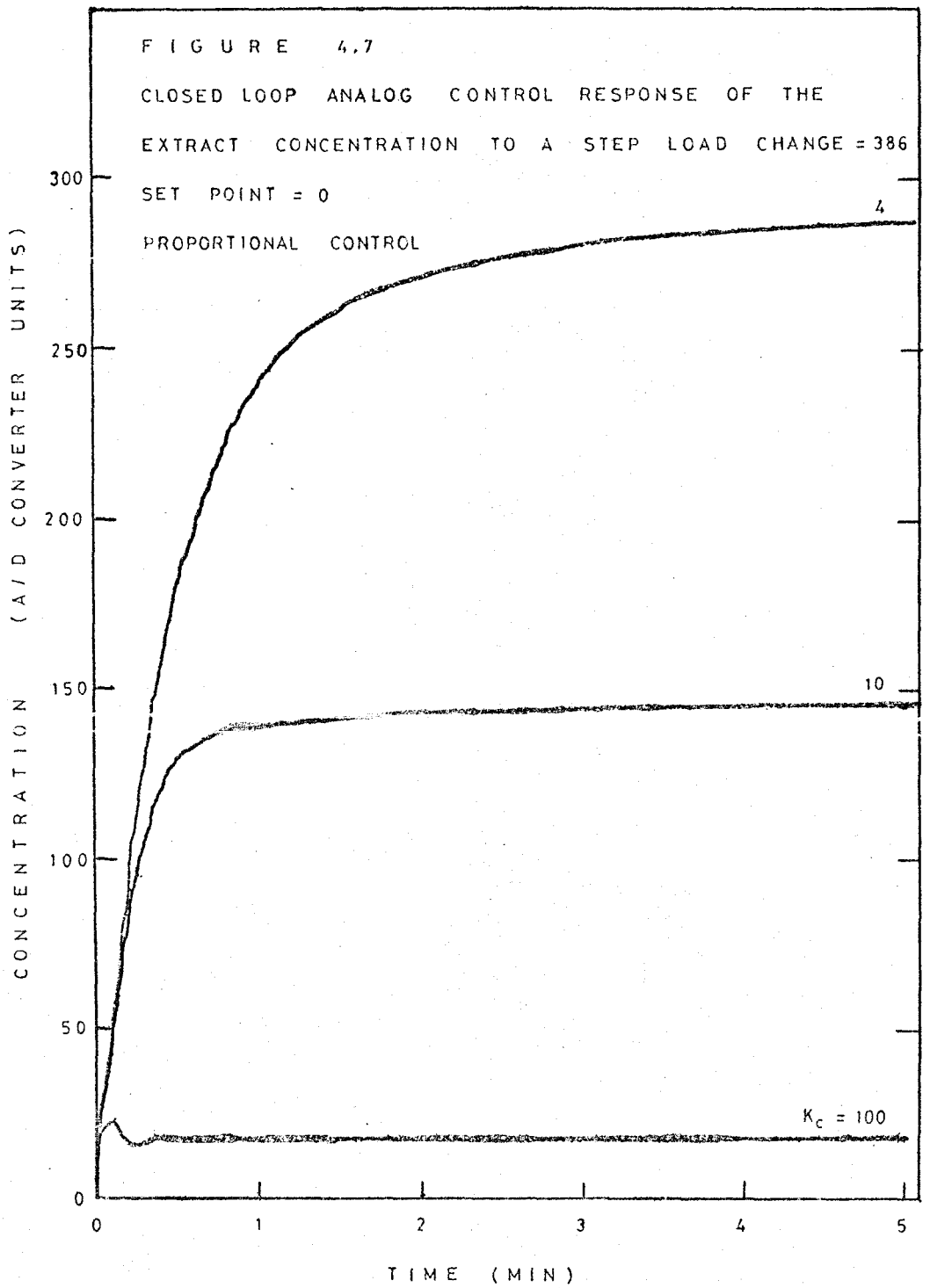


FIGURE 4.7
CLOSED LOOP ANALOG CONTROL RESPONSE OF THE EXTRACT CONCENTRATION TO A STEP LOAD CHANGE = 386
SET POINT = 0
PROPORTIONAL CONTROL
4
10
K_c = 100
CONCENTRATION (A/D CONVERTER UNITS)
TIME (MIN)
0
50
100
150
200
250
300
0
1
2
3
4
5

4.4 SELECTION OF SAMPLE PERIOD: When direct digital control is implemented, a good sampling period should be chosen. Large sampling periods can make the control system go unstable by introducing a time delay in the closed loop response. Very short sampling time may not allow enough calculation time, so that the next sampling period has begun before the calculation of the present one has been completed. The minimum sampling time then becomes the time to do all the controller calculations plus the time taken for input and output of signals.

Figures 4.8 and 4.9 show the results of a test that was performed to illustrate the effect of sample period when proportional control was used. Both the controlled variable (extract concentration) and the controller output are plotted. The extract concentration followed the same path for sample periods of one second and ten seconds. When a thirty second sample period was used, a difference in the response appeared. A sixty second sample period was used for Figure 4.9 and it shows how overshoot can occur even when low gains are used. As the sample period increases, the controlled response would be expected to oscillate as the controller output oscillates between upper and lower bounds.

Figure 4.10 is an example of proportional-reset control action using controller settings that were calculated (using the Ziegler-Nichols criterion) from one set of Bode diagrams obtained by Pollock (5). Here we see smaller sample

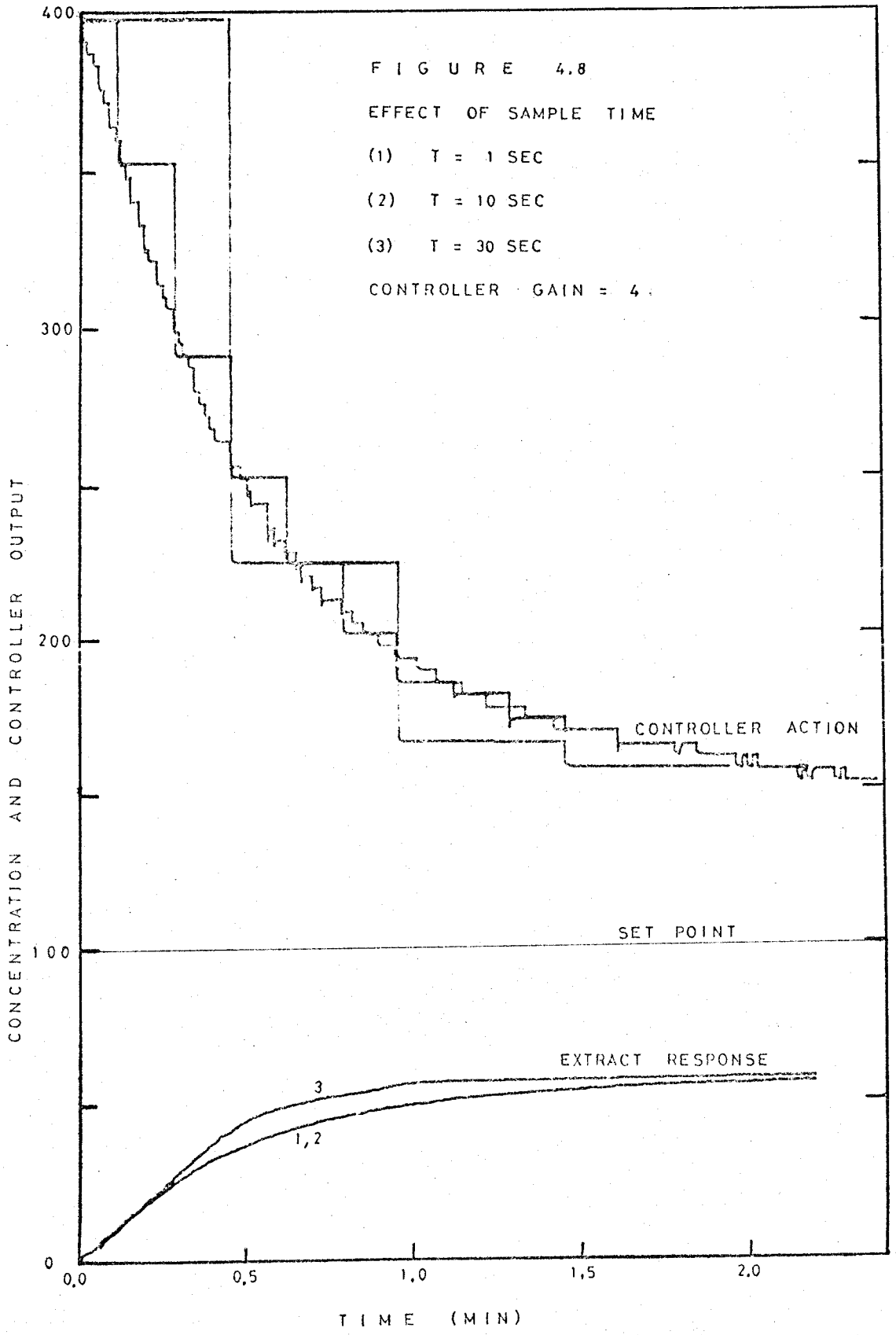


FIGURE 4.8
EFFECT OF SAMPLE TIME
(1) T = 1 SEC
(2) T = 10 SEC
(3) T = 30 SEC
CONTROLLER GAIN = 4.
CONTROLLER ACTION
SET POINT
EXTRACT RESPONSE
3
1,2
CONCENTRATION AND CONTROLLER OUTPUT
TIME (MIN)
400
300
200
100
0
0.0
0.5
1.0
1.5
2.0

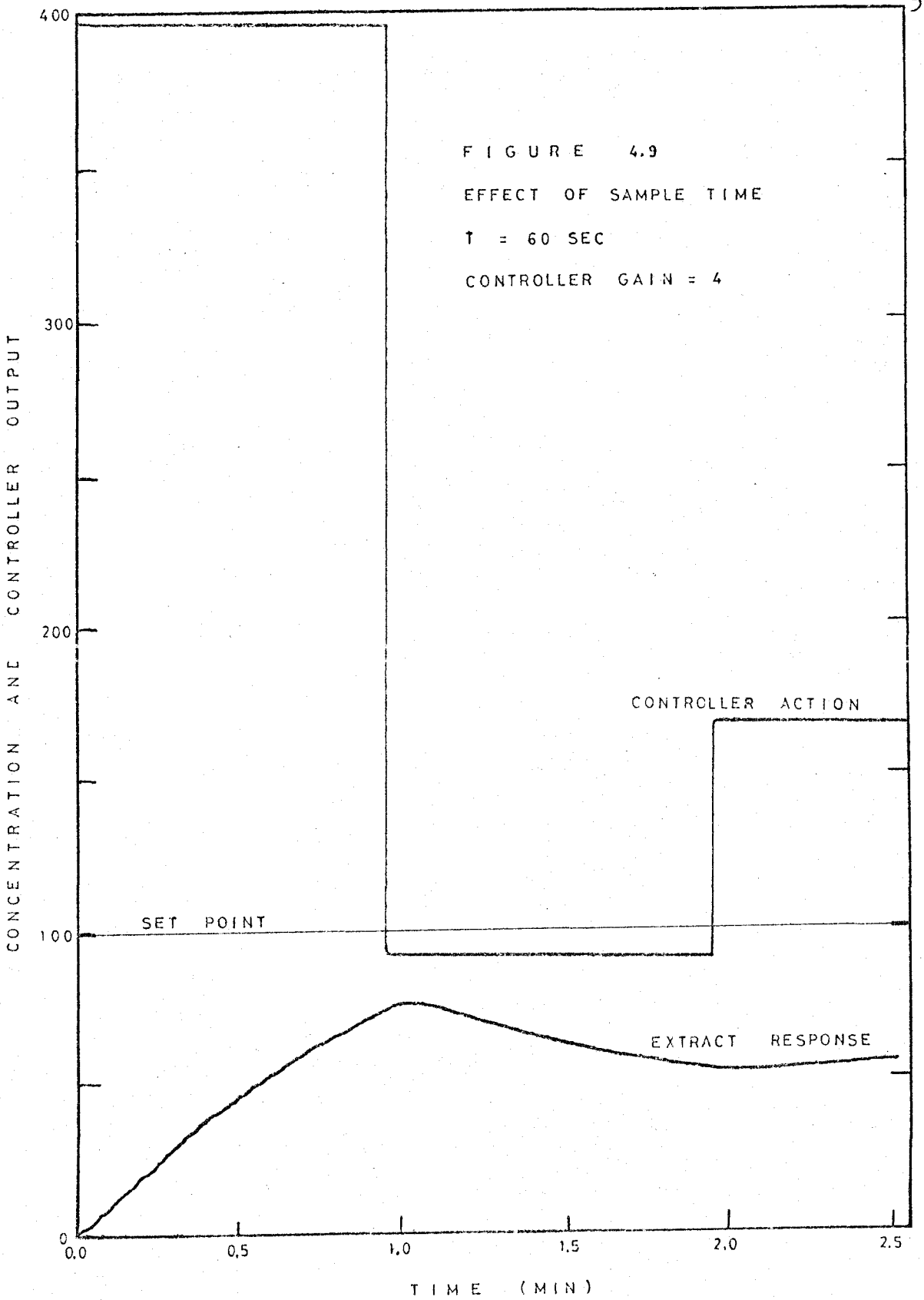
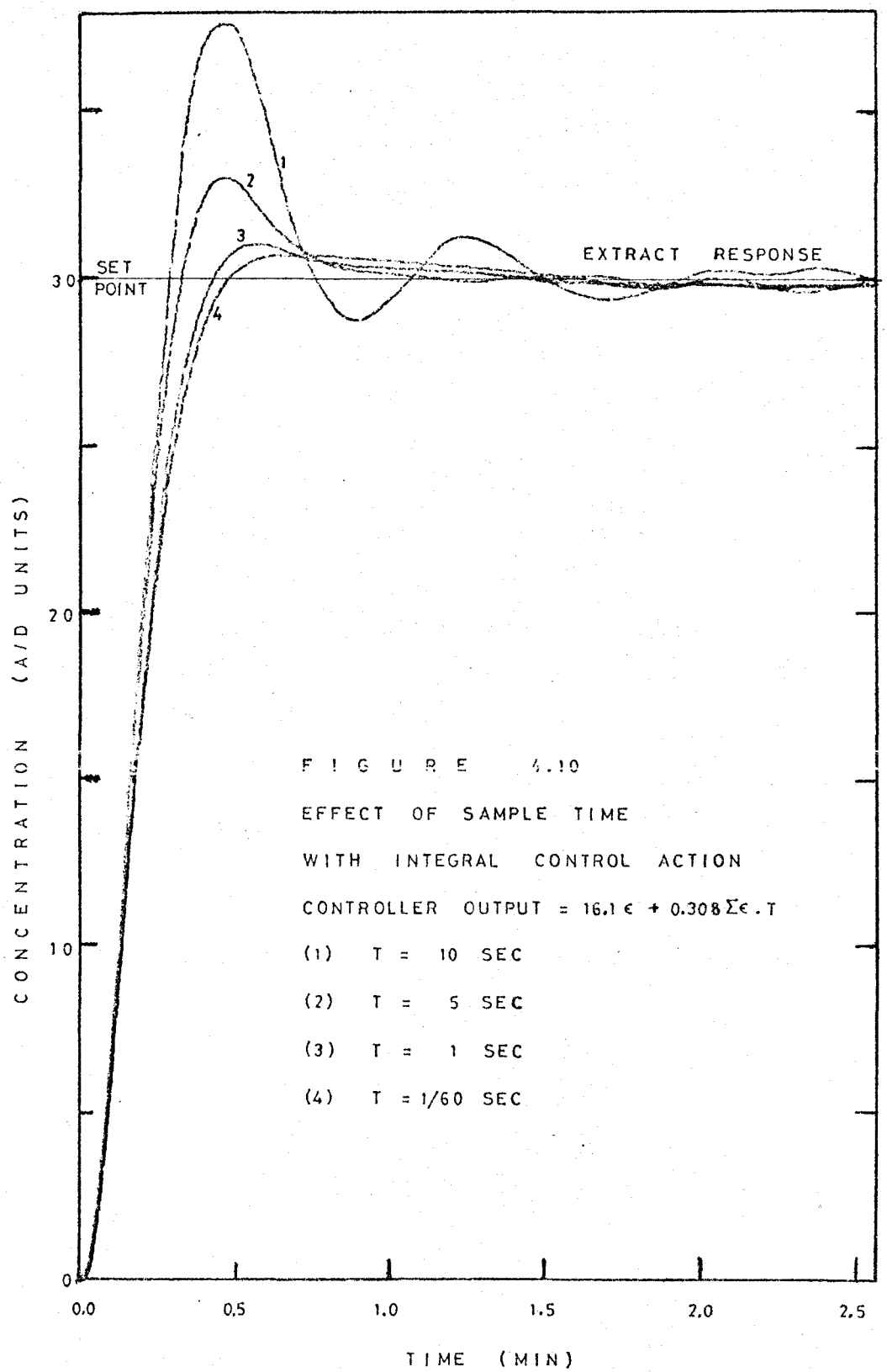


