INFORMATION TO USERS

This reproduction was made from a copy of a document sent to us for microfilming. While the most advanced technology has been used to photograph and reproduce this document, the quality of the reproduction is heavily dependent upon the quality of the material submitted.

The following explanation of techniques is provided to help clarify markings or notations which may appear on this reproduction.

1. The sign or "target" for pages apparently lacking from the document photographed is "Missing Page(s)". If it was possible to obtain the missing page(s) or section, they are spliced into the film along with adjacent pages. This may have necessitated cutting through an image and duplicating adjacent pages to assure complete continuity.

2. When an image on the film is obliterated with a round black mark, it is an indication of either blurred copy because of movement during exposure, duplicate copy, or copyrighted materials that should not have been filmed. For blurred pages, a good image of the page can be found in the adjacent frame. If copyrighted materials were deleted, a target note will appear listing the pages in the adjacent frame.

3. When a map, drawing or chart, etc., is part of the material being photographed, a definite method of "sectioning" the material has been followed. It is customary to begin filming at the upper left hand corner of a large sheet and to continue from left to right in equal sections with small overlaps. If necessary, sectioning is continued again—beginning below the first row and continuing on until complete.

4. For illustrations that cannot be satisfactorily reproduced by xerographic means, photographic prints can be purchased at additional cost and inserted into your xerographic copy. These prints are available upon request from the Dissertations Customer Services Department.

5. Some pages in any document may have indistinct print. In all cases the best available copy has been filmed.

University
Microfilms
International

300 N. Zeeb Road
Ann Arbor, MI 48106

Joshi, Dilip I.

REAL-TIME DIGITAL CONTROL FOR BIOMASS LIQUEFACTION SYSTEM

The University of Arizona M.S. 1985

PLEASE NOTE:

In all cases this material has been filmed in the best possible way from the available copy. Problems encountered with this document have been identified here with a check mark __✓__.

1. Glossy photographs or pages _____
2. Colored illustrations, paper or print _____
3. Photographs with dark background _____
4. Illustrations are poor copy _____
5. Pages with black marks, not original copy _____
6. Print shows through as there is text on both sides of page _____
7. Indistinct, broken or small print on several pages ✓
8. Print exceeds margin requirements _____
9. Tightly bound copy with print lost in spine _____
10. Computer printout pages with indistinct print _____
11. Page(s) _____ lacking when material received, and not available from school or author.
12. Page(s) _____ seem to be missing in numbering only as text follows.
13. Two pages numbered _____. Text follows.
14. Curling and wrinkled pages _____
15. Dissertation contains pages with print at a slant, filmed as received _____
16. Other _____

_____

_____

University
Microfilms
International

REAL-TIME DIGITAL CONTROL FOR BIOMASS LIQUEFACTION SYSTEM

by

Dilip Joshi

A Thesis Submitted to the Faculty of the

DEPARTMENT OF CHEMICAL ENGINEERING

In Partial Fulfillment of the Requirements
For the degree of

MASTER OF SCIENCE

In the Graduate College

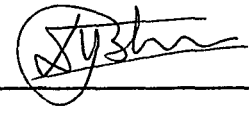
THE UNIVERSITY OF ARIZONA

1 9 8 5

STATEMENT BY AUTHOR

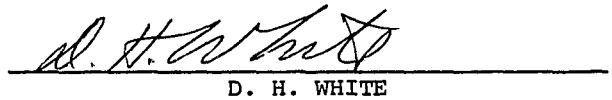
This thesis has been submitted in partial fulfillment and requirements for an advanced degree at The University of Arizona and is deposited in the University Library to be made available to borrowers under rules of the Library.

Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgment of source is made. Requests for permission for extended quotation from or reproduction of this manuscript in whole or in part may be granted by the head of the major department or the Dean of the Graduate College when in his or her judgment the proposed use of the material is in the interests of scholarship. In all other instances, however, permission must be obtained from the author.

SIGNED: 

APPROVAL BY THESIS DIRECTOR

This thesis has been approved on the date shown below:



D. H. WHITE
Professor of Chemical Engineering

12-13-85
Date

ACKNOWLEDGEMENTS

I wish to express appreciation and thank to Dr. Donald H. White, my thesis adviser, for his support and encouragement throughout the course of my graduate studies. I also thank Dr. David Wolf, Visiting Professor, for his advise and recommendation on this project. Appreciation and gratitude go to Dr. Simon Hanson and other faculty members of the Department of Chemical Engineering at the University of Arizona for their assistance and guidance.

A very special thanks goes to Mr. Sal Gonzales for his help in designing and implementing electronic hardware. Without his efforts this work could not have been completed.

I am very thankful to my father Dr. I. R. Joshi, my brother Vyomesh and sister-in-law Uma for their moral and financial support throughout the M.S. program.

I also thank my friend Lisa Humpfner for editing the thesis and Mrs. Rhoda Miller for typing it.

TABLES OF CONTENTS

TABLE OF CONTENTS-Continued

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS-Continued

LIST OF ILLUSTRATIONS-Continued

LIST OF TABLES

ABSTRACT

Described herein is a micro-processor based real-time process control system developed for complete automation for a newly developed high pressure high temperature biomass liquefaction systems. This control system is capable of switching from digital to manual or automatic control modes without any modifications. Also, complete instrumentation for both system,with required hardware and software were developed for automation and data acquisition. The develope data acquisition strategies is capable of sampling 128 data points in real-time. The developed control system was tested on the Municipal Solid Waste liquefaction experimental unit in the semi-continuous mode for real-time digital control and data acquisition.

CHAPTER 1

INTRODUCTION

Real-time digital computer control of chemical process is a fairly recent development. The first use came in the early 1960's when electrical, pneumatic and hydraulic energy driven analog controllers were dominating the process control industries. Early computer control applications were made with massive computers and snail-paced hardware without real-time mode of operation. By the 1970's the availability of mini-computers helped advance the on-line application for digital process control. This led to real-time digital control in small percentage of industrial plants in mid 1970's. The current revolution in micro-electronics and rapid decrease in the cost of hardware have made micro-computers available at economical costs and with nearly same computing power as large mini-computers.

The department of Chemical Engineering at the University of Arizona has developed a Control Real-Time Operating System (CRTOS) for the real-time Direct Digital Control (DDC) and data-acquisition of the Advanced Extruder-Reactor Biomass Liquefaction (AERBL) unit.

The AERBL unit utilizes a unique continuous process involving an extruder-feeder for the direct liquefaction of wood flour to liquid

wood-oil. Basically, the process involves feeding a very highly concentrated and highly viscous slurry into a vertical reactor without plugging the system. Typical slurry pumps are subject to feeding and plugging problems for highly viscous and highly concentrated slurry at high pressure and limited to about 12 wt% wood flour slurries. However, the AERBL unit, using the extruder-feeder can feed up to 60 wt% solids into the vertical reactor without any clogging. The overall flow diagram of the AERBL unit is shown in the Figure 1.

The same approach of direct liquefaction is also utilized for liquefaction of Municipal Solid Waste (MSW) using semi-continuous autoclave. Figure 2 shows overall flow diagram of MSW process.

Objectives of the Proposed Research

The AERBL process and the MSW process are both operated at high temperatures and high pressures. Under such process conditions automation of process is required for safety reasons. A real-time digital control system is useful for smooth and reliable operation for large amount of task and control loops.

The objectives of the proposed projects are to develop the control system strategies for biomass systems. The control system strategies are developed in such a fashion that switching of DDC to automatic or remote manual mode would be simple. The control system development utilizes the 6502 based micro-processor (Franklin ACE-1200) and CRTOS control algorithm for the real-time digital control.

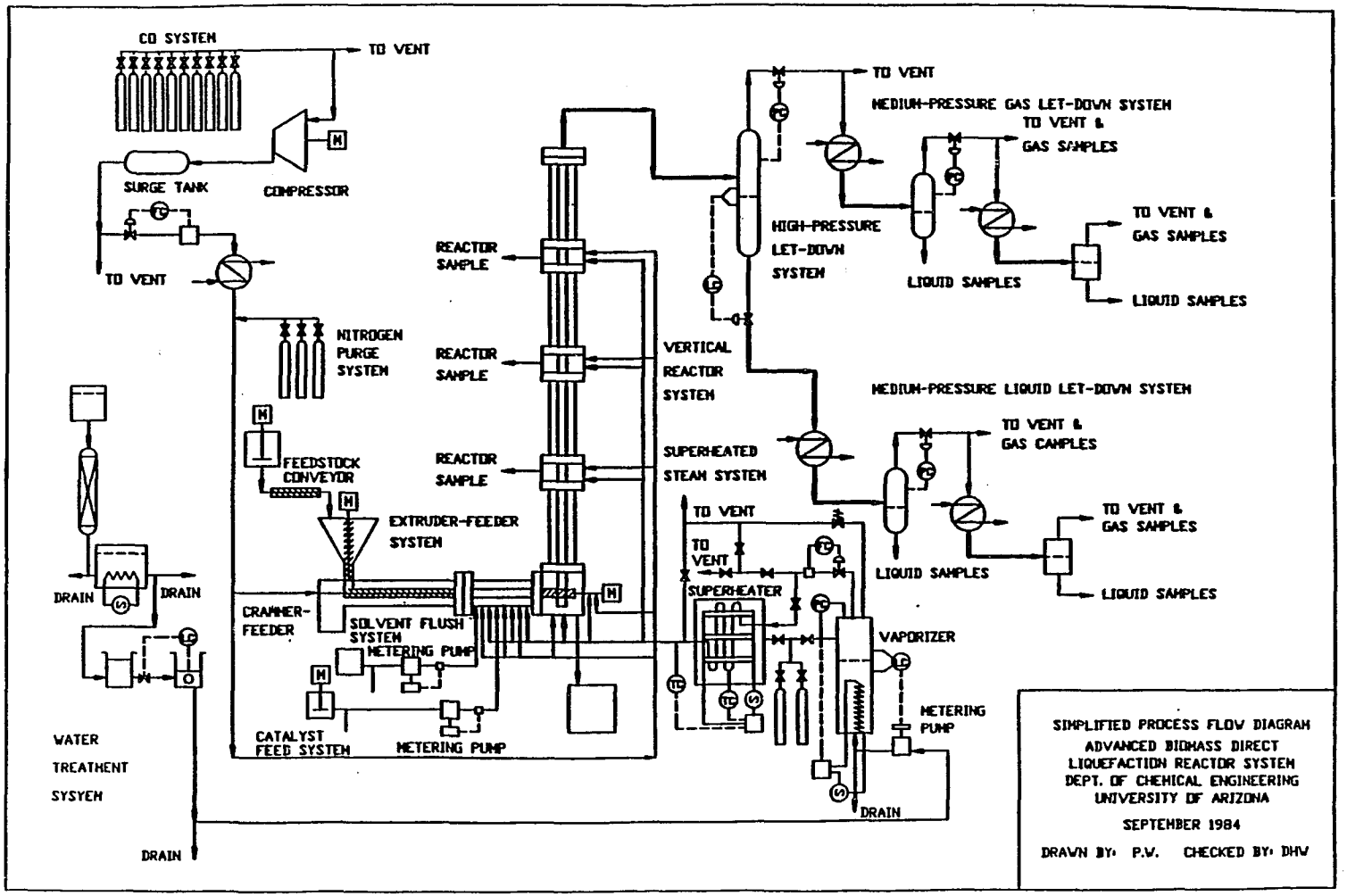


Fig 1 The overall flow diagram of the AERBL unit

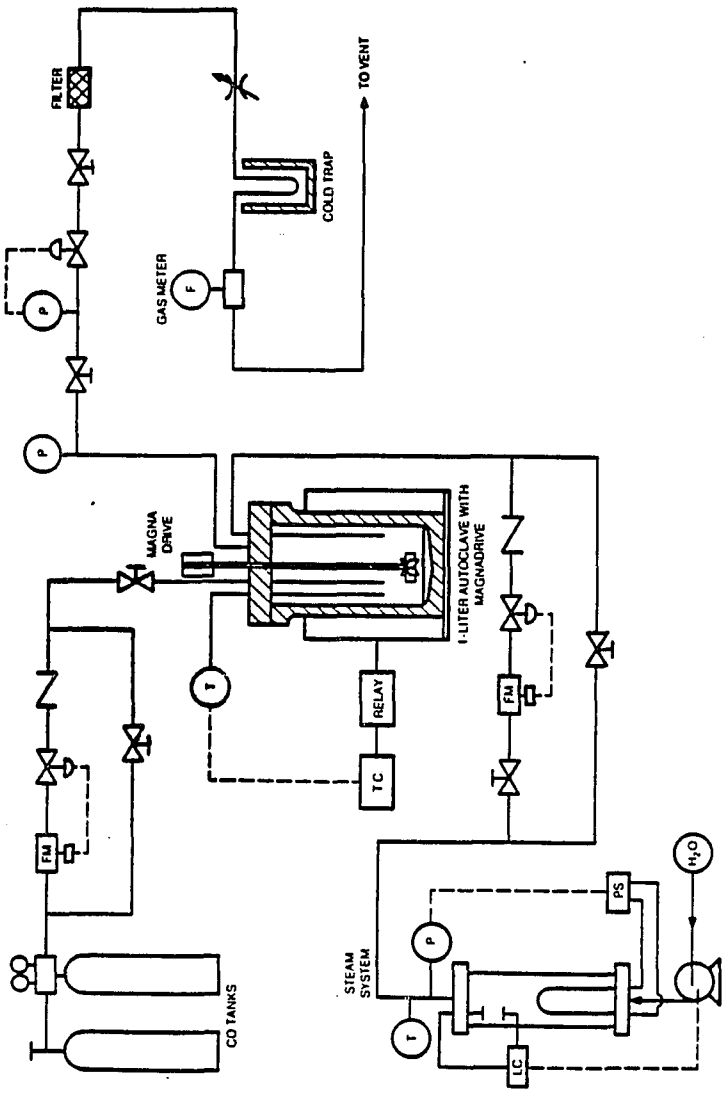


Fig 2 The overall flow diagram of the MSW process

The developed control system strategies were then tested on-line for the MSW process. The on-line testing consisted of steady-state and dynamic operation and with Proportional Integral and Derivative (PID) control algorithm response analysis and validations of fail-safe process control operation with a complete real-time micro-computer system for direct digital control. The on-line testing of control system was performed on the two control loops for the MSW process. The flow-rate of gas and off-gas pressure of autoclave were controlled. The PID controller constants, process transfer function and process dead time were determined and tuned for optimal control operation.

CHAPTER 2

THEORY

Closed Loop Response and Development of Sample-Data Digital Control System

During recent decades, analog control methods and performances have been refined and a large amount of literature is available on the subject. This data can be directly applied to developing digital controllers. Sample data systems are distinguished from continuous systems by a non-negligible sample time. A continuous control system is as shown in Figure 3.

When a micro-computer is used for several control loops, only one control loop can be serviced at a time, and a certain interval of time must lapse between the servicing of consecutive loops. The block diagram of a single-loop, micro-computer-based, closed-loop sample-data control system is shown in Figure 4.

Derivation of the closed-loop pulse transfer function for the sample-data system proceeds similar to the continuous time control system. However, unlike the continuous-time control system, the sample-data system utilizes a combination of continuous signals and discrete sample signals. The classical approach to discrete system

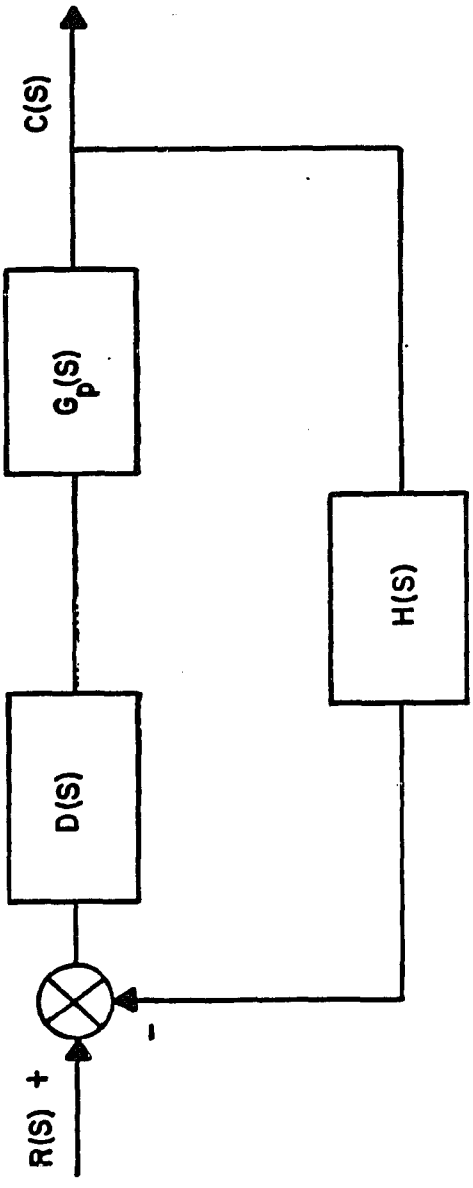


Fig 3 Block diagram of a single loop continuous control system

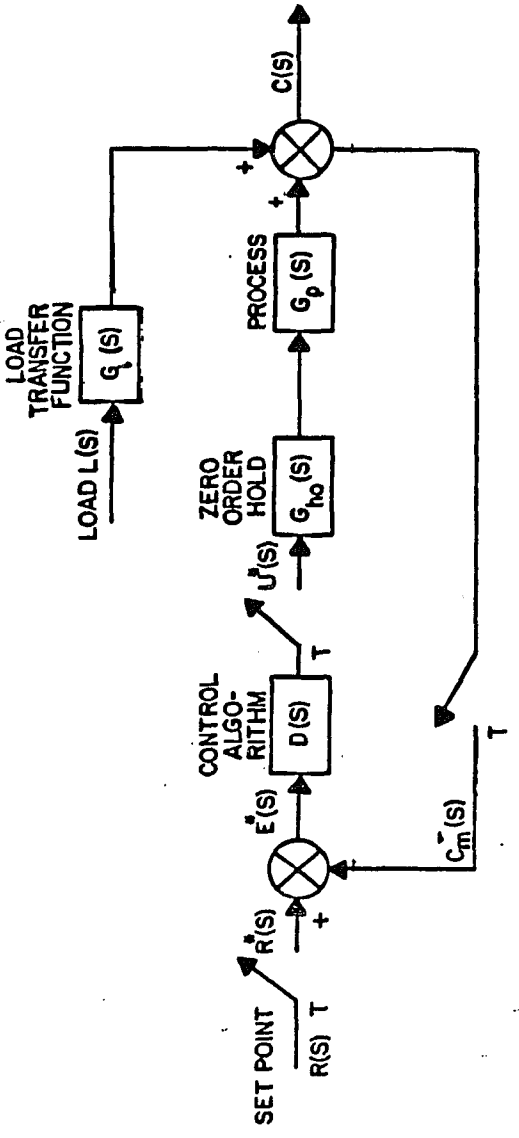


Fig 4 Block diagram of a single loop micro-computer based sample-data control system

analysis is to analyze the discrete component with Laplace transformation and then invert to Z-transforms (Franklin and Powell, 1980).

From conventional control analysis, the two blocks $G_{ho}(s)$ and $G_p(s)$ can be combined into the single block

$$G(s) = G_{ho}(s)G_p(s) \tag{2.1}$$

From Figure 4

$$C_M(s) = U^*(s)G(S) + G_L(s)L(s) \tag{2.2}$$

$$R^*(s) - C_m^*(s) = E^*(s)$$

$$U^*(s) = D(s)E^*(s)$$

where, * in all equation is the value after each sampling instant (i.e. star transform).

so substituting $U^*(s)$ from the above equation into equation (2.2) we get,

$$C_M(s) = D(s)\{R^*(s) - C_M(s)\}G(s) + G_L(s)L(s) \tag{2.3}$$

substituting $E^*(s)$ and taking star transform of equation (2.3) gives,

$$C_M^*(s) = D^*(s)R^*(s)G^*(s) - D^*(s)C_M^*(s)G^*(s) + \overline{G_L(s)L(s)}^* \tag{2.4}$$

so, $C_M^*(s)$ can be combined to give,

$$C_M^*(s) = \frac{D^*(s)R^*(s)G^*(s)}{1+D^*(s)G^*(s)} + \frac{\overline{G_L(s)L(s)}^*}{1+D^*(s)G^*(s)} \tag{2.5}$$

By taking Z-transform of equation (2.5),

$$C_M(Z) = \frac{D(Z)G(Z)-R(Z)}{1+D(Z)G(Z)} + \frac{G_L L(Z)}{1+D(Z)G(Z)} \tag{2.6}$$

For setpoint change (servo) only, Equation (2.6) becomes,

$$C_M(Z) = \frac{D(Z)G(Z)}{1+D(Z)G(Z)} \tag{2.7}$$

For closed-loop pulse transfer function with only loud change (regulators) Equation (2.6) becomes,

$$C_M(Z) = \frac{G_L L(Z)}{1+D(Z)+G(Z)} \tag{2.8}$$

Development of control algorithm by Z-transform, can be studied from Figure 5.

For setpoint change only, the Equation 2.7 can be modified to

$$D(Z) = \frac{1}{G_{ho} G_p(Z)} \cdot \frac{C(R)/R(Z)}{1-C(Z)/R(Z)} \tag{2.9}$$

and for load-change only, Equation (2.8) can be modified to

$$C(Z) = \frac{G_L L(Z)}{1+D(Z)G_{ho}G_p(Z)}$$

$$D(Z) = \frac{G_L L(Z)-C(Z)}{G_{ho} G_p(Z)C(Z)} \tag{2.10}$$

The design procedure is to select a suitable setpoint input or load input L, and specify the desired response characteristic so that Z-transform s, as indicated in the above Equation (2.9) and (2.10), to obtain D(Z) (Deshpande & Ash, 1981). Also, the poles of the control loop inside the unit circle can be determined, which are useful for the preliminary calculation of the controller constants.

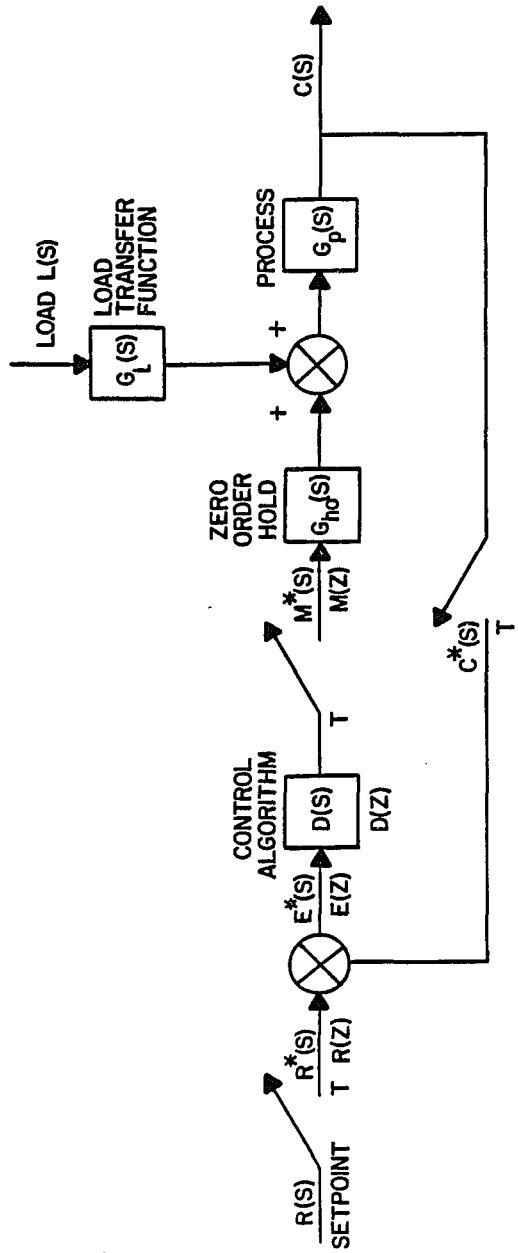


Fig 5 Closed loop sample-data control system

Proportional Integral and Derivative Digital Control Algorithm

One of the most widely-used controllers in the designing of continuous-data control systems is the Proportional Integral and Derivative (PID) controller. The Continuous, PID Control equation is

$$m(t) = K_p e(t) + K_I \int e(t)\, d + + K_D \frac{de(t)}{dt} \qquad (2.11)$$

where,

K_p = proportional gain

K_I = reset rate

K_D = derivative time

m(t)= controller output

e(t)= error (as function of time)

The same principal of PID Control can be applied to digital control. The digital or discrete equivalent of Equation 2.11 is given by Equation (2.12) (Mellichamp, 1983).

$$m(KT) = K_p \{e(KT) + TK_I \sum_{j=1}^{i} e(jT) + \frac{K_D}{T} (e(KT) - e(KT-1)T) \} \qquad (2.12)$$

where

T = sampling interval

$e_{(KT)}$ = error at K_{th} sampling interval

e(K-1)T = error at previous sampling interval

This form of PID Controller algorithm is called "Position" algorithm, since the micro-computer calculates the specific value of output at the

This form of PID Controller algorithm is called "Position" algorithm, since the micro-computer calculates the specific value of output at the i_{th} sample line. The above equation can thus be simplified for all previous error as

$$S_{i-1} = \sum_{j=1}^{i-1} e(j)$$

where S_i represents the sum of all errors. When e_i is obtained, the sum S_i is updated ($S_i = S_{i-1} + e(KT)$ and the new output m(I) is calculated from Equation (2.13).

$$m(KT) = K_p\{1 + \frac{K_D}{T})e(KT) - \{\frac{K_PK_D}{T}\}e(K-1)T + \{TK_pK_I\}Si \qquad (2.13)$$

Simplifying equation (2.13), gives

$$m(KT) = K_1e(KT) - K_2e(K-1)T + K_3S_i$$

where

$$K_1 = KP\ (1 + \frac{KD}{T})$$

$$K_2 = \frac{K_PK_D}{T}$$

$$K_3 = K_PK_TT$$

A significant amount of memory and processing time can be saved if the value of K_1, K_2 and K_3 are predetermined manually (Shlapak, 1983). Even though K_1, K_2, and K_3 do not represent the classical PID gain term, any combination of terms can be accomplished by setting a particular PID gain to zero and calculating the other constants.

A discretized version of the PID control equation for software implementation has a very important form, a steady-state value reference position u, as shown in Equation (2.15)

$$m(KT) = k_1 e(KT) - K_2 e(K-1)T + K_3 S_i + u \tag{2.15}$$

u, the software select, which eliminates the problem that can arise in developing micro-computer control software, as the PID control theory typically is developed using deviations of all input and output variables from the normal design or steady state operating conditions (Mellichamp, 1983).

The controller-discrete transfer function is expressed as (Mellichamp, 1983)

$$D(Z) = \frac{a_o + a_1 A^{-1} + a_2 Z^{-2} + \ldots\ldots + a_e Z^{-e}}{1 + b_1 Z \quad + b_2^{-1} Z \quad + \ldots\ldots + b_K Z^{-K}} \tag{2.16}$$

The controller output as the function of input in Z domain can be written as

$$\frac{M(Z)}{M(Z)} = D(Z) \tag{2.17}$$

The Discrete PID controller as shown in Equation (2.12) can be derived on the form of Equation (2.16) by rewriting Equation (2.12) as

$$m(KT) = K_P \left[e(KT) + W\sum_j e(jT) + d(e(KT) - e(K-1)T \right] \tag{2.18}$$

and taking the Z transform of this relation

$$\frac{M(Z)}{E(Z)} = D(Z) = K_P\left[\frac{(1+W+d)Z^2-(1+2s)Z+d}{Z(Z-1)}\right]$$

Finally,

$$D(Z) = K_P \left[\frac{(Z-Z_1)(Z-Z_2)}{Z(Z-1)} \right] \tag{2.20}$$

where Z_1 and Z_2 are factors of the numerator polynomial that may be real or complex. Dividing the numerator and denominator in Equation (2.20) by Z^2,

$$D(Z) = K_P\frac{\left[(1+W+d) - (1+2d)Z^{-1}+dZ^{-2}\right]}{(1-Z^{-1})} \tag{2.21}$$

Thus, the three-mode controller is a specific case of Equation (2.16) where

$a_0 = K_p (1+W + d)$

$a1 = -K_p (1+2d)$

$a_2 = k_c d$

$b_1 = -1$

The denominator term of Equation (2.21) comes from the summation term in Equation (2.12) and guarantees that offset can be eliminated.

Tuning of PID Controller

The critical phase of the implementation of PID control algorithm is the selection of the numerical values of the constants in the algorithm and how they are adjusted for different process conditions. The tuning rules are based on the experiments with a proposition controller at the stability limit or on time constant of processes. A survey of these rules is given in (Smith, 1972). The well-known and simple methods for the controller timing are the Ziegler and Nichols method and Cohen-Coon method.

The Ziegler and Nichols method is based on the attenuation criterion. This method requires that a proportional controller be implemented in the control loop and that it have the ability to change the gain, K_p. The proportional controller can be implemented by setting K_I and, K_D to zero in Equation (2.12). After establishing a particular gain, K_p, in the steady -state process, a small disturbance is introduced and the response to this disturbance is observed. The gain, K_p, is then

controller modes can be calculated according to the values shown in Table 1 for Ziegler and Nichols gain settings. (Coughanowr & Koppel).

The second method, called the Cohen-Coon method for controller gain settings, requires an empirical process model. Cohen and Coon's method involves the determination of the open-loop process reaction curve, (For small-step change, (recording the curve of measured Variable Versus time). The value of process gain, the process-time constant and heat time, are required for the gain setting.

