THE CASCADE CONTROL OF A PARTIALLY SIMULATED CONTINUOUS STIRRED TANK REACTOR

by

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TO

My Parents

and

My Wife

THE CASCADE CONTROL OF A PARTIALLY SIMULATED CONTINUOUS STIRRED TANK REACTOR

HAMID FARABI Ph.D. 1978

SUMMARY

The results of single-loop and cascade control systems are compared to show the advantages of the cascade system over the other in controlling a reactor outlet temperature. Tests were performed for both control systems on a totally simulated and on a partially simulated continuous stirred tank reactor fitted with a cooling jacket. The system disturbance is a combination of step changes in the reactor inlet temperature and throughput and in the jacket coolant inlet temperature, while the jacket flowrate is the manipulated variable.

To predict performance, the whole system is simulated on a Honeywell-316 digital computer. This study also assisted in the design of the corresponding partially simulated system.

In partial simulation some parts of the system are simulated on the computer while other parts exist as real plant items with on-line linked operation. In this particular research, reactor and jacket inlet and outlet temperatures and reactor throughput are transmitted to the computer as required data for the simulation of the mass balance and the generation of the control action. A signal representing the calculated reaction heat generation is transmitted back to the plant to implement the release of the required exothermic heat of reaction from electrical heating elements. The corrective signal from the simulated control action is also transmitted to the real control valve to regulate the coolant flow. The transmission of these signals and their conversion to the required form is controlled by the Honeywell Analogue Digital Input/Output System (HADIOS)

To confirm the partial simulation experimental results, total simulation model tests are made using the initial operating conditions of the partial simulation study. The results from the two simulation methods are very close although the total simulation could not model all features of the actual plant and its operation.

Key Words : Partial Simulation
On-line Cascade Control

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NOMENCLATURE

A	Arrhenius frequency factor (s^{-1})
A	Heat transfer area (m^2)
C	Concentration (mol/l)
C^o	Steady-state concentration (mol/l)
C'	Concentration perturbation value (mol/l)
C_o	Reactor inlet concentration (mol/l)
C_2	Reactor concentration (mol/l)
C_p	Reaction media specific heat (cal/g K)
C'_p	Jacket media specific heat (cal/g K)
c	Linear equation constant
d	Primary loop corrective signal
d'	Secondary loop corrective signal
E	Activation energy (cal/mol)
e	error value (K)
e	Primary loop error signal
e'	Secondary loop error signal
f	Correction factor
G_1-G_{10}	Open-loop transfer functions
G_{C1}	Primary controller transfer function
G_{C2}	Secondary controller transfer function
G_M	Measurement transfer function
G_{M1}	Cascade primary measurement transfer function
G_{M2}	Cascade secondary measurement transfer function
G_V	Valve transfer function
H	Enthalpy (cal/g)
H	Numerical integration and differentiation interval

I	Current (amp)
I	Primary controller integral action-time (s)
K_1-K_{10}	Open-loop transfer function gains
K_o	Single-loop controller proportional gain (kN/m^2K)
K_1	Cascade primary controller proportional gain (kN/m^2K)
K_2	Cascade secondary controller proportional gain (kN/m^2K)
K_C	Primary controller proportional gain (kN/m^2K)
K'_C	Secondary controller proportional gain (kN/m^2K)
K_M	Primary measurement gain
K'_M	Secondary measurement gain
K_V	Value gain ($l\ m^2/kN\ min$)
k	Reaction rate constant (s^{-1})
L_1-L_3	Open-loop transfer functions time constants
M	Jacket capacity (kg)
m	Jacket throughput (kg/min)
m^o	Steady state jacket throughput (kg/min)
m'	Jacket throughput perturbation value (kg/min)
m	Linear equation slope
N_p	Number of pulses
P	Pressure (kN/m^2)
Q	Heat (W)
Q_g	Heat generation (W)
Q_L	Heat loss (W)
Q_r	Heat removal (W)
R	Universal gas constant (cal/mol K)
r	Iteration number and reaction rate
R_L	Load resistance (Ω)

s	Laplace transform operator
T	Numerical integration and differentiation independent variable
T	Temperature (^{o}C)
T^{o}	Steady-state temperature (^{o}C)
T_o	Reactor inlet temperature (^{o}C)
T_1	Jacket temperature (^{o}C)
T_2	Reactor temperature (^{o}C)
T_3	Jacket inlet temperature (^{o}C)
T_D	Derivative action-time (s)
T_R	Reset-time (s)
T_{set}	Set-point (desired value) (^{o}C)
t	time (s)
U	Heat transfer coefficient (k cal/s m^2 ^{o}C)
UA	Heat transfer resistance (k cal/s ^{o}C)
u	Reactor throughput (l/min)
u^{o}	Steady-state reactor throughput (l/min)
u'	Reactor throughput perturbation value (l/min)
u_1	Jacket throughput (l/min)
V	Volume (l)
V	Voltage (V)
V_S	Supply voltage (V)
x	Interpolation independent variable
y	Interpolation dependent value

GREEK LETTERS

α	Trigger angle (^{o})
α'	(180-α) (^{o})

Δ	Increment
ϕ	Interpolation dependent variable
ε	Convergence criterion
ρ	Density (g/cm^3)
θ	Temperature perturbation variable (^oC)
θ_o	Reactor inlet temperature perturbation value (^oC)
θ_1	Jacket temperature perturbation value (^oC)
θ_2	Reactor temperature perturbation value (^oC)
θ_3	Jacket inlet temperature perturbation value (^oC)

CHAPTER 1

INTRODUCTION

The aim of the project is to investigate the advantages of a cascade control scheme over the corresponding single feedback loop system. The two schemes are studied by total simulation on a digital computer initially in order to assist in the design of equipment and subsequently for comparison with experimental test results.

The system chosen for the study is the temperature control of a jacketed continuous stirred tank reactor (CSTR). The experimental system is implemented by partial simulation in which the thermal effects exist in the equipment but the mass balance and kinetic aspects are simulated on a digital computer.

A partially simulated CSTR is chosen since there was considerable experience and background in the Department. However one significant change in the present research is the replacement of the analogue computer by the digital computer for the simulation of the mass balance and kinetics, necessitating the development of links in both directions between the plant and the computer. Another significant change is the replacement of the conventional controller by computer generated control action.

The terms total simulation and partial simulation have been introduced above. Throughout this thesis, total simulation is applied to simulation of all parts of the system on a computer (either analogue or digital) whereas partial simulation will refer to test equipment in which certain aspects are simulated by computer.

The use of partial simulation enables a system to be studied without the use of chemicals and this has the advantage of avoiding the cost of chemicals, the construction of equipment to withstand their corrosion and their hazardous properties. In addition no chemical disposal or recovery problems exist and the equipment is operable by one person. Thus in this particular case the medium flowing through the reactor is water with the reaction rate simulated in conjunction with the mass balance by the computer. The computer evaluates the reaction rate at each moment of time based upon input flowrate and temperature signals from the plant and hence the rate at which heat should be generated in the exothermic reaction is available. The computer transmits an appropriate signal to immersion heaters situated in the reaction vessel and hence the required reaction heat generation is released. The temperature of the reactor is the object of control and is adjusted by manipulation of cooling water flowrate through the jacket. The reactor temperature signal to the computer is therefore also used to generate the corrective control signal to the cooling water control valve.

In operation stepwise forcing disturbances may be made to the reactor feed temperature, to the through-put and to the temperature of the available cooling water. In operation one, two or all three of these disturbances are made to both the single loop and the cascade control systems. The change on the coolant input temperature has the particular purpose of generating a disturbance in the secondary loop when operating with cascade control.

CHAPTER 2

LITERATURE SURVEY

2.1 INTRODUCTION

The introduction in Chapter One enables three major areas of required literature survey to be identified. The first covers complex control schemes and in particular the possibilities of using them to improve the performance of single-loop feedback systems. The second covers simulation techniques especially those related to the replacement of chemicals by computer mass balance. The third covers simulation of control action as well as on-line control techniques.

2.2 SINGLE-LOOP CONTROL SYSTEM

The single feedback-loop is the commonest and easiest control system. A typical system has a block-diagram, shown in Fig.(2.1). It requires only one controller, one valve and one measurement transfer function, besides those for the plant load and corrective disturbance.

The existing theory has been developed largely for application to the single-loop control system (22,30,49,50). In chemical plant, linearised process items and three term controllers have normally been considered for the

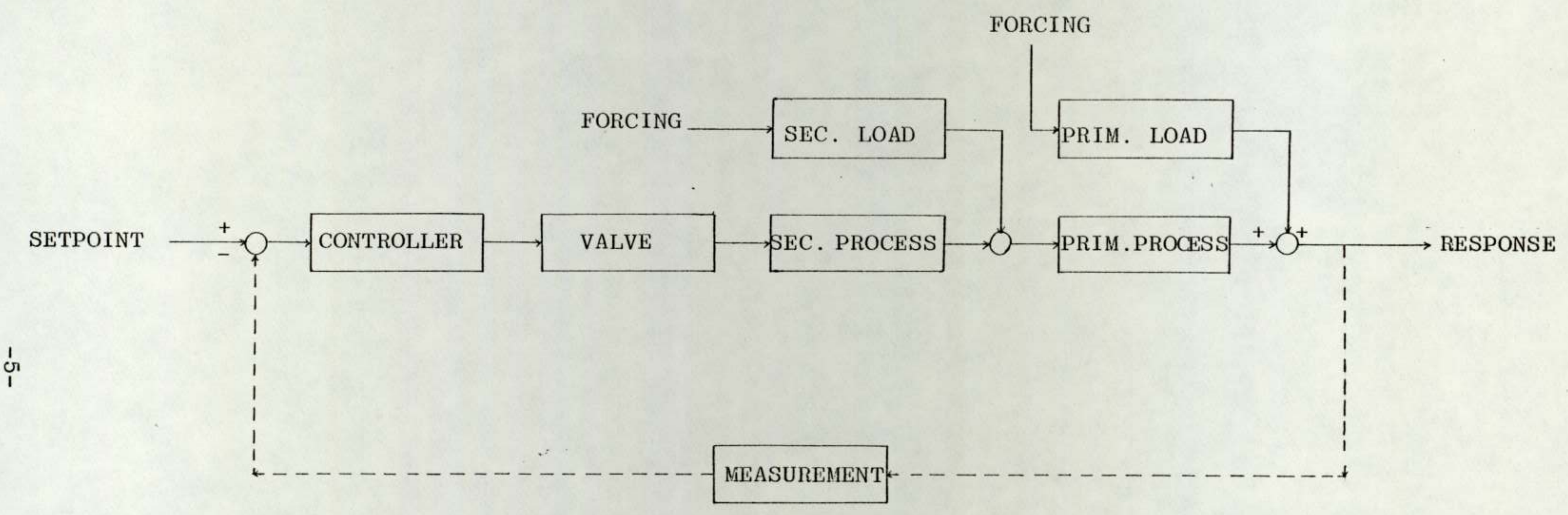


FIG.2.1 Block-diagram of a Typical Single Feedback-Loop System

control of a single non-interacting response variable. Analytical solutions and stability analysis have been developed for such systems. Some total simulation work on non-interacting responses but without linearisation has also been reported (26).

2.3 IMPROVEMENT OF THE PERFORMANCE OF A CONTROL SYSTEM

Many significant pieces of work are reported on the straightforward single-loop control system. Not much work has been reported on improved types of control system and is mostly on the theoretical rather than the practical aspects.

The nature of the process, the magnitude and location of the disturbances, and the characteristics of the controller govern the performance of a control system. Sometimes the performance of a single-loop control system can be improved by making relatively minor changes, such as adding derivative action to the controller, using a positioner to improve the valve response as Buxton (5) and Chao (9) did in their separate researches, decreasing one of the smaller time constants, or reducing a pure time delay. Usually these methods of improvement are not sufficient especially for large load changes, and other problems which require a more complex system are:

(i) not achieving a fast response

(ii) not being able to regain the desired value quickly enough because of limitation of reset-time

(iii) instability

(iv) limitation of proportional gain-band width

(v) occurrence of interactions between two response variables.

The following sections consider the various ways in which improvements may be obtained.

2.3.1 CASCADE CONTROL SYSTEM

In cascade control the set-point of one loop (the inner or secondary loop) is adjusted by another loop (the outer or primary).

Since 1947 when cascade control system came into use in the processing industries, principal emphasis has been placed on the benefits of interlocking a primary process variable (outer loop) to a secondary variable (inner loop). One of the first articles on the cascade control system was written in 1948 by J.N. Swarr (42) where six types of mechanical control systems are illustrated and it is shown how a cascade control scheme can be applied to each type. In 1954 W.R. Bailey (3), J.G. Ziegler (53), and H.J. Hartz (24) wrote articles on cascade control systems and in all cases showed that with a secondary loop a faster response and a high performance could be obtained. This situation advanced in 1956 when R.J. Franks and C.W. Worley (18) were first to determine quantitatively the relative advantage of one system over another.

They compared the performance of a cascade control system and the corresponding single-loop control system using the "ITAE No." which is the maximum of "the integral of time x arithmetic error (ITAE)".

$$\text{i.e.} \quad ITAE = \int_o^t t\,|e|\,dt$$

and the ITAE No is the maximum value of this integral in which e is the arithmetic difference between the actual output and the desired output.

The ITAE No. is the index representing rapidity with which a system recovers following a disturbance. It is thus a time weighted error and using consistent units, the performance of one system is compared directly with that of another. The study is by total analogue simulation of a system by two control schemes. The system has a transfer function P_1 consisting of three first order lags in the primary loop and P_2 consisting of two first order lags in the secondary loop; each of P_1 and P_2 has an overall gain of unity.

The performances of the control systems are investigated on the basis of their response to four types of disturbance by plotting the ITAE No. versus the ratio (0 to 10) of the dominant process lags of the two processes. They proved that if L_1 and L_2 are the dominant lags of processes P_1 and P_2 respectively, the maximum improvement (2000:1) of the cascade control over the single-loop is when the disturbance is on the secondary loop at L_1/L_2 ratio of 10.

In the same year Norman W. Gollin (21) wrote an article on cascade control systems and showed that multi-loop cascade control:-

(i) reduces the effect of disturbances

(ii) increases the natural frequency of the system

(iii) reduces the effective magnitude of some time constants

(iv) is used because the adjustment and control of the primary variable is impossible in certain single-loop systems

(v) is used because the provision in the secondary loop controller for high and low limits ceases to prevent undesirable effects produced when the secondary variable exceeds these limits.

He concluded that, a cascade control system can provide better control than is obtainable with a single-loop system in the following ways:

(i) The effect of a disturbance in the process is least when it is included in the secondary loop.

(ii) When attempting to improve the performance of any control system, one generally recognized rule is to reduce the size of the second largest lag in the system. This is achieved in cascade control by attempting to close the secondary loop around the second largest lag; this has the effect of reducing the lag.

Further advantages may be realised from cascade control, including significant time constants in the secondary loop. This was reported by P.U. Webb (47) based upon "analysis of transient response curves". Doing so reduces the overall time constant, thus greatly improving the performance of the primary variable when disturbances enter the process outside the secondary loop.

Other reports showing the advantages of cascade control are (23,39) where the integral error of a cascade control system is compared with the one achieved by using a single-loop control system. A wide range of proportional gain and reset time can be used with the system remaining stable when using a cascade control scheme (14,23,39).

It can be concluded that in setting up a cascade control the following points should be considered:

(i) Cascade control is especially effective if the inner loop is much faster than the primary loop and if the main disturbances affect the inner loop first, (33).

(ii) Stable automatic control of the whole system can be obtained with an otherwise unstable inner loop.

(iii) For the secondary controller only proportional action is recommended (4,43). The reason for omitting integral action is that the gain is usually large, and the slight offset resulting from load changes is eventually corrected by the primary controller.

2.3.2 PARALLEL CASCADE CONTROL SYSTEM

Cascade control is sometimes used in process systems where the primary and secondary transfer functions are not in series. In this type of control the secondary transfer function is used only to improve the control system, and make it into a cascade control form, but in series cascade control the secondary transfer function is part of the whole system and is enclosed within the primary loop. Fig.(2.2) shows the block-diagram of a parallel cascade control system. In this figure

G_P = Transfer function for the corrective disturbance entering the primary process.

G_{LP} = Transfer function for the load disturbance entering the primary process.

G_S = Transfer function for the corrective disturbance entering the secondary process.

G_{LS} = Transfer function for the load disturbance entering the secondary process.

G_{CP} = Transfer function of the controller in the primary loop.

G_{CS} = Transfer function of the controller in the secondary loop.

2.3.3 RATIO CONTROL

This is referred to by J.M. Douglas (14) as "pseudo-cascade control", while J.B. Arant (2) defines ratio

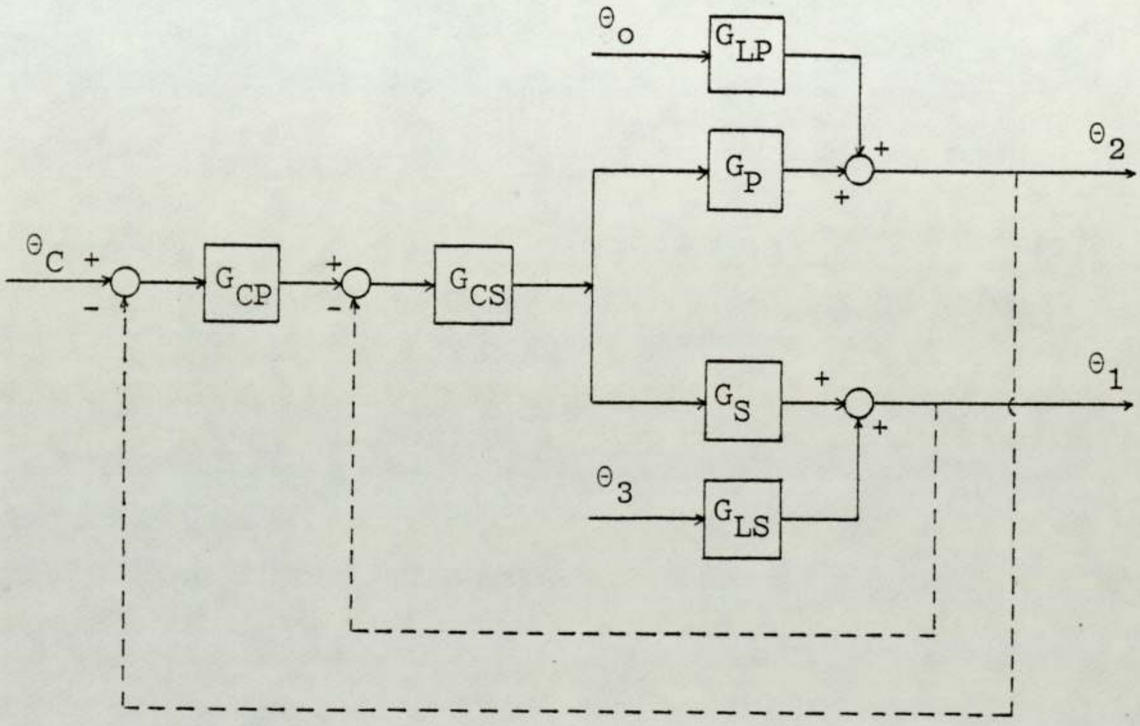


Fig. 2.2 BLOCKDIAGRAM OF A PARALLEL CASCADE CONTROL SYSTEM

control as a special form of cascade control in which a secondary variable is held in some proportion to a primary variable. The latter introduces three systems:-

(i) simple, fixed ratio,

(ii) simple, variable ratio,

(iii) ratio computation.

Parallel cascade and ratio control are not relevant to the system chosen for the present work and so no more details are given but there are examples respectively in (28,34) and (2,39).

The literature mentioned above is very limited i.e. it does not give enough information on control systems especially those which give an improved performance. Furthermore these reports have been criticised by many articles as being mostly theoretical, insufficient and inapplicable. Alan S. Foss (16) has summarised the position well when he states that "there is a wide gap between the theory of control and its applications and that the theory of chemical process control has some rugged terrain to traverse before it meets the needs of those who apply it".

Many crucial points can be extracted from a study of the control system literature, including:

(i) the quality of control is adversely affected by the lack of measurements, the errors and the delays

(ii) there is not enough information about the choice of the process variables to be controlled

(iii) elements of the performance vector (e.g. profit index, peak excursion of variables, integral squared error, state- and control-weighted quadratic index, settling time) give different measures of control performance

(iv) lack of information on stability and safety parameters make the design difficult

(v) the design of many control systems has been based on the static, rather than the dynamic, characteristics

(vi) the process system is usually made non-interacting simply because there is difficulty in designing multivariable control systems.

2.4 SIMULATION STUDIES

2.4.1 TOTAL SIMULATION OF THE SYSTEM MODEL

The system selected for study produces complicated block-diagrams and the analytical solution of these is very difficult (12). In recent years, following the development of computers, simulation by analogue and digital computer has been substituted for the analytical solution. The analogue computer provides a very fast result and does not require any numerical methods, but it has the following disadvantages (29).

(i) It can accept only linear signals and therefore non-linear signals have to be linearised.

(ii) The potentiometer settings of the computer are inaccurate and unreliable.

(iii) The amplifiers are very sensitive and can even be damaged if the computer is overloaded.

(iv) Simulation time is different from the real time.

(v) All the variables have to be scaled in a range compatible with the computer.

(vi) To set a circuit on an analogue computer requires very complicated wiring.

(vii) Only initial condition problems can be simulated.

(viii) The capital outlay is very high and the machine can only be linked to one piece of equipment at a time.

Several pieces of work have been reported on the complete simulation of a controlled system on an analogue computer. The best of those relevant to this research are (5) and (12), (See Chapter One), which are concerned with the simulation study of a CSTR containing a cooling coil and using a single-loop scheme for control of reaction temperature.

Currently simulation studies of chemical processes are turning extensively to digital computers and have been one of the major subjects of the more recent research in chemical engineering (17,35,40). Digital simulation

(i) is easy and reliable in use and only requires enough knowledge of programming and numerical analysis

(ii) is reasonably accurate (compared to analogue simulation)

(iii) has no problem of scaling

(iv) can solve boundary condition differential equations as well as initial condition ones

(v) is less expensive to run than an analogue computer and can be shared among a number of jobs.

Many books and papers have been published on the simulation of chemical processes on a digital computer, but the nearest relevant to this particular project is "the simulation of the single-loop control of a steam jacketed stirred tank (26)", but having no reaction.

2.4.2 PARTIAL SIMULATION

The partial simulation technique is a cheap and very safe method of studying a system by a combination of plant items and computer.

This project is mostly concerned with the control study of a jacketed CSTR with the mass balance simulated on a Honeywell-316 digital computer and the thermal effects existing within real plant.

The literature concerning this part of the research is very limited. The only relevant pieces of work in this field are Chao (9) who studied the optimal and adaptive control of a CSTR; Alpaz (1) who worked on a plug flow reactor, and the nearest is the work of

Buxton (5) which was the study of a CSTR using a single-loop feedback control system acting through a cooling coil. They all simulated the mass balance of their systems on an analogue computer.

No report was found of a partial simulation technique, using a digital computer, for any kind of chemical process.

2.5 ON-LINE DIGITAL CONTROL

The earliest control was entirely manual, and was later assisted by the addition of indicating and recording instruments. This was followed by local automatic control which in turn evolved into centralized automatic control. In 1958 computer process control systems made their appearance and the use of computers as elements in control systems rapidly became an accepted and very effective practice.

The objectives of computer process control are to overcome most of the deficiencies of automatic control because even the best centralized automatic control installations have the following shortcomings (32).

(i) Lack of integration, or control of the process as a whole.

(ii) Lack of consistency in results due to dependence on operators.

(iii) Awkward and costly data recording and processing.

(iv) Lack of capability to implement optimal control to attain economic objectives.

(v) Still some risk of upsets or hazardous operating conditions due to slow reaction time of operators.

The availability of the digital computer has added three capabilities to process control viz. rapid computation, data storage, and decision making. Thus the following three major functions were made available by the computer process control system:

(i) Data processing and monitoring.

(ii) Direct digital control and program control.

(iii) Optimal control.

Direct digital control by the computer process control system uses the computer instead of the automatic controllers to regulate individual variables. There are many reports on direct digital control. Although most of them consider electrical engineering control problems e.g. (6,32,35,45) the principles apply to other fields of engineering, including chemical engineering. Thus experience useful to the present work is reported on the computer implementation of controller actions, etc. For more information on the computers and process control refer to the reviews given by T.J. Williams (51,52) and article written by Carvers S. India Ltd (7).

2.6 CONCLUSION

The literature on cascade control is limited but in all articles this type of control system has been praised and several of its advantages over the single-loop control system are shown. Although direct digital control facilitates multi-loop control systems and no automatic controller is required, no practical research has been done to confirm any of those articles.

Alan S. Foss (16) has stated that "the classical theory is capable of analysing the difficulties in control problems but has nothing to suggest as a remedy". Even simulation without analysis has little to offer to the codification of knowledge of dynamical processes or to a broadly applicable solution of the control configuration. Also it should be mentioned that process modelling is a substantial and crucial task and is by no means routine.

Most of the hazards and cost problems of the chemicals exists in laboratory experimental research. Even so very few people have overcome these problems, in their research, by excluding the chemicals and simulating their effects on the computer. The partial simulation technique can bring a new useful line of research into chemical engineering laboratories.

The surveyed literature shows a scarcity of articles on the practicality of the cascade control scheme and also on partial simulation applications. Since a lot of research remains to be done with a wide range and variety of experiments in the cascade control and simulation fields, the present work set out to study both and to combine them.

CHAPTER 3

THEORETICAL DEVELOPMENTS

3.1 INTRODUCTION

In this chapter the system model is defined and its parameters calculated in accord with the assumptions made. It is also shown how the steady-state temperatures and concentration can be obtained by an iteration method.

In order to compare the cascade scheme with the single-loop control system the transfer functions of each element of the system are combined in block-diagrams to form the two overall transfer functions.

3.2 THE SYSTEM MODEL

The system consists of a CSTR with a first order irreversible exothermic reaction cooled by a jacket of significant hold-up, Fig.(3.1). The important features are considered in more detail in the following sections.

3.3 SYSTEM PARAMETERS

3.3.1 REACTION RATE CONSTANT

Because the reaction is first order and irreversible, the kinetics are:

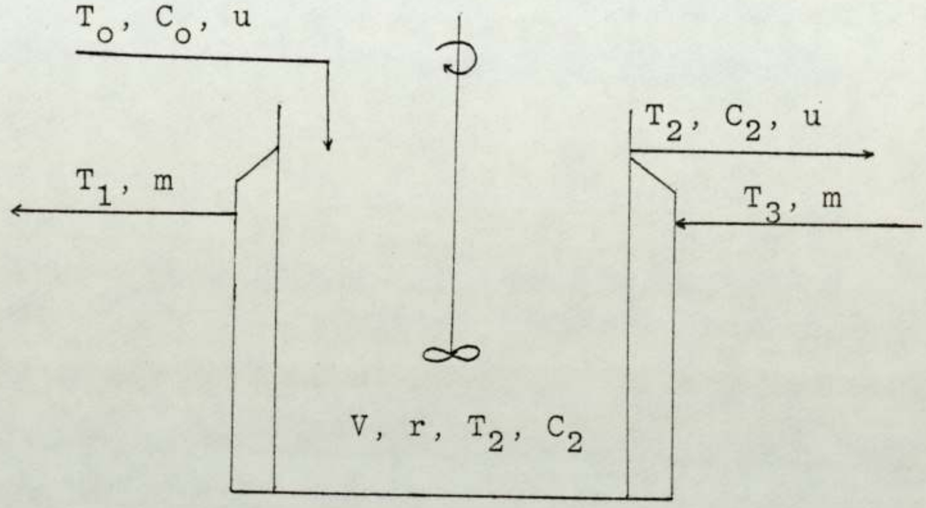


FIG.3.1 A Typical CSTR with a Cooling Jacket

$$r = k.C \tag{3.1}$$

where k is the rate constant for which the variation with temperature can be expressed in the Arrhenius form:

$$k = A \exp\left(-\frac{E}{RT}\right) \tag{3.2}$$

3.3.2 HEAT OF REACTION

The heat of reaction $(-\Delta H)$ is assumed to be constant and independent of temperature for the assumed liquid phase reaction in a temperature range 293-323 K. Its value can be checked by the energy balance of the system at steady-state conditions. Thus balancing the heat generation with the enthalpy changes of the two streams (Qr):

$$(-\Delta H)\ Vr_o = Q_r$$

$$\text{or} \quad (-\Delta H) = \frac{m^o C_p'(T_1^o - T_3^o) + \rho u^o C_p(T_2^o - T_0^o)}{-Vr_o} \tag{3.3}$$

3.3.3 HEAT TRANSFER

The resistance to heat transfer between jacket and reactor is governed by the product UA, and the rate of heat transfer is

$$Q = UA(T_2 - T_1) = mC_p'(T_1 - T_3) \tag{3.4}$$

3.3.4 STEADY-STATE TEMPERATURE AND CONCENTRATION OF THE REACTOR

The initial steady-state mass balance for the reactor is

$$u^{o}C_{o}^{o} - Vr_{o} = u^{o}C_{2}^{o} \quad (3.5)$$

Substituting for r_o from Equ.(3.1) into Equ.(3.5), gives an initial value for exit concentration as

$$C_{2}^{o} = \frac{u^{o}C_{o}^{o}}{u^{o} + Vk} \quad (3.6)$$

The corresponding initial steady-state energy balance is

$$\rho u^{o}C_{p}T_{o}^{o} = \rho u^{o}C_{p}T_{2}^{o} - VkC_{2}^{o}(-\Delta H) + UA(T_{2}^{o} - T_{1}^{o}) + Q_{L} \quad (3.7)$$

where Q_L represents heat losses.
The initial steady-state energy balance for the jacket is

$$m^{o}C_{p}'T_{3}^{o} + UA(T_{2}^{o} - T_{1}^{o}) = m^{o}C_{p}'T_{1}^{o} \quad (3.8)$$

Hence

$$T_{1}^{o} = \frac{m^{o}C_{p}'T_{3}^{o} + UAT_{2}^{o}}{m^{o}C_{p}' + UA} \quad (3.9)$$

Substituting C_2^o from Equ.(3.6) and UA from Equ.(3.8) into Equ.(3.7) gives

$$T_2^o = T_o^o + \frac{kV(-\Delta H)C_o^o}{\rho C_p(u^o + kV)} - \frac{m^o C_p'}{\rho u^o C_p}(T_1^o - T_3^o) - \frac{Q_L}{\rho u^o C_p} \quad (3.10)$$

Letting the estimated value for T_2^o be $T_2^o(r)$, Eqs.(3.2), (3.9) and (3.10) in the following form are solved by iteration

$$k(r) = A \exp\left(-\frac{E}{R(T_2^o(r) + 273)}\right) \quad (3.11)$$

$$T_1^o(r) = \frac{m^o C_p' T_3^o + UAT_2^o(r)}{m^o C_p' + UA} \quad (3.12)$$

$$T_2^o(r+1) = T_o^o + \frac{k(r)V(-\Delta H)C_o^o}{\rho C_p(u^o + k(r)V)} - \frac{m^o C_p'}{\rho u^o C_p}(T_1^o(r) - T_3^o) - \frac{Q_L}{\rho u^o C_p} \quad (3.13)$$

The iteration is continued until $T_2^o(r+1) - T_2^o(r) \leqslant \varepsilon$, and $T_2^o(r+1)$ is then T_2^o. The computer flow-diagram is shown in Appendix (A.4).

3.4 TRANSFER FUNCTION

The transfer function is obtained from the transient mass and energy balances after the non-linear terms have been linearised.

3.4.1 LINEARISATION

The normal way to linearise non-linear terms is to use the Taylor expansion truncated at the first derivatives of the function. For example, if the non-linear function has the form $f(u,v,.......z) = o$, the linearised form of the function is the initial value of the function and the first derivate term in the Taylor expansion for each variable. Thus

$$f = f_o + (\frac{\partial f}{\partial u})_o(u-u^o) + (\frac{\partial f}{\partial v})_o)(v-v^o) + ... + (\frac{\partial f}{\partial z})_o (z-z^o) \quad (3.14)$$

3.4.2 OPEN-LOOP TRANSFER FUNCTIONS OF THE REACTOR

The general transient energy and mass balances of the reactor for throughput, input concentration and temperature forcing are:

$$\rho uC_pT_o + UA(T_1-T_2) - \Delta HVr = \rho uC_pT_2 + \rho VC_p\frac{dT2}{dt} + Q_L \quad (3.15)$$

$$uC_o - Vr = uC_2 + V\frac{dC_2}{dt} \quad (3.16)$$

Linearisation of r with respect to concentration and temperature variables using Equ.(3.14) gives

$$r = r_o + (\frac{\partial r}{\partial C_2})_o(C_2 - C_2^o) + (\frac{\partial r}{\partial T_2})_o(T_2 - T_2^o) \quad (3.17)$$

Also terms uT in Equ.(3.15) and the terms uC in Equ.(3.16) are linearised in the form of

$$uT = u^oT^o + \left(\frac{\partial uT}{\partial u}\right)_o(u - u^o) + \left(\frac{\partial uT}{\partial T}\right)_o(T - T^o) \qquad (3.18)$$

$$uC = uC^o + \left(\frac{\partial uC}{\partial u}\right)_o(u - u^o) + \left(\frac{\partial uC}{\partial C}\right)_o(C - C^o) \qquad (3.19)$$

or $$uT - u^oT^o = T^o(u - u^o) + u^o(T - T^o) \qquad (3.20)$$

$$uC - u^oC^o = C^o(u - u^o) + u^o(C - C^o) \qquad (3.21)$$

Subtracting Equ.(3.7) from Equ.(3.15) and Equ.(3.5) from Equ.(3.16) and substituting $(r_1 - r_o)$ from Equ.(3.17), $(uT - u^oT^o)$ from Equ.(3.20), and $(uC - u^oC^o)$ from Equ.(3.21) and introducing "Perturbation Variables"

$$\rho C_p(u^o\Theta_o - T_o^o u') + UA(\Theta_1 - \Theta_2) - \Delta HV\{\left(\frac{\partial r}{\partial C_2}\right)_o C_2' + \left(\frac{\partial r}{\partial T_2}\right)_o \Theta_2\} =$$

$$\rho C_p(u^o\Theta_2 + T_2^o u') + \rho C_p V\frac{d\Theta_2}{dt} \qquad (3.22)$$

and

$$u^oC_o' + C_o^o u' - V\{\left(\frac{\partial r}{\partial C_2}\right)_o C_2' + \left(\frac{\partial r}{\partial T_2}\right)_o\Theta_2\} = u^oC_2' + C_2^o u' + V\frac{dC_2'}{dt} \qquad (3.23)$$

where these new variables are defined as:-

$$\Theta_o = T_o - T_o^o \qquad C_o' = C_o - C_o^o$$

$$\Theta_1 = T_1 - T_1^o \qquad C_2' = C_2 - C_2^o$$

$$\Theta_2 = T_2 - T_2^o \qquad u' = u - u^o$$

By their definition these variables all have zero values initially and so taking the Laplace transform and rearranging gives the following equations written in terms of time constants L_1 and L_2 and gains K_1 .... K_7.

$$\Theta_2(s) = \frac{K_1}{L_1 s + 1}\Theta_o(s) + \frac{K_2}{L_1 s + 1}\Theta_1(s) - \frac{K_3}{L_1 s + 1}C_2'(s) - \frac{K_4}{L_1 s + 1}u'(s) \quad (3.24)$$

$$C_2'(s) = \frac{K_5}{L_2 s + 1}C_o'(s) - \frac{K_6}{L_2 s + 1}\Theta_2(s) - \frac{K_7}{L_2 s + 1}u'(s) \quad (3.25)$$

where

$$L_1 = \frac{\rho C_p V}{\rho u^o C_p + UA + (\frac{\partial r}{\partial T_2})_o V\Delta H}$$

$$L_2 = \frac{V}{u^o + V(\frac{\partial r}{\partial C_2})_o}$$

$$K_1 = \frac{\rho u^o C_p}{\rho u^o C_p + UA + (\frac{\partial r}{\partial T_2})_o V\Delta H}$$

$$K_2 = \frac{UA}{\rho u^o C_p + UA + (\frac{\partial r}{\partial T_2})_o V\Delta H}$$

$$K_3 = \frac{V\Delta H(\frac{\partial r}{\partial C_2})_o}{\rho u^o C_p + UA + (\frac{\partial r}{\partial T_2})_o V\Delta H}$$

$$K_4 = \frac{(T_2^o - T_o^o)\rho C_p}{\rho u^o C_p + UA + (\frac{\partial r}{\partial T_2})_o V\Delta H} \quad (3.26)$$

$$K_5 = \frac{\bar{u}^o}{u^o + V(\frac{\partial r}{\partial C_2})_o}$$

$$K_6 = \frac{V(\frac{\partial r}{\partial T_2})_o}{u^o + V(\frac{\partial r}{\partial C_2})_o}$$

$$K_7 = \frac{C_2^o - C_o^o}{u^o + V(\frac{\partial r}{\partial C_2})_o}$$

or in terms of transfer functions

$$\Theta_2(s) = G_1\Theta_o(s) + G_2\Theta_1(s) - G_3C_2'(s) - G_4u'(s) \qquad (3.27)$$

$$C_2'(s) = G_5C_o'(s) - G_6\Theta_2(s) - G_7u'(s) \qquad (3.28)$$

where

$$G_1 = \frac{K_1}{L_1s + 1}$$

$$G_2 = \frac{K_2}{L_1s + 1}$$

$$G_3 = \frac{K_3}{L_1s + 1}$$

$$G_4 = \frac{K_4}{L_1s + 1} \qquad (3.29)$$

$$G_5 = \frac{K_5}{L_2s + 1}$$

$$G_6 = \frac{K_6}{L_2 s + 1}$$

$$G_7 = \frac{K_7}{L_2 s + 1}$$

3.4.3 OPEN-LOOP TRANSFER FUNCTIONS OF THE JACKET

The general transient energy balance of the jacket for input temperature and throughput forcing is:

$$mC_p'T_3 + UA(T_2 - T_1) = mC_p'T_1 + MC_p\frac{dT_1}{dt} \qquad (3.30)$$

After linearisation and writing in terms of perturbation variables

$$C_p'(m^o\Theta_3 - T_3^o\, m') + UA(\Theta_2 - \Theta_1) = C_p'(m^o\Theta_1 - T_1^o\, m') + C_p'M\,\frac{d\Theta_1}{dt}$$

(3.31)

where $\Theta_3 = T_3 - T_3^o$ and $m' = m - m^o$

Taking the Laplace transform and rearranging gives the following equation in terms of time constant L_3 and gains K_8, K_9 and K_{10}.

$$\Theta_1(s) = \frac{K_8}{L_3 s + 1}\,\Theta_3(s) + \frac{K_9}{L_3 s + 1}\,\Theta_2(s) + \frac{K_{10}}{L_3 s + 1}\,m'(s)$$

(3.32)

where

$$L_3 = \frac{MC_p'}{m^oC_p' + UA}$$

$$K_8 = \frac{m^oC_p'}{m^oC_p' + UA} \qquad (3.33)$$

$$K_9 = \frac{UA}{m^oC_p' + UA}$$

$$K_{10} = \frac{T_3^o - T_1^o}{m^oC_p' + UA}$$

or in terms of transfer functions

$$\Theta_1(s) = G_8\Theta_3(s) + G_9\Theta_2(s) + G_{10}m'(s) \qquad (3.34)$$

where

$$G_8 = \frac{K_8}{L_3s + 1}$$

$$G_9 = \frac{K_9}{L_3s + 1} \qquad (3.35)$$

$$G_{10} = \frac{K_{10}}{L_3s + 1}$$

3.4.4 CONTROL SYSTEMS

The two control systems which are used for investigation are developed below using the above open-loop transfer functions.

The block-diagram of a single-loop control system, based on Eqs.(3.27), (3.28), and (3.34) is shown in Fig.(3.2). In this block-diagram the controller transfer function is denoted as G_C, that for the control valve as G_V and that for the measuring element as G_M. The block-diagram of the cascade control scheme is shown in Fig.(3.3).

The block-diagram can be used to represent the overall transfer function between the corrective and load disturbances and the response. Thus for the single-loop control system:

$$\Theta_2(s) = \frac{G_C G_V G_{10} G_2}{D(s)} m'(s) + \frac{G_1}{D(s)} \Theta_o(s) + \frac{G_3 G_7 + G_4}{D(s)} u'(s)$$

$$- \frac{G_3 G_5}{D(s)} C_o'(s) + \frac{G_2 G_8}{D(s)} \Theta_3(s) \qquad (3.36)$$

where

$$D(s) = 1 + G_C G_V G_{10} G_2 G_M - G_2 G_9 - G_3 G_6$$

FIG. 3.2 Block Diagram of the Single Feedback-Loop Control System

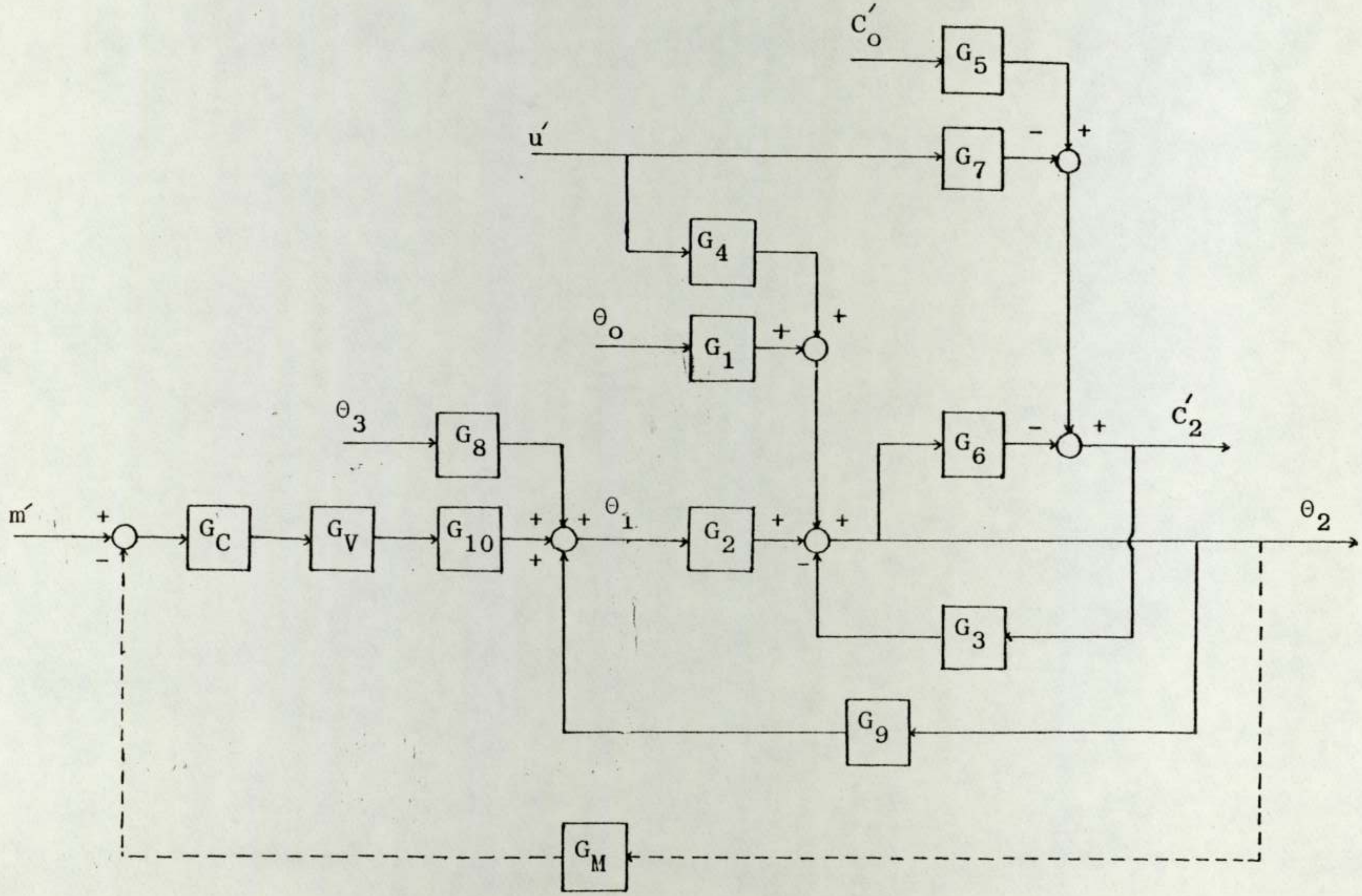
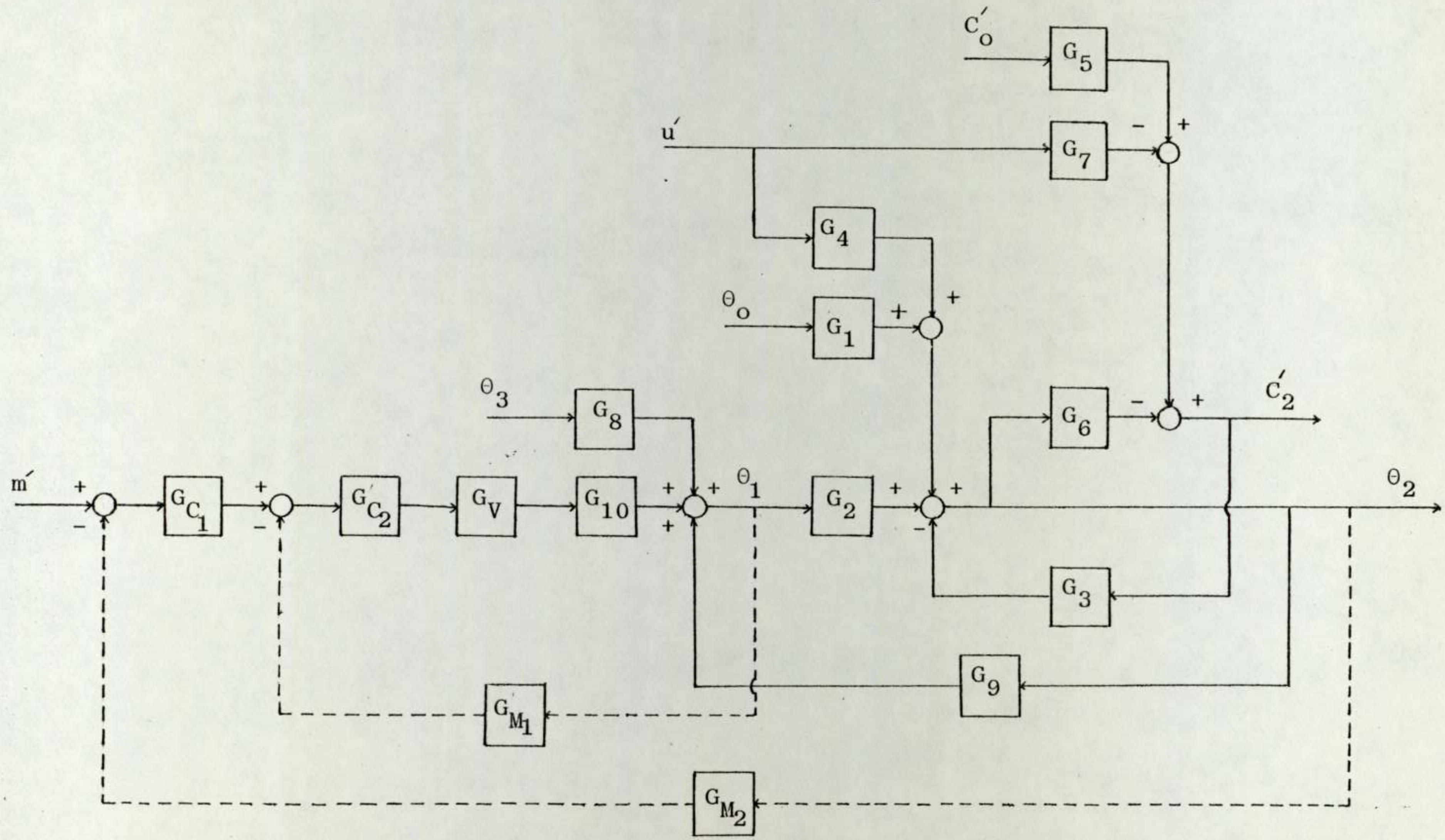


FIG. 3.3 Block Diagram of the Cascade Control System



Likewise for the cascade control system:

$$\Theta_2(s) = \frac{GG_2G_{C2}}{D'(s)} m'(s) + \frac{G_1(1+GG_{M1})}{D'(s)} \Theta_o(s) + \frac{(G_3G_7+G_4)(1+GG_{M1})}{D'(s)} u'(s)$$

$$- \frac{G_3G_5(1+GG_{M1})}{D'(s)} C_o'(s) + \frac{G_2G_8}{D'(s)} \Theta_3(s) \qquad (3.37)$$

where

$$G = G_{C1}G_VG_{10}$$

and

$$D'(s) = 1 + GG_{M1} + GG_2G_{C2}G_{M2} - G_2G_9 - G_3G_6$$

These systems are too complicated for convenient analytical solution and are therefore solved by simulation on a digital computer (Chapter 7).

By limiting the number of disturbances, the control systems become easier and analytical solutions of such reduced systems were obtained at an early stage of the work and were reported in (15).

Thus a cooling coil with a small diameter (insignificant hold-up) was used and the reactor temperature involved in the coil energy balance was assumed to be constant (5) on the basis of a large coolant flowrate. Disturbances were stepchanges in the reactor inlet temperature and in the jacket inlet temperature whereas the reactor throughput and inlet concentration were constant at all times. All the data necessary (e.g. heat transfer coefficient, enthalpy, plant dimensions, ...) were extracted from

Buxton (5) and the controllers optimum settings were found by the continuous-cycling method (54-56). Numerical results of reactor operating temperature and concentration were obtained by a straightforward computer calculation applying a FORTRAN program.

CHAPTER 4

APPARATUS/COMPUTER SYSTEM

4.1 INTRODUCTION

Simulation of the mass balance and controllers of the chosen partially simulated system requires linkages in both directions between the system and the computer so that the process measurements obtained for simulation may be used by the computer to determine the plant requirements from the mass balance and so that the control action and heat generation signal may be returned to the process.

The chemical process plant used in this research is a continuous stirred tank reactor using water as an operating medium and fitted with a cooling jacket. The CSTR is linked to a Honeywell-316 computer by a Honeywell Analogue Digital Input Output System (HADIOS). The measurements taken from the plant are conditioned and transmitted along cabling to the computer. Similarly signals from the computer are conditioned and transmitted to the appropriate part of the plant.

The schematic representation of the whole system is shown in Fig.(4.1).

4.2 APPARATUS DEVELOPMENT

FIG.4.1 Schematic Representation of the Whole System

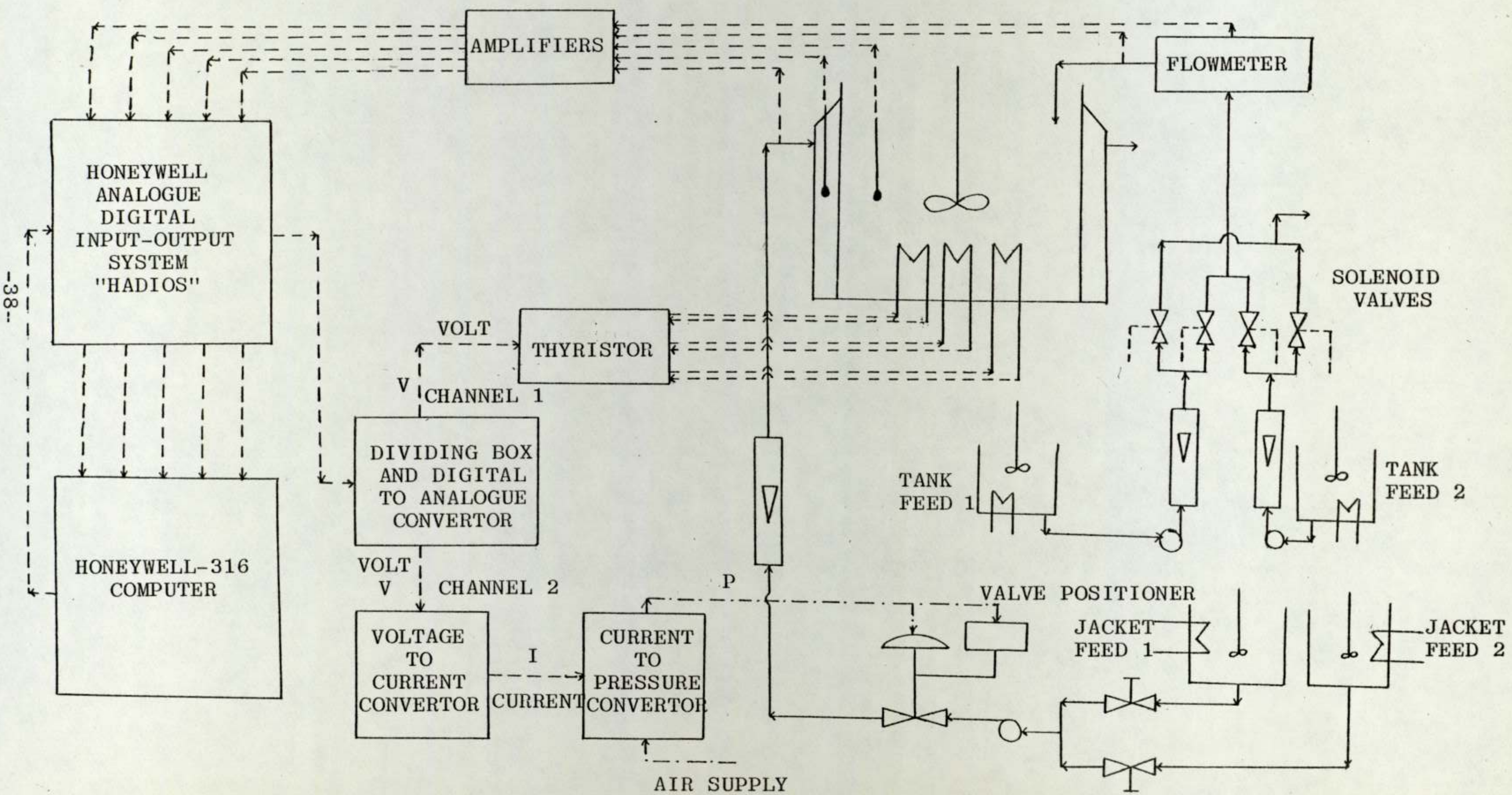
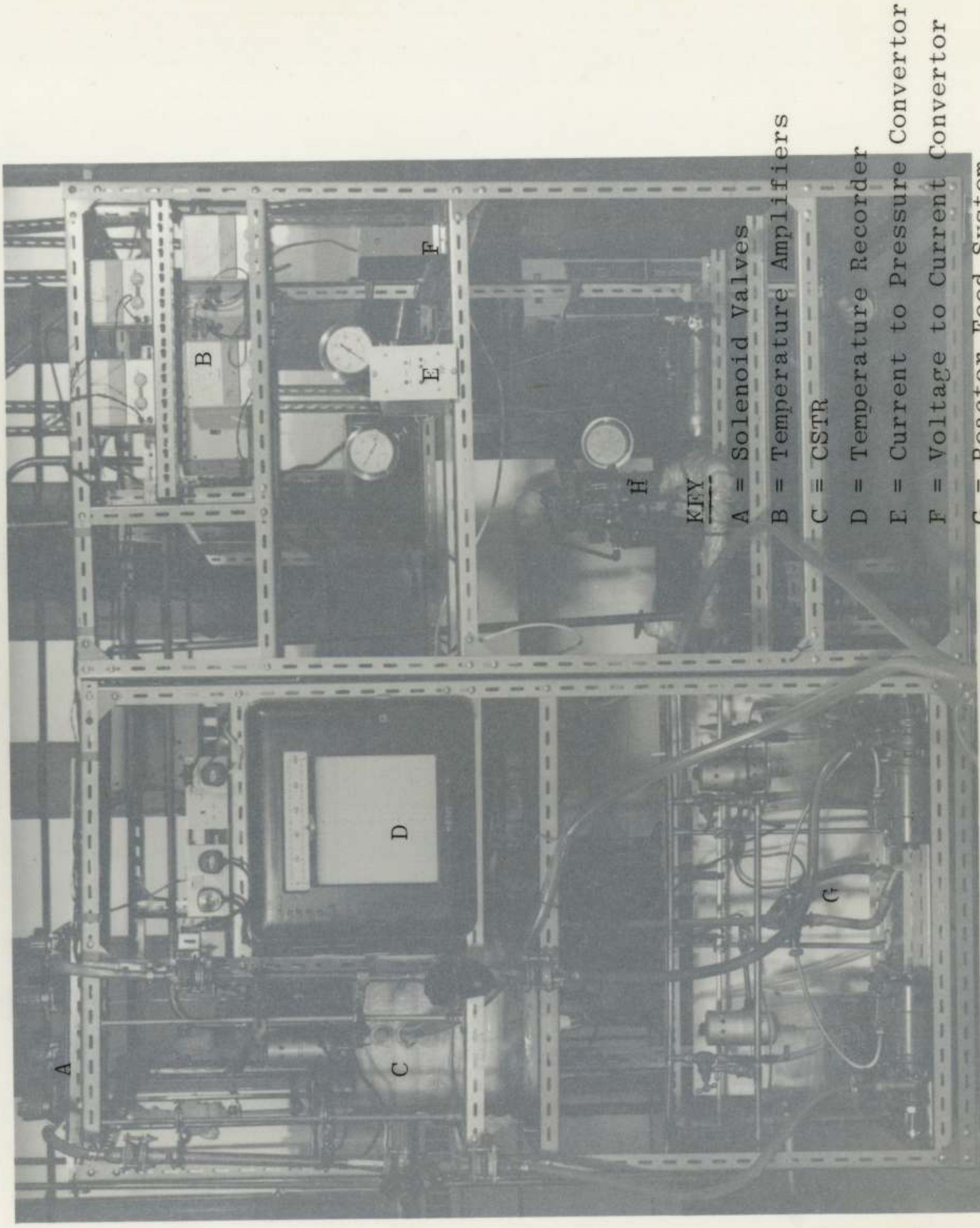


FIG. 4.2 Front View of the Apparatus



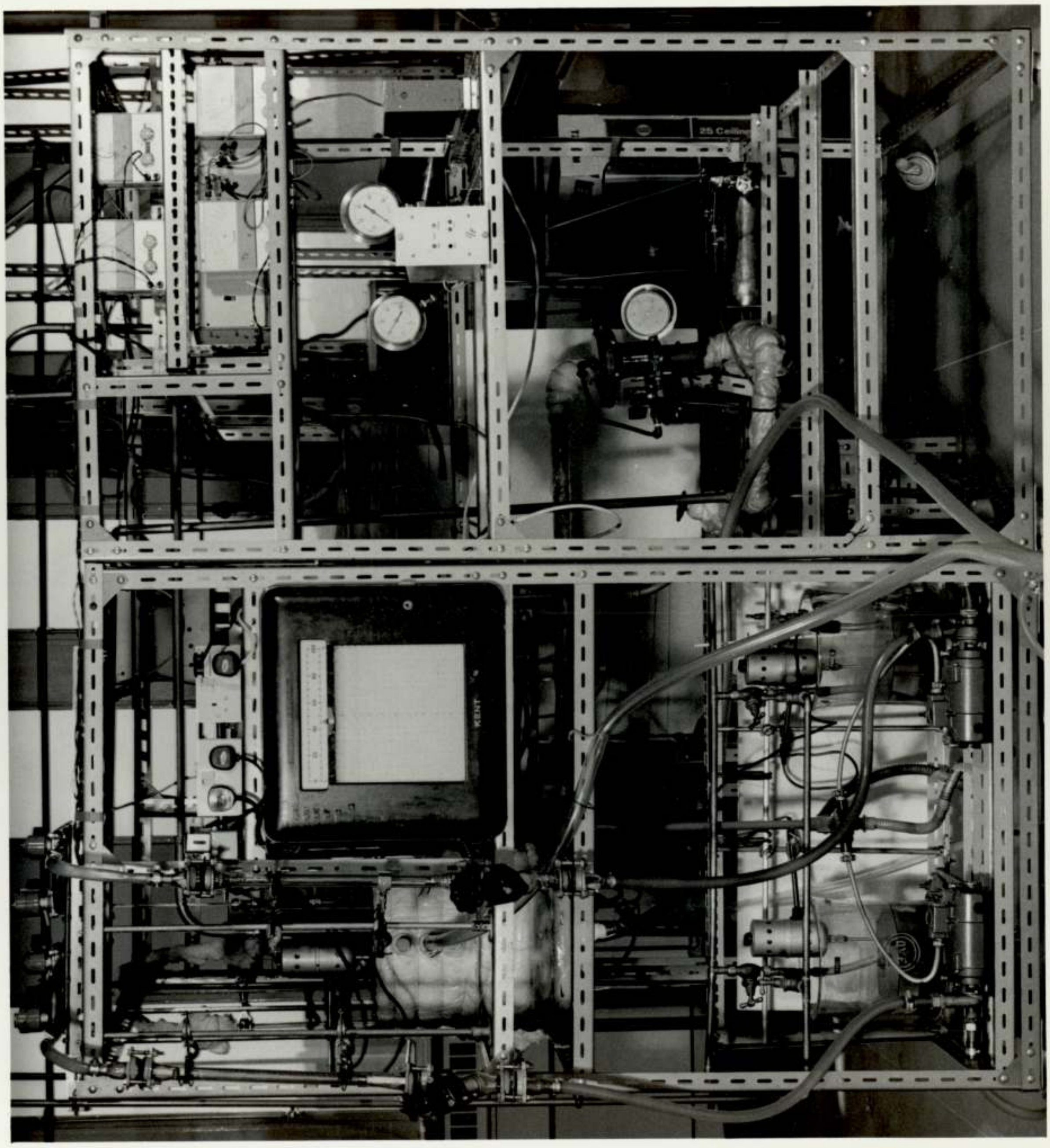

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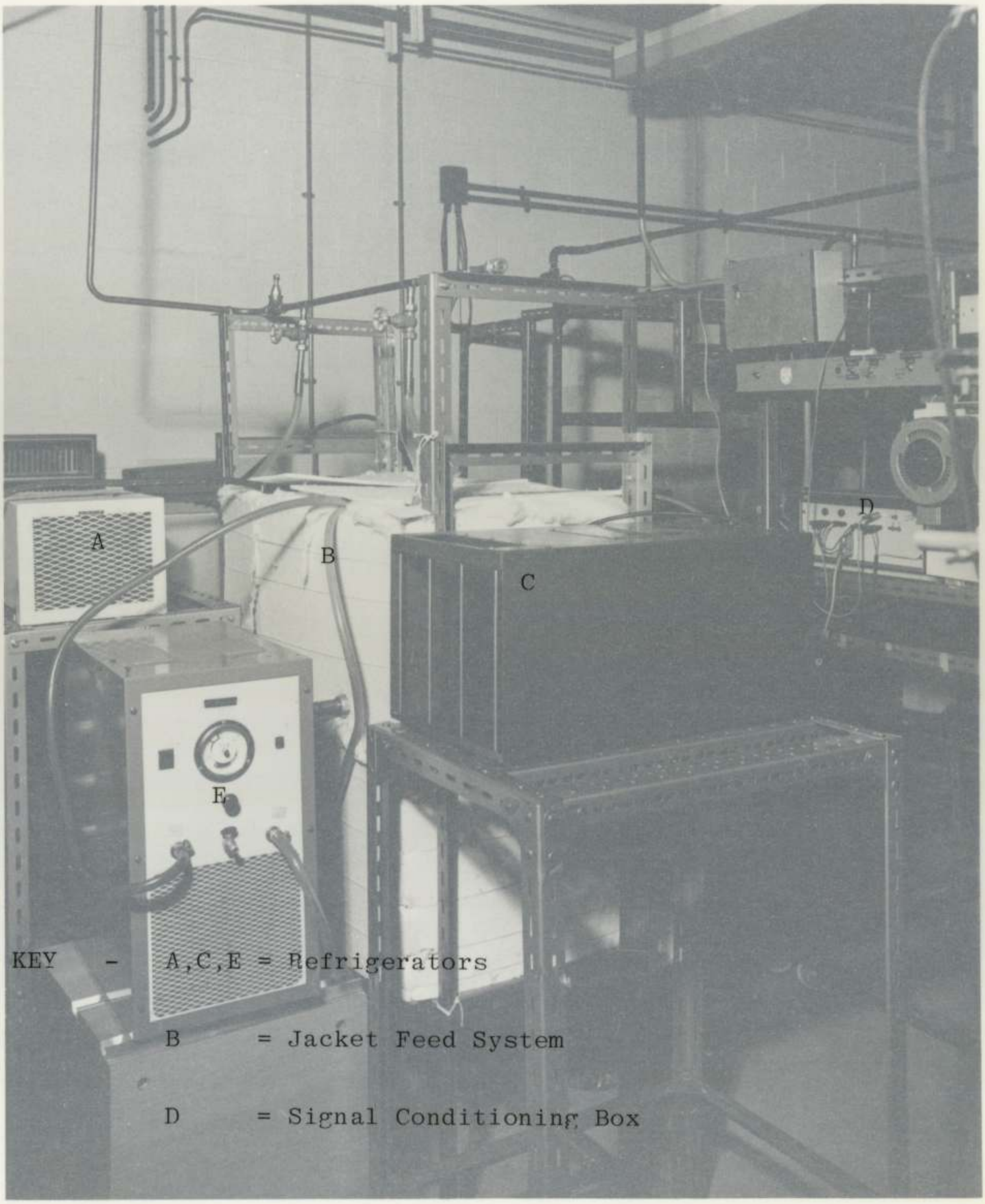
FIG. 4.3 Rear View of the Apparatus



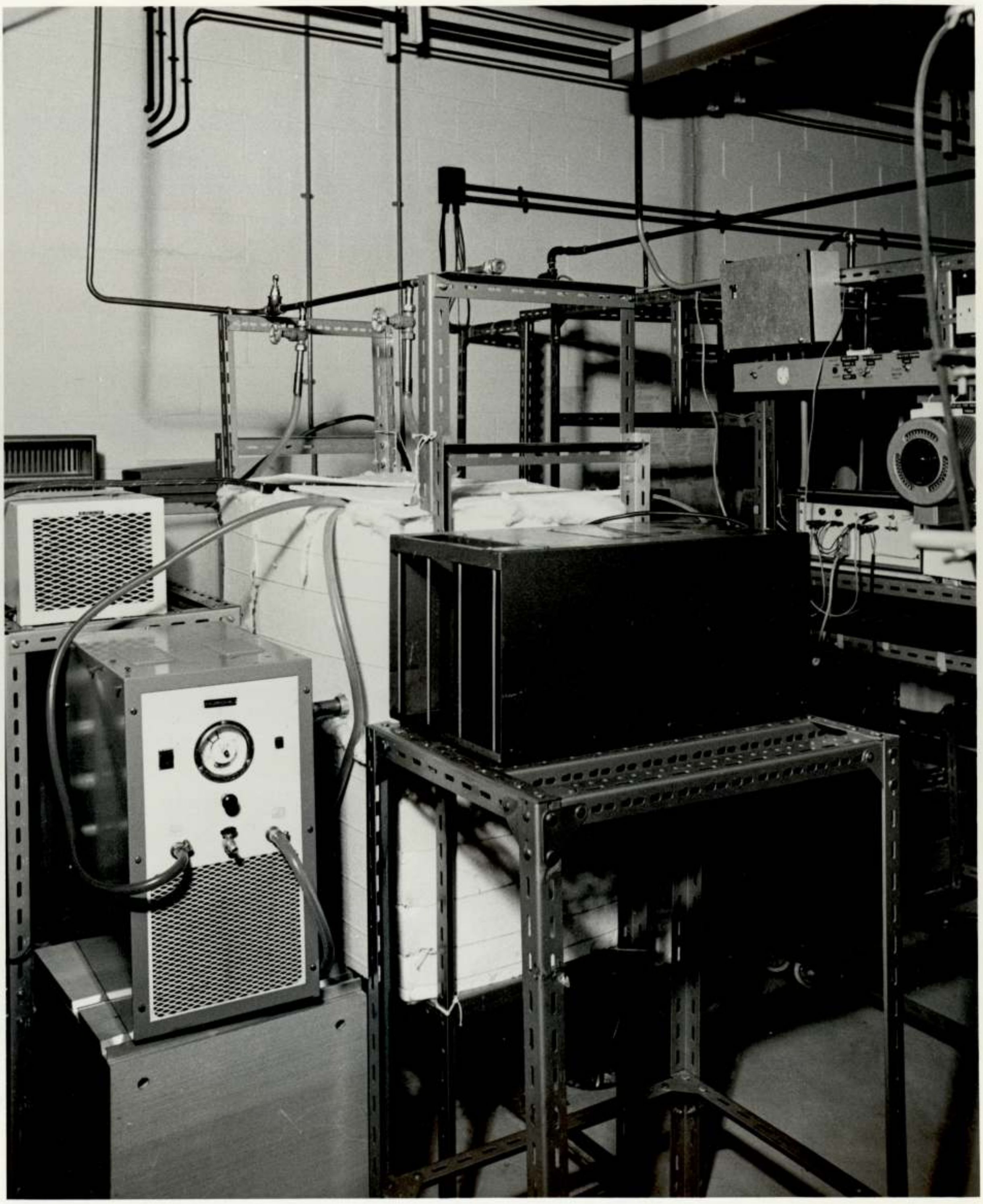
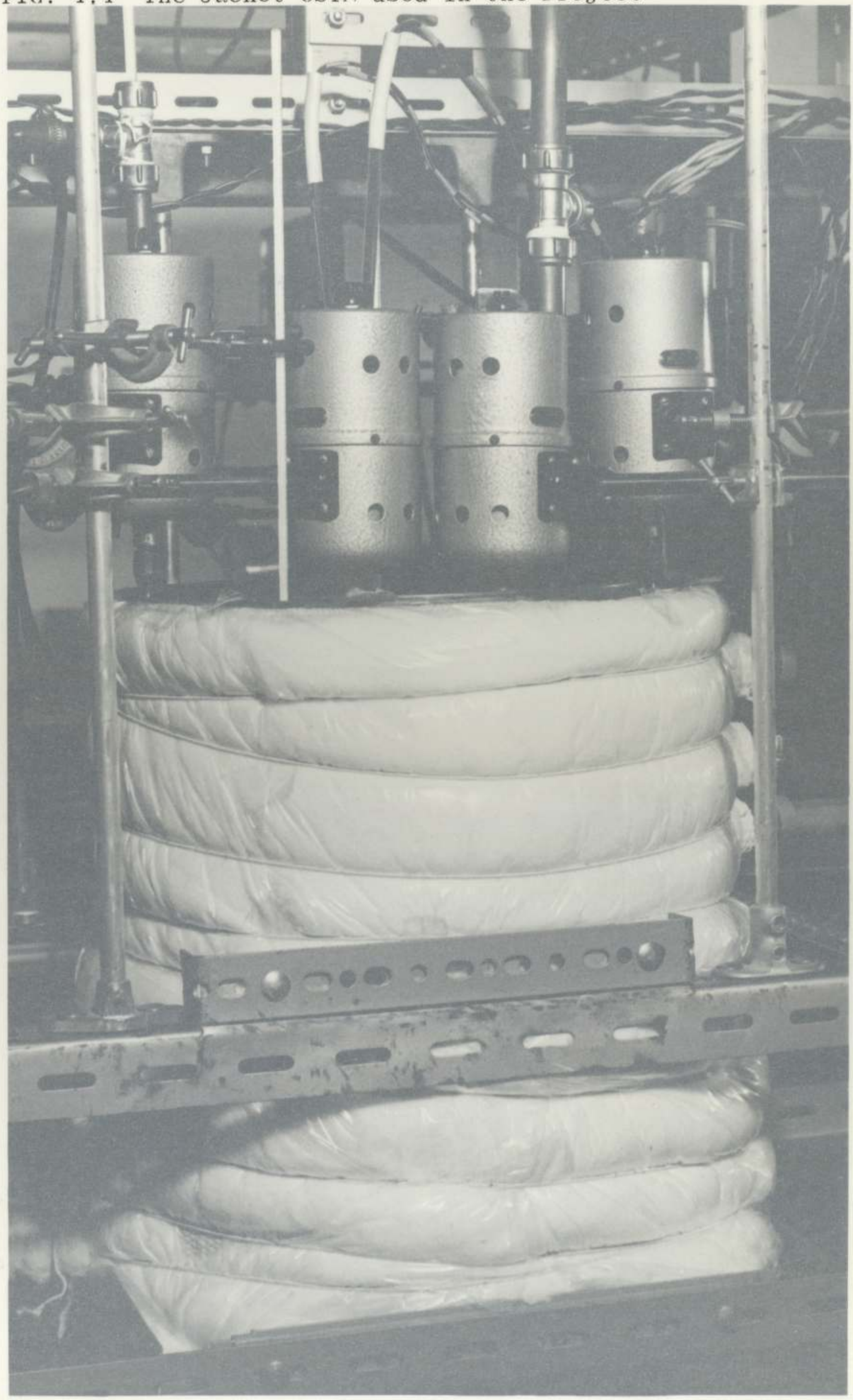
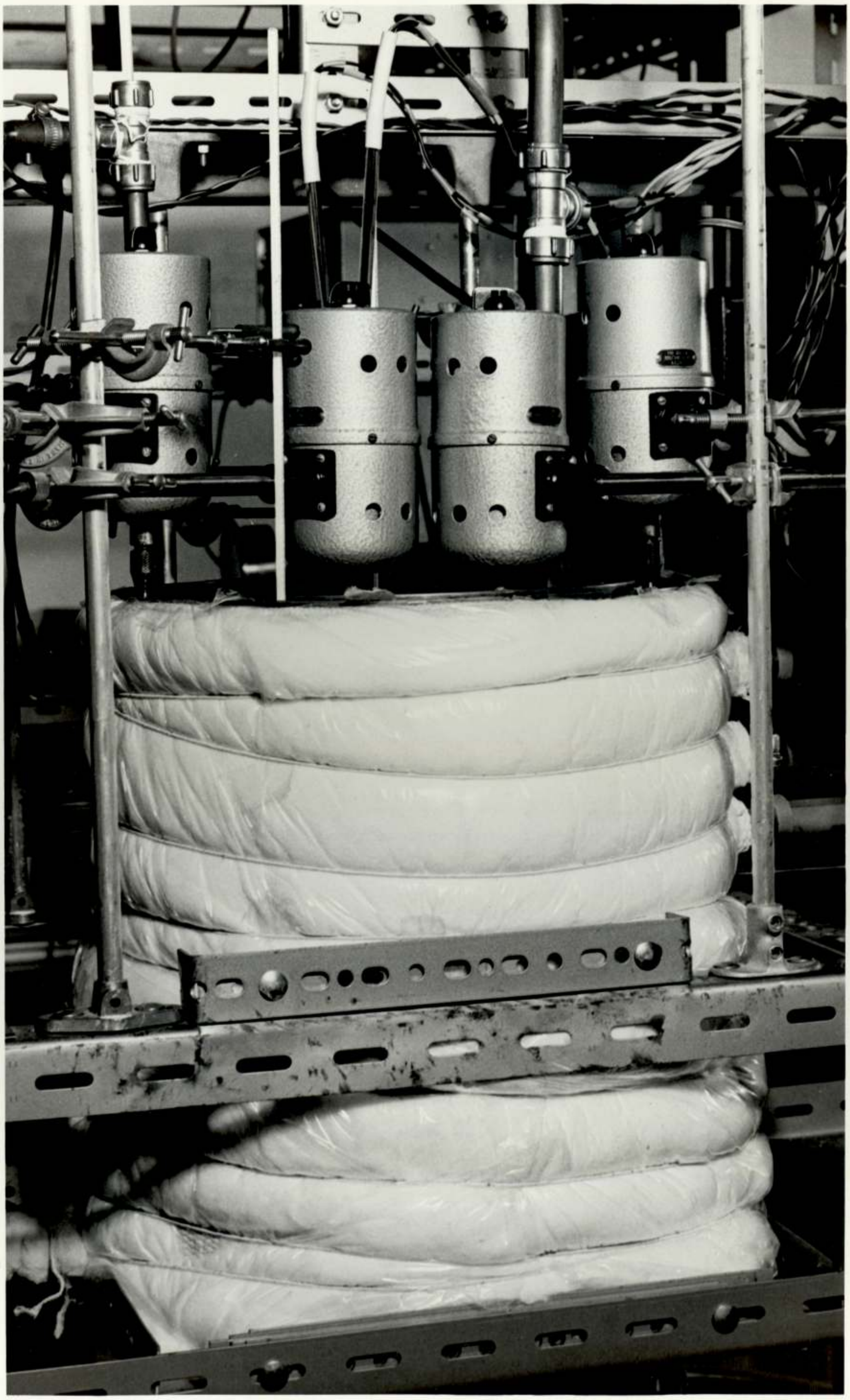


FIG. 4.4 The Jacket CSTR used in the Project





4.2.1 DESIGN OF THE REACTION VESSEL AND ITS COOLING JACKET

It was considered an advantage if the results of this research could be compared with those obtained by Buxton (5), and therefore, the reactor volume was arranged to be as near to his as possible. One difference between the two projects is the cooling system; Buxton used a small diameter cooling coil which therefore had a small residence time and probably plug flow. The present project is very much concerned with the instability problem arising from large time constants and demonstrating the advantages of using a cascade control scheme to avoid instability in their presence. A jacket with a volume approximately half the volume of the reactor in order to have a large residence time/time constant for the plant cooling system.

The schematic diagram of this jacketed reaction vessel and its dimensions is shown in Fig.(4.5). For good heat transfer copper is used for the material of construction. The reactor and the cooling jacket each have two stirrers in order to ensure that they are well-mixed vessels.

4.2.2 DESIGN OF THE FEED SYSTEMS

The feed to the reactor is supplied by combining the outlet flows from two 16 litres tanks. The tanks

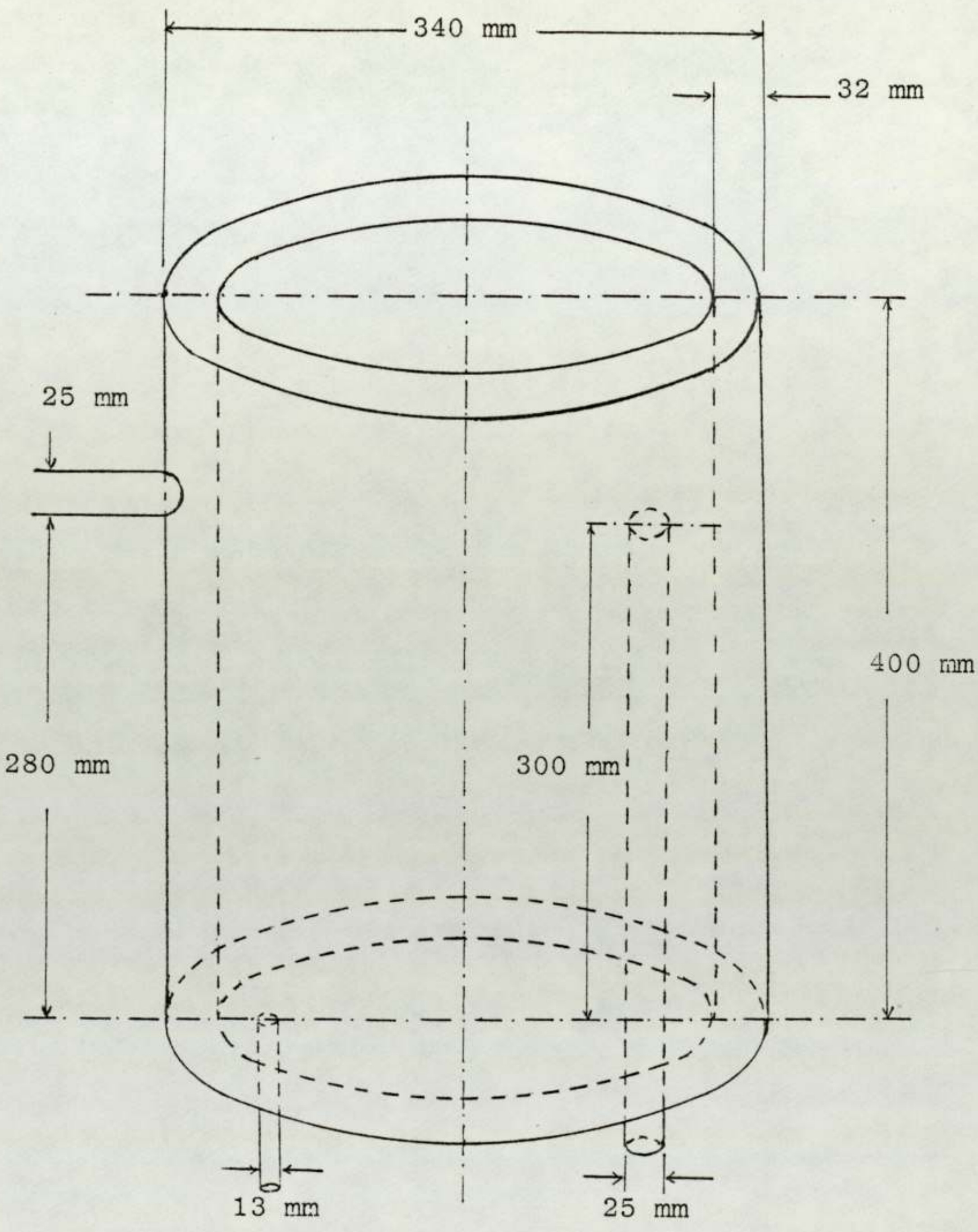


FIG.4.5 The Schematic Diagram of the Jacketed CSTR

are both stirred to produce uniform temperature and each has hot and cold mains water supply and a 3 kW immersion heater. The outlet flows are governed by four solenoid valves so that sudden changes in the reactor inlet flowrate and/or temperature can be made.

The jacket feed system consists of two tanks with a capacity of nearly 250 litres each, with refrigeration to produce a low temperature. The refrigerator coils are controlled by a thermostat and there is one heating element to compensate for any over cooling and maintain the desired temperature. Step changes are made in the inlet temperature of the jacket by two quick action valves between the jacket and its feed tanks.

4.2.3 CONTROL VALVE

A ⅜" (9.53 mm) control valve (Fisher instruments) is used to manipulate the cooling jacket flowrate. This control valve is fitted with a valve positioner to eliminate valve hysteresis. Buxton (5) and Alpaz (1) both used the same control valve and positioner. More detail of the assembly is given by them including a gain

$$K_V = 1.29 \frac{l/min}{lb/in^2} = 0.19 \frac{l/min}{kN/m^2}$$

This value is confirmed and in addition the time delay is found to be five seconds when changing from fully shut to fully open and three seconds for closing.

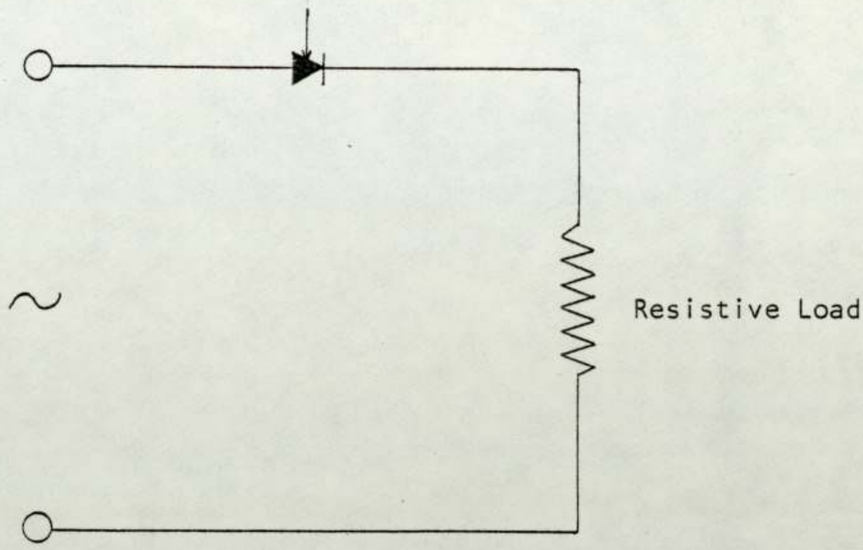
4.2.4 AVAILABLE HEAT OUTPUT

The previous work had used a 9 kW assembly of heating elements as a reasonable maximum to fit inside the reaction vessel and this same limitation is accepted here. The operating conditions of the experiments are selected so that the enthalpy rise of the throughput and the heat extracted by the cooling system are together within this 9 kW limit. Thus three immersion heaters (3 kW each) are installed in the base of the reaction vessel and plugged into the signal conditioning box (4.3.4) through a thyristor to generate any value of heat in the range 0-9 kW. The exothermic reaction heat release by the computer simulation is thus released in the reaction vessel.

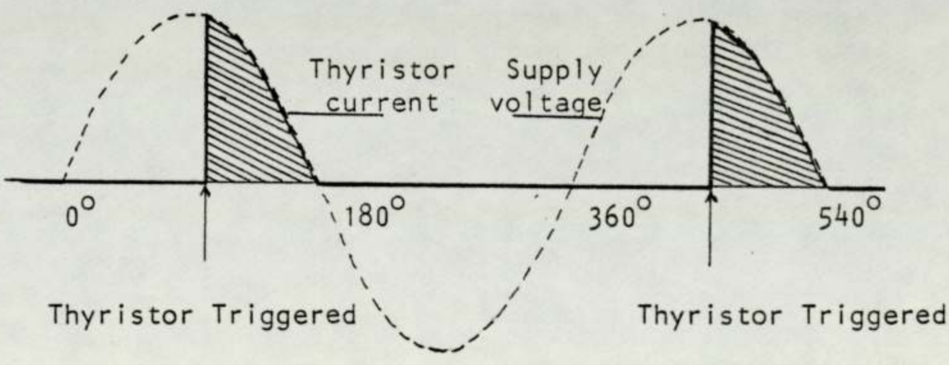
4.2.5 THYRISTOR APPLICATION

The thyristor is a semi-conductor device which operates as a controlled rectifier, i.e. it only allows a load current to flow through in one direction and then only when the thyristor is "triggered". Fig.(4.6.a) shows a thyristor which is connected in series with a resistive load across an A.C. supply. Before the thyristor is triggered no current will flow through the circuit, and when it is triggered, current flows for the remainder of the positive half-cycle of the supply (no current flow during the negative half-cycle). During the following positive half-cycle no current will flow until the thyristor is triggered again Fig.(4.6.a). The switching action of the thyristor from the non-conducting to the conducting state can be used to control the power in a circuit. The system considered here consists of a circuit having two thyristors in an inverse-parallel configuration, and a resistive load (the immersion heaters) in series, Fig.(4.7). At angle α the thyristor th_1 is triggered and applies the instantaneous supply voltage to the load. It will conduct for the remainder of the positive half-cycle, turning off at 180°. Thyristor th_2 is triggered at angle $(180+\alpha)^{\circ}$, and conducts for the same time as th_1 did, turning off at 360° and th_1 is triggered again at $(360+\alpha)^{\circ}$. The sequence is repeated and these current pulses form part of a sine wave where the duration of each pulse is $(180-\alpha)^{\circ}$ Fig.(4.7). Thus by altering the trigger angle α the output power can be controlled. The various values of the thyristor current can be calculated in terms of the supply voltage (V_S) and appropriate load resistance (R_L). Table (4.1) gives the output current, voltage, and power as a function of trigger angle. Curves of these expressions are plotted in Fig.(4.8).

In this particular project the relation between power and trigger angle is used to calibrate the output power. Thus the signal from the thyristor pair governs the heat liberated. Supply voltage is measured and



(a)



(b)

FIG. 4.6 Load Current Waveform Produced by Simple Thyristor Circuit

(a) thyristor circuit with resistive load
(b) waveform showing current flow when thyristor is triggered

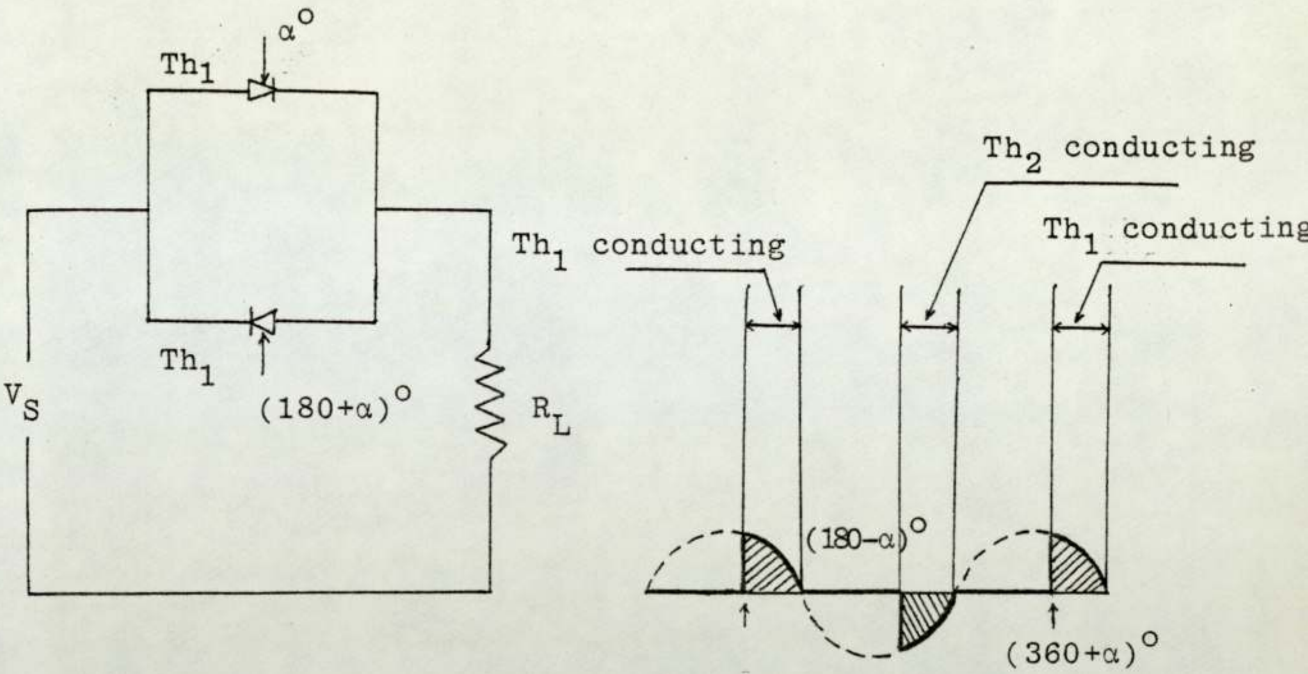
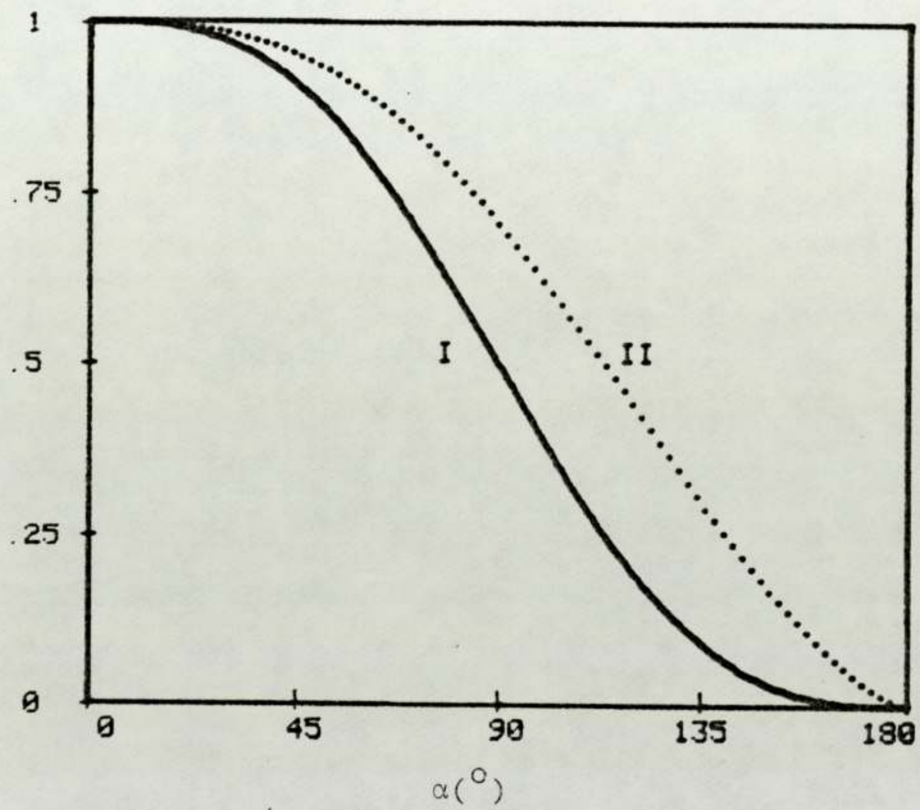


Fig. 4.7 - Circuit and wave forms for inverse-parallel configuration with resistive load

Quantity	Expression
Output Voltage	$V_S\left(\frac{\Pi - \alpha + \frac{1}{2}\text{ Sin } 2\alpha}{\Pi}\right)^{\frac{1}{2}}$
Output Current	$\frac{V_S}{R_L}\left(\frac{\Pi - \alpha + \frac{1}{2}\text{ Sin } 2\alpha}{\Pi}\right)^{\frac{1}{2}}$
Output Power	$\frac{V_S^2}{\Pi R_L}(\Pi - \alpha + \frac{1}{2}\text{ Sin } 2\alpha)$

Table 4.1 - Output voltage current and power versus trigger angle for inverse-parallel configuration with resistive load



Curve I $= \frac{\Pi - \alpha + \frac{1}{2}\,\mathrm{Sin}\,2\alpha}{\Pi}$

Curve II $= \left(\frac{\Pi - \alpha + \frac{1}{2}\,\mathrm{Sin}\,2\alpha}{\Pi}\right)^{\frac{1}{2}}$

FIG. 4.8 Universal Analysis Charts for Inverse-Parallel Configuration with Resistive Load observed to vary over a range of 244-249 V, and therefore an average of 246.5 V is used in calculations. The heating element resistances are not exactly equal and in calculation an average resistance of 18.667 Ω is used.

4.2.6 TEMPERATURE MONITORING INSTRUMENTS

For the temperature range (0 to 100°C), four Comark electronic thermometers are used to amplify the 0-4 mV signal from Al/Cr thermocouples to the range of 0-1 V. The minimum voltage change (ΔV) which can be transmitted to HADIOS (4.3.3) is 5 mV which gives a sensitivity of 0.5 deg C in the actual temperatures. This increment can be as much as half the size of a measured disturbance and is hence not sufficiently sensitive. In order to reduce this error, analogue amplifiers, with a gain of 10, are added to the two important temperature measurements. Hence the error is reduced tenfold (i.e. giving a sensitivity of 0.05 deg C) and also the voltage produced is increased in the same ratio (0-10 V for a temperature range of 0-100°C). In fact in order not to exceed the voltage acceptable to the HADIOS (0 to 5 V) the temperatures range used for the tests is limited to 0-50°C.

4.2.7 INITIAL FLOWRATE MONITORING DEVICE

An instrument was already available, for monitoring the flowrate and consists of a pressure difference device mounted in a flange assembly, which generates a pressure drop having a square root relationship with the flowrate; this connects to an electrical manometer and the produced currents are converted by a transducer to voltage (0-5 V). More details of this instrument are given in the manufacturer's manual (Elliot Process Automation Ltd).

The main problem with this device is its time lag of nearly 15 seconds. Other problems are calibrating the transducer, inaccuracy, and its size for satisfactory maintenance. An alternative was therefore selected and installed.

4.2.8 FINAL FLOWRATE MONITORING INSTRUMENT

The turbine flow meter chosen is a velocity measuring device and its operation is based upon the speed (angular velocity) of a freely supported rotor which revolves at a rate directly proportional to the flowrate of the medium. A pulse is induced in the coil of the pick-up unit, in the flow meter body, as each rotor blade cuts the magnetic field set up by a magnet installed in the pick-up. These pulses are thus generated as a number precisely proportional to each unit volume of the flow, and are amplified and squared

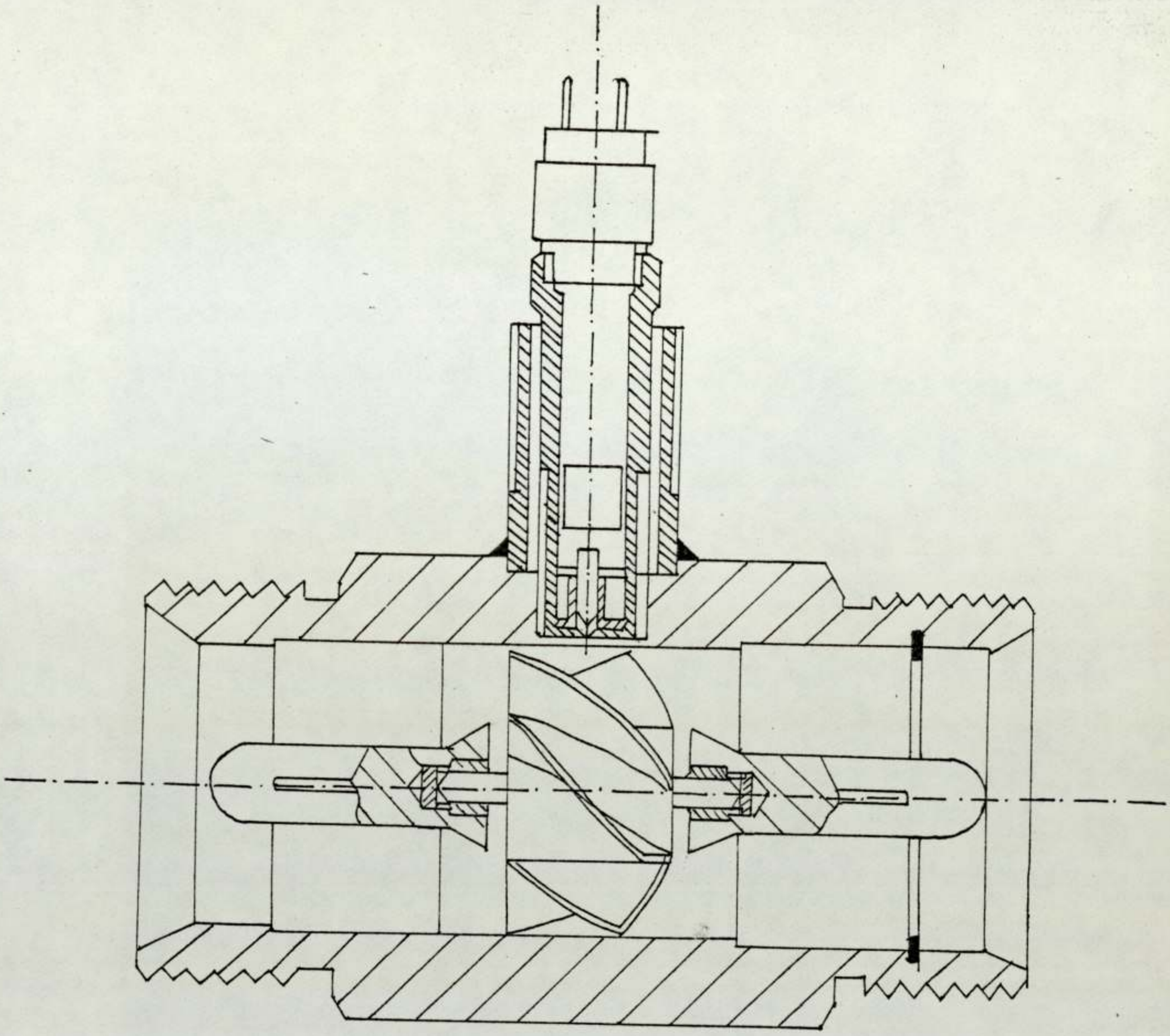


FIG.4.9 Schematic Diagram of the Turbine Flowmeter

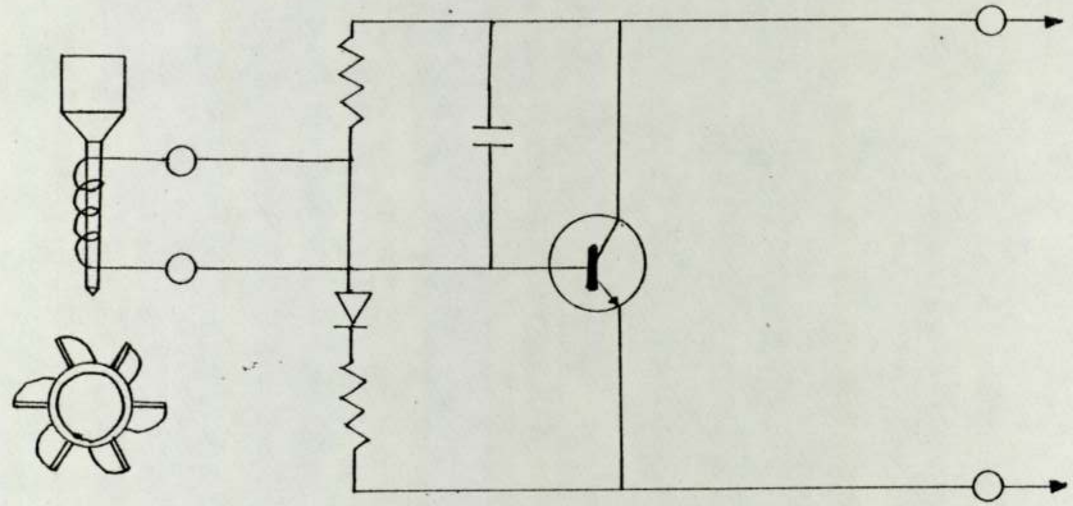


FIG.4.10 The Magnet, the Coil and the Electrical Circuit of the Turbine Flowmeter

through an electrical circuit and fed to the counter subinterface of the HADIOS (4.3.3). Fig.(4.9) shows the diagram of the turbine flow meter and Fig.(4.10) the magnet, the coil, and the electrical circuit.

4.2.9 PRESSURE MONITORING INSTRUMENT

One of the analogue signals received from the computer varies the input pressure of the control valve. This is achieved by a series of two convertors, one voltage to current (VIC) and the other current to pressure (IPC). Table (4.2) gives the important particulars of these convertors.

4.3 THE HONEYWELL-316/HADIOS DATA ACQUISITION SYSTEM

The data acquisition and processing system used consists of the following units:

- (i) Honeywell-316 Digital Computer and associated peripherals
- (ii) A Honeywell Analogue Digital Input/Output System (HADIOS)
- (iii) Remote Signal Conditioning Box

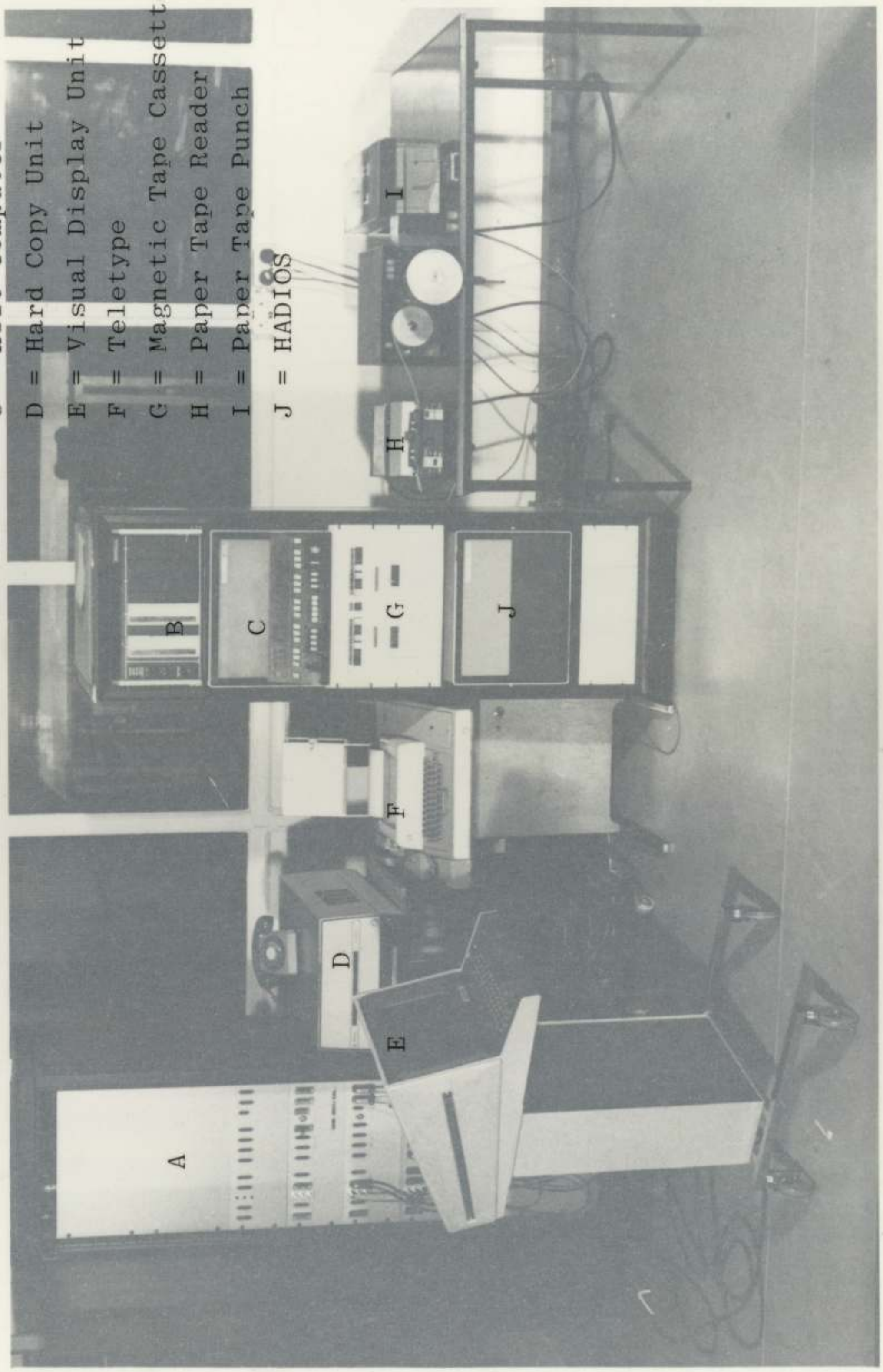
4.3.1 THE HONEYWELL-316 DIGITAL COMPUTER

Based upon the standard Honeywell publication (27) the Honeywell units used in this work are discussed

CONVERTOR	VOLTAGE TO CURRENT VIC	CURRENT TO PRESSURE IPC
Manufacturer	Lee-Dickens Ltd.	Honeywell Ltd.
Supply	200/250 V 50 HZ	20 psi
Input	0-10 V	4-20mA DC
Output	4-20mA DC	3-15 psi

TABLE 4.2 Important Particulars of the VIC and IPC Convertors

FIG. 4.11 H-316 Computer, HADIOS and Peripheral Devices



KEY

A = Control Box

B = Floppy Disc Unit

C = H316 Computer

D = Hard Copy Unit

E = Visual Display Unit

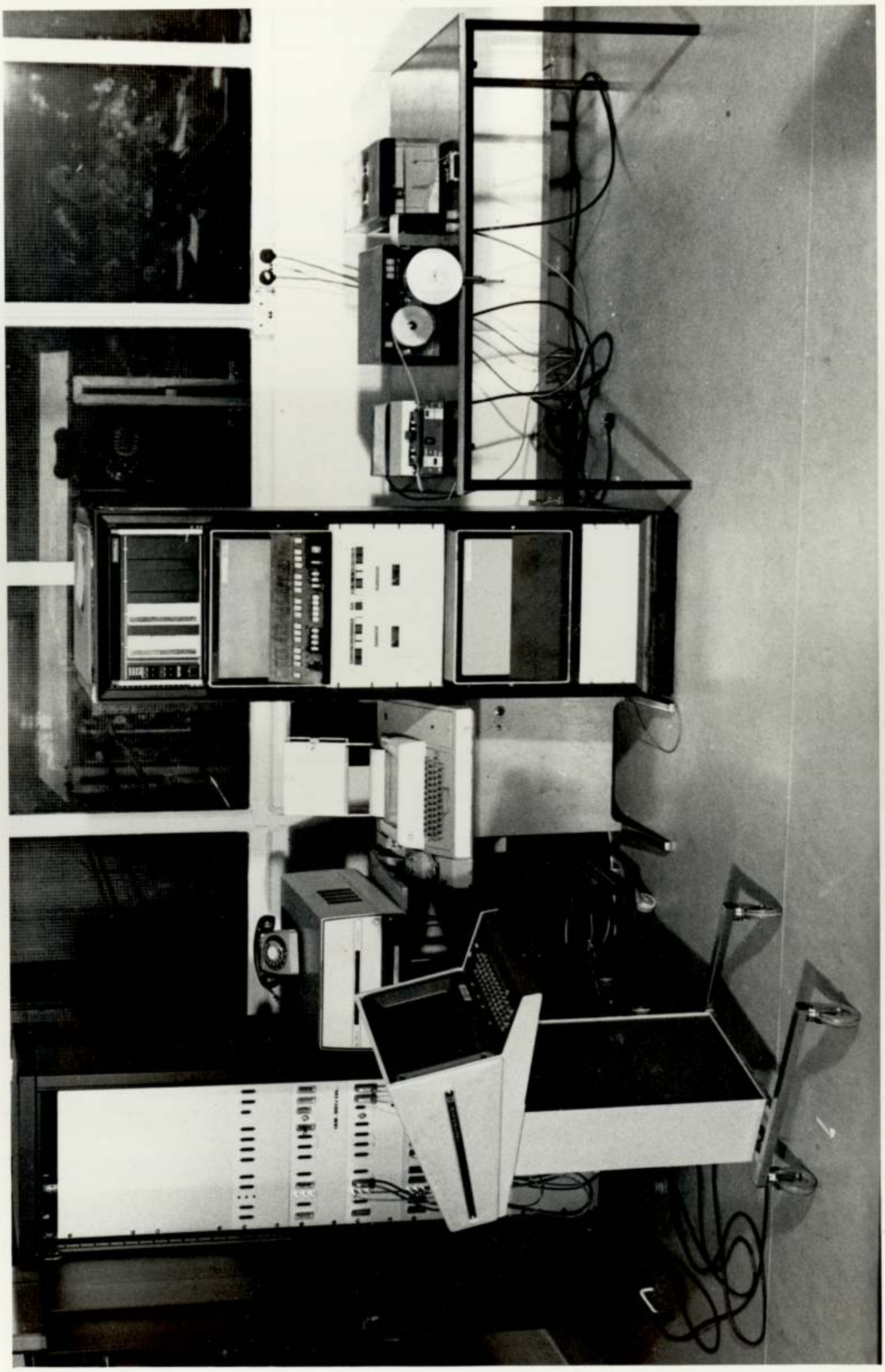
F = Teletype

G = Magnetic Tape Cassette Unit

H = Paper Tape Reader

I = Paper Tape Punch

J = HADIOS



below.

The stated objectives of the Honeywell-316 Computer are batch scientific applications and real time, on-line data processing and control. Batch scientific computation, simulation and data acquisition are therefore some of the many applications used on the Honeywell-316 computer. The Honeywell-316 computer is a stored program, parallel binary type using two's complement machine code. Source program languages available are BASIC-16 and FORTRAN, and for translation of the source program to machine code DAP-16 symbolic assembly program language is used. Seventy two commands, a memory cycle time of 1.6 s input/output data handling at a maximum word rate of 156 kHz/s, a real time clock, high speed multiply/divide and a single interrupt line are some of the Honeywell-316 characteristics. The computer used has a 16-bit coincident-current ferrite core memory which includes a single 10-bit address and 5 octal digits plus sign bit (i.e. indexing and indirect addressing). Some leading particulars of the Honeywell-316 computer are given in (27).

4.3.2 PERIPHERAL EQUIPMENT

The peripheral devices used in the present project are

(i) A Tektronic 4010-1 Visual Display Unit (VDU) which is capable of both graphical and character display and in the alphanumeric output mode operates at a rate of 200 band.

(ii) A Teletype (TTY) operating at 10 characters per second.

(iii) A high speed paper tape reader operating at 200 characters per second.

(iv) A high speed paper tape punch operating at 75 characters per second.

(v) A magnetic tape cassette unit, used both for input and output at 375 bytes per second.

(vi) A Hard Copy Unit (HCU) which produces permanent copies of the display when required. The HCU is attached to the VDU and can be operated both by a switch situated on the VDU or by programmed command.

These peripheral devices are connected to the I/O bus of the central processor. The Teletype, Visual Display Unit and Hard Copy Unit can be used both in the computer laboratory and adjacent to the plant.

4.3.3 THE HONEYWELL ANALOGUE DIGITAL INPUT/OUTPUT SYSTEM (HADIOS)

HADIOS is used in on-line applications and provides a flexible method of interfacing the Honeywell-316 computer to a wide range of input/output devices. HADIOS is a controller which addresses and controls up to fifteen subinterfaces, and is connected to the computer input/output data and control lines, which generate subsidiary data; the subinterfaces can be analogue or digital and input or output. The standard subinterfaces included in the HADIOS system used in this research are the following:

(i) High Level Analogue Inputs

This subinterface provides a maximum of thirty two separate analogue signals (0 to 5 V), being converted to a binary integer with ten bit resolution, i.e. 0 to 1023_{10}. The high level analogue inputs subinterface consists of a channel analogue to digital convertor (ADC) with a maximum conversion rate of 40 kHz, connected to two sixteen channel multiplexer subinterfaces.

(ii) High Speed Counter Input

The counter input subinterface monitors the number of changes of level of a discrete input, incremented by a positive voltage pulse from logic '0' to logic '1'. The current contents of the counter can be obtained by a programmable command.

The counter input subinterface consists of an eight bit register with a range of 0 to 255_{10} (0 to 377_8). In the non-interrupt mode, after 255_{10} pulses have been counted, the register automatically returns to zero, whereas in the interrupt mode an interrupt of the central processor is generated when the eight bit register is half-full, containing 127_{10}.

(iii) Digital Output

The sub-interface consists of sixteen parallel output lines. Until the next word is output the previous value remains. The real value of the variable (in the range of -32768_{10} to 32768_{10}) can be stored by a BASIC program and converted to its binary equivalent (one sign bit plus fifteen magnitude bits) or sixteen elements of an array having values 1 or 0, stored by BASIC program converted to the corresponding sixteen bit pattern and output. There are also other cases requiring special software, e.g. converting the digital output to an analogue signal. Two analogue outputs are needed in this research and therefore, a special unit is constructed and added to HADIOS; this consists of a digital to analogue convertor (DAC) which uses twelve of the sixteen bits of the digital output while the other four are used to build a control code to select different analogue channels. By adding a multiplexer sixteen different analogue channels (0-15) can be provided. The analogue output range is 0-10 V corresponding to a digital range of $0\text{-}32767_{10}$ transmitted from the computer.

The subinterfaces can operate when the control signals, initiated by programmable command, from the computer to the HADIOS is being output. The majority of addresses and function decoding are carried out before initiating the required function of the requested subinterface. By the interrupt mask circuits of the HADIOS controller, set by the execution of programmable commands, the system can operate under interrupt control.

Details of other facilities and address line connections between the controller and subinterface, and also details of the programmable instructions used to operate HADIOS are given in (48).

In this particular research five analogue input channels are used to record the output of four thermocouples and one transducer, while for recording the pulsed output of the turbine flow meter the counter input subinterface is used. The digital output was converted to analogue signals and sent through the selected channel to operate either the thyristor or the control valve.

4.3.4 REMOTE SIGNAL CONDITIONING BOX

The remote signal conditioning box contains all the equipment necessary

(i) to condition the signals from the measuring instruments in a form acceptable to HADIOS

(ii) to control and select the analogue output channels (converted digital signals).

The signal conditioning box was constructed and situated adjacent to the plant both for convenience and also to minimise the effects of electrical noise during the transmission of the signals to the computer room.

CHAPTER 5

COMPUTER ASPECTS OF THE RESEARCH

5.1 INTRODUCTION

As discussed in Chapter 4 the system is partially simulated on the Honeywell-316 digital computer. Some computer processing is therefore needed to prepare the measurements for the solution of the differential equation simulating the mass balance.

Controllers are also simulated and therefore to generate integral and derivative actions numerical integration and differentiation routines are required; both were developed and tested but only the integral action applied to the test results.

Prior to the transmission of the output signals the type of output from the HADIOS, conversion factors, extraction of values from data, time and order of transmission and selection of the appropriate channel for the analogue output signal all have to be considered. At the same time experimental results may be output in graphical and/or numerical form.

All of the above aspects have to be studied and their interactions put into suitable programs. Except for the transmission of signals all of these aspects are also involved in the total simulation study of the system. The software packages and BASIC-16 programs used in this project are shown with their flowcharts and programs in Appendices (A.4) and (A.5). The relevant parts of the important packages and BASIC programs are explained below:

5.2 THE ASTON SIMULATION PACKAGE - ASP

ASP was developed by Gay and Payne (19) for the purpose of interactive simulation on a digital computer. First order ordinary differential equations can be simulated and solved by either the Runge-Kutta or the modified Euler method. Higher order ordinary differential equations can be re-arranged as an equivalent set of simultaneous first order differential equations.

ASP consists of a BASIC-16 interpreter and the four following FORTRAN subroutines which can handle numerical integration and are addressed from the BASIC program.

(i) Subroutine to initialise the COMMON area of the FORTRAN subroutines and set the independent variable to zero.

(ii) Subroutine to control output and signal the end of simulation.

(iii) Subroutine to integrate the independent variable.

(iv) Subroutine to integrate the dependent variable.

Simulation is carried out by a BASIC program as in the following sections.

(a) Initialisation - In this section the independent variable is set to zero and all the necessary data and the initial value of the independent variable are input.

(b) Derivative - the coefficients of the equivalent set of first order ordinary differential equations are defined in this section.

(c) Output - This is a decision making section to find whether the output is due or if the simulation is terminated.

(d) Integration - Each step of the independent and dependent variables are integrated in this section and the results returned to the derivative section.

5.3 HADIOS EXECUTIVE PACKAGE MK2

The purpose of using HADIOS and its different subinterfaces is discussed in Chapter 4 whereas here the package which links the computer and HADIOS is being discussed.

HADIOS EXECUTIVE MK2 consists of the HADIOS EXECUTIVE PROGRAM Revision 01 and BASIC interpreter. The program is written in BASIC CALL statements to communicate with the HADIOS equipment. The following functions can be peformed by the HADIOS EXECUTIVE PROGRAM.

(i) Regular access, at the required frequency, to the HADIOS by a CALL statement in the

BASIC program.

(ii) Scanning of the HADIOS devices required by BASIC program.

(iii) Handling of all computer interrupts.

(iv) Providing an idling loop to wait for the next scan.

(v) Terminating the execution of the program.

(vi) Checking the error condition

Details of the 'CALLS' from a BASIC program are given in Appendix (A.1).

5.4 EXTENDED BASIC GRAPHICS PACKAGE

The Tektronics 4010-1 VDU is capable of providing graphical display. A set of FORTRAN subroutines are therefore provided by the manufacturers (44) for this capability.

The EXTENDED BASIC GRAPHICS package is based upon the BASIC-16 interpreter and nine FORTRAN subroutines which provide the full facilities of the Tektronics 4010-1 VDU. Full details of this package and its facilities are given in the manufacturer's manual (44) and the details of the facilities available to the BASIC program in (46).

5.5 BASIC ASTON SIMULATION PROGRAM - BASP

In the partial simulation computer program three FORTRAN subroutines are addressed for HADIOS and seven for the reduced application of EXTENDED BASIC GRAPHICS. The maximum number of CALLS available is ten and therefore there is no room for ASP subroutines. Instead BASP which is the BASIC version of ASP and using the same principles (5.2) has been written and added to the BASIC program.

5.6 INTEGRATION AND DIFFERENTIATION OF THE ERROR

The value of the error signal to the simulated controller must be integrated for the integral action component of the correcting signal to the valve and differentiated for the derivative action, if required. The differential value of the error in total simulation is obtained from the differential equation gained by the transient energy balances. For integral action, the error is integrated by ASP (5.2) or BASP (5.5). In partial simulation the energy balances are represented by the real plant, and therefore numerical integration and differentiation are used.

5.6.1 NUMERICAL INTEGRATION

The error (e) is integrated through a set of values of dependent variable relevant to the independent variable values (T) with equal interval (H). When only two points are available the trapezoidal rule is applied, when three points Simpson's rule and when four or more points Simpson's

$\frac{3}{8}$ rule. Thus

$$\int_{T_2}^{T_1} e\,dT = \frac{H}{2}(e_2 + e_1)$$ Trapezoidal Rule (5.1)

$$\int_{T_1}^{T_3} e\,dT = \frac{H}{3}(e_3 + 4e_2 + e_1)$$ Simpson's Rule (5.2)

$$\int_{T_{n-3}}^{T_n} e\,dT = \frac{3H}{8}(e_n + 3e_{n-1} + 3e_{n-2} + e_{n-3}) \quad n \geq 4$$ Simpson's $\frac{3}{8}$ Rule (5.3)

where n is number of available points.

5.6.2 NUMERICAL DIFFERENTIATION

For differentiation of the error the same principles are applied as numerical integration. Therefore after simplification

$$\frac{de_2}{dT} = \frac{1}{H}(e_2 - e_1) \qquad n = 2 \quad (5.4)$$

$$\frac{de_3}{dT} = \frac{1}{2H}(3e_3 - 4e_2 + e_1) \qquad n = 3 \quad (5.5)$$

$$\frac{de_n}{dT} = \frac{1}{6H}(11e_n - 18e_{n-1} + 9e_{n-2} - 2e_{n-3}) \quad n \geq 4 \qquad (5.6)$$

The procedures for obtaining Equations (5.1) to (5.6) are given in (8,31) and the computer programs of the integration and differentiation of error are shown in Appendix (A.5).

5.7 INTERPOLATION OF THE VARIABLES

When there is no specific function to be applied to obtain the required value of a variable, and only a set of data is available, a numerical interpolation can be used. By interpolation the value of the dependent variable can be obtained for any value of the independent variable within the given range of data. Details of different methods of interpolation and the procedures of obtaining their formulae are given in (8,31).

In this particular project Gauss's forward formula is applied to interpolate i) trigger angle for any value of power ii) voltage for any value of jacket flowrate. Thus if the value of the dependent variable, relevant to the nearest value of the independent value of the set (x_n) to the given value (x), is y_n, the required value of dependentvariable (ϕ) is

$$\phi = y_n + \alpha\delta y_{n+\frac{1}{2}} + \frac{\alpha(\alpha+1)}{2!}\delta^2 y_n + \frac{(\alpha+1)\alpha(\alpha-1)}{3!}\delta^3 y_{n+\frac{1}{2}} + \ldots\ldots \quad (5.7)$$

where

$$\alpha = \frac{x - x_n}{H}$$

H is the interval between the independent variable data in the set

$$\delta y_{n+\frac{1}{2}} = y_{n+1} - y_n$$

$$\delta y_{n-\frac{1}{2}} = y_n - y_{n-1}$$

$$\delta^2 y_n = \delta y_{n+\frac{1}{2}} - \delta y_{n-\frac{1}{2}}$$

....

....

After simplification and truncation

$$\phi = y_n + \alpha(y_{n+1}-y_n) + \frac{\alpha(\alpha-1)}{2} (y_{n+1}-2y_n+y_{n-1}) \qquad (5.8)$$

The computer programs of the interpolation of the variables are given in Appendix (A.5).

CHAPTER 6

PARTIAL SIMULATION STUDIES

This research is concerned with the study of two different control schemes and their comparison with each other. The reactor exit temperature is the control variable.

The variable which gives interaction between the mass and energy balances of the system is rate of reaction. Therefore the reactor temperature signal is transmitted to the computer to calculate the reaction rate constant and hence the concentration of the reactant, the reaction rate, and finally the reaction heat generation which is then transmitted via a thyristor to the three immersion heaters of the reaction vessel. Control action is also simulated on the computer and the control signal is transmitted from the computer to the real (actual) control valve to regulate the jacket flowrate.

This chapter covers the methods used to simulate the mass balance and the controllers. The necessary assumptions, limitations of equipment calibrations, and all the scaling required for the transmitted signals are considered.

6.1 SIMULATION OF THE MASS BALANCE

The reactor is assumed to be well-mixed with a constant hold-up. Therefore from section (3.4.2) its transient mass balance is

$$\frac{dC_2}{dt} = \frac{u}{V}(C_o - C_2) - r \qquad (6.1)$$

where

$r = k(T_2)C_2$ and T_2 is the currently transmitted value of the reactor temperature.

