



The computerized control of a double-effect evaporator
by Renee Jacqueline Amicucci

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in
Chemical Engineering
Montana State University
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Abstract:

The purpose of this investigation was to determine the optimal control configuration of a double-effect evaporator by a study of the interaction between the two effects.

Three control configurations were studied, each with different pairings of controlled and manipulated variables. The three pairings were as follows: 1. The level in the first effect was paired with the flow out of the first effect, and the level in the second effect was paired with the flow out of the second effect. The desired feed flow into the system was entered into the computer and controlled by a separate control loop.

2. The level in the first effect was paired with the flow into the first effect and the level in the second effect was paired with the flow into the second effect. The flow out of the second effect was held constant.

3. The level in the first effect was paired with the flow out of the first effect, and the level in the second effect was paired with the flow into the first effect. The liquid product rate was fixed.

An Apple II microcomputer with an Isaac laboratory interface was used to control the system.

The first configuration pairing was such that the coupling was minimized and the response satisfactory over a range of values. The second configuration responded well if the conditions were such that the feed change was not so great as to create coupling problems between the two effects. The third configuration was oscillatory and the control unsatisfactory due to the severe coupling between the two effects.

A dynamic model of the system was developed which corresponded well with the actual data.

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DOUBLE-EFFECT EVAPORATOR

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A thesis submitted in partial fulfillment
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APPROVAL

of a thesis submitted by

Renee Jacqueline Amicucci

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citation, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ABSTRACT

The purpose of this investigation was to determine the optimal control configuration of a double-effect evaporator by a study of the interaction between the two effects.

Three control configurations were studied, each with different pairings of controlled and manipulated variables. The three pairings were as follows:

1. The level in the first effect was paired with the flow out of the first effect, and the level in the second effect was paired with the flow out of the second effect. The desired feed flow into the system was entered into the computer and controlled by a separate control loop.
2. The level in the first effect was paired with the flow into the first effect and the level in the second effect was paired with the flow into the second effect. The flow out of the second effect was held constant.
3. The level in the first effect was paired with the flow out of the first effect, and the level in the second effect was paired with the flow into the first effect. The liquid product rate was fixed.

An Apple II microcomputer with an Isaac laboratory interface was used to control the system.

The first configuration pairing was such that the coupling was minimized and the response satisfactory over a range of values. The second configuration responded well if the conditions were such that the feed change was not so great as to create coupling problems between the two effects. The third configuration was oscillatory and the control unsatisfactory due to the severe coupling between the two effects.

A dynamic model of the system was developed which corresponded well with the actual data.

INTRODUCTION

The purpose of this investigation was to determine the optimal control configuration of a double-effect evaporator. However before any details can be discussed some general concepts and terms of process control must be defined. The first terms to be defined are the variables of the process, these variables are separated into three categories. The first category contains the controlled variables or the variables which are to be controlled. The second group contains the manipulated variables which are variables the controller can change in order to control the process. The third group of variables are the disturbances. These are inputs that affect the process but cannot be controlled. There is usually a delay between the time the disturbance enters the system and time any effect of the disturbance is seen; this delay is called the dead time of the system. Another term which needs to be defined is the setpoint; the setpoint is the desired value of the controlled variable. The deviation from the setpoint is called the error. The error is used in the various control concepts as the basis for making changes in the manipulated variables.

The two basic control concepts are feed-back and feed-forward control. Feed-back control is a concept which, as its name indicates, measures an error and sends it to a controller that will change a manipulated variable and try to drive the controlled variable back to the setpoint. Feed-forward control is a control concept which attempts to detect a disturbance as it enters the process and make the changes in the manipulated variable so the controlled variable remains at its setpoint. Feed-forward control attempts to make corrections before the disturbance creates an error in the controlled variable. Ideally feed-forward control would be the best approach to take, however it assumes exact measurement of all the disturbances which enter the system and a perfect model of the process,

which is generally not the case. Therefore, many control systems employ a combination of the two concepts, feed-forward to begin correcting for measured disturbances before they reach the controlled variable and feed-back control to correct for all other disturbances.

The variables in a process can be either continuous or discrete depending upon the type of control being utilized. Continuous variables are variables which are measured or manipulated constantly such as those used in analog control. This is done by the use of pneumatic or electronic control loops which give all signals as continuous functions of time. In a digital system the variables are discrete due to the discrete levels within the computer and the periodic sampling of the variables. The discrete levels within the computer were adequate for the accuracy needed in this investigation so we are only concerned with the discreteness brought about by the sampling. The variables are measured or manipulated at set intervals creating signals which are not continuous functions of time but instead are narrow pulses. The sampling interval is called the sampling period and is usually constant. The signals from the transducers and to the valves must always be continuous so when discrete variables are used the need arises for analog-to-digital (A/D) and digital-to-analog (D/A) converters. The A/D converters are used to change an analog signal to a digital signal by sampling the continuous signal at a frequency equal to the sampling period. The D/A converters change digital to analog by holding the digital signal constant between samples.

The major difference between computer control and conventional control is that computer control involves discrete signals whereas conventional control involves a continuous signal. In both types of control the measuring device senses the value of the controlled variable. In conventional control this value is sent directly to the controller where an error is calculated. An appropriate response is then generated and sent to the control element. In computerized control this value is sent to an A/D converter where it is sampled periodically by the digital computer. The error is calculated and then used in a computer program, which represents the controller, to calculate a discrete controller output. The

output signal is sent to a D/A converter and then to the control element. It may appear as if more equipment is necessary for computerized control but it should be noted that one computer can replace many conventional controllers.

With computerized controllers there is a flexibility which cannot be obtained with conventional controllers. In recent times, as more and more processes are being switched to computerized control, a variety of complex control strategies have been developed. These strategies can improve performance in some processes by compensating for dead time, decoupling multivariable control loops and various other techniques which take into account some of the complex dynamics of a system.

Fisher and Seborg [1] at the University of Alberta have done a case study of multivariable computer control with a double-effect evaporator. The objective of the control strategies discussed in the study was the maintenance of the concentration of the liquid product. The evaporator was a multivariable system with some degree of coupling. Coupling exists when a change in one manipulated variable changes, not only the controlled variable it was intended to change, but other controlled variables as well. Fisher and Seborg studied how to control the concentration while this investigation was more concerned with how the coupling affects the control. By focusing primarily on level control, the coupling and interactive effects could be studied without being concerned with maintaining concentration. With that in mind, the purpose of this investigation was to determine the optimal control configuration of an existing double-effect evaporator by a study of the coupling. To study these effects three different pairings of controlled and manipulated variables were chosen to be evaluated in this investigation. The manipulated variables were the flows into each effect and the flow out of the last effect. The controlled variables were the levels in each effect and the system throughput. The three pairings were as follows:

1. The level in the first effect was paired with the flow out of the first effect, and the level in the second effect was paired with the flow out of the second effect.

The desired feed flow into the system was entered into the computer and controlled by a separate control loop.

2. The level in the first effect was paired with the flow into the first effect and the level in the second effect was paired with the flow into the second effect. The flow out of the second effect was held constant.
3. The level in the first effect was paired with the flow out of the first effect, and the level in the second effect was paired with the flow into the first effect. The liquid product rate was fixed.

An Apple II microcomputer with an Isaac laboratory interface was used to control the system. Due to the lack of appreciable dead time and other complicating dynamics it was decided to implement proportional-integral controllers.

EXPERIMENTAL

Equipment

The first step taken toward computerizing the system was the removal of the conventional controllers and replacement by an Apple II microcomputer with a lab interface.

Figure 1 shows a simplified schematic of the double-effect evaporator system. The feed line had a pressure gage on it. The pressure could be approximately set by changing the amount of cooling water used in the second effect condenser. Typical feed rates were between 5 and 10 lb/min. There was also, on the feed line, a pneumatic control valve, valve number 1, and an orifice, labeled A in Figure 1, with a pressure transducer which measured the pressure drop across the orifice. The first effect had an external heat exchanger. The steam line entering the exchanger had an adjustable back-pressure regulator on it to vary the steam pressure if desired; for this investigation it was decided to keep the steam at 15 psig. A pressure transducer and a thermocouple (the thermocouples used were iron-constantan) were installed on the steam line. Each effect had installed on it a pressure transducer, a thermocouple and a level transducer. The radius of each effect was one foot and the heat transfer area in each approximately 10 square feet. The liquid holdup in each effect was approximately 950 pounds. The liquid product from the first effect entered the second effect through a pneumatic control valve between the effects, valve number 2 in Figure 1. The vapor from the first effect entered the heat exchanger in the second effect and heated the liquid in the second effect. The condensed vapor passed through a steam trap and into a condensate tank which was under a vacuum. The second effect was also

under a vacuum. The vapor from the second effect went to a condenser and then to a condensate tank, both of which were on the vacuum line. The liquid product was pumped out of the second effect and passed through pneumatic control valve number 3.

A new control panel was installed to hold three current-to-pressure converters, three voltage-to-current converters and the connector strips for the wiring as well as the air pressure regulator. A three way switch was also used to facilitate shutdown and restart procedures.

Procedure

Three different control configurations were investigated. In the figures showing control configurations the dashed lines denote the pairings of controlled variables to manipulated variables, the pairing was done via the computer which was not shown in the figures. The first configuration, shown in Figure 2, was where the feed flow was input by the operator, and was checked and adjusted by a separate control loop. The level in the first effect determined the flow out of the first effect, and the level in the second effect determined the flow out of the second effect. The second method of control, shown in Figure 3, involved a cascade control loop on the feed line. Cascade control was a type of control where the output of one control loop, the primary controller, manipulated the setpoint of another control loop, the secondary controller. Cascade control was utilized when there were frequent variations in a manipulated variable. The feed line pressure was not constant on the evaporator system so the feed into the first effect varied constantly. The secondary controller checked the actual flow through the orifice and compared it with the setpoint. An appropriate manipulation of the valve on the feed line was then made. The setpoint of the flow rate was manipulated by the primary controller, which, in this instance, was the level controller for the first effect. In this method, the level in the first effect determined the setpoint of the feed flow into the system, and the level in the second effect determined

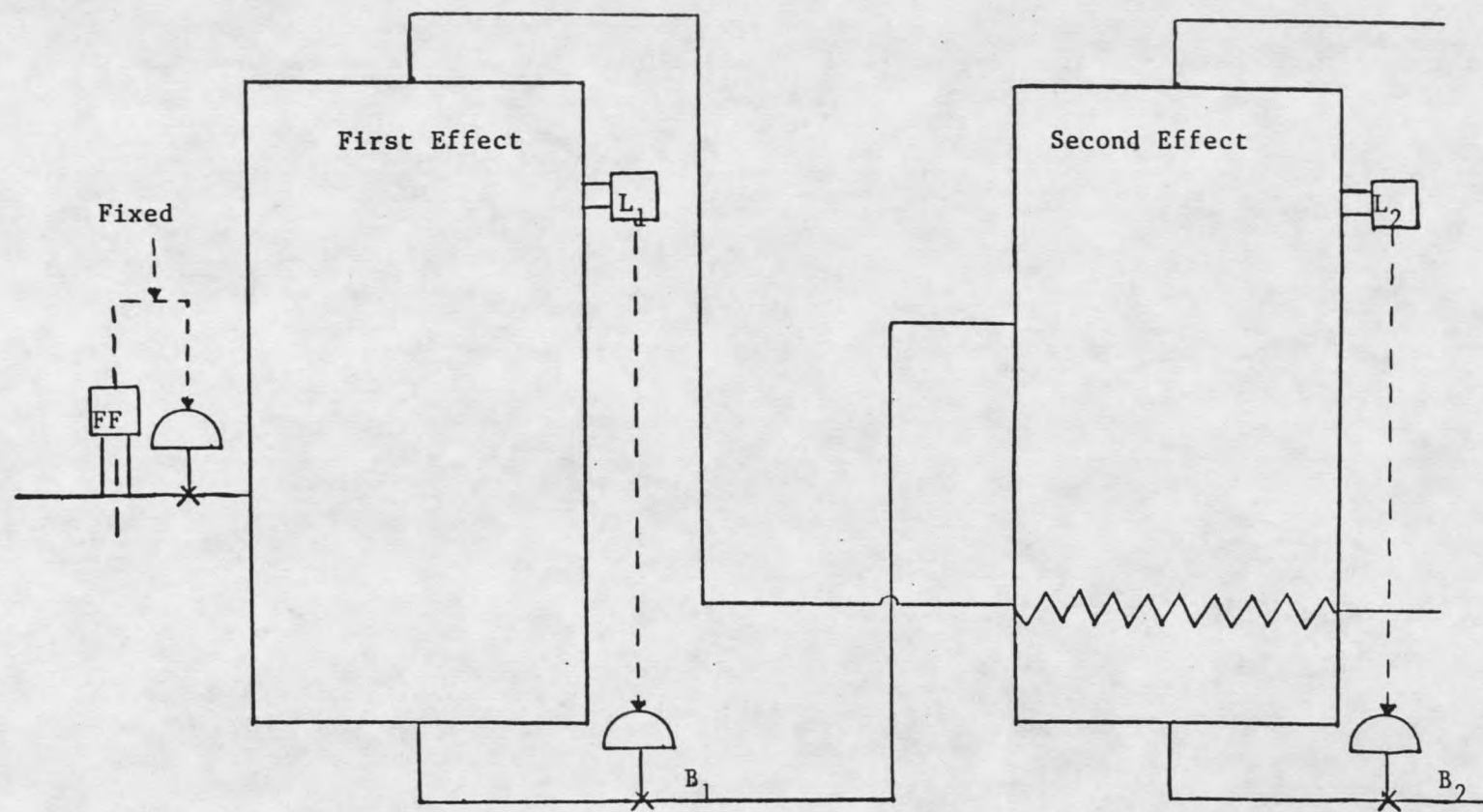


Figure 2. First control configuration.

