NEW DESIGN METHODS IN CHEMICAL ENGINEERING-- THE SYNTHESIS OF CONTROL SYSTEMS

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In recent years chemical engineers have become aware of the success which others have achieved in the design of high performance systems. I am referring especially to those electromechanical designs broadly referred to as servomechanisms where special attention has been focused on dynamic behavior and the suppression of transients arising from disturbances.

Chemical engineering faculties have responded to the recognized need and are including in their curricula various amounts of control-oriented subject matter and are fostering closer affiliation with their counterparts in other departments in order to reinforce their own efforts. As a consequence more and more chemical engineers, especially those with graduate training, reach industry with excellent backgrounds in education and training in the new control-oriented disciplines.

I wonder, however, if the teachers get much feedback from their efforts. Perhaps you may question if this special training is being used, and if so to what ends. You may like to know the nature of the problems encountered, the techniques used to attack the problems, and the degree of success in achieving a solution.

Most certainly the demand for chemical engineers with a control engineering speciality is increasing. Recruitment of personnel of this caliber becomes increasingly difficult, and there is healthy competition between industry and colleges. The ability of industry to convert the most recent theoretical developments into reality at an acceptable rate often is responsible for talented personnel returning to academic ranks.

However, some notable accomplishments have occurred. The most spectacular is the increased use of computers for on-line, open- or closed-loop control. In all, a total of 159 control computers have been sold to date, about one-third to chemical, petroleum, and allied industries. (1) For such work chemical engineers with strong theoretical inclinations combined with aptitude for model building and programming are in demand. The objective is to design a scheme of plant management which will improve and maintain a desired optimum. To date I do not know of a case where the basic concepts of production have been altered because of the availability of the computer. The process design has usually been quite conventional. Special measuring and control components may be added to accommodate the computer, but usually the computer is superimposed on the process to give over-all guidance to a more-or-less conventionally designed control system.

The major deterrent to effecting new designs lies in the lack of understanding of the complex processes found in chemical engineering. Theoretical formulations have on one hand been sometimes over-simplified or on the other made over-complicated -- in each instance leading to design procedures having limitations in utility. One way of eliminating the above dilemma is to use experimental data, but this suffers because of the time and expense involved in acquiring the desired information, and indeed may be even more limited in utility unless suitable pilot plants or prototype facilities are already available. A happy combination of both appears to be the sound approach.

For the last five years I have been heavily engrossed in experimental work, both with small and large scale processes. The plant work has usually been directed toward the solution of a problem on an existing process. Thus, the process design has been already established in the large, only minor changes being feasible. However, auxiliary systems have required redesign, these being the systems necessary for control.

As an illustration of a typical control system synthesis for an existing plant, I shall describe an actual case. All steps will be described, including the experimental work and terminating with the recommended scheme for control. An analysis of the problem will be made followed by a description of the methods of testing and data collection, reduction, and interpretation. The reasoning used to arrive at an acceptable control configuration will be presented which will be supported by theoretical deductions. Finally, it will be shown where the experimentally determined information is utilized in order to arrive at the best design.

Proprietary considerations prohibit revelation of the details of the process, but this need not detract from the value of the example.

The function of the process was to remove a condensable product from a gaseous mixture generated in a reactor and to discharge noncondensable gases into a common manifold for processing elsewhere. In this particular process it was important to maintain the pressure in the reactor at a very precise value; namely, within about ± 1/4" of water around some established level. It was the objective of the study to design a control system for this purpose.

The problem was made especially difficult because of the uncontrolled disturbances associated with the reactor. Gas evolution, and hence pressure, within the reactor was highly dependent upon the energy absorbed therein and energy supply was subject to random variations. In addition, transitory changes in the effluent gas temperature could occur, these giving rise to pressure changes.

The gas, approximately 15,000 cu. ft./min., was conducted to a large, distributed-type condensing unit, thence to a scrubber, and was finally removed by compressors from which it was discharged into a main serving as a manifold for other similar units.

Since the main pressure was subject to random variations, disturbances from this source could also enter the system. These, however, were always greatly attenuated because of the virtually constant displacement characteristics of the compressors and the relatively high pressure gain across them.

It seems invariably true that the general configuration of a control scheme is conceived by logical reasoning, using qualitative performance data on critical processing items. However, once a scheme is selected the detailed descriptions are used to compare performance of one scheme with another or with some established criteria. Thus, mathematical formulations do not necessarily contribute to the conceptions, but are necessary for verification. This case was typical in this respect.

In this instance some basic requirements for satisfactory operation are obvious:

1. For each specific mass flow rate a given pressure gradient between reactor and compressor suction must exist in order to assure the appropriate flow.