FIGURE 4.9

EFFECT OF SAMPLE TIME

τ = 60 SEC

CONTROLLER GAIN = 4



F I G U R E 4.10

EFFECT OF SAMPLE TIME

WITH INTEGRAL CONTROL ACTION

CONTROLLER OUTPUT = $16.1\epsilon + 0.308\Sigma\epsilon . T$

(1) T = 10 SEC

(2) T = 5 SEC

(3) T = 1 SEC

(4) T = 1/60 SEC

periods introducing differences in the response. This is due to the fact that the closed loop response is already less stable than that of Figure 4.8 because of the higher gain and the reset action.

From Figures 4.8, 4.9, 4.10 one could conclude that a sample period of one second would be fast enough to maintain an analog-like controlled response of the extract concentration for the controller settings used.

Let us consider the proportional control case again. Figure 4.11 illustrates how increasing the controller gain with a fixed sample period of ten seconds makes the system be unstable in the closed loop. The response curves with gains of 4, 12 and 100 are shown along with the controller outputs for gains of 4 and 12. The controller output with a gain of 100 was not shown because it oscillated between the upper and lower bounds. In fact when a gain of only 12 was used, the control output remained on the upper bound for the first three sample periods (30 seconds).

Figure 4.12 illustrates what happens when the unstable case of the previous paragraph is corrected by reducing the sample period to one second. Good control results.

The sampling period is especially important when derivative action is used. Even with the analog computer models there was noise present and this noise was sufficient to cause the controller output to oscillate wildly (Figure 4.13). The sample period was then increased from 0.1

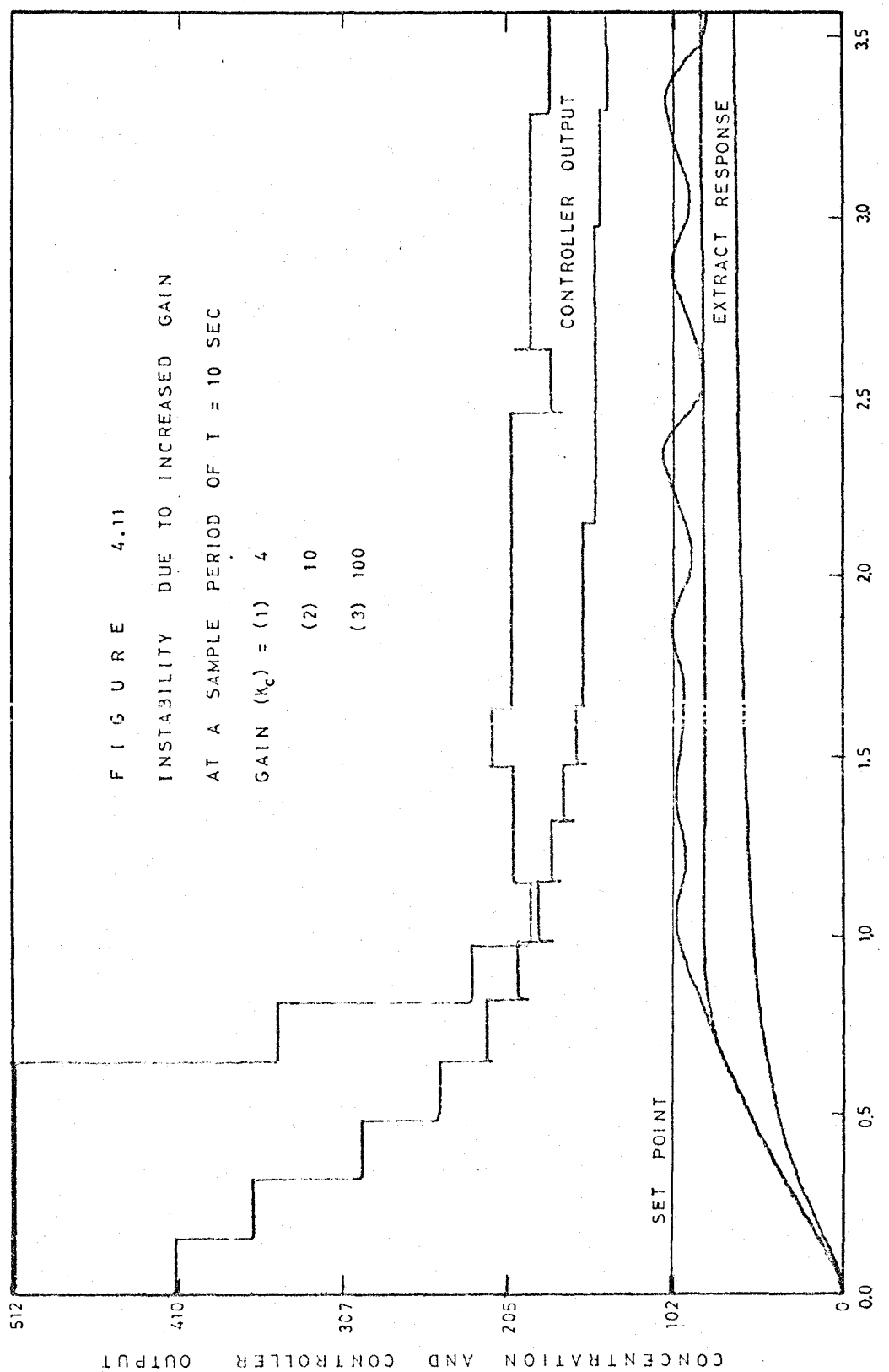


FIGURE 4.11
INSTABILITY DUE TO INCREASED GAIN
AT A SAMPLE PERIOD OF T = 10 SEC
GAIN (K_c) = (1) 4
(2) 10
(3) 100
CONTROLLER OUTPUT
EXTRACT RESPONSE
SET POINT
CONCENTRATION AND CONTROLLER OUTPUT
TIME (MIN)
512
410
307
205
102
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5

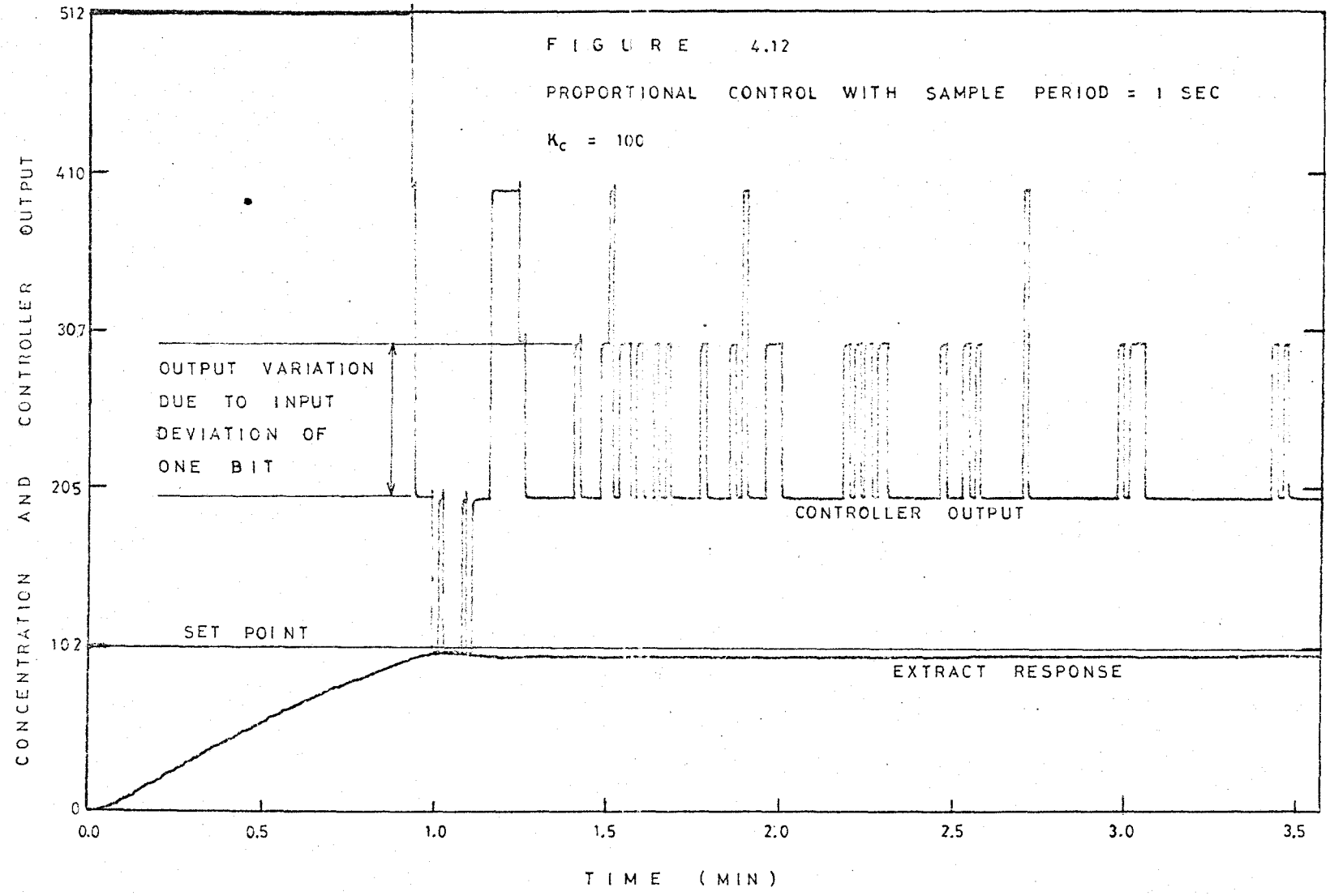


FIGURE 4.12
PROPORTIONAL CONTROL WITH SAMPLE PERIOD = 1 SEC
K_c = 100
OUTPUT VARIATION DUE TO INPUT DEVIATION OF ONE BIT
CONTROLLER OUTPUT
SET POINT
EXTRACT RESPONSE
CONCENTRATION AND CONTROLLER OUTPUT
512
410
307
205
102
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
TIME (MIN)