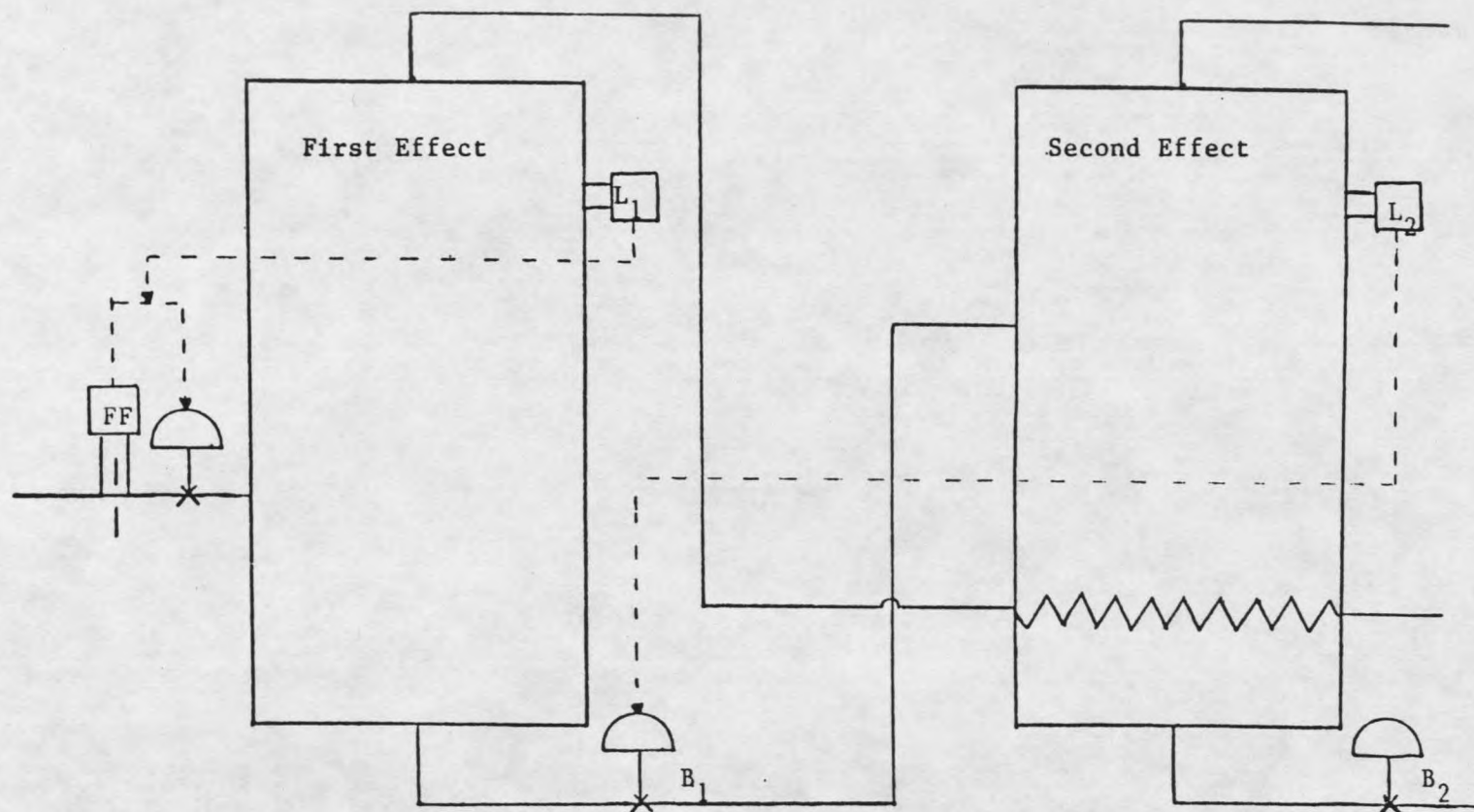


Figure 3. Second control configuration.

the flow into that effect. The flow out of the second effect was set by a stationary valve and the product pump. The third configuration, shown in Figure 4, was a mixture of the first two methods, the liquid product flow out of the second effect was still a constant. However, now the level in the second effect controlled the feed flow into the system, with a cascade loop as in the second configuration, while the level in the first effect determined the flow out of the first effect. Proportional-integral controllers were used in all three control configurations. Copies of the main programs were included in the Appendices.

Smaller computer programs were written in order to find the control constants for the proportional-integral (PI) controllers. A more detailed explanation of the PI equation was included in the Theory section of this thesis. These programs utilized a trial and error approach where the operator entered a gain constant (K_c) and an integral time (τ_I) for a specific valve into the computer, and the program plugged into the PI equation:

$$V_m = V_{(m-1)} + K_c (e_m - e_{(m-1)} + (T/\tau_I) e_m)$$

where: V was the controller output

T was the sampling period

e was the error, the deviation from the setpoint

m (subscript) indicated the m th sampling period

The feed valve control constants were found by hooking the computer up to the evaporator and running a program which checked the actual value of the feed flow, calculated from the reading of the pressure transducer across the orifice, with the desired value. The program printed out the actual value and the valve movement. If the valve was not responding satisfactorily, the program was started again with new constants. The control constants for the other two valves, labeled 2 and 3 in Figure 1, were found in a slightly different manner. Approximate values were chosen for one set of valve constants while the other set, for the other valve, were asked for by the computer program every run. The computer printed out the actual level and the valve moment only for the valve being tested. If the

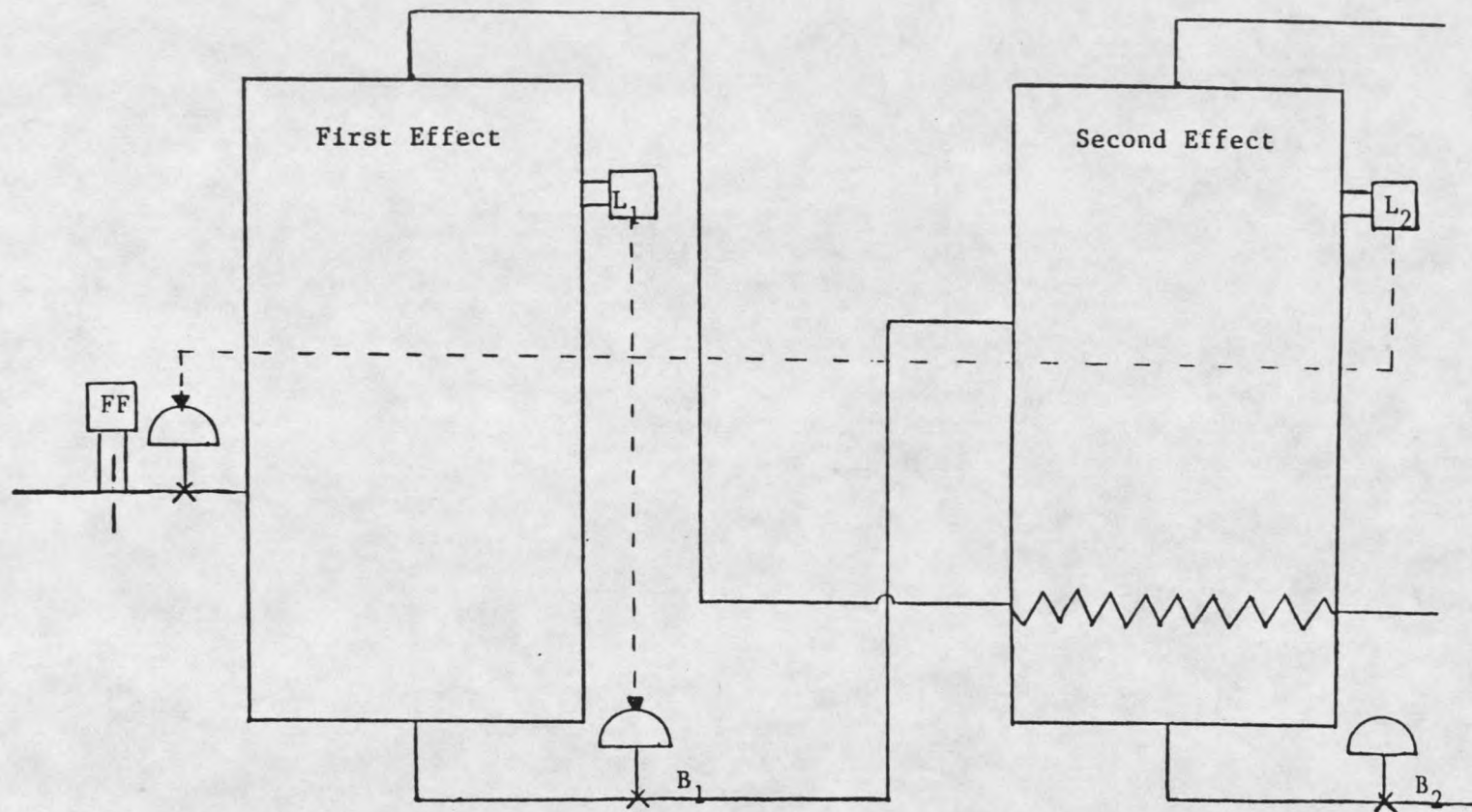


Figure 4. Third control configuration.

response was not acceptable, new control constants were tried until it was acceptable. Once one valve was responding properly the procedure was repeated to find the other set of valve control constants, using the previously determined values for the first valve rather than approximate values. The sampling periods were determined from experimental data using a procedure outlined in *Chemical Process Control* [2]. The procedure needed to be modified for the evaporator system because, unlike the process used in the book, the liquid levels in the evaporator do not level off to a steady value after a deviation; they keep increasing. This was dealt with by using the controlled process response curve, which does level off, to find a process time constant. Using this method will give a time constant somewhat faster than the actual process, which will in turn give a shorter sampling period. The sampling period used was twenty seconds, this value could have been larger but seemed to work quite well. Two sampling periods were needed; one for the level control loops and one for the feed control loop. The sampling period for the level control loops was determined as explained previously, the feed control loop presented a different problem. The response of the feed flow rate to a change in pressure is very fast; therefore due to the practical limitations of the computer system the sampling period used in the feed control loop was chosen to be fifteen seconds. This value was chosen because it was relatively small so the computer will sample at short intervals and it is smaller than the sampling period used for the levels, which is necessary in order to utilize cascade control.

Once the constants had been determined the performance of the three configurations could be evaluated. The main programs were run, each using a different configuration for control. After the system had reached steady-state with one configuration the operator could input a deviation. For the first configuration the deviation could be in the feed flow rate or the setpoint of the levels; for the second and third configurations the deviations could be either liquid product rate or the setpoint of the levels. The system's reaction to the disturbance was recorded by the program, and the configuration with the best control

could be evaluated by comparison of the responses. The deviation used for comparison with other configurations was the setpoint change of the level in the first effect.

THEORY

Proportional-Integral Controller

A proportional-integral controller utilizes both the proportional action, which moves the control valve directly proportional to the magnitude of the error, and the integral action which moves the valve based on the time integral of the error. A development of the proportional-integral equation is given by Deshpande and Ash [3]. The equation for the proportional-integral controller, or PI controller, in continuous variable form is:

$$V_{(t)} = V_{(0)} + K_c (e_{(t)} + (1/\tau_I) \int_0^t e_{(t)} dt) \quad (1)$$

where: $V_{(t)}$ is the controller output at time t

$V_{(0)}$ is the output at time $t=0$

K_c is the controller gain, the number of units change in output signal for each unit of error signal under proportional control action

$e_{(t)}$ is the error signal, deviation from setpoint

τ_I is the integral time

In discrete variable form, at the m th sampling period this equation becomes by numerical integration of Equation 1:

$$V_{(m)} = V_{(0)} + K_c (e_m + (1/\tau_I) \sum_{i=0}^m e_i T) \quad (2)$$

where: T is the sampling period

A similar equation is obtained for the $(m-1)$ th sampling instant.

$$V_{(m-1)} = V_{(0)} + K_c (e_{m-1} + (1/\tau_I) \sum_{i=0}^{m-1} e_i T) \quad (3)$$

If these two equations are subtracted from each other ($V_{(m)} - V_{(m-1)}$) the resulting equation is the velocity form of the digital PI controller:

$$V_{(m)} = V_{(m-1)} + K_c [(e_m - e_{m-1}) + (T/\tau_1) e_m] \quad (4)$$

Model

A dynamic model of the double-effect evaporator was developed to simulate the system. The model required the utilization of various equations. An energy balance for each effect is given by Fisher and Seborg [4] as:

$$d(W_n \times HL_n)/dt = F_n \times HLF_n - O_n \times HV_n - B_n \times HL_n - EL_n + Q_n \quad (5)$$

where: W_n is the weight of the liquid holdup in the nth effect

HL_n is the enthalpy of the liquid in the nth effect

t is time

F_n is the feed flow rate into the nth effect

HLF_n is the enthalpy of the feed

O_n is the overhead vapor flow rate

HV_n is the enthalpy of the vapor

B_n is the bottoms flow rate

EL_n is the environmental heat losses

Q_n is the heat added to the nth effect

Expressing the enthalpies in terms of temperatures and simplifying by using zero as the reference temperature, Equation 5 becomes:

$$W_n/L_n \times Cp(T_n \times dL_n/dt + L_n \times dT_n/dt) = Q_n + F_n \times Cp \times TF_n - O_n(Cp \times T_n + VL_n) - EL_n - B_n \times Cp \times T_n \quad (6)$$

where: T_n is the temperature in the nth effect

TF_n is the temperature of the feed into the nth effect

L_n is the level of liquid in the nth effect

C_p is the heat capacity of the liquid

VL_n is the latent heat of vaporization of the liquid in the nth effect

Another equation necessary to develop the model is a mass balance which is as follows:

$$dW_n/dt = F_n - O_n - B_n \quad (7)$$

A flow diagram of the double-effect evaporator is shown in Figure 1. F_n for the first effect is the feed into the system, FF , and TF_n is the temperature of the feed, TF . The energy balance for the first effect, with rearranging becomes:

$$dT_1/dt = ((FF \times C_p(TF - T_1) - O_1 \times VL_1 - EL_1 + Q_1) / (W_1/L_1 \times C_p) - T_1 \times dL_1/dt) / L_1 \quad (8)$$

However, the overhead vapor from the first effect, O_1 , heats the second effect, which means:

$$O_1 \times VL_1 = U_2 \times A_2 (T_1 - T_2) \quad (9)$$

where U_2 is the overall heat transfer coefficient of the vapor entering the second effect and A_2 is the heat transfer area. Substituting Equation 9 into Equation 8 gives the form of the energy balance used in the model:

$$dT_1/dt = ((FF \times C_p(TF - T_1) - U_2 \times A_2 (T_1 - T_2) - EL_1 + Q_1) / (W_1/L_1 \times C_p) - T_1 \times dL_1/dt) / L_1 \quad (10)$$

Q_1 is calculated using the equation:

$$Q_1 = U_1 \times A_1 (TS - T_1) \quad (11)$$

here TS is the temperature of the steam, U_1 is the overall heat transfer coefficient and A_1 is the heat transfer area of the first effect.