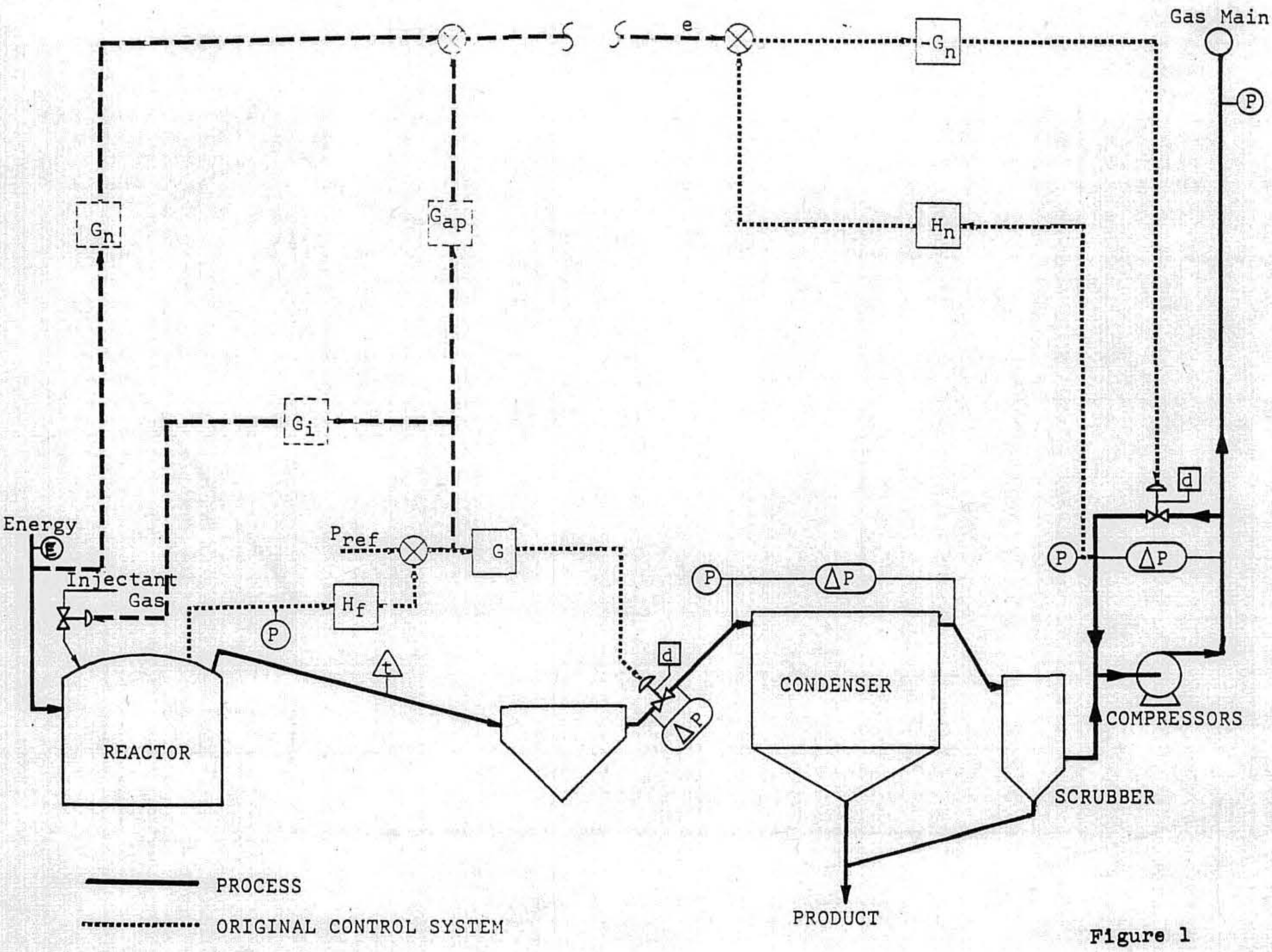


Figure 1

2. Since it is desirable that the reactor pressure be constant, it is then necessary that the compressor suction change in the manner required to insure the appropriate flow through the system.
3. Some means of compensating for very sudden changes in reactor pressure must be made.
4. To account for relatively slow changes in the system, such as fouling in the effluent lines and gas processing apparatus, some means must be provided to adjust the compressor suction pressure to compensate.
5. Because the gas handling system was rather distributed, an appreciable delay time or transportation lag could be expected.

A control system existed on the process but was not entirely satisfactory, especially when sudden interruptions in energy supply occurred. It was also quite sensitive to partial plugging in the lines. For these reasons and others, a detailed study was warranted. The work began with an experimental investigation.

Twelve channels of recording oscillographs were installed, primary measurements being made with very sensitive and responsive transducers. Pressures and pressure drops were sensed with Statham strain-gage transducers, valve displacements with multi-turn potentiometers, temperatures by bare thermocouples and energy by a suitable combination of variables.