This differential equation is then simulated on the Honeywell-316 digital computer and solved numerically by the ASP package or the BASP program (Section 5) with the initial conditions obtained from the steady-state mass and energy balances of the reactor (3.3.4). The programs and flowcharts of the calculations are given in Appendices (A.5) and (A.4) respectively.

6.2 SIMULATION OF THE CONTROLLERS

The control action selected for the primary loop is proportional plus integral and assumed to be ideal i.e. each action is generated independently of the other. Thus d the corrective signal is given by

$$d = K_C(e + \frac{1}{T_R}\int_o^t edt)$$

where the error signal $e = (T_2 - T_{set})$
Hence for the single-loop control system the jacket flowrate is corrected by the value $(K_V d)$ where K_V is the valve gain.

For cascade control the corrective signal of the primary controller adjusts the set-point of the secondary controller. For the secondary control loop, proportional action only with a gain of K_C' is used without integral action (Chapter 2). Therefore the jacket flowrate is corrected by $(K_V d')$ in which $d' = K_C' e$ is the corrective signal from the secondary controller and $e' = (T_1 - T_{set} + d)$ is the error signal into the secondary controller.

Proportional gains (K_C and K_C') and reset-time (T_R) are set at their optimum values defined by Ziegler, J.G. and Nichols, N.B. (54-56). Hence the reaction curve method for the primary controller and the continuous-cycling method for the secondary controller (23) are used. These settings, without constraints are used in the total simulation to predict the results (8.1). New settings are obtained when the system limitations such as coolant flowrate, heat generation and pure time delays are considered (8.2,8.3).

6.3 SIMULATION TIME

Simulation time depends on the step length of the integration of the differential equations and the integration of the error signal. The step length is chosen to be the same as the HADIOS interrupt frequency which itself depends on the time delays involved in the system.

6.4 TIME DELAYS

The major time delays contributing to the overall time delay are from

6.4.1 CONTROL VALVE (Section 4)

A demanded change in jacket flowrate during an interrupt is unlikely to cover the whole control valve range. Therefore the maximum probable valve delay in each interrupt is assumed to be 2-3 seconds.

6.4.2 TRANSMISSION OF THE COUNTER INPUT SIGNAL

For each interrupt the counter subinterface needs at least two seconds to count the pulses produced by the flowmeter. Therefore a delay of two seconds must be considered when the counter is used.

6.4.3 COMPUTER

The calculation of the functions, integrations, differentiations and interpolations in the simulation part plus the transmission of the analogue input and digital output signals and also the requirement of outputting the data are all time consuming. A total of four seconds is needed for each interrupt cycle to implement this set of operations which is in excess of the time delay of the control valve.

6.5 INTERRUPT FREQUENCY

The interrupt frequency is defined as the time which the computer is interrupted for the required signals to be transmitted and is equal to the time delays produced by the computer together with the counter subinterface. Therefore the interrupt frequency in this research is six seconds if the counter is used and four seconds if the counter signal is not transmitted.

6.6 LIMITATIONS OF THE EQUIPMENT

The control valve used to regulate the jacket flowrate is capable of altering the flowrate in the range of 0 to 9.75 l/min. Because the heat transfer coefficient has a large deviation from its constant value at low values of jacket flowrate (7.3.2) the available flow is limited to 0.5 to 9.75 l/min.

The heat generation is limited to 9 kW which is the maximum heat produced by the immersion heaters (4.2.4).

These limits are implemented in the simulation part of the system.

6.7 SCALING OF THE VARIABLES

Analogue input, digital output, and counter input signals must be scaled to the ranges available within HADIOS. The procedure of scaling each variable is as follows.

6.7.1 TEMPERATURES AS ANALOGUE INPUTS

The analogue input with a range of 0 to 5 V is converted by an analogue to digital convertor in the equivalent range of 0 to 1023_{10} for temperatures in the range of 0 to 100°C (4.2.6) the scaling factor is $\frac{5\text{x}100}{1023}$ f where f is the correction factor and is calculated from the relationship of the expected and real values. The amplifiers used for the inlet feed temperatures of the reactor and jacket have a correction factor of $f = \frac{4.78}{5.00}$ and the correction factor for the amplification of the temperatures of the reactor and jacket is $f = \frac{4.85}{5\text{x}10}$.

6.7.2 JACKET FLOWRATE AND HEAT GENERATION

The digital output having a range of 0 to 32767_{10} is converted to an analogue signal with a range of 0 to 10 V and transmitted via one of the two available channels (4.3.3).

The jacket flowrate is calibrated in terms of voltage and scaled to the range 0 to 32767_{10}. The calculated heat generation value is transmitted to the thyristor as the trigger angle (4.2.5) in the range of 0 to 180^{o} and is scaled to the range 0 to 32767_{10}.

6.7.3 REACTOR THROUGHPUT

Flowmeter pulses are counted by the eight bit register of the counter interface (4.3.3), therefore, the time between the present value being output at a clock interrupt and the first half-full counter interrupt is input and scaled to a range of 0 to 127_{10} of the eight bit register. A calibration was prepared for reactor throughput versus number of pulses.

6.8 CALIBRATION OF THE VARIABLES

The variables which must be calibrated are

6.8.1 HEAT OUTPUT OF THE IMMERSION HEATERS VERSUS TRIGGER ANGLE

From Table 4.1 the relation between the heat output and the trigger angle is

$$Q = \frac{V_S^2}{\Pi R_L} (\Pi - \alpha + \tfrac{1}{2} \text{Sin } 2\alpha)$$

which gives a trigger angle of 0^{o} for 3 kW and 180^{o}

for no heat. After some modification the following relationship is obtained for the trigger angle of 0 to 180^{o} for power of 0 to 3 kW

$$Q = \frac{V_S^2}{\Pi R_L} (\alpha' - \tfrac{1}{2} \sin 2\alpha')$$

where

$$\alpha' = 180 - \alpha$$

The Newton-Raphson method is applied to obtain values of trigger angle for values of power with equal interval. These values are tabulated and plotted in Appendix (A.5). From these tabulated values the trigger angle, for any other value of power, can be obtained by interpolation methods. Computer programs of this calibration and interpolation are shown in Appendix (A.2).

6.8.2 JACKET FLOWRATE VERSUS ANALOGUE OUTPUT VOLTAGE

The values of jacket flowrate obtained for each specific voltage are tabulated and plotted in Appendix (A.2). The values of jacket flowrate with equal intervals were used to calculate relevant voltages by inverse interpolation. These values are also tabulated and plotted in Appendix (A.5). Therefore the voltage equivalent to any jacket flowrate can be obtained by interpolation methods.

6.8.3 REACTOR THROUGHPUT VERSUS NUMBER OF PULSES

Different values of the reactor flowrate are set on a rotameter and the corresponding number of pulses, registered by the counter subinterface via the flowmeter, are recorded. The change of the flowrate (u) vs. number of pulses (Np) is almost linear. (Table A.2.4 and Fig.A.2.4). Thus

$$u = mNp + c \qquad (6.3)$$

Coefficients m and c are found by application of the least squares principle as

$$m = \frac{\sum_{i=1}^{n} Np_i u_i - \frac{1}{n}\left(\sum_{i=1}^{n} Np_i \sum_{i=1}^{n} u_i\right)}{\sum_{i=1}^{n} Np_i^2 - \frac{1}{n}\left(\sum_{i=1}^{n} Np_i\right)^2} \qquad (6.4)$$

and

$$c = \bar{u} - m\overline{Np}$$

where

$$\bar{u} = \frac{1}{n}\sum_{i=1}^{n} u_i \quad \text{and} \quad \overline{Np} = \frac{1}{n}\sum_{i=1}^{n} Np_i$$

The computer program of this calculation is given in Appendix (A.5). These coefficients of the linear equation, for this particular research, are constant at m = 0.035 and c = 0.183.

6.9 DELAY IN THE TRANSIENT RESPONSE

The distance between the solenoid valves and the reactor gives a time lag of 20 seconds for a reactor flowrate of 3 l/min. Also there is a time lag of 110 seconds for the jacket flowrate of 1 l/min caused by the distance between the jacket and its feedtanks. These delays are considered in the start of each run i.e. a computer program is written to keep the computer idle for a time equal to the time lag after the change of the system (e.g. stepchanges in jacket inlet or tank inlet temperatures) for the transient response. The computer program is given in Appendix (A.5).

CHAPTER 7

SIMULATION STUDIES OF THE SYSTEMS

7.1 INTRODUCTION

Theoretical studies of the systems are developed in Chapter 3 where the derived overall transfer function has to be inverted to obtain the response equation. Inaccuracy arises in the analytical solution from the linearisation of a number of non-linear terms. The computer is usually needed to calculate the different terms involved in the response equation of the analytical solution where many functions (e.g. sin, exp, log, ...) are solved accurately numerically. The analytical solution is also time consuming.

Considering these factors and also the advantages of simulation over the analytical solution (2.4) the latter was not pursued. Instead the different parts of the system are simulated on a digital computer and combined to obtain the total simulation of the system. Appropriate numerical analysis is used for iteration, interpolation, integration and differentiation.

The differential equations obtained from the reactor mass and energy balances (3.4.2) and for jacket energy balance (3.4.3) are:

$$\frac{dC_2}{dt} = \frac{u}{V}(C_o - C_2) - r \qquad (7.1)$$

$$\frac{dT_2}{dt} = \frac{u}{V}(T_o - T_2) + \frac{UA}{\rho VC_p}(T_1 - T_2) - \frac{\Delta Hr}{\rho C_p} - \frac{Q_L}{\rho VC_p} \qquad (7.2)$$

$$\frac{dT_1}{dt} = \frac{m}{M}(T_3 - T_1) + \frac{UA}{MC'_p}(T_2 - T_1) \qquad (7.3)$$

These differential equations are then solved by the ASP package (5.2) or the BASP program (5.5) to obtain the open-loop response values of C_2, T_2 and T_1 versus time. The corresponding results for the control systems are achieved by addition of equations for the measuring element, controllers and control valve in the form:

The signal produced by the measuring element is $K_M T$, and the error signal e at fixed set point is $-K_M T$. The corrective signal is

$$K_C\left(e + \frac{1}{T_R}\int_o^t e\,dt + T_D \frac{de}{dt}\right)$$

The signal produced by the control valve is K_V multiplied by the corrective signal.

Total simulation is first applied for prediction of the results and then for the confirmation of the experimental results.

7.2 TOTAL SIMULATION TO PREDICT THE RESULTS

The system chosen has some similarities to the one used by Buxton (5), and therefore relevant data are extracted from his thesis. Some changes were necessary to fulfill the objectives of the research (Chapter 2).

The special assumptions made for this study are:

(i) The overall heat transfer coefficient had a constant value. The average of the values extracted from Buxton (5) is used for this purpose even though his data referred to a coil.

(ii) The heat loss to atmosphere is negligible.

(iii) The measuring element gain is equal to unity.

(iv) All pure time lags are negligible.

(v) Enthalpy change on reaction is independent of the temperature and is constant.

The results of this simulation are given in Appendix (A.3) and discussed in Chapter 8.

7.3 TOTAL SIMULATION TO CONFIRM THE RESULTS

Here the total simulation of the system is based upon the data in partial simulation (Chapter 6), and therefore, all the necessary assumptions and limitations of the variables have to be taken into account. Those which are important are:

7.3.1 MIXING

The reactor and jacket are both assumed to be well-mixed in the model. To confirm that this was achieved the following tests were done

(i) Probing with thermocouple

A thermocouple is used to probe all areas in the reactor and jacket. No fluctuation is found in the measured temperature of the reactor. The measured temperature of the jacket is also constant when the jacket flowrate is above 2 l/min. For lower flowrates (0.5-2 l/min) mixing is not complete and some temperature differences exist near the feed inlet.

(ii) Testing by tracer

The mixing characteristics of the jacket were studied by an undergraduate student (25). The results which he obtained confirmed the probe tests.

7.3.2 HEAT TRANSFER COEFFICIENT

The product of heat transfer coefficient U and area A is used in simulation. Its value is obtained from the partial simulation steady-state results (Appendix A.3) and is constant and independent of jacket flowrate when this is greater than 2 l/min. Different values of UA are obtained for lower flowrates and therefore for the flowrate range 0.5 to 2 l/min UA is calibrated (Appendix A.2). For flowrates less than 0.5 l/min the heat transfer coefficient has a large deviation and therefore flowrate is assumed to be limited to 0.5 l/min.

7.3.3 JACKET INLET TEMPERATURE

Again for low values of jacket flowrate the jacket inlet temperature deviates from its intended constant value. This phenomenon is due to the long distance between the jacket and its feed tank (nearly 5 m), and therefore for flowrates less than 2 l/min an average temperature is considered.

7.3.4 HEAT LOSSES

The total heat losses of the system are assumed to be the difference between the heat generation and heat removal. Therefore

$$Q_L = Q_g - Q_r \tag{7.4}$$

and

$$\% \text{ of heat losses} = \frac{Q_L}{Q_g} \times 100 \tag{7.5}$$

7.3.5 SIMULATION TIME

Simulation time depends on the integration step-length which is then assumed to be the same as that in partial simulation (6.3).

7.3.6 SIMULATION OF THE MEASURING ELEMENT

The measuring element time lag is very small in comparison with the system lag and its gain is assumed to be equal to unity.

7.3.7 SIMULATION OF THE CONTROL VALVE

The delay of the control valve is covered by the total time delay of the system (6.4.3) and its gain K_V is obtained and given in (4.2.3).

7.3.8 LIMITATIONS OF THE VARIABLES

As shown in (6.6) the jacket flowrate is limited to a range of 0.5 to 9.75 l/min and heat generated by the immersion heaters to 9 kW. These limits are considered when the whole system is simulated as well as when partially simulated.

CHAPTER 8

RESULTS AND DISCUSSION

8.1 INTRODUCTION

The results of the three types of study of the system are obtained and discussed separately in this Chapter. These studies are total simulation to predict the system performance and to assist equipment design, partial simulation for the main series of experiments and further total simulation to confirm the experimental results. Many tests have been done on each of these parts, firstly under steady-state conditions and then using different types and sizes of disturbance for the transient response.

The control study is the major aim of this particular research and a comparison is made between single-loop and cascade control schemes. The results of each control system under a variety of disturbances are obtained and compared to show the advantage of the one scheme over the other.

The optimum controller settings are obtained by the reaction curve method, the continuous-cycling method and trial and error depending on the conditions and constraints of the system. These settings are optimum ones based upon the definition given by J.G. Ziegler and N.B. Nichols (54-56).

The results are given in both graphical form and as numerical data and include all the necessary information to distinguish them from one another.
N.B. the proportional gain is given in $\frac{lbf/in^2}{^{o}C}$ which should be multiplied by 6.89 to give $\frac{kN/m^2}{K}$ (SI units).

8.2 TOTAL SIMULATION TO PREDICT THE SYSTEM PERFORMANCE AND TO ASSIST EQUIPMENT DESIGN

The whole system is simulated on the Honeywell-316 digital computer (7.2) based upon the data extracted from Buxton (5). The first objective is the prediction of performance of both single-loop and cascade control schemes, to investigate the effect of different stepchanges on the various response variables. Secondly the results are used to design suitable equipment on which similar tests could be performed.
Table (8.1) shows the values extracted from Buxton and Table (8.2) the values chosen especially for this particular research.

All the results are available but because the purpose of this project is the comparison of the two control systems when they have their best response (See Chapter 2), only selected results, therefore, are given in this thesis to show the best predicted optimum controller settings and the variation of different variables in the system with time. The results are all graphical and included on each is all the relevant operating information. Stable systems, and

VARIABLE	MAGNITUDE	UNIT
u^o	3.0	l/min
V	16.0	l
m^o	1.0	kg/min
C_o^o	1.0	mol/l
ρ	1.0	kg/l
C_p	1.0	cal/g ^oC
$(-\Delta H)$	35400	cal/mol
A	6.3×10^{15}	s^{-1}
E	24000	cal/mol
R	1.987	cal/mol K

TABLE 8.1 Values Extracted from Buxton (5)

VARIABLE	MAGNITUDE	UNIT
M	8	kg
UA	99	cal/h ^oC
T_o^o	20	^oC
T_3^o	5.8	^oC

TABLE 8.2 Values Chosen Especially for the Simulation Study to Predict the System Performance

three unstable systems are briefly discussed below.

8.2.1 STEPCHANGE IN THE REACTOR INLET TEMPERATURE T_o

Fig. (A.3.1) shows three unstable systems having high proportional gain and low integral action-time being disturbed by a stepchange in the reactor inlet temperature. A stable system can therefore be obtained by decreasing the proportional gain and increasing the reset-time.

A stepchange of 20 deg C is applied as the disturbance in the forcing variable of the system (T_o). Figs. (A.3.2-3) each show the response of the single-loop system and its corresponding cascade loop. The difference between the two single-loops is the proportional gain settings (K_o = 0.6 and K_o = 0.15) for the controller. The one with higher proportional gain has a faster response, is more oscillatory and its system requires a higher range of jacket flowrate.

8.2.2 SIMULTANEOUS STEPCHANGES IN T_o AND T_3

A stepchange of 20 deg C in the reactor inlet temperature and a stepchange with a number of values of the jacket inlet temperature are made to investigate the effect of the secondary variable (See Chapter 2). Figs. (A.3.4-6) show the variation of the response versus time when the stepchange on the jacket temperature is +5 deg C, -5 deg C and -10 deg C respectively. The main response difference between these systems is the variation of their jacket flowrates. The system in Fig. (A.3.4) requires a large range of jacket flow-rate whereas the one in Fig. (A.3.5) needs a smaller range. Although both are outside the cooling flowrate available, only the system shown in Fig. (A.3.6) uses a jacket flowrate within the maximum possible range proposed for this research (6.6). The system behaviour is as can be anticipated with a stepchange in the jacket inlet temperature. Thus control is easier when the jacket temperature change is in the opposite direction to the one in the reactor inlet temperature. If they are in the same direction they should have a low value to be within the available coolant flow.

8.2.3 SIMULTANEOUS STEPCHANGES IN T_0, T_3 and $\bar{u}_0$

The reactor throughput ($\bar{u}_0$) is another forcing stepchange disturbance added to the previous ones to ensure full utilisation of the system possibilities. Large values of these disturbances are selected to see the effect of size on different response variables of the system observed. Fig. (A.3.7) shows that the range of jacket flowrate is reasonable and feasible for the partial simulation study.

The theoretical results reported in the above study are only intended to be useful for the design of different parts of the plant and for a guide in the investigation of the range of different variables and parameters (See also Chapter 7).

8.3 PARTIAL SIMULATION RESULTS

Some steady-state and one hundred and seventy eight unsteady-state open-loop or closed-loop tests have been done. The observations are of the variation of the reactor temperature as the control variable, jacket temperature as the secondary variable, as well as reactor concentration, jacket flowrate and reaction heat generation versus time. The initial tests are on the open-loop system to establish the feasible range of parameters. Subsequent tests cover the two different control schemes. Each control system starts with proportional action and integral action is added in the later tests. This work identifies a need to modify the temperature amplifiers to achieve more sensitive measurements (4.2.6).

One hundred and nineteen of these tests have been done to develop the equipment and examine suitable conditions for the main purpose of this project. All of these tests are available and although they contribute to an understanding of the system are not included in the thesis. Fig. (A.3.8) shows just one example of how the original insensitive amplifiers affect the results.

After the above preparation some steady-state results, based upon different jacket flowrate values, are obtained and then unsteady-state tests done with the same system being controlled by both single-loop and cascade control schemes separately for different stepchanges made on different forcing configurations.

8.3.1 RANGES OF PARAMETERS

The range of parameters are based upon the constraints of the system already established and are the following.

8.3.1.1 REACTOR FEED TEMPERATURE AND CONCENTRATION

The reactor temperature is limited to a maximum of 50^{o}C because the reaction heat generation cannot exceed its maximum of 9 kW (6.6) and also the amplifiers which measure this temperature will give a voltage outside the range acceptable to HADIOS (0.5V) if the reactor temperature exceeds 50^{o}C (4.2.6). Therefore a range of 10-20^{o}C is chosen for the reactor inlet temperature so that with the maximum heat of reaction the above temperature is not exceeded. A reactor feed concentration compatible with the chosen combination of reaction heat generation and reactor feed temperature is 1.0 g/l and is kept constant through the whole series of tests.

8.3.1.2 REACTOR FLOWRATE

Mixing tests confirm that for a very low flowrate, stagnation exists in the reactor. A very high reactor throughput gives the problem of short circuiting and also causes an increase in the reaction heat generation beyond the capacity of the immersion heaters. A range of 2-4 l/min is chosen to avoid both problems.

8.3.1.3 REACTION HEAT ($-\Delta H$)

For the reason of comparison with the previous research and also the designed coolant capacity a value of $-\Delta H$ = 34500 cal/mol (144.44 kJ/mol) is extracted from Buxton (5) and accepted for this particular project.

8.3.1.4 STIRRER SPEED

A medium-high speed motor setting of 5 is used for good mixing and is the maximum value which does not give vortices and spillage.

8.3.2 OPEN-LOOP STEADY-STATE RESULTS

The parameters are set at their normal values and then with different jacket flowrates in the range 0.5-9.75 l/min the variables at steady-state conditions are measured. The variables obtained directly are reactor temperature, jacket temperature and reactor flowrate while the calculated ones are reactor concentration, reaction heat generation, heat transfer resistance (UA) and percentage heat loss. The results are given in Table (A.3.1)

Unsteady-state results are based on a combination of different controller settings and on different stepchange disturbances. Table (8.3) shows the initial steady-state condition of each experiment and Table (8.4) the operating parameters, the integral error and the integral value of the absolute error.

8.3.3 SINGLE-LOOP CONTROL RESULTS WITH DIFFERENT CONTROLLER SETTINGS

Figs. (A.3.9-24) show the transient results of the single-loop control being disturbed by a positive stepchange on the reactor inlet temperature. Different trial and error values of the controller settings are selected to find the best possible settings; although in some experiments the settings are the same, the stepchanges are varying to see the effect in the presence of these particular settings. The best of these are experiments 122, 143 and 150 with controller settings of $K_o = 0.2$ and $I = 60$. The responses of these experiments have relatively faster return to their desired value and have a moderate oscillation. The stepchange in experiment 143 is very large and it is seen that both experiments 143 and 150 have measurement noise which affects the results.

Also a negative disturbance is made in the reactor inlet temperature for which the results are

TABLE 8.3 The Initial Steady-State Condition for Partial Simulation Experiments

Experiment No.	$T_o^o(^oC)$	$T_1^o(^oC)$	$T_2^o(^oC)$	$T_3^o(^oC)$	u^o(l/min)	$\dot{m}^o$(Kg/min)	C_2^o(mol/l) x 10^2	Q_g(W)
109	11.9	32.7	39.4	14.2	3.1	1.0	2.9	7167
120	14.0	33.9	39.2	15.9	2.5	1.0	2.4	5738
121	13.1	33.2	38.5	14.9	2.9	1.0	3.0	6668
122	12.6	32.9	38.4	14.5	2.9	1.0	3.0	6590
123	12.6	32.2	37.5	14.5	2.8	1.0	3.3	6427
124	12.6	30.1	36.3	13.6	3.0	1.0	3.9	6755
125	13.1	32.7	39.0	14.0	3.0	1.0	2.9	6909
127	12.6	32.3	36.9	14.0	2.8	1.0	3.5	6481
128	13.1	32.7	37.8	14.5	2.9	1.0	3.3	6724
129	10.8	29.8	35.8	12.6	3.0	2.0	4.2	6737
130	10.8	30.3	36.1	12.6	3.0	1.0	4.1	6745
135	10.3	29.8	35.1	12.2	2.8	1.0	4.4	6423
136	12.6	32.6	37.1	14.5	2.8	1.0	3.3	6284

TABLE 8.3 (continued)

Experiment No.	T_o^o (^oC)	T_1^o (^oC)	T_2^o (^oC)	T_3^o (^oC)	$\dot{u}^o$ (l/min)	$\dot{m}^o$ (kg/min)	C_2^o (mol/l) x 10^2	Q_g (W)
142	10.8	29.7	34.7	12.6	2.7	1.0	4.4	6084
143	12.6	31.9	36.9	14.0	2.9	1.0	3.6	6550
150	13.1	31.5	36.4	14.5	2.7	1.0	3.7	6138
151	12.2	30.7	35.8	13.6	2.6	1.0	3.8	5998
152	21.5	9.8	31.4	4.2	2.5	8.5	6.2	5620
154	20.1	16.2	33.5	12.2	2.7	8.5	5.1	6042
155	21.5	10.3	33.0	4.2	2.8	8.5	5.7	6268
156	21.5	16.6	35.9	11.7	2.8	8.5	4.0	6449
157	21.5	17.1	34.9	12.6	2.6	8.5	4.1	5802
160	9.8	21.8	32.5	9.8	3.0	2.0	6.4	6652
161	10.3	21.7	32.9	10.3	3.0	2.0	6.1	6675
162	10.3	28.8	36.4	12.1	3.0	1.0	4.0	6825
163	9.8	29.1	37.2	11.7	3.0	1.0	3.6	6849

TABLE 8.3 (continued)

Experiment No.	$T_o^o(^oC)$	$T_1^o(^oC)$	$T_2^o(^oC)$	$T_3^o(^oC)$	u^o(l/min)	m^o(ig/min)	C_2^o(mol/l) x 10^2	Q_g(W)
164	10.2	28.5	36.5	11.2	3.0	1.0	3.9	6828
165	10.3	29.4	37.2	12.2	3.0	1.0	3.6	6851
166	20.1	15.4	34.2	9.4	3.0	8.5	5.2	6739
167	20.6	10.3	32.5	5.1	3.0	9.0	6.4	6652
168	20.8	14.8	34.3	9.8	3.0	9.0	5.1	6742
169	17.9	9.9	30.4	4.7	3.0	9.0	8.2	6523
170	18.1	15.8	34.4	10.8	3.0	9.0	5.0	6748
171	18.2	10.3	31.1	5.1	3.0	9.0	7.5	6572
172	10.8	29.1	37.6	12.6	3.0	1.0	3.5	6861
173	10.5	27.0	35.7	7.5	3.0	1.0	4.3	6800
174	10.3	27.6	36.4	9.4	3.0	1.0	4.0	6824
175	10.3	29.6	37.5	12.6	3.0	1.0	3.5	6855
176	10.9	30.2	37.3	13.1	3.0	1.0	3.6	6852
178	11.5	30.1	38.6	12.6	3.0	1.0	3.1	6889

TABLE 8.4 Operating Parameters, Integral Error and Integral Values of Absolute Error of Partial Simulation Experiments

EXPERIMENT NO.	GRAPH NO.	CONTROL SYSTEM	K(lbf/in^2 ^oC)	I(s)	STEPCHANGES IN T_o(K)	T_3(K)	u(l/min)	INTEGRAL OF e	$\|e\|$
109	(A.3.8)	S.L.	0.2	40	2.58	-	-	+438	662
120	A.3.9-a,b,c	S.L.	0.25	40	9.81	-	-	+ 95	503
121	A.3.10-12	S.L.	0.15	40	7.94	-	-	+378	778
122	A.3.13-15	S.L.	0.2	60	8.41	-	-	+381	691
123	A.3.16-18	S.L.	0.25	40	7.94	-	-	+332	873
124	A.3.31-33	CAS.	6.5,0.65	40	3.27	-	-	+ 90	154
125	A.3.34-36	CAS.	2,0.2	40	9.81	-	-	+591	622
127	A.3.37-39	CAS.	4,0.4	40	8.41	-	-	+172	291
128	A.3.40-42	CAS.	5,0.5	40	10.28	-	-	+188	305
129	A.3.49-51	CAS.	5,0.5	60	8.88	-7.94	-	+199	273
130	A.3.43-45	CAS.	5,0.4	40	7.48	-	-	+182	360
135	A.3.52-54	CAS.	6.5,0.65	40	13.55	-6.07	-	+228	356
136	A.3.55-57	CAS.	6.5,0.65	60	9.35	-9.35	-	+144	212

TABLE 8.4 (continued)

EXPERIMENT NO.	GRAPH NO.	CONTROL SYSTEM	K(lbf/in^2 ^oC)	I(s)	STEPCHANGES IN T_o(K)	T_3(K)	u(l/min)	INTEGRAL OF e	$\|e\|$
142	A.3.58-60	CAS.	6,0.6	50	8.88	-7.48	-	+164	244
143	A.3.19-21	S.L.	0.2	60	9.35	-	-	+1451	1451
150	A.3.22-24	S.L.	0.2	60	8.41	-	-	+950	960
151	A.3.46-48	CAS.	5,0.5	60	9.35	-	-	+249	319
152	A.3.64-66	CAS.	5,0.5	60	-9.81	7.48	-	-252	428
154	A.3.67-69	CAS.	5,0.5	60	-6.54	-4.21	-	-250	908
155	A.3.28-30	S.L.	0.2	60	-9.35	7.94	-	-1495	1582
156	A.3.25-27	S.L.	0.3	60	-9.35	-	-	-858	2263
157	A.3.61-63	CAS.	5,0.5	60	-8.41	-	-	-260	645
160	A.3.70-72	S.L.	0.2	60	7.94	-	-	+1348	1351
161	A.3.73-75	CAS.	5,0.5	60	7.48	-	-	+229	327
162	A.3.97-99	CAS.	5,0.5	60	9.35	-7.01	-	+160	249
163	A.3.77-79	S.L.	0.2	60	10.28	-	-	+760	1192

TABLE 8.4 (continued)

EXPERIMENT NO.	GRAPH NO.	CONTROL SYSTEM	K(lbf/in^2 ^oC)	I(s)	STEPCHANGES IN			INTEGRAL OF	
					T_o(K)	T_3(K)	u(l/min)	e	|e|
164	A.3.94-96	S.L.	0.2	60	9.91	-6.07	-	+514	1040
165	A.3.80-82	CAS.	5,0.5	60	9.81	-	-	+171	267
166	A.3.87-89	CAS.	5,0.5	60	-9.81	-	-	-223	664
167	A.3.104-106	CAS.	5,0.5	60	-9.81	5.39	-	-249	520
168	A.3.84-86	S.L.	0.2	60	-10.0	-	-	-1423	2727
169	A.3.101-103	S.L.	0.2	60	-7.20	5.61	-	-1082	1283
170	A.3.90-92	CAS.	5,0.5	60	-6.91	-	-	-220	408
171	A.3.107-109	CAS.	5,0.5	60	-7.48	5.42	-	-155	286
172	A.3.118-120	CAS.	5,0.5	60	6.45	-	1.0	+190	255
173	A.3.111-113	S.L.	0.2	60	6.73	2.62	-	+769	952
174	A.3.114-116	CAS.	5,0.5	60	7.01	0.94	-	+105	192
175	A.3.121-123	S.L.	0.2	60	6.82	-	1.0	+850	924
176	A.3.125-127	S.L.	0.2	60	6.82	-8.22	1.0	+550	894
178	A.3.128-130	CAS.	5,0.5	60	6.26	-7.48	1.0	+111	175

shown in Figs (A.3.25-27). The value of the stepchange is large and with the initial value of jacket flowrate u_1^o = 8.5 l/min the jacket flowrate reaches its minimum limit and therefore the results will be affected.

This effect can be reduced by, in addition, making a positive stepchange disturbance on the jacket inlet temperature. The results are shown in Figs. (A.3.28-30). The problem of this experiment is its measurement noise.

8.3.4 CASCADE CONTROL RESULTS WITH DIFFERENT CONTROLLER SETTINGS

Similar to Section(8.3.3) a positive stepchange disturbance is made on the inlet reactor temperature of the system, this time being controlled by the cascade control scheme having different controller settings. The results are shown in Figs. (A.3.31-48). Experiment 125 gives a response with a slow return to its desired value; experiments 127 and 130 have the same problem and also are oscillatory. A faster return but still oscillatory is obtained in experiment 128. The best of these is experiment 151 with the proportional gains of K_1 = 5 and K_2 = 0.5 for the primary and secondary controllers respectively and the integral action-time of I = 60 for the primary controller.

Different stepchange disturbances are also made on the jacket inlet temperature and the results are shown in Figs. (A.3.49-60). Again the results achieved are consistent with the design values when large values of disturbance are used (experiment 135). The best experiments are those having controller settings of K_1 = 5, K_2 = 0.5 and I = 60 (expts. 129 and 136).

This scheme is also tried for the negative step-change disturbances on the reactor inlet temperature with and without any disturbance on the jacket inlet temperature. The results are shown in Figs. (A.3.61-69); among these the results of experiment 157 show that the jacket flowrate reaches its minimum limit of 0.5 l/min which affects the result while in experiment 154 the results are affected by the measurement noises. Experiment 152 has a very good response with the above controller settings i.e. K_1 = 5, K_2 = 0.5 and I = 60.

The above experiments give the best settings found of K_o = 0.2 and I = 60 for single-loop and K_1 = 5, K_2 = 0.5 and I = 60 for cascade control. These settings are selected therefore for the following experiments with the aim of comparing the response of single-loop and the corresponding cascade system under different disturbances.

8.3.5 POSITIVE STEP IN T_O

Figs. (A.3.70-72) show the results of a positive stepchange disturbance in the reactor inlet temperature with an initial jacket flowrate of 2 l/min and Figs. (A.3.73-75) show the results of the corresponding cascade control system. The jacket flowrate of both systems reaches its maximum limit and the results are affected to give a larger recovery time. Also the measurement noise peaks of experiment 161 affect the response through the control actions.

Both experiments are repeated with an initial value of jacket flowrate of 1 l/min and the results are shown in Figs. (A.3.77-82). The jacket flowrate range is therefore less limited and even though the disturbance has a bigger value, the maximum coolant flowrate is operative for a shorter time.

These two pairs of experiments are compared and shown in Figs. (A.3.76, A.3.83) which confirms that the response of the cascade control returns to its set-point faster than that of the single-loop. The quantitative comparison of the systems integral value of absolute error showing the extent of improvement is given in Table (8.4).

8.3.6 NEGATIVE STEP IN T_o

The results of one experiment (168) using the single-loop control scheme are shown in Figs. (A.3.84-86) while Figs. (A.87-92) show the results of two experiments on the corresponding cascade control system. These experiments are 166 and 170 with an initial jacket flowrate of 8.5 and 9 l/min respectively. The jacket flowrate of experiment 166 is at its lower limits for a larger time than the one of experiment 170. This is because the latter has a wider range for its jacket flowrate and a smaller disturbance.

In Fig. (A.3.93), comparison has been made between the control variable of the experiments 166 and 168. The advantage of cascade control is apparent from this comparison and the corresponding integrated errors.

8.3.7 SIMULTANEOUS POSITIVE STEP IN T_o AND NEGATIVE STEP IN T_3

The system has constraints which do not always allow disturbances to be selected arbitrarily. Because of coolant flowrate limitation the stepchanges are made in different directions. Figs. (A.3.94-96) show the results for the single-loop control system with a positive step in T_o and a negative step in T_3 and Figs. (A.3.97-99) represent the results of the corresponding cascade control. These two experiments are compared in Fig. (A.3.100). Referring to this graph and the integrated errors of Table (8.4), it can be seen that the performance of the cascade control system has the greater improvement when a disturbance occurs in the secondary loop.

8.3.8 SIMULTANEOUS NEGATIVE STEP IN T_o AND POSITIVE STEP IN T_3

The disturbances in this section have opposite sign to those in Section 8.3.7. Experiment 169 is on single-loop and its results are shown in (A.3.101-103) and experiment 167 is on cascade control. Figs. (A.3.104-106) show the results of this experiment including its jacket flowrate which is limited because of the high value of disturbance in T_o and low value of disturbance in T_3. The latter experiment is repeated for a lower value of disturbance on T_o and its results are shown in Figs. (A.3.107-109).

Experiments 169 and 171 are compared and shown in Fig. (A.3.110) which again shows very good improvement in the performance of the cascade control system.

8.3.9 SIMULTANEOUS POSITIVE STEP IN T_o AND POSITIVE STEP IN T_3

Small positive steps are made on both T_o and T_3 to show the results of the system when both disturbances are in the same direction. The experimental results on the single-loop and cascade control systems are shown in Figs. (A.3.111-116). The control variables of these systems are compared in Fig. (A.3.117). It shows the improvement to be more if the steps are in the same direction. Because of the system constraints, tests with large steps in the same direction are not possible.

8.3.10 SIMULTANEOUS POSITIVE STEP IN T_o AND POSITIVE STEP IN u_o

In experiments 175 for single-loop and 172 for cascade, two positive steps one on T_o and the other on u_o are made and the results shown in Figs. (A.3.118-123). In both experiments, because of a large reactor flow-rate value, the reaction heat generation reaches its limit of 9 kW. These experiments are compared in Fig. (A.3.124).

8.3.11 SIMULTANEOUS POSITIVE STEP IN T_o, POSITIVE STEP IN u_o AND NEGATIVE STEP ON T_3

Figs. (A.3.125-127) show the results of the single-loop control system having three disturbances as a positive step on T_o, a positive step on u_o and a nagative step on T_3. Similar disturbances are made on the cascade control system and its results are shown in Figs. (A.3.128-130). Again the reaction heat generation reaches its limit of 9 kW.

These two experimnets are compared in Fig. (A.3.131) which shows similar improvement to that achieved in earlier tests.

8.4 TOTAL SIMULATION TO CONFIRM THE RESULTS

The whole system is again simulated on the Honeywell-316 digital computer this time based upon the conditions achieved in partial simulation (8.3). The results are in both numerical and graphical form but only the latter is presented in this thesis.

All the variables at the steady-state conditions are those of partial simulation and the heat loss is assumed to be four per cent (Table 8.3).

For ease of comparison the results of both partial simulation experiments and total simulation model tests are put next to each other. Most model tests are very near to their corresponding partial simulation results and only when there is considerable noise from the measuring device do they deviate, e.g. experiments 154 and 155 in Figs. (A.3.67-69) and (A.3.28-30). This is because noise gives a wrong value to the error and causes the integral action to deviate.

N.B. The experimental data in the tables and graphs are as output by the computer although the physical data is not known to this accuracy.

CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

9.1 CONCLUSIONS

The prediction of the system performance and its design based upon the available literature, and the analysis of the partial simulation experimental data generated in this research and its comparison with the total simulation model tests lead to the following conclusions.

9.1.1 CONCLUSIONS RELATED TO THE AVAILABLE LITERATURE

(i) The reports on the improvement of control systems especially those on cascade control are very limited and are mostly theoretical rather than practical. The information given in these reports is inadequate and insufficient for the design of the equipment needed for experimental work.

(ii) There are some reports on the total simulation technique using the analogue or digital computer but largely on simple problems. Very few control systems with the interaction of variables are considered. Although these few reports give an idea of the utilisation of the technique and its advantages over analytical solutions they have very few points to offer for the design of the plant.

(iii) The use of the partial simulation technique to study control systems is confined to the simulation of the control action. The simulation of the mass balance, with the actual energy balance in the system, has been applied only in a few cases including three previous pieces of ph.D. research in this department. These works and the present one exploit the advantages of partial simulation when possibly hazardous, corrosive and expensive chemicals are replaced by a cheap and safe liquid. The system mass balance is simulated on a computer while its effect on the reaction heat generation is considered in the actual energy balance. Some of the advantages of partial simulation are:

(a) The operation is safe and has no health hazard or risk of explosion.

(b) Any exothermic reaction of any order may be considered and studied.

(c) The operation is rapid i.e. there is no loss of time in handling chemicals.

(d) The operational cost is low and it is therefore possible to afford more experiments than if chemicals were used.

(e) Stability analysis can be studied over a wide range, governed only by the physical specification of the equipment, without any risk of explosion and waste.

(iv) Not many reports cover the study of on-line and computer control in the wide range of chemical engineering research. Most of the studies are on electrical engineering problems and supply sufficient information for control applications in other engineering fields including chemical engineering.

9.1.2 CONCLUSIONS RELATED TO THE PARTIAL SIMULATION EXPERIMENTS

(i) The equipment is capable of consistent and reproducible operation.

(ii) The system is flexible for application of both control schemes and a variety of forcing disturbances.

(iii) The reactor temperature range of 0-50^{o}C is sufficient to obtain results for the major aspects of this research i.e. to obtain enough data to be able to compare the two control schemes under different disturbances.

(iv) The required jacket flowrate in most of the experiments is within the control valve range.

(v) For large forcing disturbances or multiple disturbances in the same direction the jacket flowrate becomes limited by the valve capacity.

(vi) Cascade control requires a wider range of jacket flowrate than the single-loop control system.

This is because disturbances in the inner and outer loop have to be counter-acted simultaneously, and is consistent with the more effective control observed.

(vii) The pure time delay of the control valve is covered by the interrupt frequency of HADIOS.

(viii) For large disturbances in the reactor flowrate the reaction heat generation cannot be achieved because more than 9 kW are required.

(ix) The variation of mains supply voltage affects the heat generated by the heating elements through the thyristor.

(x) The measurement noise affects the error value, therefore the control action and hence the response.

(xi) The interrupt frequency covers the delay in the transmission of the adjusting signal to the heating elements and their pure time lag.

(xii) The Honeywell-316 is a reliable and simple mini computer which can be operated easily in on-line applications.

(xiii) The Honeywell Analogue Digital Input/Output System provides a flexible method of interfacing the computer to a wide range of input/output devices. The HADIOS EXECUTIVE PACKAGE MK2 provides simple programming to transmit and control the signals.

(xiv) The BASP program (Chapter 5) is capable of solving any ordinary differential equation of any order but is slower than the ASP package due to its BASIC program.

(xv) Both the steplength of the integration and also the interrupt frequency are arranged to be equal to the total time spent on calculation of the different functions and transmission of the signals which covers the total pure time delay of the equipment devices.

(xvi) The partial simulation experimental results are very satisfactory provided that the disturbances on the system are kept within their design bounds.

(xvii) The controller settings are set at their optimum which is affected by the system constraints.

(xviii) A better performance and a faster response are demonstrated to be major advantages of the cascade control over the corresponding single-loop system and are shown by comparing the response curves of the two systems. Also the integrated error and the integrated value of the absolute error are calculated for quantitative comparison.

(xix) For systems which tend to have single-loop instability problems, the usefulness of cascade control is confirmed for the case when there is a large time lag in the secondary loop.

(xx) Cascade control is more effective if (a) the disturbance is on the secondary loop and (b) if there are disturbances in both loops they are all in the same direction.

(xxi) The major problem in operating the equipment is the limited available computer time i.e. there are many demands on the Honeywell-316 computer of the department for both on-line application and straightforward computation.

9.1.3 CONCLUSIONS RELATED TO THE TOTAL SIMULATION MODEL TESTS

(i) The simulation steplength is chosen to be equal to one of the partial simulation, which includes the delays of the system, for the purpose of good comparison.

(ii) The heat loss used is that calculated from the partial simulation steady-state operation as the difference between the heat generation and the heat removal.

(iii) Because in partial simulation only some parts of the system are real. The results are very close to those of the total simulation model tests.

(iv) Total simulation results are different from those of partial simulation in the presence of measurement noise.

9.2 RECOMMENDATIONS

(i) Other different types of reaction with different order can usefully be introduced into the existing equipment, because of instability possibilities.

(ii) A variety of jacket sizes could be tested by the existing equipment and hence the control study of the system with different jacket time constant, which is the secondary loop dominant lag, can be investigated.

(iii) By installation of a control valve actuated by computer different types of forcing disturbances can be applied and their effects on the open-loop and closed-loop systems can be studied.

(iv) All work so far simulating heat of reaction has concentrated on exothermic reactions but the question of the endothermic reaction might be investigated by replacement of the heating elements with some refrigerating system.

(v) The alternatives to the cascade method which could be investigated are:

  (a) Ratio control of which is a special case of cascade control on the existing plant.

  (b) Parallel cascade control the results of which can be compared with those of this particular research. In that system the secondary variable is of a separate plant and not one of the system variables and can be the temperature of another stirred vessel.

  (c) Addition of feedforward control action to the feedback system and would require another control valve.

  (d) The system response variables (reactor temperature and concentration) are interacting but the only control variable is the reactor temperature in the present work. If both response variables are to be controlled then an interacting control system results and would be an interacting extension of the work.

APPENDICES

APPENDIX 1

HADIOS EXECUTIVE PACKAGE MK2

'CALLS' FROM A BASIC PROGRAM

APPENDIX 1

HADIOS EXECUTIVE PACKAGE MK2 'CALLS' FROM A BASIC PROGRAM

A.1.1 INTER-SCAN BASIC PROCESSING SUBROUTINES

The two following subroutines are to scan or to terminate the communication with the HADIOS:

(i) Scanning subroutine to give the necessary information to the executive for the setting up of regular scanning of the HADIOS device and is addressed by

CALL (1, $P_1, P_2, P_3, P_4, P_5, P_6, P_7, P_8, P_9, P_{10}$, A(0))

where the arguments are

- P_1 - HADIOS devices selected - see Table A.1.1.
- P_2 - Honeywell real time clock interrupt frequency (s)
- P_3 - Total number of real time clock interrupts required
- P_4 - Ensemble number (>1) - only applicable for analogue inputs
- P_5 - First analogue input channel number
- P_6 - Last analogue input channel number
- P_7 - Type of counter scanning required - see (48)
- P_8 - Counter preset value
- P_9 - Type of digital input required - see (48)
- P_{10} - Type of digital output required - see (48)

Data Storage A(I) - the data values transmitted to or from the HADIOS EXECUTIVE PROGRAM are stored in the Array A(I).

(ii) Termination subroutine being addressed by CALL (2). Data Storage A(I) - the data values transmitted to or received from the HADIOS EXECUTIVE PROGRAM are stored in the array A(I). For more details see (48).

A.1.2 ADDITIONAL SUBROUTINE

Besides the two subroutines discussed above additional subroutines for special purposes can be loaded to the HADIOS EXECUTIVE (48). In this particular project the digital output is converted to an analogue signal and output via a selected channel to the relevant equipment (4.3.3). For this purpose a subroutine is added to the HADIOS EXECUTIVE which is addressed by CALL (3,N,X) from the BASIC program. N is the channel number and X is the variable which is to be output (0 to 32767_{10}). Whenever N is set to zero the channels hold the existing value of the variables until they are updated. N.B. this subroutine must not be situated within the BASIC programing section of the program.

VALUE OF P_1	DEVICES SELECTED
1	Analogue Inputs Only
8	Counter Inputs Only
9	Analogue + Counter
64	Digital Input Only
65	Digital Input + Analogue
72	Digital Input + Counter
73	Digital Input + Counter + Analogue
512	Digital Output Only
513	Digital Output + Analogue
520	Digital Output + Counter
521	Digital Output + Analogue + Counter
576	Digital Output + Digital Input
577	Digital Output + Digital Input + Analogue
584	Digital Output + Digital Input + Counter
585	Digital Output + Digital Input + Counter + Analogue

TABLE A.1.1 - DEVICES SELECTED TABLE

APPENDIX 2

CALIBRATION

TABLE A.2.1 Heat Output of the Immersion Heaters for Trigger Angle

Q_g(w)	$\alpha(^o)$	Q_g(w)	$\alpha(^o)$	Q_g(w)	$\alpha(^o)$
0	0	1100	74.7	2200	105.5
50	24.1	1150	76.2	2250	106.9
100	30.5	1200	77.6	2300	108.5
150	35.2	1250	79.0	2350	110.0
200	38.9	1300	80.4	2400	111.5
250	42.2	1350	81.8	2450	113.1
300	45.0	1400	83.2	2500	114.8
350	47.6	1450	84.6	2550	116.5
400	50.1	1500	86.0	2600	118.2
450	52.3	1550	87.3	2650	120.0
500	54.4	1600	88.7	2700	121.8
550	56.4	1650	90.1	2750	123.8
600	58.4	1700	91.4	2800	125.8
650	60.2	1750	92.8	2850	127.9
700	62.0	1800	94.2	2900	130.2
750	63.7	1850	95.6	2950	132.6
800	65.4	1900	96.9	3000	135.3
850	67.0	1950	98.3	3050	138.2
900	68.6	2000	99.7	3100	141.5
950	70.2	2050	101.1	3150	145.3
1000	71.7	2100	102.6	3200	150.0
1050	73.2	2150	104.0	3250	156.8

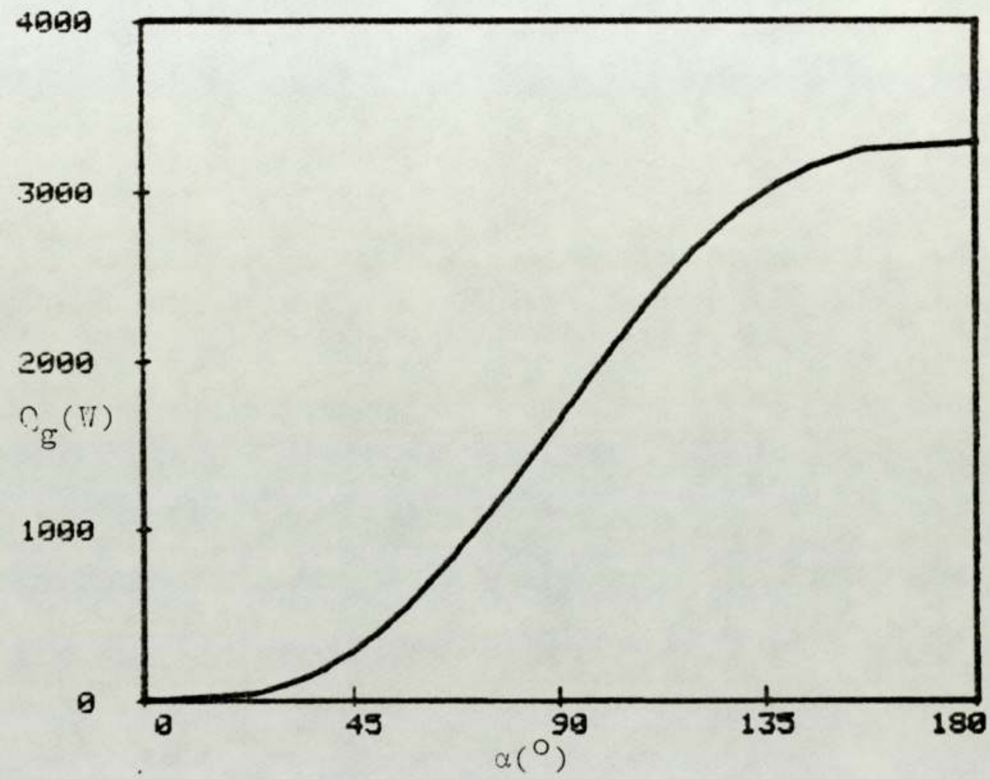


FIG. A.2.1 Heat Output of the Immersion Heaters Versus Trigger Angle

VOLTAGE (V)	JACKET FLOWRATE (l/min)
.25	9.7
.5	9.65
.75	9.7
1	9.575
1.25	9.45
1.5	9.25
1.75	9.125
2	8.65
2.25	8.35
2.5	7.8
2.75	7.35
3	6.8
3.25	6.35
3.5	5.85
3.75	5.45
4	5.09
4.25	4.7
4.5	4.35
4.75	4.03
5	3.7
5.25	3.5
5.5	3.2
5.75	2.93
6	2.7
6.25	2.45
6.5	2.2
6.75	2
7	1.8
7.25	1.613
7.5	1.4
7.75	1.25
8	1.125
8.25	1
8.5	.9
8.75	.825
9	.75
9.25	.675
9.5	.65
9.75	.625
10	.6

TABLE A.2.2 Jacket Flowrate for Analogue Output Voltage with Equal Interval

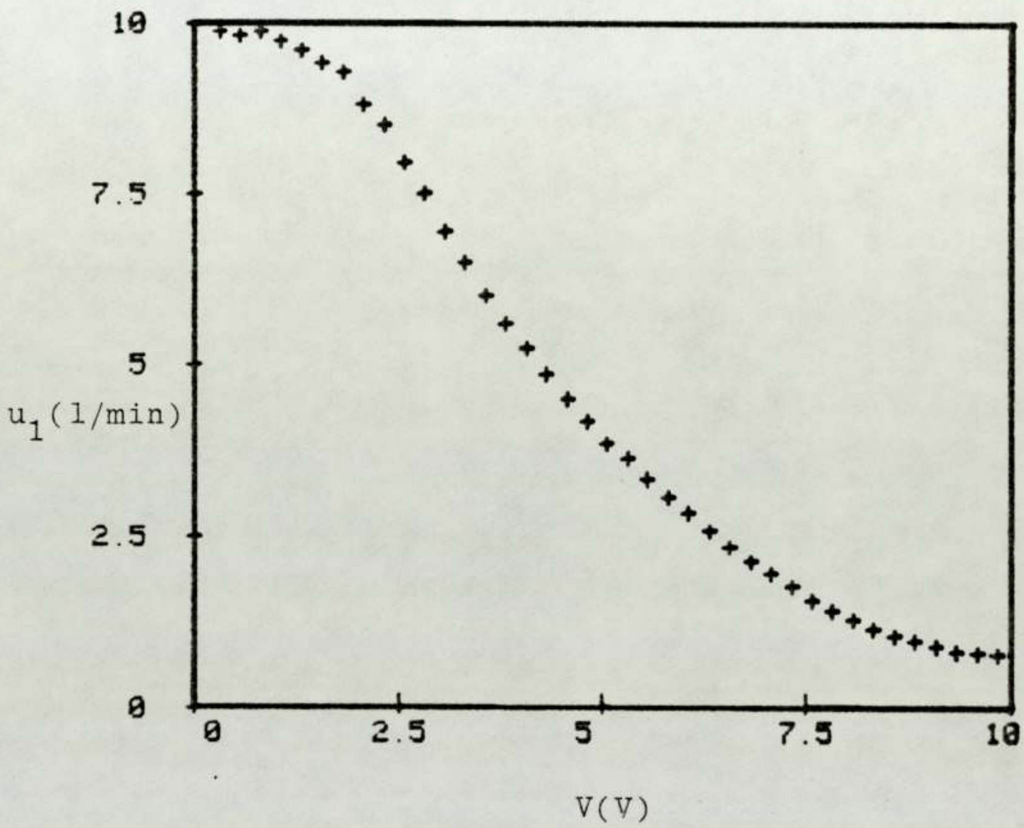


FIG. A.2.2 Jacket Flowrate versus Analogue Output Voltage with Equal Interval

JACKET FLOWRATE (l/min)	VOLTAGE (V)
.75	9
1	8.25
1.25	7.75
1.5	7.35
1.75	7.05
2	6.75
2.25	6.45
2.5	6.18
2.75	5.9
3	5.65
3.25	5.38
3.5	5.15
3.75	4.9
4	4.7
4.25	4.5
4.5	4.32
4.75	4.15
5	4.02
5.25	3.85
5.5	3.7
5.75	3.55
6	3.4
6.25	3.3
6.5	3.15
6.75	3.02
7	2.88
7.25	2.77
7.5	2.65
7.75	2.52
8	2.41
8.25	2.3
8.5	2.15
8.75	1.95
9	1.8
9.25	1.5
9.5	1.25

TABLE A.2.3 Analogue Output Voltage for Jacket Flowrate with Equal Interval

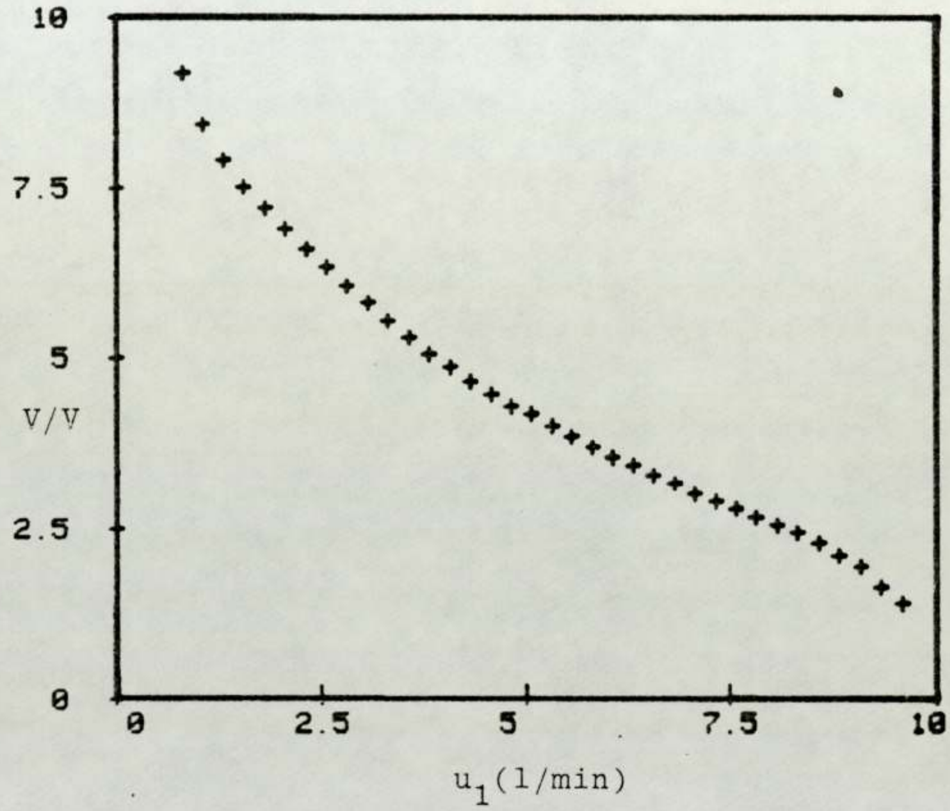


FIG. A.2.3 Analogue Output Voltage Versus Jacket Flowrate with Equal Interval

NO. OF PULSES [illegible]	REACTOR THROUGHPUT (1/min)
68.3	2.625
72.1	2.75
76.5	2.825
80.4	3
84	3.125
87.1	3.25
92	3.375
95.5	3.5
99	3.625
101.5	3.75
105.3	3.825
108	4
111.2	4.125
115.5	4.25
118.3	4.375
122.2	4.5
127	4.625
129.5	4.75
133.5	4.825
137.1	5

TABLE A.2.4 Number of Turbine Flowmeter Pulses for Reactor Throughput

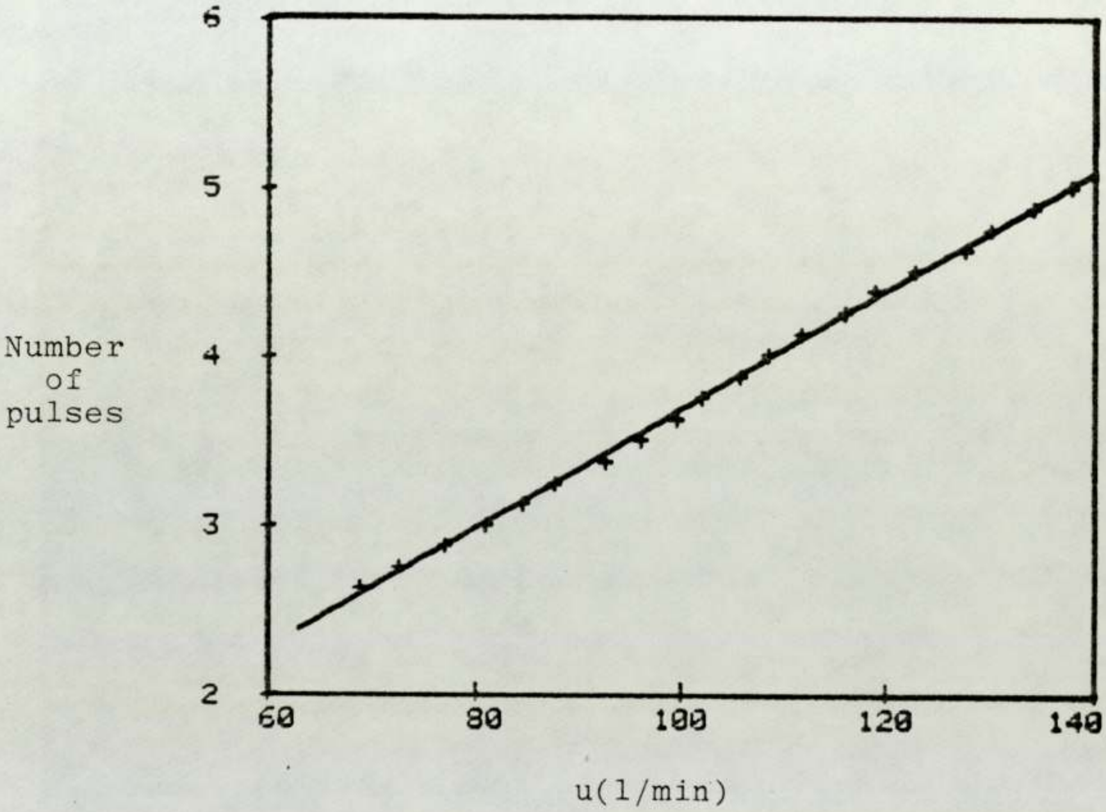


FIG. A.2.4 Number of Turbine Flowmeter Pulses Versus Reactor Throughput

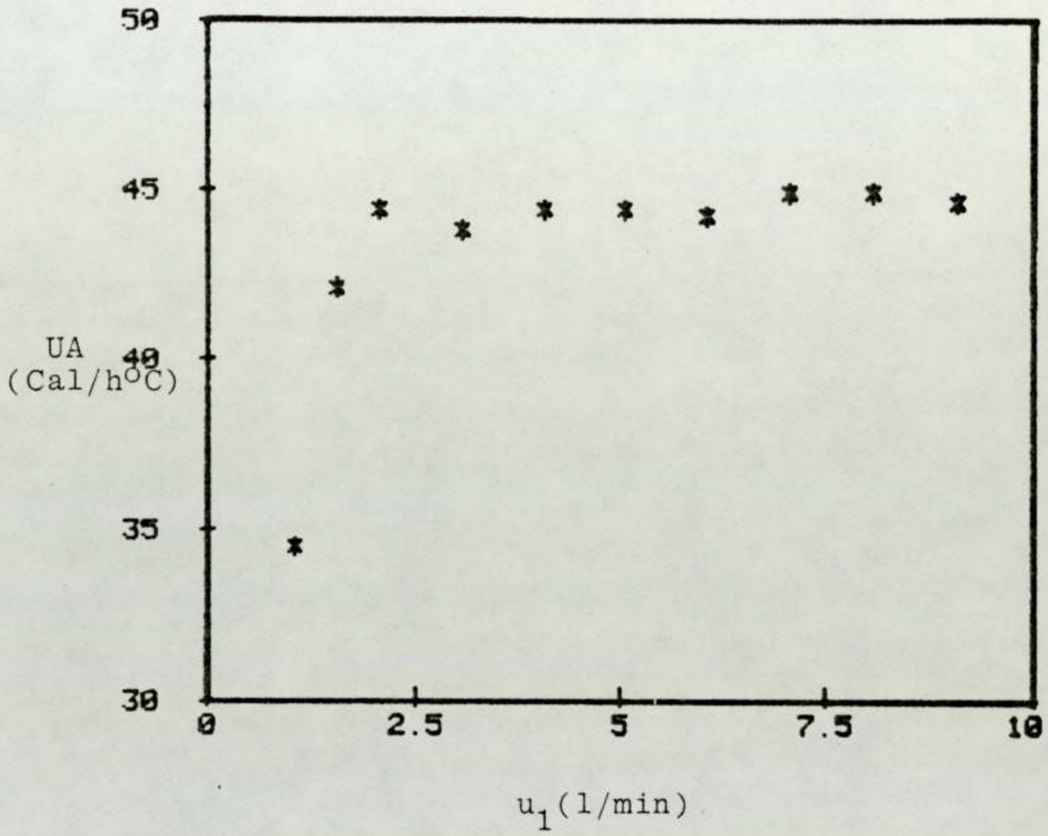


FIG. A.2.5 Heat Transfer Resistance (UA) Versus Jacket Flowrate

APPENDIX 3

EXPERIMENTAL AND MODEL TEST RESULTS

u_1(l/min)	T_o(^oC)	T_1(^oC)	T_2(^oC)	T_3(^oC)	UA(Cal/h^{o}C)	Q_g(W)	Q_r(W)	% Q_L
1	11.7	30.4	38.6	13.6	34.2	6890	6800	1.3
1.5	11.8	27.6	36.5	12.8	41.8	6826	6706	1.8
2.0	11.7	25.2	35.0	12.2	44.1	6773	6688	1.3
3.0	11.7	21.6	33.0	11.7	43.5	6679	6522	2.4
4.0	11.7	19.3	31.6	11.2	44.1	6603	6433	2.6
5.0	12.5	18.8	32.1	11.8	44.1	6633	6552	1.2
6.0	12.3	17.5	30.7	11.7	43.9	6546	6274	4.1
7.0	12.6	16.8	30.3	11.7	44.6	6516	6208	4.7
8.0	12.5	16.4	30.3	11.7	44.6	6519	6330	2.9
9.0	12.1	15.9	30.1	11.7	44.3	6502	6406	1.5

TABLE A.3.1 Partial Simulation Steady-State Experiments

FIG.
A.3.1

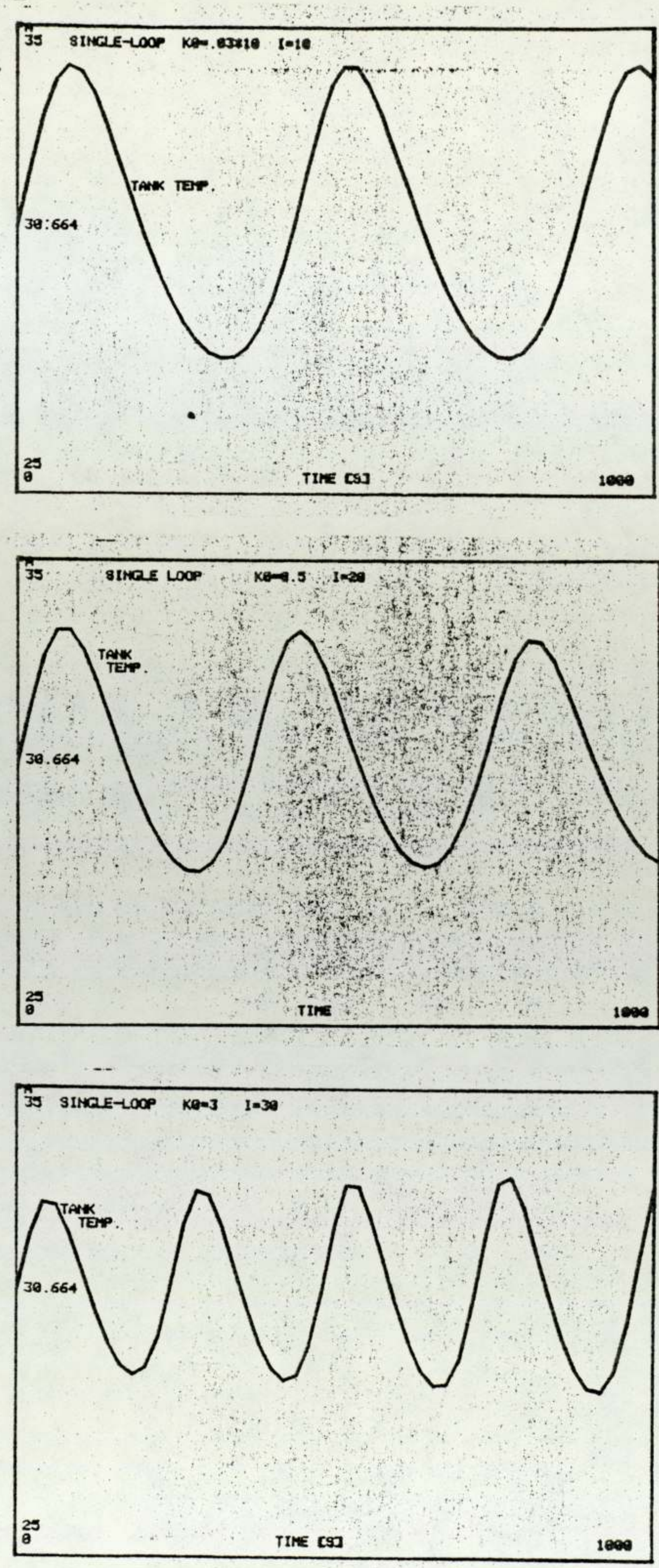

35
SINGLE-LOOP K0=.03*10 I=10
TANK TEMP.
30.664
25
0
TIME [S]
1000
35
SINGLE LOOP K0=0.5 I=20
TANK
TEMP.
30.664
25
0
TIME
1000
35
SINGLE-LOOP K0=3 I=30
TANK
TEMP.
30.664
25
0
TIME [S]
1000

FIG. A.3.2.

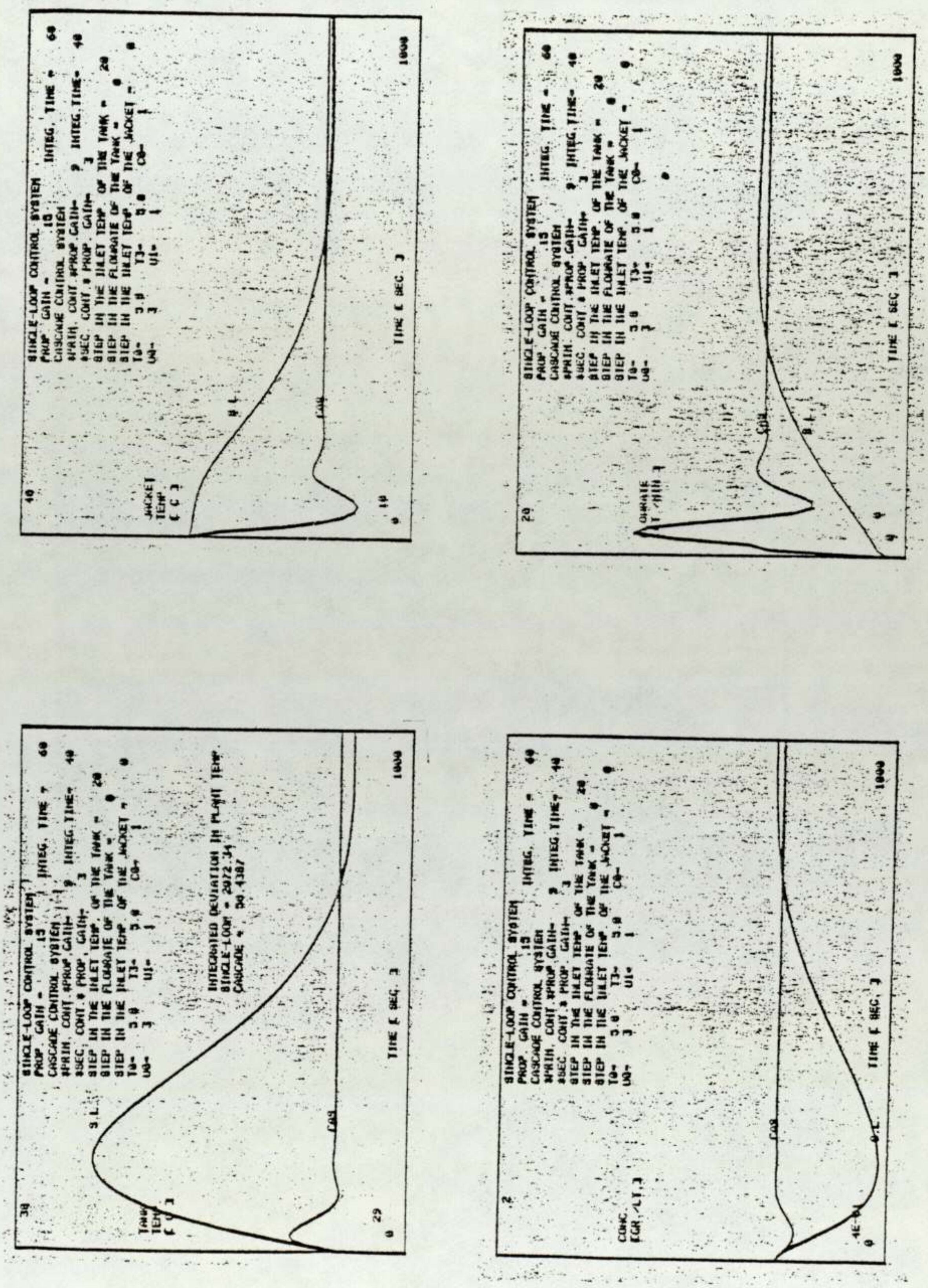


FIG. A.3.3

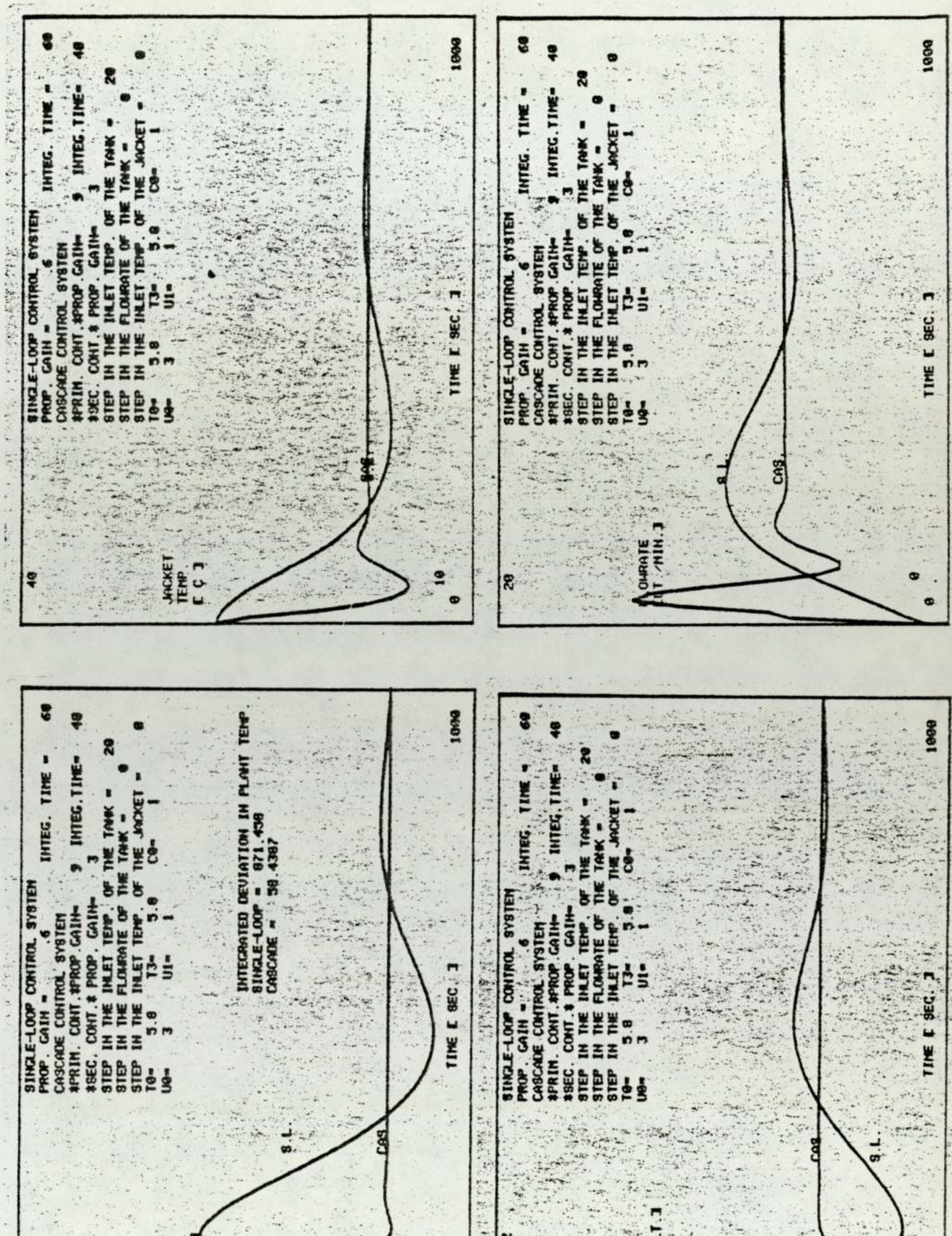

SINGLE-LOOP CONTROL SYSTEM
PROP. GAIN = .6 INTEG. TIME = 60
CASCADE CONTROL SYSTEM
$PRIM. CONT.$PROP.GAIN= 9 INTEG.TIME= 40
$SEC. CONT.$ PROP. GAIN= 3
STEP IN THE INLET TEMP. OF THE TANK = 20
STEP IN THE FLOWRATE OF THE TANK = 0
STEP IN THE INLET TEMP. OF THE JACKET = 0
T0= 5.8 T3= 5.8 C0= 1
U0= 3 U1= 1
INTEGRATED DEVIATION IN PLANT TEMP.
SINGLE-LOOP = 871.438
CASCADE = 58.4387
TANK TEMP. [C]
38
29
0
1000
TIME [SEC.]
S.L.
CAS
JACKET TEMP. [C]
40
10
CONC. [GR./LT.]
.2
.4E-01
20
0
S.L.
CAS

FIG. A.3.4

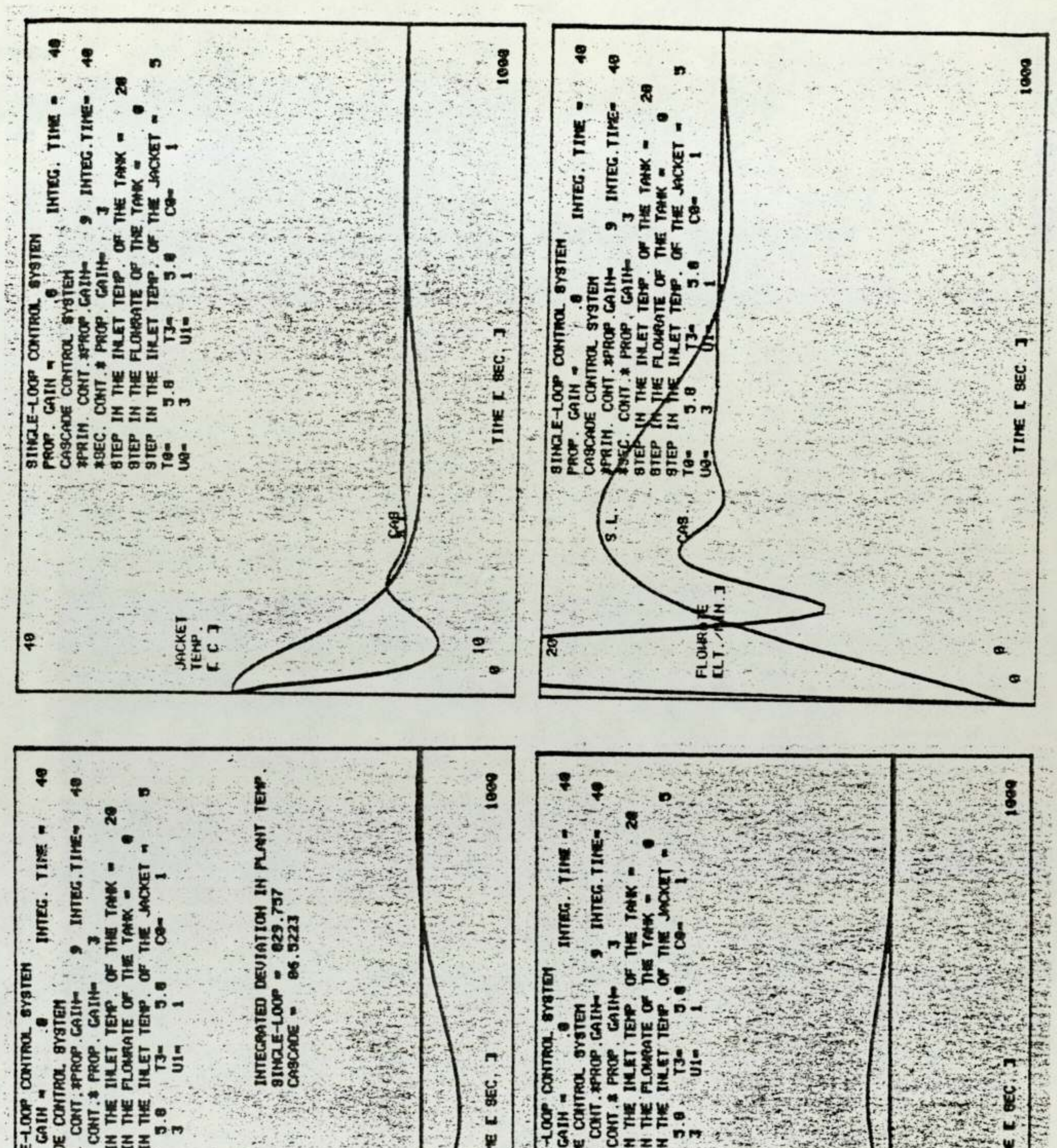

SINGLE-LOOP CONTROL SYSTEM
PROP. GAIN = .8 INTEG. TIME = 40
CASCADE CONTROL SYSTEM
#PRIM. CONT.#PROP.GAIN= 9 INTEG.TIME= 40
#SEC. CONT.# PROP. GAIN= 3
STEP IN THE INLET TEMP. OF THE TANK = 20
STEP IN THE FLOWRATE OF THE TANK = 0
STEP IN THE INLET TEMP. OF THE JACKET = 5
T0= 5.8 T3= 5.8 C0= 1
U0= 3 U1= 1
INTEGRATED DEVIATION IN PLANT TEMP.
SINGLE-LOOP = 829.757
CASCADE = 86.5223
TANK TEMP. [C]
JACKET TEMP. [C]
FLOWRATE [LT./MIN.]
CONC. [GR./LT.]
S.L.
CAS
TIME [SEC.]
1000

FIG. A.3.5

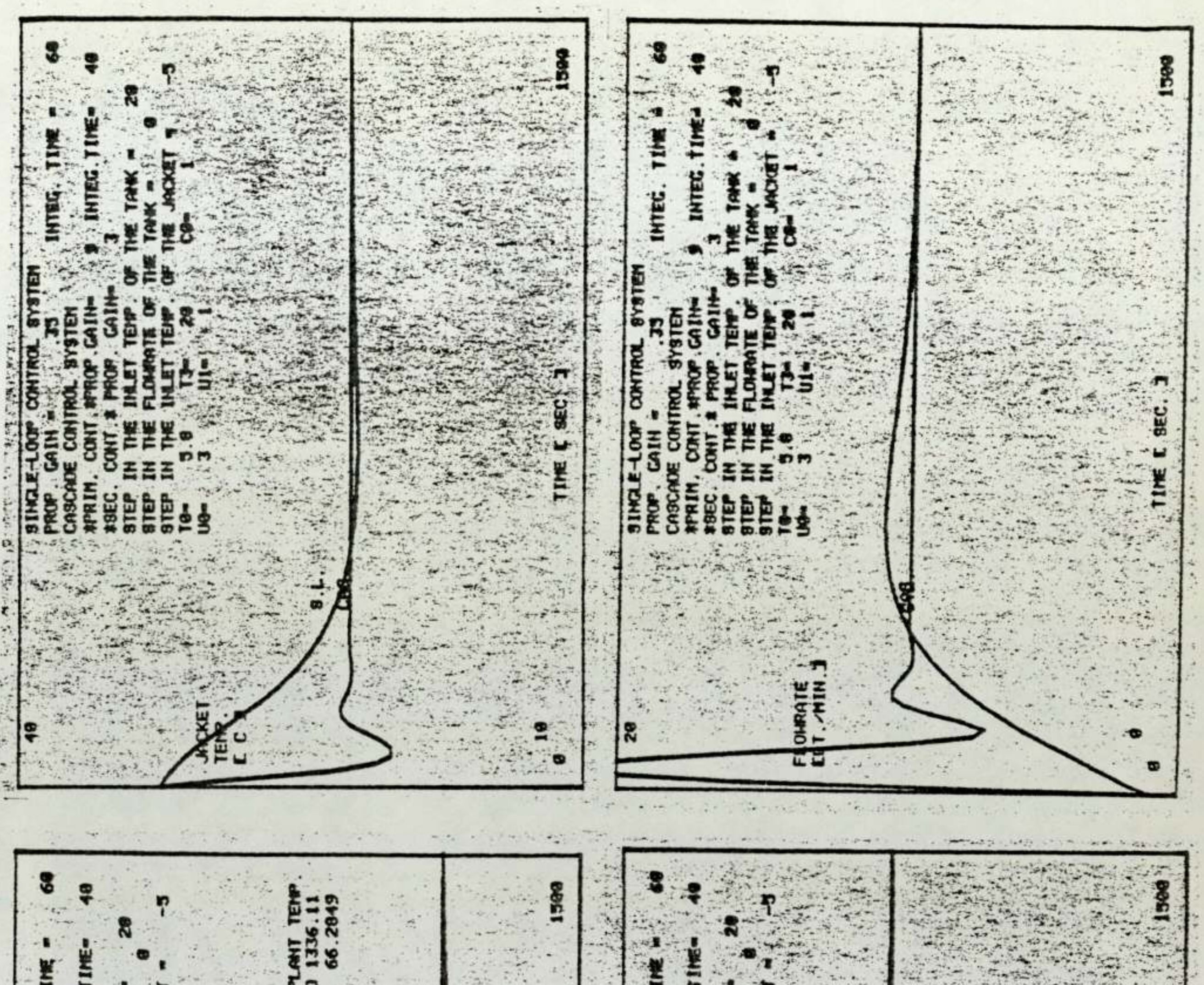

SINGLE-LOOP CONTROL SYSTEM
PROP. GAIN = .35 INTEG. TIME = 60
CASCADE CONTROL SYSTEM
#PRIM. CONT. #PROP.GAIN= 9 INTEG.TIME= 40
#SEC. CONT.# PROP. GAIN= 3
STEP IN THE INLET TEMP. OF THE TANK = 20
STEP IN THE FLOWRATE OF THE TANK = 0
STEP IN THE INLET TEMP. OF THE JACKET = -5
T0= 5.8 T3= 20 C0= 1
U0= 3 U1= 1
INTEGRATED DEVIATION IN PLANT TEMP.
SINGLE-LOOP = 1115.37 AND 1336.11
CASCADE = 34.5403 AND 66.2849
TANK TEMP. [C]
S.L.
CAS
40
33
0
1500
TIME [SEC.]
SINGLE-LOOP CONTROL SYSTEM
PROP. GAIN = .35 INTEG. TIME = 60
CASCADE CONTROL SYSTEM
#PRIM. CONT. #PROP.GAIN= 9 INTEG.TIME= 40
#SEC. CONT.# PROP. GAIN= 3
STEP IN THE INLET TEMP. OF THE TANK = 20
STEP IN THE FLOWRATE OF THE TANK = 0
STEP IN THE INLET TEMP. OF THE JACKET = -5
T0= 5.8 T3= 20 C0= 1
U0= 3 U1= 1
JACKET TEMP. [C]
S.L.
CAS
40
10
0
1500
TIME [SEC.]
SINGLE-LOOP CONTROL SYSTEM
PROP. GAIN = .35 INTEG. TIME = 60
CASCADE CONTROL SYSTEM
#PRIM. CONT. #PROP.GAIN= 9 INTEG.TIME= 40
#SEC. CONT.# PROP. GAIN= 3
STEP IN THE INLET TEMP. OF THE TANK = 20
STEP IN THE FLOWRATE OF THE TANK = 0
STEP IN THE INLET TEMP. OF THE JACKET = -5
T0= 5.8 T3= 20 C0= 1
U0= 3 U1= 1
CONC. [GR./LT.]
S.L.
CAS
1
0
0
1500
TIME [SEC.]
SINGLE-LOOP CONTROL SYSTEM
PROP. GAIN = .35 INTEG. TIME = 60
CASCADE CONTROL SYSTEM
#PRIM. CONT. #PROP.GAIN= 9 INTEG.TIME= 40
#SEC. CONT.# PROP. GAIN= 3
STEP IN THE INLET TEMP. OF THE TANK = 20
STEP IN THE FLOWRATE OF THE TANK = 0
STEP IN THE INLET TEMP. OF THE JACKET = -5
T0= 5.8 T3= 20 C0= 1
U0= 3 U1= 1
FLOWRATE [LT./MIN.]
CAS
20
0
0
1500
TIME [SEC.]

FIG. A.3.6

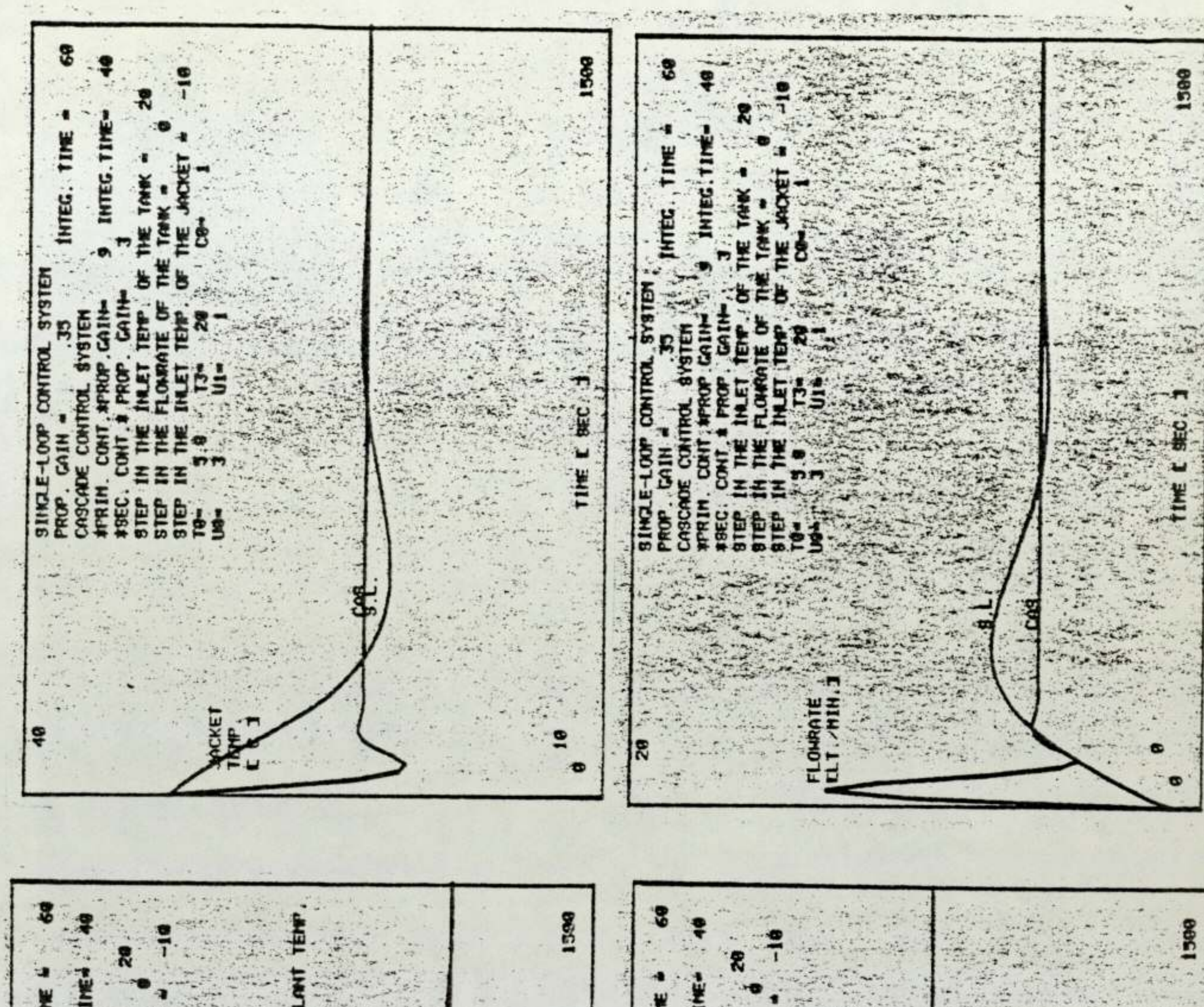

SINGLE-LOOP CONTROL SYSTEM
PROP. GAIN = .35 INTEG. TIME = 60
CASCADE CONTROL SYSTEM
*PRIM. CONT.*PROP.GAIN= 9 INTEG.TIME= 40
SEC. CONT. PROP. GAIN= 3
STEP IN THE INLET TEMP. OF THE TANK = 20
STEP IN THE FLOWRATE OF THE TANK = 0
STEP IN THE INLET TEMP. OF THE JACKET = -10
T0= 5.8 T3= 20 C0= 1
U0= 3 U1= 1
INTEGRATED DEVIATION IN PLANT TEMP.
SINGLE-LOOP = 1030.72
CASCADE = 50.9239
TANK TEMP. [C]
JACKET TEMP. [C]
FLOWRATE [LT./MIN.]
CONC. [GR./LT.]
S.L.
CAS
TIME [SEC.]
1500

FIG. A.3.7

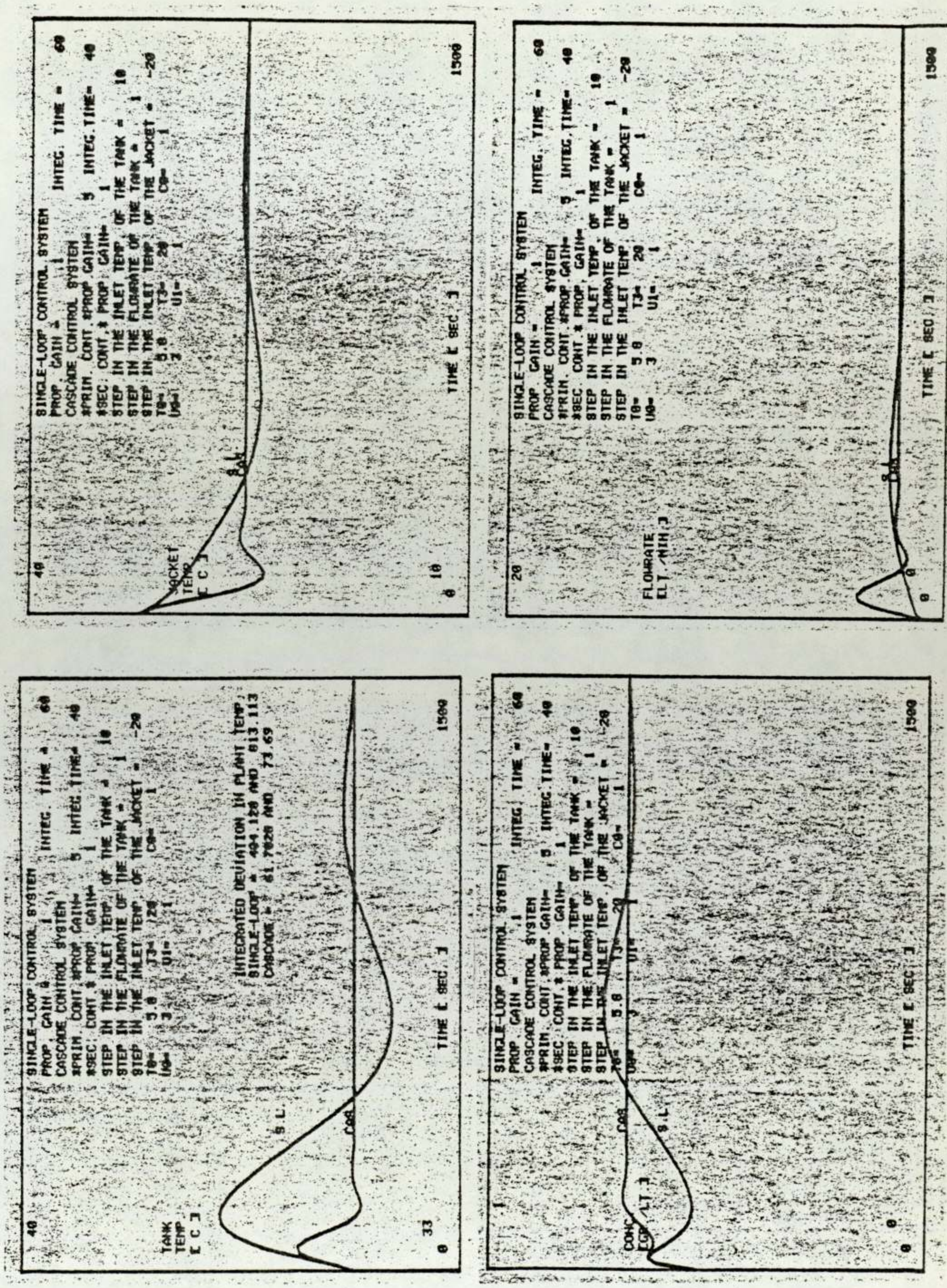
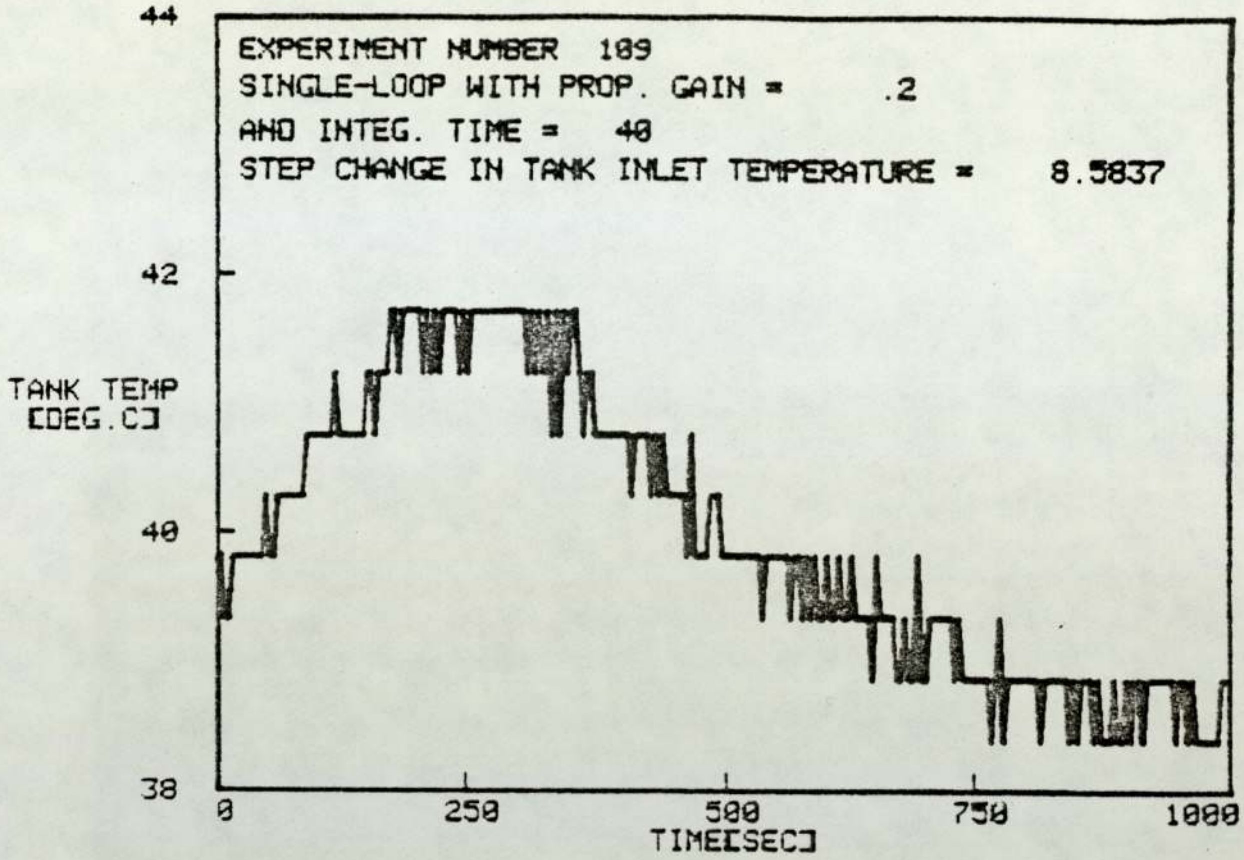
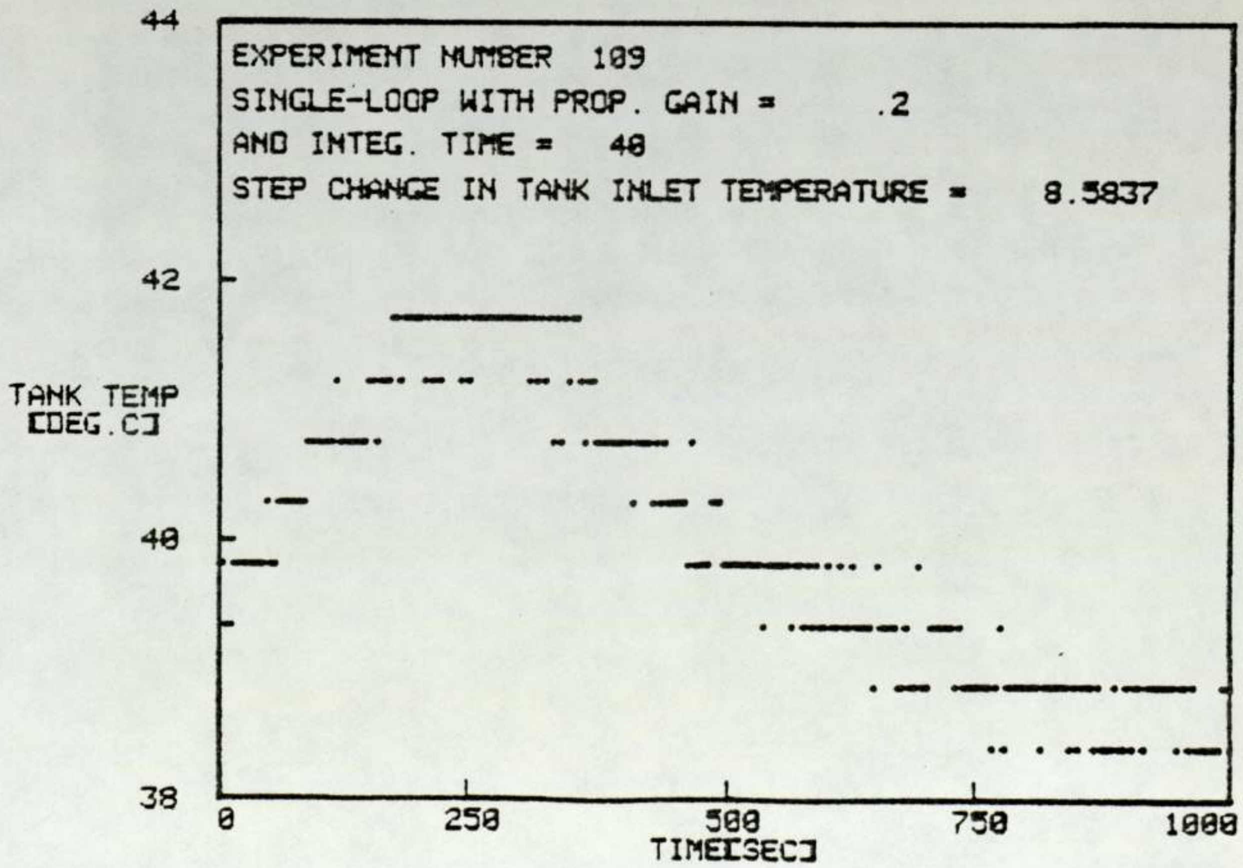

SINGLE-LOOP CONTROL SYSTEM
PROP. GAIN = 1 INTEG. TIME = 60
CASCADE CONTROL SYSTEM
#PRIM. CONT.#PROP.GAIN= 5 INTEG.TIME= 40
#SEC. CONT.# PROP. GAIN= 1
STEP IN THE INLET TEMP. OF THE TANK = 10
STEP IN THE FLOWRATE OF THE TANK = 1
STEP IN THE INLET TEMP. OF THE JACKET = -20
T0= 5.8 T3= 20 C0= 1
U0= 3 U1= 1
JACKET TEMP. [C]
S.L.
CAS.
TIME [SEC.]
40
10
0
1500
FLOWRATE [LT./MIN.]
20
0
TANK TEMP. [C]
INTEGRATED DEVIATION IN PLANT TEMP.;
SINGLE-LOOP = 404.128 AND 813.113
CASCADE = 61.7828 AND 73.69
33
CONC. [GR./LT.]

FIG. A.3.8

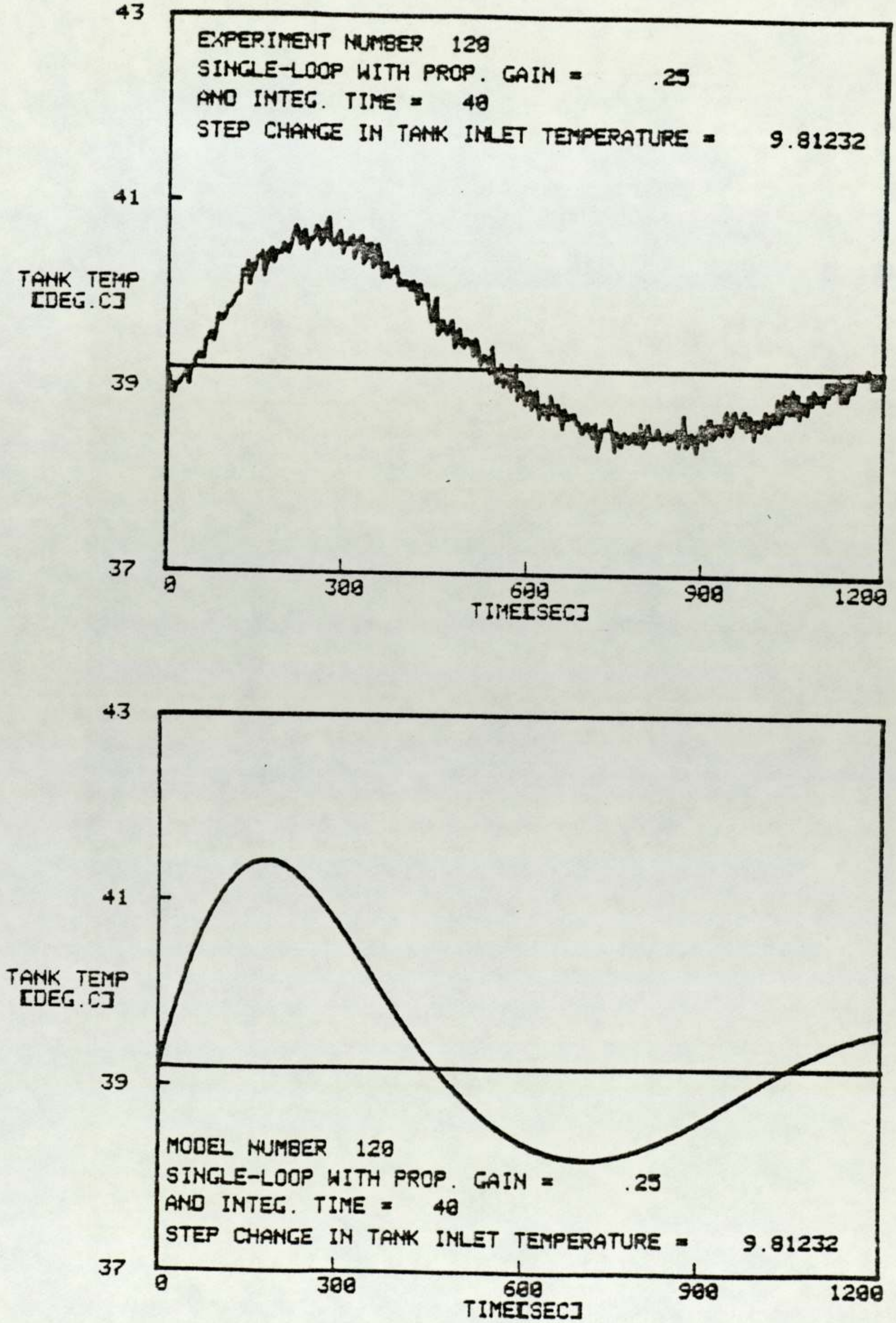


EXPERIMENT NUMBER 109
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 8.5837
44
42
40
38
TANK TEMP
[DEG.C]
0
250
500
750
1000
TIME[SEC]



EXPERIMENT NUMBER 109
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 8.5837
44
42
40
38
TANK TEMP
[DEG.C]
0
250
500
750
1000
TIME[SEC]

FIG. A.3.9a



EXPERIMENT NUMBER 120
SINGLE-LOOP WITH PROP. GAIN = .25
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 9.81232
TANK TEMP [DEG.C]
43
41
39
37
0
300
600
900
1200
TIME[SEC]
MODEL NUMBER 120
SINGLE-LOOP WITH PROP. GAIN = .25
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 9.81232
TANK TEMP [DEG.C]
TIME[SEC]

FIG. A.3.9b

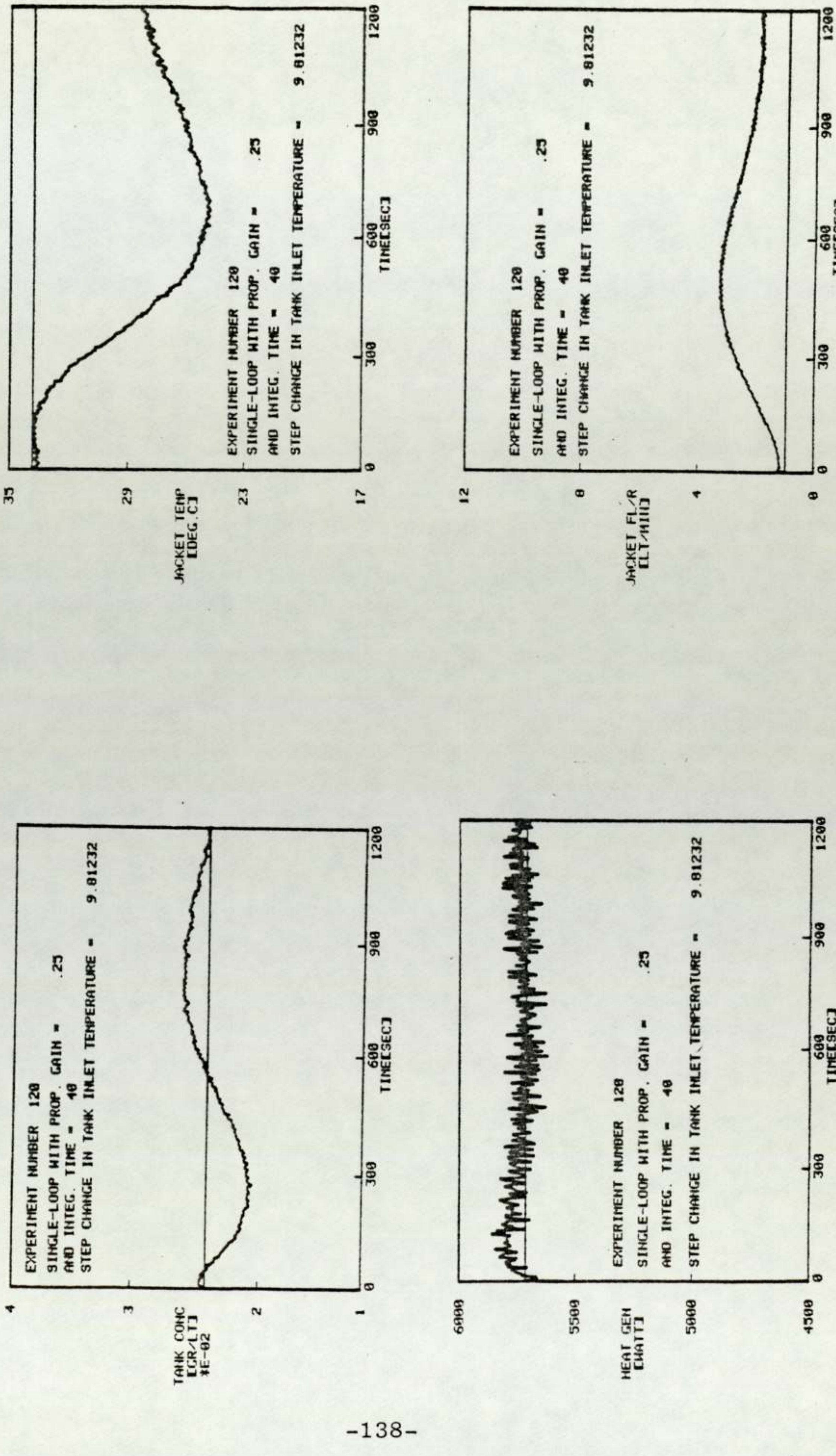
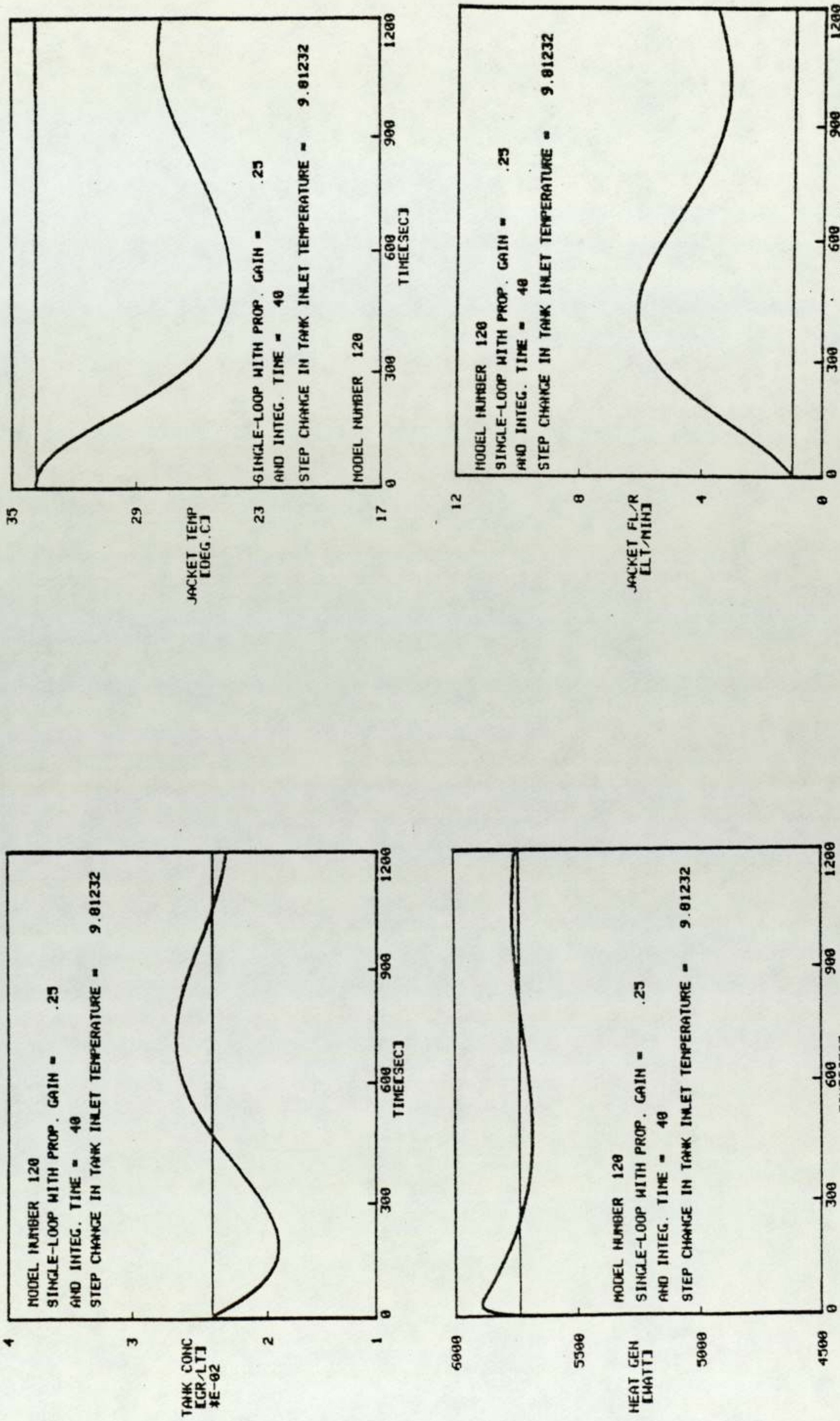
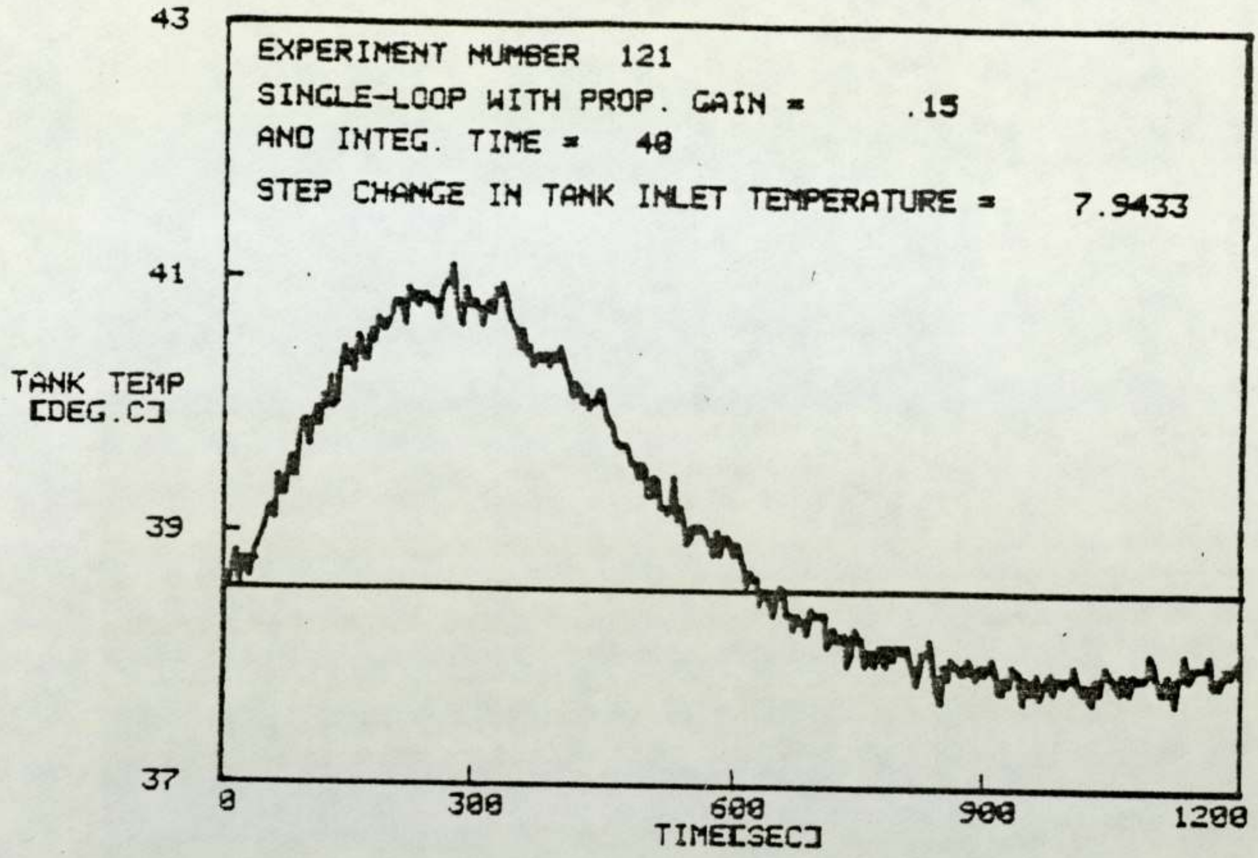

EXPERIMENT NUMBER 120
SINGLE-LOOP WITH PROP. GAIN = .25
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 9.81232
JACKET TEMP [DEG.C]
35
29
23
17
0
300
600
900
1200
TIME[SEC]
EXPERIMENT NUMBER 120
SINGLE-LOOP WITH PROP. GAIN = .25
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 9.81232
JACKET FL/R [LT/MIN]
12
8
4
0
0
300
600
900
1200
TIME[SEC]
EXPERIMENT NUMBER 120
SINGLE-LOOP WITH PROP. GAIN = .25
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 9.81232
TANK CONC [GR/LT] *E-02
4
3
2
1
0
300
600
900
1200
TIME[SEC]
EXPERIMENT NUMBER 120
SINGLE-LOOP WITH PROP. GAIN = .25
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 9.81232
HEAT GEN [WATT]
6000
5500
5000
4500
0
300
600
900
1200
TIME[SEC]

FIG. A.3.9c


MODEL NUMBER 120
SINGLE-LOOP WITH PROP. GAIN = .25
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 9.81232
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
JACKET TEMP [DEG.C]
JACKET FL/R [LT/MIN]
TIME[SEC]

FIG, A,3,10


EXPERIMENT NUMBER 121
SINGLE-LOOP WITH PROP. GAIN = .15
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 7.9433
43
41
39
37
TANK TEMP [DEG.C]
0
300
600
900
1200
TIME[SEC]

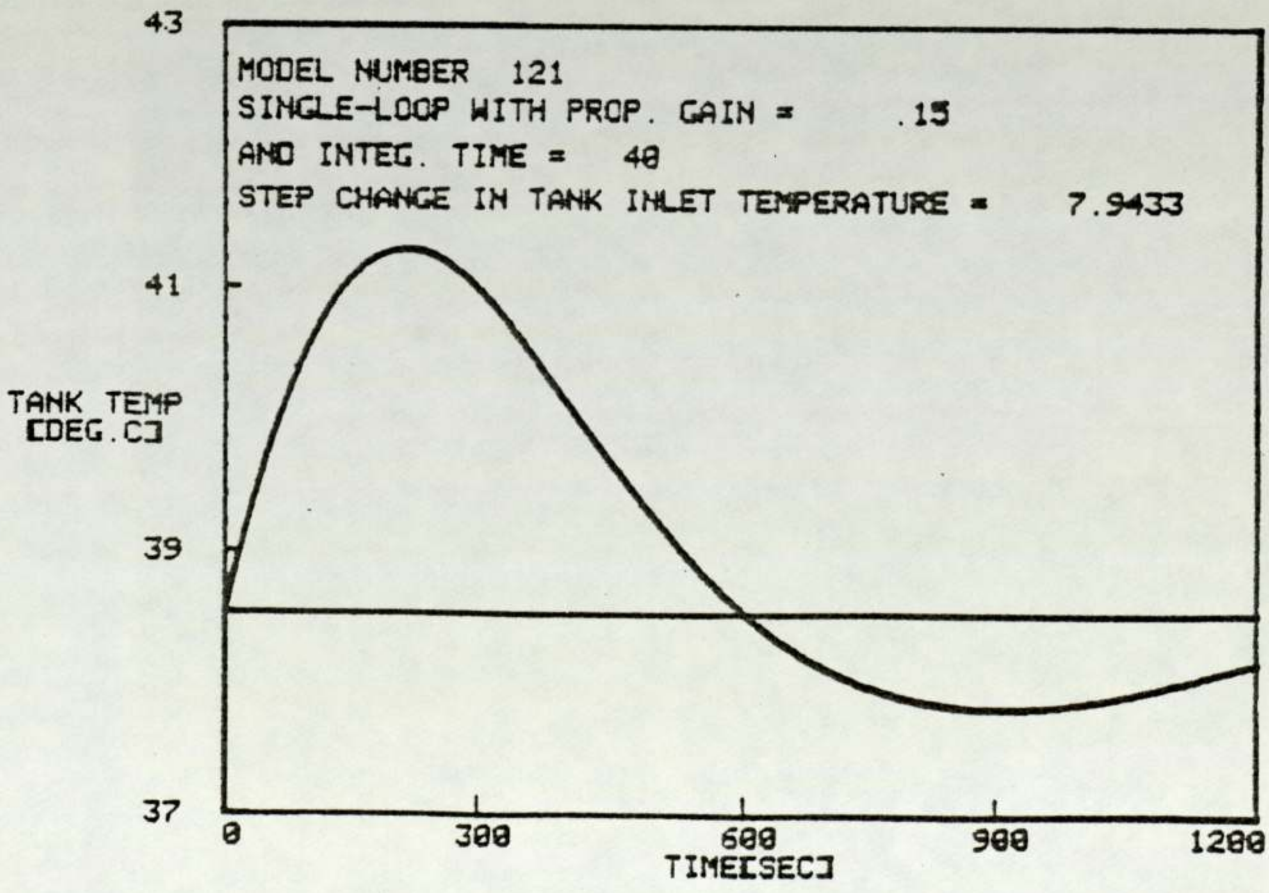
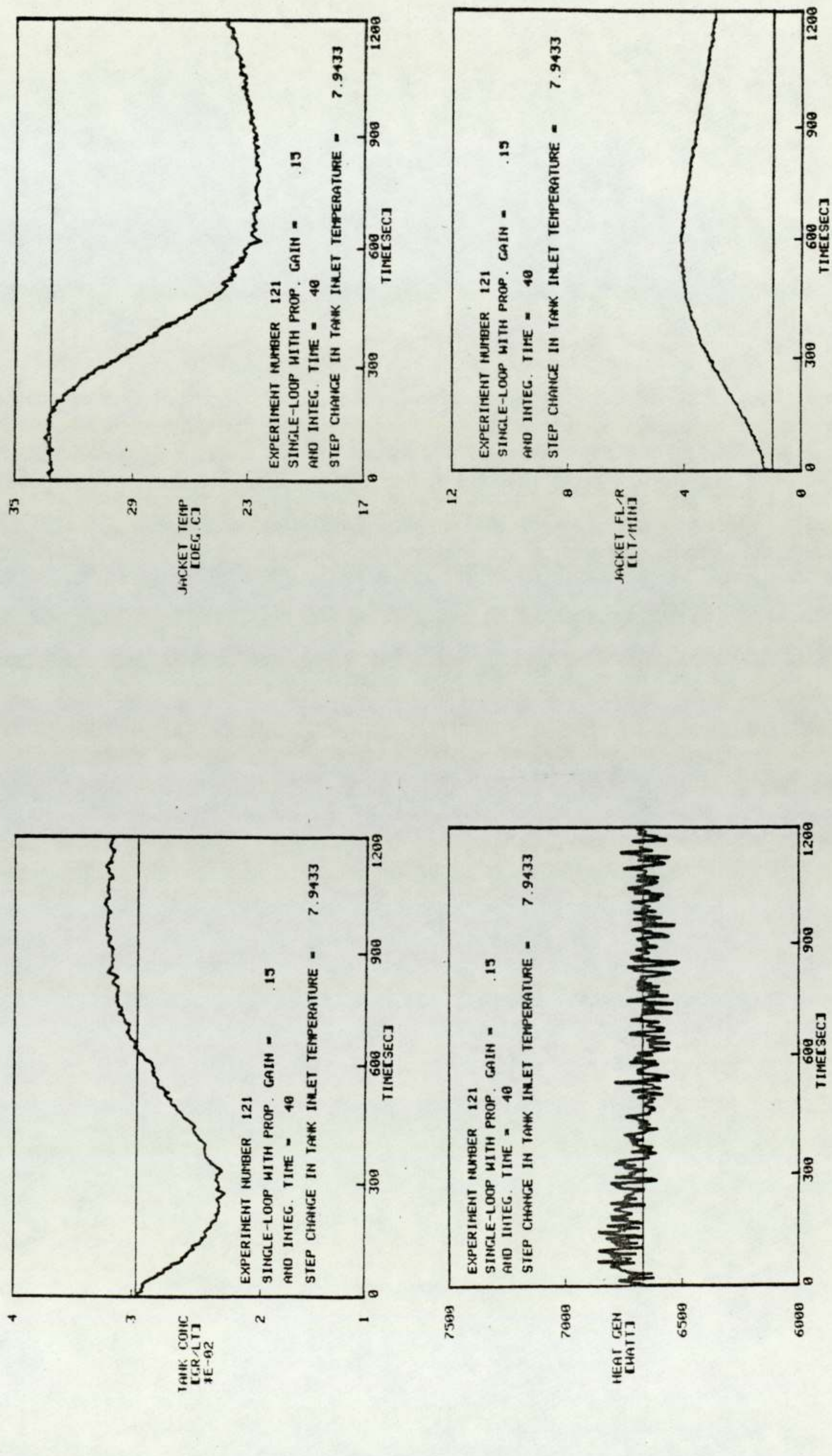