The feed into the second effect is the bottoms flow out of the first effect and the temperature of the liquid in the first effect. The temperature in the second effect is essentially constant because the pressure is fairly constant due to the vacuum pump. Therefore $dT_2/dt = 0$, which makes the energy balance for the second effect as follows:

$$O_2 = (Q_2 - B_2 \times Cp(T_2 - T_1) - EL_2 - (W_2 / L_2 \times Cp \times T_2) dL_2 / dt) / (Cp(T_2 - T_1) + V \cdot L_2) \quad (12)$$

where Q_2 is found by Equation 9.

The liquid flow rates are found from the characteristics of the control valves. The equation for the flow through a control valve is [5] :

$$F = C_v \times f_{(x)} \times \sqrt{(dP/SG)} \quad (13)$$

where: F is the flow rate (lb/min)

C_v is the valve constant

x is the valve stem position, fraction of wide open

$f_{(x)}$ is the valve flow characteristic

SG is the specific gravity relative to water

dP is the pressure drop over the valve (psi)

The valve flow characteristic, $f_{(x)}$, is found experimentally and is commonly one of the following three; linear trim, square root trim and equal percentage trim. If constant pressure drop is assumed, a half open linear valve gives approximately 50 percent of maximum flow, a square root valve gives about 70 percent while an equal percentage valve gives around 15 percent. The valve between the two effects and the valve after the second effect, valves 2 and 3 respectively in Figure 1, are linear so $f_{(x)} = x$; the feed valve is a square root valve which means $f_{(x)} = \sqrt{x}$. C_v was found experimentally as it was not given by the manufacturers of the valves. The pressure drop, dP , is different for each valve. For valve number 1, on the feed line, the pressure drop is the difference between the feed line pressure and the pressure in the first effect which is determined from the temperature in the first effect. The pressure drop across valve number 2 is determined by the pressure in each effect. The product pumps' outlet pressure is approximately constant on one side of valve number 3, while the other side is at atmospheric pressure. Therefore, for valve number 3 the square root quantity is a constant and can be found experimentally as part of the valve

constant. The variable in Equation 13 is therefore x . The x is the controller output $V_{(m)}$ in Equation 4. The simulation of digital control was accomplished by allowing the valves to move only at the sample times, so although the simulation was continuous the control was digital.

The environmental heat losses were experimentally determined as were the overall heat transfer coefficients, U_1 and U_2 and the heat transfer areas A_1 and A_2 . In summary the equations used in the model are as follows:

First effect

$$dT_1/dt = ((FF \times Cp(T_F - T_1) - U_2 \times A_2(T_1 - T_2) - EL_1 + Q_1) / (W_1/L_1 \times Cp) - T_1 \times dL_1/dt) / L_1 \quad (10)$$

$$Q_1 = U_1 \times A_1(T_S - T_1) \quad (11)$$

$$dW_1/dt = FF - (U_2 \times A_2(T_1 - T_2)) / (VL_1 - B_1) \quad (15)$$

$$B_1 = 12.25 \times x \times \sqrt{(P_1 - P_2)} \quad (16)$$

Second effect

$$O_2 = (U_2 \times A_2(T_1 - T_2) - B_2 \times Cp(T_2 - T_1) - EL_2 - (W_2/L_2 \times Cp \times T_2)dL_2/dt) / (Cp(T_2 - T_1) + VL_2) \quad (12)$$

$$dW_2/dt = B_1 - O_2 - B_2 \quad (17)$$

$$B_2 = 33.5 \times x \quad (18)$$

The model works by assuming for the first iteration the levels in both effects are at their setpoints. The temperature of the first effect, T_1 , is calculated using Equation 10 and a fourth-order Runge Kutta numerical integration subroutine. The bottoms flow rate, B_1 , is then determined by the controller and the valve equations; if it is not a sample time, the valve position remains constant. A new level is calculated using the mass balance equation, Equation 15, during each iteration to replace the previous level which in turn changes B_1 and T_1 . Once B_1 and T_1 are known, for each iteration, the overhead flow rate from the

second effect, O_2 , can be calculated using Equation 12, and values for B_2 and L_2 can be generated from Equations 18 and 17 respectively. After a period of time, when steady-state has been achieved, the setpoint for the level in the first effect is changed to a preset value. This setpoint deviation is implemented by use of a counter inside the program. A copy of the Fortran program is included in the Appendices.

RESULTS AND DISCUSSION

The response curves from two runs of each configuration have been plotted in the succeeding figures. The step change disturbance used in the three configurations was a change in the setpoint of the level in the first effect. The setpoint for level 2 was 5 feet. Each configuration was run twice to show reproducibility.

The first configuration was shown in Figure 2. For the first run the feed rate was approximately 10 lb/min with a pressure in the second effect of 2.2 psia. The response curve was plotted in Figure 5, where it can be seen that the control was satisfactory. There was a small overshoot in the level of the first effect but it was too small to be of any importance. The liquid level in the second effect showed the coupling effects. When the valve between the effects closed so the level in the first effect could increase to its new set point, the level in the second effect decreased and visa versa. Every move the middle valve made while trying to keep the level in the first effect at its setpoint disrupted the level in the second effect. The model response curve for the same conditions as the response in Figure 5 was plotted in Figure 6. The large dip which occurred when the valve between the two effects closed was larger in the process response curve probably because of the leakage through the liquid product valve, which was noticed during the experiments. The second run response curve was plotted in Figure 7, the feed for this run was approximately 10.0 lb/min with a pressure of 4.6 psia in the second effect. The control was satisfactory at the higher pressure also.

The coupling involved in the second configuration, shown in Figure 3, was more complicated. The reverse configuration meant the movements of the middle valve to maintain the level in the second effect would disrupt the liquid level in the first effect. Disruption of

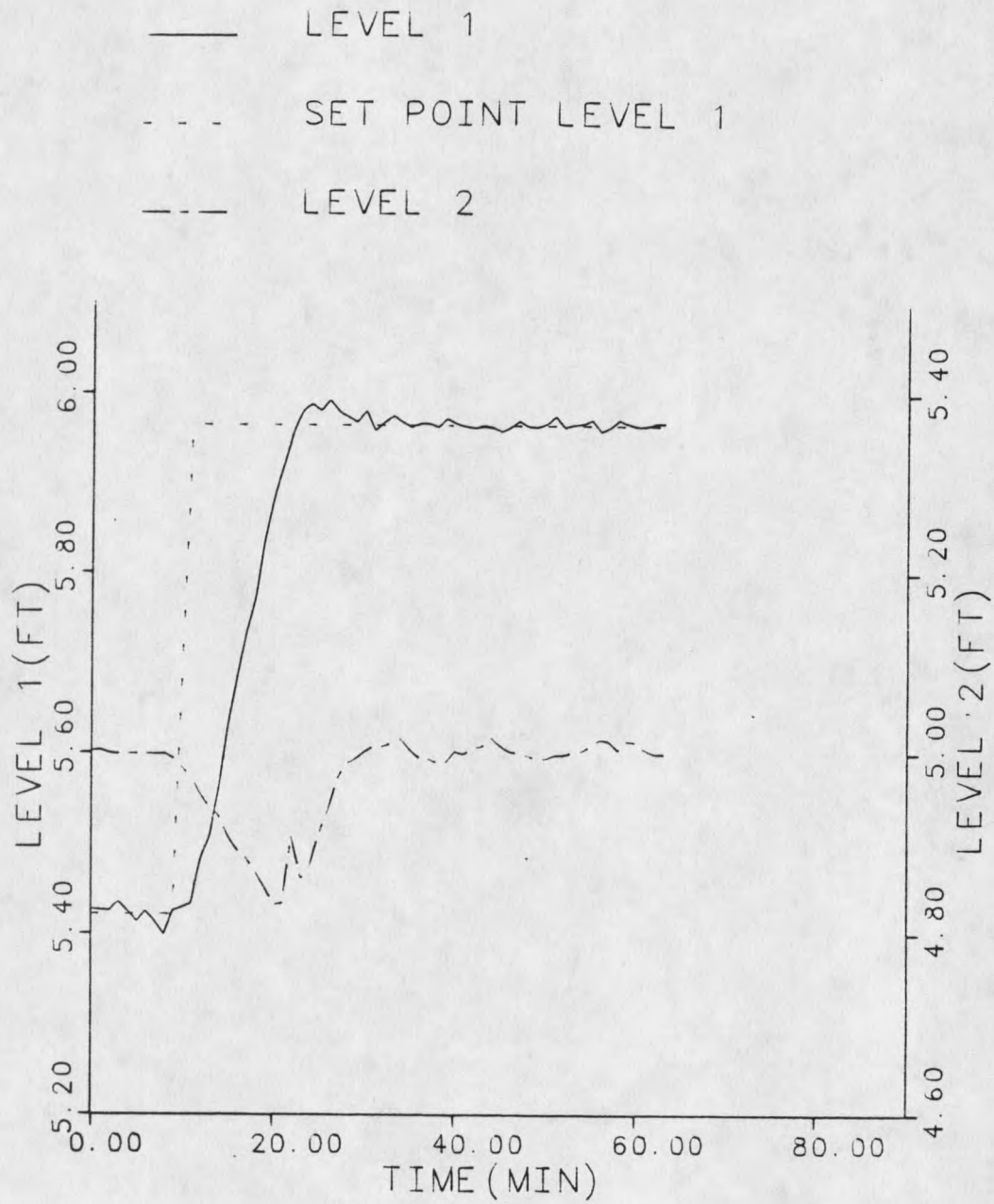


Figure 5. Process response curve of the first configuration with a feed rate of 10 lb/min and a pressure of 2.2 psia in the second effect.

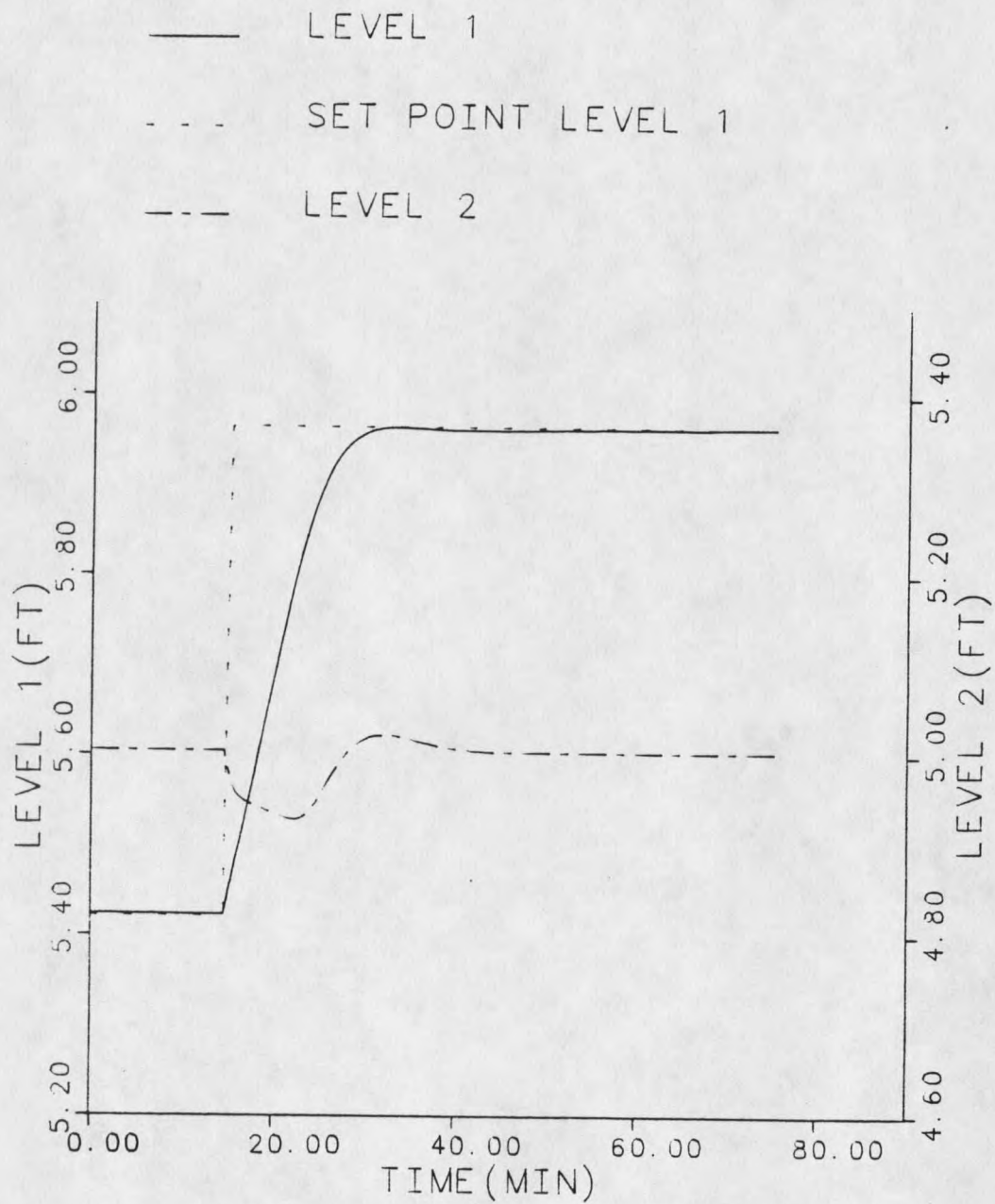


Figure 6. Model response curve of the first configuration with a feed rate of 10 lb/min and a pressure of 2.2 psia in the second effect.