Both of these tuning techniques are based on the continuous controller and the sample time systems. An extra parameter must be taken into consideration for the discrete version of the control algorithm, Smith, 1972, has suggested using one-half the value of sample time added to the process dead time as the process dead time. These approximations improve controller performance for different gain settings. The gain settings are not exact, and final optimum settings must be selected on-line only (Mellichamp, 1983).

Instrumentation

The measurement and transmission of process data is critical to the successful operation of any system comprising processes and real-time computers, whether the objective is data acquisition or process control. The process has two distinct parts: (1) the selection of optimum conditions for the process and (2) the maintenance of the process at chosen conditions. The second part is further divided into three

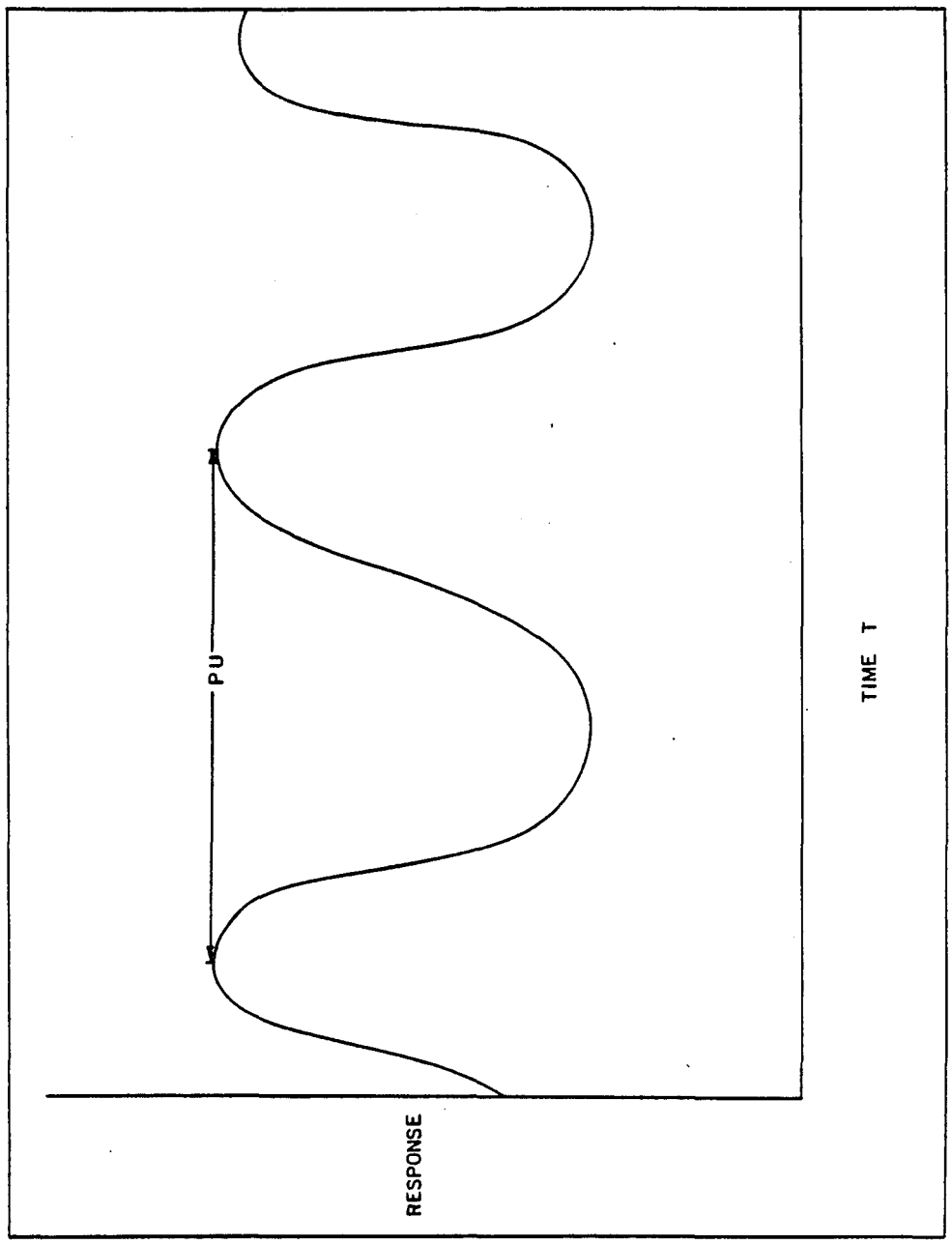


Fig 6 Qualitative oscillatory response of the process variable

Table 1

Ziegler and Nechols Gain Setting

Controller Type	Continuous equation	K_P	K_I	K_D
Proportional	$m = K_P e(t)$	$0.5\ K_u$		
Proportional Integral	$m = K_P(e(t)+\int e(t)$	$0.45K_u$	$P_u/1.2$	
PID	$m = K_P(e(t)+\int e(t)+de(t)/dt$	$0.6K_u$	$P_u/2.0$	$P_u/8.0$

The process has two distinct parts: (1) the selection of optimum conditions for the process and (2) the maintenance of the process at chosen conditions. The second part is further divided into three sections: (1) controller, (2) final control element and (3) measuring instrument.

The final control element is the device that has a direct influence on the process. It provides the required changes in the dynamic variable to bring the dynamic variable to the set-point conditions. (Johnson, 1982). Typically, the final control elements are the device which regulates the flow of fluids (materials) or energy into the process, i.e. control valves, power relay, pump, etc.

The measuring element is used to determine the value of quantity or condition. It also refers transduction of the variable into some corresponding analog variable. The transducer is a device that transforms the initial measurement and energy conversion of a dynamic variable into analog, electrical or pneumatic information. Further, transformation or signal conditioning may be required to complete the measurement function. Commonly used transducers for process control are temperature, pressure, flow, level and force.

Factors to consider in selecting instrumentation are listed in Table 2 (Oliver, 1971). Transducer input/output relations are most important for the selection. Accuracy of the instrument is the resultant of all errors of measurement that play a part in the use of instruments. Repeatability of the instrument is the variation in the output of the

Table 2

Selecting Instrument Transducers

Characteristics of Input Variable
Range (maximum and minimum values to be measured)
    Overload protection
    Frequency response
    Transient response
    Resonant frequency
Transducer Input/Output Relation
    Accuracy
    Repeatability
    Linearity
    Sensitivity
    Resolution
    Friction
    Hysteresis/backlash
    Threshold/noise level
    Stability
      Zero drift
      Loss of calibration with time
Overall System
    Output characteristics
    Size and weight
    Power requirements
    Accessories needed
    Mounting requirements
    Environment of transducer location
    Crosstalk
    Effect of presence of transducer on measured quantity
    Need for corrections dependent on other transducers
Measurement Reliability
    Ease and speed of calibrating and testing
    Time available for calibration prior to and/or during use
    Duration of mission
    Stability against drift of zero point and proportionality constant
    Vulnerability to sudden failure (probability of proper performance for a given life time)
    Fail safety (will transducer failure represent system failure or invalidate data from other transducers)
    Failure recognition (will transducer failure be immediately apparent so that subsequent erroneous data can be rejected)
Purchase
    Availability and delivery; is item oo-the shelf?
    Any development necessary for operation
    Availability of calibration and test data from manufacturer
    price
    Previous experience with seller

instrument under steady-state conditions when a constant level of input is repeatedly applied. High accuracy and repeatability is desired in any instrument.

Linearity is a measurement of deviation of the plotted instrument response from the straight time. Linear output of the instrument cannot be better than the repeatability. Hysteresis is a common effect on the instrument. It is a summation of all effects, where output assumes different values when the same input is applied first in increasing and then in a decreasing direction. Resolution is the degree to which small increments of measured value can be differed in terms of transducers output. High resolution of an instrument is desired for optimum performance of process control and data acquisition. All the factors in Table 2 are important for the selection of instrumentation and should be taken into consideration before purchasing instruments.

No matter what type of transducer has been chosen, the manner in which it is connected to the computer affects the performance of the control loop and data acquisition. Also, when the process is more than 20 feet away from the control room, a high level of noise will be picked up by the instrument signal and the voltage will drop across the signature.

Proper shielding, screening, grounding and use of current loop signals will minimize these difficulties. The general points on low-level signal wiring listed in Mellichamp, 1983, P.93, should be considered for better performance of instruments through proper signal

conditioning. The 4-20 ma current loop is essential for the AERBL process as the process is 50 feet away from the control room. The 16 ma range of this loop carrier is less noise and is unaffected by voltage drop across the signal line.

Hardware Considerations

There are some basic problems involved in the application of a digital computer to control and data acquisition. Many of these problems are encountered in the input and output of control variables to the computer. That is, the problems are encountered at the interface between the "real world" and the "computer world". Process interface is composed of two subsystems. One part is interface control and data acquisition hardware and the other is process interface (Mellichamp, 1983, P.235.

Interface control hardware serves to decode commands originating from the computer, to control interface operation, to provide status information to the computer through its Input/Output (I/O) system, and to transmit information to and from the devices that make up the unidentifiable process interface. The real world is fundamentally digital (binary). This has a number of consequences. One problem is finding a method of converting analog data to digital data of binary numbers for the input system. Another is finding a method to convert digital data of binary numbers to analog data for the output system. A third consequence is that of accounting for the loss of information when analog data is converted to digital form.

The conversion of analog data to digital data is done by an Analog to Digital Converter (ADC). Digital data to analog data conversion is performed by a Digital to Analog Converter (DAC). Obviously, an ADC/DAC pair provides a two-way communication link between a computer and process that understands analog signals. The selection of ADC/DAC and its theory will be discussed in Chapter 3.

The real-time operating system and control algorithm require a real-time clock to service or execute the real-time programs. A real-time clock is an interval timer connected to the computer I/O interface so that the computer can be interrupted when a particular interval of time has lapsed. The clock time is referred to as the Basic System Time (BST) on real-time computing. At certain BST's the CPU is interrupted to start execution of an interrupt handler routine, which is usually referred to as a task scheduler. The task scheduler then determines which program will be executed next by examining each program clock and priority status (Shlapak, 1983).

Process related interface hardware for analog quantities such as thermocouples, pressures transducers, flowmeters etc. have output in milli-volts, milliamp, or volts. Amplifiers, resistors and capacitors are used in the circuit to convert these output to the ADC compatible inputs. The DAC output is on volt range, while final control elements use milliamps as an input signal, which, also require voltage to current conversion. The amplifiers, with resistance are used for these conversion circuits to scale the input and output signal for the ADC and

DAC. The block diagram in Figure 7 summarizes the general computer/process communication for real-time digital control and the data acquisition system.

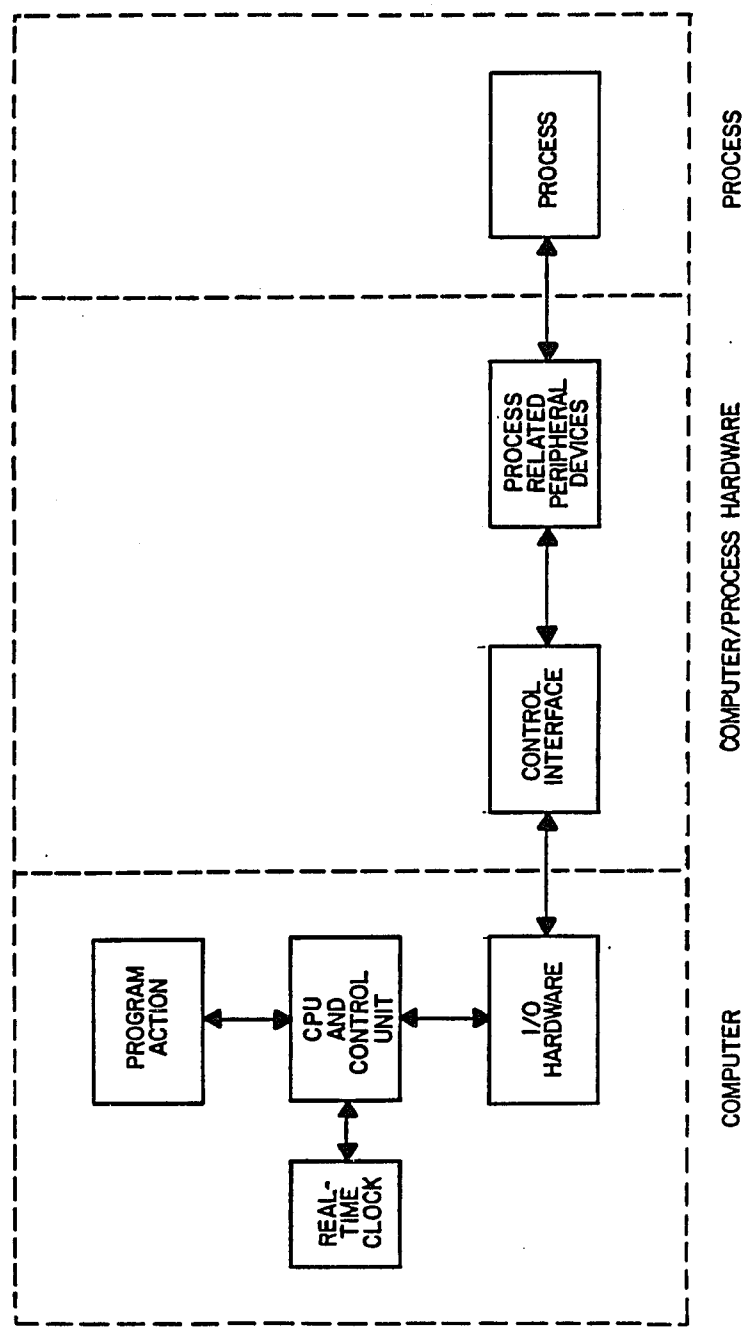


Fig 7 Computer/process communication for real-time digital control and data acquisition

CHAPTER 3

DEVELOPMENT OF CONTROL STRATEGIES

Background

Control system developments based on digital computers are fundamentally the same as those incorporating analog instrumentation hardware and control (Skrokov, 1980). Digital control system projects require a thorough understanding of hardware and software complexity since these systems usually control larger numbers of process units in one control scheme than do conventional analog instrument control loops. When a micro-computer is used as part of a closed-loop system, it should be treated as just another block in this control loop in regard to flowsheet design and specification production during the system development phase. Any control system development must begin with the production of typical flow charts, outlining control strategies to be used in the system.

In computer control System development; one should include the following four phases:

(i) The conceptual development phase: System engineering analysis, control diagram production for the process;

(ii) Instrumentation development phase: Calculation and selection of proper measuring and final control elements for control and data acquisition;

(iii) Hardware development phase: Configuration and specification of the computer hardware, instrumentation interfacing and man-machine interfacing;

(iv) Software development phase: Process control language choice and development.

Development of control systems for the Municipal Solid Waste (MSW) project and the Advance Extruder-Reactor Biomass Liquefaction (AERBL) unit requires major design consideration for high temperature and high pressure conditions. Extra effort was made in the development of control strategies to be able to switch from Direct Digital Control (DDC) mode to either automatic or manual control mode when it was necessary. The AERBL is an experimental research unit and the ability to switch the control mode was useful since complete computer control of the unit was beyond the scope of an MS thesis.

The overall control flow charts for the MSW project and the AERBL unit are shown in Figure 1 and 2, respectively. Comparing both figures, there are some similarities between the processes. Even though the MSW process is a semi-continuous process and the AERBL unit is a continuous process, both processes use CO and steam as an input stream to the reactor. Also, since process conditions are quite similar, as both

the processes require high temperature and high pressure , most of the instrumentation and hardware specifications are the same for both processes. The software for the real-time control algorithm is the same for both processes, as the discrete Proportional Integral Derivative (PID) algorithm is used for DDC. Conceptual development for the control systems is the only major difference between the processes.

In the following sections of the chapter, only the conceptual development phases of the control strategies will be presented for both processes.

Conceptual Development

The conceptual development of the control system involves process analysis and decision-making based on that analysis, concerning the particular control modes and strategies for all systems of the unit. The control modes most commonly used are the open-loop or closed-loop modes. In the closed-loop mode, control action is directly manipulated by the digital controller of a micro-computer, while in the open-loop control mode, a micro-computer is used only to correct and measure the information. The most commonly used control strategies are feed-back and feed-forward corrected algorithms. Both the MSW project and the AERBL unit utilize a closed-loop feed-back control algorithm. Feed-back control strategies in DDC allow proper correction from the setpoint and provide tight process control.

Municipal Solid Waste (MSW) Liquefaction Conceptual Development
Conceptual Development

The municipal Solid Waste Liquefaction process is semi-continuous. Carbon Monoxide (CO) and steam flows continuously into the autoclave at a pre-determined flow rate. The batch volume of the reactant containing the carrier oil and MSW is liquefied inside the autoclave at 300-400°C and 1000-3000 psi requiring about 30-60 minutes residence time.

As shown in Figure 1, there are four process variables: flow of CO, flow of steam, temperature of autoclave and pressure of autoclave. Each process variable has an effect on the process conditions for liquefaction and residence time. For simple design consideration, each process variable represents an individual control loop with its own measuring and final control element.

The first variable, carbon monoxide (CO) inlet flow rate, is measured by a volumetric flow meter. The controller output is manipulated from the flow meter feed-back signal for desired control action of the final control element. The flow-rate of CO is very dependent on the inlet pressure of the flow meter and pressure drop across the flow meter.

The second variable, the steam flow rate is controlled in a similar fashion as the CO flow rate. A volumetric flowmeter is used to measure flow through the control valve to the autoclave.

The third variable, the temperature of the autoclave, involves an interactive control loop with regard to the total amount of heat produced by the electrical heater and steam. A thermocouple signal is fed back to manipulate the temperature controller output signal, which is used to drive the time-proportional power relay.

The final variable, the off-gas pressure in the autoclave, also involves an interactive control loop. Off-gas pressure depends on the pyrolysis of MSW, CO pressure and steam pressure inside the autoclave. This can be isolated and controlled by using a pressure transducer as a feed-back signal to the controller. The effect of the input variables, CO and steam, can be obtained by using the controller in the manual mode and controlling other variables close to the setpoint. Figure 8 shows a DDC configuration for the M.S.W. Process.

Advanced Extruder-Reactor Biomass Liquefaction (AERBL) Unit Conceptual Development

Because operating conditions of the AERBL unit are very severe, the initial control strategy for the unit is to operate continuously for a minimal period of time. For this task, minimum and non-interactive control loops were chosen for DDC. It was felt that this would make the control system less complex and more controllable at the initial stage of operation. The switching of an interactive control mode can be achieved once several successful runs have been made and the dynamic response has been studied in detail.

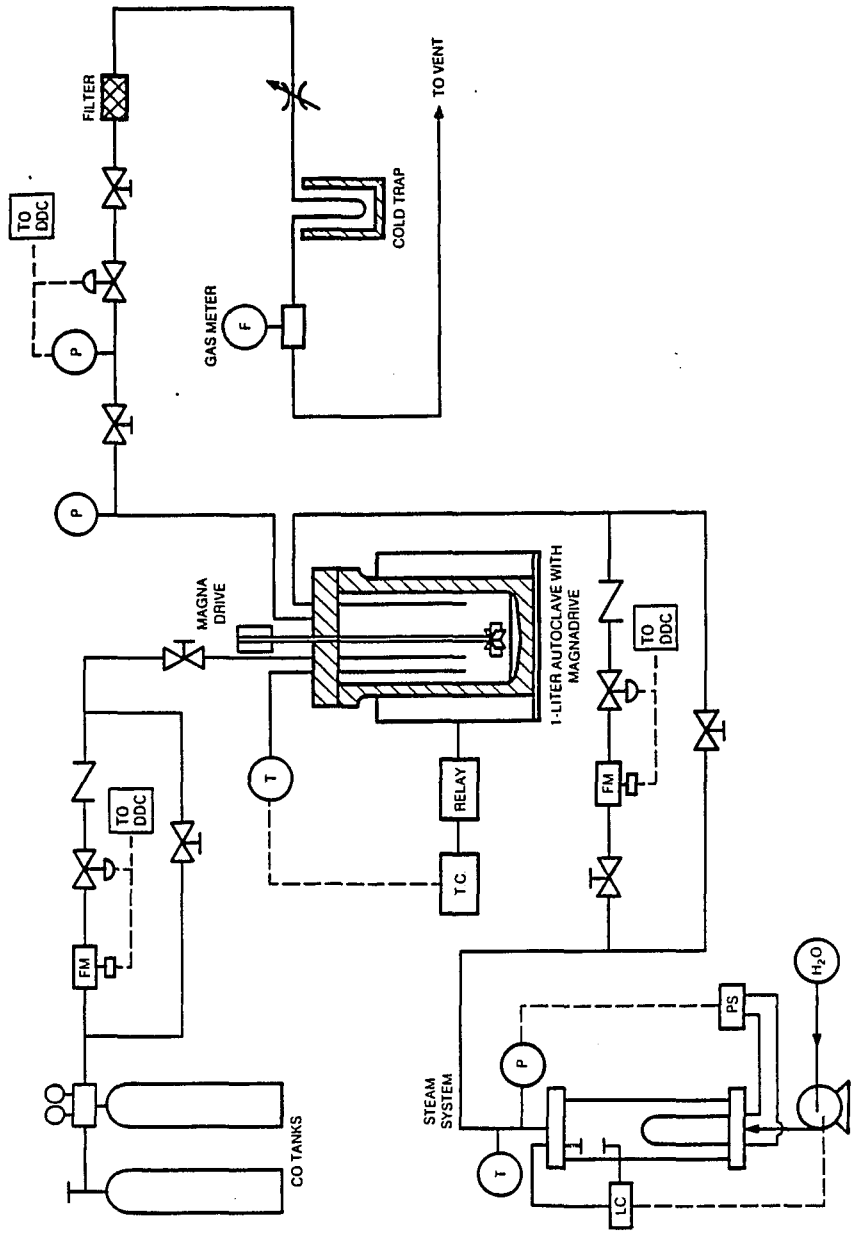


Fig 8 DDC configuration for the MSW process

The AERBL process is operated in a continuous mode, as shown in Figure 9. The overall unit process is quite complex and requires better understanding of the process variables. To simplify the process, it has been divided into several individual systems:

1. Extruder-feeder system
2. Carbon monoxide system
3. Superheated steam system
4. Vertical reactor system
5. Off-gas letdown vessel system
6. Liquid-product let-down Vessel System

Extruder-feeder System. In the Extruder-feeder system, wood flour and carrier oil are mixed together and fed by the Cramer-feeder into the extruder-feeder at a constant flow-rate. The extruder-feeder is utilized to feed highly concentrated slurries into the reactor at 3000 psi and 150C. The important controllable parameters are flow rate and temperature of the extruder-feeder. A hydraulic valve is necessary to maintain a constant flow rate of the highly viscous material of the extruder-feeder. This control loop is fairly complex, as the slurry is a pseudo-homogeneous non-newtonian liquid. Also, many unidentified process variables are involved which could make this loop interactive. Initially, flow through the extruder-feeder is controlled by adjusting the screw speed manually. An analog temperature controller is used to control the barrel temperature of the extruder-feeder. With further

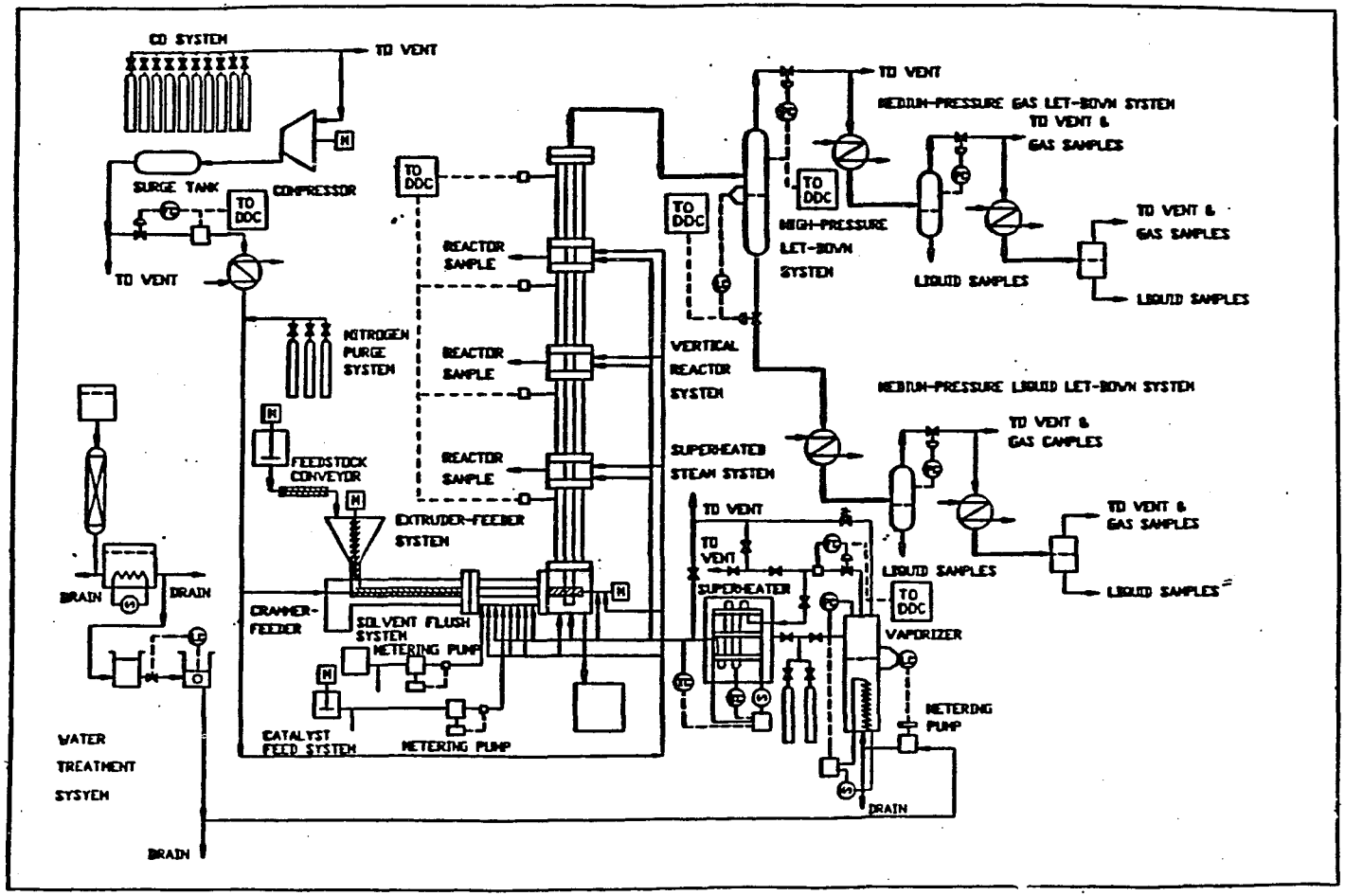


Fig 9 DDC configuration for the AERBL unit

automation, direct digital control strategies can be utilized for both of these loops.

Carbon Monoxide System. Carbon monoxide (CO) is used to increase the reaction rate for the AERBL process. CO reacts with the steam and a water-gas shift reaction takes place inside the reactor. The CO system has a compressor which compresses the CO gas to 3200 psi. This compressed gas is then fed into the mixing zone at the bottom of the reactor. The flow rate of CO into the reactor is an important variable for control and liquefaction. A DDC loop operated by a micro-computer is desired to control about 24 lb/hr maximum flow of CO to the reactor mixing zone. This flow controller is a non-interactive first-order control loop. The use of a flow meter as a measuring element would make it easier for the controller to manipulate output to the final control element (control valve). This system has an advantage over other systems of the AERBL unit because the controller operates at a low temperature, as CO is heated after passing through the flow controller.

A pressure controller on the surge tank will be used to regulate a constant upstream pressure of 3000 psi to the flow meter for smooth flow control. This control loop will be interactive with the flow control loop, as flow of CO through the valve depends on both upstream and downstream pressure of the flow meter. The pressure controller will be implemented in the second phase of development of the CO System.

Superheated Steam System. The superheated steam system is a unique system because of its severe process conditions. The pressure, 3200 psi and the temperature, 950°C, lie above the critical pressure and temperature of a vaporizer.Because of these conditions, tight control is essential for this system. The system is divided into three sub-sections: Feed water system, vaporizer system and superheater system.

The feed water system is operated at room temperature and atmospheric pressure. No sophisticated control is required for this system, which is a simple unit-operation.

The vaporizer system is the most unstable and complex sub-system of the superheated steam process. In this system, water is vaporized near its critical temperature and pressure. Three control loops are implemented for precise control of the system. A high pressure metering pump is used as the final control element for the water level inside the vaporizer. A pressure control loop is used to keep pressure under the critical point. A pressure transducer signal is used to manipulate the controller output to the heater relay. A temperature controller is not needed for the critical temperature, as steam has a linear relationship of pressure and temperature. Flow rate of steam to the reactor mixing zone is also an important control variable. Flow rate of steam, measured by the volumetric flow meter, is used to regulate the flow through the final control element (control valve) by the flow controller.

The superheater has a temperature controller for its silicon heaters to prevent the overheating of the steam. A signal from a thermocouple is fed back to manipulate the controller output to the three-phase power relays.

Complete discussion of the steam superheater design, instrumentation and operating procedure can be found in the M.S. Thesis, Reyes, expected 1985.