MODEL NUMBER 121
SINGLE-LOOP WITH PROP. GAIN = .15
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 7.9433
43
41
39
37
TANK TEMP [DEG.C]
0
300
600
900
1200
TIME[SEC]

FIG. A.3.11



JACKET TEMP [DEG C]
EXPERIMENT NUMBER 121
SINGLE-LOOP WITH PROP. GAIN = .15
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 7.9433
TIME[SEC]
JACKET FL/R [LT/MIN]
EXPERIMENT NUMBER 121
SINGLE-LOOP WITH PROP. GAIN = .15
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 7.9433
TIME[SEC]
TANK CONC [GR/LT] *E-02
EXPERIMENT NUMBER 121
SINGLE-LOOP WITH PROP. GAIN = .15
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 7.9433
TIME[SEC]
HEAT GEN [WATT]
EXPERIMENT NUMBER 121
SINGLE-LOOP WITH PROP. GAIN = .15
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 7.9433
TIME[SEC]

FIG. A.3.12

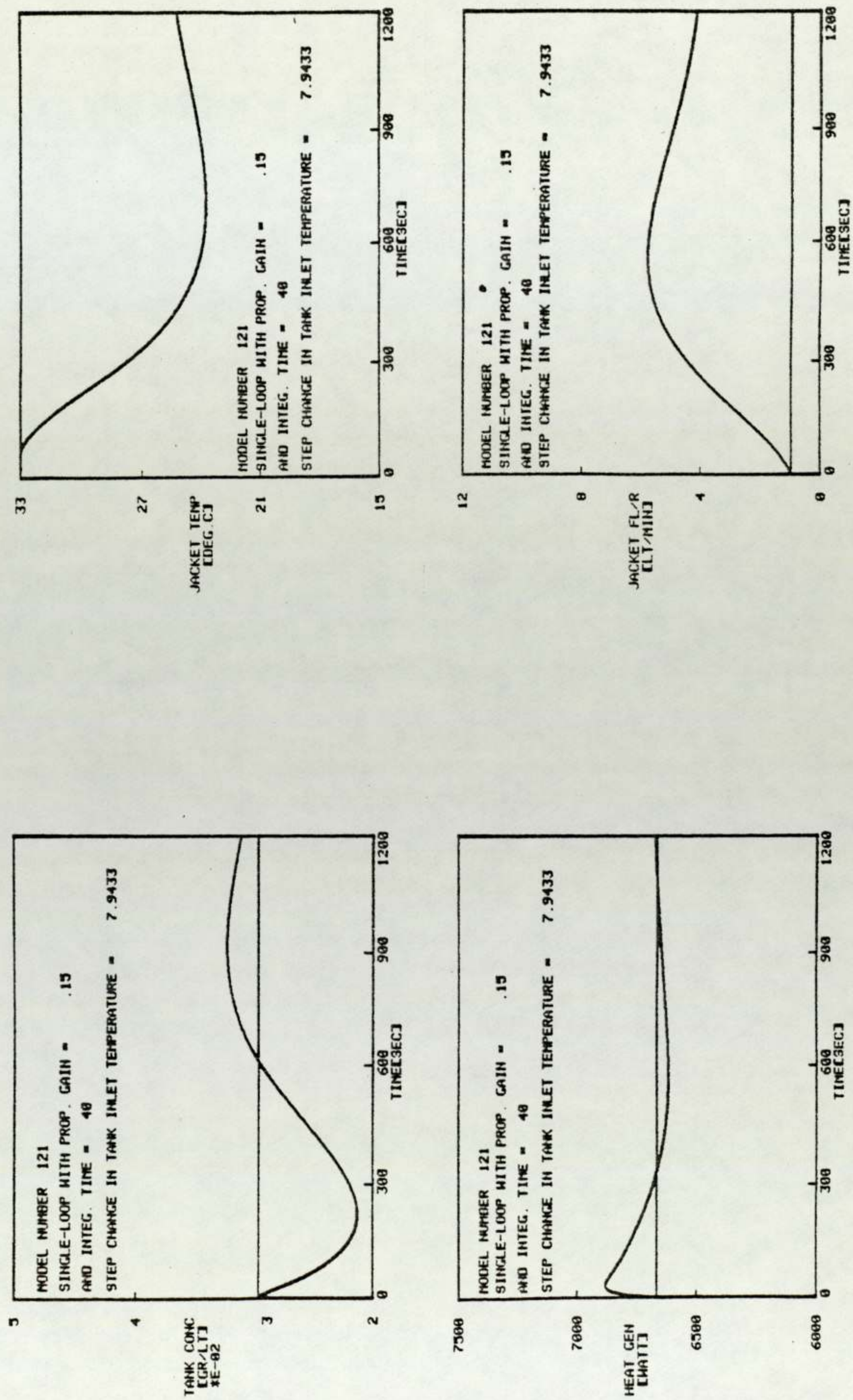
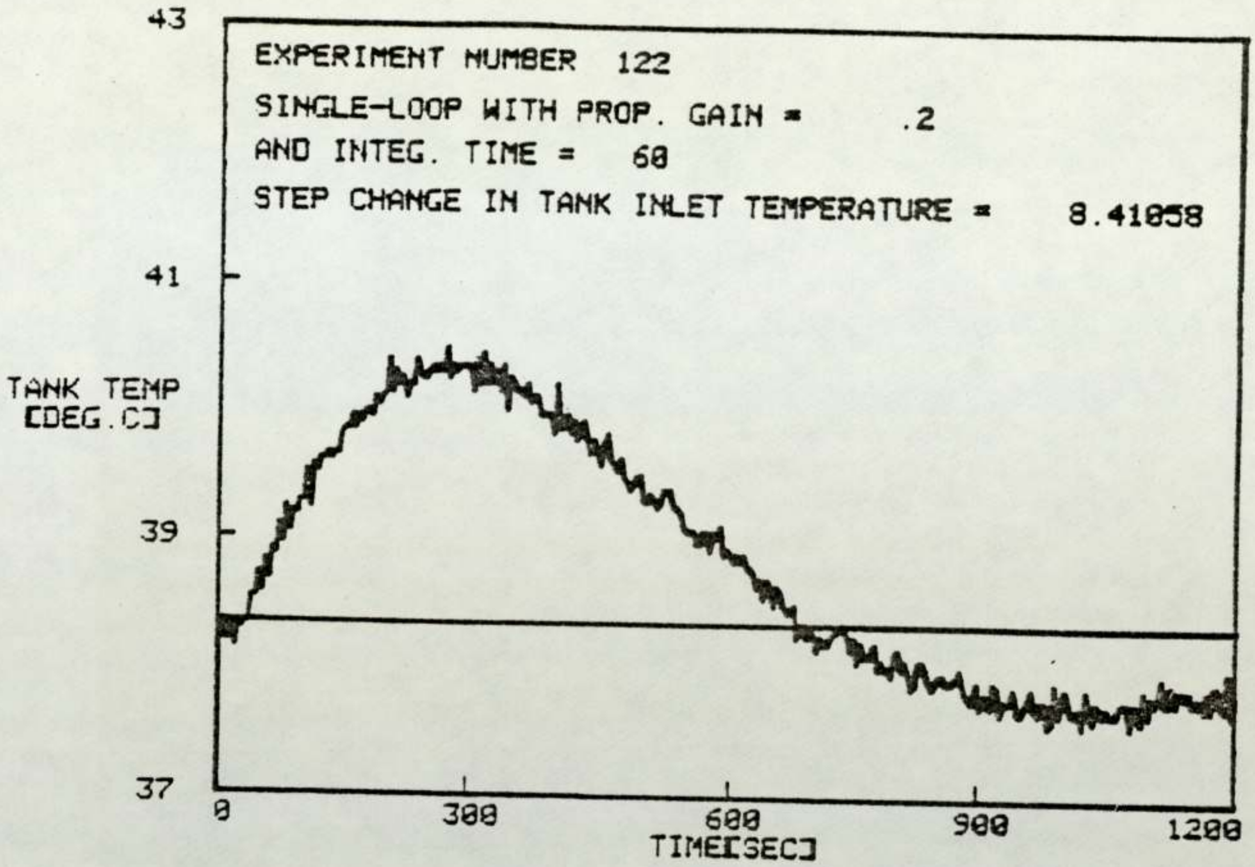

MODEL NUMBER 121
SINGLE-LOOP WITH PROP. GAIN = .15
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 7.9433
JACKET TEMP [DEG.C]
JACKET FL/R [LT/MIN]
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
TIME[SEC]

FIG. A.3.13


EXPERIMENT NUMBER 122
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 8.41058
43
41
39
37
TANK TEMP [DEG.C]
0
300
600
900
1200
TIME[SEC]

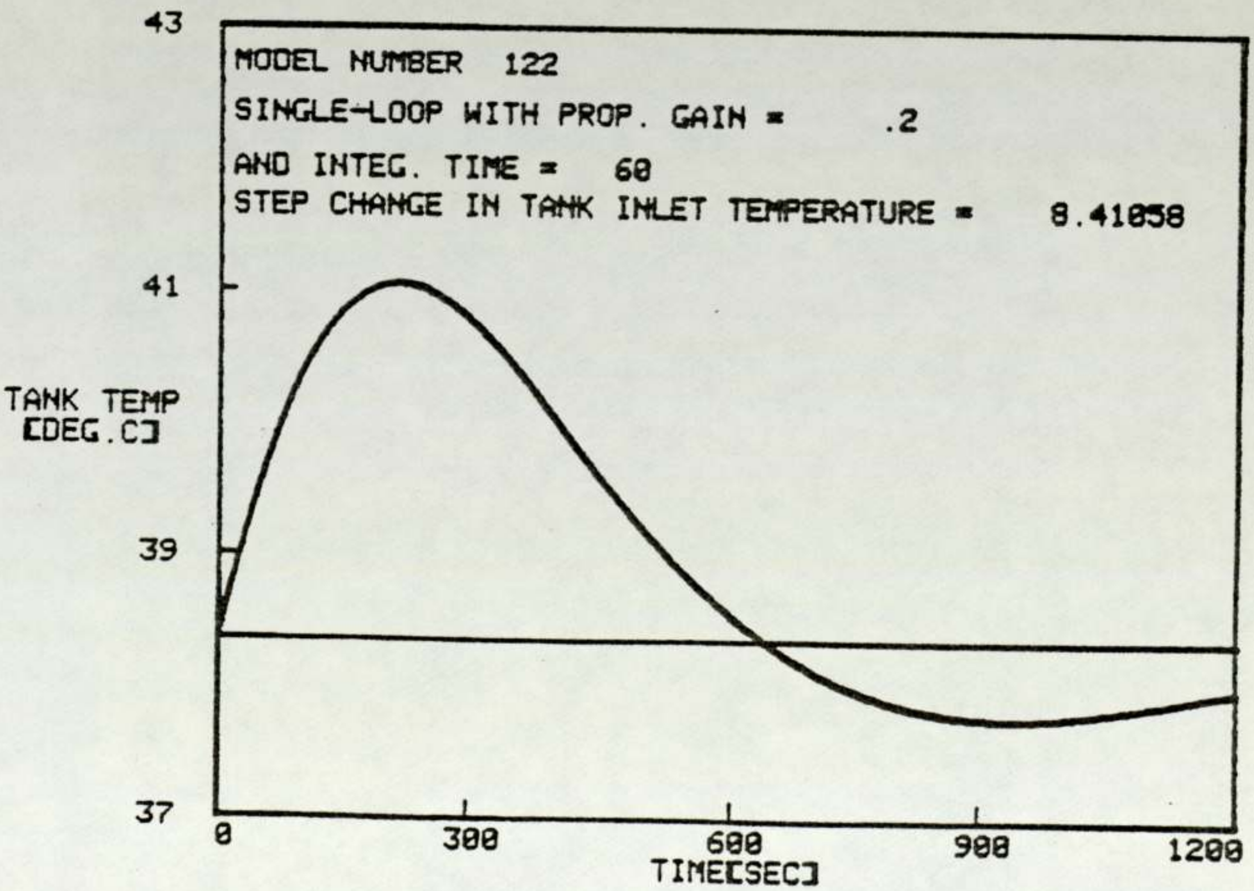

MODEL NUMBER 122
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 8.41058
43
41
39
37
TANK TEMP [DEG.C]
0
300
600
900
1200
TIME[SEC]

FIG. A.3.14

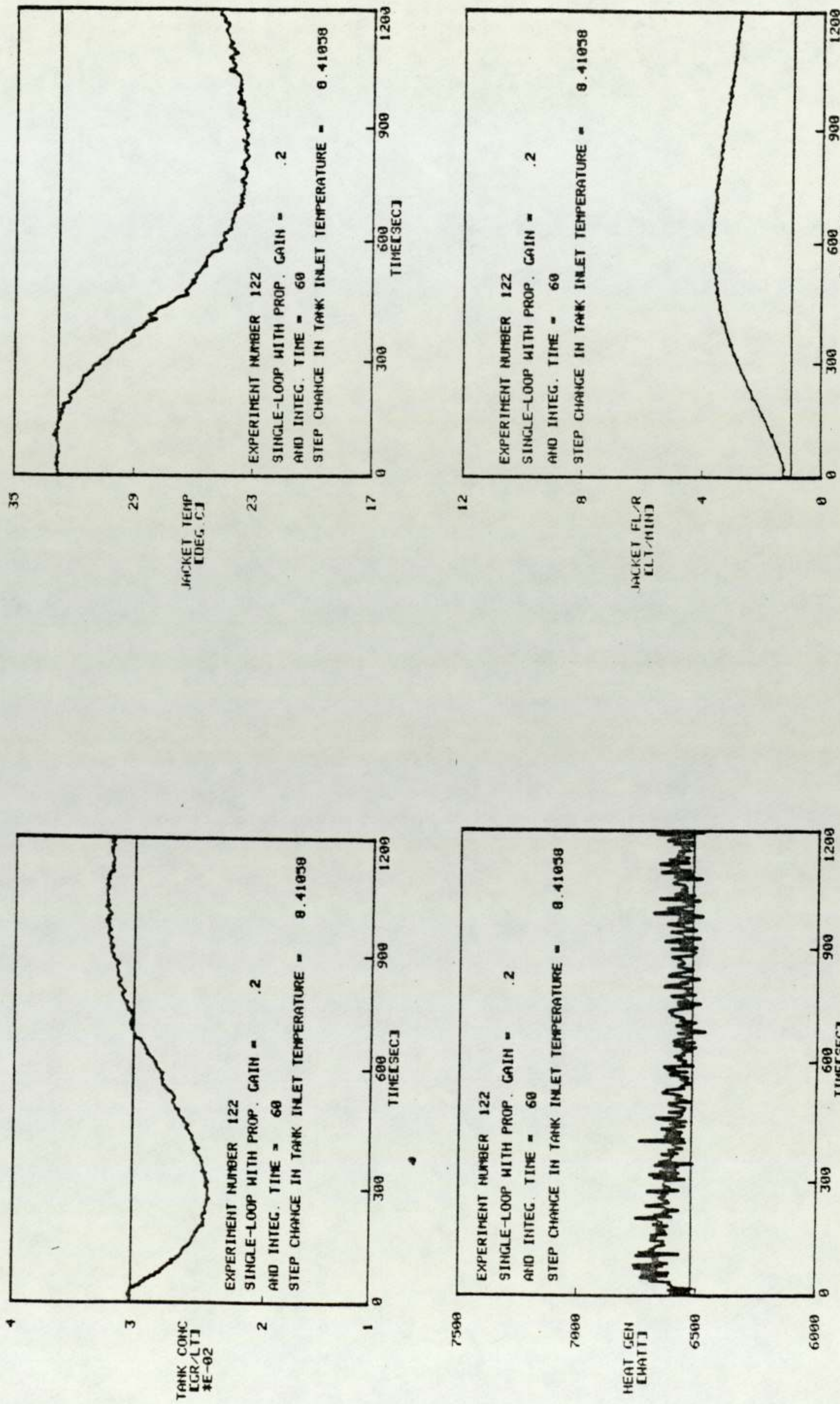
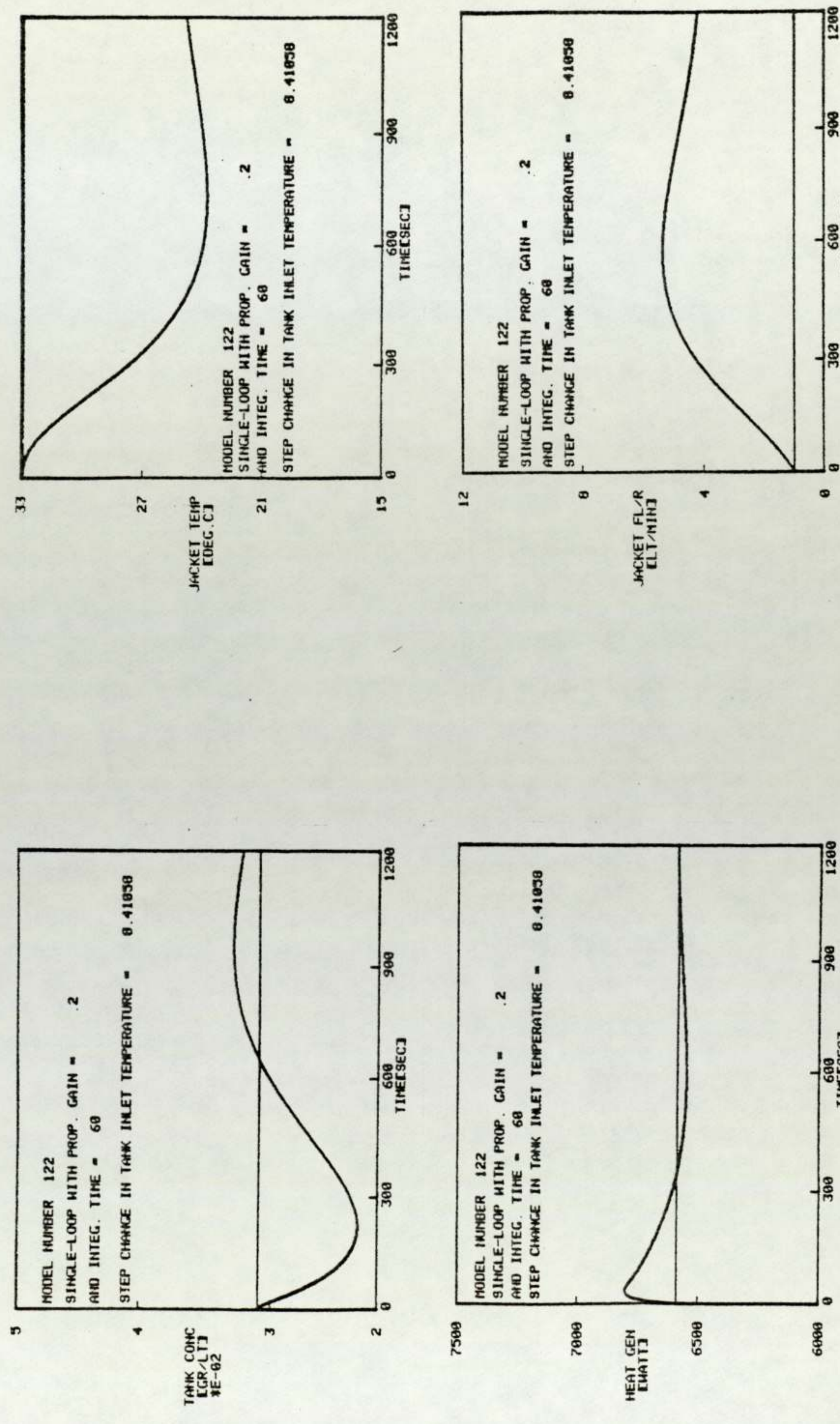
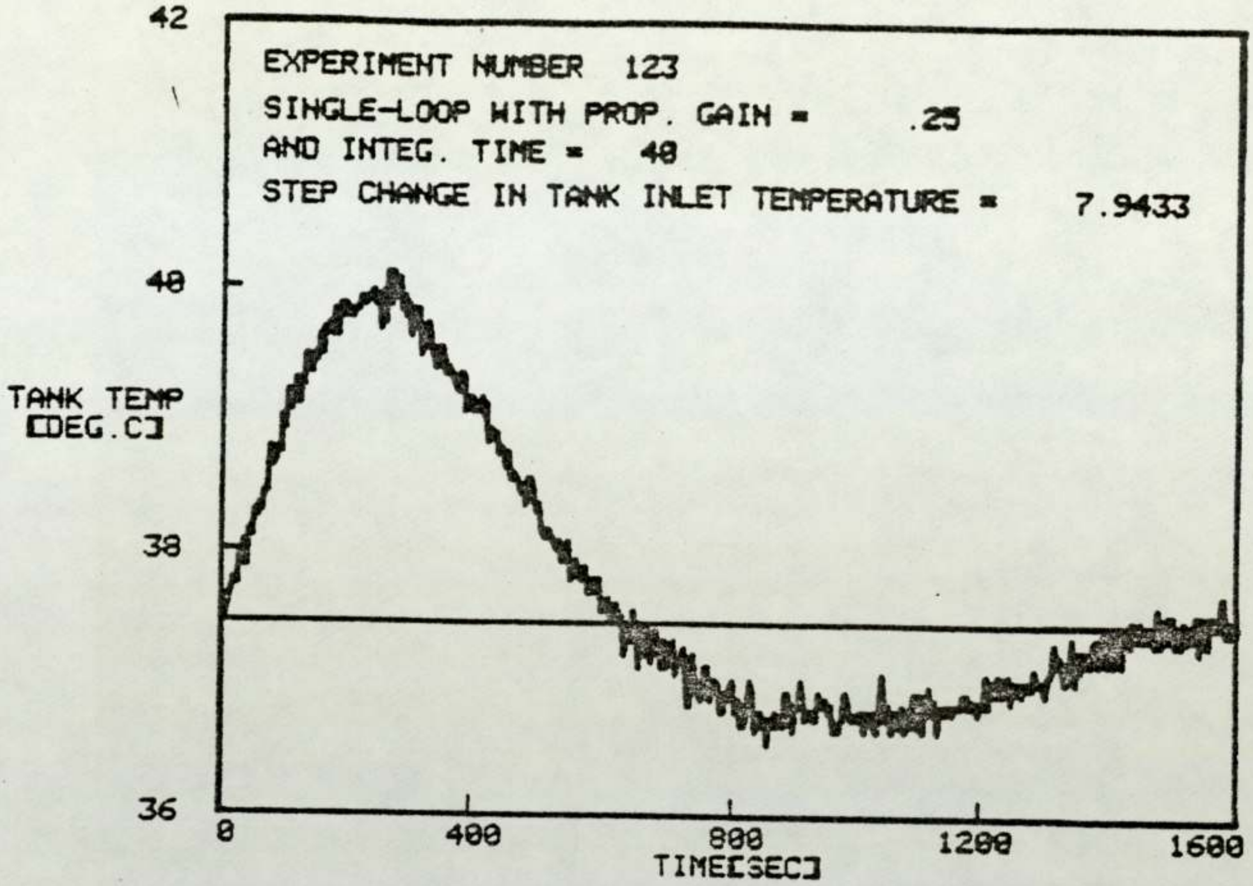

EXPERIMENT NUMBER 122
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 0.41058
JACKET TEMP [DEG C]
JACKET FL/R [LT/MIN]
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
TIME[SEC]
0
300
600
900
1200
35
29
23
17
12
8
4
3
2
1
7500
7000
6500
6000

FIG. A.3.15

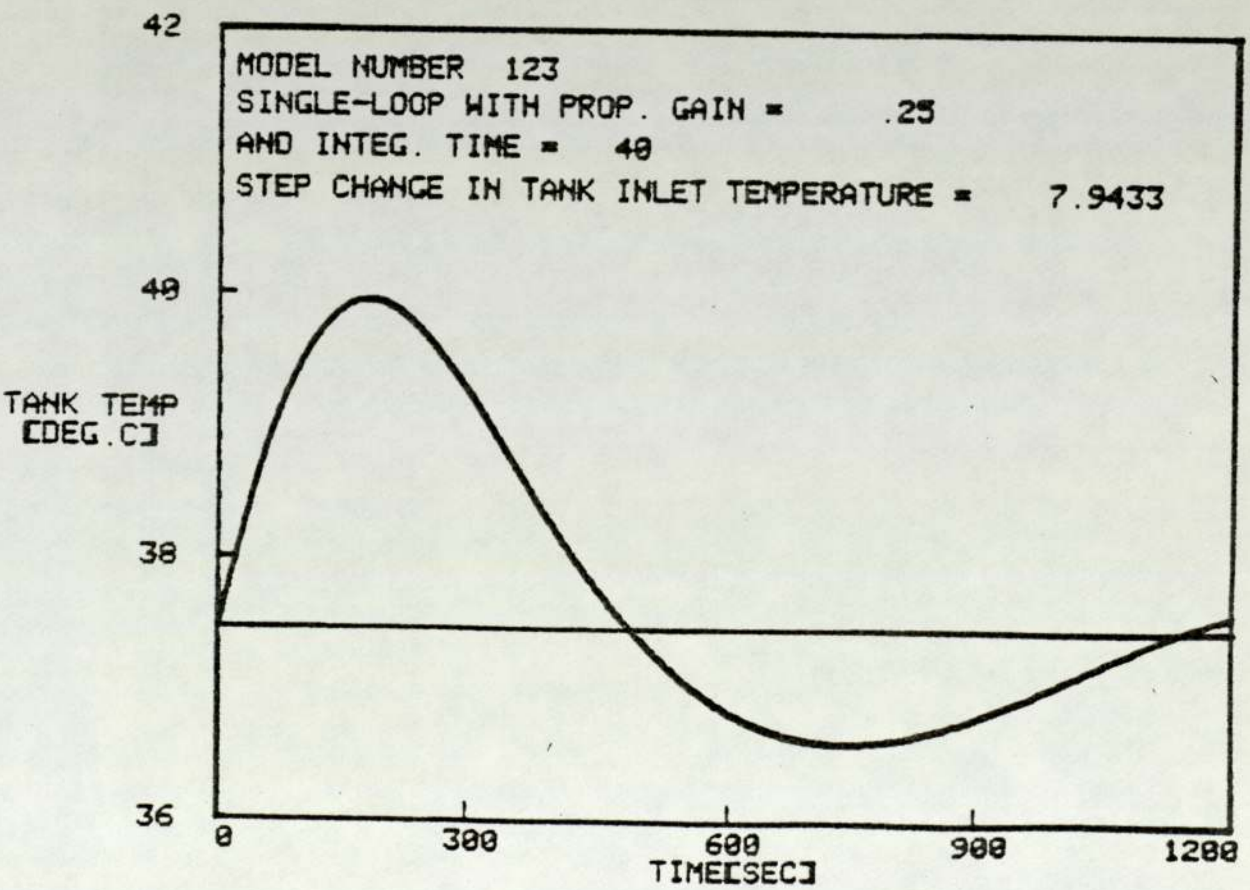


MODEL NUMBER 122
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 0.41050
JACKET TEMP [DEG.C]
JACKET FL/R [LT/MIN]
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
TIME[SEC]

FIG. A.3.16

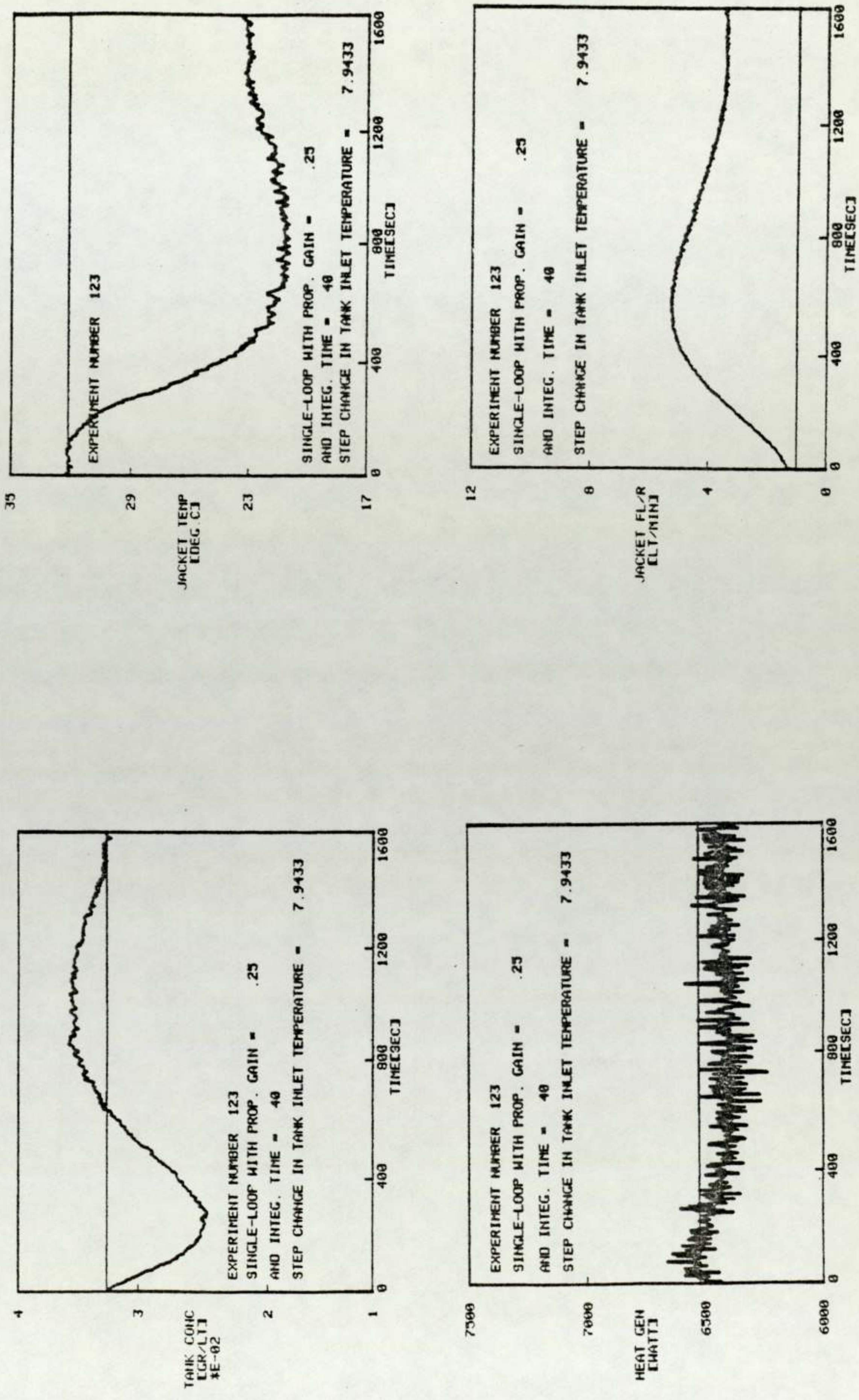


EXPERIMENT NUMBER 123
SINGLE-LOOP WITH PROP. GAIN = .25
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 7.9433
42
40
38
36
TANK TEMP [DEG.C]
0
400
800
1200
1600
TIME[SEC]



MODEL NUMBER 123
SINGLE-LOOP WITH PROP. GAIN = .25
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 7.9433
42
40
38
36
TANK TEMP [DEG.C]
0
300
600
900
1200
TIME[SEC]

FIG. A.3.17



EXPERIMENT NUMBER 123
SINGLE-LOOP WITH PROP. GAIN = .25
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 7.9433
JACKET TEMP [DEG.C]
35
29
23
17
0
400
800
1200
1600
TIME[SEC]
EXPERIMENT NUMBER 123
SINGLE-LOOP WITH PROP. GAIN = .25
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 7.9433
JACKET FL/R [LT/MIN]
12
8
4
0
0
400
800
1200
1600
TIME[SEC]
EXPERIMENT NUMBER 123
SINGLE-LOOP WITH PROP. GAIN = .25
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 7.9433
TANK CONC [GR/LT] *E-02
4
3
2
1
0
400
800
1200
1600
TIME[SEC]
EXPERIMENT NUMBER 123
SINGLE-LOOP WITH PROP. GAIN = .25
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 7.9433
HEAT GEN [WATT]
7500
7000
6500
6000
0
400
800
1200
1600
TIME[SEC]

FIG. A.3.18

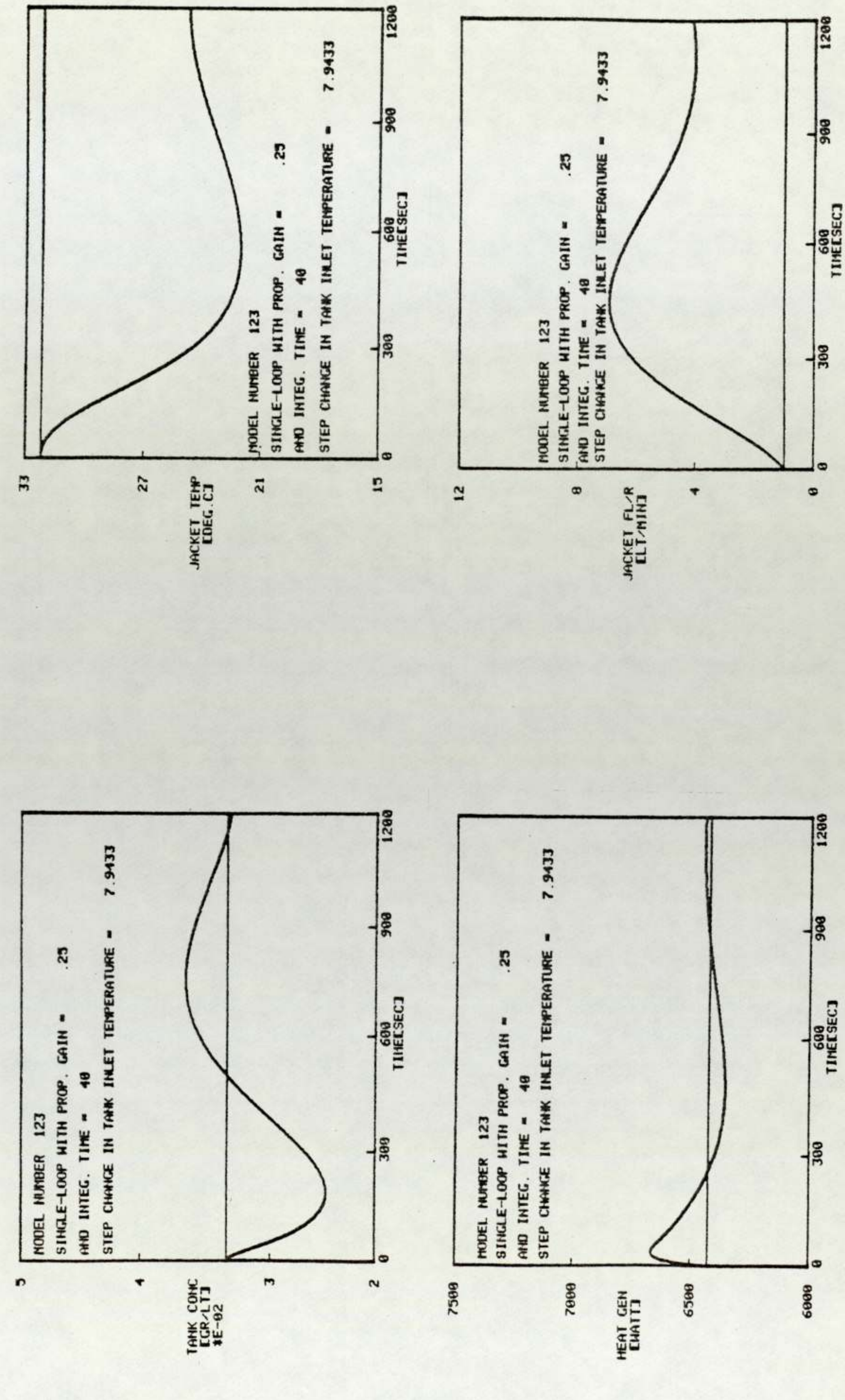
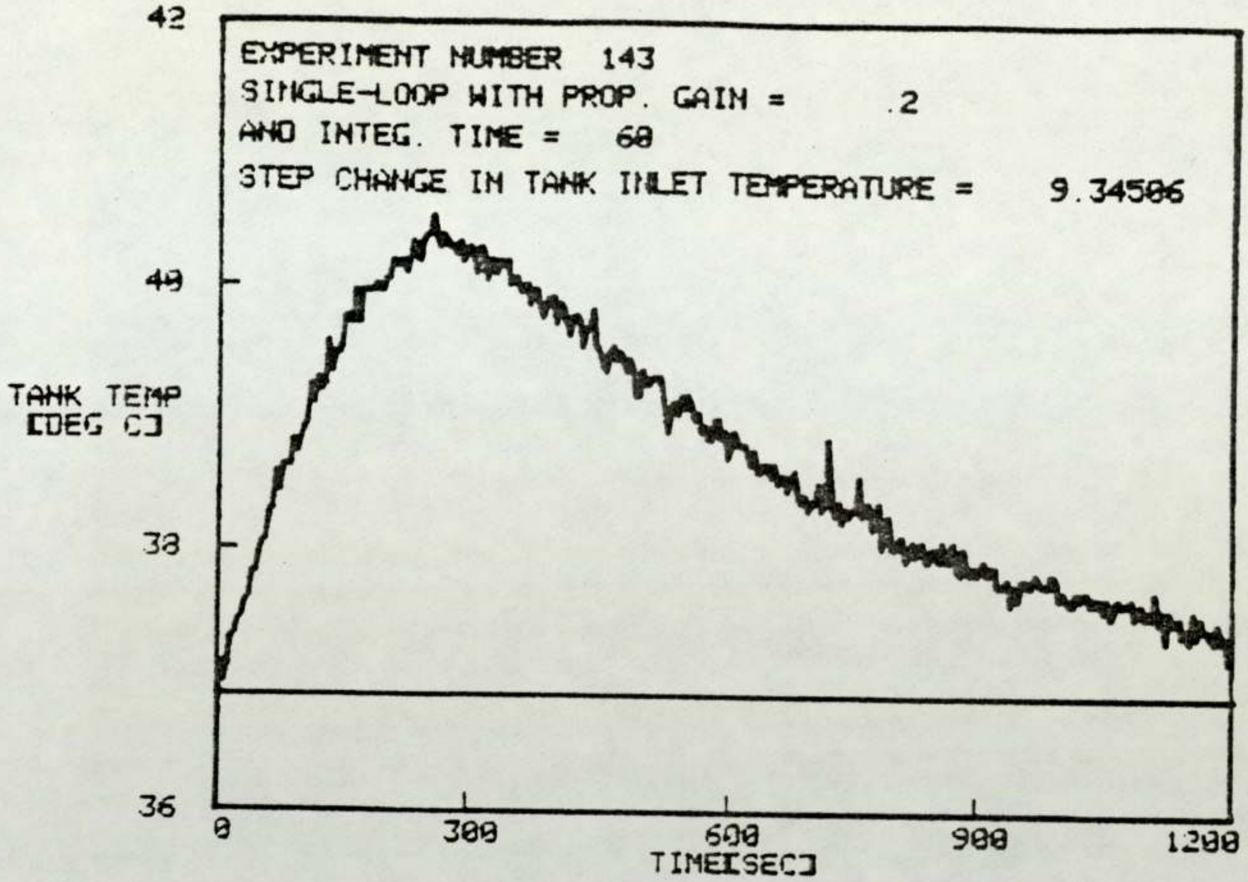

MODEL NUMBER 123
SINGLE-LOOP WITH PROP. GAIN = .25
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 7.9433
JACKET TEMP [DEG.C]
33
27
21
15
0
300
600
900
1200
TIME[SEC]
JACKET FL/R [LT/MIN]
12
8
4
0
TANK CONC [GR/LT] *E-02
5
4
3
2
HEAT GEN [WATT]
7500
7000
6500
6000

FIG. A.3.19


EXPERIMENT NUMBER 143
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 9.34506
42
40
38
36
TANK TEMP
[DEG C]
0
300
600
900
1200
TIME[SEC]

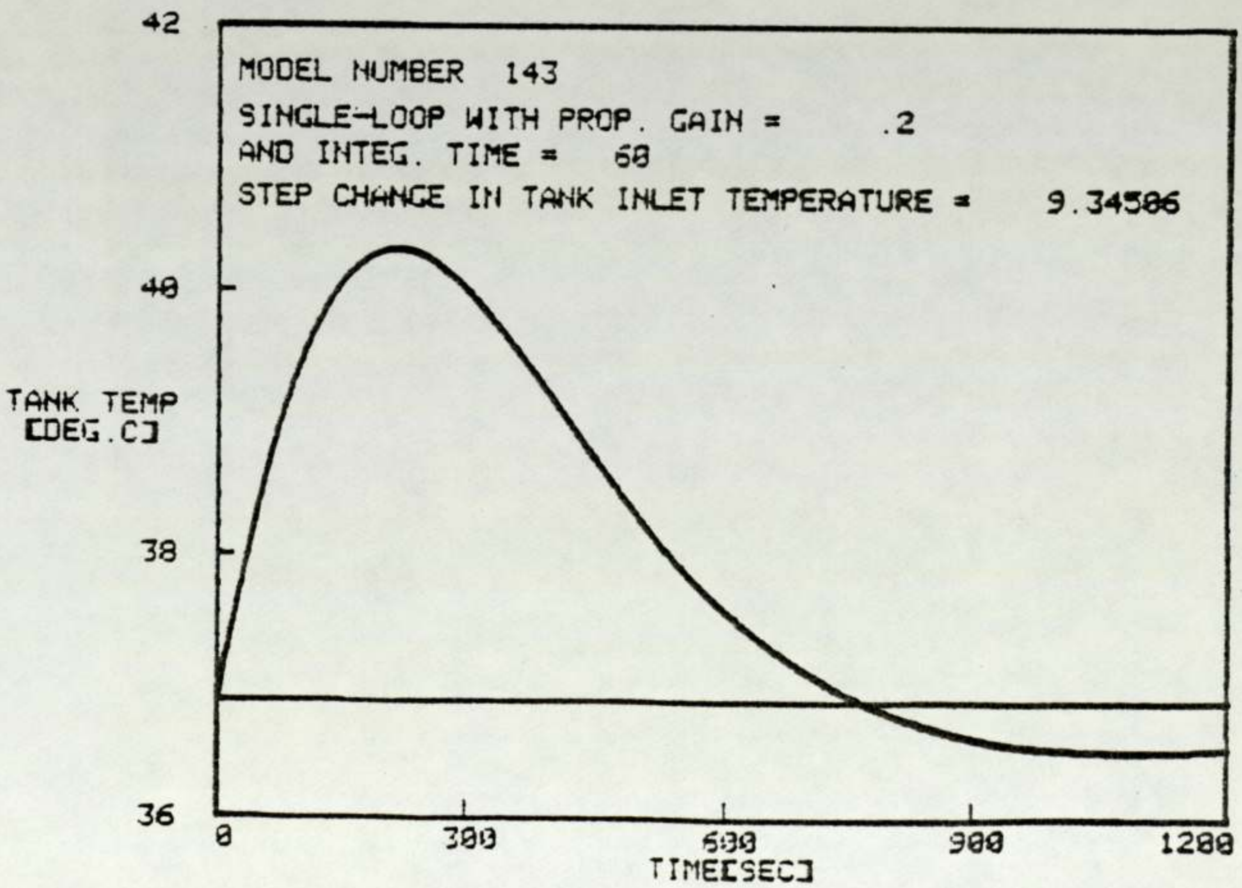

MODEL NUMBER 143
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 9.34506
42
40
38
36
TANK TEMP
[DEG.C]
0
300
600
900
1200
TIME[SEC]

FIG. A.3.20

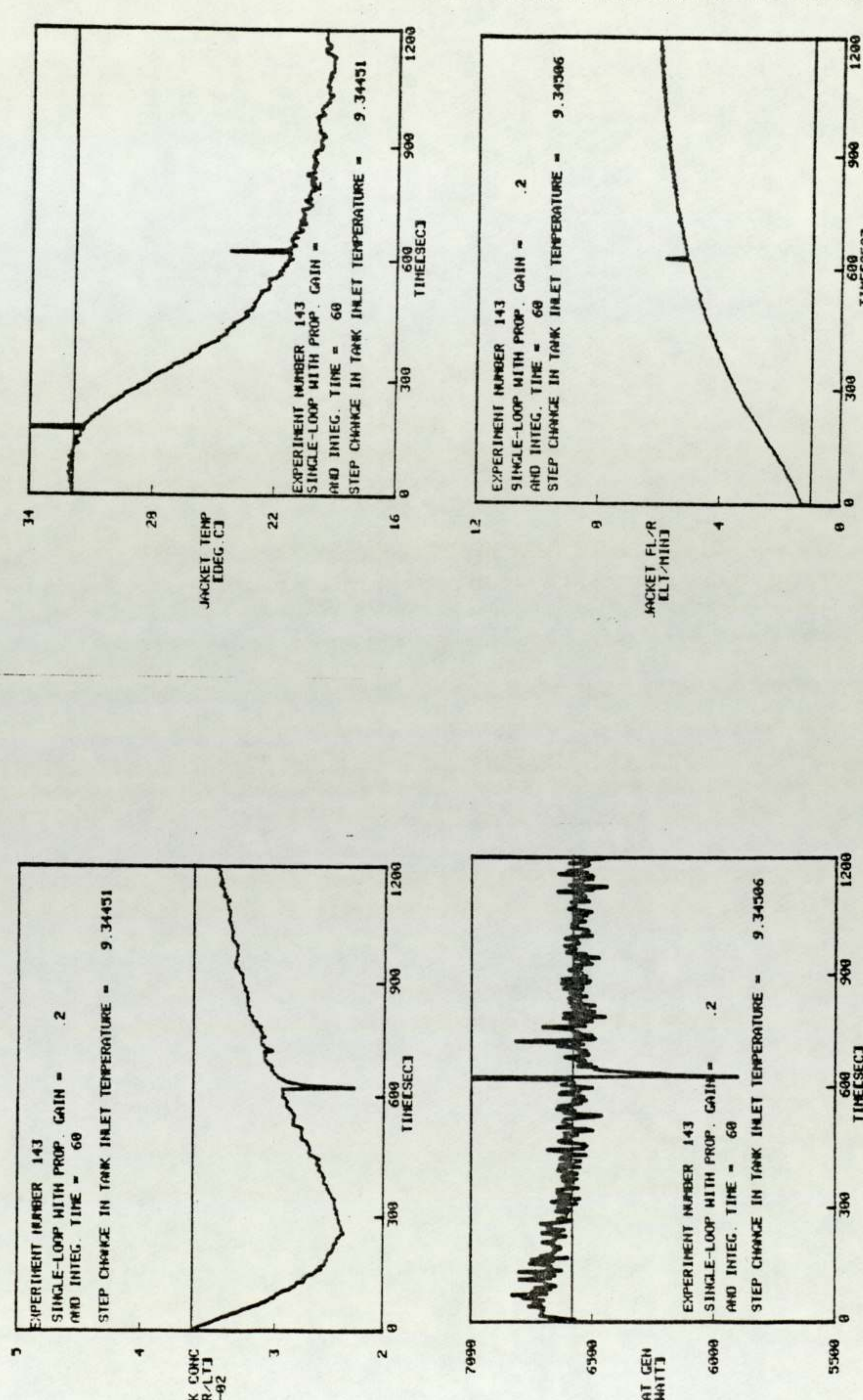

EXPERIMENT NUMBER 143
SINGLE-LOOP WITH PROP. GAIN =
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 9.34451
JACKET TEMP [DEG.C]
TIME[SEC]
EXPERIMENT NUMBER 143
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 9.34506
JACKET FL/R [LT/MIN]
TIME[SEC]
EXPERIMENT NUMBER 143
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 9.34451
TANK CONC [GR/LT] *E-02
TIME[SEC]
EXPERIMENT NUMBER 143
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 9.34506
HEAT GEN [WATT]
TIME[SEC]

FIG. A.3.21

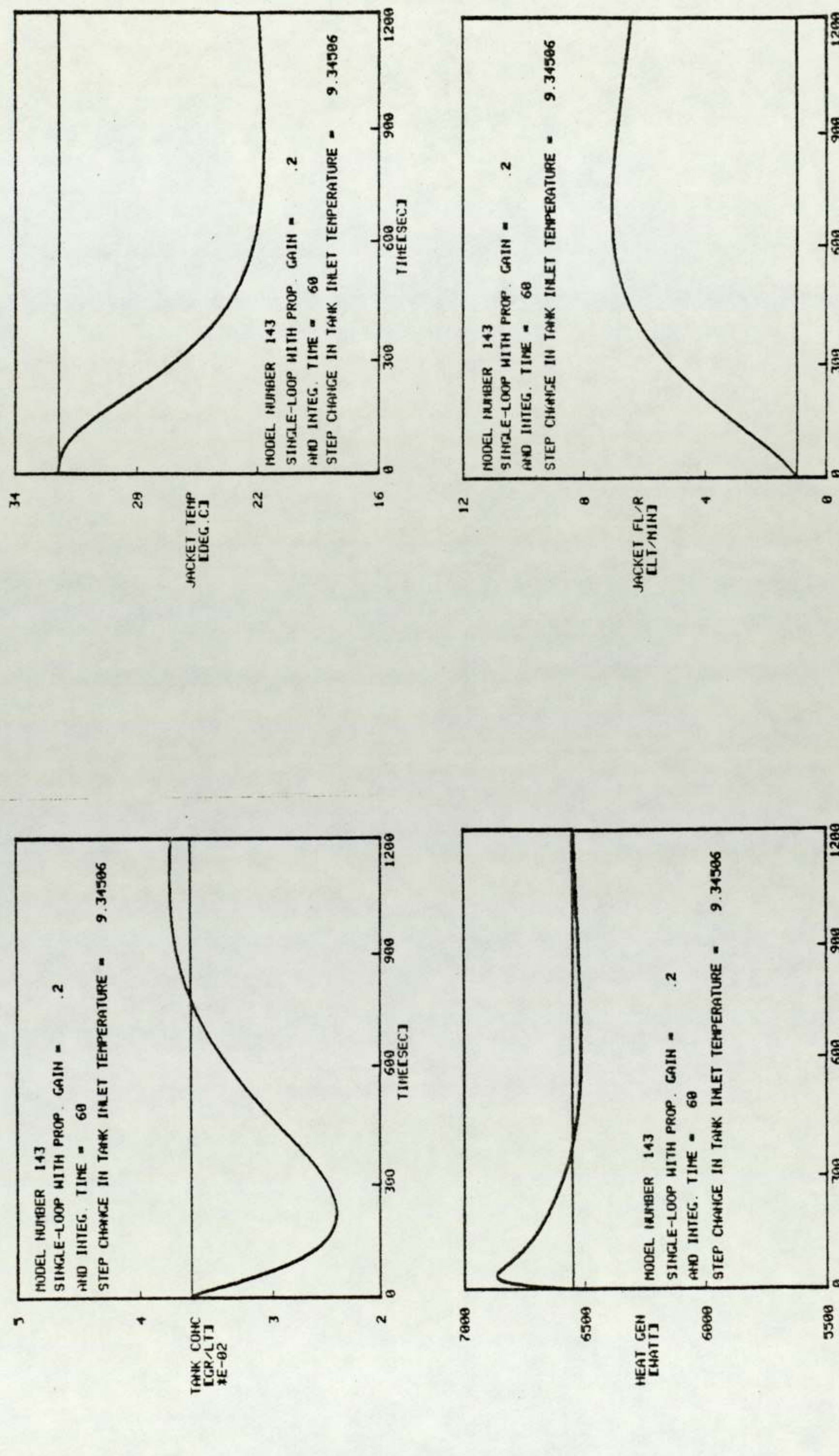
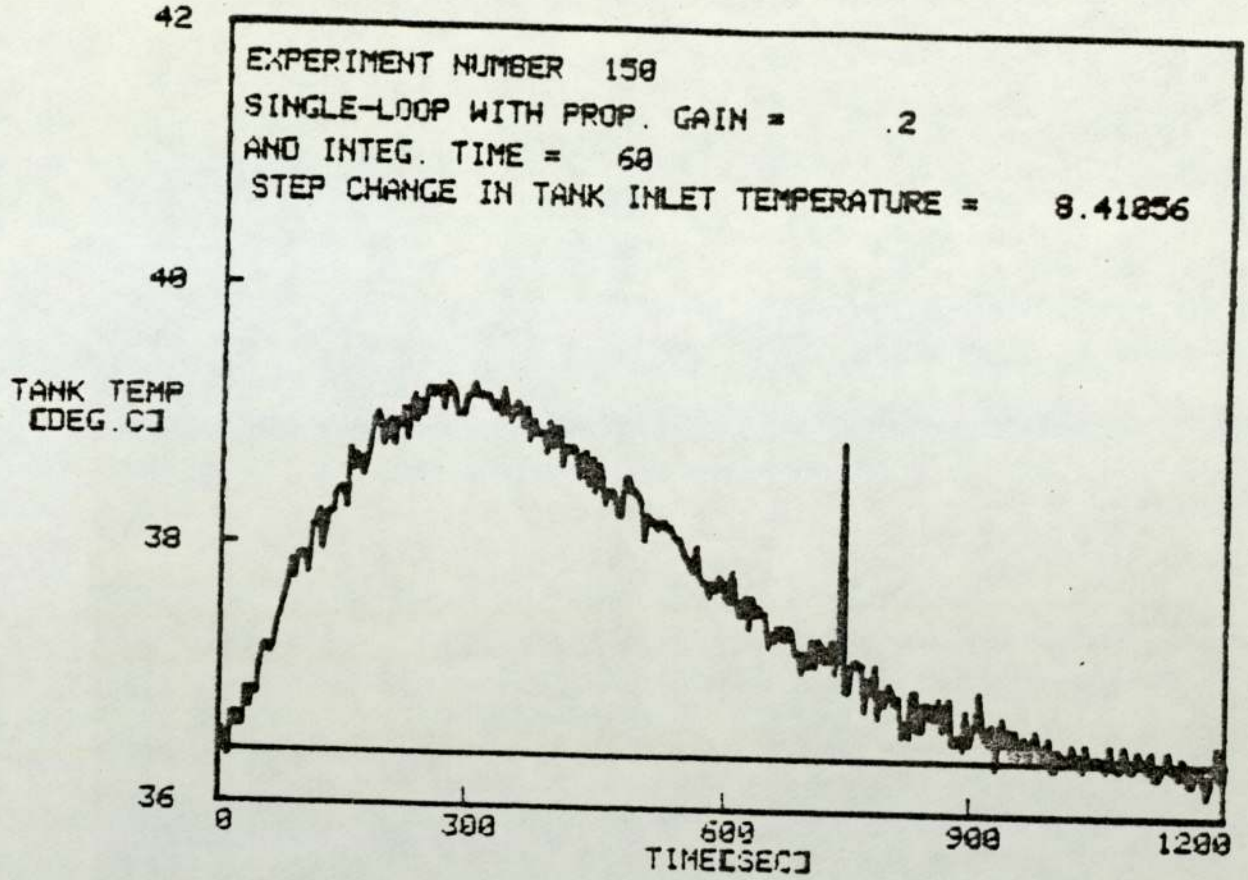
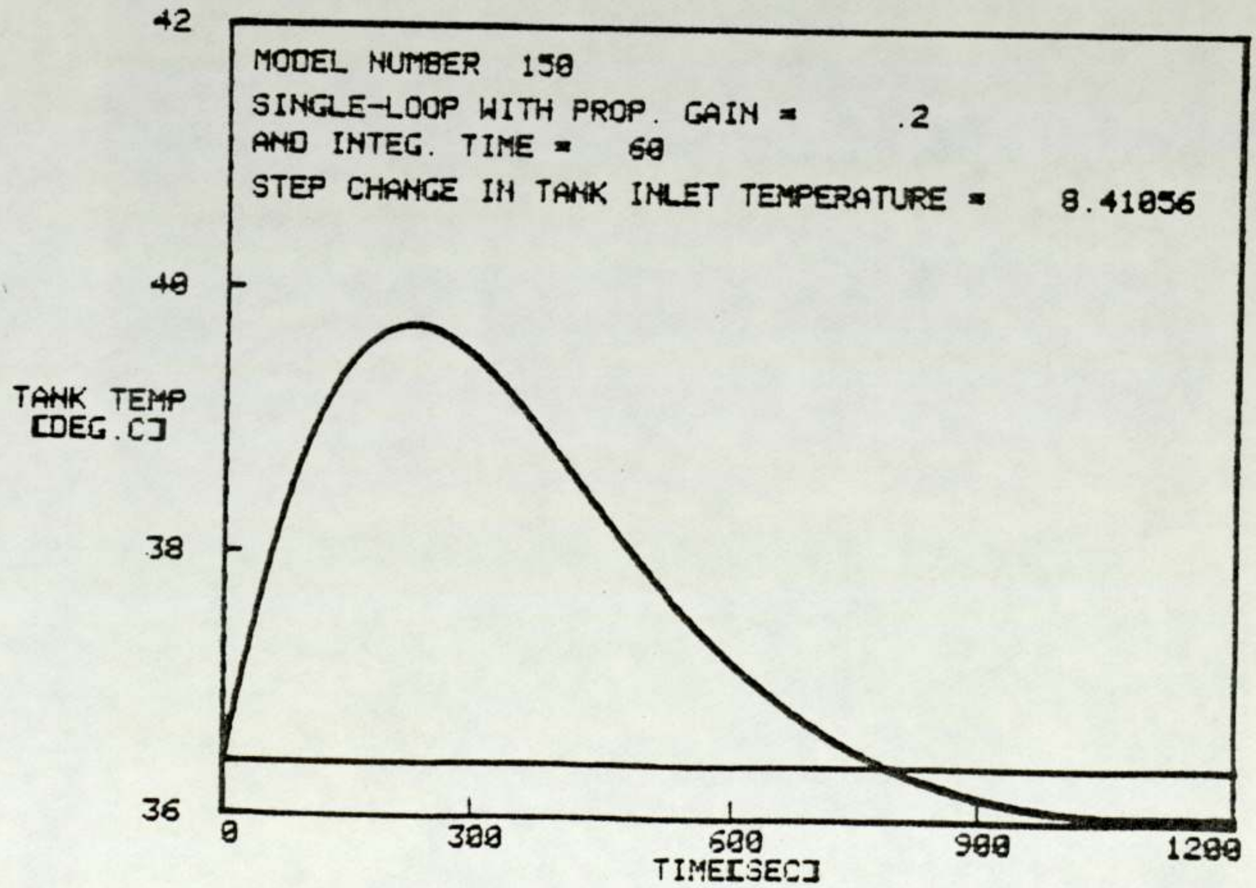

MODEL NUMBER 143
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 9.34506
JACKET TEMP [DEG.C]
JACKET FL/R [LT/MIN]
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
TIME[SEC]
0
300
600
900
1200
34
28
22
16
12
8
4
0
5
4
3
2
7000
6500
6000
5500

FIG. A.3.22

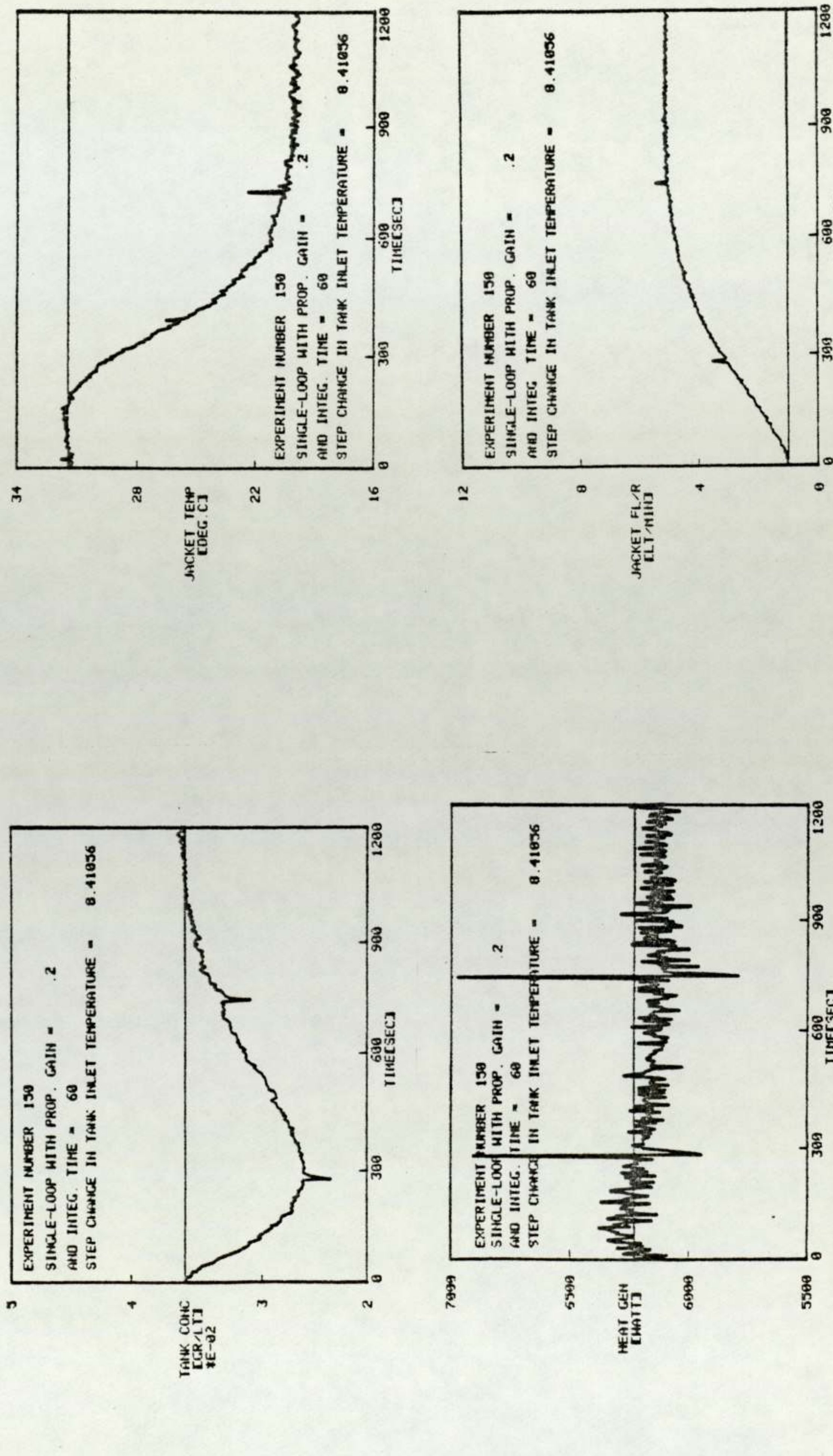


EXPERIMENT NUMBER 150
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 8.41056
42
40
TANK TEMP [DEG.C]
38
36
0
300
600
900
1200
TIME[SEC]



MODEL NUMBER 150
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 8.41056
42
40
TANK TEMP [DEG.C]
38
36
0
300
600
900
1200
TIME[SEC]

FIG. A.3.23



EXPERIMENT NUMBER 150
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 0.41056
JACKET TEMP [DEG C]
TIME[SEC]
EXPERIMENT NUMBER 150
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 0.41056
JACKET FL/R [LT/MIN]
TIME[SEC]
EXPERIMENT NUMBER 150
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 0.41056
TANK CONC [GR/LT] *E-02
TIME[SEC]
EXPERIMENT NUMBER 150
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 0.41056
HEAT GEN [WATT]
TIME[SEC]

FIG. A.3.24

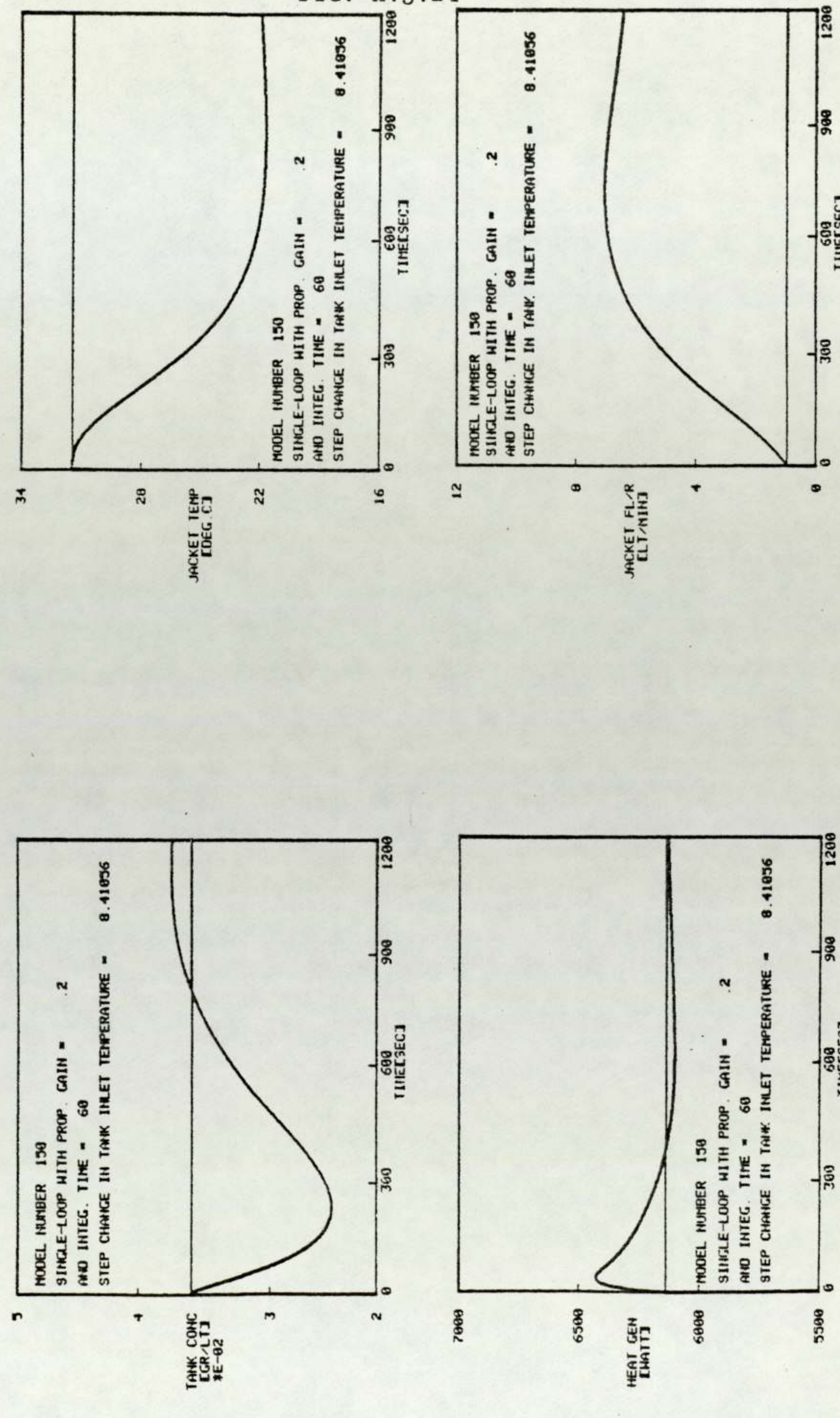
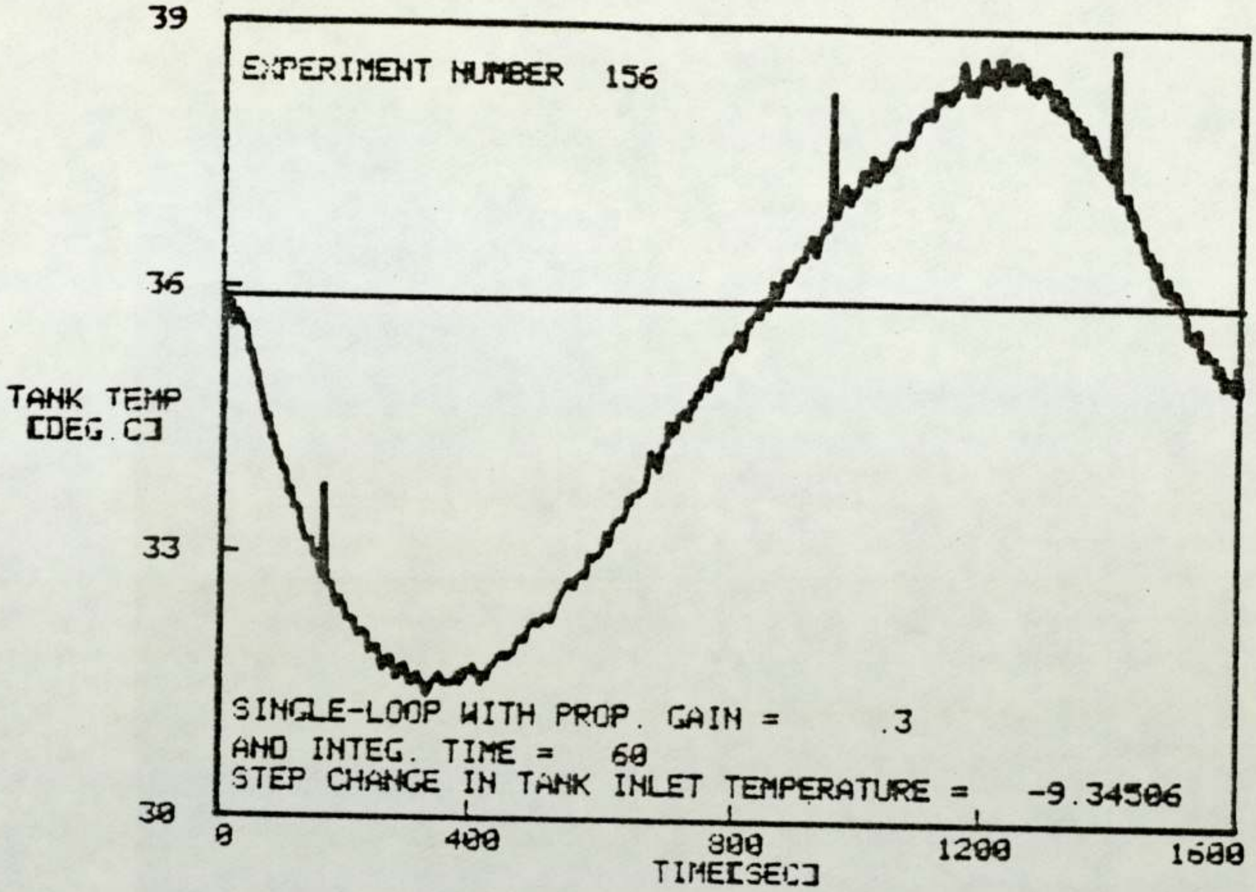

MODEL NUMBER 150
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 8.41056
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
JACKET TEMP [DEG.C]
JACKET FL/R [LT/MIN]
TIME[SEC]

FIG. A.3.25


EXPERIMENT NUMBER 156
39
36
33
30
TANK TEMP
[DEG.C]
SINGLE-LOOP WITH PROP. GAIN = .3
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -9.34506
0
400
800
1200
1600
TIME[SEC]

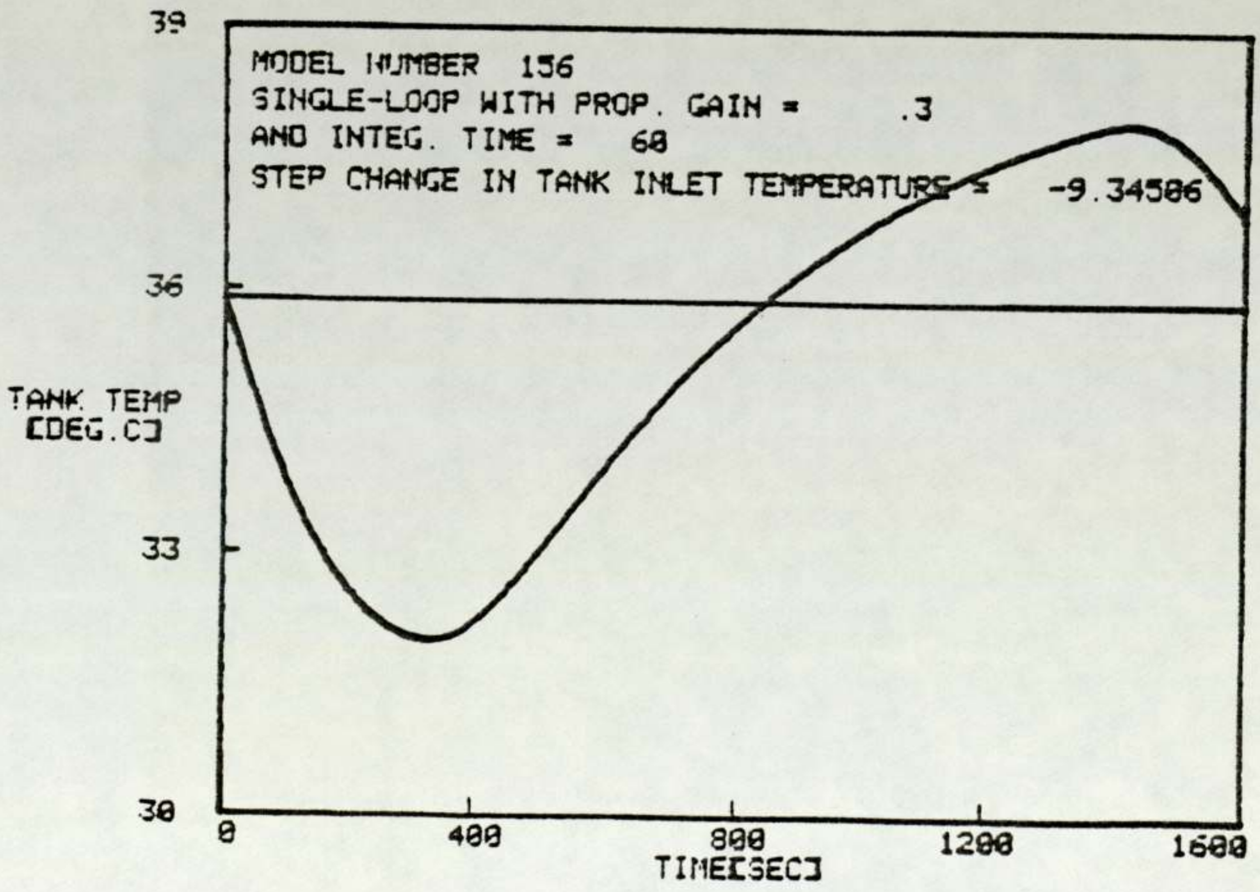
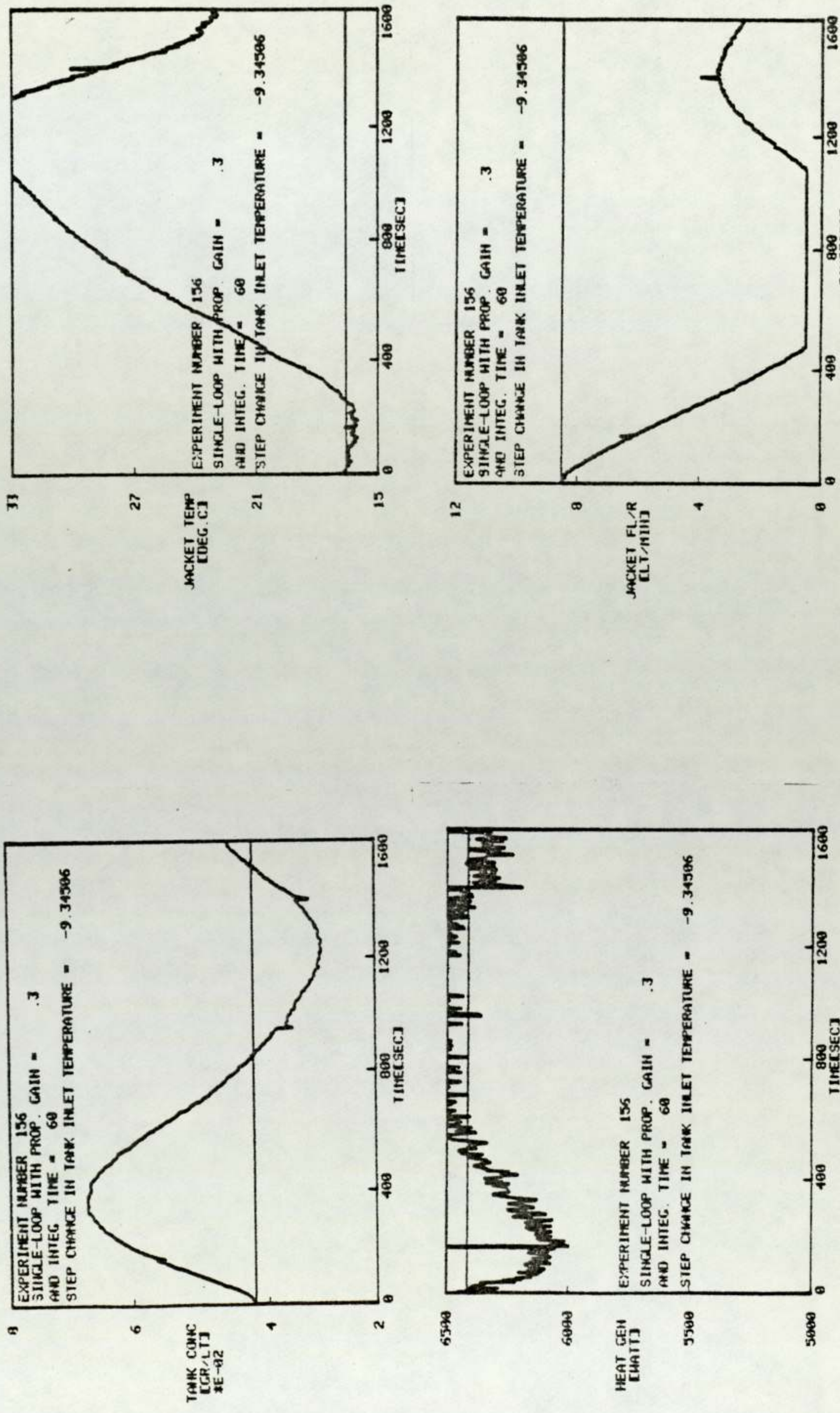

MODEL NUMBER 156
SINGLE-LOOP WITH PROP. GAIN = .3
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -9.34506
39
36
33
30
TANK TEMP
[DEG.C]
0
400
800
1200
1600
TIME[SEC]

FIG. A.3.26



EXPERIMENT NUMBER 156
SINGLE-LOOP WITH PROP. GAIN = .3
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -9.34506
JACKET TEMP [DEG.C]
JACKET FL/R [LT/MIN]
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
TIME[SEC]

FIG. A.3.27

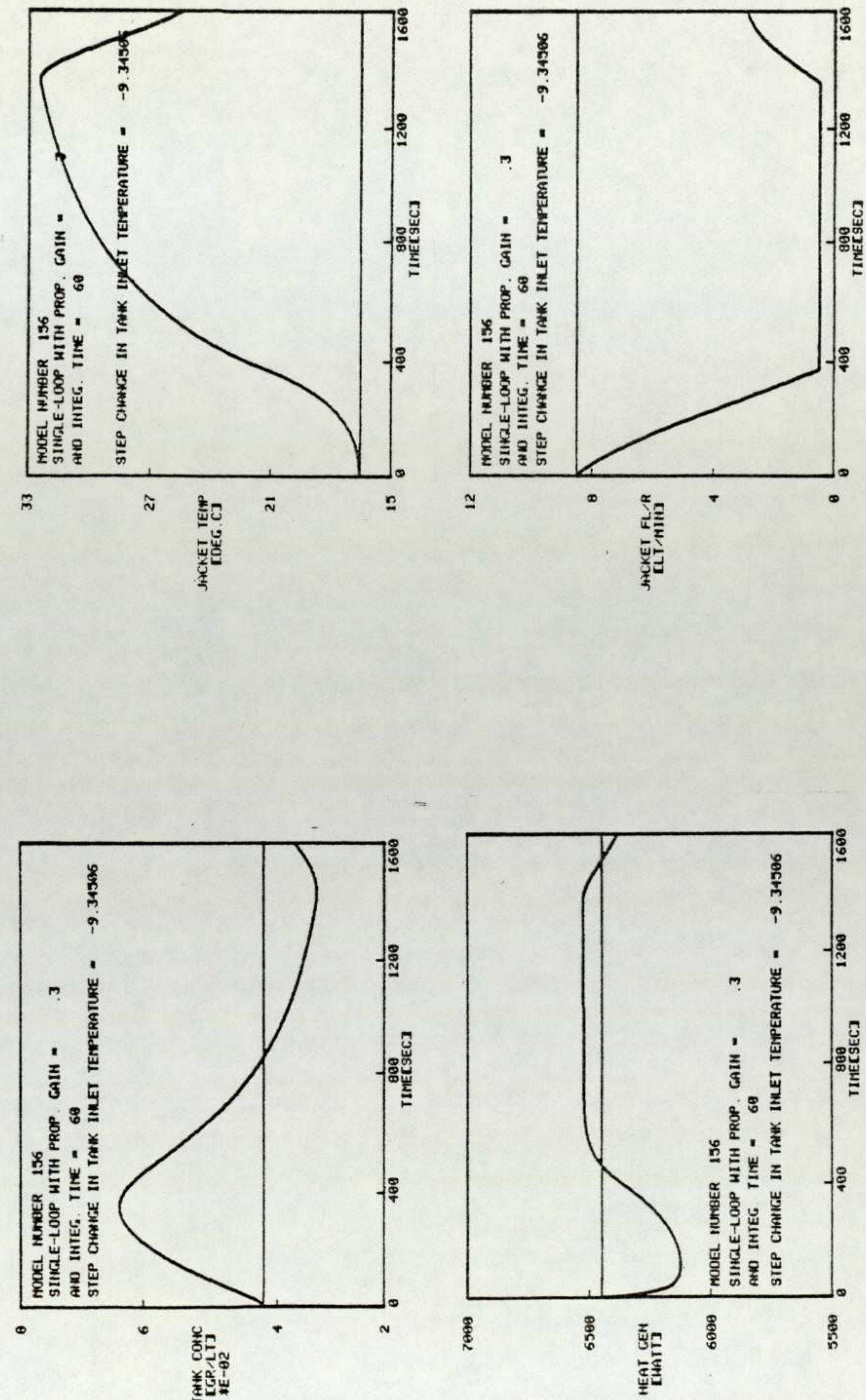
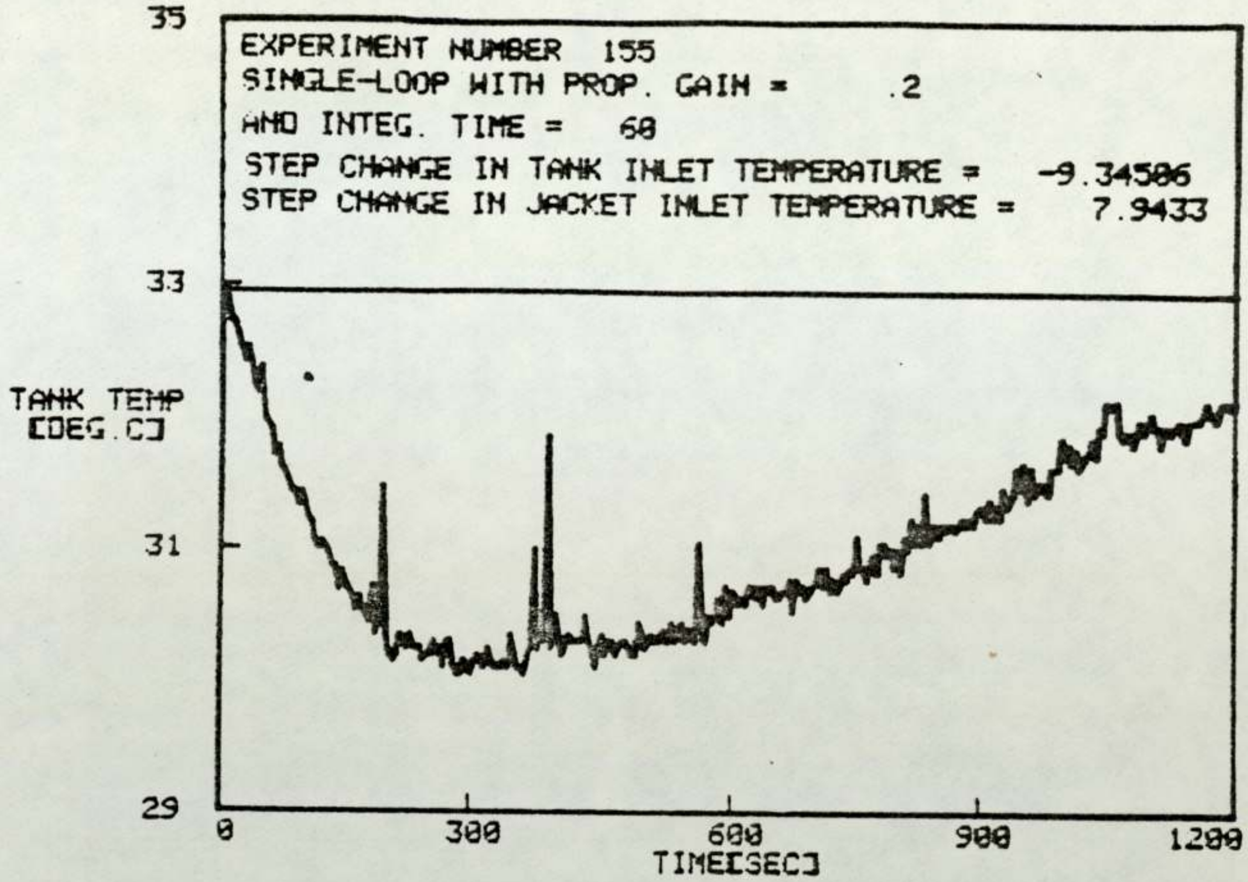

MODEL NUMBER 156
SINGLE-LOOP WITH PROP. GAIN = .3
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -9.34506
JACKET TEMP [DEG.C]
33
27
21
15
0
400
800
1200
1600
TIME[SEC]
MODEL NUMBER 156
SINGLE-LOOP WITH PROP. GAIN = .3
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -9.34506
JACKET FL/R [LT/MIN]
12
8
4
0
0
400
800
1200
1600
TIME[SEC]
MODEL NUMBER 156
SINGLE-LOOP WITH PROP. GAIN = .3
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -9.34506
TANK CONC [GR/LT] *E-02
8
6
4
2
0
400
800
1200
1600
TIME[SEC]
MODEL NUMBER 156
SINGLE-LOOP WITH PROP. GAIN = .3
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -9.34506
HEAT GEN [WATT]
7000
6500
6000
5500
0
400
800
1200
1600
TIME[SEC]

FIG. A.3.28


EXPERIMENT NUMBER 155
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -9.34506
STEP CHANGE IN JACKET INLET TEMPERATURE = 7.9433
35
33
31
29
TANK TEMP [DEG.C]
0
300
600
900
1200
TIME[SEC]

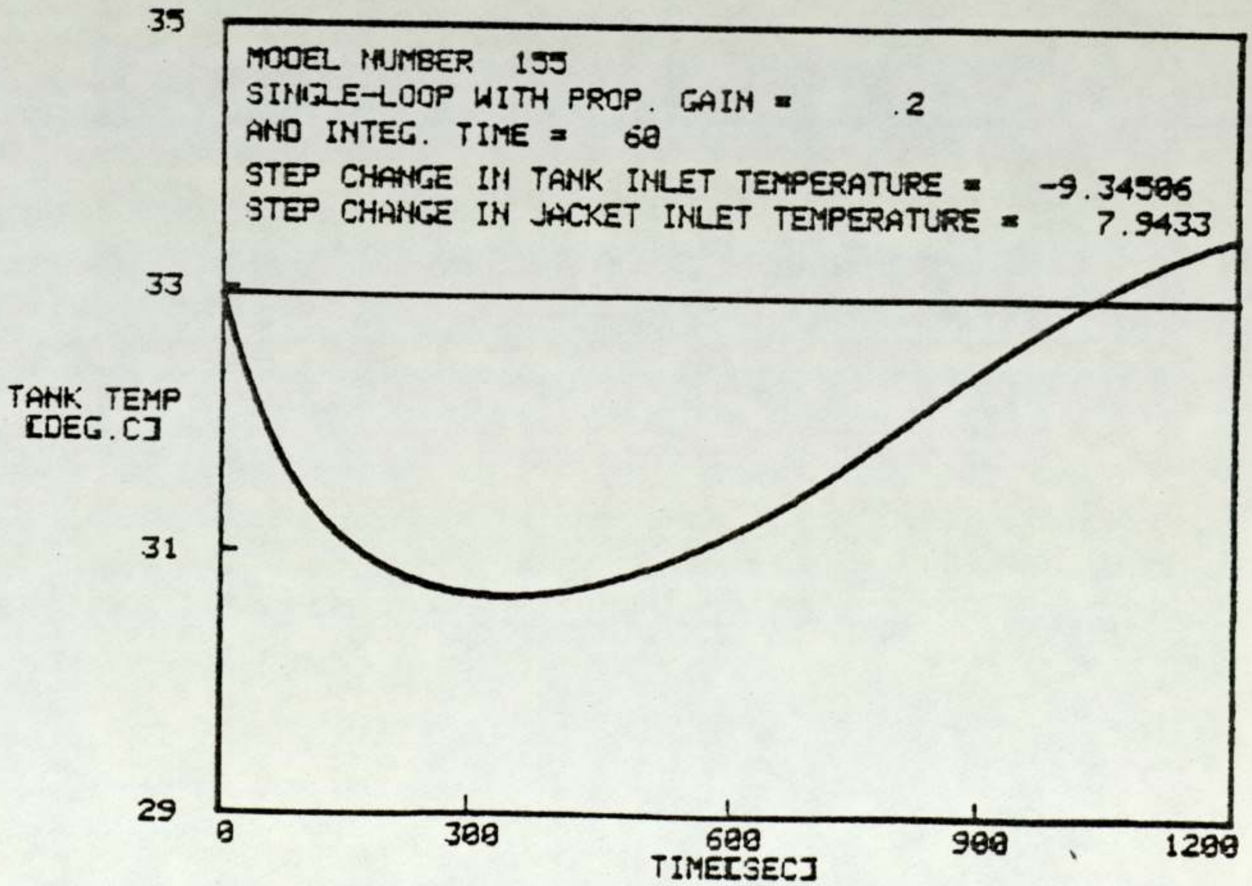

MODEL NUMBER 155
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -9.34506
STEP CHANGE IN JACKET INLET TEMPERATURE = 7.9433
35
33
31
29
TANK TEMP [DEG.C]
0
300
600
900
1200
TIME[SEC]

FIG. A.3.29

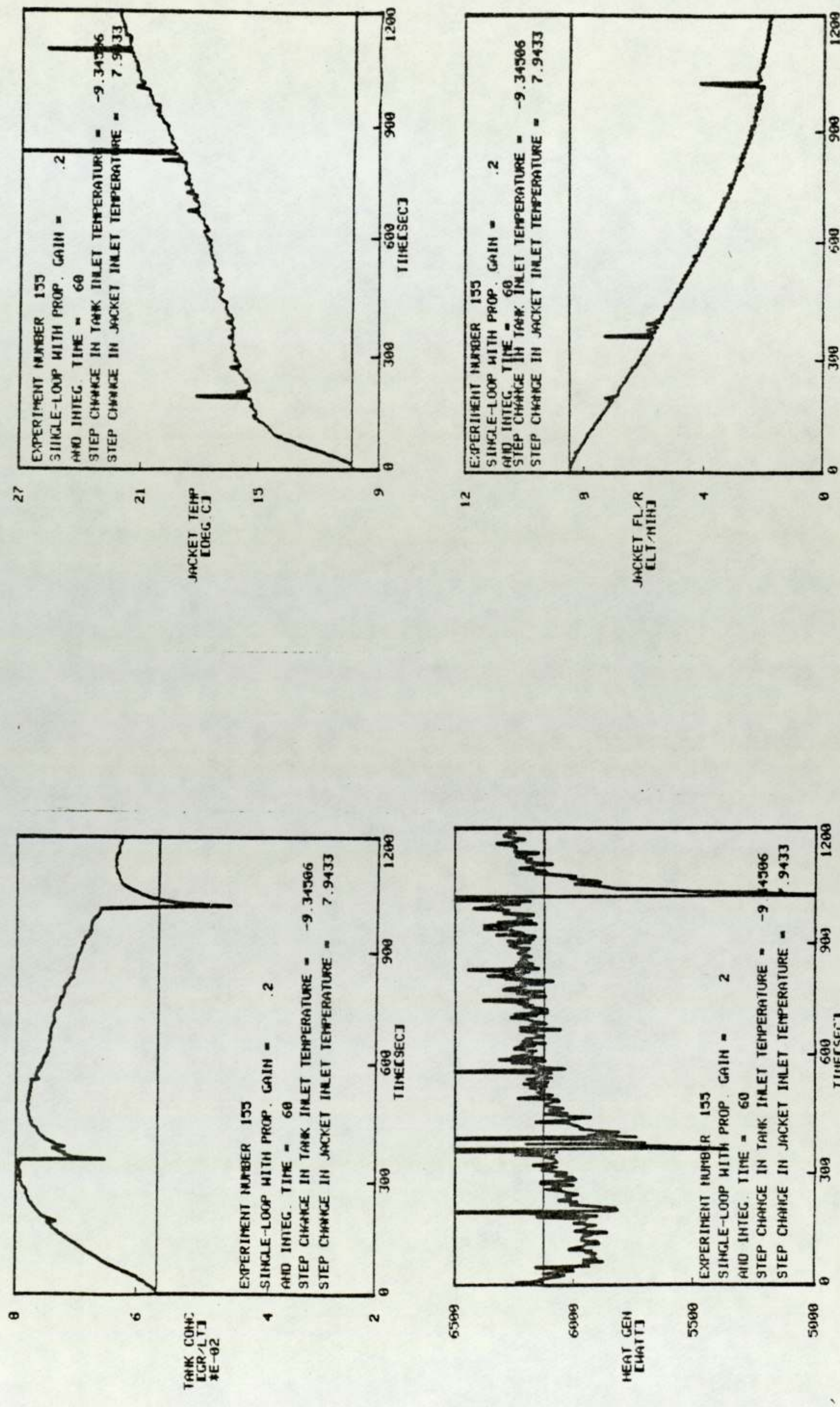
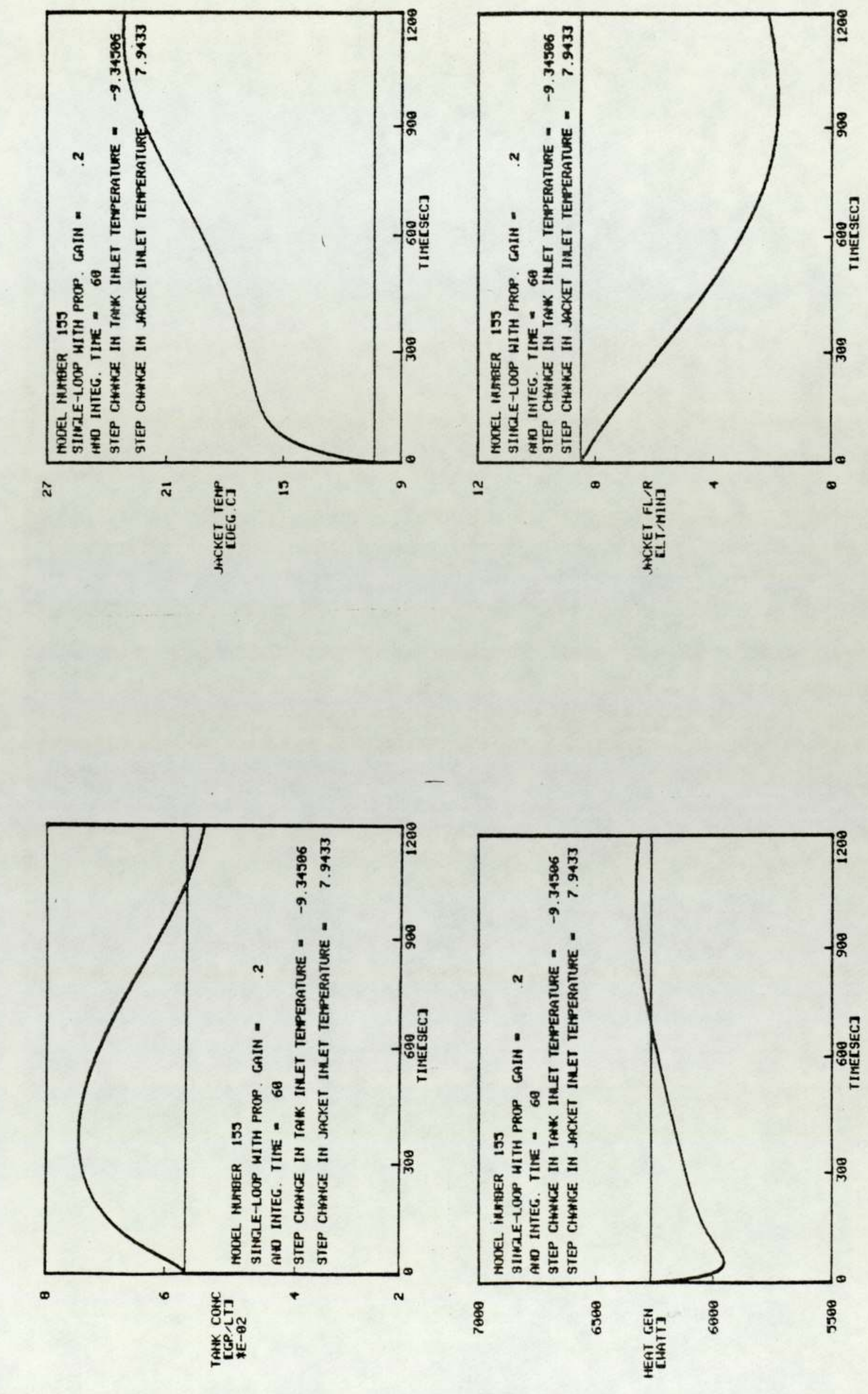
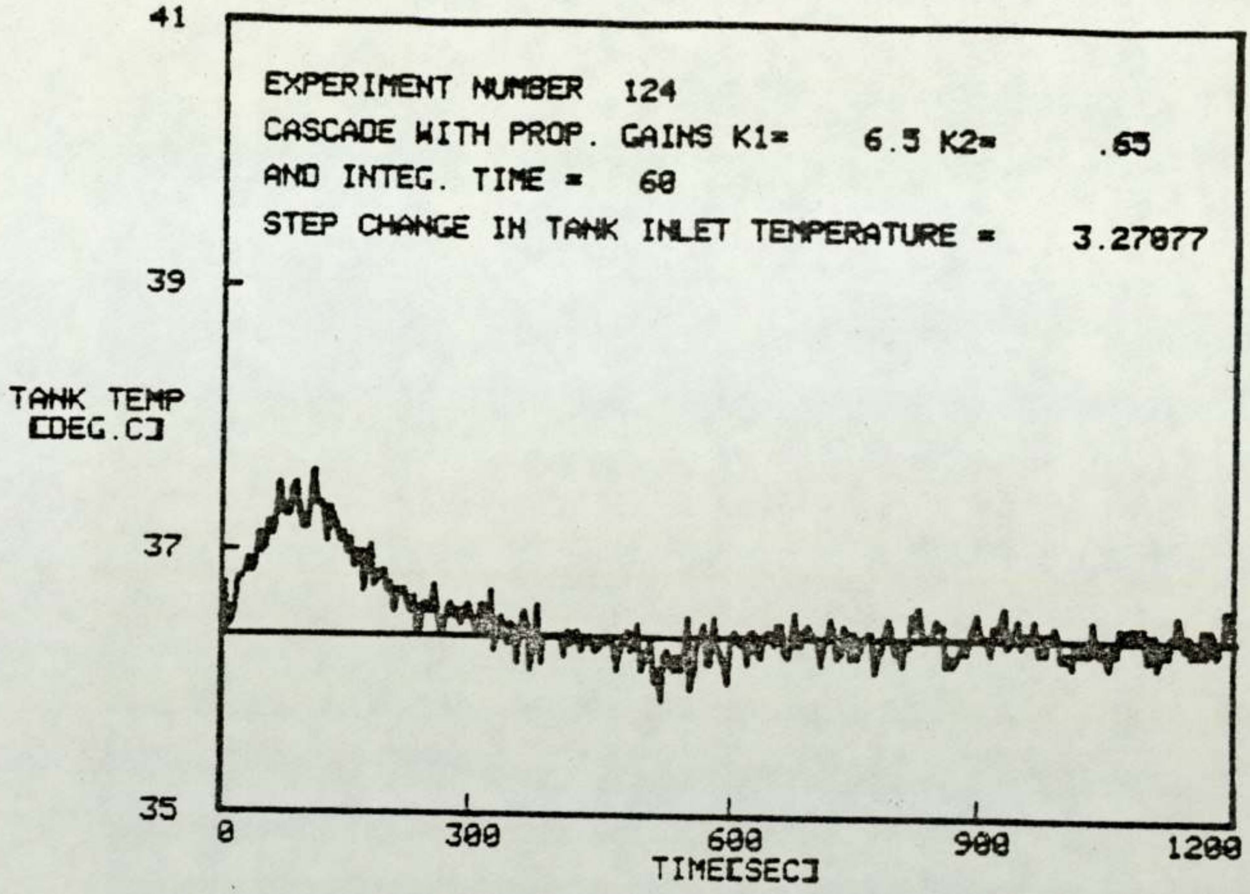

EXPERIMENT NUMBER 155
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -9.34506
STEP CHANGE IN JACKET INLET TEMPERATURE = 7.9433
JACKET TEMP [DEG.C]
JACKET FL/R [LT/MIN]
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
TIME[SEC]

FIG. A.3.30



MODEL NUMBER 155
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -9.34506
STEP CHANGE IN JACKET INLET TEMPERATURE = 7.9433
JACKET TEMP [DEG.C]
27
21
15
9
0
300
600
900
1200
TIME[SEC]
JACKET FL/R [LT/MIN]
12
8
4
0
TANK CONC [GP/LT] *E-02
8
6
4
2
HEAT GEN [WATT]
7000
6500
6000
5500

FIG. A,3,31


EXPERIMENT NUMBER 124
CASCADE WITH PROP. GAINS K1= 6.5 K2= .65
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 3.27077
TANK TEMP [DEG.C]
41
39
37
35
0
300
600
900
1200
TIME[SEC]

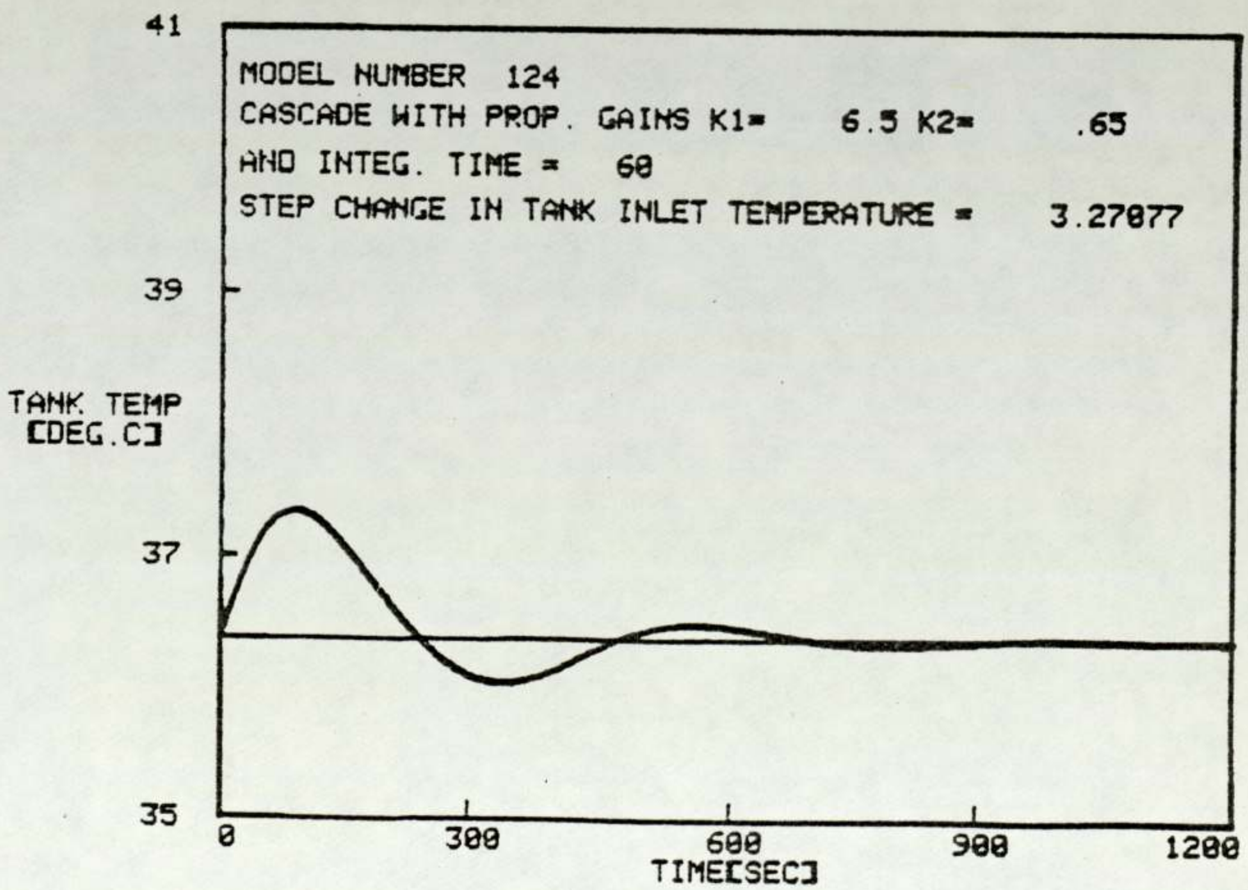
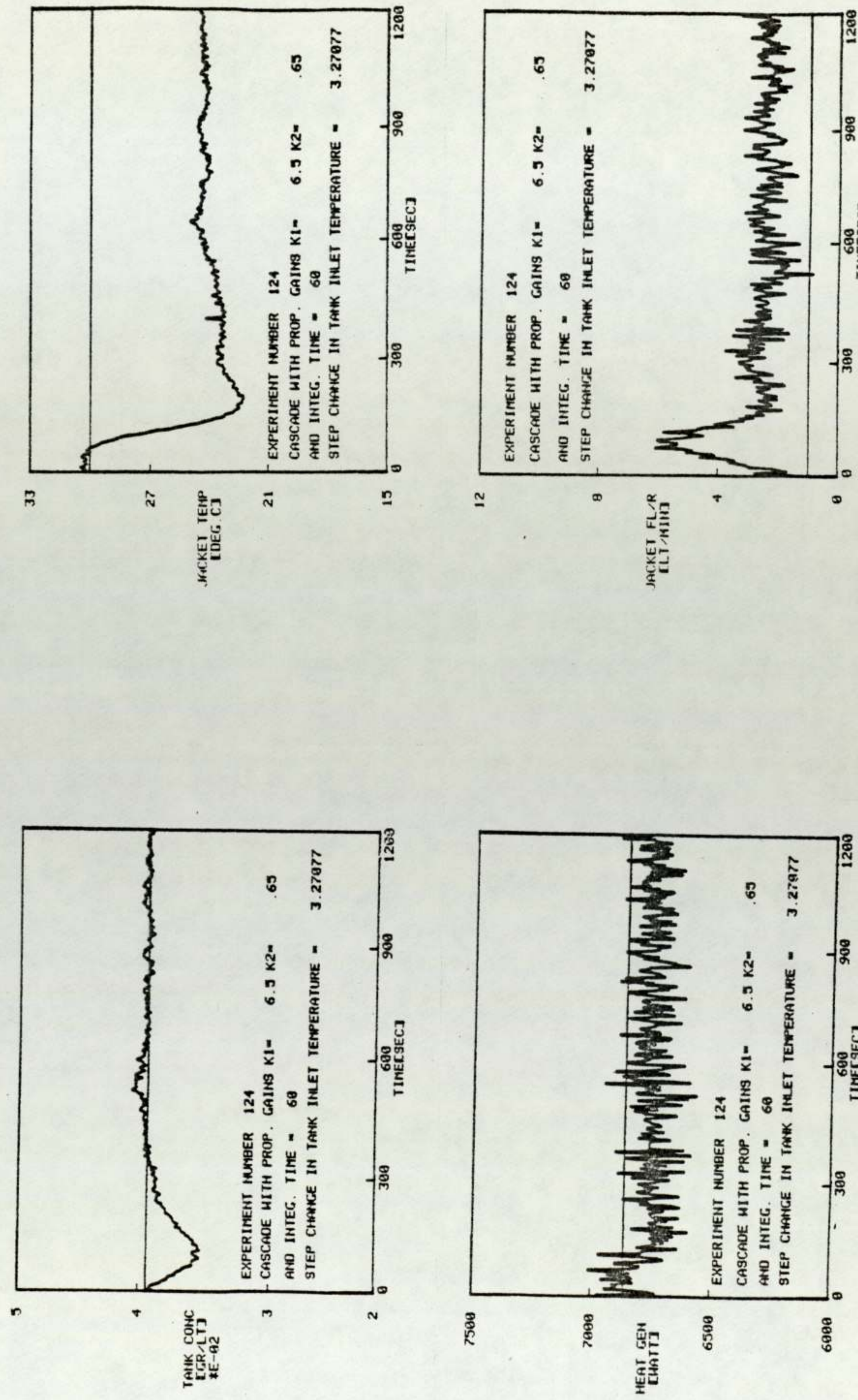
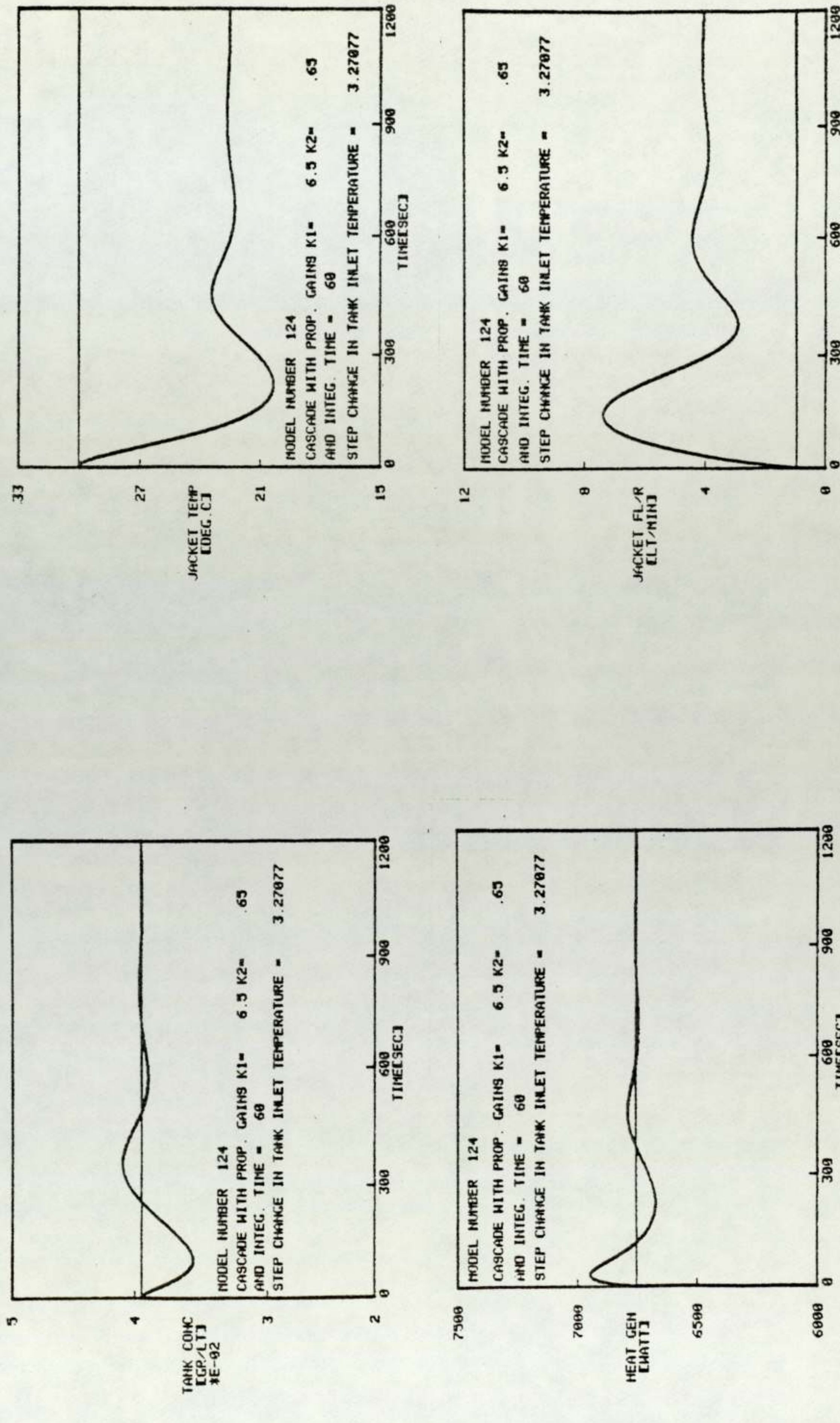

MODEL NUMBER 124
CASCADE WITH PROP. GAINS K1= 6.5 K2= .65
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 3.27077
TANK TEMP [DEG.C]
41
39
37
35
0
300
600
900
1200
TIME[SEC]

FIG. A.3.32



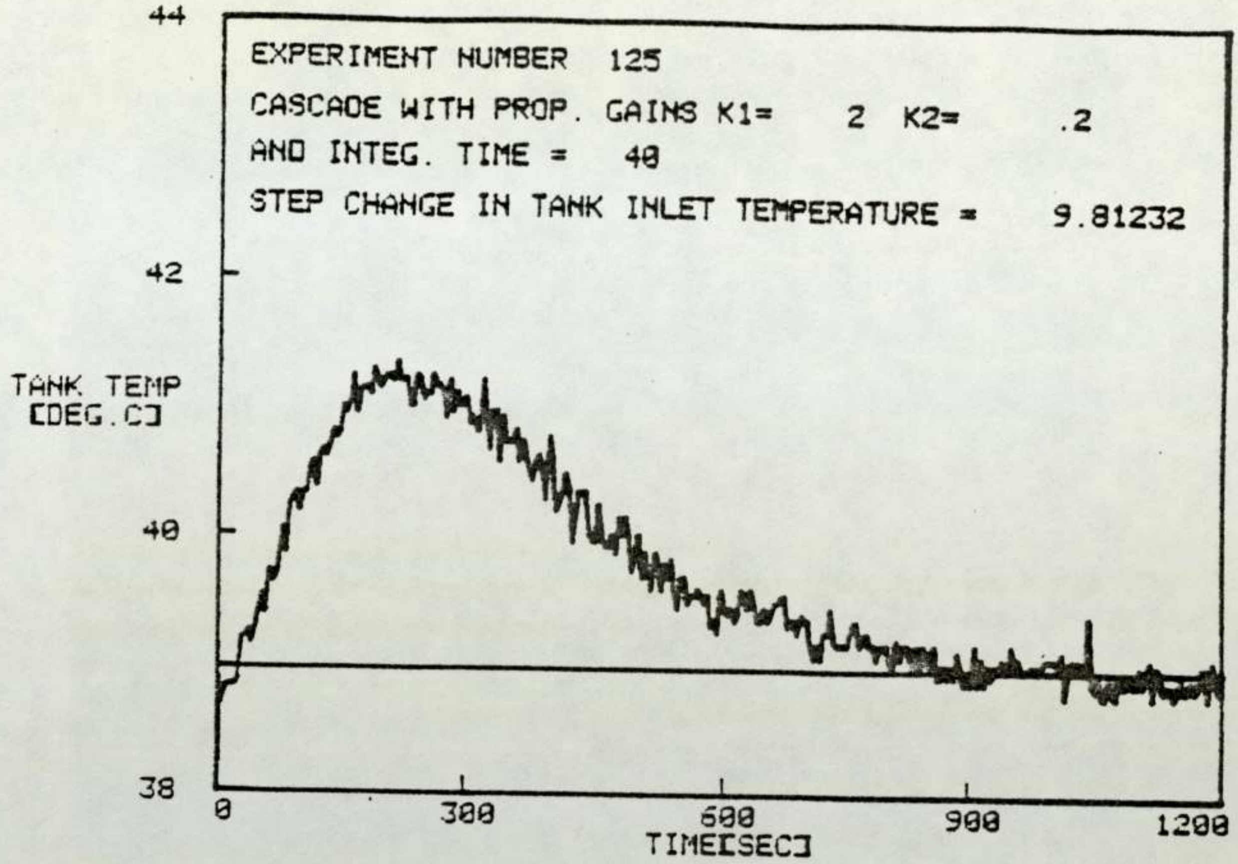
TANK CONC [GR/LT] *E-02
JACKET TEMP [DEG.C]
HEAT GEN [WATT]
JACKET FL/R [LT/MIN]
TIME[SEC]
EXPERIMENT NUMBER 124
CASCADE WITH PROP. GAINS K1= 6.5 K2= .65
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 3.27077

FIG. A.3.33

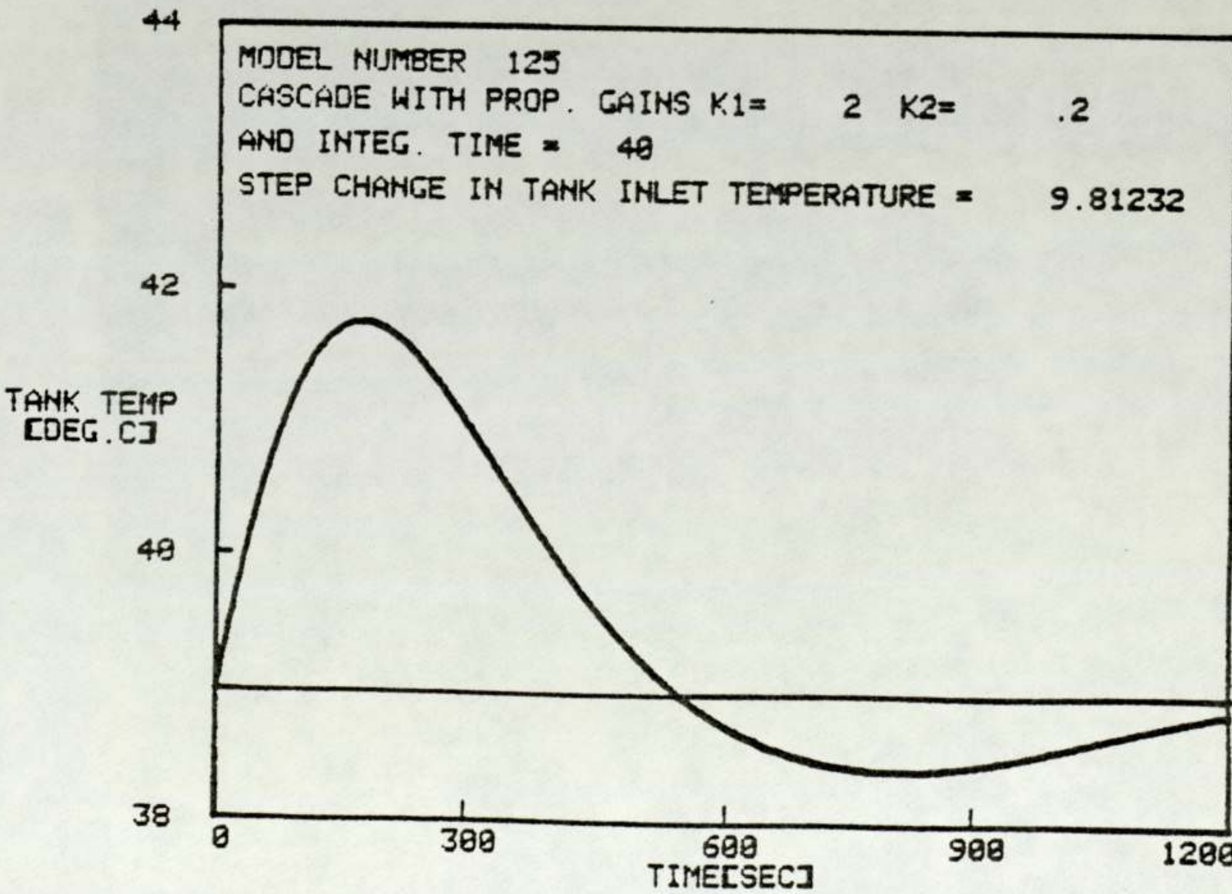


JACKET TEMP [DEG.C]
33
27
21
15
0
300
600
900
1200
TIME[SEC]
MODEL NUMBER 124
CASCADE WITH PROP. GAINS K1= 6.5 K2= .65
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 3.27077
JACKET FL/R [LT/MIN]
12
8
4
0
0
300
600
900
1200
TIME[SEC]
MODEL NUMBER 124
CASCADE WITH PROP. GAINS K1= 6.5 K2= .65
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 3.27077
TANK CONC [GR/LT] *E-02
5
4
3
2
0
300
600
900
1200
TIME[SEC]
MODEL NUMBER 124
CASCADE WITH PROP. GAINS K1= 6.5 K2= .65
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 3.27077
HEAT GEN [WATT]
7500
7000
6500
6000
0
300
600
900
1200
TIME[SEC]
MODEL NUMBER 124
CASCADE WITH PROP. GAINS K1= 6.5 K2= .65
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 3.27077

FIG. A.3.34



EXPERIMENT NUMBER 125
CASCADE WITH PROP. GAINS K1= 2 K2= .2
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 9.81232
44
42
40
38
TANK TEMP [DEG.C]
0
300
600
900
1200
TIME[SEC]



MODEL NUMBER 125
CASCADE WITH PROP. GAINS K1= 2 K2= .2
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 9.81232
44
42
40
38
TANK TEMP [DEG.C]
0
300
600
900
1200
TIME[SEC]