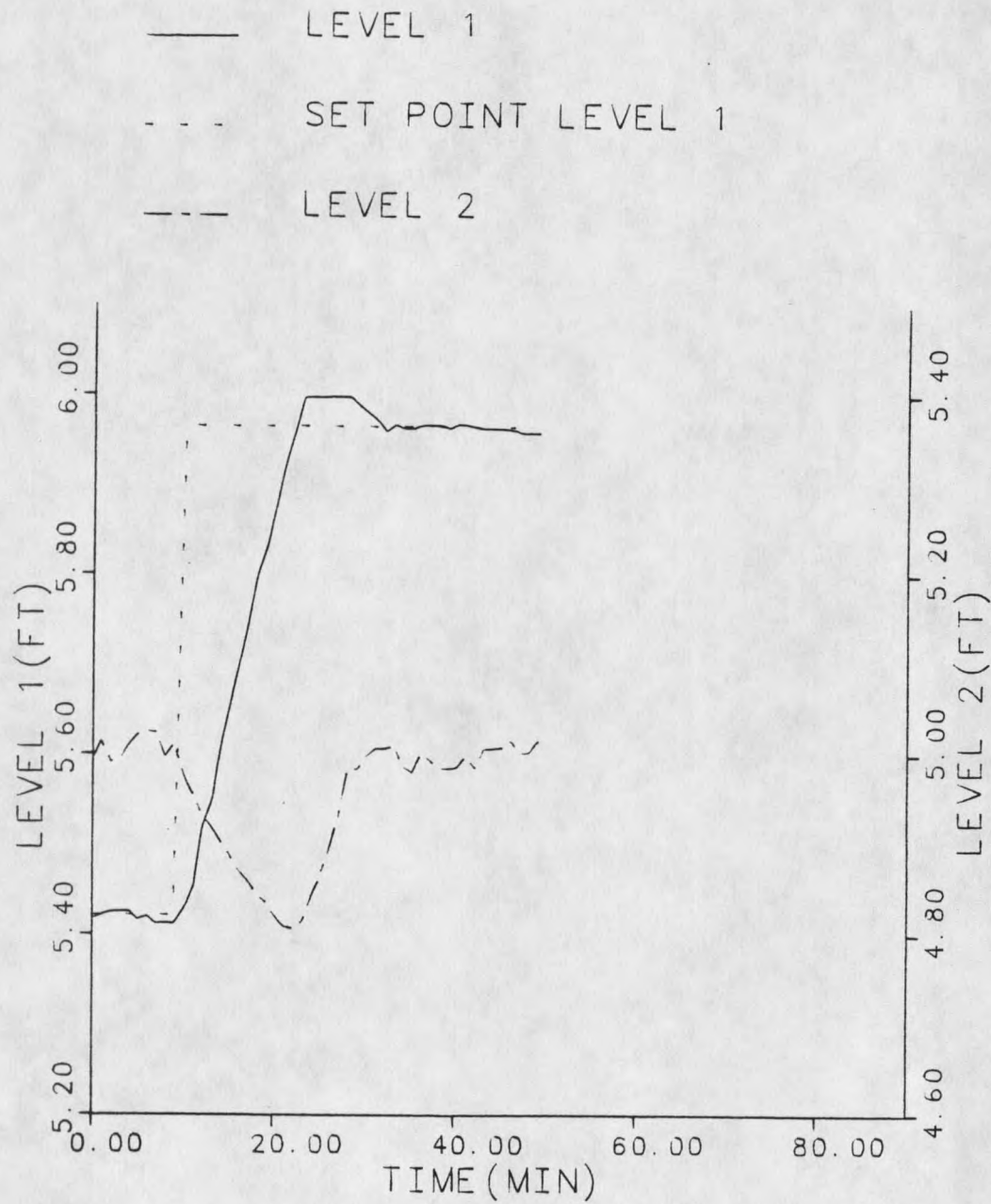


Figure 7. Process response curve of the first configuration with a feed rate of 10 lb/min and a pressure of 4.6 psia in the second effect.

the level in the first effect would disrupt the feed flow into the first effect. If the disruption was large enough, the temperature in the first effect could change which would change the pressure; which would, in turn, change the liquid flow rate through the middle valve. Also, if the liquid stopped boiling it would change the heat entering the second effect as well. The response curves for the second configuration were plotted in Figures 8 and 9. The curves showed that for the conditions of the run the coupling effects were minimal and the control was quite good. The level fluctuations in the first effect shown in Figure 8 were small enough to be observed through the glass porthole on the side of the effect. The lower pressure could have had some effect on the control and thereby created the oscillations, however, the model response, shown in Figure 10, does not indicate the given pressure change would cause oscillatory behavior. The general model was modified to determine if hysteresis in the movement of the valves could help account for the discrepancies between the model and process response curves. This was done by incorporating some hysteresis in the valve between the two effects and then the effect the hysteresis had on the control was evaluated. The degree of hysteresis was unknown so a value of ten percent was chosen for the study. This value was fairly high but again, this was only to study the effect of the hysteresis in a qualitative manner, not quantitative. The hysteresis model response curves were plotted in Figures 11 and 12. The conditions of the run in Figure 11 corresponded to those of the run plotted in Figure 8. The two curves were quite similar which indicated the oscillation may have been due, in part, to some valve hysteresis. The lower pressure had some effect also, because Figure 12, which corresponded to Figure 9, depicted a run at the higher pressure and it did not show oscillatory behavior. The actual hysteresis was probably not ten percent since the oscillation in the level in the second effect were quite a bit larger with the hysteresis model than in the actual process. The general model, without the hysteresis, was used for all the other model response curves in this

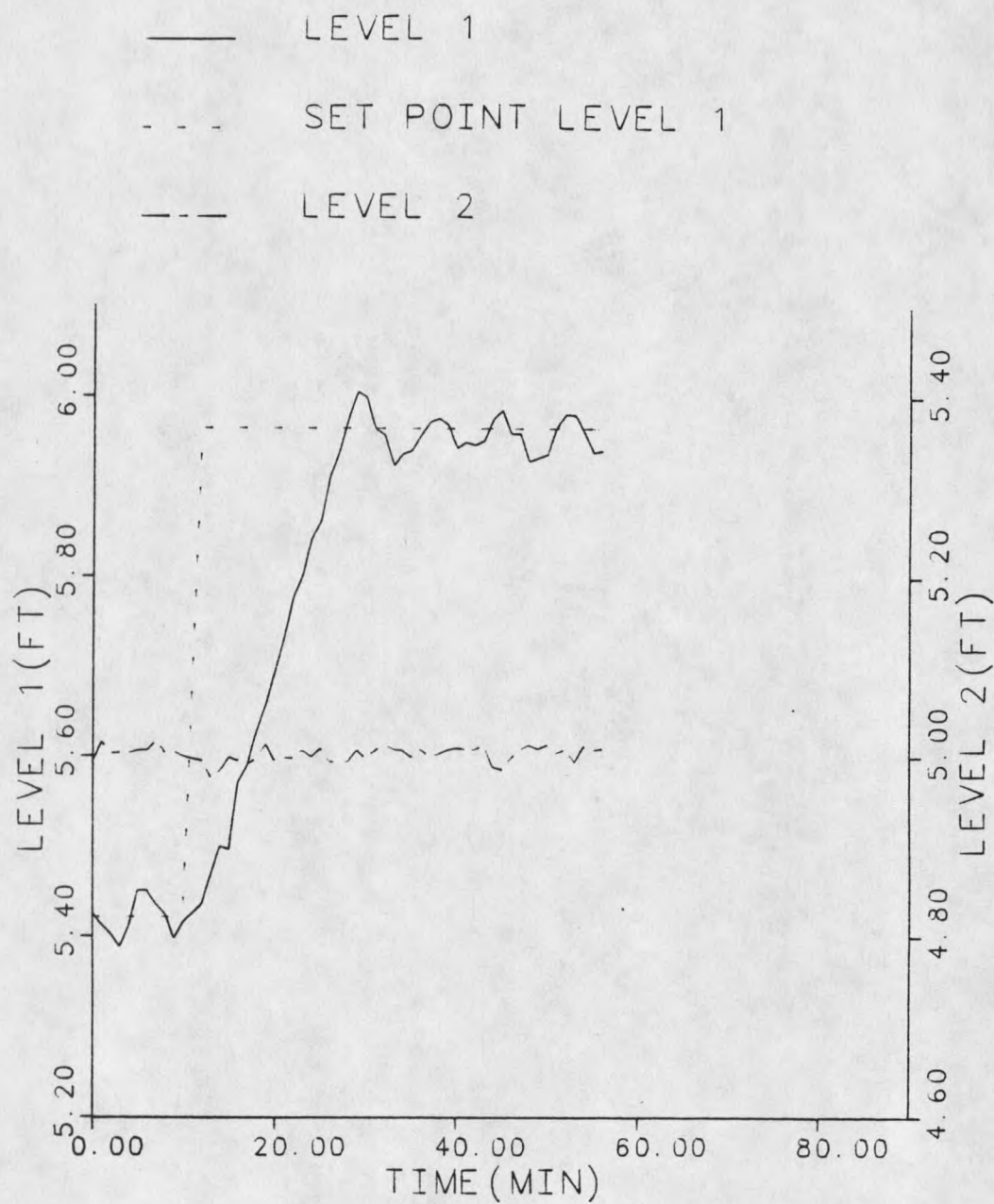


Figure 8. Process response curve of the second configuration with a liquid product rate of 6 lb/min and a pressure of 3.1 psia in the second effect.

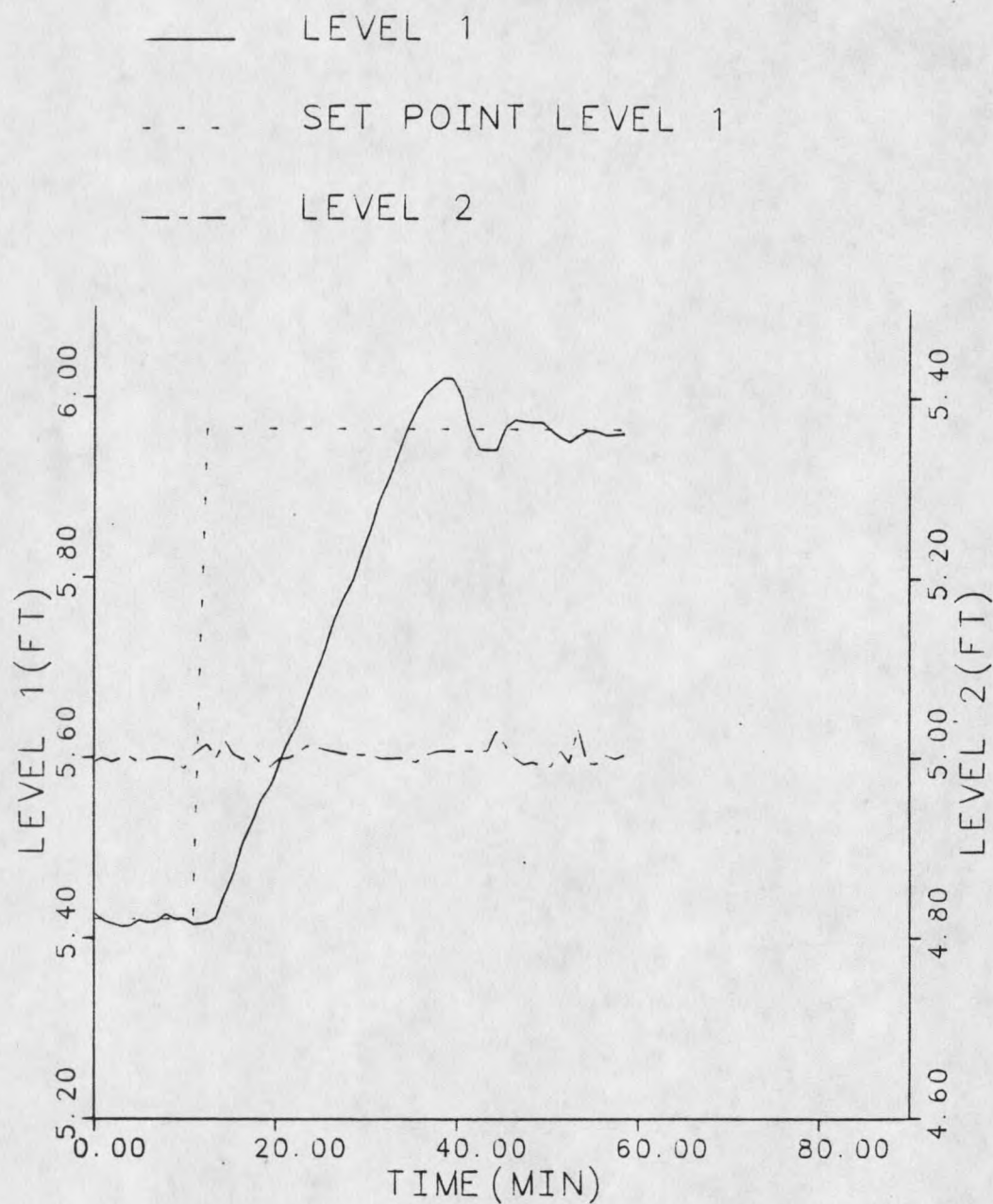


Figure 9. Process response curve of the second configuration with a liquid product rate of 6 lb/min and a pressure of 5.3 psia in the second effect.