Vertical Reactor System. Wood flour, carrier oil, CO and steam are reacted in a vertical plug-flow reactor at 3000 psi and 350°C. The conversion of wood flour to wood oil varies with reaction time, reaction temperature and reaction pressure. Initial design of the vertical reactor system has three reactor sections, but the final development phase will consist of four reactor sections. Four independent PID temperature control loops are required for the four reactor sections in order to maintain the reaction temperature at a desired setpoint value. The pressure of the reactor is maintained by the off-gas pressure of the let-down vessel. This is discussed further in the next section.

The thermocouple signal is used to manipulate the temperature controller output. Time proportional power relays will be used as final control elements to regulate the current inside the electrical heaters.

Off-Gas Let-down Vessel System. The gas and liquid from the reactor is flashed inside the high-pressure let-down vessel. The gas and liquid let-down systems are treated separately to provide better understanding of the control system strategies.

The off-gas pressure of the let-down vessel control loop is one of the most critical and complex loops involved in the AERBL unit. The Control Valve is not only used to regulate the off-gas pressure of the let-down vessel but also, the reactor pressure is maintained by this control loop. Pressure let-down from 3000-750 psi is achieved in this operation. This control loop is both a multi-variable and interactive. This control loop has an extruder-feeder flow rate, a CO flow rate and a steam flow rate as disturbances. Also let-down vessel temperature, product liquid level and off-gas pressure are three coupled control variables involved in the control loop. A complete analysis of these control variables and disturbances is important for the computer modeling and simulation of control loops before the implementation of the digital control strategies. Isermann, 1981 and Harris & Billing 1981, have developed tuning methods and analysis for the multi-variable control loop, which can be used to improve performance of the control loop.

The second stage of the off-gas pressures let-down involves another control loop. This loop is similar to the above loop. The control of the loop will be achieved in the second phase of the unit development.

Liquid-Product Let-down Vessel System. The flashed liquid product inside the let-down vessel is a liquid wood oil and unreacted wood flour. To maintain stability within the let-down vessel and reactor, the liquid level is kept constant. If any major disturbance occurs inside the let-down vessel, it will affect the entire system, especially the reactor process conditions. Continuous liquid-level measurement and control will stabilize the liquid-product let-down vessel system. The continuous level measurement signal is used to manipulate the controller output. This control loop is also multi-variable and interacting with the same disturbances and control variables as described in the off-gas let-down system. Modeling and simulation will be required for better control performance. Tuning and analysis of the controller can be achieved by using the multi-variable tuning procedure described by Isermann, 1981.

Instrumentation Development and Specification

The MSW project and the AERBL unit are experimental research projects with severe process operating conditions. Measurement of process variables and their fluctuations are necessary for the stipulation of the flow patterns, dynamic response of the controller, heat balance, mass balance and other process calculations. Table 3 shows the initial instrumentation required by the AERBL unit for the measurements, final control elements, safe operations, and emergency shutdown operations.

Table 3

Instrumentation For the AERBL Unit

Measuring Elements	Total Amount
Pressure Transducer	24
Thermocouple	45
OFF/ON Valves	40
Level Sensor	4
Flowmeter	2
	115

Final Control Elements	Total Amount
Control Valves	4
Power Relays	8
	12

In order to reduce noise and voltage fluctuations in signal processing and transmission, 4-20 ma output from the transducers and 4-20 ma input for the final control elements were essential, as the control room is more than 50 feet away from the process instruments.

The instrumentation justification and procurement of each individual system is described in detail in this section.

Extruder-feeder System

The extruder-feeder system utilizes two major pieces of equipment, a Cramer-feeder and a single screw extruder-feeder. Extruder-feeder and Cramerfeeders are widely used in the plastic industries for the extrusion processes. In the AERBL unit, the extruder-feeder is important for feeding highly-concentrated slurries of wood-flour and carrier-oil into the reactor.

Pressure and temperature distributions of the non-newtonian slurries inside the extruder are useful to calculate the pressure drop and viscosity of the slurries. Seven pressure transducers and thermocouples are mounted on the extruder-feeder in three different zones; melting zone, compression zone and feeding zone. This data are needed for the complete analysis of the process dynamics. A schematic layout of the instrumentation is shown in Figure 10.

It would be difficult to mount all the instruments individually on the 4 ft. long and 1-3/4" I.D. extruder-feeder barrel. Figure 11 details the mounting of a pressure transducer and a thermocouple onto the same mounting hole. A 6" long stainless steel threaded tube filled with

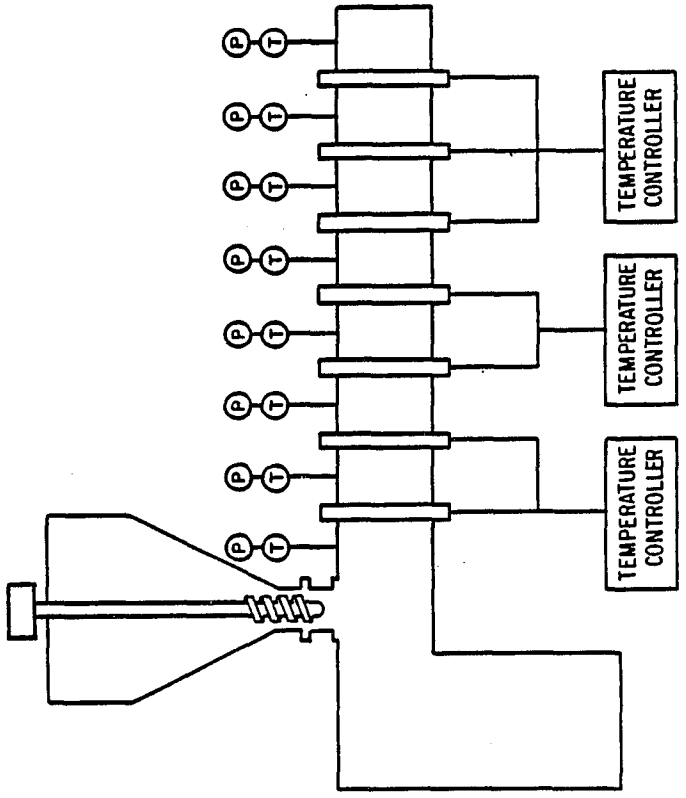


Fig 10 Schematic instrumentation layout for the extruder-feeder system

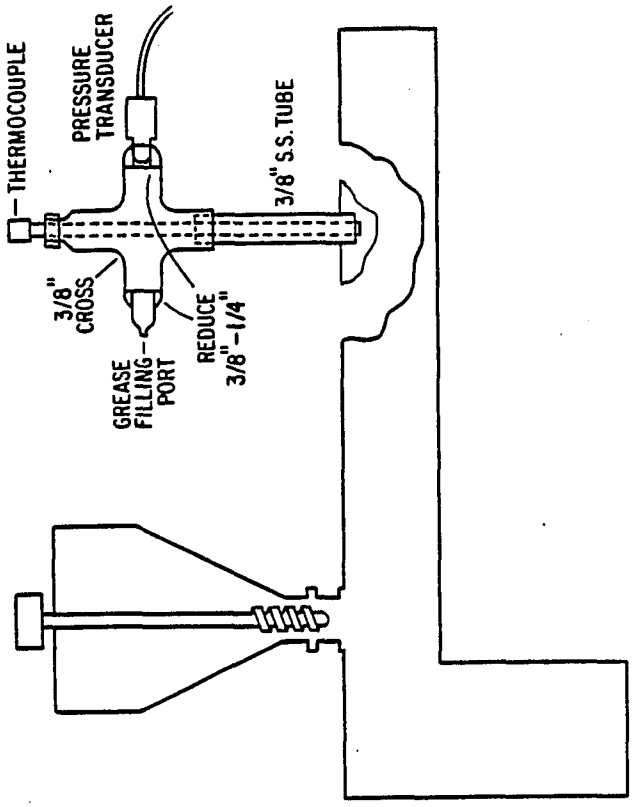


Fig 11 Schematic of detail mounting of instrumentation on the extruder barrel

high temperature silicon grease is used to isolate the high temperature from the pressure transducers. The relationship between length of tube and temperature is shown in Figure 12 (Dynisco, Technical data sheets).

Precise Sensors Inc.'s Model #113-3, flushed diaphragm pressure transducers were specified for pressure measurement on the extruder-feeder. These transducers have a combined non-linearity and hysteresis of less than ± 0.25% of Full Scale Output (FSO) with repeatability of less than 0.081% and a rise time of 10 micro-seconds. The maximum operating temperature of the transducer is 149°C and pressure ranges are from 0-3000 to 0-5000 psi. Highly sensitive signal conditioners are used to convert the 30 mv FSO to 4-20 ma current outputs for 0.1 to 500 ohms load. These Precise Sensors Inc. signal conditioners are matched with their pressure transducers and have a ± 0.02% of range measurement accuracy with infinite resolution.

The extruder-feeder system uses seven thermocouples to measure the slurry temperature which ranges from 40°C to 150°C ,depending on the thermocouple location on the barrel. Twvele inch long Iron constantant ungrounded thermocouples were specified for good resolution at these temperatures. The Omega Engineering Inc.'s model #1CSS316U-12 with a 3/16 inch sheath diameter can be used at temperatures as high as 760°C with almost linear output in mV.

In the second phase of control system development, a hydraulically actuated control valve will be used as a final control

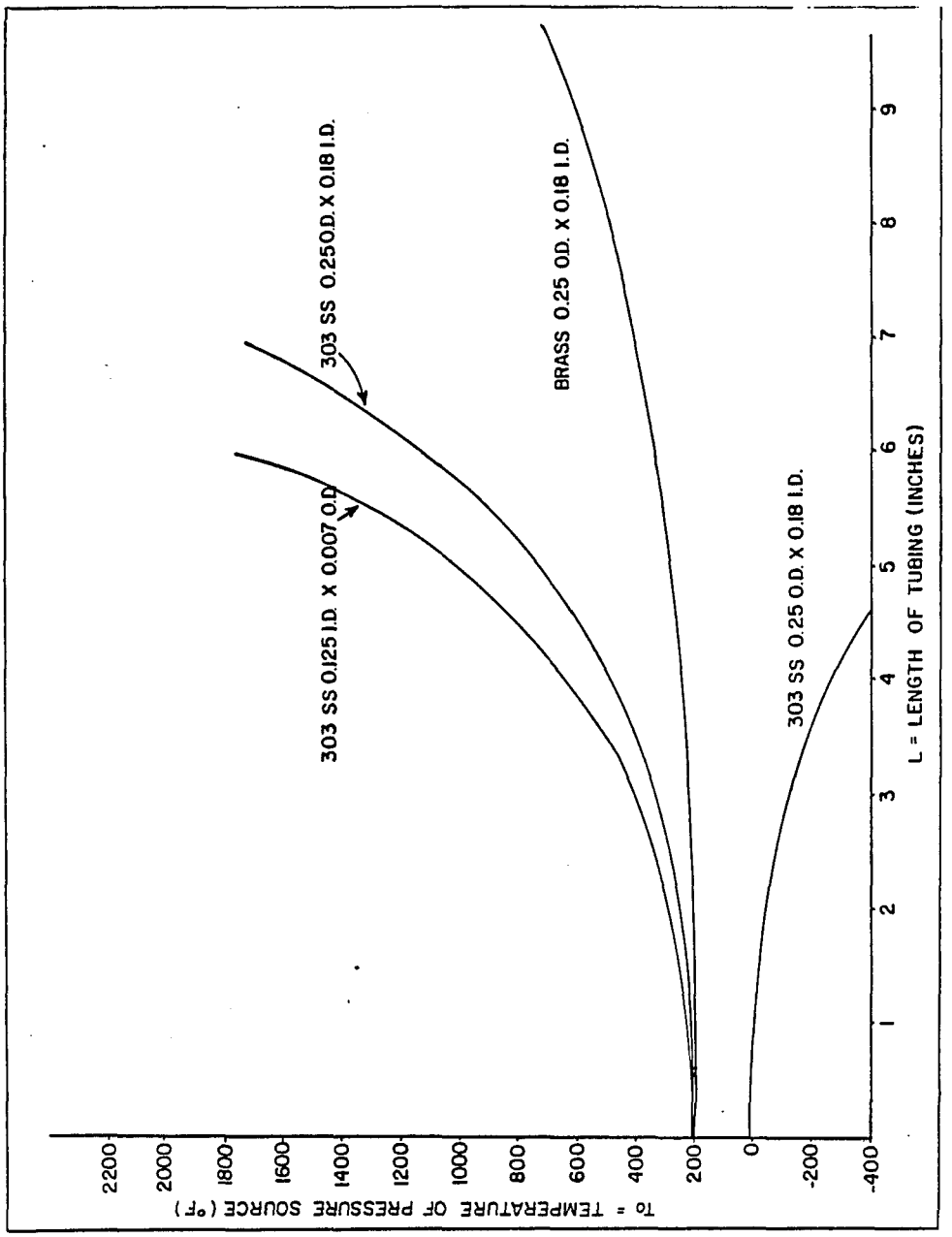


Fig 12 Tubing length to isolate transducer from temperature source

element to control the flowrate through the extruder. Initially, flow is controlled manually by a predetermined RPM of the screw.

Carbon Monoxide System

Initial Carbon Monoxide (CO) System instrumentation design was based on the 3-accumulator system (May-July 1983 Quarterly Report). The availability of a high pressure CO gas compressor from the Albany Liquefaction Facility simplified the design of this system. Figure 13 shows a schematic of the CO System instrumentation layout.

Three separate pressure transducers are used to measure compressor output, surge tank pressure and CO inlet pressure near the mixing zone. Precise Sensor Inc.'s Model #5550 pressure transducer with ranges of 0-5000 psi were specified for pressure measurement. These rigid strain-gauge transducers have a combined non-linearity and hysteresis of less than ± 0.35 FSO with repeatability of ± 0.08%. The maximum operating temperature of Model #5550 is 149°C. These transduser specifications are matched with their signal conditioners to convert the 0-30 mv transducer signal to 4-20 ma current output and 0.02% of range measurement accuracy.

Three thermocouples are used for the CO system. One measures surge tank temperature to calculate mass flow through the volumetric flowmeter, and the other two calculate heat balance and measure the CO gas temperature at the inlet and outlet of the heat-exchanger. Ungrounded iron constantant thermocouples, as described in the Extruder-feeder System Section are also specified for this system.

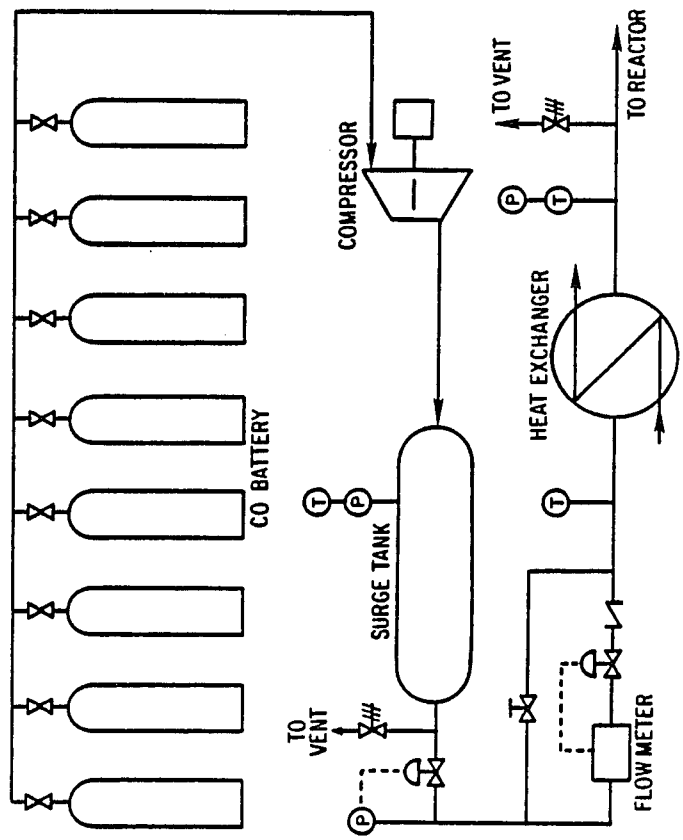


Fig 13 Schematic instrumentation layout for the CO system

Flow Technology Inc.'s flow transducer Model #FTO-N2-GJS was specified for carbon monoxide flowrate measurement . This turbine-type flow transducer has a flow range from 0.002 to 0.030 ACFM (1.5 to 23.5 lb/hr) at 57°C and 3100 psi. Turbine flow meters have ± 0.2% repeatability with 0.3% calibration accuracy. The inherently non-linear transducer is linearized by using the pulse converter, Flow Technology Model #PRC-408AA2BZT. The 0.5 to 3500 Hz modulated carrier frequency is converted to 4-20 ma and a 1-5V dual output signal to the controllers. The pulse converter has linearity of 0.2% of FSO.

As the final control element in the control loop, the control valve restricts flow through the flow meter. At the design condition of 24 lb/hr CO at 57°C and at a 200 psi pressure drop across the valve, the calculated flow coefficient (C_v) is 0.01. Masoneilan Model #29000 Series MICROPACK Control Valve, which is designed for a low C_v (flow rate) at as much as 3600 psi pressure, was specified. The MICROPACK is an economical and a compact control valve, with a hand wheel on the top of the valve that can be opened or closed manually in case of emergency or when the computer is down. The rangeability ratio of the control valve is 500:1 for the specified C_v of 0.04. This means that minimum controllable CO flow through the valve is about 0.18 lb/hr. The flow characteristic of the valve is linear for the spring-opposed rolling diaphragm with a force amplifying lever actuator. The sensitivity and the repeatability is 0.1% with a full stroke time of less than one second.

Two ON/OFF Air-Operated Valves (AOV) are used to release the CO gas pressure to the vent line for safe operation of the unit. The air-operated ON/OFF valves are driven remotely by electrically-actuated, low-pressure, ON/OFF solonoid valves. The first AOV is used to open the surge tank when pressure has exceeded the maximum allowable pressure of the tank. A high alarm signal from the pressure transducer is used to actuate the solonoid valve to open the AOV. Another AOV is used in the same way, but after the heat- exchanger. Autoclave Engineers Inc.'s medium pressure (up to 20,000 psi) AOVs are specified for this operation with an air to open type of actuated diaphragm.

Superheated Steam System

The vaporizer, where boiling at the critical pressures and temperatures occurs, is one of the most important components of the superheated steam system. Most of the instrumentation of the system lies in and around the vaporizer. The vaporizer has two level point switches, the high and the low, for level control; a pressure transducer and a power relay for pressure control of the heaters; a thermocouple; and a flow controller with a flowmeter and control valve as the measuring and final control elements. The superheater has two thermocouples and two pressure transducers for the calculation of temperature and pressure drop across the superheater. Five ON/OFF AOVs are used for safe operation of the system and as bypass lines. Figure 14 shows a schematic layout of the instrumentation.

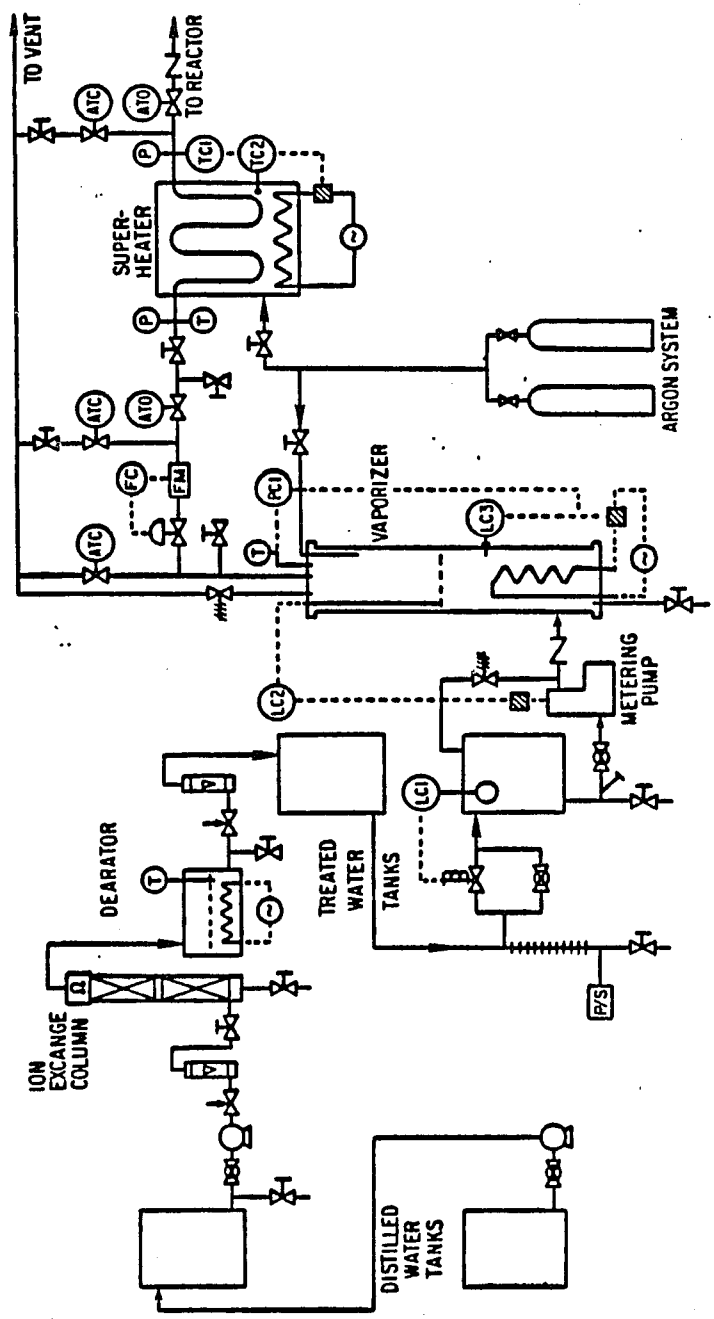


Fig 14 Schematic instrumentation layout for the superheated steam system

Precise Sensors Inc's Model #5550 pressure transducers were specified with the same specifications as described in the CO system section. In order to isolate the transducers from the high temperatures, 6-9" of stainless-steel tube coil is used. The maximum operating temperature of the pressure transducer is 149°C.

Iron-constantant ungrounded thermocouple probes are used in the vaporizer. The specification of the thermocouples are the same as described in the Extruder-feeder System Section. Superheater operating temperatures are around 900-950°C. The cromal constantant thermocouples were specified for the sub-system as they provide the best resolution and accuracy at this temperature and maximum temperature measurement by the Iron constantant thermocouple is 760°C.

Initially, the flow controller was to measure the flowrate of steam after the superheater. But in the superheater there are no disturbances or obstructions to change the flowrate from the vaporizer. The revised design consists of a flow meter and control valve. This arrangement increased the availability of the flow meter and the control valve. Maximum steam flowrate is constrained to at 40 lbs/hr to the reactor mixing zone. The flowrate of the saturated steam is measured by the precise turbine flow meter, specially made by Flow Technology Inc. This flow meter can measure the flowrate from 0.0035 to 0.70 ACFM at 370°C and 3100 psi. A pulse converter is used to change frequency output from the flow meter to 4-20 ma or 1-5V output signal.

A critical service control valve is needed to control the low flowrate to the reactor at 3100 psi and 370°C. A Masoneilan Model #5061 Wee-Willie control valve is designed for this type of low flowrate and high pressure and temperature application. The Wee-Willie Valve is also a custom-made angle-control valve with an alloy 25 trim and plug. The actuator of the valve is DOMOTOR, which has high thrust, stiffners and large stroke for smooth flow control. An extended bonnet is used for higher temperature applications of the steam.

The calculated C_V of the valve is 0.005 for a 200 psi pressure drop across the valve. Trimset "A" was specified, which has a C_V range from 0.00001 to 0.01. The rangeability of the C_V ratio is in excess of 100:1 with linear flow characteristics.

The initial control strategy for this control system is to use the microprocessor-based process controllers, as the superheated steam is an experimental unit and needs tight control for its safe operation. In the second phase of the research, these four loops will be switched to the DDC mode.

Five ON/OFF, high pressure AOVs with low-pressure electrically-actuated solonoid valves were specified for safe operation. Out of five AOVs, two AOVs, normally closed and one normally open AOV are installed before the superheater and the other two normally closed AOVs are implemented after the superheater for emergency shutdown and safe operation.

Vertical Reactor System

Reactants are pumped by the extruder-feeder into the vertical reactor at 3000 psi and 150°C. Saturated steam and CO is also injected at the bottom of the reactor. The vertical reactor system has four sections with three intermediate connecting spools and two flanges.

Data from the thermocouples, pressure transducers and sampling ports are required to obtain Residence Time Distribution (RTD), and the pressure and temperature relationships of the reactor system. Each section of the reactor has five thermocouples at equal distance measuring the wall temperatures of the reactor. Each spool and the flange has a thermocouple, a pressure transducer and a sampling port to measure the actual temperature, pressure and conversion of slurry, respectively. Figure 15 shows a schematic of the instrumentation layout for the vertical reactor system.

Four PID control loops have four power relays as the final control elements to drive the heaters at the desired reaction temperature in the each reactor section.

Five normally closed AOVs and five normally open AOVs were needed for the sampling system at each reactor spool and the flange. The AOVs are driven by low-pressure, electrically-actuated solonoid valves. Autoclave Engineers Inc. AOVs were specified for the sampling operation.

All 25 thermocouples in the reactor are 12" long ungrounded iron constantant probes, the same as described in the Extruder-feeder system section.

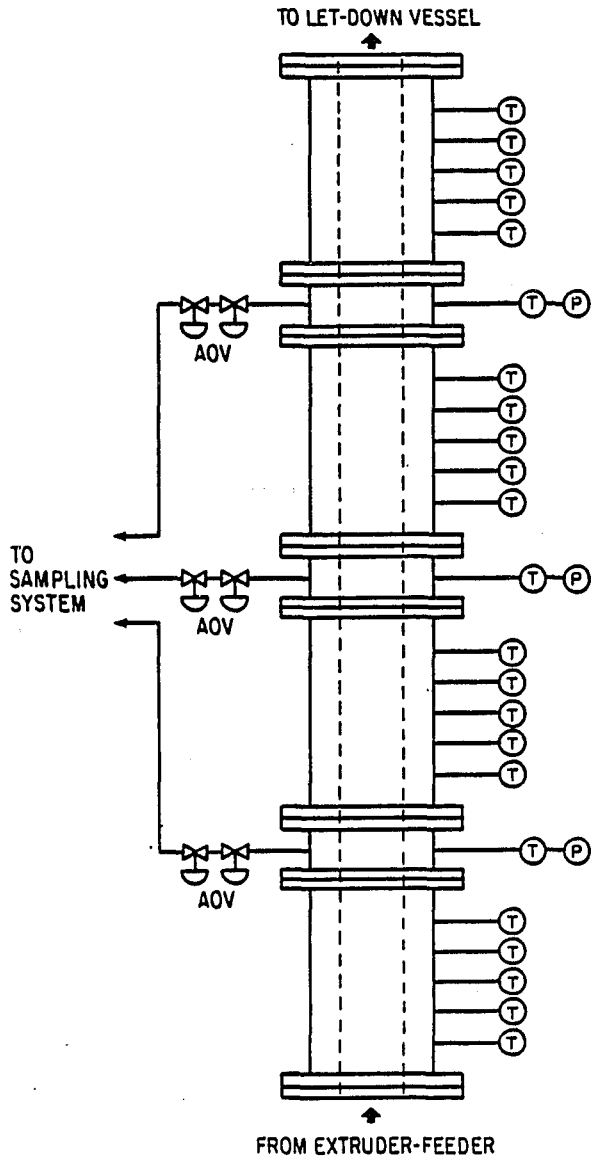


Fig 15 Schematic instrumentation for the vertical reactor system

In order to avoid plugging of slurry and inaccuracy of pressure measurement of the transducers, a flush-diaphragm type of pressure transducer is essential for this system. Dynisco pressure transducers are well known to the plastic industries for this purpose. These stain-gauge transducers are designed for use at high temperature and pressure applications. In addition, they can be mounted easily on the reactor without any temperature isolation techniques. Dynisco Model #PT 462E pressure transducers, with a range of 0-5000 psi, were specified. These transducers have a combined error of non-linearity and hysteresis of ± 1.0% of FSO and repeatability within ± 0.2% of FSO, with infinite resolution. The maximum operating temperature of the transducers is 400°C with 80% of FSO internal shunt calibration resistance. Dynisco Model #SCM 600 matched signal conditioners are used to convert the pressure transducer signals 10-40 millivolts (mv) to 4-20 ma output signals. The linearity of the signal conditions is 0.1% of FSO with a response time of only 10 milliseconds from 10% to 90% FSO and accuracy of 0.1% of FSO.

Off-Gas Letdown Vessel System

The Off-gas letdown vessel system is one of the most critical systems of the AERBL unit . This system contains four thermocouples, three pressure transducers, a control valve as a final control element and twelve ON/OFF AOVs as shown in Figure 16.