Figure 1 indicates the process scheme, the location of measuring elements during the experimental work, and the original and revised control systems.

The following tests were conducted at various levels of production with the system on open loop or manual control.

1. Dynamic tests to determine the response of reactor, compressor suction, and other pressures to
   a. change in reactor energy input,
   b. change in displacement of existing compressor bypass valve,
   c. change in displacement of existing series throttling valve,
   d. direct injection of an inert gas into the reactor.
2. Static tests to determine
   a. performance characteristics of valves,
   b. sensitivity of reactor pressure to valve displacements,
   c. pressures and pressure gradients at various locations in the system.
3. Extended observations to note general process behavior, influence of disturbances, and performance of control system.

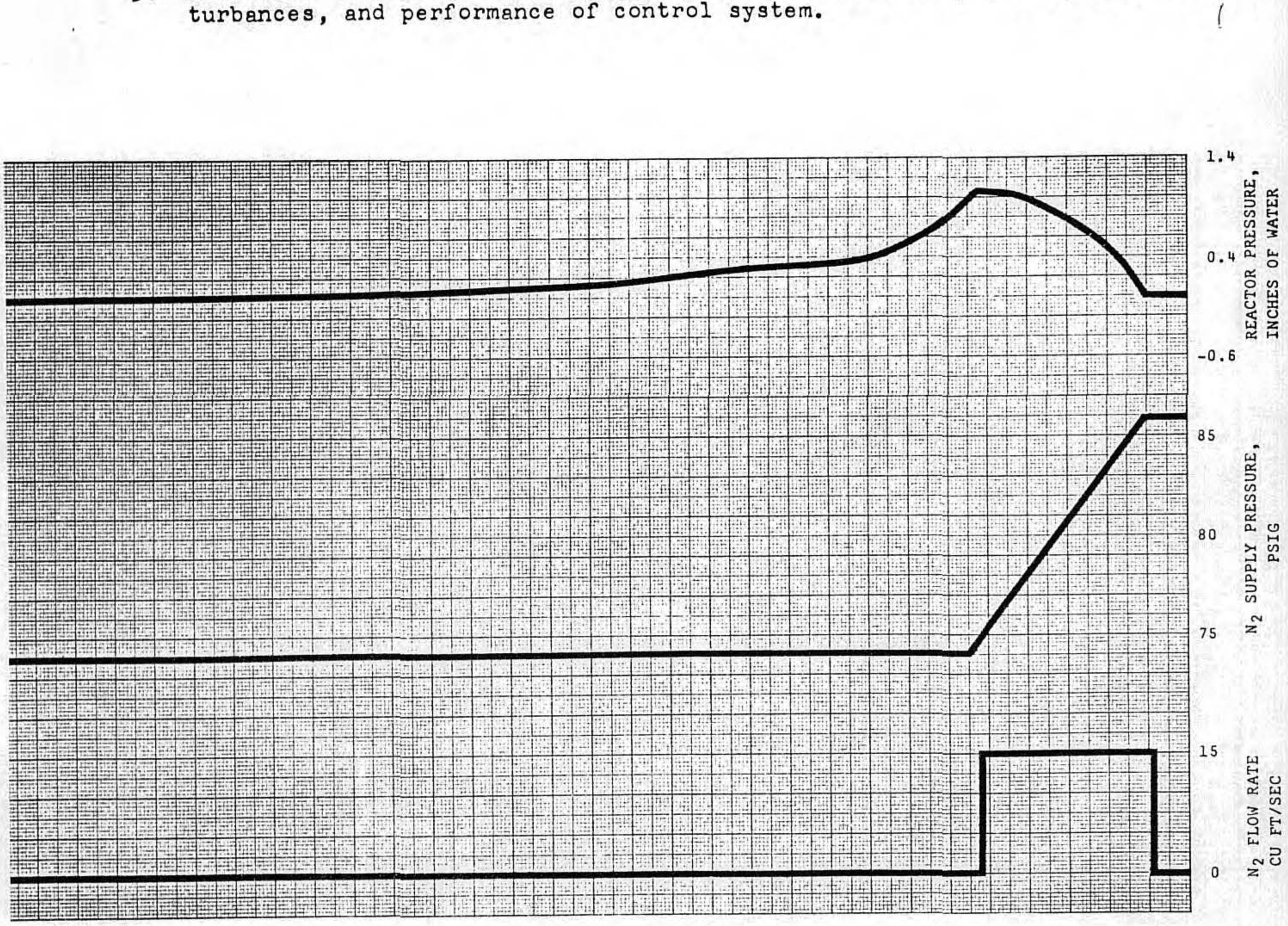


Figure 2

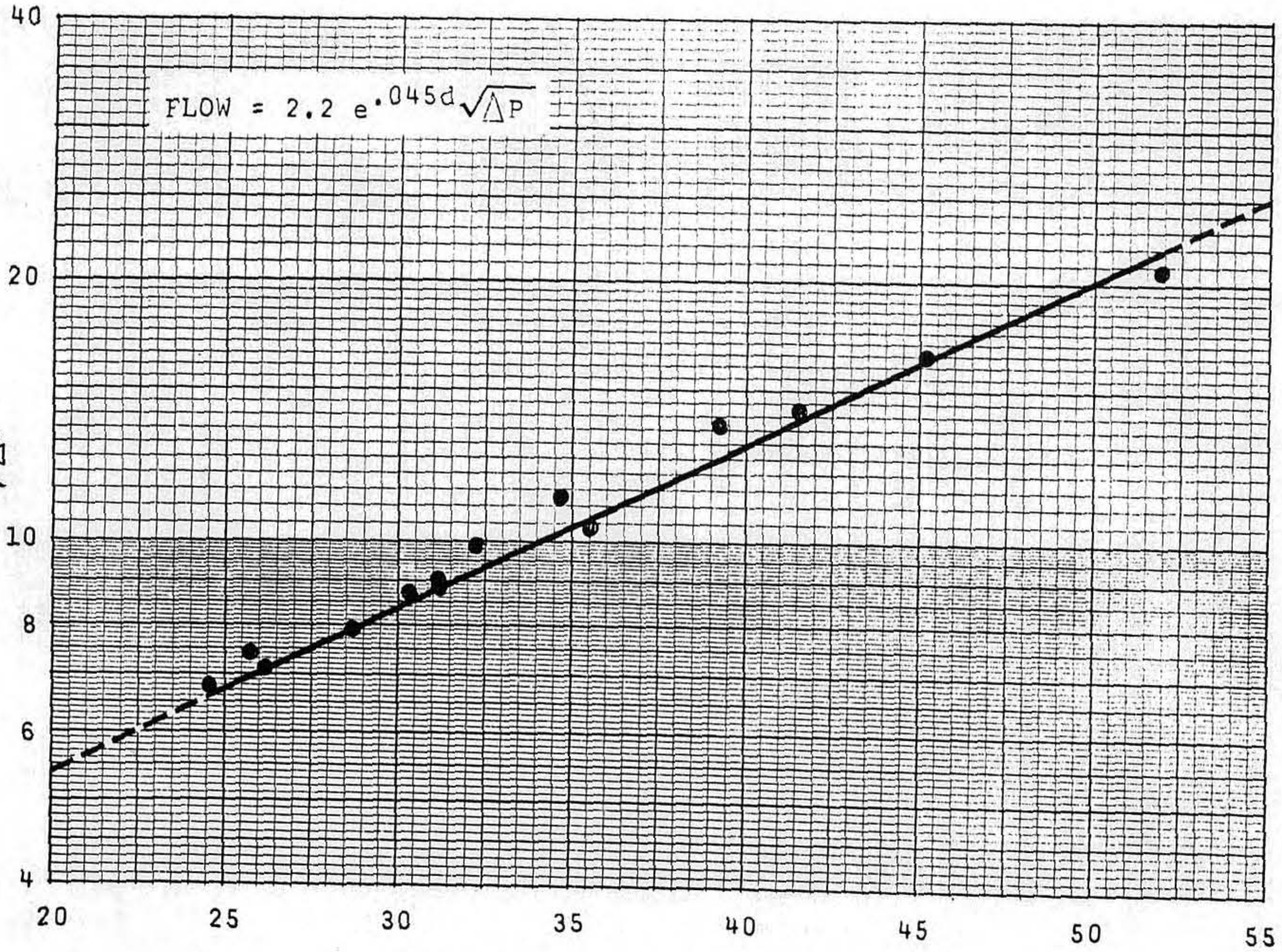


Figure 3

All dynamic tests were conducted by the pulse method [2,3,4] and were reduced to frequency response via a digital computing routine, delay time between records being extracted visually prior to processing. In this method an input is caused to vary in a pulse-like manner and the resulting outputs measured. In Figure 2 are presented records of typical results from a test wherein nitrogen was injected from a pressurized vessel into the reactor in order to measure the pressure response.

Figure 6 shows the corresponding frequency response information.

Important static data were also obtained, typified by Figures 3 and 4.

In view of the nature of the system, the requirements, and the information obtained, a control scheme was formulated.