FIG. A.3.35

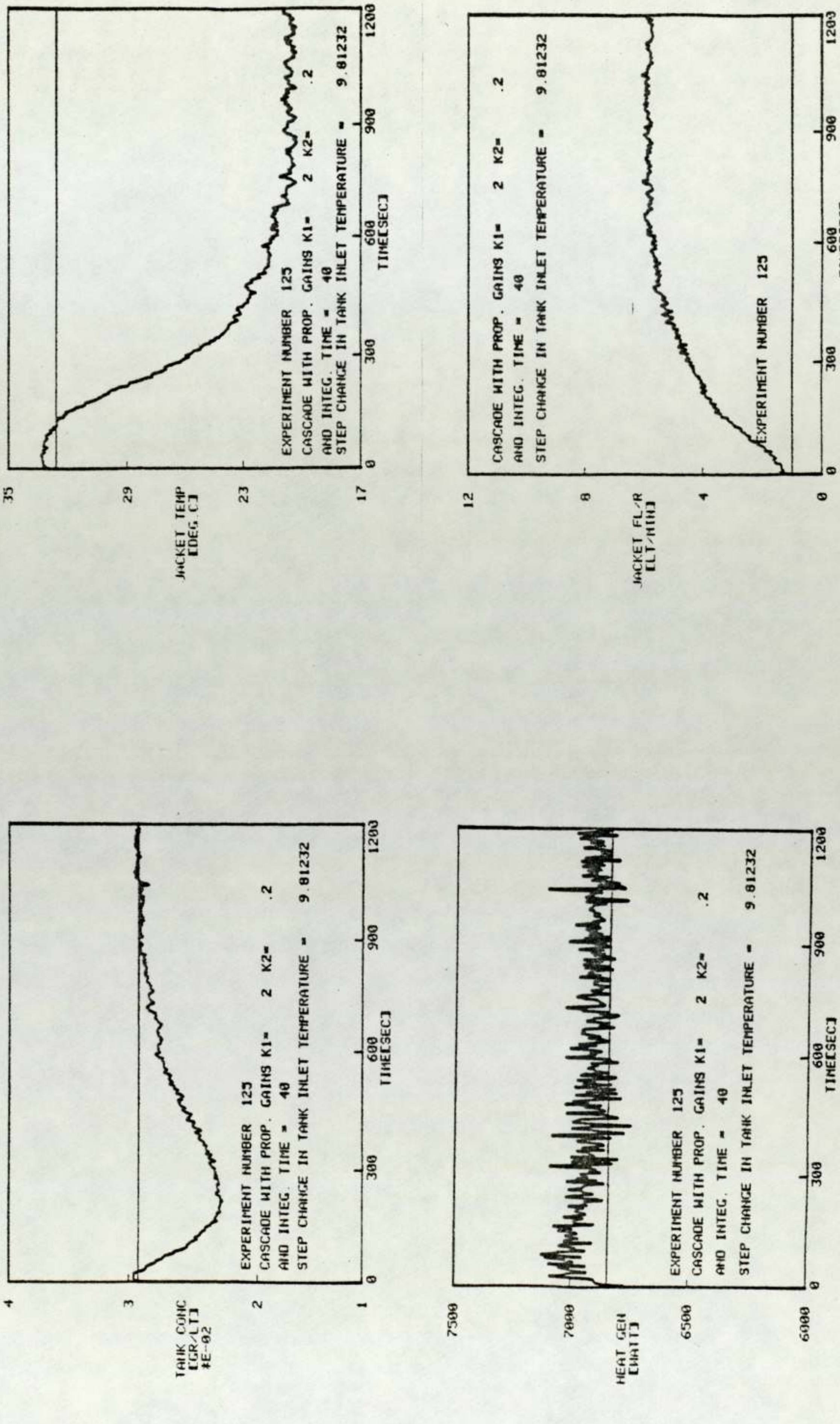
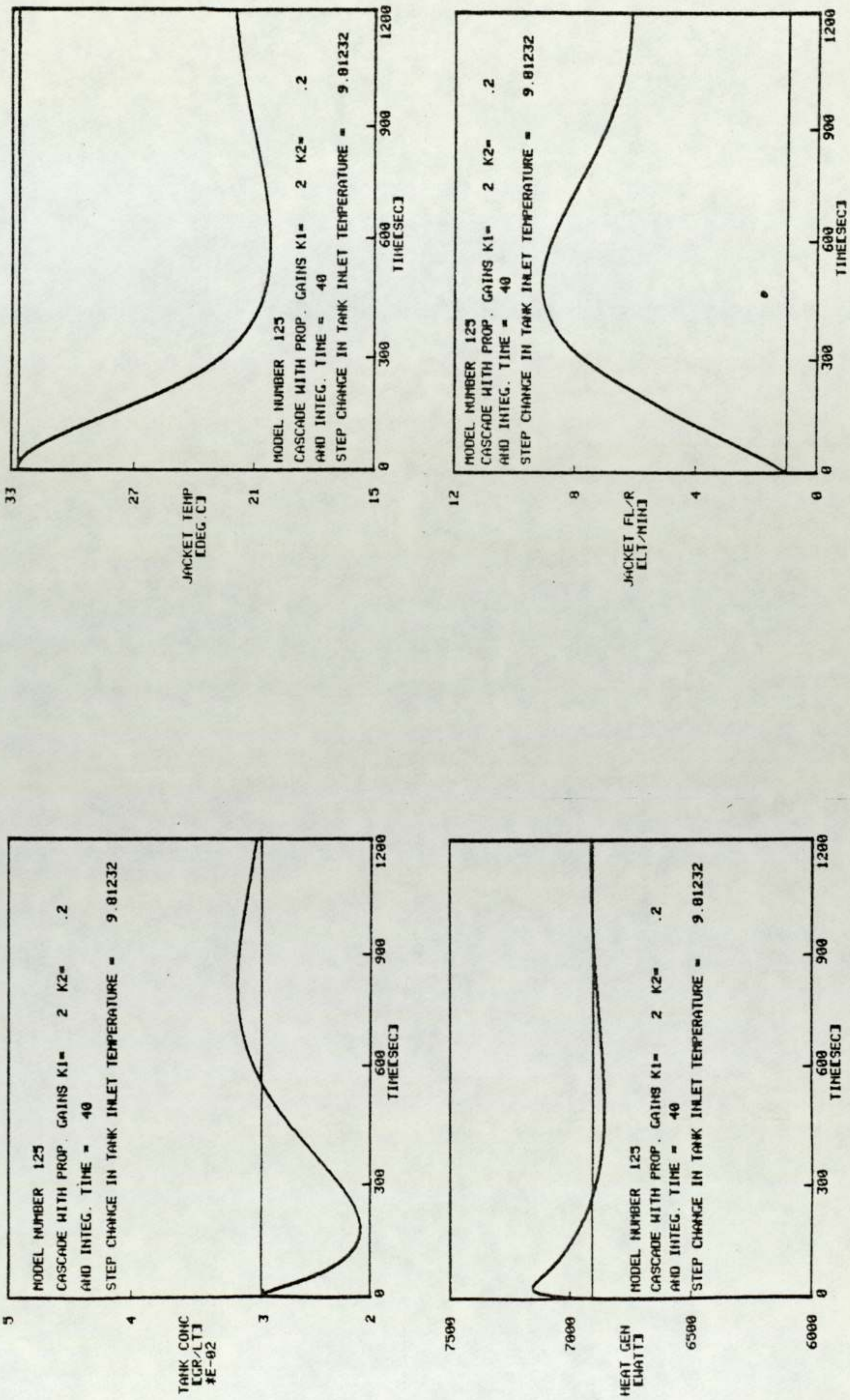
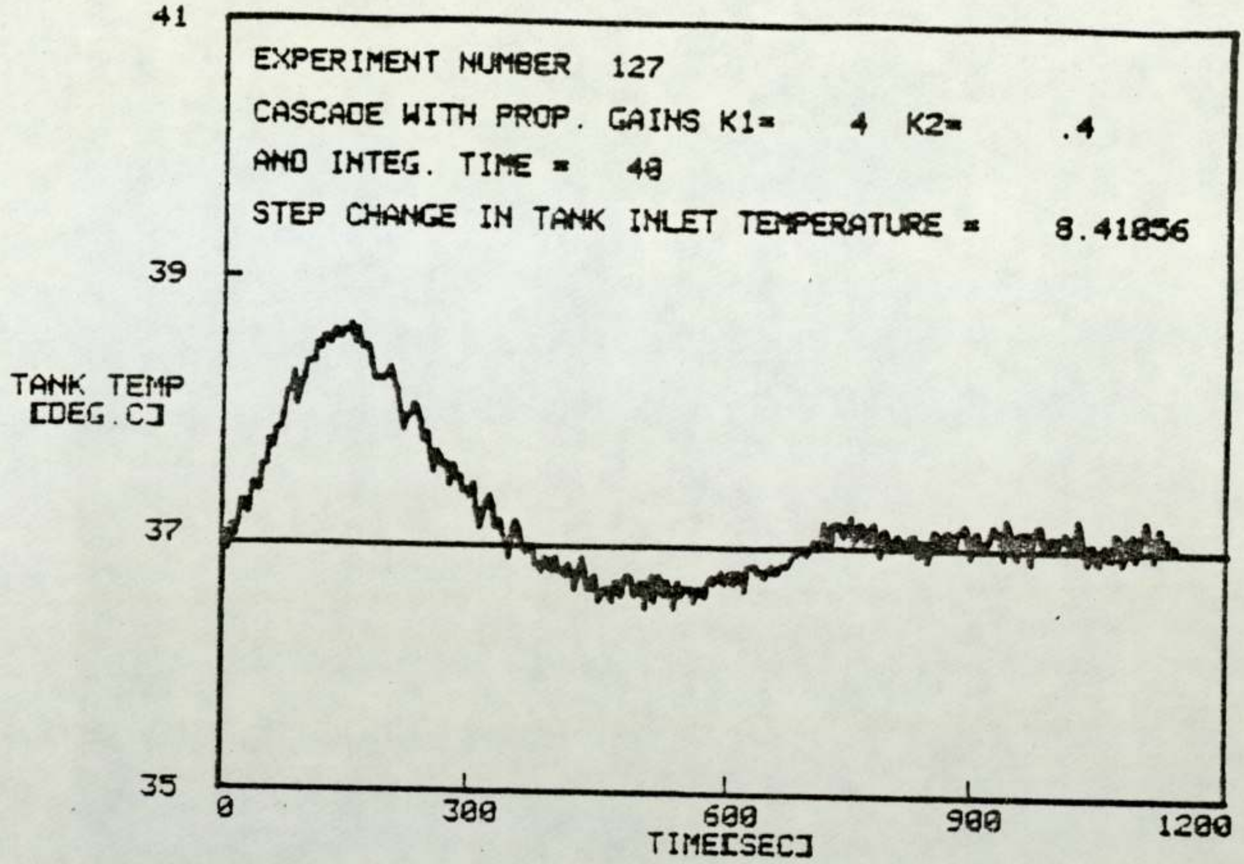

EXPERIMENT NUMBER 125
CASCADE WITH PROP. GAINS K1= 2 K2= .2
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 9.81232
JACKET TEMP [DEG. C]
JACKET FL/R [LT/MIN]
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
TIME[SEC]

FIG. A.3.36



MODEL NUMBER 125
CASCADE WITH PROP. GAINS K1= 2 K2= .2
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 9.81232
JACKET TEMP [DEG.C]
33
27
21
15
0
300
600
900
1200
TIME[SEC]
MODEL NUMBER 125
CASCADE WITH PROP. GAINS K1= 2 K2= .2
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 9.81232
JACKET FL/R [LT/MIN]
12
8
4
0
0
300
600
900
1200
TIME[SEC]
MODEL NUMBER 125
CASCADE WITH PROP. GAINS K1= 2 K2= .2
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 9.81232
TANK CONC [GR/LT] *E-02
5
4
3
2
0
300
600
900
1200
TIME[SEC]
MODEL NUMBER 125
CASCADE WITH PROP. GAINS K1= 2 K2= .2
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 9.81232
HEAT GEN [WATT]
7500
7000
6500
6000
0
300
600
900
1200
TIME[SEC]

FIG. A,3.37


EXPERIMENT NUMBER 127
CASCADE WITH PROP. GAINS K1= 4 K2= .4
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 8.41056
41
39
37
35
TANK TEMP [DEG.C]
0
300
600
900
1200
TIME[SEC]

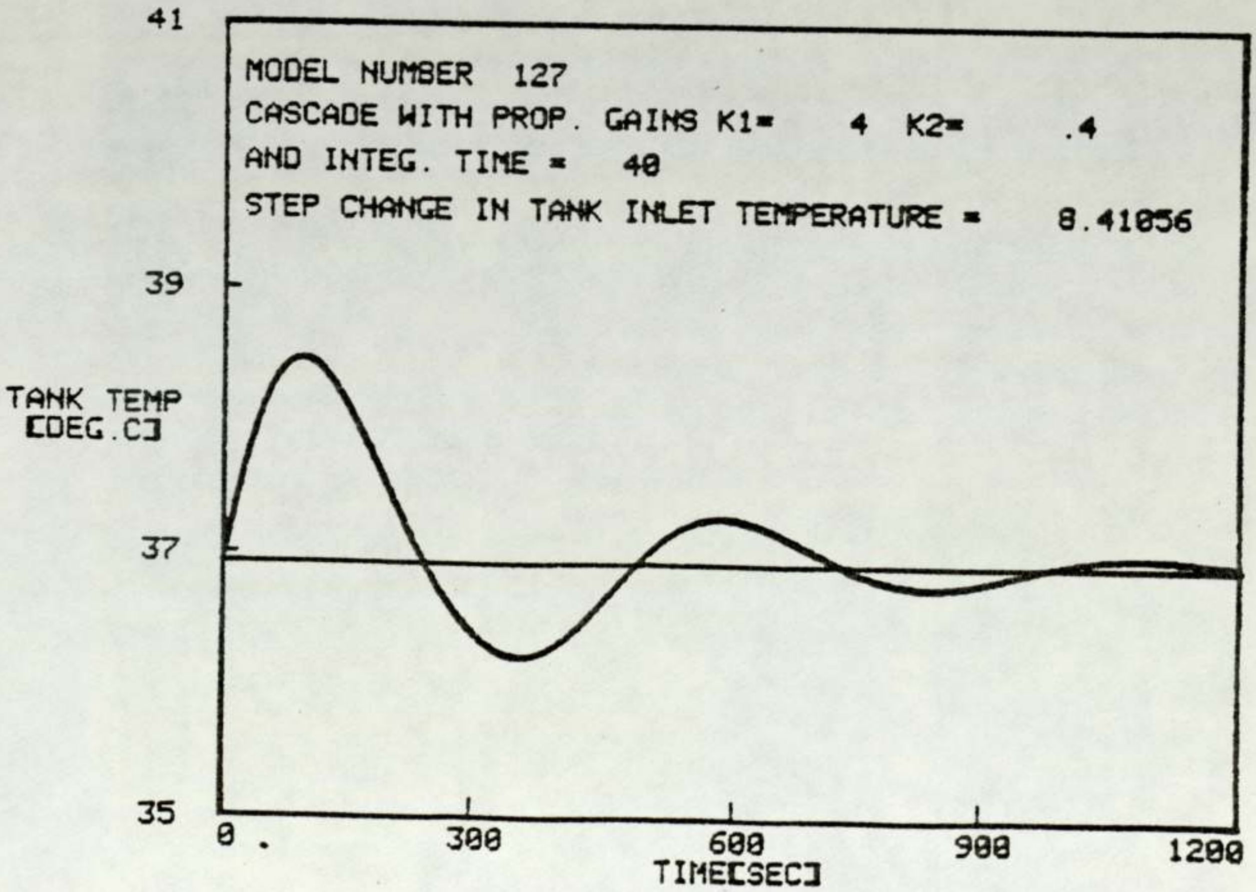

MODEL NUMBER 127
CASCADE WITH PROP. GAINS K1= 4 K2= .4
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 8.41056
41
39
37
35
TANK TEMP [DEG.C]
0 .
300
600
900
1200
TIME[SEC]

FIG. A.3.38

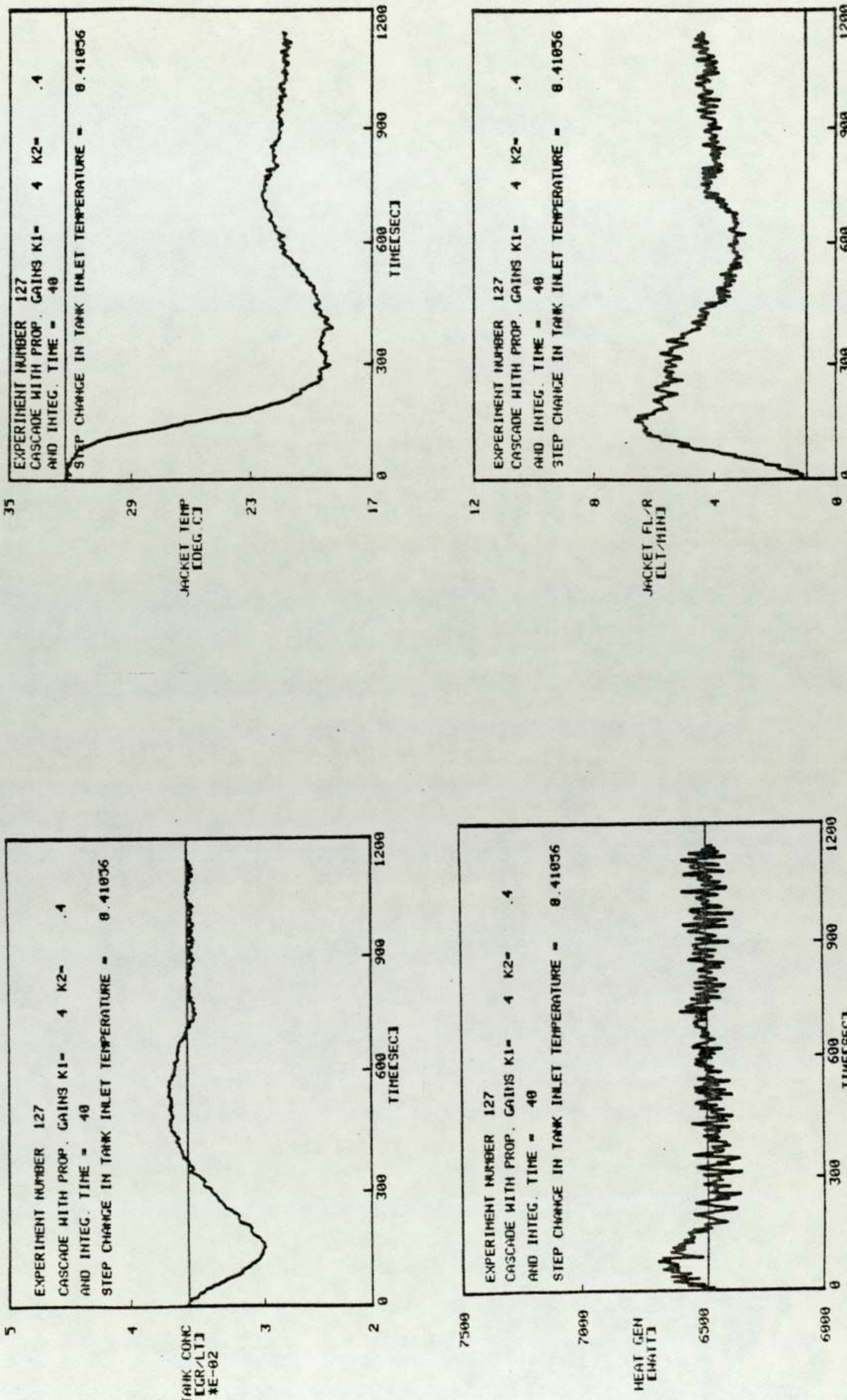

EXPERIMENT NUMBER 127
CASCADE WITH PROP. GAINS K1= 4 K2= .4
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 0.41056
JACKET TEMP [DEG C]
JACKET FL/R [LT/MIN]
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
TIME[SEC]

FIG. A.3.39

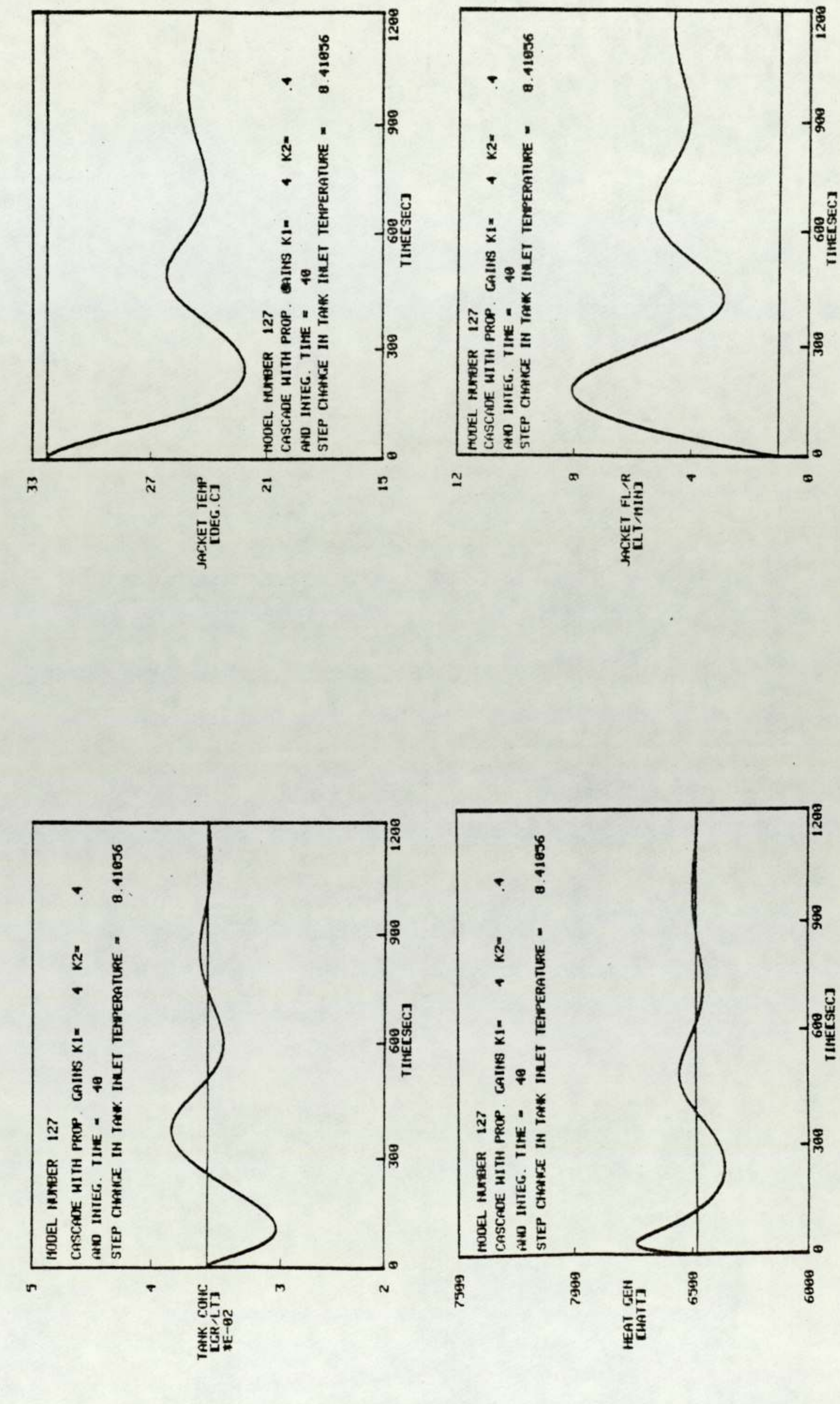
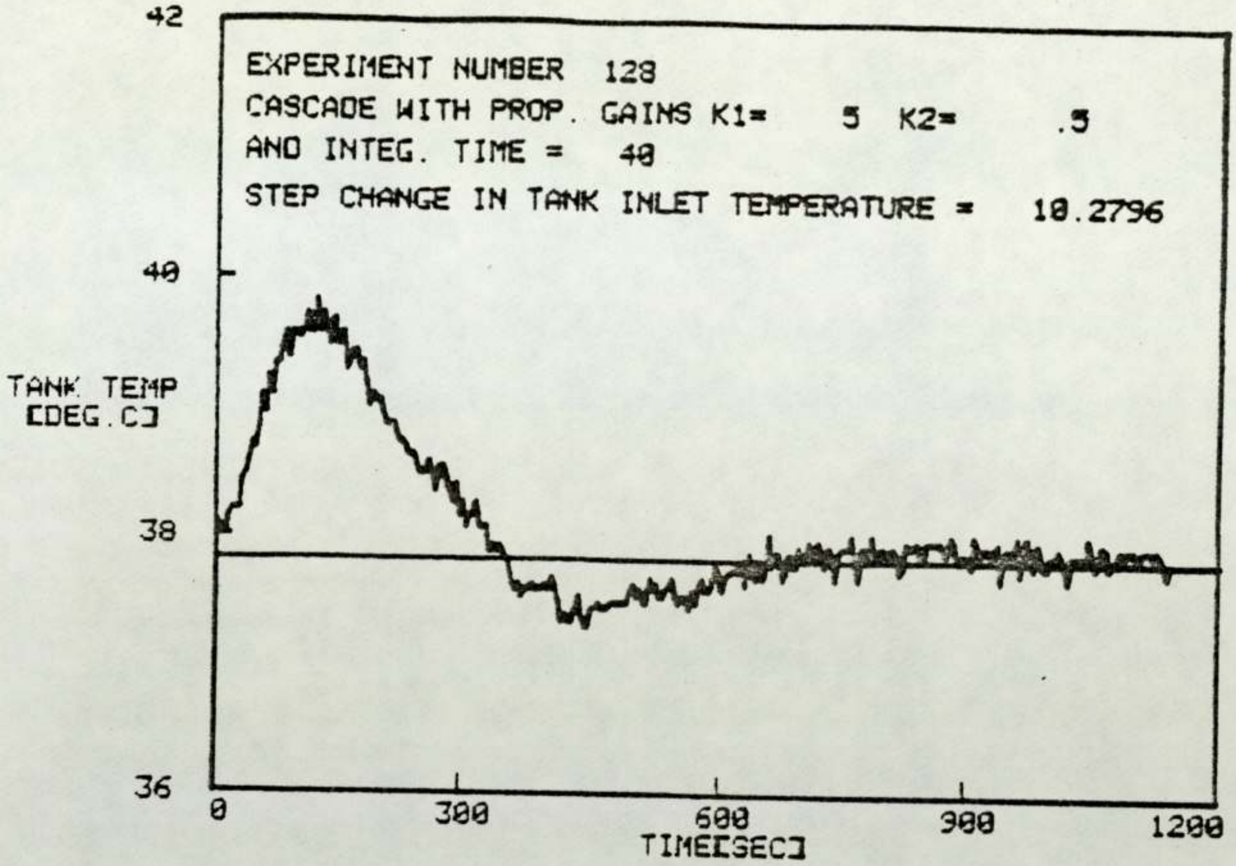

MODEL NUMBER 127
CASCADE WITH PROP. GAINS K1= 4 K2= .4
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 8.41056
JACKET TEMP [DEG.C]
JACKET FL/R [LT/MIN]
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
TIME[SEC]

FIG. A.3.40


EXPERIMENT NUMBER 128
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 10.2796
TANK TEMP [DEG.C]
42
40
38
36
0
300
600
900
1200
TIME[SEC]

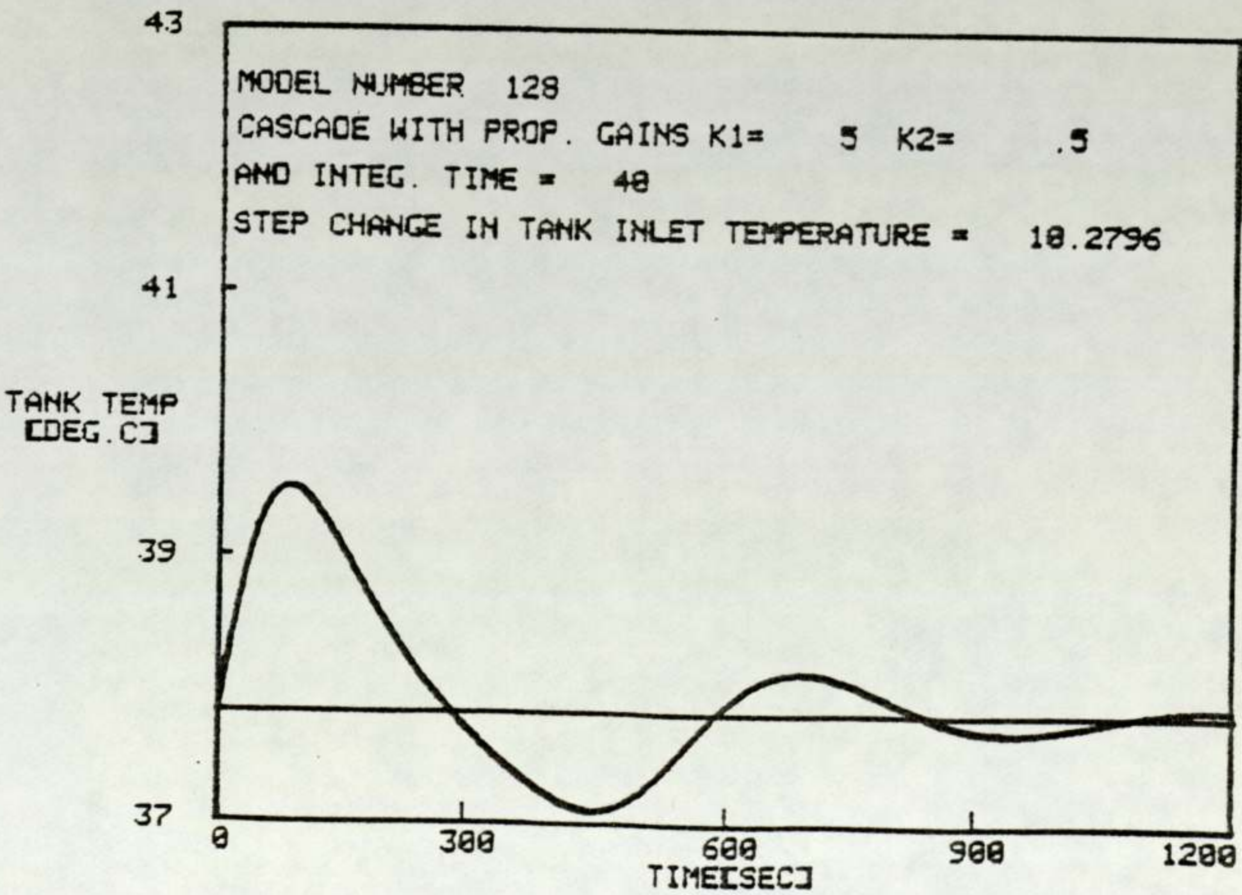
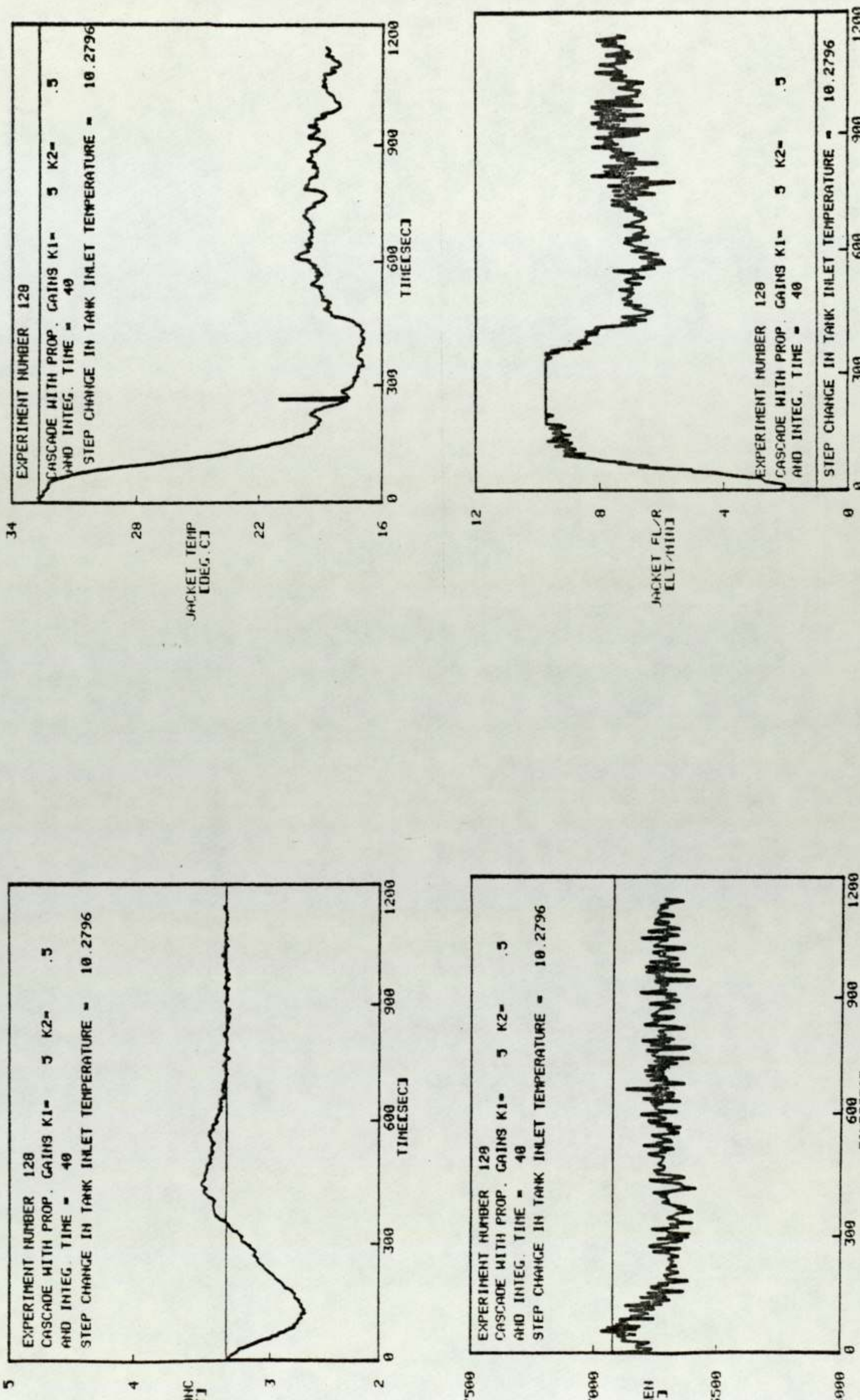

MODEL NUMBER 128
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 10.2796
TANK TEMP [DEG.C]
43
41
39
37
0
300
600
900
1200
TIME[SEC]

FIG. A.3.41



EXPERIMENT NUMBER 128
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 10.2796
JACKET TEMP [DEG.C]
34
28
22
16
TIME[SEC]
0
300
600
900
1200
JACKET FL/R [LT/MIN]
12
8
4
0
TANK CONC [GR/LT] *E-02
5
4
3
2
HEAT GEN [WATT]
7500
7000
6500
6000

FIG. A.3.42

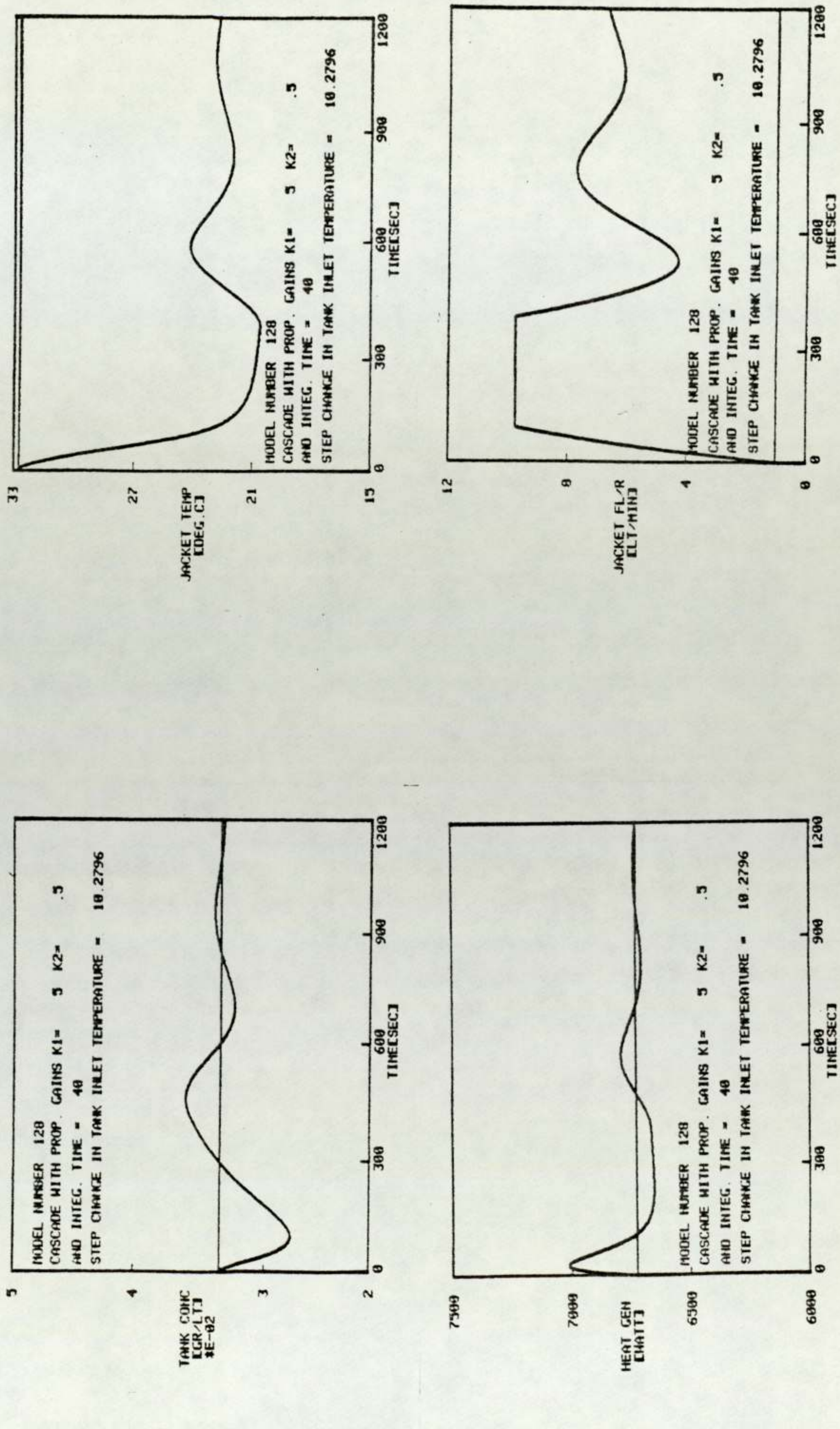
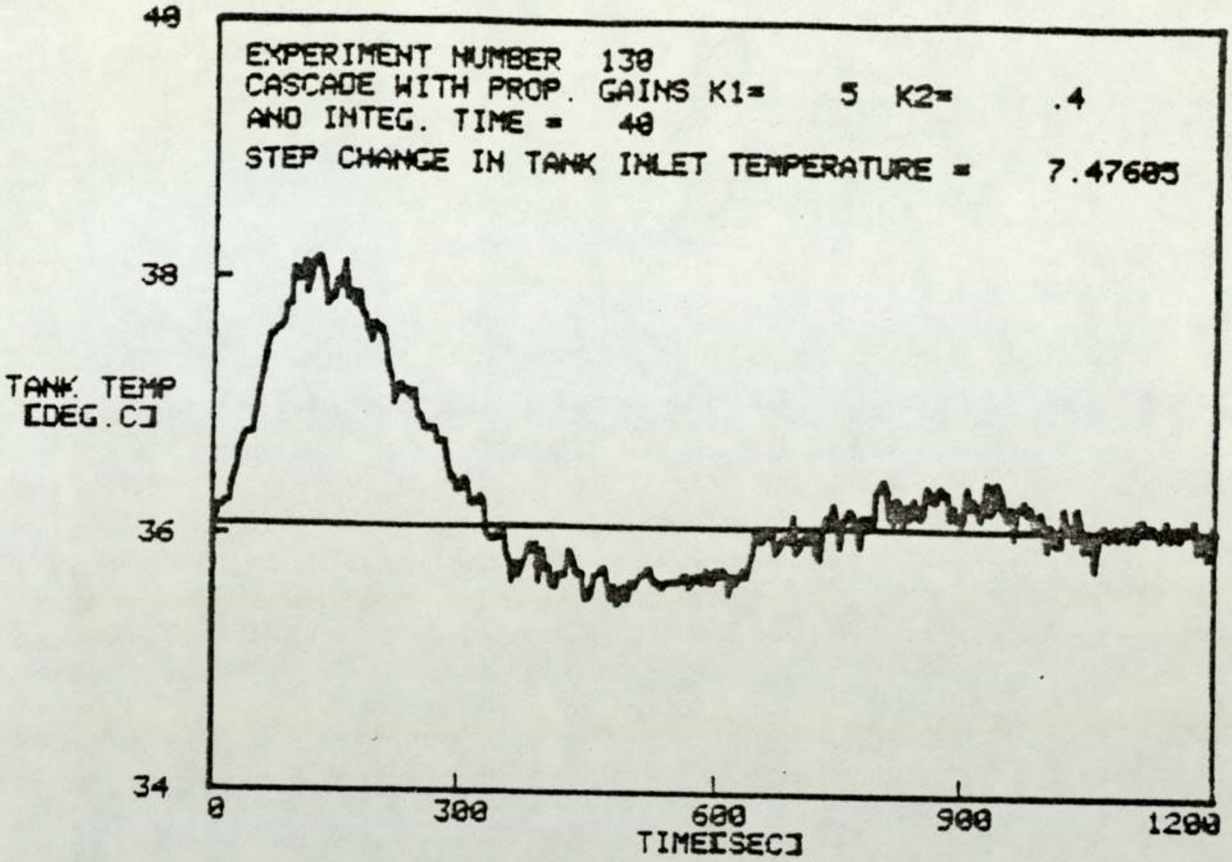

MODEL NUMBER 128
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 10.2796
JACKET TEMP [DEG.C]
33
27
21
15
JACKET FL/R [LT/MIN]
12
8
4
0
TANK CONC [GR/LT] *E-02
5
4
3
2
HEAT GEN [WATT]
7500
7000
6500
6000
0
300
600
900
1200
TIME[SEC]

FIG. A.3.43


EXPERIMENT NUMBER 130
CASCADE WITH PROP. GAINS K1= 5 K2= .4
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 7.47605
40
38
36
34
TANK TEMP [DEG.C]
0
300
600
900
1200
TIME[SEC]

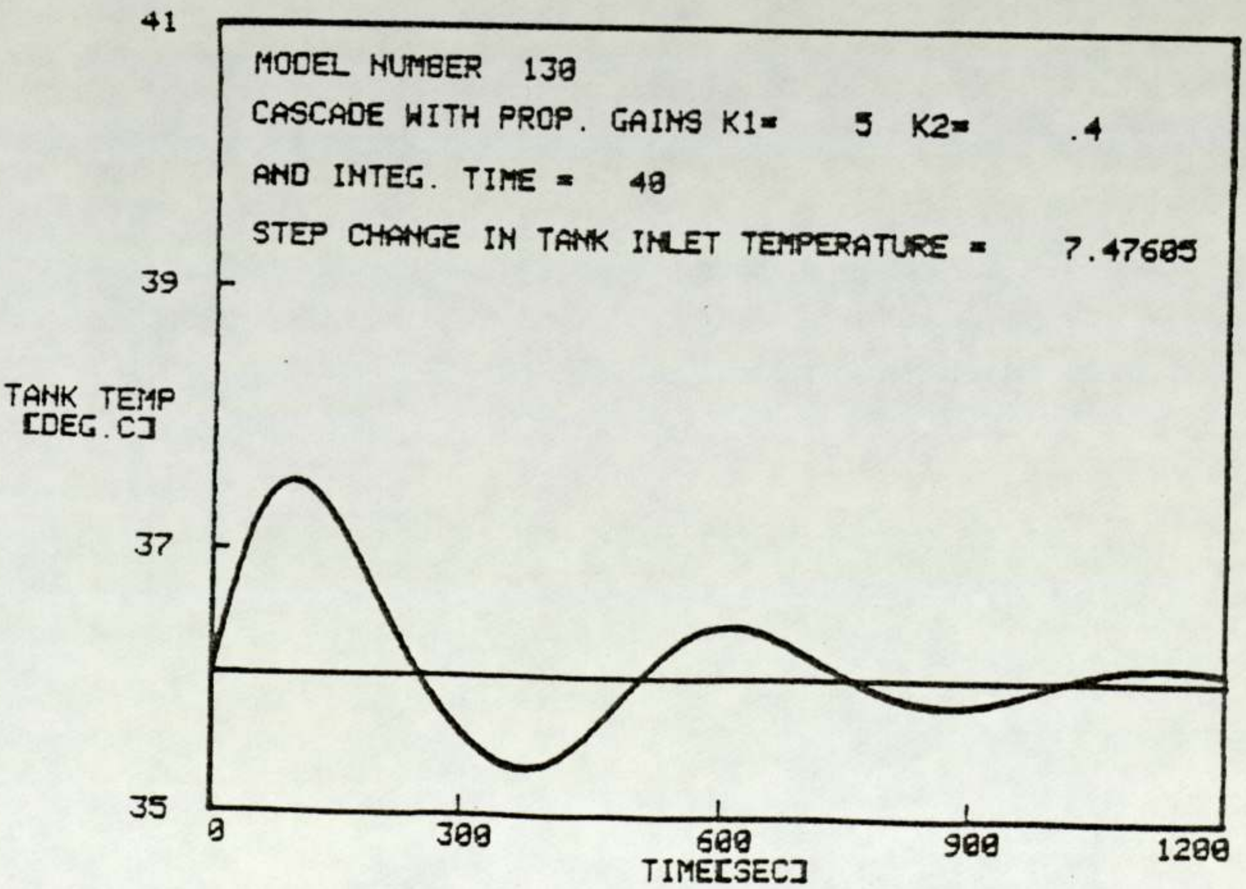
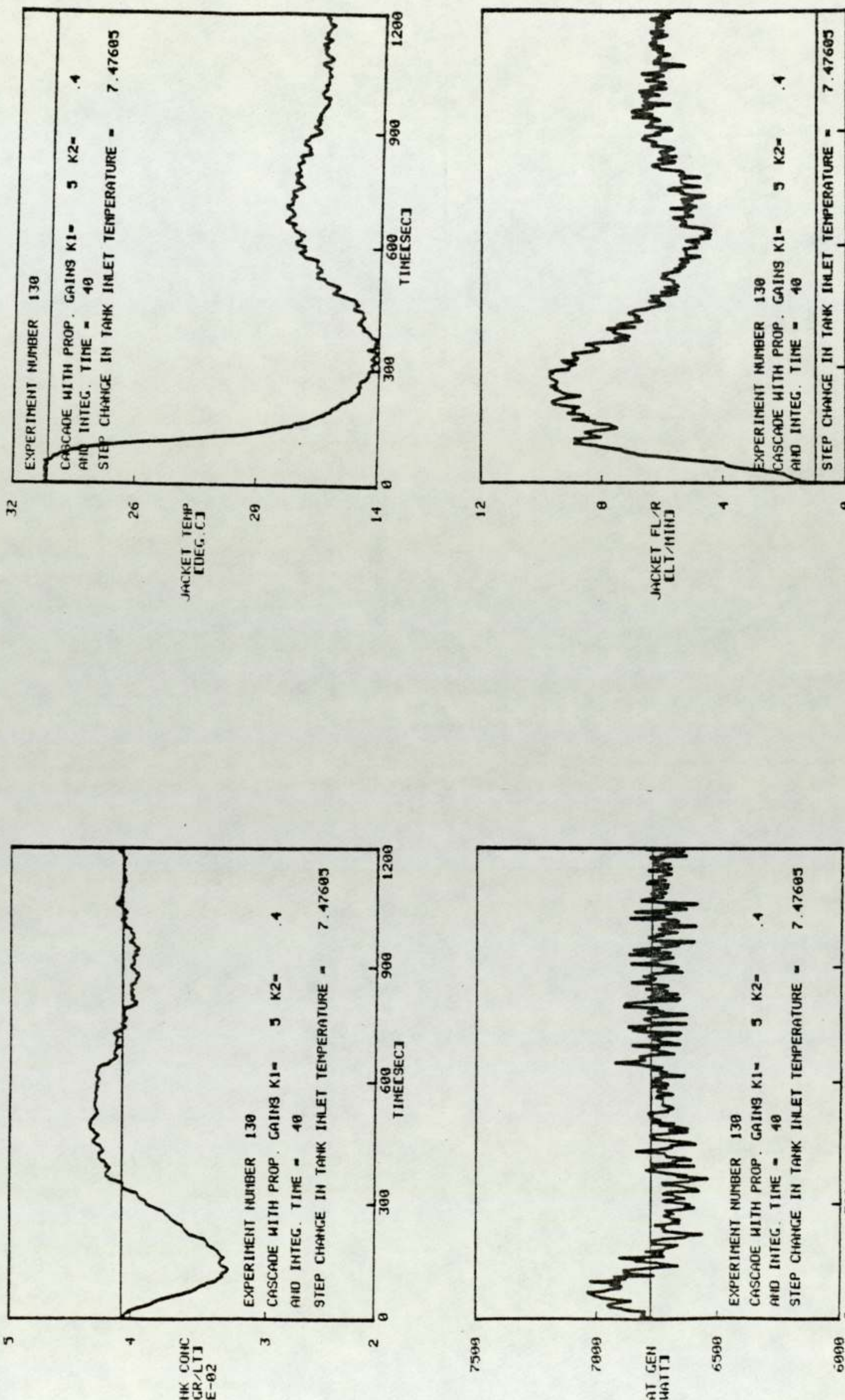

MODEL NUMBER 130
CASCADE WITH PROP. GAINS K1= 5 K2= .4
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 7.47605
41
39
37
35
TANK TEMP [DEG.C]
0
300
600
900
1200
TIME[SEC]

FIG. A.3.44



EXPERIMENT NUMBER 130
CASCADE WITH PROP. GAINS K1= 5 K2= .4
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 7.47605
JACKET TEMP [DEG.C]
32
26
20
14
TIME[SEC]
0
300
600
900
1200
EXPERIMENT NUMBER 130
CASCADE WITH PROP. GAINS K1= 5 K2= .4
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 7.47605
JACKET FL/R [LT/MIN]
12
8
4
0
TIME[SEC]
0
300
600
900
1200
EXPERIMENT NUMBER 130
CASCADE WITH PROP. GAINS K1= 5 K2= .4
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 7.47605
TANK CONC [GR/LT] *E-02
5
4
3
2
TIME[SEC]
0
300
600
900
1200
EXPERIMENT NUMBER 130
CASCADE WITH PROP. GAINS K1= 5 K2= .4
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 7.47605
HEAT GEN [WATT]
7500
7000
6500
6000
TIME[SEC]
0
300
600
900
1200

FIG. A.3.45

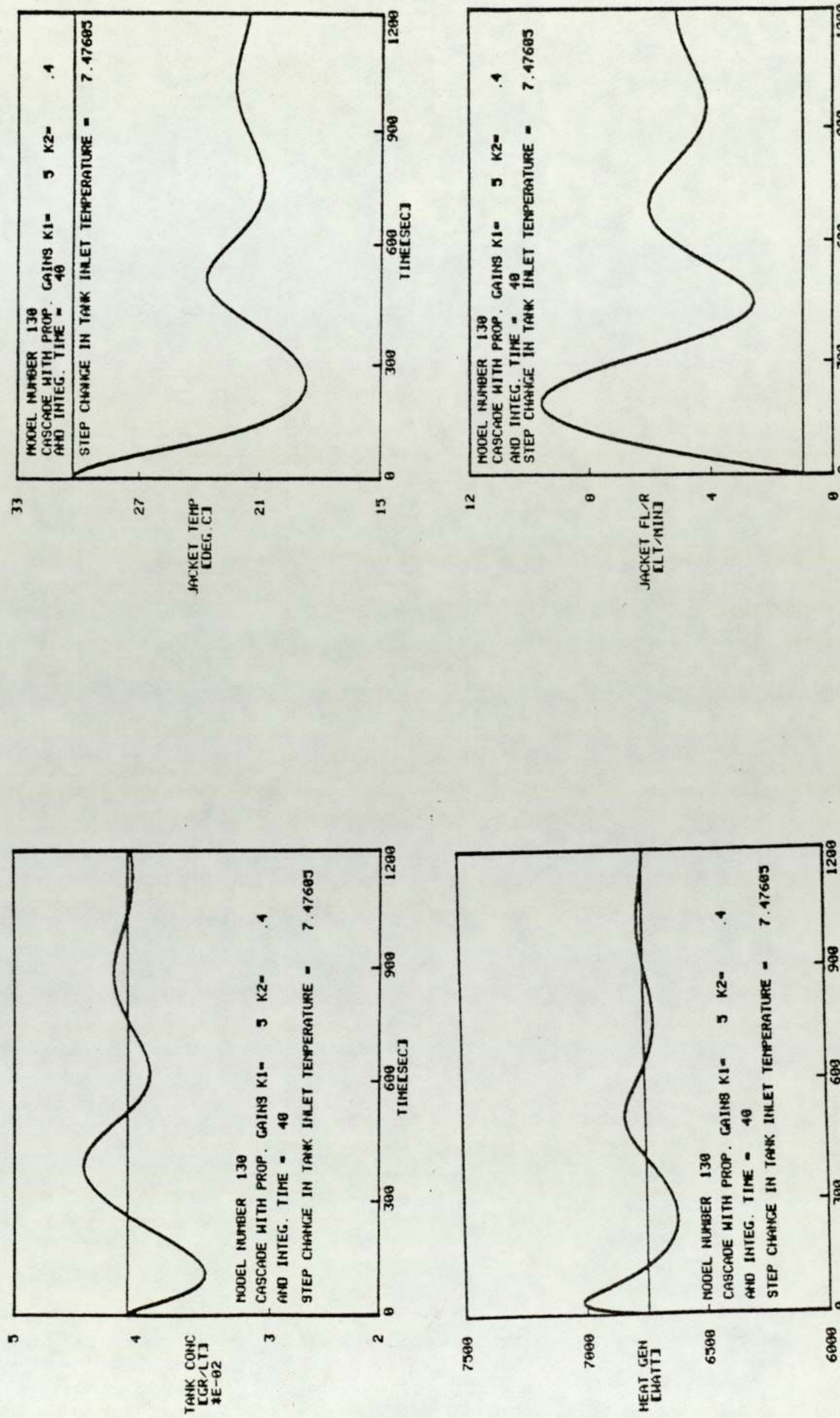
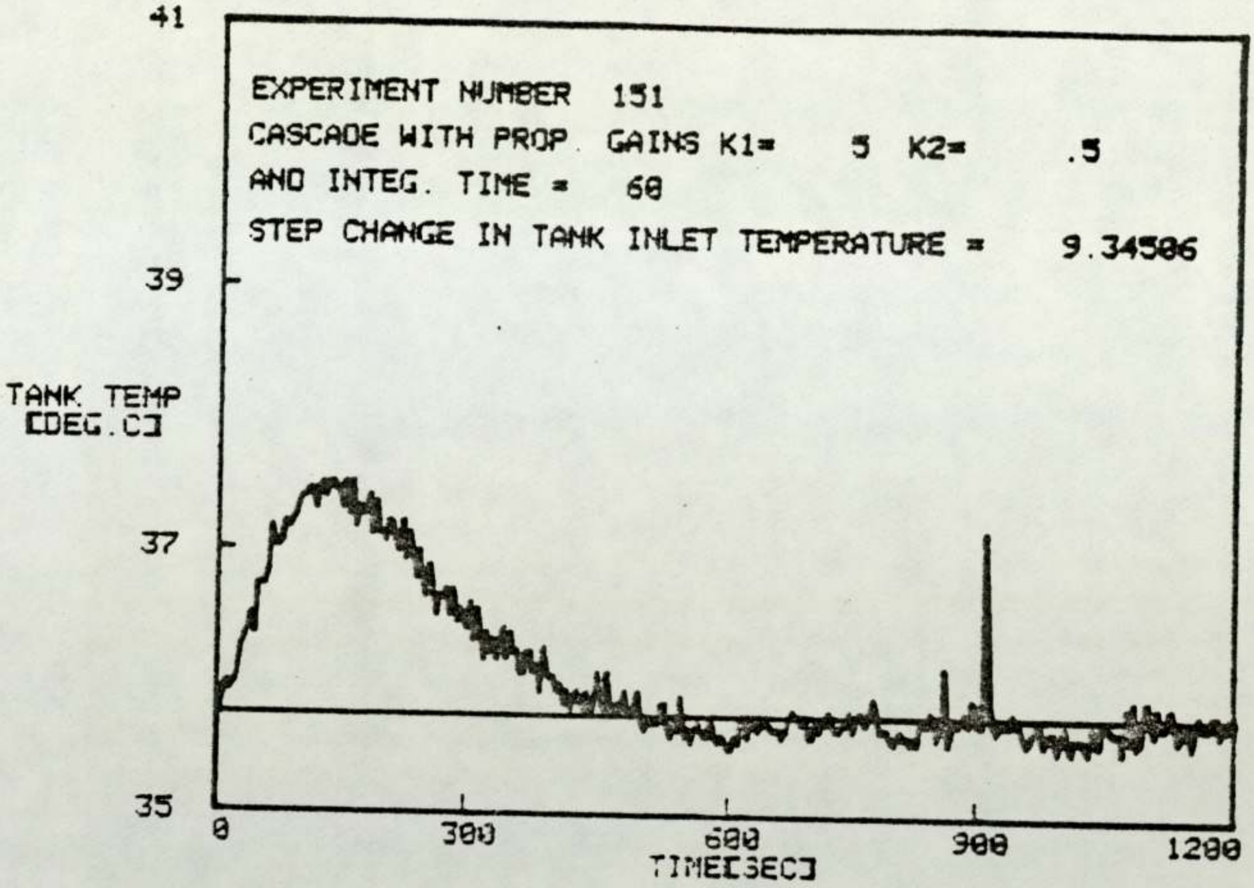

MODEL NUMBER 130
CASCADE WITH PROP. GAINS K1= 5 K2= .4
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 7.47605
JACKET TEMP [DEG.C]
JACKET FL/R [LT/MIN]
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
TIME[SEC]
0
300
600
900
1200
33
27
21
15
12
8
4
0
5
4
3
2
7500
7000
6500
6000

FIG. A.3.46


EXPERIMENT NUMBER 151
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 9.34506
41
39
37
35
TANK TEMP
[DEG.C]
0
300
600
900
1200
TIME[SEC]

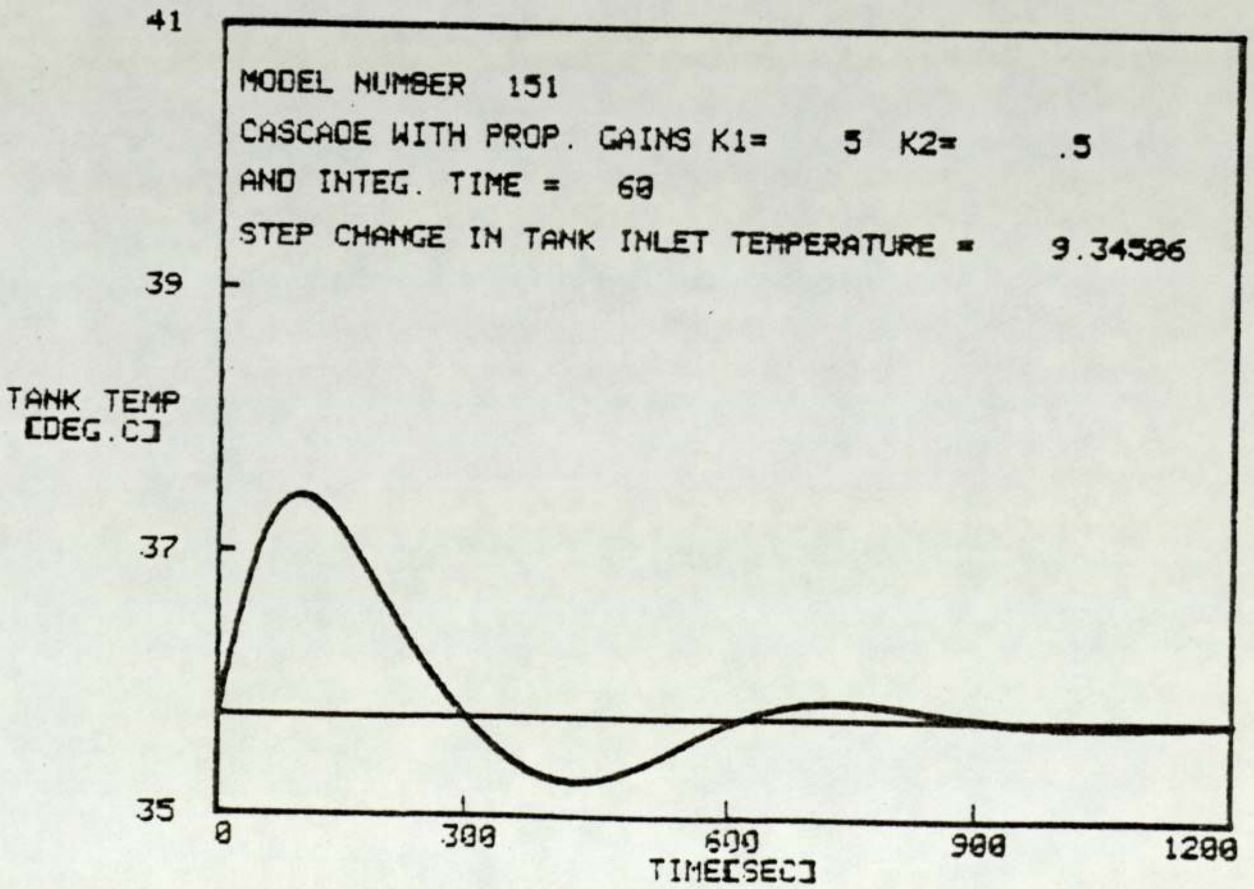

MODEL NUMBER 151
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 9.34506
41
39
37
35
TANK TEMP
[DEG.C]
0
300
600
900
1200
TIME[SEC]

FIG. A.3.47

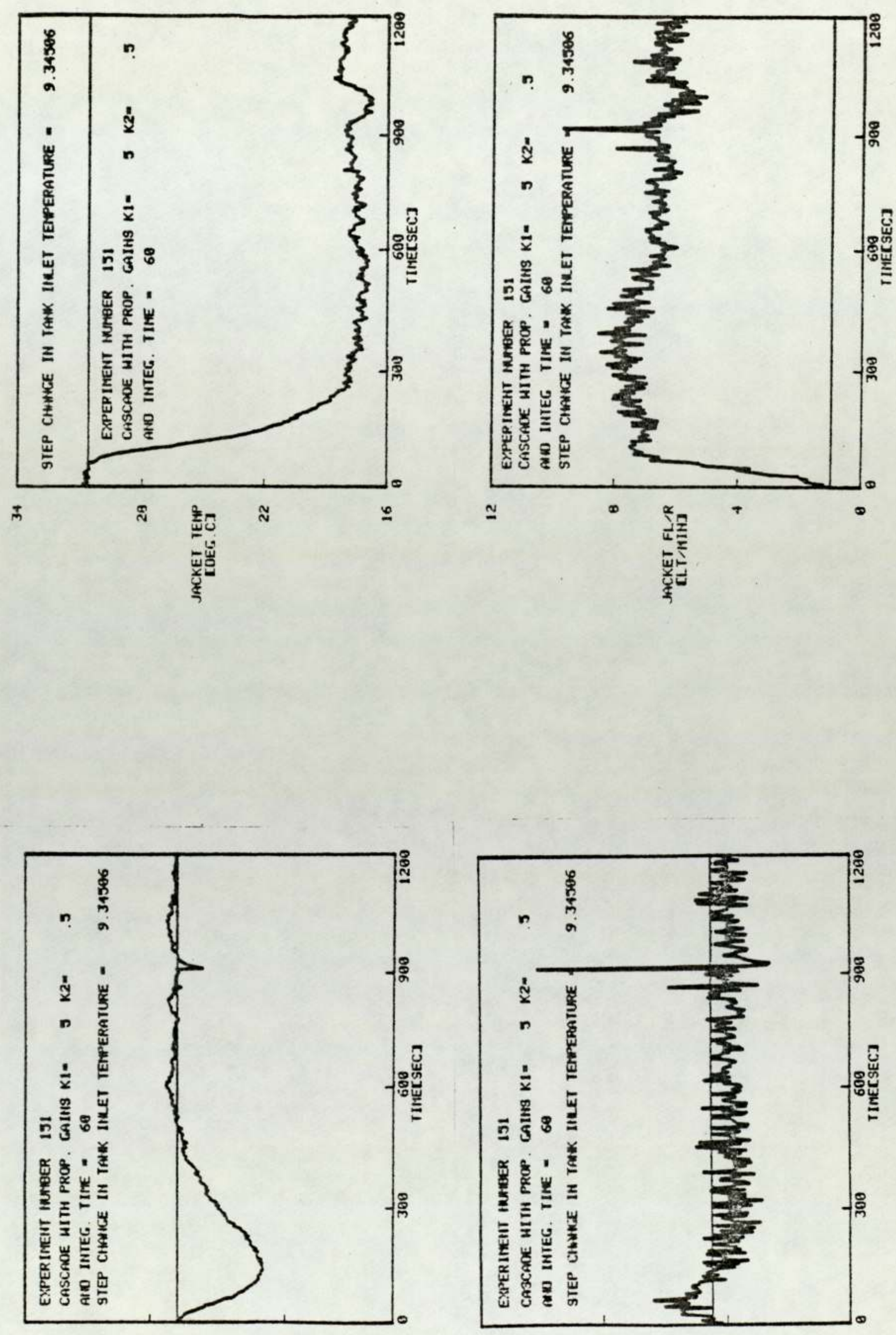

EXPERIMENT NUMBER 151
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 9.34506
JACKET TEMP [DEG.C]
JACKET FL/R [LT/MIN]
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
TIME[SEC]

FIG. A.3.48

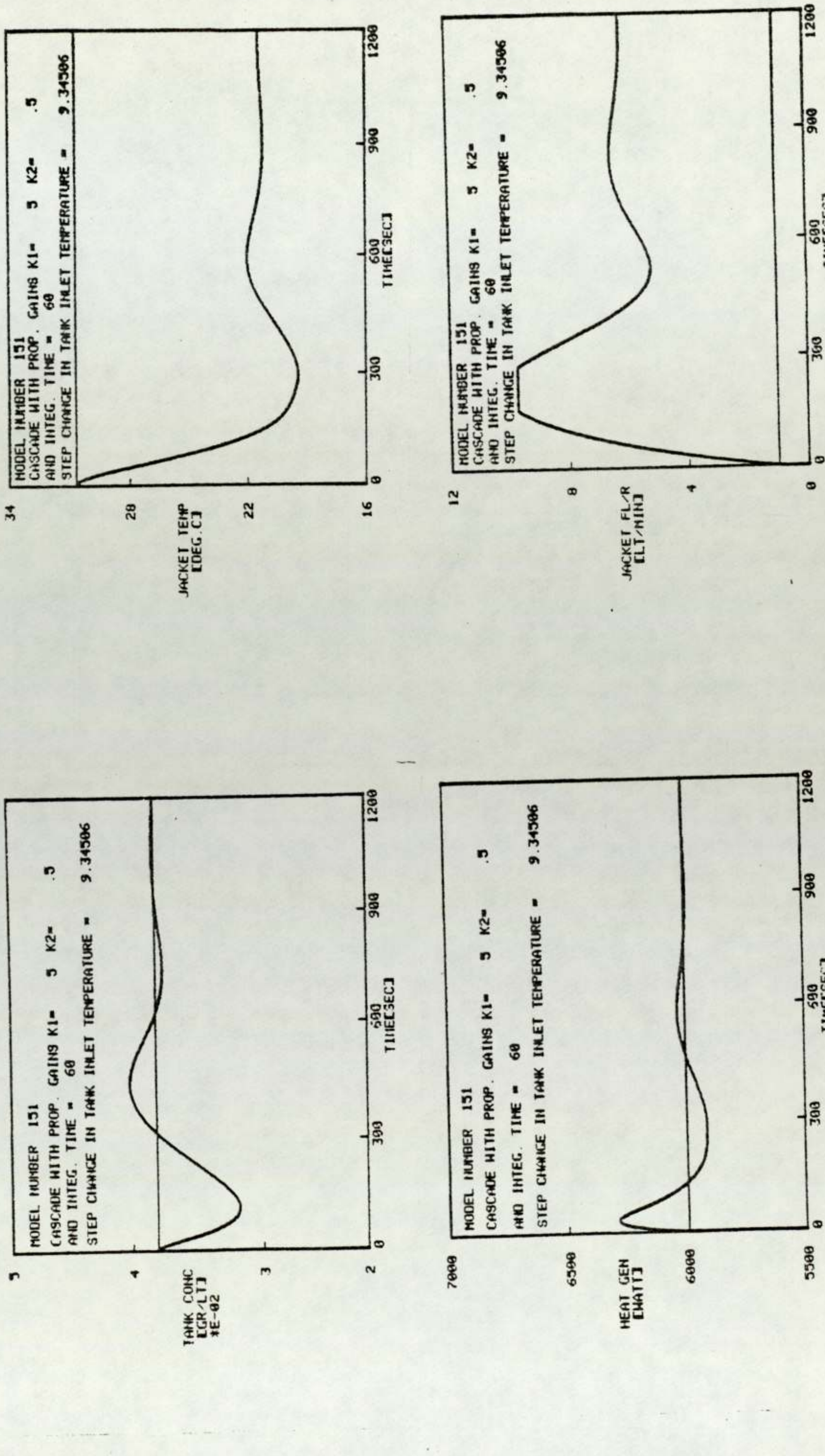
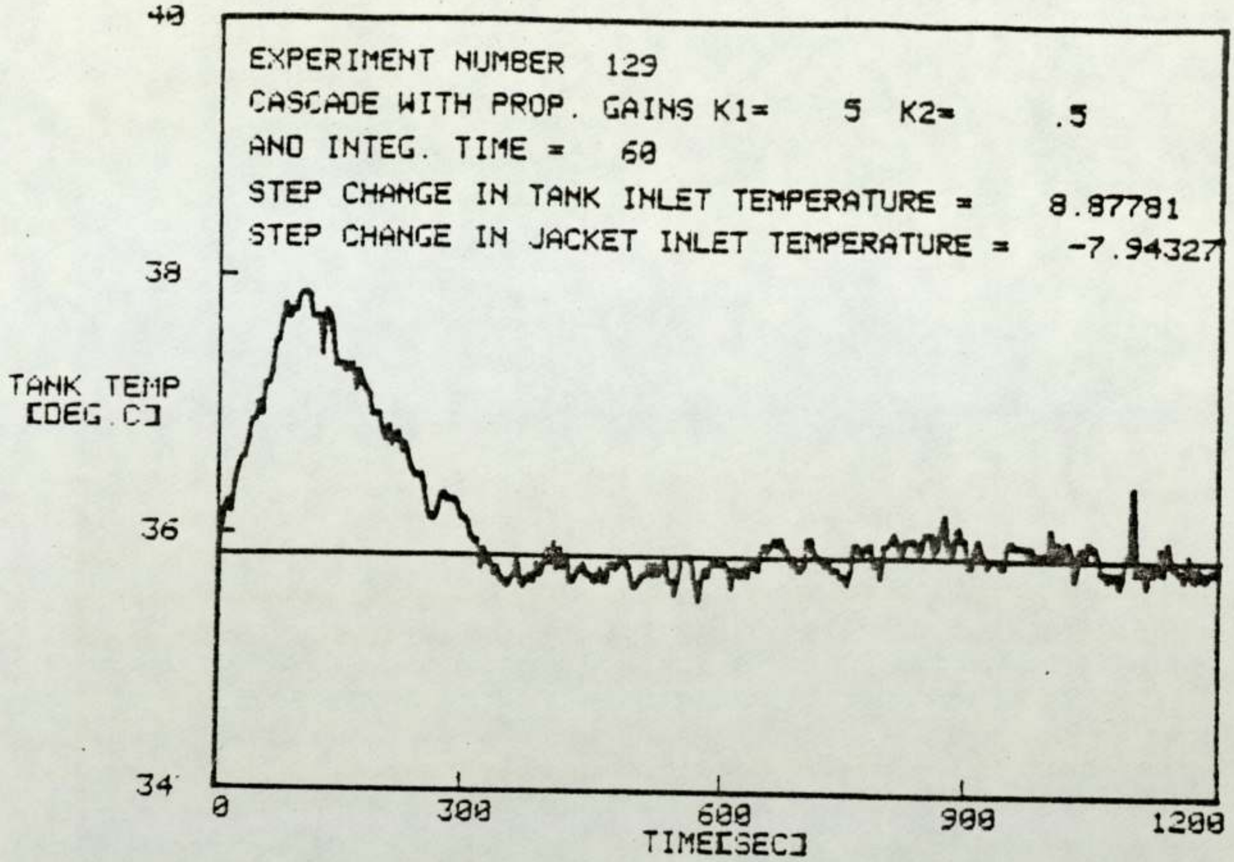
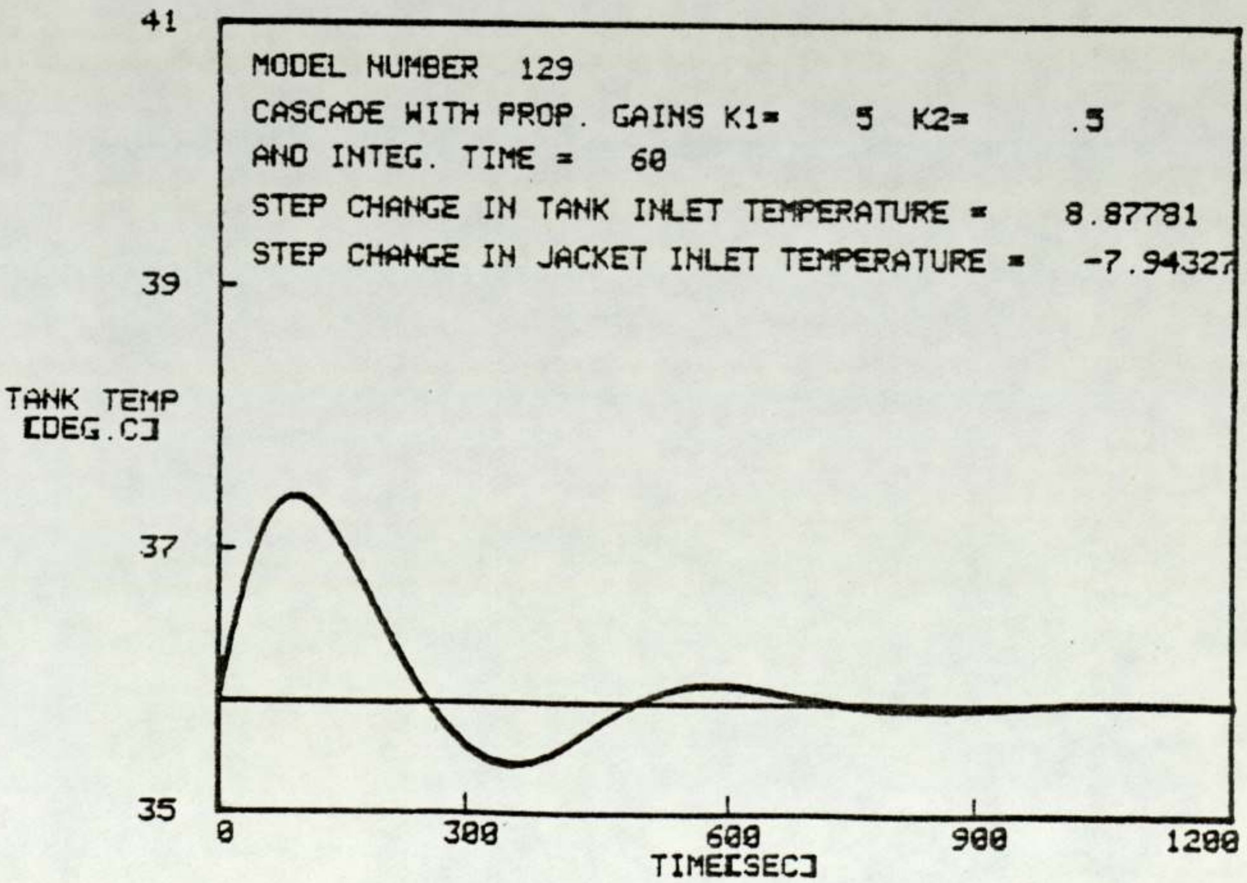

MODEL NUMBER 151
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 9.34506
JACKET TEMP [DEG.C]
JACKET FL/R [LT/MIN]
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
TIME[SEC]

FIG. A.3.49

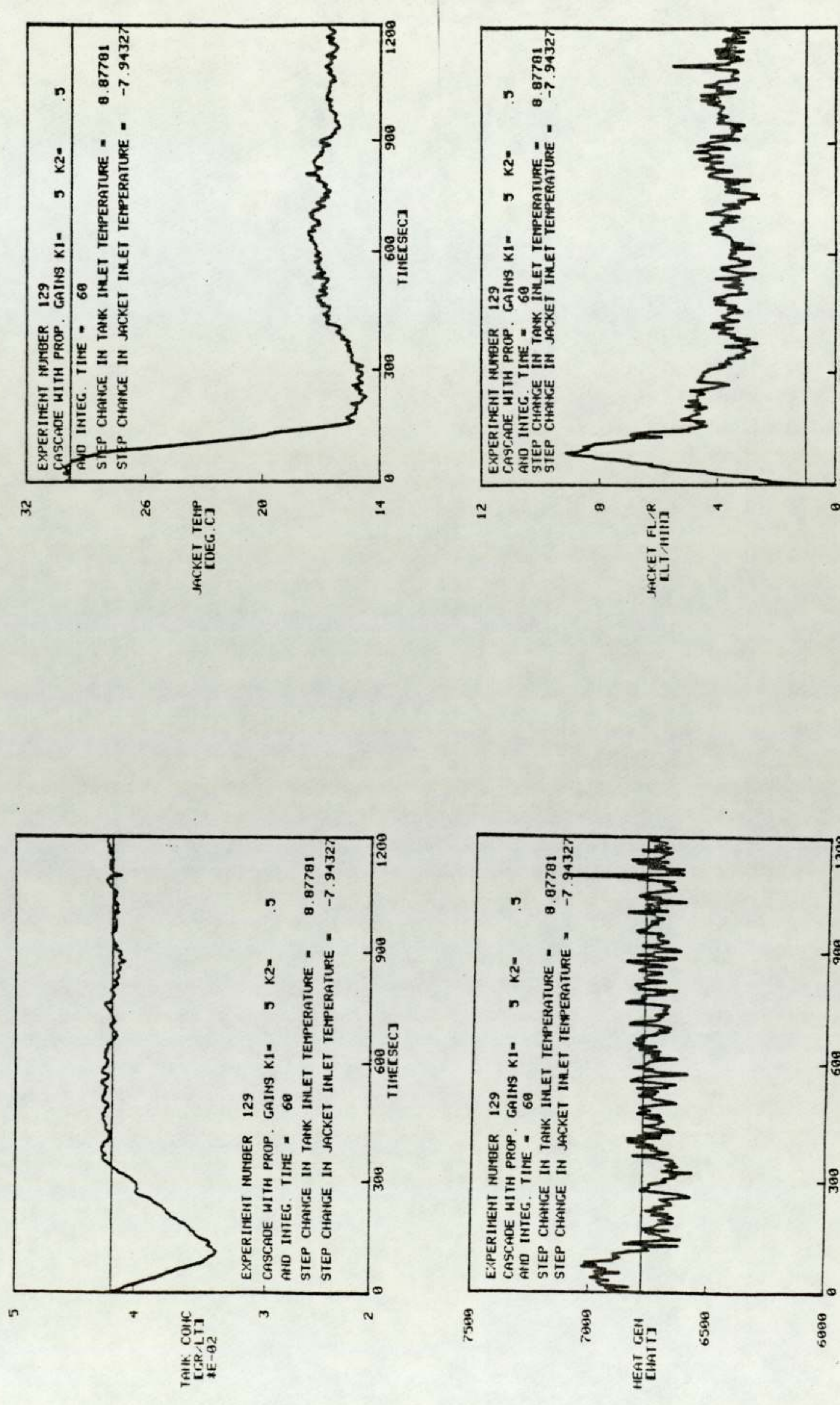


EXPERIMENT NUMBER 129
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 8.87781
STEP CHANGE IN JACKET INLET TEMPERATURE = -7.94327
TANK TEMP [DEG.C]
40
38
36
34
0
300
600
900
1200
TIME[SEC]



MODEL NUMBER 129
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 8.87781
STEP CHANGE IN JACKET INLET TEMPERATURE = -7.94327
TANK TEMP [DEG.C]
41
39
37
35
0
300
600
900
1200
TIME[SEC]

FIG. A.3.50



EXPERIMENT NUMBER 129
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 8.87781
STEP CHANGE IN JACKET INLET TEMPERATURE = -7.94327
JACKET TEMP [DEG.C]
JACKET FL/R [LT/MIN]
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
TIME[SEC]

FIG. A.3.51

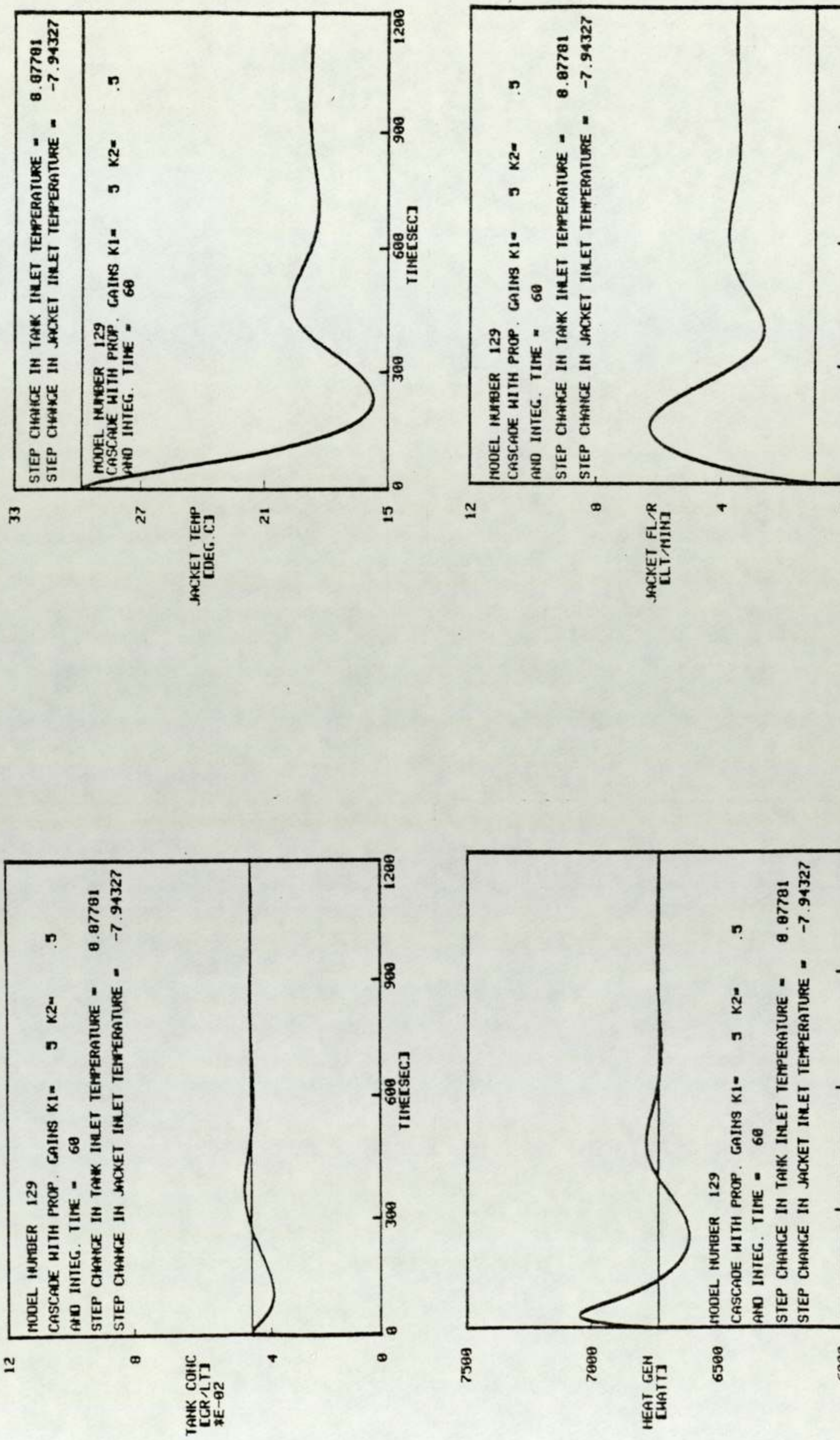
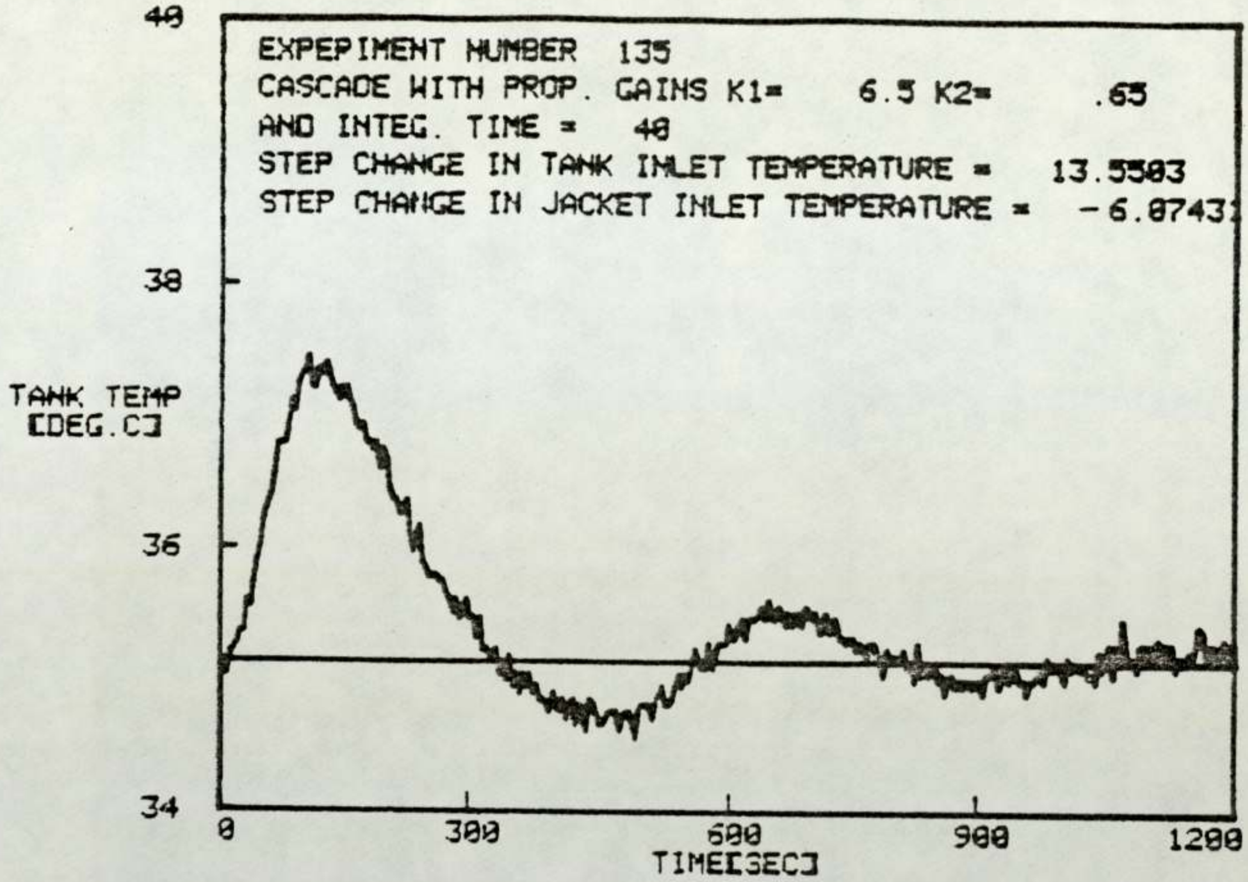

MODEL NUMBER 129
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 8.07781
STEP CHANGE IN JACKET INLET TEMPERATURE = -7.94327
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
JACKET TEMP [DEG.C]
JACKET FL/R [LT/MIN]
TIME[SEC]
0
300
600
900
1200
12
8
4
0
7500
7000
6500
6000
33
27
21
15

FIG. A.3.52


EXPEPIMENT NUMBER 135
CASCADE WITH PROP. GAINS K1= 6.5 K2= .65
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 13.5503
STEP CHANGE IN JACKET INLET TEMPERATURE = -6.07431
40
38
36
34
TANK TEMP [DEG.C]
0
300
600
900
1200
TIME[SEC]

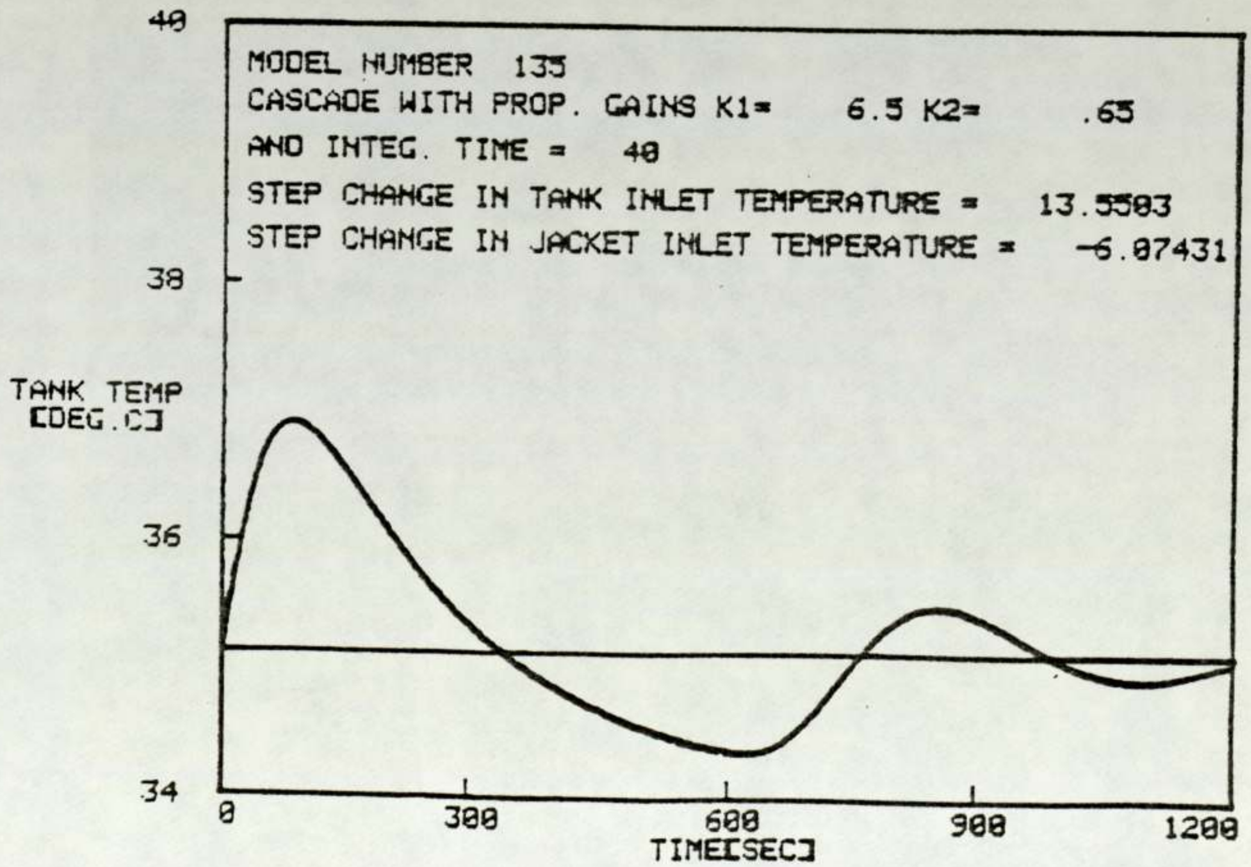

MODEL NUMBER 135
CASCADE WITH PROP. GAINS K1= 6.5 K2= .65
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 13.5503
STEP CHANGE IN JACKET INLET TEMPERATURE = -6.07431
40
38
36
34
TANK TEMP [DEG.C]
0
300
600
900
1200
TIME[SEC]

FIG. A.3.53

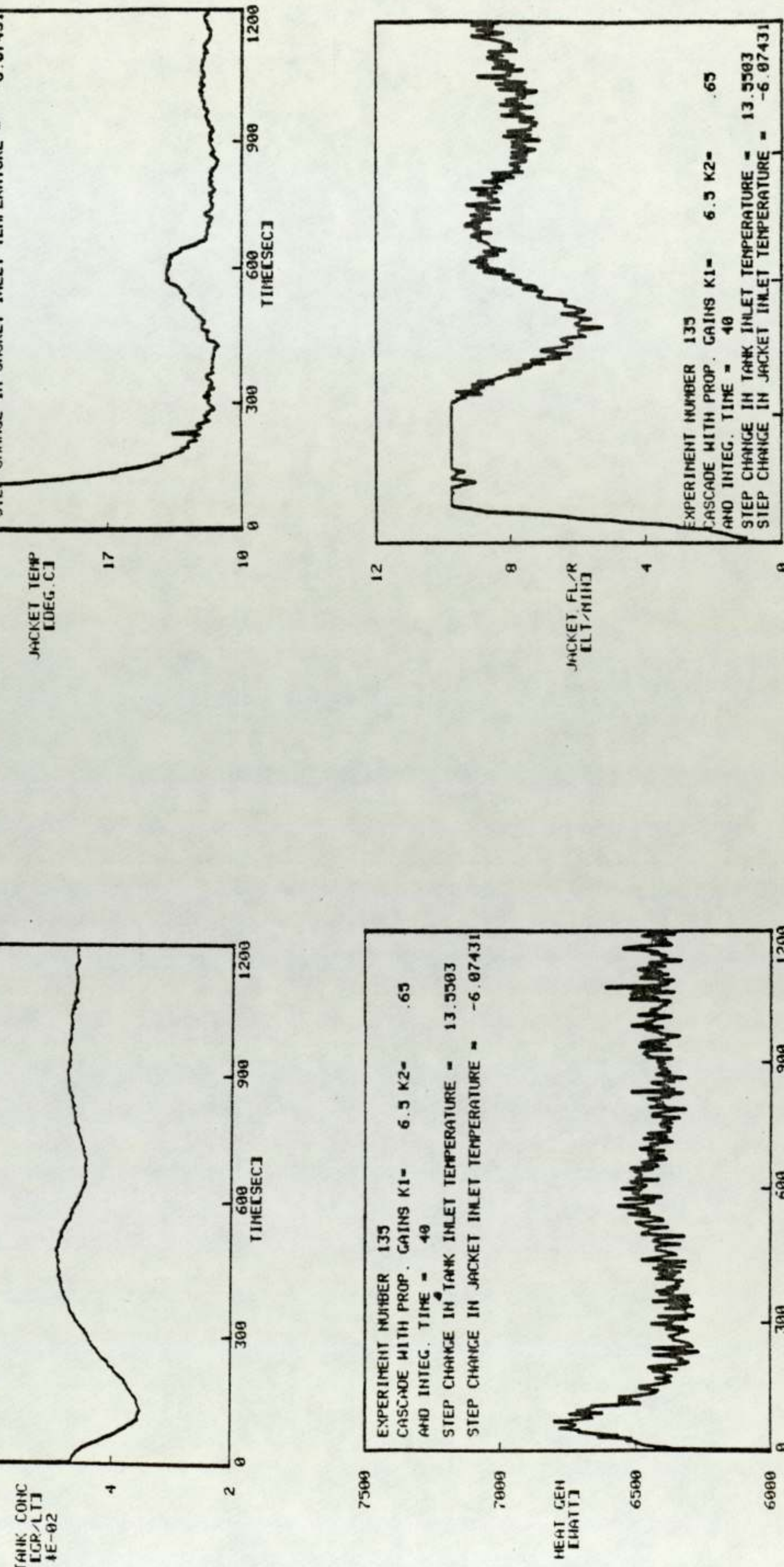

EXPERIMENT NUMBER 135
CASCADE WITH PROP. GAINS K1= 6.5 K2= .65
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 13.5503
STEP CHANGE IN JACKET INLET TEMPERATURE = -6.07431
JACKET TEMP [DEG.C]
JACKET FL/R [LT/MIN]
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
TIME[SEC]

FIG. A.3.54

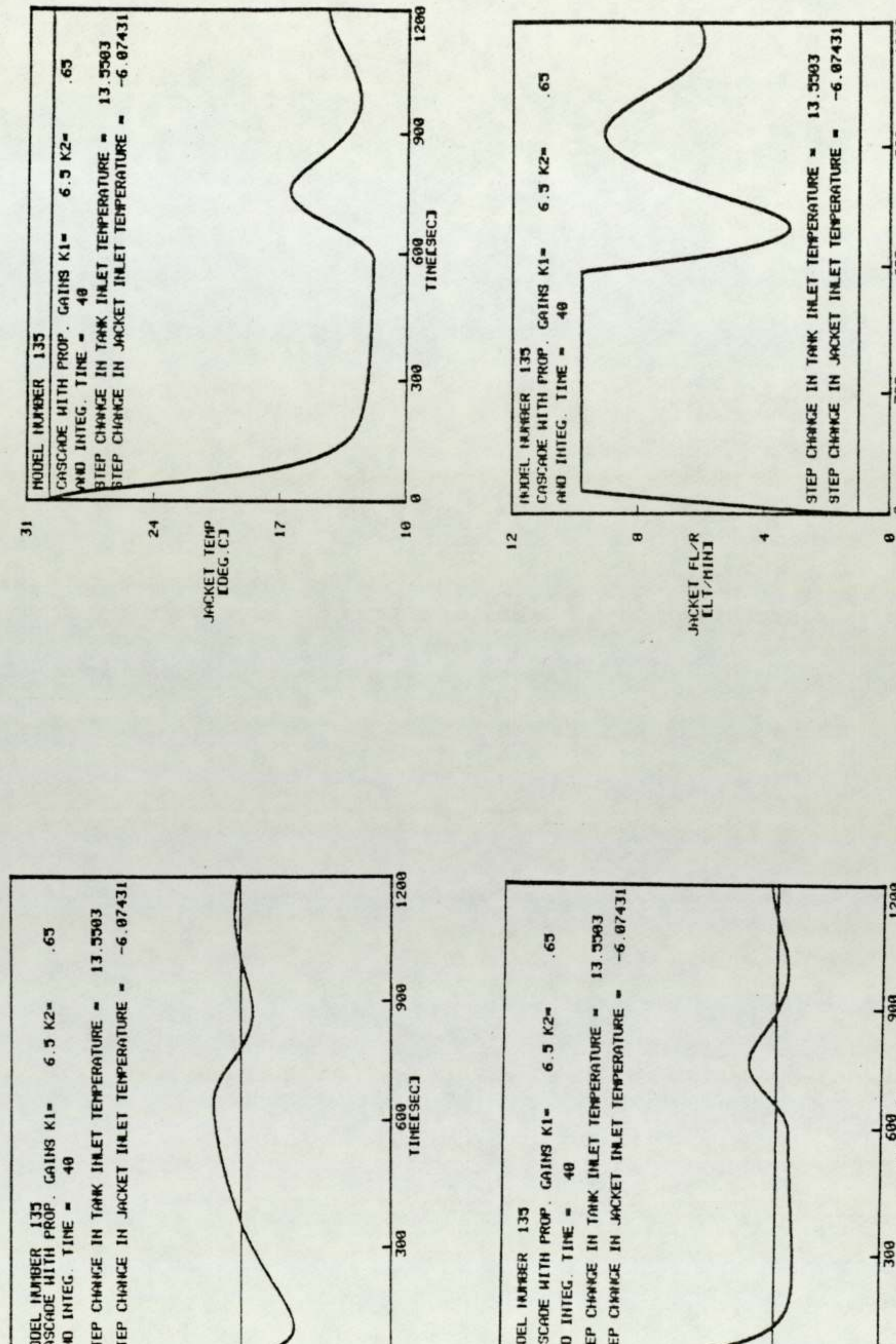
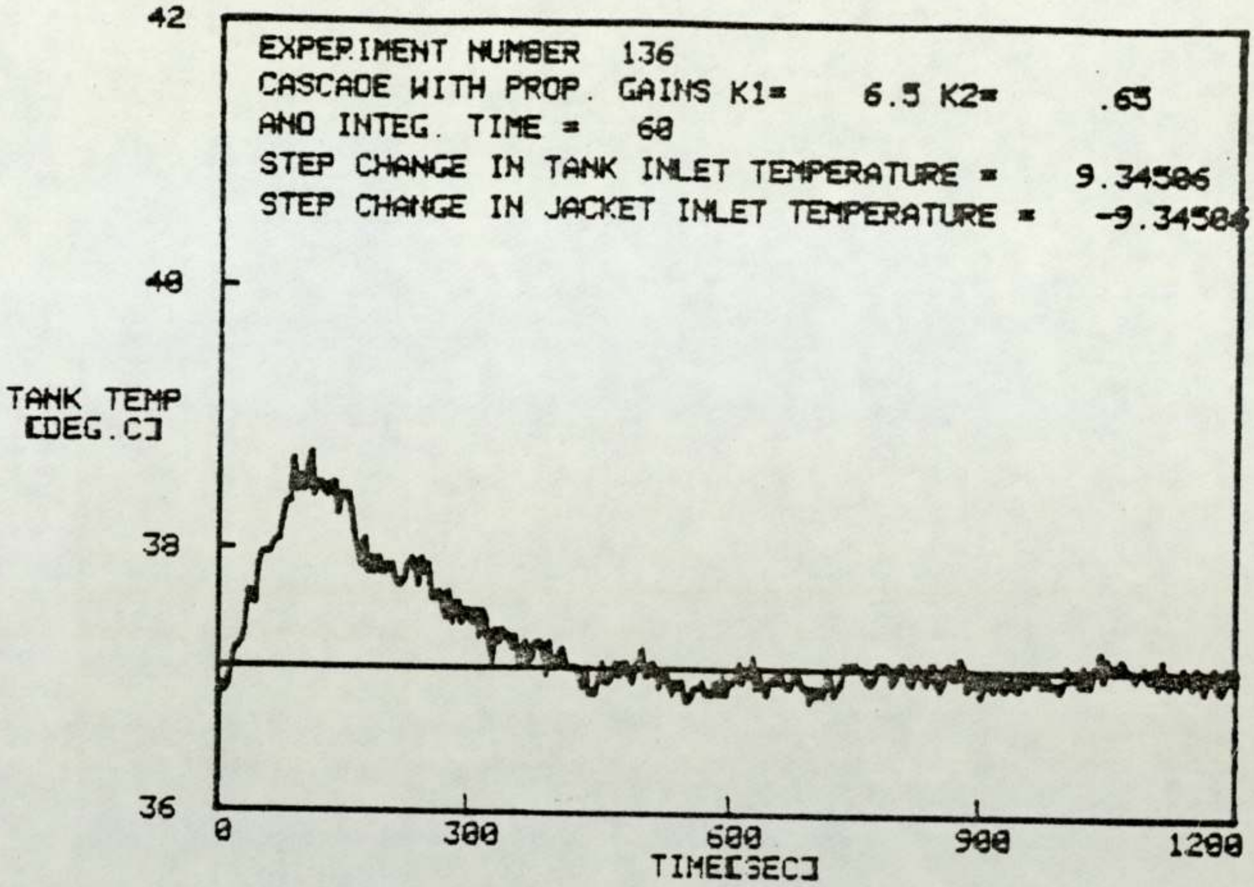

MODEL NUMBER 135
CASCADE WITH PROP. GAINS K1= 6.5 K2= .65
AND INTEG. TIME = 40
STEP CHANGE IN TANK INLET TEMPERATURE = 13.5503
STEP CHANGE IN JACKET INLET TEMPERATURE = -6.07431
JACKET TEMP [DEG.C]
31
24
17
10
JACKET FL/R [LT/MIN]
12
8
4
0
TANK CONC [GR/LT] *E-02
8
6
4
2
HEAT GEN [WATT]
7500
7000
6500
6000
TIME[SEC]
0
300
600
900
1200

FIG. A.3.55


EXPERIMENT NUMBER 136
CASCADE WITH PROP. GAINS K1= 6.5 K2= .65
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 9.34506
STEP CHANGE IN JACKET INLET TEMPERATURE = -9.34506
TANK TEMP [DEG.C]
42
40
38
36
0
300
600
900
1200
TIME[SEC]

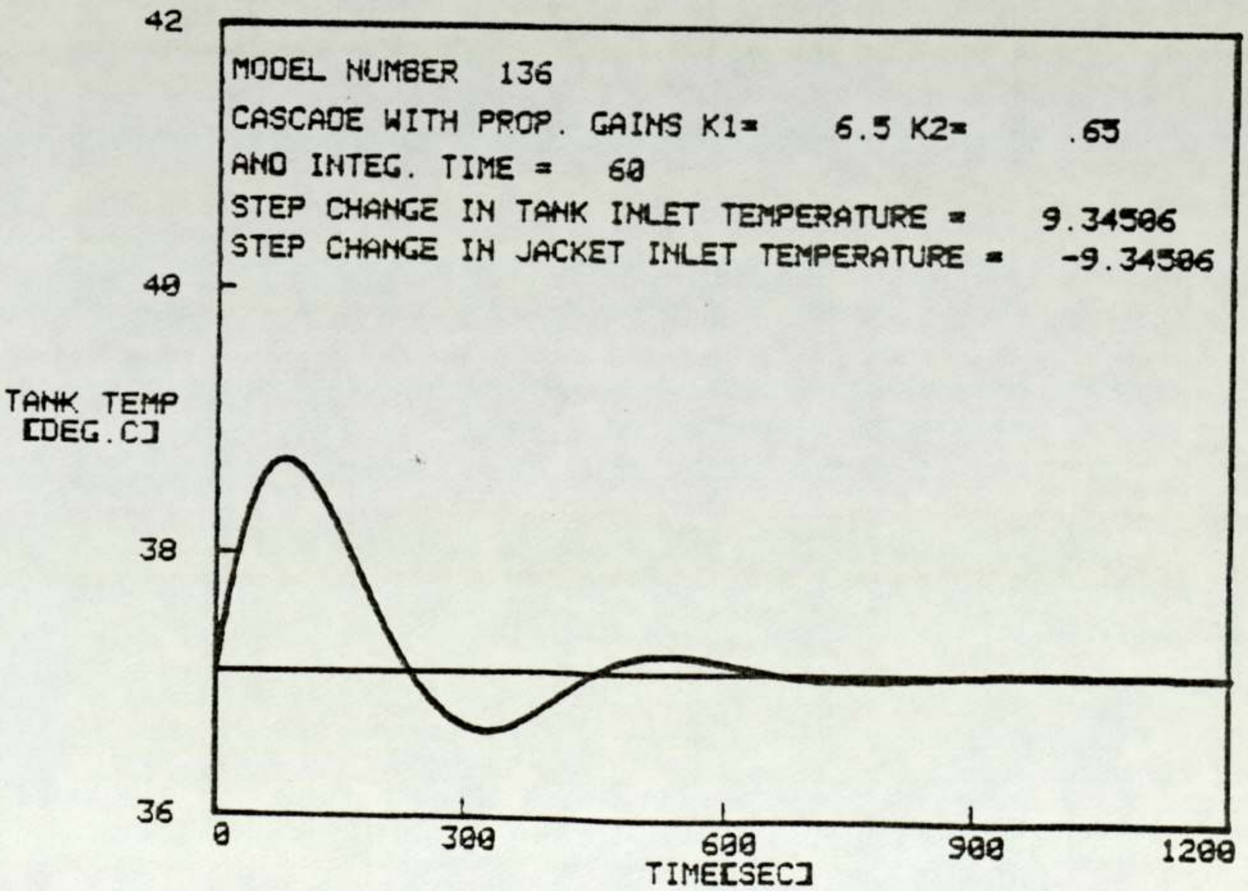
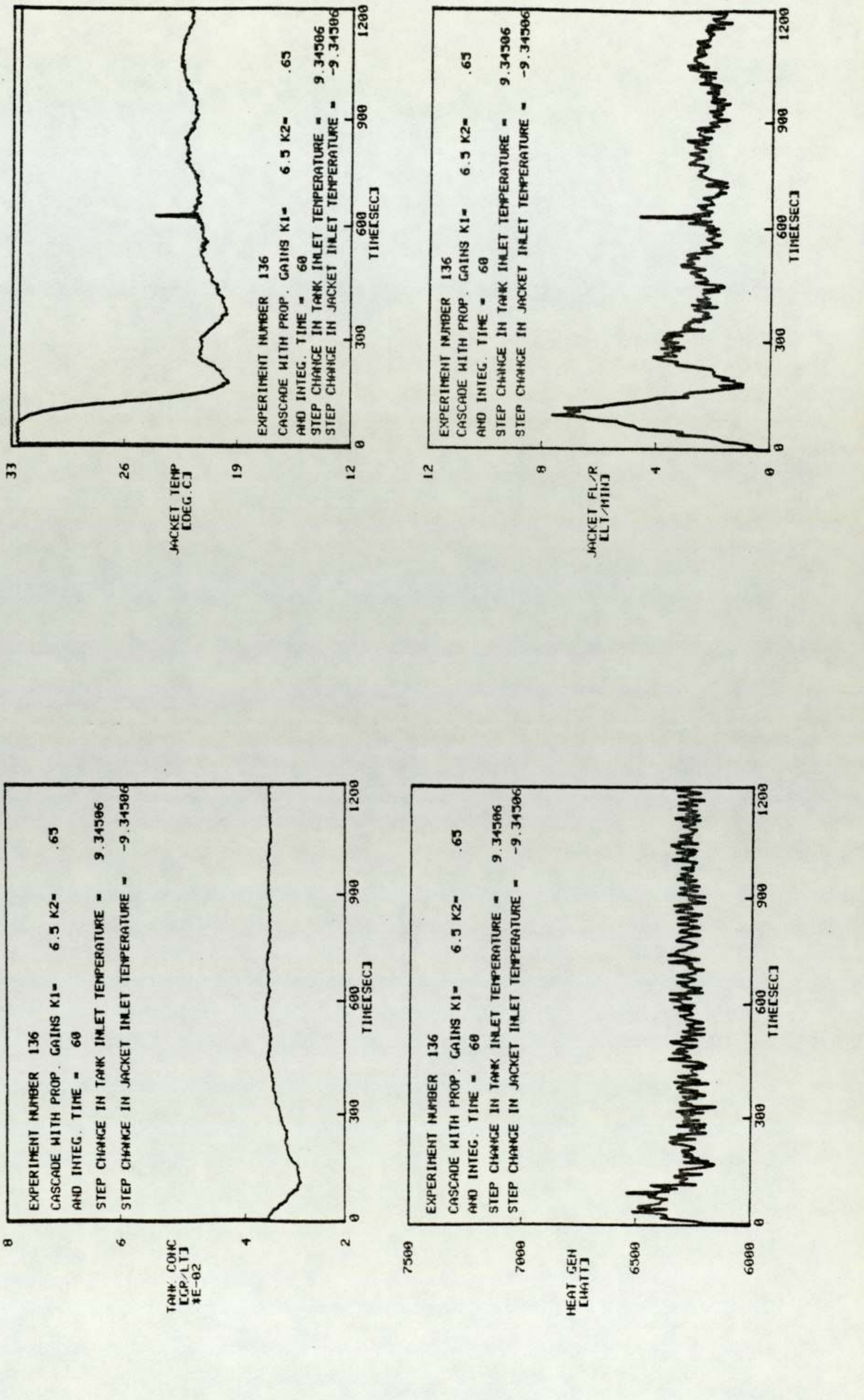

MODEL NUMBER 136
CASCADE WITH PROP. GAINS K1= 6.5 K2= .65
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 9.34506
STEP CHANGE IN JACKET INLET TEMPERATURE = -9.34506
TANK TEMP [DEG.C]
42
40
38
36
0
300
600
900
1200
TIME[SEC]

FIG. A.3.56



EXPERIMENT NUMBER 136
CASCADE WITH PROP. GAINS K1= 6.5 K2= .65
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 9.34506
STEP CHANGE IN JACKET INLET TEMPERATURE = -9.34506
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
JACKET TEMP [DEG.C]
JACKET FL/R [LT/MIN]
TIME[SEC]

FIG. A.3.57

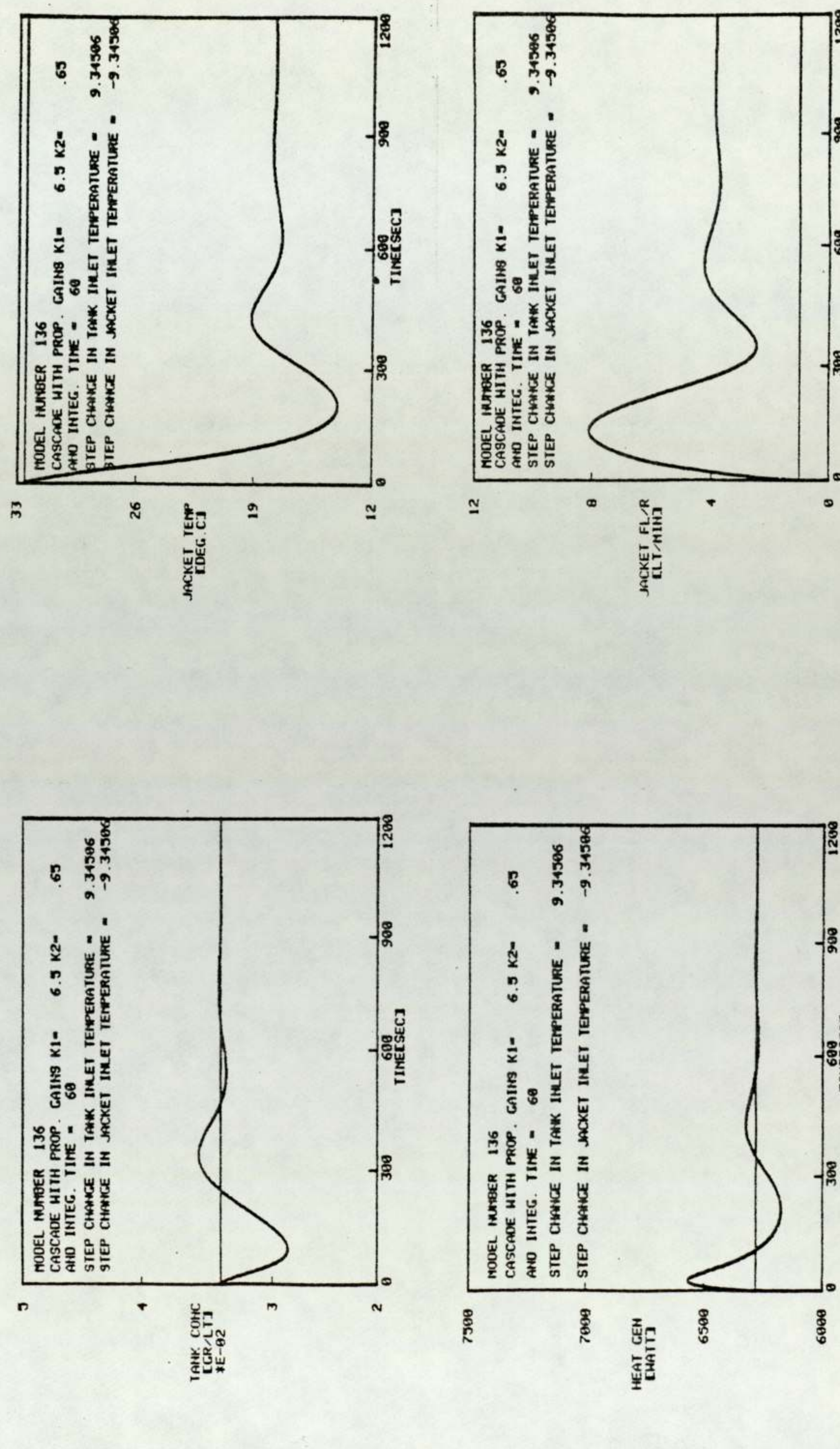
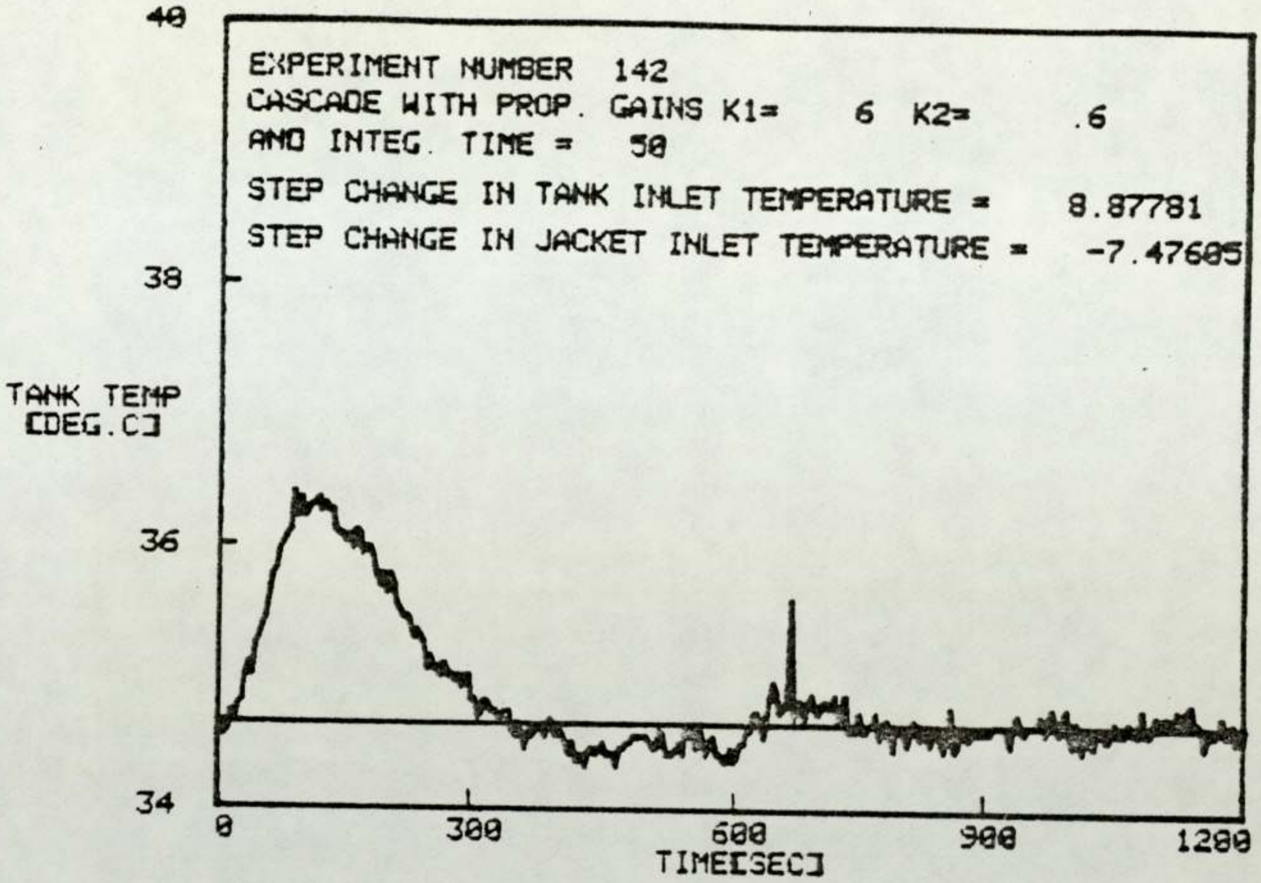
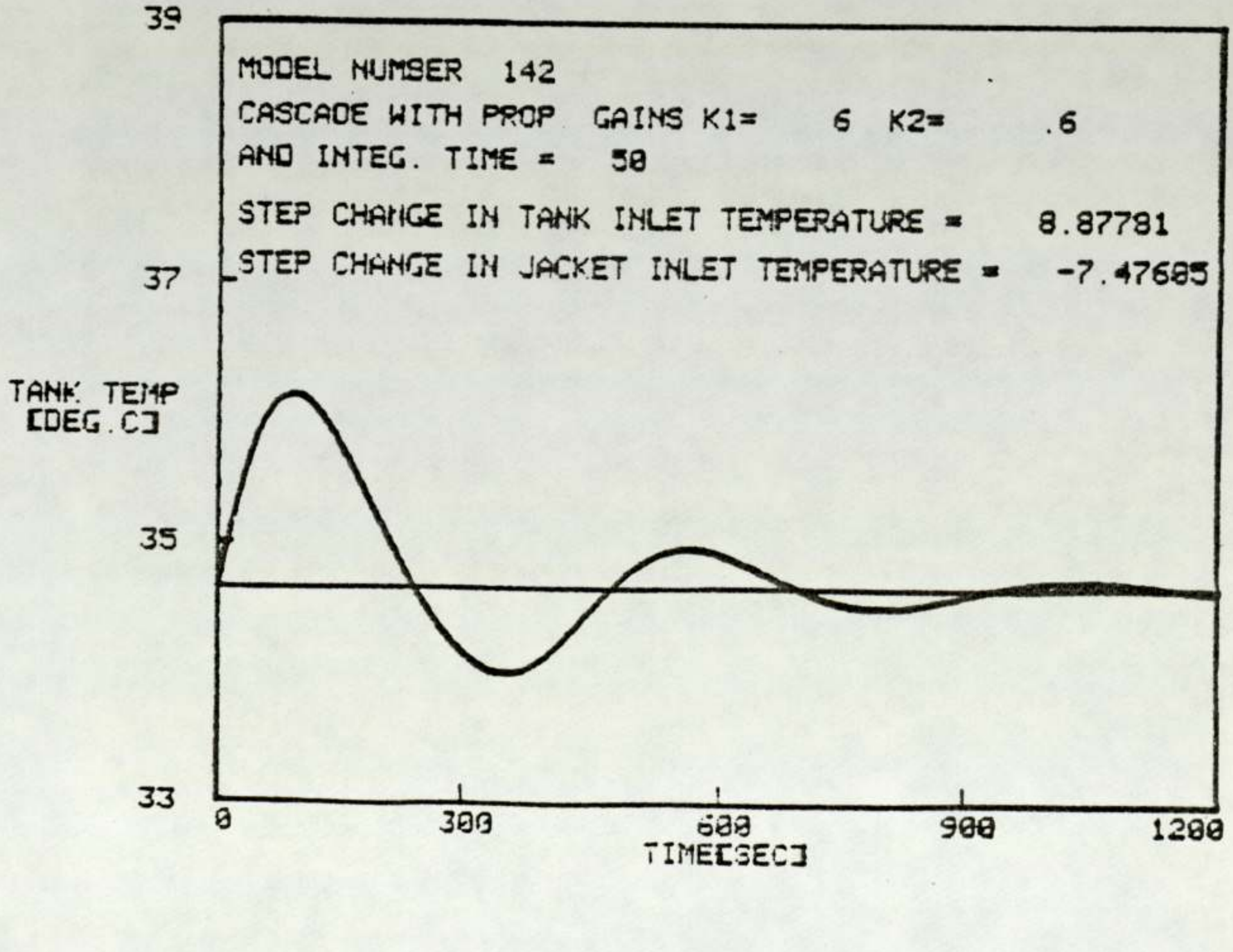

MODEL NUMBER 136
CASCADE WITH PROP. GAINS K1= 6.5 K2= .65
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 9.34506
STEP CHANGE IN JACKET INLET TEMPERATURE = -9.34506
JACKET TEMP [DEG.C]
33
26
19
12
0
300
600
900
1200
TIME[SEC]
MODEL NUMBER 136
CASCADE WITH PROP. GAINS K1= 6.5 K2= .65
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 9.34506
STEP CHANGE IN JACKET INLET TEMPERATURE = -9.34506
JACKET FL/R [LT/MIN]
12
8
4
0
0
300
600
900
1200
TIME[SEC]
MODEL NUMBER 136
CASCADE WITH PROP. GAINS K1= 6.5 K2= .65
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 9.34506
STEP CHANGE IN JACKET INLET TEMPERATURE = -9.34506
TANK CONC [GR/LT] *E-02
5
4
3
2
0
300
600
900
1200
TIME[SEC]
MODEL NUMBER 136
CASCADE WITH PROP. GAINS K1= 6.5 K2= .65
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 9.34506
STEP CHANGE IN JACKET INLET TEMPERATURE = -9.34506
HEAT GEN [WATT]
7500
7000
6500
6000
0
300
600
900
1200
TIME[SEC]