Initial operating procedures for the Off-gas let-down vessel system are to control pressure of the let-down vessel and purge out all

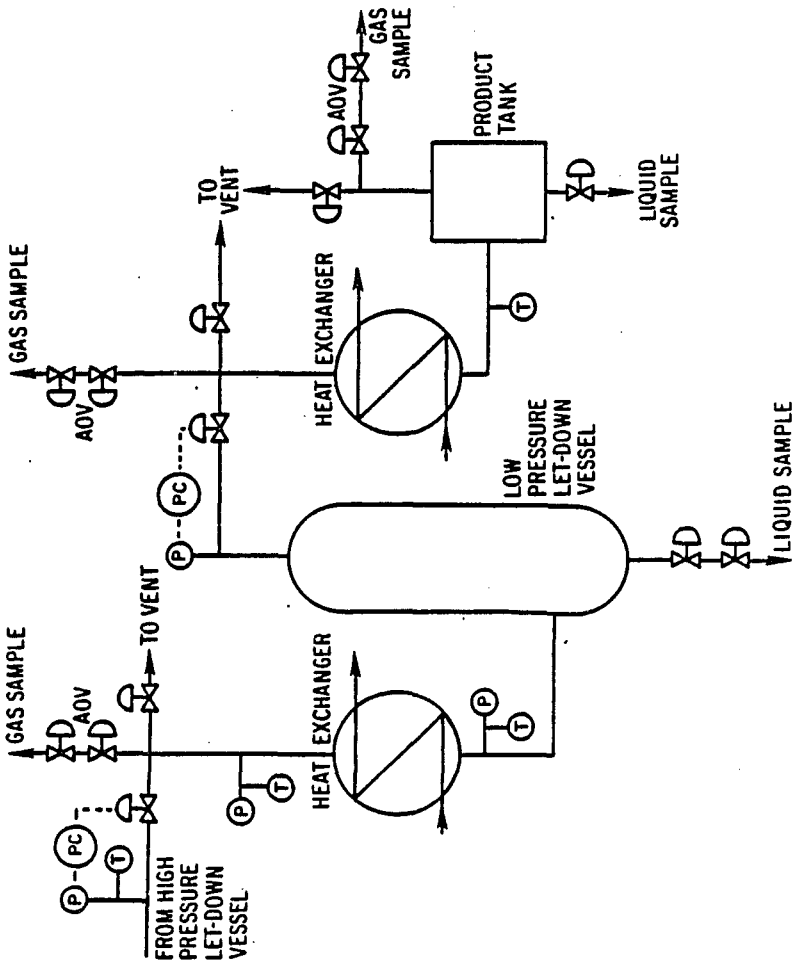


Fig 16 Schematic instrumentation layout for the off-gas let-down vessel system

the gas to the vent. Two heat exchangers, a medium-pressure let-down vessel and a light-product recovery will be installed in the latter part of the development of the unit.

The pressure transducers specified for the first stage of the pressure let-down system were the Dynisco Model #PT462E with a 0-5000 psi range and the Dynisco Model #SCM600 matching signal conditioners. The specifications are the same as described in the Vertical reactor system section. Pressure transducers used after the first heat exchanger could be lower temperature transducers, such as Precise Sensor Inc.'s Model #113-3. These are as accurate as the Dynisco transducers but can be used up to 150°C and are more economical.

Iron constantant ungrounded thermocouples are within the range of these process conditions 12" long thermocouples with the same specifications as those of the extruder-feeder system are also used for temperature measurement.

Masoneilan's Model #29000 service MICROPACK Control Valve with a C_V of 0.6 was specified as the final control element for the off-gas pressure controller. The estimated C_V for the valve is 0.01 at 350°C and 3000 psi. Specifications of the valve are the same as described in the CO system section except for a difference in the flow coefficient (C_V).

Twelve AOVs were specified for the emergency pressure relief and sampling system. Out of the 12 AOVs, four are normally open and the other eight AOVs are normally closed.

Liquid-product Let-down Vessel System

Flashing of the reactor-product into the liquid and gas phase is achieved inside the high pressure let-down vessel. The flashed liquid-product is maintained at a two-foot level inside the high pressure let-down vessel. A liquid level sensor is required for continuous level measurement at 3000 psi and 350°C. Many possible level measurements were considered for this application, but only two kinds of sensors could be used at these process conditions. The differential pressure transducer, which measures gas and liquid differential pressure, is one of the sensors that could be used for level measurement with some difficulties in accuracy and calibration. The calculated differential pressure of liquid and gas inside the vessel is about 5-10 inches of water. This is a sufficient differential pressure to allow level measurement with temperature isolation tubes and some degree of error. Precise calibration of the transducers is necessary after each run to maintain a high degree of accuracy and less error. The other sensor option is to use a non-contacting measurement device, such as a gamma-ray level sensor. These sensors are linear and accurate but very costly.

The final control element of the level controller is an angle control valve, Masoneilan Model #3600-61. This valve is designed for highly-concentrated slurries at high pressures and temperatures. The body of the control valve is made of 316 stainless steel with an ASA-rated 2500 lb, 1/2 inch screw connection to withstand high pressure. The calculated C_v of the valve is 0.6 at 3000 psi and 350°C. In the

first stage, let-down pressure ranges from 3000 psi to 750 psi. Cavitation inside the valve could be one of the problems encountered, when pressure drop (ΔP) across the valve is high. The stream-link angle-body valve is recommended to reduce cavitation, as the "flow to open" type of valve will increase the allowable ΔP more than three times with the increasing of the critical flow factor C_f (Masonelian Inc., Handbook of Control Valve Sizing),

where,

$$\Delta P_{crit} = C_f^2 \, (\Delta P_s) \qquad (3.1)$$

ΔP_S = Upstream pressure, psi - vapor pressure of liquid at flowing temperature in psi

C_f = Critical flow factor.

Cavitation also can be reduced by selecting a valve location at a lower deviation in the piping system, as it reduces the pressure drop across the valve to below ΔP_{crit}. This option might not be agreeable to the AERBL unit as high pressure drop is encountered across the valve for pressure let-down.

The liquid-product system has three pressure transducers, four thermocouples and eleven ON/OFF AOVs for measurement, sampling system and emergency relief as shown in Figure 17.

Pressure transducers utilized before the first exchanger are Dynisco's Model #PT462E, at a 0-5000 psi range. Specifications are the

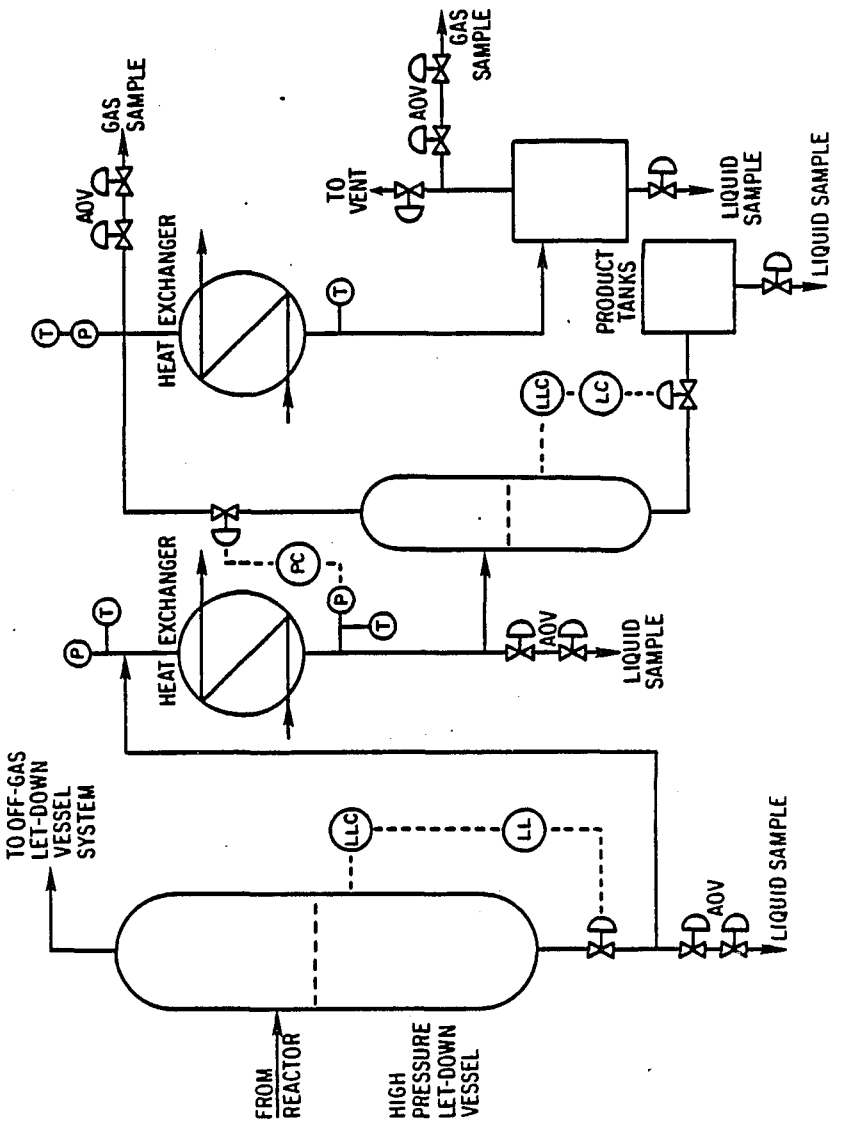


Fig 17 Schematic instrumentation layout for the liquid let-down vessel system

same as described in the Vertical reactor system section. Low temperature, economical pressure transducers such as Precise Sensor Inc.'s Model #113-3 can be used after the heat exchanger.

Iron constantant, ungrounded thermocouple probes are used with the same specifications as described in the Extruder-feeder system section. The AOVs are mainly used for the sampling system and emergency pressure release. All AOVs are actuated by low-pressure solonoid valves.

Initial control strategy for this system is to use the D.D.C. for the high-pressure, let-down vessel and manual control for the medium-pressure let-down vessel. The second phase of development will consist of implementing the remaining D.D.C. loops and instrumentation.

Table 4 shows the complete instrumentation and final control elements of the individual systems of the AERBL unit.

Municipal Solid Waste Process Instrumentation

The Municipal Solid Waste (MSW) process is smaller than the AERBL unit. The MSW unit uses the CO system and superheated steam system from the AERBL unit in a simple form, as shown in Figure 18.

The MSW System Off-gas pressure is controlled by a pressure controller, similar to the Off-gas System in the AERBL unit without much disturbance. The same control valve and pressure transducer are used for Off-gas pressure control.

In the CO flow control loop, the CO flow rate is controlled directly from the CO tank. The same flow meter and control valve, as

Table 4

Instrumentation And Final Control Elements Required By

Each Individual System Of The AERBL Unit

System	Pressure transducer	Termo-couples	Flow meter	Liquid level	Heater relays	Control valve	On/Off valve
Extruder-feeder	7	7	0	0	2	0	0
CO	3	2	1	0	0	1	2
Superheated Steam	3	3	1	2	2	1	5
Vertical Reactor	5	25	0	0	4	0	10
Off-gas let-down Vessel	3	4	0	0	0	1	12
Liquid-product let-down vessel	3	4	0	2	0	1	11

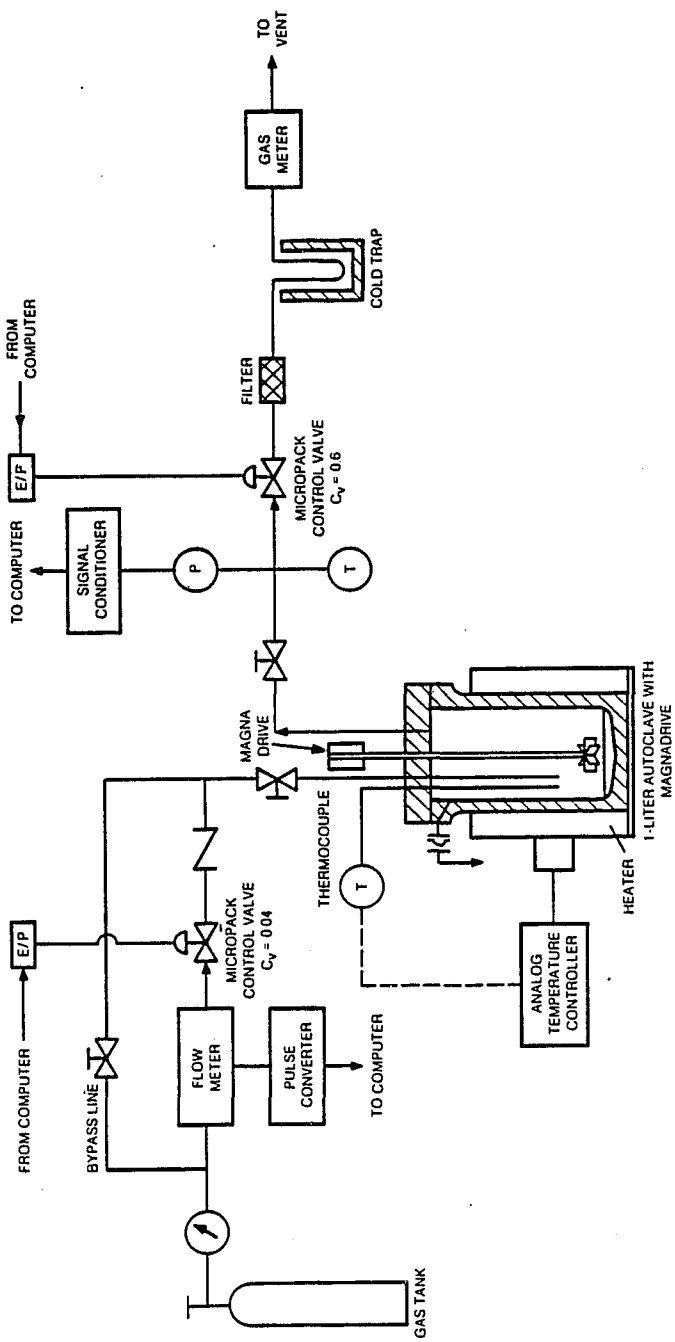


Fig. 18 Schematic instrumentation layout for the MSW process

described in the CO system section is used for this control loop. From the superheated steam system, saturated steam is used initially until a steam system is developed for producing superheated steam.

The Hardware Development

Digital computer interface hardware is composed of two sub-systems, interface control hardware and process control hardware, as described in Chapter 2 . Before discussing the development of the hardware, it is important to overview the 6502 based Franklin ACE-1200 micro-computer system.

The 6502 based micro-processor is used for the direct digital control, data acquisition and the real-time scheduler. The ACE-1200 system utilizes a 6502-based 8-bit micro-processor with 64 kilobytes of memory, two floppy disk-drive units and a floppy disk controller card. The resident ROM has Franklin Basic and Franklin Assembly monitor routines. The micro-processor board hardware is compatible with the APPLE-IIe micro-computer. The compatability of the mother board hardware allows many custom-made hardwares to be used for the ACE-1200 system. The Franklin ACE-1200 mother board has seven expansion slots available for I/O operations and System expansion.

A Z-80 based micro-processor board with another 64K of memory and an 80-column board are also available for the system when they are needed. These features are not useful at the present time, as the control real-time operating system (CRTOS) is based on 6502 instruction codes. The transfer of 6502 codes to Z-80 instruction codes can be

achieved with little difficulty. However, interrupting both micro-processors in the time-sharing facilities will require communication routines. Also, the 6502 clock speed is only 1 MHZ while the Z-80 microprocessors work at 3 MHZ clock speed. Another major setback of using both processors at the time sharing environment routine and the CRTOS routine is that it will be difficult to fit into the present size of memory of the Franklin ACE-1200.

Interface Control Hardware

The micro-processor commands for the input/output (I/O) depend upon the hardware design of the micro-computer. There are two common methods for producing the commands by the micro-computer; memory mapping and isolation of the I/O ports. The 6502 based micro-processor control System uses the memory mapping procedure. In this method, the decoder causes the micro-computer to function as though it were reading or writing to memory, so the "port" becomes effectively like a memory address. A block of memory addresses is set aside as the input and output channels. For input, the micro-processor system simply reads these memory locations and for output operation, the computer simply writes to these memory locations.

A Digital to Analog Converter (DAC) for the analog output system is used to convert the digital-word (binary numbers) to the equivalent analog voltage. The digital word is considered as a percentage or fraction of the same reference signal, (Johnson, 1984, P.78).

$$V_{out} = \alpha V_{ref} \tag{3.2}$$

where

$$\alpha = \text{fraction} = b_1 2^{-1} + b_2 2^{-2} + b_3 2^{-3} + \ldots + bn^{2^{-n}}$$

b_1, b_2, ... bn = binary numbers, b_1 = Most Significant Bit (MSB)

The resolution of DAC becomes

$$\Delta V_{out} = 2^{-n} V_{ref} \tag{3.3}$$

Where,

ΔV_{out} = Step size of output and voltage

For an 8-bit DAC, step size of output voltage will be 0.039v/step. So, for 00(Hexadecimal)-FF(Hexadecimal) with 0-10v range DAC the minimum output voltage would be 0.039v. As the DAC word length is an 8-bit maximum, output voltage at FF(hexadecimal) will be 9.9961v because of the quantization (resolution) of the DAC.

The AERBL unit initially has eight control loops, which require eight output channels to the DAC. Interactive structure Inc.'s Model #A03, 8- bit output system is designed for 8 individual channel configurations. The A03 can be used at 0-10v in the unipolar voltage range and -5 to ± 5v for the bipolar range. Linearity of the A03 is ± 1 LSB and conversion time is 3 microseconds.

The Analog to Digital Converter (ADC) is used for converting analog signals into their corresponding binary numbers. The analog input system is normally made of ADC, multiplexers and sample holds. Analog

signals are generally represented in fixed-point forms. The quantization unit Δ (resolution) is given by the word length (WL) of ADC. Isermann, 1981, P.457, defines decimal numerical range NR of the word length WL in bits for unipolarity as

$$NR = 2^{WL} - 1 \tag{3.4}$$

and

$$\Delta = \frac{1}{NR} = \frac{1}{2^{WL}-1} \approx \frac{1}{2^{WL}} \tag{3.5}$$

To find the required word length of ADC Katz; 1981, P.190, suggests,

$$WL \geq 1 + \log_2 \left(\frac{e_{max}}{e_{min}}\right) \tag{3.6}$$

where,

$$\frac{e_{min}}{e_{max}} = \% \text{ Sensitivity of transducer} \tag{3.6}$$

so,

$$WL \geq 1 + \log_2 (\% \text{ Sensitivity of transducer})^{-1} \tag{3.7}$$

For example, the Dynisco pressure transducer's sensitivity is 3.33mv/v and their signal conditioners are:

4 mv/v, so for 5v full scale output of ADC,

$$WL \geq 1 + \left(\frac{3.33}{5000}\right)^{-1} \tag{3.8}$$

This simplifies to the following equation:

$$WL \geq 8.31 \tag{3.9}$$

Therefore, ADC word length must be 10 bits or more for proper representation of the signal. For 10-bit ADC word length, resolution will be 0.098%, but for 12-bit word length, ADC resolution will be 0.024%.

Interactive structures Inc's Analog input system #AI13 was specified for the control and data acquisition systems. The AI13 is a 12-bit ADC with 16 input channels and eight different input, full scale ranges in unipolar and bipolar modes. The conversion time of each input signal is 20 microseconds. The 12-bit ADC for the 0-5v unipolar input range measures input step up to 0.00122v per unit numbers {1(Hexadecimal)}.

The closed-loop digital controller can encounter numerical difficulties using fixed-point and truncation arithmetic. This is caused by the deadband of the ADC and the controller. Katz, 1981, P.195, recommends that the ADC resolution should be determined by the maximum allowable value of the closed-loop limit cycle.

For the ADC:

$$(WL + 1)_{arithmetic} = 4 + (WL + 1)_{ADC} \qquad (3.10)$$

from Eqn (3.9) $(WL + 1)_{ADC}$ is 7.31

which simplifies to

$$(WL)_{arithmetic} \approx 11.31 \approx 12 \text{ bits} \quad (3.11)$$

And for the DAC:

$$(WL + 1)_{DAC} = (WL + 1)_{ADC}^{-2} \quad (3.12)$$

Which simplifies to,

$$(WL)_{DAC} = 6.31 \approx 7 \text{ bits} \quad (3.12)$$

The ADC word length value is within the range of the A113. ADC for arithmetic and the DAC Word Length values are also withinthe range of the A03 8-bit DAC.

A real-time clock is an important auxiliary or peripheral device for real-time process control and data acquisition. The real-time clock has an interval-timer connected to the micro-computer I/O interface, so that the micro-processor can be interrupted at specific intervals of time. Real-time operating systems with control algorithms use these interrupts to schedule the real-time programs or the control programs.

An interval timer circuit using a 6532 timer chip was developed and constructed by Shlapak, 1983, for the 6502 based micro-processor control system (Franklin ACE-1200) to operate the Control Real-Time Operating System (CRTOS). The keyboard activation circuit was developed to generate IRQ interrupts by keyboard depression. Implementation of the ADC and the DAC on the Franklin ACE-1200 expansion slot started crashing the interval-timer clock circuit after a few hours of operation. A

mis-match logic circuit of the interval timer necessitated the custom-made real-time clock board.

"Thunderclock Plus" is a real-time clock with three software selectable interrupt rates at 64, 256, and 2048 Hz. This real-time clock has a built-in interval timer and a clock, which provides month, date, day, hour, minute and second. A combination of the clock and interval timer is used to run and store the real-time data acquisition program, as time from the clock is useful for analysis of the data. The Thunderclock has on-card batteries to keep the clock/calendar running when the power of the computer is off.

Figure 19 illustrates the new 6502 based microprocessor (Franklin ACE-1200) system control hardware after complete hardware installation, including I/O module expansion. The 6502-based microprocessor is the heart of the Franklin ACE-1200 system. Out of eight expansion slots of the ACE-1200 system, the I/O device occupies four slots and one slot each is occupied by the real-time clock and the disk drive controller board. Slot #7 on the ADC board is dedicated to PID controllers for feed-back measurement and Slot #5 is multiplexed from 16 to 128 channels for data acquisition.

Process Control Hardware

Process interface hardwares are used to make I/O hardwares compatible with the process transducers and other analog devices.

The ADC uses 0-5v as input but most of the process signals are all in 4-20 ma, 0-10v or mv range. The conversion of the signal is made

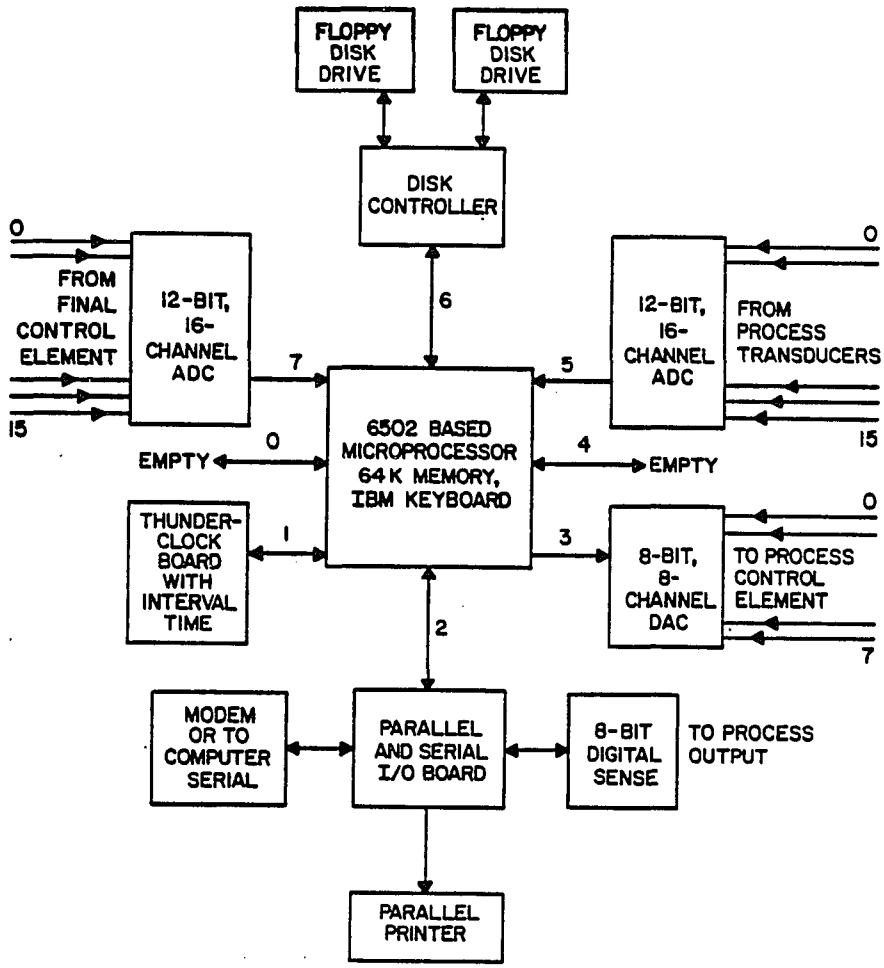


Fig 19 Franklin ACE-1200 micro-computer system control hardware

by developing two circuits: one for 4-20 ma input to 0-5v output and another for 0-25 mv input signals of thermocouples to 0-5v output.

To transform 4-20 ma to 0-5v, resistors of equal calibration to the transducers of the signal conditioners input impedance are used across the input current signal. For better accuracy and resolution, operational amplifiers (Op-amps) can be used.

For the other circuit, thermocouple output is measured in mv_S, which are amplified into volts. For 50 feet of cable, from the process area to the control room, mv signals will create a voltage drop across the line.

Noises from other signals in the line may also create a voltage dropacross the line. Figure 20 illustrates the op-amps circuit for each thermocouple signal. The op-amps is used to amplify the signal at a gain of 200. The circuit has zero and span calibration features. Thermocouples interfacing with the electronic cold junction for n numbers of thermocouples are shown in Figure 21. Note that only common (negative) leads of thermocouples are tied together at the cold junction.

The DAC has 0-10v output and all the final control elements use 4-20 ma as an input signal. A conversion from the 0-10v to the 4-20 ma circuit is needed for interfacing the DAC to the process. The op-amps circuit for voltage to current conversion is shown in Figure 22 for each DAC channel. The op-amps are calibrated by resistors for each final control element and their input load impedance. The zero and the span calibrations are included in the circuit for final adjustment.

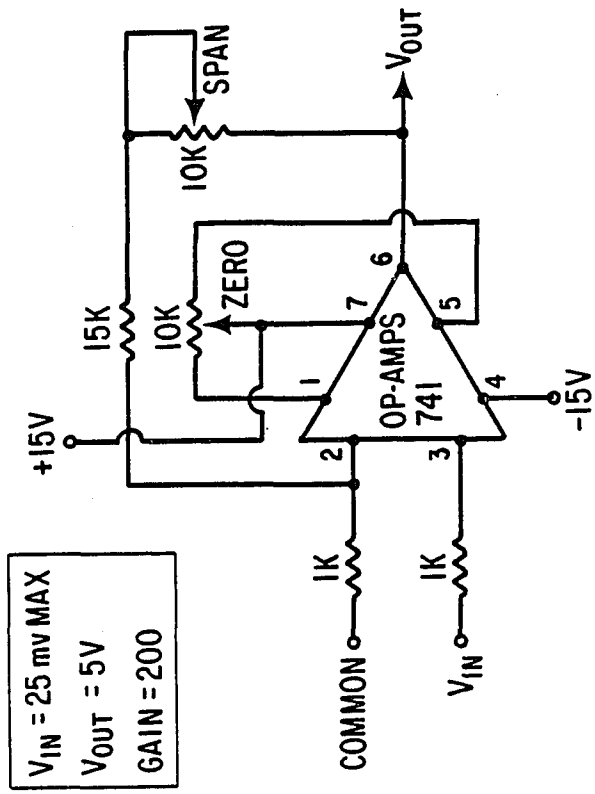


Fig 20 Op-amps circuit for the thermocouples

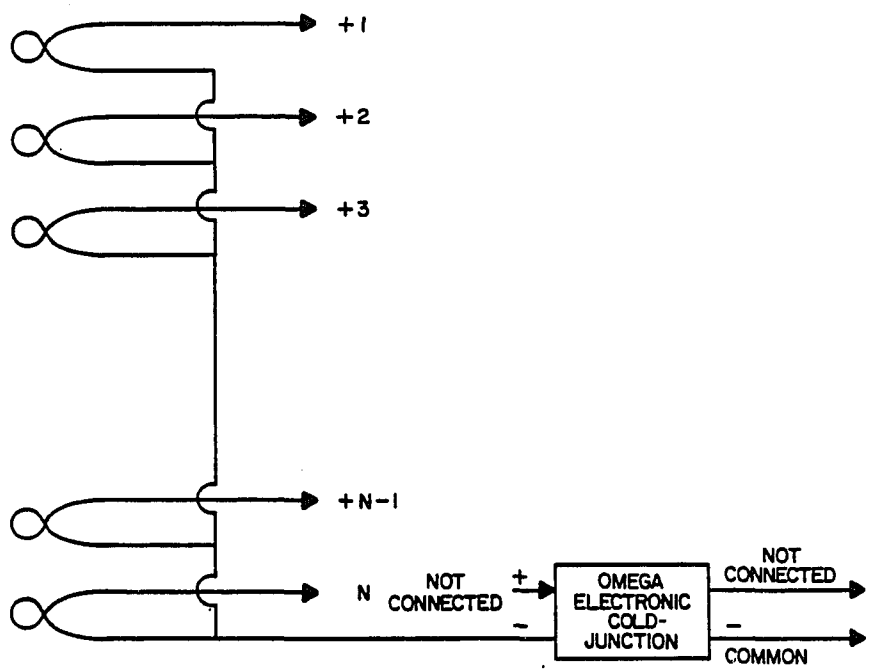


Fig 21 N-number of thermocouples interfacing with electronic cold junction

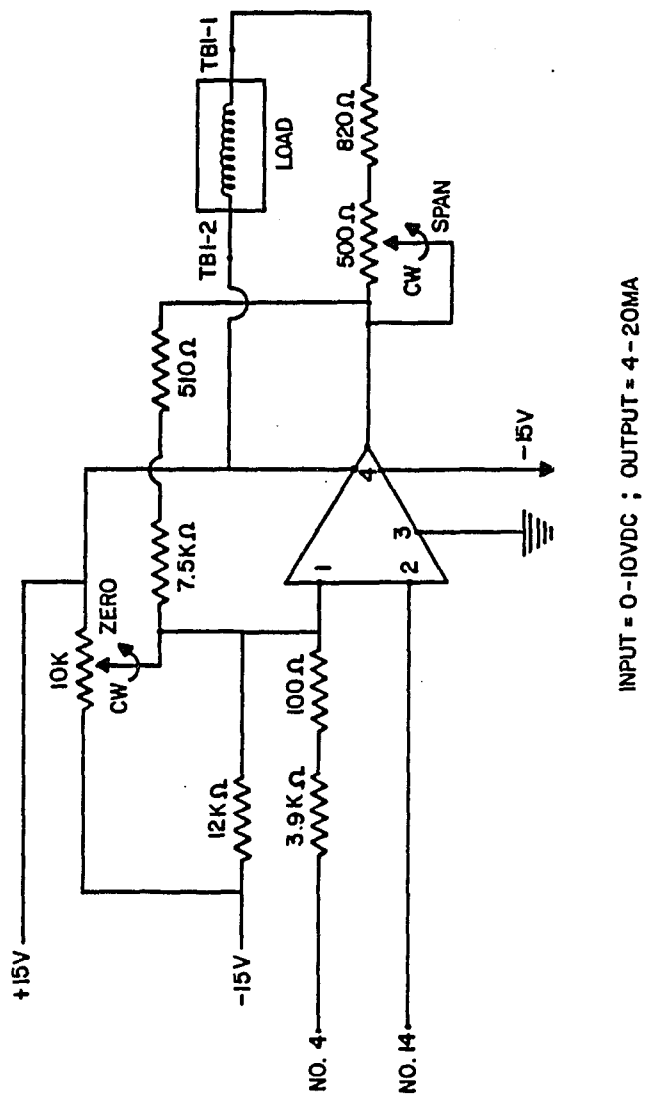


Fig 22 Op-amps circuit for the voltage to current conversion for the DAC

The Software Design

The Control Real-Time Operating System (CRTOS) Software, written by Shlapak, 1983, was adopted as the control algorithm for the AERBL unit and the MSW process. This software was written for sixteen PID control algorithms and eight real-time schedule programs. The PID control algorithm can be expanded up to 256 control loops when necessary.