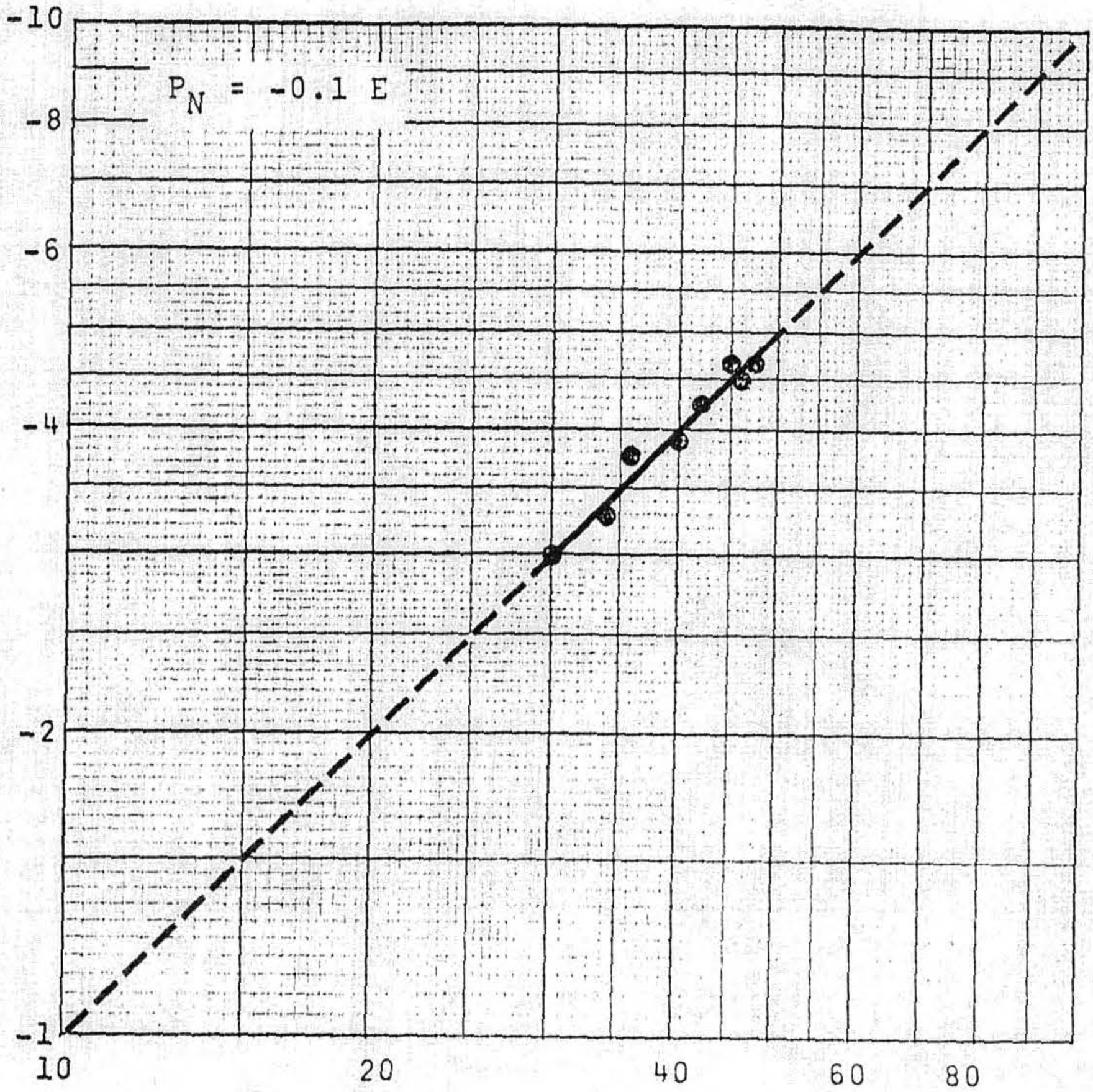
The scheme visualized relatively fast control systems at the terminals of the process with a means of loosely connecting the two.

1. A tight control of reactor pressure by regulation of the directly injected gas stream.
2. A tight control of compressor suction through bypass control.
3. Adjustment of compressor suction pressure in accordance with energy input using feedforward control of the set point of the suction pressure regulator.
4. A means of recognizing slow changes in system behavior (fouling, etc.) by sensing reactor pressure and allowing this to adjust the set point of the compressor suction pressure controller.

A complete block diagram representing process and control systems is shown in Figure 5. Symbols are defined in the list of nomenclature.

The objective of the experimental work was to determine the character of each block. Upon completing the data reduction, information was on hand enabling a detailed design to be made.

