

PERFORMANCE OF AN AUTOMATIC CONTROL SYSTEM
FOR AN INDUSTRIAL TYPE CONTINUOUS
FRACTIONAL DISTILLATION COLUMN

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I. INTRODUCTION

The techniques used in the distillation of liquids is in many respects ages old. Many of the principles which are fundamental in the design of present-day distillation apparatus were developed by the middle-age alchemists and distillery masters.

With the advent of reliable continuous distillation units and the growing demand for petroleum and other chemical products requiring large scale distillation units, the problem of the measurement and control of distillation processes has become increasingly complex. At the present time, for even small distillation columns, manual control is being replaced by automatic control, and larger units are approaching a state of control that could almost be called automation. It is easy to justify the expenditure for automatic control systems because a single failure in manual control might result in the waste of raw materials which would more than pay for a good control system. Losses also occur in production when temperature, pressure, flow rates, and other variables drift from the optimum conditions.

In spite of the great advances made recently in both the art and science of automatic control, the complex grouping of controls required for a distillation unit still represent a formidable design problem. At the present time it appears that the solution of the design problem must depend greatly upon empirical knowledge of the performance of actual distillation towers with automatic control systems.

The purpose of this investigation was to operate an automatically controlled ten-plate bubble-cap fractional distillation column and to determine the effect of the controller gains on the performance of the column.

II. LITERATURE REVIEW

The following sections contain a review of the literature on distillation and automatic control. Emphasis was placed on automatic control systems and the dynamics of the controlled systems. In the first few paragraphs several important definitions are given in respect to distillation.

Distillation

Distillation is the separation of the constituents of a liquid mixture by partial vaporization of the mixture and separate recovery of vapor and residue⁽⁶⁾. The more volatile constituents of the original mixture are obtained in increased concentration in the vapor; the less volatile in greater concentration in the liquid residue. The completeness of the separation depends upon certain properties of the components involved and upon the arrangement of the distillation process. Although separation by distillation can never yield a component in an absolutely pure form, in practice any purity that is economically warranted may be obtained.

Continuous Distillation. In continuous distillation, at least one feed is continuously introduced into the column, and at least two streams are continuously discharged from the apparatus. In all continuous distillation operations the exit stream enriched, with respect to the feed, in the more volatile component is called the

"product", "distillate", or "tops". The other exit stream depleted in the more volatile component is called the "bottoms" or "tails". In referring to the equipment in which distillation is performed such terms as "still", "column", "tower", and "fractionator" are used interchangeably.

Distillation may be carried out under non-continuous or batch conditions. This method of operation will not be considered further in this paper.

Fractional Distillation. As defined by Carey⁽⁶⁾, fractional distillation is a distillation carried out in such a way that the vapor rising from a still comes in contact with a condensed portion of vapor previously evolved from the same still. A transfer of material and of heat result from this contact, resulting in a greater enrichment of the more volatile components in the vapor. The term "rectification" is also used interchangeably with the term "fractional distillation".

The condensed vapors returned during fractional distillation are termed "reflux". The reflux ratio is defined as the ratio of reflux returned to the column to product both expressed in mols per unit of time⁽⁴¹⁾.

In addition to rectification there are two other important ways in which distillation may be performed⁽²⁾. The first of these is "equilibrium" or "flash" distillation and the second is "simple" or "differential" distillation. Equilibrium distillation involves

vaporizing a definite fraction of a batch of liquid, while keeping all of the liquid and all of the vapor in intimate contact. At the end of the operation the vapor is withdrawn and condensed and would be, ideally, in equilibrium with the liquid.

In differential distillation the vapor generated by vaporizing the liquid is withdrawn from contact with the liquid and condensed as fast as it is formed⁽²⁾. As the distillate is always richer in the more volatile component than the remaining liquid, as the distillation continues, the residue becomes progressively depleted of the more volatile component.

Multicomponent Distillation. Distillation involving a feed mixture having more than two principle components is defined as multicomponent distillation. In the previous paragraphs it was implicitly assumed that the mixture to be distilled was composed of two components which were designated as the more volatile and less volatile components. In general, however, the liquid mixture to be distilled contains more than two components. In this case all of the previous definitions are still correct if for "more volatile", "relatively more volatile" is read and similarly for "less volatile".

In a multicomponent mixture all of the components, except the least volatile, are relatively more volatile. Also all of the components, except the most volatile, are relatively less volatile. Used in this sense the terms lose virtually all significance. However, it is customary to select one component, the least volatile

component of the product that is relatively enriched with respect to the feed, and base the "more volatile" statements on this component. By the same reasoning the less volatile statements are customarily based on the most volatile component of the tails which is relatively depleted with respect to the feed. The two components selected are called the "light key" and the "heavy key", respectively.

Liquid-Vapor Phase Relationships

The following sections contain a review of a few basic considerations and definitions for the liquid-vapor phase relations of importance in fractional distillation.

Vapor Pressure. The vapor pressure of a liquid at any given temperature is the pressure of the vapor for which the vapor and liquid phases of the substance would be in equilibrium⁽⁶⁾. Although a liquid mixture would have a "vapor-pressure" by this definition, it is customary to restrict the term vapor pressure to pure liquids. The vapor pressure is a function of the temperature and substance only.

Duhring's Rule. Duhring's rule is among the more convenient and useful principles for plotting and estimating vapor pressure data. This rule states that the temperature at which one liquid exerts a given vapor pressure is a linear function of the temperature at which a second liquid exerts the identical vapor pressure⁽⁴²⁾. If the temperature at which two liquids exert the same vapor pressure are

plotted against each other, a straight line would be obtained if the liquids actually do obey Duhring's rule. It has been found that the greater is the similarity between the two liquids; e.g., where the two liquids concerned are chemically related as are benzene and toluene, the closer the resulting plot approximates a straight line. The rule is expressed by the following equation (42):

$$T_B = \frac{T_B^{\circ}}{T_A^{\circ}} T_A$$

where:

T_B = temperature of liquid B at which the vapor pressure of A and B are equal, °K

T_A = temperature of reference liquid A corresponding to the vapor pressure of A and B at T_B , °K

T_B° = temperature difference from T_B at which the vapor pressure of A and B are equal, °K

T_A° = temperature of reference liquid B corresponding to the vapor pressure of A and B at T_B° , °K.

Clausius-Clapeyron Equation. The Clausius-Clapeyron equation may be used to correlate the vapor pressure of a liquid. This equation is as follows (16);

$$d \ln p = -\frac{\Delta H}{R} d (1/T)$$

where:

p = vapor pressure of liquid at temperature T , atm

ΔH = molal latent heat of vaporization of the liquid, cal/mol

T = temperature of liquid, °K

R = gas constant, cal/mol-°K.

The Clausius-Clapeyron equation suggests that there is a useful correlation between the reciprocal of the absolute temperature and the logarithm of the vapor pressure. For most substances a plot of this equation will give a substantially straight line over narrow temperature ranges (15).

Volatility and Relative Volatility. Volatility is generally used to compare the vapor pressure of one pure substance with another, the substance having the higher vapor pressure at a given temperature being termed the more volatile. Vapor pressure alone does not define the ease of separation of the components from liquid mixtures since the vapor pressure of each is lowered by the presence of other liquids.

For a solution of more than one component the volatility is defined as follows (7):

$$K_1 = \frac{y_1}{x_1} \pi$$

where:

K_1 = volatility of component 1, atm

π = total vapor pressure of the mixture, atm

y_1 = concentration of 1 in the vapor phase,
mol fraction

x_1 = concentration of 1 in liquid phase, mol
fraction.

The ratio of two volatilities is known as the relative volatility, α , and is given by the following equation (13):

$$\alpha_j = \frac{K_1}{K_j} = \frac{y_1 x_j}{y_j x_1}$$

where:

α_j = relative volatility, ratio of volatility
of ith component based on the jth component,
dimensionless

x_j = concentration of j in liquid phase, mol
fraction

y_j = concentration of j in the vapor phase, mol
fraction.

This gives a valuable relation between the ratio of the mol fractions of two components, say A and B, in the vapor and the

same ratio in the liquid. While α varies with temperature and pressure it remains fairly constant for many systems.

Upon examining the equation it can be seen that when the relative volatility is one, no separation is possible. Furthermore the larger the value of the relative volatility the easier will be the separation.

Raoult's Law. Raoult's law relates the partial vapor pressure of a component in a liquid mixture to its concentration in the liquid and vapor pressure at the same temperature. It generally applies well to the components in solutions so dilute that the properties of the solvent are not greatly different from those of the pure solvent. According to this law the partial pressure of the component varies linearly from zero to the full vapor pressure as its mol fraction varies from zero to unity. Raoult's law may be expressed as follows (17):

$$P_i = P_i^{\circ} x_i$$

where:

P_i = partial pressure of ith component, atm

P_i° = vapor pressure of ith component in the pure state, atm

x_i = concentration of the ith component in the solution, mol fraction.

A system in which the liquid mixture was ideal and all the vapors were ideal gases would follow Raoult's law. In using this relation for engineering work on hydrocarbon systems some errors are introduced because of the non-ideality of solutions and the vapors.

Henry's Law. In an ideal solution Henry's law, as well as Raoult's, is an exact law. According to Henry's law the partial pressure of a component over a solution is proportional to its mol fraction in the liquid. Henry's law can be expressed as⁽¹⁷⁾:

$$P_i = k x_i$$

where:

P_i = partial pressure of ith component, atm

x_i = concentration of ith component in the liquid mixture, mol fraction

k = an experimentally determined constant, atm

Henry's law is different from Raoult's law in that the proportionality constant k is not the vapor pressure of the pure solute but is a constant that must be evaluated experimentally for each solution. Over a limited range of variables a linear equilibrium relationship is found for all systems.

Non-ideal Systems. In an ideal system it is assumed that the components have no effect on each other. Each component acts independently and its volatility is a function only of its

concentration in the liquid phase and its vapor pressure at the temperature of the system. Raoult's law expresses this condition.

But in a non-ideal system the molecules do not behave in a mixture as they would independently. Their tendency to escape from the liquid phase to the vapor phase may be less or more than that which would be expected from their measured vapor pressure.

The second law of thermodynamics states that in an equilibrium phase change at constant temperature and pressure, the free energy of a component must be the same in both phases. Stated mathematically⁽⁴⁴⁾:

$$\Delta F_{iL} = \Delta F_{iV}$$

where:

ΔF_{iL} = free energy of component i in liquid phase,
Btu/lb mol

ΔF_{iV} = free energy of component i in vapor phase,
Btu/lb mol.

The fugacity which is related to the free energy of any component in solution must then be equal to the fugacity of the given substance in the vapor phase if both are measured from the same reference state. Therefore fugacity is the real measure of the escaping tendency of any component from a given system which may be expressed as follows:

$$f_{iL} = f_{iV}$$

where:

f_{iL} = fugacity of component i in liquid phase, atm

f_{iV} = fugacity of component i in vapor phase, atm.

Gilliland⁽³²⁾ develops the basic ideas of free energy and fugacity and shows how it may be applied to multicomponent systems.

Tabulated values of the fugacity of the simple hydrocarbons may be found in Maxwell⁽³¹⁾ and Perry⁽³⁶⁾.

Multicomponent Distillation Calculations

The first analytical approach to fractionation was made by Sorel in 1893. His method is based on tray-to-tray calculations of material, enthalpy, and equilibrium balances. This is still the only completely valid analysis of fractionation for both binary and multicomponent systems. The main disadvantage is that it takes too long and sufficiently accurate enthalpy information is not always available⁽⁴⁵⁾. Other simpler methods include graphical solutions by Savaritt⁽⁴³⁾ and Thiele⁽⁴⁶⁾.

Theoretical Plate Concept. The distillation tower involves the countercurrent flow of liquid across a plate with vapor rising through this plate. The whole distillation scheme depends upon the nature of this contact.

Therefore a "theoretical" or "equilibrium" plate may be defined as a plate holding a pool of liquid from which rises a vapor whose average composition is in equilibrium with a liquid whose composition is the average of that of the liquid leaving the plate⁽⁴⁾. In order to perform these calculations either the nature of the contact must be known in detail or assumed. The following general assumptions are generally made to simplify the calculations: vapor leaving the plate is well mixed, liquid leaving the plate is well mixed, and vapor leaving the plate is in equilibrium with the liquid leaving the plate at the temperature and pressure existing at the liquid gas interface.

Material and Enthalpy Balances. An overall material and enthalpy balance can be written for any continuous fractional distillation column. This is the first step to any analytical approach to fractionation.

The material balance can be written as a simple relation stating that the material entering the column or an individual plate in the column is equal to the material leaving the column or the plate. Neither the vapor flow rate nor the liquid flow rate is necessarily the same above or below the feed tray but they are related by the material balance around any plate in the tower.

Similarly an overall enthalpy balance can be written on the total enthalpy input to the total enthalpy output of the column or for each individual plate in the column. However, for most hydrocarbon systems it is assumed that all the enthalpy entering a given plate is passed to the next plate. Thus the enthalpy balance for each individual plate is generally neglected without introducing appreciable errors. This is actually equivalent to assuming that no heat is lost from the tower, reflux returns as a saturated liquid, and constant molar upflow through the column.

Plate-to-Plate Calculations. A method of calculating the number of theoretical plates required for a specific multicomponent separation and reflux ratio was presented by Lewis and Matheson⁽²⁹⁾. This method involves the use of equilibrium data combined with material balance equations. The composition of the liquid and

vapor on each plate in the rectifying section is found by starting with the desired overhead product composition and reflux ratio and calculating stepwise from plate to plate down the tower by means of material balance and equilibrium relationships until the feed plate is reached. Similarly, the composition of liquid and vapor on the plates below the feed plate is found by starting at the bottom of the tower and calculating stepwise up the tower until the feed plate is reached.

The following paragraphs summarize the stepwise calculations for the rectifying section of the column. It is impracticable to cover these relations in complete detail in a review of this length. Prior to commencing plate-to-plate calculations, an overall material balance has to be completed for the feed, product, and bottoms.

Plate Equilibrium Calculations. The composition of a component in the vapor phase leaving each plate may be calculated by substituting into the following equation (38):

$$y_{i_n} = \frac{K_i x_i}{\sum K_i x_i}$$

where:

- y_{i_n} = composition of component i in the vapor leaving the plate n, mol fraction
- K_i = volatility of component i at the assumed temperature of plate n, atm
- x_i = composition of component i leaving the plate n, mol fraction
- $\sum K_i x_i$ = summation of the product of the mol fraction and the vapor pressure at the assumed temperature of plate n for each of the components on plate n.

This relation arises because y_i is the concentration of a component in the vapor rising from plate n which is assumed to be in equilibrium with the same component, x_i, in the liquid phase, flowing down from plate n to plate n + 1.

In actual calculations, using this equation a trial-and-error procedure is used until the summation of the partial pressures for all various components is equal to the column pressure. Beginning with the composition of the vapor leaving the column, a temperature is assumed for each plate, and the partial pressure of each component in the vapor is calculated using the appropriate equilibrium relation.

If the summation of the partial pressures is equal to the column pressure the assumed temperature was correct. If not, another temperature must be assumed until this condition is met.

Plate Operating Line Calculations. The composition of component i in the vapor leaving plate n + 1 is calculated from the equation (38);

$$y_{i_{n+1}} = \frac{L x_{i_n} + P y_{i_p}}{V}$$

where:

- $y_{i_{n+1}}$ = composition of component i in the vapor rising from plate n + 1, mol fraction
- L = column downflow, mols per unit time
- x_{i_n} = composition of component i on plate n, mol fraction
- P = algebraic sum of output and input streams above plate n + 1, mols per unit time
- y_{i_p} = composition of component i in the product, mol fraction
- V = column upflow, mols per unit time.

Each theoretical plate calculation consists of equilibrium and an operating line calculation.