The CRTOS has three main programs: the PID, the RTTS (Real-Time Task Scheduler) and the interactive I/O programs for screen. For complete discussion of software algorithms, readers can refer to M.S. Thesis, Shlapak, 1983.

The CRTOS program was not tested with the ADC and the DAC for the Franklin-ACE-1200 system. Modification of the program was done to make the ADC and the DAC board compatible to the CRTOS. Also, the new real-time clock board required modification of the CRTOS, as Thunderclock generates IRQ interrupt vectors. The CRTOS was using an NMI interrupt vector.

The PID algorithm of CRTOS was originally written and tested for the KIM 6502-microprocessor at the laboratory control apparatus in the Department of Chemical Engineering, University of Arizona. The control apparatus uses negative input and output voltages, while the AERBL unit utilizes positive input and output voltages for the process instrumentation. As the PID algorithms were transfered to the Franklin

ACE-1200 system without modification from the KIM microprocessor, I/O routine modification was done for the positive input and output voltages.

The discrete PID Equation (2.15) has an important term, "u". A steady-state value reference position, u, defines the actual output of the computer system for the particular control loop (Millichamp, 1983). The selection of u in the original CRTOS version cannot exceed 80 (Hexadecimals) for negative numbers and 7F (Hexadecimals) for positive numbers, otherwise overflow of the DAC might occur (Shlapak, 1983). The selection of u will change everytime an error changes from negative to positive or visa versa. The above output algorithm was completely revised to overcome positive or negative errors. This is shown in Appendix A. New routines accept steady-state value position form 00 (Hexadecimal) to FF (Hexadecimal) and manipulate the output for positive or negative error without changing the value reference position, u. The output routine detects possible DAC overflow and prevents it by resetting the controller output to the minimum or maximum value of the DAC.

Data Acquisition Strategy

As described in *Instrumentation Development and Specification* Section, 115 data points are required by the AERBL unit for mass balance, heat balance and residence time distribution calculation. A data acquisition system is developed for data collection. The standard ADC board has sixteen multiplexed channels. This board is multiplexed to 128 channels using sixteen Burr Brown 8-bit multiplexer. An individual channel is selected by utilizing the three external bits. The 6502 based

Franklin ACE-1200 has annucitor special locations from C058 to C05F (Hexadecimal) for the game I/O. Each annunictor (four one-bit output) has two addresses available for the ON/OFF state. Figure 23 shows the schematic strategy for multiplexing the 16 channels to 128 channels. Desired channels are accessed by first addressing the multiplexer through the proper ADC channel and then selecting the required channel by the annucitor bits. A data-acquisition, real-time algorithm is written by sampling each channel in sequential fashion, incrementing a sampled channel by one after reading each channel. The sample data are stored in the memory and then transferred to the floppy disks for permanent storage.

The data acquisition program is scheduled by the real-time task scheduler of the CRTOS. Extra care is needed to schedule the data acquisition routine, as the PID routine uses the same clock. Small sampling periods of the PID controller can crash the CRTOS. The transfer of data from memory to floppy disks is possible when the real-time clock is off, as the disk drive uses the Direct Memory Access (DMA), which can also crash the real-time clock. A proper operating and scheduling procedure is useed to run the data acquisition program.

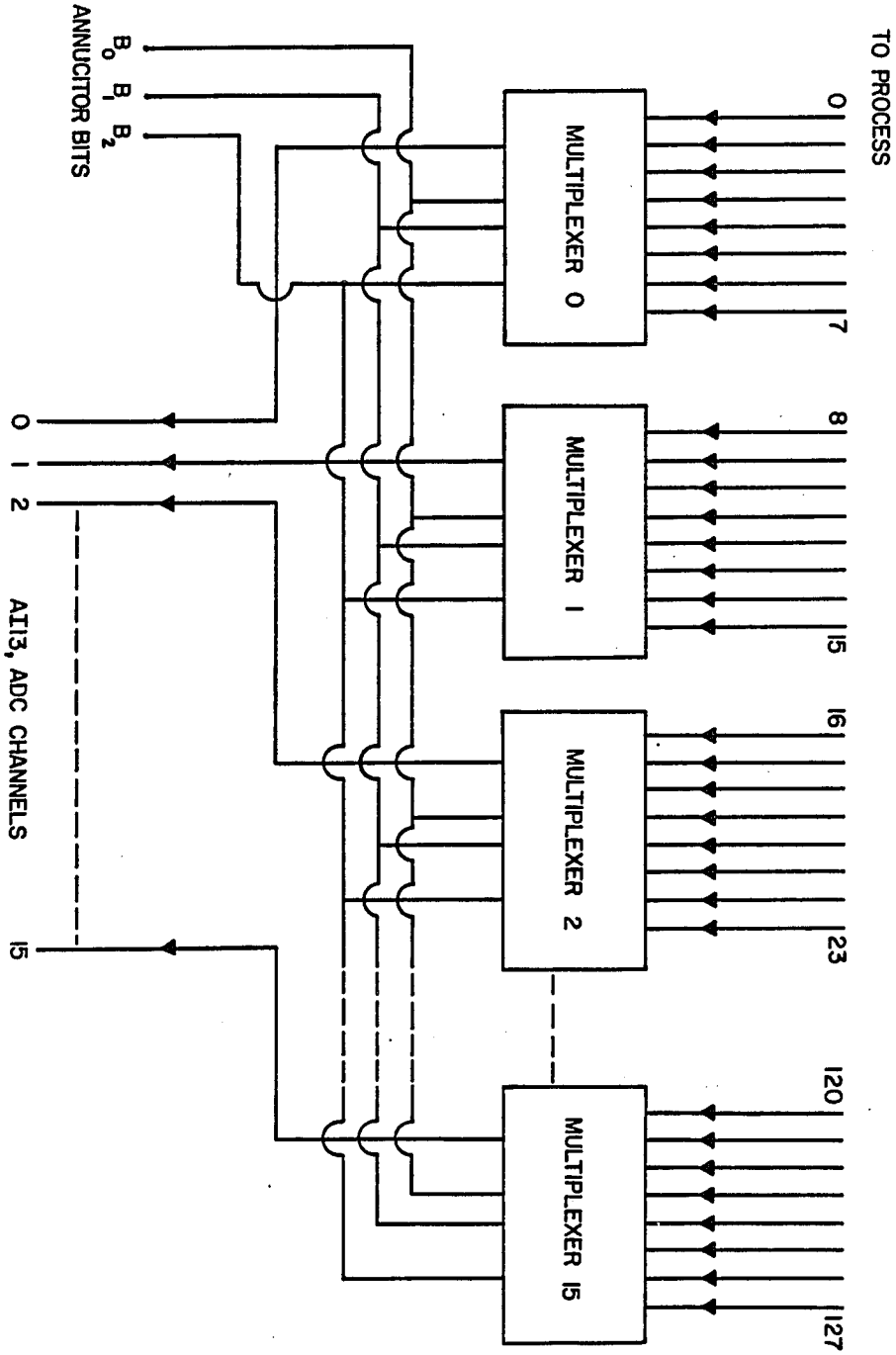


Fig 23 Schematic diagram of the mulitiplexer circuit for the 16 channel to 128 channels

CHAPTER 4

EXPERIMENTAL SET-UP AND PROCEDURES

The control system strategies developed in Chapter 3 have to be analyzed and tested on-line for performance with their respective processes. The MSW project and the AERBL unit processes have some similarities as described in the last chapter, and both processes use the same instrumentation, hardware and software. The control algorithm developed for the Franklin ACE-1200 system and its hardware were never tested on-line with any process or control apparatus. The modified control algorithm with its hardware for the Franklin ACE-1200 system was tested on-line for the MSW process. The AERBL unit is still in the development stage, as equipment set-up and construction of the initial phase is still underway. Also, the principle and the procedure developed for the MSW process control system can be applied for the AERBL unit control system.

The MSW process is semi-continuous, as CO and steam are fed continuously to the batch mass of the reactant inside the autoclave. As, mentioned in the Conceptual Development Section of Chapter 3, the control system has four control loops: carbon monoxide (CO) flow, steam flow, temperature of autoclave, and off-gas pressure. Because of low

level of funding for this project, all the instrumentation and hardware for the MSW process are borrowed from the AERBL unit.

Although the MSW process has four control loops in its conceptual design, the control system performance was tested using any two direct digital controllers for CO flow and off-gas pressure and an analog temperature controller. The inavailability of steam, due to on going development and construction of the superheated-steam system eliminated the use of steam flow control to the autoclave for initial runs. Also, as described in the last Chapter, most of the controllers for superheated steam systems are micro-processor based custom made controllers. The temperature of the autoclave is controlled by an analog controller because of the availability of an on-hand controller and because power relays for the AERBL unit are yet to be specified.

Equipment Set-up

The equipment set-up for the MSW process consists of an autoclave, a CO system and an off-gas system as shown in Figure 24. A one-liter autoclave is used for the liquefaction of solid waste. The autoclave has a magnetic drive unit for the stirrer and one input and one output stream. Temperature of the autoclave is controlled by an analog controller with a power relay. Iron constantant thermocouple wire is used for measuring the temperature of the autoclave and the feed-back to the analog controller.

CO gas flow to the autoclave is maintained continuously by the MICROPACK control valve with a C_v of 0.04 (as described in section for

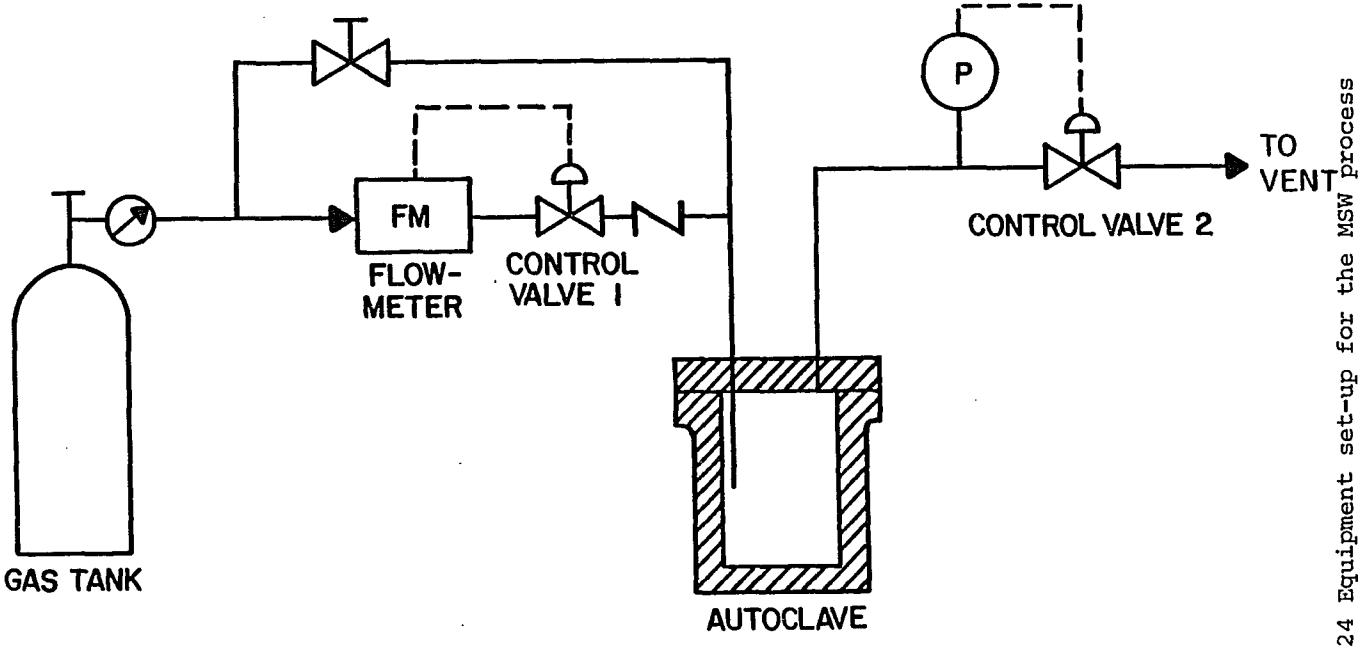


Fig 24 Equipment set-up for the MSW process

CO) . The precise turbine flow-meter measures the gas flow and feed-back to the computer digital controller. A bypass line and check valve is connected in the line to minimize the over speeding of the turbine rotor at start-up and shut-down operation. Over speeding of the rotor can damage the shaft and jewel bearing of the flow-meter. Extra care was taken for the start-up, and shut-down procedure for the flow transducer. Maximum flow through the transducer at 3100 psi for CO gas is 25 lb/hr and a low C_V control valve matches this low flow control application.

Pressure of the autoclave is maintained continuously by an off-gas control valve, which is a MICROPACK with a 0.6 C_V. A 3000 psi Dynisco pressure transducer is mounted upstream of the valve to measure off-gas pressure (autoclave pressure) and feed-back to the digital controller in order to manipulate output to the control valve. A cold trap is used to condense the light gas below 0°C. The total amount of gas produced and unreacted CO gas is measured by the gas meter to complete the mass balance of the process.

Instrumentation Calibration

Calibration of all instrumentation is essential to reduce the error of the instruments. Calibration of the flow-meter, pressure transducer and control valves was done using nitrogen gas. The control valves were calibrated by connecting the nitrogen gas cylinder upstream of the valves. The zero (3 psi) and full span (15 psi) signal to the control valve were calibrated from the Electro-Pneumatic Transducer

(EPT). Total shut-off of the valve was achieved by adjusting the plug and force balance spring. The C_v of the CO control valve was checked for hysteresis as shown in Figure 25. This plot also gives information regarding flow through the valve at given signals of the computer. This is useful to approximate the gas flow at certain openings of the control valve.

The flow-meter and its pulse converter were calibrated for the low flow rate by the manufacturer. The flow-meter and control valve relationship was analyzed at 1500 psi upstream pressure and room temperature. Openings of the control valve and flow rate in voltage are plotted in Figure 26. It is important to note that maximum flow rate was achieved by only a 22% (hexadecimal) opening of the valve for a 500 psi pressure drop.

The 3000 psi pressure transducer was calibrated for 2800 psi by adjusting the zero and span at the signal conditioner.

Hardware Implementation and Calibration

The MSW process uses the same process and control interface hardware as described in chapter 3 for the AERBL unit. Control hardware utilizes two Analog to Digital Converter (ADC) channels, two Digital to Analog Converter (DAC) channels, and a real-time clock. The ADC was calibrated for each channel by supplying known voltages to the 16 individual channels and reading the equivalent binary numbers from the micro-computer. The DAC was also calibrated for eight individual

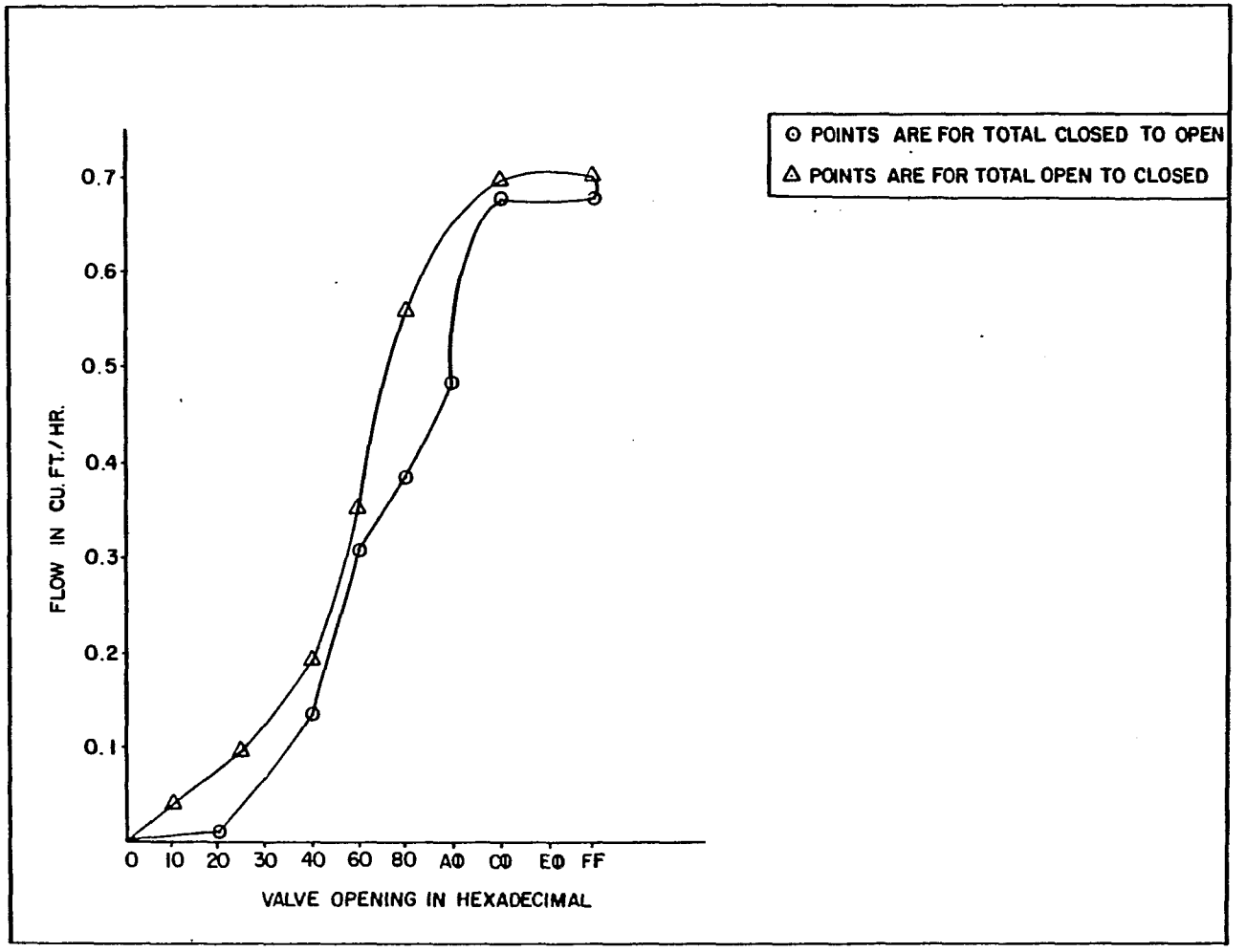


Fig 25 CO control valve hysteresis plot

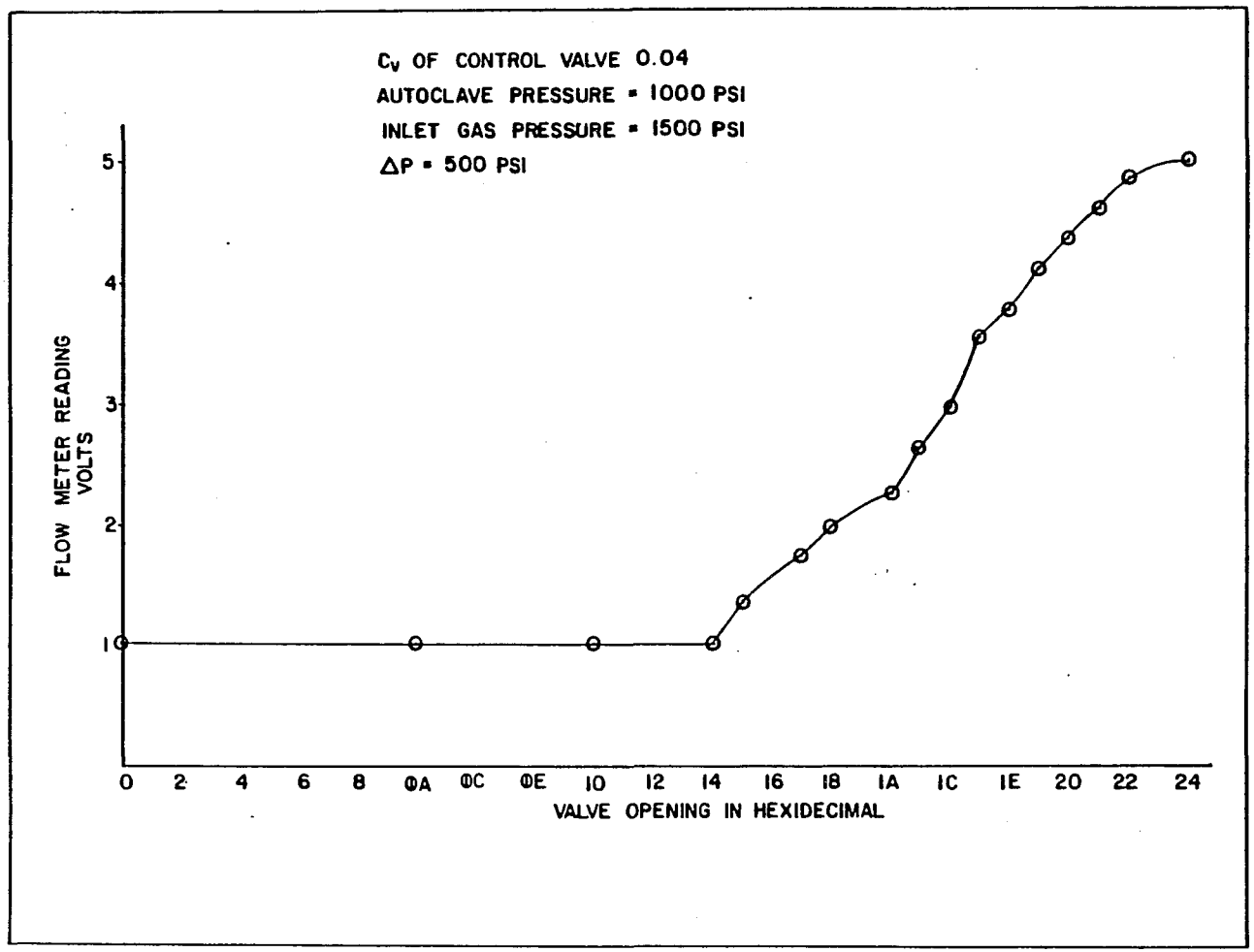


Fig 26 Plot of flowmeter and control valve calibration

channels. The binary numbers were stand-out from the micro-computer and the output voltage was read on the digital voltmeter.

The process interface hardware consists of a 0-10v to 0-5v conversion for the input for the ADC and a 0-10v to 4-20 ma output signal conversion for the EPT of the control valves. The 0-10 to 0-5 conversion was made by using equal amounts of resistance across the input signal. The 0-10 to 4-20 ma signal conversion circuit is the same as shown in Figure 22. The calibration of 4 ma and 20 ma (zero and span) was repeated several times to ensure the right signal to the final control element (control valve) from the digital controller.

A block diagram of the microcomputer to the MSW process after the implementation of the control and process hardware interface is shown in Figure 27.

Experimental Procedures

Three sets of experiments were used to control the semi-continuous autoclave. The first set of experiments was for the sole purpose of controlling the off-gas pressure of the autoclave. The second set of experiments focused on the control of gas flow by keeping the off-gas valve open at a certain position. The last set of experiments involved the control of both gas flow and off-gas pressure of the autoclave.

The experimental procedure for the semi-continuous autoclave involve the following steps:

(1) Weigh the reactants with the glass liners and place them inside the autoclave.

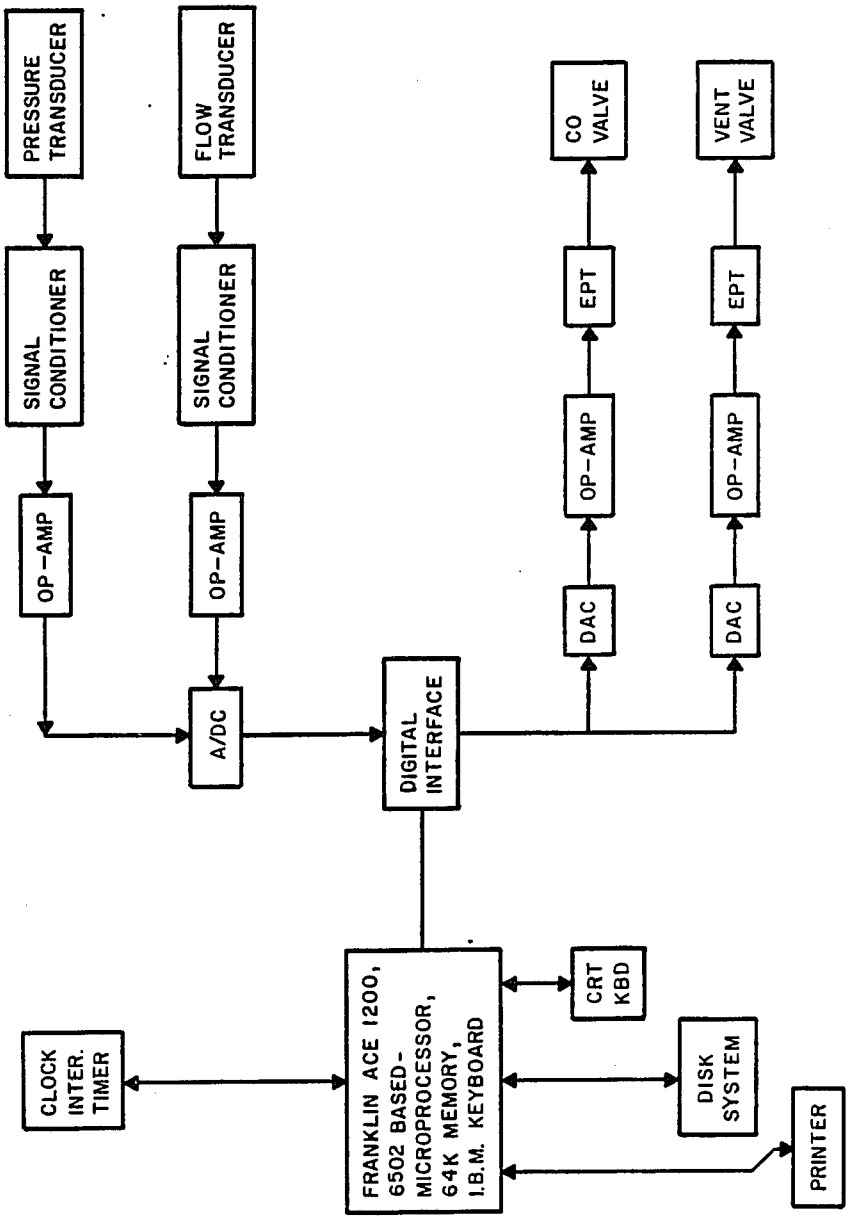


Fig 27 Interfac block diagram of the Franklin ACE-1200 micro-computer control system to the MSW process

(2) Bolt down the autoclave at required torque.

(3) Connect the gas cylinder to the autoclave and open the by-pass line to fill the autoclave at a predetermined pressure. Do not open the flow control valve.

(4) Check the leaks around all the fittings and the bolt encloser of the autoclave.

(5) Connect the off-gas line to the autoclave and open the manual valve slowly, keeping the off-gas control valve closed.