Since both the gas injection control and terminal bypass control systems must be fast compared with the other control functions, each was considered separately. For compressor suction control the following criteria were used -



As a regulator system

$$\frac{P_n}{e} = \frac{-G_n G_{nv} G_{nn}}{1 + G_n G_{nv} G_{nn} H_n} \approx 1$$

As a disturbance-suppressor and assuming distrubances were equivalent to a variation in control valve displacement

$$\frac{P_n}{D} = \frac{G_{nn}}{1 + G_{nn} G_{nv} G_n H_n} \approx 0$$

Similarly for the gas injection system

$$\frac{P_f}{P_{ref}} = \frac{G_i G_{iv} G_{if}}{1 + G_i G_{iv} G_{if} H_f} \approx 1$$

$$\frac{P_f}{P_w} = \frac{G_{if}}{1 + G_i G_{iv} G_{if} H_f} \approx 0$$

For the suction control system both criteria are satisfied if

$G_{nv}\, G_n\, H_n \gg 1$ since then

$$\frac{P_n}{e} = \frac{1}{H_n}$$

To maintain the required high gain in spite of attenuation in G_{nv} and/or G_{nn} usually requires that G_n contain compensating dynamics. Thus if

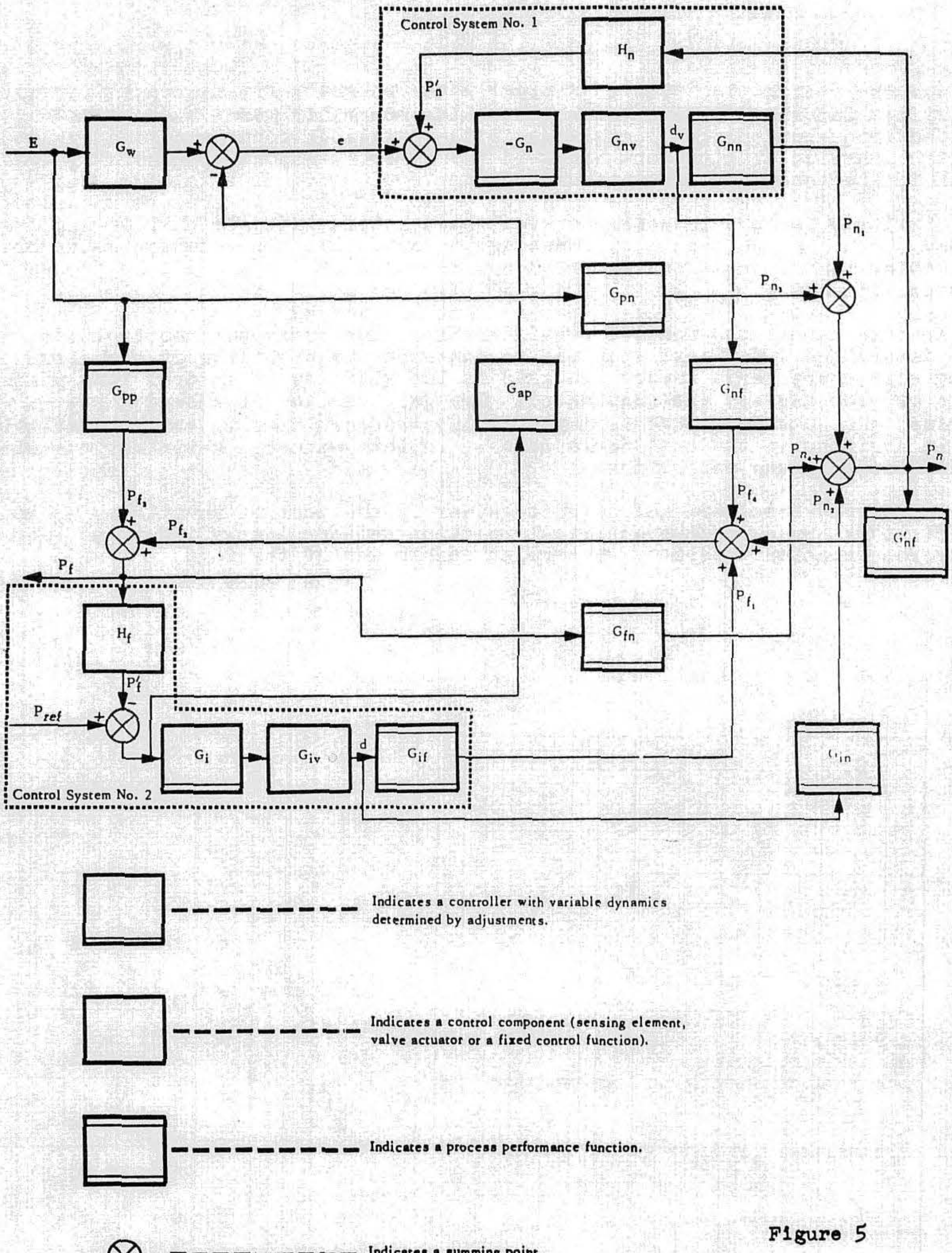

Control System No. 1
H_n
P'_n
E
G_w
e
$-G_n$
G_{nv}
d_v
G_{nn}
P_{n_1}
P_{n_3}
G_{pn}
G_{pp}
G_{ap}
G_{nf}
P_{n_4}
P_n
P_{n_2}
P_{f_3}
P_{f_2}
P_{f_4}
G'_{nf}
P_f
P_{f_1}
H_f
G_{fn}
P'_f
P_{ref}
G_i
G_{iv}
d
G_{if}
G_{in}
Control System No. 2
Indicates a controller with variable dynamics determined by adjustments.
Indicates a control component (sensing element, valve actuator or a fixed control function).
Indicates a process performance function.
Indicates a summing point.