Number of Theoretical Steps. Alternately repeating first the plate equilibrium calculation and the plate operating line calculation from plate n down the column until the desired composition of the feed is obtained will give the number of theoretical stages required for the rectifying section of the column. The number of theoretical stages calculated would be applicable only to the column and system used in the calculations.

If the results from the equilibrium and operating line equations were plotted for each component each plate would be one point on a curve similar to the McCabe-Thiele Diagram⁽⁴⁷⁾. Because of the complexity of the diagram that would be required for multicomponent problems, the usual procedure is not to calculate the number of stages graphically but analytically.

Method of calculating the minimum number of theoretical steps is by use of the Fenske equation⁽²⁶⁾. However this equation is restricted to the separation of only two components of a multicomponent system, the light key component and the heavy key component. Maxwell⁽³³⁾ gives a complete procedure for solving multicomponent problems analytically based solely on the separation of the light and the heavy key components.

Location of the Feed Plate. The proper location of the feed tray may be obtained by studying the results of plate-to-plate calculations and assigning the feed to the tray with a composition similar to the feed composition. The feed may be preheated to the temperature of the calculated feed tray.

Another method of locating the approximate feed tray, is to assume that the ratio of the minimum number of theoretical stages above the feed composition to the minimum number of theoretical stages in the entire tower is the same as the ratio of actual plates above the feed to the actual total number of plates.

Column and Plate Efficiency. Because of the large number of factors which influence plate efficiency of a fractionating tower, any fundamental formula accounting for even the most important variables would be quite involved. Therefore, a simple empirical correlation of the limited data on hydrocarbon mixtures is probably the best method of predicting plate efficiency.

Overall Column Efficiency. The relation between the performance of actual and theoretical plates is expressed as a plate efficiency. The use of an over-all column efficiency was proposed first by Lewis⁽²⁸⁾. The over-all column efficiency is equal to the number of theoretical plates necessary for a given separation divided by the number of actual plates required to perform the same separation. This efficiency has no fundamental mass-transfer basis, but it serves as an easily applied and valuable design factor and is therefore widely used.

Murphree Plate Efficiency. The Murphree plate efficiency is based on more fundamental concepts than the over-all column efficiency but even in this case the basic relations employed are more qualitative than quantitative⁽³⁹⁾.

Murphree developed a vapor-phase tray efficiency by assuming as the mechanism a bubble of vapor rising through liquid on a plate. It was assumed that the bubble was in contact with a liquid of constant composition, and that the composition in the bubble changed continuously by mass transfer. Although Murphree applied this relationship to the whole plate, in many cases there are considerable differences in the compositions of the liquids at various points on a plate. However, for convenience, the value of the Murphree plate efficiency defined below is often used⁽⁴⁹⁾:

$$E_g = \frac{y_n - y_{n+1}}{y_n^* - y_{n+1}}$$

where:

- E_g = Murphree gas efficiency, fraction
- y_n = average composition of component i entering plate n, mol fraction
- y_{n+1} = average composition of component i leaving plate n + 1, mol fraction
- y_n^* = composition of i in the vapor in equilibrium with a liquid flowing from plate n, mol fraction.

Factors Influencing Plate Efficiency. The factors that influence the effectiveness of contact between vapor and liquid, therefore effect plate efficiency, may be classified into three groups⁽³⁾: first, those that have to do with the design and construction of the plate and the flow of liquid across it; second, those that control the interdiffusion of components between liquid and vapor as the bubbles pass through the liquid layer on the plate; and third, those that control the entrainment of fine particles from one plate to that above it.

Experimental Data on Plate Efficiencies. Although a considerable number of investigations of plate efficiencies have been reported, it is difficult to obtain an exact picture because of the large number of unknown factors affecting the results.

Lewis and Smoley⁽³⁰⁾ studied the plate efficiency in the rectification of mixtures of benzene-toluene; benzene-toluene-xylene; and naphtha and mixtures of pinene and aniline in naphtha in a fractionating column comparable to the column used in this study. The investigators found an average plate efficiency of 60 per cent for the benzene-toluene mixture, 75 per cent for the ternary mixture, and 80 to 95 per cent for the naphtha mixtures. The Murphree plate efficiency was found to be 70 per cent for the benzene-toluene system.

Brown⁽⁵⁾, Treybal⁽⁴⁸⁾, and Robinson and Gilliland⁽⁴⁰⁾, have published information related to bubble-cap distillation columns and using hydrocarbon systems similar to the column and the hydrocarbon system used in this study.

Automatic Instrumentation

Dow(18) states that the most conspicuous labor-savers in a chemical plant today are: larger equipment, to reduce the cost of the initial investment and the cost of operating per unit of product; automatic analysis, to reduce the cost of making routine tests at regular intervals and to secure results more quickly and more exactly, with the chance of error due to the personal factor reduced; automatic operation of the equipment, which is governed by the automatic analyzer; and a continuous process which is both automatically controlled and operated. Automatic process control is used to obtain the best possible finished product with the lowest possible processing cost.

While automatic control systems are not perfect, they are usually far more dependable than manual control and they are being used more and more whenever they can be economically justified.

Definition of Terms. Unfortunately as each manufacturer developed and improved his controllers he found that names were not available to describe some of the various controller responses and process characteristics encountered. For many items there are several names. A set of proposed process control terms has been published by Moore(34).

Several simplified definitions are listed below which are important for an understanding of automatic instrumentation.

Automatic Controller. An automatic controller is a mechanism which measures the value of a variable quantity or condition subject to change with time and operates to maintain it within limits⁽¹²⁾. This mechanism or automatic control system can be of the self-acting type that obtains energy for the operation of the final control element from the measuring element or it may be of the pneumatic or electric type which amplifies the power obtained from the measuring element by using air or electric amplifiers to operate the final control element.

Controlled Variable. A quantity or condition which is measured and controlled by an automatic controller is the "measured" or "controlled" variable⁽¹²⁾. The variables which are most frequently controlled in industrial processes are those which are most easily measured. Many unit processes include variables such as pressure, flow rate, liquid-level, and temperature which are important in many chemical reactions and in distillation.

Indirectly controlled variables as uniformity, quality, cost, and waste can not be easily measured during the process and therefore are not directly controlled. These variables are controlled indirectly to some extent by their relation to the directly controlled variables.

The Primary Sensing Element. The primary sensing element is that part of the control system which utilizes energy from the measured medium to reproduce a condition representing the value of the measured variable. The sensing element performs the measurement of the process variable being measured. Although there are many conditions which may require control, there are actually only a few different variables being measured. Several of the variables are temperature, fluid-flow, pressure, and liquid level, of which temperature is the most important controlled variable in industrial processes(22).

Several sensing elements used in the measurement of temperature are the thermocouple, potentiometer, pressure thermometer, and the resistance thermometer. For fluid flow measurement, the differential flowmeter is the most common sensing element. The bourdon tube, the spiral, and the helix are the most common actuating or sensing elements for pressure gages. The measurement of liquid level is essentially a measurement of head or pressure or differential pressure.

Control Point. The control point is the value of the controlled variable which, at any instant of time, the automatic controller operates to maintain.

Deviation. Deviation is the difference at any instant between the value of the controlled variable and the control point or a selected reference value⁽³⁴⁾. Drift is sustained deviation and is usually indicative of a poor control system for the process being controlled.

Sensitivity. Sensitivity denotes the smallest change in value of a measured variable to which an instrument responds⁽²¹⁾. Dead zone is the opposite of sensitivity in that it is the largest change in a variable that does not produce a change in reading. Sensitivity causes a hysteresis effect, readings that are not alike when a point is approached from opposite sides.

Controller Element. The controller element interprets the indication of changes in the variable supplied by the measuring means and produces the corrective action necessary to maintain the desired balance within the process⁽²³⁾. The nature of the corrective action the controller produces is called the mode of control. This mode, as well as lag and the dead zone, constitute the controller characteristics.

Final Control Element. That part of the control system that is used for controlling the measured variable is the final control element⁽¹⁹⁾. Therefore the sensing element is the first part of an instrument and utilizes energy from the measured medium and sends out a signal. The converting

element or controller picks up this signal and merely transforms or adds to this signal in such a method to be useful to the final control element.

Proportional Band and Reset Rate. The throttling rate or as sometimes called, the proportional band is the range of values through which the controlled variable must vary in order to cause the final control element to move from one extreme to the other extreme. The proportional band is expressed as:

$$b = \frac{100}{e}$$

where:

b = proportional band, dimensionless

e = error, per cent of scale.

The ratio between the actual rate of response and that from a proportional response following a single action of the measuring element is the reset rate.

Dynamic and Static Characteristics. The static characteristics of an instrument are, in general, those that should be considered when an instrument is used to measure a condition not varying with time. Desirable characteristics for this type of instrument are those of accuracy, reproducibility, and sensitivity. The dynamic characteristics of an instrument are those that become important when the measured variable varies with time. The desired characteristics are speed of response and fidelity⁽²⁰⁾.

Since automatic control operation is based upon the correction of a deviation, before a controller can act, a deviation, no matter how small, must occur. Thus, an automatic control system must be evaluated in terms of moving or dynamic conditions, not steady or static conditions(25).

The Importance of Measurement. The fundamental purpose of an automatic controller is to maintain at a predetermined value the condition it regulates. This is accomplished by utilizing a measuring system to detect variations in the controlled variable and having this measuring system actuate a mechanical device for applying a corrective action which tends to remove the initial variation(11). In order to have accurate control of a variable, it must be first accurately measured.

In an automatic control circuit there must be a deviation in the measuring system before any corrective action can be taken by the control mechanism. If the measuring system is slow in responding to changes then there will be a delay in applying a correction by the controller, probably causing further deviation before the correction becomes effective. For best results the measuring system should respond to variations of the process as quickly as possible.

Basic Control System Theory

Automatic control is accomplished by a circle of events, beginning with a change in the controlled variable and ending ultimately with a forced return of the variable to the desired level. This circle of events, or the control system is actually a series of units combined to produce a useful result with little or no human supervision.

This control system may be an open system where the output of the process has no effect upon the input of the process or it may be a closed system. The open system is generally unsuitable for process control systems because the output is not a function of itself. However in the closed system, energy input to the system is some function of the relation of the output itself to the desired value. This type of system is called a feedback control system and is generally used in control work.

The Parts of a Control System. A control system is made up of five essential parts which are⁽⁸⁾: The process, the measuring means, the error-detecting mechanism, the controller, and the final control element.

However, in many systems these five are not readily seen as separate units but in composites of two or more units. A block diagram, Figure 1, page 30, represents a single-feedback control system. The lines between the blocks represent signals sent from one unit to the next and these signals may be in any form of

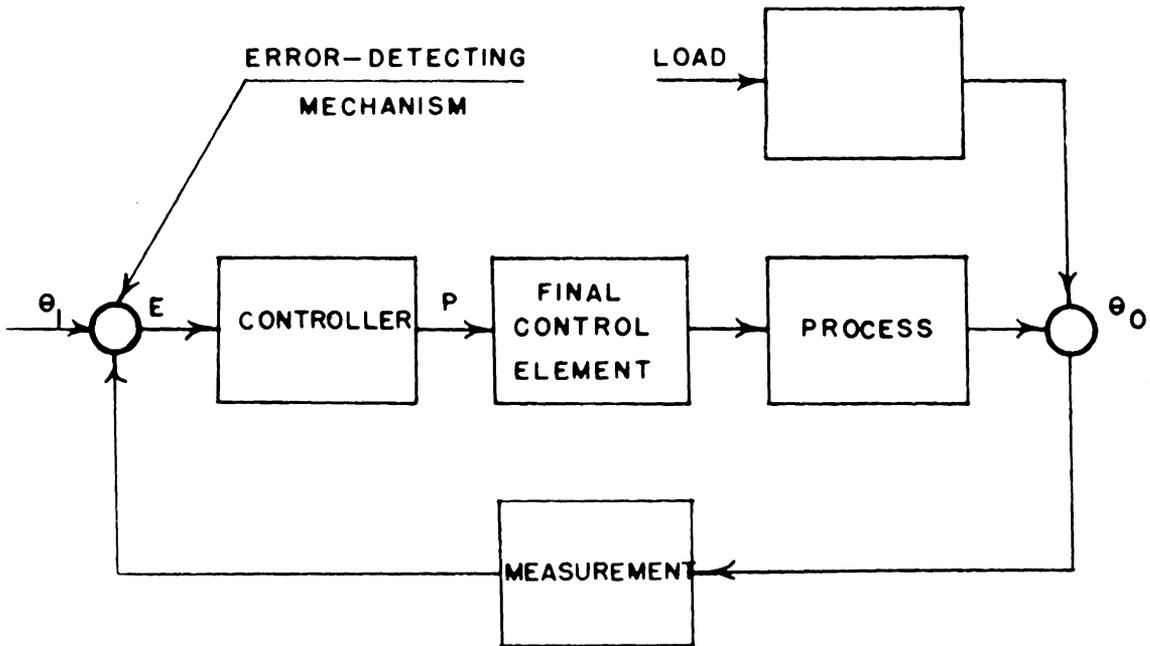


FIGURE 1. CONTROL SYSTEM BLOCK
DIAGRAM

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CHEMICAL ENGINEERS", P.5. JOHN WILEY &
SONS, INC., NEW YORK, N.Y., 1956

potential such as an electric voltage, or a pneumatic or hydraulic pressure.

Any operation or series of operations that produces a desired final result is a process. The process may involve a mechanical operation, an electric circuit, or a chemical reaction, or any combination of these three.

The capacitance of a process is a measure of the quantity of energy or material which can be stored per unit of potential. In the flow of a liquid through a pipe, for example, no liquid is stored; therefore the capacity of this system would be zero. In the flow of a liquid through an accumulator however the liquid may be at any level in the tank and therefore there is a finite capacity which depends upon the design.

Control System Mechanisms. The instrument that detects the process variable to be controlled is called the measuring means and may be any instrument such as a thermometer or pressure gage.

The error-detecting mechanism is a device that compares the measured variable with the desired value of the measured variable, the difference being the error.

The controller is a mechanism that responds to any error indicated by the error-detecting mechanism. The output of the controller is some predetermined function of error and is sent to the final control element which effects the material or energy input to the process.

The process load is usually considered as any factor that effects the process output in addition to the control system.

Controller Modes. In analyzing a specific control problem, a choice must be made among the various modes of control available. The controller is a mechanism that reacts to the error signal and produces an output signal proportional to some function of the error, and generally the more difficult the control problem, the more complicated will be the required controller mode.

Each type of controller has a clearly defined mode which may be one of several types. But only two different types of modes, those applicable in controlling the distillation column in this study, will be discussed. However, Peters⁽³⁵⁾ and Van Antwerpen⁽⁵⁰⁾ have a complete discussion on the basic control theory of automatic control instruments and controller modes.

Proportional Mode. The proportional or throttling mode is a type of controller action in which the final control element is positioned in proportion to the magnitude of the deviation of the controlled variable from the set point.

The output signal of the controller is directly proportional to the error and is expressed as⁽⁹⁾:

$$p = -\frac{1}{b} e + P_0$$

where:

p = controller output signal, dimensionless

b = proportional band, dimensionless

e = error, dimensionless

P_0 = a constant depending upon the manual-reset position, dimensionless.

It can be seen from the equation that the output signal changes only when the error is changing. Another important characteristic is that the proportional mode produces an output signal differing from that at the control point only when there is an error.

Proportional-Reset Mode. In order to obtain satisfactory system responses in many processes, it is desirable to combine two or more modes of control. One of the more advantageous combinations is that of the proportional and the automatic reset modes. When two or more modes are combined, the final response of the combination is the sum of the individual responses, therefore:

$$p = \frac{1}{b} [e + R \int e dt] + P_0$$

where:

- p = controller output signal, dimensionless
- P_0 = a constant depending upon the manual-reset position, dimensionless
- b = proportional band, dimensionless
- e = error, dimensionless
- R = reset rate, reciprocal minutes
- t = time, minutes.