FIG. A.3.58

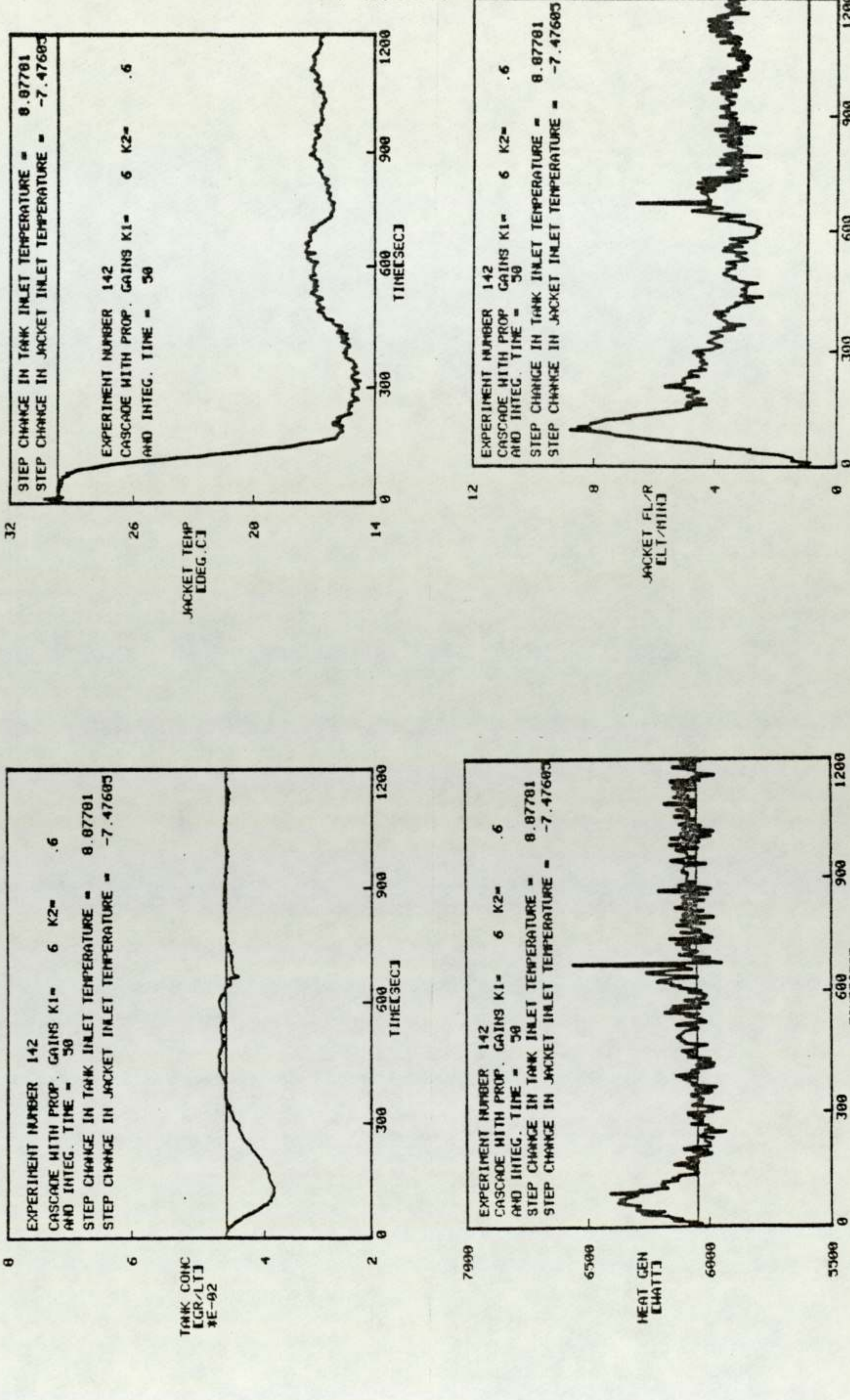


40
38
36
34
TANK TEMP
[DEG.C]
EXPERIMENT NUMBER 142
CASCADE WITH PROP. GAINS K1= 6 K2= .6
AND INTEG. TIME = 50
STEP CHANGE IN TANK INLET TEMPERATURE = 8.87781
STEP CHANGE IN JACKET INLET TEMPERATURE = -7.47685
0
300
600
900
1200
TIME[SEC]



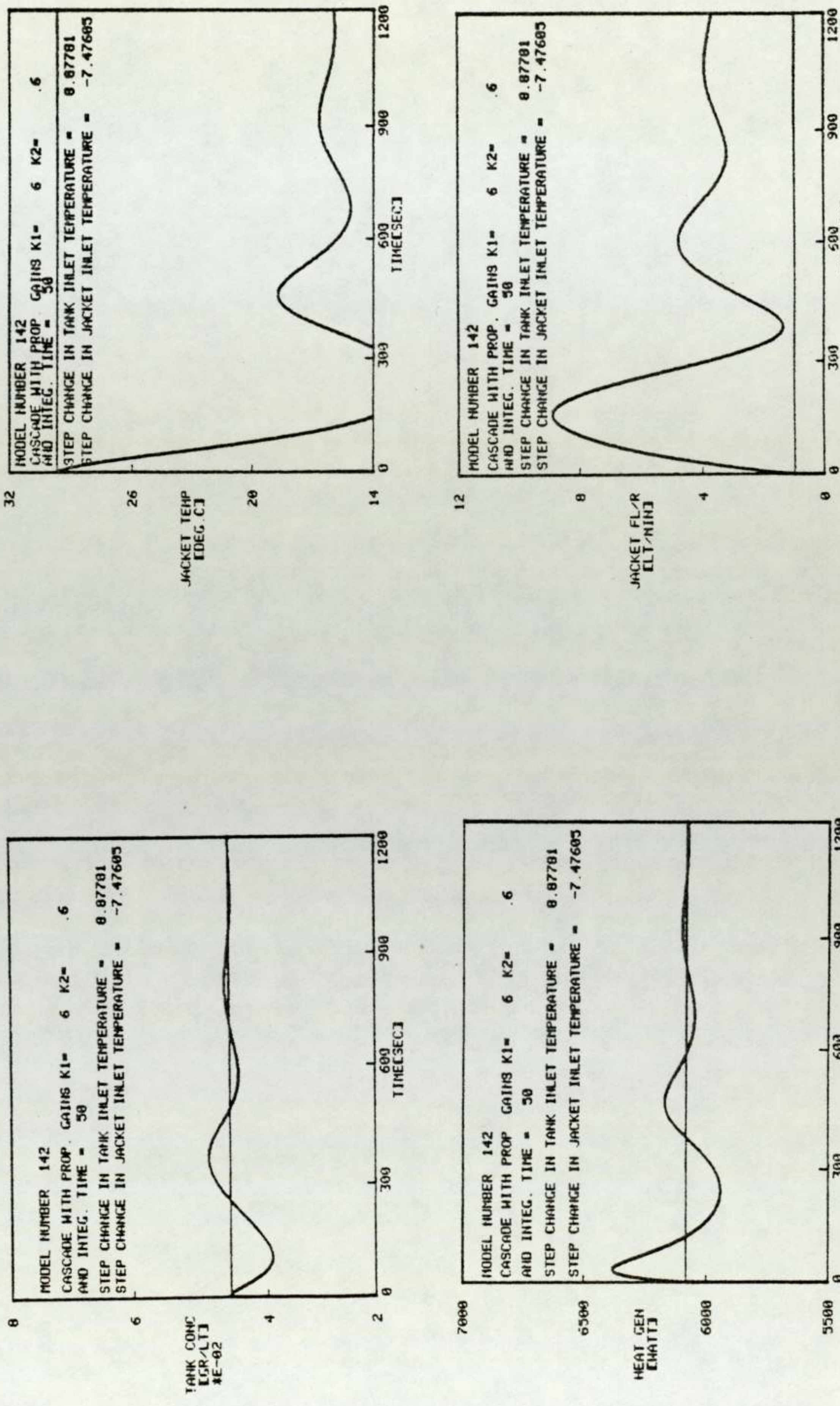
39
37
35
33
TANK TEMP
[DEG.C]
MODEL NUMBER 142
CASCADE WITH PROP GAINS K1= 6 K2= .6
AND INTEG. TIME = 50
STEP CHANGE IN TANK INLET TEMPERATURE = 8.87781
STEP CHANGE IN JACKET INLET TEMPERATURE = -7.47685
0
300
600
900
1200
TIME[SEC]

FIG. A.3.59



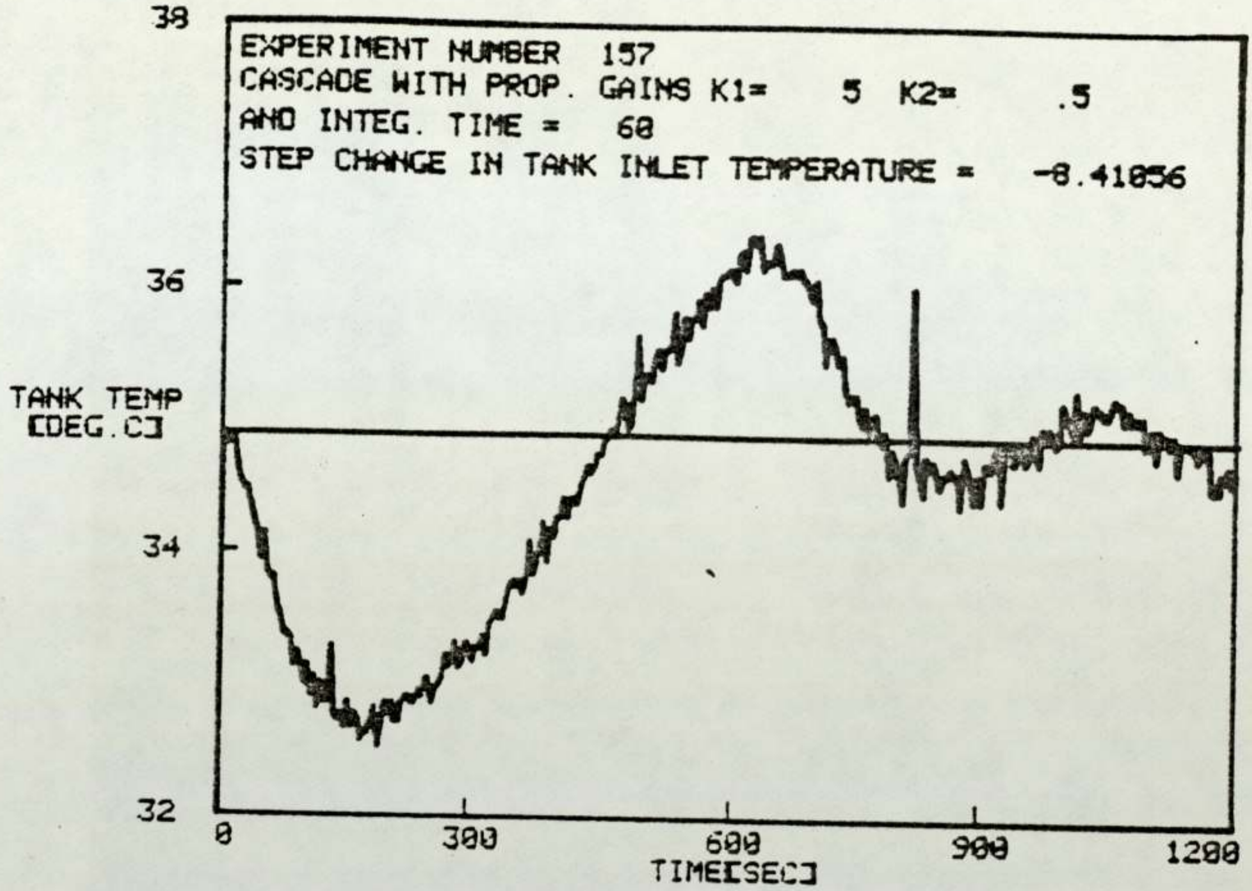
STEP CHANGE IN TANK INLET TEMPERATURE = 8.07781
STEP CHANGE IN JACKET INLET TEMPERATURE = -7.47685
EXPERIMENT NUMBER 142
CASCADE WITH PROP. GAINS K1= 6 K2= .6
AND INTEG. TIME = 50
JACKET TEMP [DEG.C]
TIME[SEC]
EXPERIMENT NUMBER 142
CASCADE WITH PROP. GAINS K1= 6 K2= .6
AND INTEG. TIME = 50
STEP CHANGE IN TANK INLET TEMPERATURE = 8.07781
STEP CHANGE IN JACKET INLET TEMPERATURE = -7.47685
JACKET FL/R [LT/MIN]
TIME[SEC]
EXPERIMENT NUMBER 142
CASCADE WITH PROP. GAINS K1= 6 K2= .6
AND INTEG. TIME = 50
STEP CHANGE IN TANK INLET TEMPERATURE = 8.07781
STEP CHANGE IN JACKET INLET TEMPERATURE = -7.47685
TANK CONC [GR/LT] *E-02
TIME[SEC]
EXPERIMENT NUMBER 142
CASCADE WITH PROP. GAINS K1= 6 K2= .6
AND INTEG. TIME = 50
STEP CHANGE IN TANK INLET TEMPERATURE = 8.07781
STEP CHANGE IN JACKET INLET TEMPERATURE = -7.47685
HEAT GEN [WATT]
TIME[SEC]

FIG. A.3.60



MODEL NUMBER 142
CASCADE WITH PROP. GAINS K1= 6 K2= .6
AND INTEG. TIME = 50
STEP CHANGE IN TANK INLET TEMPERATURE = 8.87781
STEP CHANGE IN JACKET INLET TEMPERATURE = -7.47605
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
JACKET TEMP [DEG.C]
JACKET FL/R [LT/MIN]
TIME[SEC]

FIG. A.3.61


38
36
34
32
TANK TEMP
[DEG.C]
EXPERIMENT NUMBER 157
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -8.41056
0
300
600
900
1200
TIME[SEC]

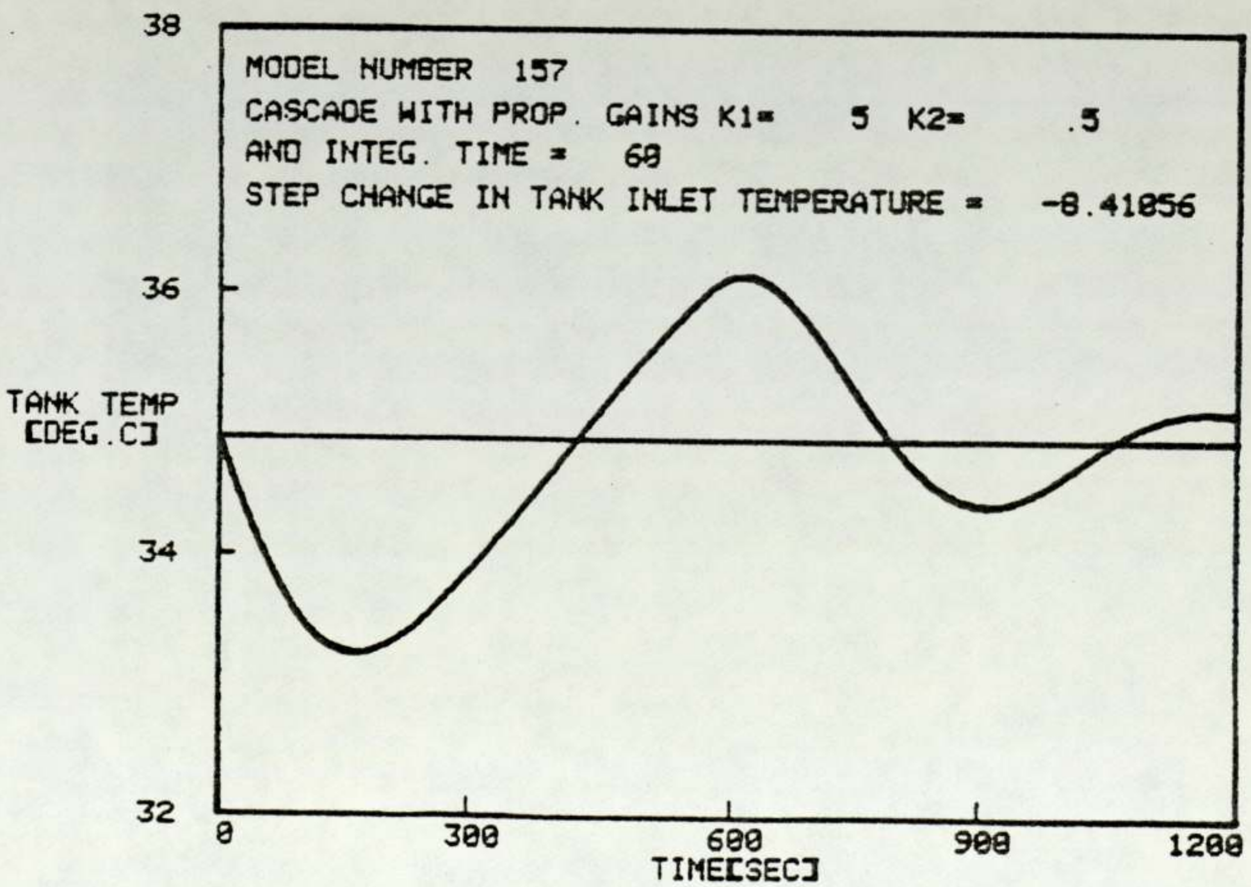
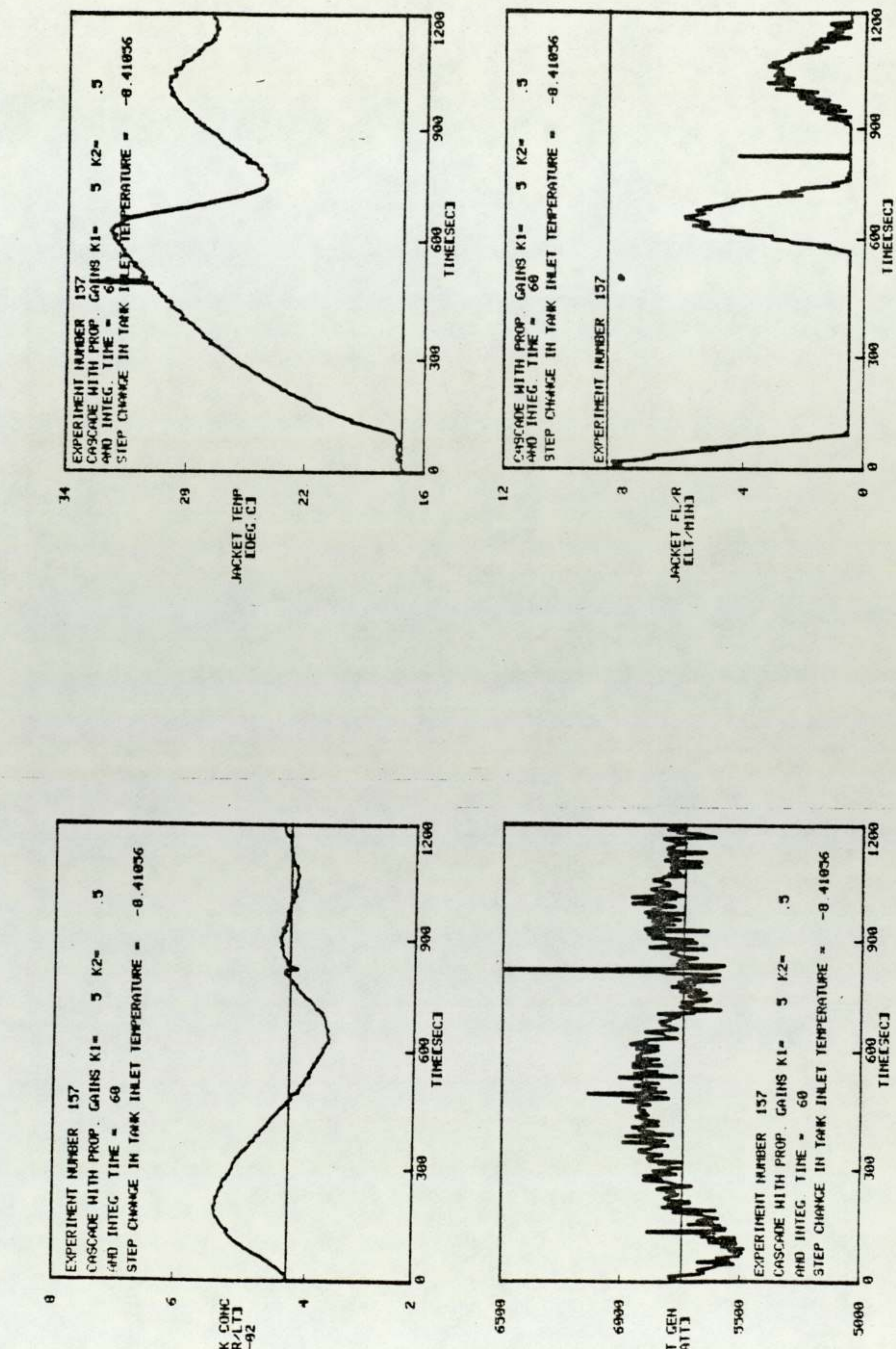

38
36
34
32
TANK TEMP
[DEG.C]
MODEL NUMBER 157
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -8.41056
0
300
600
900
1200
TIME[SEC]

FIG. A.3.62



EXPERIMENT NUMBER 157
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -8.41056
JACKET TEMP [DEG.C]
JACKET FL/R [LT/MIN]
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
TIME[SEC]
0
300
600
900
1200
16
22
28
34
0
4
8
12
2
4
6
8
5000
5500
6000
6500

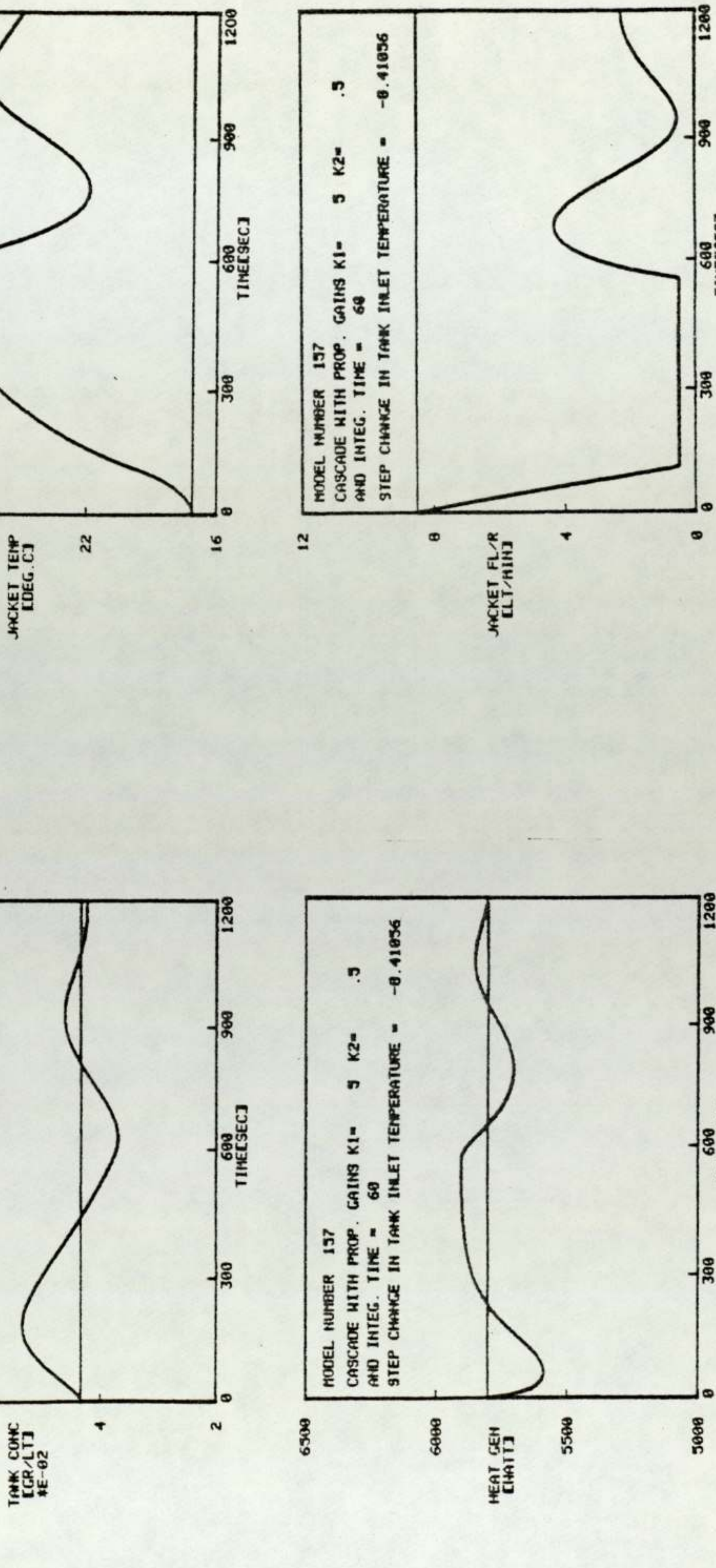
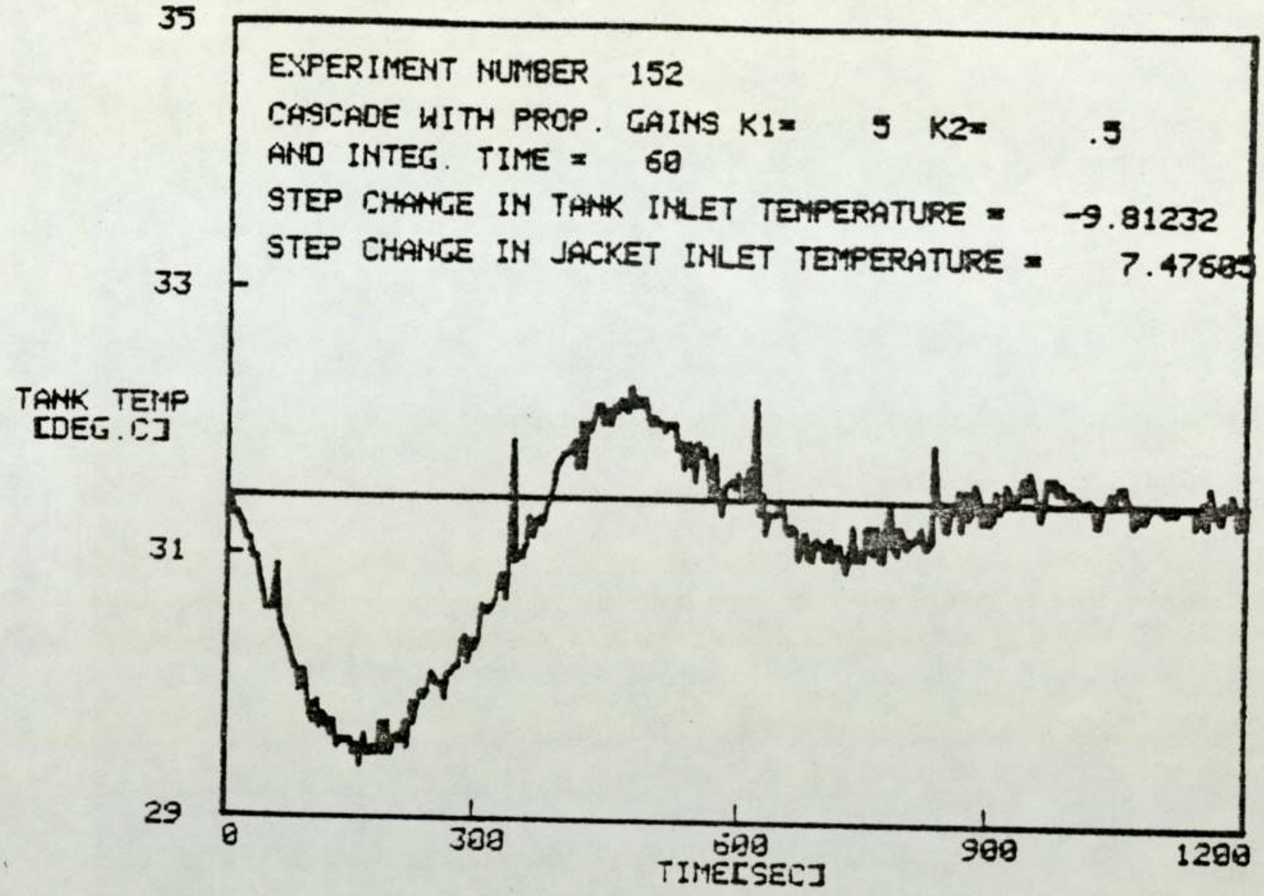
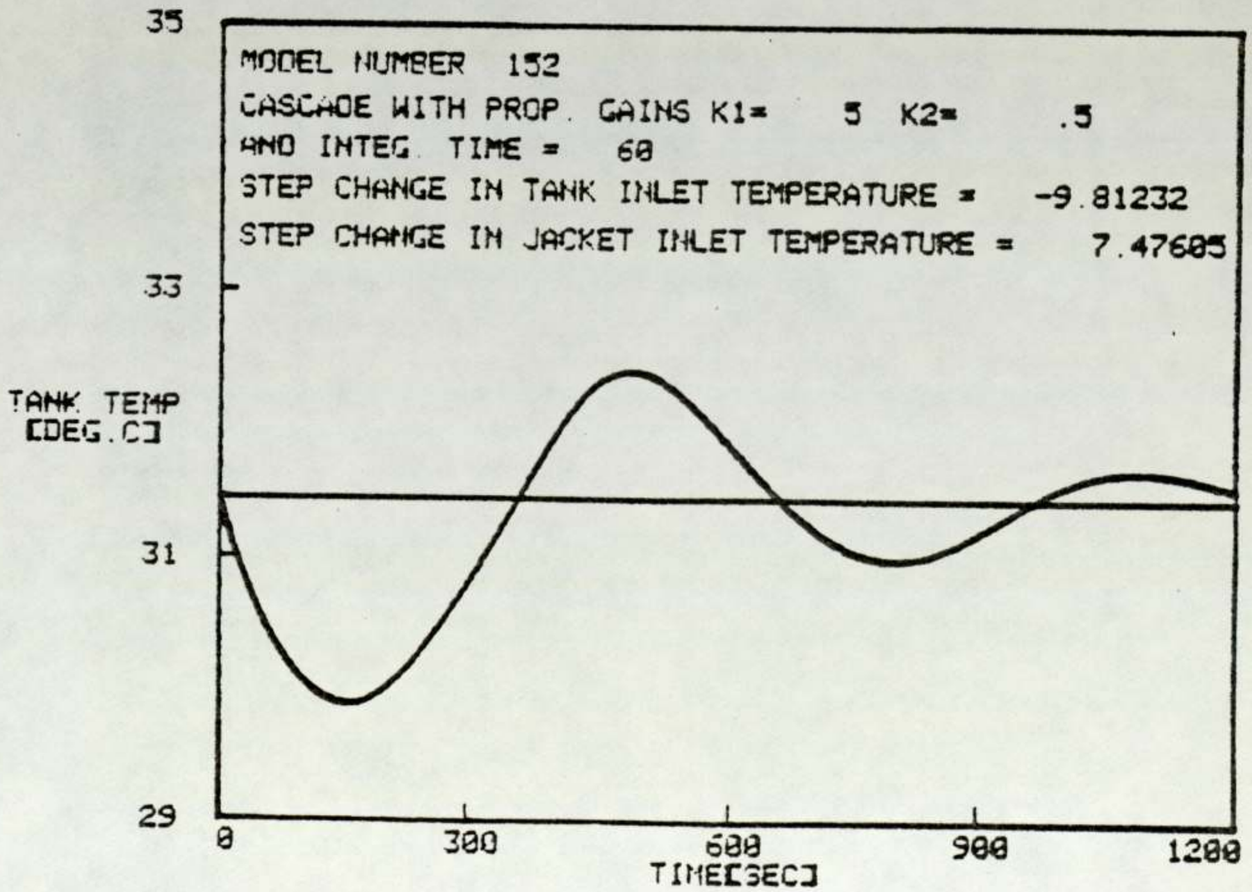

CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -8.41056
MODEL NUMBER 157
JACKET TEMP [DEG.C]
34
28
22
16
0
300
600
900
1200
TIME[SEC]
MODEL NUMBER 157
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -8.41056
JACKET FL/R [LT/MIN]
12
8
4
0
TANK CONC [GR/LT] *E-02
8
6
4
2
HEAT GEN [WATT]
6500
6000
5500
5000

FIG. A.3.64



35
33
31
29
EXPERIMENT NUMBER 152
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -9.81232
STEP CHANGE IN JACKET INLET TEMPERATURE = 7.47605
TANK TEMP [DEG.C]
0
300
600
900
1200
TIME[SEC]



35
33
31
29
MODEL NUMBER 152
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -9.81232
STEP CHANGE IN JACKET INLET TEMPERATURE = 7.47605
TANK TEMP [DEG.C]
0
300
600
900
1200
TIME[SEC]

FIG. A.3.65

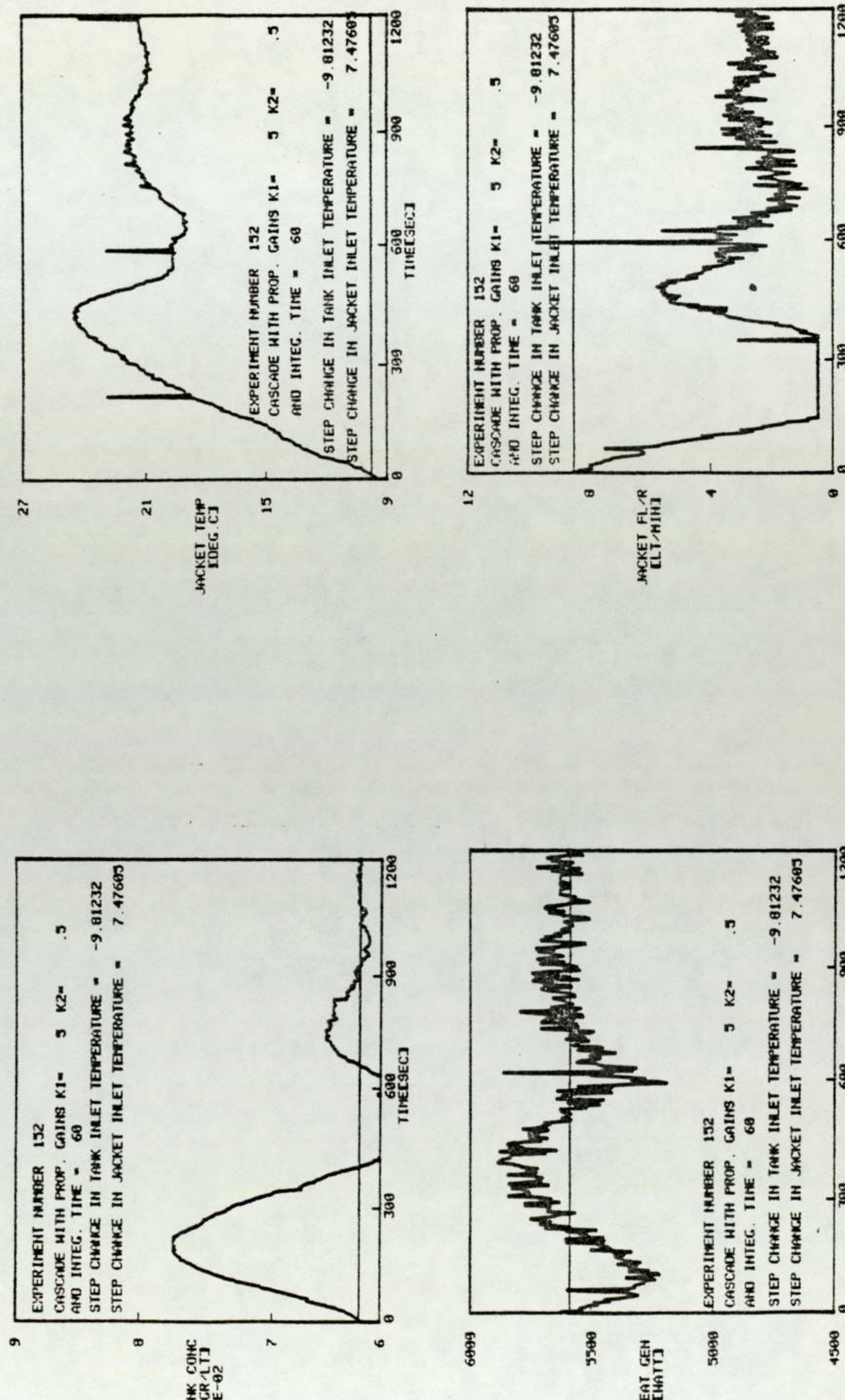

EXPERIMENT NUMBER 152
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -9.81232
STEP CHANGE IN JACKET INLET TEMPERATURE = 7.47605
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
JACKET TEMP [DEG.C]
JACKET FL/R [LT/MIN]
TIME[SEC]

FIG. A.3.66

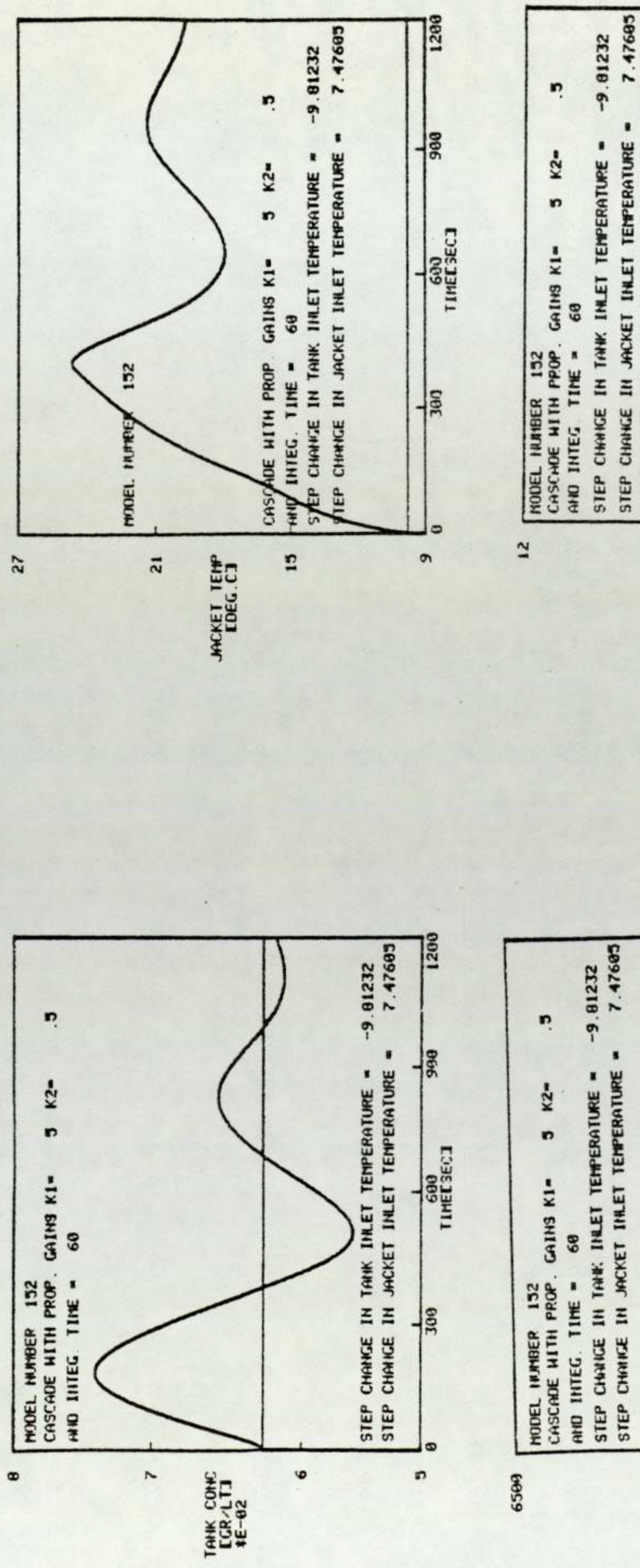
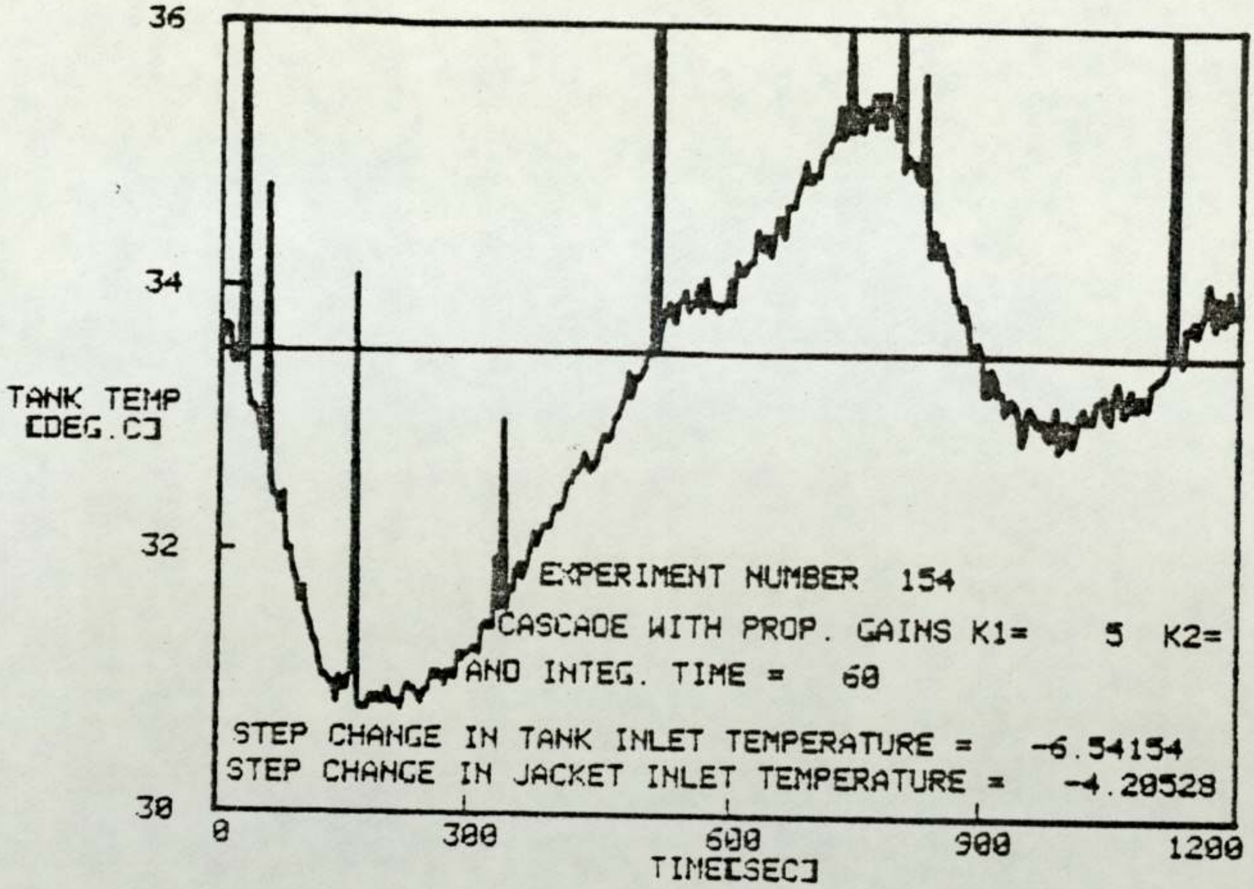

MODEL NUMBER 152
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -9.81232
STEP CHANGE IN JACKET INLET TEMPERATURE = 7.47605
JACKET TEMP [DEG.C]
JACKET FL/R [LT/MIN]
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
TIME[SEC]
0
300
600
900
1200
27
21
15
9
12
8
4
7
6
5
6500
6000
5500
5000

FIG. A.3.67


36
34
32
30
TANK TEMP
[DEG.C]
0
300
600
900
1200
TIME[SEC]
EXPERIMENT NUMBER 154
CASCADE WITH PROP. GAINS K1= 5 K2=
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -6.54154
STEP CHANGE IN JACKET INLET TEMPERATURE = -4.20528

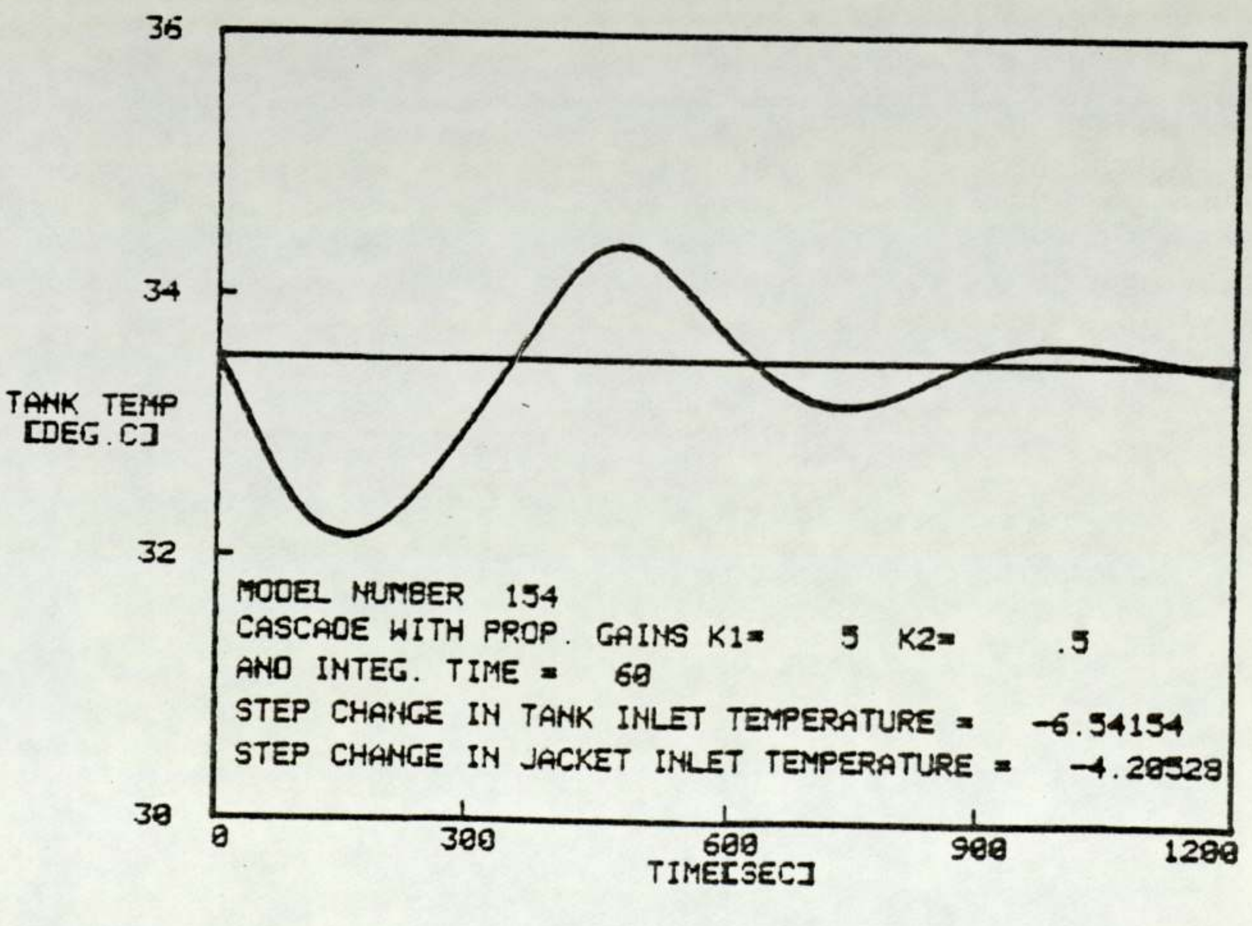
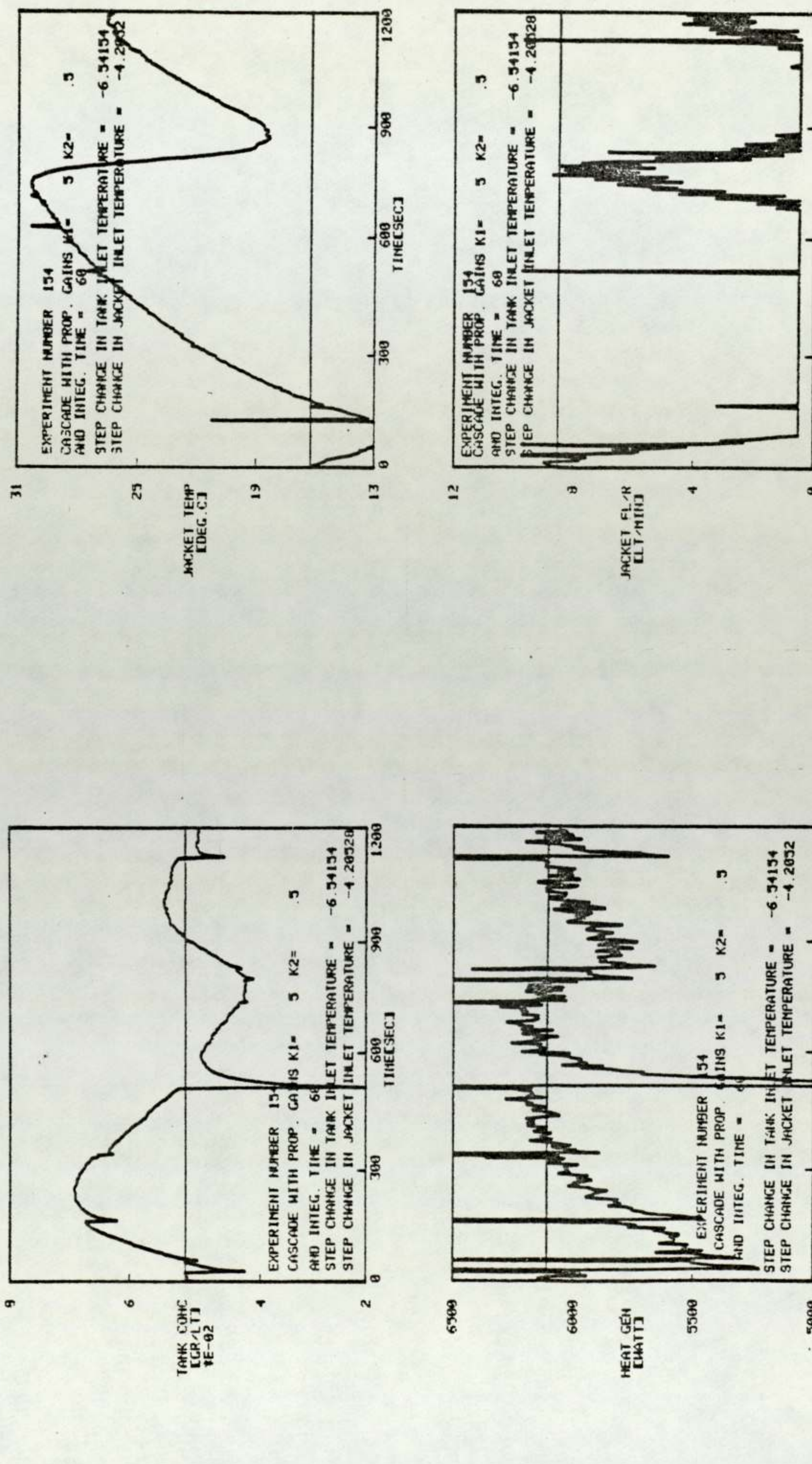

36
34
32
30
TANK TEMP
[DEG.C]
0
300
600
900
1200
TIME[SEC]
MODEL NUMBER 154
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -6.54154
STEP CHANGE IN JACKET INLET TEMPERATURE = -4.20528

FIG. A.3.68



EXPERIMENT NUMBER 154
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -6.34154
STEP CHANGE IN JACKET INLET TEMPERATURE = -4.20328
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
JACKET TEMP [DEG.C]
JACKET FL/R [LT/MIN]
TIME[SEC]

FIG. A,3.69

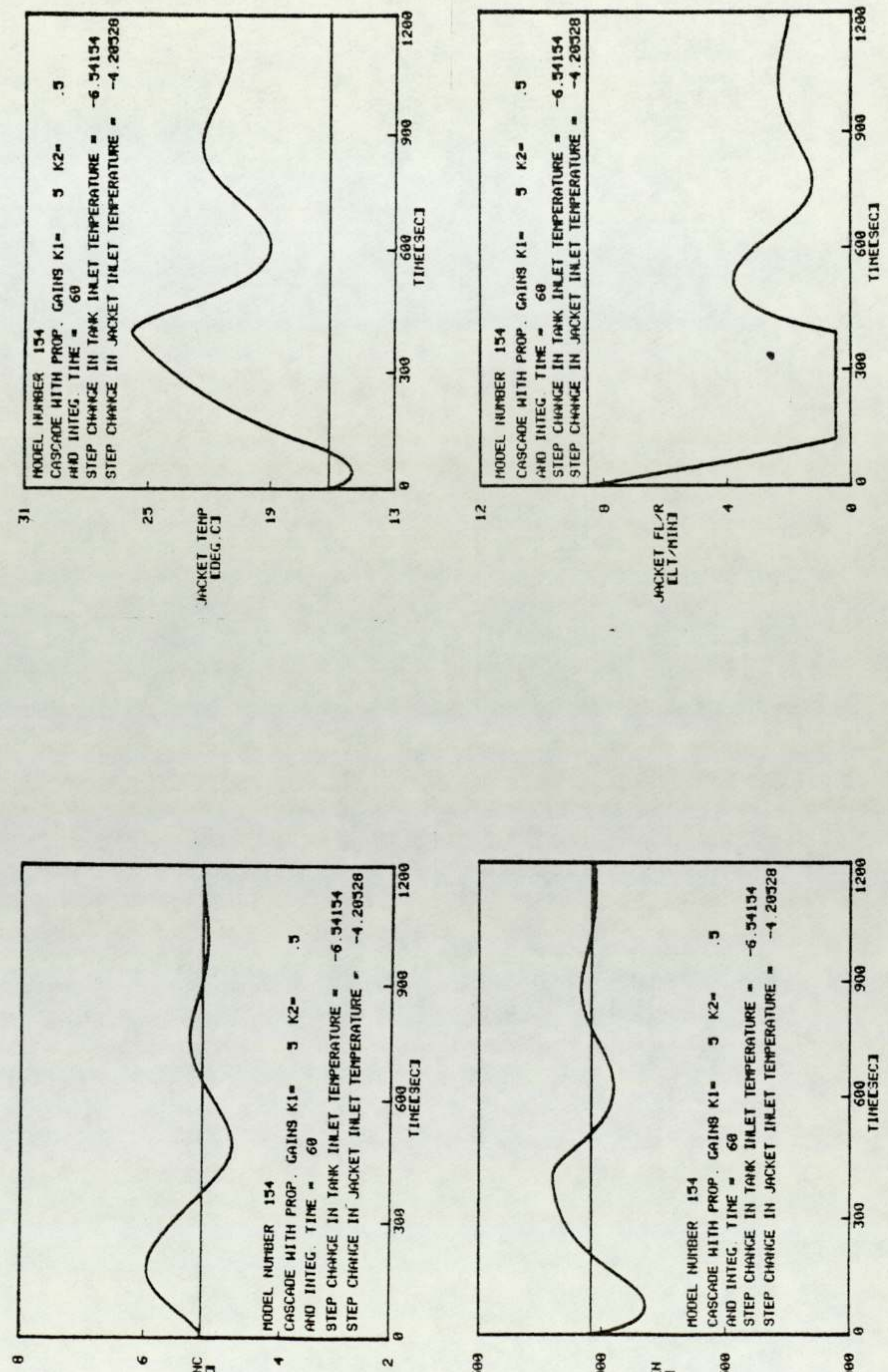
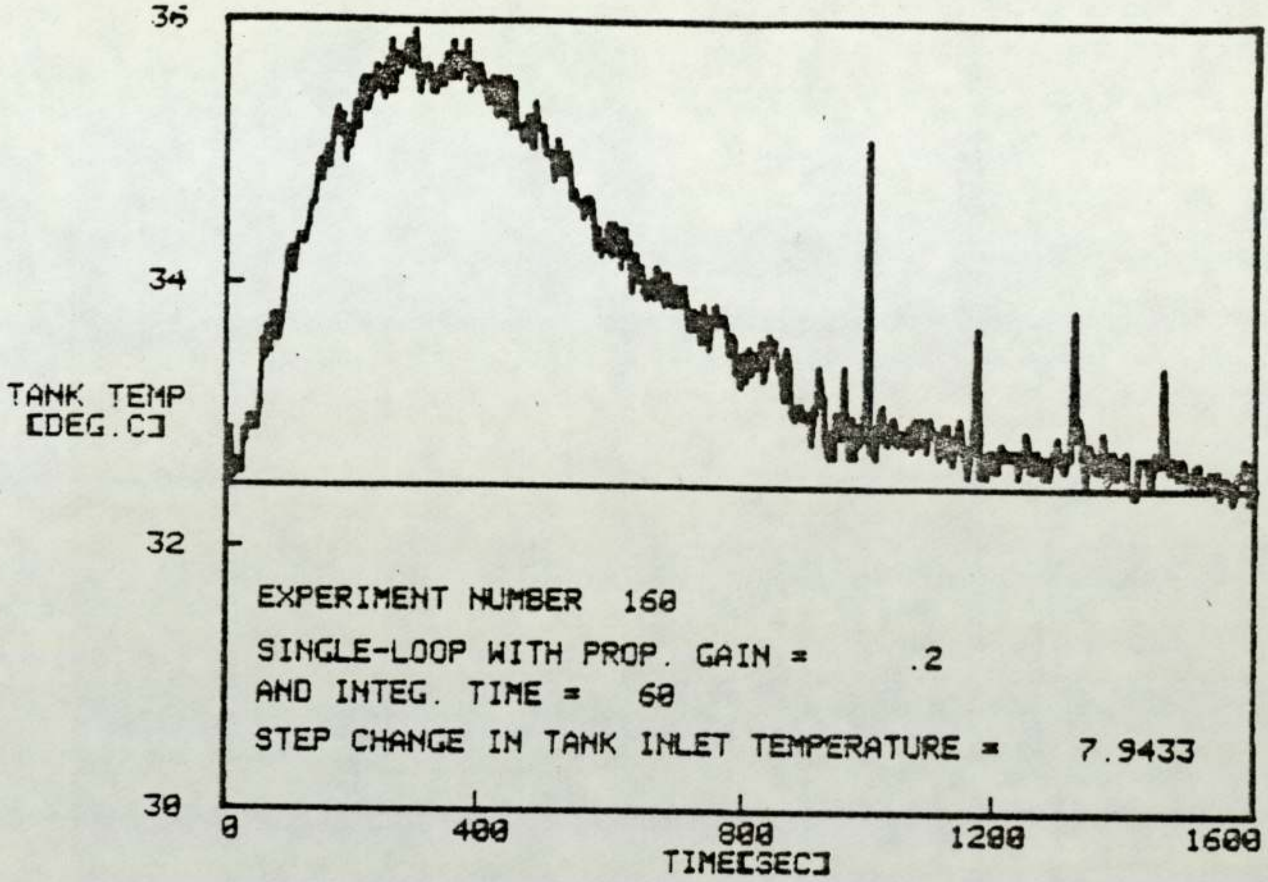

MODEL NUMBER 154
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -6.54154
STEP CHANGE IN JACKET INLET TEMPERATURE = -4.20528
JACKET TEMP [DEG.C]
JACKET FL/R [LT/MIN]
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
TIME[SEC]
0
300
600
900
1200
13
19
25
31
4
8
12
2
6
5000
5500
6000
6500

FIG. A.3.70


36
34
32
30
TANK TEMP
[DEG.C]
EXPERIMENT NUMBER 160
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 7.9433
0
400
800
1200
1600
TIME[SEC]

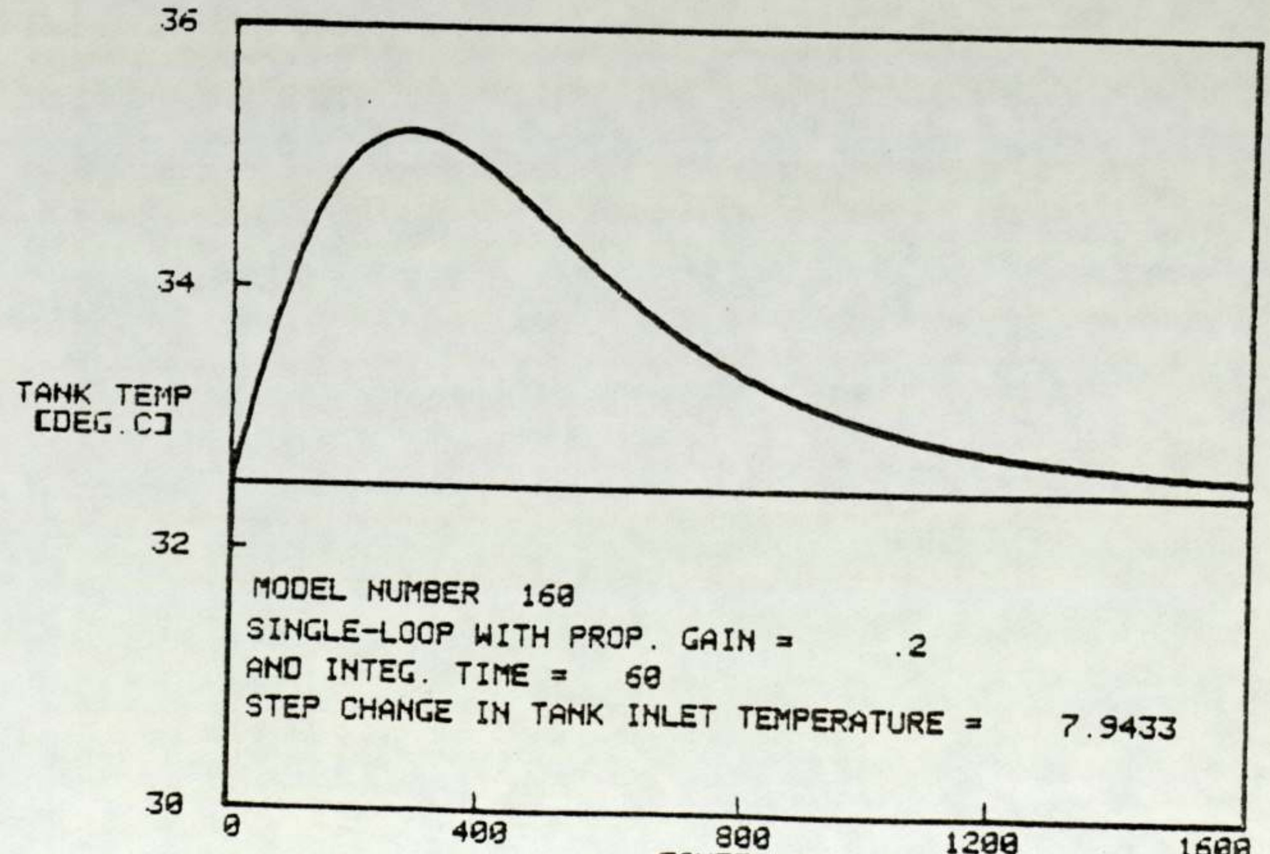
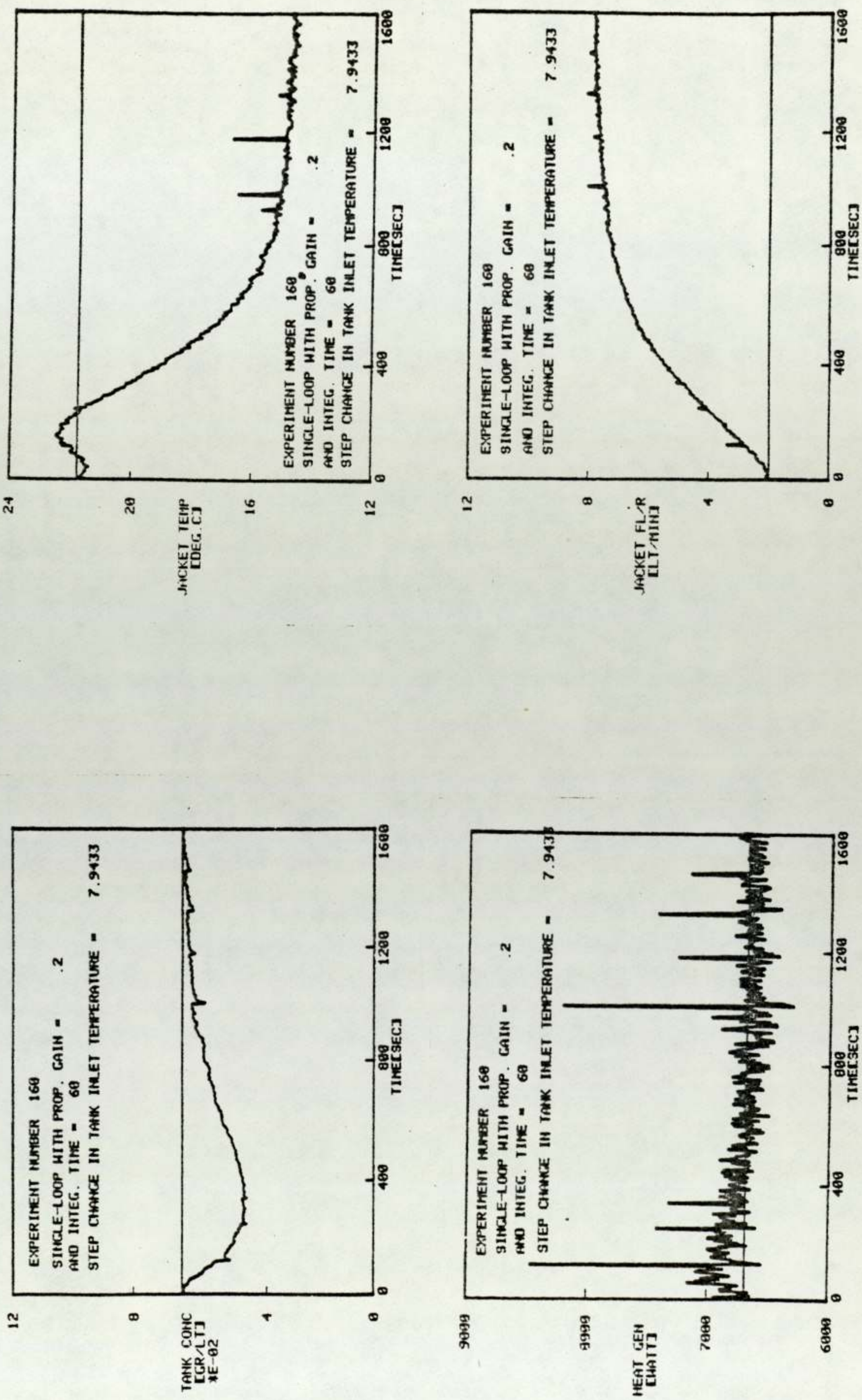

36
34
32
30
TANK TEMP
[DEG.C]
MODEL NUMBER 160
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 7.9433
0
400
800
1200
1600
TIME[SEC]

FIG. A.3.71



EXPERIMENT NUMBER 160
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 7.9433
JACKET TEMP [DEG.C]
JACKET FL/R [LT/MIN]
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
TIME[SEC]

FIG. A.3.72

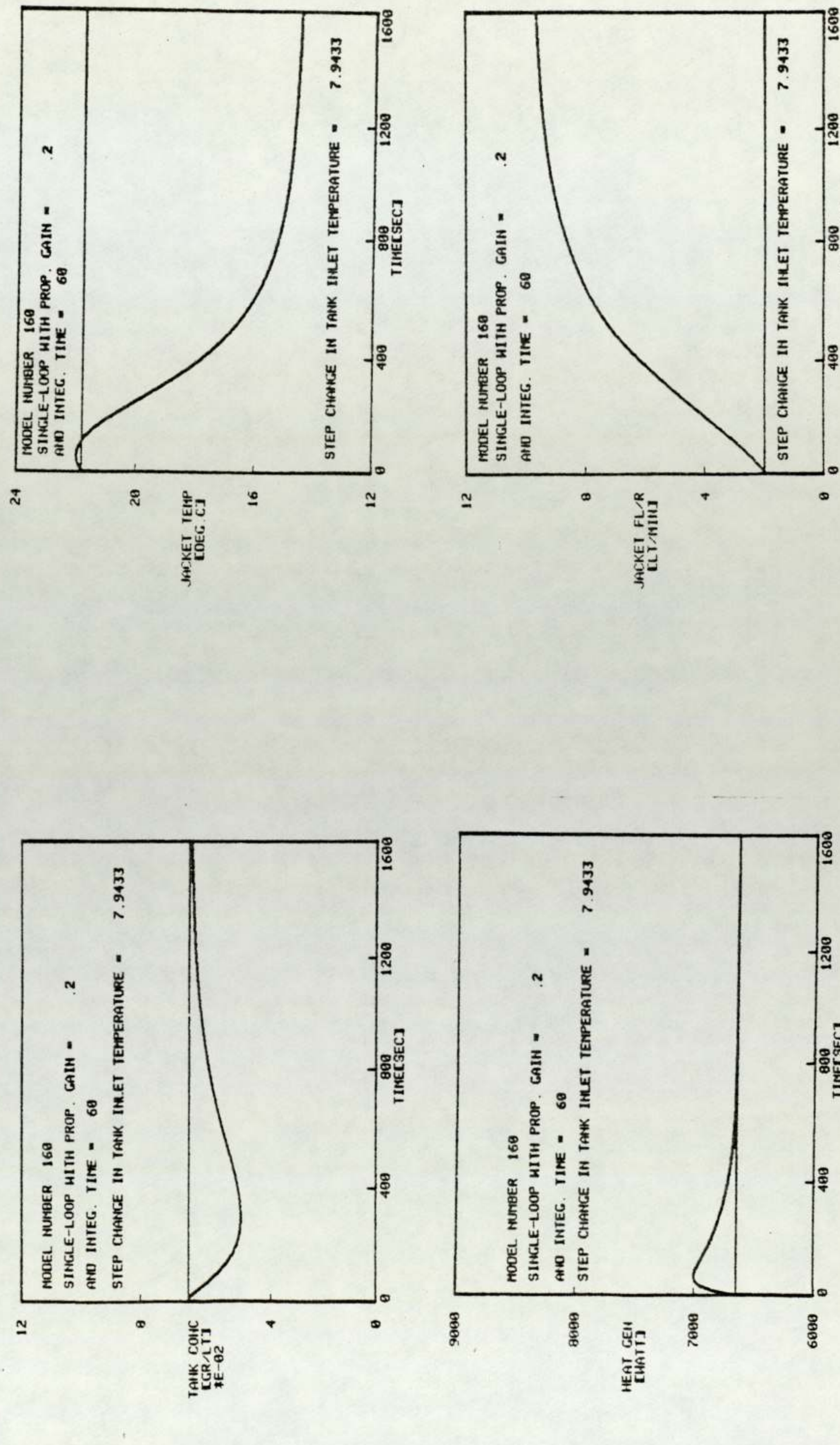
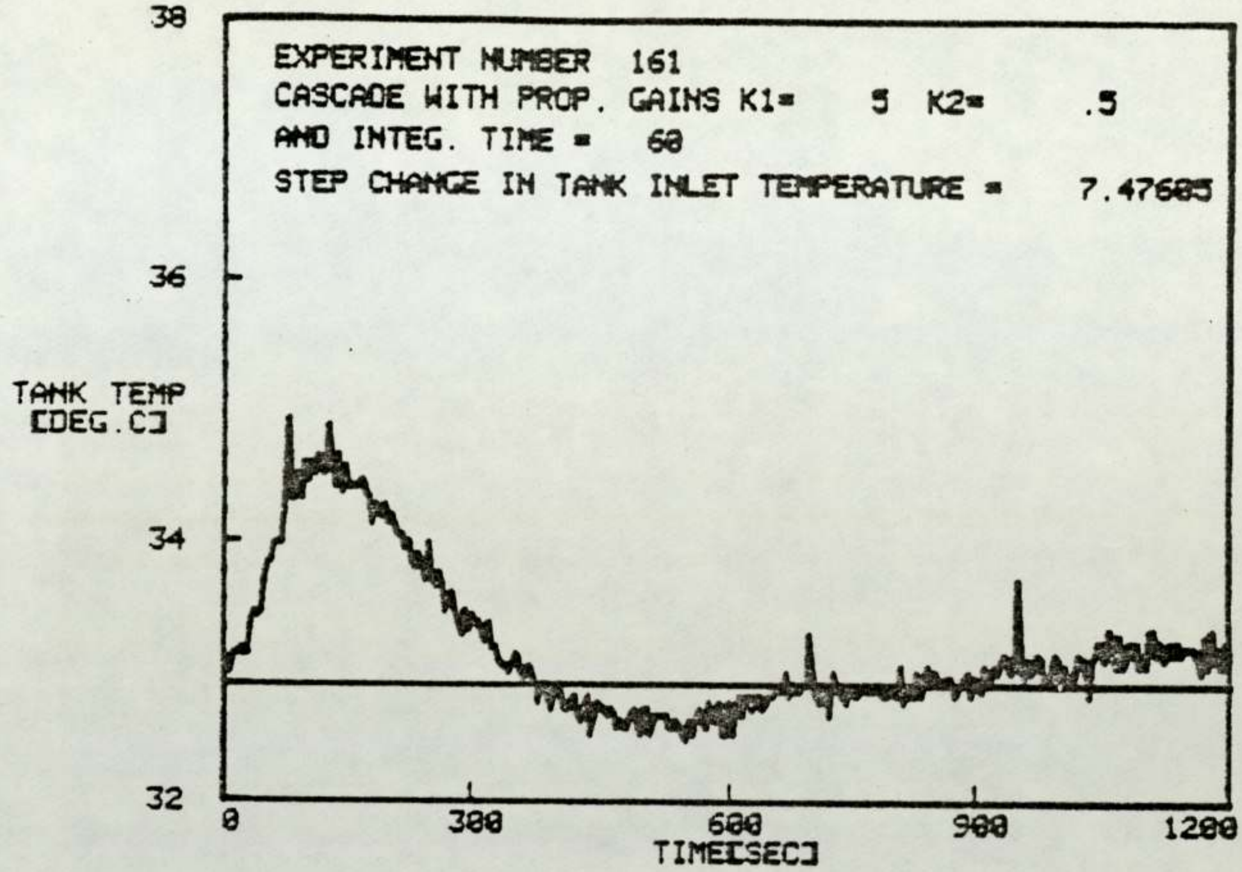

MODEL NUMBER 160
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 7.9433
JACKET TEMP [DEG.C]
JACKET FL/R [LT/MIN]
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
TIME[SEC]

FIG. A.3.73


EXPERIMENT NUMBER 161
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 7.47685
TANK TEMP [DEG.C]
38
36
34
32
0
300
600
900
1200
TIME[SEC]

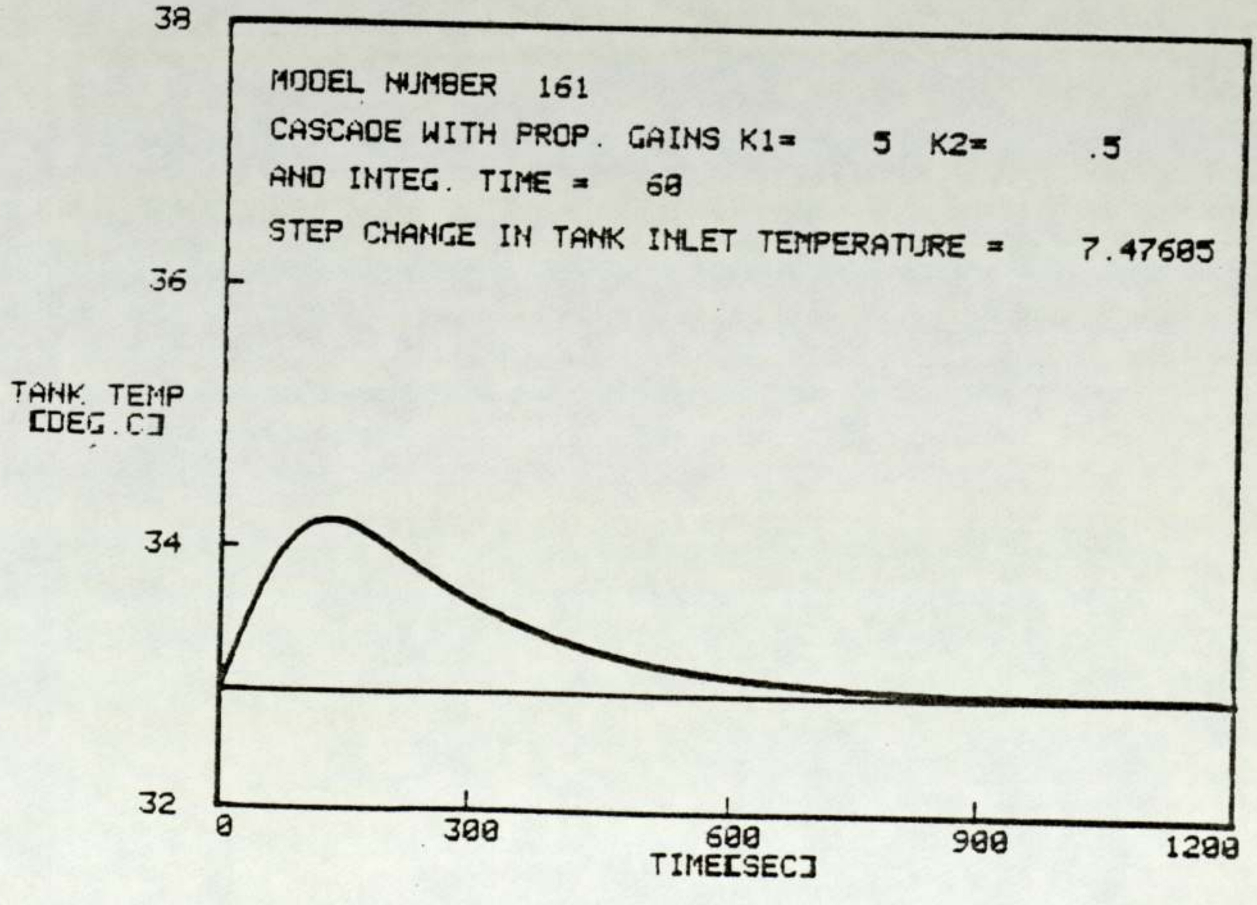
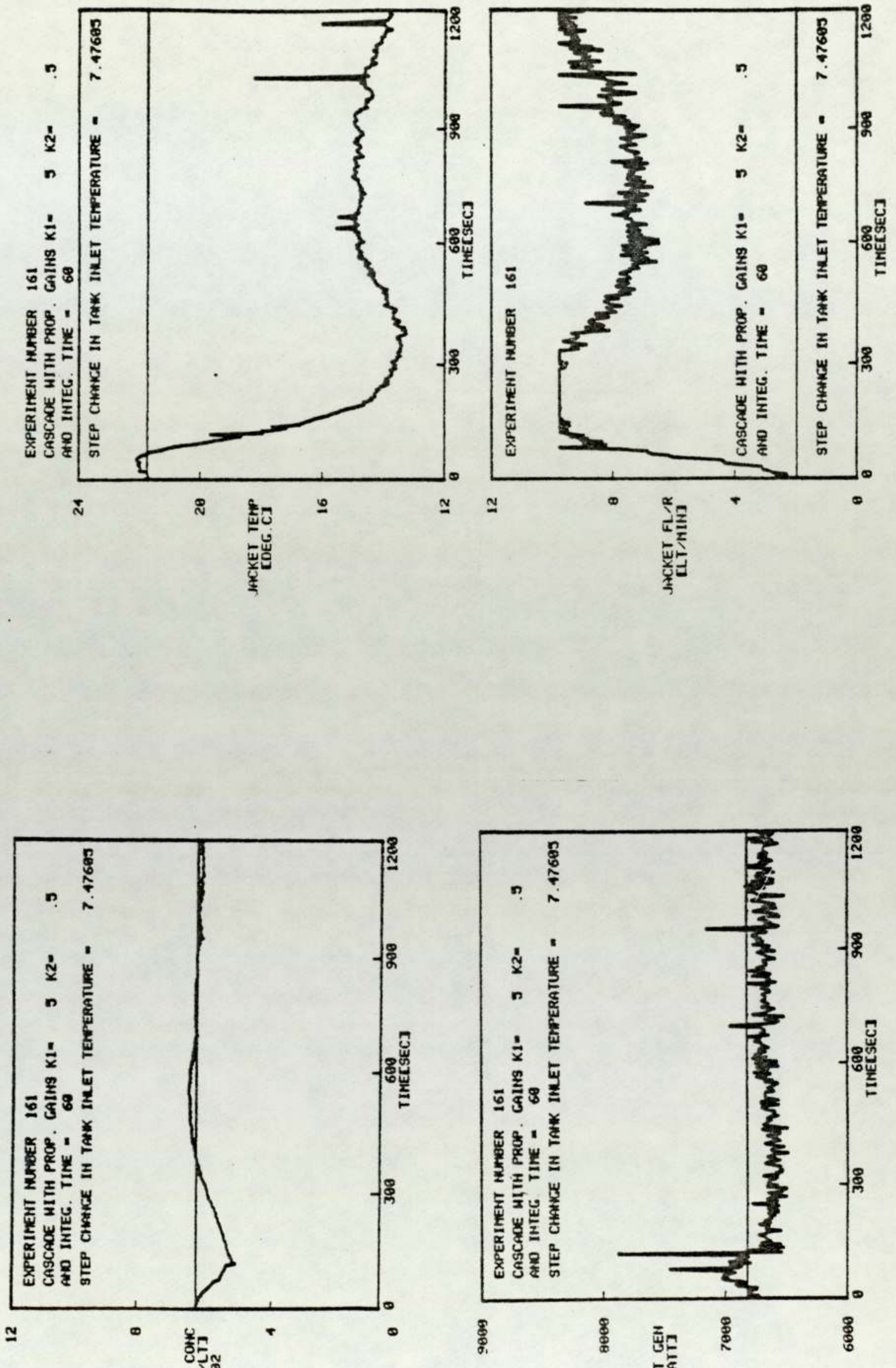
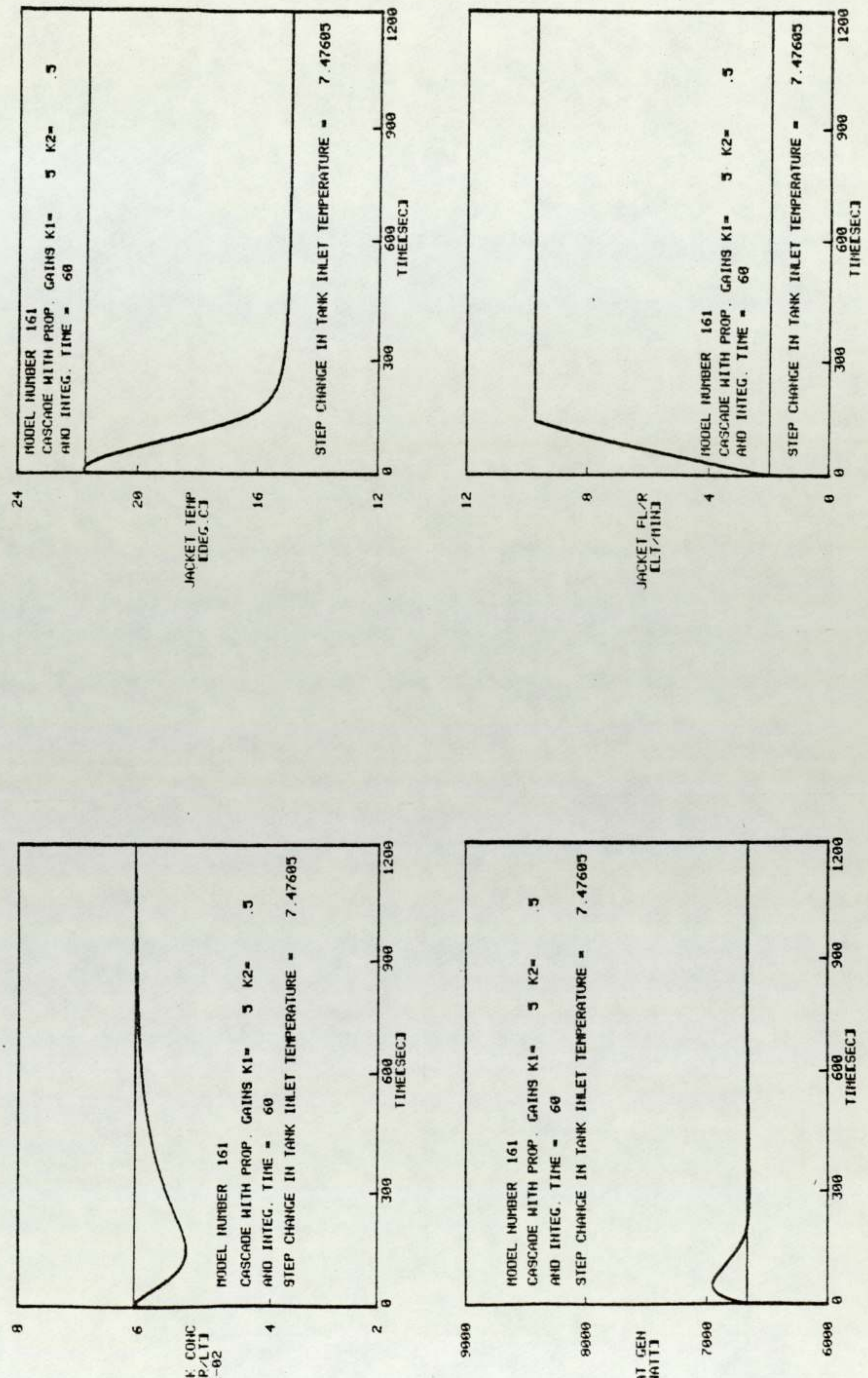

MODEL NUMBER 161
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 7.47685
TANK TEMP [DEG.C]
38
36
34
32
0
300
600
900
1200
TIME[SEC]

FIG. A.3.74



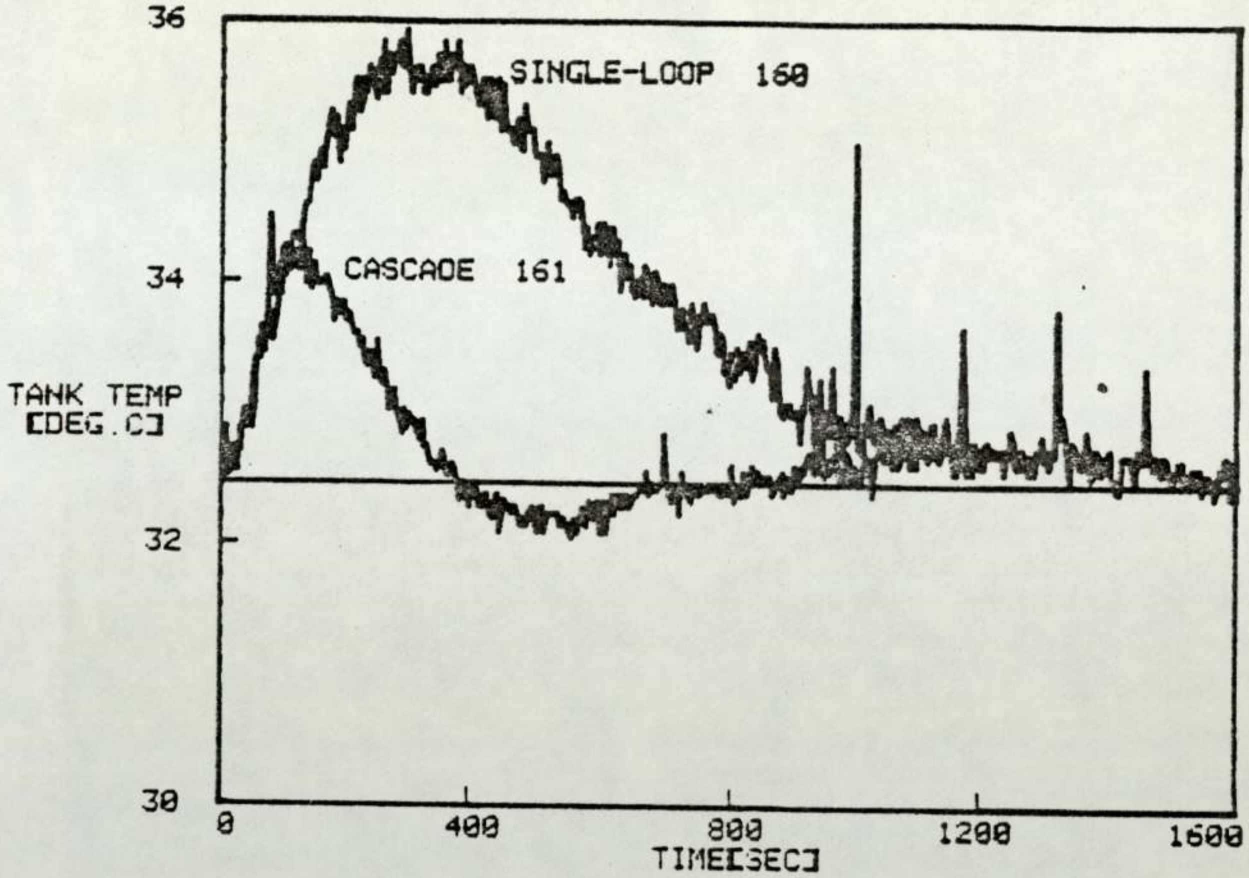
EXPERIMENT NUMBER 161
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 7.47605
JACKET TEMP [DEG.C]
JACKET FL/R [LT/MIN]
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
TIME[SEC]

FIG. A.3.75



MODEL NUMBER 161
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 7.47605
JACKET TEMP [DEG.C]
JACKET FL/R [LT/MIN]
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
TIME[SEC]

FIG. A.3.76


SINGLE-LOOP 160
CASCADE 161
TANK TEMP
[DEG.C]
36
34
32
30
0
400
800
1200
1600
TIME[SEC]

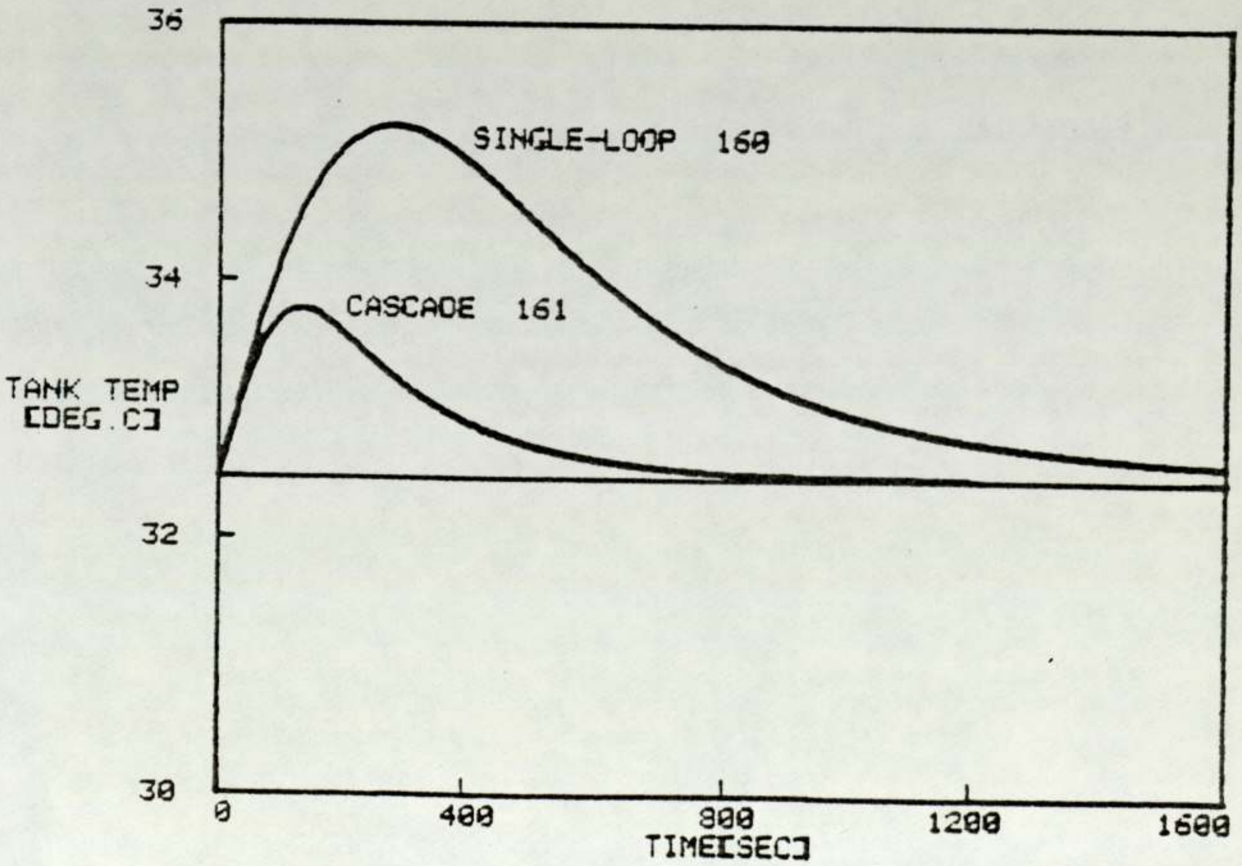

SINGLE-LOOP 160
CASCADE 161
TANK TEMP
[DEG.C]
36
34
32
30
0
400
800
1200
1600
TIME[SEC]

FIG. A.3.77

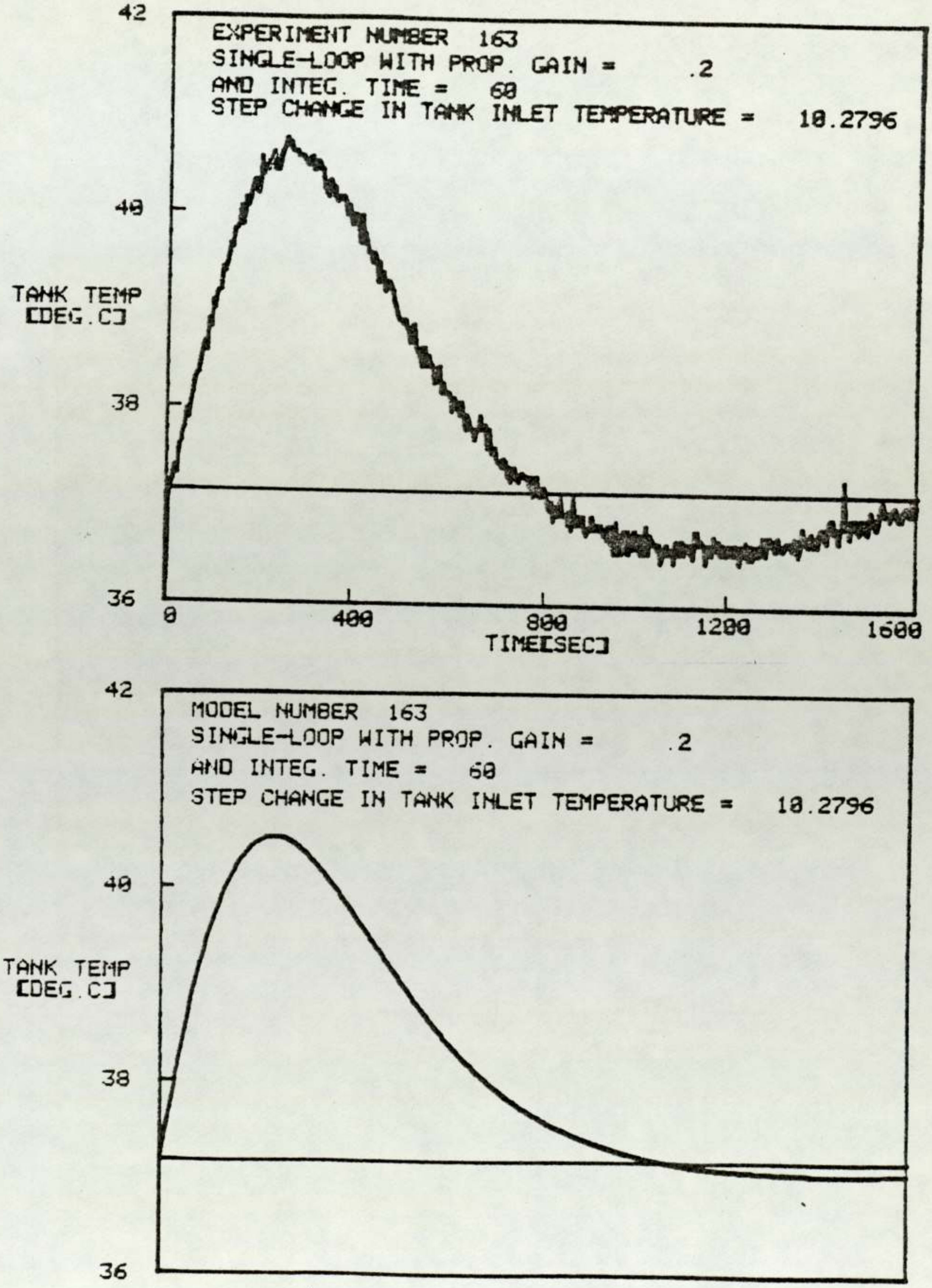

EXPERIMENT NUMBER 163
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 10.2796
TANK TEMP [DEG.C]
42
40
38
36
0
400
800
1200
1600
TIME[SEC]
MODEL NUMBER 163
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 10.2796
TANK TEMP [DEG.C]
42
40
38
36

FIG. A.3.78

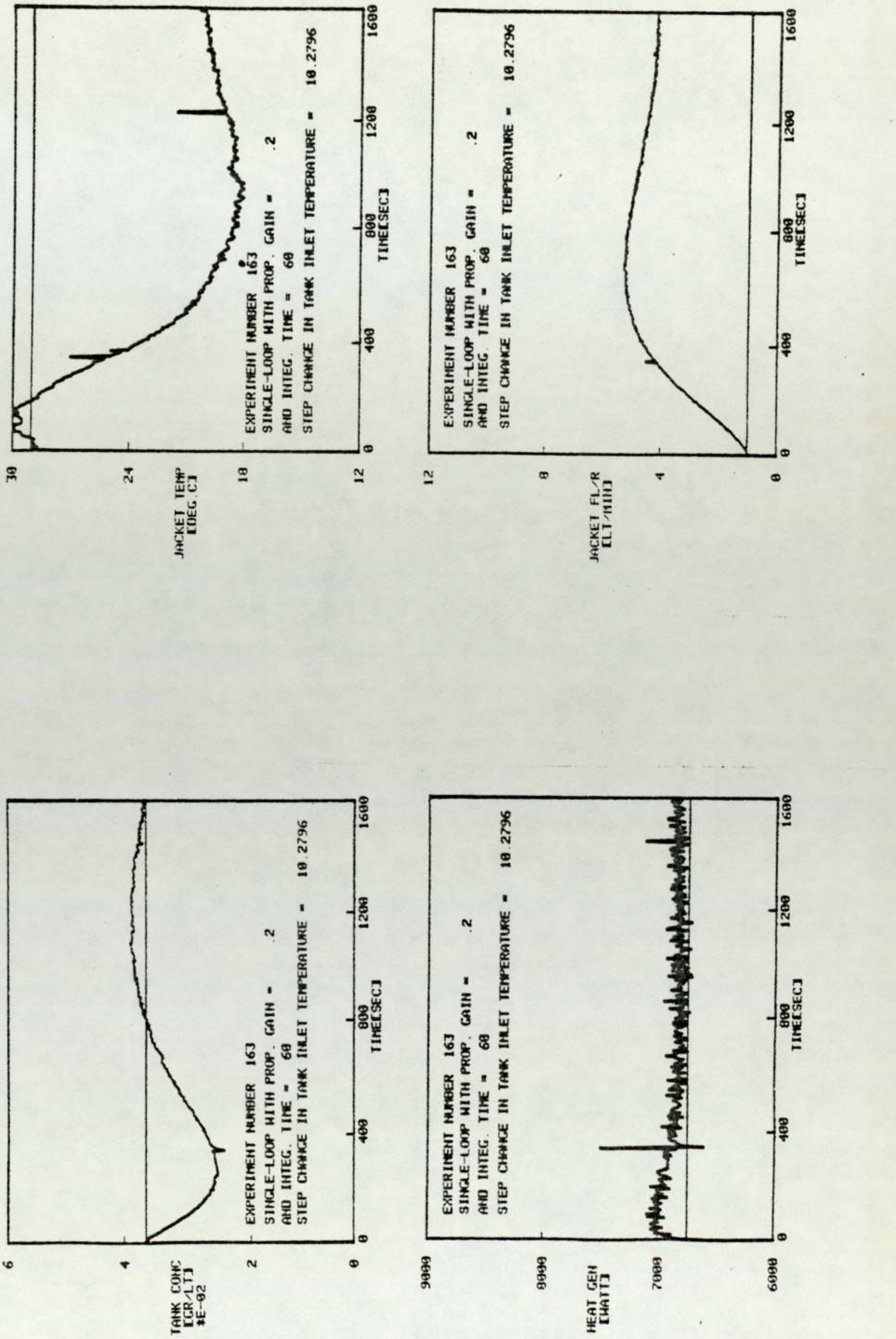
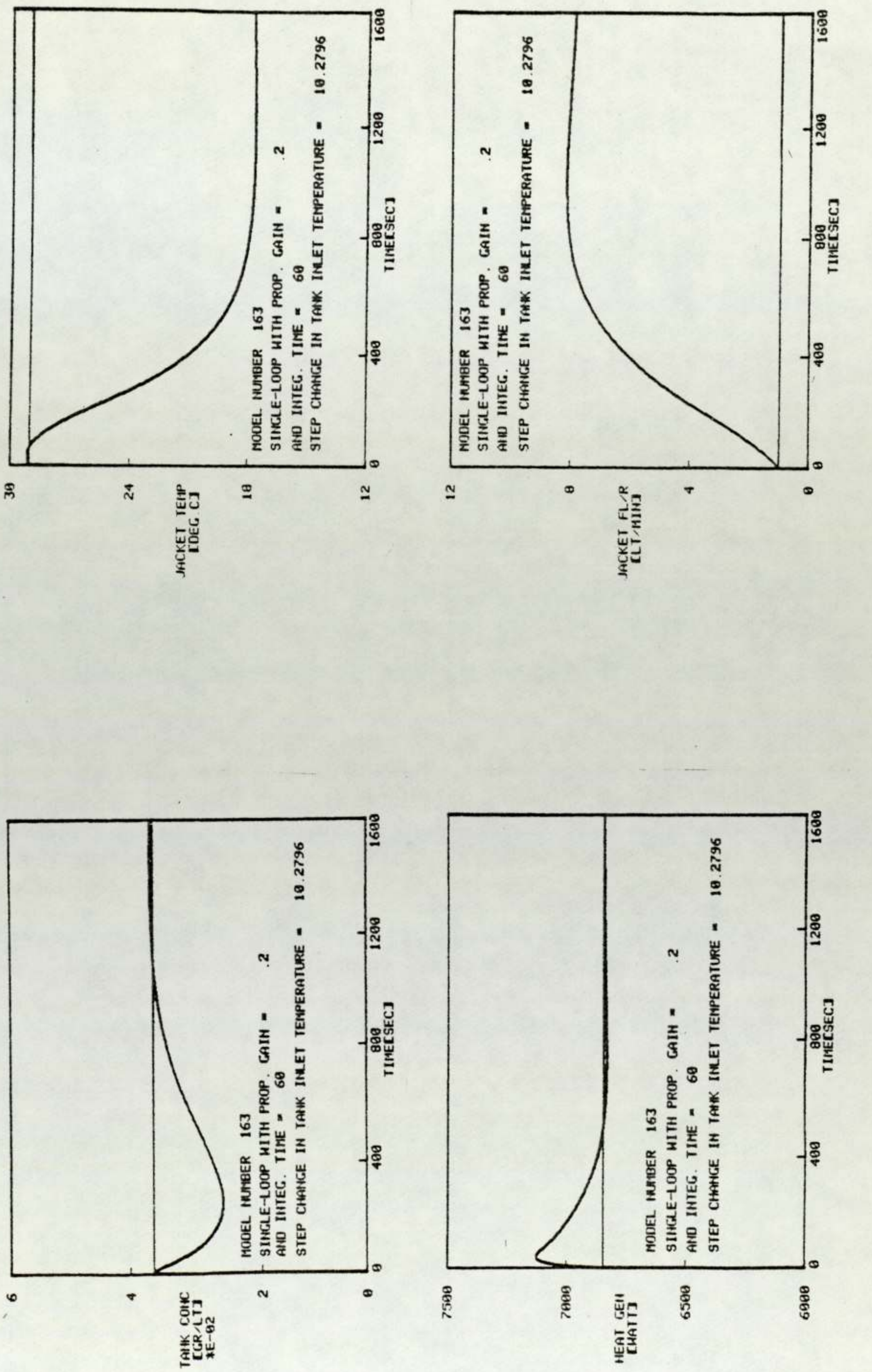
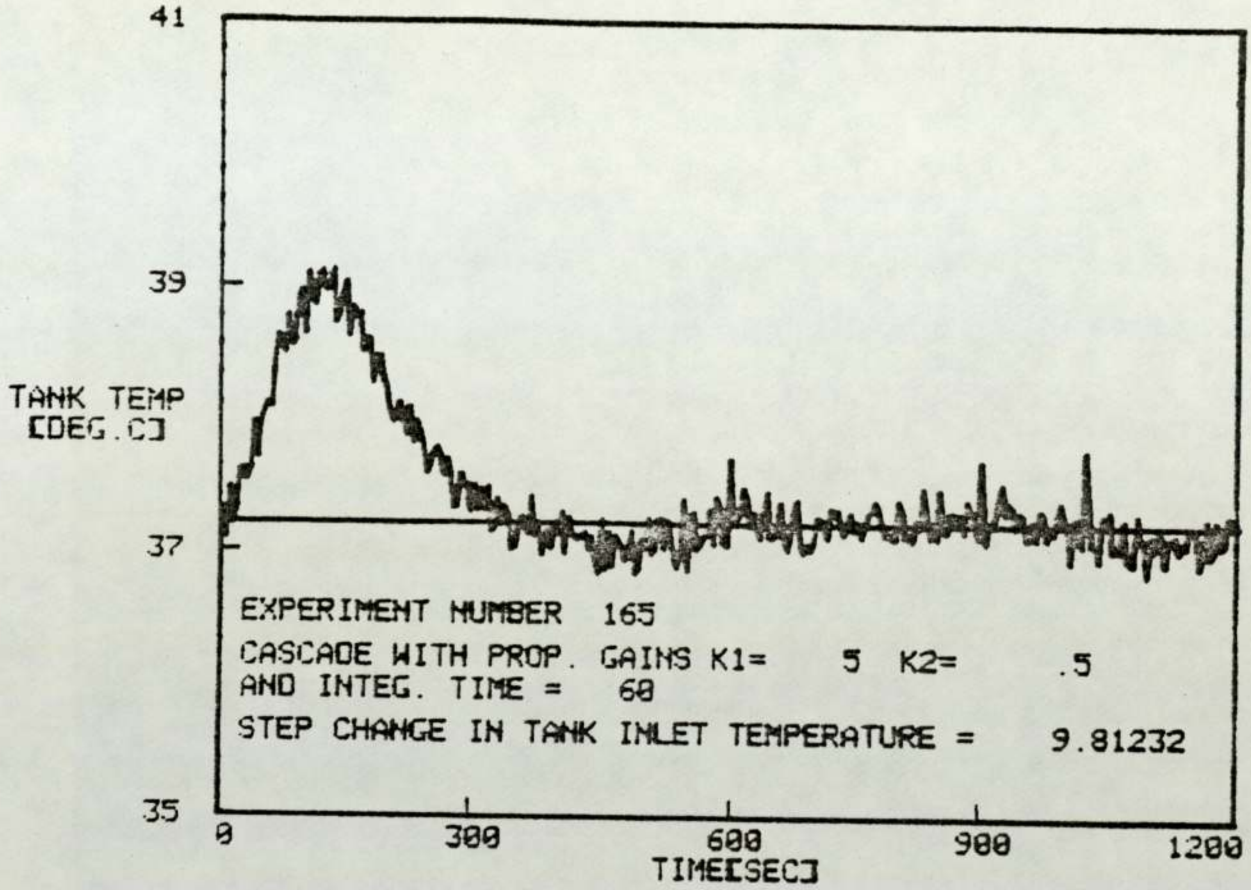

JACKET TEMP [DEG.C]
30
24
18
12
EXPERIMENT NUMBER 163
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 10.2796
0
400
800
1200
1600
TIME[SEC]
JACKET FL/R [LT/MIN]
12
8
4
0
EXPERIMENT NUMBER 163
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 10.2796
0
400
800
1200
1600
TIME[SEC]
TANK CONC [GR/LT] *E-02
6
4
2
0
EXPERIMENT NUMBER 163
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 10.2796
0
400
800
1200
1600
TIME[SEC]
HEAT GEN [WATT]
9000
8000
7000
6000
EXPERIMENT NUMBER 163
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 10.2796
0
400
800
1200
1600
TIME[SEC]

FIG. A.3.79



JACKET TEMP [DEG C]
30
24
18
12
MODEL NUMBER 163
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 10.2796
0
400
800
1200
1600
TIME[SEC]
JACKET FL/R [LT/MIN]
12
8
4
0
MODEL NUMBER 163
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 10.2796
0
400
800
1200
1600
TIME[SEC]
TANK CONC [GR/LT] *E-02
6
4
2
0
MODEL NUMBER 163
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 10.2796
0
400
800
1200
1600
TIME[SEC]
HEAT GEN [WATT]
7500
7000
6500
6000
MODEL NUMBER 163
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 10.2796
0
400
800
1200
1600
TIME[SEC]

FIG. A.3.80


41
39
37
35
TANK TEMP
[DEG.C]
EXPERIMENT NUMBER 165
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 9.81232
0
300
600
900
1200
TIME[SEC]

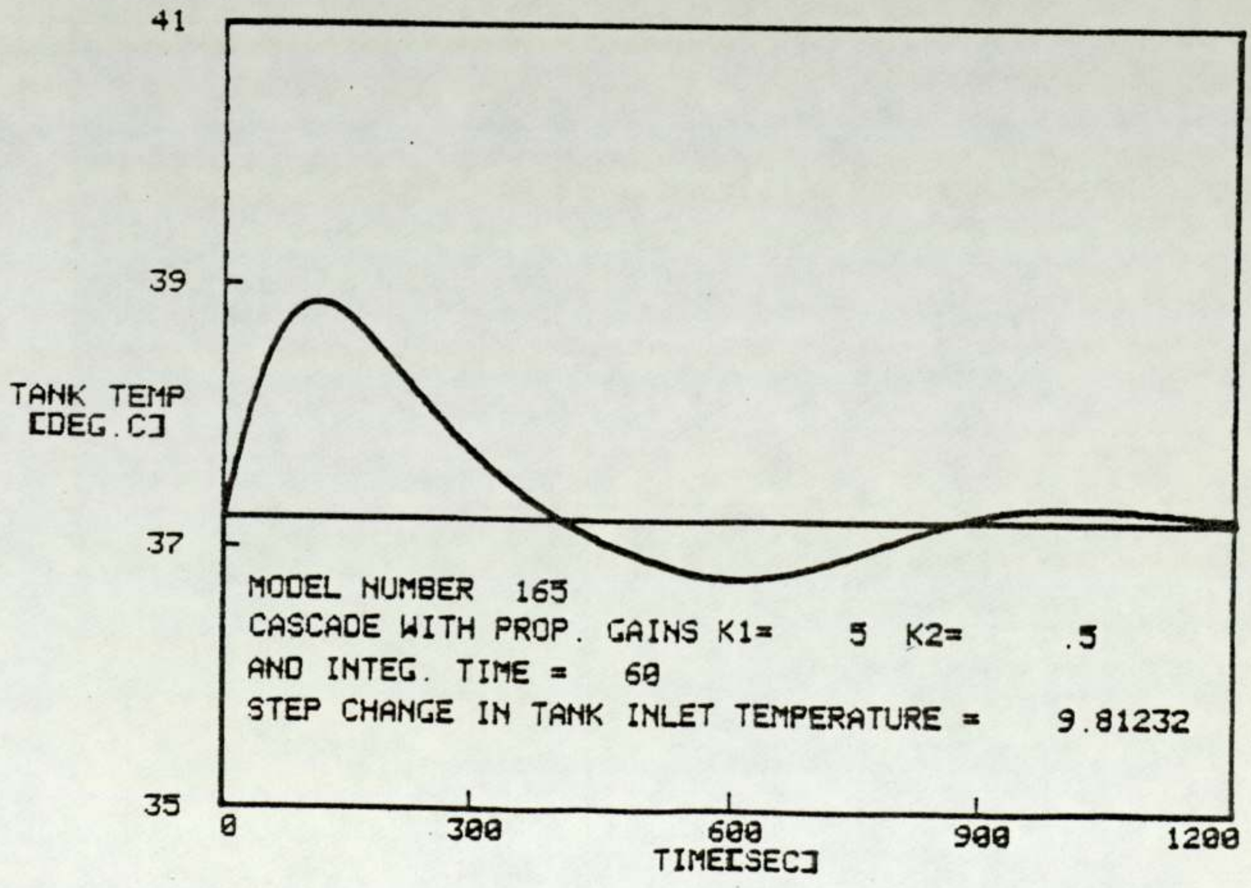

41
39
37
35
TANK TEMP
[DEG.C]
MODEL NUMBER 165
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 9.81232
0
300
600
900
1200
TIME[SEC]

FIG. A.3.81

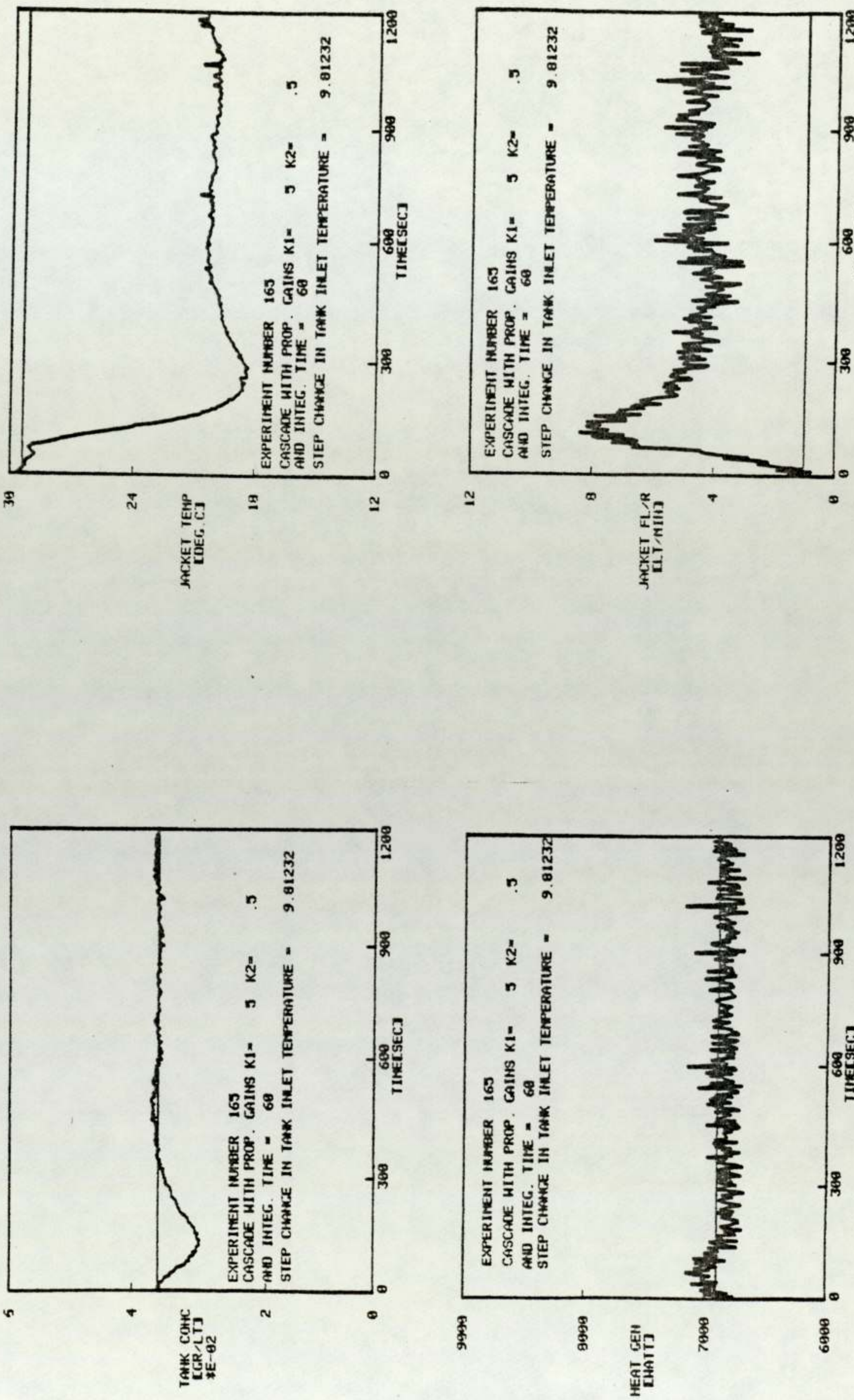
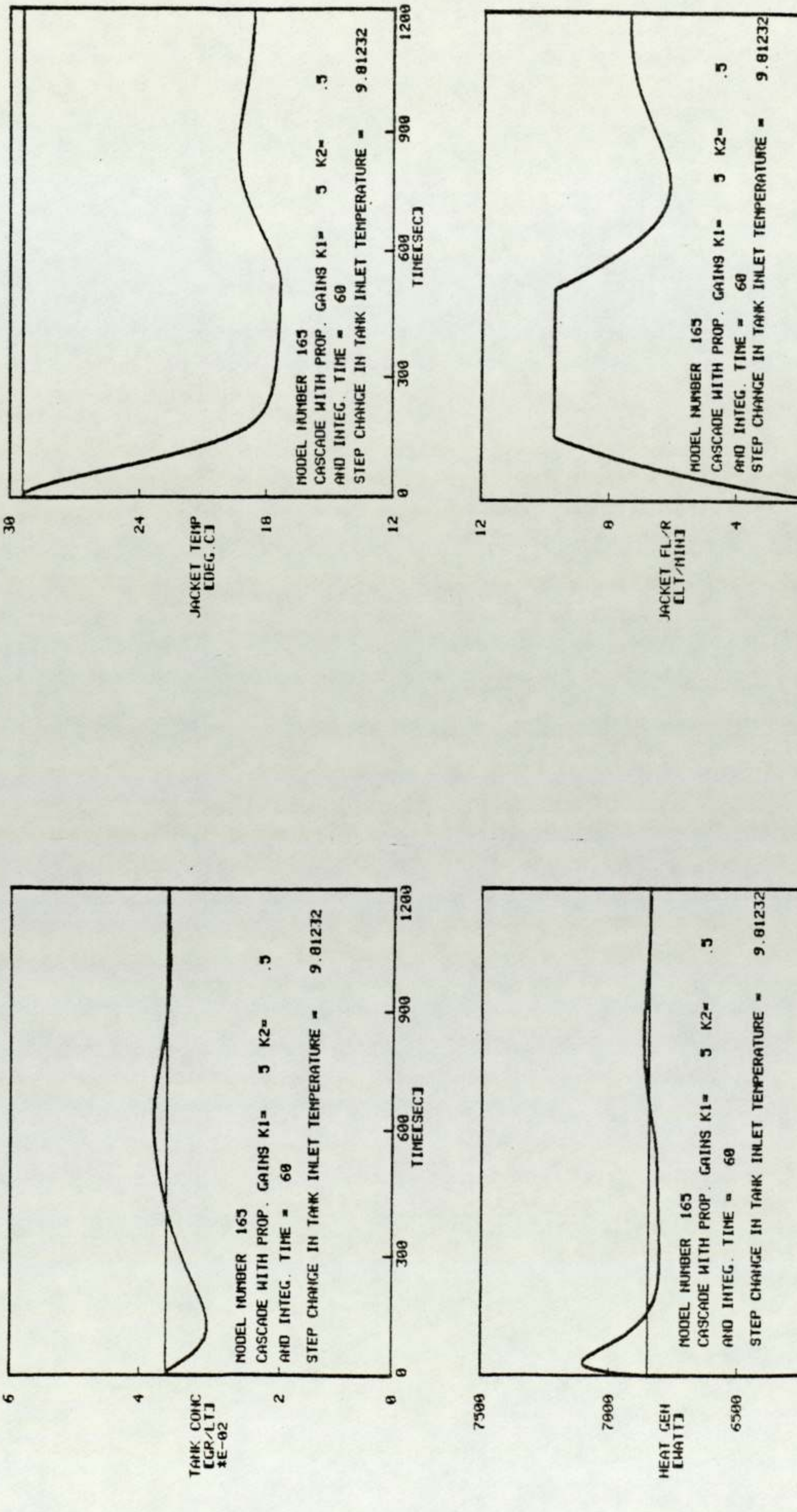
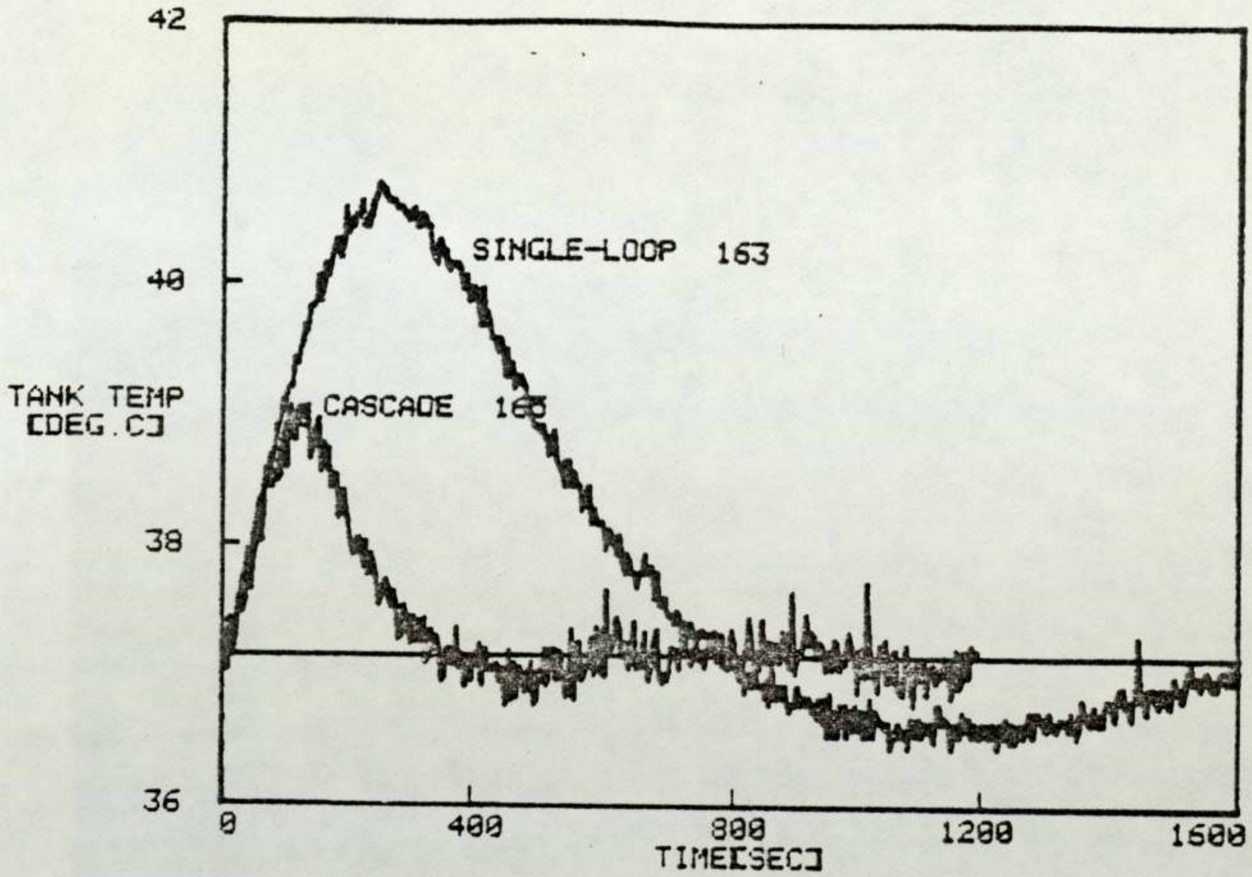