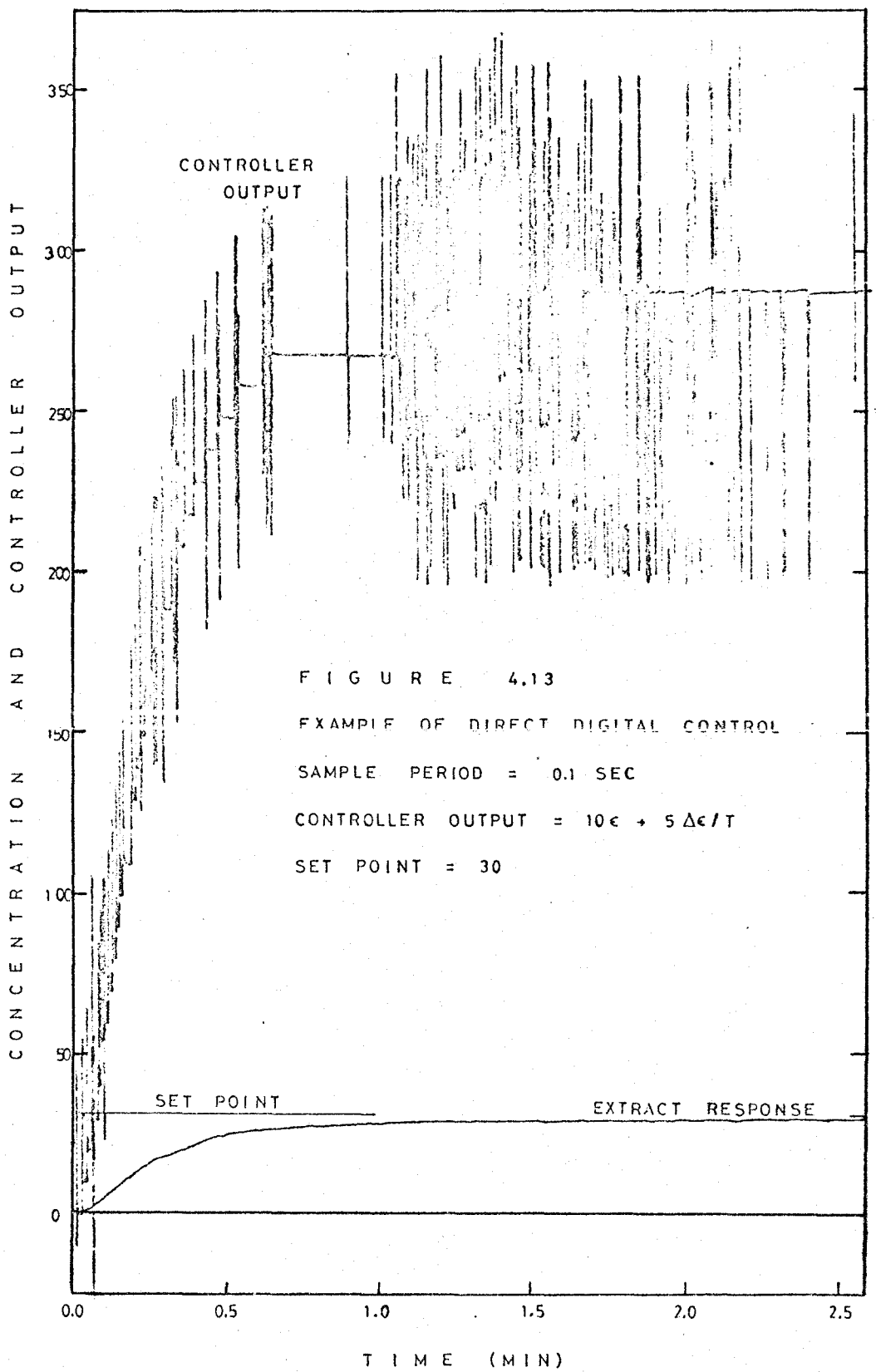


FIGURE 4.13

EXAMPLE OF DIRECT DIGITAL CONTROL

SAMPLE PERIOD = 0.1 SEC

CONTROLLER OUTPUT = $10\epsilon + 5\Delta\epsilon/T$

SET POINT = 30

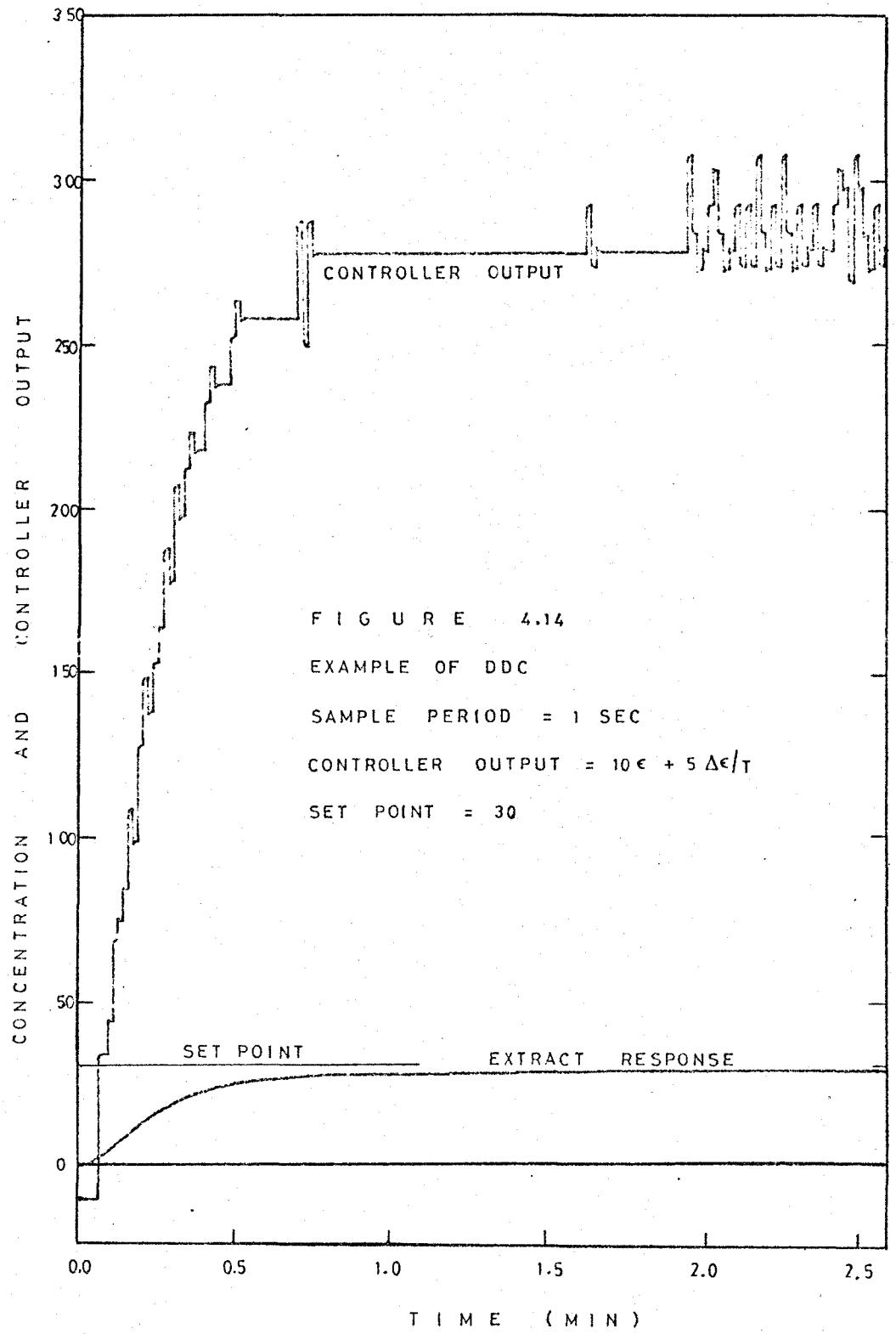


FIGURE 4.14

EXAMPLE OF DDC

SAMPLE PERIOD = 1 SEC

CONTROLLER OUTPUT = $10\epsilon + 5\Delta\epsilon/T$

SET POINT = 30

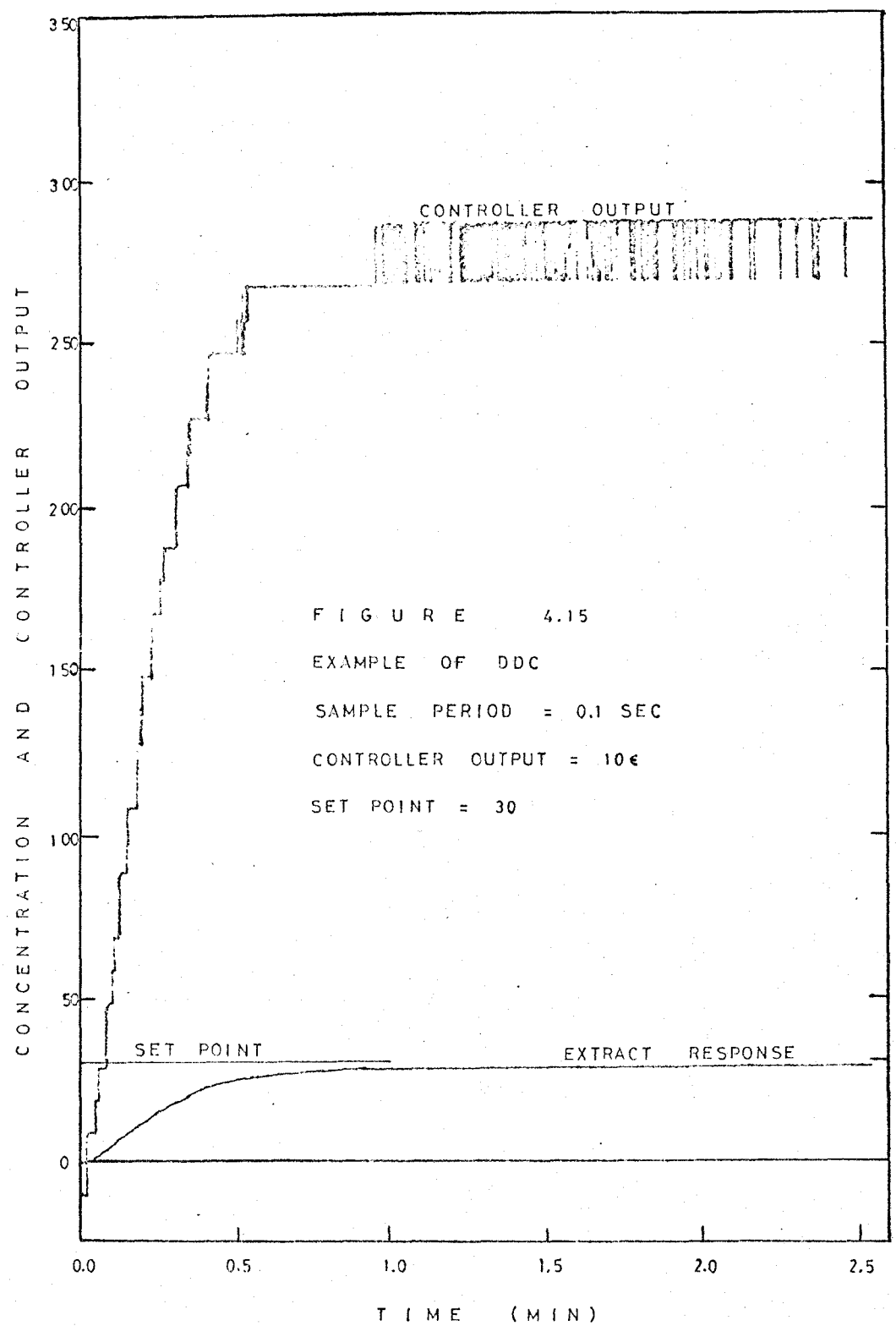


FIGURE 4.15

EXAMPLE OF DDC

SAMPLE PERIOD = 0.1 SEC

CONTROLLER OUTPUT = 10€

SET POINT = 30

seconds to 1.0 second and the same disturbance was introduced and the same control action was used. Figure 4.14 shows how the controller outputs are similar except that the one having the larger sample period has a less violent controller output. For comparison, Figure 4.15 represents the response with a 0.1 second sample period but having no derivative action on the controller.

Input voltages, read from the A/D converters, were passed directly to the controller subroutine. Filtering of the sampled data was not done. Had input filtering been used, a large portion of the noise could have been damped out, and shorter sample periods could have been used.

A further example of the effect of sample time is shown in Figures 4.16 and 4.17 with respective sample rates of sixty times per second and one time per second. Each diagram shows the extract closed loop response curves of three different controller configurations. The relative shapes of the curves are what would be expected; however, the control with the larger sample period shows ripples in the response. The short sample period example shows a smoother response. The reason lies in the fact that the large output due to the derivative action was retained for one second at a time allowing the system more time in which to respond. The fraction response in 1/60 second on the other hand would be minimal and any ripples are too small to be noticed.