It can be seen from the equation that increasing the reset rate or decreasing the proportional band will tend to cause cycling.

This combination, proportional-reset mode, is useful for the control of most processes especially if there are large load changes that occur slowly. The reset action avoids any offset. This mode always attempts to return

the measured variable to the control point after any load change. When lags in the system are large, it is necessary to increase the proportional band and decrease the reset rate greatly to prevent cycling. Consequently then the reaction to load changes will be slow, and the resulting system response may not be satisfactory.

Adjustment of Controllers

Adjustment of the controller is necessary in order to obtain the most efficient operation of the process. In practice analytical treatments of process control systems is not yet possible requiring empirical methods for adjusting these controllers. Some of these techniques are quite superior to hit-or-miss techniques which may result in a hopeless situation and should be avoided if possible. Ceaglske⁽¹⁰⁾ lists three procedures that may be used as empirical adjustments for controllers, and these methods will be discussed in the following paragraphs.

Trial and Error. For the trial and error method enough trials have to be made with a systematic set of combinations of the proportional band and reset rate so that optimum conditions may be determined. This method requires considerable time because of the many combinations of the adjustments possible. Also it may not be economically feasible to use this method on a large scale plant process.

Ziegler and Nichols Method. Ziegler and Nichols developed a set of empirical equations which are useful in finding the proper adjustments for processes having two or more capacities. A reaction curve is required for the process in order to apply these equations. The reaction curve may be obtained experimentally by changing the energy input a small amount and observing the behavior of the measured variable. Figure 2, page 37, shows a typical curve obtained experimentally.

When using a proportional mode controller the empirical equation is⁽⁹⁾:

$$b = \frac{100 N L}{\Delta P}$$

where:

- b = proportional band, dimensionless
- N = slope of the curve, per cent of range per minute
- L = time lag, minutes
- Δp = ratio of the energy input change to the total possible energy input, dimensionless.

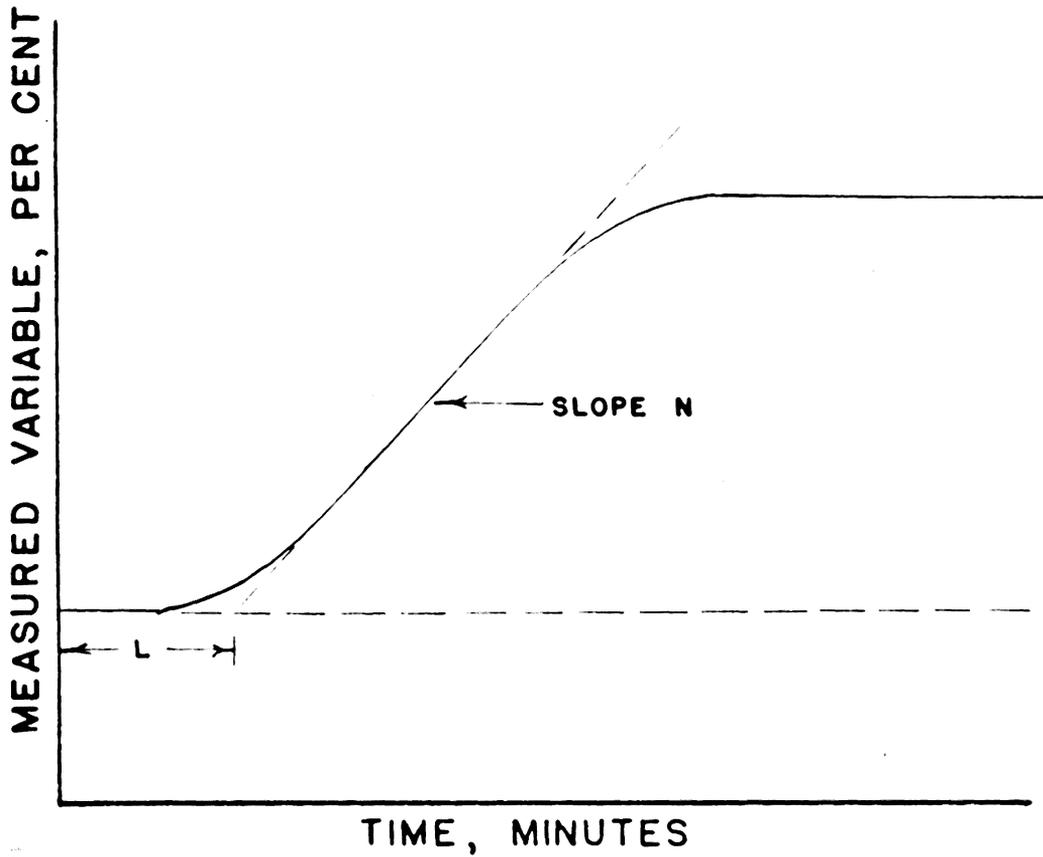


FIGURE 2. RESPONSE OF A PROCESS TO AN ENERGY INPUT CHANGE

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If the controller is the proportional-reset mode type then the empirical equations are⁽⁹⁾:

$$b = \frac{110 N L}{\Delta P}$$

$$R = \frac{0.3}{L}$$

where:

R = reset rate, reciprocal minutes.

This method breaks down because some processes will not produce a reaction curve similar to Figure 2, page 37. It is also sometimes undesirable to disturb a process enough to obtain a reaction curve.

Procedure Recommended by the Manufacturer. Most automatic controllers come with a set of directions giving a definite procedure in order to obtain satisfactory controller settings. Unless other information is available it is probably best to follow the manufacturer directions.

Manufacturer procedure generally suggests adjusting the proportional band first after adjusting the other modes to zero or as low a value as is possible. For proper adjustment it is only necessary to reduce the proportional band from a maximum setting by increments until noticeable instability is present and then backing up until the desired stability is obtained. If the controller is a proportional mode only then proper adjustment has been obtained but is usually checked by moving the control point a

small distance from the previous setting, holding for a few seconds and returning to the exact previous setting. If this disturbance causes a recovery similar to the kind desired then the controller is properly adjusted.

However if the controller is a proportional-reset mode then after adjusting the proportional band it is checked as before but while doing so the period of cycling in minutes is noted. Some multiple of the reciprocal of this cycling time is generally used to obtain the reset rate. Once again the stability of the control on a recovery is checked and fine adjustments are made as needed. If a controller with a rate mode is used it is adjusted similar to the reset mode, by first adjusting the proportion band and then the reset rate and finally the rate mode.

Distillation Column Control

For efficient operation of a continuous distillation column, Minneapolis-Honeywell Regulator Company⁽²⁷⁾ recommends the usage of at least three primary control elements. These three include the use of flow rate controllers on the feed and steam lines and a liquid level controller to regulate the rate of bottoms discharge. These controllers are the minimum elements necessary to control a simple distillation installation using a feed with a constant composition. A more complex installation would require the use of a temperature controller to adjust the reflux rate to provide for

constant overhead product, a liquid level controller to maintain constant level in the reflux accumulator, and temperature controllers on the feed preheater and the product condenser⁽¹⁴⁾.

Selecting Controller Modes. For a process such as a distillation column having long transfer lags and slow reaction rates, proportional control is the simplest mode providing sufficient corrective action to avoid excessive cycling. If the load is subject to changes then reset response is necessary to avoid permanent offset of the measured variable from the set point.

Heat exchangers with their multiple capacities sometimes possess large transfer lag. These systems are difficult to control because they require wide proportional bands. The fractional distillation column is an example of the multiple-capacity heat exchanger. Feed enters the side of the tower and the relatively more volatile components pass up through a large number of bubble trays, with each tray itself constituting a thermal capacity and separated from the succeeding tray by the resistance to the flow of heat.

In the proportional-reset control of a continuous distillation column process, rate of load change is as important as the magnitude of load change. A load changing rapidly would result in an appreciable error. Conversely, a load changing at a slow rate may be counteracted with negligible error. Consequently, if all the variables affecting the operation of the process can be maintained

fairly steady, the deviation of the main controlled variable can be held quite close to the limits desired⁽²⁴⁾.

Mathematically Selecting Controller Settings. Williams and Harnett⁽⁵¹⁾ have made a study of automatic control in a continuous distillation column by using an analog computer simulation method. Studies of this type using mathematical models to represent an automatically controlled process are becoming more important with the installation of new control systems because of the complexity and the desired perfection of control. By using models a complete system can be designed in advance of the installation of the automatic controllers saving time, money, and materials.

III. EXPERIMENTAL

The experimental section of this thesis contains the purpose of investigation, detailed plan of experimentation, including the review of the literature and the treatment of the experimental data, materials, apparatus, methods of procedure, data and results, and sample calculations used throughout the investigation.

Purpose of the Investigation

The purpose of this investigation was to operate an automatically controlled ten-plate bubble-cap fractional distillation column and to determine the effect of the controller gains on the performance of the column.

Plan of Experimentation

The investigation was carried out under the general plan contained in the following paragraphs.

Literature Review. The purpose of the literature review was to review the general principles of fractional distillation and automatic control theory. Special emphasis was placed on instrumentation and control systems already applied to distillation columns.

Procedure. The fractionating column and all off-site equipment including heat exchangers, pumps, and piping was checked and repaired, if necessary, for satisfactory operation.

All control and recording instruments were given a preliminary check for proper operation, and the recording instruments were calibrated throughout the ranges that were encountered during the experimental tests.

The experimental portion of this thesis consisted of a series of tests in which the response of the accumulator liquid level, fractionating column liquid level, condensate temperature, and feed flow rate controllers were studied to determine optimum settings for these controllers. After completing a preliminary series of tests in which approximate regions of satisfactory operation were determined, the fractionating unit was then run continuously for several days until nearly steady state conditions existed throughout the unit.

During this period of nearly steady operation adjustments were made in the controller settings to determine more accurately the regions of satisfactory operation. The general procedure was to make at two hour increments adjustments in the control settings for the accumulator liquid level and condensate temperature controllers and at four hour increments adjustments to the fractionating column level controller. During the period of two or four hours between changes, the operation of the entire unit

was observed for satisfactory operation or for any irregularities. Although the regions of satisfactory operation are quite sharp, within this region the observations on operation are qualitative. During all of these tests the nominal value of the set points were constant.

For an examination of the test period the best settings for each controller were noted and set into the controller. After this the fractionating unit was tested once again in order to determine the time required for the entire unit to come to steady state from a cold start.

Materials

The following paragraphs contain a listing of the materials used in the test operations of the automatically controlled hydrocarbon fractionation column.

Air. Compressed air at 50 lb/sq in., gage, filtered and reduced to 20 lb/sq in., gage. Supplied by the Nash Hytor air compressor in the Unit Operations Laboratory, Chemical Engineering Department, Virginia Polytechnic Institute, Blacksburg, Virginia. Used as supply air for the pneumatic control instruments.

Heavy Virgin Naphtha. Boiling range 225-316° F at 23.15 inch Hg pressure. An A.S.T.M. boiling range curve for this material is shown in Figure 6, page 70. Obtained from the Baltimore Refinery of the Esso Standard Oil Co. Used as one component of the feed mixture for the fractionating tower.

Hexane. Commercial grade, boiling range 145-158 °F at 28.15 inch Hg pressure. An A.S.T.M. boiling range curve for this material is shown in Figure 5, page 69. Obtained from Hercules Powder Co., Radford, Virginia. Used as one component of the feed mixture for the fractionating column.

Mercury. Technical grade, triple distilled. Obtained from Mexican Metals, Inc., New York, N.Y. Used in the manometer legs of the indicating flow transmitters.

Steam. Supplied at 70 lb/sq in., gage. Obtained from the steam mains of the Unit Operations Laboratory, Chemical Engineering Department, Virginia Polytechnic Institute, Blacksburg, Virginia. Used to heat the column calandria and feed preheater.

Water. Tap, temperature approximately 50 °F, supplied at 80 lb/sq in., gage. Obtained from the water mains of the Unit Operations Laboratory, Chemical Engineering Department, Virginia Polytechnic Institute, Blacksburg, Virginia. Used for condensing overhead vapor product, cooling bottoms stream, preliminary tests on the fractionating column, and, calibrating product and reflux flow rate recorders.

Apparatus

Included in the following section is a listing of all apparatus installed in the hydrocarbon fractionation unit and the instrument panel board.

Clock. Electric, Telechron, model No 1HA1608, sweep second hand, 115 v, 60 cy, 2 w. Manufactured by the General Electric Co., Ashland, Mass. Used for timing operation periods.

Column, Distillation. Size 2 x 21-1/3 ft, constructed of 24-inch diameter A.S.T.M. A-106 grade A pipe, design pressure 350 lb/sq in., design temperature 150 °F, contains 10 plates spaced 1 ft apart each having twenty-two 2-inch bubble-caps, integral calandria constructed of 1-inch extra heavy pipe having total heating area of 60 sq ft. Manufactured in and a gift of the Baltimore Refinery of the Esso Standard Oil Co. Used as the hydrocarbon fractionation column.

Controller and Recorder. Air-O-Line, proportional plus reset, 24-hour electric clock chart drive. Manufactured by the Brown Instrument Co., Division of Minneapolis-Honeywell Regulator Co., Philadelphia, Pa. Presented by the Baltimore Refinery, Esso Standard Oil Co. Used in conjunction with a differential pressure transmitter to record and control the feed stream flow rate to the distillation column.

Controller and Recorder. Fulscope temperature controller, serial No 122RM2038, 11-1/2 inch bulb immersion, temperature range 0-250 °C, proportional plus reset, integral manual by-pass, mechanical 24-hour chart drive. Manufactured by the Taylor Instrument Co., Rochester, N.Y. Given by the Union Carbide Chemicals Co., Charleston, West Virginia. Used to control steam flow into column calandria and record temperature in reboiler.

Controller and Recorder. Stabilog temperature controller, serial No C61090, range 0-200 °C, 5-inch bulb immersion, tubing length 50 ft, proportional plus reset. Manufactured by the Foxboro Co., Foxboro, Mass. Donated by the Union Carbide Chemicals Co., Charleston, West Virginia. Used to control the flow rate of cooling water to the tops condenser and to record the condensate temperature leaving the condenser.

Controller and Recorder. Stabilog temperature controller, serial No C61090, range 0-250 °C, 5-inch bulb immersion, tubing length 35 ft, proportional plus reset. Manufactured by the Foxboro Co., Foxboro, Mass. Presented by the Union Carbide Chemicals Co., Charleston, West Virginia. Used to control the flow of cooling water to the bottoms cooler and to record the temperature of the bottoms stream leaving the cooler.

Controller and Recorder. Stabilog temperature controller, serial No C32362, range 0-300 °F, 10-inch bulb immersion, tubing length 50 ft, proportional plus reset. Manufactured by the Foxboro

Co., Foxboro, Mass. Given by the Union Carbide Chemicals Co., Charleston, West Virginia. Used to control the flow of steam to the feed preheater and to record the temperature of the feed leaving the preheater.

Controller and Recorder. Air-O-Line, proportional plus reset, mechanical flow controller, model No 220131-X99, serial No 402891, mechanical 24-hour clock drive. Manufactured by the Brown Instrument Co., Division of Minneapolis-Honeywell Regulator Co., Division of Minneapolis-Honeywell Regulator Co., Philadelphia, Pa. Donated by the Baltimore Refinery of the Esso Standard Oil Co. Used to regulate the discharge rate of the bottoms by the measurement of the liquid level in the reboiler and to record the liquid level in the reboiler.

Controller and Recorder. Air-O-Line, proportional plus reset, mechanical flow controller, model No 702P26C14-91-74, serial No 601817, mechanical 24-hour clock drive. Manufactured by the Brown Instrument Co., Division of Minneapolis-Honeywell Regulator Co., Philadelphia, Pa. Donated by the Baltimore Refinery of the Esso Standard Oil Co. Used to regulate the flow of distillate from the accumulator drum by measuring the liquid level in the drum and to record this liquid level.