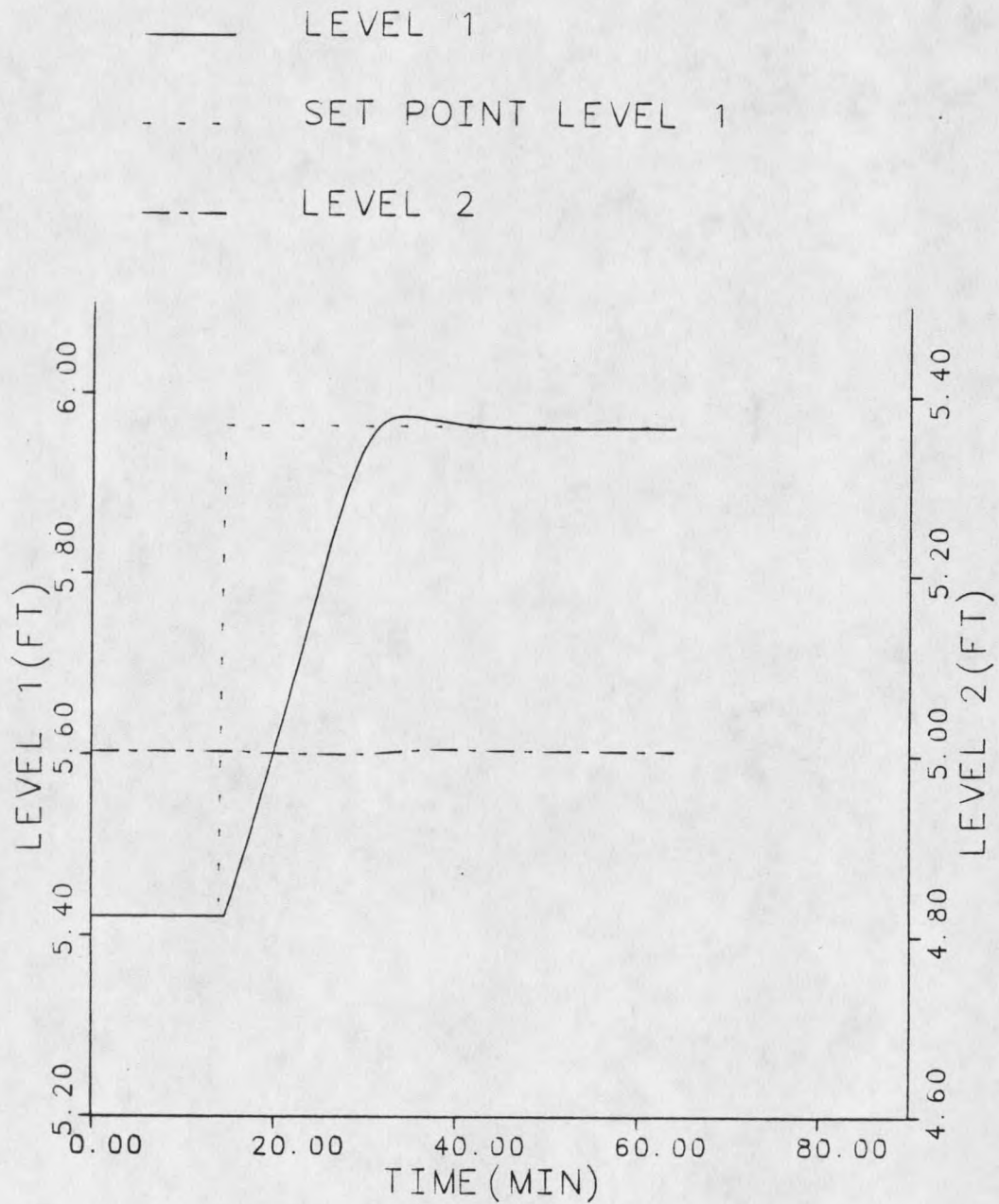


Figure 10. Model response curve of the second configuration with a liquid product rate of 6 lb/min and a pressure of 3.1 psia in the second effect.

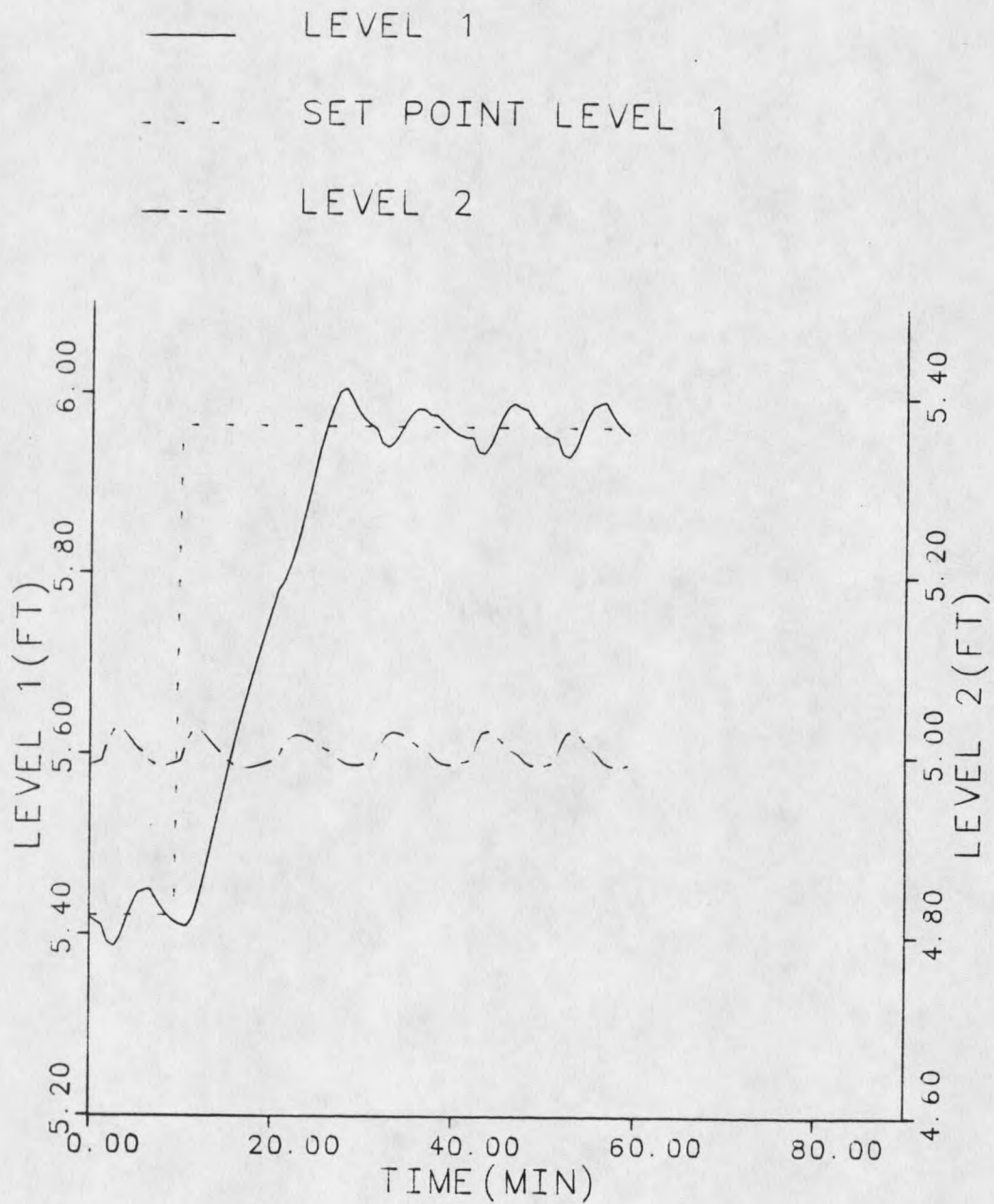


Figure 11. Hysteresis model response curve of the second configuration with a liquid product rate of 6 lb/min and a pressure of 3.1 psia in the second effect.

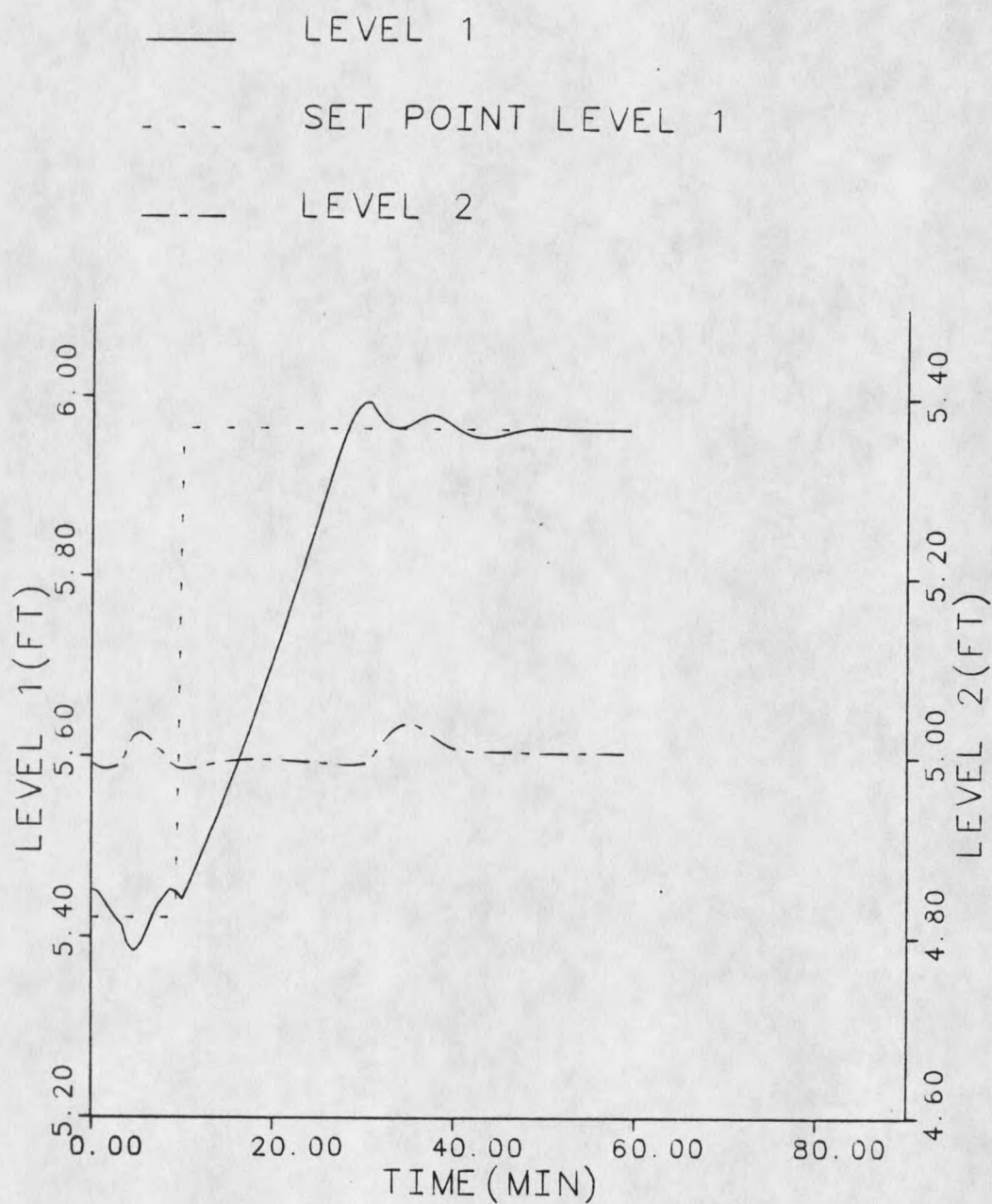


Figure 12. Hysteresis model response curve of the second configuration with a liquid product rate of 6 lb/min and a pressure of 5.3 psia in the second effect.

thesis. Another factor which may have effected the performance of the model was the removal of the cascade control on the feed line. The cascade was not needed in the model because there were no fluctuations in the feed line pressure. The pressure in the second effect was greater for the run shown in Figure 9; this accounted for the slower response as the feed into the first effect was dependent on the pressure in the first effect which was dependent on the pressure in the second effect. Therefore, the lower pressure in the second effect decreased the pressure in the first effect which increased the feed flow into the first effect.

In the third configuration, shown in Figure 4, there was coupling from the first effect to the second effect because of the middle valve. There was also coupling from the second effect to the first due to the feed valve. This situation, according to Deshpande and Ash [3], could cause oscillations and sometimes instability. Figures 13 and 14 were the response curves for the third configuration. The figures showed quite a bit of oscillation. Although the system was not unstable, the control was far from satisfactory. If the system was allowed to run long enough the variations in the levels decreased to what they were before the step change. The model response, shown in Figure 15, was similar to the response of the actual apparatus except the oscillations were smaller and faster after the initial overshoot. One possible reason for the discrepancies between the model and the process was again the difficulties involved in the modeling of the valves.

The valve constants which gave the best control in the various configurations were given in Table 1.

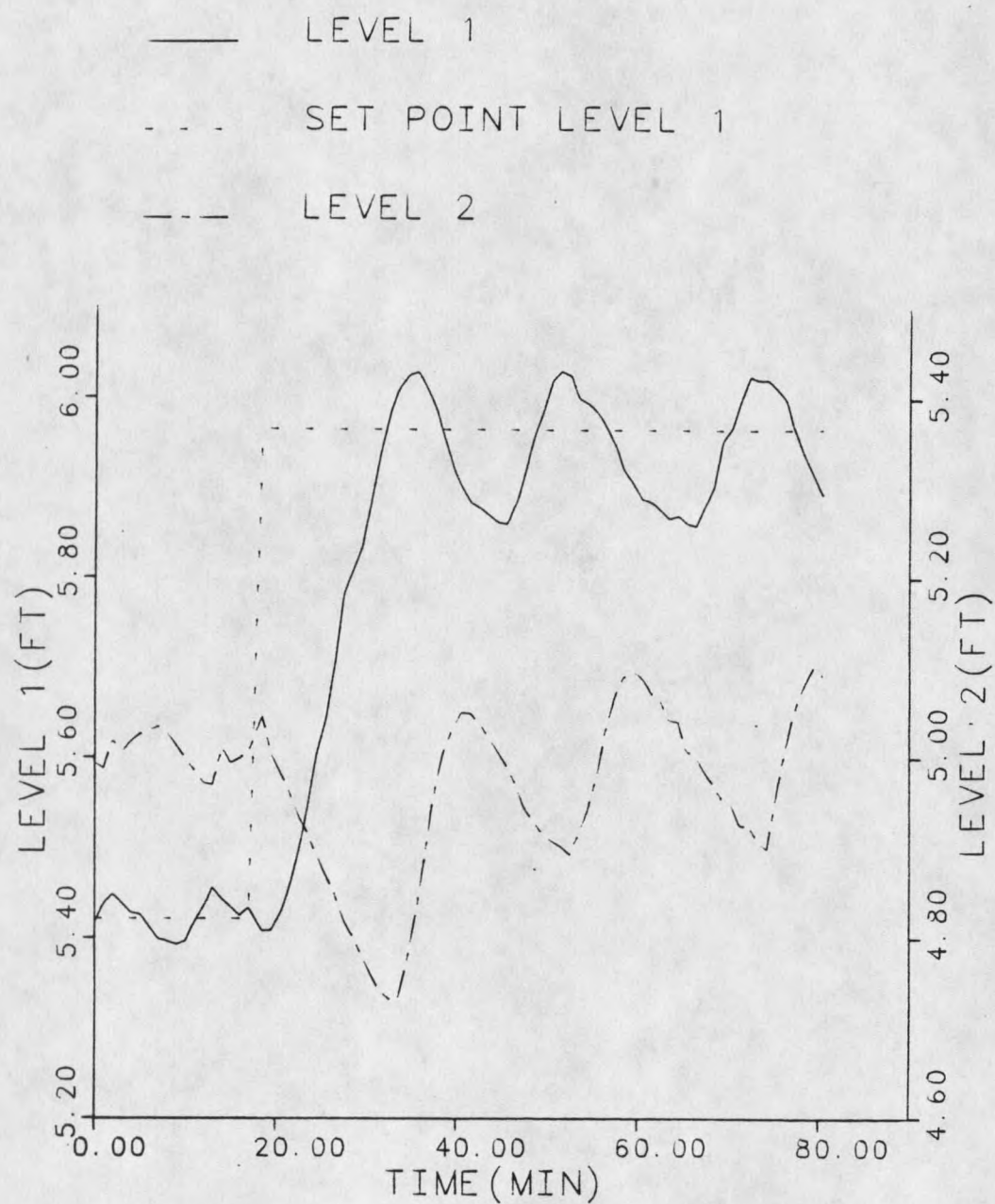


Figure 13. Process response curve of the third configuration with a liquid product rate of 6 lb/min and a pressure of 5.5 psia in the second effect.