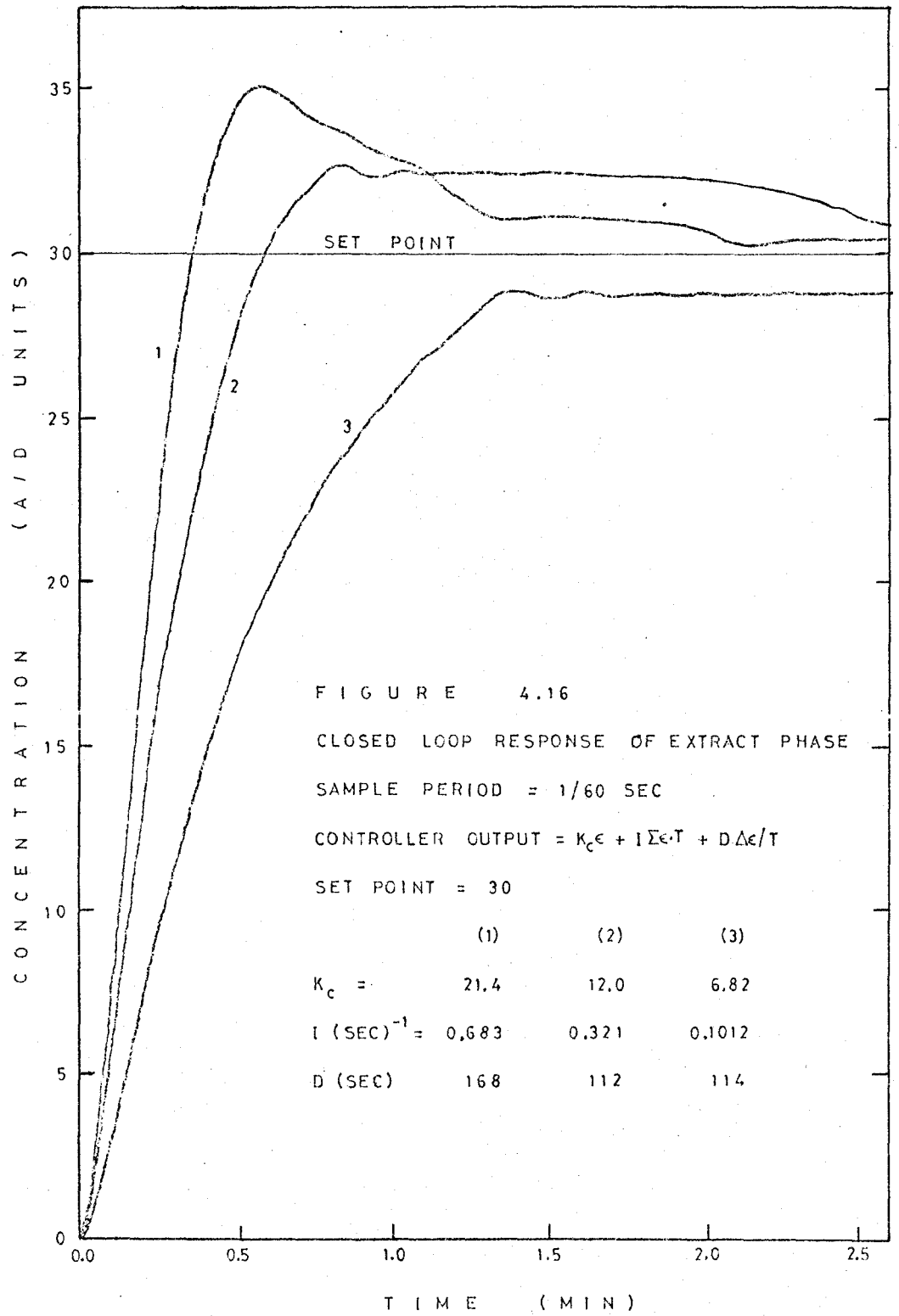


FIGURE 4.16

CLOSED LOOP RESPONSE OF EXTRACT PHASE

SAMPLE PERIOD = 1/60 SEC

CONTROLLER OUTPUT = $K_c\epsilon + I\Sigma\epsilon \cdot T + D\Delta\epsilon/T$

SET POINT = 30

	(1)	(2)	(3)
K_c =	21.4	12.0	6.82
I $(SEC)^{-1}$ =	0.683	0.321	0.1012
D (SEC)	168	112	114

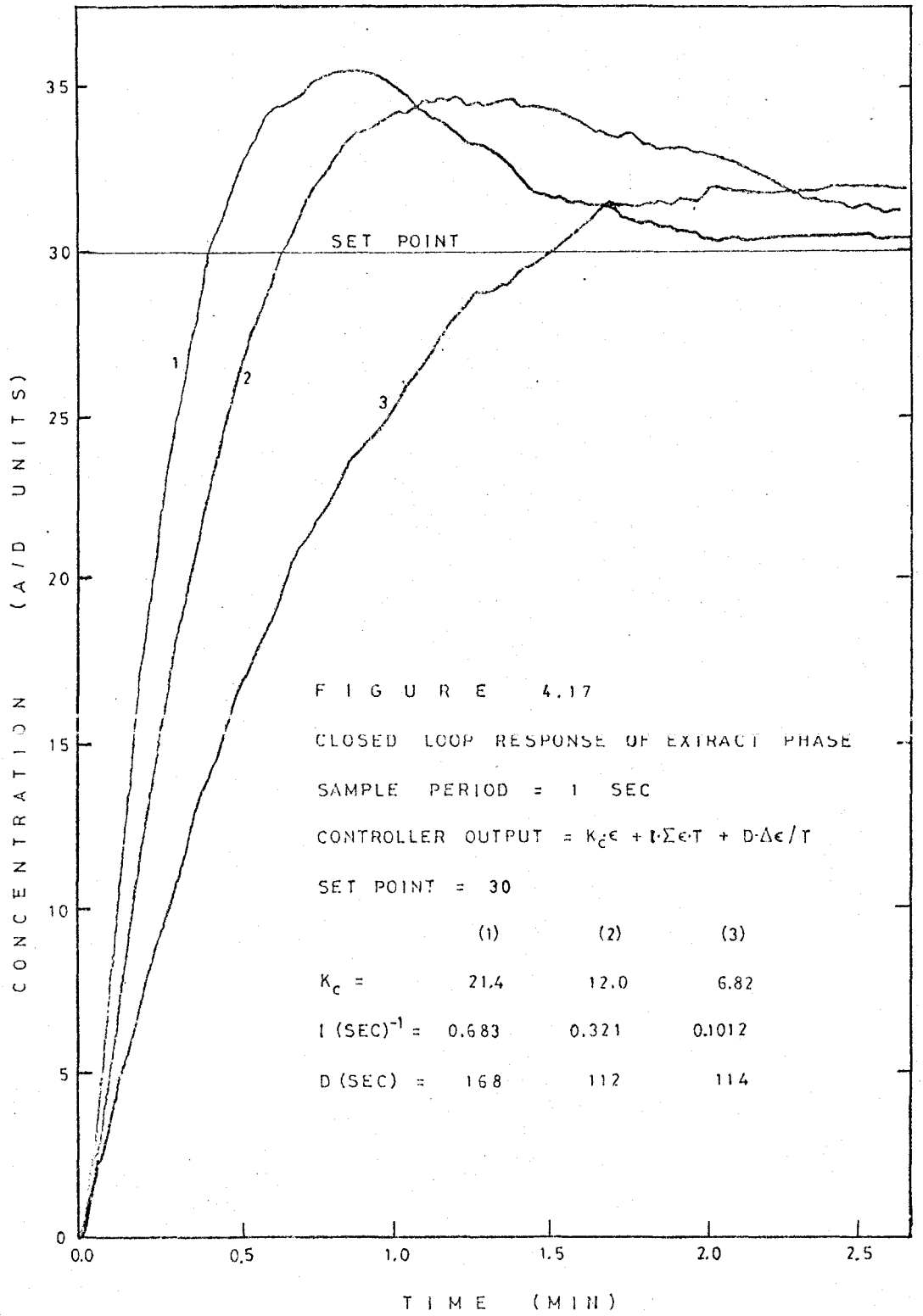


FIGURE 4.17

CLOSED LOOP RESPONSE OF EXTRACT PHASE

SAMPLE PERIOD = 1 SEC

CONTROLLER OUTPUT = $K_c\epsilon + I\cdot\Sigma\epsilon\cdot T + D\cdot\Delta\epsilon/T$

SET POINT = 30

	(1)	(2)	(3)
K_c =	21.4	12.0	6.82
I $(SEC)^{-1}$ =	0.683	0.321	0.1012
D (SEC) =	168	112	114

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS FROM CHANGEOVER POLICY STUDIES:

1) It is possible to calculate a policy of changeover controls on a small control computer. Available data storage space is the limiting factor.

2) The method of Torng (7) which was used in these studies requires the lesser core space of the two methods investigated by Pang (3). That method should be used if a reasonably large problem is to be solved.

3) Entire calculation time is five to six minutes for the largest problem solved. This could be reduced greatly by pre-calculation of (i) the transition and delta (E and D) matrices (ii) all of the linear programming starting matrix except for the last column of that matrix.

4) Implementation of a calculated control scheme is straightforward with a dedicated control computer.

5) The stringent accuracy used by Pang is unnecessary. Such accuracy in the calculation of a control policy was not used because of inaccuracies in modelling, noise, calculation effort and the compounding of errors due to truncation when a large number of calculations are done. Truncation is especially important when only seven figure arithmetic is used.

5.2 CONCLUSIONS FROM DDC STUDIES:

1) The complete model of the extraction column as used by Pang (3) for his control studies was not used for this thesis because of the difficulty in representing a time delay accurately on the analog computers. When his controller parameters were used, the model responded more slowly than with other stable controller configurations.

2) No difference was detected in the controlled variable response between proportional analog control and proportional digital control with a sample rate of 60 times per second. Controller gains up to 100 were used.

3) New controller parameters were calculated for the analog model which was wired up on the analog computers. Little difference in control was seen when any two of the control configurations were compared. This was because the high gains used easily saturated the controller output. Proportional control was the best at high gain.

4) Short sample periods in combination with derivative control (and no filtering) causes the controller output to oscillate wildly. Longer sample periods lessen the severity of the oscillation but introduce rippling into the response of the controlled variable.

5) The fact that larger sample periods make the closed loop system less stable has been demonstrated. Very large sample periods used with high gain was shown to make the system oscillate.

5.3 RECOMMENDATIONS FOR THE CHANGEOVER CALCULATION:

1) The calculation time should be reduced before the program is used to do an on-line changeover calculation. As many of the calculations as possible should be performed in advance and the results stored on magnetic tape or disk.

2) Matrix exponentiation should be done by the method indicated in equation 3.2 to save time and make convergence faster.

That is, $e^{NAT} = (e^{AT})^N$

where N is an integer.

3) The need for having the linear programming result and its transpose reside in core at the same time should be eliminated. This can be achieved by writing a transposition subroutine which makes the transposed result overwrite the original matrix. The size of the problem that can be calculated entirely in core will then be increased.

4) The matrix subroutines should be altered to permit partitioned operations of matrices on disk. This will increase the execution time but will allow much larger problems to be solved. Disk storage will then be the limiting factor rather than core storage.

5.4 RECOMMENDATIONS FOR DDC:

1) Fixed point controller subroutines should be used (i) to avoid roundoff errors that occur in converting floating point numbers to fixed point numbers, (ii) to make

the minimum sample period to some value significantly less than 12 ms so that a large number of loops may be handled efficiently.

2) The facility to have multiple control loops should be added. This will necessitate the alteration of the executive program.

3) Sampled data should be filtered to remove noise when derivative action is used. This will allow shorter sample times with less violent oscillations in the controller output and will reduce rippling in the controlled variable.

6. NOMENCLATURE

A	n x n matrix of system coefficients
B	n x m control coefficient matrix
C	vector of slack variables
D	n x m delta matrix
E	n x n transition matrix = exp(AT)
F	heavy phase flowrate (raffinate)
G	intermediate matrix in changeover calculation (eqn 2.2)
i	subscript denoting stage number
K_c	proportional gain
K_{EA}	overall mass transfer coefficient
m	equilibrium constant defined by y = mx
n	number of state variables
N	total number of control time intervals to complete a changeover policy
P	objective function for linear programming calculation = ΣW_i
p	fraction of heavy phase feed that mixes in the top stage
q	fraction of solvent feed that mixes in the bottom stage
S	light phase flowrate (solvent)
t	time
T	control time interval = sampling period
U	n x 1 control matrix
V	stage volume
W_E	stage holdup of light phase

W_R	stage holdup of heavy phase
W	vector of artificial slack variables
x_i	concentration of solute in light phase of stage i
X	n x 1 vector of state variables
X(N)	state variables at control time N
X_0	initial states before changeover
X_T	final states after changeover
y_i	concentration of solute in heavy phase of stage i
y^*	concentration in light phase that would be in equilibrium with x
α	lower bound of control
β	upper bound of control

7. REFERENCES

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8. ACKNOWLEDGEMENTS

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The author also wishes to thank his wife, Hazel, for typing this report.

9. APPENDICES

A. DESCRIPTION OF LIQUID-LIQUID EXTRACTION COLUMN

B. DEVELOPMENT OF UNBOUNDED CONTROL SCHEME EQUATIONS

C. SUPERNOVA PROGRAM TO CALCULATE CHANGEOVER POLICY

D. TRANSITION AND DELTA MATRICES (E AND D)

E. TELETYPE INPUT FOR DIRECT DIGITAL CONTROLLER

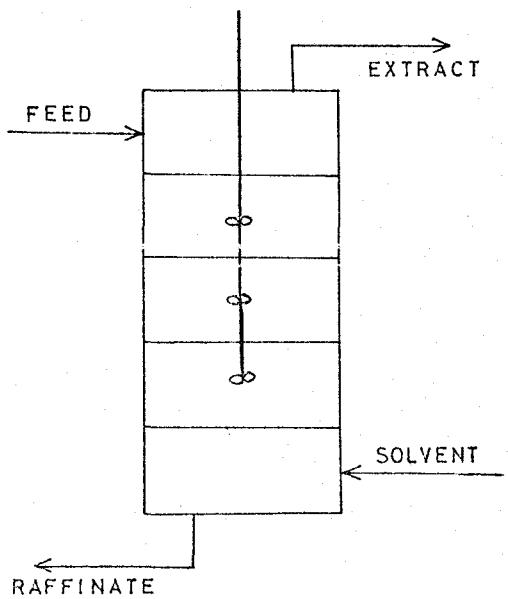
F. ASSEMBLER LISTINGS OF DDC SUBROUTINES

G. CONTROLLER ALGORITHM

APPENDIX A

COLUMN DESCRIPTION

The extraction column studied had three mechanically mixed stages with settling zones for both the light and heavy phases. A schematic of the column is shown below.



The stages were separated by half-inch teflon plates. Each stage was 4 inches high and was mixed by straight blade stirrers on a common shaft. The column was made of standard three-inch O.D. pyrex glassware.

Flow rates can go as high as 500 cc/min. in each phase if the two phases are water and MIBK or DIBK.

APPENDIX B

DEVELOPMENT OF UNBOUNDED CONTROL SCHEME EQUATIONS

Consider the linear system

$$\dot{X} = AX + BU \tag{B1}$$

where A = n x n system matrix

B = n x m control matrix

X = n x 1 state matrix

Premultiply by e^{-At} and rearrange

(where t is time)

$$e^{-At}\dot{X} - e^{-At}AX = e^{-At}BU \tag{B2}$$

$$\frac{d}{dt}(e^{-At}X) = e^{-At}BU \tag{B3}$$

integrating from t = 0 to t = T we get

$$e^{-AT}X_T - X_0 = \int_0^T e^{-At}BUdt \tag{B4}$$

where X_0 is the initial state and X_T is the final state or

$$X_T = e^{AT}(X_0 + \int_0^T e^{-At}BUdt) \tag{B5}$$

If A, B and U are constant, then rearranging we get

$$X_T = e^{AT}X_0 + \int_0^T (e^{AT-At})BUdt \tag{B6}$$

Let s = T - t

Then ds = -dt and the limits are s = T to 0

$$\therefore X_T = e^{AT}X_0 + \int_T^0 e^{As}(-ds)BU \tag{B7}$$

$$\text{or} \quad X_T = e^{AT}X_0 + \int_0^T e^{As}dsBU \tag{B8}$$

if we set

$$E = e^{AT} \quad (n \times n \text{ matrix}) \tag{B9}$$

and

$$D = \int_0^T e^{As}dsB \quad (n \times m \text{ matrix}) \tag{B10}$$

and rewrite equation (B8) for any time interval k with an m x 1 control vector U(k)

$$X_{(k)} = EX_{(k-1)} + DU_{(k)} \tag{B11}$$

A series of N equations of that type can be set up for N control intervals. Eliminating the intermediate state variables from the set and retaining only the initial and final states we derive:

$$X(N) = E^N X(0) + E^{N-1}DU(1) + E^{N-2}DU(2)....+ E^0 DU(N) \tag{B12}$$

$$X(N) = E^N X(0) + GU \tag{B13}$$

where

$$G = E^{N-1}D,\ E^{N-2}D\ .\ .\ .\ .\ . \tag{B14}$$

if there are no constraints on U then the controls may be calculated immediately:

$$U = G^{-1}[X(N) - E^N X(0)] \tag{B15}$$

This solution will be of dimension Nm x 1 and exists if G^{-1} exists and if $Nm \geq n$. G^{-1} exists if G is square and if the system is controllable.