EXPERIMENT NUMBER 165
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 9.81232
JACKET TEMP [DEG.C]
JACKET FL/R [LT/MIN]
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
TIME[SEC]

FIG. A.3.82



MODEL NUMBER 165
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 9.81232
JACKET TEMP [DEG.C]
JACKET FL/R [LT/MIN]
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
TIME[SEC]

FIG. A.3.83


42
40
38
36
TANK TEMP [DEG.C]
SINGLE-LOOP 163
CASCADE 165
0
400
800
1200
1600
TIME[SEC]

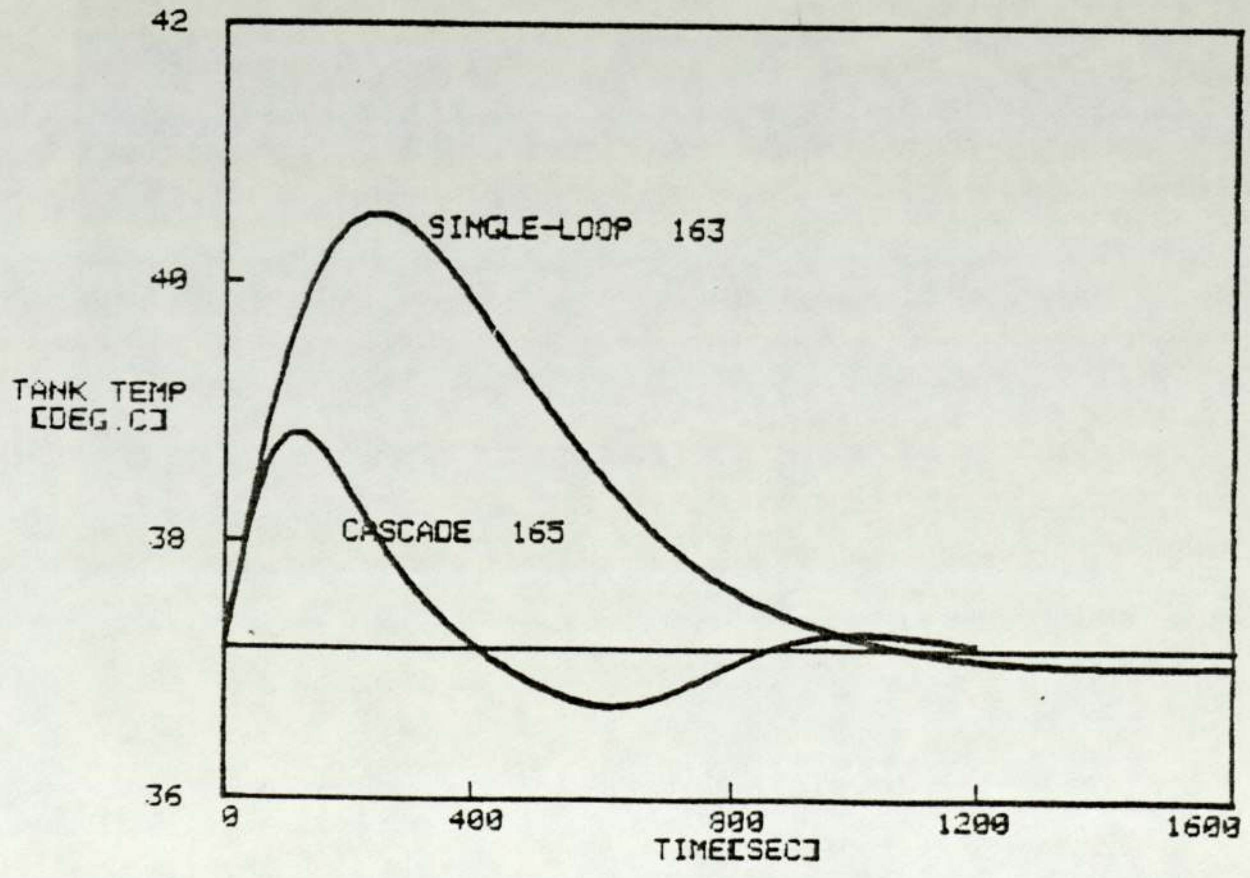
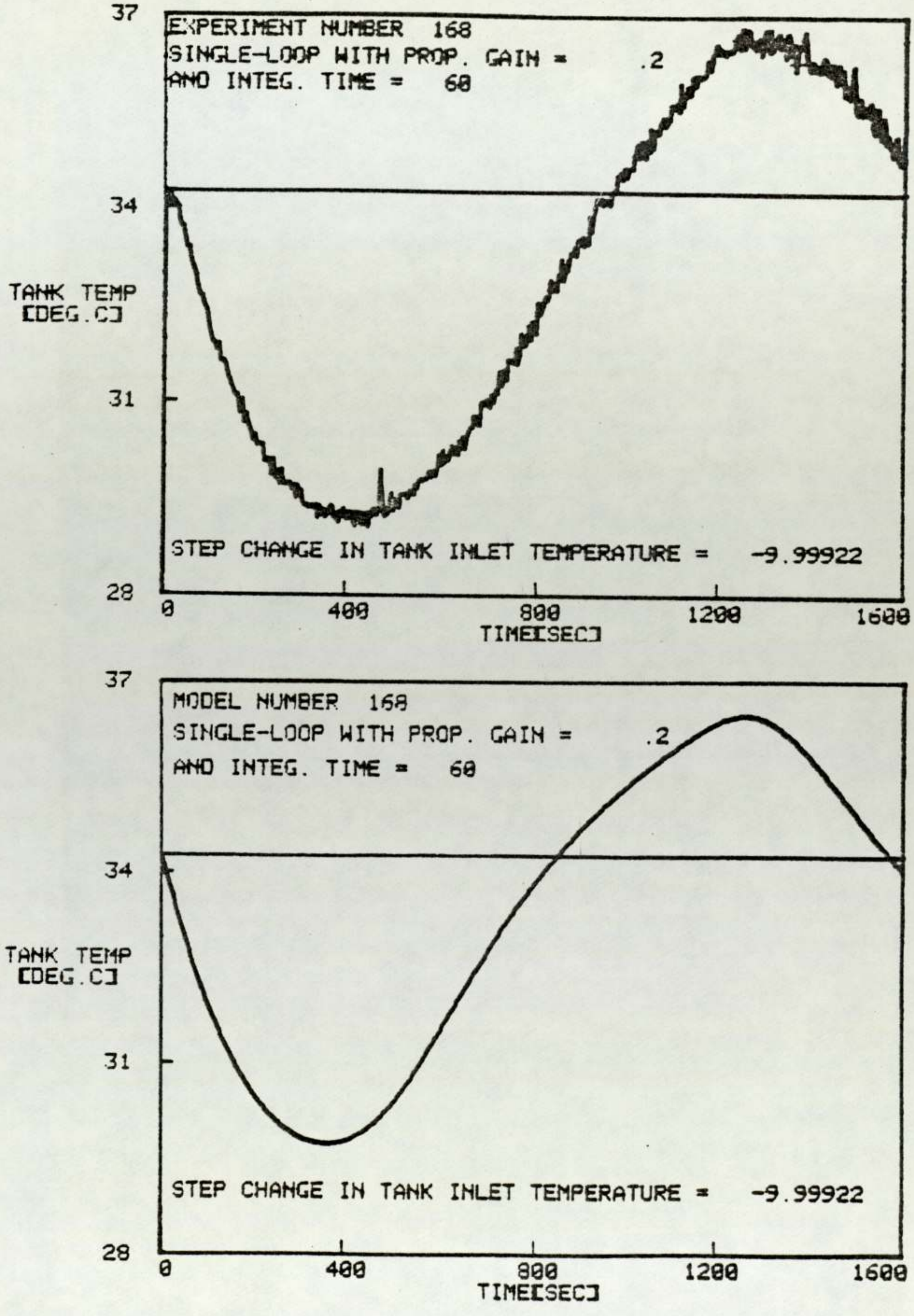
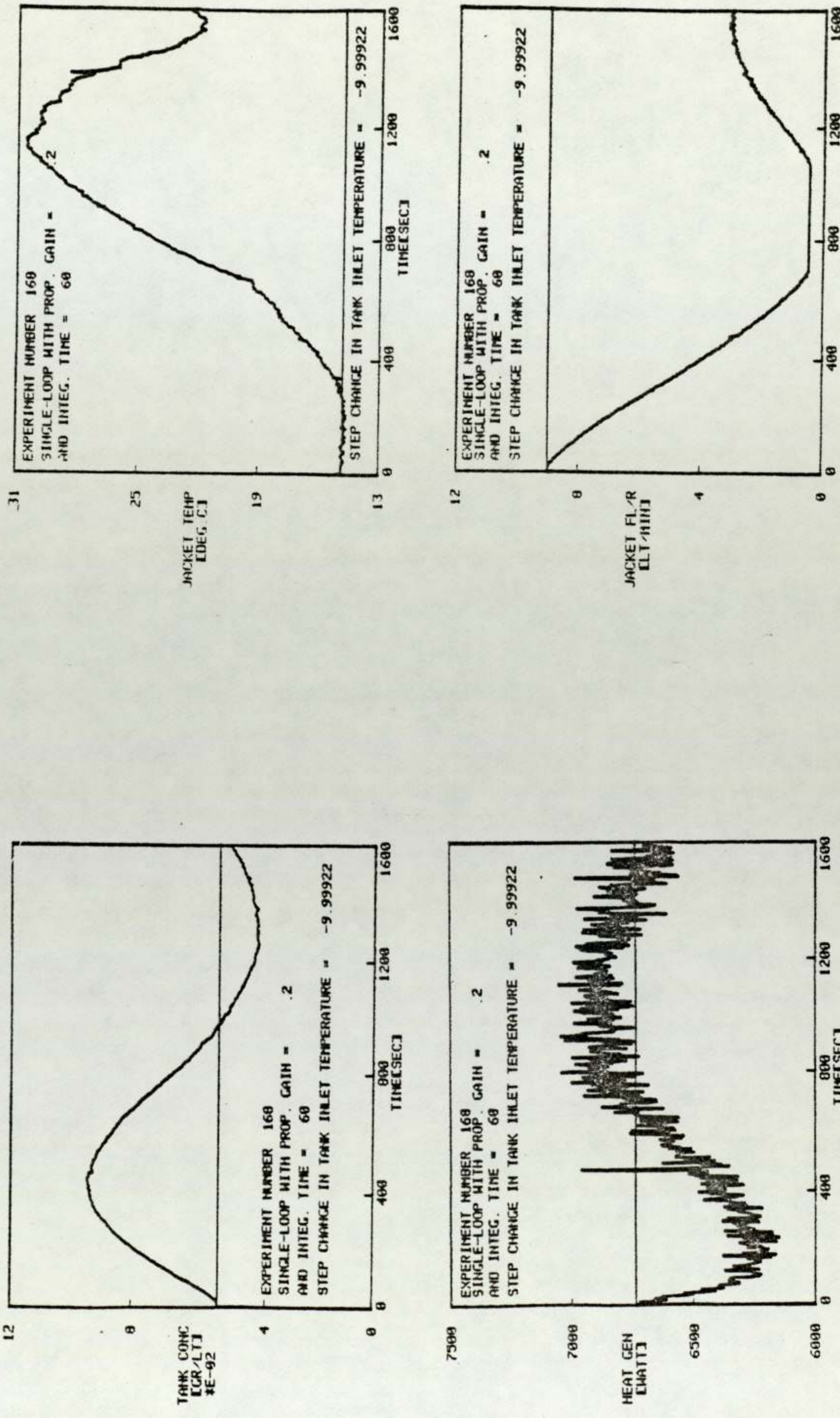

42
40
38
36
TANK TEMP [DEG.C]
SINGLE-LOOP 163
CASCADE 165
0
400
800
1200
1600
TIME[SEC]

FIG. A.3.84



EXPERIMENT NUMBER 168
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
37
34
31
28
TANK TEMP [DEG.C]
STEP CHANGE IN TANK INLET TEMPERATURE = -9.99922
0
400
800
1200
1600
TIME[SEC]
MODEL NUMBER 168
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
37
34
31
28
TANK TEMP [DEG.C]
STEP CHANGE IN TANK INLET TEMPERATURE = -9.99922
0
400
800
1200
1600
TIME[SEC]

FIG. A,3,85



EXPERIMENT NUMBER 160
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -9.99922
JACKET TEMP [DEG C]
31
25
19
13
0
400
800
1200
1600
TIME[SEC]
JACKET FL/R [LT/MIN]
12
8
4
0
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
7500
7000
6500
6000

FIG. A.3.86

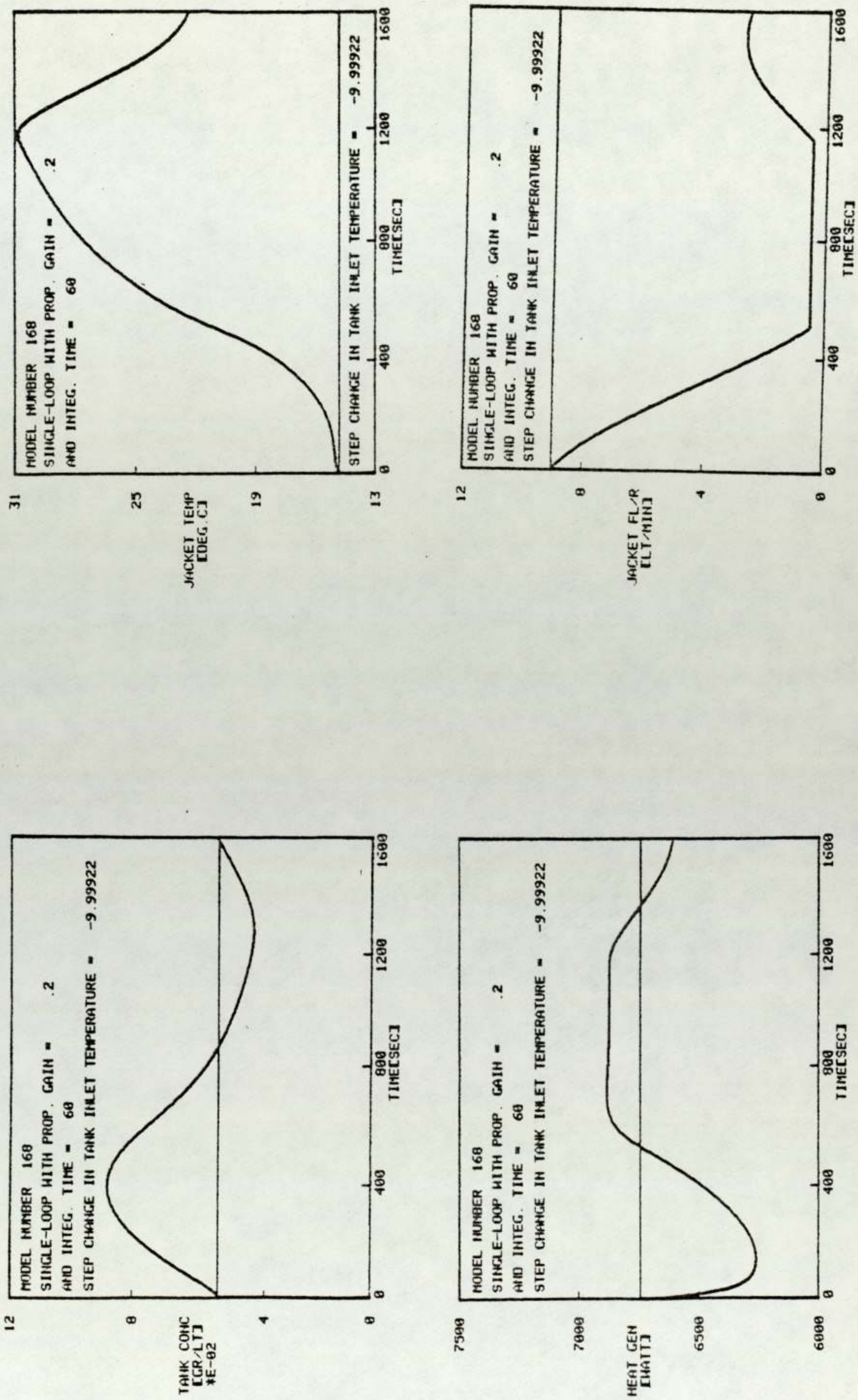
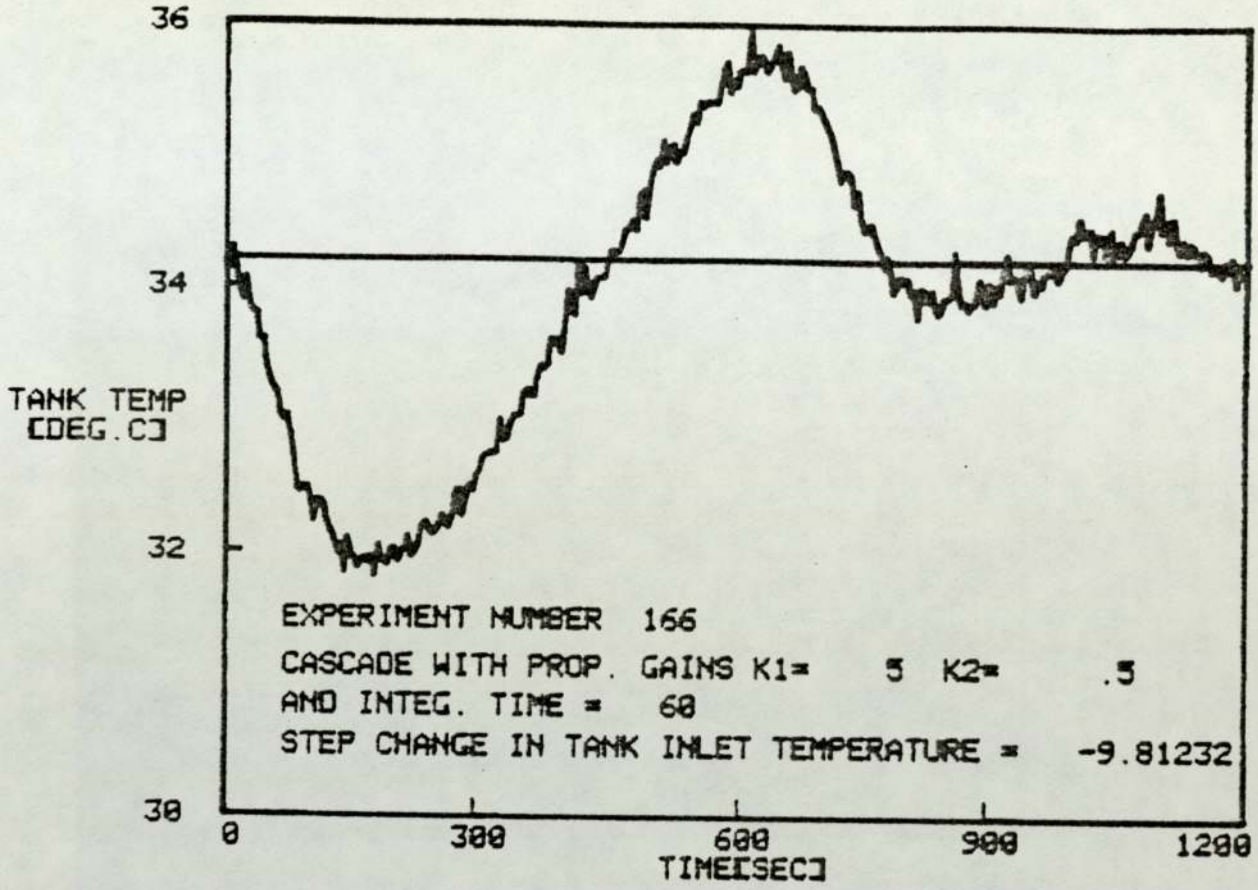

MODEL NUMBER 160
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -9.99922
JACKET TEMP [DEG.C]
TIME[SEC]
MODEL NUMBER 160
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -9.99922
JACKET FL/R [LT/MIN]
TIME[SEC]
MODEL NUMBER 160
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -9.99922
TANK CONC [GR/LT] *E-02
TIME[SEC]
MODEL NUMBER 160
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -9.99922
HEAT GEN [WATT]
TIME[SEC]

FIG. A.3.87


36
34
32
30
TANK TEMP
[DEG.C]
EXPERIMENT NUMBER 166
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -9.81232
0
300
600
900
1200
TIME[SEC]

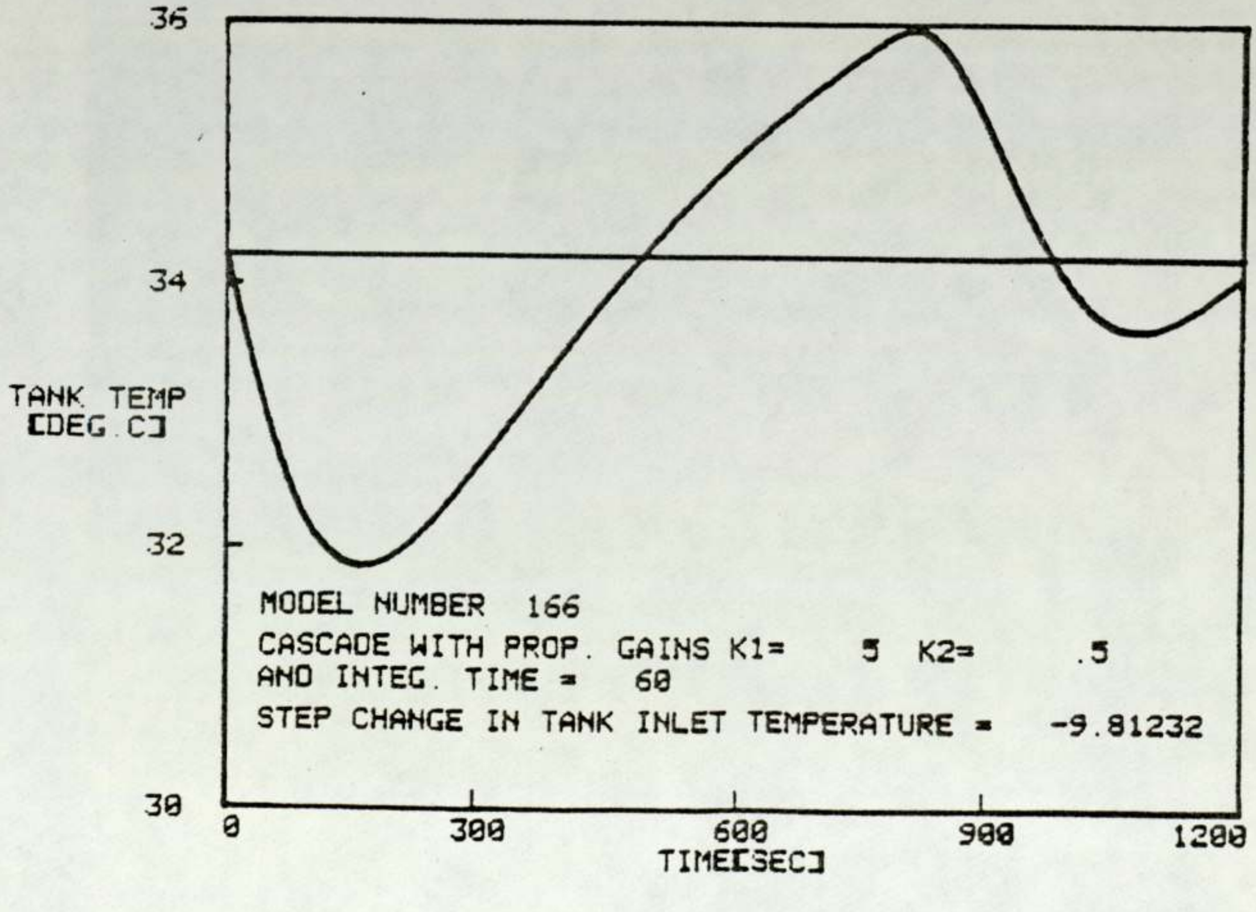

36
34
32
30
TANK TEMP
[DEG.C]
MODEL NUMBER 166
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -9.81232
0
300
600
900
1200
TIME[SEC]

FIG. A.3.88

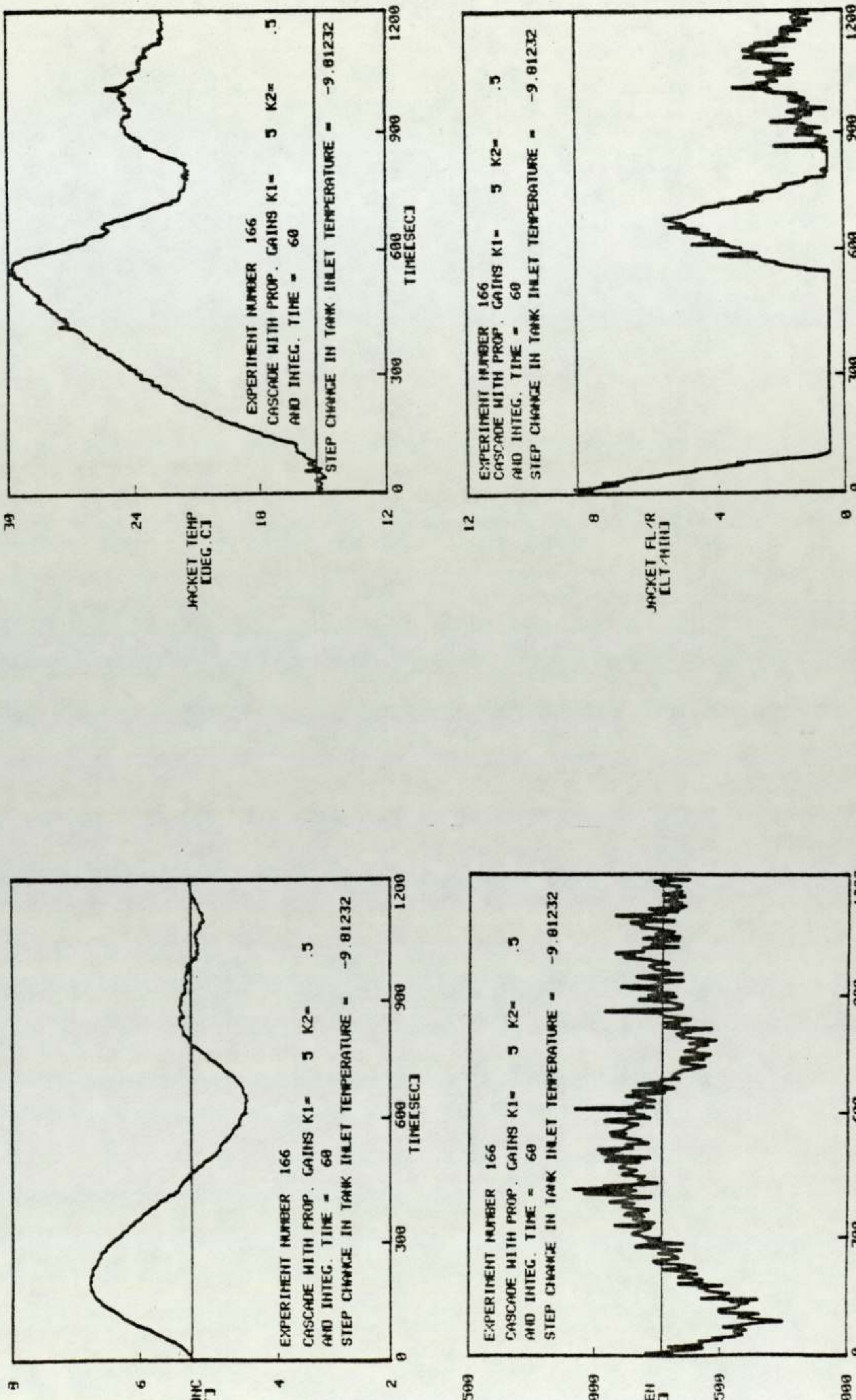

EXPERIMENT NUMBER 166
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -9.81232
JACKET TEMP [DEG.C]
JACKET FL/R [LT/MIN]
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
TIME[SEC]

FIG. A.3.39

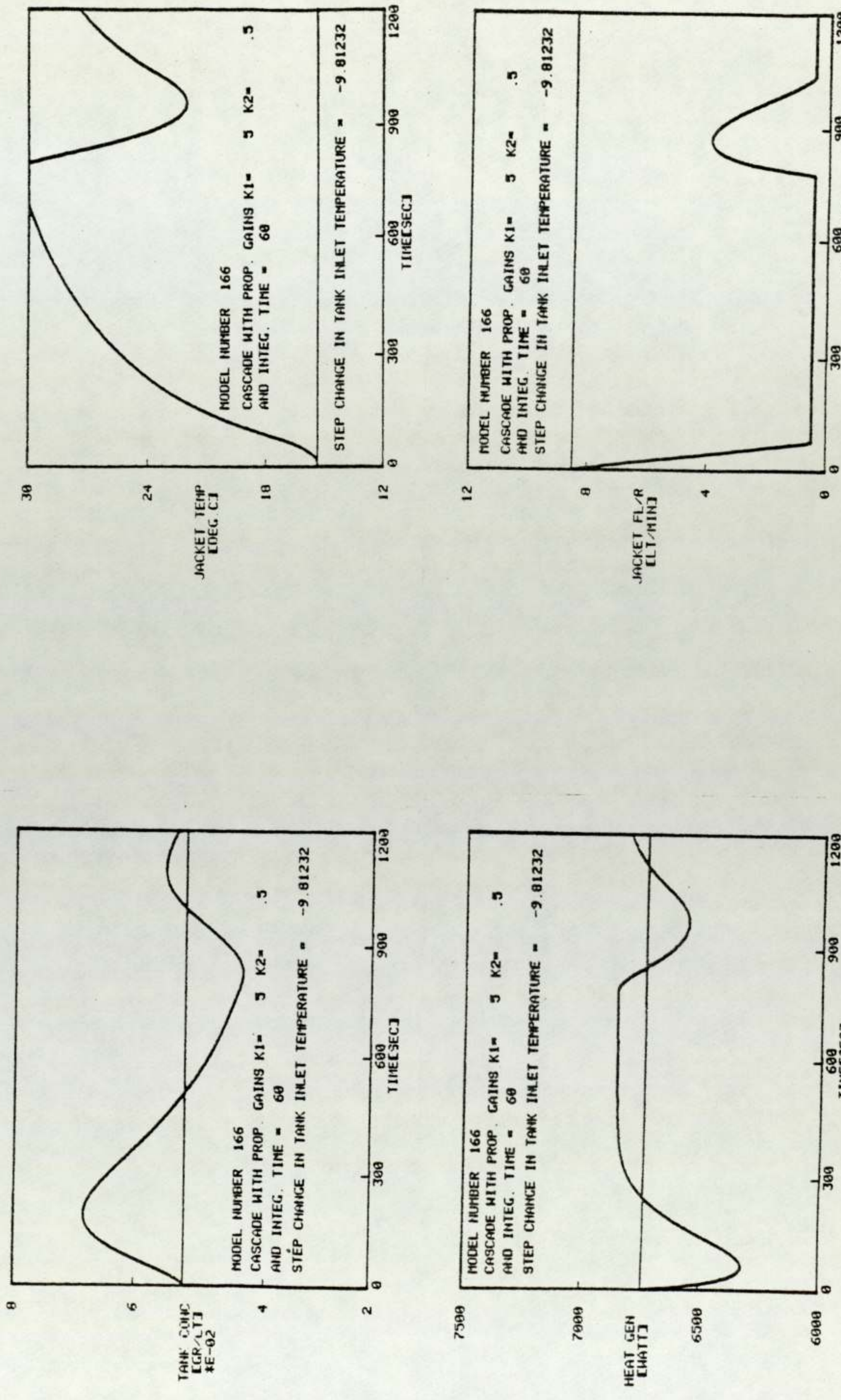
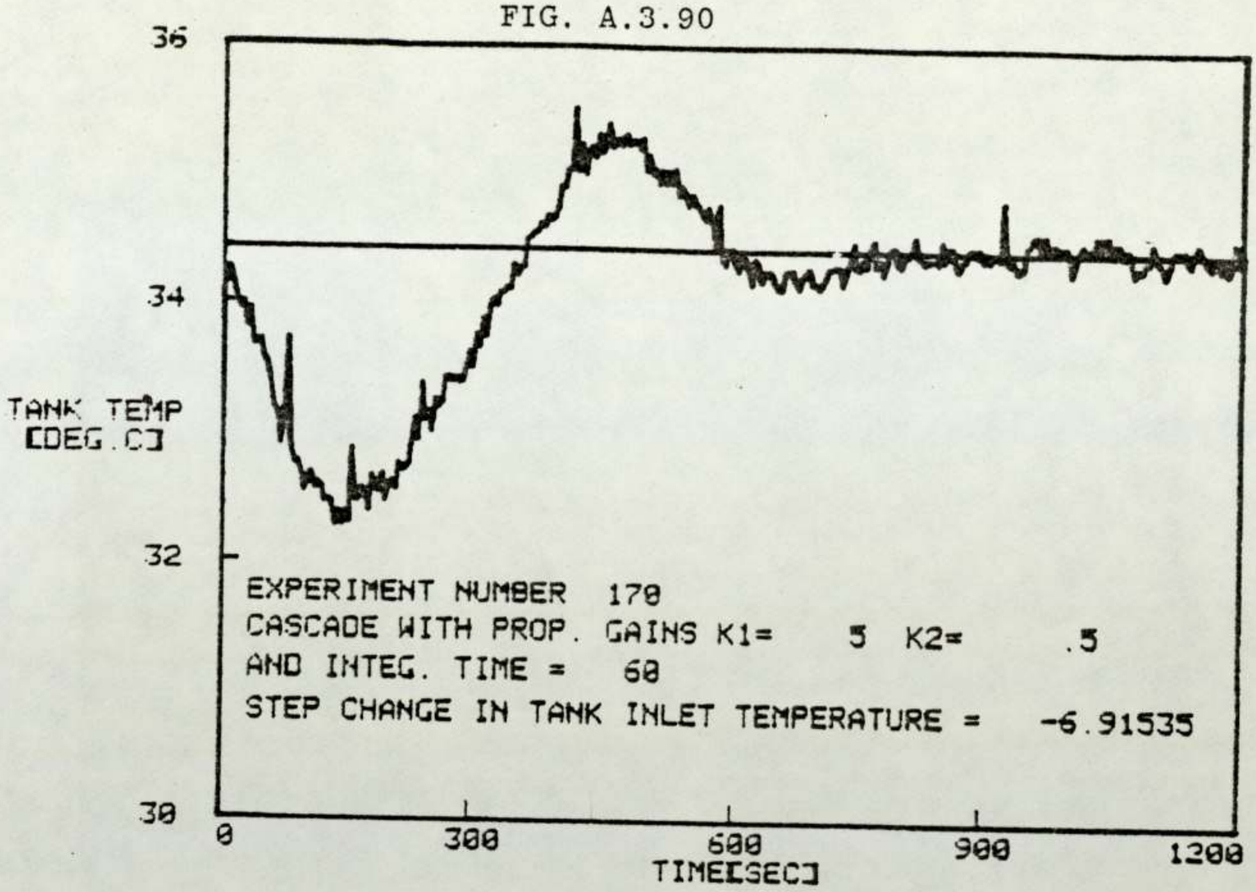

MODEL NUMBER 166
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -9.81232
JACKET TEMP
[DEG.C]
TIME[SEC]
JACKET FL/R
[LT/MIN]
TANK CONC
[GR/LT]
*E-02
HEAT GEN
[WATT]

FIG. A.3.90


36
34
32
30
TANK TEMP
[DEG.C]
EXPERIMENT NUMBER 170
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -6.91535
0
300
600
900
1200
TIME[SEC]

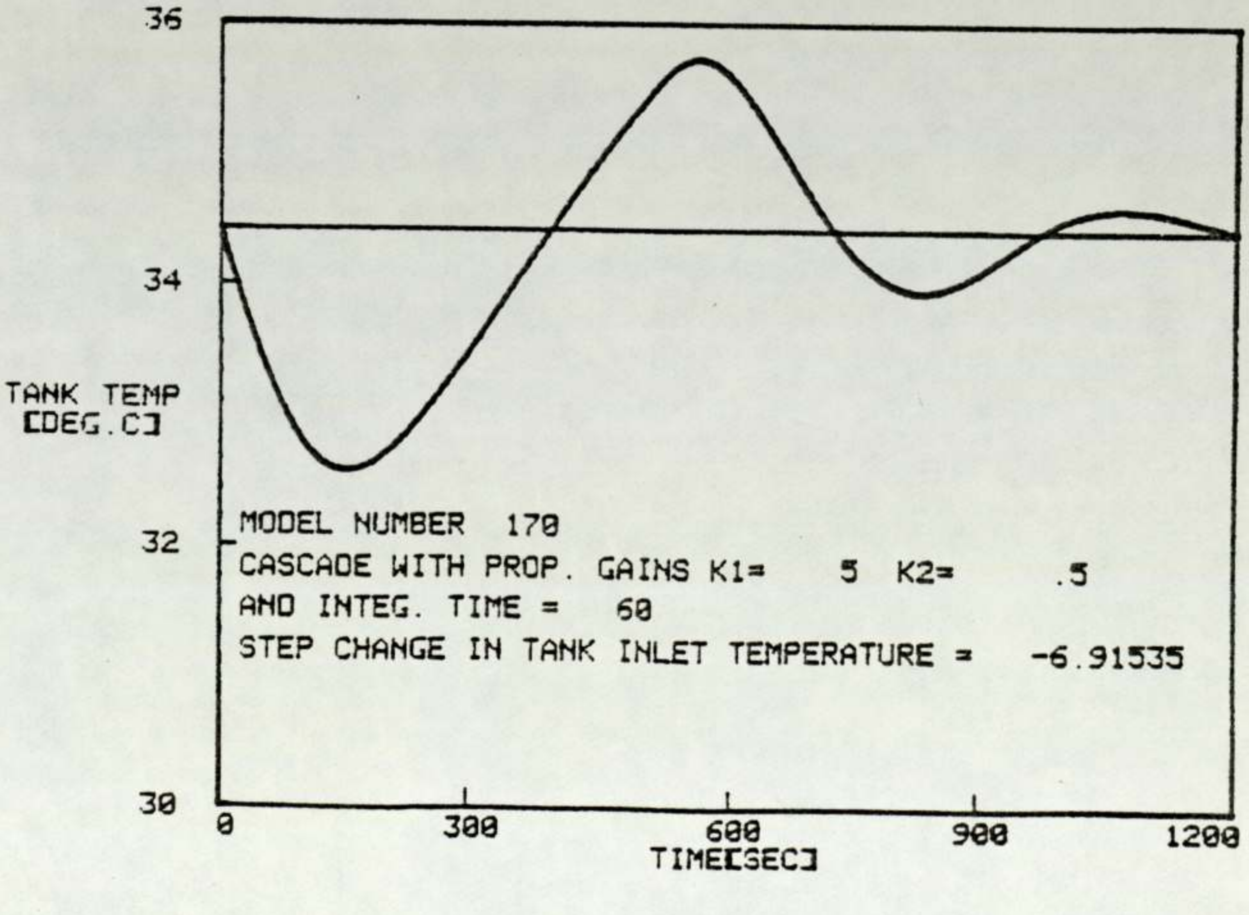

36
34
32
30
TANK TEMP
[DEG.C]
MODEL NUMBER 170
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -6.91535
0
300
600
900
1200
TIME[SEC]

FIG. A.3.91

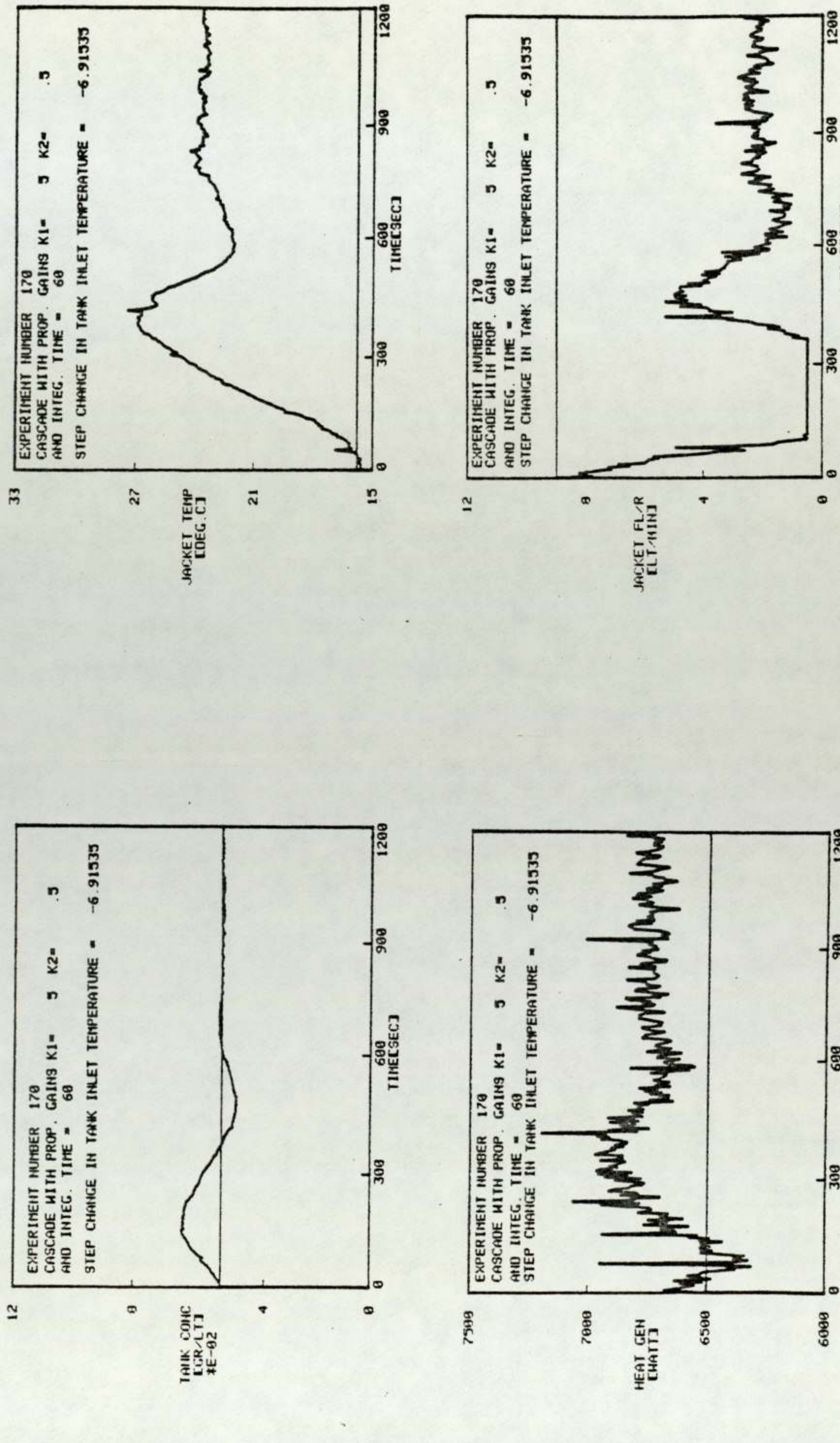

EXPERIMENT NUMBER 170
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -6.91535
JACKET TEMP [DEG.C]
JACKET FL/R [LT/MIN]
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
TIME[SEC]

FIG. A.3.92

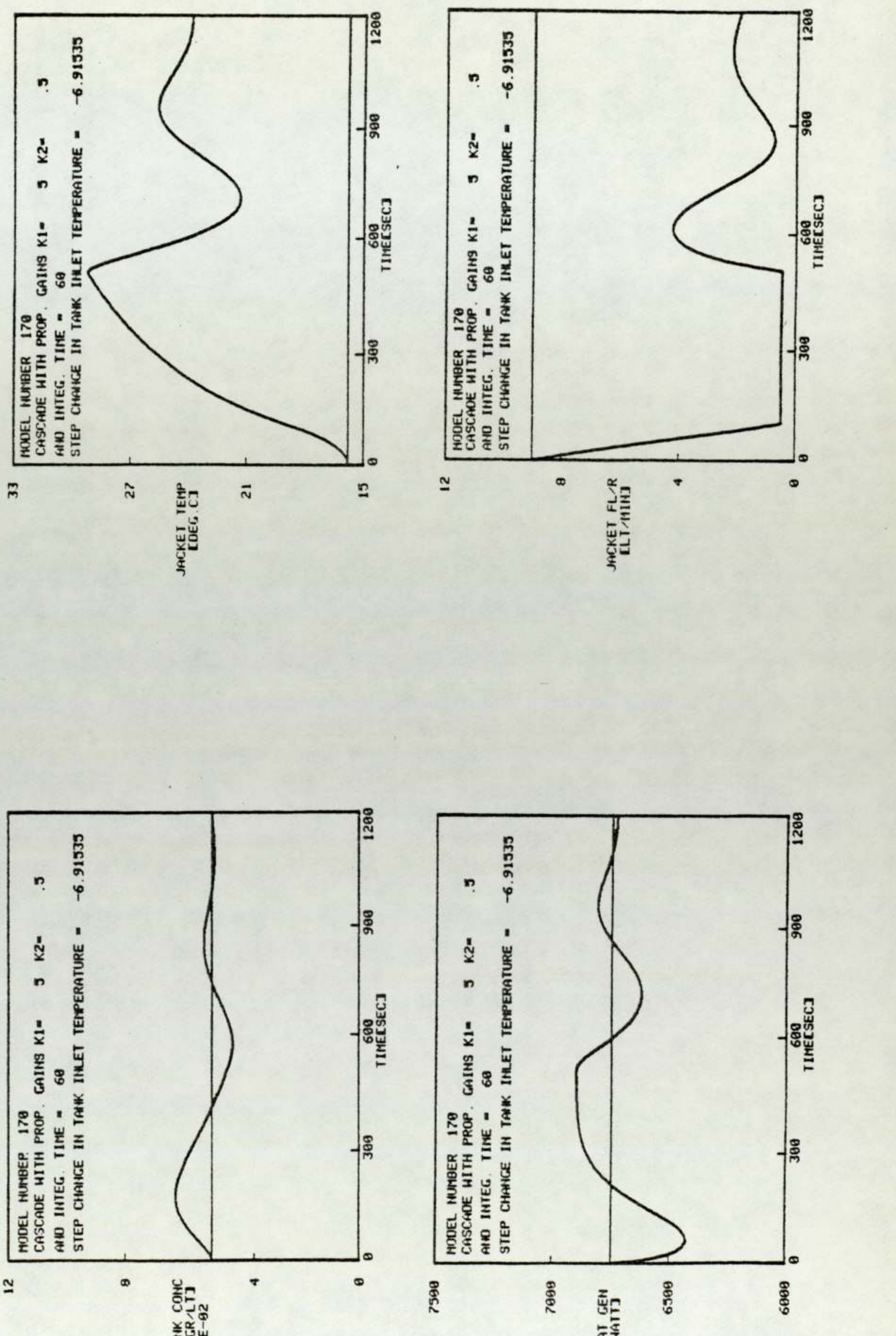
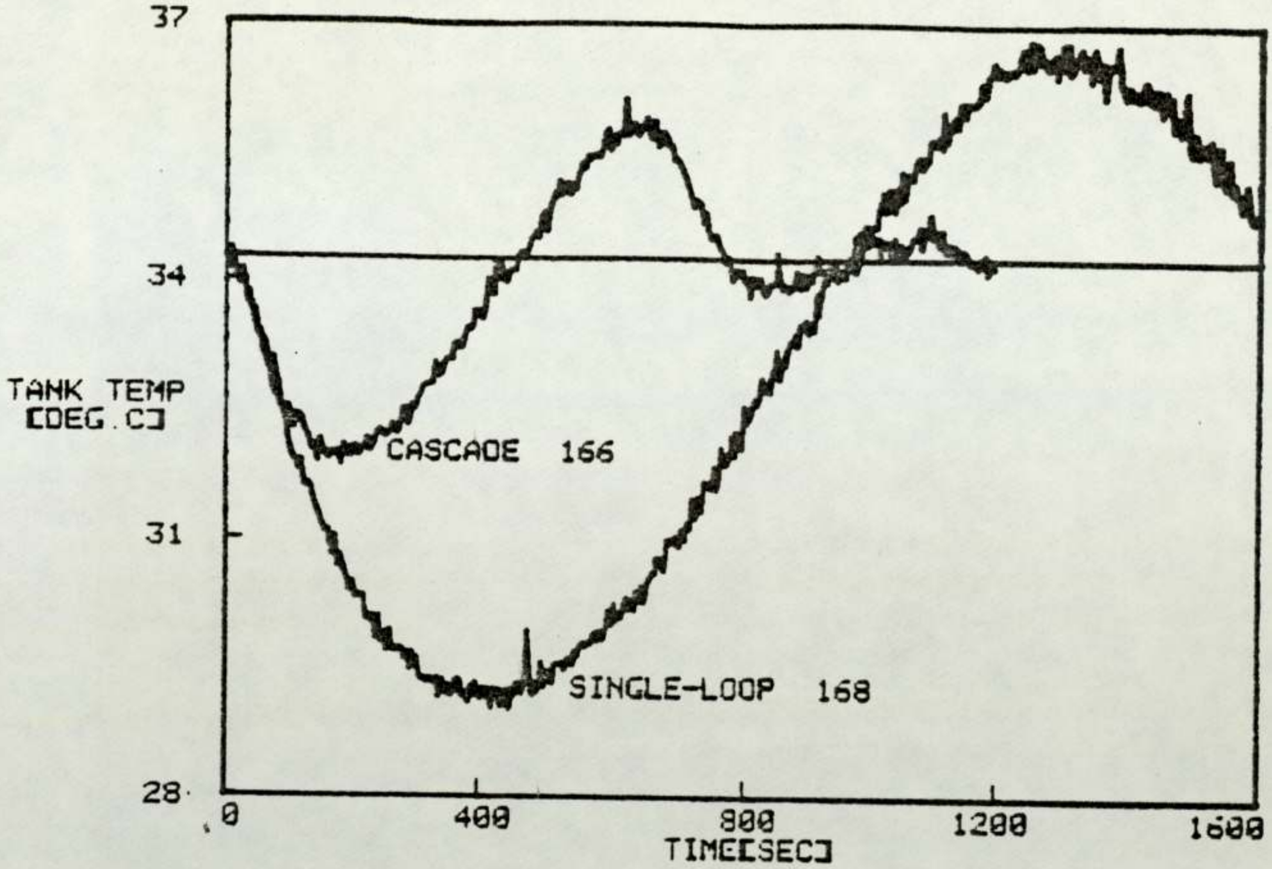
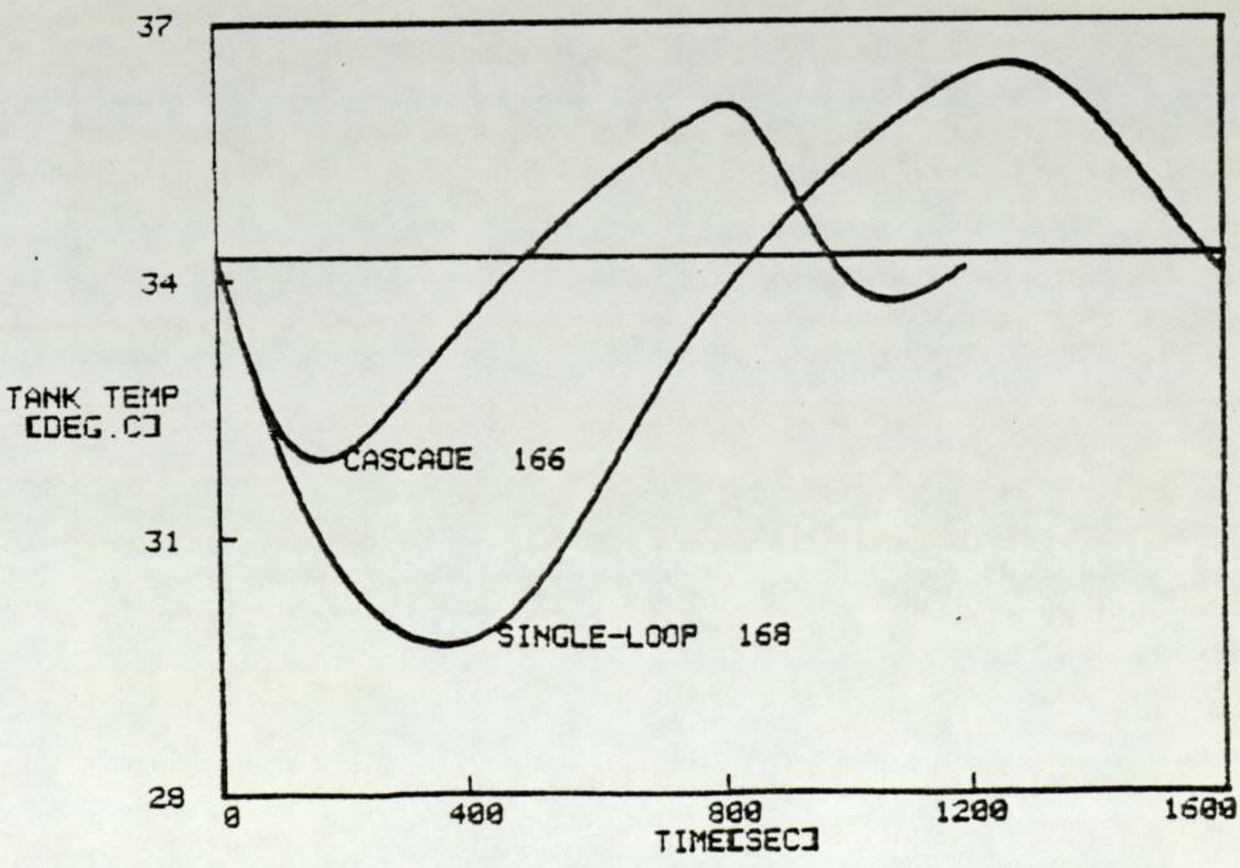

MODEL NUMBER 170
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -6.91535
JACKET TEMP [DEG.C]
TIME[SEC]
JACKET FL/R [LT/MIN]
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]

FIG. A.3.93

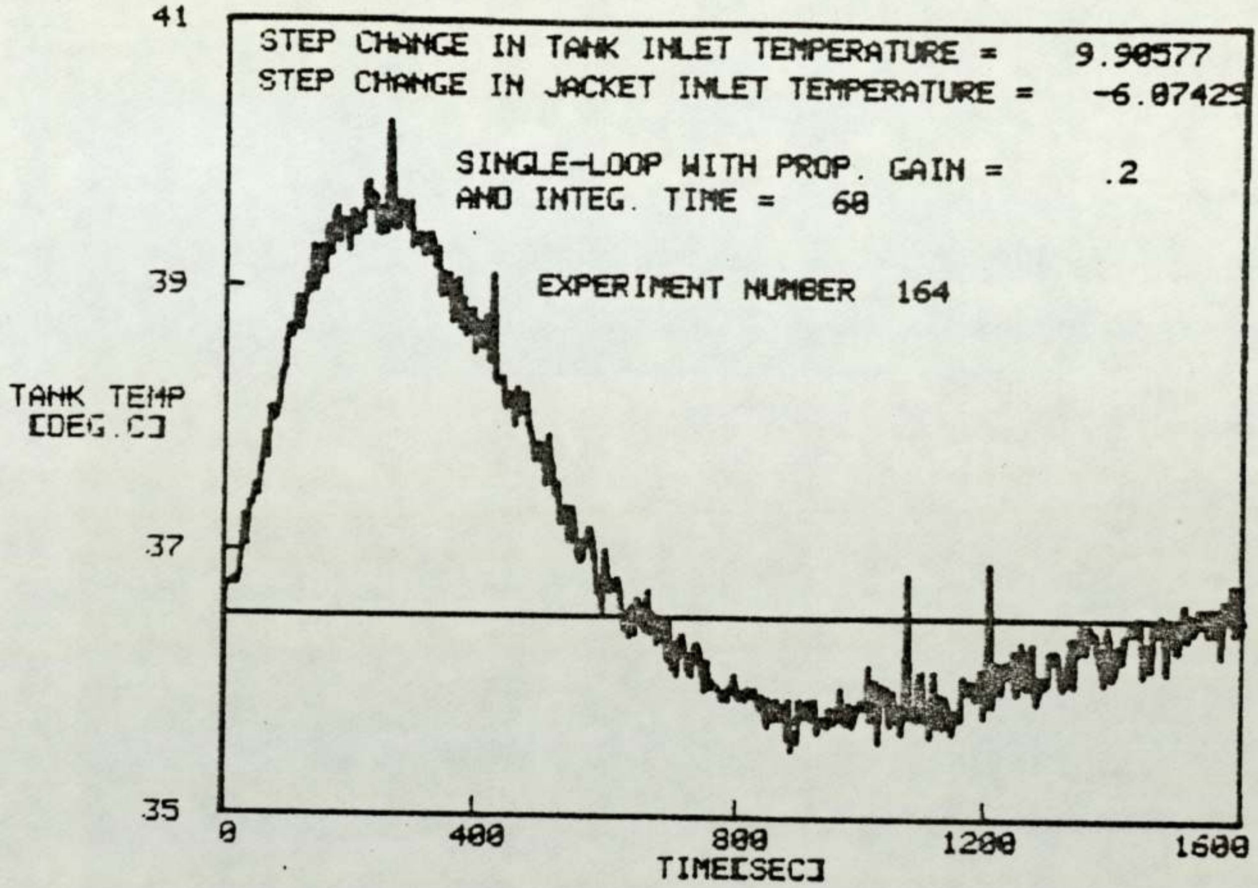


37
34
31
28
TANK TEMP
[DEG.C]
CASCADE 166
SINGLE-LOOP 168
0
400
800
1200
1600
TIME[SEC]

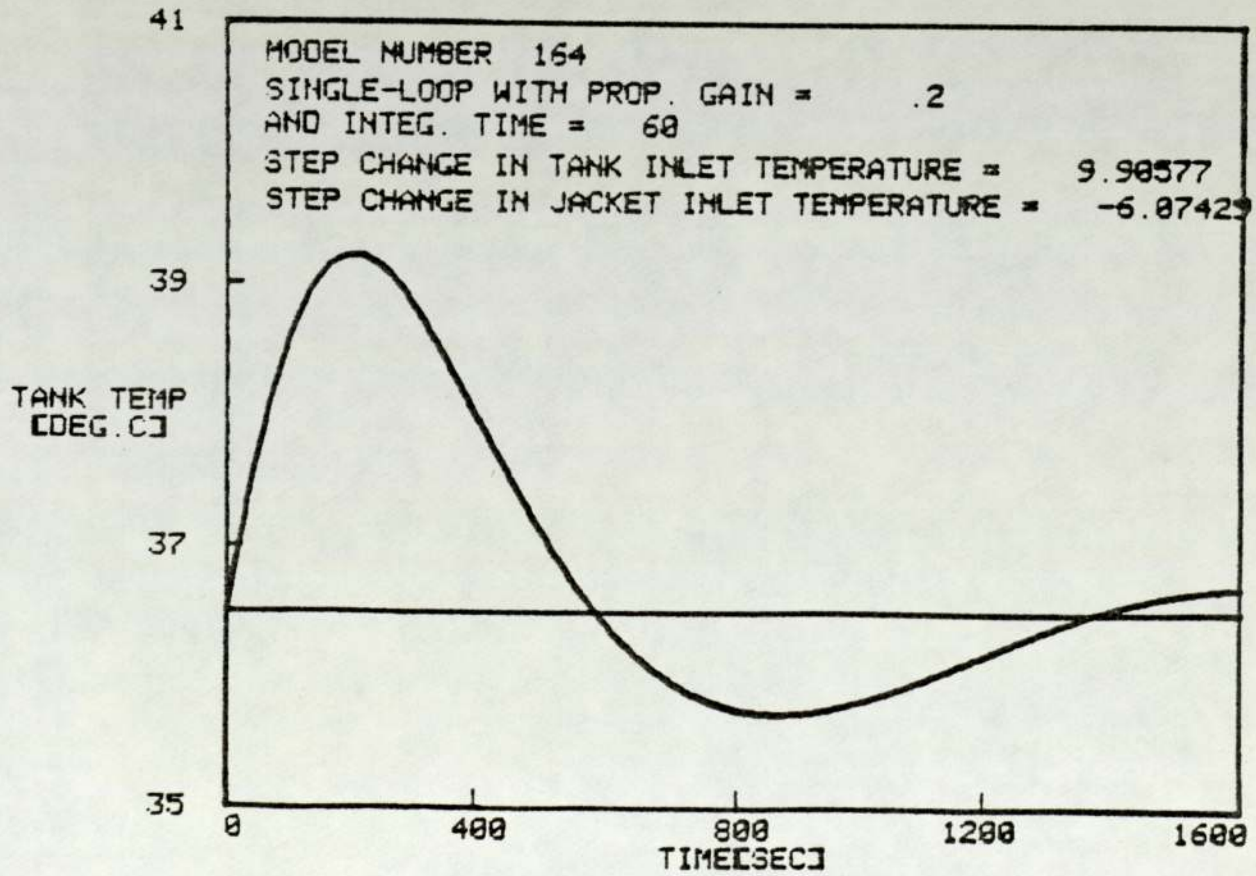


37
34
31
28
TANK TEMP
[DEG.C]
CASCADE 166
SINGLE-LOOP 168
0
400
800
1200
1600
TIME[SEC]

FIG. A.3.94



41
39
37
35
TANK TEMP
[DEG.C]
STEP CHANGE IN TANK INLET TEMPERATURE = 9.90577
STEP CHANGE IN JACKET INLET TEMPERATURE = -6.07429
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
EXPERIMENT NUMBER 164
0
400
800
1200
1600
TIME[SEC]



41
39
37
35
TANK TEMP
[DEG.C]
MODEL NUMBER 164
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 9.90577
STEP CHANGE IN JACKET INLET TEMPERATURE = -6.07429
0
400
800
1200
1600
TIME[SEC]

FIG. A.3.95

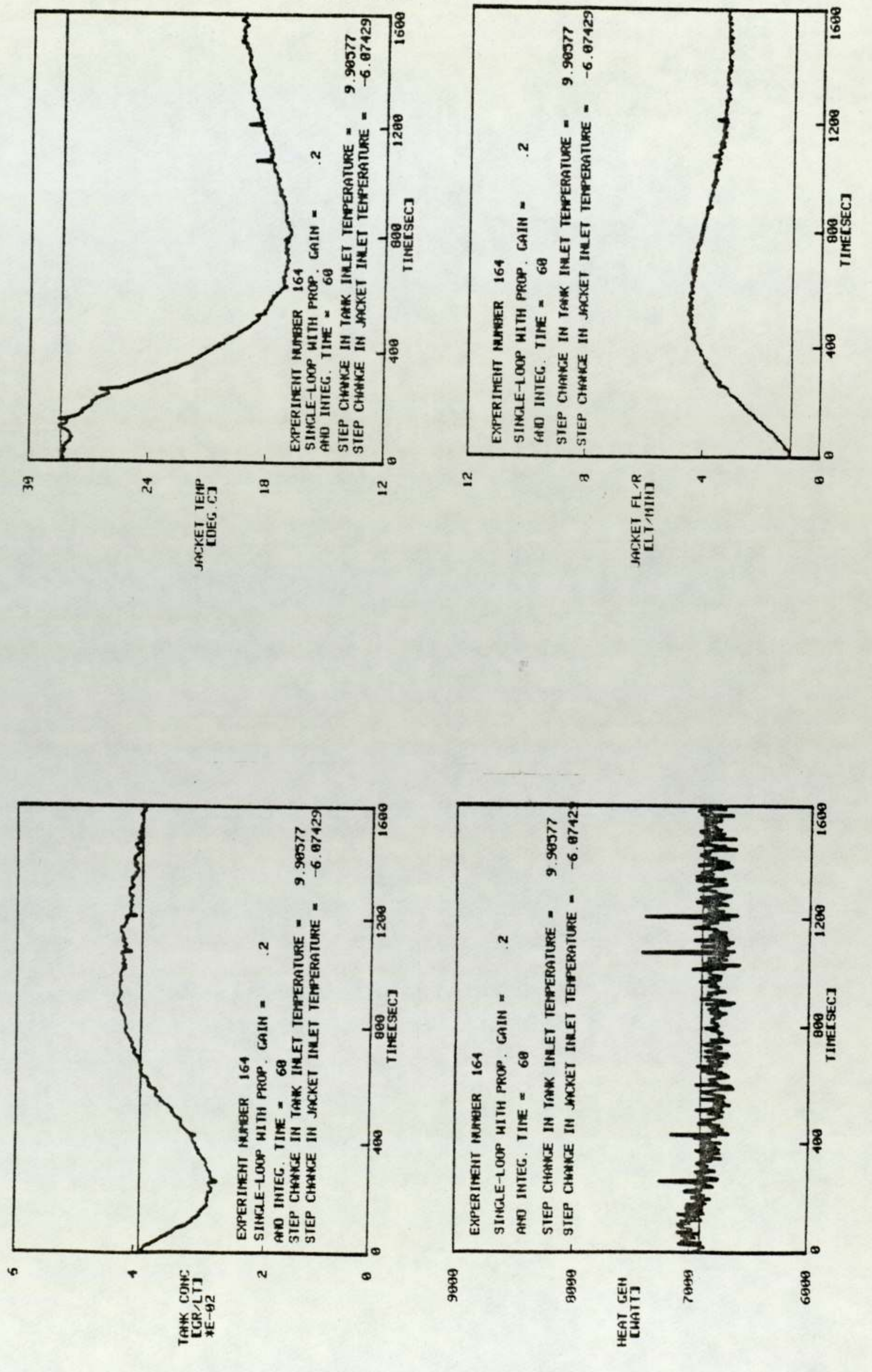
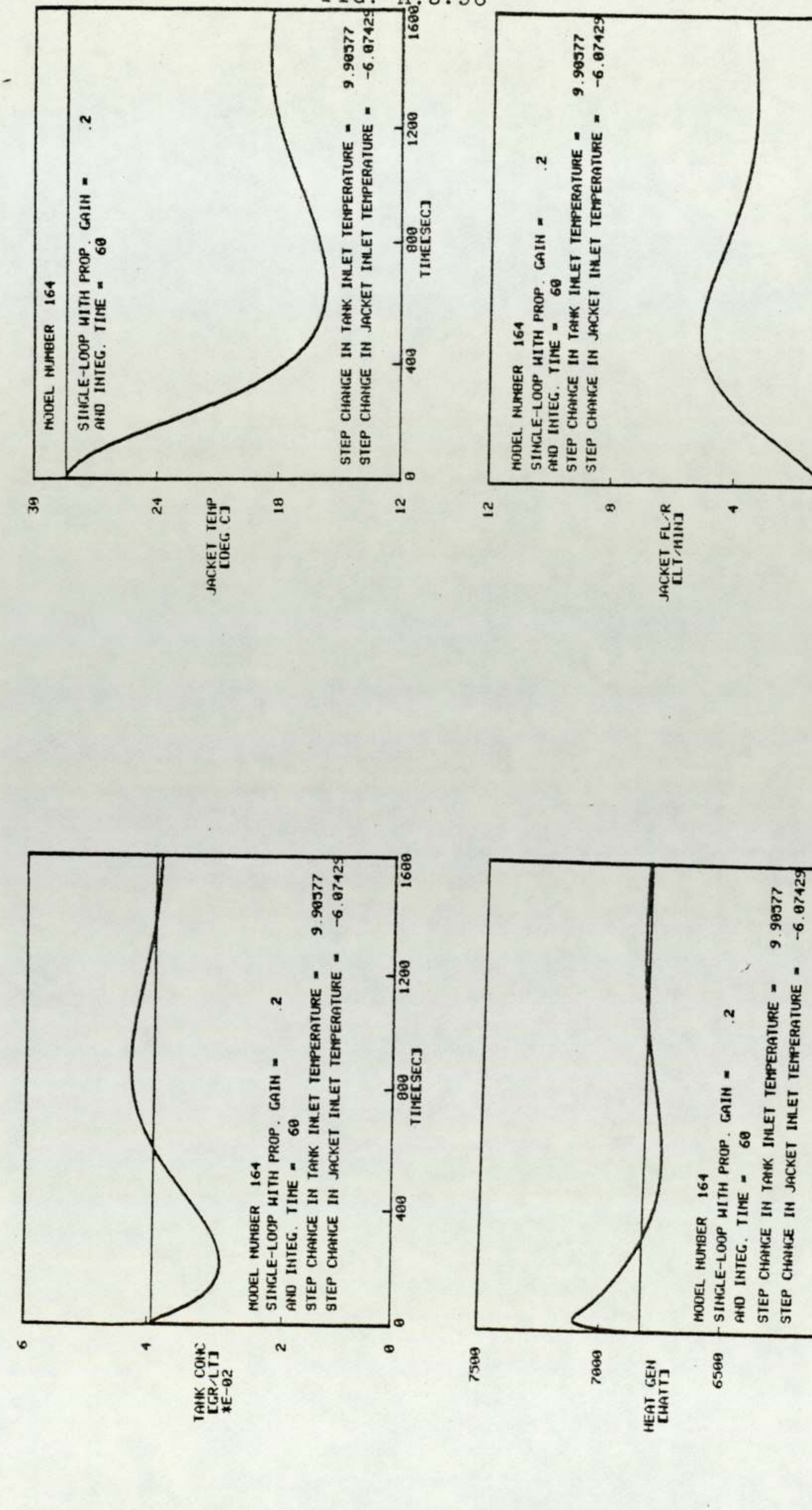
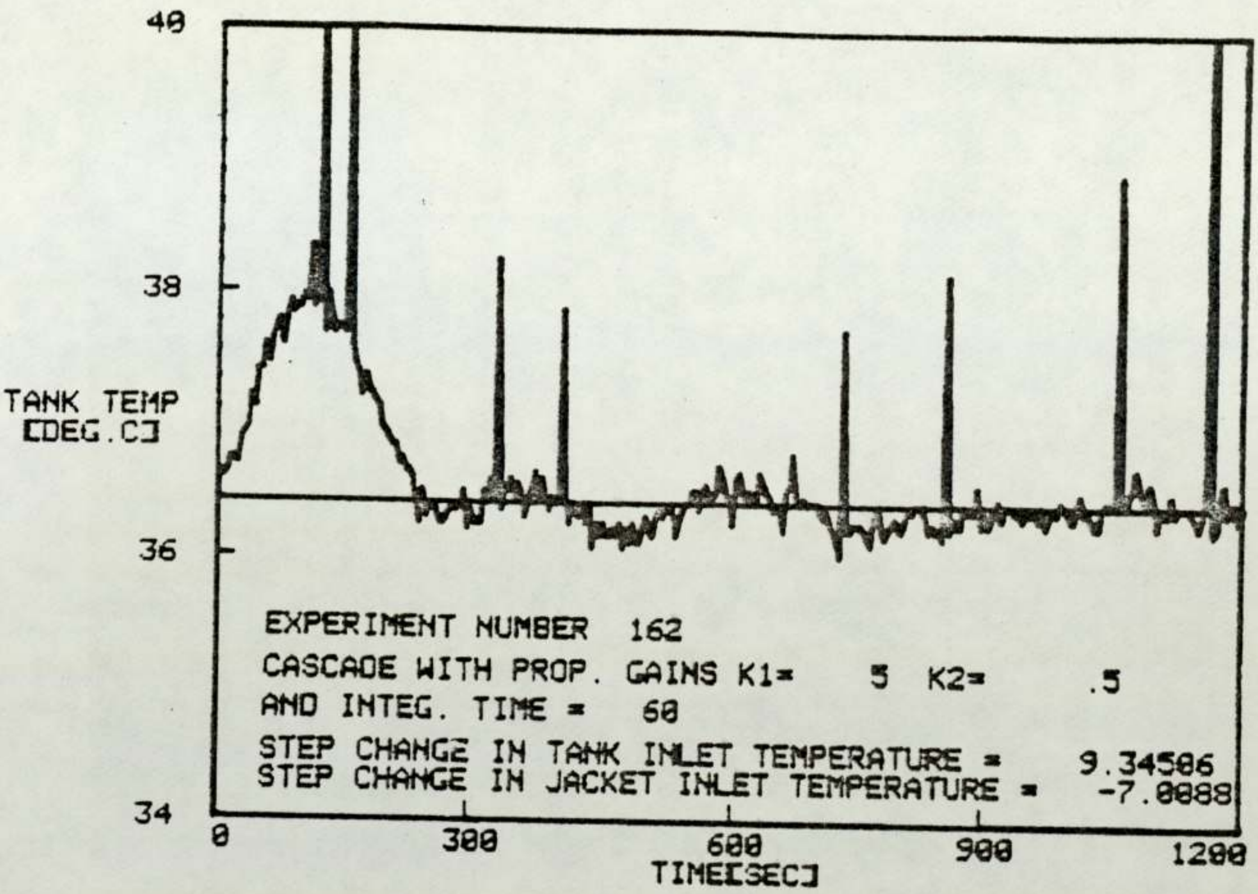

EXPERIMENT NUMBER 164
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 9.90577
STEP CHANGE IN JACKET INLET TEMPERATURE = -6.07429
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
JACKET TEMP [DEG.C]
JACKET FL/R [LT/MIN]
TIME[SEC]
0
400
800
1200
1600

FIG. A.3.96

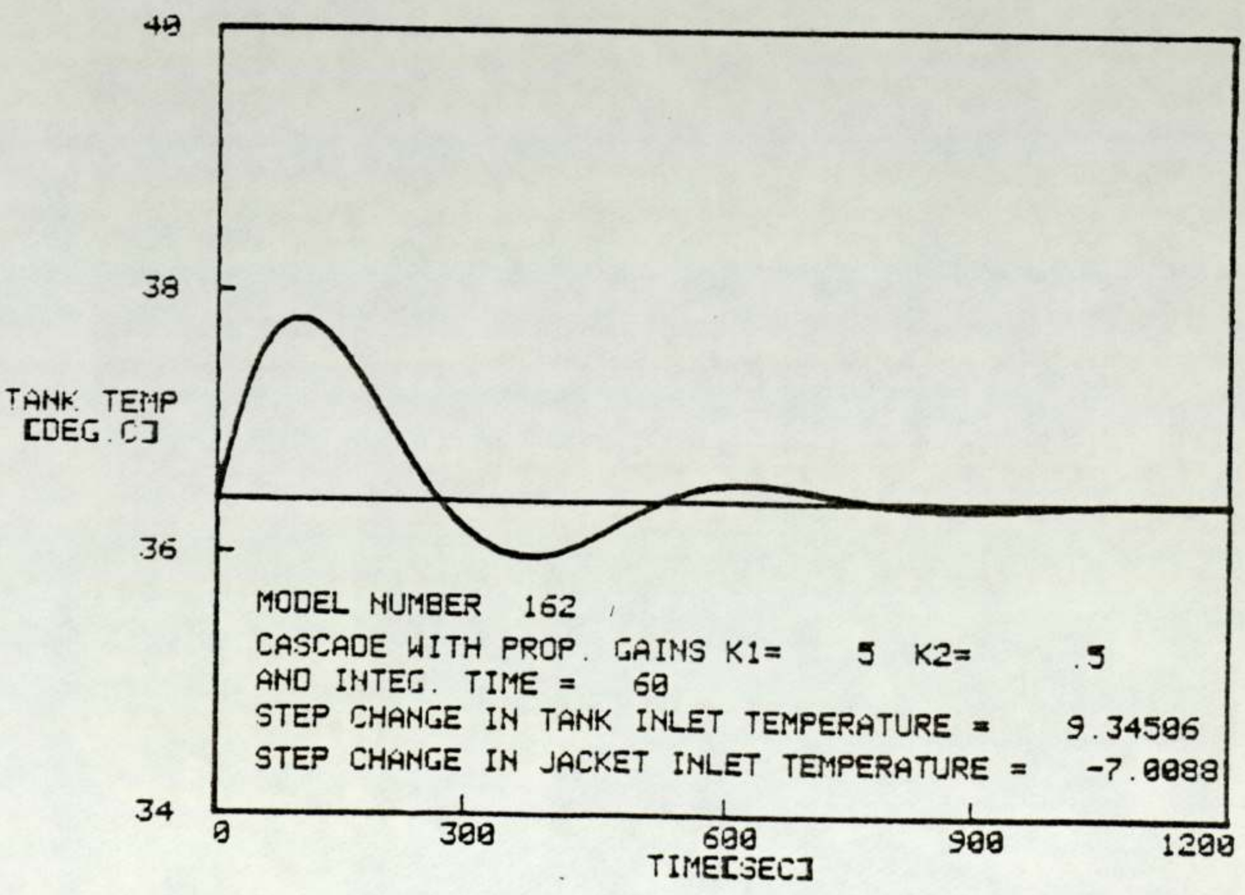


MODEL NUMBER 164
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 9.90577
STEP CHANGE IN JACKET INLET TEMPERATURE = -6.07429
JACKET TEMP [DEG C]
JACKET FL/R [LT/MIN]
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
TIME[SEC]

FIG. A.3.97



40
38
36
34
TANK TEMP
[DEG.C]
EXPERIMENT NUMBER 162
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 9.34506
STEP CHANGE IN JACKET INLET TEMPERATURE = -7.0088
0
300
600
900
1200
TIME[SEC]



40
38
36
34
TANK TEMP
[DEG.C]
MODEL NUMBER 162
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 9.34506
STEP CHANGE IN JACKET INLET TEMPERATURE = -7.0088
0
300
600
900
1200
TIME[SEC]

FIG. A.3.98

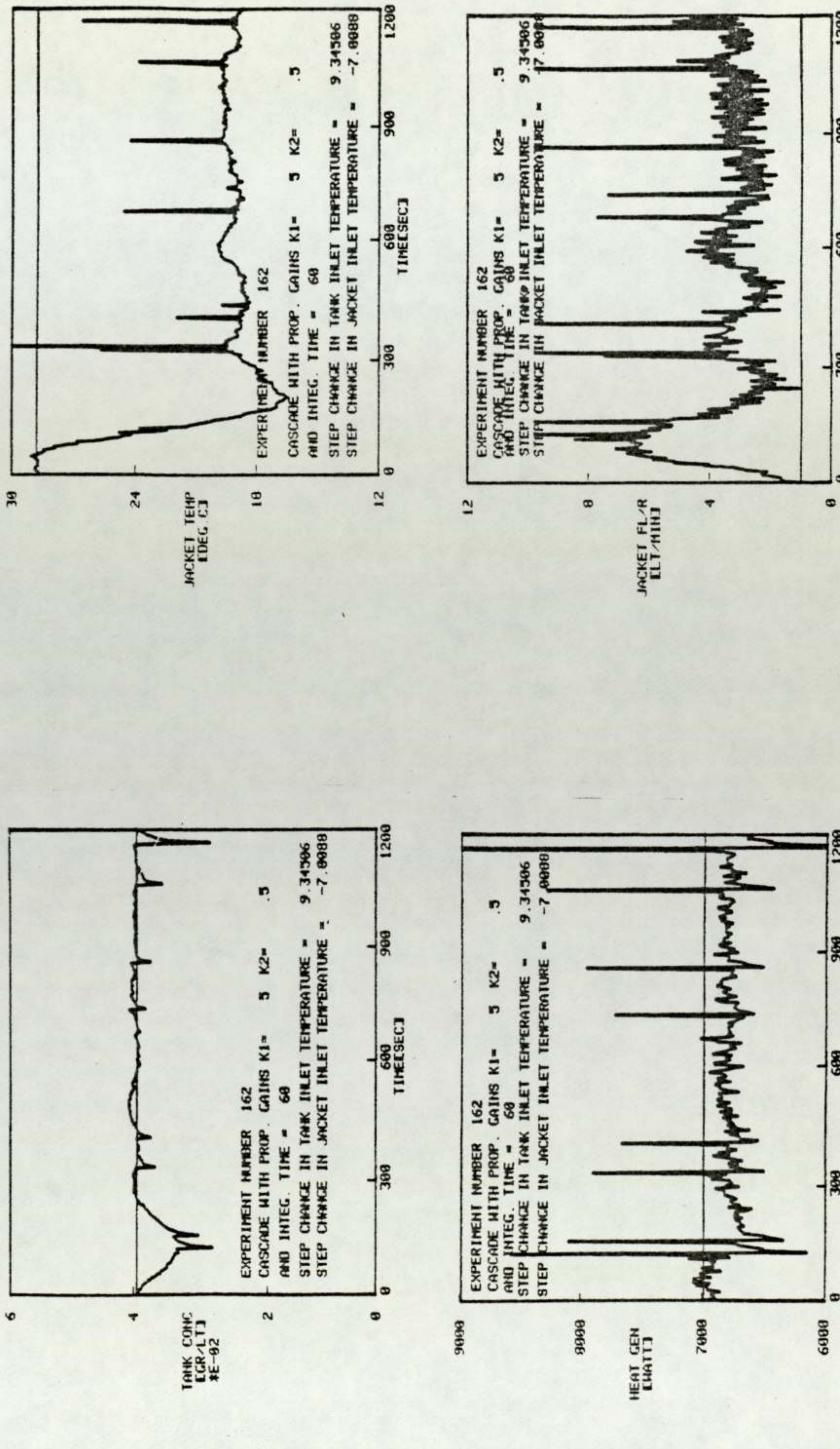

JACKET TEMP [DEG C]
JACKET FL/R [LT/MIN]
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
TIME[SEC]
EXPERIMENT NUMBER 162
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 9.34506
STEP CHANGE IN JACKET INLET TEMPERATURE = -7.0000

FIG. A.3.99

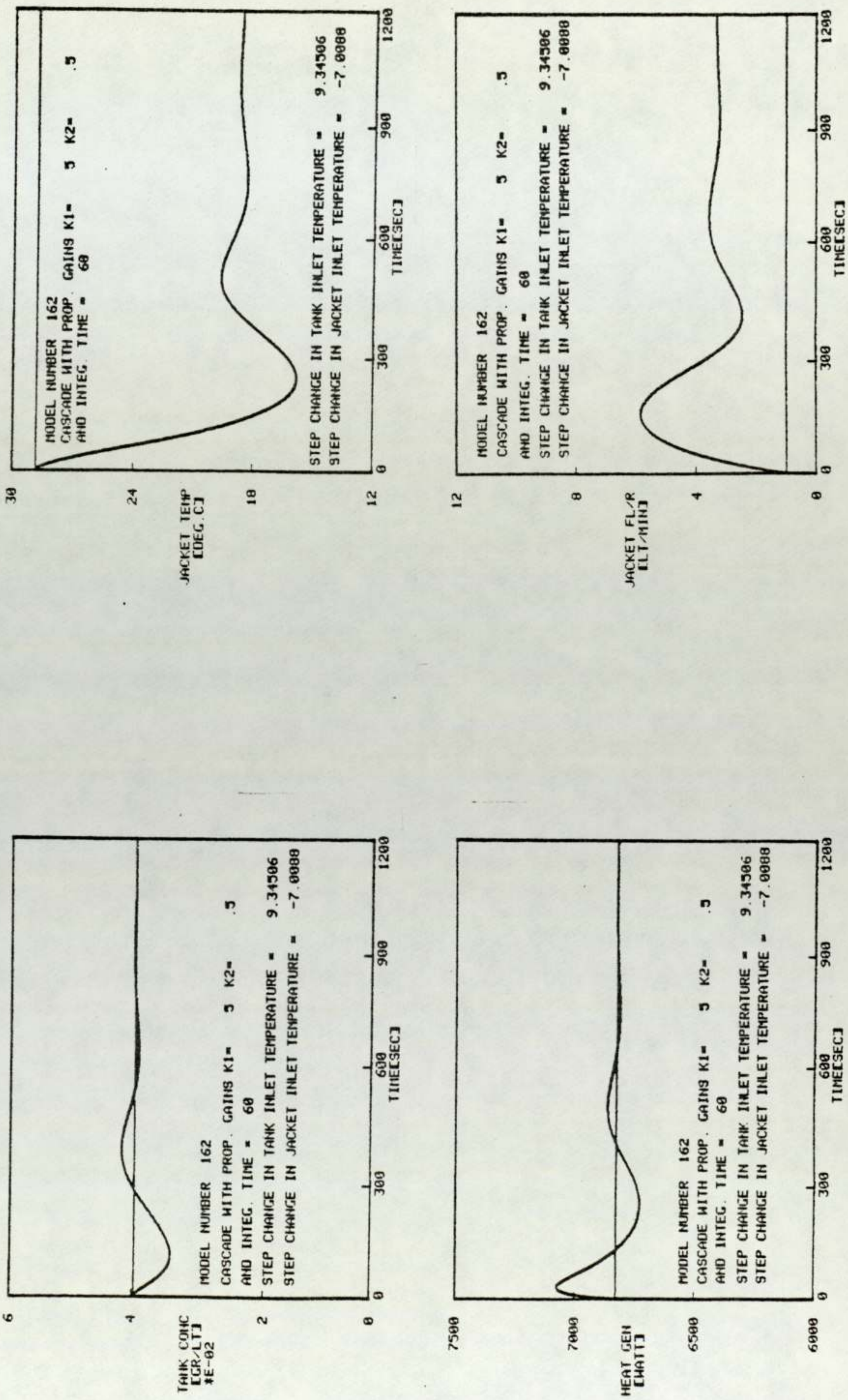
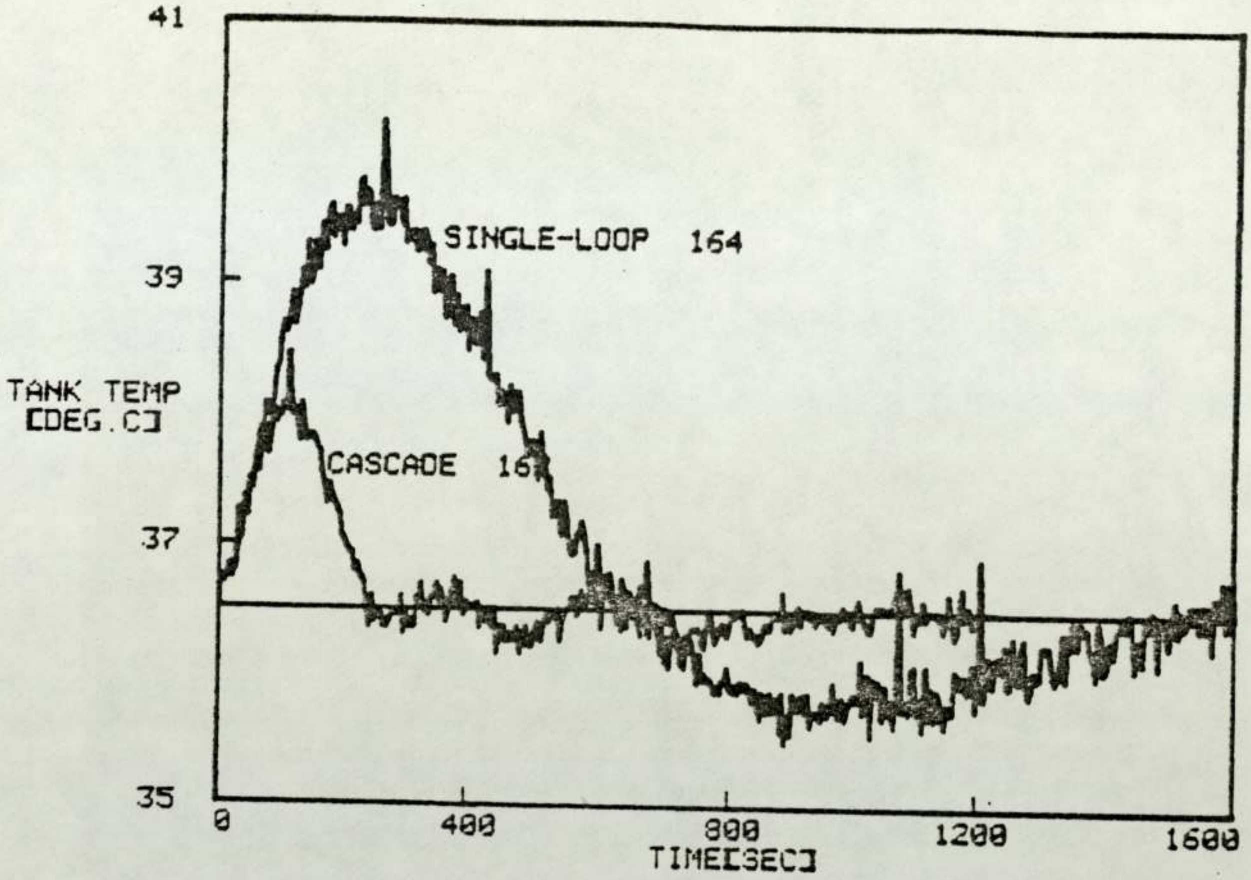

MODEL NUMBER 162
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 9.34506
STEP CHANGE IN JACKET INLET TEMPERATURE = -7.0000
JACKET TEMP [DEG.C]
30
24
18
12
JACKET FL/R [LT/MIN]
12
8
4
0
TANK CONC [GR/LT] *E-02
6
4
2
0
HEAT GEN [WATT]
7500
7000
6500
6000
0
300
600
900
1200
TIME[SEC]

FIG. A.3.100


41
39
37
35
TANK TEMP
[DEG.C]
SINGLE-LOOP 164
CASCADE 16
0
400
800
1200
1600
TIME[SEC]

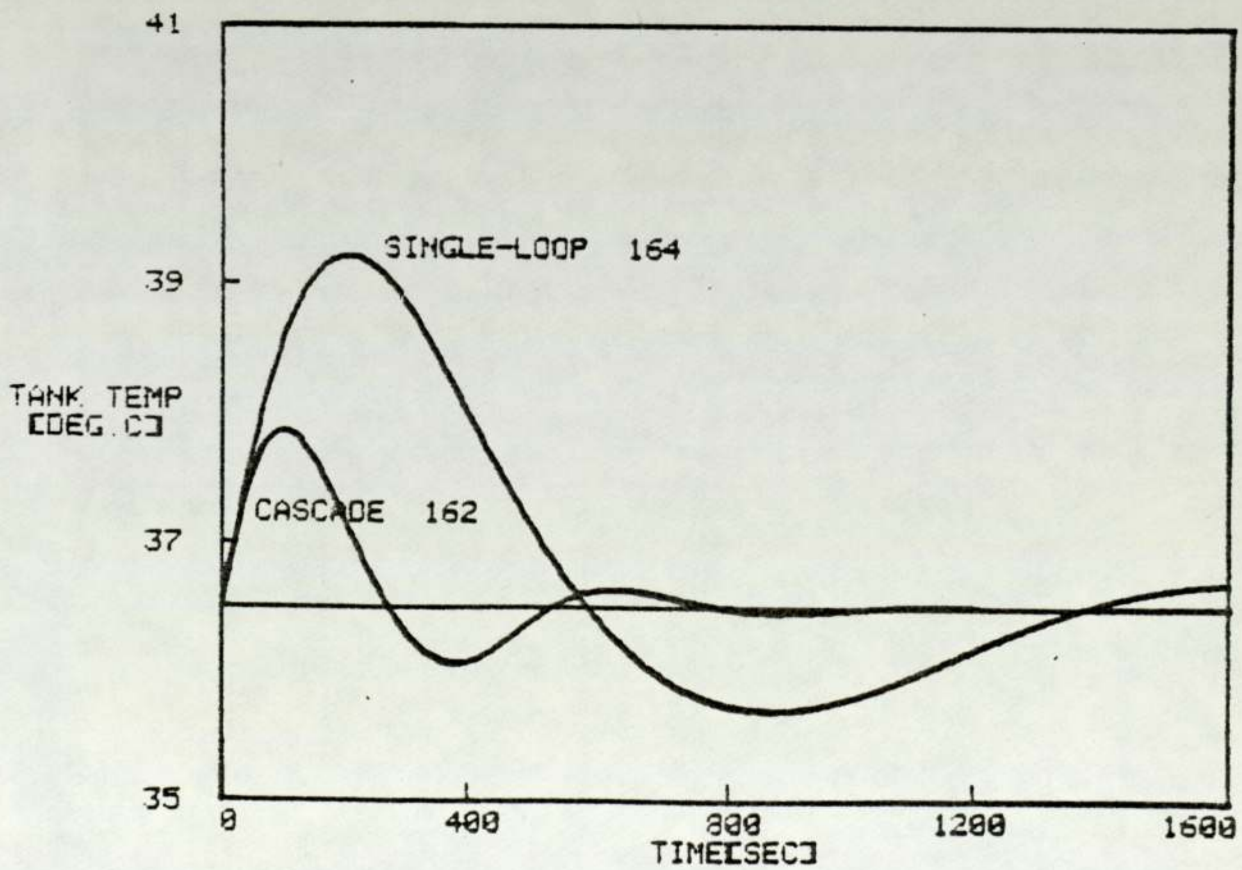
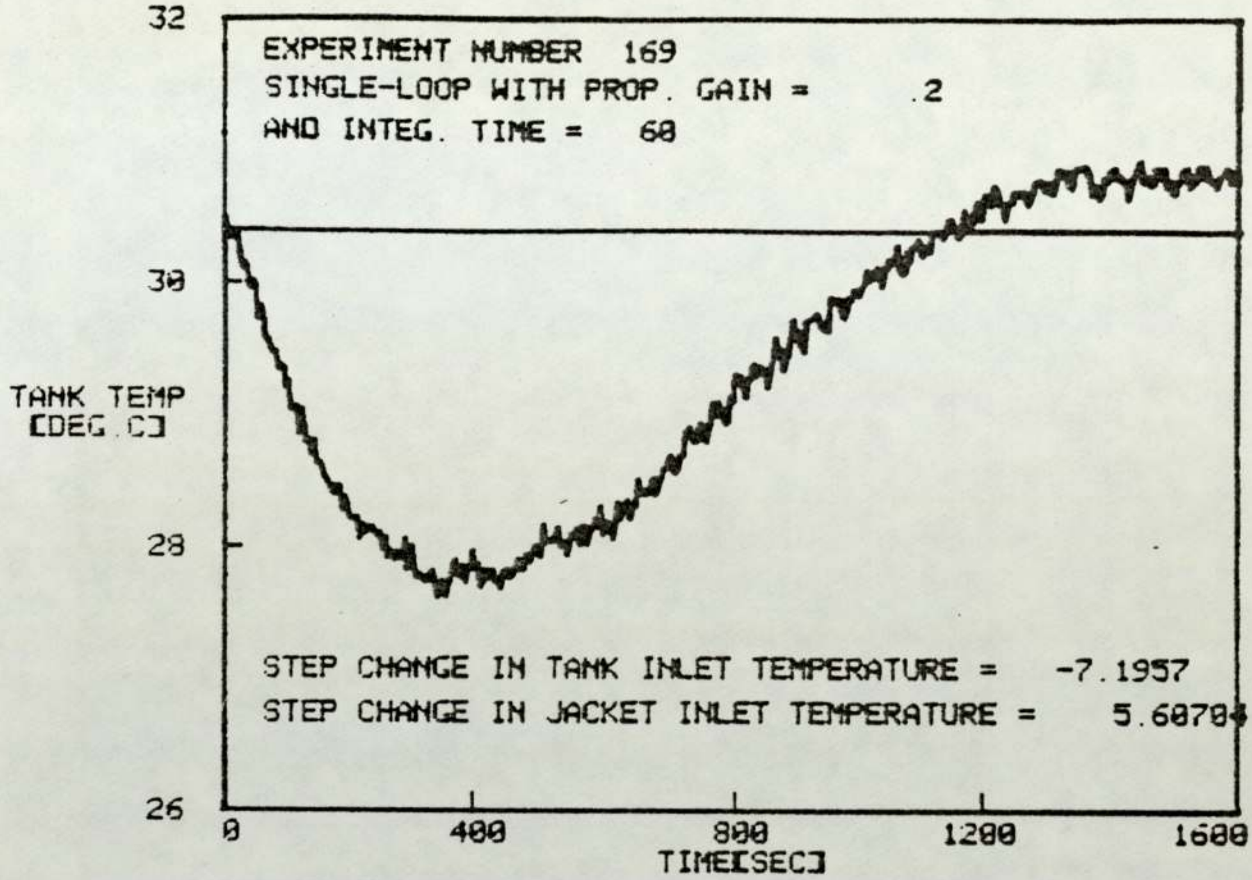
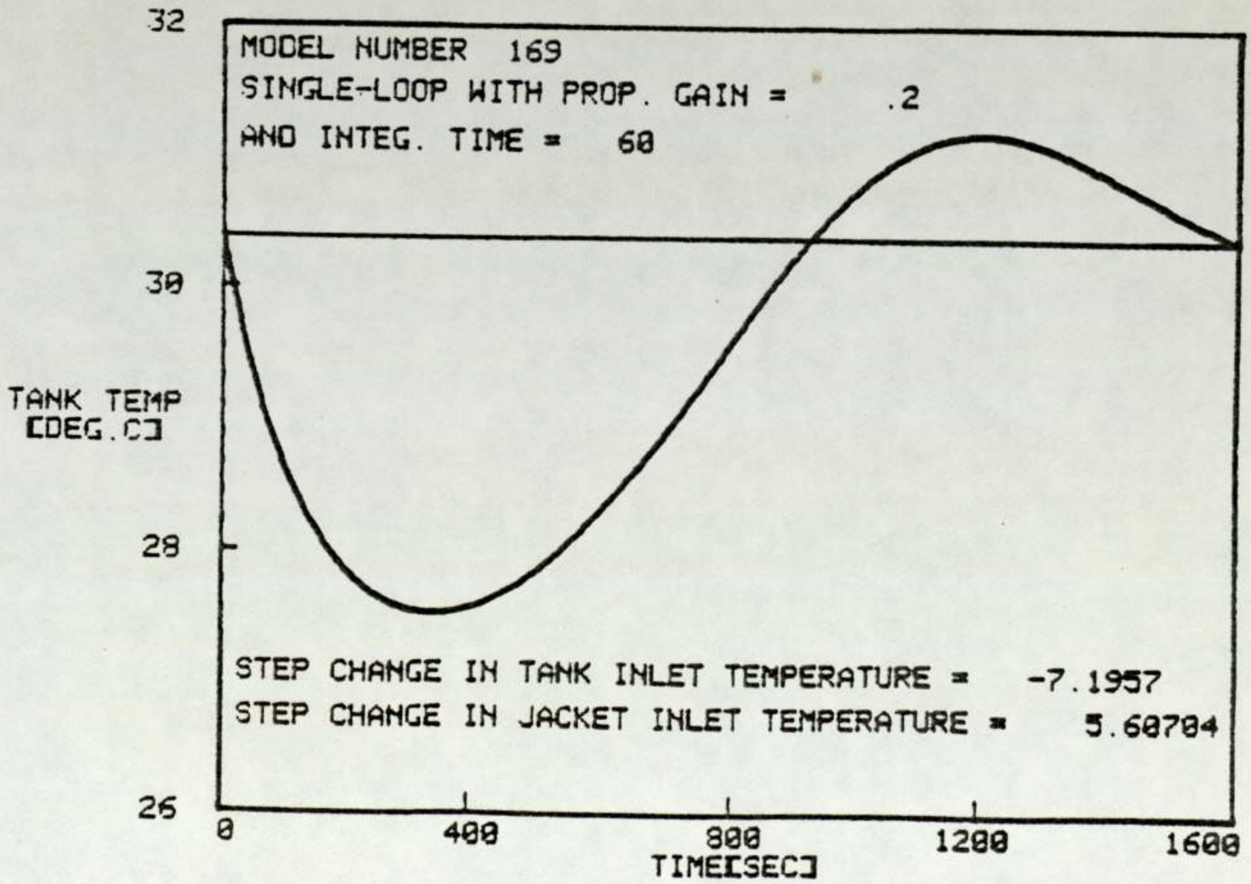

41
39
37
35
TANK TEMP
[DEG.C]
SINGLE-LOOP 164
CASCADE 162
0
400
800
1200
1600
TIME[SEC]

FIG. A.3.101



32
30
28
26
TANK TEMP
[DEG.C]
EXPERIMENT NUMBER 169
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -7.1957
STEP CHANGE IN JACKET INLET TEMPERATURE = 5.60704
0
400
800
1200
1600
TIME[SEC]



32
30
28
26
TANK TEMP
[DEG.C]
MODEL NUMBER 169
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -7.1957
STEP CHANGE IN JACKET INLET TEMPERATURE = 5.60704
0
400
800
1200
1600
TIME[SEC]

FIG. A.3.102

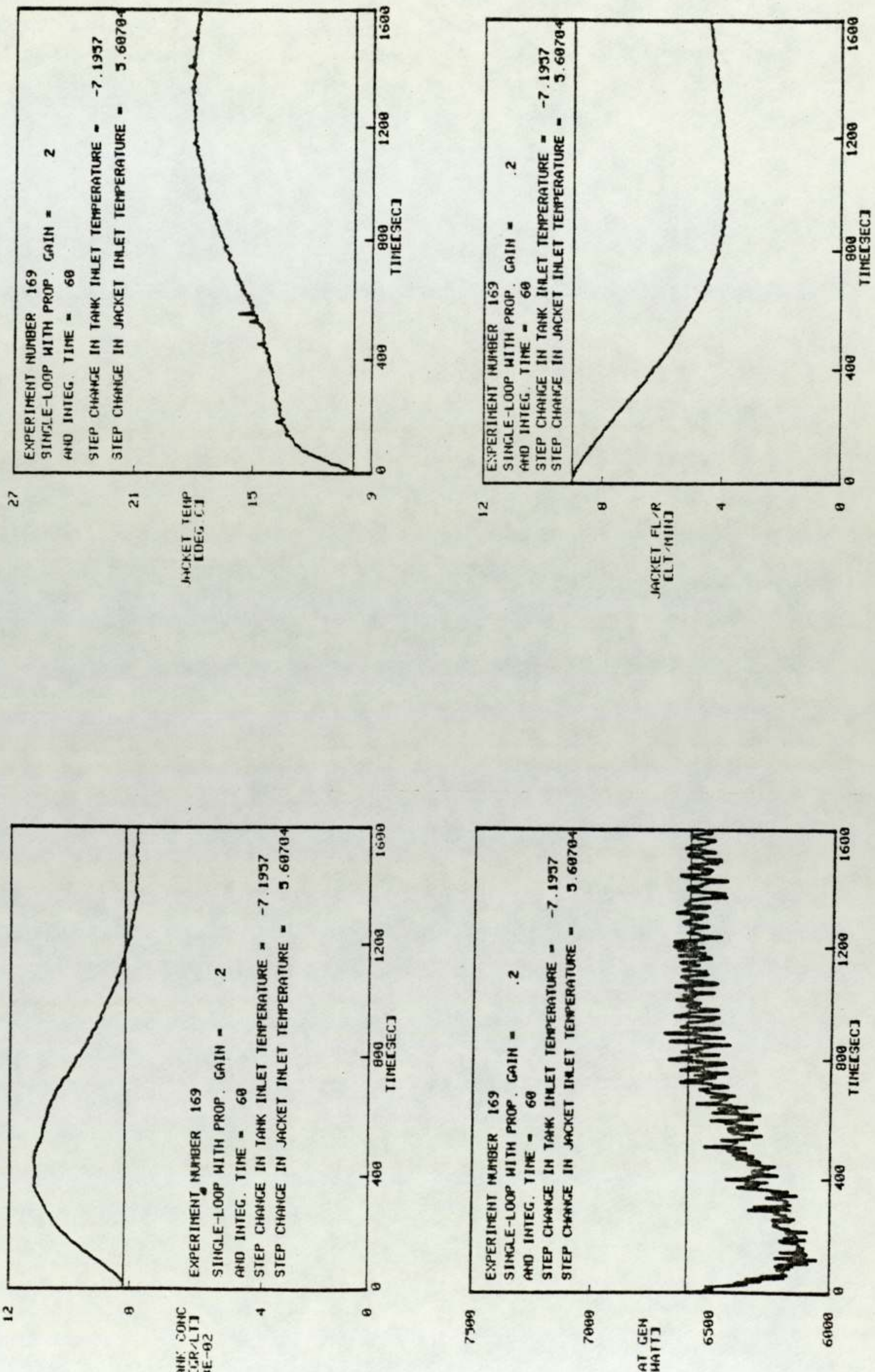

EXPERIMENT NUMBER 169
SINGLE-LOOP WITH PROP. GAIN = 2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -7.1937
STEP CHANGE IN JACKET INLET TEMPERATURE = 5.60704
JACKET TEMP [DEG C]
TANK CONC [GR/LT] *E-02
JACKET FL/R [LT/MIN]
HEAT GEN [WATT]
TIME[SEC]

FIG. A.3.103

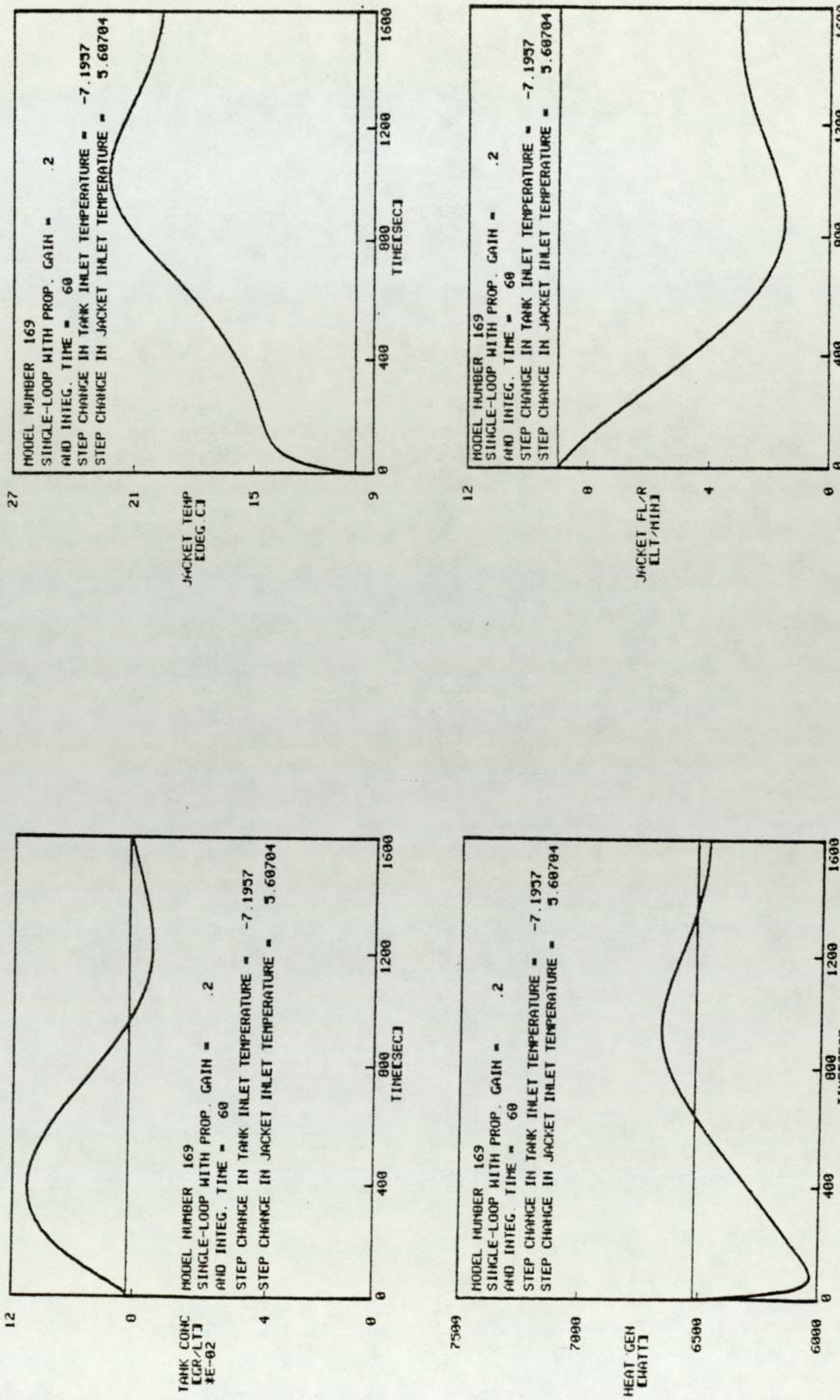
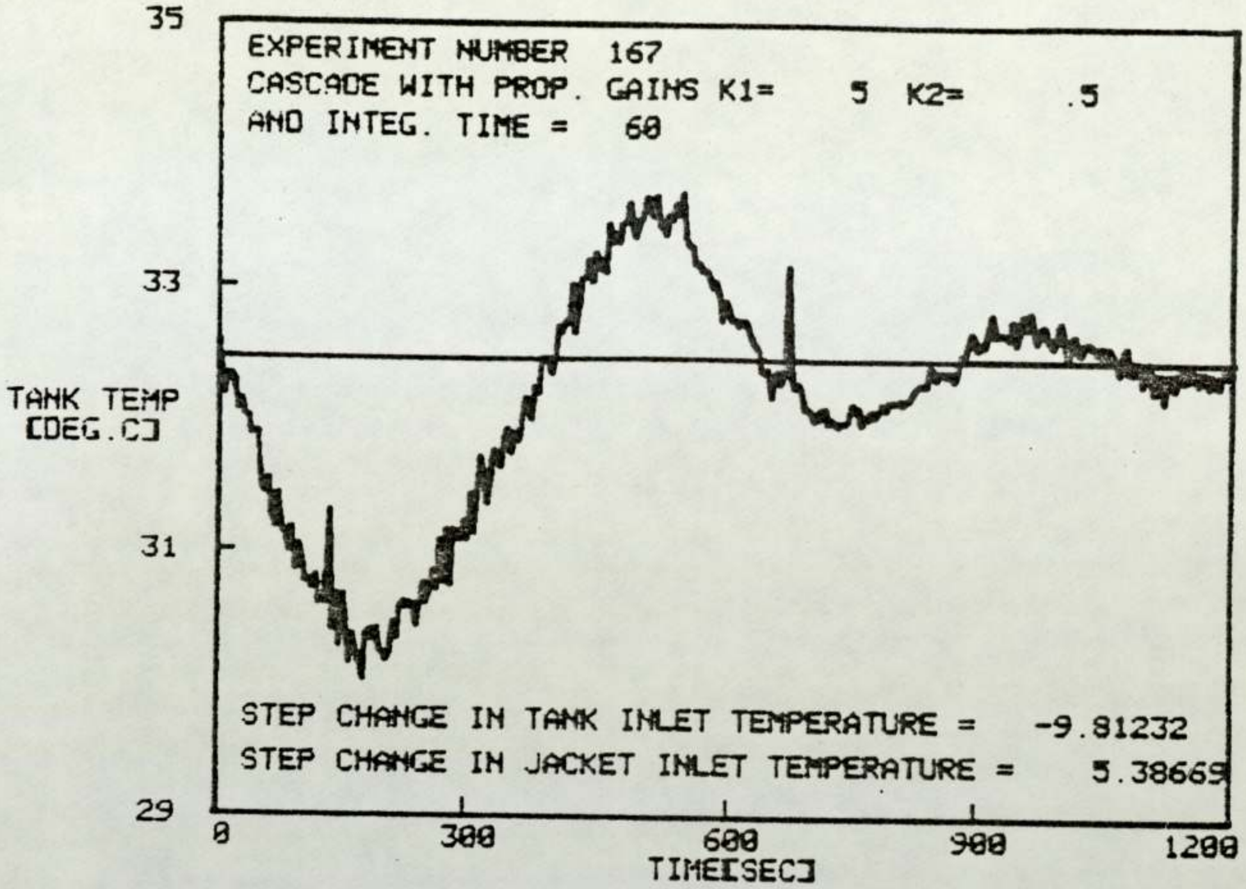

MODEL NUMBER 169
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -7.1957
STEP CHANGE IN JACKET INLET TEMPERATURE = 5.60704
JACKET TEMP [DEG.C]
JACKET FL/R [LT/MIN]
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
TIME[SEC]

FIG. A.3.104


EXPERIMENT NUMBER 167
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -9.81232
STEP CHANGE IN JACKET INLET TEMPERATURE = 5.38669
TANK TEMP [DEG.C]
35
33
31
29
0
300
600
900
1200
TIME[SEC]

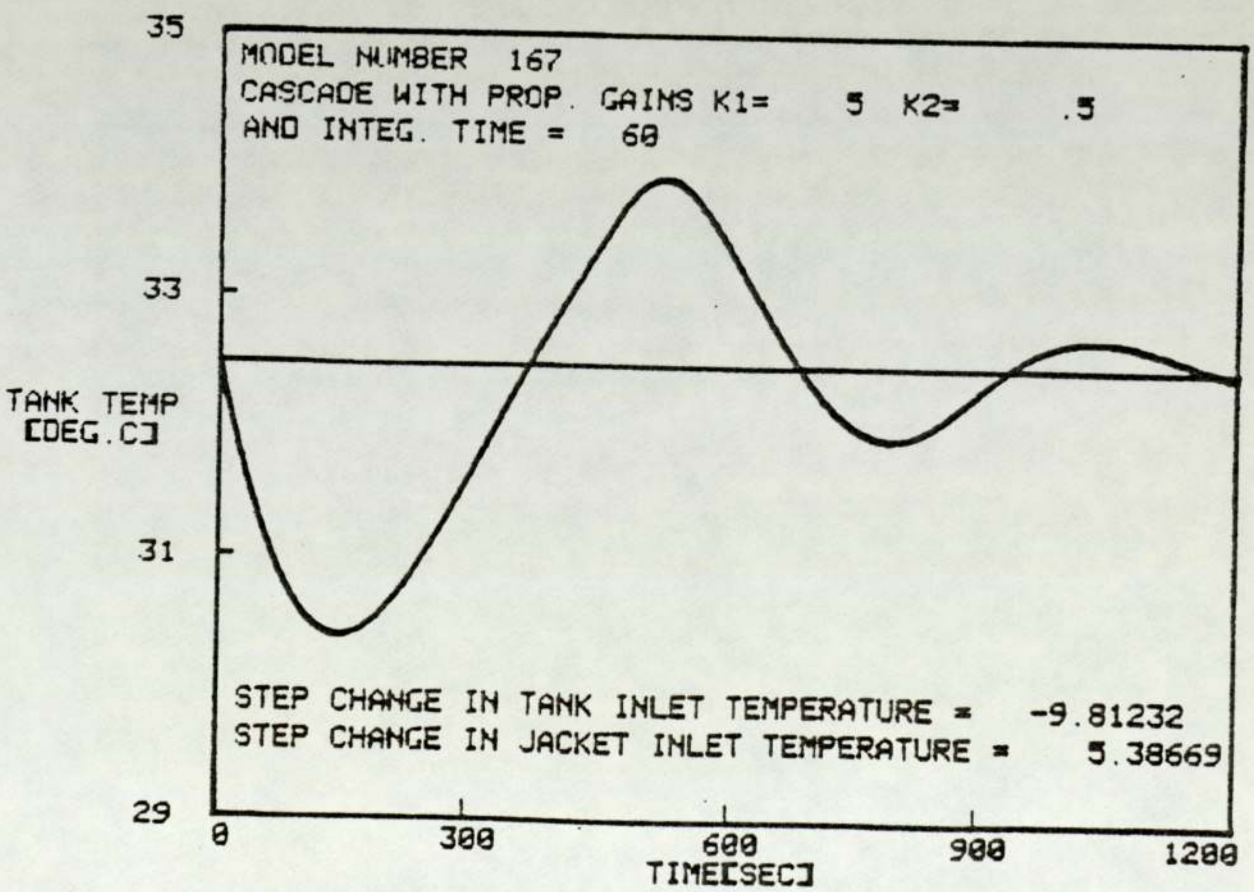

MODEL NUMBER 167
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -9.81232
STEP CHANGE IN JACKET INLET TEMPERATURE = 5.38669
TANK TEMP [DEG.C]
35
33
31
29
0
300
600
900
1200
TIME[SEC]

FIG. A.3.105

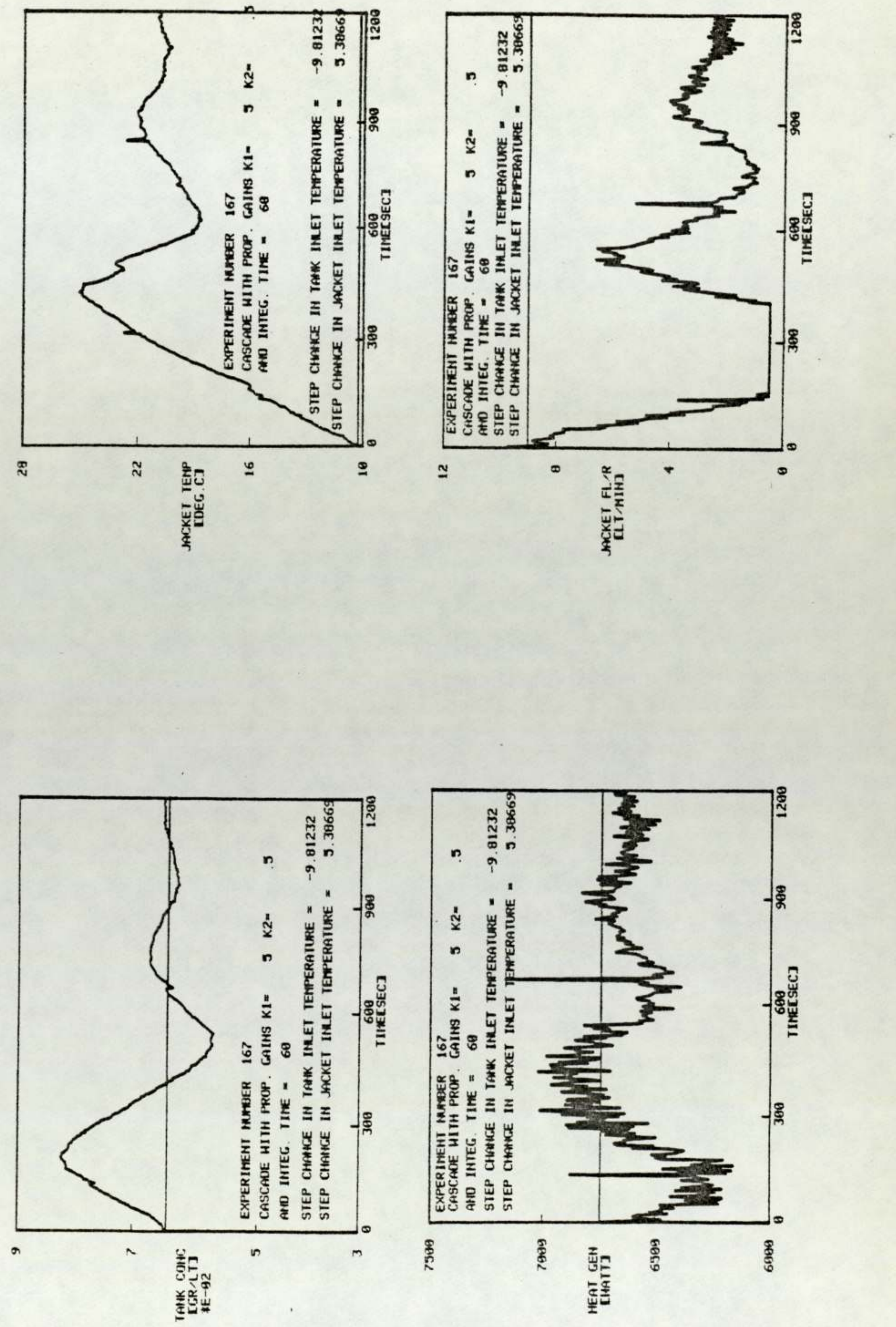

EXPERIMENT NUMBER 167
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -9.81232
STEP CHANGE IN JACKET INLET TEMPERATURE = 5.30669
JACKET TEMP [DEG.C]
JACKET FL/R [LT/MIN]
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
TIME[SEC]

FIG. A.3.106

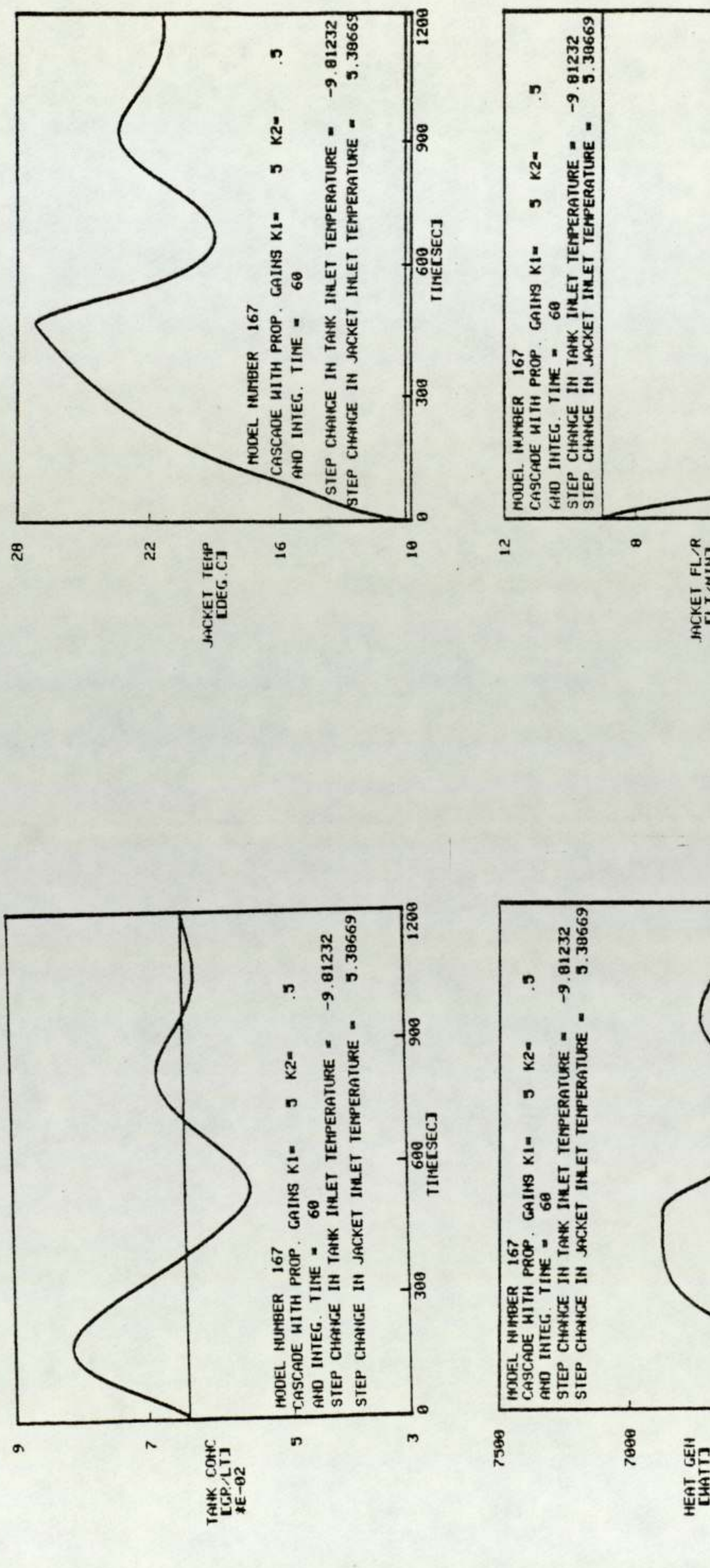
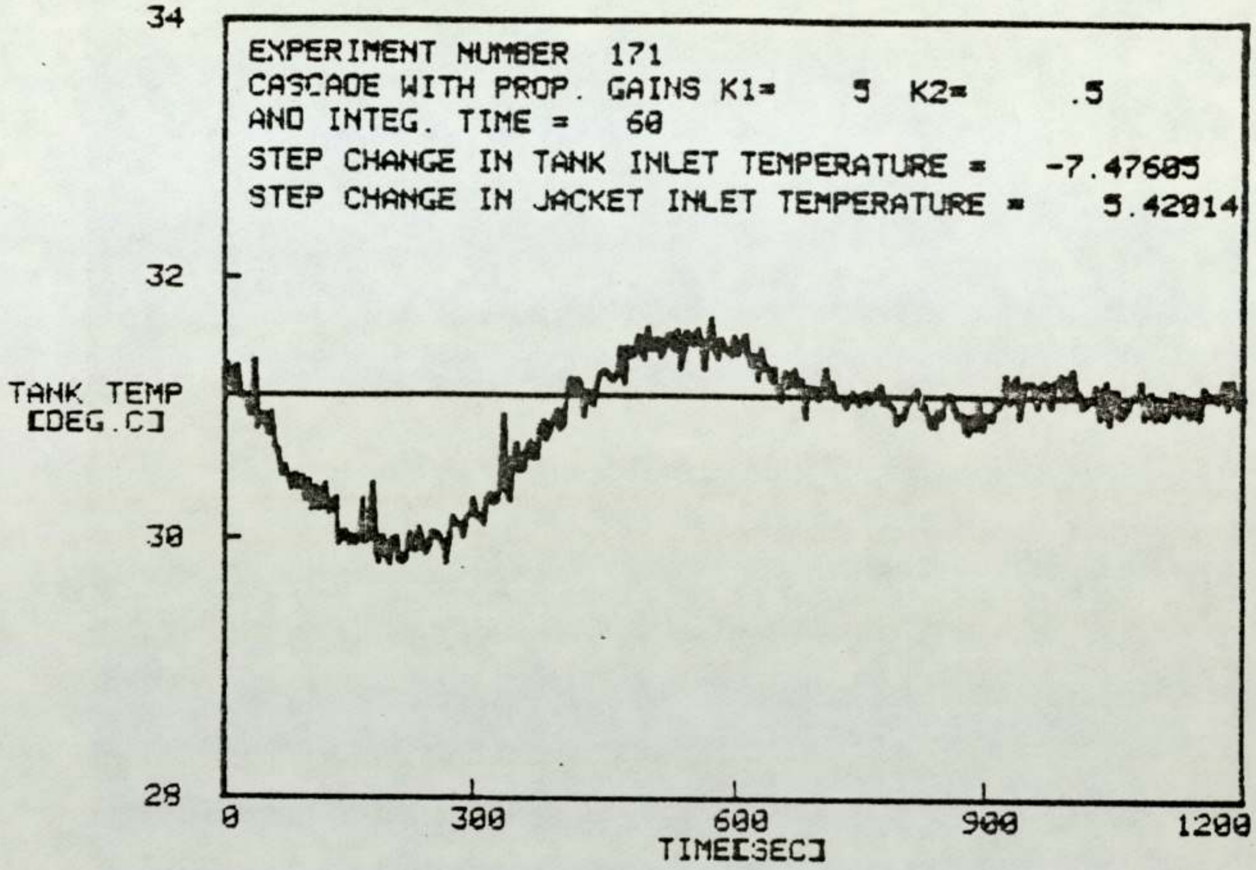