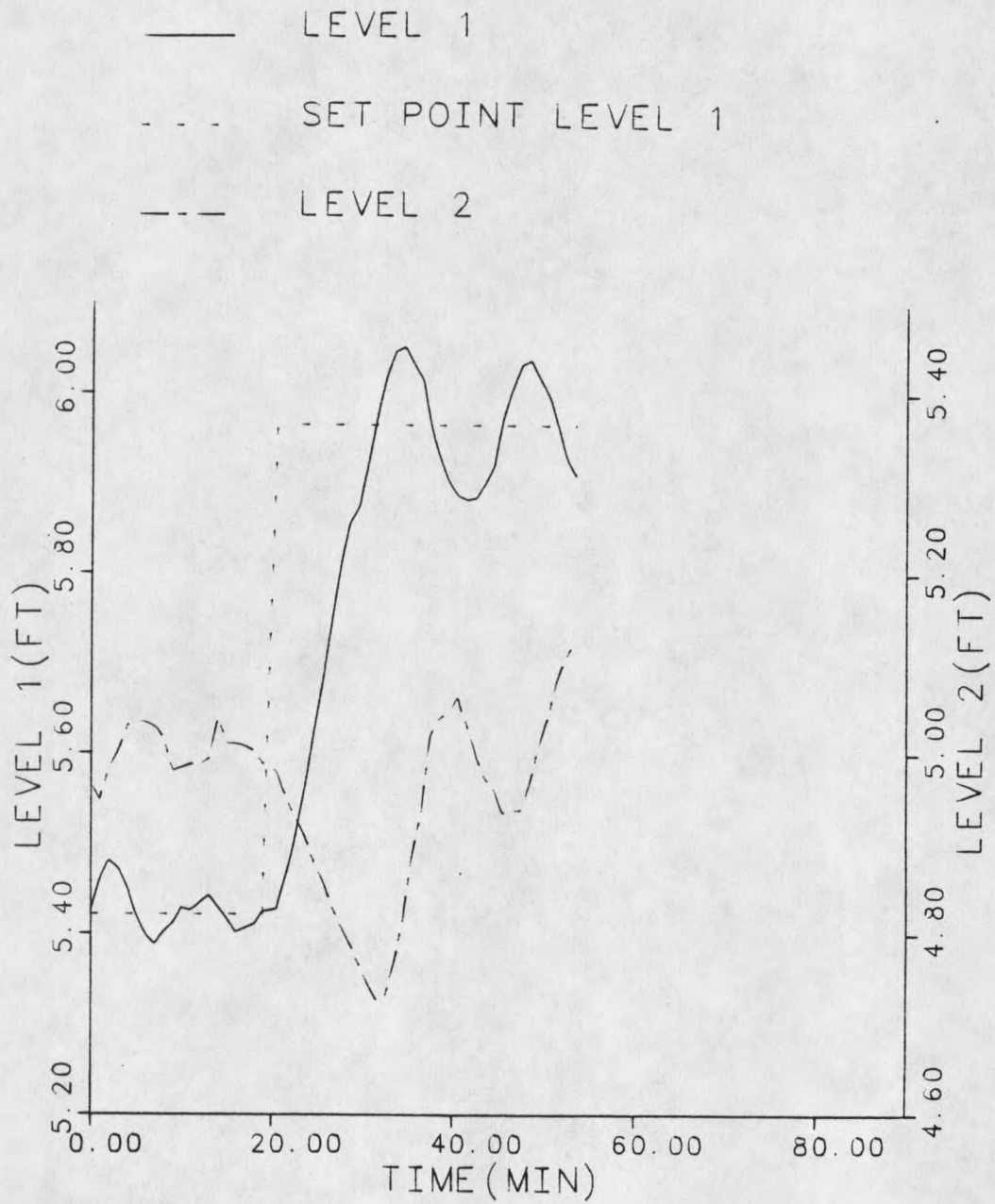


Figure 14. Process response curve of the third configuration with a liquid product rate of 6 lb/min and a pressure of 4.7 psia in the second effect.

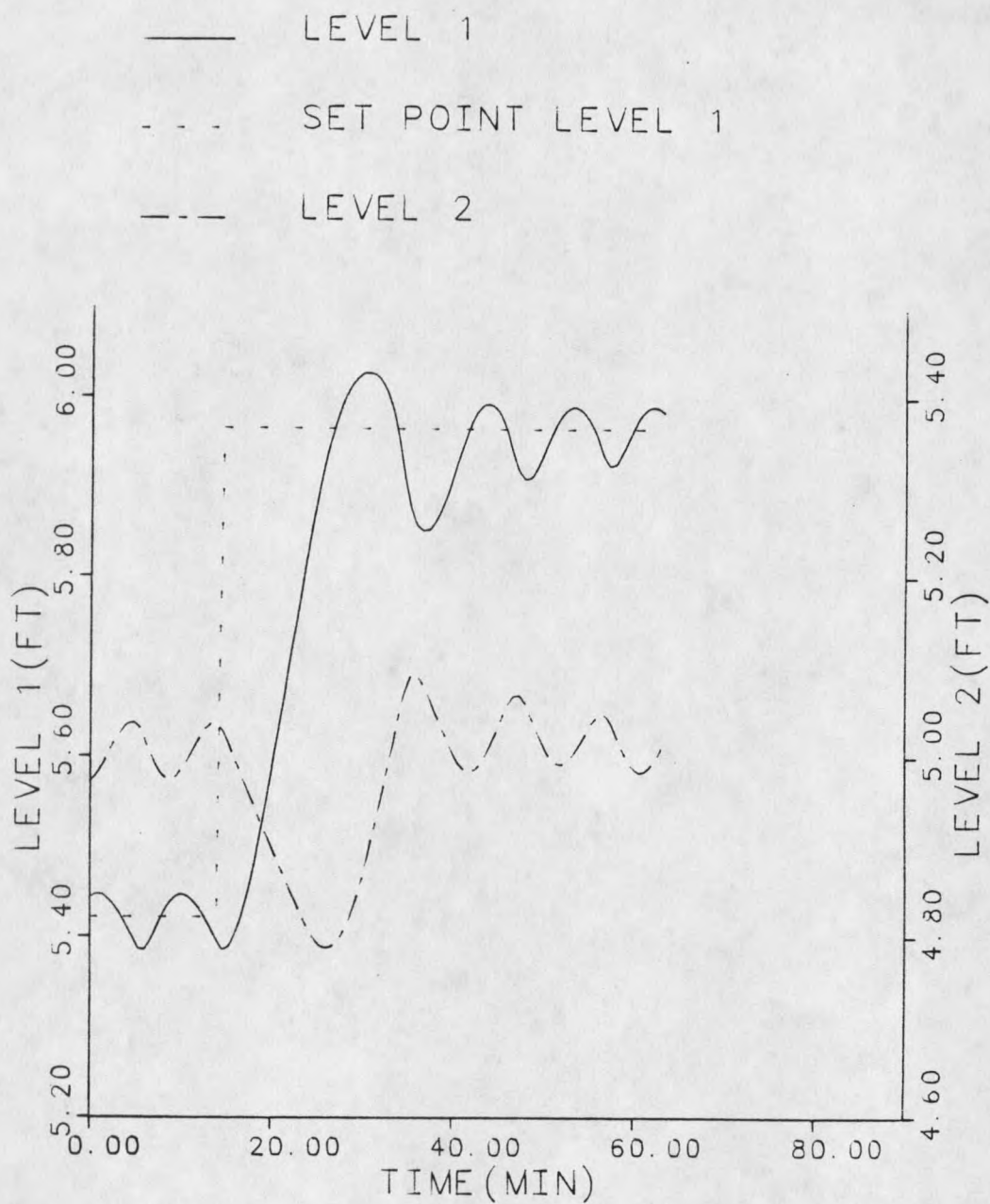


Figure 15. Model response curve of the third configuration with a liquid product rate of 6 lb/min and a pressure of 4.7 psia in the second effect.

Table 1. Control Constants.

	Feed		First Effect		Second Effect	
	τ_l (min)	K_c^* (psi/psi)	τ_l (min)	K_c^* (psi/ft)	τ_l (min)	K_c^* (psi/ft)
First Configuration	.2	.98	5.0	4.9	5.0	2.4
Second Configuration	.2	.98	5.0	4.9	3.0	4.9
Third Configuration	.2	.98	3.0	4.9	5.0	4.9

* $K_c \times 10^3$.

CONCLUSIONS

The first configuration and the second configuration had the best response curves of the three configurations examined. The third configuration was very oscillatory due to the severe coupling of the controlled and manipulated variables. The second configuration could become oscillatory if the conditions are such that the coupling between the feed flow into the first effect and the temperature in the first effect becomes severe, in which case the pressure in the first effect could decrease to the point of being lower than the pressure in the second effect. The pairing in the first configuration was such that the coupling problems are minimized.

The dynamic model of the system compared well with the experimental results.

SUGGESTIONS FOR FUTURE RESEARCH

1. Incorporate dynamic matrix control, which is a new control strategy used by Shell Oil Company, to see how it compares with the proportional-integral controllers. Dynamic matrix control is reportedly very good for interactive systems [6].
2. Install a feed tank and, using a glycol solution as the feed, try to control the liquid product concentration. Since the apparatus is being used as an undergraduate Chemical Engineering Lab, controlling the product concentration would make the lab more interesting.

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REFERENCES CITED

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APPENDICES

APPENDIX A

SIMULATION MODEL COMPUTER PROGRAM

C*****THIS IS A MODEL FOR THE DOUBLE EFFECT
 C*****FOR THE SECOND CONFIGURATION
 C A=SURFACE AREA
 C B=BOTTOMS FLOW RATE
 C CP=SPECIFIC HEAT
 C CV=VALVE CONSTANT FOR LIQ PROD VALVE
 C DL1=CHANGE IN L1
 C DL2=CHANGE IN L2
 C E=ERROR IN L1
 C E1=PREVIOUS E
 C E2=ERROR IN L2
 C E21=PREVIOUS E2
 C EF=ERROR IN FEED FLOW
 C EF1=PREVIOUS EF
 C EL=ENVIRONMENTAL LOSSES
 C FF=FEED FLOW RATE
 C HL=LIQUID ENTHALPY
 C HV=VAPOR ENTHALPY
 C KC=GAIN CONSTANT;KCF FOR FEED, KC1&KC2 FOR 1ST&2ND EFFECTS
 C L1=LEVEL IN EFFECT 1
 C L2=LEVEL IN EFFECT 2
 C M=CONTROLLER OUTPUT FROM L1
 C M1=PREVIOUS M
 C N=COUNTER
 C NSF=NEW SFF
 C O=OVERHEAD VAPOR FLOW RATE
 C Q=ENERGY ADDED TO SYSTEM
 C $Q1=HVS*SF=U1*A1(TEMPS-TEMP1)$
 C $Q2=HV1*O1=U2*A2(TEMP1-TEMP2)$
 C RHO=DENSITY
 C RHOF=DENSITY OF THE FEED
 C SF=SET FEED FLOW RATE
 C SFR=STEAM FLOW RATE
 C T=TIME
 C TAU=INTEGRAL TIME; TAU1,TAU2 FOR FEED,1ST&2ND EFFECTS

```

C      TEMP=TEMPERATURE
C      TFSAMP=SAMPLING PERIOD FOR FEED FLOW LOOP
C      TSAMP=SAMPLING PERIOD FOR LEVEL CONTROL LOOPS
C      V=CONTROLLER OUTPUT FROM L2
C      V1=PREVIOUS V
C      VF=CONTROLLER OUTPUT FROM FF
C      VF1=PREVIOUS VF
C      W=LIQUID HOLDUP
C*****THIS MODEL ASSUMES THE PRESS, IN THE 2ND EFFECT IS CONSTANT,
C      THE RESPONSE TO TEMP CHANGES IS FAST SO THERE IS NO HEAT ACCUM.
C      IN WALLS AND A CONST. STEAM PRESSURE
      COMMON/CPR/NPR
      DIMENSION RHO(4), HV(7), HL(23), TEMP(23), TEMPR(4), VL(23)
      DIMENSION P(23)
      REAL L1,L2,NSF,M,M1,KCF,KC1,KC2
      REAL NSL,LPW,NLPW
      DATA RHO/62.,61.2,60.1,58.8/
      DATA TEMPR/100.,150.,200.,250./
      DATA HL/1.996,12.041,22.058,32.058,42.046,52.029,62.01,
* 71.992,81.97,91.96,101.95,111.95,121.95,131.96,141.98,
* 152.01,164.06,166.08,168.09,172.11,176.14,180.17,184.20/
      DATA VL/1074.4,1068.7,1063.1,1057.4,1051.8,1046.1,1040.5,
* 1034.8,1029.1,1023.3,1017.5,1011.7,1005.8,999.8,993.8,
* 987.8,980.4,979.1,977.9,975.4,972.8,970.3,967.8/
      DATA TEMP/34.,44.,54.,64.,74.,84.,94.,104.,114.,124.,134.,
* 144.,154.,164.,174.,184.,196.,198.,200.,204.,208.,212.,216./
      DATA P/.096.,14192.,20625.,29497.,41550.,57702.,79062.,1.06965,
* 1.4299,1.8901,2.4717,3.1997,4.1025,5.2124,6.5656,8.203,10.605,
* 11.058,11.526,12.512,13.568,14.696,15.901/
C*****CONTROL SET UP FOR SECOND CONFIGURATION
      WRITE(6,*)'INPUT 1 FOR LPW CHANGE AND 2 FOR LEVEL'
      READ(5,*)J
      IF(J.EQ.1)GO TO 7
      IF(J.EQ.2)GO TO 8
7      WRITE(6,*)'INPUT LPW & NEW NLPW'

```

```

      READ(5,*)LPW,NLPW
      I1=200
      I2=1500
      GO TO 15
8     WRITE(6,*)'LEVEL CHANGE INPUT LPW'
      READ(5,*)LPW
      I1=1500
      I2=300
C*****INITIALIZING SECTION
15    WRITE(6,*)'INPUT P2'
      READ(5,*)P2
      TEMP2=FUN1(P2,23,P,TEMP)
      NSL=5.74
      HV1=1140.5
      HV2=1132.2
      HL1=154.02
      HL2=132.96
      RHOF=62.4
      RHO1=60.1
      TSAMP=2./3.
      TFSAMP=.25
      J=6
      WRITE(6,*)'INPUT KCF,KC1,KC2'
      READ(5,*)KCF,KC1,KC2
      WRITE(6,*)'INPUT TAU1,TAU2'
      READ(5,*)TAU1,TAU2
      FF=7.
      SF=FF
      J=J+1
      L1=5.4
      SL1=3491.00
      VL1=3491.0
      NSL=4000
      L2=5.