APPENDIX C

SUPERNOVA PROGRAM TO CALCULATE CHANGEOVER POLICY

```
                .TITL   PNDC
                .ENT    PNDC
                .EXTD   FTABI,FTABO,CRLF,MULT,MULTA,FFIXT,FHALT
                .EXTD   MXTRN,MXMUL,MXINV,MXMOV,MXADD,MXSUB,MXZER
                .EXTD   MXUNT,MXEXP,MXAUG,LNPRO,MXDGL
                .EXTN   CTRL FINI FETR
                .EXTD   LOC4,LOC5,LOC7

                .ZREL
00000-000000    PAC3:   0

00001-100000    FF:     FEXT                    ;PAGE ZERO PROGRAM FOR DEBUGGING
00002-070477            READS   2               ;AND INTERMEDIATE PRINT OUT OF
00003-050011-           STA     2 AA            ;FLOATING POINT TABLES
00004-063077            HALT
00005-060477            READS   0
00006-040016-           STA     0 MV
00007-177777            FETR

00010-006002$           FJSR@   FTABO
00011-000000    AA:     0
00012-000016-           MV
00013-000017-           FV

00014-100000            FEXT
00015-063077            HALT
00016-000000    MV:     0
00017-000005    FV:     5

                ;PROGRAM READS IN DATA TO CALCULATE CHANGEOVER
                ;POLICY, DOES THE CALCULATION AND CALLS THE
                ;CONTROL OUTPUT ROUTINE

                ;MATRIX ROUTINES ARE DESCRIBED IN THE CHEMICAL
                ;ENGINEERING SUPERNOVA LIBRARY MANUAL

                ;INPUT MAY BE FROM TTY TAPE OR TTY KEYBOARD

                .NREL
00000'054000-   PNDC:   STA     3 PAC3  ;SAVE RETURN IF USED AS A S/R
00001'020467            LDA     0 .SEVN ;SET UP FLOATING POINT
00002'040026$           STA     0 LOC7
00003'006003$           JSR@    CRLF
00004'177777            FINI
00005'000007-           FETR

00006'120000            FDFC    0               ;CONTROL TIME INTERVAL

00007'042457            FSTA@   0 .T
00010'024454            FLDA    1 CTIME ;NUMBER OF CLK PULSES/MIN
00011'104100            FMPY    0 1
00012'046455            FSTA@   1 .TT   ;NO OF CLK PULSES/ PER
```

```
00013'076454            FFIX0   .TT     ;CONTROL TIME INTERVAL

00014'120000            FDFC    0

00015'040454            FSTA    0 NN    ;NO OF STATE VARIABLES
00016'074453            FFIX    NN

00017'120000            FDFC    0

00020'040453            FSTA    0 MM    ;NO OF CONTROL VARIABLES
00021'074452            FFIX    MM

00022'006017$           FJSR0   MXUNT   ;NXN UNIT MATRIX
00023'005723'           I
00024'000072'           N

00025'006001$           FJSR0   FTABI   ;N X N SYSTEM MATRIX
00026'011343'           A
00027'000072'           N
00030'000072'           N

00031'006001$           FJSR0   FTABI   ;N X M CONTROL MATRIX
00032'011653'           B
00033'000072'           N
00034'000074'           M

00035'006001$           FJSR0   FTABI   ;N X 1 INITIAL STATES
00036'001747'           IC
00037'000230'           ONE
00040'000072'           N

00041'100000            FEXT
00042'006003$           JSR0    CRLF
00043'000005'           FETR

00044'120030            FDFC    0       ;NO OF CONTROL TIME INTERVALS

00045'040564            FSTA    0 SMP
00046'074563            FFIX    SMP

00047'006023$           FJSR0   MXDGL   ;NXN DIAG MATRIX OF T
00050'007363'           T
00051'000072'           N
00052'007363'           T

00053'006011$           FJSR0   MXMUL   ;FORM AT  [NXN]
00054'011343'           A
00055'000072'           N
00056'000072'           N
00057'007363'           T
00060'000072'           N
00061'000072'           N
```

```
00062'010203'           AT

00063'000412'           FJMP    ST

00064'042352  CTIME:    60000.0
00065'060000
00066'007363' .T:       T
00067'001102' .TT:      TT
00070'001111' .SEVN:    SEVN
00071'000000  NN:       0
00072'000000  N:        0
00073'000000  MM:       0
00074'000000  M:        0

00075'006012S ST:       FJSR0   MXINV   ;FORM INVERSE OF A
00076'011343'           A
00077'006543'           AINV
00100'000072'           N
00101'000470'           DETNT

00102'006020S           FJSR0   MXEXP
00103'010203'           AT
00104'000072'           N
00105'000235'           TERM
00106'002003'           WORK
00107'010633'           PHI

00110'006015S           FJSR0   MXSUB   ;FORM PHI-I
00111'005723'           I
00112'000072'           N
00113'000072'           N
00114'010633'           PHI
00115'002003'           WORK

00116'006011S           FJSR0   MXMUL   ;FORM AINV[PHI-I]
00117'002003'           WORK
00120'000072'           N
00121'000072'           N
00122'006543'           AINV
00123'000072'           N
00124'000072'           N
00125'006233'           U

00126'006011S           FJSR0   MXMUL   ;FORM DELTA=AINV [PHI-I] B
00127'006233'           U
00130'000072'           N
00131'000072'           N
00132'011653'           B
00133'000072'           N
00134'000074'           M
00135'010513'           DELTA
```

```
00136'006017$           FJSR@   MXUNT    ;NOW CALC G
00137'011773'           WRK2
00140'000072'           N

00141'100000            FEXT
00142'030730            LDA     2 N
00143'024731            LDA     1 M
00144'006004$           JSR@    MULT
00145'127000            ADD     1 1
00146'044466            STA     1 MSMPL+1
00147'030463            LDA     2 SAMPL
00150'050721            STA     2 NN
00151'150400            NEG     2 2
00152'150000            COM     2 2
00153'006004$           JSR@    MULT
00154'030462            LDA     2 .GT
00155'147000            ADD     2 1
00156'044427            STA     1 AGT
00157'030453            LDA     2 SAMPL
00160'024714            LDA     1 M
00161'006004$           JSR@    MULT
00162'044447            STA     1 SMP
00163'000043'           FETR

00164'006013$ PS:       FJSR@   MXMOV    ;TRANSFORM COL OF G INTO ROW
00165'011773'           WRK2
00166'000072'           N
00167'000072'           N
00170'002003'           WORK

00171'006011$           FJSR@   MXMUL
00172'002003'           WORK
00173'000072'           N
00174'000072'           N
00175'010513'           DELTA
00176'000072'           N
00177'000074'           M
00200'006233'           U

00201'006010$           FJSR@   MXTRN
00202'006233'           U
00203'000072'           N
00204'000074'           M
00205'000000  AGT:       0

00206'100000            FEXT
00207'020776            LDA     0 AGT
00210'024424            LDA     1 MSMPL+1
00211'122400            SUB     1 0
00212'040773            STA     0 AGT
00213'000163'           FETR
00214'014655            FDSZ    NN       ;LAST TIME CONTROL POINT?
00215'000402            FJMP    .+2
```

```
00216'000423            FJMP    END     ;YES

00217'006011S           FJSR0   MXMUL   ;NO, FORM NEXT AUGMENT OF G
00220'010633'           PHI
00221'000072'           N
00222'000072'           N
00223'002003'           WORK
00224'000072'           N
00225'000072'           N
00226'011773'           WRK2

00227'000735            FJMP    PS

00230'000001  ONE:      1
00231'000000  SMP:      0
00232'000000  SAMPL:    0
00233'000000  MSMPL:    0.0
00234'000000
00235'000050  TERM:     50
00236'007053' .GT:      GT
00237'007673' .G:       G
00240'010203' .AT:      AT

00241'006010S FND:      FJSR0   MXTRN
00242'007053'           GT
00243'000231'           SMP
00244'000072'           N
00245'007673'           G

00246'006002S           FJSR0   FTABO
00247'007673'           G
00250'000072'           N
00251'000231'           SMP

00252'006011S           FJSR0   MXMUL   ;PHI**N
00253'010633'           PHI
00254'000072'           N
00255'000072'           N
00256'002003'           WORK
00257'000072'           N
00260'000072'           N
00261'011773'           WRK2

00262'006011S           FJSR0   MXMUL   ;PHI**N * IC
00263'011773'           WRK2
00264'000072'           N
00265'000072'           N
00266'001747'           IC
00267'000072'           N
00270'000230'           ONE
00271'001267'           PNX0
```

```
00272'006017S           FJSR@   MXUNT
00273'011773'           WRK2
00274'000231'           SMP

00275'006021S           FJSR@   MXAUG
00276'011773'           WRK2
00277'000231'           SMP
00300'000231'           SMP
00301'007673'           G
00302'000072'           N
00303'000231'           SMP
00304'011773'           WRK2

00305'100000            FEXT
00306'022416            LDA@    0 .N     ;NO OF STATE VARIABLES
00307'024722            LDA     1 SMP    ;NO OF CONTROL VARIABLES
00310'123000            ADD     1 0
00311'040417            STA     0 NSMP   ;N+SMP
00312'101400            INC     0 0
00313'040416            STA     0 NSMP1  ;N+SMP+1
00314'127000            ADD     1 1
00315'044411            STA     1 SMP2   ;2*SMP
00316'022406            LDA@    0 .N
00317'123000            ADD     1 0
00320'040407            STA     0 NSMP2  ;N+2*SMP
00321'101400            INC     0 0
00322'042403            STA@    0 .NSP   ;N+2*SMP+1
00323'000415            JMP     CON

00324'000072' .N:       N
00325'000472' .NSP:     NSP21
00326'000000  SMP2:     0
00327'000000  NSMP2:    0
00330'000000  NSMP:     0
00331'000000  NSMP1:    0
00332'000231' .SMP:     SMP
00333'000074' .M:       M
00334'000000  WN:       0
00335'000000  WNM:      0
00336'000000  OA:       0
00337'001313' .OBJ:     OBJ

00340'030676  CON:      LDA     2 .GT    ;ADDRESS OF SAVED GT
00341'022771            LDA@    0 .SMP
00342'040773            STA     0 WNM
00343'020774            LDA     0 .OBJ
00344'040772            STA     0 OA
00345'000213'           FETR
00346'102400  FL2:      FSUB    0 0
00347'066755            FLD3    0.N
00350'070764            FST3    WN
00351'025000  FL1:      FLDA    1 0 2
```

```
00352'104000            FIC2
00353'123000            FADD    1 0
00354'014760            FDSZ    WN
00355'000774            FJMP    FL1
00356'100400            FNEG    0 0
00357'042757            FSTA0   0 0A
00360'010756            FISZ    0A
00361'010755            FISZ    0A
00362'014753            FDSZ    WNM
00363'000763            FJMP    FL2

00364'006016$           FJSR0   MXZER
00365'011143'           MZERO
00366'000472'           NSP21
00367'000230'           ONE

00370'006021$           FJSR0   MXAUG
00371'001313'           OBJ
00372'000231'           SMP
00373'000230'           ONE
00374'011143'           MZERO
00375'000330'           NSMP
00376'000230'           ONE
00377'001313'           OBJ

00400'006010$           FJSR0   MXTRN
00401'011773'           WRK2
00402'000330'           NSMP
00403'000231'           SMP
00404'002003'           WORK

00405'006017$           FJSR0   MXUNT
00406'011773'           WRK2
00407'000330'           NSMP

00410'006021$           FJSR0   MXAUG
00411'002003'           WORK
00412'000231'           SMP
00413'000330'           NSMP
00414'011773'           WRK2
00415'000330'           NSMP
00416'000330'           NSMP
00417'002003'           WORK

00420'006001$           FJSR0   FTABI   ;INPUT UPPER LIMITS OF CONTROL
00421'001773'           BETA
00422'000230'           ONE
00423'000074'           M

00424'006001$           FJSR0   FTABI   ;INPUT FINAL STATES
00425'011653'           B
00426'000230'           ONE
```

```
00427'000072'           N

00430'006015$           FJSR@   MXSUB
00431'001267'           PNX@
00432'000072'           N
00433'000230'           ONE
00434'011653'           B
00435'001267'           PNX@

00436'100000            FEXT
00437'030776            LDA     2 .-2
00440'036664            LDA@    3 .N
00441'054673            STA     3 WN
00442'000345'           FETR
00443'102400            FSUB    @ @
00444'025000            FLDA    1 @ 2
00445'104000            FIC2
00446'122400            FSUB    1 @
00447'014665            FDSZ    WN
00450'000774            FJMP    .-4
00451'040417            FSTA    @ DETNT

00452'006021$           FJSR@   MXAUG
00453'001313'           OBJ
00454'000230'           ONE
00455'000327'           NSMP2
00456'000470'           DETNT
00457'000230'           ONE
00460'000230'           ONE
00461'001313'           OBJ

00462'100000            FEXT
00463'022412            LDA@    @ .SAMP
00464'040407            STA     @ SC
00465'022646            LDA@    @ .M
00466'040406            STA     @ M1
00467'000407            JMP     CCC

00470'000000  DETNT:    0.0
00471'000000
00472'000000  NSP21:    0
00473'000000  SC:       0
00474'000000  M1:       0
00475'000232' .SAMP:    SAMPL

00476'000442' CCC:      FETR

00477'006013$           FJSR@   MXMOV
00500'001773'           BETA
00501'000074'           M
00502'000230'           ONE
00503'011773'           WRK2
```

```
00504'014767  LPSC:   FDSZ    SC
00505'000402          FJMP    .+2
00506'000420          FJMP    NXT

00507'006021$         FJSR0   MXAUG
00510'011773'         WRK2
00511'000474'         M1
00512'000230'         ONE
00513'001773'         BETA
00514'000074' ZM:     M
00515'000230'         ONE
00516'011773'         WRK2

00517'100000          FEXT
00520'026774          LDA0    1 ZM
00521'020753          LDA     0 M1
00522'123000          ADD     1 0
00523'040751          STA     0 M1
00524'000476'         FETR
00525'000757          FJMP    LPSC

00526'006021$ NXT:    FJSR0   MXAUG
00527'011773'         WRK2
00530'000074'         M
00531'000232'         SAMPL
00532'001267'         PNX0
00533'000230'         ONE
00534'000072'         N
00535'011773'         WRK2

00536'006021$         FJSR0   MXAUG
00537'002003'         WORK
00540'000327'         NSMP2
00541'000330'         NSMP
00542'011773'         WRK2
00543'000230'         ONE
00544'000330'         NSMP
00545'002003'         WORK

00546'006010$         FJSR0   MXTRN
00547'002003'         WORK
00550'000472'         NSP21
00551'000330'         NSMP
00552'011773'         WRK2

00553'006002$         FJSR0   FTAB0   ;OUTPUT ORIG OBJ FN
00554'001313'         OBJ
00555'000472'         NSP21
00556'000230'         ONE

00557'006021$         FJSR0   MXAUG
```

```
00560'001313'           OBJ
00561'000230'           ONE
00562'000472'           NSP21
00563'011773'           WRK2
00564'000330'           NSMP
00565'000472'           NSP21
00566'002003'           WORK

00567'100000            FEXT
00570'020517            LDA     0 .WORK
00571'024701            LDA     1 NSP21
00572'127000            ADD     1 1
00573'123000            ADD     1 0
00574'040406            STA     0 CNSTR
00575'000524'           FETR

00576'006022$           FJSR0   LNPRO   ;LINEAR PROGRAMMING S/R
00577'000327'           NSMP2
00600'002003'           WORK
00601'000330'           NSMP
00602'000000  CNSTR:    0
00603'001531'           FEAS

00604'006002$           FJSR0   FTABC   ;OUTPUT RESULT
00605'002003'           WORK
00606'000331'           NSMP1
00607'000472'           NSP21

00610'006010$           FJSR0   MXTRN
00611'002003'           WORK
00612'000331' NN1:      NSMP1
00613'000472' NN2:      NSP21
00614'011773'           WRK2

00615'100000            FEXT
00616'032774            LDA0    2 NN1
00617'026774            LDA0    1 NN2
00620'153000            ADD     2 2
00621'020534            LDA     0 .WRK2
00622'006005$           JSR0    MULTA
00623'146400            SUB     2 1
00624'131000            MOV     1 2
00625'121400            INC     1 0
00626'101400            INC     0 0
00627'040407            STA     0 SLM
00630'000575'           FETR
00631'021000            FLDA    0 0 2
00632'024421            FLDA    1 MIN
00633'107015            FADD#   0 1 FSGE;SOLUTION TO LP OBTAINED?
00634'000410            FJMP    NOSOL   ;NO SOLUTION

00635'006013$           FJSR0   MXMOV   ;SOLUTION OBTAINED
```

```
00636'000000  SLM:    0
00637'000330'         NSMP
00640'000230'         ONE
00641'002003'         WORK

00642'100000          FEXT
00643'000415          JMP     LCC

00644'100000  NOSOL:  FEXT
00645'006003S         JSR@    CRLF
00646'000630'         FETR

00647'140000          FFDC    0         ;OUTPUT VALUE OF OBJ FN

00650'100000          FEXT
00651'006003S         JSR@    CRLF
00652'006007S         JSR@    EHALT     ;GO TO ERROR HALT S/R

00653'040420  MIN:    1.0               ;CONVERGENCE VALUE FOR OBJ FN
00654'000000
00655'001313' .OB:    OBJ
00656'000231' SS:     SMP
00657'000000  TNSM:   0

00660'022776  LCC:    LDA@    0 SS      ;CONVERT LP RESULT TO
00661'040516          STA     0 .AA     ;AN OUTPUT CONTROL VECTOR
00662'022730          LDA@    0 NN1     ;NSMP1
00663'100400          NEG     0 0
00664'040773          STA     0 TNSM
00665'030470          LDA     2 .WRK2
00666'020767          LDA     0 .OB
00667'040020          STA     0 20
00670'014020          DSZ     20
00671'000646' R1:     FETR
00672'021000          FLDA    0 0 2
00673'104000          FIC2
00674'101014          FMOV#   0 0 SZR
00675'000413          FJMP    NZR
00676'010761          FISZ    TNSM
00677'000773          FJMP    R1+1
00700'100000          FEXT
00701'022711  F1:     LDA@    0 NN1
00702'100400          NEG     0 0
00703'040754          STA     0 TNSM
00704'014473          DSZ     .AA
00705'000764          JMP     R1
00706'000415          JMP     CTN

00707'002003' .WORK:  WORK

00710'100000  NZR:    FEXT
00711'020746          LDA     0 TNSM
```

```
00712'100400            NEG     0 0
00713'101400            INC     0 0
00714'042020            STA0    0 20
00715'010742            ISZ     TNSM
00716'000402            JMP     .+2
00717'000762            JMP     F1
00720'151400            INC     2 2
00721'151400            INC     2 2         ;LOOP INCREASES AC2 TO
00722'000773            JMP     .-5         ;START OF NEXT ROW

00723'020432  CTN:      LDA     0 .WRK2
00724'040453            STA     0 .AA
00725'020762            LDA     0 .WORK
00726'026730            LDA0    1 SS
00727'044453            STA     1 WK
00730'030725            LDA     2 .OB
00731'035000  CLP:      LDA     3 0 2
00732'151400            INC     2 2
00733'026657            LDA0    1 NN1
00734'166400            SUB     3 1
00735'127000            ADD     1 1
00736'107000            ADD     0 1
00737'044720            STA     1 TNSM
00740'000671'           FETR
00741'022716            FLDA0   3 TNSM
00742'042435            FSTA0   0 .AA
00743'100000            FEXT
00744'010433            ISZ     .AA
00745'010432            ISZ     .AA
00746'014434            DSZ     WK
00747'000762            JMP     CLP
00750'022430            LDA0    0 SAL
00751'101400            INC     0 0
00752'040427            STA     0 SMPL1
00753'000740'           FETR

00754'006021$           FJSR0   MXAUG
00755'011773'  .WRK2:   WRK2
00756'000232'           SAMPL
00757'000074'           M
00760'011143'           MZERO
00761'000074'           M
00762'000230'           ONE
00763'011773'           WRK2

00764'006010$           FJSR0   MXTRN
00765'011773'           WRK2
00766'001001'           SMPL1
00767'000074'           M
00770'002003'           WORK

00771'006002$           FJSR0   FTAB0       ;OUTPUT CONTROL VECTOR
```

```
00772'002003'           WORK
00773'000074'           M
00774'001001'           SMPL1

00775'100000            FEXT
00776'000005            JMP     CLL

00777'000000  .AA:      0
01000'000232' SAL:      SAMPL
01001'000000  SMPL1:    0
01002'000000  WK:       0

01003'022653  CLL:      LDA0    0 SS     ;SMP
01004'026424            LDA0    1 .MS
01005'123000            ADD     1 0
01006'040502            STA     0 SMPM   ;SMP+M
01007'040770            STA     0 .AA
01010'030677            LDA     2 .WORK
01011'000753'           FETR
01012'024472            FLDA    1 C51
01013'021000  CVLP:     FLDA    0 0 2
01014'120100            FMPY    1 0
01015'041000            FSTA    0 0 2
01016'104000            FIC2
01017'014760            FDSZ    .AA
01020'000773            FJMP    CVLP

01021'006006S           FJSR0   FFIXT    ;CONVERT FLOATING POINT
01022'002003'           WORK             ;TABLE TO FIXED POINT
01023'011773'           WRK2
01024'001110'           SMPM

01025'006016S           FJSR0   MXZER
01026'011143' .MZ:      MZERO
01027'000072'           N
01030'000074' .MS:      M

01031'100000            FEXT
01032'020774            LDA     0 .MZ
01033'040436            STA     0 CVTR+1;SET UP CONVERTER DATA ADDRESS
01034'040436            STA     0 CVTR+2
01035'040436            STA     0 CVTR+3
01036'024743            LDA     1 SMPL1 ;NO OF SAMPLE POINTS
01037'030716            LDA     2 .WRK2 ;FOR ADRS'S OF CONT'L VECTORS
01040'020447            LDA     0 AAA
01041'040736            STA     0 .AA
01042'022766            LDA0    0 .MS
01043'100400            NEG     0 0
01044'052733  STL:      STA0    2 .AA
01045'133000            ADD     1 2
01046'010731            ISZ     .AA
01047'101404            INC     0 0 SZR
```

```
01050'000774            JMP     STL
01051'006003S           JSR@    CRLF
01052'034434            LDA     3 C777  ;10 BIT MASK
01053'030702            LDA     2 .WRK2
01054'024434            LDA     1 SMPM
01055'124400            NEG     1 1

01056'021000  SCALE:    LDA     0 0 2   ;CONVERT TO 10 BIT PRECISION
01057'116433            SUB#    0 3 SNC
01060'161000            MOV     3 0
01061'041000            STA     0 0 2
01062'151400            INC     2 2
01063'125404            INC     1 1 SZR
01064'000772            JMP     SCALE

01065'102520            SUBZL   0 0
01066'061170            DOAS    0 70    ;CLOSE RELAY TO START PLOTTER

01067'006412            JSR@    DOIT    ;OUTPUT CONTROLS
01070'000000  CVTR:     0
01071'000000            0
01072'000000            0
01073'000000            0
01074'001001'           SMPL1
01075'001102'           TT

01076'102400            SUB     0 0
01077'061170            DOAS    0 70    ;OPEN RELAY TO STOP PLOTTER
01100'002377            JMP     @377

01101'177777  DOIT:     CTRL
01102'000000  TT:       0.0
01103'000000
01104'041063  C51:      51.2
01105'031463
01106'000777  C777:     777
01107'001070' AAA:      CVTR
01110'000000  SMPM:     0
      000012            .RDX    10.
      000156  SEVN:     .BLK    110
      000024  PNX0:     .BLK    2*10
      000216  OBJ:      .BLK    2*71
      000216  FEAS:     .BLK    2*71
      000024  IC:       .BLK    2*10
      000010  BETA:     .BLK    2*4
      003720  WORK:     .BLK    2000
      000310  I:        .BLK    2*10*10
      000310  U:        .BLK    2*10*10
      000310  AINV:     .BLK    2*10*10
      000310  GT:       .BLK    2*10*10
      000310  T:        .BLK    2*10*10
      000310  G:        .BLK    2*10*10
```

```
000310  AT:       .BLK  2*10*10
000120  DELTA:    .BLK  2*10*4
000310  PHI:      .BLK  2*10*10
000200  MZERO:    .BLK  2*64
000310  A:        .BLK  2*10*10
000120  B:        .BLK  2*10*4
000310  WRK2:     .BLK  2*10*10

                  .END
```

```
                .TITL   CTRL
                .ENT    CTRL
                .EXTD   EHALT,MULT

                ;NEEDS FOUR CONTROL VECTORS

                ;CALLING SEQUENCE:

                ;JSR    CTRL
                ;AD0
                ;AD1
                ;AD2
                ;AD3
                ;SMPL   -NUMBER OF SAMPLES
                ;DT     -SAMPLE TIME IN SECONDS
                ;RETURN

                .NREL
00000'054514    CTRL:   STA     3 AC3
00001'050512            STA     2 AC2
00002'044510            STA     1 AC1
00003'040506            STA     0 AC0
00004'021400            LDA     0 0 3
00005'040020            STA     0 20
00006'014020            DSZ     20
00007'021401            LDA     0 1 3
00010'040021            STA     0 21
00011'014021            DSZ     21
00012'021402            LDA     0 2 3
00013'040022            STA     0 22
00014'014022            DSZ     22
00015'021403            LDA     0 3 3
00016'040023            STA     0 23
00017'014023            DSZ     23
00020'031405            LDA     2 5 3   ;SAMPLE TIME
00021'021000            LDA     0 0 2
00022'025001            LDA     1 1 2
00023'125005            MOV     1 1 SNR
00024'006001$           JSR@    EHALT
00025'101400            INC     0 0
00026'044470            STA     1 TMR1  ;NO OF CLOCK PULSES PER SAMPLE
00027'040466            STA     0 TMR0
00030'023404            LDA@    0 4 3   ;NO OF SAMPLES
00031'040457            STA     0 SMPS
00032'102520            SUBZL   0 0     ;GENERATE BINARY 1
00033'101140            MOVOL   0 0     ;GENERATE BINARY 11
00034'061114            DOAS    0 RTC   ;START  CLOCK
00035'063514            SKPBZ   RTC
00036'000777            JMP     .-1
00037'060114            NIOS    RTC
00040'000413            JMP     OUT
00041'063514    LOOP:   SKPBZ   RTC     ;WAIT CLOCK
```

```
00042'000777            JMP     .-1
00043'060114            NIOS    RTC
00044'014454            DSZ     WT1
00045'000774            JMP     LOOP
00046'014451            DSZ     WTØ
00047'000772            JMP     LOOP
00050'014440            DSZ     SMPS
00051'000402            JMP     OUT
00052'001406            JMP     6 3
00053'126400  OUT:      SUB     1 1
00054'022020            LDA@    Ø 20        ;CONTROL Ø
00055'063523            SKPBZ   DACV
00056'000777            JMP     .-1
00057'066023            DOB     1 DACV
00060'061023            DOA     Ø DACV
00061'125400            INC     1 1         ;CONTROL 1
00062'022021            LDA@    Ø 21
00063'063523            SKPBZ   DACV
00064'000777            JMP     .-1
00065'066023            DOB     1 DACV
00066'061023            DOA     Ø DACV
00067'125400            INC     1 1         ;CONTROL 2
00070'022022            LDA@    Ø 22
00071'063523            SKPBZ   DACV
00072'000777            JMP     .-1
00073'066023            DOB     1 DACV
00074'061023            DOA     Ø DACV
00075'125400            INC     1 1         ;CONTROL 3
00076'022023            LDA@    Ø 23
00077'063523            SKPBZ   DACV
00100'000777            JMP     .-1
00101'066023            DOB     1 DACV
00102'061023            DOA     Ø DACV
00103'020412            LDA     Ø TMRØ
00104'040413            STA     Ø WTØ
00105'020411            LDA     Ø TMR1
00106'040412            STA     Ø WT1
00107'000732            JMP     LOOP
00110'000000  SMPS:     Ø
00111'000000  AC0:      Ø
00112'000000  AC1:      Ø
00113'000000  AC2:      Ø
00114'000000  AC3:      Ø
00115'000000  TMR0:     Ø
00116'000000  TMR1:     Ø
00117'000000  WT0:      Ø
00120'000000  WT1:      Ø
              .END
```