MODEL NUMBER 167
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -9.81232
STEP CHANGE IN JACKET INLET TEMPERATURE = 5.38669
TANK CONC [GR/LT] *E-02
JACKET TEMP [DEG.C]
HEAT GEN [WATT]
JACKET FL/R [LT/MIN]
TIME[SEC]

FIG. A.3.107


EXPERIMENT NUMBER 171
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -7.47605
STEP CHANGE IN JACKET INLET TEMPERATURE = 5.42014
34
32
30
28
TANK TEMP [DEG.C]
0
300
600
900
1200
TIME[SEC]

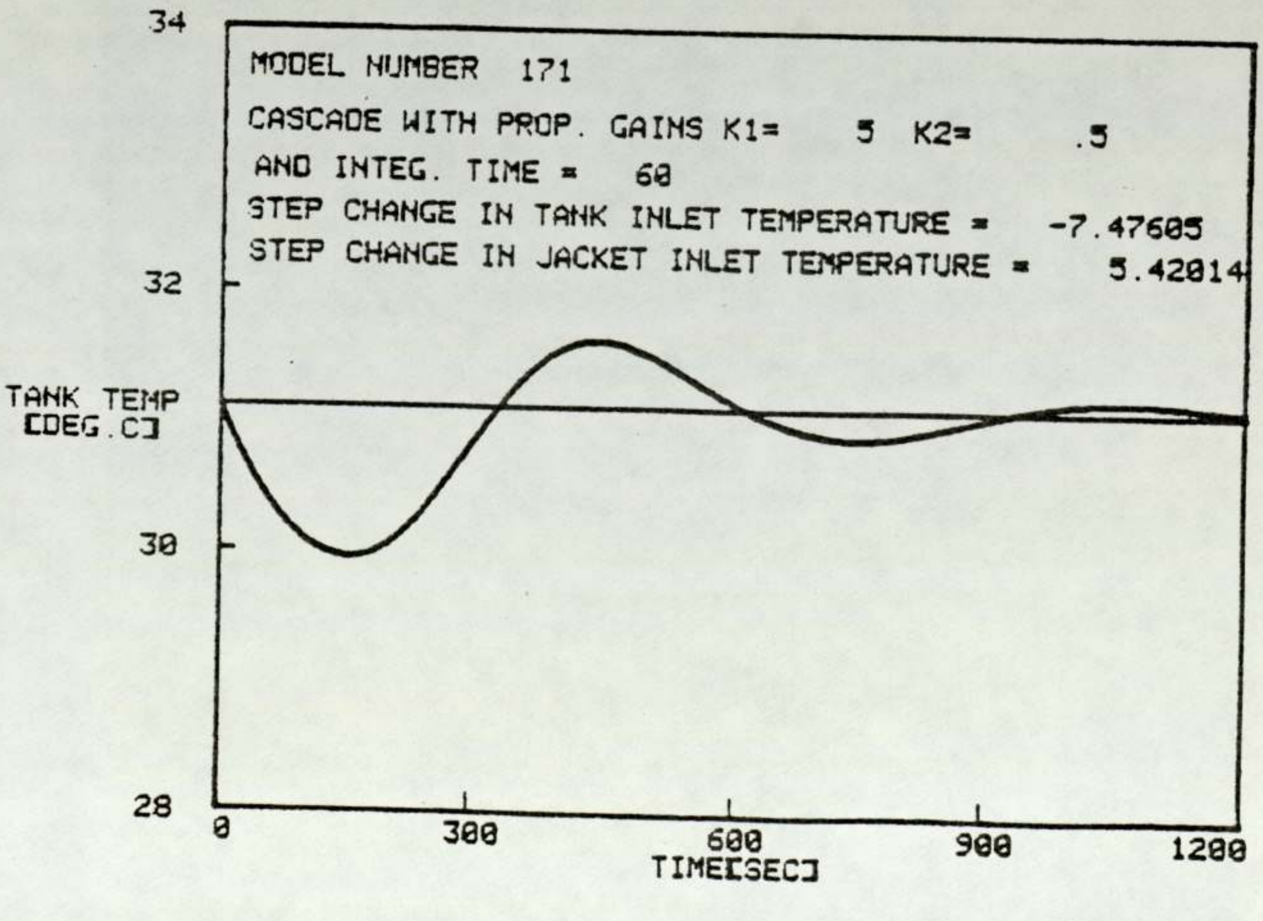
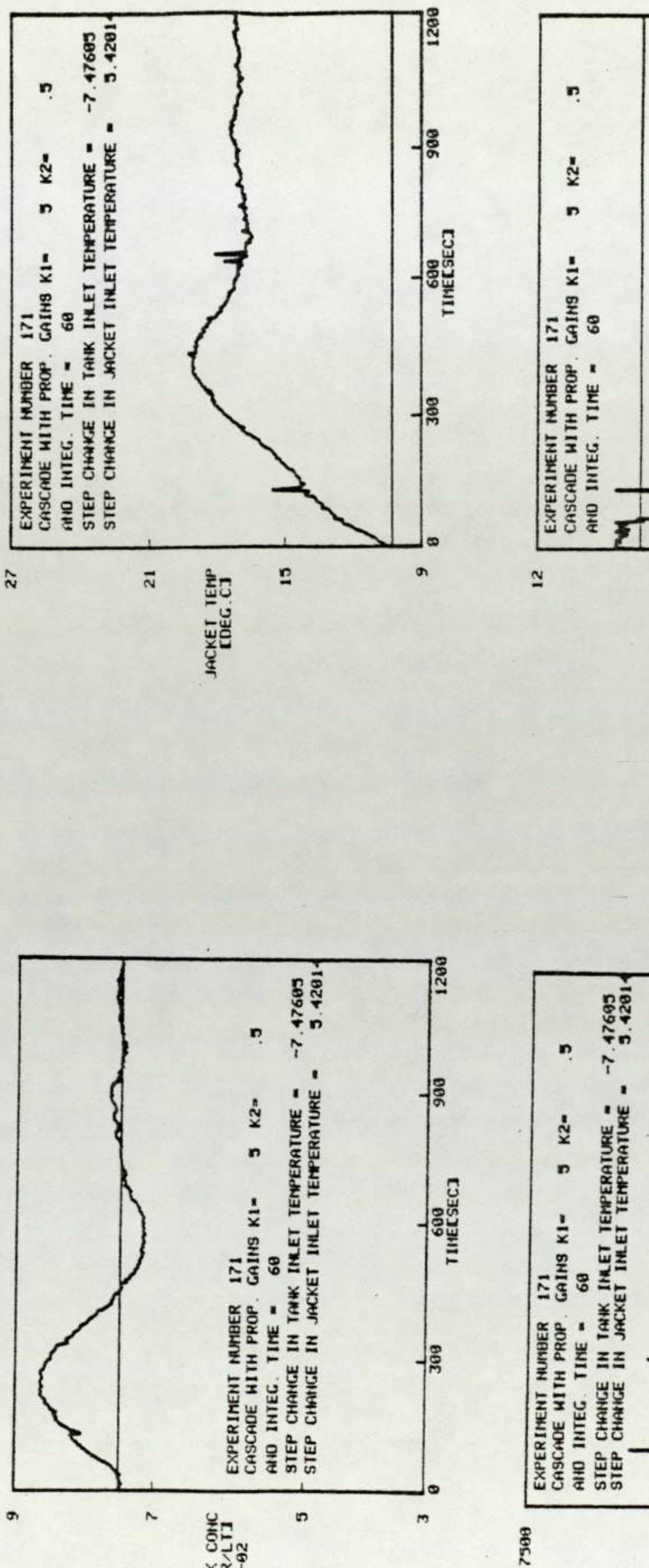

MODEL NUMBER 171
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -7.47605
STEP CHANGE IN JACKET INLET TEMPERATURE = 5.42014
34
32
30
28
TANK TEMP [DEG.C]
0
300
600
900
1200
TIME[SEC]

FIG. A.3.108



EXPERIMENT NUMBER 171
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -7.47605
STEP CHANGE IN JACKET INLET TEMPERATURE = 5.4201
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
JACKET TEMP [DEG.C]
JACKET FL/R [LT/MIN]
TIME[SEC]

FIG. A.3.109

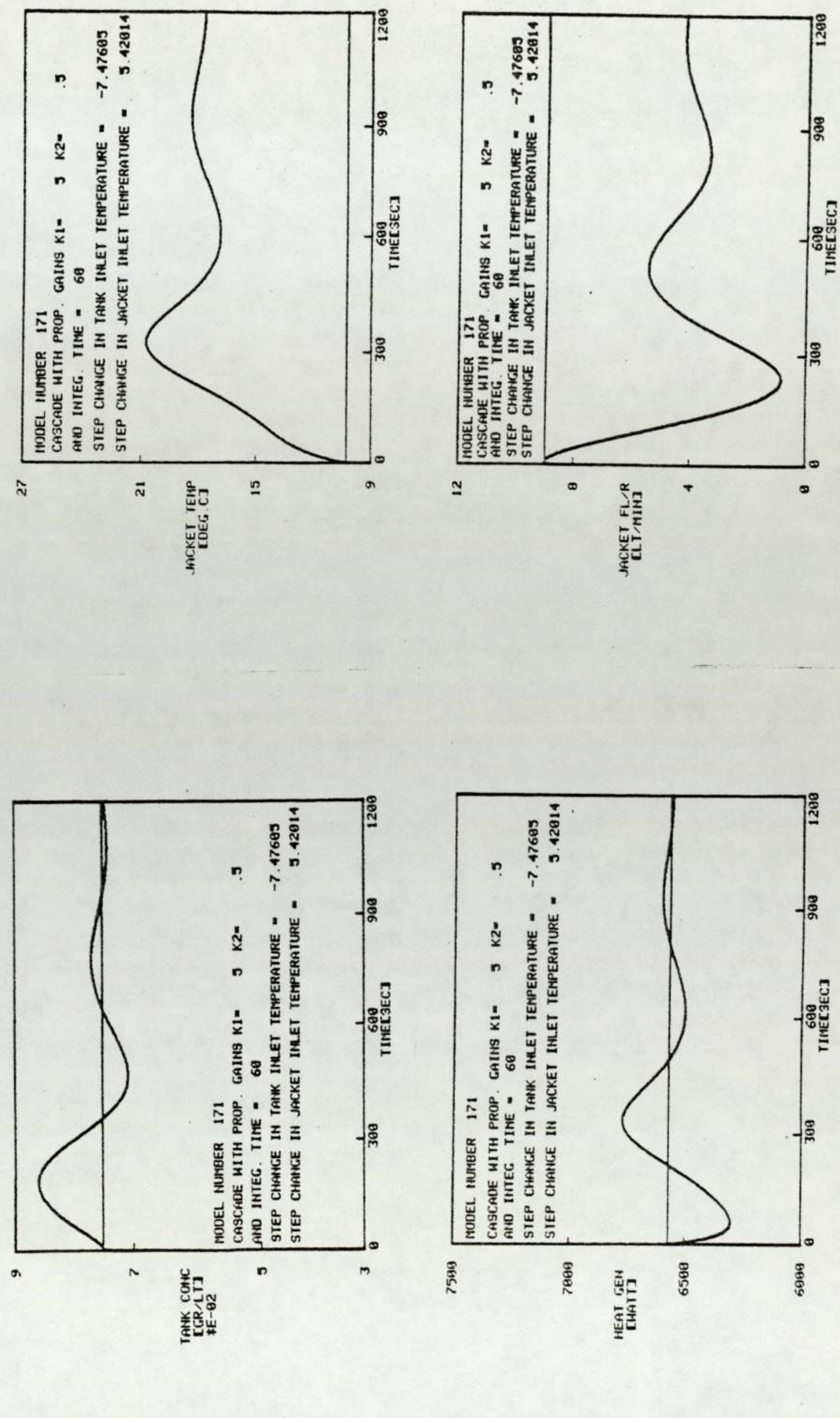
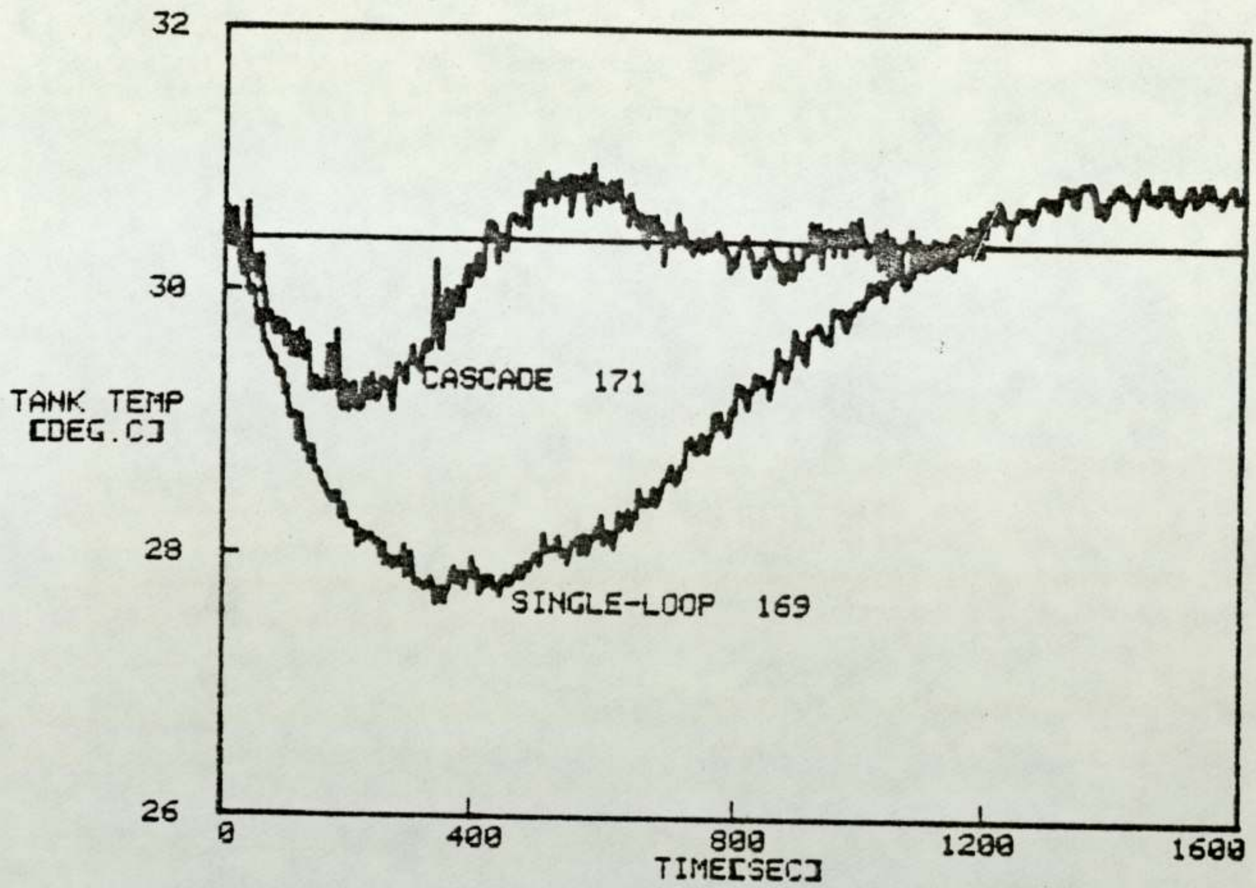

MODEL NUMBER 171
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = -7.47605
STEP CHANGE IN JACKET INLET TEMPERATURE = 5.42014
JACKET TEMP [DEG.C]
JACKET FL/R [LT/MIN]
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
TIME[SEC]
0
300
600
900
1200

FIG. A.3.110


32
30
28
26
TANK TEMP
[DEG.C]
CASCADE 171
SINGLE-LOOP 169
0
400
800
1200
1600
TIME[SEC]

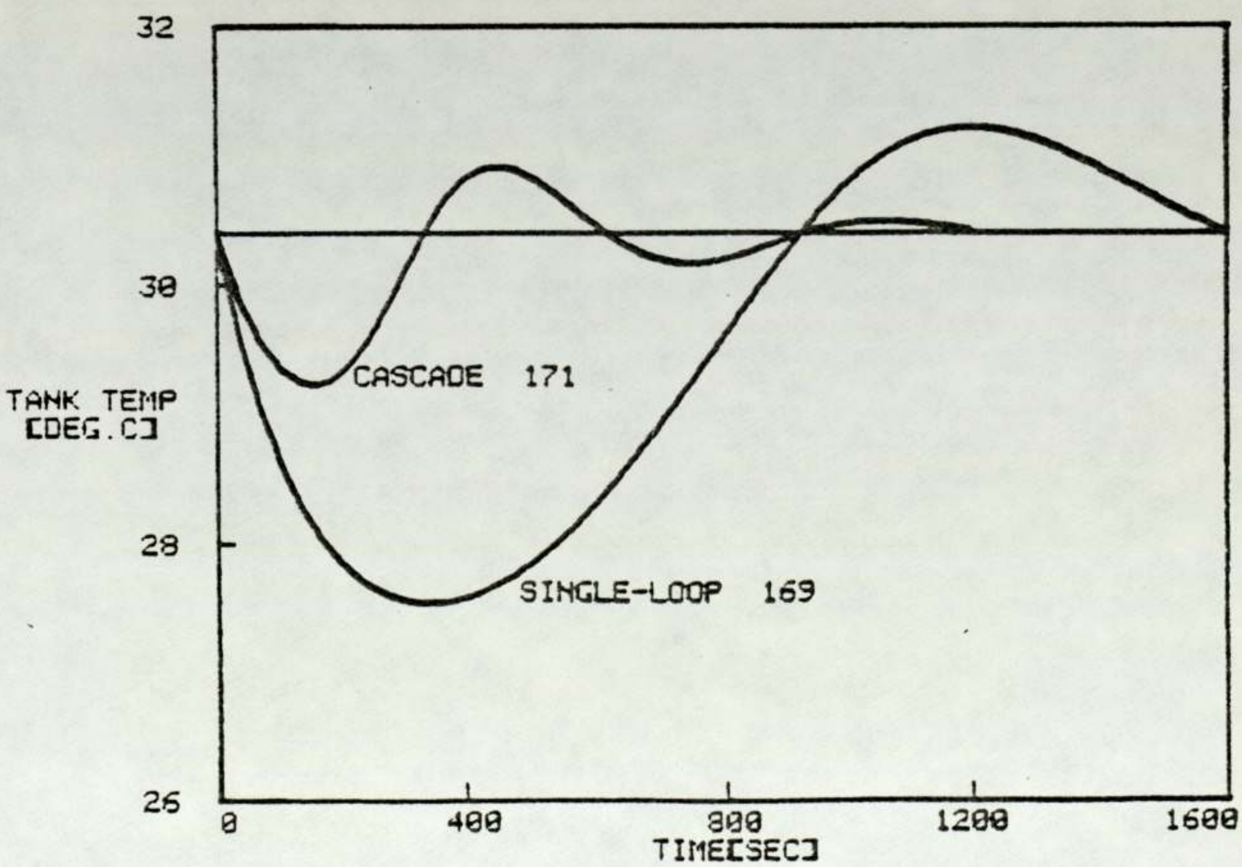
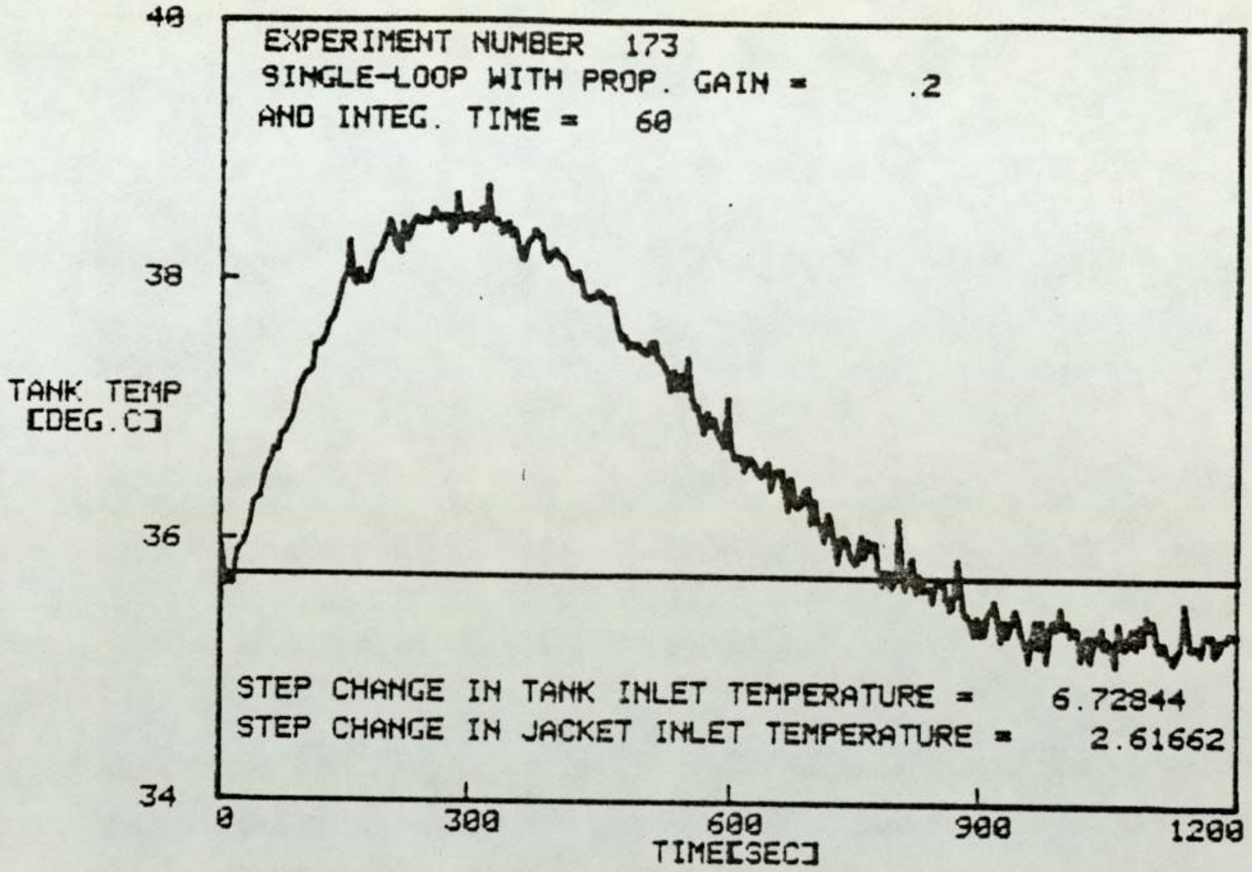
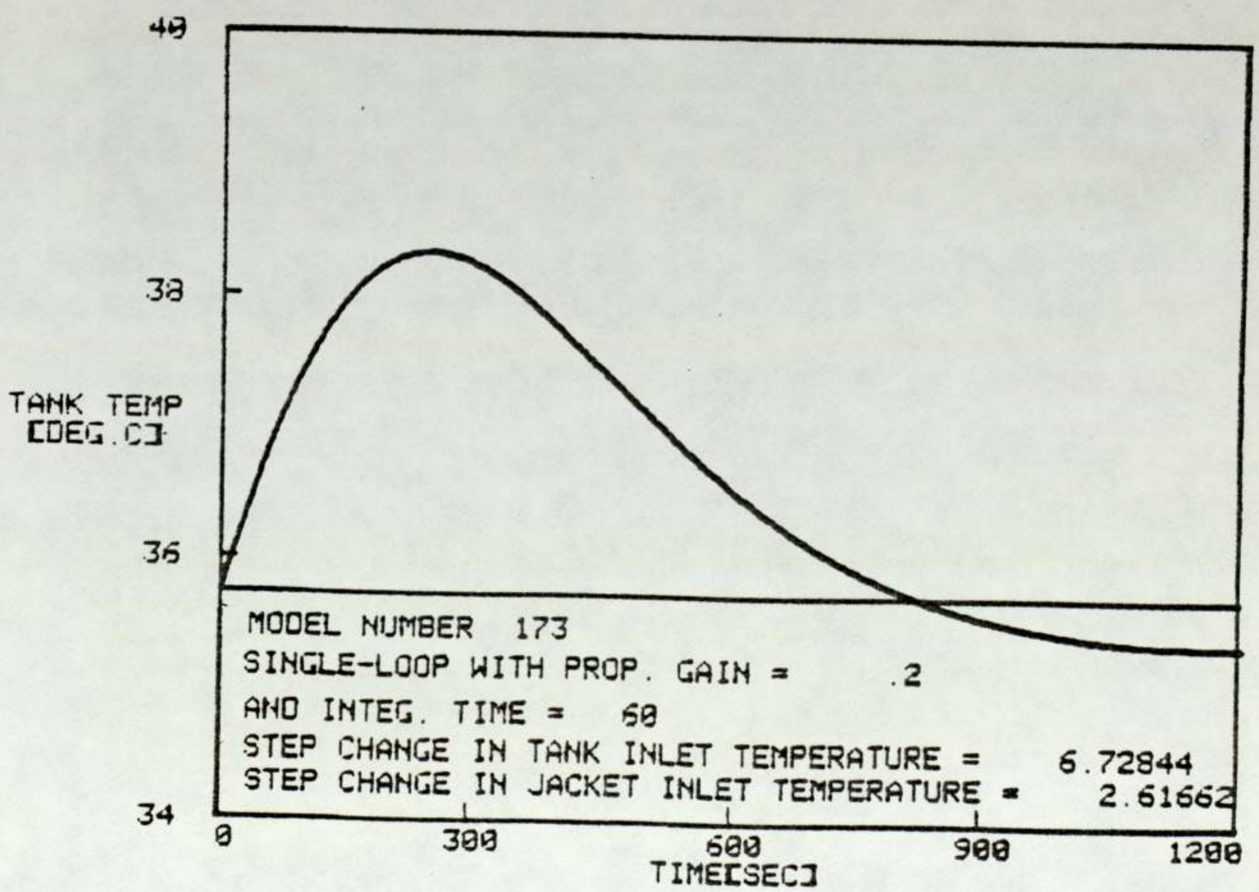

32
30
28
26
TANK TEMP
[DEG.C]
CASCADE 171
SINGLE-LOOP 169
0
400
800
1200
1600
TIME[SEC]

FIG. A.3.111

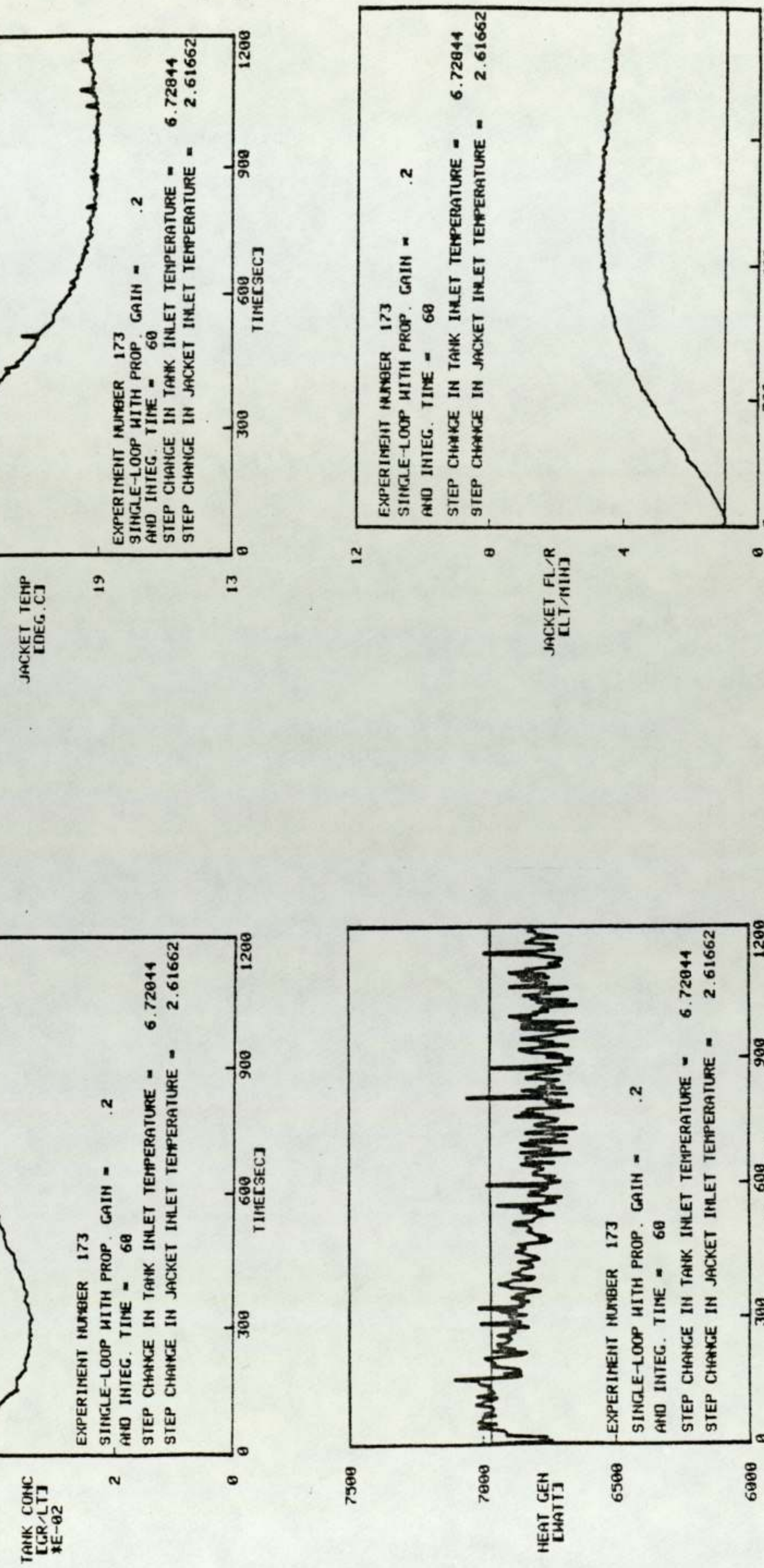


EXPERIMENT NUMBER 173
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 6.72844
STEP CHANGE IN JACKET INLET TEMPERATURE = 2.61662
TANK TEMP [DEG.C]
TIME[SEC]
40
38
36
34
0
300
600
900
1200



MODEL NUMBER 173
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 6.72844
STEP CHANGE IN JACKET INLET TEMPERATURE = 2.61662
TANK TEMP [DEG.C]
TIME[SEC]
40
38
36
34
0
300
600
900
1200

FIG. A.3.112



JACKET TEMP [DEG.C]
31
25
19
13
0
300
600
900
1200
TIME[SEC]
EXPERIMENT NUMBER 173
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 6.72044
STEP CHANGE IN JACKET INLET TEMPERATURE = 2.61662
JACKET FL/R [LT/MIN]
12
8
4
0
TANK CONC [GR/LT] *E-02
6
4
2
0
HEAT GEN [WATT]
7500
7000
6500
6000

FIG. A.3.113

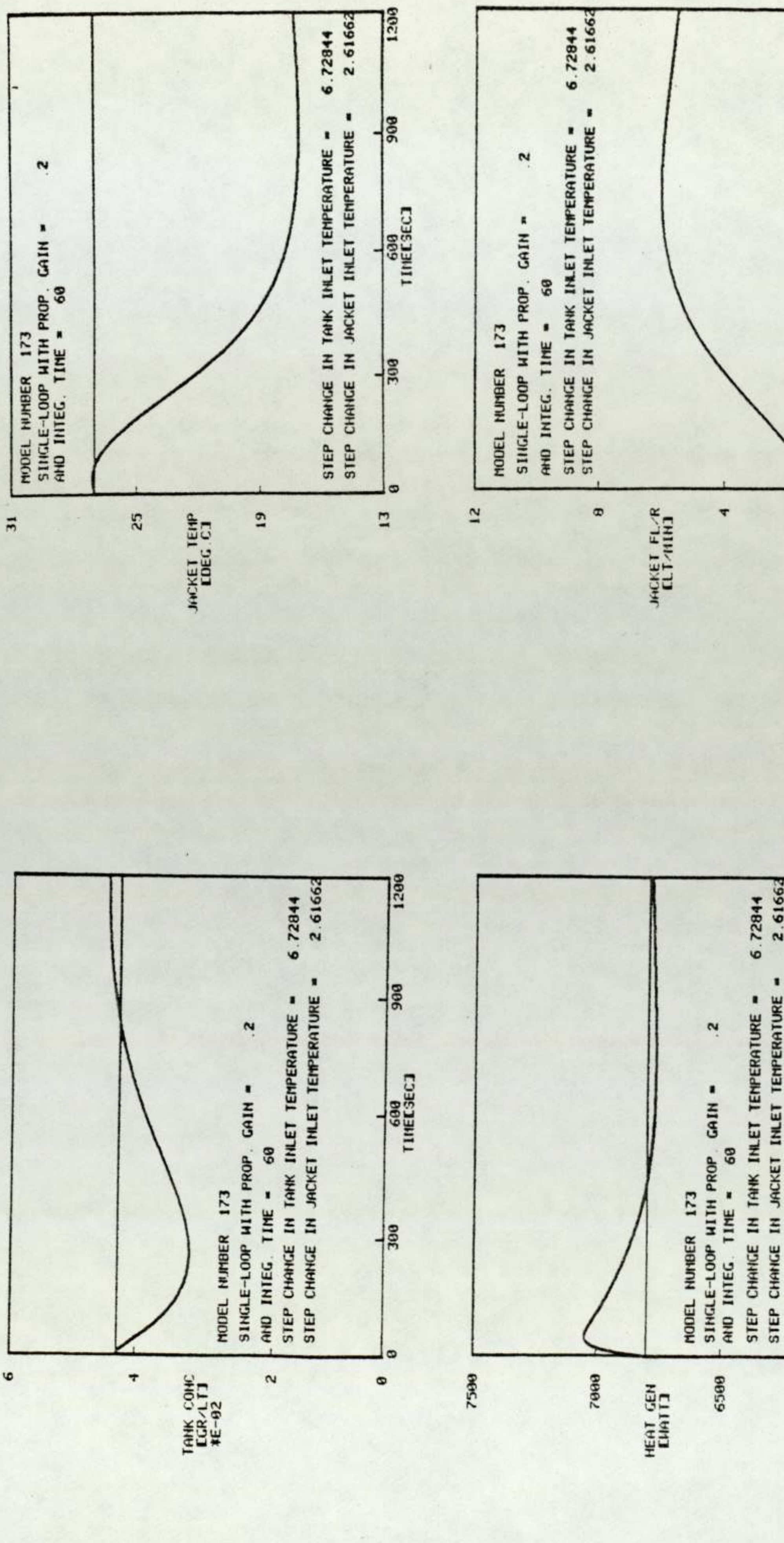
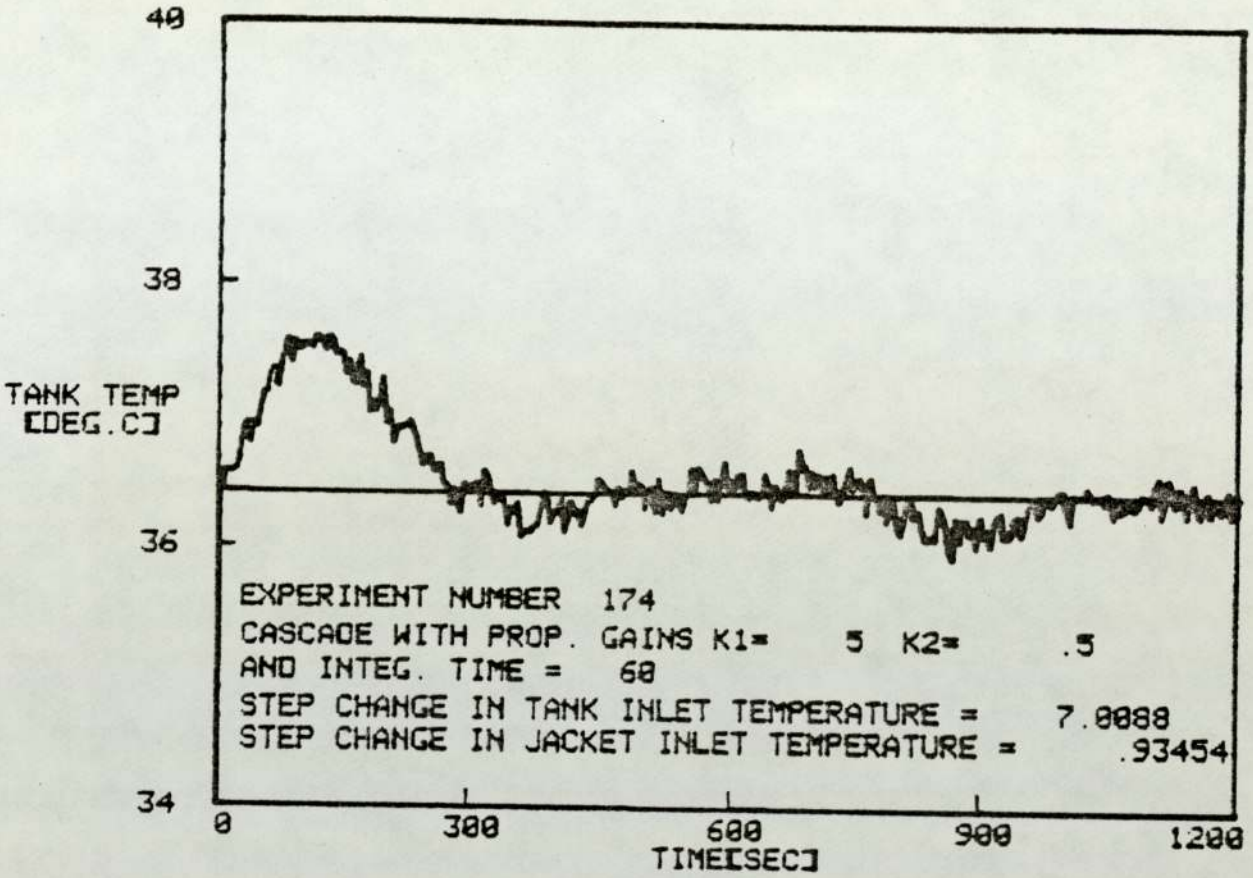

MODEL NUMBER 173
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 6.72844
STEP CHANGE IN JACKET INLET TEMPERATURE = 2.61662
JACKET TEMP [DEG.C]
JACKET FL/R [LT/MIN]
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
TIME[SEC]
0
300
600
900
1200
31
25
19
13
12
8
4
6
2
7500
7000
6500
6000

FIG. A.3.114


40
38
36
34
TANK TEMP
[DEG.C]
EXPERIMENT NUMBER 174
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 7.0088
STEP CHANGE IN JACKET INLET TEMPERATURE = .93454
0
300
600
900
1200
TIME[SEC]

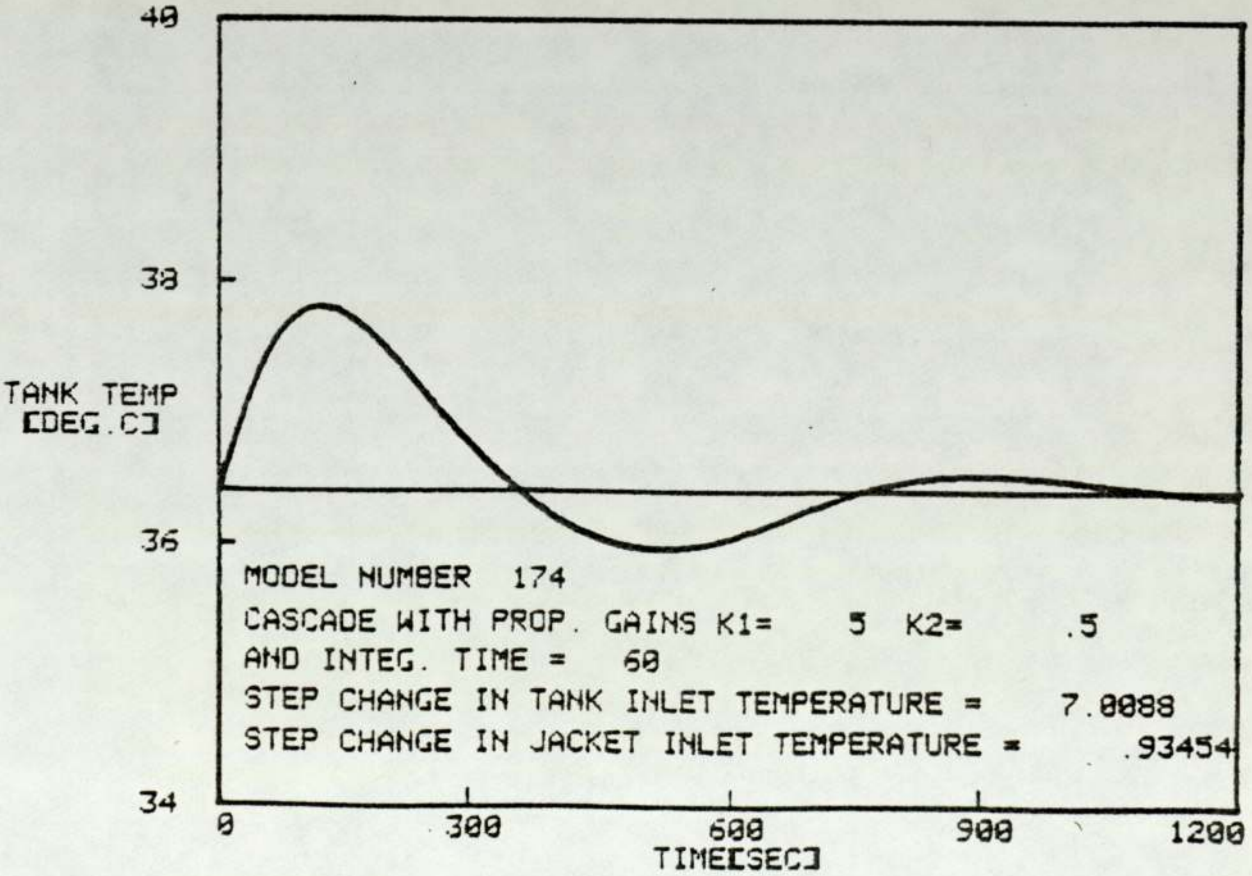

40
38
36
34
TANK TEMP
[DEG.C]
MODEL NUMBER 174
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 7.0088
STEP CHANGE IN JACKET INLET TEMPERATURE = .93454
0
300
600
900
1200
TIME[SEC]

FIG. A.3.115

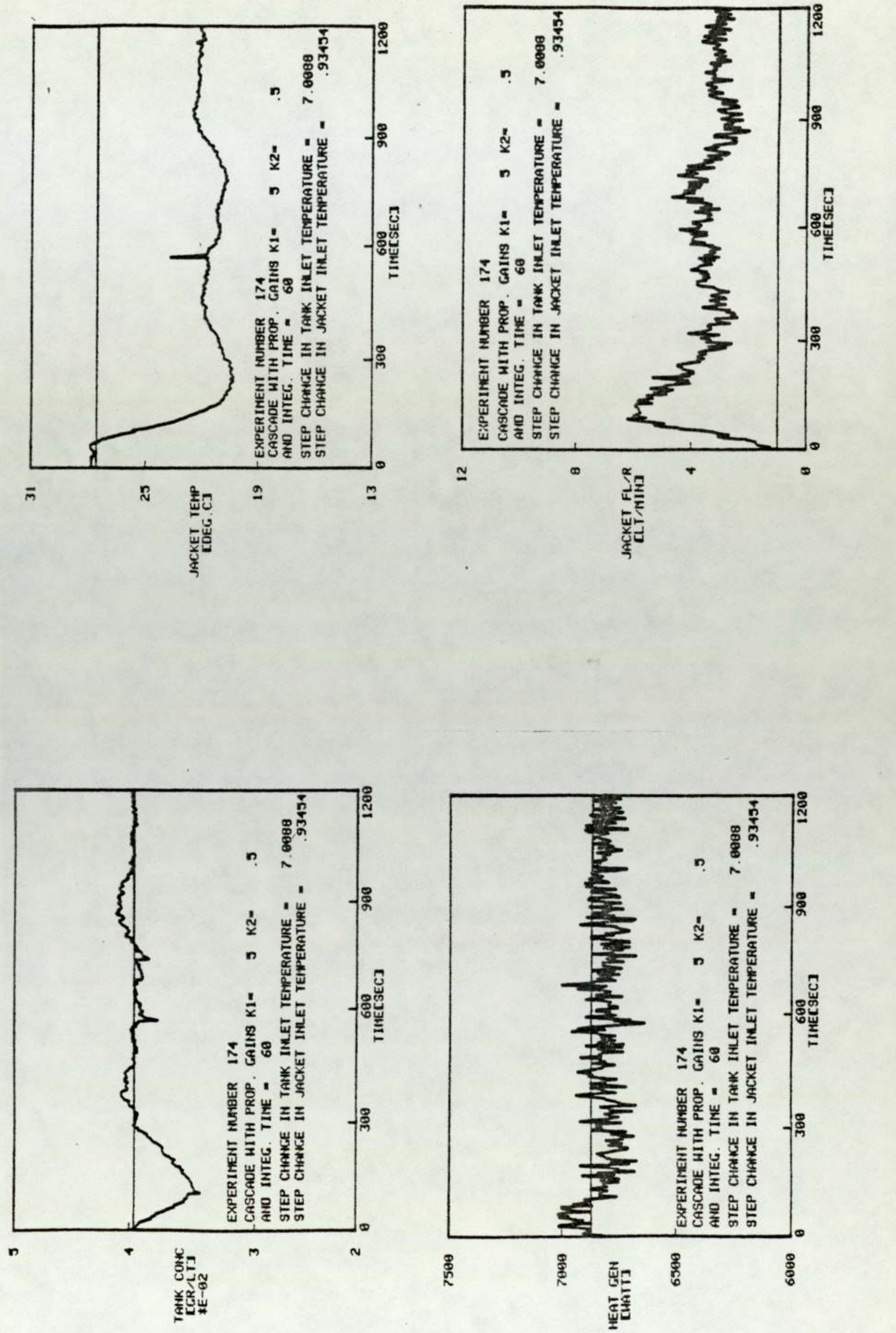
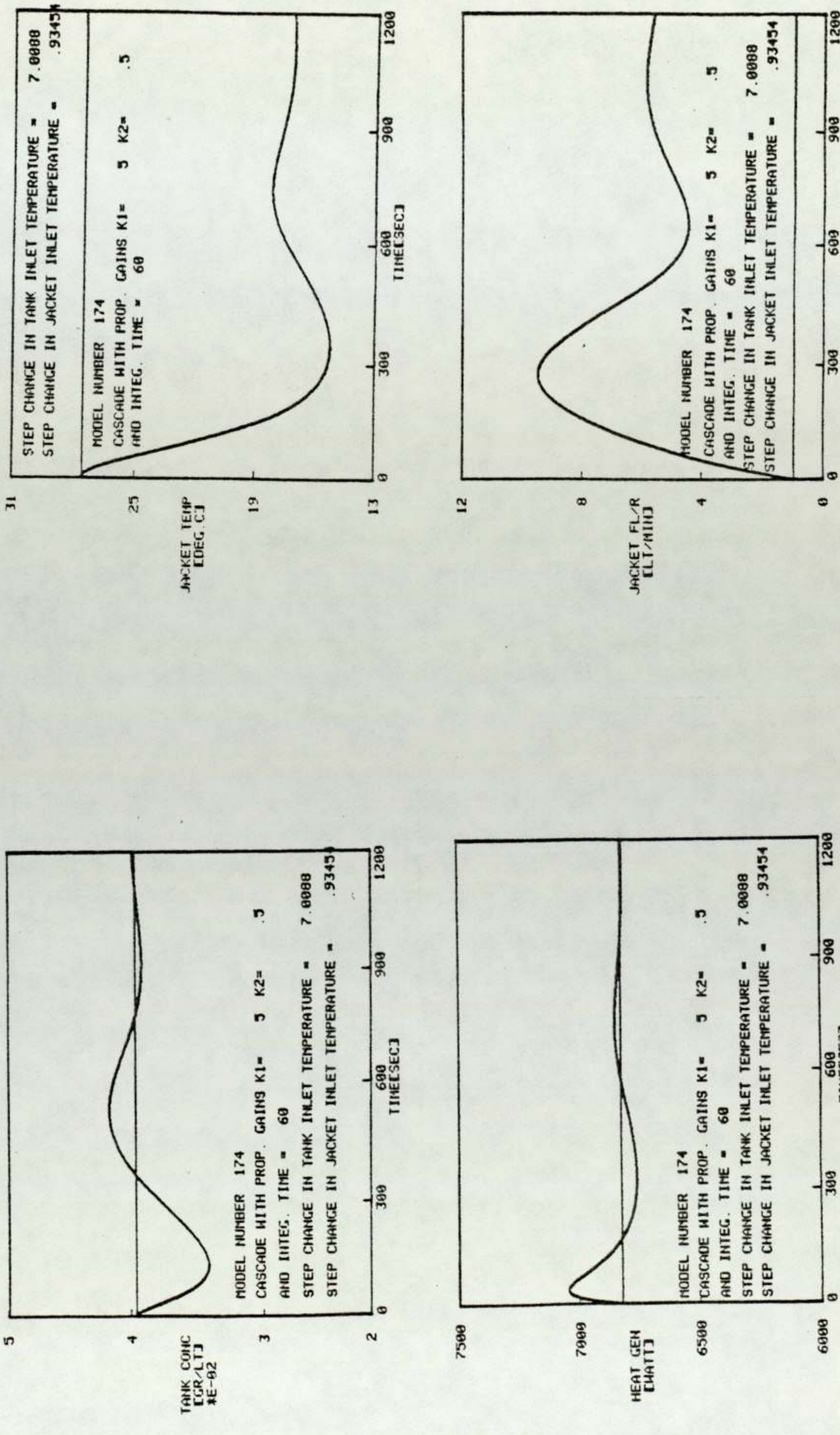
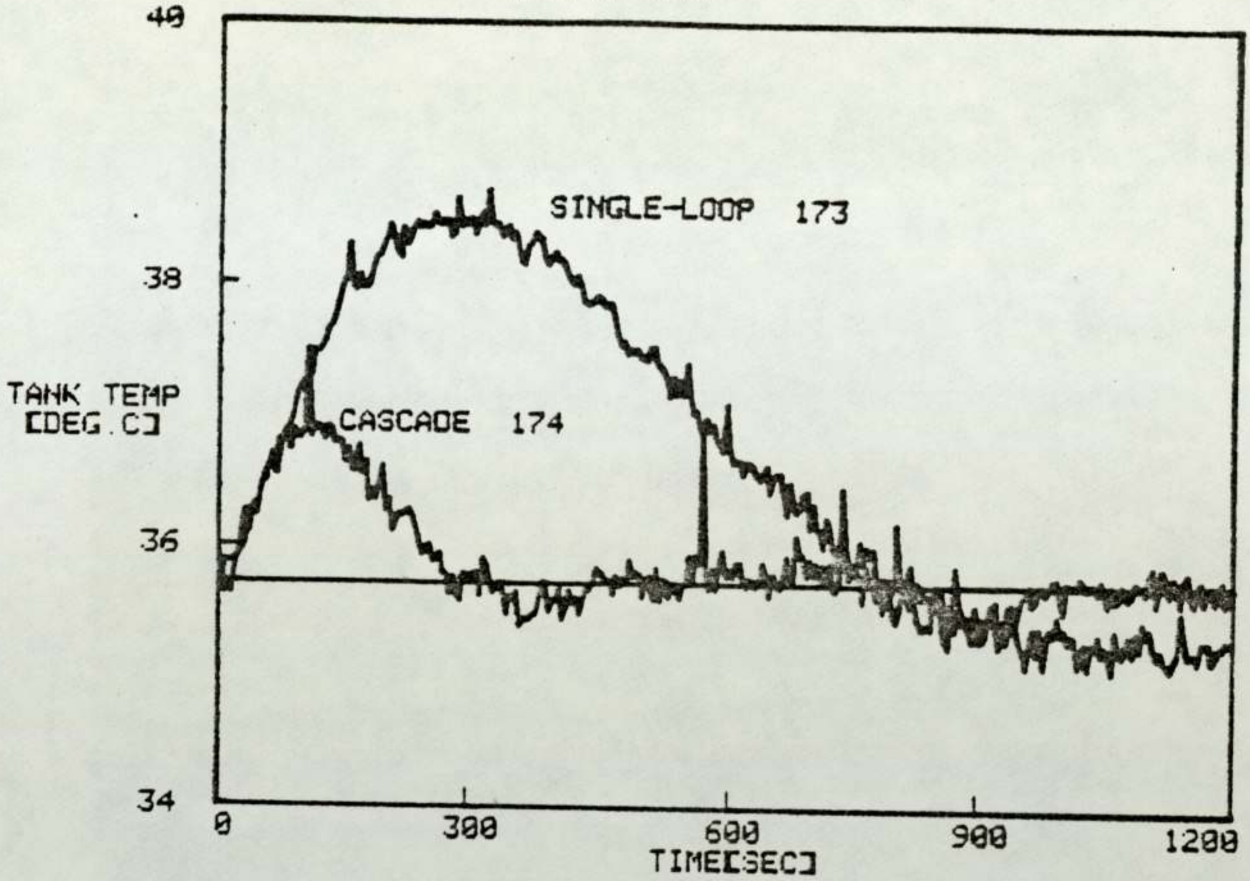

JACKET TEMP [DEG.C]
TIME[SEC]
EXPERIMENT NUMBER 174
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 7.0000
STEP CHANGE IN JACKET INLET TEMPERATURE = .93454
JACKET FL/R [LT/MIN]
TIME[SEC]
EXPERIMENT NUMBER 174
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 7.0000
STEP CHANGE IN JACKET INLET TEMPERATURE = .93454
TANK CONC [GR/LT] *E-02
TIME[SEC]
EXPERIMENT NUMBER 174
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 7.0000
STEP CHANGE IN JACKET INLET TEMPERATURE = .93454
HEAT GEN [WATT]
TIME[SEC]
EXPERIMENT NUMBER 174
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 7.0000
STEP CHANGE IN JACKET INLET TEMPERATURE = .93454

FIG. A.3.116

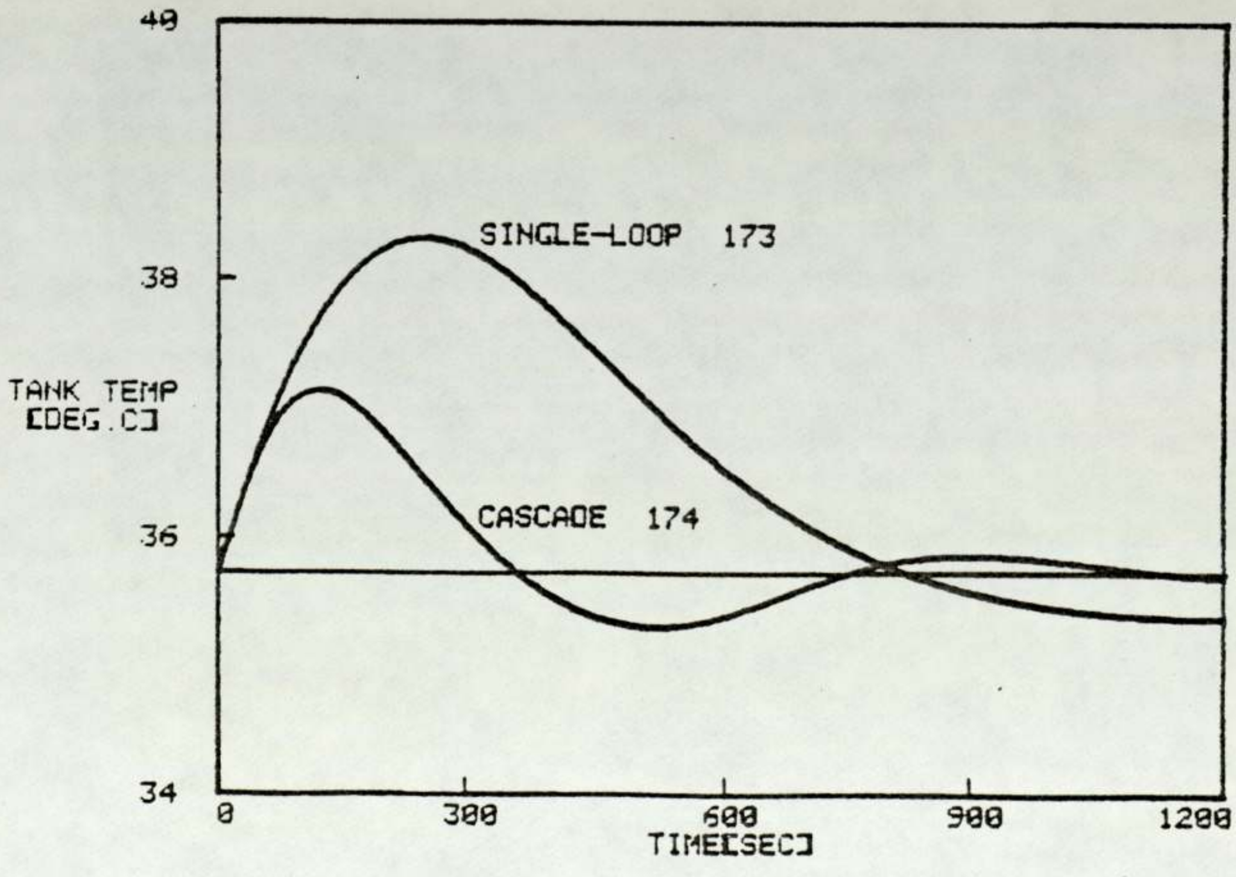


STEP CHANGE IN TANK INLET TEMPERATURE = 7.0000
STEP CHANGE IN JACKET INLET TEMPERATURE = .93454
MODEL NUMBER 174
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
JACKET TEMP [DEG.C]
TIME[SEC]
JACKET FL/R [LT/MIN]
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]

FIG. A.3.117

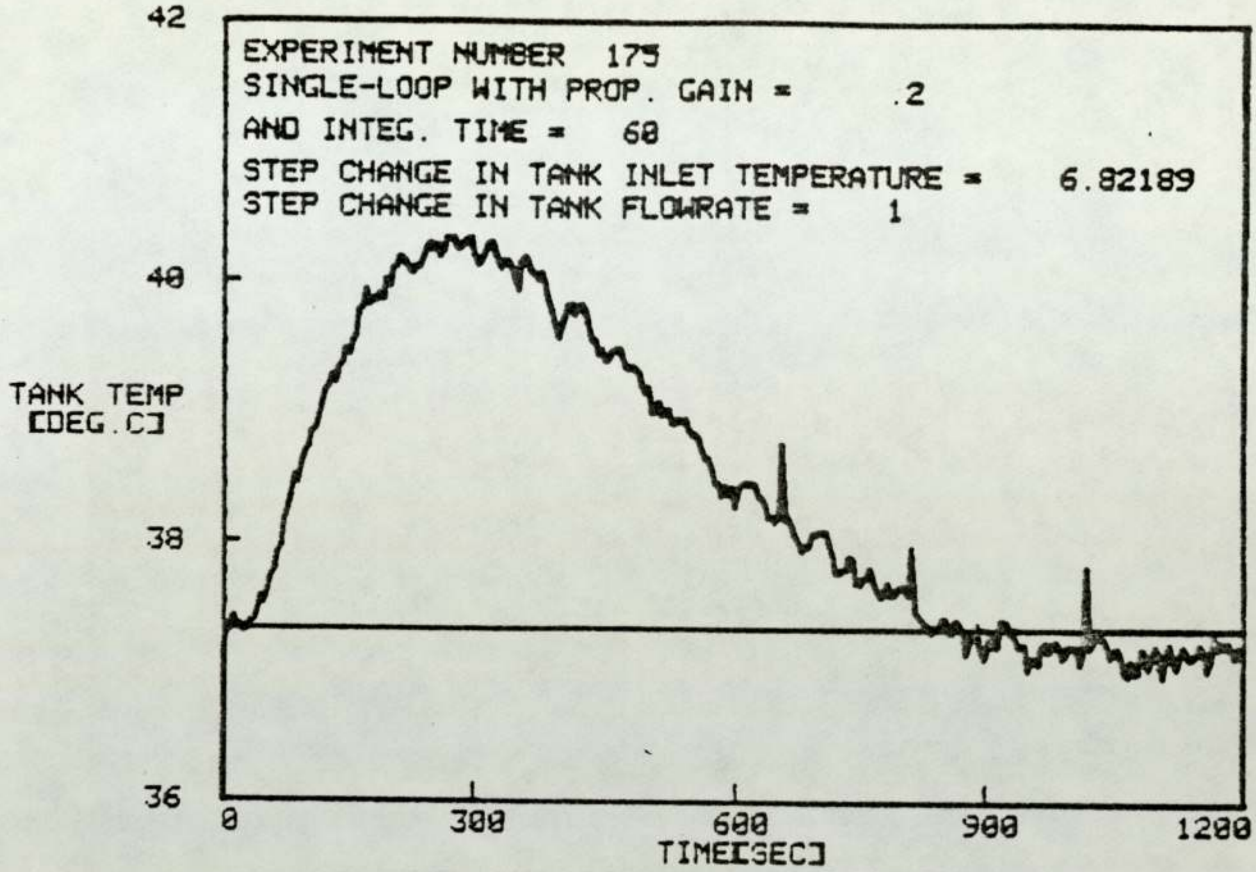


40
38
36
34
TANK TEMP
[DEG.C]
SINGLE-LOOP 173
CASCADE 174
0
300
600
900
1200
TIME[SEC]



40
38
36
34
TANK TEMP
[DEG.C]
SINGLE-LOOP 173
CASCADE 174
0
300
600
900
1200
TIME[SEC]

FIG. A.3.118


EXPERIMENT NUMBER 175
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 6.82189
STEP CHANGE IN TANK FLOWRATE = 1
42
40
38
36
TANK TEMP [DEG.C]
0
300
600
900
1200
TIME[SEC]

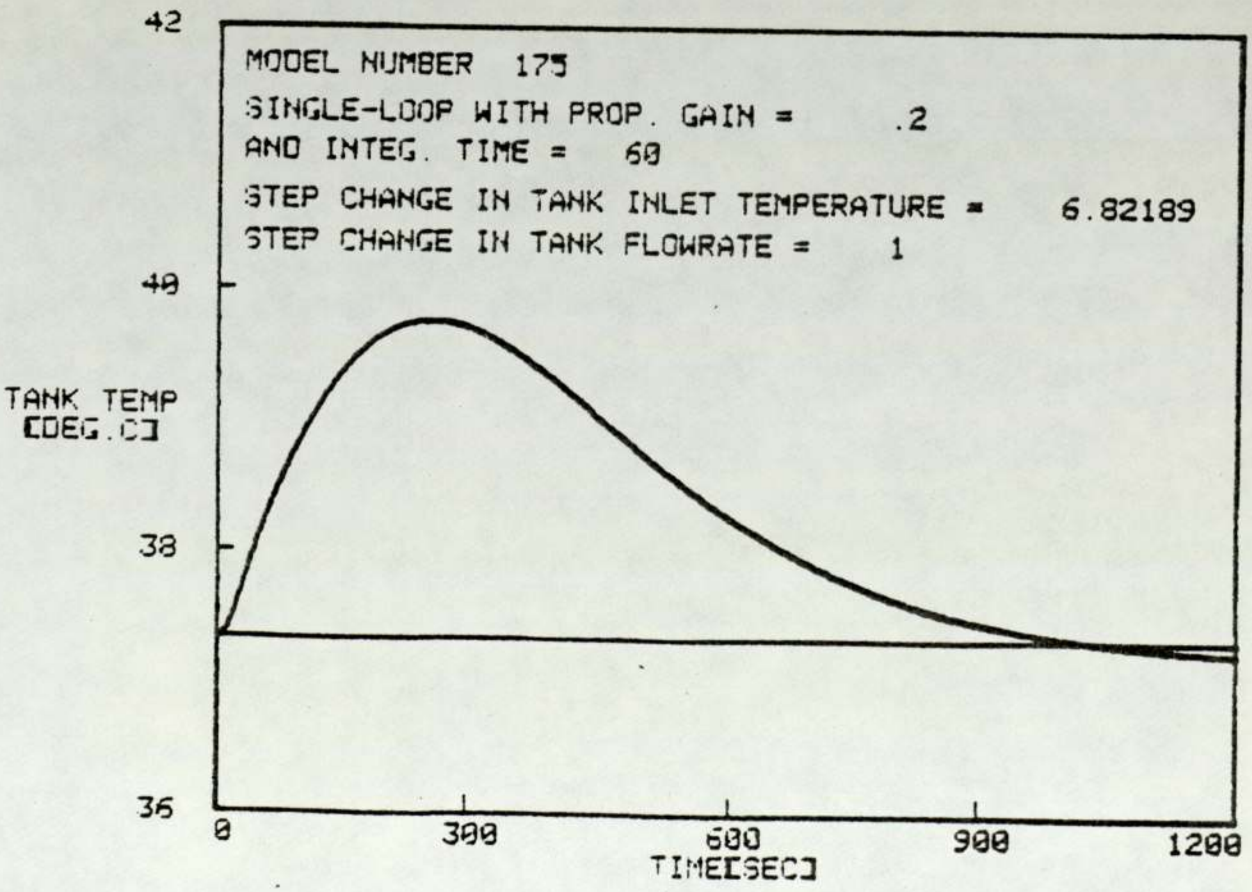
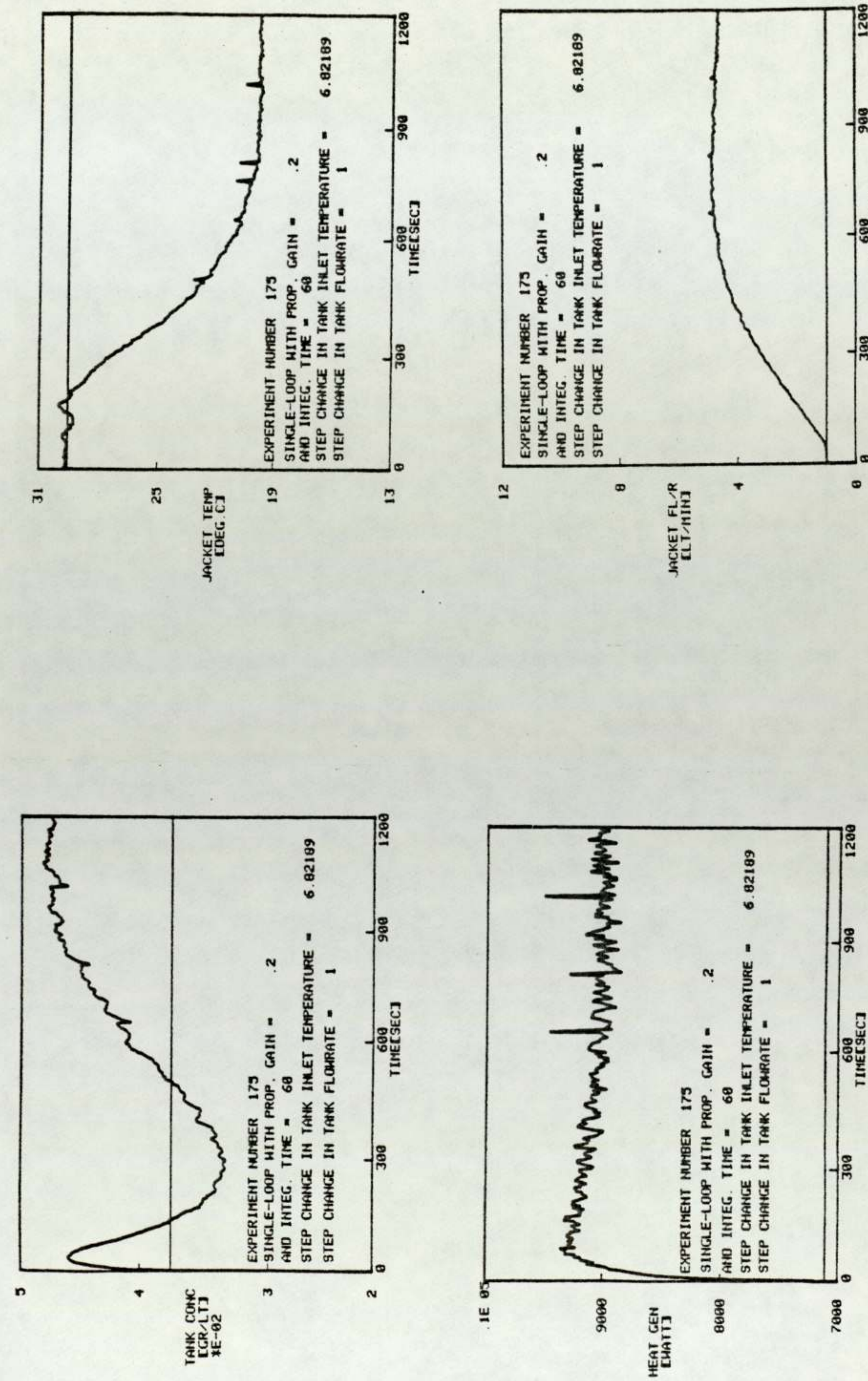
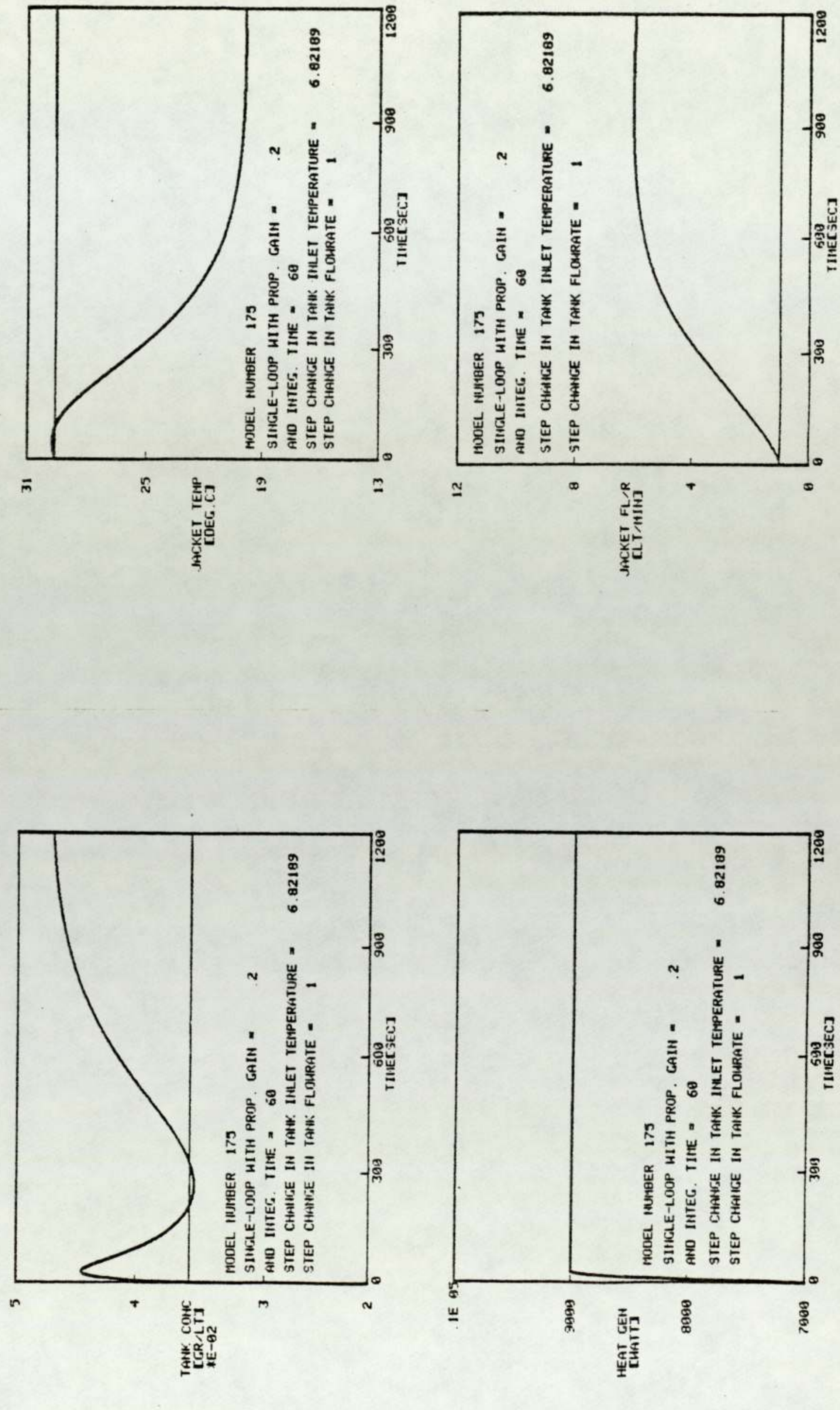

MODEL NUMBER 175
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 6.82189
STEP CHANGE IN TANK FLOWRATE = 1
42
40
38
36
TANK TEMP [DEG.C]
0
300
600
900
1200
TIME[SEC]

FIG. A.3.119



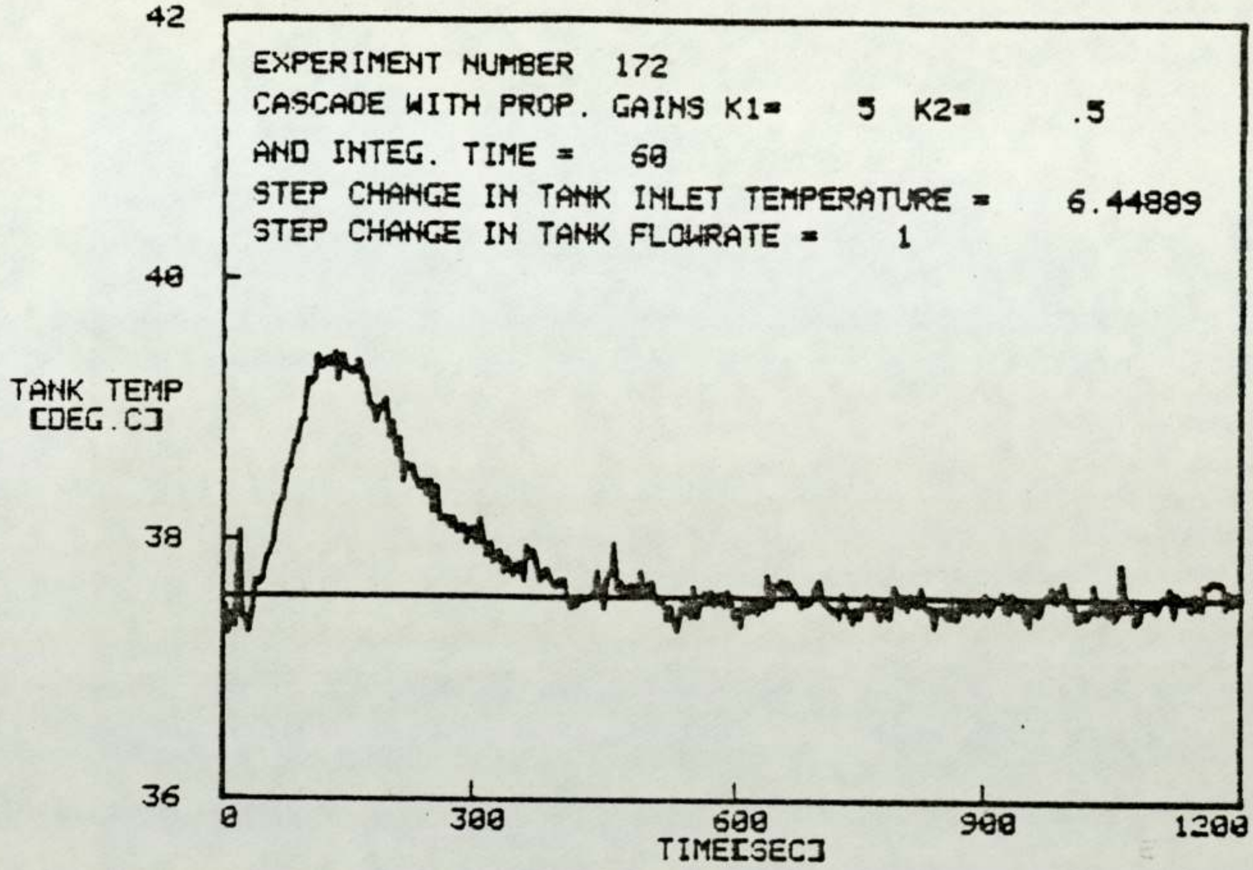
JACKET TEMP [DEG.C]
EXPERIMENT NUMBER 175
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 6.02189
STEP CHANGE IN TANK FLOWRATE = 1
TIME[SEC]
JACKET FL/R [LT/MIN]
EXPERIMENT NUMBER 175
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 6.02189
STEP CHANGE IN TANK FLOWRATE = 1
TIME[SEC]
TANK CONC [GR/LT] *E-02
EXPERIMENT NUMBER 175
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 6.02189
STEP CHANGE IN TANK FLOWRATE = 1
TIME[SEC]
HEAT GEN [WATT]
1E 05
EXPERIMENT NUMBER 175
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 6.02189
STEP CHANGE IN TANK FLOWRATE = 1
TIME[SEC]

FIG. A.3.120



JACKET TEMP [DEG.C]
31
25
19
13
0
300
600
900
1200
TIME[SEC]
MODEL NUMBER 175
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 6.82189
STEP CHANGE IN TANK FLOWRATE = 1
JACKET FL/R [LT/MIN]
12
8
4
0
TANK CONC [GR/LT] *E-02
5
4
3
2
HEAT GEN [WATT]
.1E 05
9000
8000
7000

FIG. A.3121


EXPERIMENT NUMBER 172
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 6.44889
STEP CHANGE IN TANK FLOWRATE = 1
42
40
38
36
TANK TEMP [DEG.C]
0
300
600
900
1200
TIME[SEC]

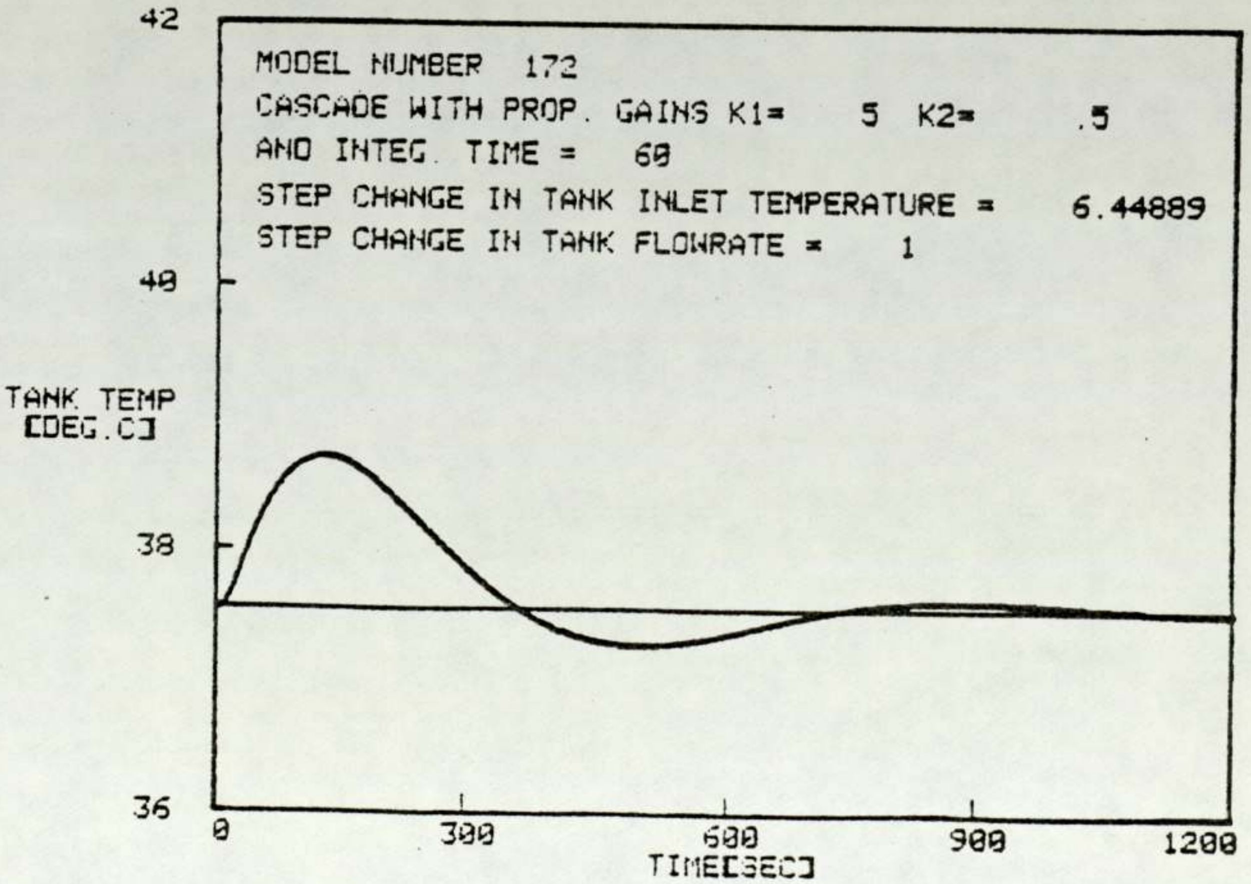

MODEL NUMBER 172
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 6.44889
STEP CHANGE IN TANK FLOWRATE = 1
42
40
38
36
TANK TEMP [DEG.C]
0
300
600
900
1200
TIME[SEC]

FIG. A.3.122

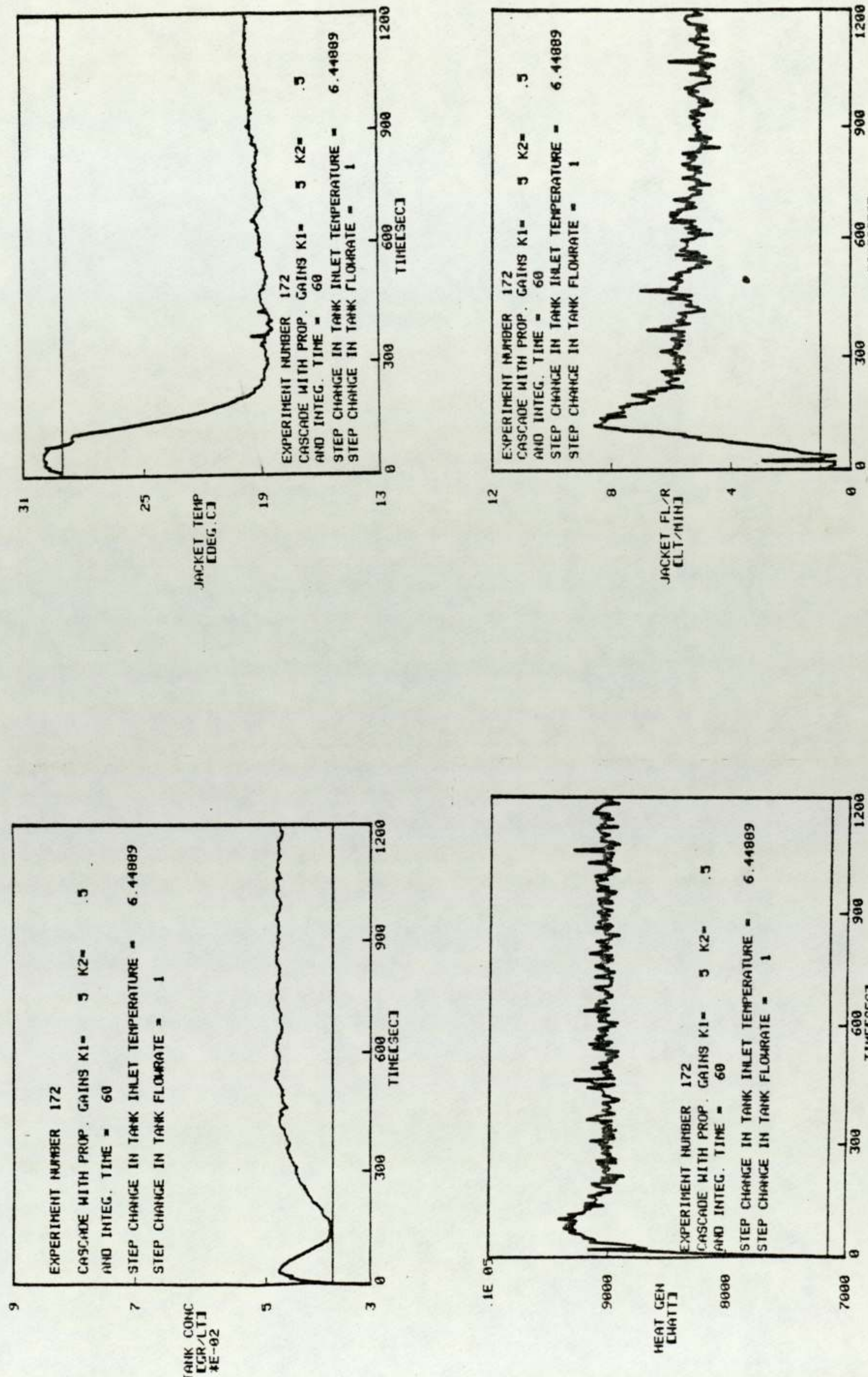

EXPERIMENT NUMBER 172
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 6.44889
STEP CHANGE IN TANK FLOWRATE = 1
JACKET TEMP [DEG.C]
JACKET FL/R [LT/MIN]
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
TIME[SEC]
1E 05

FIG. A.2123

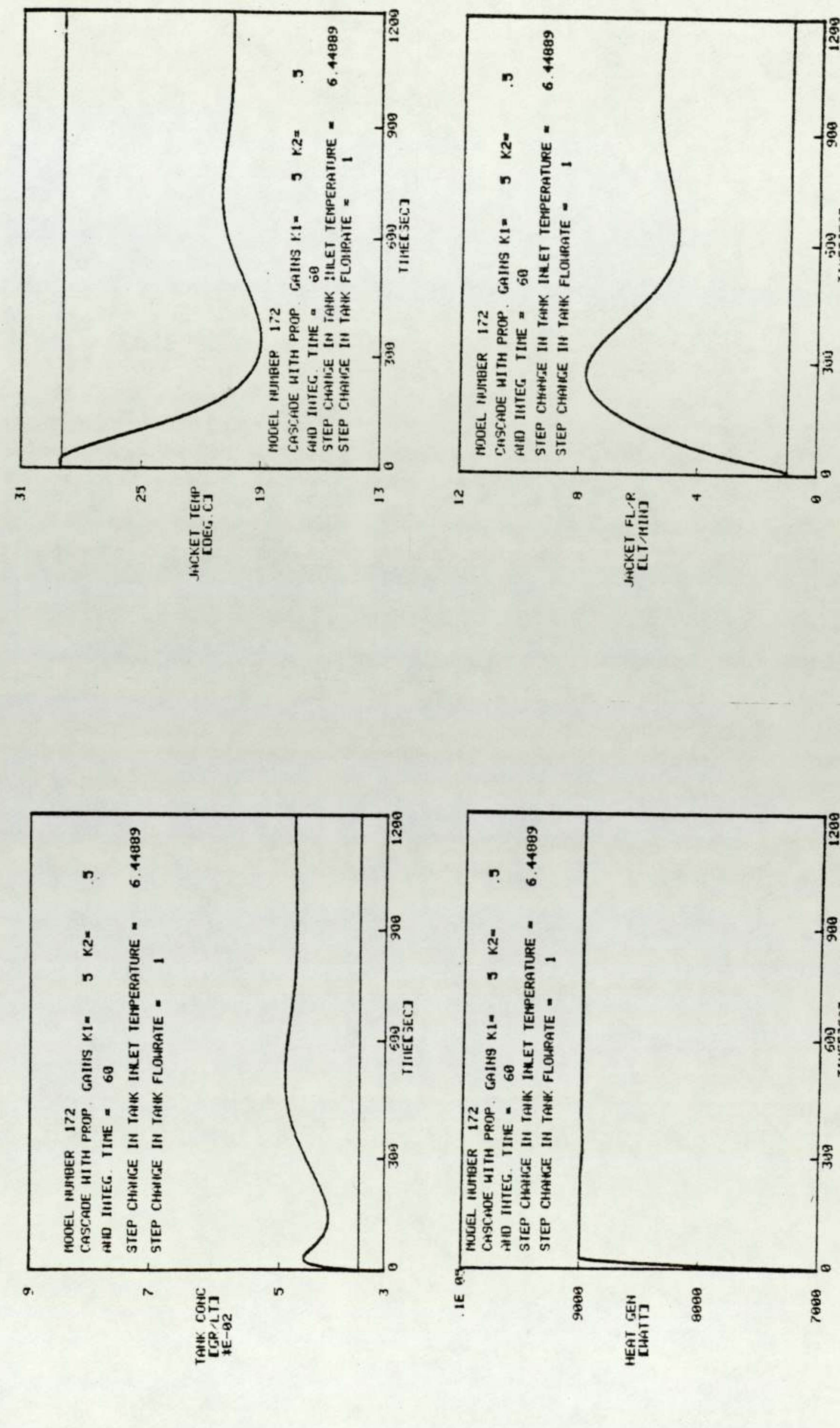
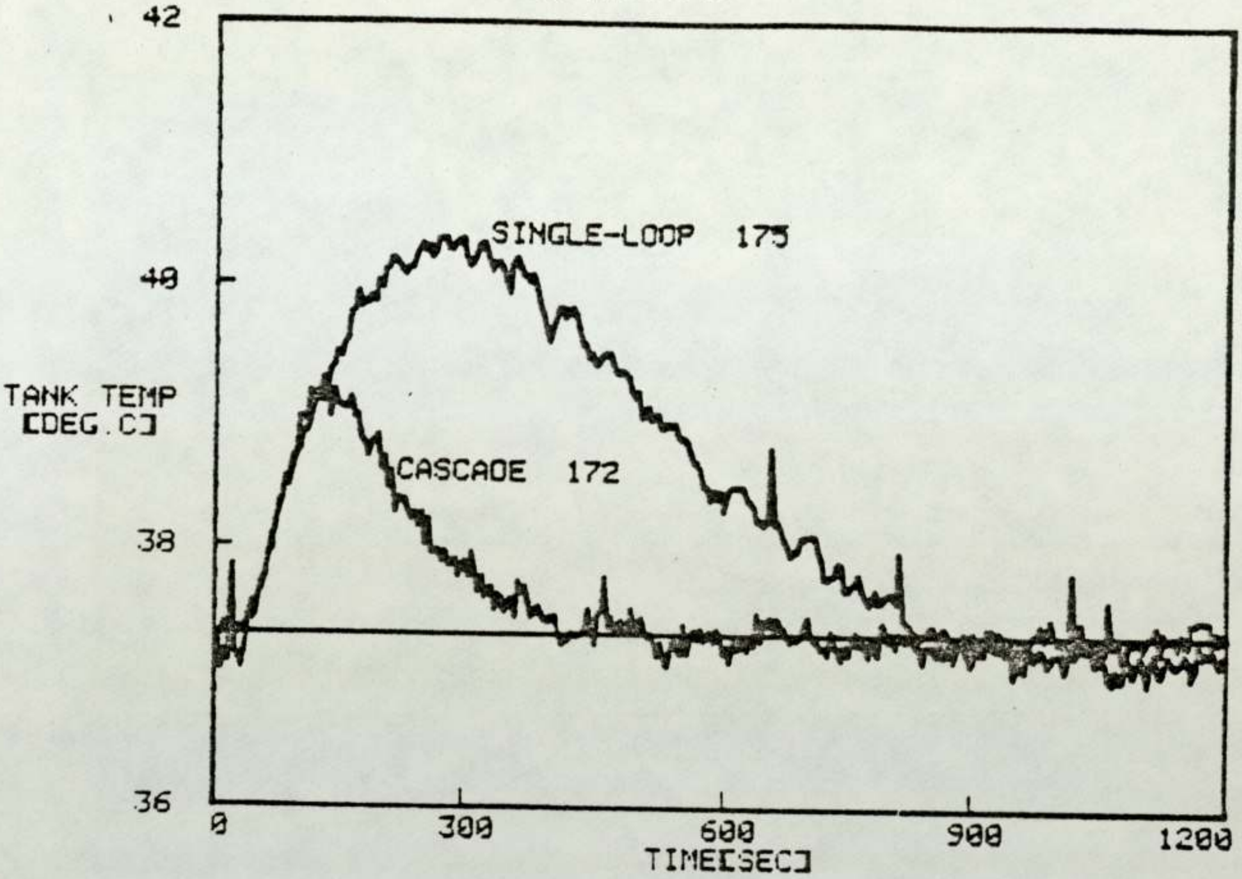

MODEL NUMBER 172
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 6.44889
STEP CHANGE IN TANK FLOWRATE = 1
JACKET TEMP [DEG.C]
JACKET FL/R [LT/MIN]
TANK CONC [GR/LT] *E-02
HEAT GEN [WATT]
TIME[SEC]

FIG. A.3.124


42
40
38
36
TANK TEMP
[DEG.C]
SINGLE-LOOP 175
CASCADE 172
0
300
600
900
1200
TIME[SEC]

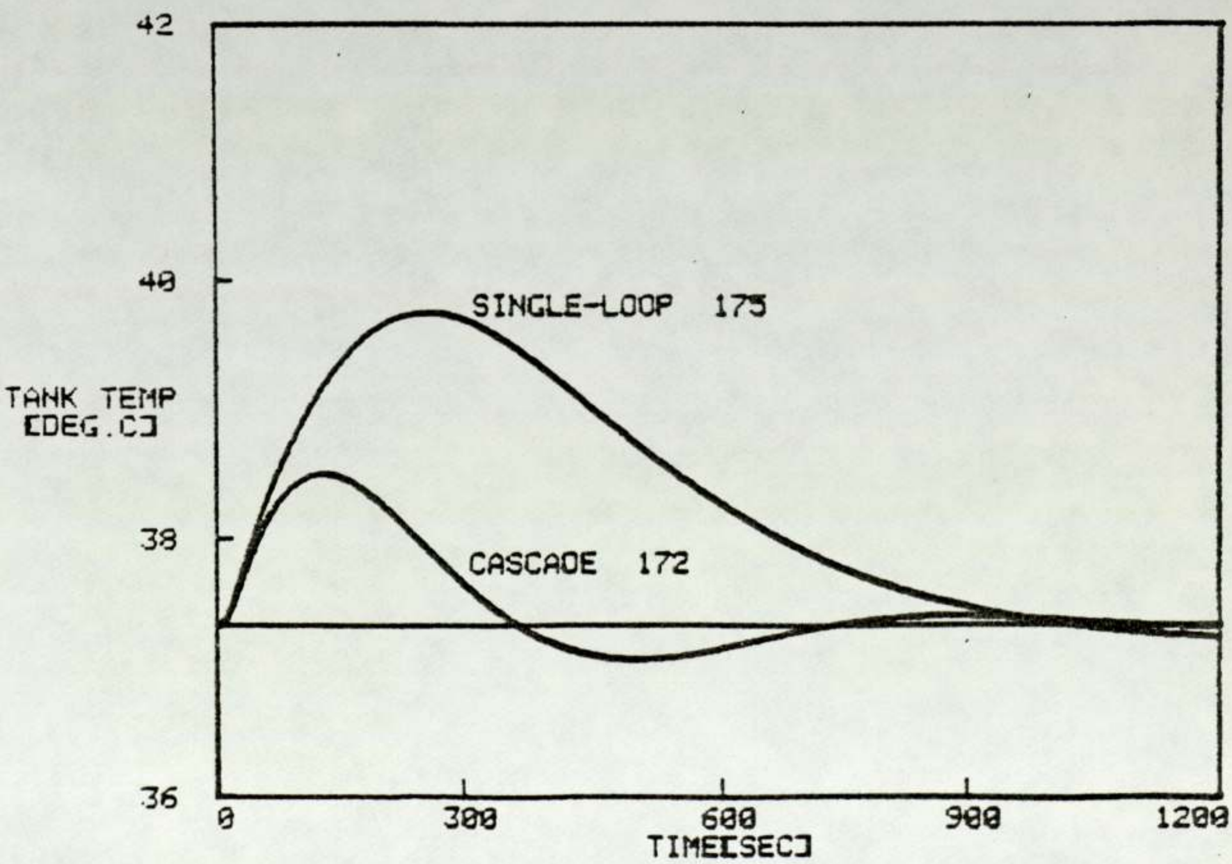
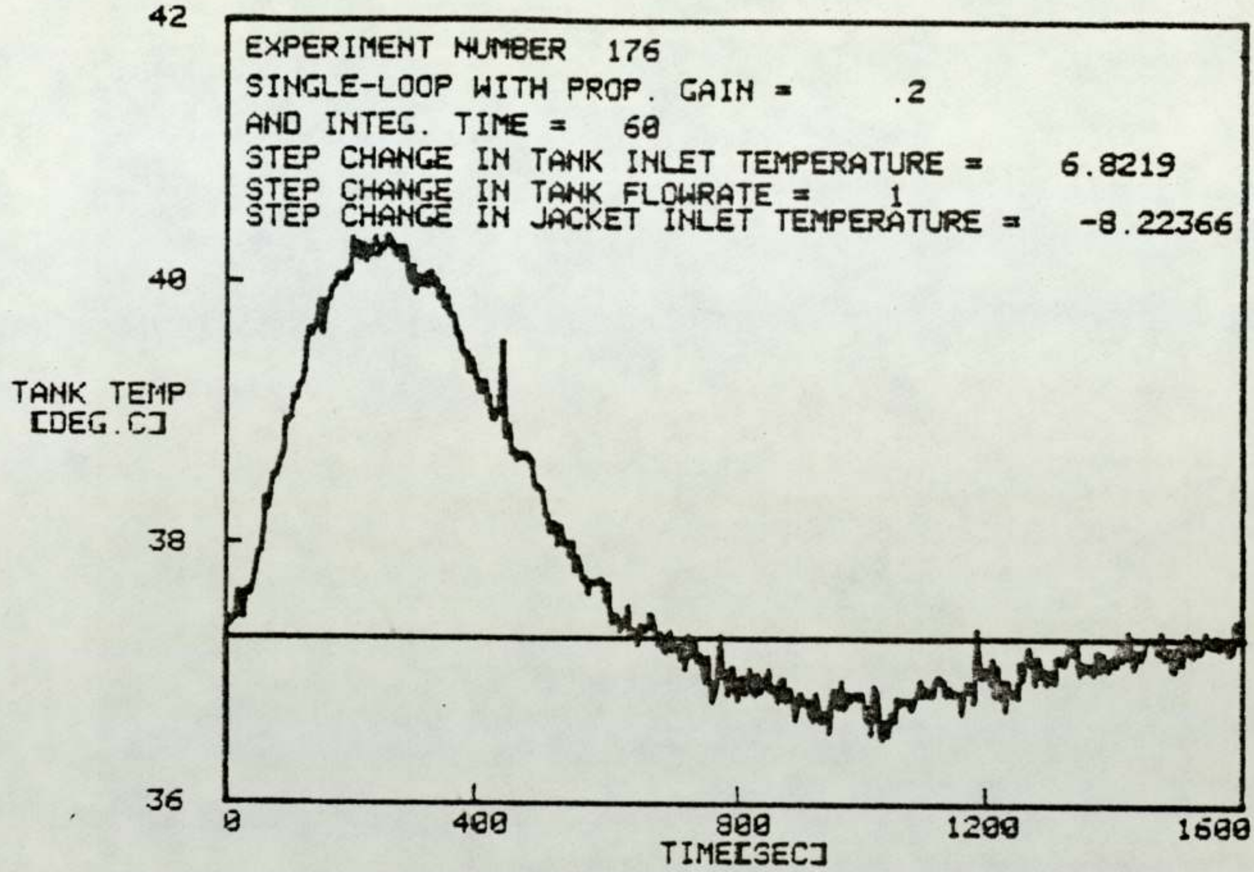

42
40
38
36
TANK TEMP
[DEG.C]
SINGLE-LOOP 175
CASCADE 172
0
300
600
900
1200
TIME[SEC]

FIG. A.3.125


EXPERIMENT NUMBER 176
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 6.8219
STEP CHANGE IN TANK FLOWRATE = 1
STEP CHANGE IN JACKET INLET TEMPERATURE = -8.22366
42
40
38
36
TANK TEMP [DEG.C]
0
400
800
1200
1600
TIME[SEC]

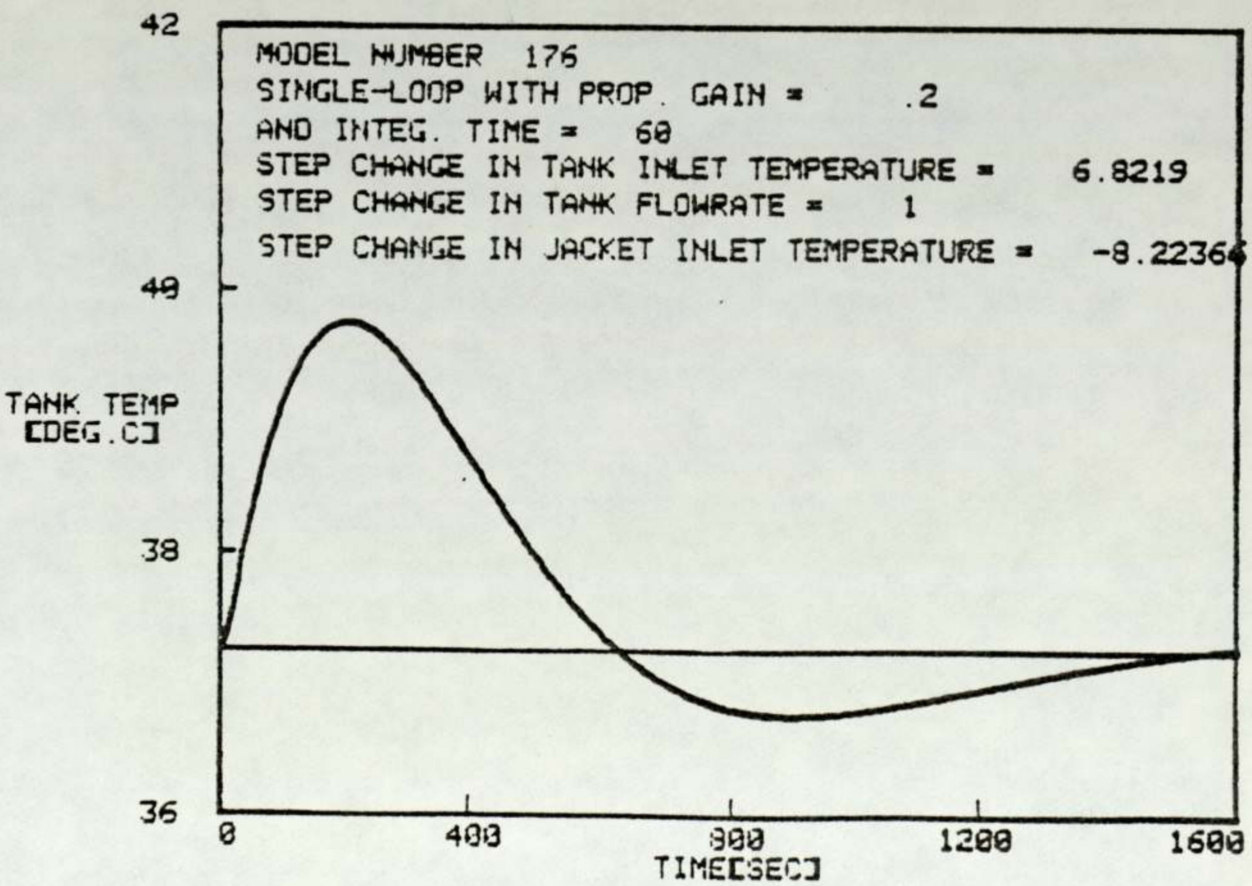
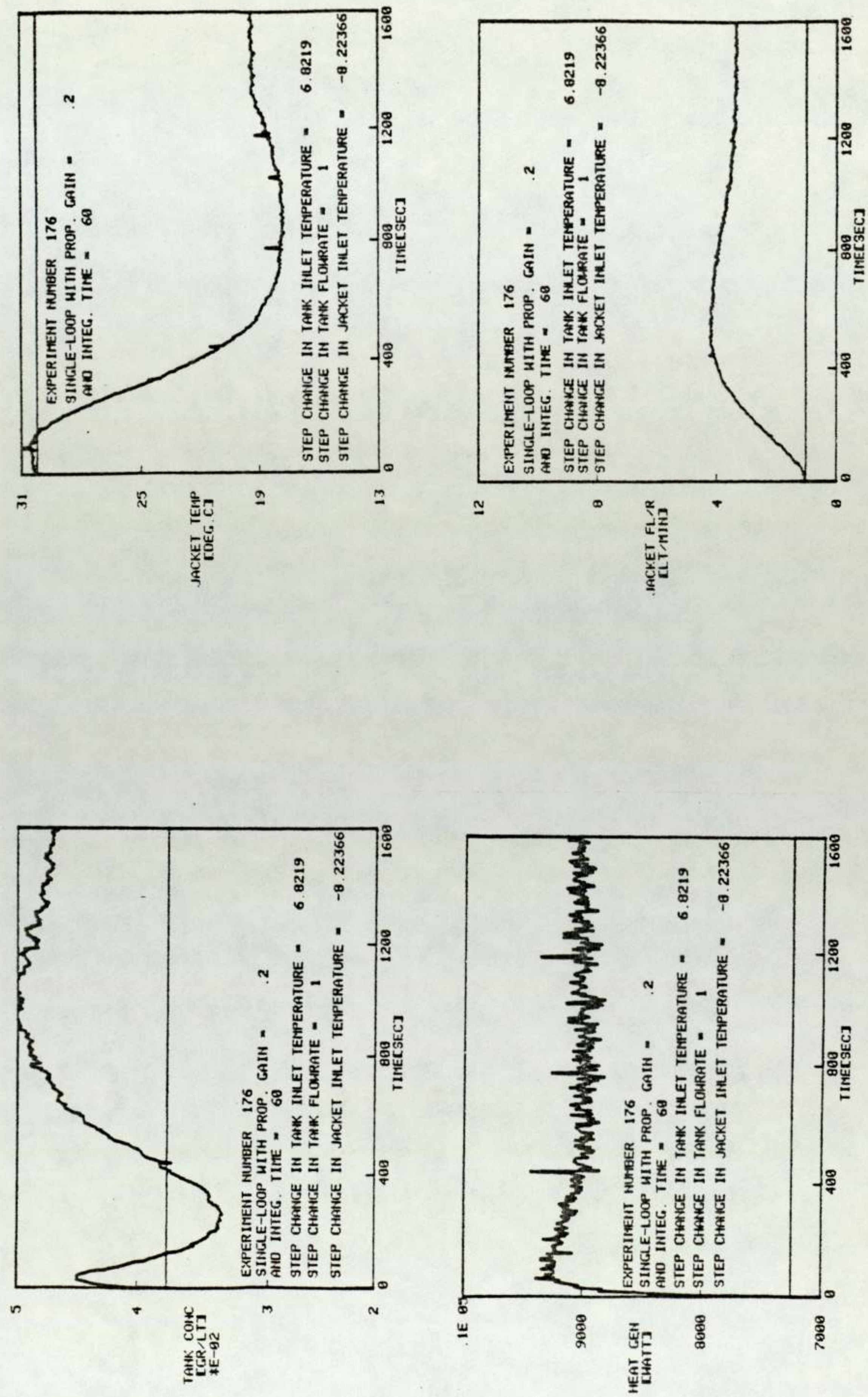

MODEL NUMBER 176
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 6.8219
STEP CHANGE IN TANK FLOWRATE = 1
STEP CHANGE IN JACKET INLET TEMPERATURE = -8.22366
42
40
38
36
TANK TEMP [DEG.C]
0
400
800
1200
1600
TIME[SEC]

FIG. A.3.126



EXPERIMENT NUMBER 176
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 6.8219
STEP CHANGE IN TANK FLOWRATE = 1
STEP CHANGE IN JACKET INLET TEMPERATURE = -8.22366
JACKET TEMP [DEG.C]
31
25
19
13
0
400
800
1200
1600
TIME[SEC]
EXPERIMENT NUMBER 176
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 6.8219
STEP CHANGE IN TANK FLOWRATE = 1
STEP CHANGE IN JACKET INLET TEMPERATURE = -8.22366
JACKET FL/R [LT/MIN]
12
8
4
0
0
400
800
1200
1600
TIME[SEC]
EXPERIMENT NUMBER 176
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 6.8219
STEP CHANGE IN TANK FLOWRATE = 1
STEP CHANGE IN JACKET INLET TEMPERATURE = -8.22366
TANK CONC [GR/LT] *E-02
5
4
3
2
0
400
800
1200
1600
TIME[SEC]
EXPERIMENT NUMBER 176
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 6.8219
STEP CHANGE IN TANK FLOWRATE = 1
STEP CHANGE IN JACKET INLET TEMPERATURE = -8.22366
HEAT GEN [WATT]
.1E 05
9000
8000
7000
0
400
800
1200
1600
TIME[SEC]

FIG. A.3.127

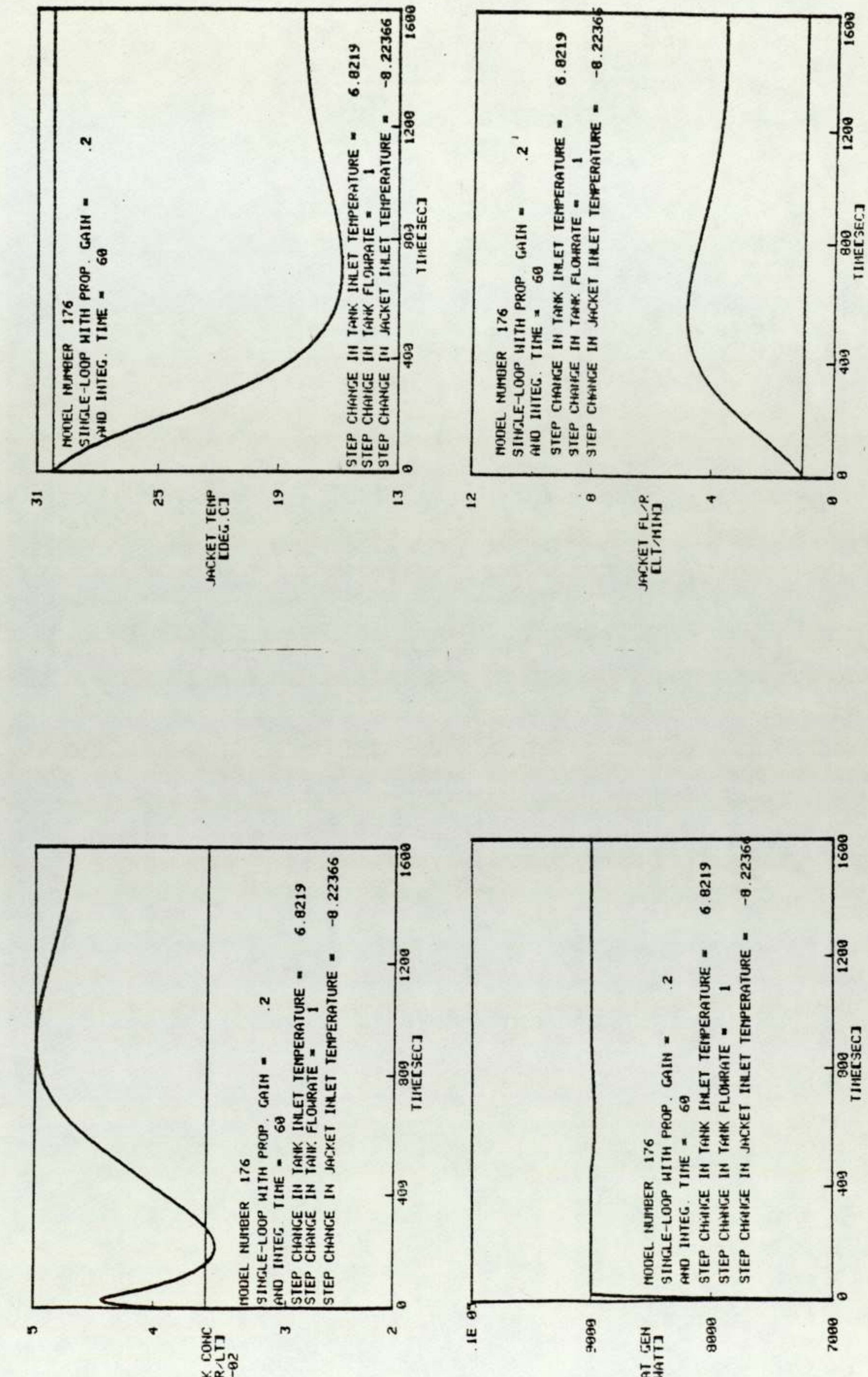

MODEL NUMBER 176
SINGLE-LOOP WITH PROP. GAIN = .2
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 6.8219
STEP CHANGE IN TANK FLOWRATE = 1
STEP CHANGE IN JACKET INLET TEMPERATURE = -8.22366
TANK CONC [GR/LT] *E-02
JACKET TEMP [DEG.C]
HEAT GEN [WATT]
JACKET FL/R [LT/MIN]
TIME[SEC]
0
400
800
1200
1600

FIG. A.3.128

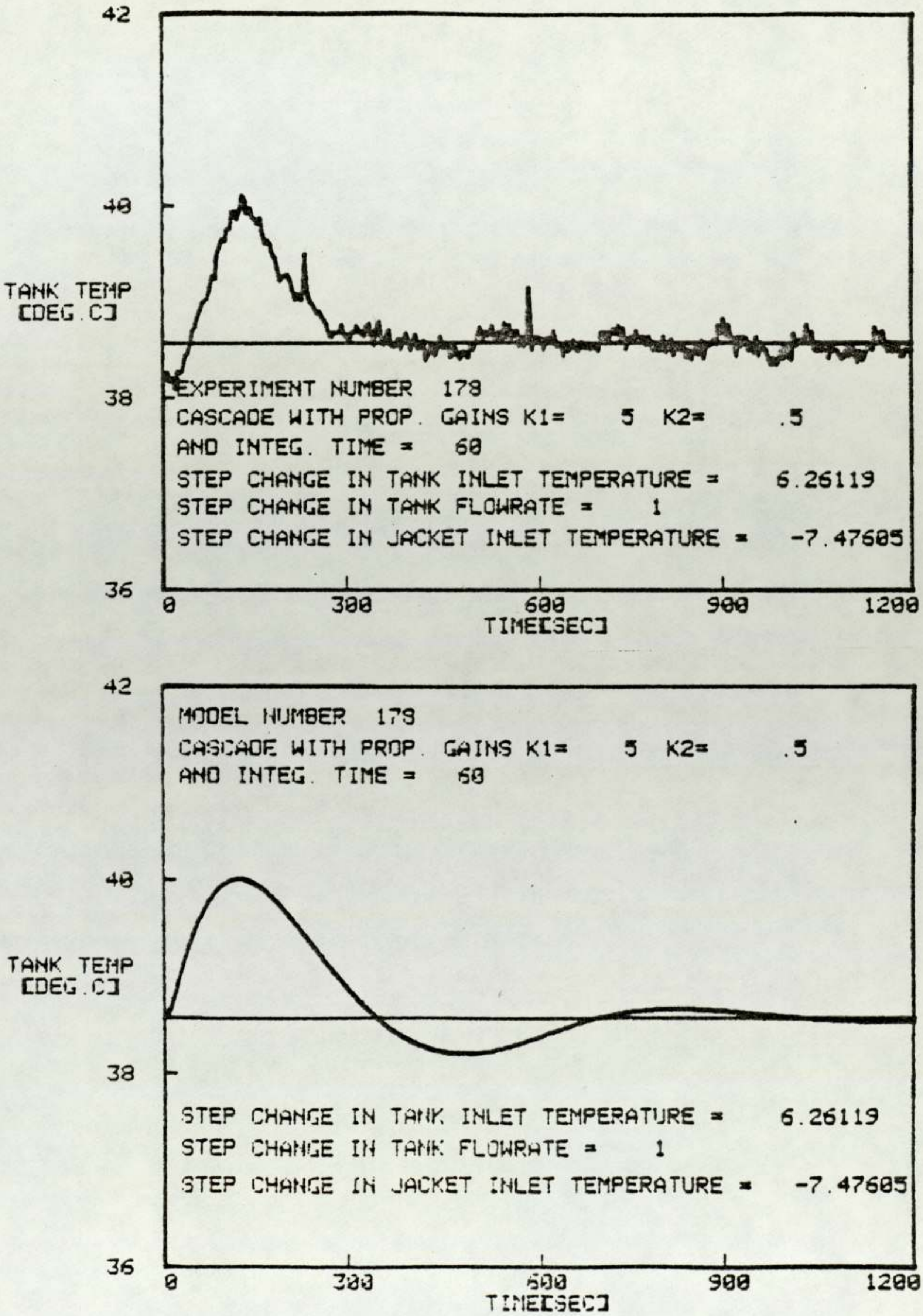

42
40
TANK TEMP
[DEG.C]
38
36
EXPERIMENT NUMBER 178
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 6.26119
STEP CHANGE IN TANK FLOWRATE = 1
STEP CHANGE IN JACKET INLET TEMPERATURE = -7.47605
0
300
600
900
1200
TIME[SEC]
MODEL NUMBER 178
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 6.26119
STEP CHANGE IN TANK FLOWRATE = 1
STEP CHANGE IN JACKET INLET TEMPERATURE = -7.47605
TIME[SEC]

FIG. A.3.129

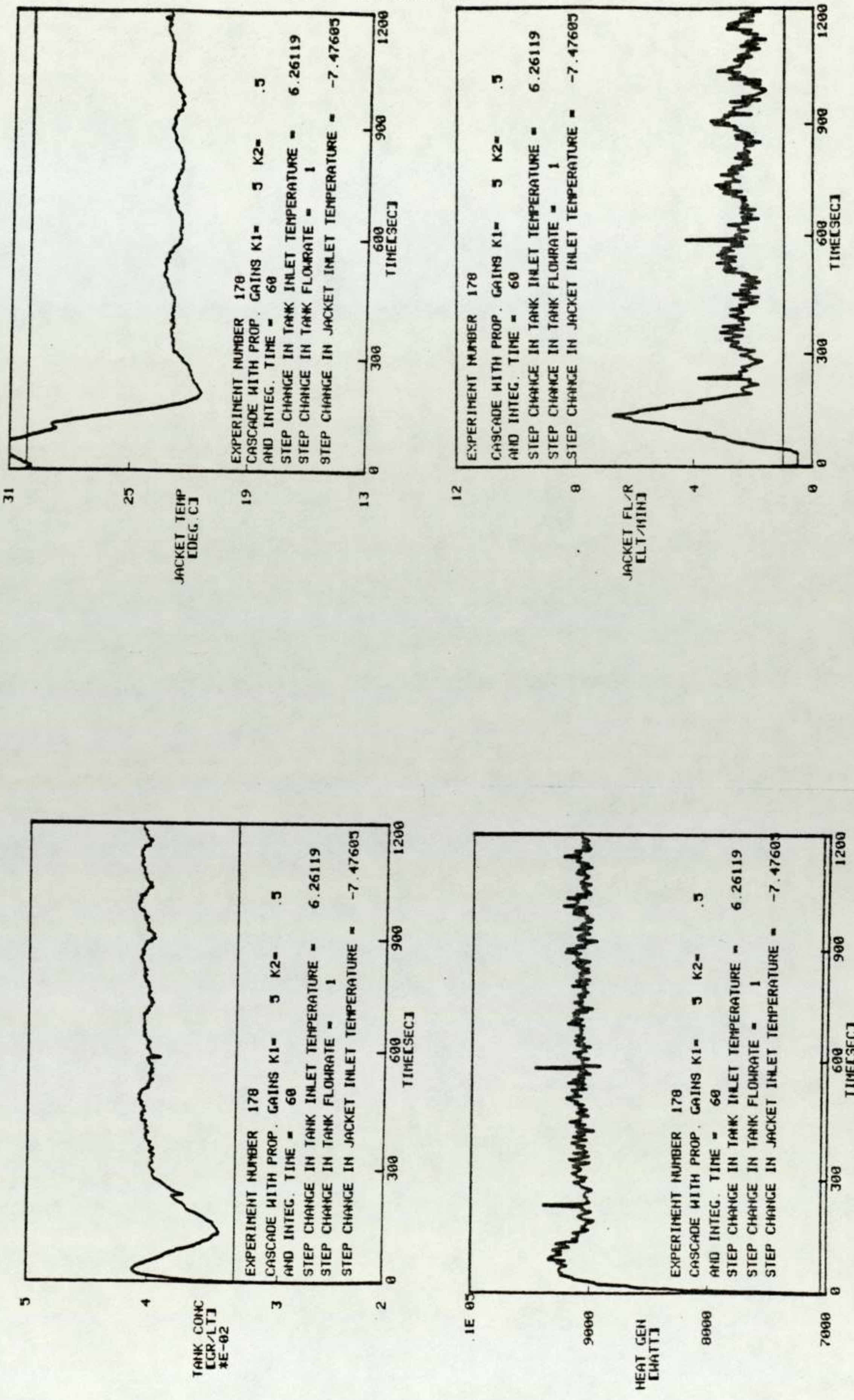

JACKET TEMP [DEG.C]
31
25
19
13
0
300
600
900
1200
TIME[SEC]
EXPERIMENT NUMBER 178
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 6.26119
STEP CHANGE IN TANK FLOWRATE = 1
STEP CHANGE IN JACKET INLET TEMPERATURE = -7.47605
JACKET FL/R [LT/MIN]
12
8
4
0
TANK CONC [GR/LT] *E-02
5
4
3
2
HEAT GEN [WATT]
.1E 05
9000
8000
7000