Control Panel, Manual. Range 0-30 lb/sq in., gage, consists of supply air pressure gage, 4 position pneumatic switch, and pressure reducing valve. Manufactured by the Taylor Instrument Co.,

Rochester, N.Y. Presented by the Union Carbide Chemicals Co., Charleston, West Virginia. Used to operate pneumatic motor valves manually.

Control Panel, Master. Consists of pressure reducing valve and inlet and outlet pressure gages, range 0-60 lb/sq in., gage. Constructed in the Chemical Engineering Department, Virginia Polytechnic Institute, Blacksburg, Virginia. Used to reduce air pressure from compressor to 20 lb/sq in., gage, air pressure required for operation of pneumatic instruments.

Control, Pushbutton Station. Type SD-2, class 15-020, model No 1253069, start-stop. Manufactured by the Westinghouse Electric Corp., Pittsburgh, Pennsylvania. Used for remote control of motor pumps.

Filter, Air. Mild steel, constructed from discarded inverted bucket type steam trap housing, 6-inch height, packed with treated fiber air filter media. Constructed in the Chemical Engineering Department, Virginia Polytechnic Institute, Blacksburg, Virginia. Used to filter air supply from compressor to control panel.

Heat Exchanger. Single pass, countercurrent, shell and tube type; contact surface of nineteen 5/8-inch copper tubes 45.5 inches long enclosed in mild steel shell. Presented by the Union Carbide Chemicals Co., Charleston, West Virginia. Used as the feed preheater.

Heat Exchanger. Single pass, countercurrent, shell and tube type; contact surface of eighty-nine 3/4-inch admiralty metal tubes

69 inches long enclosed in mild steel shell. Manufactured by the M.W. Kellogg Co., New York, N.Y. Donated by the Baton Rouge Refinery of the Esso Standard Oil Co. Used as the overhead vapor condenser.

Heat Exchanger. Four-pass, shell and tube type; contact surface of thirty-seven 3/4-inch copper tubes 79 inches long enclosed in mild steel shell. Manufactured by the Ingersoll-Rand Co., New York, N.Y. Presented by the Union Carbide Chemicals Co., Charleston, West Virginia. Used as the bottoms cooler.

Motor. Electric, type CSP, induction, class 1, style 1261426, serial No 546, 2 hp, 3490 rpm, 60 cy, 3 ph, 220 v, 5.6 amp per terminal. Manufactured by the Westinghouse Electric Corp., Pittsburgh, Pennsylvania. Given by the Union Carbide Chemicals Co., Charleston, West Virginia. Two used; one to drive accumulator and one to drive feed pumps.

Motor. Electric, type CSP, induction, class 1, style 1261426, serial No 2046, 1.5 hp, 3450 rpm, 60 cy, 3 ph, 220 v, 4.6 amp per terminal. Manufactured by the Westinghouse Electric Corp., Pittsburgh, Pennsylvania. Presented by the Union Carbide Chemicals Co., Charleston, West Virginia. Used to drive bottoms pump.

Potentiometer Pyrometer. Electronik, model No 156x63P48, serial No 540265, temperature range 0-500 °F, 110-125 v, 0.45 amp, 60 cy, 50 w, 48-point indicator. Manufactured by the Brown Instrument Co., Division of the Minneapolis-Honeywell Regulator Co.,

Philadelphia, Pennsylvania. Given by the Baltimore Refinery of the Esso Standard Oil Co. Used in conjunction with chromel-alumel thermocouples to determine temperatures at various points in the column and offsite equipment.

Pump. Centrifugal, size 204, type ECD, serial No KE-465, capacity 20,000, head 40 lb. Manufactured by the Economy Pumps Inc., Hamilton, Ohio. Presented by the Union Carbide Chemicals Co., Charleston, West Virginia. Used to pump bottoms stream.

Pump. Centrifugal, size 254, type ECD, serial No KED-463, capacity 25,000, head 40 lb. Manufactured by the Economy Pumps Inc., Hamilton, Ohio. Donated by the Union Carbide Chemicals Co., Charleston, West Virginia. Two used; one to pump reflux and product streams and one to pump feed stream.

Receiver, Recording. Metric mechanical flow meter, model No 39005, operating pressure 100 lb/sq in., gage, range 0-100 inches of water. Manufactured for the Metric Metal Works by the Taylor Instrument Co., Rochester, N.Y. Presented by the Baltimore Refinery of the Esso Standard Oil Co. Used to record steam flow rate to calandria.

Receiver, Recording. Flow, two pen, 12-inch diameter chart, electric 24-hour chart drive, input air range 3-15 lb/sq in., gage. Manufactured by the Brown Instrument Co., Division of the Minneapolis-Honeywell Regulator Co., Philadelphia, Pennsylvania. Donated by the Baltimore Refinery of the Esso Standard Oil Co.

Three used to record terminal stream flow rates of the column and offsite equipment.

Receiver, Recorder. Transet, serial No 78JF7148, two pen recording receiver. Electric 24-hour chart drive, 12-inch diameter chart, input air range 3-15 lb/sq in., gage. Manufactured by the Taylor Instrument Co., Rochester, N.Y. Donated by the Union Carbide Chemicals Co., Charleston, West Virginia. Used to record the reflux flow rate.

Starter, Magnetic. Model No CR7006B101B, size 0, 3 ph, 220 v, 60 cy, heater No 81D549. Manufactured by the General Electric Co., Schenectady, N.Y. Used to start the product and reflux pump.

Starter, Magnetic. Size 0, form 2, type 1, series No 61AH57, 220 v, 3 ph, 60 cy. Manufactured by the Allen-Bradley Co., Milwaukee, Wis. Used to start the bottoms pump.

Starter, Magnetic. Size 0, form 2, type 1, series No 536706, 220 v, 3 ph, 60 cy. Manufactured by the Allen-Bradley Co., Milwaukee, Wis. Used to start the feed pump.

Switch Box. Single throw, fusible, 3 pole, catalog No 88352, 60 amp, 230 v, 7.5 hp max. Manufactured by the Square D Co., Detroit, Mich. Used in the pump motor control circuit.

Switch Box. Single throw, fusible, 2 pole, catalog No N33, 30 amp, 125 v, 2 hp max. Manufactured by the Wadsworth Electric Manufacturing Co., Inc., Covington, Ky. Used in the electric clock drive circuit.

Tank. Capacity 500-gal, mild steel, welded construction, 4-ft O.D., 6 ft long. Donated by the Union Carbide Chemicals Co., Charleston, W. Va. Used as a feed storage tank.

Tank. Capacity 20-gal, mild steel, welded construction, 14.5-inch O.D., 39-inch height less support, 55-inch overall height including angle iron tripod support, contains 15-ft heating coil of 1/4-inch copper tubing. Donated by the Union Carbide Chemicals Co., Charleston, W. Va. Used as the reflux accumulator drum.

Tank. Knock-out, constructed of a 9-inch section of 3-inch mild steel pipe, welded ends, equipped with drain cock. Constructed in the Chemical Engineering Department, Virginia Polytechnic Institute, Blacksburg, Va. Used in the air line from the compressor to the panel board to remove entrained particles from the supply air.

Thermocouples. Fifteen chromel-alumel, type K, 14 gage, equipped with 304 stainless steel protecting tube 12 inches long fitted with 1/2-inch mounting thread, catalog No 5B10S. Manufactured by the Brown Instrument Co., Division of Minneapolis-Honeywell Regulator Co., Philadelphia, Pa. Used in conjunction with the Brown precision indicator to determine the operating temperatures in the column and offsite equipment.

Thermocouple Lead Wire. Catalog No 5W2A14, for use with type K chromel-alumel thermocouples, weather-proof over polyvinyl insulation, 16 gage. Manufactured by the Brown Instrument Co., Division of the

Minneapolis-Honeywell Regulator Co., Philadelphia, Pa. Used to extend thermocouples from head assembly to precision indicator.

Transmitter. Mercury manometer type, range 0-54.57 inches of water, transmits 3-15 lb/sq in., gage, indicating type. Manufactured by the Brown Instrument Co., Division of the Minneapolis-Honeywell Regulator Co., Philadelphia, Pa. Presented by the Baltimore Refinery of the Esso Standard Oil Co. Used in conjunction with the recorders and the temperature and flow controllers to measure the flow rates of the terminal streams of the column and offsite equipment.

Transmitter. Differential pressure transmitter, serial No J-49075, range 0-50 inches, working pressure 750 lb/sq in., gage. Manufactured by the Foxboro Co., Foxboro, Mass. Donated by Union Carbide Chemicals Co., Charleston, W. Va. Used as the liquid level transmitter on the reflux accumulator drum.

Trap, Steam. Anderson Super Silvertop, model No 110, capacity 400 lb/hr, operating pressure 80 lb/sq in., gage. Manufactured by the V.D. Anderson Co., Cleveland, Ohio. Used on the feed preheater to facilitate the removal of steam condensate.

Trap, Steam. Anderson Super Silvertop, model No 120, capacity 1320 lb/hr, operating pressure 80 lb/sq in., gage. Manufactured by the V.D. Anderson Co., Cleveland, Ohio. Used on the calandria to facilitate the removal of steam condensate.

Valve, Diaphragm Motor. Size 1/2-inch, 250 lb/sq in., gage, bronze body, 3/8-inch diameter cut-away type inner valve, air to open action, serial No J-1188. Manufactured by the Mason-Neilan Regulator Co., Boston, Mass. Presented by the Union Carbide Chemicals Co., Charleston, W. Va. Used to throttle product stream.

Valve, Diaphragm Motor. Size 1/2-inch, Lunkenheimer bronze body, stainless steel trim, single seat cut-away plug type inner valve, air to open action. Manufactured by the Foxboro Co., Foxboro, Mass. Presented by the Union Carbide Chemicals Co., Charleston, W. Va. Used to throttle the feed stream.

Valve, Diaphragm Motor. Size 1/2-inch, AE make, Lunkenheimer bronze body, stainless steel trim, cut-away plug, single seat type, air to open action. Manufactured by the Foxboro Co., Foxboro, Mass. Presented by the Union Carbide Chemicals Co., Charleston, W. Va. Used to throttle the bottoms discharge stream.

Valve, Diaphragm Motor. Size 1/2-inch, bronze body, stainless steel trim, cut-away type inner valve, air to open action. Manufactured by the Bristol Co., Waterbury, Conn. Used in conjunction with valve positioner to regulate flow of distillate from reflux accumulator drum.

Valve, Diaphragm Motor. Size 1-inch, cast steel body, stainless steel trim, cut-away type inner valve, flange fitting, air to close action. Manufactured by the Foxboro Co., Foxboro, Mass. Presented by the Union Carbide Chemicals Co., Charleston, W. Va. Used to

throttle steam flow to calandria section of column.

Valve, Diaphragm Motor. Size 1/2-inch, bronze body, stainless steel trim, cut-away plug, single seat type inner valve, air to open action. Manufactured by the Foxboro Co., Foxboro, Mass. Presented by the Union Carbide Chemicals Co., Charleston, W. Va. Three used; one to throttle water flow to bottoms cooler, one to throttle water flow to tops condenser, and one to throttle steam flow to feed preheater.

Method of Procedure

This section contains an outline of the operational procedure of the distillation column and the detailed procedure used in performing the tests in which data was taken. In addition an outline of the preliminary testing and maintenance work is included.

Preliminary Testing. The initial step in this investigation was to operate the distillation column to determine the actual operating performance of the entire unit and to locate defective or unsatisfactorily operating equipment. Several tests were made testing various methods of operation and checking defective or repaired equipment.

The performance of the various control systems were noted during these preliminary tests, but no attempt at systematic adjustment of the controller settings were made. Some adjustments

had to be made, however, as the unit was essentially not operable at the start of this investigation. The calibration of the feed, product, bottoms, and reflux flow rates and the bottoms, condensate, feed, and plate temperatures were checked and compared to those recorded by Richard(37).

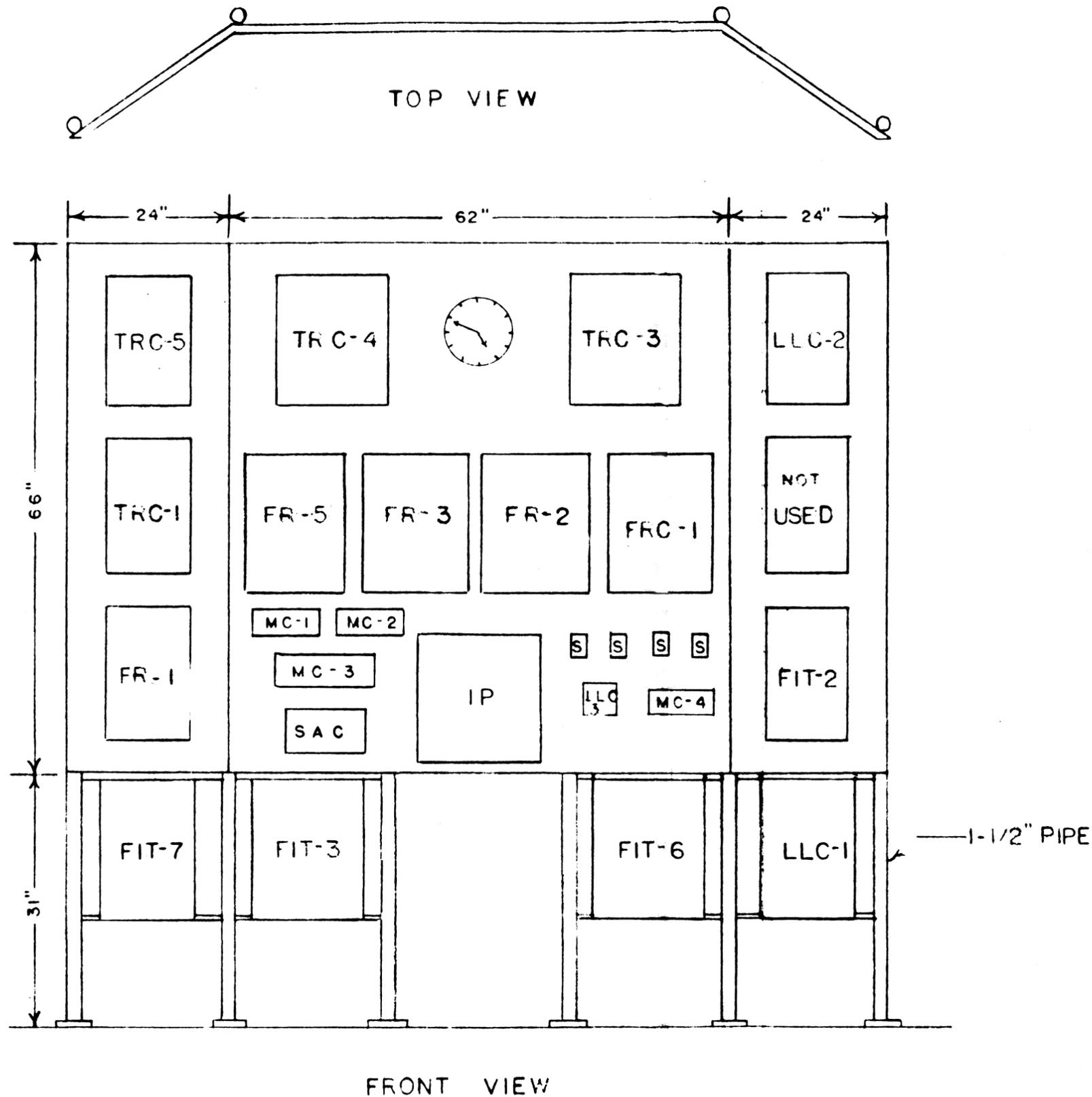
Repairs and Modifications of Equipment. The information obtained during these preliminary tests suggested several modifications of the equipment. The repairs or modifications listed in the following paragraphs were performed prior to commencing tests on the control system.