ALGORITHM FOR CONTROL POLICY CALCULATION

1. INPUT: T, n, m, A, B, N, X(0)
2. Calculate clock counter for one control interval
3. Calculate: A*T, A^{-1}, and PHI = exp(A*T)
4. Set up identity matrix, I
5. Calculate D = A^{-1}*(PHI - I)*B
6. Set up G = D*PHI^{N-1}, D*PHI^{N-2}, . . . D*PHI^{2}, D*PHI, D
7. INPUT objective function coefficients for P = ΣW_i
8. INPUT upper limits on control, BETA
9. INPUT final conditions, X(N)
10. Calculate X(N) - PHI^{N}*X(0)
11. Set up linear programming matrix
12. Call linear programming subroutine
13. If objective function went to zero, skip 14.
14. OUTPUT objective function to teletype and HALT
15. Obtain control policy from LP matrix
16. OUTPUT control policy to teletype
17. Convert controls to integer numbers and store
18. Start clock and plotter
19. OUTPUT controls through A/D converters at control times
20. Stop plotters and HALT

APPENDIX D

TABLE D1

TRANSITION MATRIX (E)

Calculated by Program of Appendix C

.80271	.04086	.00283	.01682	.00011	.00240	.00002	.00024	.00000	.00002
.12678	.30752	.07615	.32010	.00524	.07624	.00130	.01045	.00001	.00085
.06397	.00187	.86078	.07035	.00087	.01396	.00021	.00176	.00000	.00014
.00909	.00020	.21625	.43068	.02098	.20005	.00658	.03903	.00008	.00390
.00252	.00005	.06738	.00306	.89041	.03825	.00103	.00661	.00001	.00063
.00013	.00000	.00485	.00016	.11815	.53342	.05064	.19144	.00073	.02567
.00007	.00000	.00257	.00008	.06689	.00156	.84984	.08104	.00027	.01019
.00001	.00000	.00030	.00001	.01112	.00019	.25072	.39495	.00466	.08979
.00001	.00000	.00025	.00001	.00947	.00016	.23550	.01303	.72866	.00815
.00000	.00000	.00000	.00000	.00014	.00000	.00444	.00020	.02136	.10144

Control Time Interval = 0.1 minutes

APPENDIX D CONTINUED

TABLE D2

TRANSITION MATRIX E

Calculated by Pang (3)

.8026	.04088	.00228	.01683	.00011	.00240	.00002	.00024	.00000	.00002
.1269	.3075	.07603	.3200	.00524	.07615	.00130	.01042	.00001	.00084
.06398	.00187	.8606	.07022	.00087	.01392	.00021	.00175	.00000	.00014
.00908	.00020	.2159	.4306	.02098	.1998	.00656	.03893	.00008	.00388
.00253	.00005	.06741	.00306	.8906	.03823	.00103	.00659	.00001	.00062
.00013	.00000	.00486	.00016	.1183	.5336	.05057	.1912	.00073	.02554
.00006	.00000	.00257	.00008	.06692	.00156	.8498	.08113	.00028	.01016
.00001	.00000	.00030	.00001	.01112	.00019	.2506	.3948	.00469	.08930
.00000	.00000	.00025	.00001	.00948	.00016	.2360	.01306	.7318	.00634
.00000	.00000	.00000	.00000	.00014	.00000	.00447	.00020	.02153	.1003

Control Time Interval = 0.1 minutes

APPENDIX D CONTINUED

TABLE D3

DELTA MATRICES (D)

Calculated by Pang (3) on CDC 6400		Calculated by Supernova (Appendix C)	
.1480 E+00	.6759 E-05	.1480 E+00	.6854 E-05
.1303 E-01	.4581 E-03	.1302 E-01	.4622 E-03
.5618 E-02	.7050 E-04	.5617 E-02	.7144 E-04
.5523 E-03	.2736 E-02	.5533 E-03	.2757 E-02
.1448 E-03	.4172 E-03	.1450 E-03	.4204 E-03
.5529 E-05	.2616 E-01	.5792 E-05	.2633 E-01
.2765 E-05	.9822 E-02	.3102 E-05	.9865 E-02
.2083 E-06	.1746 E+00	.3891 E-06	.1757 E+00
.1611 E-06	.9202 E-02	.3749 E-06	.1220 E-01
.1383 E-08	.8665 E+00	.2536 E-07	.8714 E+00

Control Time Interval = 0.1 minutes

APPENDIX D CONTINUED

TABLE D4

DELTA MATRICES

Calculated by Pang (3) on CDC 6400		Calculated by Supernova (Appendix C)	
.443 E+00	.300 E-02	.4430 E+00	.3030 E-02
.838 E-01	.400 E-02	.8377 E-01	.4043 E-01
.643 E-01	.105 E-01	.6427 E-01	.1061 E-01
.165 E-01	.772 E-01	.1649 E-01	.7800 E-01
.659 E-02	.195 E-01	.6575 E-02	.1972 E-01
.795 E-03	.221 E+00	.7895 E-03	.2228 E+00
.495 E-03	.122 E+00	.4896 E-03	.1226 E+00
.108 E-03	.438 E+00	.1065 E-03	.4420 E+00
.109 E-03	.751 E-01	.1038 E-03	.8693 E-01
.218 E-05	.965 E+00	.6867 E-05	.9716 E+00

Control Time Interval = 0.4 minutes

APPENDIX D CONTINUED

TABLE D5

DELTA MATRICES

Calculated by Pang (3) on CDC 6400		Calculated by Supernova (Appendix C)	
.560 E+00	.991 E-02	.5602 E+00	.1002 E-01
.125 E+00	.808 E-01	.1249 E+00	.8122 E-01
.118 E+00	.287 E-01	.1181 E+00	.2905 E-01
.365 E-01	.128 E+00	.3650 E-01	.1288 E+00
.180 E-01	.433 E-01	.1795 E-01	.4368 E-01
.285 E-02	.291 E+00	.2728 E-02	.2882 E+00
.198 E-02	.196 E+00	.1971 E-02	.1979 E+00
.534 E-03	.486 E+00	.5168 E-03	.4902 E+00
.596 E-03	.136 E+00	.5808 E-03	.1508 E+00
.133 E-04	.966 E+00	.7561 E-04	.9700 E+00

Control Time Interval = 0.6 minutes

APPENDIX E

SAMPLE OF TELETYPE COMMANDS FOR DDC

The following page is a demonstration of the commands that are used in changing controller parameters for the DDC program.