(6) Connect the heater and start heating the autoclave using an analog temperature controller.

(7) Start using the off-gas pressure controller and maintain the gas pressure.

(8) Close the manual valve in the bypass line of the CO system and increase the outlet pressure of the cylinder to a determined higher value than the autoclave pressure.

(9) Turn on the flow controller and maintain a constant flow to the autoclave.

In the first set of experiments the off-gas pressure of the autoclave is constantly maintained at the predetermined value. The flow control valve is kept closed and the by-pass line manual valve is kept open for constant flow of the gas. The second set of experiments follows the same procedure except the off-gas control valve is kept open

at certain positions and the flow controller is used to keep flow constant.

The first set of experiments were made without the continuous insertion of gases into the autoclave and just maintaining the pressure of the autoclave at a predetermined value. The complete on-line testing of the controller, its parameter estimation and results are discussed in Chapter 5 for all three sets of experiments.

Digital Redesign

A steady-state performance of the digital controller and its transient response necessitate the development of a mathematical model with the controller gain and sample rate. This model is based on Z-transforms analysis of the controller, as Laplace transforms cannot be used for the discrete time system, Kuo,1980 . Digital redesign is accomplished by transforming the Laplace domain transfer functions into the Z domain, then choosing a sample rate to determine the closed-loop Z-transform functions (Shlapak, 1983). From these transfer functions, characteristic polynomials and time domain forms are obtained for various controller gains. The closed-loop analysis for the transient and steady-state single-loop feed-back mode with Proportional (P), Proportional-Integral (PI) and Proportional-Integral-Derivative (PID) controllers were analyzed with first-order process elements to reduce the overall order of the closed-loop system. The CO flow control loop and off-gas pressure controller loop are also first-order when they are used non-interactively (separately).

Figure 28 shows a block diagram of the continuous time domain model and discrete time domain model for process, controller transfer function, sample hold for DAC and sampling operation.

The process transfer function $G_p(s)$ of the first order system

$$GP(s) = \frac{X}{\tau S+1} \tag{4.1}$$

where X is the open loop gain and τ is the first order time constant. The first order sample hold of DAC is

$$H(s) = \frac{1-e^{-st}}{s} \tag{4.2}$$

where T is sampling time.

Combining the process and sample hold transfer functions,

$$H(s) * G_p(s) = \frac{X}{\tau s+1} * \frac{1-e^{-st}}{s} \tag{4.3}$$

Taking Z transform

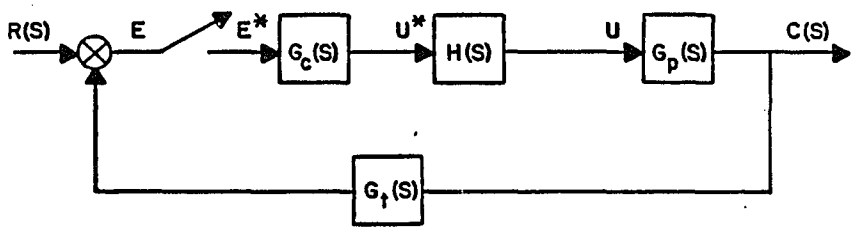
$$H\,G_p(Z) = (1-Z^{-1})\; Z\; [\frac{X}{s(\tau s+1)}] \tag{4.4}$$

This further simplifies to Equation (4.5)

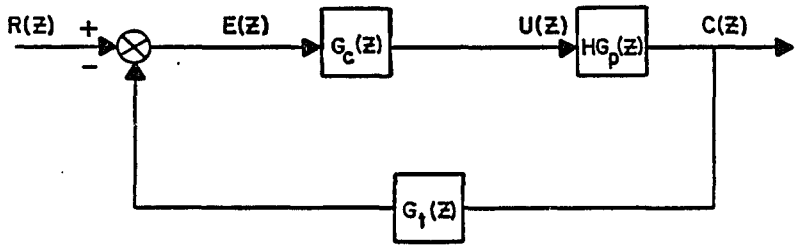
$$H\,G_p(Z) = \frac{A}{Z-B} \tag{4.5}$$

where A (1 = et/τ)x/τ and

B = e/τ



CONTINUOUS TIME LAPLACE FORM MODEL



DISCRETE TIME Z-DOMAIN MODEL

Fig 28 Block diagram of continuous time-domain model and discrete time Z-domain model

The controller transfer function is obtained from discrete PID Equation (4.6)

$$u(KT) = K_P\, e(KT) + u(KT-T) + K_I T\, e(KT-T) + K_D/T\, [e(KT) - e(KT-1)] \quad (4.6)$$

The Z-transform of the above equation leads to

$$u(Z) = K_P(Z) + \frac{K_I T}{Z-1} E(Z) + K_D/T \frac{Z-1}{Z} E(Z) \quad (4.7)$$

The controller transfer function is defined as

$$G_C(Z) = \frac{u(Z)}{E(Z)} \quad (4.8)$$

$$G_C(Z) = K_P + \frac{K_I T}{Z-1} + \frac{KD}{T} \frac{Z-1}{Z} \quad (4.9)$$

The closed-loop transfer function from Figure (4.5) will be

$$G_C = \frac{C(Z)}{R(Z)} = \frac{G_c(Z)\ HG_p(Z)}{1+G_C(Z)\ G_T(Z)\ HG_P(Z)} \quad (4.10)$$

So the proportional controller Equation (4.10) is reduced by substituting Equation (4.9) and (4.5) to obtain

$$G_C = \frac{AK_P}{A-B + K_T K\ A}$$

where transducer gain is K_T

For PI control, Equation (4.10) becomes

$$G_C = \frac{Z^2 A\, K_P K_I (A T K_P K_I - A K_P)}{Z^2 + Z(A K_P - B - 1) + B - A K_P - 2 K_P K_I K_T} \tag{4.12}$$

and for PID control, it becomes

$$G_C = \frac{Z^2 (T K_P A + A K_P K_D) + Z(T^2 A K_P K_I - T K_P - 2 A K_P K_D) + A K_P K_D}{Z^2 T + Z^2 (T K_P A - B - 1 + A K_P K_D T) + Z(B - T K_P A + T^2 A K_P K_I - 2 K_P K_D T + A K_P K_D T)} \tag{4.13}$$

The characteristic equations for P, PI and PID control modes are denominators of Equation (4.11), (4.12) and (4.13), which are useful in examining control performance

A FORTRAN program is available for the calculation of the closed-loop sample data system (Deshpande, Ash, 1981). This program was modified for the position PID algorithm. The program has flexibility to analyze the load changes and set-point changes in the closed-loop performance. A detailed discussion of the program and its results can be found in Chapter 5.

CHAPTER - 5

ON-LINE TESTING AND RESULTS

The On-line testing of the Municipal Solid Waste (MSW) process control strategy consisted of five phases. The first phase involved testing the dynamic behavior of process identification. The transient step testing method was used for the process analysis of each individual control loop. In the second phase of testing, the PID controllers were tuned and their parameters were estimated. The Ziegler/Nichols (Z/N) method for the controller parameter estimation was used for each control loop. The third phase involved the simulation of the closed-loop, sampled-data system for the individual control loop of the MSW process.

Simulation was done through the use of the process and controller parameters. The program simulates the output response of the controlled variable, at the various sample instants. The last phase of testing involved the testing of the performance of the PID/PI controller of the MSW process. In this phase, the controller was tuned to an optimum level by using the information obtained in the previous four phases.

Identification of Process Parameters

Process transfer function identification is achieved either by developing a mathematical process model or by testing the transient response of the process. The transient response technique is used when the process itself is unknown and the chemical dynamic model is unavailable. This technique consists of subjecting the disturbance to the process, while it is operating under steady-state conditions with the feed-back controller and recording the resultant transient response. The disturbance could be step, pulse, ramp or sinusoidal input.

Step input disturbance was tested on both control loops and the dynamic response was recorded. The notion of a transfer function is involved in the development of the model parameter and therefore, some care was exercised in selecting the size of the step input. Step size selection is essential as the output data for the response can be distinguished from process noise.

The step input disturbance for the pressure controller was applied at the steady-state condition as shown in Figure 29. During this test the autoclave was maintained at 1000 psi by using the PI control mode for the pressure controller. The step input disturbance was applied by opening the control valve #1 from 07% (Hexadecimal) to 32% (Hexadecimal). Gas tank pressure was regulated at 400 psi. Input step pressure disturbance and output pressure controller dynamic response are plotted in Figure 30 and 31.

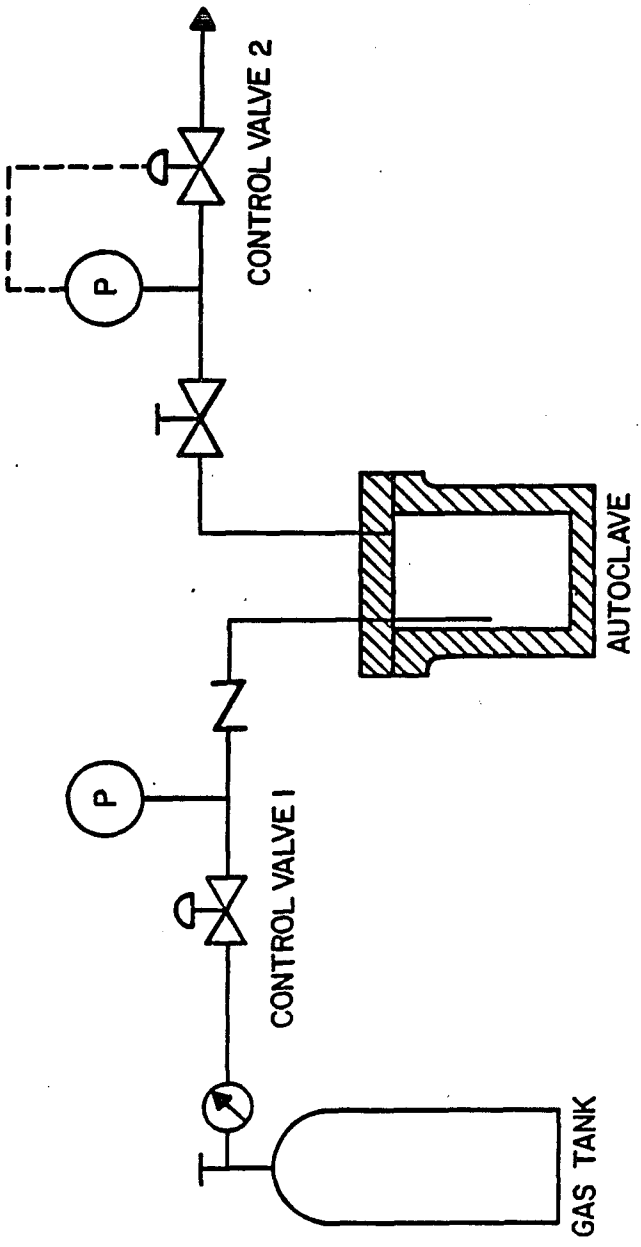


Fig 29 Schematic flow diagram for step-testing for the pressure controller

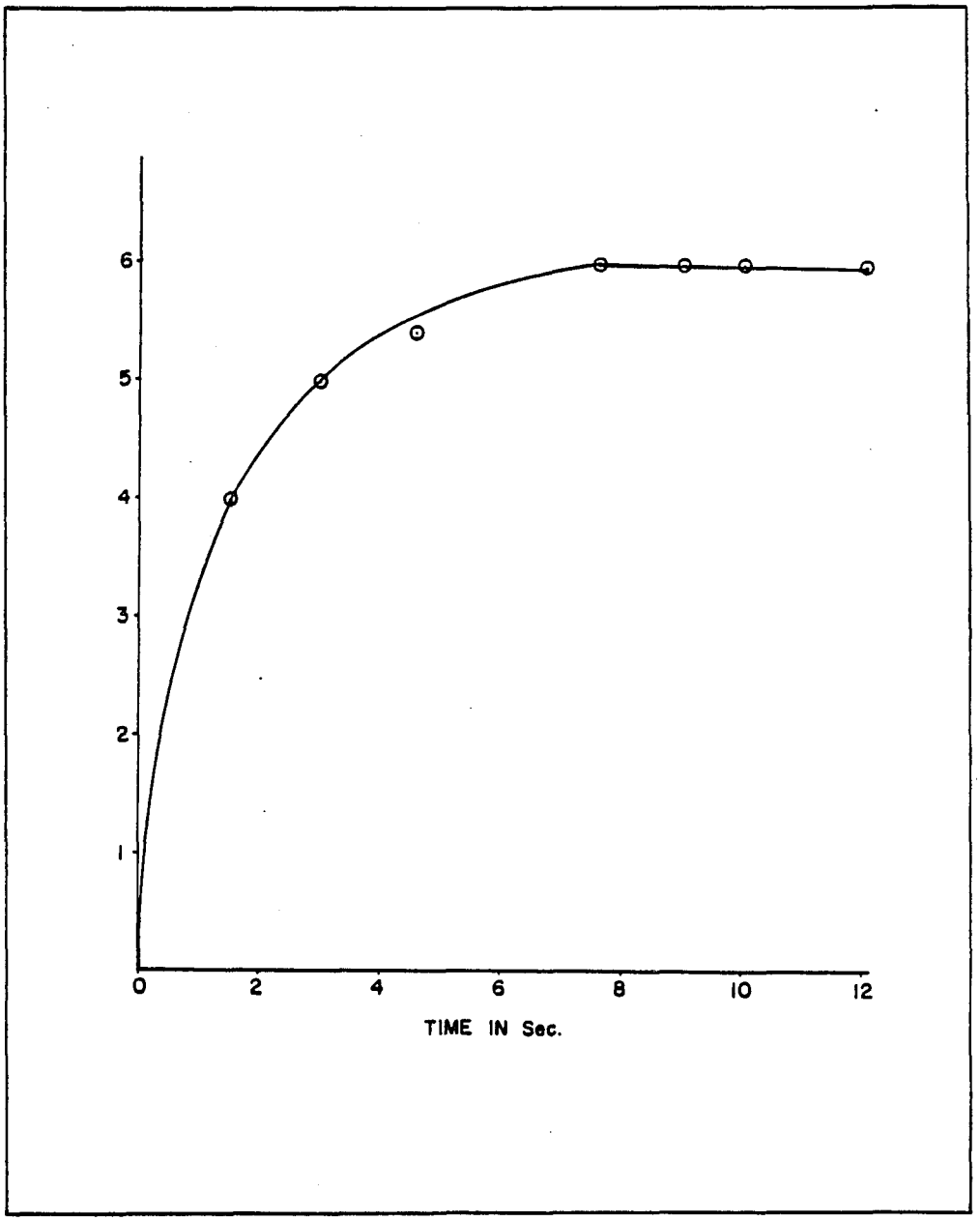


Fig 30 The step input disturbance of the pressure controller

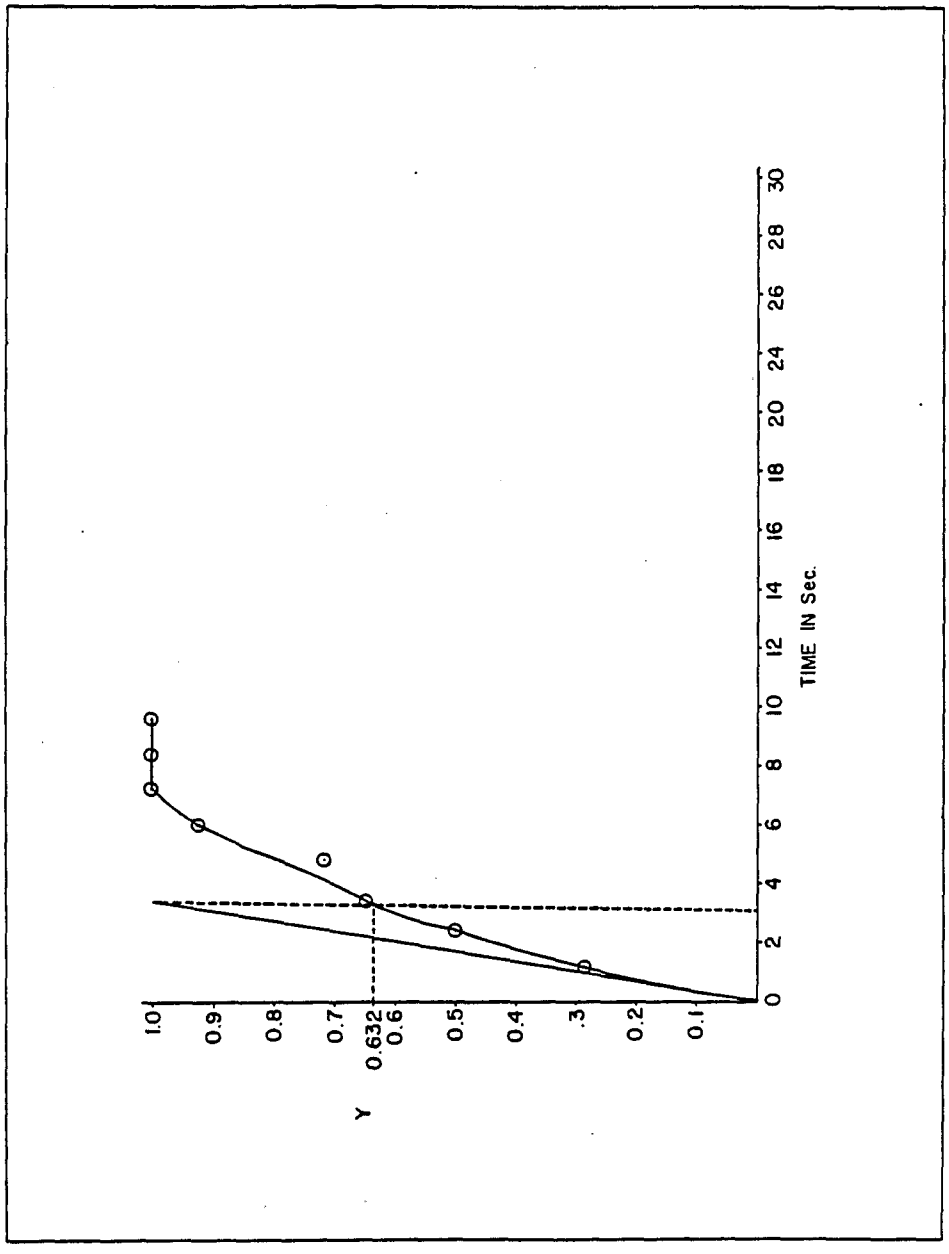


Fig 31 The step response of the pressure controller

Figure 30 of the dynamic response of the controller shows a first-order behavior without any dead time for the process. Smith and Cecil, 1972, discuss the method of first-order model approximation/digital controller design. This technique uses a graphical fit of the actual step response as shown in Figure 31.

The time delay of the process is chosen at the intersection of the time axis and the tangent line, which is drawn at the point of inflection of the step response. The process time delay for the pressure control loop is zero. If the tangent line is extended to intersect the steady-state line. (X(t)=1), the point of intersection corresponds to the time constant of the process. The pressure controller process time constant from Figure 31 is 3.4 sec. This time constant was also determined by the method suggested by Miller, 1967, the time at which the process response attains 63.2% of the final value on the process gain from Figure 30 and 31 is 1.04.

The flow control loop step response was tested by using the flow control feed-back loop and the step input disturbance inside the autoclave. As shown in Figure 32, control valve #2 was opened from 0A (Hexadecimal) to 0D (Hexadecimal) step disturbance. The input step function and output response were recorded. Plots of the time vs the input step function are shown in Figure 33 and 34, respectively.

For the pressure control loop, step analysis of the response is done by the same method as described above . The calculated dead time of the process was zero and the process gain was 1.0. The time constant

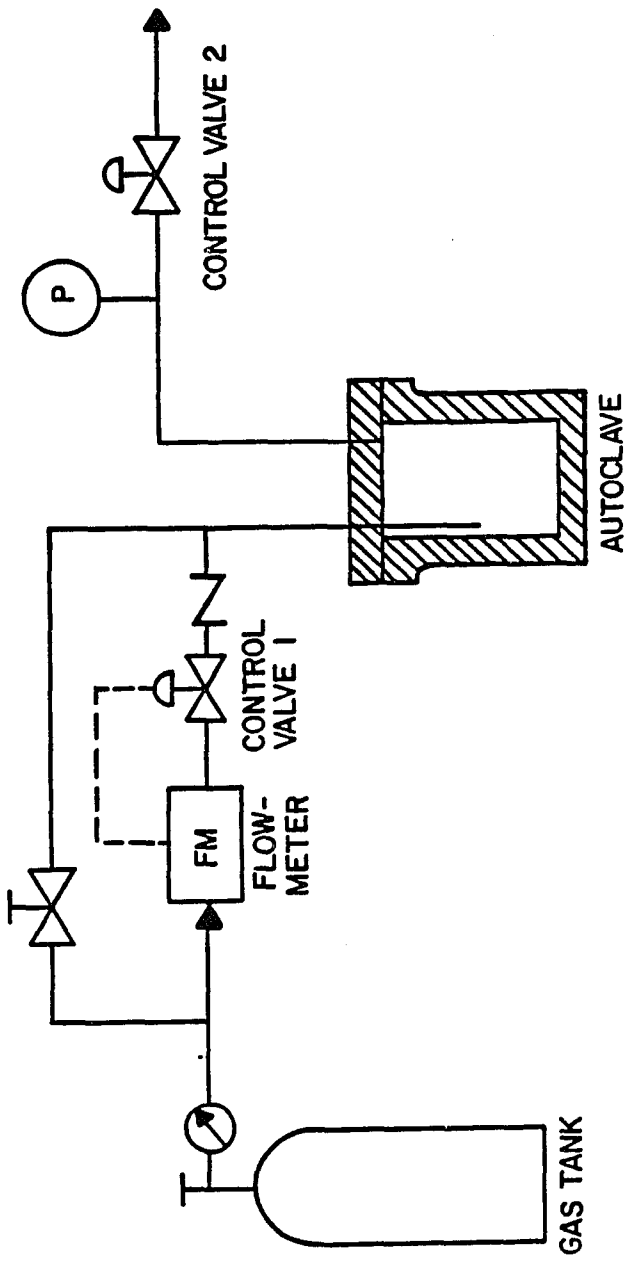


Fig 32 Schematic flow diagram of the step-testing for the flow controller

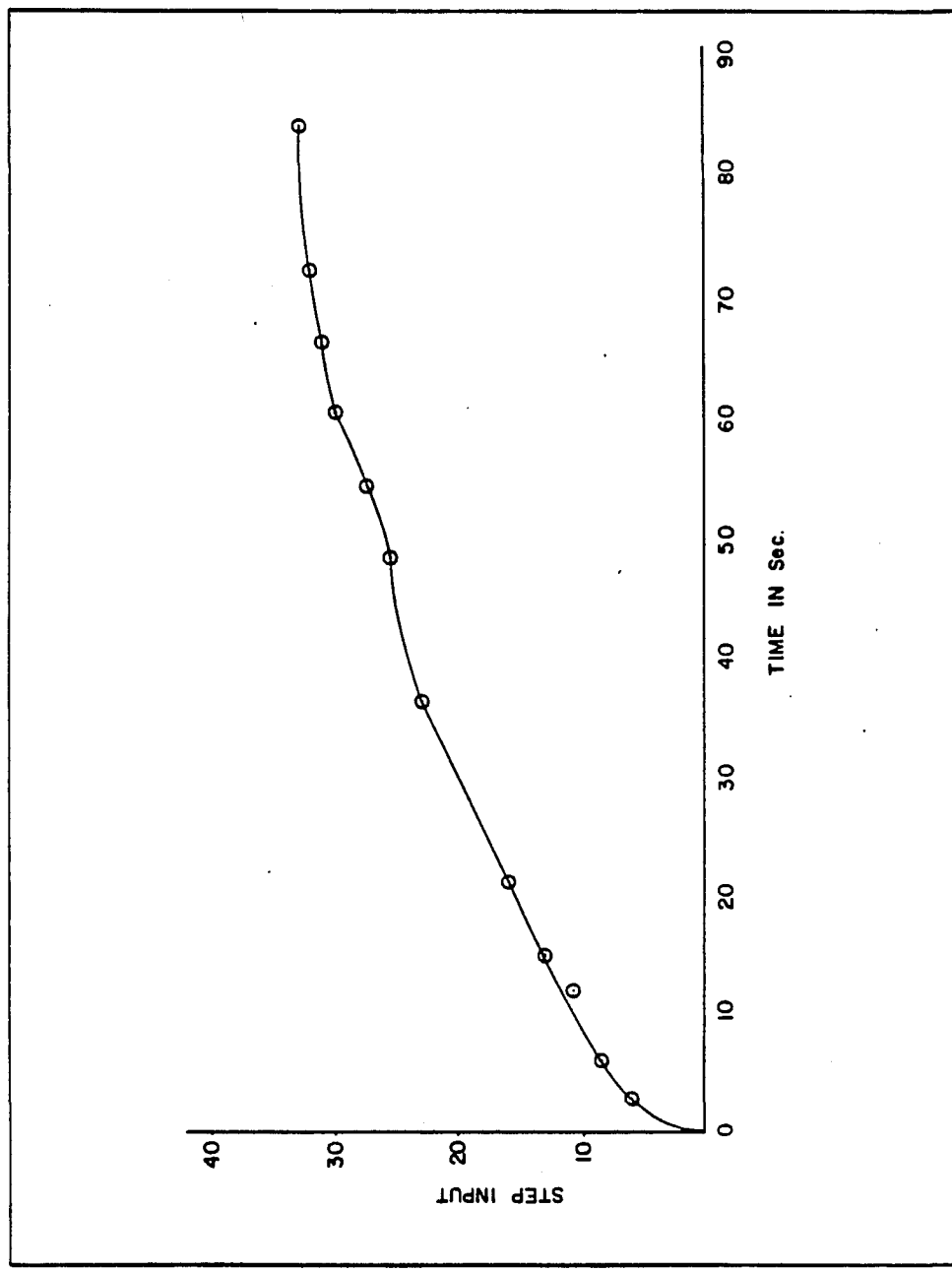


Fig 33 The step input disturbance of the flow controller

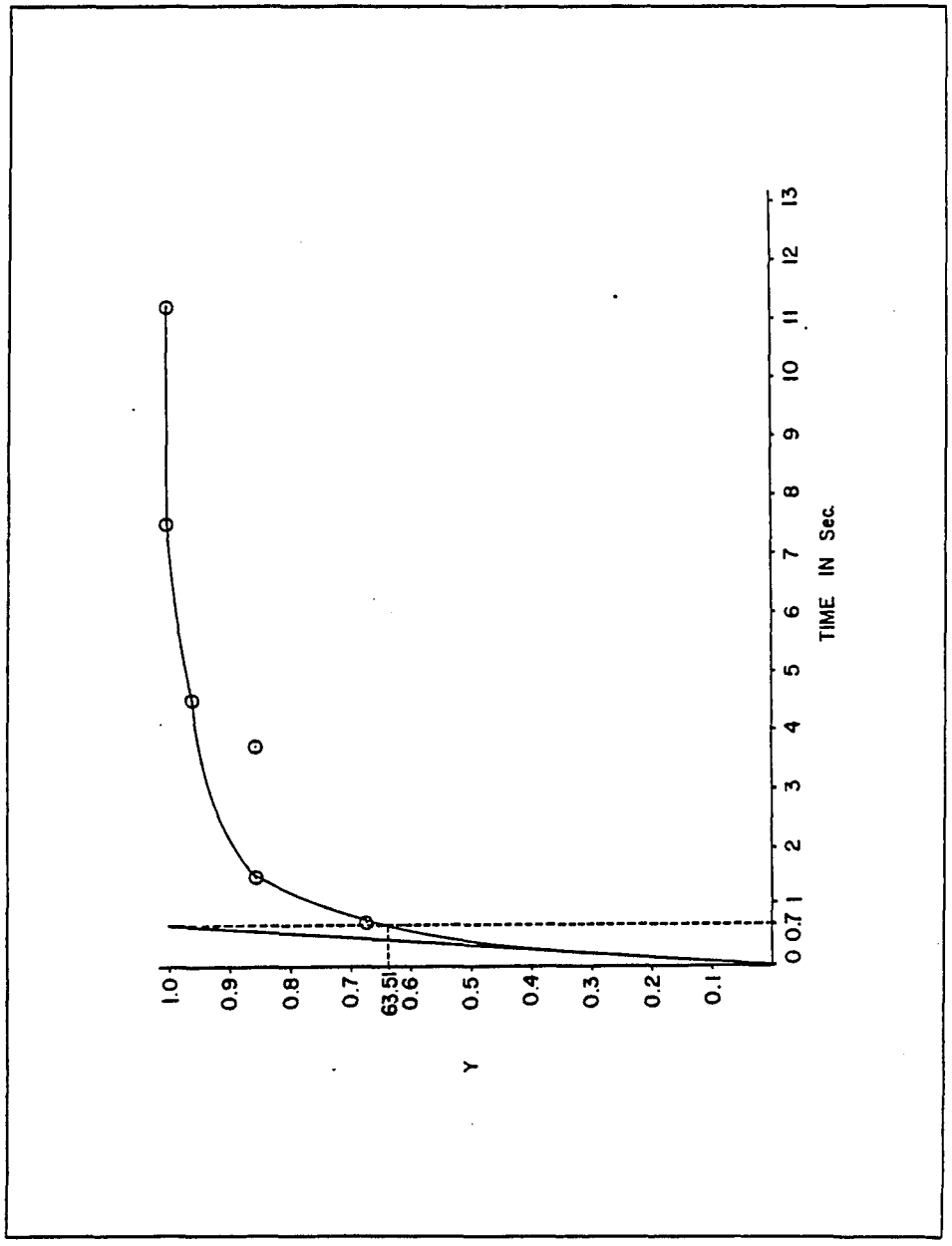


Fig 34 The step response of the flow controller

of the process was 0.7 sec in both methods. Table 5 summarizes the process parameter for both control loops.