Feed and Bottoms Pumps. Both the feed and bottoms pumps were found to be damaged because of previous lack of proper maintenance. The thrust bearings on both pumps had failed some time in the past. The end free play which accrued without the thrust bearings caused rapid wear of the impeller, radial bearings, water seal rings, and shaft. The excessive shaft wear and vibrations made satisfactory packing of the pump impossible, the condition which actually led to a careful check of the internal parts of the pumps. Upon inspection it was found that both pumps required a complete overhaul including replacement of all internal parts in one pump and all parts except the impeller in the other pump. The proper parts were ordered for both pumps. After rebuilding both pumps, they were placed back in service and tested and found to be satisfactory.

Seal Pots. The accumulator and the distillation column liquid level controllers, Figure 3, page 59, operated unsatisfactorily during the preliminary tests. While the unit was in operation the upper seal pots for each of the controllers, Figure 4, page 60, were examined and found to be empty. Under this condition the recording unit for both controllers indicated both columns were more than full while actually the accumulator and the distillation column were nearly empty.

The seal pots could have been filled by hand whenever a test were started. However a simpler and more permanent solution was to connect a purge line to both seal pots of the accumulator and the column. Whenever the feed pump is running the seal pots can now be filled.

Installation of Thermocouples. During the preliminary test it was observed that there was no way of determining the temperatures of the feed entering the preheater, bottoms leaving the fractionating column, cooling water entering and leaving the tops and bottoms heat exchangers, and steam condensate temperatures. These temperatures are important in order to follow the complete operation of the bottoms, tops, feed, and reflux streams and their relationship with the overall hydrocarbon fractionation unit. Thermocouples were installed in the process lines and connected to the multipoint

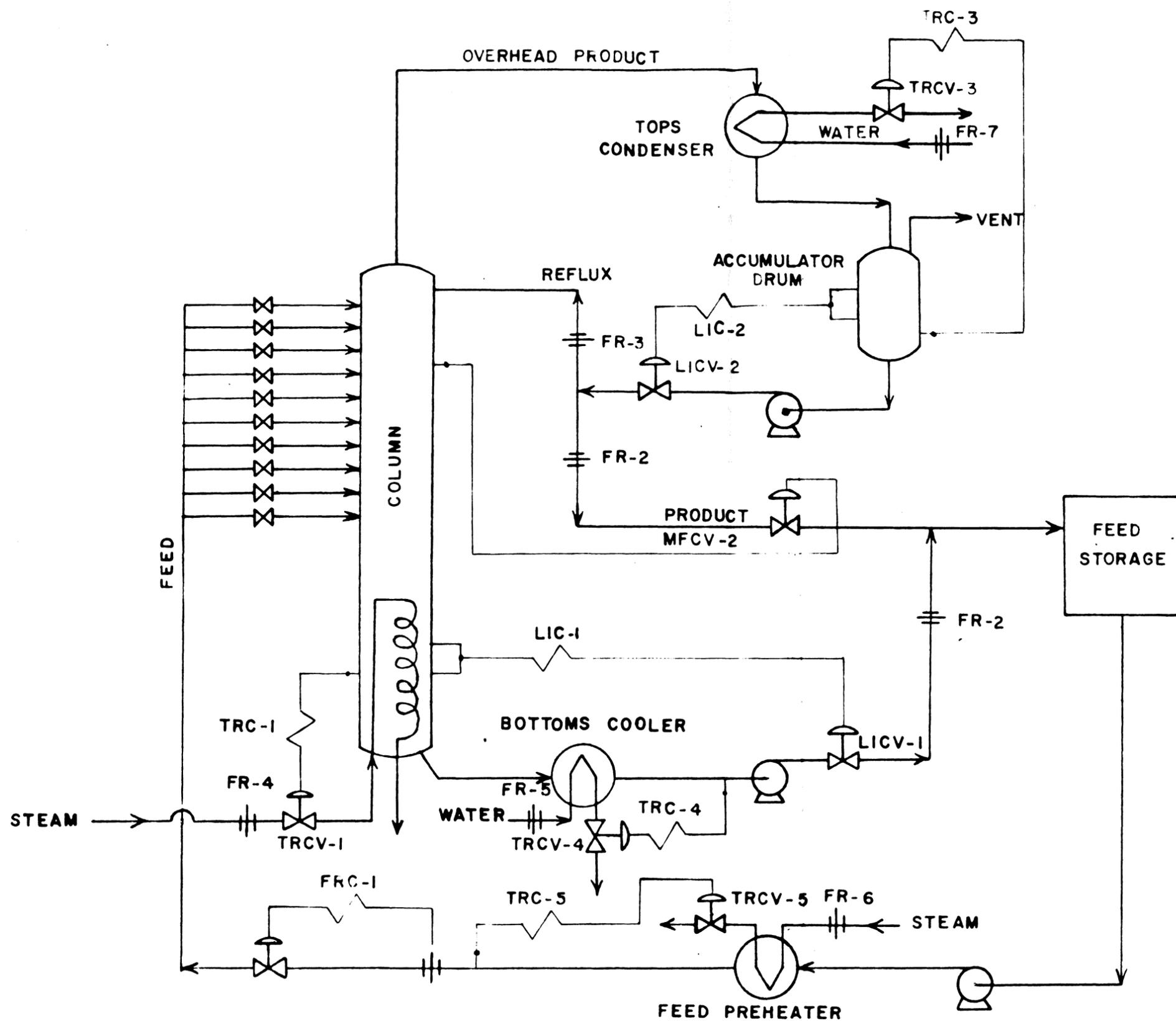


LEGEND

- FR - FLOW RECORDER
- FIT - FLOW TRANSMITTER
- TRC - TEMPERATURE RECORDER-CONTROLLER
- FRC - FLOW RECORDER-CONTROLLER
- LLC - LIQUID LEVEL CONTROLLER
- MC - MANUAL CONTROL PANEL
- SAC - SUPPLY AIR CONTROL
- IP - INDICATING POTENTIOMETER
- S - REMOTE MOTOR SWITCH

NOTE
 PANEL CONSTRUCTED OF 3/4" PLYWOOD

DEPARTMENT OF CHEMICAL ENGINEERING VIRGINIA POLYTECHNIC INSTITUTE BLACKSBURG, VIRGINIA	
CONTROL PANEL FOR THE HYDROCARBON FRACTIONATION UNIT	
SCALE: 1" = 16"	DATE: 8-28-56 CASE NO: 599
DRAWN BY: P. L. Cooper	FILE NO: 56
CHECKED BY:	FIGURE NO: 3
APPROVED BY: J. L. R. / 28/56	SHEET NO: 1



LEGEND

- LIC - LEVEL INDICATOR AND CONTROLLER
- LICV - LEVEL INDICATOR AND CONTROLLER VALVE
- FR - FLOW RECORDER
- FRC - FLOW RECORDER AND CONTROLLER
- FRCV - FLOW RECORDER AND CONTROLLER VALVE
- TRC - TEMPERATURE RECORDER AND CONTROLLER
- TRCV - TEMPERATURE RECORDER AND CONTROLLER VALVE
- MFCV - MANUAL FLOW CONTROL VALVE

DEPARTMENT OF CHEMICAL ENGINEERING
 VIRGINIA POLYTECHNIC INSTITUTE
 BLACKSBURG, VIRGINIA

INSTRUMENTATION DIAGRAM FOR
 FRACTIONATING COLUMN AND
 ACCESSORY EQUIPMENT

SCALE: NONE DATE 6-11 CASE NO: 599
 DRAWN BY: W.C. Richard FILE NO: 57
 CHECKED BY: FIGURE NO: 4
 APPROVED BY: *RCV 6/14/57* SHEET NO: 1

indicating potentiometer to measure the temperature of the streams mentioned above. Even though a heat balance can not be completed over the entire unit through the use of these additional thermocouples, these temperatures aid in giving a good overall picture of the operating conditions throughout the unit.

Starting Procedure. The control panel for the distillation column, Figure 3, page 59, was referred to throughout the explanation of the operating procedure. First the usual preliminary check was made to see that the wiring and piping were in good condition. This could prevent a possible fire of the inflammable components or wasting of the feed stock. Safety is always paramount when operating equipment of this type.

After this preliminary check the Nash Hytor which supplies the panel board with at least 40 pounds per square inch, gage, air pressure was started. The supply air control valve on the panel board was set at 20 pounds per square inch, gage, air pressure.

After air was supplied to the instruments, the electric clocks that operate instruments FRC-1, FR-1, FR-2, FR-3, FR-5, and LLC-2 were turned on. Instruments TRC-1, TRC-3, TRC-4, TRC-5, and LLC-1 contain hand-wound clocks, which were wound. Next the proper instrument charts were placed on the instruments as indicated on the name plate of each instrument. The date and purpose of each chart was written on the chart itself for future record purposes

and the control settings of each instrument were recorded.

Cooling water for the tops condenser and bottoms cooler was turned on manually by turning the water line valve, located to the rear and to the right of the panel board. Instruments TRC-3, TRC-4, and MC-2 were now set on manual control, and the valve air pressure was adjusted to 18, 5, and 13 pounds per square inch, gage, respectively. The indicating potentiometer, located on the panel board, was turned on and after allowing it to warm up for several minutes, the potentiometer was standardized in accordance with the instructions outlined on the inside of the instrument.

After standardizing the potentiometer, the steam line block valve was opened one-quarter turn to make certain that all the steam condensate had drained out of the steam line. The steam line drain was closed and then the steam valve was opened completely. This steam valve is located to the right and behind the panel board. The steam was now flowing from the inside of the building to the calandria and to the feed preheater. The set point on instrument TRC-1 was set on 125, corresponding to 257 °F, and steam was now flowing to the calandria section, Figure 4, page 60, of the column. The feed flow rate was set by moving the set point on instrument FRC-1 to the predetermined value of 30. The feed pump motor switch was turned on at the control panel and feed was now entering the column at plate five.

The bottoms pump was cut on as soon as instrument LLC-1, indicating the liquid level in the column, was reading eight on the chart. The set point of instruments LLC-1, LLC-2, TRC-3, and TRC-5 were changed to 8, 35, 76, and 140, respectively.

The accumulator pump switch was turned on when the temperature of plate nine reached 160 °F, as shown by the potentiometer and the level in the reflux accumulator has reached the control point 35 as recorded by instrument LLC-2.

After completing all the instructions as listed in the above paragraphs the fractionating column was now operating automatically. The various flow rates, temperatures, and liquid levels were allowed to steady out.

Control System Response Tests. In the preliminary testing of the unit the instrument response of the accumulator liquid level, fractionating column liquid level, condensate temperature, and the feed flow rate controller was observed. The control settings giving the best response were used in the start up of the main test.

During this test, the fractionating unit was run continuously for several days. When the fractionating unit was at nearly steady operations adjustments were made in the controller settings to determine more accurately the regions of satisfactory operation. The general procedure was to make at two hour increments adjustments in the control settings for the accumulator liquid level and the condensate temperature controllers and at four hour increments

adjustments to the fractionating column liquid-level controller.

The first controller adjustment used was a minimum reset rate and proportional band. At the time interval stated for each controller, the proportional band was increased to a maximum or until the recorder indicated that the controller was drifting excessively. At this time the reset rate was increased every two or four hours while the proportional band was kept at the highest previously tested setting. When the recorder indicated again an unsatisfactory control, the reset rate and proportional band settings were reduced step wise in an attempt to circle the region of satisfactory operation.

During the period between the two and four hour changes, the operation of the entire unit was observed for satisfactory operation or any irregularities. The nominal value of the set points were held constant during all the tests.

From an examination of the test period several of the best settings for each controller were noted. The column was then purposely upset when using these settings in order to test under more strenuous conditions these settings.

The fractionating unit was tested once again using the best control settings located in order to determine the time required for the entire unit to come to steady-state from a cold start.

Shutdown Procedure. After completing all the tests required, the first step in the shutdown procedure was to manually shut off

the steam valve, located inside the building and behind the panel board. The set point of instrument TRC-1 was now changed from 125 to zero. Next the set point of instrument FRC-1 was changed to zero and feed pump was shut off at the control panel. As soon as the temperature on the ninth plate was below 145 °F, below the boiling point of hexane, the reflux and bottoms pump were shut off.

Next the cooling water to the heat exchanger and the tops condenser was shut off manually. The electric clocks were stopped. All of the charts were now removed from the instruments on the panel board. The potentiometer was cut off. The supply air control valve was shut off thus preventing any air from reaching the control instruments. Finally the Nash Hytor was stopped, thus completing the shutdown procedure.

Data and Results

The following paragraphs describe the data and results obtained from the study of the automatic instrumentation of the fractional distillation column.

Analysis and Physical Properties of Feed Mixtures. Tables I and II, pages 67 and 68, present an analysis and the physical properties for the components of the feed stock, commercial grade hexane and heavy virgin naphtha. The analysis is given in weight per cent and the physical properties include distillation curve data. An A.S.T.M. distillation curve for commercial grade hexane is represented by Figure 5, page 69, and Figure 6, page 70, represents the heavy virgin naphtha A.S.T.M. distillation curve.

Calibration of Instruments. A calibration of feed flow controller set points, bottoms, product, and reflux flow rate recorders and the feed, bottoms, and product temperature recorders for the fractionating unit are presented in Tables III and IV, pages 71 and 72. All flow rates are expressed in pounds per minute and temperatures as °F. Figures 7 to 10, pages 73 to 76, are a graphical representation of data recorded during the calibration of the feed, bottoms, product, and reflux flow rates. The calibration of the feed, bottoms, and product temperature recorders are represented in Figures 11 to 13, pages 77 to 79.

TABLE I

Analysis of Components of Feed Mixture
for Distillation Column

Heavy Virgin Naphtha ⁽¹⁾		Hexane ⁽²⁾	
Compound	Weight Per Cent	Compound	Weight Per Cent
Benzene	0.2	n-C ₆	56.3
Toluene	2.0	3-me C ₅	13.4
C ₈ Aromatics	6.6	n-C ₄	0.5
C ₉ Aromatics	3.6	1-C ₅ , n-C ₅	0.3
C ₁₀ Aromatics	0.6	2, 2-dime C ₄	trace
Naphthalenes	0.2	Cyclo C ₅ , 2-me C ₅ ,) 2, 3-dime C ₄)	8.9
Indan	0.1		
Naphthenes	35.1	MeCyclo C ₅) 2, 2,2-dime C ₅ ,)	14.4
Paraffins	47.7	2, 4-dime C ₅)	
Condensed naphthenes	3.9	Cyclo C ₆ ,) 3, 3-dime C ₅ ,) 2, 3-dime C ₅)	2.3
		Benzene	4.2

(1) Analysis by mass spectrophotometry

(2) Analysis by gas-liquid partition chromatography

Know, W.T.: Personal Communication, March 29, 1957, Linden, New Jersey.