The first two characters of any command (one line of input followed by a carriage return) are examined by the input subroutine. If these two characters are SE (set point), GA (gain), RA (reset rate), DE (derivative time) or SA (sample time) then any additional characters are ignored until an "=" is typed. The next series of characters must be the value of the parameter followed by a carriage return. If the first two characters are not SE, GA, RA, DE or SA then an error indication is typed out and the user may enter the correct name.

Before the typed parameters are passed to the controller subroutine, two consecutive carriage returns must be typed.

```
SA=10
GA=2.19
RA=.1
DE=20
DE=10
SE=200
SE=0
RA=0
RA=.5
SE=200
SE=0
GA=5
SE=-18
SE=44
GA=.0001
SA=.0166667
SAMPLE RATE=4.101
RATE =100.2
GAIN=0.00001
RA=0
SET POINT =-400
SE=31
IN
ERROR
P
ERROR
PR
ERROR
SET=0
GAIN=0
RA=0
SA=0
SA=.100001
DERIVATIVE TIME=151.3
DERIVATIVE ACTION=151.3
DE=151.3
DER=0
```

APPENDIX F

LISTINGS OF DDC SUBROUTINES

```
                .TITL   DEMON
                .ENT    RSTRT
                .EXTN   TTISR RTCSR TSTC

                .NREL

00000'020410    RSTRT:  LDA     0 SLEV  ;INIT POINTER TO INTERRUPT
00001'040467            STA     0 LEVEL ;STORAGE LOCATIONS
00002'102400            SUB     0 0
00003'040464            STA     0 CMASK ;SET MASK INITIALLY TO 0
00004'020416            LDA     0 .INTR ;SET LOC 1 AT INITIALIZATION
00005'040001            STA     0 1     ;TIME
00006'002401            JMP     0.+1
00007'177777            TSTC
00010'000312'   SLEV:   DEVICE+200
00011'000000    ADINC:  0
00012'020411    PFAIL:  LDA     0 .RETR ;SET LOC1 TO
00013'040001            STA     0 1     ;POWER FAIL RETURN ADDRS
00014'020410            LDA     0 .JMP1 ;SET LOC0 TO
00015'040000            STA     0 0     ;POWER FAIL RETURN INSTR
00016'063077            HALT
00017'020403    PRTRN:  LDA     0 .INTR ;RETURN NORMAL INTERRUPT
00020'040001            STA     0 1     ;ADDRESS IN LOC1
00021'000441            JMP     RTP     ;POWER FAIL RESTORE
00022'000025'   .INTR:  INTR            ;NORMAL INTERRUPT ADDRESS
00023'000017'   .RETR:  PRTRN           ;P.F. RETIURN ADDRS
00024'002001    .JMP1:  JMP     @1      ;P.F. RETURN INSTR
00025'056443    INTR:   STA 3,@LEVEL    ;AC3
00026'034442            LDA 3,LEVEL     ;POINTER
00027'051401            STA 2,1,3       ;AC2
00030'045402            STA 1,2,3       ;AC1
00031'041403            STA 0,3,3       ;AC0
00032'101100            MOVL 0,0
00033'041404            STA 0,4,3       ;CARRY BIT
00034'020000            LDA 0,0
00035'041405            STA 0,5,3       ;LOCATION 000000
00036'020431            LDA 0,CMASK     ;CURRENT MASK
00037'041406            STA 0,6,3
00040'024426            LDA 1,SVEN      ;NO OF ITEMS PER INTERRUPT
00041'137000            ADD 1,3         ;RESET STORAGE POINTER
00042'054426            STA 3,LEVEL
00043'063777    POWER:  SKPDZ CPU       ;HALT IF POWER FAILS
00044'000746            JMP PFAIL
00045'062177            DOBS 0 CPU      ;ENABLE INTERRUPT
00046'061677            DIBC 0 CPU      ;ACKNOWLEDGE & CLEAR
00047'101015            MOV #0,0,SNR
00050'000421            JMP RESTR
00051'030441    NWMSK:  LDA 2,DEVICE    ;STRTNG ADDRS OF MASK TABLE
00052'113000            ADD 0,2         ;ADD DEVICE NO TO GET MSK ADRS
00053'025000            LDA 1,0,2       ;LOAD MASK OF THAT DEVICE
00054'044413            STA 1,CMASK
00055'000401            JMP .+1
```

```
00056'030433            LDA 2,ADRS      ;STRTNG ADDRS OF S/R ADDRS TABLE
00057'113000            ADD 0,2         ;PLUS DEV CODE=S.A. OF S/R
00060'066177            DOBS 1 CPU      ;MASK OUT AND ENABLE
00061'007000            JSR 00,2        ;GO TO SERVICE ROUTINE
00062'060277  RTP:      INTDS           ;RETURN FROM SERVICE
00063'030405            LDA 2 LEVEL
00064'021377            LDA 0 -1 2      ;LAST MASK BEFORE INTERRUPT
00065'000756            JMP POWER       ;HAS POWER FAILED?
00066'000007  SVEN:     7               ;SEVEN ITEMS STORED
00067'000000  CMASK:    0               ;CURRENT MASK
00070'000000  LEVEL:    0               ;TOP OF STACK
00071'034777  RESTR:    LDA 3,LEVEL     ;STACK POINTER
00072'020774            LDA 0 SVEN      ;NO OF ITEMS PER INTERRUPT
00073'116400            SUB 0,3         ;NEW STACK POINTER
00074'054774            STA 3,LEVEL     ;RESET IT
00075'021406            LDA 0,6,3       ;RESET MASK
00076'040771            STA 0,CMASK
00077'021405            LDA 0,5,3
00100'040000            STA 0,0         ;LOCATION 000000
00101'021404            LDA 0,4,3       ;CARRY
00102'101200            MOVR 0,0
00103'021403            LDA 0,3,3       ;AC0
00104'025402            LDA 1,2,3       ;AC1
00105'031401            LDA 2,1,3       ;AC2
00106'035400            LDA 3,0,3       ;AC3
00107'060177            INTEN           ;ENABLE
00110'002000  RTN:      JMP @0          ;RETURN TO BACKGROUND
00111'000212' ADRS:     DEVICE+100
00112'000112' DEVICE:   DEVICE
      000122' .LOC DEVICE+10            ;DEVICE MASKS
00122'000003            3
00123'000001            1
00124'000037            37
00125'000007            7
00126'000007            7
00127'000017            17
00130'000077            77
00131'000017            17
00132'000177            177
00133'000377            377
00134'000077            77
00135'000377            377
      000222' .LOC DEVICE+110           ;DEVICE SUBROUTINE
00222'177777            TTISR
00223'000416'           TTOSR
00224'000414'           PTRSR
00225'000412'           PTPSR
00226'177777            RTCSR
00227'000000            0
00230'000000            0
00231'000000            0
00232'000000            0
```

```
00233'000422'           ADCSR
00234'000000            0
00235'000420'           DACSR
      000312' .LOC DEVICE+200
      000100  .BLK 100
00412'060213  PTPSR:  NIOC    PTP     ;DUMMY SUBROUTINES WHICH
00413'001400          JMP     0 3     ;ARE NOT TO BE SERVICED ON
00414'060212  PTRSR:  NIOC    PTR     ;OCCURRANCE OF INTERRUPTS
00415'001400          JMP     0 3
00416'060211  TTOSR:  NIOC    TTO
00417'001400          JMP     0 3
00420'060223  DACSR:  NIOC    DACV
00421'001400          JMP     0 3
00422'060221  ADCSR:  NIOC    ADCV
00423'001400          JMP     0 3
      000000' .END    RSTRT
```

```
                .TITL   DEMO
                .ENT    TSTC TTISR RTCSR
                .EXTN   FINI FETR
                .EXTD   LOC6 LOC7
                .EXTN   CONTR DACSR ADCSR DTS10 S10TD

                .NREL

00000'020532  TSTC:   LDA     0 SEVN  ;WRITEABLE AREA
00001'040002$         STA     0 LOC7
00002'020515          LDA     0 LOC40 ;GETC ADDRESS
00003'040040          STA     0 40
00004'020514          LDA     0 LOC41 ;PUTC ADDRESS
00005'040041          STA     0 41
00006'006515          JSR@    .CRLF   ;RESET TTY CARRIAGE
00007'006514          JSR@    .CRLF
00010'177777          FINI
00011'177777          FETR
00012'102400          FSUB    0 0     ;ZERO ALL CONTROLLER SETTINGS
00013'040530          FSTA    0 KC
00014'040531          FSTA    0 RATE
00015'040532          FSTA    0 TD
00016'040533          FSTA    0 X0
00017'040534          FSTA    0 DT    ;AND SAMPLE TIME
00020'100000          FEXT

00021'062677          IORST
00022'060177          INTEN
00023'102400          SUB     0 0     ;GEN ZERO
00024'000401          JMP     .+1
00025'061114          DOAS    0 RTC   ;FREQ=60 CPS
00026'101700          INCS    0 0     ;1ST CNTRL TIME SHOULD BE LARGE
00027'040504          STA     0 CCNT  ;1ST CLK TIME
00030'040504  LOOP:   STA     0 CNT   ;STORE CLK COUNTER
00031'000011'         FETR
00032'024507          FLDA    1 SIXTY ;SET CLK TIME TO
00033'020520          FLDA    0 DT    ;PRESENT DT
00034'120100          FMPY    1 0
00035'040502          FSTA    0 ELD   ;SAVE
00036'074501          FFIX    ELD     ;CONVERT TO INTEGER
00037'100000          FEXT
00040'020500          LDA     0 ELD+1 ;LOAD INTEGER
00041'101005          MOV     0 0 SNR ;ZERO?
00042'101400          INC     0 0     ;DO NOT LEAVE CNTR AS ZERO
00043'000765          JMP     LOOP    ;REPEAT

00044'060114  RTCSR:  NIOS    RTC     ;RESTART CLOCK
00045'014466          DSZ     CCNT    ;DECREMENT COUNTER
00046'001400          JMP     0 3     ;IF NONZERO, RETURN TO EXEC

00047'054446          STA     3 R3    ;SAVE RETURN ADDRESS
00050'020464          LDA     0 CNT   ;TIMER
```

```
00051'040462            STA     0 CCNT  ;RESET CLK CNTR
00052'006453            JSR@    .ADC    ;INPUT A SIGNAL
00053'000162'           X+1             ;AT X+1
00054'006446            JSR@    .STD    ;CONVERT TO DOUBLE PRECISION
00055'000161'           X
00056'020001S           LDA     0 LOC6  ;SAVE FP LOCS 6 & 7
00057'040437            STA     0 SIX
00060'020002$           LDA     0 LOC7
00061'040447            STA     0 SVN
00062'020445            LDA     0 RSEVN
00063'040002$           STA     0 LOC7
00064'000010'           FINI
00065'000031'           FETR
00066'060473            FFLO    X       ;CONVERT TO FLOATING PT
00067'006446            FJSR@   CNTR    ;DO CONTROLLER CALC'N
00070'000143'           KC
00071'000145'           RATE
00072'000147'           TD
00073'000151'           X0
00074'000153'           DT
00075'000155'           EL
00076'000157'           LASTX
00077'000161'           X
00100'000163'           INT
00101'000165'           OUT
00102'074463            FFIX OUT        ;CONVERT OUTPUT TO DBL PRECISION
00103'100000            FEXT
00104'020424            LDA     0 SVN   ;RESTORE FP LOCS 6 & 7
00105'040002$           STA     0 LOC7
00106'020410            LDA     0 SIX
00107'040001S           STA     0 LOC6
00110'006411            JSR@    .DTS    ;CONVERT OUTPUT TO 10 BITS
00111'000165'           OUT
00112'006412            JSR@    .DAC    ;OUTPUT CONTROL
00113'000166'           OUT+1
00114'002401            JMP     @R3     ;RETURN TO EXEC

00115'000000  R3:       0
00116'000000  SIX:      0
00117'000367' LOC40:    GETC
00120'000401' LOC41:    PUTC
00121'177777  .DTS:     DTS10
00122'177777  .STD:     S10TD
00123'000405' .CRLF:    CRLF
00124'177777  .DAC:     DACSR
00125'177777  .ADC:     ADCSR
00126'000775' TSEVN:    WTTI
00127'000617' RSEVN:    WRTC
00130'000000  SVN:      0
00131'000000  TSVN:     0
00132'000441' SEVN:     SEVEN
00133'000000  CCNT:     0
```

```
00134'000000  CNT:    0
00135'177777  CNTR:   CONTR
00136'000000  WORD:   0
00137'000000  ELD:    0.0       ;TEMP STORAGE FOR TIMER CALC
00140'000000
00141'041074  SIXTY:  60.0      ;CLK FREQ (SEC**-1)
00142'000000
00143'000000  KC:     0.0       ;PROPORTIONAL CONSTANT
00144'000000
00145'000000  RATE:   0.0       ;RESET RATE
00146'000000
00147'000000  TD:     0.0       ;DERIVATIVE TIME
00150'000000
00151'000000  X0:     0.0       ;SET POINT
00152'000000
00153'000000  DT:     0.0       ;SAMPLE TIME
00154'000000
00155'000000  EL:     0.0       ;LAST ERROR
00156'000000
00157'000000  LASTX:  0.0       ;LAST READING
00160'000000
00161'000000  X:      0.0       ;PRESENT INPUT
00162'000000
00163'000000  INT:    0.0       ;INTEGRAL SUMMATION
00164'000000
00165'000000  OUT:    0.0       ;CONTROLLER OUTPUT
00166'000000

00167'054533  TTISR:  STA       3 AC3    ;TTY S/R
00170'050533          STA       2 AC2    ;SAVE ACC'S
00171'030001$         LDA       2 LOC6   ;SAVE FP LOCS 6 & 7
00172'050532          STA       2 T6
00173'030002$         LDA       2 LOC7
00174'050735          STA       2 TSVN
00175'030731          LDA       2 TSEVN
00176'050002$         STA       2 LOC7
00177'000064'         FINI
00200'000065'         FETR
00201'040545          FSTA      0 FAC0   ;SAVE PRESENT CONTROLLER
00202'020741          FLDA      0 KC     ;SETTINGS IN
00203'040531          FSTA      0 TKC    ;TEMP STORAGE AREA
00204'020741          FLDA      0 RATE
00205'040531          FSTA      0 TTR
00206'020741          FLDA      0 TD
00207'040531          FSTA      0 TTD
00210'020741          FLDA      0 X0
00211'040531          FSTA      0 TX0
00212'020741          FLDA      0 DT
00213'040531          FSTA      0 TDT
00214'100000          FEXT
00215'004552  BGN:    JSR       GETC     ;INPUT A CHARACTER
00216'034507          LDA       3 CR
```

```
00217'116405          SUB     0 3 SNR ;CR?
00220'000457          JMP     DEPOS   ;YES, REDEPOSIT SETTINGS
00221'115300          MOVS    0 3
00222'054714          STA     3 WORD
00223'004544          JSR     GETC    ;NEXT CHARACTER
00224'034712          LDA     3 WORD
00225'163000          ADD     3 0     ;TWO CHARACTER WORD
00226'034524          LDA     3 RA
00227'116405          SUB     0 3 SNR ;RATE?
00230'000435          JMP     RAT     ;YES