Figure 5

$G_{nv} = \frac{K_n}{(1+\tau_n s)}$ and $G_{nn} = \frac{K_{nn}}{(1+\tau_{nn} s)}$ it is well to provide in G_n the elements of

$$K \frac{(1+\tau_n s)\ (1+\tau_{nn} s)}{K_n \qquad K_{nn}}$$

insofar as practicable. The objective is to provide sufficient gain and to cancel system denominator terms with controller numerator terms thus extending the desired frequency response consistent with realizable components and system stability. Physical limitations exist in the control components generally available which implies compromises.

Similarly for the injection system the criteria indicate that $G_i\ G_{iv}\ G_{if}$ should be as high as possible. Once again controller characteristics should tend to compensate for the drooping frequency response of G_{iv} and G_{if} as frequency increases.

In this manner the general requirements of the individual control systems were determined. The next step was to consider the stability of each loop. Using elementary servo theory the gain in the vicinity of an open loop phase angle of -180 degrees was considered. The gain should not exceed unity at -180 degrees, and some departure from this is desirable. Many rules are available to aid in arriving at the best performance. In this manner a satisfactory value for controller gain was established.

The two systems were next tied together by the control functions, G_w and G_{ap}. The first was based on the empirical relation between energy input and required compressor suction pressure. The relationship was of the form