TABLE II

Physical Properties of Components of Feed Mixture
for Distillation Column

Normal Boiling Curve Per Cent Volume Distilled	Boiling Point(1)	
	Hexane	Heavy Virgin Naphtha
%	°F	°F
0	145	225
10	149	248
20	151	255
30	151	261
40	152	266
50	152	273
60	153	280
70	153	289
80	154	298
90	158	316
Molecular weight	87.87	120
Specific gravity, 25 °C	0.684	0.753
Specific heat, Btu/lb-°F Liquid	0.565	0.607
Latent heat of vaporization, Btu/lb	138	152
Refractive Index, n_D	1.3824	1.4200

(1) Atmospheric pressure, 28.40 inches mercury

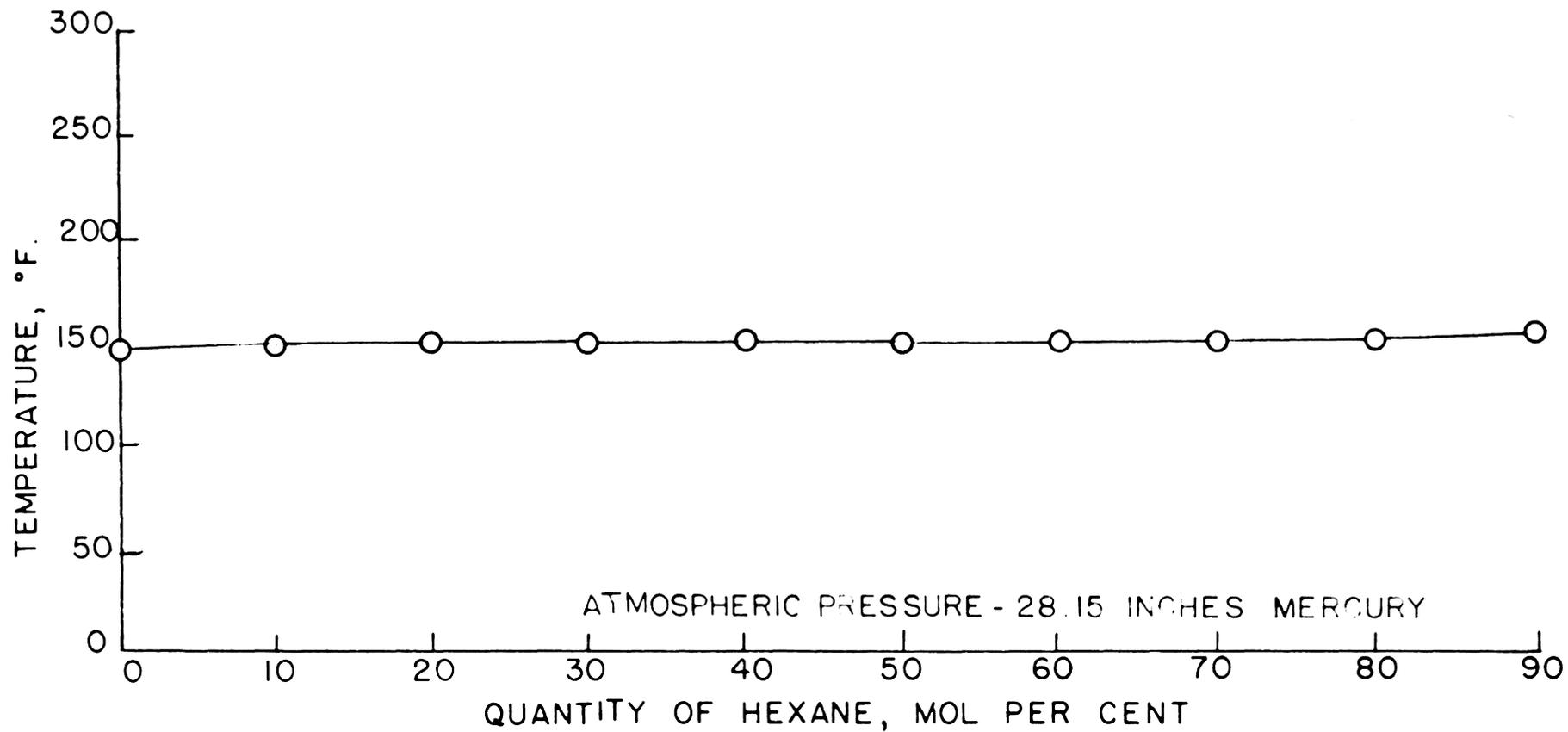
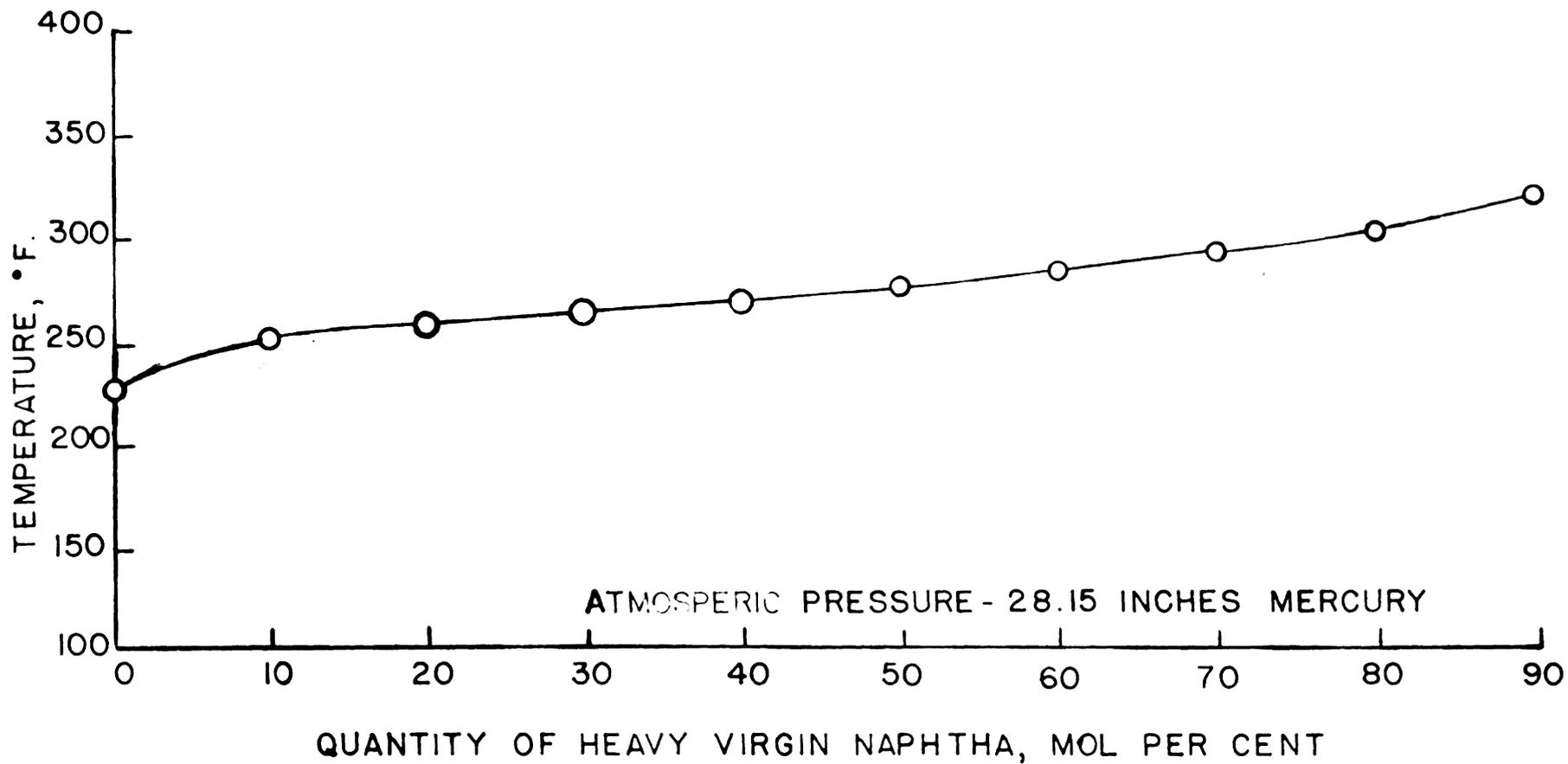


FIGURE 5. DISTILLATION CURVE FOR COMMERCIAL
GRADE HEXANE



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FIGURE 6. DISTILLATION CURVE FOR HEAVY
VIRGIN NAPHTHA

TABLE III

Calibration of Feed Flow Controller Setpoint and Bottoms, Product, and Reflux
Flow Recorders for the Hydrocarbon Fractionating Unit

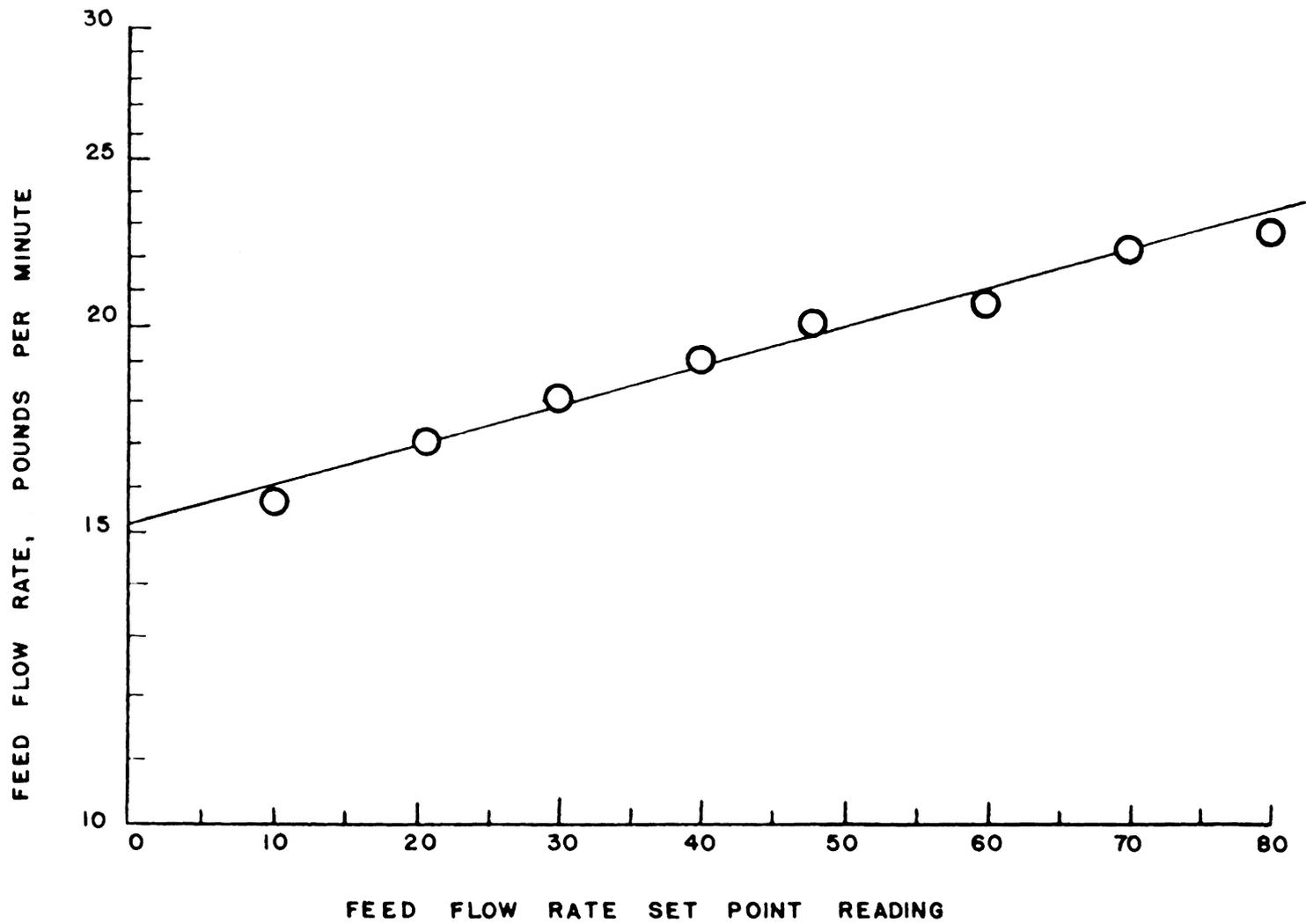
Feed		Bottoms		Product		Reflux	
Chart Value	Flow Rate						
	lb/min		lb/min		lb/min		lb/min
10.0	15.63	14.0	5.44	4.0	7.85	15.0	9.78
20.0	17.00	22.0	6.81	18.0	11.46	27.5	12.50
30.0	18.13	29.5	8.00	24.0	11.67	40.5	14.85
40.0	19.00	40.0	9.25	28.0	12.23	41.5	15.07
50.0	20.00	51.0	10.88	37.5	13.32	50.5	16.50
60.0	20.50	56.0	11.25	44.5	14.22	61.0	18.00
70.0	22.13	70.5	13.69	54.0	15.27	74.5	20.00
80.0	22.50	86.5	14.88	62.0	16.00	99.5	22.52
--	--	--	--	70.0	16.78	--	--
--	--	--	--	73.0	17.03	--	--

TABLE IV

Calibration of Feed, Bottoms, and Product
Temperature Recorders for the Hydrocarbon
Fractionating Unit

Temperature °F	Chart Value		
	Feed	Bottoms	Product
91	—	64	72
100	117	68	75
108	118	73	77
110	124	74	79
118	130	78	83
122	132	82	—*
131	135	86	87
149	145	95	97
158	150	99	102
165	156	103	107
168	158	106	108