00231'034523          LDA     3 DE    ;NO
00232'116405          SUB     0 3 SNR ;DERIVATIVE?
00233'000434          JMP     DER     ;YES
00234'034522          LDA     3 GA    ;NO
00235'116405          SUB     0 3 SNR ;GAIN?
00236'000433          JMP     GAIN    ;YES
00237'034521          LDA     3 SE    ;NO
00240'116405          SUB     0 3 SNR ;SET POINT?
00241'000432          JMP     SETPT   ;YES
00242'034520          LDA     3 SA    ;NO
00243'116405          SUB     0 3 SNR ;SAMPLE TIME?
00244'000431          JMP     SAM     ;YES
00245'004552          JSR     ERROR   ;NO, SHOULD BE ONE OF ABOVE
00246'000747          JMP     BGN     ;START AGAIN
00247'004520  LP:     JSR     GETC    ;GET NEXT CHARACTER
00250'034500          LDA     3 EQUAL
00251'116405          SUB     0 3 SNR ;" = "?
00252'000405          JMP     NUMB    ;YES, GET FP NO
00253'034476          LDA     3 COLON
00254'116405          SUB     0 3 SNR ;" : "?
00255'000402          JMP     NUMB    ;YES, GET FP NO,.
00256'000771          JMP     LP      ;NO, IGNORE CHAR
00257'000200' NUMB:   FETR
00260'120000          FDFC    0       ;INPUT NO.
00261'041000          FSTA    0 0 2   ;STORE IN TEMP AREA
00262'100000          FEXT
00263'004522          JSR     CRLF    ;NEXT LINE
00264'000731          JMP     BGN     ;START  AGAIN
00265'030443  RAT:    LDA     2 .TR   ;LOAD RESET RATE ADDRS
00266'000761          JMP     LP
00267'030442  DER:    LDA     2 .TD   ;LOAD DERIV ADDRS
00270'000757          JMP     LP
00271'030436  GAIN:   LDA     2 .KC   ;LOAD GAIN ADDRS
00272'000755          JMP     LP
00273'030437  SETPT:  LDA     2 .X0   ;LOAD SET PT ADDRS
00274'000753          JMP     LP
00275'030436  SAM:    LDA     2 .DT   ;LOAD SAMPLE TIME ADDRS
00276'000751          JMP     LP

00277'000257' DEPOS:  FETR            ;RESTORES DATA AS IT NOW EXISTS
00300'020434          FLDA    0 TKC   ;IN TEMPORARY DATA AREA
00301'040642          FSTA    0 KC
```

```
00302'020434            FLDA    0 TTR
00303'040642            FSTA    0 RATE
00304'020434            FLDA    0 TTD
00305'040642            FSTA    0 TD
00306'020434            FLDA    0 TX0
00307'040642            FSTA    0 X0
00310'020434            FLDA    0 TDT
00311'040642            FSTA    0 DT
00312'020434            FLDA    0 FAC0
00313'100000            FEXT
00314'030615            LDA     2 TSVN  ;RESTORE LOC7 FOR FP
00315'050002$           STA     2 LOC7
00316'030406            LDA     2 T6    ;RESTORE LOC6
00317'050001$           STA     2 LOC6
00320'030403            LDA     2 AC2   ;RESTORE AC2
00321'002401            JMP     @AC3

00322'000000  AC3:      0
00323'000000  AC2:      0
00324'000000  T6:       0
00325'000015  CR:       15
00326'000012  LF:       12
00327'000334' .KC:      TKC     ;TEMP DATA STORAGE ADDRESSES
00330'000336' .TR:      TTR
00331'000340' .TD:      TTD
00332'000342' .X0:      TX0
00333'000344' .DT:      TDT
00334'000000  TKC:      0.0     ;TEMP DATA STORAGE AREA
00335'000000
00336'000000  TTR:      0.0
00337'000000
00340'000000  TTD:      0.0
00341'000000
00342'000000  TX0:      0.0
00343'000000
00344'000000  TDT:      0.0
00345'000000
00346'000000  FAC0:     0.0
00347'000000
00350'000075  EQUAL:    75
00351'000072  COLON:    72

      000001  .TXTM     1
      000352  RA:       .TXT    "RA"
00352'051101
00353'000000
      000354  DE:       .TXT    "DE"
00354'042105
00355'000000
      000356  GA:       .TXT    "GA"
00356'043501
00357'000000
```

```
      000360  SE:     .TXT    "SE"
00360'051505
00361'000000
      000362  SA:     .TXT    "SA"
00362'051501
00363'000000
00364'000105  E:      "E
00365'000122  R:      "R
00366'000117  O:      "O

00367'063610  GETC:   SKPDN    TTI       ;INPUT CHAR FROM TTY
00370'000777          JMP      .-1
00371'054406          STA      3 A3      ;SAVE RETURN ADDRS
00372'060610          DIAC     0 TTI
00373'034405          LDA      3 C177    ;7 BIT MASK
00374'163400          AND      3 0
00375'004404          JSR      PUTC      ;ECHO
00376'002401          JMP      @A3       ;RETURN

00377'000000  A3:     0
00400'000177  C177:   177
00401'063511  PUTC:   SKPBZ    TTO       ;OUTPUT CHAR TO TTY
00402'000777          JMP      .-1
00403'061111          DOAS     0 TTO
00404'001400          JMP      0 3

00405'040410  CRLF:   STA      0 C0      ;SAVE ACC'S
00406'054410          STA      3 C3      ;OUTPUTS "CR" THEN "LF"
00407'020716          LDA      0 CR
00410'004771          JSR      PUTC
00411'020715          LDA      0 LF
00412'004767          JSR      PUTC
00413'020402          LDA      0 C0      ;RESTORE ACC'S
00414'002402          JMP      @C3

00415'000000  C0:     0
00416'000000  C3:     0

00417'040420  ERROR:  STA      0 E0      ;OUTPUT "ERROR" TO TTY
00420'054420          STA      3 E3
00421'004764          JSR      CRLF
00422'020742          LDA      0 E
00423'004756          JSR      PUTC
00424'020741          LDA      0 R
00425'004754          JSR      PUTC
00426'020737          LDA      0 R
00427'004752          JSR      PUTC
00430'020736          LDA      0 O
00431'004750          JSR      PUTC
00432'020733          LDA      0 R
00433'004746          JSR      PUTC
00434'004751          JSR      CRLF
```

```
00435'020402            LDA     0 E0
00436'002402            JMP     0E3

00437'000000  E0:       0
00440'000000  E3:       0
      000156  SEVEN:    .BLK  110.          ;WRITEABLE AREA
      000156  WRTC:     .BLK  110.
      000156  WTTI:     .BLK  110.

                .END
```

```
                .TITL   ANALG
                .ENT    DACSR ADCSR

                ;INPUT AND OUTPUT OF DATA THROUGH CHANNEL ZERO
                ;OF ADCV AND DACV RESPECTIVELY

                ;CALLING SEQUENCE:


                ;1)     JSR     DACSR
                ;       DATA ADDRESS
                ;       RETURN


                ;2)     JSR     ADCSR
                ;       DATA    ADDRESS
                ;       RETURN


                .NREL
00000'040424    DACSR:  STA     0 AC0   ;SAVE AC0
00001'102400            SUB     0 0     ;CODE FOR OUTPUT CHANNEL
00002'063523            SKPBZ   DACV    ;WAIT UNTIL DACV IS CLEAR
00003'000777            JMP     .-1
00004'062023            DOB     0 DACV  ;SET UP OUTPUT CHANNEL
00005'023400            LDA0    0 0 3   ;GET OUTPUT WORD
00006'061023            DOA     0 DACV  ;OUTPUT DATA
00007'020415            LDA     0 AC0   ;RESTORE AC0
00010'001401            JMP     1 3     ;RETURN



00011'040413    ADCSR:  STA     0 AC0   ;SAVE AC0
00012'102400            SUB     0 0     ;CODE FOR INPUT CHANNEL
00013'063521            SKPBZ   ADCV    ;WAIT UNTIL ADCV IS CLEAR
00014'000777            JMP     .-1
00015'061121            DOAS    0 ADCV  ;START INPUT CHANNEL
00016'063521            SKPBZ   ADCV    ;WAIT UNTIL DONE
00017'000777            JMP     .-1
00020'062621            DICC    0 ADCV  ;INPUT DATA AND CLEAR
00021'043400            STA0    0 0 3   ;STORE DATA
00022'020402            LDA     0 AC0   ;RESTORE AC0
00023'001401            JMP     1 3     ;RETURN

00024'000000    AC0:    0

                .END
```

```
                .TITL   DPADC
                .ENT    DTS10 S10TD

                .NREL

                ;CONVERTS DOUBLE PRECISION SIGNED INTERGERS
                ;TO 10 BIT SIGNED INTEGERS


                ;CALLING SEQUENCE:
                ;       JSR     DTS10
                ;       ADR     -ADDRESS OF DOUBLE PRECISION WORD
                ;       RETURN

00000'040435    DTS10:  STA     0 AC0
00001'044435            STA     1 AC1
00002'050435            STA     2 AC2
00003'031400            LDA     2 0 3
00004'126400            SUB     1 1
00005'021000            LDA     0 0 2
00006'045000            STA     1 0 2
00007'025001            LDA     1 1 2
00010'152400            SUB     2 2
00011'101113            MOVL#   0 0 SNC
00012'000405            JMP     POS
00013'150000            COM     2 2
00014'124404            NEG     1 1 SZR ;LOW ORDER NEGATE
00015'100001            COM     0 0 SKP
00016'100400            NEG     0 0
00017'101004    POS:    MOV     0 0 SZR
00020'000404            JMP     OFLOW
00021'020417            LDA     0 MAX
00022'106433            SUBZ#   0 1 SNC
00023'000402            JMP     SGN
00024'024414    OFLOW:  LDA     1 MAX
00025'151004    SGN:    MOV     2 2 SZR
00026'124400            NEG     1 1
00027'031400            LDA     2 0 3
00030'045001            STA     1 1 2
00031'020404            LDA     0 AC0
00032'024404            LDA     1 AC1
00033'030404            LDA     2 AC2
00034'001401            JMP     1 3
00035'000000    AC0:    0
00036'000000    AC1:    0
00037'000000    AC2:    0
00040'000777    MAX:    777


                ;THE NEXT PART CONVERTS 10 BIT SIGNED INTEGERS
```

```
                ;TO DOUBLE PRECISION SIGNED INTEGERS

                ;CALLING SEQUENCE:

                        ;JSR     S1@TD
                        ;ADR     -ADDRESS OF DOUBLE PRECISION WORD
                        ;RETURN

00041'040774    S1@TD:  STA     0 AC@
00042'050775            STA     2 AC2
00043'031400            LDA     2 @ 3
00044'021001            LDA     0 1 2
00045'101120            MOV#L   @ @
00046'102462            SUBC    @ @ S#C
00047'100000            COM     @ @
00050'041000            STA     @ @ 2
00051'020764            LDA     0 AC@
00052'030765            LDA     2 AC2
00053'001401            JMP     1 3

                .END
```

```
                .TITL   CONTR
                .ENT    CONTR
                ;CONTROLLER MODULE (FLOATING POINT)

                ;CALLING SEQUENCE:
                ;       FJSR    CONTR
                ;       KC      -ADDRESS OF PROPORTIONAL GAIN
                ;       RATE    -ADDRESS OF RESET RATE
                ;       TD      -ADDRESS OF DERIVATIVE TIME
                ;       XØ      -ADDRESS OF SET POINT
                ;       DT      -ADDRESS OF SAMPLE TIME
                ;       EL      -ADDRESS OF LAST ERROR
                ;       LASTX   -ADDRESS OF CURRENT READING
                ;       X       -ADDRESS OF CURRENT READING
                ;       INT     -ADDRESS OF INTEGRAL SUMMATION
                ;       OUT     -ADDRESS OF OUTPUT VALUE
                ;RETURN

                .NREL

00000'040440    CONTR:  FSTA    0 FAC0
00001'044441            FSTA    1 FAC1
00002'050442            FSTA    2 FAC2
00003'027407            FLDA@   1 7 3   ;CURRENT INPUT
00004'047406            FSTA@   1 6 3   ;SAVE INPUT FOR NEXT TIME
00005'023403            FLDA@   0 3 3   ;SET POINT
00006'122400            FSUB    1 0     ;CURRENT ERROR
00007'027405            FLDA@   1 5 3   ;LAST ERROR
00010'043405            FSTA@   0 5 3   ;SAVE ERROR FOR NEXT TIME
00011'106400            FSUB    0 1     ;-LAST DE
00012'124400            FNEG    1 1     ;LAST DE
00013'033404            FLDA@   2 4 3   ;TIME INTERVAL
00014'144200            FDIV    2 1     ;DE/DT
00015'140100            FMPY    2 0     ;E*DT
00016'033402            FLDA@   2 2 3   ;DERIV TIME
00017'144100            FMPY    2 1     ;DERIV TERM
00020'033401            FLDA@   2 1 3   ;RESET RATE
00021'140100            FMPY    2 0
00022'151004            FMOV    2 2 FSZR;OMIT INT TERM IF RATE=0
00023'033410            FLDA@   2 10 3  ;LAST INTEGRAL VALUE
00024'143000            FADD    2 0     ;INTEGRAL TERM
00025'043410            FSTA@   0 10 3  ;SAVE INTEGRAL
00026'123000            FADD    1 0     ;TWO TERM SUM
00027'027405            FLDA@   1 5 3   ;REENTER CURRENT ERROR
00030'033400            FLDA@   2 0 3   ;PROPORTIONAL GAIN
00031'144100            FMPY    2 1
00032'123000            FADD    1 0
00033'043411            FSTA@   0 11 3  ;RETURN THREE TERM OUTPUT
00034'020404            FLDA    0 FAC0
00035'024405            FLDA    1 FAC1
00036'030406            FLDA    2 FAC2
00037'001412            FJMP    12 3    ;RETURN TO CALLING PROGRAM
```

```
00040'000000  FAC0:   0.0
00041'000000
00042'000000  FAC1:   0.0
00043'000000
00044'000000  FAC2:   0.0
00045'000000

              .END
```

R

APPENDIX G

ALGORITHM FOR FLOATING POINT 3-MODE POSITION CONTROLLER

$$\text{Controller output} = K_c * e_i + T * I * \sum_{j=0}^{i} e_j + D * (e_i - e_{i-1})/T$$

where K_c = controller gain

I = reset rate

D = derivative time

T = sample time

e_i = error for control time i

ALGORITHM:

1. save accumulators
2. calculate error, e_i, and $(e_i - e_{i-1})/T$
3. save e for next e_{i-1}
4. calculate $D*(e_i - e_{i-1})/T$
5. calculate $T*I*\sum_{j=0}^{i} e_j$ and add to result of step 4
6. calculate K_c and add to result of step 5 to get output
7. store output
8. restore accumulators and return