Tuning of the Controller

Although the control algorithms are relatively simple, implementing them in a closed-loop environment requires some understanding of what the parameters do and how they are adjusted for different processes. As described in Chapter 2, there are two well-known methods for controller tuning, the Ziegler-Nichols (Z/N) and Cohen-Coon methods. The MSW process was tuned by using the Z/N method. This method is simple and does not require any process parameter identification. A proportional controller was applied to the control loop and then was increased until the process became unstable. This gain is known as critical gain.

For the off-gas control loop, the critical gain was 3 and the period of oscillation was measured at 1.5 sec as shown in appendix B. For the flow control loop, the critical gain and period of oscillation were measured at 0.5 and 3.75, respectively.

The Z/N controller gain settings were calculated from Table 1 for both control loops. Table 6 shows the calculated Z/N settings for off-gas pressure and the flow controller.

As mentioned in of chapter 2, the PID control equation has been modified for the software algorithm for the PID controller routine. This modification saves a significant amount of processing time and

Table 5

Process Parameter for the Control Loops

Parameter	Pressure Controller	Flow Controller
Process dead time (sec)	0.0	0 .0
Process time constant (sec)	3.4	0.7
Process gain	1.04	1.0

Table 6

Ziegler-Nichols Controller Gain Setting

For Off-Gas Pressure Control Loop

Controller Type	K_p	K_I	K_D
Proportional	1.5	--	--
Proportional-Integral	1.36	1.25	--
Proportional-Integral-Derivative	1.76	0.75	0.187

For Flow Control Loop

Controller Type	K_p	K_I	K_D
Proportional	0.25	--	--
Proportional-Integral	0.22	3.12	--
Proportional-Integral-Derivative	0.29	1.87	0.468

memory as the values of K_1, K_2 and K_3, as shown in Equation (2.15) are predetermined manually by the operator.

$$m(KT) = K_1 e(KT) - K_2 e(K-1)T + K_2 S_i + u \qquad (2.15)$$

where

$$K_1 = \left(1 + \frac{K_D}{T}\right) K_p$$

$$K_2 = \frac{K_p K_D}{T}$$

$$K_3 = K_p K_I T$$

where K_P, K_D, K_I are proportional, derivative and integral gains respectively.

Calculated parameters for the modified PID equation are shown in Table 7 for both control loops. These parameters change as sampling time is changed from its original value.

The modified PID controller parameters were then tested each control loop. Appemdix 2 shows the results of proportional, PI and PID controller responses. For the pressure control loop, the best performance of the controller is achieved by the PI controller. The derivative term of the off-gas pressure controller makes the PID controller unstable. Layben, 1973, P.328, describes the controller tuning rules of thumb for different kinds of control loops. Pressure control loops are very fast and tight loops, where PI controllers are atmost exclusively used in process control industries. Also, for flow

Table 7

Modified PID controller parameter for both controllers

For Off-Gas Pressure Controller

Sampling Time = 0.25 sec

Control Mode	K_1	K_2	K_3
Proportional	1.5	--	--
Proportional-Integral	1.36	--	0.42
Proportional-Integral-Derivative	2.9	1.31	0.33

For Flow Controller

Sampling Time = 0.5 sec

Control Mode	K_1	K_2	K_3
Proportional	0.25	--	--
Proportional	0.22	--	0.34
Proportional-Integral-Derivative	0.55	0.26	0.27

control loops, PI and PID controllers are used mostly with low gains or wide proportional-bands. These rules match the calculated, modified gains of the flow control loop.

The proportional setting for the off-gas pressure controller and flow controller shows an off-set from the set-point. These off-sets can be regulated to the desired value by adjusting the steady-state valve reference position, "u", in the controller. The PI setting for the off-gas pressure control loop holds the set-point at the desired value without much oscillation. Also, for the flow control loop, the PI controller is fast and maintains the control variables at the set-point. The PID controller for the flow loop has an excellent response with almost no oscillation. The flow control loop was given an external disturbance in load and the performance of the controller was excellent at maintaining the desired set-point. Both control loops also were tested for set-point change (servo problem) and the performance of the controllers were stable and maintained the control variables as close as possible for the set-point.

Simulation of Closed-loop Sampled-data System

The digital redesign of the controller, as discussed in last chapter , determines the output value at each sampling instant. A computer program was developed for calculating the output value of the PID "position" algorithm. This program determines the transient closed-loop response of sampled data control systems to setpoint (servo)

or load (regulator) changes. The program is based on one or two time constant pulse dead time modes for first order or second order systems.

The simulation program requires the value of process gain, time constants, sampling time and dead time for the process control loop. The three constants of the PID control algorithm are used to calculate controller output. The computer program solves the following equation in Z-transform by multiplication and long division.

For set point change

$$C(Z) = \frac{D(Z)\ HG(Z)\ R(Z)}{1 + D(Z)\ HG(Z)} \tag{5.1}$$

For load changes

$$A(Z) = \frac{LG(Z)}{1 + D(Z)HG(Z)} \tag{5.2}$$

$$R(Z) = (a + bZ^{-1} + cZ^{-2})/(D + EZ^{-1} + FZ^{-2})$$

where

C(Z)= Output value

D(Z)= PID controller value

HG(Z)= Zero order hold and process transfer function

The simulated output value of the computer program and actual digital controller output is plotted for the PI off-gas controller in Figure 35. Actual controller output is closed to the simulated output but with less overshoot. The process parameter and controller parameter were used from Table 5 and 6, respectively, for the off-gas pressure control-loop.

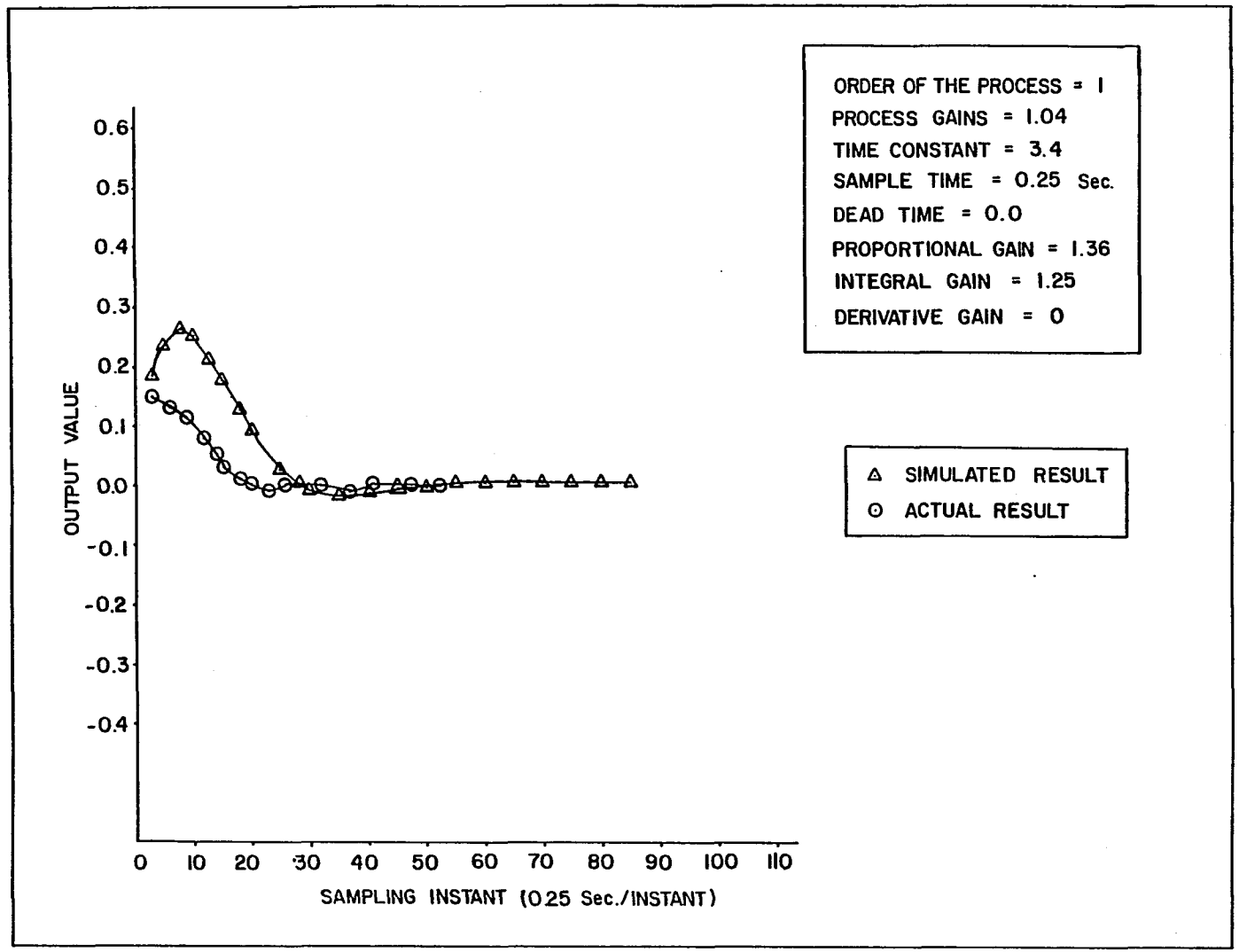


Fig 35 Performance of simulated and actual response of PI off-gas controller

Figure 36 plots the PID flow control-loop. Simulated output and actual output are very close to each. The actual output of the off-gas pressure loop becomes stable after 10 sampling instants after the simulated output. Both Figure 35 and 36 show that the digital controller output and simulated output are close to each other and get stable within 30 sec or less. Both controllers were tight and maintained the set-point once it reached the steady-state value. Also, the Z/N-tuned parameters were optimul for both control loops with almost no offset or oscillation.

Performance of Flow and Off-gas Pressure Controller for Semi-Continuous Operation

Once the controller parameters and process parameters were identified for each control loop, both control loops were tested for semi-continuous operation for the autoclave. The experimental procedure and set-up are described in Chapter 4. The pressure control loop in the autoclave is the dominating control loop. Flow to the autoclave is dependent on the pressure inside the autoclave, so if the pressure of the autoclave is maintained at a pre-determined value, the flow rate of the gas will be maintained at a constant rate. As discussed in the last section , the pressure control is tight and maintains the set-point as close as possible without much oscillation.

Off-gas pressure was maintained at 937 psi inside the autoclave and a continuous gas flow rate was maintained at 5.11 lb/hr. The performance of both control loops is shown in appendix B. Both

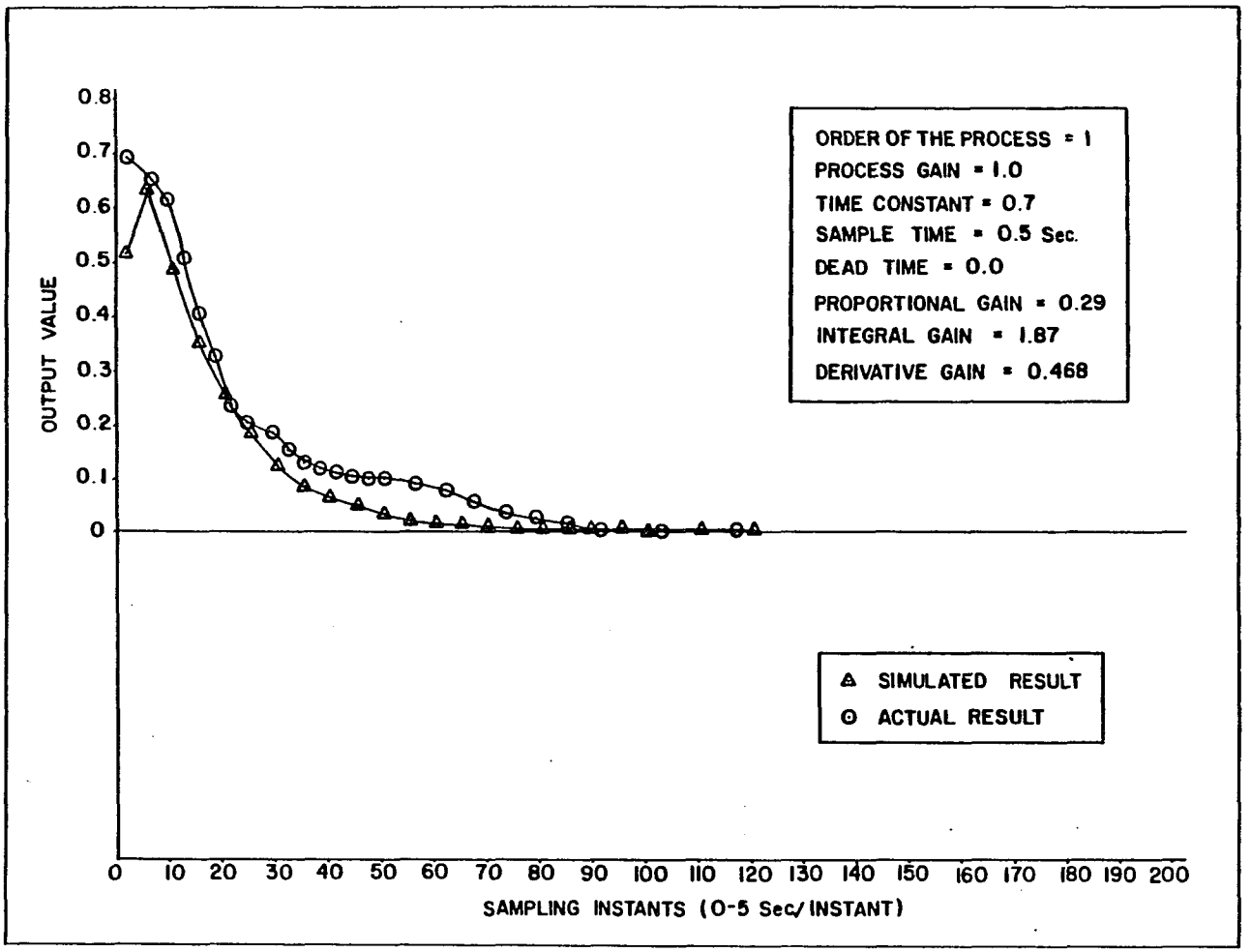


Fig 36 Performance of simulated and actual response of PID flow controller

controllers have excellent response without much oscillation. The pressure controller was affected when gas flow was started continuously but reached the steady-state in less than 3 sec. without making output unstable. This instability was also reflected for the same amount of time in the flow control loop because the flow control loop is interacting with the pressure control loop. the interacting behavior of both controllers was also noticed when the pressure controller parameters were changed and the response was not tight for 45 sec. As shown in Appendix B. The flow controller was not tight and was oscillatory until the pressure controller was unstable. These results show that for tight and continuous flow control, the pressure control has to be superior and must maintain the set-point with minimal oscillation.

The optimum control parameters for both control-loops are shown in Table 8. These parameters will change if the sample time changes. The user has to manipulate these parameters by the same calculation. Table 9 shows the optimum controller parameter without sample time, which can be used directly by plugging the predetermined
Sample time for each control loop increases in the sample time might make the control loop unstable, so care should be taken in selecting the proper sample time. For pressure and flow both controllers are fast, so high sample rates are preferable.

Table 8

Optimum Controller Parameters For Both Control Loops

Parameters	Off-Gas Pressure Control Loop	Flow Control Loop
K_1	1.5	0.5
K_1	0.0	0.25
K_3	0.5	0.25
u	0.8%	0.0
Sample time	1 BST (0.25 sec)	2 BST (0.5 sec)

Table 9

Optimum Controller Parameter Without Sample Time

Parameters	Off-gas Pressure Control loop	Flow Control loop
K_1	1.5	(1+0.46/T)0.29
K_2	0.0	0.133/T
K_3	1.7 * T	0.522 * T
u	08%	00%
Sample time	T	T

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The proposed process control system and instrumentation that was designed and developed adequately satisfies the requirements set forth for the MSW process, with a high degree of flexibility as to switch to different control modes. The AERBL control system was developed completely for the initial phase of the unit. The Control System is now being tested separately for each subsystem of the AERBL unit. On-line testing of the new 6502 based micro-processor Franklin-ACE-1200 control system hardware and software was achieved. The usefulness of simulation models in predicting the PID/PI controller output was found to be directly related to the actual output of the digital controller. Both controllers were properly tuned for optimum conditions resulting in tight control over the reaction inside the autoclave. The proposed control system concepts are important for the AERBL unit and the MSW process as the two share many similarities. Results of the thesis program are well documented, flexible and useful for both processes under high pressure and high temperature conditions. The new 6502 based micro-processor

(Franklin ACE-1200) control system is also very flexible and can be used for both processes.

Recommendations

Several recommendations can be made for the operation of both control systems.

(1) The MSW process control system can be expanded initially to three control loops when the steam superheater system is completed: flow of CO, flow of steam and off-gas pressure loops.

(2) In latter stages of the research, the temperature loop can be implemented with the DDC configuration using the micro-processor control system. No additional hardware or software is required for these control loops.

(3) The off-gas control valve C_V is too high for this application. A lower C_V control valve will improve the off-gas control loop for the DDC.

(4) The CO flowmeter should be handled very carefully, as overspeeding and sudden pressure drop can damage the turbine bearing.

(5) A mass flow meter would be a good choice for this application, as there are no moving parts inside the flowmeter.

(6) The AERBL unit control system should be tested part by part and the control parameters should be tuned for each individual control loop.

(7) Modeling and simulation of each control loop will help in understanding the response and behavior of each control variable.

Simple and non-interactive control loops would be initially chosen for the micro-processor control system.

(8) The 6502 based Franklin ACE-1200 micro-computer might not be able to handle all the control loops and data acquisition programs in real-time. A new micro-computer with at least 640K memory would be ideal for the complete real-time control and data acquisition system.

APPENDIX A

PROGRAM LISTING

```
502 PID     CLD                 PID
503         CLC             PROPORTIONAL-INTEGRAL-DERIVATIVE
504         LDA  TRANS,X     REGISTER = CONTROLLER #
505         ORA  #$00       A/D GAIN 0TO +5 VOLT
506         TAY
507         NOP
508         NOP
509         NOP
510         NOP
511         NOP
512         STY  AI13
513         LDY  #$00
514 PIDL1   INY               CHANNEL NUMBER IN ACCUMULATOR
515         CPY  #$10       DELAY LOOP FOR A/D CONVERSION
516         BNE  PIDL1
517         LDA  AI13+1
518         STA  TMHI,X     STORE A/D HIGH BYTE
519         LDA  AI13
520         STA  TMLO,X     STORE A/D LOW BYTE
521         LDA  VLVDIR,X
522         BEQ  ERROR
523         LDA  TMLO,X     2'S COMPLEMENT A/D INPUT
524         EOR  #$FF
525         CLC
526         ADC  #$01
527         STA  TMLO,X
528         LDA  TMHI,X
529         EOR  #$0F
530         ADC  #$00
531         STA  TMHI,X
532 ERROR   SEC               CALCULATE ERROR
533         LDA  TSPLO,X
534         SBC  TMLO,X
535         STA  EiLO
536         LDA  TSPHI,X
537         SBC  TMHI,X
538         STA  EiHI
539         JSR  Si           CALCULATE EACH TERM OF THE
540         JSR  K1Ei         PID CONTROL EQUATION
541         JSR  K2Eo
542         JSR  K3Si
543         LDA  EiHI
544         STA  E0HI
545         LDA  EiLO
546         STA  E0LO
547         CLC
548         LDA  K1EiLO       ADD K1 AND K3 TERMS
549         ADC  K3SiLO
550         STA  KTEMLO
551         LDA  K1EiHI
552         ADC  K3SiHI
553         STA  KTEMHI
554         SEC
```

```
555             LDA  KTEMLO     SUBTRACT K2 TERM FROM
556             SBC  K2E0LO     K1 AND K2 TERMS
557             STA  MPIDLO
558             LDA  KTEMHI
559             SBC  K2E0HI,X
560             STA  MPIDHI
561             BMI  MiADD
562             JMP  MiSUB
563 MiADD        LDA  MPIDLO     POSITIVE DAC CORRECTION
564             EOR  #$FF
565             CLC
566             ADC  #$01
567             STA  MPIDLO
568             LDA  MPIDHI
569             EOR  #$FF
570             ADC  #$00
571             STA  MPIDHI
572             BEQ  BITEIGHT   IS CALCULATED PID ERROR ONLY 8 BITS ?
573             ASL
574             BCS  BIT16      CHAQUE FOR 16 BITS PID ERROR
575             ASL
576             BCS  BIT16
577             ASL
578             BCS  BIT16
579             ASL
580             BCS  BIT16
581             CLC
582             LDA  MPIDLO      CORRECTION FOR 12 BITS  PID ERROR
583             LSR  MPIDHI
584             RORA
585             LSR  MPIDHI
586             RORA
587             LSR  MPIDHI
588             RORA
589             LSR  MPIDHI
590             RORA
591             STA  MPIDLO
592             JMP  BIT8       8 BIT DAC OUTPUT ROUTINE
593 BITEIGHT    LDA  MPIDLO     CORRECTION FOR 8 BITS PID ERROR
594             LSRA
595             LSRA
596             LSRA
597             LSRA
598             STA  MPIDLO
599             JMP  BIT8
600 BIT16       LDA  MPIDHI     CORRECTION FOR 16 BITS PID ERROR
601             STA  MPIDLO
602 BIT8        LDA  MPIDLO     LIMIT DAC OUTPUT
603             BMI  ADD2
604             CLC
605             LDA  REFPOS,X
606             ADC  MPIDLO
607             BCS  ADD1
608             STA  Mi,X
609             JMP  TODAC
```

```
610 ADD1     LDA  MXOPN       LIMIT MAXIMUM DAC OUTPUT
611          STA  Mi,X
612          JMP  TODAC
613 ADD2     LDA  REFPOS,X    CHAQUE FOR DAC  OVERFLOW
614          CLC
615          BMI  ADD3
616          ADC  MPIDLO
617          BCS  ADD1
618          STA  Mi,X
619          JMP  TODAC
620 ADD3     LDA  MPIDLO      LIMIT DAC OVERFLOW
621          STA  Mi,X
622          JMP  TODAC
623 MiSUB    LDA  MPIDHI      NEGATIVE DAC CORRECTION
624          BEQ  BIT         IS CLACULATED PID ERROR 8 BITS OR MORE ?
625          ASL
626          BCS  SIXTNBIT    CHAQUE FOR 16 BITS PID ERROR
627          ASL
628          BCS  SIXTNBIT
629          ASL
630          BCS  SIXTNBIT
631          ASL
632          BCS  SIXTNBIT
633          CLC              CORRECTION FOR 12 BITS PID ERROR
634          LDA  MPIDLO
635          LSR  MPIDHI
636          RORA
637          LSR  MPIDHI
638          RORA
639          LSR  MPIDHI
640          RORA
641          LSR  MPIDHI
642          RORA
643          STA  MPIDLO
644          JMP  EIGHTBIT    TO 8 BIT DAC OUTPUT ROUTINE
645 BIT      LDA  MPIDLO      CORRECTION FOR 8 BITS PID ERROR
646          LSRA
647          LSRA
648          LSRA
649          LSRA
650          STA  MPIDLO
651          JMP  EIGHTBIT
652 SIXTNBIT LDA  MPIDHI      CORRECTION FOR 16 BITS PID ERROR
653          STA  MPIDLO
654 EIGHTBIT SEC              LIMIT DAC NEGATIVE OUTPUT
655          LDA  REFPOS,X
656          SBC  MPIDLO
657          BCC  SUB1
658          STA  Mi,X
659          JMP  TODAC
```

```
660 SUB1    LDA  MXCLS      LIMIT MINIMUM DAC OUTPUT
661         STA  Mi,X
662         JMP  TODAC
663 Si      CLC             S(i) TERM CALCULATION
664         LDA  EiLO       PLUS ANTI-WINDUP FEATURE
665         ADC  SiLO
666         STA  SiLO
667         LDA  EiHI
668         ADC  SiHI
669         STA  SiHI
670         BPL  SB1
671         CLC
672         LDA  SiLO
673         ADC  #$00
674         LDA  SiHI
675         ADC  #$08
676         BMI  SB2
677         RTS
678 SB2     LDA  #$00       LIMIT NEGATIVE WINDUP
679         STA  SiLO
680         LDA  #$F8
681         STA  SiHI
682         RTS
683 SB1     CLC
684         LDA  SiLO
685         ADC  #$00
686         LDA  SiHI
687         ADC  #$78
688         BMI  SB3
689         RTS
690 SB3     LDA  #$FF       LIMIT POSITIVE WINDUP
691         STA  SiLO
692         LDA  #$07
693         STA  SiHI
694         RTS
695 K1Ei    LDA  EiLO       K1E(i) TERM CALCULATION
696         PHA
697         LDA  EiHI
698         PHA
699         LDA  K1NULO,X
700         PHA
701         LDA  K1NUHI
702         PHA
703         LDA  K1DIV,X
704         PHA
705         JSR  KTERM
706         PLA
707         STA  K1EiHI
708         PLA
709         STA  K1EiLO
710         RTS
```

```
711 K2Eo    LDA  E0LO      K2E(0) TERM CALCULATION
712         PHA
713         LDA  E0HI,X
714         PHA
715         LDA  K2NULO,X
716         PHA
717         LDA  K2NUHI
718         PHA
719         LDA  K2DIV,X
720         PHA
721         JSR  KTERM
722         PLA
723         STA  K2E0HI,X
724         PLA
725         STA  K2E0LO
726         RTS
727 K3Si    LDA  SiLO      K3S(i) TERM CALCULATION
728         PHA
729         LDA  SiHI
730         PHA
731         LDA  K3NULO,X
732         PHA
733         LDA  K3NUHI
734         PHA
735         LDA  K3DIV,X
736         PHA
737         JSR  KTERM
738         PLA
739         STA  K3SiHI
740         PLA
741         STA  K3SiLO
742         RTS
743 KTERM   PLA            GENERAL ROUTINE FOR CALCULATING
744         STA  POINTLO   K TERMS IN THE PID EQUATION
745         PLA
746         STA  POINTHI
747         PLA
748         STA  KDIVLO
749         PLA
750         STA  BHI
751         PLA
752         STA  BLO
753         PLA
754         STA  AHI
755         PLA
756         STA  ALO
757         LDA  AHI
758         BPL  KTRMPOS
759         JSR  CMPLA
760         JSR  MULT16
761         JSR  DIV16
762         JSR  CMPLC
763         JMP  KTRMCNT
```

```
764 KTRMPOS   JSR  MULT16
765           JSR  DIV16
766 KTRMCNT   LDA  CLO
767           PHA
768           LDA  CHI
769           PHA
770           LDA  POINTHI
771           PHA
772           LDA  POINTLO
773           PHA
774           RTS
775 MULT16    LDA  #$00       16 BIT MULTIPLICATION BY
776           STA  CHI        SHIFT AND ADD
777           STA  CLO
778           CLC
779           LDY  #$00
780 MLTRPT    LSR  AHI
781           ROR  ALO
782           BCS  MLTADD
783           JMP  MLTCNT
784 MLTADD    LDA  CLO
785           CLC
786           ADC  BLO
787           STA  CLO
788           LDA  CHI
789           ADC  BHI
790           STA  CHI
791 MLTCNT    ASL  BLO
792           ROL  BHI
793           INY
794           CPY  #$11
795           BNE  MLTRPT
796           RTS
797 DIV16     LDA  KDIVLO     16 BIT DIVION BY
798           BEQ  NODIV      SHIFT AND SUBTRACT
799           STX  XDTEMP
800           LDA  #$00
801           STA  KDIVHI
802           STA  DTEMPL
803           STA  DTEMPH
804           TAY
805 DIVRPT    ASL  CLO        CLO<
806           ROL  CHI        CHI<
807           ROL  DTEMPL     DTEMPL<
808           ROL  DTEMPH     DTEMPH<
809           SEC
810           LDA  DTEMPL     A=DTEMP
811           SBC  KDIVLO     SUB KDIVL
812           TAX
813           LDA  DTEMPH     A=DTEMPH
814           SBC  KDIVHI     SUB KDIVH
815           BCC  DIVCNT
816           STX  DTEMPL     DTEMPL=X
817           STA  DTEMPH     DTEMPH=A
818           INC  CLO        CLO+1
```