* Thermocouple lead line broken



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FIGURE 7. CALIBRATION OF FEED FLOW RATE CONTROLLER SET POINT

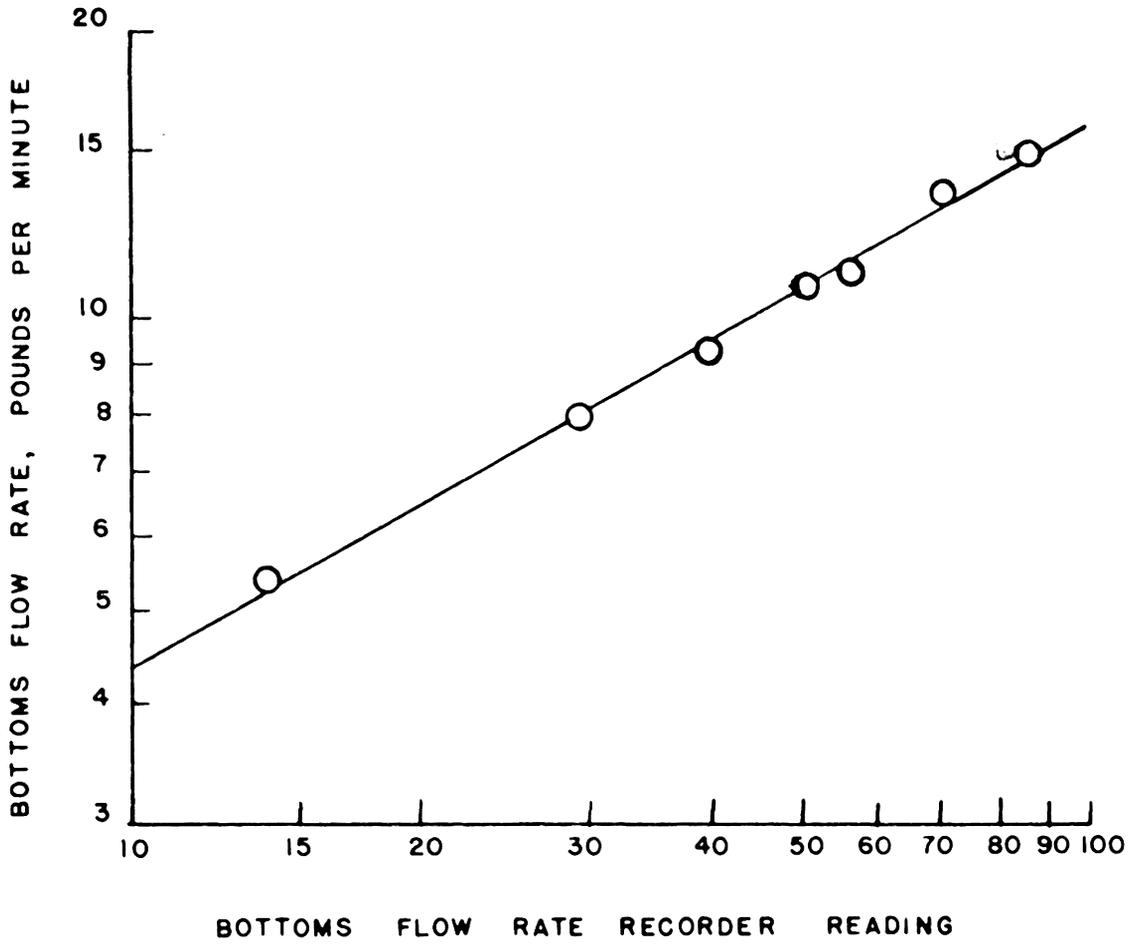


FIGURE 8. CALIBRATION OF BOTTOMS FLOW RATE RECORDER

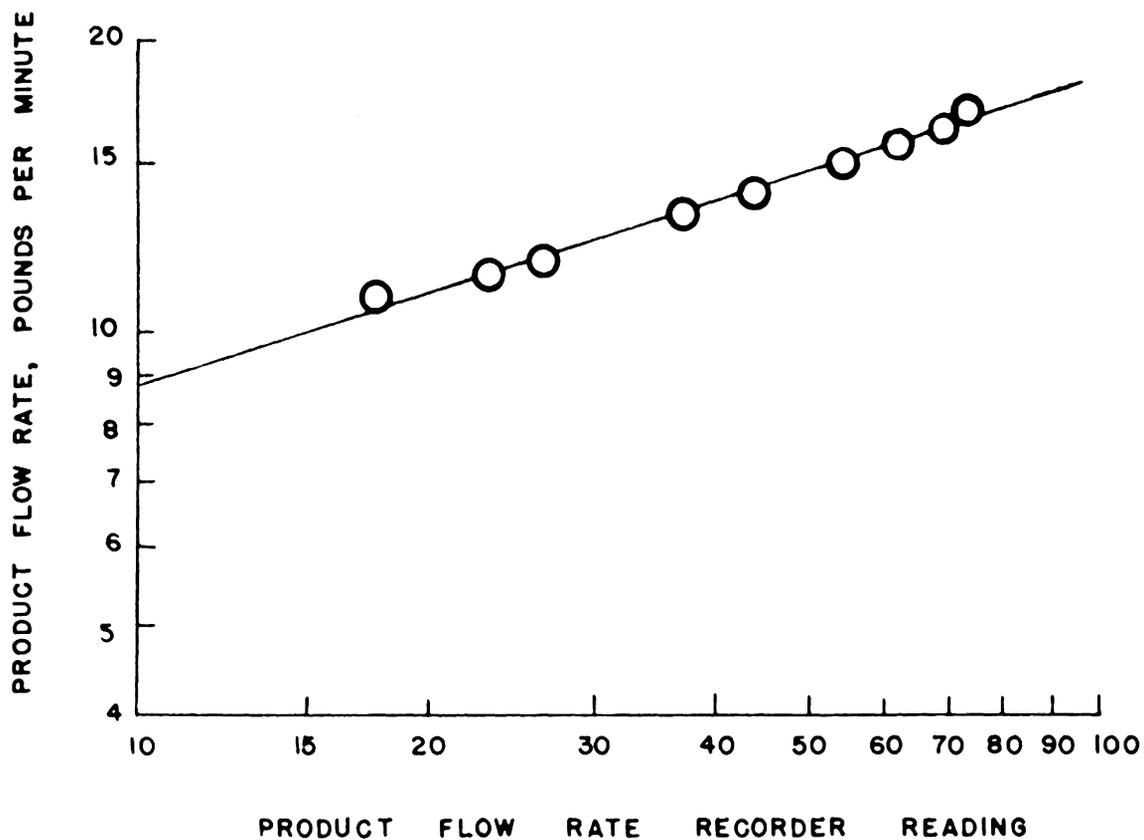


FIGURE 9. CALIBRATION OF PRODUCT FLOW RATE RECORDER

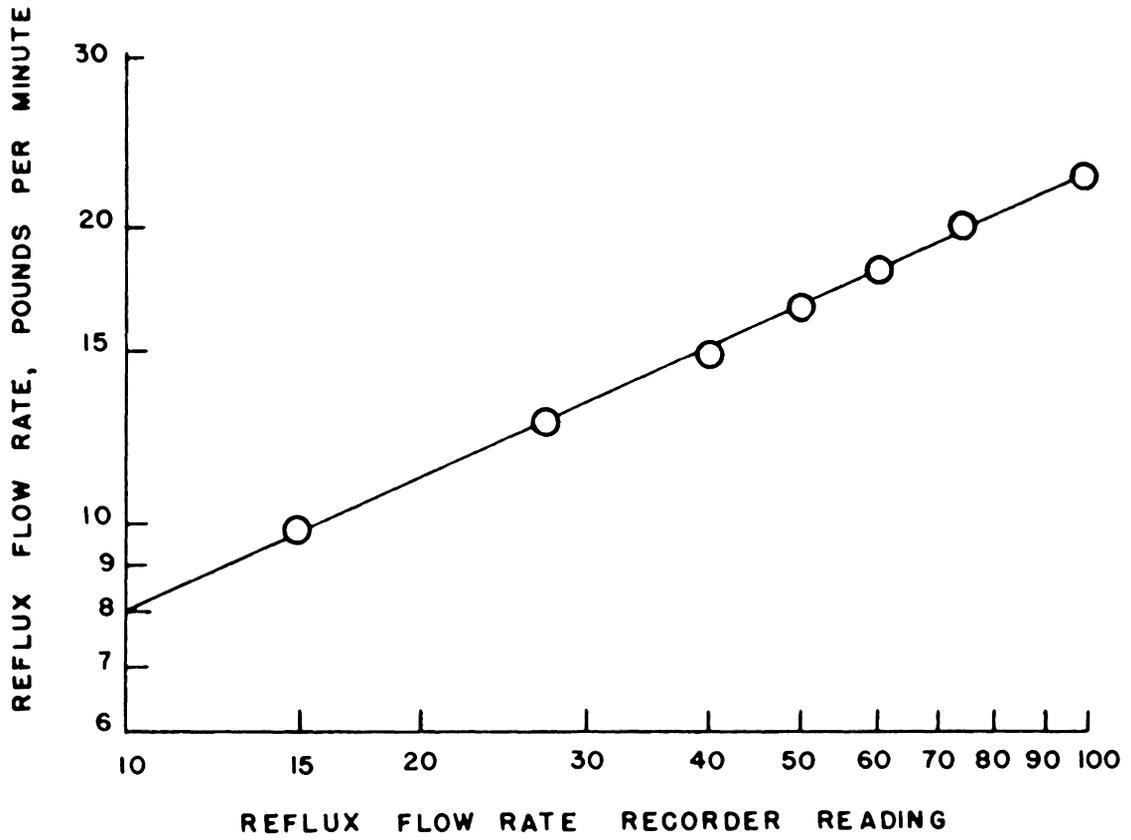


FIGURE 10. CALIBRATION OF REFLUX FLOW RATE RECORDER

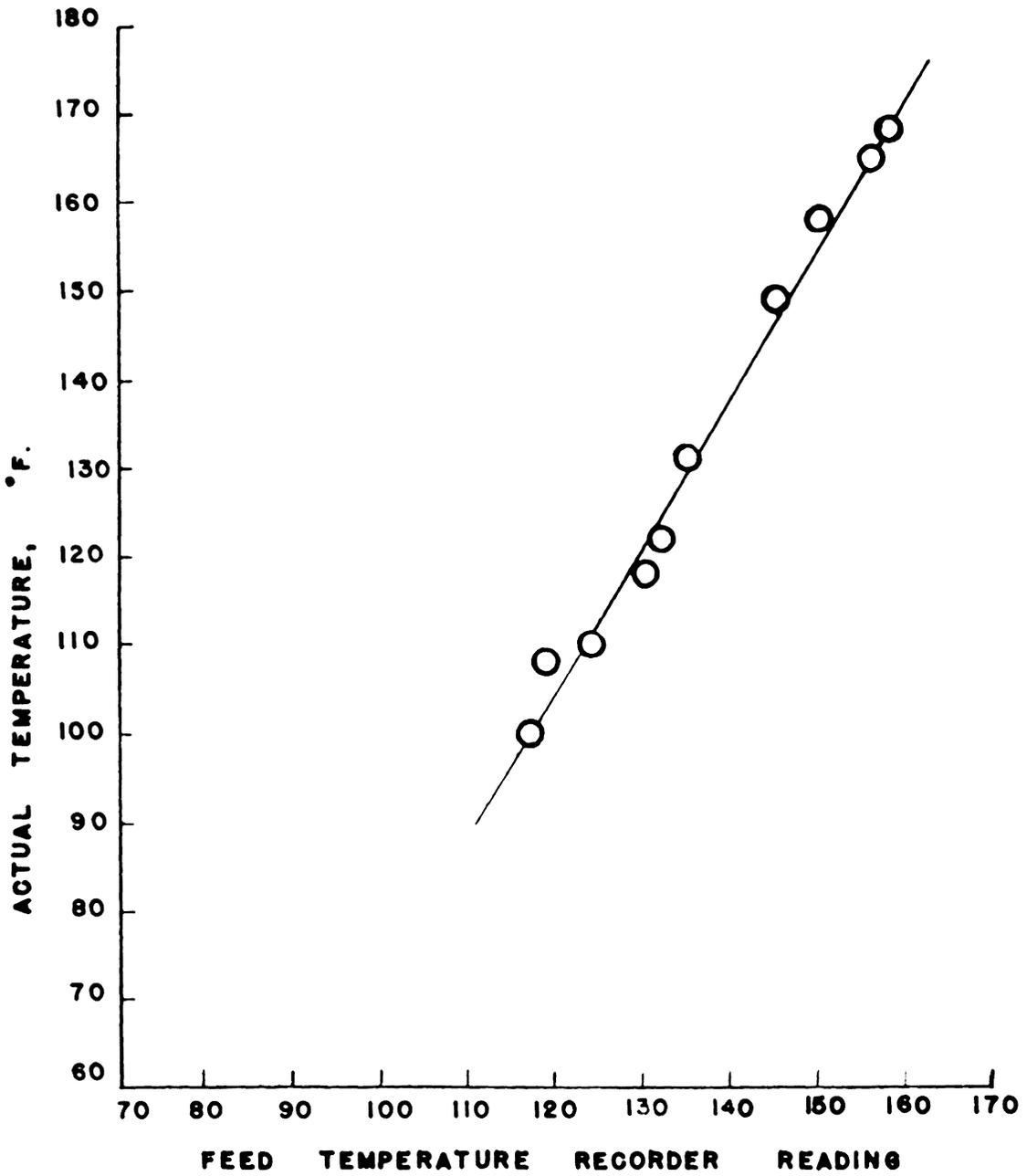


FIGURE II. CALIBRATION CURVE FOR FEED TEMPERATURE RECORDER

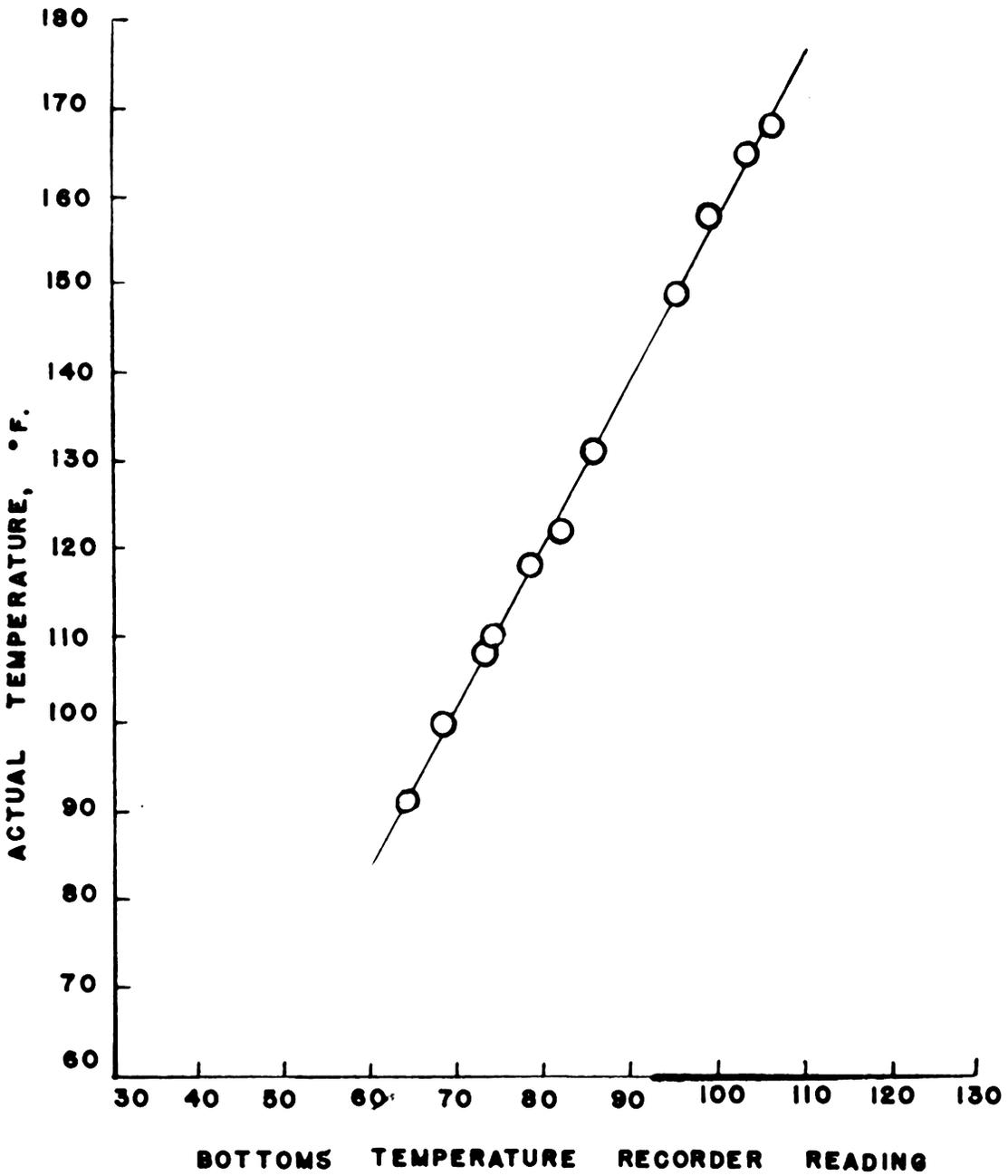


FIGURE 12. CALIBRATION CURVE FOR
BOTTOMS TEMPERATURE RECORDER

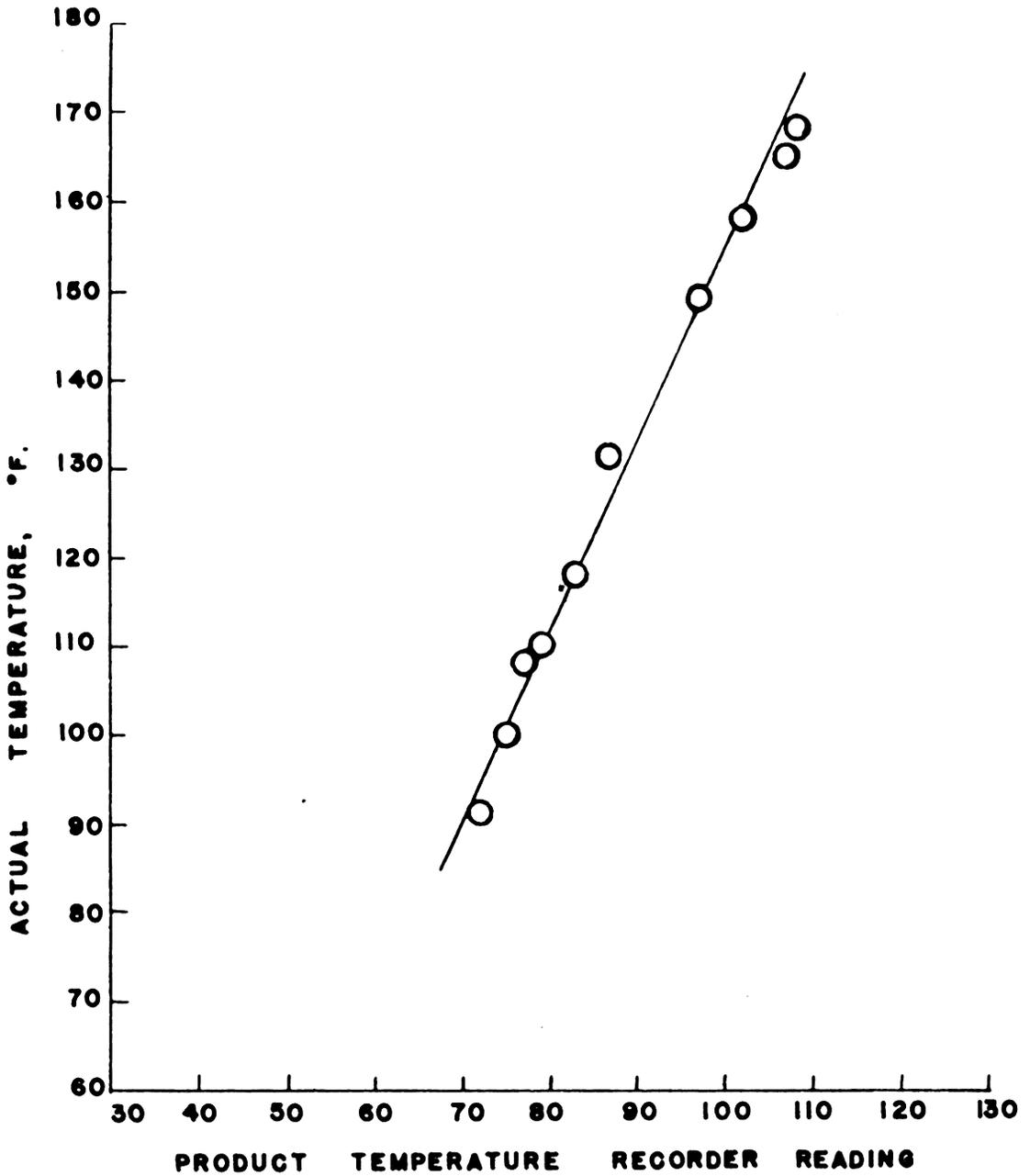


FIGURE 13. CALIBRATION CURVE FOR
PRODUCT TEMPERATURE RECORDER

Response of Control Systems. The fractionating column liquid level controller control settings and responses are presented in Table V, page 82. Figures 14 and 15, pages 83 and 84, are graphical representation of the column liquid level control system responses and the recommended control settings for this controller. Figures 16 and 17, pages 85 and 86, show photographs of typical recorder charts for the column liquid level and bottoms flow rate recorders.

Table VI, page 87, are the control settings and responses for the accumulator liquid level controller. The control system responses and recommended control settings for the accumulator liquid level controller are graphically represented by Figures 18 and 19, pages 88 and 89. Typical recorder charts for the accumulator liquid level and reflux flow rate recorders are shown by photographs in Figures 20 and 21, pages 90 and 91.