$$P_n = -KE$$

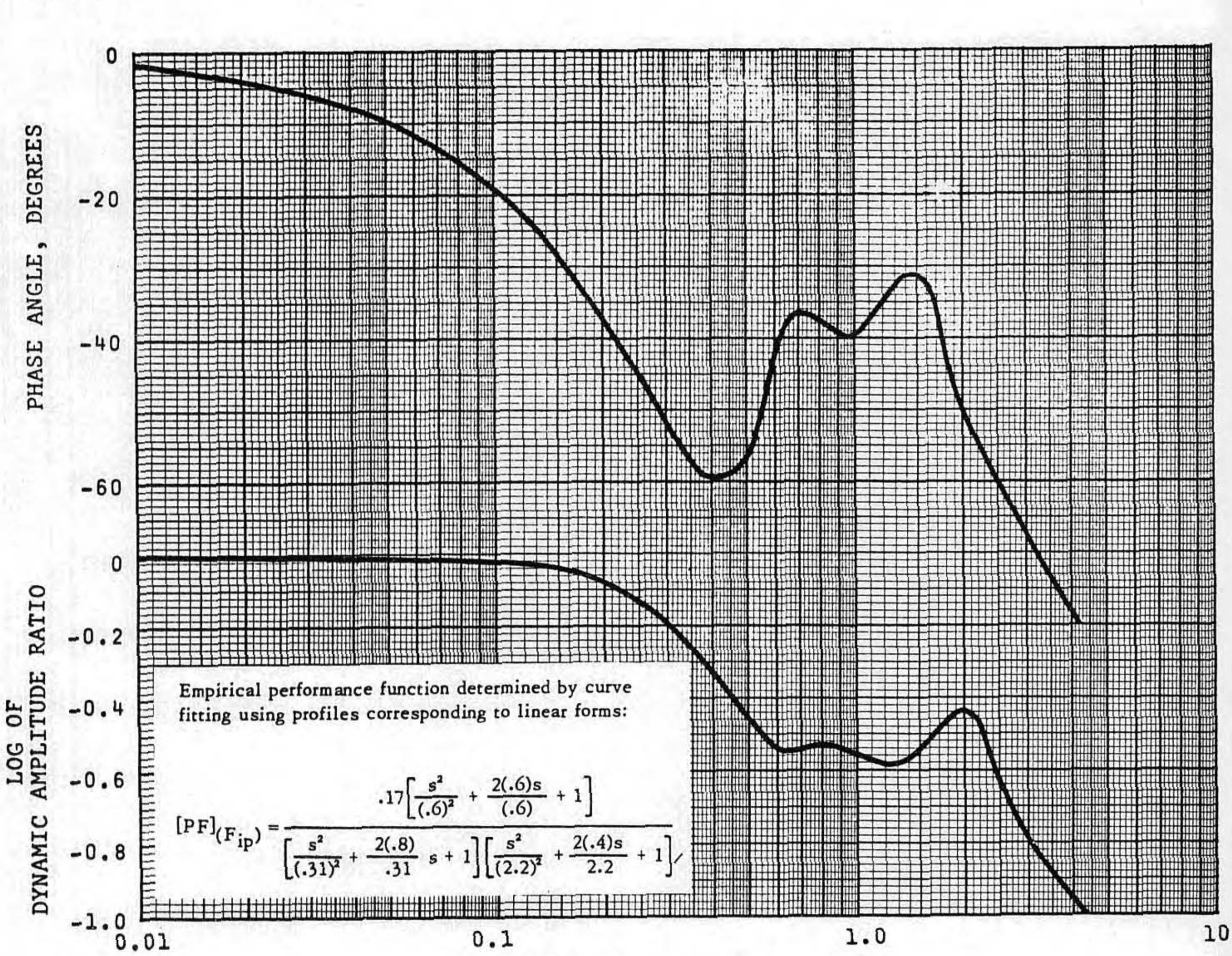


Figure 6

Also, since the corrective action should not occur before the reactor pressure distrubance appeared at the compressor suction, some attempt was made to create delay time in the control loop to match that in the process. A first order time lag element was used as an approximation. The feed forward element thus became

$$G_w = \frac{-K\ E}{(1+\tau s)}$$

Finally the block shown as G_{ap} was selected. This control component was provided to adjust the compressor suction pressure to compensate for slow changes in system characteristics. G_{ap} was thus required to produce an output which was the integral of the input. The form of control function chosen for this service was

$$\frac{K\ (1+\tau s)}{s},$$

which was closely approximated by conventional components.

The experimental data were used to enable selection of control components and for arriving at the appropriate adjustments of controllers. For example, although Figure 6 shows that the relationship between changes in injection gas flow rate and reactor pressure is rather complex, for part of the synthesis the approximation can be made that the performance function is first order with a time constant of about 4 seconds. (Reciprocal of the breakpoint frequency of about 0.25 rad/sec).This means that a valve actuator having its largest time constant equal to 0.4 seconds or less will be quite satisfactory. Thus pneumatic components will suffice. In addition, the time constant τ in the integration component, G_{ap}, should be 10 seconds or more if isolation of the terminal control system was to be achieved in some measure. The integration would then not be effective at frequencies above 0.1 radian per second.

The compressor suction pressure control required high performance components. Moreover, positioning of a large valve to make small changes in a large flow rate was involved. This system called for precision components and a hydraulic system was selected. To help compensate for the valve actuator and process some derivative action was introduced in controller, G_n. Frequently, however, some hydraulic components inherently provide some lead action so that none need be deliberately added. Experimental studies on the control gear is generally required to determine if these properties exist and at what frequency.

The above approach to the design of the appropriate control system is usually adequate and optimum performance can generally be attained by minor adjustments during operation.

However, if further verification is warranted, the entire ensemble may be modeled on the analog computer and the best controller functions determined by a systematic study.

The procedure for designing control systems for existing plants can be summarized as follows.

1. Study the plant to ascertain the fundamental phenomena involved and its operating principles.
2. Design and conduct an experimental program to determine important performance functions.
3. Based on the principles involved and bearing the data in mind, formulate the best control scheme in a qualitative manner.
4. Establish control criteria and determine the more exact nature of the particular control functions utilizing data from the experimental studies.
5. Construct the complete block diagram, or equivalent, in order to study over-all behavior, possible interactions, stability and performance under extreme conditions.
6. If warranted, extend the study using an analog model.

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NOMENCLATURE

Performance Functions

G_w relation between compressor suction pressure and energy (energy signal in - voltage signal out)

G_n controller function (voltage signal in - voltage signal out)

G_{nv} bypass valve actuator (voltage signal in - displacement out)

G_{nn} process between recycle valve and compressor suction (valve displacement in - compressor suction pressure out)

H_n compressor suction pressure sensor (compressor suction pressure in - voltage signal out)

G_{nf} process between recycle valve and reactor pressure (valve displacement in - reactor pressure out)

G_{pn} process between energy disturbance and compressor suction pressure (energy disturbance in - compressor suction pressure out)

G_{pp} process between energy disturbance and reactor pressure (energy disturbance in - reactor pressure out)

G_{ap} controller function (voltage signal in - voltage signal out)

H_f reactor pressure sensor (reactor pressure in - voltage signal out)

G_i controller function (voltage signal in - voltage signal out)

G_{iv} injection valve actuator and voltage to pneumatic signal transducer (voltage signal in - valve displacement out)

G_{if} process between injection valve and reactor pressure (valve displacement in - reactor pressure out)

G_{in} process between injection valve and compressor suction pressure (valve displacement in - compressor suction pressure out)

G_{fn} process between reactor pressure and compressor suction pressure (reactor pressure in - compressor suction pressure out)

G'_{nf} process between compressor suction pressure and reactor pressure (compressor suction pressure in - reactor pressure out)