FIG. A.3.130

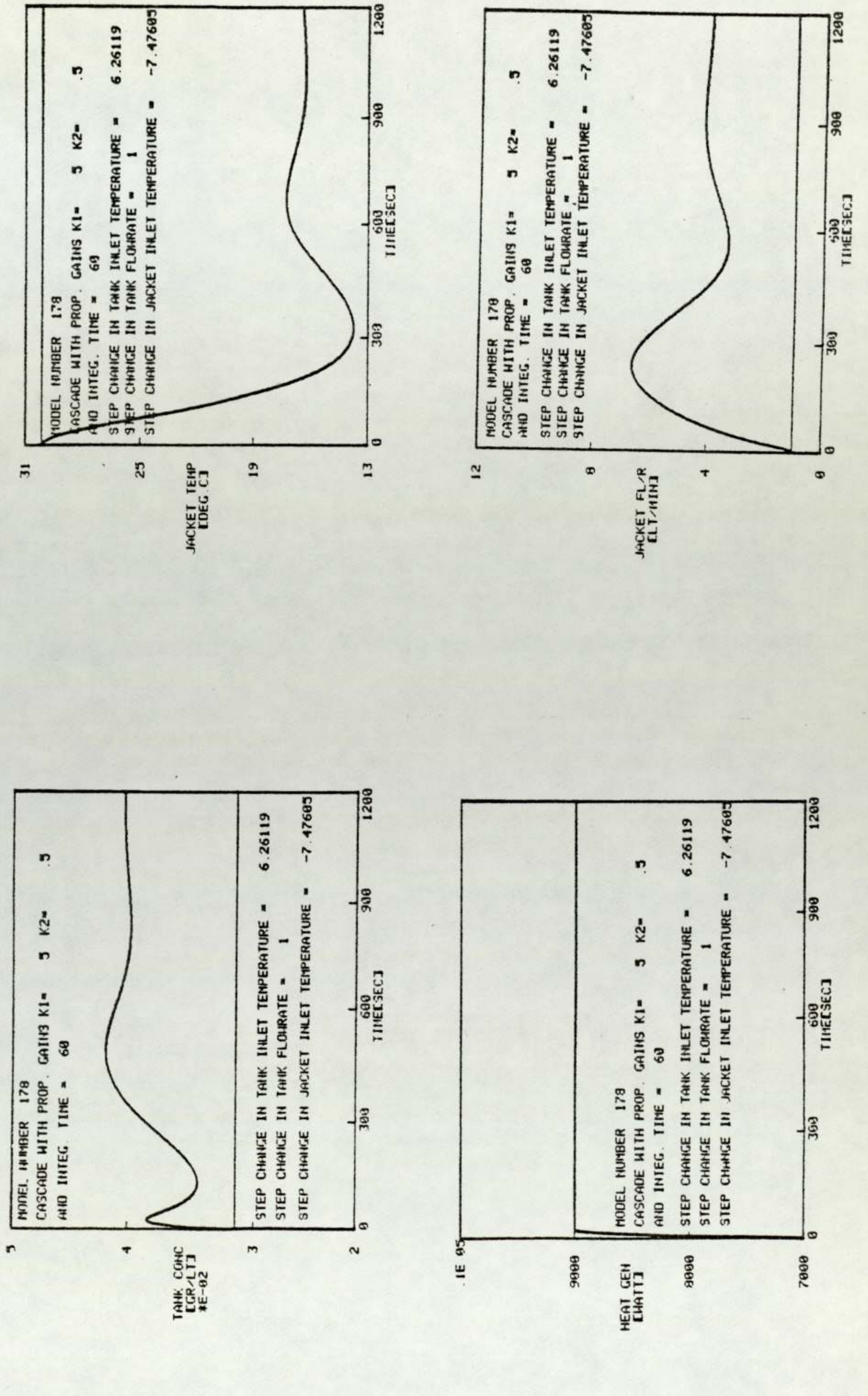
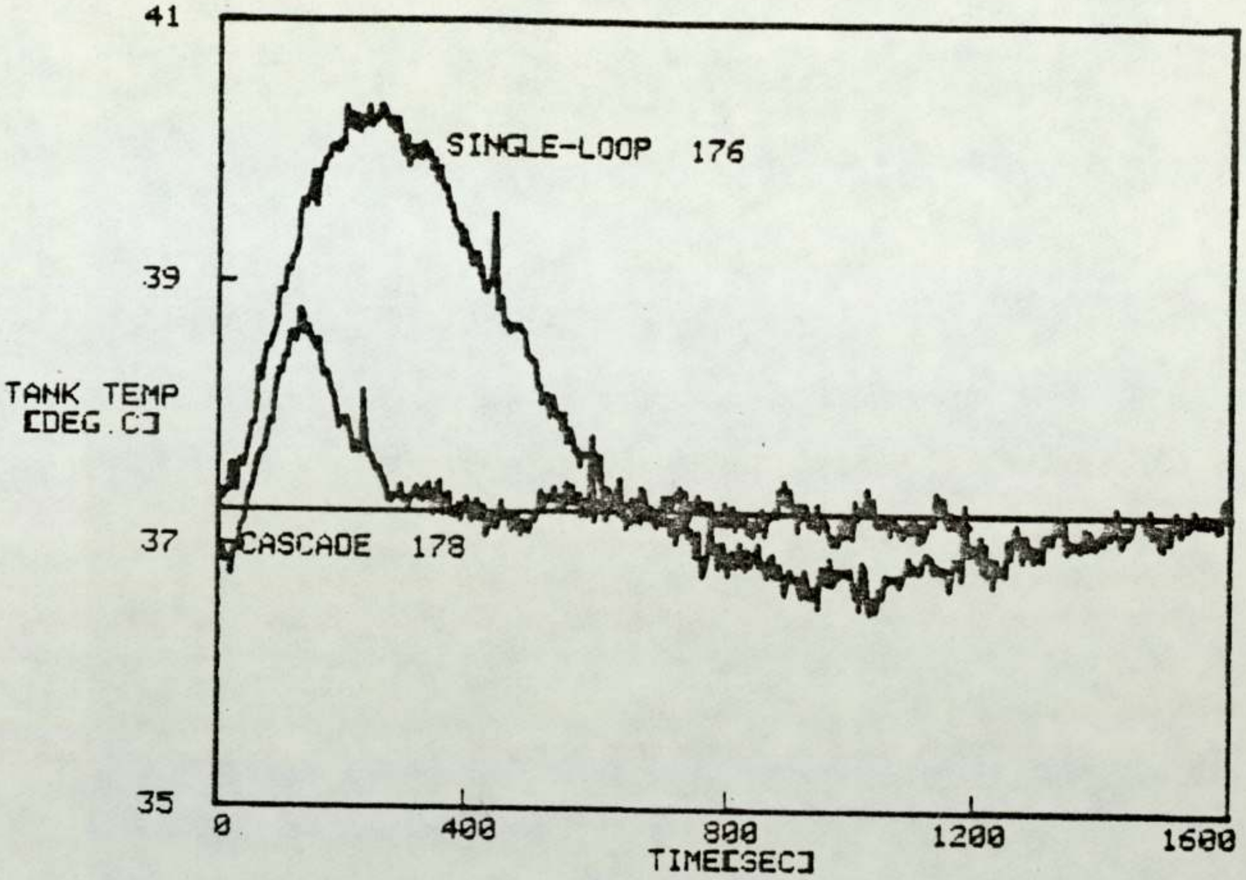
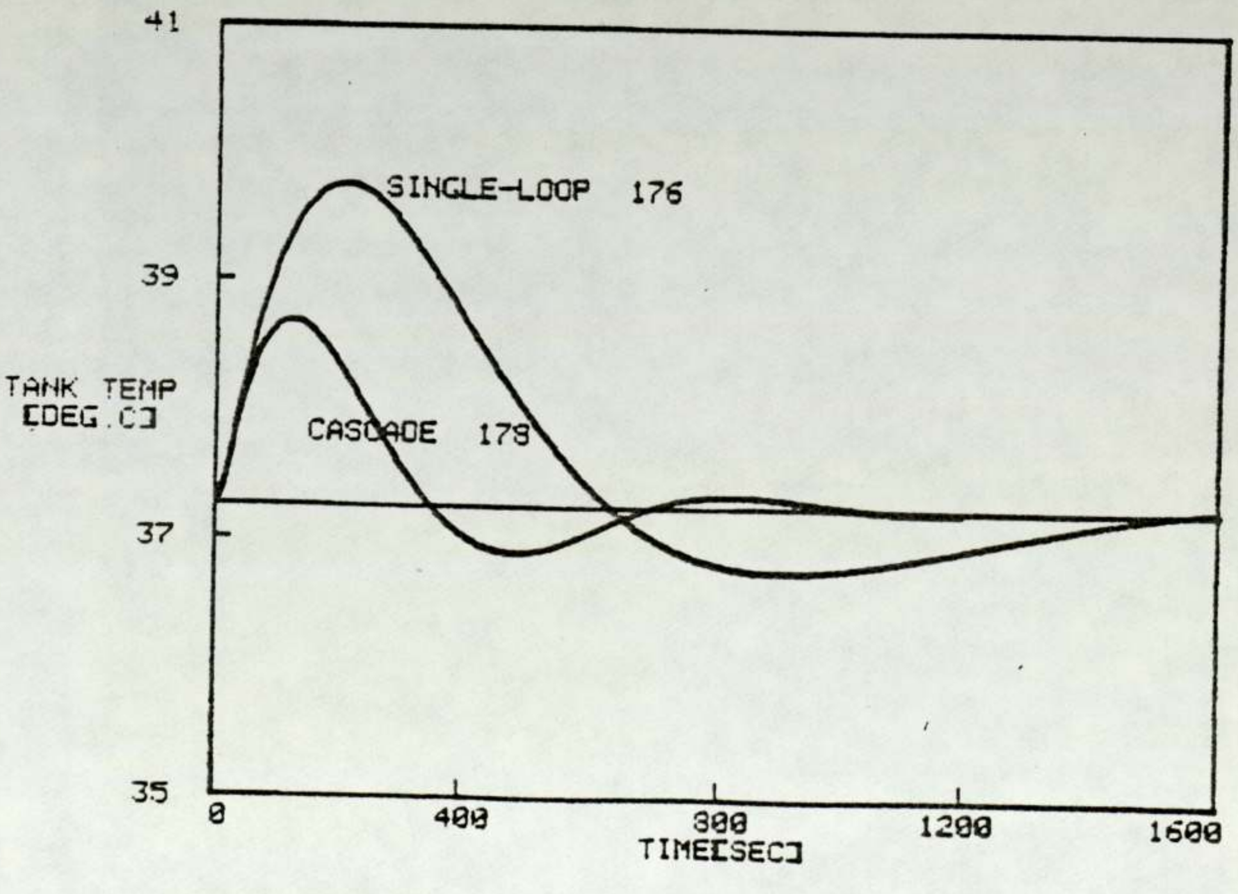

MODEL NUMBER 178
CASCADE WITH PROP. GAINS K1= 5 K2= .5
AND INTEG. TIME = 60
STEP CHANGE IN TANK INLET TEMPERATURE = 6.26119
STEP CHANGE IN TANK FLOWRATE = 1
STEP CHANGE IN JACKET INLET TEMPERATURE = -7.47605
TANK CONC [GR/LT] *E-02
JACKET TEMP [DEG.C]
HEAT GEN [WATT]
JACKET FL/R [LT/MIN]
TIME[SEC]
0
300
600
900
1200
5
4
3
2
31
25
19
13
.1E 05
9000
8000
7000
12
8
4
0

FIG. A.3.131

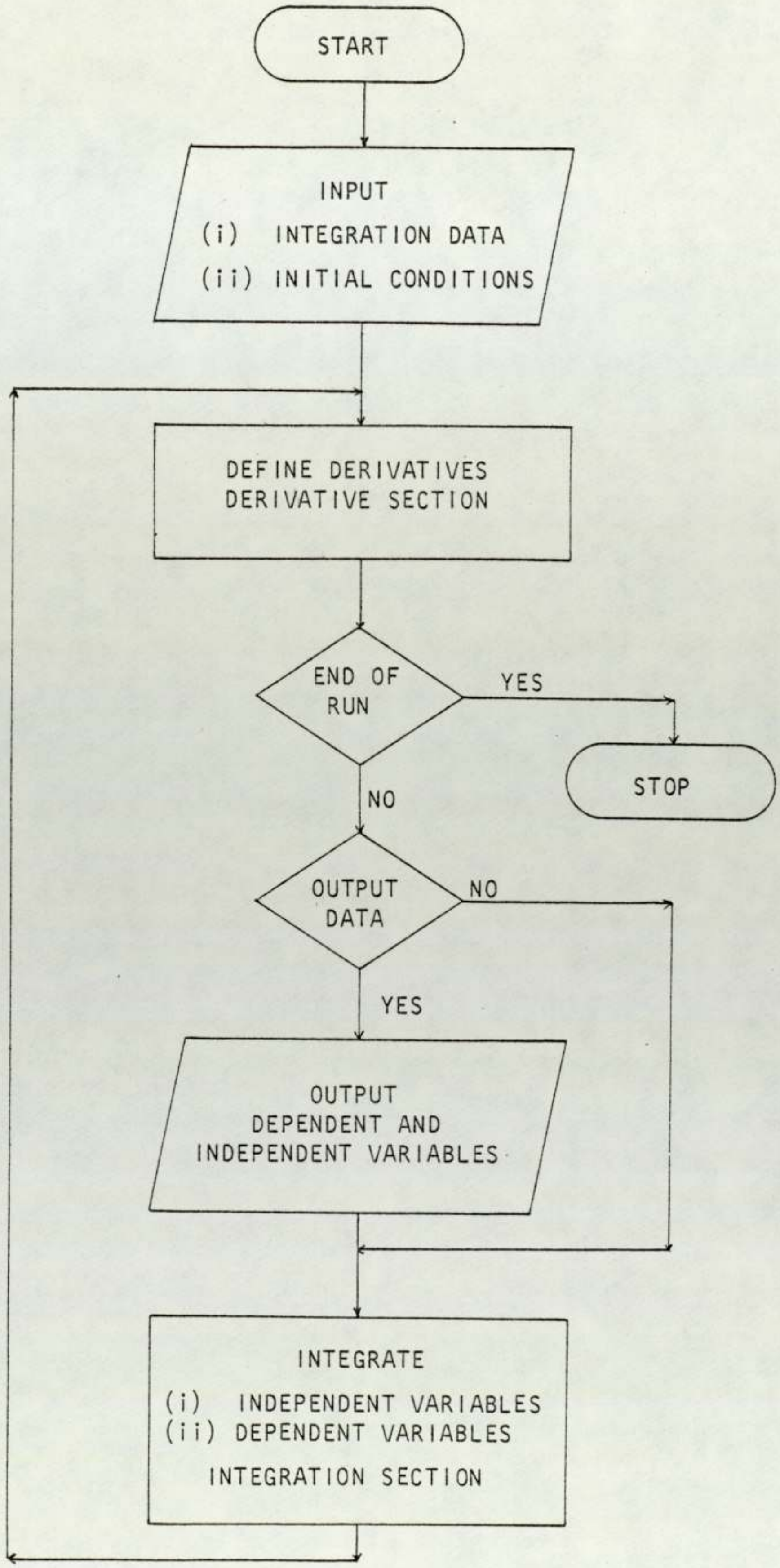

41
39
37
35
TANK TEMP
[DEG.C]
SINGLE-LOOP 176
CASCADE 178
0
400
800
1200
1600
TIME[SEC]


41
39
37
35
TANK TEMP
[DEG.C]
SINGLE-LOOP 176
CASCADE 178
0
400
800
1200
1600
TIME[SEC]

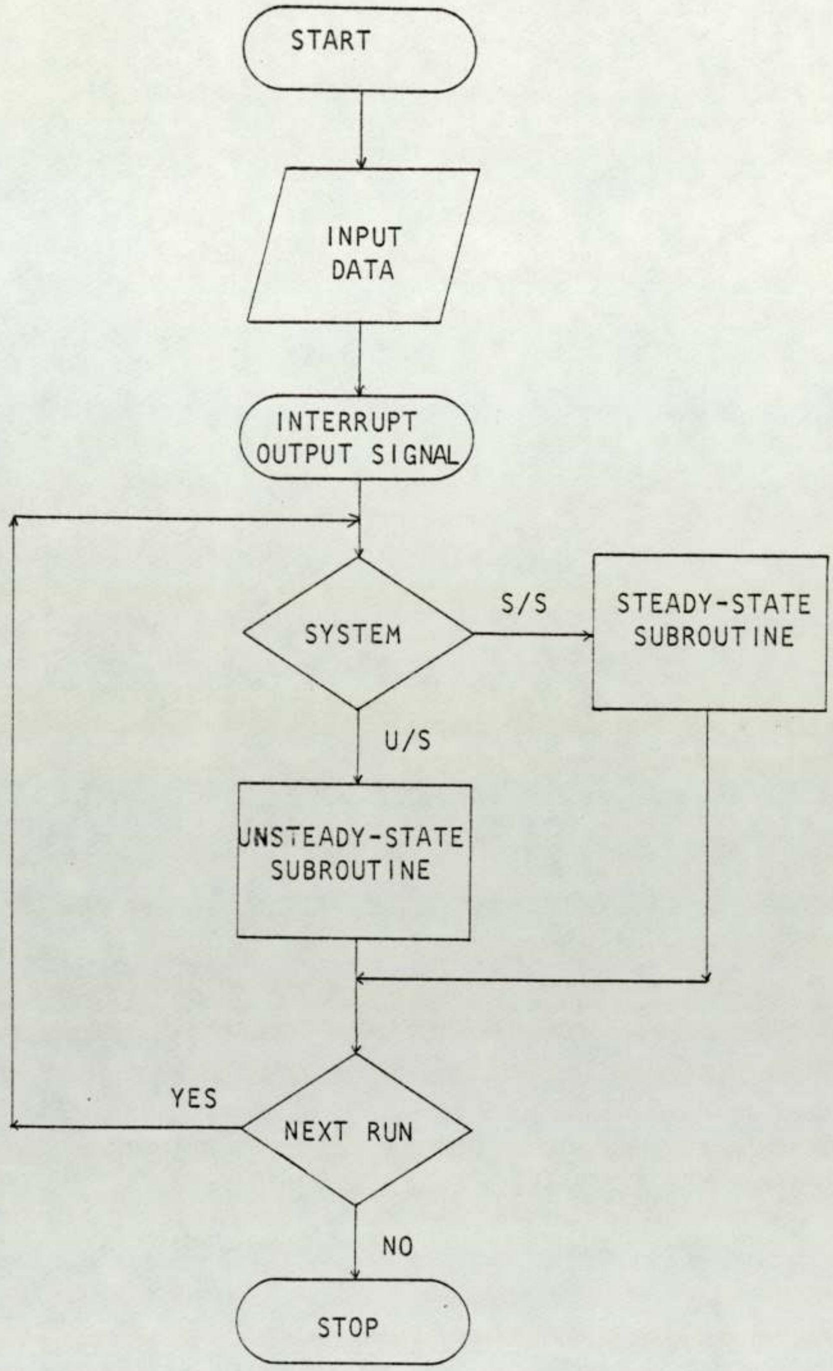
APPENDIX 4

COMPUTER FLOW DIAGRAMS

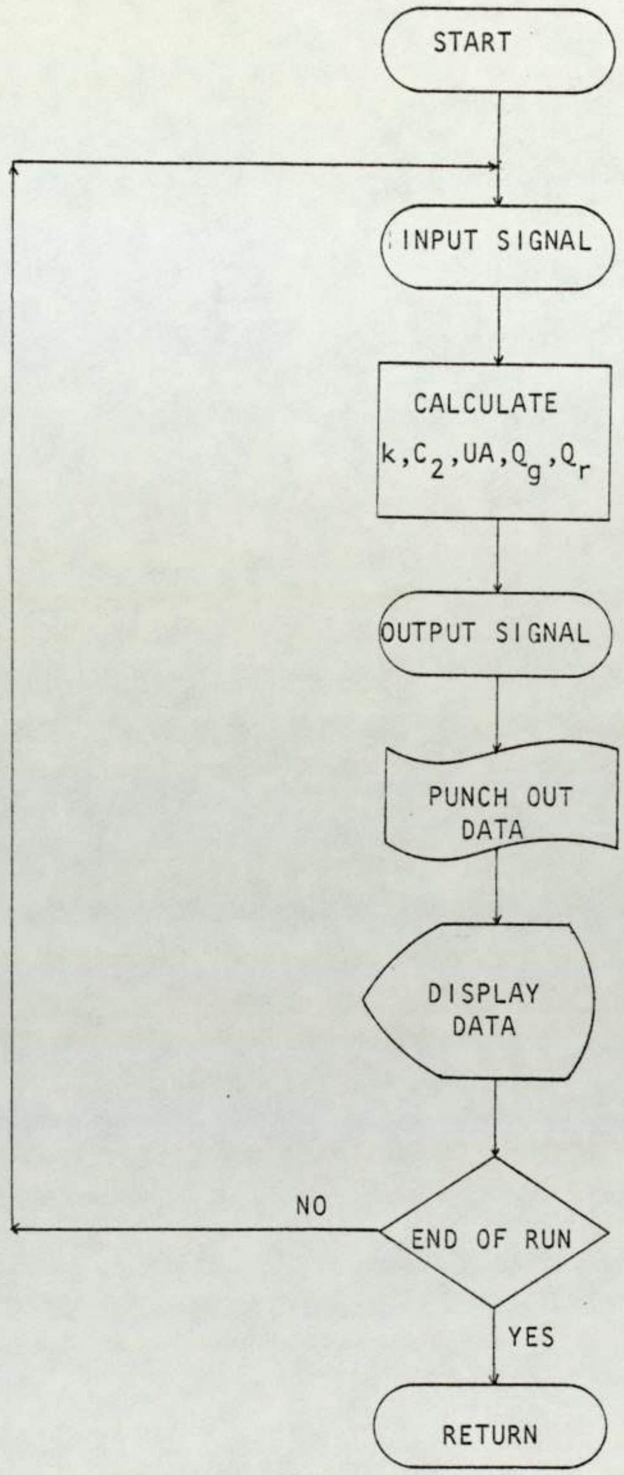
A.4.1 ASP OR BASP COMPUTER FLOW DIAGRAM



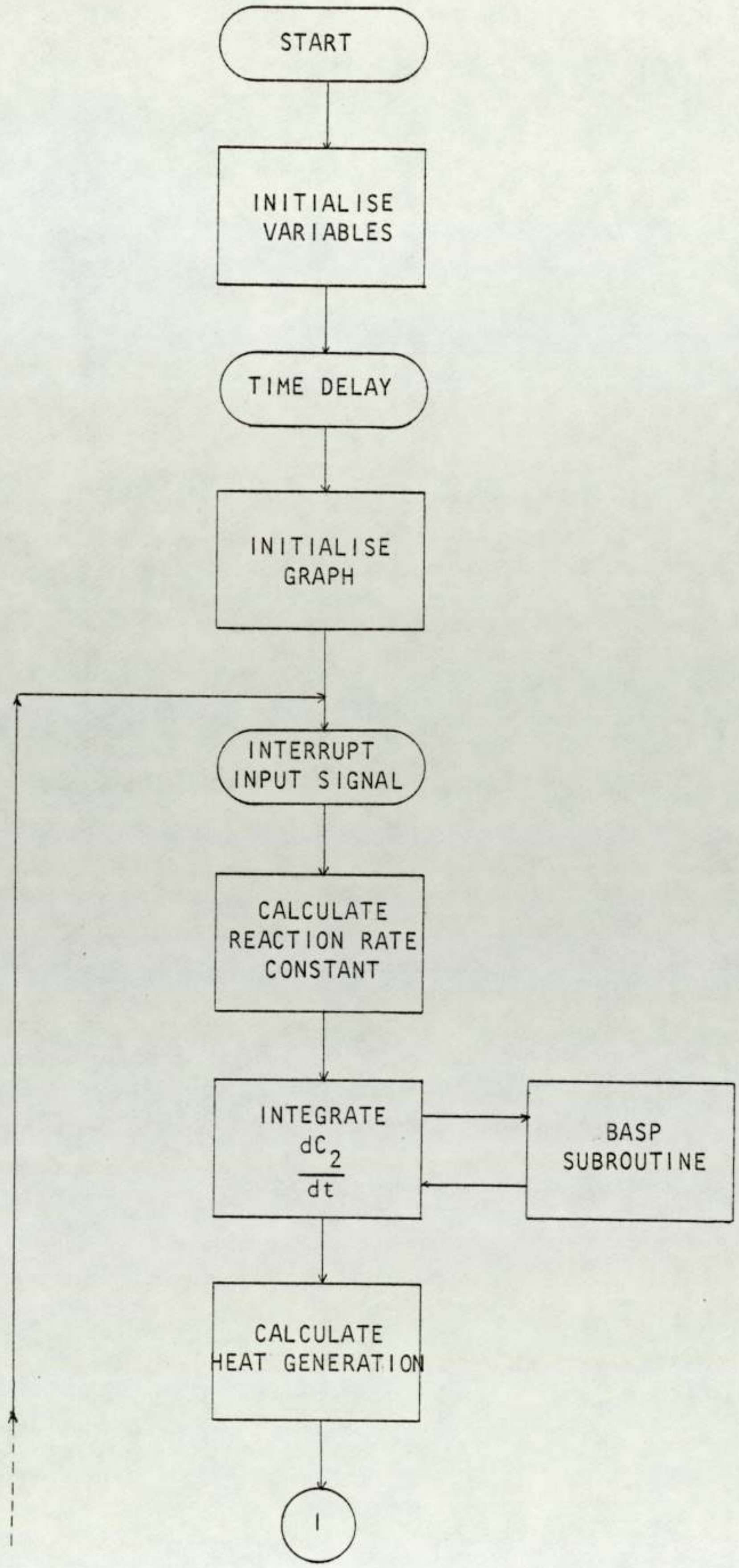
A.4.2 PARTIAL SIMULATION MAIN COMPUTER FLOW DIAGRAM



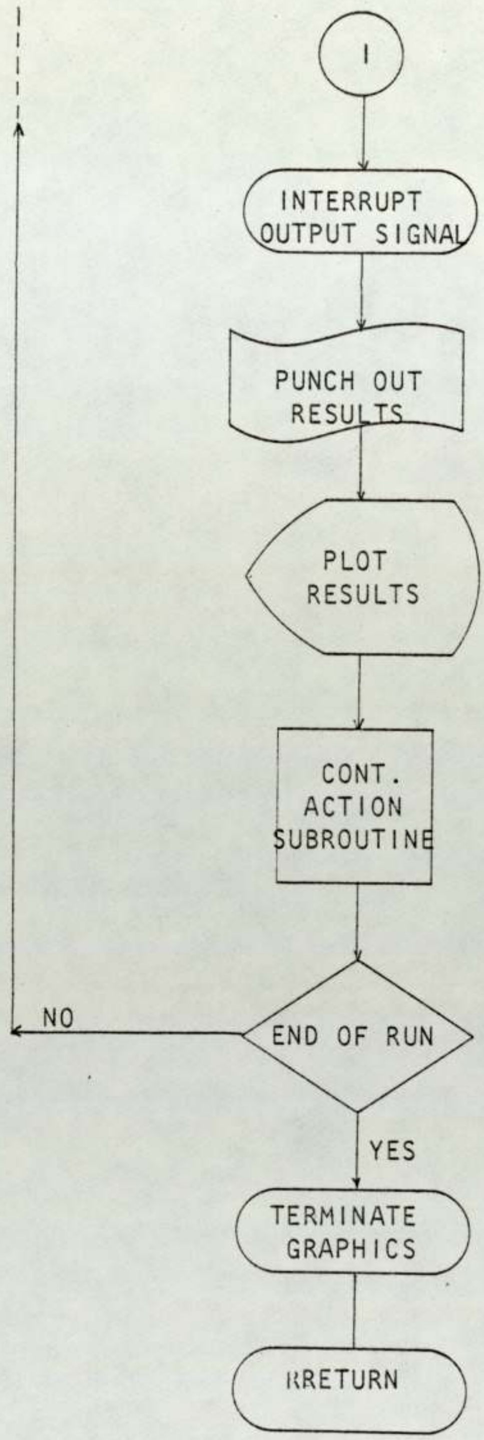
A.4.3 PARTIAL SIMULATION STEADY-STATE COMPUTER FLOW DIAGRAM



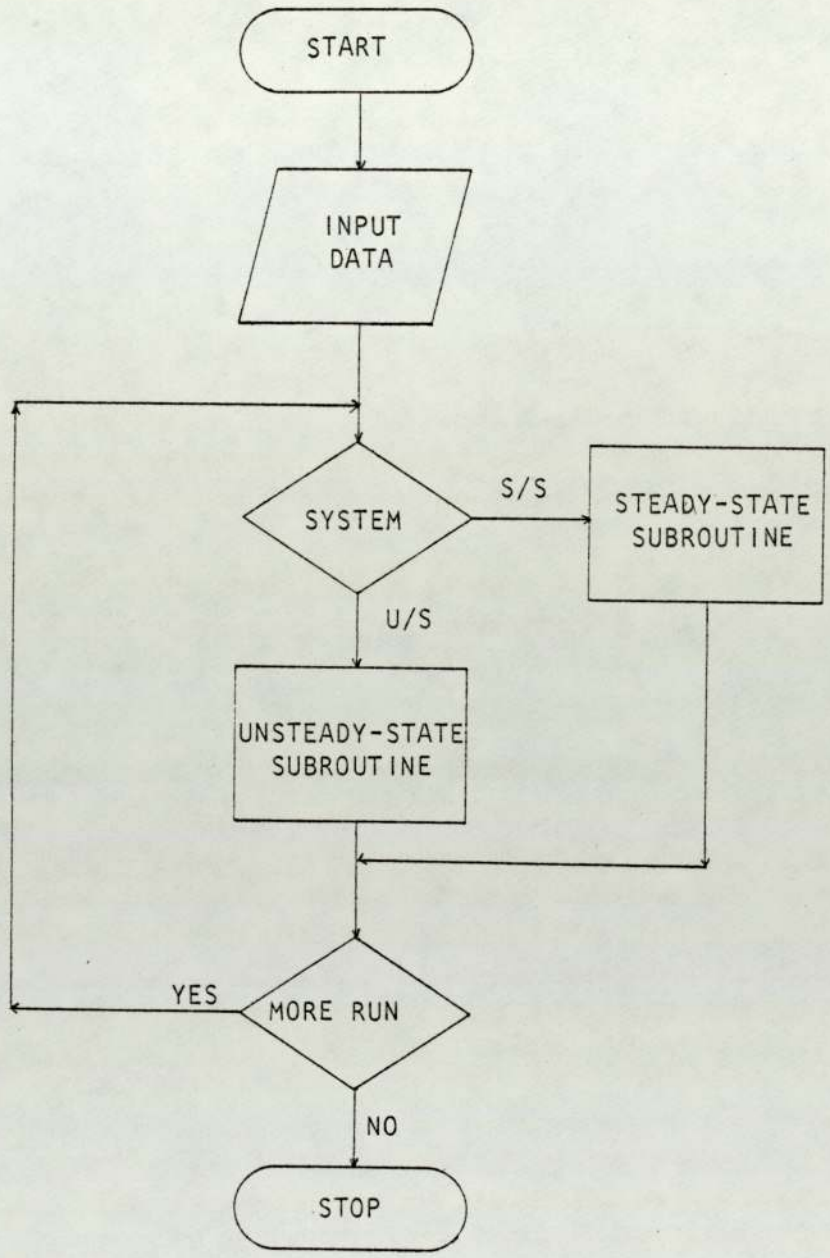
A.4.4 PARTIAL SIMULATION UNSTEADY-STATE COMPUTER FLOW DIAGRAM



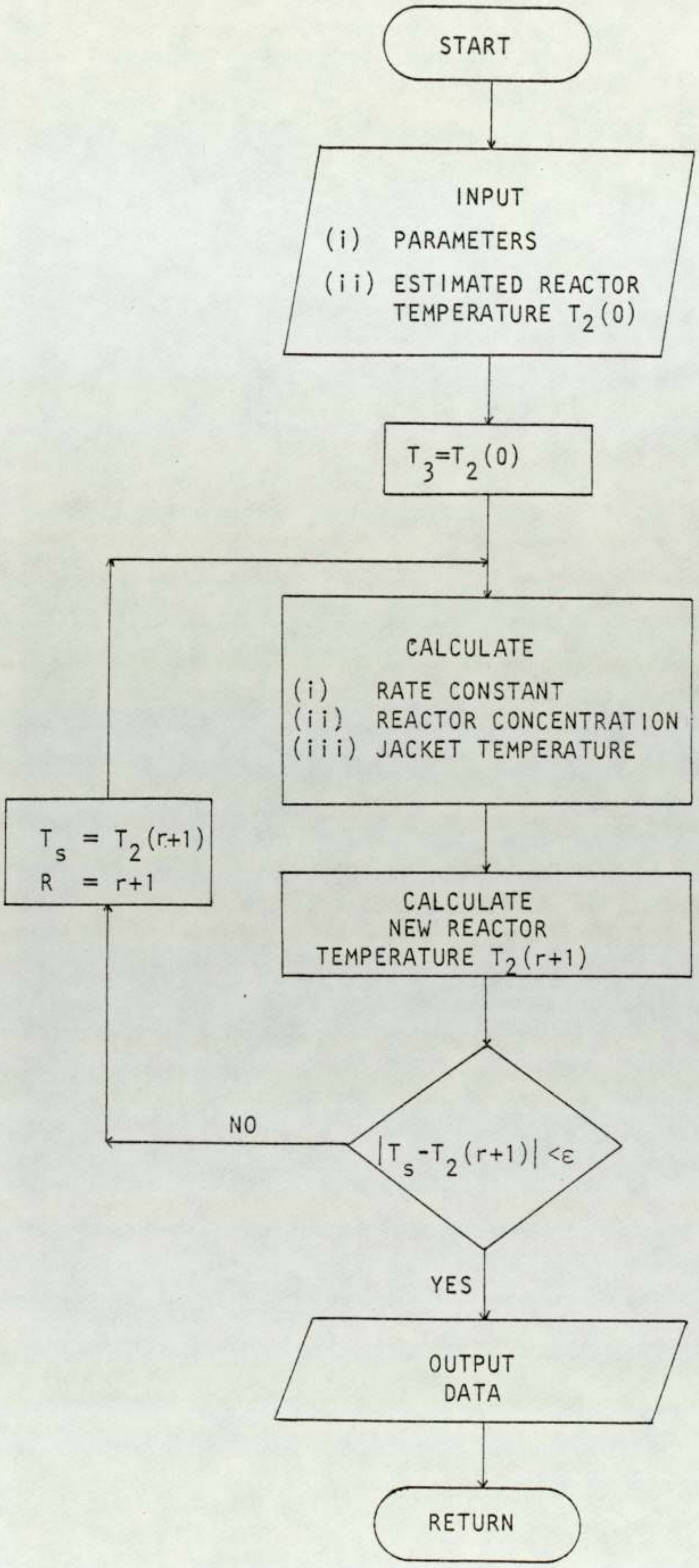
CONTINUED ....


I
INTERRUPT OUTPUT SIGNAL
PUNCH OUT RESULTS
PLOT RESULTS
CONT. ACTION SUBROUTINE
END OF RUN
NO
YES
TERMINATE GRAPHICS
RRETURN

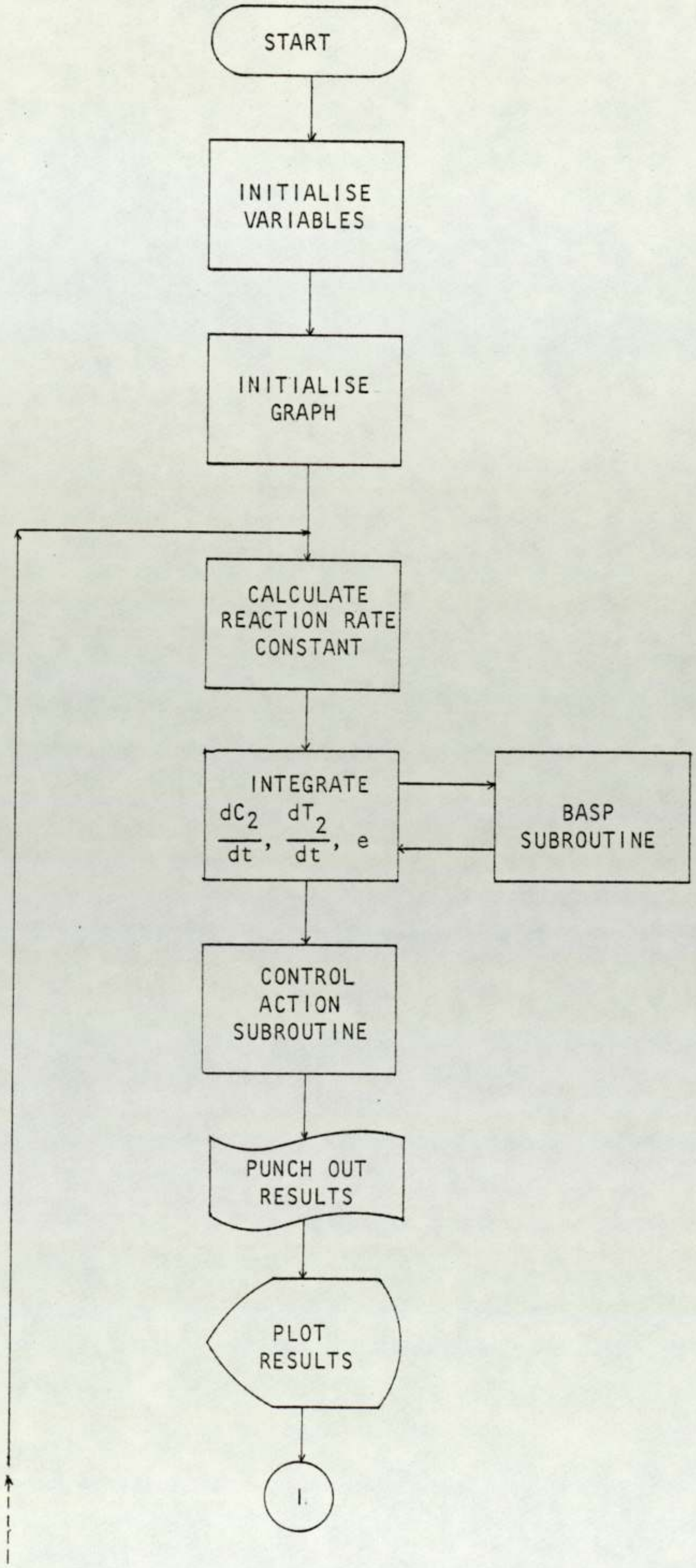
A.4.5 TOTAL SIMULATION MAIN COMPUTER FLOW DIAGRAM



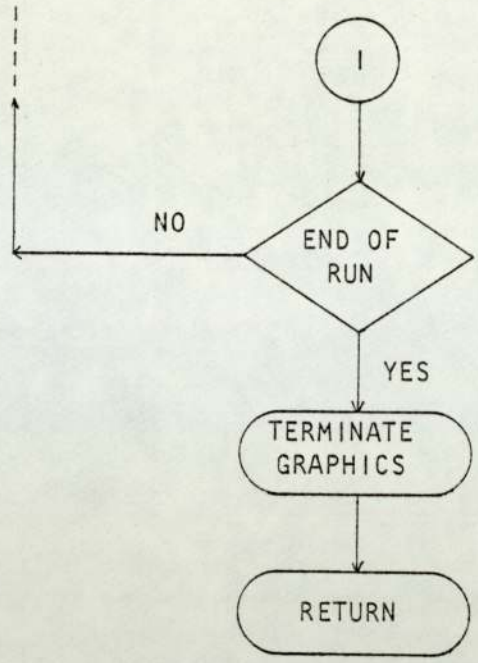
A.4.6 TOTAL SIMULATION STEADY-STATE COMPUTER FLOW DIAGRAM



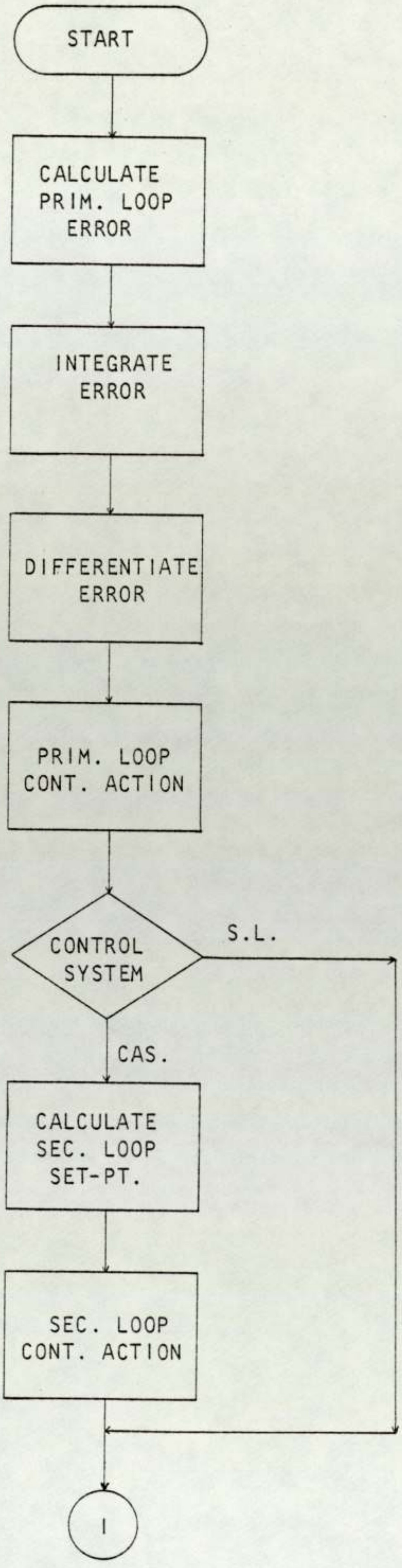
A.4.7 TOTAL SIMULATION UNSTEADY-STATE COMPUTER FLOW DIAGRAM



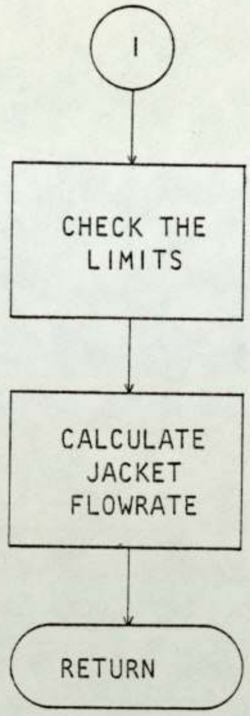
CONTINUED ....


I
NO
END OF
RUN
YES
TERMINATE
GRAPHICS
RETURN

A.4.8 CONTROL ACTION COMPUTER FLOW DIAGRAM



CONTINUED ....


1
CHECK THE LIMITS
CALCULATE JACKET FLOWRATE
RETURN

APPENDIX 5

COMPUTER PROGRAMS

A.5.1 Total Simulation to Predict the Results

```
1   REM          ###### TOTAL SIMULATON ######
2   REM          ###### PREDICT RESULTS ######
3   REM
4   REM
10   DIM X(100),J(100),Y(100),Z(100)
11   DIM R(100),N(100),Q(100),W(100)
90   REM
91   REM         ****** INPUT PARAMETERS ******
92   REM
100   READ V,V1,U0,U1,A4,A6
102   DATA 16,8
104   DATA 3,1
106   DATA 1,1000
108   A0=A4*A6
110   U0=U0/60:U1=U1/60
115   M1=U1*A6:M2=V1*A6
117   M0=M1
120   READ E0,A5,R0
130   DATA .24E05,.63E16,1.987
140   READ H9,U9,L
150   DATA -.3494E05
151   DATA 99,0
160   T0=20
163   T3=5.8
165   C0=1
180   A1=V*H9/(A0*U0):A2=M1/(A0*U0)
181   A3=L/(A0*U0)
185   REM
186   REM         ****** STEADY-STATE ******
187   REM
190   REM
191   REM          ****** ESTIMATED REACTOR TEMPERATURE ******
200   READ T2
210   DATA 20
220   T9=T2
225   REM
226   REM         ****** CALCULATE ******
227   REM
228   REM         $$$$$$ RATE CONSTANT $$$$$$
229   REM
230   K9=A5*EXP(-E0/(R0*(T2+273)))
235   REM
236   REM         $$$$$$ JACKET TEMPERATURE $$$$$$
237   REM
240   T1=(M1*T3+U9*T2)/(M1+U9)
245   REM
246   REM         $$$$$$ REACTOR CONCENTRATION $$$$$$
247   REM
250   C2=U0*C0/(U0+K9*V)
```

```
255  REM
256  REM        $$$$$$ NEW REACTOR TEMPERATURE $$$$$$
257  REM
26Ø  T2=TØ-K9*A1*C2-A2*(T1-T3)-A3
265  REM
266  REM        $$$$$$ CHECK THE NEW AND OLD VALUES $$$$$$
267  REM
27Ø  IF ABS(T9-T2)>.1E-Ø3 THEN  GOTO 22Ø
271  REM        ****** OUTPUT DATA ******
272  PRINT TAB(25);"STEADY-STATE"
273  PRINT
275  PRINT TAB(5);"JACKET";TAB(16);"TANK";TAB(26);"CONC.";
276  PRINT TAB(36);"RATE CONST."
28Ø  PRINT T1;T2;C2;K9
285  REM
286  REM        ****** UNSTEADY-STATE ******
287  REM
29Ø  T(Ø)=TØ:T(1)=T1:T(2)=T2:T(3)=T3
292  C(2)=C2
293  M(1)=M1:K(4)=K9
295  U(Ø)=UØ
3ØØ  REM
3Ø1  REM        ****** INITIALISE VARIABLES ******
3Ø2  REM
31Ø  S1=Ø
312  S2=1Ø
314  S3=Ø
32Ø  PRINT : PRINT
325  PRINT "S1=";S1,"S2=";S2,"S3=";S3
33Ø  TØ=T(Ø)+S1:UØ=U(Ø)+S2/6Ø:T3=T(3)+S3
345  T5=T(2)
347  T6=T(1)
362  R2=4
37Ø  REM
371  REM        ****** CONTROLLER SETTINGS ******
372  REM
38Ø  KØ=1
385  I7=6Ø
39Ø  K1=8.5
392  K2=1
393  K3=1.29
395  I9=4Ø
396  I8=2
4ØØ  K(Ø)=.1
4Ø1  K(1)=.5
4Ø2  FOR Q1=1,1Ø
4Ø3  KØ=K(Ø)+KØ
4Ø5  K1=K(1)+K1
```

```
406  REM
407  REM        ****** SELECT CONTROL SCHEME ******
408  REM
410  FOR G2=1,2
412  IF G2=2 THEN K5=K1:I6=1/I9: GOTO 425
414  K5=K0
419  I6=1/I7
425  E1=500
426  Y5=E1/2
427  P=E1/100
428  H8=P/2
430  PRINT : PRINT
431  P4=E1/P/5
432  PRINT TAB(2);"UNSTEADY-STATE";
433  IF G2=2 THEN 437
434  PRINT TAB(25);"SINGLE-LOOP CONTROL SYSTEM": PRINT
435  PRINT TAB(5);"PROP. GAIN=";K0;TAB(35);"INTEGRAL TIME=";I7
436  GOTO 446
437  PRINT TAB(25);"CASCADE CONTROL SYSTEM": PRINT
440  PRINT TAB(2);"**PRIM. CONT.**  PROP. GAIN=";K1;"INTEG. TIME=";
443  PRINT
445  PRINT TAB(2);"**SEC. CONT. **  PROP. GAIN=";K2
446  PRINT
470  REM
471  REM        ###### START OF INTEGRATION ######
472  REM
473  REM
474  REM        ****** CALL FOR INITIALISATION ******
475  REM
500  CALL (1,T)
501  T1=T(1):T2=T(2)
502  I=-1:C2=C(2)
503  PRINT TAB(2);"TIME";TAB(9);"FLOWRATE";
504  PRINT TAB(19);"JACKET TEMP.";TAB(33);"TANK TEMP.";
505  PRINT TAB(47);"CONC.";TAB(60);"ERROR"
506  M1=M(1):K9=K(4)
507  I0=0:I2=0
510  K9=A5*EXP(-E0/(R0*(T2+273)))
515  REM
516  REM        ****** SET DIFFERENTIAL EQUATIONS ******
517  REM
520  R1=K9*C2
530  D1=M1*(T3-T1)/M2+U9*(T2-T1)/(M2*A4)
540  D2=(T0-T2)*U0/V+(T1-T2)*U9/(V*A0)-H9*R1/A0
550  D3=(C0-C2)*U0/V-R1
555  D6=ABS(T2-T5)
560  D4=T5-T2
```

```
566  REM         ****** CONTROL ACTION ******
567  REM
568  REM         $$$$$$ SINGLE-LOOP SCHEME $$$$$$
569  REM
570  M5=D4+I6*I0
572  IF G2=1 THEN L6=K5*M5: GOTO 590
573  REM
574  REM         $$$$$$ CASCADE SCHEME $$$$$$
575  REM
577  L5=K5*M5+T6
580  D5=L5-T1
585  L6=K2*D5
590  M6=M0-L6
595  REM
596  REM         ****** CALL TO OUTPUT DATA OR TERMINATE RUN ******
597  REM
600  CALL (2,P,E1,F1,F2)
602  IF I*P>=Y5 THEN  IF G2=2 THEN 604
603  GOTO 610
604  FOR I1=Y5/P,E1/P
605  I=I+1
606  R(I)=R(I-1):N(I)=N(I-1):Q(I)=Q(I-1):W(I)=W(I-1)
608  NEXT I1
609  GOTO 700
610  IF F2=1 THEN 630
615  REM
616  REM         ****** PRINT OUT DATA ******
617  REM
620  GOSUB 800
625  REM
626  REM         ****** TERMINATE THE RUN ******
627  REM
630  IF F1=2 THEN 700
633  REM
634  REM         ****** INTEGRATION SECTION ******
635  REM
637  REM         $$$$$$ INTEGRATE INDEPENDENT VARIABLES $$$$$$
638  REM
640  CALL (3,T,H8,R2)
645  REM
646  REM         $$$$$$ INTEGRATE DEPENDENTE VARIABLES $$$$$$
650  CALL (4,T1,D1)
660  CALL (4,T2,D2)
670  CALL (4,C2,D3)
680  CALL (4,I0,D4)
683  CALL (4,I2,D6)
685  M1=M6*K3
690  GOTO 510
```

```
700  PRINT : PRINT
704  PRINT TAB(15);"ABS. VALUE OF THE INTEGRATED DEVIATION "
705  PRINT TAB(15);"IN PLANT TEMP. =";I2
709  PRINT
710  PRINT TAB(15);"INTEGRATED DEVIATION IN PLANT TEMP. =";
711  PRINT -I0
730  INPUT G1
740  IF G2=1 THEN I3=I2:I5=I0: GOTO 750
745  GOSUB 1000
750  NEXT G2
770  NEXT Q1
780  REM
781  REM       ****** END OF MAIN PROGRAM ******
782  REM
790  END
800  REM       ###### OUTPUT DATA SUBROUTINE ######
801  REM
802  REM
810  PRINT TAB(1);T;TAB(3);M1*60/1000;
811  PRINT TAB(17);T1;TAB(29);T2;
812  PRINT TAB(43);C2;TAB(54);D4
817  IF G2=1 THEN 820
818  PRINT TAB(55);D5
820  I=I+1
822  IF G2=1 THEN 830
824  N(I)=T1:Q(I)=T2:R(I)=C2
826  W(I)=M1*60/1000
828  GOTO 840
830  J(I)=T1:X(I)=T2:Y(I)=C2
835  Z(I)=M1*60/1000
836  REM
837  REM       ****** END OF SUBROUTINE ******
838  REM
840  RETURN
```

```
1000  REM       ###### GRAPHICS SUBROUTINE ######
1001  REM
1002  REM
1003  REM
1004  REM       ****** ENTER GRAPHICS ******
1010  CALL (5)
1020  E=0
1040  E2=40:E3=50:E4=10
1050  E5=20:E6=50:E7=30
1060  E8=0:E9=.2:F9=.2
1070  O1=0:O2=20:O3=20
1999  REM
2000  REM       ****** PLOT REACTOR TEMPERATURE VS. TIME ******
2001  REM
2010  CALL (6,0,E1,E2,E4)
2020  CALL (7,2,0,E2,E)
2030  CALL (7,1,E1,E2,E)
2040  CALL (7,1,E1,E3,E)
2050  CALL (7,1,0,E3,E)
2060  CALL (7,1,0,E2,E)
2070  CALL (7,2,0,X(0),E)
2100  FOR I1=1,I
2105  P1=I1*P
2110  CALL (7,2,P1-P,X(I1-1),E)
2120  CALL (7,1,P1,X(I1),E)
2130  CALL (7,2,P1-P,Q(I1-1),E)
2140  CALL (7,1,P1,Q(I1),E)
2150  NEXT I1
2180  P1=E2:P2=E3:P3=E4
2190  GOSUB 8000
2195  CALL (8,7)
2200  CALL (7,2,E1/30,P2-P3/3,E)
2205  CALL (8,7)
2210  PRINT "TANK"
2215  CALL (7,2,E1/30,P2-(P3/3+P3/30),E)
2220  CALL (8,7)
2225  PRINT "TEMP."
2230  CALL (7,2,E1/30,P2-(P3/3+P3/15),E)
2235  CALL (8,7)
2240  PRINT "[ C ]"
2250  GOSUB 8400
```

```
2260  CALL (7,2,E1/2,P1+P3/2,E)
2270  CALL (8,7)
2280  PRINT "INTEGRATED DEVIATION IN PLANT TEMP."
2290  CALL (7,2,E1/2,P1+P3/2-P3/30,E)
2300  CALL (8,7)
2310  PRINT "SINGLE-LOOP =";-I5;"AND";I3
2315  CALL (7,2,E1/2,P1+P3/2-P3/15,E)
2320  CALL (8,7)
2325  PRINT "CASCADE =";-I0;"AND";I2
2400  CALL (7,2,E1*7/30,X(P4),E)
2403  FOR I4=1,4
2404  READ B5
2405  CALL (8,B5)
2410  NEXT I4
2415  CALL (7,2,E1*7/30,Q(P4),E)
2417  FOR I4=1,4
2418  READ B5
2420  CALL (8,B5)
2425  NEXT I4
2430  DATA 83,46,76,46,67,65,83,46
2440  REM
2441  REM        ****** LEAVE GRAPHICS ******
2442  REM
2450  CALL (9)
3199  REM
3200  REM        ****** PLOT JACKET TEMPERATURE VS. TIME ******
3202  REM
3203  REM        ****** ENTER GRAPHICS ******
3204  REM
3210  CALL (5)
3220  CALL (6,0,E1,E5,E7)
3225  CALL (7,2,0,E5,E)
3230  CALL (7,1,E1,E5,E)
3235  CALL (7,1,E1,E6,E)
3240  CALL (7,1,0,E6,E)
3245  CALL (7,1,0,E5,E)
3250  CALL (7,2,0,J(0),E)
3255  FOR I1=1,I
3260  P1=I1*P
3263  CALL (7,2,P1-P,J(I1-1),E)
3265  CALL (7,1,P1,J(I1),E)
3267  CALL (7,2,P1-P,N(I1-1),E)
3268  CALL (7,1,P1,N(I1),E)
3270  NEXT I1
```

```
3280  P1=E5:P2=E6:P3=E7
3290  GOSUB 8000
3295  CALL (8,7)
3300  CALL (7,2,E1/30,P2-P3/3,E)
3305  CALL (8,7)
3310  PRINT "JACKET"
3315  CALL (7,2,E1/30,P2-(P3/3+P3/30),E)
3320  CALL (8,7)
3325  PRINT "TEMP."
3330  CALL (7,2,E1/30,P2-(P3/3+P3/15),E)
3335  CALL (8,7)
3340  PRINT "[ C ]"
3350  GOSUB 8400
3400  CALL (7,2,E1*7/30,J(P4),E)
3403  FOR I4=1,4
3404  READ B5
3405  CALL (8,B5)
3410  NEXT I4
3415  CALL (7,2,E1*7/30,N(P4),E)
3417  FOR I4=1,4
3418  READ B5
3420  CALL (8,B5)
3425  NEXT I4
3430  DATA 83,46,76,46,67,65,83,46
3435  REM
3436  REM       ****** LEAVE GRAPHICS ******
3437  REM
3440  CALL (9)
4299  REM
4300  REM       ****** PLOT REACTOR CONCENTRATION VS. TIME ******
4301  REM
4302  REM       ****** ENTER GRAPHICS ******
4303  REM
4310  CALL (5)
4320  CALL (6,0,E1,E8,F9)
4325  CALL (7,2,0,E8,E)
4330  CALL (7,1,E1,E8,E)
4335  CALL (7,1,E1,E9,E)
4340  CALL (7,1,0,E9,E)
4345  CALL (7,1,0,E8,E)
4350  CALL (7,2,0,Y(0),E)
4355  FOR I1=1,I
4360  P1=I1*P
4363  CALL (7,2,P1-P,Y(I1-1),E)
4365  CALL (7,1,P1,Y(I1),E)
4367  CALL (7,2,P1-P,R(I1-1),E)
4368  CALL (7,1,P1,R(I1),E)
4370  NEXT I1
```

```
4380  P1=E8:P2=E9:P3=F9
4390  GOSUB 8000
4395  CALL (8,7)
4400  CALL (7,2,E1/30,P2-P3/3,E)
4405  CALL (8,7)
4410  PRINT "CONC."
4415  CALL (7,2,E1/30,P2-(P3/3+P3/30),E)
4420  CALL (8,7)
4425  PRINT "[GR./LT.]"
4430  GOSUB 8400
4500  CALL (7,2,E1*7/30,Y(P4),E)
4503  FOR I4=1,4
4504  READ B5
4505  CALL (8,B5)
4510  NEXT I4
4515  CALL (7,2,E1*7/30,R(P4),E)
4517  FOR I4=1,4
4518  READ B5
4520  CALL (8,B5)
4525  NEXT I4
4540  REM
4541  REM        ****** LEAVE GRAPHICS ******
4542  REM
4550  CALL (9)
5399  REM
5400  REM        ****** PLOT JACKET FLOWRATE VS. TIME ******
5401  REM
5402  REM         ****** ENTER GRAPHICS ******
5410  CALL (5)
5420  CALL (6,0,E1,01,03)
5425  CALL (7,2,0,01,E)
5430  CALL (7,1,E1,01,E)
5435  CALL (7,1,E1,02,E)
5440  CALL (7,1,0,02,E)
5445  CALL (7,1,0,01,E)
5450  CALL (7,2,0,Z(0),E)
```

```
5455  FOR I1=1,I
5460  P1=I1*P
5463  CALL (7,2,P1-P,Z(I1-1),E)
5465  CALL (7,1,P1,Z(I1),E)
5467  CALL (7,2,P1-P,W(I1-1),E)
5468  CALL (7,1,P1,W(I1),E)
5470  NEXT I1
5480  P1=O1:P2=O2:P3=O3
5490  GOSUB 8000
5495  FOR I2=1,10
5496  CALL (8,7)
5497  NEXT I2
5500  CALL (7,2,E1/30,P2-P3/3,E)
5505  CALL (8,7)
5510  PRINT "FLOWRATE"
5515  CALL (7,2,E1/30,P2-(P3/3+P3/30),E)
5520  CALL (8,7)
5525  PRINT "[LT./MIN.]"
5530  GOSUB 8400
5600  CALL (7,2,E1*7/30,Z(P4),E)
5603  FOR I4=1,4
5604  READ B5
5605  CALL (8,B5)
5610  NEXT I4
5615  CALL (7,2,E1*7/30,W(P4),E)
5617  FOR I4=1,4
5618  READ B5
5620  CALL (8,B5)
5625  NEXT I4
5630  DATA 83,46,76,46,67,65,83,46
5640  REM
5641  REM        ****** LEAVE GRAPHICS ******
5642  REM
5650  CALL (9)
6000  REM        ****** END OF GRAPHICS ******
6001  REM
6500  REM        ****** END OF SUBROUTINE ******
6501  REM
6510  RETURN
```

```
8000 REM        ###### PRINT IN THE GRAPHS SUBROUTINE ######
8001 REM
8010 CALL (7,2,E1/3,P2-P3/30,E)
8015 CALL (8,7)
8030 PRINT "SINGLE-LOOP CONTROL SYSTEM "
8040 CALL (7,2,E1/3,P2-P3/15,E)
8045 CALL (8,7)
8050 PRINT "PROP. GAIN = ";K0,"INTEG. TIME = ";I7
8060 CALL (7,2,E1/3,P2-P3/10,E)
8070 CALL (8,7)
8100 PRINT "CASCADE CONTROL SYSTEM "
8110 CALL (7,2,E1/3,P2-P3*4/30,E)
8115 CALL (8,7)
8120 PRINT "*PRIM. CONT.*PROP.GAIN=";K1;"INTEG.TIME=";I9
8130 CALL (7,2,E1/3,P2-P3*5/30,E)
8135 CALL (8,7)
8140 PRINT "*SEC. CONT.* PROP. GAIN=";K2
8200 CALL (7,2,E1/3,P2-P3*6/30,E)
8205 CALL (8,7)
8210 PRINT "STEP IN THE INLET TEMP. OF THE TANK = ";S1
8220 CALL (7,2,E1/3,P2-P3*7/30,E)
8225 CALL (8,7)
8230 PRINT "STEP IN THE FLOWRATE OF THE TANK = ";S2
8240 CALL (7,2,E1/3,P2-P3*8/30,E)
8245 CALL (8,7)
8250 PRINT "STEP IN THE INLET TEMP. OF THE JACKET = ";S3
8300 CALL (7,2,E1/3,P2-P3*9/30,E)
8305 CALL (8,7)
8310 PRINT "T0=";T(0),"T3=";T(3),"C0=";C0
8320 CALL (7,2,E1/3,P2-P3/3,E)
8325 CALL (8,7)
8330 PRINT "U0=";U(0)*60,"U1=";U1*60
8340 RETURN
8400 REM          DATA OF THE GRAPHS
8410 CALL (7,2,E1*3/8,P1+P3/30,E)
8415 CALL (8,7)
8420 PRINT "TIME [ SEC. ]"
8425 CALL (7,2,E1/50,P2-P3/30,E)
8430 CALL (8,7)
8435 PRINT P2
8440 CALL (7,2,E1/50,P1+P3/15,E)
8445 CALL (8,7)
8450 PRINT P1
8455 CALL (7,2,E1/30,P1+P3/30,E)
8460 CALL (8,7)
8465 PRINT "0"
8470 CALL (7,2,E1*27/30,P1+P3/30,E)
8475 CALL (8,7)
8480 PRINT E1
8490 REM
8491 REM       ****** END OF SUBROUTINE ******
8492 REM
8500 RETURN
```

A.5.2 Partial Simulation

```
10   REM         ######  PARTIAL SIMULATION  ######
11  REM
12  REM
100  B1=1
110  DIM A(68)
111  DIM I(17)
112  DIM L(25),M(60)
113  REM
114  REM    ****  INPUT THE REQUIRED DATA  ****
115  REM
116  GOSUB 2000
120  GOSUB 2100
122  GOSUB 2150
192  REM
193  REM     ****  INITIAL JACKET FLOWRATE  ****
194  REM
200  M1=9
205  GOSUB 860
297  REM
298  REM     ****  SYSTEM OF STUDY  ****
299  REM
300  PRINT : PRINT
304  REM
305  PRINT "## INPUT ##  1 S/S  2 S.L.  3 CAS. "
306  REM
310  FOR A5= 1, 5
312  L(20)=4: GOSUB 4200
315  NEXT A5
320  INPUT A1
322  IF A1<0 THEN  STOP
323  IF A1>3 THEN 310
327  A2=1:I0,I2=0
328  IF A1<2 THEN 340
329  REM
330  REM     ****  UNSTEADY-STATE IS CHOSEN  ****
331  REM
332  GOSUB 500
333  GOTO 300
337  REM
338  REM     **** STEADY-STATE IS CHOSEN  ****
339  REM
340  GOSUB 400
352  M0=M1
353  T4=T1:T5=T2
355  T6=T0:T7=U0:T8=T3
360  IF A1=0 THEN 310
365  GOTO 300
369  REM
370  REM     ****  END OF MAIN PROGRAM  ****
371  REM
```

```
397  REM
398  REM              ######  STEADY-STATE SUBROUTINE  ######
399  REM
400  B1=1
403  IF A1=0 THEN A7=10
404  REM              ****  INPUT TEMPERATURES SIGNALS  ****
405  GOSUB 700
407  U0=3
408  GOTO 415
409  REM              ****  INPUT REACTOR FLOWRATE SIGNAL  ****
410  GOSUB 750
415  K9=U4*EXP(-U5/(T2+273))
417  C2=C0/(1+K9*V*U1/U0)
419  IF ABS(T1-T2)<.1E-02 THEN U9=M1*U3*(T1-T3)/.1E-02: GOTO 422
420  U9=M1*U3*(T1-T3)/(T2-T1)
422  Q1=U0*U3*(T2-T0)+M1*U3*(T1-T3)
430  Q0=Q3*K9*C2
434  REM              ****  OUTPUT HEAT GENERATION SIGNAL  ****
435  GOSUB 830
440  IF A2<A7-10 THEN 470
445  Q2=Q0-Q1*4.18
447  Q4=Q2/Q0*100
448  IF A1=0 THEN 470
449  REM              ****  OUTPUT REQUIRED DATA  ****
450  GOSUB 900
470  A2=A2+1
475  IF A2<=A7 THEN 405
488  REM              ****  END OF SUBROUTINE  ****
490  RETURN
```

```
497  REM
498  REM             ######  UNSTEADY-STATE SUBROUTINE  ######
499  REM
500  B1=1
509  REM             ****  INITIALISE "BASP"  ****
510  GOSUB 6000
515  GOSUB 9250
519  REM             ****  TIME DELAY  ****
520  P1=20
521  GOSUB 1400
524  REM             ****  OUTPUT INITIAL DATA  ****
525  GOSUB 950
530  GOSUB 3000
547  REM             ****  START OF THE LOOP  ****
548  REM             ****  INPUT TEMPERATURS SIGNALS  ****
550  GOSUB 700
555  K9=U4*EXP(-U5/(T2+273))
559  REM             ****  MASS BALANCE SIMULATION  ****
560  GOSUB 1700
564  REM             ****  OUTPUT HEAT GENERATION SIGNAL  ****
565  Q0=Q3*K9*C2
570  GOSUB 830
574  REM             ****  PLOT RESULTS  ****
575  GOSUB 3100
580  GOSUB 930
585  GOSUB 5350
590  A2=A2+1
600  IF A2<=A9 THEN 550
601  REM             ****  END OF THE LOOP  ****
603  GOTO 610
604  REM             ****  INPUT REACTOR FLOWRATE SIGNAL  ****
605  GOSUB 750
609  REM             ****  TERMINATE GRAPHICS  ****
610  GOSUB 3400
638  REM             ****  END OF SUBROUTINE  ****
640  RETURN
```

```
697  REM      ****  TEMPERATURES ( ANALOGUE INPUTS ) SUBROUTINE *
698  REM
699  REM
700  P0=1:P1=2:P2,P3=1:P4=19:P5=22:P6,P7,P8,P9=0
705  P3=5
717  GOSUB 1100
720  T1=A(19)*A8
723  T2=A(20)*A8
725  T3=A(21)*A6
728  T0=A(22)*A6
745  RETURN
```

```
747  REM      ****  REACTOR FLOWRATE ( COUNTER ) SUBROUTINE  ****
748  REM
749  REM
750  P0=520:P1,P2,P6=2:P3=10:P4,P7=0:P5=31:P8,P9=1
760  N3=0
761  GOSUB 1100
762  U0=.351E-01*U2+.182687
770  RETURN
```

```
820  REM       **** DIGITAL OUTPUT SUBROUTINES ****
821  REM
827  REM            **** HEAT GENERATION ****
829  REM
830  N=1
832  IF Q0>9000 THEN Y0=9000: GOTO 836
834  Y0=Q0
836  GOSUB 1500
838  X=Z3*.32767E05/3.1416
850  GOTO 870
857  REM
858  REM            **** JACKET FLOWRATE ****
859  REM
860  N=2
864  J4=M1
866  GOSUB 1550
868  X=J7*.32767E05/10
870  P0=512:P1,P5,P9=2:P2,P3,P4=1:P6,P7,P8=0
872  GOSUB 1000
875  N=0
876  GOSUB 1000
880  RETURN
```

```
895  REM             ######  PRINT OUT SUBROUTINES  ######
896  REM
899  REM
900  REM              ****  STEADY-STATE  ****
901  REM
905  PRINT "T1="T1;"T2="T2;"T0="T0;"T3="T3
910  PRINT "Q0="Q0;"C2="C2;"U9="U9;"K9="K9
912  PRINT "Q1="Q1*4.18;"Q2="Q2;"ERROR="Q4
913  PRINT "U0="U0: PRINT
920  RETURN
930  REM   **** INITIAL VALUES FOR UNSTEADY-STATE TESTS ****
935  PRINT T1;",";T2;",";T3;",";T0
937  PRINT C2;",";M1;",";Q0
945  RETURN
949  REM
950  REM           •  ****  UNSTEADY-STATE  ****
951  REM
955  CALL (10): CALL (10)
960  PRINT A9;",";R7;",";L(24);",";L(25)
965  PRINT T0;",";T3;",";U0;",";U9;",";Q4
970  CALL (10): CALL (10)
990  RETURN
```

```
1490  REM              ######  INTERPOLATION SUBROUTINES  ######
1491  REM
1492  REM
1499  REM
1500  REM        **** ANALOGUE VOLTAGE VERSUS HEAT GENERATION ****
1501  REM
1502  Y4=Y0/3
1504  IF (Y4-1000),1506,1506,1510
1506  Y5=1:Y6=20
1508  GOTO 1518
1510  IF (Y4-2000),1512,1512,1516
1512  Y5=21:Y6=40
1514  GOTO 1518
1516  Y5=41:Y6=65
1518  Y7=ABS(Y4-Y(Y5))
1520  Y8=Y5
1522  FOR Y9=Y5+1,Y6
1524  IF ABS(Y4-Y(Y9))>=Y7 THEN 1530
1526  Y8=Y9
1528  Y7=ABS(Y4-Y(Y9))
1530  NEXT Y9
1532  Z0=(Y4-Y(Y8))/(Y(Y8)-Y(Y8-1))
1533  Z4=Z(Y8)+Z0*(Z(Y8+1)-Z(Y8))
1535  Z3=Z4+Z0*(Z0-1)*(Z(Y8+1)-2*Z(Y8)+Z(Y8-1))/2
1536  RETURN
1549  REM
1550  REM        **** ANALOGUE VOLTAGE VERSUS JACKET FLOWRATE ****
1551  REM
1556  J5=1
1558  J3=ABS(J4-J(1))
1560  FOR J2=2,35
1562  IF ABS(J4-J(J2))>=J3 THEN 1570
1564  J3=ABS(J4-J(J2)):J5=J2
1570  NEXT J2
1576  J6=(J4-J(J5))/(J(J5)-J(J5-1))
1580  J7=K(J5)+J6*(K(J5+1)-K(J5))+J6*(J6-1)*(K(J5+1)-2*K(J5)+K(J5-1)
1590  RETURN
```

```
1599  REM
1600  REM         ######  NUMERICAL INTEGRATION SUBROUTINE  ######
1601  REM
1602  REM
1625  IF (A2-2), 1627, 1630, 1633
1627  I(0)=D2:I0=0:I(3)=I0: GOTO 1650
1630  I(1)=D2:I0=R6*(I(0)+I(1))/2:I(4)=I0: GOTO 1650
1633  IF A2>3 THEN 1640
1635  I(2)=D2:I0=R6*(I(0)+4*I(1)+I(2))/3
1637  I(5)=I0: GOTO 1650
1640  I(0)=I(1):I(1)=I(2):I(2)=D2
1643  I0=R6*(I(0)+4*I(1)+I(2))/3+I(3)
1645  I(3)=I(4):I(4)=I(5):I(5)=I0
1647  REM
1648  REM              ******  END OF SUBROUTINE  ******
1649  REM
1650  RETURN
```

```
1658  REM         ######  NUMERICAL DIFFERENTIATION SUBROUTINE  ######
1659  REM
1660  REM
1665  IF (A2-2), 1667, 1670, 1673
1667  I(6)=D2:I8=0: GOTO 1690
1670  I(7)=D2:I8=(I(7)-I(6))/R6
1671  GOTO 1690
1673  IF (A2-4), 1675, 1677, 1680
1675  I(8)=D2:I8=(3*I(8)-4*I(7)+I(6))/2/R6
1676  GOTO 1690
1677  I(9)=D2:I8=(11*I(9)-8*I(8)+5*I(7)-2*I(6))/6/R6
1678  GOTO 690
1680  I(6)=I(7):I(7)=I(8):I(8)=I(9):I(9)=D2
1683  I8=(11*I(9)-18*I(8)+9*I(7)-2*I(6))/6/R6
1687  REM
1688  REM         ******  END OF SUBROUTINE  ******
1689  REM
1690  RETURN
```

```
1700  REM        ######  MASS BALANCE SIMULATION SUBROUTINE  ######
1701  REM
1702  REM
1710  D1=(C0-C2)*U0/U1/V-K9*C2
1715  GOSUB 7000
1720  IF R9=2 THEN A4=1
1725  IF R8=2 THEN  STOP
1730  GOSUB 8000
1735  S8=C2
1736  S9=D1
1740  GOSUB 9000
1745  C2=S8
1746  D1=S9
1750  IF A4>1 THEN 1710
1755  A4=2
1759  REM
1760  REM        ******  END OF SUBROUTINE  ******
1761  REM
1790  RETURN
```

```
1950  REM        ######  DERIVATIVE OF ABS. ERROR SUBROUTINE  ######
1951  REM
1952  REM
1955  IF (A2-2),1956,1960,1970
1956  I(10)=D3:I2,I(13)=0
1957  GOTO 1990
1960  I(11)=D3
1961  I2=R6*(I(10)+I(11))/2
1962  I(14)=I2
1965  GOTO 1990
1970  IF A2>3 THEN 1980
1972  I(12)=D3
1973  I2=R6*(I(10)+4*I(11)+I(12))/3
1975  I(15)=I2
1976  GOTO 1990
1980  I(10)=I(11)
1981  I(11)=I(12)
1982  I(12)=D3
1983  I2=R6*(I(10)+4*I(11)+I(12))/3+I(13)
1985  I(13)=I(14)
1986  I(14)=I(15)
1987  I(15)=I2
1988  REM
1989  REM        ******  END OF SUBROUTINE  ******
1990  REM
1991  RETURN
```

```
2000  REM        ######  PROGRAM PARAMETERS  ######
2001  REM
2002  REM
2003  REM
2005  C0=1
2007  V=17.3
2010  H9=.34E05
2013  R4=4
2015  S4=4
2017  R6=4
2020  R7=1600
2021  A7=200
2023  A9=400
2025  U1=60
2027  U3=1000/60
2030  U4=.63E16
2032  U5=.24E05/1.987
2040  A6=4.78*100/1023
2045  A8=4.85*10/1023
2050  K3=1.29
2060  Q3=H9*V*4.18
2065  N0=169
2070  L(24)=26
2071  L(25)=6
2090  RETURN
```

```
2092 REM        ###### INTERPOLATION DATA ######
2093 REM
2094 REM
2098 REM        ****** HEAT OUTPUT VS. TRIGGER ANGLE ******
2099 REM
2100 B1=1
2101 DIM Y(70),Z(70)
2102 Y1=50
2104 Y(0)=0:Z(0)=0
2110 FOR Y2=1,65
2112 Y(Y2)=Y(Y2-1)+Y1
2114 READ Z(Y2)
2115 GOTO 2118
2116 PRINT Y2,Y(Y2),Z(Y2),Z(Y2)*180/3.1416
2118 NEXT Y2
2120 DATA .419988,.532975,.613898,.679532,.735927,.786054
2122 DATA .831593,.873633,.912902,.949921,.985075,1.01866
2124 DATA 1.05091,1.08201,1.11212,1.14135,1.16982,1.19762
2126 DATA 1.22483,1.25151,1.27773,1.30354,1.329,1.35413
2128 DATA 1.37899,1.40362,1.42804,1.45229,1.4764,1.5004
2130 DATA 1.52432,1.54818,1.57203,1.59586,1.61974,1.64367
2132 DATA 1.66768,1.6918,1.71607,1.74051,1.76515,1.79004
2134 DATA 1.81521,1.84069,1.86655,1.89281,1.91954,1.94681
2136 DATA 1.97467,2.00322,2.03254,2.06274,2.09395,2.12633
2138 DATA 2.16007,2.1954,2.23263,2.27216,2.31452,2.36048
2140 DATA 2.41115,2.46833,2.53518,2.6183,2.73691
2145 RETURN
2146 REM
2147 REM        ****** JACKET FLOWRATE VS. VOLTAGE ******
2148 REM
2149 REM
2150 DIM J(40),K(40)
2156 J1=.25
2158 J(0)=.75:K(0)=9
2160 FOR J0=1,36
2162 J(J0)=J(J0-1)+J1
2164 READ K(J0)
2165 GOTO 2168
2166 PRINT J0,J(J0),K(J0)
2168 NEXT J0
2172 DATA 8.25,7.75,7.35,7.05,6.75,6.45,6.18,5.9
2174 DATA 5.65,5.38,5.15,4.9,4.7,4.5,4.32,4.15,4.02,3.85,3.7
2176 DATA 3.55,3.4,3.3,3.15,3.02,2.88,2.77,2.65,2.52
2178 DATA 2.41,2.3,2.15,1.95,1.8,1.5,1.25,0
2185 RETURN
```

```
3000  REM         ###### GRAPHICS INITIALISATION SUBROUTINE ######
3001  REM
3002  REM
3003  REM
3005  L(1)=1:L(2)=0:L(3)=0
3007  GOSUB 4100
3010  L(22)=0:L(23)=R7
3020  L(4)=1
3022  L(5)=L(22):L(6)=L(23):L(7)=L(24):L(8)=L(25)
3026  GOSUB 4120
3030  L(4)=2
3032  L(5)=120:L(6)=850
3034  L(7)=70:L(8)=650
3036  GOSUB 4120
3038  L(5)=L(22):L(6)=L(23):L(7)=L(24):L(8)=L(25)
3040  L(9)=1
3042  L(10)=L(5):L(11)=L(7): GOSUB 4140
3044  L(9)=3
3045  L(10)=L(5)+L(6): GOSUB 4140
3047  L(11)=L(7)+L(8): GOSUB 4140
3049  L(10)=L(5): GOSUB 4140
3051  L(11)=L(7): GOSUB 4140
3055  L(20)=4: GOSUB 4200
3060  L(9)=1:L(10)=0:L(11)=T2: GOSUB 4140
3070  L(9)=3:L(10)=R7:L(11)=T2: GOSUB 4140
3075  L(9)=1:L(10)=0:L(11)=T2: GOSUB 4140
3090  REM
3091  REM         ****** END OF SUBROUTINE ******
3092  REM
3095  RETURN
```

```
3100  REM         ###### GRAPHICS PLOTTING SUBROUTINE ######
3101  REM
3102  REM
3110  L(9)=3
3120  L(10)=R0:L(11)=T2
3125  GOSUB 4140
3129  REM
3130  REM         ****** END OF SUBROUTINE ******
3131  REM
3150  RETURN
```

```
3200  REM          ###### GRAPHICS CURSER SUBROUTINES ######
3201  REM
3202  REM
3203  REM
3230  GOSUB 3350
3235  PRINT "GRAPH NO.=";N0
3237  GOSUB 3360
3238  IF A1=3 THEN 3244
3240  PRINT "SINGLE-LOOP WITH PROP. GAIN =";K0
3241  GOSUB 3360
3242  PRINT "                 AND INTEG. TIME =";1/I6
3243  GOTO 3247
3244  PRINT "CASCADE WITH PROP. GAINS K1=";K1;"K2=";K2
3245  GOSUB 3360
3246  PRINT "AND INTEG. TIME =";I5
3247  GOSUB 3360
3248  PRINT "STEP CHANGE IN TANK INLET TEMPERATURE =";T0-T6
3249  GOTO 3257
3250  PRINT "STEP CHANGE IN TANK FLOWRATE =";U0-T7
3254  GOSUB 3360
3255  PRINT "STEP CHANGE IN JACKET INLET TEMPERATURE=";T3-T8
3257  GOSUB 3360
3260  PRINT "0"
3262  GOSUB 3360
3265  PRINT R7
3267  GOSUB 3360
3270  PRINT L(24)
3272  GOSUB 3360
3275  PRINT L(24)+L(25)
3277  GOSUB 3360
3280  PRINT T5
3290  REM
3291  REM          ****** END OF FIRST SUBROUTINE ******
3292  REM
3300  RETURN
3350  L(16)=0
3355  L(9)=4
3357  L(20)=2
3360  GOSUB 4180
3365  L(10)=L(18):L(11)=L(19)
3370  GOSUB 4140: GOSUB 4200
3374  REM
3375  REM          ****** END OF SECOND SUBROUTINE ******
3376  REM
3380  RETURN
```

```
3492  REM        ###### CO-ORDINANTS SUBROUTINES ######
3493  REM
3494  REM        ****** X-DIRECTION ******
3495  REM
35ØØ  Q8=54
351Ø  L(9)=1
353Ø  L(1Ø)=Ø
3532  L(11)=L(24)+L(25)/28
3534  GOSUB 414Ø
3535  L(2Ø)=2
3536  CALL (9,L(2Ø))
3537  REM
3538  REM        ****** TIME [SECOND] ******
3539  REM
354Ø  PRINT
3541  PRINT TAB(13+Q8/4);"L";
3542  PRINT TAB(13+Q8/2);"L";
3543  PRINT TAB(13+Q8*3/4);"L"
3545  PRINT TAB(13);"Ø";
3546  PRINT TAB(1Ø+Q8/4);R7/4;
3547  PRINT TAB(1Ø+Q8/2);R7/2;
3548  PRINT TAB(1Ø+Q8*3/4);R7*3/4;
3549  PRINT TAB(8+Q8);R7
355Ø  PRINT TAB(9+Q8/2);
3551  PRINT "TIME[SEC]"
356Ø  REM
3561  REM        ****** END OF SUBROUTINE ******
3562  REM
359Ø  RETURN
3599  REM
36ØØ  REM        ****** Y-DIRECTION ******
36Ø1  REM
36Ø7  PRINT : PRINT
36Ø9  PRINT TAB(6);L(24)+L(25);
361Ø  PRINT TAB(13);"-"
3612  FOR I=1,8: PRINT : NEXT I
3615  PRINT TAB(6);L(24)+L(25)*2/3;
3616  PRINT TAB(13);"-"
362Ø  PRINT : PRINT : PRINT
```

```
3625  IF (C5-2),3632,3638,3644
3628  REM
3629  REM       ****** RECTOR TEMPERATURE [DEG.C] ******
3630  REM
3632  PRINT TAB(2);"TANK TEMP"
3634  GOTO 3640
3635  REM
3636  REM       ****** JACKET TEMPERATURE [DEG.C] ******
3637  REM
3638  PRINT "JACKET TEMP"
3640  PRINT TAB(3);"[DEG.C]"
3641  GOTO 3675
3642  IF (C5-4),3646,3658,3670
3643  REM
3644  REM       ****** REACTOR CONCENTRATION [GR/LT] ******
3645  REM
3646  PRINT TAB(2);"TANK CONC"
3648  PRINT TAB(3);"[GR/LT]"
3649  PRINT TAB(3);"*E-02"
3650  GOTO 3675
3652  REM
3654  REM       ****** JACKET FLOWRATE [LT/MIN] ******
3656  REM
3658  PRINT "JACKET FL/R"
3660  PRINT TAB(2);"[LT/MIN]"
3661  GOTO 3675
3665  REM
3666  REM       ****** HEAT GENERATION [WATT] ******
3667  REM
3670  PRINT TAB(2);"HEAT GEN"
3671  PRINT TAB(3);"[WATT]"
3675  PRINT : PRINT : PRINT
3678  PRINT TAB(6);L(24)+L(25)/3;
3680  PRINT TAB(13);"-"
3685  FOR I=1,7: PRINT : NEXT I
3686  IF C5=3 THEN 3690
3687  PRINT
3690  PRINT TAB(6);L(24)
3691  REM
3692  REM       ****** END OF SUBROUTINE ******
3693  REM
3695  RETURN
```

```
4000  REM       ###### EXTENDE-GRAPHICS "CALLS" SUBROUTINES ######
4001  REM
4002  REM
4003  REM
4090  REM       ****** ENTER OR LEAVE GRAPHICS ******
4091  REM
4100  CALL (4,L(1),L(2),L(3))
4110  RETURN
4114  REM
4115  REM       ****** SET VIRTUAL OR SCREEN WINDOW ******
4116  REM
4120  CALL (5,L(4),L(5),L(6),L(7),L(8))
4130  RETURN
4134  REM
4135  REM       ****** PLOT ******
4136  REM
4140  CALL (6,L(9),L(10),L(11))
4150  RETURN
4154  REM
4155  REM       ****** PLOT DASH ******
4156  REM
4160  CALL (7,L(12),L(13),L(14),L(15))
4170  RETURN
4174  REM
4175  REM       ****** CURSER ******
4176  REM
4180  CALL (8,L(16),L(17),L(18),L(19))
4190  RETURN
4194  REM
4195  REM       ****** CAMMANDS OUTSIDE GRAPHICS ******
4196  REM
4200  CALL (9,L(20))
4210  RETURN
4214  REM
4215  REM       ****** COPY COMMON AREA OR IN COMMON AREA ******
4216  REM
4220  CALL (10,L(21),M(1))
4230  RETURN
4239  REM
4240  REM       ****** END OF E/G "CALLS" SUBROUTINES ******
```

```
5347  REM        ###### CONTROL ACTION SUBROUTINE ######
5348  REM
5349  REM
5350  REM
5352  D2=T5-T2
5354  D3=ABS(D2)
5356  GOSUB 1600
5358  GOSUB 1950
5360  GOTO 5365
5362  GOSUB 1660
5363  IF A1=3 THEN 5370
5364  REM        ********* SINGLE-LOOP SCHEME *********
5365  REM
5366  M2=K0*(D2+I6*I0)
5367  GOTO 5380
5368  REM        ********* CASCADE SCHEME *********
5369  REM
5370  M3=K1*(D2+I7*I0)
5375  D4=M3+T4-T1
5377  M2=K2*D4
5380  M6=K3*M2
5385  M1=M0-M6
5390  IF M1<.5 THEN M1=.5
5392  IF M1>9.75 THEN M1=9.75
5393  GOSUB 860
5394  REM
5395  REM        ****** END OF SUBROUTINE ******
5396  REM
5400  RETURN
```

```
5900  REM        ###### BASIC ASTON SIMULATION PROGRAM-BASP ######
5901  REM        ######              SUBROUTINES              ######
5902  REM
5903  REM
5904  REM
5910  REM        ****** INITIALISE ******
5911  REM
6000  DIM R(20),S(20)
6010  R0=0:R1=0:S1=0:S2=0
6020  FOR S0=1,20
6030  R(S0)=0:S(S0)=0
6040  NEXT S0
6045  REM
6046  REM        ****** END OF SUBROUTINE ******
6047  REM
6050  RETURN
```

```
6901  REM        ****** OUTPUT DATA OR TERMINATE RUN ******
6902  REM
7000  IF R1=0 THEN 7050
7010  IF R1<R3-S5/2 THEN 7030
7020  IF S1=2 THEN 7080
7025  IF S2=4 THEN 7080
7030  R9=1
7040  RETURN
7050  R8=1
7060  R3=0
7080  R9=2
7090  R3=R3+R6
7100  IF R1>R7-S4/2 THEN 7120
7110  RETURN
7120  R3=0
7130  R1=0
7140  R8=2
7147  REM
7148  REM        ****** END OF SUBROUTINE ******
7149  REM
7150  RETURN
```

```
7902 REM         ****** INTEGRATE INDEPENDENT VARIABLES ******
7903 REM
8000 R5=R4
8010 S3=0
8020 IF R5=4 THEN 8110
8030 S1=S1+1
8040 ON S1 GOTO 8070,8100,8050
8050 S1=1
8070 S5=S4
8080 R0=R1+S5
8090 R1=R0
8100 RETURN
8110 S2=S2+1
8120 ON S2 GOTO 8170,8220,8190,8220,8130
8130 S2=1
8170 S5=S4/2
8180 GOTO 8080
8190 R0=R0+S5
8200 S5=2*S5
8210 R1=R0
8214 REM
8215 REM         ****** END OF SUBROUTINE ******
8216 REM
8220 RETURN


8901 REM         ****** INTEGRATE DEPENDENT VARIABLES ******
8902 REM
9000 S3=S3+1
9010 IF R5=4 THEN 9070
9020 ON S1 GOTO 9030,9050
9030 R(S3)=S9
9035 S8=S8+S9*S5
9040 RETURN
9050 S8=S8+(S9-R(S3))*S5/2
9060 RETURN
9070 ON S2 GOTO 9080,9120,9120,9180
9080 R(S3)=S9
9090 S(S3)=S8
9100 S8=S8+S9*S5
9110 RETURN
9120 R(S3)=R(S3)+2*S9
9130 S8=S(S3)+S9*S5
9140 RETURN
9180 R(S3)=(R(S3)+S9)/6
9190 S8=S(S3)+R(S3)*S5
9195 REM
9196 REM         ****** END OF SUBROUTINE ******
9197 REM
9200 RETURN
```

```
9240  REM         ###### CONTROLLER SETTINGS SUBROUTINE ******
9241  REM
9242  REM
9250  IF A1=3 THEN 9266
9251  GOTO 9260
9252  REM
9253  REM         ****** SINGLE-LOOP SCHEME ******
9254  REM
9255  PRINT " INPUT K0 & I4 FOR SINGLE-LOOP "
9256  REM
9260  INPUT K0,I4
9262  I6=1/I4
9265  GOTO 9280
9266  REM
9267  REM         ****** CASCADE SCHEME ******
9268  REM
9270  PRINT " INPUT K1 & K2 & I5 FOR CASCADE "
9271  REM
9275  INPUT K1,K2,I5
9277  I7=1/I5
9278  REM
9279  REM         ****** END OF SUBROUTINE ******
9280  RETURN
```

A.5.3 Total Simulation to Confirm the Results

```
10  REM       ######  TOTAL SIMULATION  ######
11  REM       ######  CONFIRM RESULTS   ######
12  REM
13  REM
100  REM
110  DIM L(25)
111  DIM K(401),W(401),Y(401),Z(401)
112  REM
113  REM       ****** INPUT PARAMETERS ******
114  REM
115  GOSUB 2000
120  GOSUB 2000
124  REM
125  REM       ****** INITIAL VALUE ******
126  REM
137  REM       $$$$$$ TEST NUMBER $$$$$$
140  INPUT N0
147  REM       $$$$$$ FORCING VARIABLES $$$$$$
148  REM
150  INPUT T0,T3,U0,M1
154  REM
155  REM       ****** INPUT STEP CHANGES ******
156  REM
170  INPUT X0,X1,X2
297  REM
298  REM       ****** SYSTEM OF STUDY ******
299  REM
300  REM
305  PRINT " ## INPUT ##  1 S/S  2 S.L.  3 CAS. "
310  FOR A5=1,5
312  L(20)=4: GOSUB 4200
315  NEXT A5
320  INPUT A1
322  IF A1<0 THEN  STOP
323  IF A1>3 THEN 300
327  A2=1:I0,I2=0
328  REM
330  IF A1>1 THEN 370
331  REM
332  REM       ****** STEADY-STATE IS CHOSEN ******
333  REM
340  GOSUB 5000
352  M0=M1
353  T4=T1:T5=T2
355  T6=T0:T7=U0:T8=T3
365  GOTO 300
366  REM
367  REM       ****** UNSTEADY-STATE IS CHOSEN ******
368  REM
380  GOSUB 5200
382  GOSUB 3350
383  PRINT
384  GOSUB 3500
485  C5=1
487  GOSUB 3200
490  GOSUB 3600
492  FOR I=1,7: PRINT : NEXT I
```

```
495  REM       ****** PLOT JACKET TEMPERATURE VS. TIME ******
496  REM
497  REM
500  C5=2:R0=0:A2=1:B9=T4
502  L(24)=12
503  L(25)=24
510  GOSUB 3000
520  GOSUB 3500
522  L(9)=3
530  T1=K(A2)
533  L(10)=R0:L(11)=T1
538  GOSUB 4140
540  R0=R0+4
542  A2=A2+1
550  IF A2<=A9 THEN 530
555  GOSUB 3200
560  GOSUB 3600
565  FOR I=1,7: PRINT : NEXT I
```

```
595  REM       ****** PLOT REACTOR CONCENTRATION VS. TIME ******
596  REM
597  REM
600  C5=3:R0=0:A2=1
602  L(24)=2
603  L(25)=3
607  B9=W(1)*100
618  GOSUB 3000
620  GOSUB 3500
622  L(9)=3
630  C2=W(A2)*100
633  L(10)=R0
635  L(11)=C2
638  GOSUB 4140
640  R0=R0+4
642  A2=A2+1
650  IF A2<=A9 THEN 630
655  GOSUB 3200
660  GOSUB 3600
665  FOR I=1,7: PRINT : NEXT I
```

```
695   REM        ****** PLOT JACKET FLOWRATE VS. TIME ******
696   REM
697   REM
700   C5= 4: R0=0: A2= 1
702   L(24)=0
703   L(25)=12
707   B9=Y(1)
718   GOSUB 3000
720   GOSUB 3500
722   L(9)=3
730   M1=Y(A2)
733   L(10)=R0
735   L(11)=M1
738   GOSUB 4140
740   R0=R0+ 4
742   A2=A2+ 1
750   IF A2<=A9 THEN 730
755   GOSUB 3200
760   GOSUB 3600
765   FOR I=1,7: PRINT : NEXT I


795   REM        ****** PLOT HEAT GENERATION VS. TIME ******
796   REM
797   REM
800   C5= 5: R0= 0: A2= 1
802   L(24)=6000
803   L(25)=1500
807   B9=Z(1)
818   GOSUB 3000
820   GOSUB 3500
822   L(9)=3
830   Q0=Z(A2)
833   L(10)=R0
835   L(11)=Q0
838   GOSUB 4140
840   R0=R0+ 4
842   A2=A2+ 1
850   IF A2<=A9 THEN 830
855   GOSUB 3200
860   GOSUB 3600
865   FOR I=1,7: PRINT : NEXT I
870   REM
871   REM        ****** END OF GRAPHICS ******
872   REM
873   REM        ****** TERMINATE GRAPHICS ******
874   REM
880   L(2)=2: GOSUB 4200
885   L(1)=3: GOSUB 4100
886   REM
887   REM        ****** END OF MAIN PROGRAM ******
888   REM
890   END
```

```
900  REM        ###### OUTPUT DATA SUBROUTINE ######
901  REM
902  REM
930  PRINT R0;",";T1;",";T2
932  PRINT T0;",";T3;",";C2
934  PRINT M1;",";Q0
940  REM
941  REM        ****** END OF SUBROUTINE ******
942  REM
945  RETURN
```

```
1998  REM        ###### PARAMETERS SUBROUTINE ######
1999  REM
2000  REM
2002  R3=0
2003  T2=30
2007  V=17.3
2008  V1=8.532
2010  H9=.34E05
2013  S4=4
2015  R4=4
2017  R6=4
2020  R7=1200
2023  A9=R7/R6
2025  U1=60
2027  U3=1000/60
2030  U4=.63E16
2032  U5=.24E05/1.987
2035  K3=1.29
2040  C0=1
2050  A2=1:R0=0
2070  L(24)=36
2071  L(25)=6
2080  U9=37
2085  Q4=1-.4E-01
2087  REM
2088  REM        ****** END OF SUBROUTINE ******
2089  REM
2090  RETURN
```

```
5000  REM        ###### STEADY-STATE SUBROUTINE ######
5001  REM
5002  REM
5090  REM
5091  REM        ****** ASSUME REACTOR TEMPERATURE ******
5092  REM
5094  T9=T2
5095  REM
5096  REM        ****** CALCULATE ******
5097  REM
5098  REM        $$$$$$ RATE CONSTANT $$$$$$
5099  REM
5100  K9=U4*EXP(-U5/(T2+273))
5101  REM
5102  REM        $$$$$$ REACTOR CONCENTRATION $$$$$$
5103  REM
5105  C2=C0/(1+K9*V*U1/U0)
5106  REM
5107  REM        $$$$$$ JACKET TEMPERATURE $$$$$$
5108  REM
5110  T1=(M1*U3*T3+U9*T2)/(M1*U3+U9)
5111  REM
5112  REM        $$$$$$ HEAT GENERATION $$$$$$
5113  REM
5115  Q0=H9*K9*V*C2*4.18
5116  REM
5117  REM        $$$$$$ NEW REACTOR TEMPERATURE $$$$$$
5118  REM
5120  T2=T0+(Q4*Q0/4.18-M1*U3*(T1-T3))/(U0*U3)
5121  REM
5122  REM        $$$$$$ CHECK THE OLD AND NEW VALUES $$$$$$
5123  REM
5125  IF ABS(T9-T2)>.1E-03 THEN 5095
5126  REM
5127  REM        $$$$$$ TERMINATE THE LOOP $$$$$$
5128  REM
5130  PRINT "T1="T1;"T2="T2;"T3="T3;"T0="T0
5135  PRINT "C2="C2;"K9="K9
5138  REM
5139  REM        ****** END OF SUBROUTINE ******
5140  REM
5150  RETURN
```

```
5195  REM        ###### UNSTEADY-STATE SUBROUTINE ######
5196  REM
5197  REM
5198  REM
5199  REM        ****** INITIALISE VARIABLES ******
5200  REM
5201  GOSUB 6000
5202  REM
5203  REM        ****** STEP-CHANGES ******
5204  REM
5205  T0=T6+X0
5206  T3=T3+X1
5207  U0=U0+X2
5208  B9=T5
5209  REM
5210  REM        ****** CONTROLLER SETTINGS ******
5211  REM
5212  GOSUB 9250
5213  REM
5214  REM        ****** ENTER GRAPHICS ******
5215  REM
5216  GOSUB 3000:L(9)=3
5217  REM
5218  REM        ****** SET DIFFERENTIAL EQUATIONS ******
5219  REM
5220  K9=U4*EXP(-U5/(T2+273))
5223  Q0=K9*C2*V*H9*4.18
5224  IF Q0>9000 THEN Q0=9000
5225  D5=(M1*U3*(T3-T1)+U9*(T2-T1))/(V1*1000)
5230  D6=(U0*U3*(T0-T2)+U9*(T1-T2)+Q4*Q0/4.18)/(V*1000)
5235  D1=(C0-C2)*U0/U1/V-K9*C2
5240  D2=T5-T2
5241  D3=ABS(D2)
5242  REM
5243  REM        ****** CONTROL ACTION ******
5244  REM
5245  GOSUB 5350
5246  REM
```

```
5264  REM
5265  IF R8=2 THEN 5335
5266  REM
5267  REM        ****** INTEGRATION SECTION ******
5268  REM
5270  GOSUB 8000
5280  S8=T1:S9=D5
5283  GOSUB 9000
5285  T1=S8:D5=S9
5290  S8=T2:S9=D6
5293  GOSUB 9000
5295  T2=S8:D6=S9
5300  S8=C2:S9=D1
5303  GOSUB 9000
5305  C2=S8:D1=S9
5310  S8=I0:S9=D2
5313  GOSUB 9000
5315  I0=S8:D2=S9
5320  S8=I2:S9=D3
5323  GOSUB 9000
5325  I2=S8:D3=S9
5330  IF A4>1 THEN 5220
5331  REM
5332  REM        ****** END OF INTEGRATION ******
5333  REM
5334  A4=2
5335  FOR I=1,10:L(20)=4
5336  GOSUB 4200: NEXT I
5337  GOTO 5345
5338  GOSUB 3200
5340  L(20)=2: GOSUB 4200
5341  L(1)=3: GOSUB 4100
5342  REM
5343  REM        ****** END OF SUBROUTINE ******
5344  REM
5345  RETURN
```

```
3000  REM        ###### GRAPHICS INITIALISATION SUBROUTINE ######
3001  REM
3002  REM
3003  REM
3005  L(1)=1:L(2)=0:L(3)=0
3007  GOSUB 4100
3010  L(22)=0:L(23)=R7
3020  L(4)=1
3022  L(5)=L(22):L(6)=L(23):L(7)=L(24):L(8)=L(25)
3026  GOSUB 4120
3030  L(4)=2
3032  L(5)=120:L(6)=850
3034  L(7)=70:L(8)=650
3036  GOSUB 4120
3038  L(5)=L(22):L(6)=L(23):L(7)=L(24):L(8)=L(25)
3040  L(9)=1
3042  L(10)=L(5):L(11)=L(7): GOSUB 4140
3044  L(9)=3
3045  L(10)=L(5)+L(6): GOSUB 4140
3047  L(11)=L(7)+L(8): GOSUB 4140
3049  L(10)=L(5): GOSUB 4140
3051  L(11)=L(7): GOSUB 4140
3055  L(20)=4: GOSUB 4200
3060  L(9)=1:L(10)=0:L(11)=T2: GOSUB 4140
3070  L(9)=3:L(10)=R7:L(11)=T2: GOSUB 4140
3075  L(9)=1:L(10)=0:L(11)=T2: GOSUB 4140
3090  REM
3091  REM        ****** END OF SUBROUTINE ******
3092  REM
3095  RETURN
```

```
3100  REM        ###### GRAPHICS PLOTTING SUBROUTINE ######
3101  REM
3102  REM
3110  L(9)=3
3120  L(10)=R0:L(11)=T2
3125  GOSUB 4140
3129  REM
3130  REM        ****** END OF SUBROUTINE ******
3131  REM
3150  RETURN
```

```
3200  REM        ###### GRAPHICS CURSER SUBROUTINES ######
3201  REM
3202  REM
3203  REM
3230  GOSUB 3350
3235  PRINT "GRAPH NO.=";N0
3237  GOSUB 3360
3238  IF A1=3 THEN 3244
3240  PRINT "SINGLE-LOOP WITH PROP. GAIN =";K0
3241  GOSUB 3360
3242  PRINT "               AND INTEG. TIME =";1/I6
3243  GOTO 3247
3244  PRINT "CASCADE WITH PROP. GAINS K1=";K1;"K2=";K2
3245  GOSUB 3360
3246  PRINT "AND INTEG. TIME =";I5
3247  GOSUB 3360
3248  PRINT "STEP CHANGE IN TANK INLET TEMPERATURE =";T0-T6
3249  GOTO 3257
3250  PRINT "STEP CHANGE IN TANK FLOWRATE =";U0-T7
3254  GOSUB 3360
3255  PRINT "STEP CHANGE IN JACKET INLET TEMPERATURE=";T3-T8
3257  GOSUB 3360
3260  PRINT "0"
3262  GOSUB 3360
3265  PRINT R7
3267  GOSUB 3360
3270  PRINT L(24)
3272  GOSUB 3360
3275  PRINT L(24)+L(25)
3277  GOSUB 3360
3280  PRINT T5
3290  REM
3291  REM        ****** END OF FIRST SUBROUTINE ******
3292  REM
3300  RETURN
3350  L(16)=0
3355  L(9)=4
3357  L(20)=2
3360  GOSUB 4180
3365  L(10)=L(18):L(11)=L(19)
3370  GOSUB 4140: GOSUB 4200
3374  REM
3375  REM        ****** END OF SECOND SUBROUTINE ******
3376  REM
3380  RETURN
```

```
3492  REM         ###### CO-ORDINANTS SUBROUTINES ######
3493  REM
3494  REM         ****** X-DIRECTION ******
3495  REM
3500  Q8=54
3510  L(9)=1
3530  L(10)=0
3532  L(11)=L(24)+L(25)/28
3534  GOSUB 4140
3535  L(20)=2
3536  CALL (9,L(20))
3537  REM
3538  REM         ****** TIME [SECOND] ******
3539  REM
3540  PRINT
3541  PRINT TAB(13+Q8/4);"L";
3542  PRINT TAB(13+Q8/2);"L";
3543  PRINT TAB(13+Q8*3/4);"L"
3545  PRINT TAB(13);"0";
3546  PRINT TAB(10+Q8/4);R7/4;
3547  PRINT TAB(10+Q8/2);R7/2;
3548  PRINT TAB(10+Q8*3/4);R7*3/4;
3549  PRINT TAB(8+Q8);R7
3550  PRINT TAB(9+Q8/2);
3551  PRINT "TIME[SEC]"
3560  REM
3561  REM         ****** END OF SUBROUTINE ******
3562  REM
3590  RETURN
3599  REM
3600  REM         ****** Y-DIRECTION ******
3601  REM
3607  PRINT : PRINT
3609  PRINT TAB(6);L(24)+L(25);
3610  PRINT TAB(13);"-"
3612  FOR I=1,8: PRINT : NEXT I
3615  PRINT TAB(6);L(24)+L(25)*2/3;
3616  PRINT TAB(13);"-"
3620  PRINT : PRINT : PRINT
```

```
3625  IF (C5-2),3632,3638,3644
3628  REM
3629  REM         ****** RECTOR TEMPERATURE [DEG.C] ******
3630  REM
3632  PRINT TAB(2);"TANK TEMP"
3634  GOTO 3640
3635  REM
3636  REM         ****** JACKET TEMPERATURE [DEG.C] ******
3637  REM
3638  PRINT "JACKET TEMP"
3640  PRINT TAB(3);"[DEG.C]"
3641  GOTO 3675
3642  IF (C5-4),3646,3658,3670
3643  REM
3644  REM         ****** REACTOR CONCENTRATION [GR/LT] ******
3645  REM
3646  PRINT TAB(2);"TANK CONC"
3648  PRINT TAB(3);"[GR/LT]"
3649  PRINT TAB(3);"*E-02"
3650  GOTO 3675
3652  REM
3654  REM         ****** JACKET FLOWRATE [LT/MIN] ******
3656  REM
3658  PRINT "JACKET FL/R"
3660  PRINT TAB(2);"[LT/MIN]"
3661  GOTO 3675
3665  REM
3666  REM         ****** HEAT GENERATION [WATT] ******
3667  REM
3670  PRINT TAB(2);"HEAT GEN"
3671  PRINT TAB(3);"[WATT]"
3675  PRINT : PRINT : PRINT
3678  PRINT TAB(6);L(24)+L(25)/3;
3680  PRINT TAB(13);"-"
3685  FOR I=1,7: PRINT : NEXT I
3686  IF C5=3 THEN 3690
3687  PRINT
3690  PRINT TAB(6);L(24)
3691  REM
3692  REM         ****** END OF SUBROUTINE ******
3693  REM
3695  RETURN
```

```
4000 REM      ###### EXTENDE-GRAPHICS "CALLS" SUBROUTINES ######
4001 REM
4002 REM
4003 REM
4090 REM      ****** ENTER OR LEAVE GRAPHICS ******
4091 REM
4100 CALL (4,L(1),L(2),L(3))
4110 RETURN
4114 REM
4115 REM      ****** SET VIRTUAL OR SCREEN WINDOW ******
4116 REM
4120 CALL (5,L(4),L(5),L(6),L(7),L(8))
4130 RETURN
4134 REM
4135 REM      ****** PLOT ******
4136 REM
4140 CALL (6,L(9),L(10),L(11))
4150 RETURN
4154 REM
4155 REM      ****** PLOT DASH ******
4156 REM
4160 CALL (7,L(12),L(13),L(14),L(15))
4170 RETURN
4174 REM
4175 REM      ****** CURSER ******
4176 REM
4180 CALL (8,L(16),L(17),L(18),L(19))
4190 RETURN
4194 REM
4195 REM      ****** CAMMANDS OUTSIDE GRAPHICS ******
4196 REM
4200 CALL (9,L(20))
4210 RETURN
4214 REM
4215 REM      ****** COPY COMMON AREA OR IN COMMON AREA ******
4216 REM
4220 CALL (10,L(21),M(1))
4230 RETURN
4239 REM
4240 REM      ****** END OF E/G "CALLS" SUBROUTINES ******
```

```
5347  REM        ###### CONTROL ACTION SUBROUTINE ######
5348  REM
5349  REM
535Ø  REM
5352  D2=T5-T2
5354  D3=ABS(D2)
5356  GOSUB 16ØØ
5358  GOSUB 195Ø
536Ø  GOTO 5365
5362  GOSUB 166Ø
5363  IF A1=3 THEN 537Ø
5364  REM        ********* SINGLE-LOOP SCHEME *********
5365  REM
5366  M2=KØ*(D2+I6*IØ)
5367  GOTO 538Ø
5368  REM        ********* CASCADE SCHEME *********
5369  REM
537Ø  M3=K1*(D2+I7*IØ)
5375  D4=M3+T4-T1
5377  M2=K2*D4
538Ø  M6=K3*M2
5385  M1=MØ-M6
539Ø  IF M1<.5 THEN M1=.5
5392  IF M1>9.75 THEN M1=9.75
5393  GOSUB 86Ø
5394  REM
5395  REM        ****** END OF SUBROUTINE ******
5396  REM
54ØØ  RETURN
```

```
5900  REM        ###### BASIC ASTON SIMULATION PROGRAM-BASP ######
5901  REM        ######            SUBROUTINES             ######
5902  REM
5903  REM
5904  REM
5910  REM        ****** INITIALISE ******
5911  REM
6000  DIM R(20),S(20)
6010  R0=0:R1=0:S1=0:S2=0
6020  FOR S0=1,20
6030  R(S0)=0:S(S0)=0
6040  NEXT S0
6045  REM
6046  REM        ****** END OF SUBROUTINE ******
6047  REM
6050  RETURN


6901  REM        ****** OUTPUT DATA OR TERMINATE RUN ******
6902  REM
7000  IF R1=0 THEN 7050
7010  IF R1<R3-S5/2 THEN 7030
7020  IF S1=2 THEN 7080
7025  IF S2=4 THEN 7080
7030  R9=1
7040  RETURN
7050  R8=1
7060  R3=0
7080  R9=2
7090  R3=R3+R6
7100  IF R1>R7-S4/2 THEN 7120
7110  RETURN
7120  R3=0
7130  R1=0
7140  R8=2
7147  REM
7148  REM        ****** END OF SUBROUTINE ******
7149  REM
7150  RETURN
```

```
7902  REM        ****** INTEGRATE INDEPENDENT VARIABLES ******
7903  REM
8000  R5=R4
8010  S3=0
8020  IF R5=4 THEN 8110
8030  S1=S1+1
8040  ON S1 GOTO 8070,8100,8050
8050  S1=1
8070  S5=S4
8080  R0=R1+S5
8090  R1=R0
8100  RETURN
8110  S2=S2+1
8120  ON S2 GOTO 8170,8220,8190,8220,8130
8130  S2=1
8170  S5=S4/2
8180  GOTO 8080
8190  R0=R0+S5
8200  S5=2*S5
8210  R1=R0
8214  REM
8215  REM        ****** END OF SUBROUTINE ******
8216  REM
8220  RETURN
```

```
8901  REM        ****** INTEGRATE DEPENDENT VARIABLES ******
8902  REM
9000  S3=S3+1
9010  IF R5=4 THEN 9070
9020  ON S1 GOTO 9030,9050
9030  R(S3)=S9
9035  S8=S8+S9*S5
9040  RETURN
9050  S8=S8+(S9-R(S3))*S5/2
9060  RETURN
9070  ON S2 GOTO 9080,9120,9120,9180
9080  R(S3)=S9
9090  S(S3)=S8
9100  S8=S8+S9*S5
9110  RETURN
9120  R(S3)=R(S3)+2*S9
9130  S8=S(S3)+S9*S5
9140  RETURN
9180  R(S3)=(R(S3)+S9)/6
9190  S8=S(S3)+R(S3)*S5
9195  REM
9196  REM        ****** END OF SUBROUTINE ******
9197  REM
9200  RETURN
```

```
9240  REM        ###### CONTROLLER SETTINGS SUBROUTINE ******
9241  REM
9242  REM
9250  IF A1=3 THEN 9266
9251  GOTO 9260
9252  REM
9253  REM        ****** SINGLE-LOOP SCHEME ******
9254  REM
9255  PRINT " INPUT K0 & I4 FOR SINGLE-LOOP "
9256  REM
9260  INPUT K0,I4
9262  I6=1/I4
9265  GOTO 9280
9266  REM
9267  REM        ****** CASCADE SCHEME ******
9268  REM
9270  PRINT " INPUT K1 & K2 & I5 FOR CASCADE "
9271  REM
9275  INPUT K1,K2,I5
9277  I7=1/I5
9278  REM
9279  REM        ****** END OF SUBROUTINE ******
9280  RETURN
```

A.5.4 Graphics

```
10   REM        ###### GRAPHICS PROGRAM ######
11   REM
12   REM
90   DIM L(25),K(400),J(400),W(400),Y(400),Z(400)
93   R0=0
99   REM
100  REM        ****** INPUT PARAMETERS ******
101  REM
102  REM
105  PRINT "INPUT GRAPH NUMBER"
106  INPUT N0
110  PRINT "INPUT CONTROL SYSTEM"
112  INPUT A1
120  PRINT "INPUT CONTROLLER SETTINGS"
122  IF A1=3 THEN 130
124  PRINT "SINGLE-LOOP INPUT K0,I4"
126  INPUT K0,I4
128  GOTO 140
130  PRINT "CASCADE INPUT K1,K2,I5"
132  INPUT K1,K2,I5
140  PRINT "INPUT STEP CHANGES"
142  INPUT X0,X1,X2
150  PRINT " INPUT STEADY-STATE CONDITIONS"
152  INPUT T4,T5
160  PRINT "INPUT L(24),L(25)"
162  INPUT L(24),L(25)
170  PRINT " PRESS SENSE SWITCH 3"
172  INPUT A5
175  REM
176  REM        ****** INPUT STEADY-STATE VALUE ******
177  REM
180  INPUT A9,R7,R1,R2
185  INPUT T0,T3,U0,U9,Q4
187  T6=T0:T7=U0:T8=T3
200  REM
201  REM        ****** ENTER GRAPHICS ******
202  REM
203  REM        ****** SET THE COORDINATES ******
204  REM
205  A2=1
285  S1=T5
287  GOSUB 3000
290  GOSUB 3500
295  L(9)=3
```

```
299   REM
300   REM          ****** START INPUTTING VALUES ******
301   REM          ****** UNSTEADY-STATE ******
302   REM
310   INPUT T1,T2,T3,T0
315   INPUT C2,M1,Q0
330   K(A2)=T1
332   J(A2)=T2
334   W(A2)=C2
336   Y(A2)=M1
338   Z(A2)=Q0
340   REM
341   REM          ****** PLOT REACTOR TEMPERATURE VS. TIME ******
342   REM
350   L(10)=R0
351   L(11)=T2
355   GOSUB 4140
360   R0=R0+4
375   A2=A2+1
380   IF A2<=A9 THEN 300
385   C5=1
400   GOSUB 3400
405   GOSUB 3600
410   FOR I=1,7: PRINT : NEXT I
```

```
495  REM        ****** PLOT JACKET TEMPERATURE VS. TIME ******
496  REM
497  REM
500  C5=2:R0=0:A2=1:B9=T4
502  L(24)=12
503  L(25)=24
510  GOSUB 3000
520  GOSUB 3500
522  L(9)=3
530  T1=K(A2)
533  L(10)=R0:L(11)=T1
538  GOSUB 4140
540  R0=R0+4
542  A2=A2+1
550  IF A2<=A9 THEN 530
555  GOSUB 3200
560  GOSUB 3600
565  FOR I=1,7: PRINT : NEXT I
```

```
595  REM        ****** PLOT REACTOR CONCENTRATION VS. TIME ******
596  REM
597  REM
600  C5=3:R0=0:A2=1
602  L(24)=2
603  L(25)=3
607  B9=W(1)*100
618  GOSUB 3000
620  GOSUB 3500
622  L(9)=3
630  C2=W(A2)*100
633  L(10)=R0
635  L(11)=C2
638  GOSUB 4140
640  R0=R0+4
642  A2=A2+1
650  IF A2<=A9 THEN 630
655  GOSUB 3200
660  GOSUB 3600
665  FOR I=1,7: PRINT : NEXT I
```

```
695  REM        ****** PLOT JACKET FLOWRATE VS. TIME ******
696  REM
697  REM
7ØØ  C5= 4: RØ=Ø: A2=1
7Ø2  L(24)=Ø
7Ø3  L(25)=12
7Ø7  B9=Y(1)
718  GOSUB 3ØØØ
72Ø  GOSUB 35ØØ
722  L(9)=3
73Ø  M1=Y(A2)
733  L(1Ø)=RØ
735  L(11)=M1
738  GOSUB 414Ø
74Ø  RØ=RØ+4
742  A2=A2+1
75Ø  IF A2<=A9 THEN 73Ø
755  GOSUB 32ØØ
76Ø  GOSUB 36ØØ
765  FOR I=1,7: PRINT : NEXT I


795  REM        ****** PLOT HEAT GENERATION VS. TIME ******
796  REM
797  REM
8ØØ  C5= 5: RØ=Ø: A2=1
8Ø2  L(24)=6ØØØ
8Ø3  L(25)=15ØØ
8Ø7  B9=Z(1)
818  GOSUB 3ØØØ
82Ø  GOSUB 35ØØ
822  L(9)=3
83Ø  QØ=Z(A2)
833  L(1Ø)=RØ
835  L(11)=QØ
838  GOSUB 414Ø
84Ø  RØ=RØ+4
842  A2=A2+1
85Ø  IF A2<=A9 THEN 83Ø
855  GOSUB 32ØØ
86Ø  GOSUB 36ØØ
865  FOR I=1,7: PRINT : NEXT I
87Ø  REM
871  REM        ****** END OF GRAPHICS ******
872  REM
873  REM        ****** TERMINATE GRAPHICS ******
874  REM
88Ø  L(2)=2: GOSUB 42ØØ
885  L(1)=3: GOSUB 41ØØ
886  REM
887  REM        ****** END OF MAIN PROGRAM ******
888  REM
89Ø  END
```

```
3ØØØ  REM        ###### GRAPHICS INITIALISATION SUBROUTINE ######
3ØØ1  REM
3ØØ2  REM
3ØØ3  REM
3ØØ5  L(1)=1:L(2)=Ø:L(3)=Ø
3ØØ7  GOSUB 41ØØ
3Ø1Ø  L(22)=Ø:L(23)=R7
3Ø2Ø  L(4)=1
3Ø22  L(5)=L(22):L(6)=L(23):L(7)=L(24):L(8)=L(25)
3Ø26  GOSUB 412Ø
3Ø3Ø  L(4)=2
3Ø32  L(5)=12Ø:L(6)=85Ø
3Ø34  L(7)=7Ø:L(8)=65Ø
3Ø36  GOSUB 412Ø
3Ø38  L(5)=L(22):L(6)=L(23):L(7)=L(24):L(8)=L(25)
3Ø4Ø  L(9)=1
3Ø42  L(1Ø)=L(5):L(11)=L(7): GOSUB 414Ø
3Ø44  L(9)=3
3Ø45  L(1Ø)=L(5)+L(6): GOSUB 414Ø
3Ø47  L(11)=L(7)+L(8): GOSUB 414Ø
3Ø49  L(1Ø)=L(5): GOSUB 414Ø
3Ø51  L(11)=L(7): GOSUB 414Ø
3Ø55  L(2Ø)=4: GOSUB 42ØØ
3Ø6Ø  L(9)=1:L(1Ø)=Ø:L(11)=T2: GOSUB 414Ø
3Ø7Ø  L(9)=3:L(1Ø)=R7:L(11)=T2: GOSUB 414Ø
3Ø75  L(9)=1:L(1Ø)=Ø:L(11)=T2: GOSUB 414Ø
3Ø9Ø  REM
3Ø91  REM        ****** END OF SUBROUTINE ******
3Ø92  REM
3Ø95  RETURN
```

```
31ØØ  REM        ###### GRAPHICS PLOTTING SUBROUTINE ######
31Ø1  REM
31Ø2  REM
311Ø  L(9)=3
312Ø  L(1Ø)=RØ:L(11)=T2
3125  GOSUB 414Ø
3129  REM
313Ø  REM        ****** END OF SUBROUTINE ******
3131  REM
315Ø  RETURN
```

```
3200  REM        ###### GRAPHICS CURSER SUBROUTINES ######
3201  REM
3202  REM
3203  REM
3230  GOSUB 3350
3235  PRINT "GRAPH NO.=";N0
3237  GOSUB 3360
3238  IF A1=3 THEN 3244
3240  PRINT "SINGLE-LOOP WITH PROP. GAIN =";K0
3241  GOSUB 3360
3242  PRINT "                AND INTEG. TIME =";1/I6
3243  GOTO 3247
3244  PRINT "CASCADE WITH PROP. GAINS K1=";K1;"K2=";K2
3245  GOSUB 3360
3246  PRINT "AND INTEG. TIME =";I5
3247  GOSUB 3360
3248  PRINT "STEP CHANGE IN TANK INLET TEMPERATURE =";T0-T6
3249  GOTO 3257
3250  PRINT "STEP CHANGE IN TANK FLOWRATE =";U0-T7
3254  GOSUB 3360
3255  PRINT "STEP CHANGE IN JACKET INLET TEMPERATURE=";T3-T8
3257  GOSUB 3360
3260  PRINT "0"
3262  GOSUB 3360
3265  PRINT R7
3267  GOSUB 3360
3270  PRINT L(24)
3272  GOSUB 3360
3275  PRINT L(24)+L(25)
3277  GOSUB 3360
3280  PRINT T5
3290  REM
3291  REM        ****** END OF FIRST SUBROUTINE ******
3292  REM
3300  RETURN
3350  L(16)=0
3355  L(9)=4
3357  L(20)=2
3360  GOSUB 4180
3365  L(10)=L(18):L(11)=L(19)
3370  GOSUB 4140: GOSUB 4200
3374  REM
3375  REM        ****** END OF SECOND SUBROUTINE ******
3376  REM
3380  RETURN
```

```
3492  REM        ###### CO-ORDINANTS SUBROUTINES ######
3493  REM
3494  REM        ****** X-DIRECTION ******
3495  REM
3500  Q8=54
3510  L(9)=1
3530  L(10)=0
3532  L(11)=L(24)+L(25)/28
3534  GOSUB 4140
3535  L(20)=2
3536  CALL (9,L(20))
3537  REM
3538  REM        ****** TIME [SECOND] ******
3539  REM
3540  PRINT
3541  PRINT TAB(13+Q8/4);"L";
3542  PRINT TAB(13+Q8/2);"L";
3543  PRINT TAB(13+Q8*3/4);"L"
3545  PRINT TAB(13);"0";
3546  PRINT TAB(10+Q8/4);R7/4;
3547  PRINT TAB(10+Q8/2);R7/2;
3548  PRINT TAB(10+Q8*3/4);R7*3/4;
3549  PRINT TAB(8+Q8);R7
3550  PRINT TAB(9+Q8/2);
3551  PRINT "TIME[SEC]"
3560  REM
3561  REM        ****** END OF SUBROUTINE ******
3562  REM
3590  RETURN
3599  REM
3600  REM        ****** Y-DIRECTION ******
3601  REM
3607  PRINT : PRINT
3609  PRINT TAB(6);L(24)+L(25);
3610  PRINT TAB(13);"-"
3612  FOR I=1,8: PRINT : NEXT I
3615  PRINT TAB(6);L(24)+L(25)*2/3;
3616  PRINT TAB(13);"-"
3620  PRINT : PRINT : PRINT
```

```
3625  IF (C5-2),3632,3638,3644
3628  REM
3629  REM        ****** RECTOR TEMPERATURE [DEG.C] ******
3630  REM
3632  PRINT TAB(2);"TANK TEMP"
3634  GOTO 3640
3635  REM
3636  REM        ****** JACKET TEMPERATURE [DEG.C] ******
3637  REM
3638  PRINT "JACKET TEMP"
3640  PRINT TAB(3);"[DEG.C]"
3641  GOTO 3675
3642  IF (C5-4),3646,3658,3670
3643  REM
3644  REM        ****** REACTOR CONCENTRATION [GR/LT] ******
3645  REM
3646  PRINT TAB(2);"TANK CONC"
3648  PRINT TAB(3);"[GR/LT]"
3649  PRINT TAB(3);"*E-02"
3650  GOTO 3675
3652  REM
3654  REM        ****** JACKET FLOWRATE [LT/MIN] ******
3656  REM
3658  PRINT "JACKET FL/R"
3660  PRINT TAB(2);"[LT/MIN]"
3661  GOTO 3675
3665  REM
3666  REM        ****** HEAT GENERATION [WATT] ******
3667  REM
3670  PRINT TAB(2);"HEAT GEN"
3671  PRINT TAB(3);"[WATT]"
3675  PRINT : PRINT : PRINT
3678  PRINT TAB(6);L(24)+L(25)/3;
3680  PRINT TAB(13);"-"
3685  FOR I=1,7: PRINT : NEXT I
3686  IF C5=3 THEN 3690
3687  PRINT
3690  PRINT TAB(6);L(24)
3691  REM
3692  REM        ****** END OF SUBROUTINE ******
3693  REM
3695  RETURN
```

```
4000  REM        ###### EXTENDE-GRAPHICS "CALLS" SUBROUTINES ######
4001  REM
4002  REM
4003  REM
4090  REM        ****** ENTER OR LEAVE GRAPHICS ******
4091  REM
4100  CALL (4,L(1),L(2),L(3))
4110  RETURN
4114  REM
4115  REM        ****** SET VIRTUAL OR SCREEN WINDOW ******
4116  REM
4120  CALL (5,L(4),L(5),L(6),L(7),L(8))
4130  RETURN
4134  REM
4135  REM        ****** PLOT ******
4136  REM
4140  CALL (6,L(9),L(10),L(11))
4150  RETURN
4154  REM
4155  REM        ****** PLOT DASH ******
4156  REM
4160  CALL (7,L(12),L(13),L(14),L(15))
4170  RETURN
4174  REM
4175  REM        ****** CURSER ******
4176  REM
4180  CALL (8,L(16),L(17),L(18),L(19))
4190  RETURN
4194  REM
4195  REM        ****** CAMMANDS OUTSIDE GRAPHICS ******
4196  REM
4200  CALL (9,L(20))
4210  RETURN
4214  REM
4215  REM        ****** COPY COMMON AREA OR IN COMMON AREA ******
4216  REM
4220  CALL (10,L(21),M(1))
4230  RETURN
4239  REM
4240  REM        ****** END OF E/G "CALLS" SUBROUTINES ******
```

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