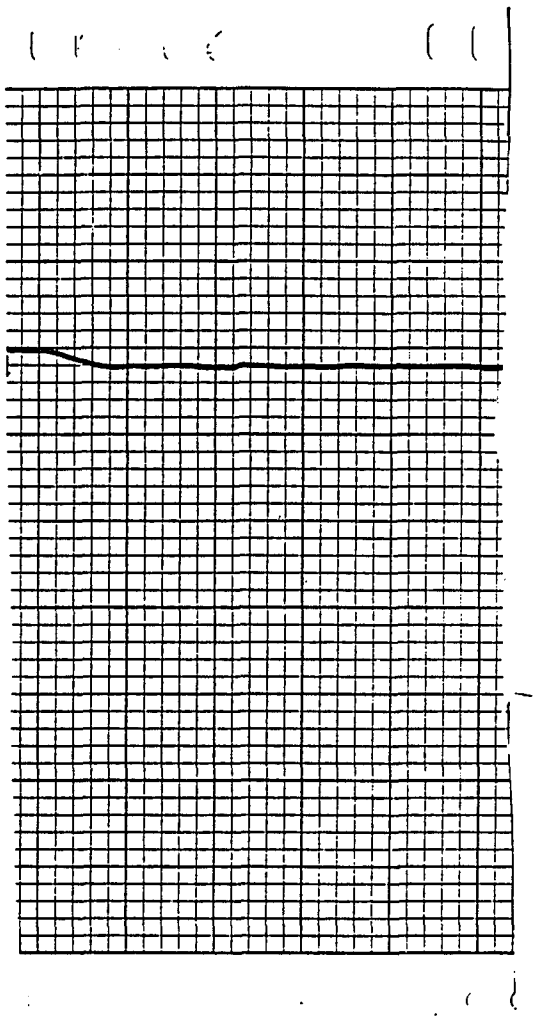
```
819 DIVCNT   INY
820          CPY  #$10
821          BNE  DIVRPT
822          LDX  XDTEMP
823          LDA  CHI
824          BMI  ZERO
825          RTS
826 ZERO     LDA  #$00
827          STA  CLO
828          STA  CHI
829 NODIV    RTS
830 CMPLA    LDA  ALO          2'S COMPLEMENT ROUTINES
831          EOR  #$FF         FOR K TERMS
832          CLC
833          ADC  #$01
834          STA  ALO
835          LDA  AHI
836          EOR  #$FF
837          ADC  #$00
838          STA  AHI
839          RTS
840 CMPLC    LDA  CLO
841          EOR  #$FF
842          CLC
843          ADC  #$01
844          STA  CLO
845          LDA  CHI
846          EOR  #$FF
847          ADC  #$00
848          STA  CHI
849          RTS
850 TODAC    PHA               OUTPUT TO DAC CHANNEL
851          TXA
852          ASL
853          TAX               SET ZERO PAGE X POINTER
854          PLA               FOR DAC CHANNEL
855          STA  (DAC,X)      LOAD DAC CHANNEL
856          RTS
857
858 GAINCD    HEX  00
859 XSAVE     HEX  00
860 PGRUN     HEX  07
861 STAT      HEX  01,00,00,00,00,00,00,03
862 PGCLOCK   HEX  00,00,00,00,00,00,00,00
863 PGCNT     HEX  01,00,00,00,00,00,00,01
864 PGX       HEX  00,00,00,00,00,00,00,00
865 PGY       HEX  00,00,00,00,00,00,00,00
866 PGA       HEX  00,00,00,00,00,00,00,00
867 PGP       HEX  00,00,00,00,00,00,00,00
868 PGCL      HEX  00,00,00,00,00,00,00,00
869 PGCH      HEX  00,00,00,00,00,00,00,00
870 PGSTRTL   HEX  00,00,00,00,00,00,00,00
871 PGSTRTH   HEX  03,00,00,00,00,00,00,00
872
```

```
873 TRANS    HEX  00,00,00,00,00,00,00,00,00,00,00,00,00,00,00,00
874 VLVDIR   HEX  00,00,00,00,00,00,00,00,00,00,00,00,00,00,00,00
875 TMLO     HEX  00,00,00,00,00,00,00,00,00,00,00,00,00,00,00,00
876 TMHI     HEX  00,00,00,00,00,00,00,00,00,00,00,00,00,00,00,00
877 TSPLO    HEX  00,00,00,00,00,00,00,00,00,00,00,00,00,00,00,00
878 TSPHI    HEX  00,00,00,00,00,00,00,00,00,00,00,00,00,00,00,00
879 Mi       HEX  00,00,00,00,00,00,00,00,00,00,00,00,00,00,00,00
880 K1NULO   HEX  00,00,00,00,00,00,00,00,00,00,00,00,00,00,00,00
881 K1DIV    HEX  01,01,01,01,01,01,01,01,01,01,01,01,01,01,01,01
882 K2NULO   HEX  00,00,00,00,00,00,00,00,00,00,00,00,00,00,00,00
883 K2DIV    HEX  01,01,01,01,01,01,01,01,01,01,01,01,01,01,01,01
884 K3NULO   HEX  00,00,00,00,00,00,00,00,00,00,00,00,00,00,00,00
885 K3DIV    HEX  01,01,01,01,01,01,01,01,01,01,01,01,01,01,01,01
886 REFPOS   HEX  00,00,00,00,00,00,00,00,00,00,00,00,00,00,00,00
887
888 EiLO     HEX  00
889 EiHI     HEX  00
890 K1EiLO   HEX  00
891 K1EiHI   HEX  00
892 E0LO     HEX  00
893 E0HI     HEX  00
894 K2E0LO   HEX  00
895 K2E0HI   HEX  00
896 SiLO     HEX  00
897 SiHI     HEX  00
898 K3SiLO   HEX  00
899 K3SiHI   HEX  00
900 MPIDLO   HEX  00
901 MPIDHI   HEX  00
902 K1NUHI   HEX  00
903 K2NUHI   HEX  00
904 K3NUHI   HEX  00
905 MXERR    HEX  7F
906 MXCLS    HEX  00
907 MXOPN    HEX  FF
908 CTRCNT   HEX  00,00,00,00,00,00,00,00,00,00,00,00,00,00,00,00
909 CTRCLK   HEX  00,00,00,00,00,00,00,00,00,00,00,00,00,00,00,00
910 CTSTAT   HEX  00,00,00,00,00,00,00,00,00,00,00,00,00,00,00,00
911
912 INL      HEX  00
913 INH      HEX  00
914 HOLD     HEX  03
915 OPSTAT   HEX  00
916 OPT1P1   HEX  FF
917 OPT2P1   HEX  FF
918 YOFFST   HEX  00
919 ZPADD    HEX  00
920 ASCHR1   HEX  00
921 ASCHR2   HEX  00
922 ZPA      HEX  00
923 XTEM     HEX  00
924 KTEMLO   HEX  00
925 KTEMHI   HEX  00
```

```
926 ALO       HEX  00
927 AHI       HEX  00
928 BLO       HEX  00
929 BHI       HEX  00
930 CLO       HEX  00
931 CHI       HEX  00
932 POINTLO   HEX  00
933 POINTHI   HEX  00
934 KDIVLO    HEX  00
935 KDIVHI    HEX  00
936 DTEMPL    HEX  00
937 DTEMPH    HEX  00
938 XDTEMP    HEX  00
939 CLKFLG    HEX  00
940 KBD       =    $C000
941 KBDSTRB   =    $C010
942 MONITOR   =    $FF69
943 CROUT1    =    $FD8B
944 HOME      =    $FC58
945 ADRWPRT   =    $1400
946 ADPRTHI   =    $1401
```

APPENDIX B

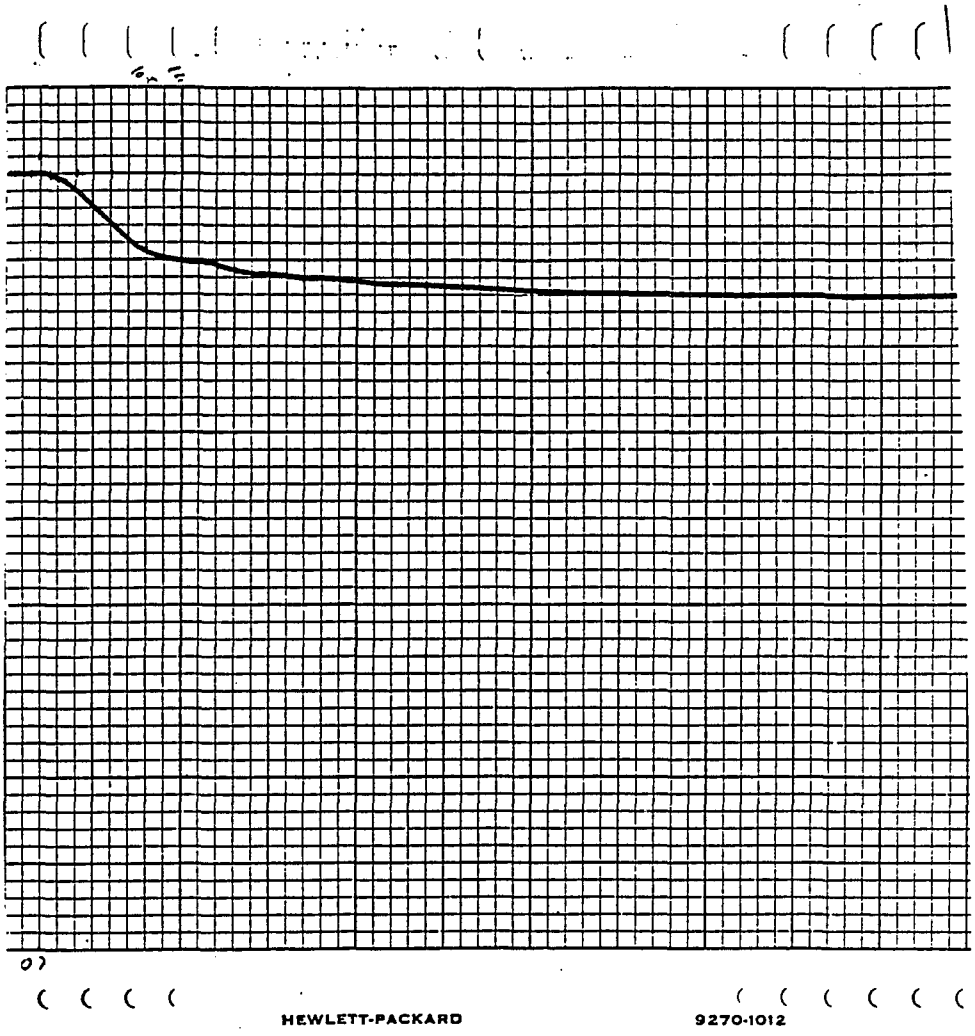
PERFORMANCE AND RESULTS OF THE CONTROLLER



Setpoint = 1000 psi = 55% (Hexadecimal)

$K_1 = 1.5$
$K_2 = 0.0$
$K_3 = 0.5$
$u = 0.0$

PI Off-gas Controller Performance



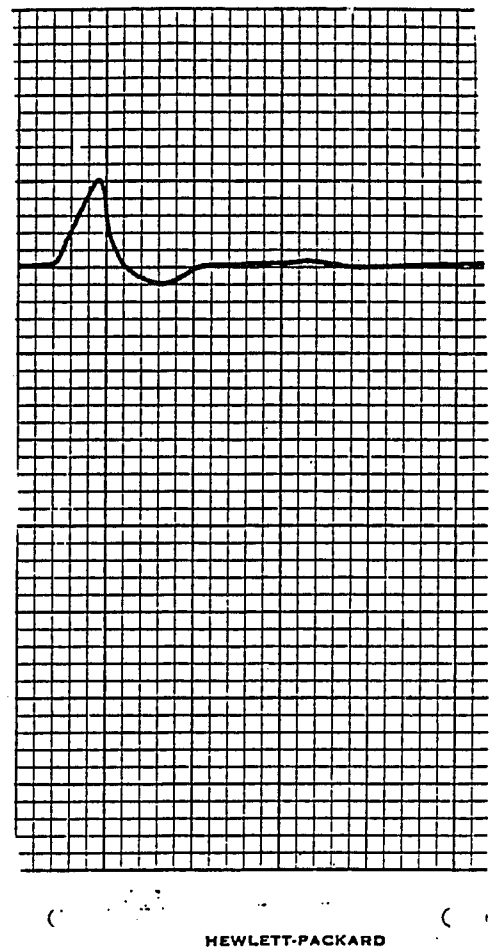
Setpoint = 5.11 lb/hr = 68% (Hexadecimal)

$K_1 = 0.5$

$K_2 = 0.25$

$K_3 = 0.25$

PID Flow Controller Performance

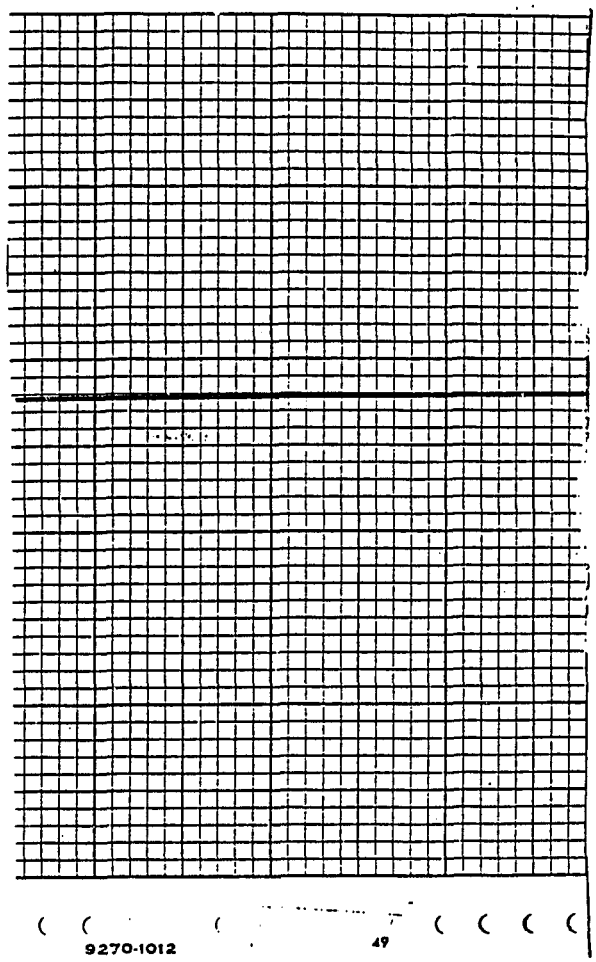


$K_1 = 0.5$

$K_2 = 0.25$

$K_3 = 0.25$

PID Flow Controller With Load Disturbance



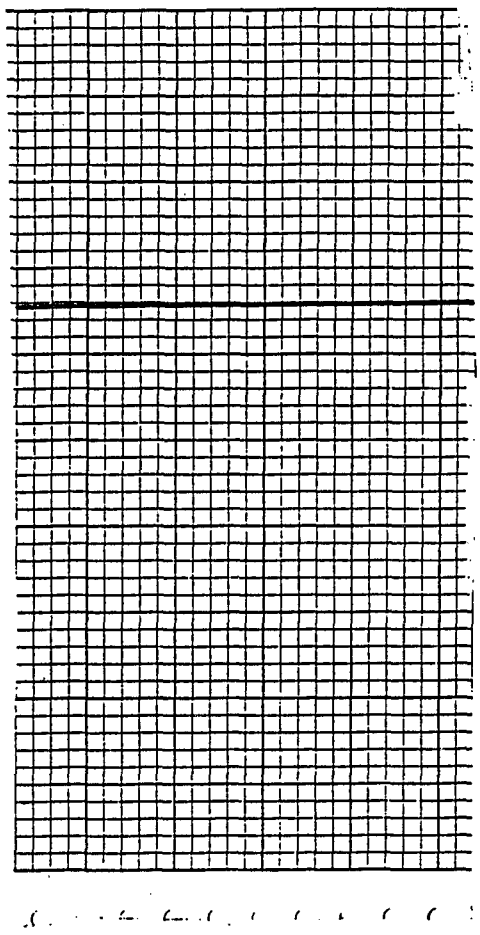
Setpoint = 1500 psi = 80% (Hexadecimal)

K_1 = 1.5

K_3 = 0.5

u = 08

PI Off-gas Controller Performance for Setpoint Change



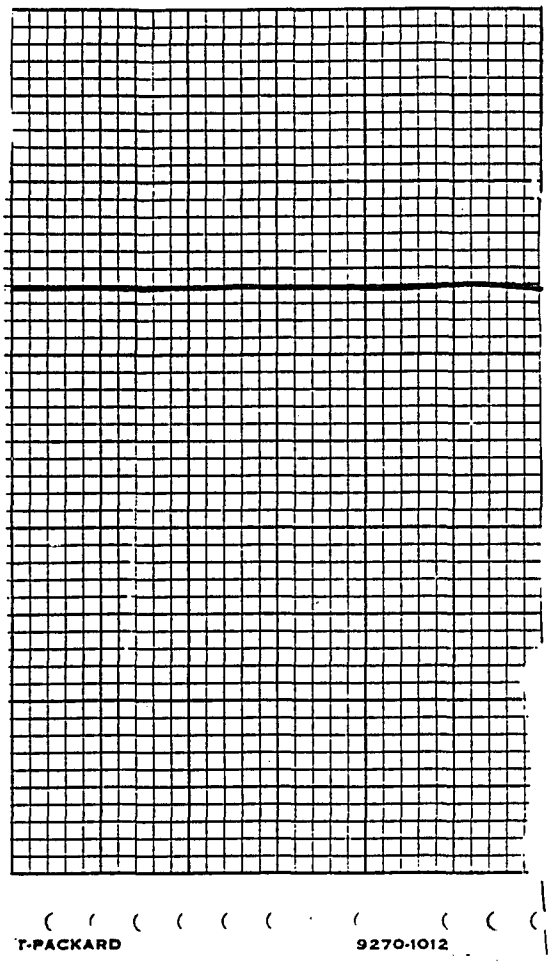
Setpoint = 1200 psi = 66% (Hexadecimal)

K_1 = 1.5

K_3 = 0.5

u = 08

PI Off-gas Controller Performance for Setpoint Change (Cont)



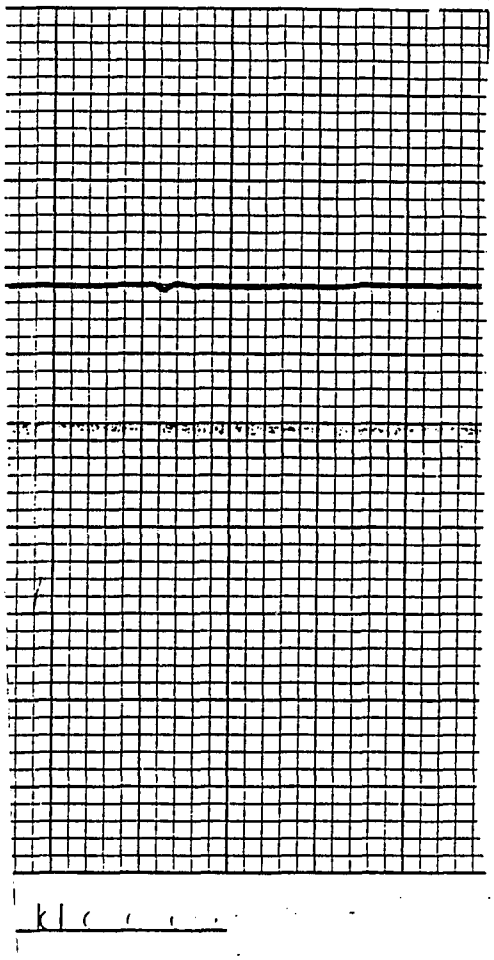
Setpoint = 1125 psi = 60% (Hexadecimal)

K_1 = 1.5

K_3 = 0.5

u = 08

PI Off-gas Pressure Controller Performance for Setpoint Change (Cont)



Off-gas Controller Response
Setpoint = 937 psi = 50% (Hexadecimal)

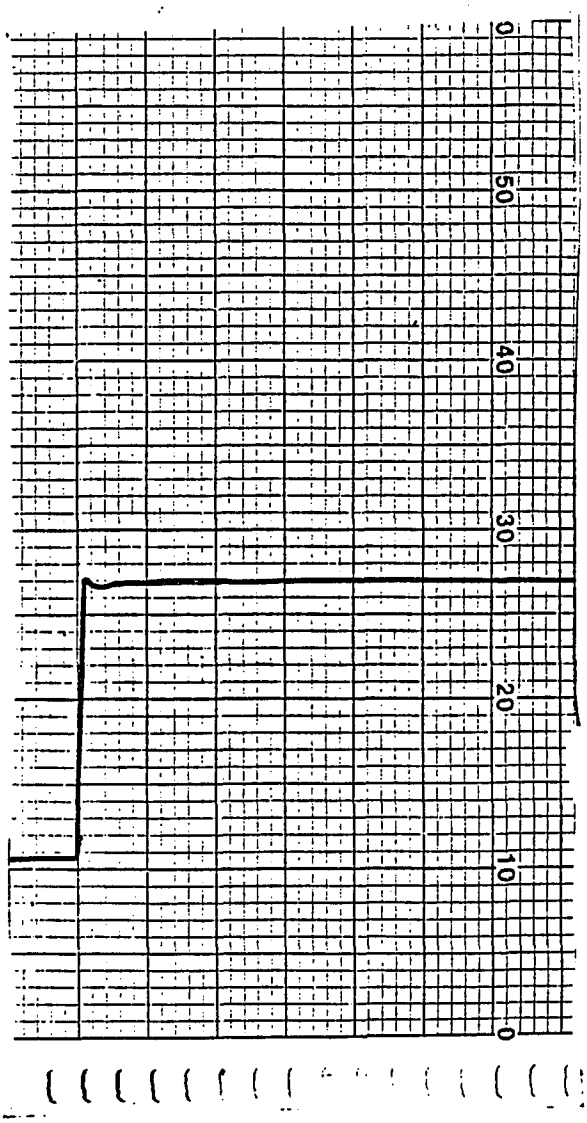
K_1 = 1.5

K_3 = 0.5

u = 08

Sample time = 0.25 sec.

PID/PI Performance of Both Controller in Semicontinuous Operation



Flow Controller Response
Setpoint = 5.11 lb/hr. = 68% (Hexadecimal)

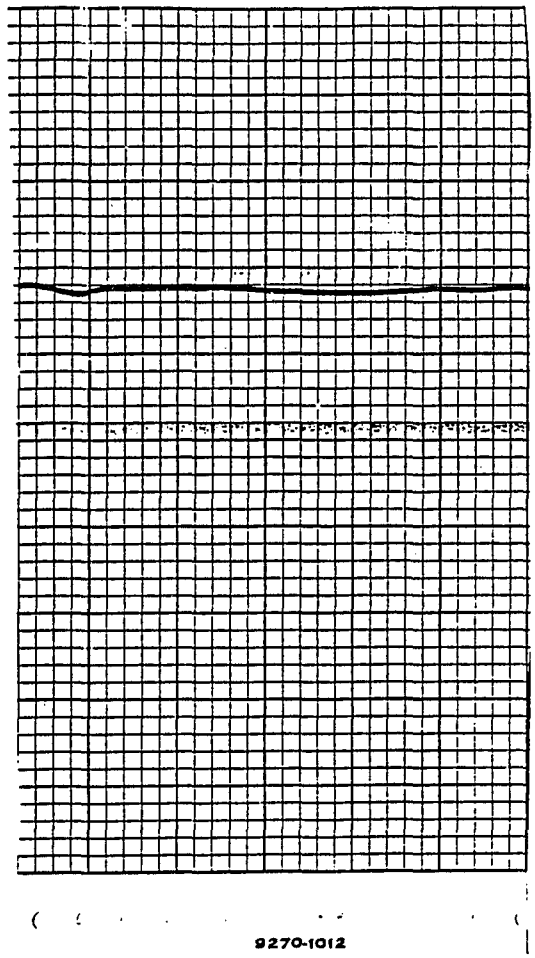
$K_1 = 0.5$

$K_2 = 0.25$

$K_3 = 0.25$

Sample time = 0.5 sec.

PI/PID Performance of Both Controller in Semicontinuous Operation (Cont)



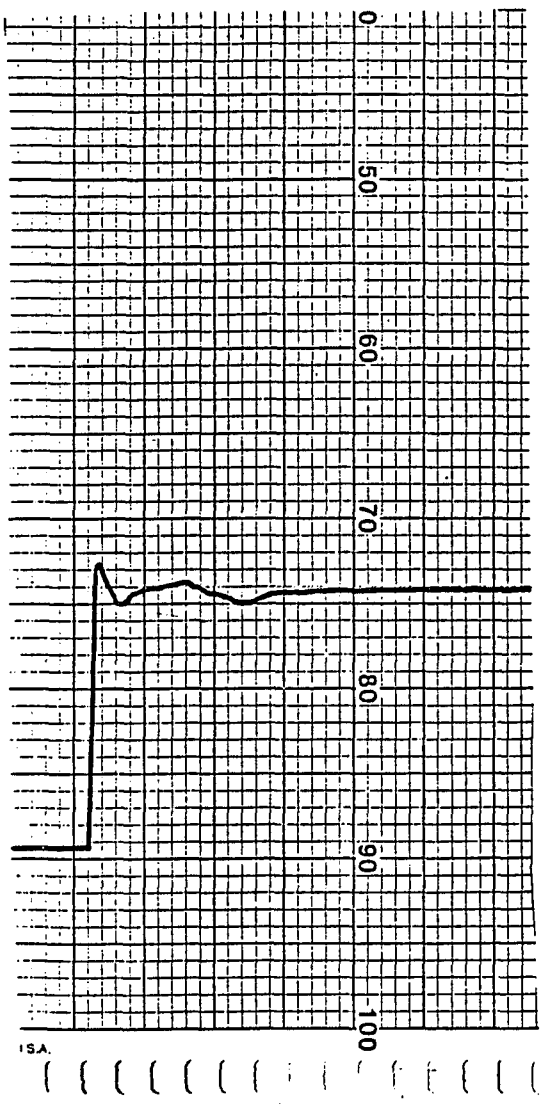
$K_1 = 1.0$

$K_3 = 0.5$

u = 08

Sample time = 0.25 sec

PI/PID Control Performance in Semicontinuous Operation, with Different PI Off-gas Controller Value



$K_1 = 0.5$

$K_2 = 0.25$

$K_3 = 0.25$

Sample time = 0.5 sec.

PI/PID Control Performance in Semicontinuous Operation, With Different PI Off-gas Controller Value (Cont)

ABBREVIATIONS

ADC	Analog to Digital Conveter
AERBL	Advance Extruder-feeder Reactor Biomass Liquefaction
AOV	Air Operated Valve
BST	Basic System Time
CO	Carbon Monoxide
CPU	Central Processing Unit
CRTOS	Control Real-Time Operating System
C(s)	Output Of Control-loop
DAC	Digital to Analog Converter
DDC	Direct Digital Control
D(s)	Control Alogorithm
EPT	Electro-Pneumatic Transducer
FSO	Full Scale Output
$G_{ho}(s)$	Zero Order Hold Transfer Function
$G_L(s)$	Load Transfer Function
$G_p(s)$	Process Transfer Function
Hz	Hertz
I/O	Input/Output
LSB	Least Significant Bit
ma	Milliamp
MSB	Most Significant Bit
MSW	Municipal Solid Waste

mv	millivolt
Op-amp	Operational Amplifiers
P	Proportional
PI	Proportional Integral
PID	Proportional Integral andDerivative
ROM	Read Only Memory
R(s)	Set-point
RTD	Residence Time Distribution
RTTS	Real-Time Task Scheduler
T	Time
Z/N	Ziegler-Nichols

REFERENCES

Bennett, S. and D.A. Linkens. Real-Time Computer Control. London: Peter Peregrinus Ltd., 1984.

Coughanowr & Koppel. Process Systems Analysis and Control. New York, McGraw-Hill, Inc., 1965.

Deshpande, Pradeep and Ash, Raymond. Elements of Computer Process Control with Advanced Control Applications. Research Triangle Park, N.C.

Instrument Society of America, 1981. Dynisco Technical Data Sheets. Norwood, Mass, Dynisco.

Franklin, G.J. and Powell, J.D., Digital Control of Dynamic System. Reading, Mass, Addision-Wesley, 1980.

Harris, C.J. and Billings, S.A. Self Tuning and Adaptive Control Theory and Application. New York, The Institute of Electrical Engineers, 1981.

Isermann, Rolf, Digital Control System. Berlin, Springer-Verlag, 1981.

Johnson, Curtis. Microprocessor-Based Process Control. Englewood Cliffs, N.J., Prentice-Hall, Inc., 1984.

Johnson, Curtis. Process Control Instrument Technology. Second Edition, New York, John Wiley & Sons, Inc. 1982.

Katz, Paul. Digital Control Using Microprocessors. Englewood Cliffs, N.J., Prentice-Hall International, 1981.

Luyben, W.L. Process Modeling Simulation and Control for Chemical Engineers. New York, McGraw Hill, Inc., 1973.

Masoneilan Handbook for Control Valve Sizing. Sixth Edition, Norwood, Mass, Masoneilan International, Inc., 1977.

Mellichamp, Duncan, A. Real-Time Computing with Application to Data Acquisition and Control. New York, Van Nostrand Reinhold Company, Inc., 1983.

Miller, J.A., et al. A Comparison of Controller Tuning Techniques. Control Engineering, Vol. 14, No. 12, Dec. 1967, P.72.

Oliver, Frank J. Practical Instrumentation Transducers. New York, Hayden Book Company, Inc., 1971.

Reyes, Byron Fernando. Development Of A High Pressure, High Temperature Superheated Steam System. M.S. Thesis, University Of Arizona, 1985(Expected)

Shlapak, Nick. Microprocessor-Based Real-Time Process Control of Biomass Liquefaction. M.S. Thesis, University of Arizona, 1983.

Sheingold, David H. Transducer Interfacing Handbook, A Guide to Analog Signal Conditioning. Norwood, Mass. Analog Devices Inc., 1980.

Skrokov, M. Robert. Mini- and Microproessor Control in Industrial Processes. Handbook of Systems and Application Strategies. New York, Van Nostrand Reinhold Company, 1980.

Smith, Cecil L. Digital Computer Process Control. San Francisco, In-text Education Publishers, 1972.