```

VL2=3652.
SL2=3652.
IP=0
P1=8.57
PA=11.8
TEMPF=34.
TEMP1=186.
TEMPA=70.
TEMPS=248.
HLF=1.996
HVS=949.5
T=0.
DT=.03
CPL=1.
R=1.
N=0
A2=A1
M=3072.
V1=3072.
 $VF1=(FF/2.64)**2/33.4*2048+2048$
EL1=10000.
 $EL2=1022.2+1101.+1695.57+1882.6$
PI=3.1416
O1=39.
UA1=1900.
UA2=1500.

C*****IF IT IS NOT SAMPLING TIME SKIP VALVE MOVEMENT
1 IF(T.LT.TF)GO TO 10
MF=MF+1
TF=MF*TFSAMP
EF=SF-FF
 $VF=VF1+KCF*(EF-EF1+(TFSAMP/TAUF)*EF)$
IF(VF.LT.2048.)VF=2048.
IF(VF.GT.4095.)VF=4095.
VF1=VF

```

      EF1=EF
C*****CALCULATE FEED FLOW RATE THROUGH THE VALVE
C      FF=CV*SQRT(X)*SQRT(DEL P)
10      FF=2.64*SQRT((M-2048)/2048)*(41.8-P1)**.5
      A1=PI*R**2
C*****CALCULATE CHANGE IN TEMPERATURE
C      DTEMP1(F/MIN)=(FF(LB/HR)*(BTU/LBF)(F)-BTU/HRF(F)
C      +BTU/HRF(F)-EL1(BTU/HR)/((FT**2)(LB/FT**3)(BTU/LBF)*MIN/HR)-
C      F(FT/MIN))/FT
      DTEMP1=((FF*CPL*60.*(TEMPF-TEMP1)-UA2*(TEMP1-TEMP2)+*A1*
& (TEMPS-TEMP1)-EL1)/(A1*RHO1*CPL*60)-TEMP1*DL1)/L1
C*****INTERPOLATE LATENT HEAT, DENSITY, AND FIRST EFFECT PRESSURE
      HVL1=FUN1(TEMP1,23,TEMP,VL)
      RHO1=FUN1(TEMP1,4,TEMPR,RHO)
      P1=FUN1(TEMP1,23,TEMP,P)
C*****CALCULATE THE HEAT ADDED TO THE FIRST EFFECT
      Q1=UA1*(TEMPS-TEMP1)
C*****CALCULATE THE OVERHEAD VAPOR FLOW RATE
      O1=UA2*(TEMP1-TEMP2)/HVL1
      A1=PI*R**2
C*****IF IT IS NOT A SAMPLING TIME SKIP VALVE MOVEMENT
      IF(T.LT.TL1)GO TO 11
      ML=ML+1
      TL1=ML*TSAMP
      E=SL1-VL1
C*****CALCULATE MOVE FROM LEVEL IN FIRST EFFECT
      M=M1+KC1*((E-E1)+(TSAMP/TAU1)*E)
      IF(M.LT.2048.)M=2048.
      IF(M.GT.3332.)M=3332.
      M1=M
      E1=E
      E2=SL2-VL2
C*****CALCULATE MOVE FROM LEVEL IN SECOND EFFECT
      V=V1+KC2*(E2-E21+(TSAMP/TAU2)*E2)
      E21=E2

```

```

      IF(V.LT.2048.)V=2048.
      IV(V.GT.4095.)V=4095.
      V1=V
C*****CALCULATE LIQUID FLOW FROM FIRST EFFECT TO SECOND
C      B1=CV*X*SQRT(DEL P)
11      B1=12.25*(V-2048)/2048*(P1-P2)**.5
C      DW1DT(LB/MIN)=LB/MIN-LB/MIN-LB/HR/(MIN/HR)
C*****CALCULATE THE LIQUID HOLDUP IN THE FIRST EFFECT
      DW1DT=FF-B1-O1/60.
C*****CALCULATE THE CHANGE IN THE LEVEL IN THE FIRST EFFECT
C      DL1(FT/MIN)=LB/MIN/((LB/FT**3)*(FT**2))
      DL1=(DW1DT)/(RHO1*PI)
      RHO2=61.2
C      Q2(BTU/HR)=O2(LB/HR)*LAMDA AT T1(BTU/LB)
      Q2=O1*975.4
C      O2(LB/HR)=(LB/MIN(MIN/HR)(BTU/LB)-BTU/HR+BTU/HR)/BTU/LB.
      O2=(-EL2+Q2-B2*60.*(TEMP2-TEMP1)-DL2*60.*TEMP2*A2*RHO2*
& CPL)/(CPL*(TEMP2-TEMP1)+999.2)
      IF(O2.LT.0.)O2=0.
      IF(T.LT.TL2)GO TO 4
      KL=KL+1
      TL2=KL*TSAMP
      CV=50.
      B2=LPW
C      DL2(FT/MIN)=(LB/MIN-LB/MIN-LB/HR(MIN/HR))/(LB/FT**3(FT**2))
4      DL2=(B1-B2-O2/60.0)/(RHO2*PI)
      SLN=(SL1-2048.)/936.+3.88
      SLI=(SL2-2048.)/936.+3.28
      CALL PRNTE(TSAMP,400.,NF,T,FF,SLN,L1,L2)
      IF(NPR.NE.1)GO TO 20
      GO TO 50
20      GO TO (6,5),NF
6      CALL INTI(T,DT,1)
      CALL INT(TEMP1,DTEMP1)
      CALL INT(L2,DL2)

```

```
VL1=(L1-3.88)*936.+2048.  
CALL INT(L1,DL1)  
VL2=(L2-3.29)*936.+2048.  
GO TO 1  
50 N=N+1  
IF(N.GT.I2)SL1=NSL  
IF(N.GT.I1)LPW=NLPW  
WRITE(3,*)T,SLN,L1,SLI,L2  
GO TO 20  
5 END
```

APPENDIX B

FIRST CONFIGURATION
COMPUTER PROGRAM

```

1  PRINT CHR$(9)"80N"
3  LIST
4  PRINT CHR$(9)"I"
5  END
10  REM  INITIALIZING SECTION
15  C1 = 4095:C2 = 2047
20  KF = 2:K1 = 10:K2 = 5
30  IT = 2:I1 = 5:I2 = 5
60  PM = .25:PN = 20 / 60
80  PRINT "INPUT FEED FLOW RATE"
90  INPUT SF
91  PRINT "INPUT LEVEL,OLD=3491"
92  INPUT S1
100 PRINT CHR$(9)"80N"
110 PR# 1
115 PRINT "FEED FLOW RATE="SF
116 PRINT "LEVEL SET ="S1
120 PRINT SPC( 1);"TIME"; SPC(
    7);"TS C"; SPC( 6);"FEED"; SPC(
    6);"T2 C"; SPC( 5);"P1 PSIA"
    ; SPC( 4);"P2 PSIA"; SPC( 5)
    ;"L1"; SPC( 8);"L2"
130 PR# 0
135 SF = (SF / .52)**2 + 2048
140 S2 = 3652
150 UP = SF
160 BT = 0:YT = 0:Y = 9 / 60:B =
    10 / 60
170 TX = 2142
180 DEF FN TEMP(X) = .404 * (X -
    2048)
190 NI = 0.
200 MI = 0.
210 M = PM / 60
220 N = PN / 60
230 & AOUT,(C#) = 1,(DV) = SF
240 & AOUT,(C#) = 2,(DV) = 4095
250 & AOUT,(C#) = 3,(DV) = 2047
420 REM  CONTROL SECTION
430 & TIME TO HR,MN,SC
440 TIME = HR + MN / 60 + SC / 36
    00
450 NI = NI + N
460 MI = MI + M
470 YT = YT + Y
480 BT = 1 / 60
490 TF = TIME + MI
500 TL = TIME + NI
520 TB = TIME + BT
530 REM  SUBROUTINE FOR CONTROL

```

```

535 XD = FRE (0)
540 & TIME TO HO,MU,SE
550 TM = HO + MU / 60 + SE / 3600
555 IF TM >= TF THEN GOSUB 75
    0
560 & TIME TO HU,MT,SN
570 TN = HU + MT / 60 + SN / 3600

575 IF TN >= TL THEN GOSUB 90
    0
580 & TIME TO HT,ME,SD
590 TT = HT + ME / 60 + SD / 3600

595 IF TT >= TB THEN GOSUB 11
    60
640 & WRDEV,(D#) = 0,(W#) = 2,(D
    V) = 0
650 & AIN,(TU) = TU,(C#) = 1,(D#
    ) = 0
660 IF TU > TX THEN GOTO 680
670 GOTO 530
680 & BUZZ ON
690 & PAUSE = 1
700 PRINT "NEED MORE COOLING H2O
    "

710 PRINT "ON VACUUM PUMP"
720 & BUZZ STOP
730 GOTO 530
740 REM FEED SECTION
750 & ASUM,(TV) = FP,(C#) = 6,(S
    W) = 10
760 FP = FP / 10
770 EF = SF - FP
780 VF = VP + KF * (EF - EP + 1 /
    IT * EF * PM)
790 IF VF < 2047 THEN VF = 2047
800 IF VF > 4095 THEN VF = 4095
810 & AOUT,(DV) = UF,(C#) = 1
820 VP = VF
830 EP = EF
840 MI = MI + M
850 TF = TIME + MI
860 & BIN,(TV) = SD,(XM) = 65535

870 IF SD > 0 THEN GOTO 1060
880 RETURN
890 REM LEVEL SECTION
900 & ASUM,(TV) = L1,(C#) = 1,(S
    W) = 20

```

```

910  & ASUM,(TV) = L2,(C#) = 2,(S
      W) = 20
920  L1 = L1 / 20
930  L2 = L2 / 20
940  E1 = L1 - S1:E2 = L2 - S2
950  V1 = C1 + K1 * (E1 - X1 + 1 /
      I1 * E1 * PN)
960  V2 = C2 + K2 * (E2 - X2 + 1 /
      I2 * E2 * PN)
970  IF V1 < 2047 THEN V1 = 2047
980  IF V1 > 4095 THEN V1 = 4095
990  IF V2 < 2047 THEN V2 = 2047
1000 IF V2 > 4095 THEN V2 = 4095

1010 & AOUT,(DV) = V1,(C#) = 2
1020 & AOUT,(DV) = V2,(C#) = 3
1030 C1 = V1:C2 = V2:X1 = E1:X2 =
      E2
1040 NI = NI + N:TL = TIME + NI
1050 RETURN
1060 IF SD > 1 GOTO 1080
1070 GOTO 20
1080 PRINT "SYSTEM SHUTDOWN"
1130 END
1160 REM DATA COLLECTION
1161 DEF FN TEMP(X) = .404 * (X
      - 2048)
1162 & ASUM,(TU) = FP,(C#) = 6,(
      SW) = 10
1163 FP = FP / 10
1164 F = ((FP - 2048) .5) * .52

1165 F$ = STR$ (F)
1166 F$ = LEFT$ (F$,4)
1170 & WRDEV,(D#) = 0,(DU) = 0,(
      W#) = 2
1180 & AIN,(C#) = 0,(TV) = TS,(D
      #) = 0,(FU) = FN TEMP(RAW%)

1181 TS$ = STR$ (TS)
1182 TS$ = LEFT$ (TS$,5)
1190 & AIN,(C#) = 2,(TV) = T1,(D
      #) = 0,(FU) = FN TEMP(RAW%)

1191 T1$ = STR$ (T1)
1192 T1$ = LEFT$ (T1$,5)
1200 & AIN,(C#) = 3,(TV) = T2,(D
      #) = 0,(FU) = FN TEMP(RAW%)

1201 T2$ = STR$ (T2)

```

```
1202 T2$ = LEFT$ (T2$,5
1210 & AIN,(C#) = 3,(TV) = P1
1211 = .007326 * P1 - 15
1212 P1$ = STR$ (P1)
1213 P1$ = LEFT$ (P1$,4)
1220 & AIN,(C#) = 4,(TV) = P2
1221 P2 = .007326 * P2 - 15
1222 P2$ = STR$ (P2)
1223 P2$ = LEFT$ (P2$,4)
1240 L1$ = STR$ (L1)
1241 L1$ = LEFT$ (L1$,4)
1250 L2$ = STR$ (L2)
1251 L2$ = LEFT$ (L2$,4)
1260 PR# 1
1270 PRINT CHR$ (9)"N"
1280 PRINT HT": "ME": "SD; SPC( 4)
      ;TS$; SPC( 5);F$; SPC( 5);T2
      $; SPC( 5);P1$; SPC( 7);P2$.
      SPC( 7);L1$; SPC( 6);L2$
1284 BT = BT + 1 / 60
1285 TB = TIME + BT
1286 PRINT CHR$ (9)"I"
1287 PR# 0
1290 RETURN
1300 END
```

APPENDIX C

SECOND CONFIGURATION
COMPUTER PROGRAM

```

2  PRINT CHR$(9)"80N"
3  LIST
4  PRINT CHR$(9)"I"
5  END
9  REM CONTROL PROGRAM FOR SECON
    D CONFIGURATION
10  REM INITIALIZING SECTION
15  C1 = 4095:C2 = 2047
20  KF = 2:K1 = 10:K2 = 10
30  IT = .1:I1 = 2:I2 = 3
60  PM = .25:PN = 20 / 60
80  PRINT "INPUT LIQUID PROD. RAT
    E"
81  INPUT LPW
91  & AOUT,(DU) = LPW,(C#) = 3
92  PRINT "INPUT LEVEL, OLD=3491"

93  INPUT S1
100 PRINT CHR$(9)"80N"
110 PR# 1
115 PRINT "LIQ. PROD. RATE="LPW
117 PRINT "L1="S1
120 PRINT SPC( 1);"TIME"; SPC(
    7);"TS C"; SPC( 6);"T1 C"; SPC(
    6);"T2 C"; SPC( 5);"P1 PSIA"
    ; SPC( 4);"P2 PSIA"; SPC( 5)
    ;"L1"; SPC( 8);"L2"

130 PR# 0
150 UP = SF
160 BT = 0:YT = 0:Y = 9 / 60:B =
    10 / 60
170 TX = 2142
180 DEF FN TEMP(X) = .404 * (X -
    2048)
190 NI = 0.
200 MI = 0.
210 M = PM / 60
220 N = PN / 60
230 & AOUT,(C#) = 1,(DU) = SF
240 & AOUT,(C#) = 2,(DU) = 3000
250 & AOUT,(CL) = 3,(DU) = LPW
420 REM CONTROL SECTION
430 & TIME TO HR,MN,SC
440 TIME = HR + MN / 60 + SC / 36
    00
450 NI = NI + N
460 MI = MI + M
470 YT = YT + Y
480 BT = 1 / 60
490 TF = TIME + MI

```

```

500 TL = TIME + NI
520 TB = TIME + BT
530 REM SUBROUTINE FOR CONTROL
535 XD = FRE (0)
540 & TIME TO HO,MU,SE
550 TM = HO + MU / 60 + SE / 3600

555 IF TM >= TF THEN GOSUB 75
    0
560 & TIME TO HU,MT,SN
570 TN = HU + MT / 60 + SN / 3600

575 IF TN >= TL THEN GOSUB 90
    0
580 & TIME TO HT,ME,SD
590 TT = HT + ME / 60 + SD / 3600

600 IF TT >= TB THEN GOSUB 11
    60
640 & WRDEV,(D#) = 0,(W#) = 2,(D
    U) = 0
650 & AIN,(TU) = TU,(C#) = 1,(D#
    ) = 0
660 IF TU > TX THEN GOTO 680
670 GOTO 530
680 & BUZZ ON
690 & PAUSE = 1
700 PRINT "NEED MORE COOLING H2O
    ."

710 PRINT "ON VACUUM PUMP"
720 & BUZZ STOP
730 GOTO 530
740 REM FEED SECTION
750 & ASUM,(TU) = FP,(C#) = 6,(S
    W) = 10
760 FP = FP / 10
770 EF = SF - FP
780 UF = UP + KF * (EF - EP + 1 /
    IT * EF * PM)
790 IF UF < 2047 THEN UF = 2047
800 IF UF > 4095 THEN UF = 4095
810 & AOUT,(DU) = UF,(C#) = 1
820 UP = UF
830 EP = EF
840 MI = MI + M
850 TF = TIME + MI
860 & BIN,(TU) = SD,(XM) = 65535

870 IF SD > 0 THEN GOTO 1060
880 RETURN

```

```

890  REM LEVEL SECTION
900  & ASUM,(TU) = L1,(C#) = 1,(S
    W) = 20
910  & ASUM,(TU) = L2,(C#) = 2,(S
    W) = 20
920  L1 = L1 / 20
930  L2 = L2 / 20
940  E1 = S1 - S1:E2 = S2 - L2
950  U1 = C1 + K1 * (E1 - X1 + 1 /
    I1 * E1 * PN)
960  U2 = C2 + K2 * (E2 - X2 + 1 /
    I2 * E2 * PN)
970  IF U1 < 2047 THEN U1 = 2047
980  IF U1 > 4095 THEN U1 = 4095
990  IF U2 < 2047 THEN U2 = 2047
1000 IF U2 > 4095 THEN U2 = 4095

1005 SF = ((U1 - 2047) / 2047) *
    590 + 2020
1010 & AOUT,(DU) = U2,(C#) = 2
1020 & AOUT,(DU) = LPW,(C#) = 3
1030 C1 = U1:C2 = U2:X1 = E1:X2 =
    E2
1040 NI = NI + N:TL = TIME + NI
1050 RETURN
1060 IF SD > 1 GOTO 1080
1070 GOTO 80
1080 PRINT "SYSTEM SHUTDOWN"
1130 END
1160 REM DATA COLLECTION
1161 DEF FN TEMP(X) = .404 * (X
    - 2048)
1170 & WRDEV,(D#) = 0,(DU) = 0,(
    W#) = 2
1180 & AIN,(C#) = 0,(TU) = TS,(D
    #) = 0,(FU) = FN TEMP(RAW%)

1181 TS$ = STR$ (TS)
1182 TS$ = LEFT$ (TS$,5)
1190 & AIN,(C#) = 2,(TU) = T1,(D
    #) = 0,(FU) = FN TEMP(RAW%)

1191 T1$ = STR$ (T1)
1192 T1$ = LEFT$ (T1$,5)
1200 & AIN,(C#) = 3,(TU) = T2,(D
    #) = 0,(FU) = FN TEMP(RAW%)

1201 T2$ = STR$ (T2)
1202 T2$ = LEFT$ (T2$,5)

```

```
1210 & AIN,(C#) = 3,(TU) = P1
1211 P1 = .007326 * P1 - 15
1212 P1$ = STR$ (P1)
1213 P1$ = LEFT$ (P1$,4)
1220 & AIN,(C#) = 4,(TU) = P2
1221 P2 = .007326 * P2 - 15
1222 P2$ = STR$ (P2)
1223 P2$ = LEFT$ (P2$,4)
1240 L1$ = STR$ (L1)
1241 L1$ = LEFT$ (L1$,4)
1250 L2$ = STR$ (L2)
1251 L2$ = LEFT$ (L2$,4)
1260 PR# 1
1270 PRINT CHR$ (9)"N"
1280 PRINT HT":ME":SD; SPC( 4)
      ;T$; SPC( 5);T1$; SPC( 5);T
      2$; SPC( 5);P1$; SPC( 7);P2$
      ; SPC( 7);L1$; SPC( 6);L2$
1284 BT = BT + 1 / 60
1285 TB = TIME + BT
1286 PRINT CHR$ (9)"I"
1287 PR# 0
1290 RETURN
1300 END
```

APPENDIX D

THIRD CONFIRMATION
COMPUTER PROGRAM

```

1  PRINT CHR$(9)"80N"
3  LIST
4  PRINT CHR$(9)"I"
5  END
10 REM INITIALIZING SECTION
15 C1 = 3071:C2 = 3071
20 KF = 2:K1 = 10:K2 = 10
30 IT = .1:I1 = 3:I2 = 2
40 U1 = 3071
60 PM = .25:PN = 20 / 60
70 S1 = 3491:S2 = 3652:SF = 3000
80 PRINT "INPUT LIQUID PROD. RATE"
   E"
90 INPUT LPW
91 & AOUT,(DU) = LPW,(C#) = 3
95 PRINT "INPUT LEVEL, OLD=3491"

96 INPUT S1
100 PRINT CHR$(9)"80N"
110 PR# 1
111 PRINT "K1="K1," K2="K2
112 PRINT "I1="I1," I2="I2
115 PRINT "LIQ. PROD. RATE="LPW
117 PRINT "L1="S1
120 PRINT SPC( 1);"TIME"; SPC(
    7);"TS C"; SPC( 6);"T1 C"; SPC(
    6);"T2 C"; SPC( 5);"P1 PSIA"
    ; SPC( 4);"P2 PSIA"; SPC( 5)
    ;"L1"; SPC( 8);"L2"
130 PR# 0
135 U2 = 3071
150 UP = SF
160 BT = 0:YT = 0:Y = 9 / 60:B =
    10 / 60
170 TX = 2142
180 DEF FN TEMP(X) = .404 * (X -
    2048)
190 NI = 0.
200 MI = 0.
210 M = PM / 60
220 N = PN / 60
230 & AOUT,(C#) = 1,(DU) = SF
240 & AOUT,(C#) = 2,(DU) = 3000
250 & AOUT,(C#) = 3,(DU) = LPW
420 REM CONTROL SECTION
430 & TIME TO HR,MN,SC
440 TIME = HR + MN / 60 + SC / 36
    00
450 NI = NI + N
460 MI = MI + M
470 YT = YT + Y

```

```

480  BT = 1 / 60
490  TF = TIME + MI
500  TL = TIME + NI
520  TB = TIME + BT
530  REM SUBROUTINE FOR CONTROL
535  XD = FRE (0)
540  & TIME TO HO,MU,SE
550  TM = HO + MU / 60 + SE / 3600

555  IF TM >= TF THEN GOSUB 75
    0
560  & TIME TO HU,MT,SN
570  TN = HU + MT / 60 + SN / 3600

575  IF TN >= TL THEN GOSUB 90
    0
580  & TIME TO HT,ME,SD
590  TT = HT + ME / 60 + SD / 3600

630  IF TT >= TB THEN GOSUB 11
    60
640  & WRDEV,(D#) = 0,(W#) = 2,(D
    U) = 0
650  & AIN,(TU) = TU,(C#) = 1,(D#
    ) = 0
670  GOTO 530
680  & BUZZ ON
690  & PAUSE = 1
700  PRINT "NEED MORE COOLING H2O
    "

710  PRINT "ON VACUUM PUMP"
720  & BUZZ STOP
730  GOTO 530
740  REM FEED SECTION
750  & ASUM,(TU) = FP,(C#) = 6,(S
    W) = 10
760  FP = FP / 10
770  EF = SF - FP
780  UF = UP + KF * (EF - EP + 1 /
    IT * EF * PM)
790  IF UF < 2047 THEN UF = 2047
800  IF UF > 4095 THEN UF = 4095
810  & AOUT,(DU) = UF,(C#) = 1
811  PRINT "LEVEL"SF,L2,U2
812  PRINT "FEED"UF,FP
813  PRINT "L1,U1",L1,U1
820  UP = UF
830  EP = EF
840  MI = MI + M
850  TF = TIME + MI
860  & BIN,(TU) = SD,(XM) = 65535

```

```

870   IF SD > 0 THEN GOTO 1060
880   RETURN
890   REM LEVEL SECTION
900   & ASUM,(TU) = L1,(C#) = 1,(S
      W) = 20
910   & ASUM,(TU) = L2,(C#) = 2,(S
      W) = 20
920   L1 = L1 / 20
930   L2 = L2 / 20
940   E1 = L1 - S1:E2 = S2 - L2
950   U1 = C1 + K1 * (E1 - X1 + 1 /
      I1 * E1 * PN)
960   U2 = C2 + K2 * (E2 - X2 + 1 /
      I2 * E2 * PN)
970   IF U1 < 2047 THEN U1 = 2047
980   IF U1 > 4095 THEN U1 = 4095
990   IF U2 < 2047 THEN U2 = 2047
1000  IF U2 > 4095 THEN U2 = 4095

1005  SF = ((U1 - 2047) / 2047) *
      590 + 2020
1010  & AOUT,(DU) = U2,(C#) = 2
1020  & AOUT,(DU) = LPW,(C#) = 3
1030  C1 = U1:C2 = U2:X1 = E1:X2 =
      E2
1040  NI = NI + N:TL = TIME + NI
1050  RETURN
1060  IF SD > 1 GOTO 1080
1070  GOTO 80
1080  PRINT "SHUTDOWN PROCEDURE"
1130  END
1160  REM DATA COLLECTION
1161  DEF FN TEMP(X) = .404 * (X
      - 2048)
1170  & WRDEV,(D#) = 0,(DU) = 0,(
      W#) = 2
1180  & AIN,(C#) = 0,(TU) = TS,(D
      #) = 0,(FU) = FN TEMP(RAW%)

1181  TS$ = STR$ (TS)
1182  TS$ = LEFT$ (TS$,5)
1190  & AIN,(C#) = 2,(TU) = T1,(D
      #) = 0,(FU) = FN TEMP(RAW%)

1191  T1$ = STR$ (T1)
1192  T1$ = LEFT$ (T1$,5)
1200  & AIN,(C#) = 3,(TU) = T2,(D
      #) = 0,(FU) = FN TEMP(RAW%)

1201  T2$ = STR$ (T2)
1202  T2$ = LEFT$ (T2$,5

```

```
1210 & AIN,(C#) = 3,(TU) = P1
1211 P1 = .007326 * P1 - 15
1212 P1$ = STR$ (P1)
1213 P1$ = LEFT$ (P1$,4)
1220 & AIN,(C#) = 4,(TU) = P2
1221 P2 = .007326 * P2 - 15
1222 P2$ = STR$ (P2)
1223 P2$ = LEFT$ (P2$,4)
1240 L1$ = STR$ (L1)
1241 L1$ = LEFT$ (L1$,4)
1250 L2$ = STR$ (L2)
1251 L2$ = LEFT$ (L2$,4)
1260 PR# 1
1270 PRINT CHR$ (9)"N"
1280 PRINT HT": "ME": "SD; SPC( 4)
      ;TS$; SPC( 5);T1$; SPC( 5);T
      2$; SPC( 5);P1$; SPC( 7);P2$
      ; SPC( 7);L1$; SPC( 6);L2$
1284 BT = BT + 1 / 60
1285 TB = TIME + BT
1286 PRINT CHR$ (9)"I"
1287 PR# 0
1290 RETURN
1300 END
```

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