The control settings and responses for the condensate temperature controller are presented in Table VII, page 92. Figures 22 and 23, pages 93 and 94, are graphical representations of the condensate temperature control system responses and the recommended condensate temperature controller settings. Figures 24 and 25, pages 95 and 96, are photographs of typical recorder charts for the condensate temperature and condenser cooling water flow rate recorders.

The control settings and responses for the feed rate controller are presented in Table VIII, page 97, and Figure 26, page 98, are the recommended control settings for the feed rate controller.

The theoretical and operational optimum control settings for the column liquid level, accumulator liquid level, condensate temperature, and the feed rate controllers are presented in Table IX, page 99.

TABLE V

Control Settings and Responses for the Fractionating Column Liquid Level Controller

Setting		Observation		Figure ⁽⁴⁾	Cycling Period
Proportional Band	Reset Rate ⁽¹⁾	Controlled Variable ⁽²⁾	Controlling Medium ⁽³⁾		
Per Cent					Cycles per min
1	0	cycling	good	<u>A</u>	0.33
5	0	excellent	excellent	<u>B</u>	-
10	0	excellent	excellent	<u>C</u>	-
20	0	excellent	good	-	-
40	0	excellent	good	-	-
80	0	drifting	drifting	<u>G</u>	-
40	1/3	drifting	good	-	-
20	1/3	cycling	good	-	0.23
10	1/3	cycling	good	-	0.33
20	2/3	good	drifting	-	-

(1) Dial revolutions

(2) Bottoms flow rate

(3) Fractionating column liquid level

(4) Refers to Figures 16 and 17, pages 85 and 86

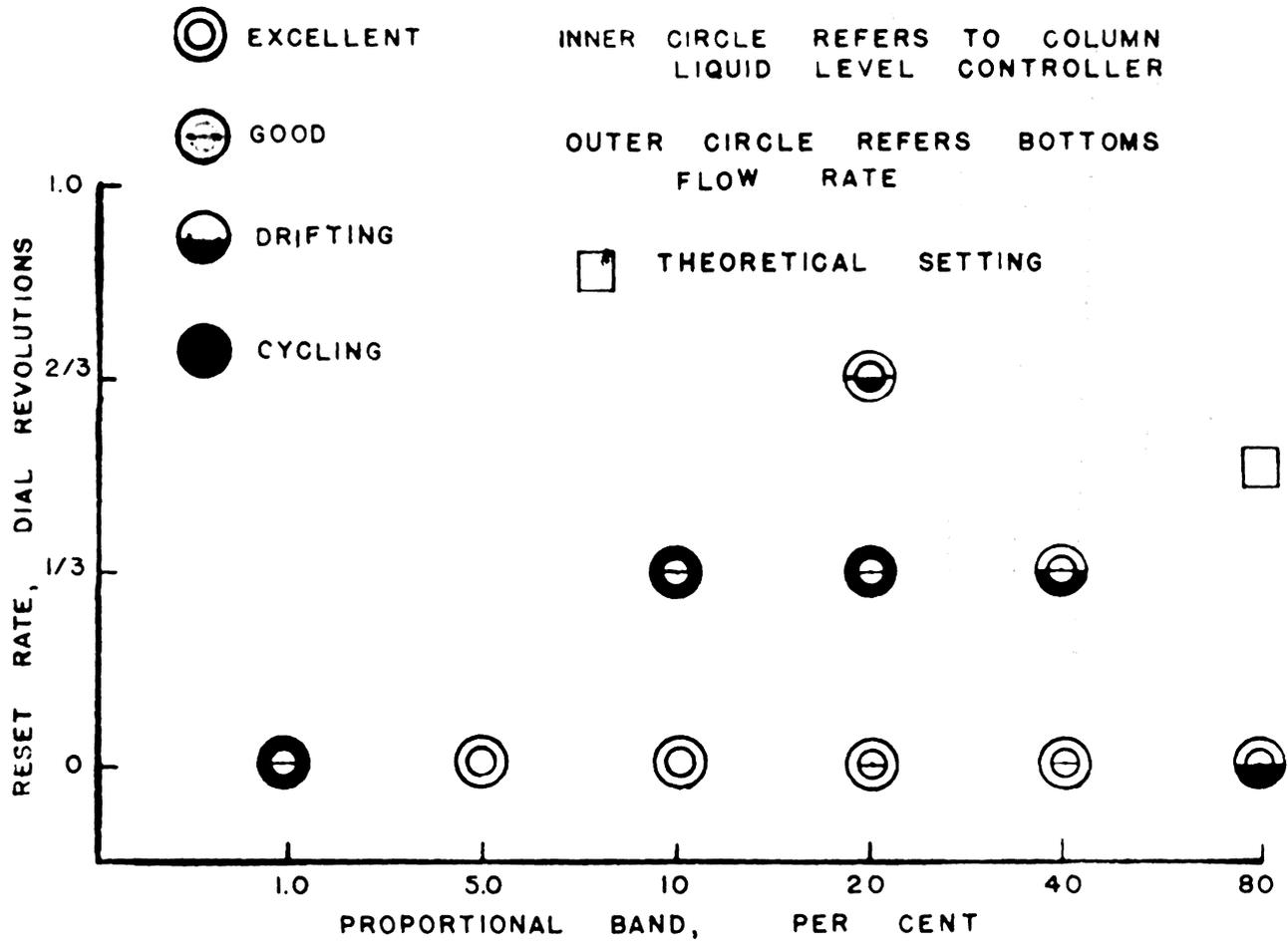


FIGURE 14. COLUMN LIQUID LEVEL CONTROL SYSTEM RESPONSE

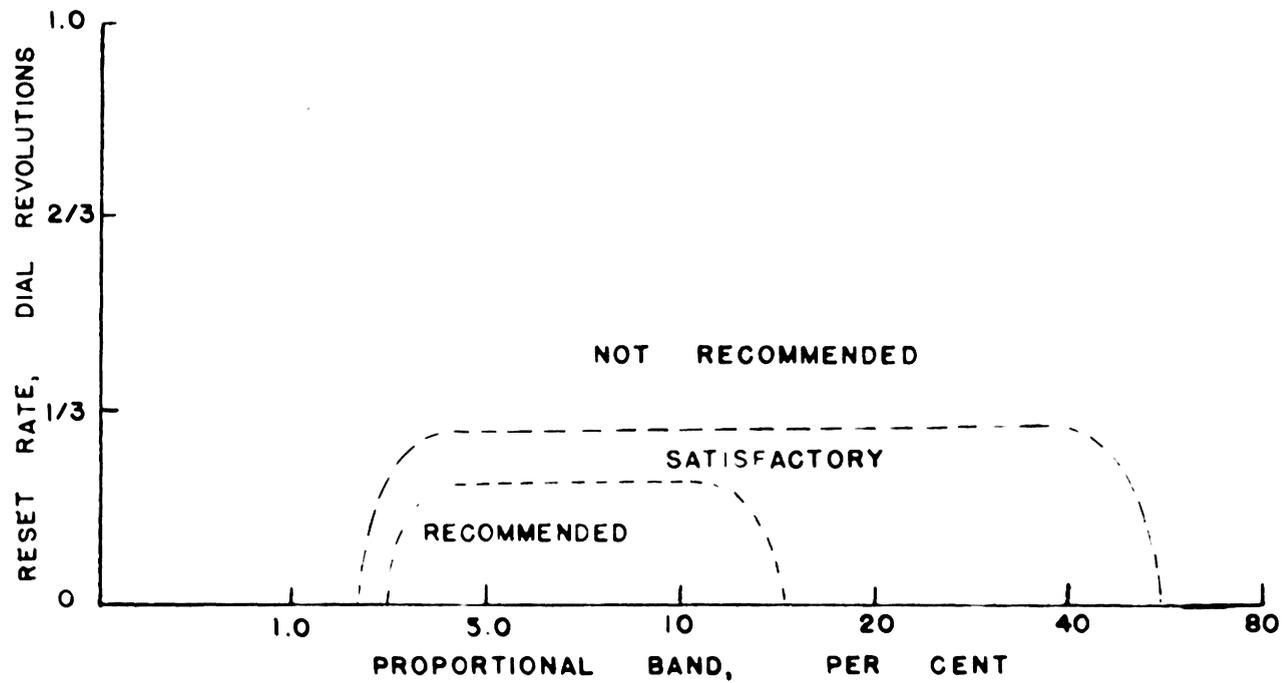


FIGURE 15. RECOMMENDED CONTROLLER SETTINGS
FOR COLUMN LIQUID LEVEL CONTROLLER

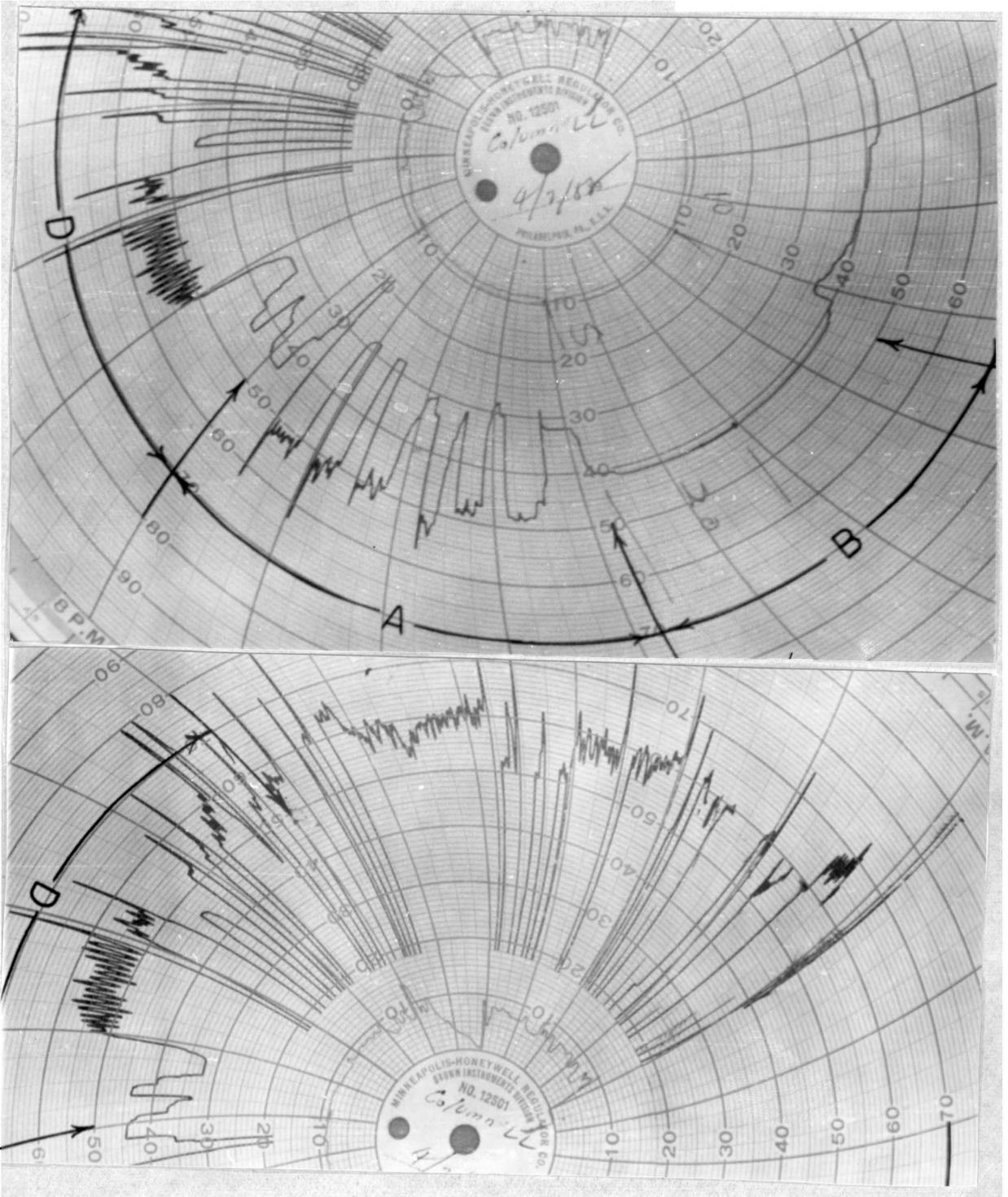


Figure 16. Typical Recorder Charts for Column

Liquid Level and Bottoms Flow Rate

Top: Adjusting Column Liquid Level Controller

Bottom: Column Startup Period

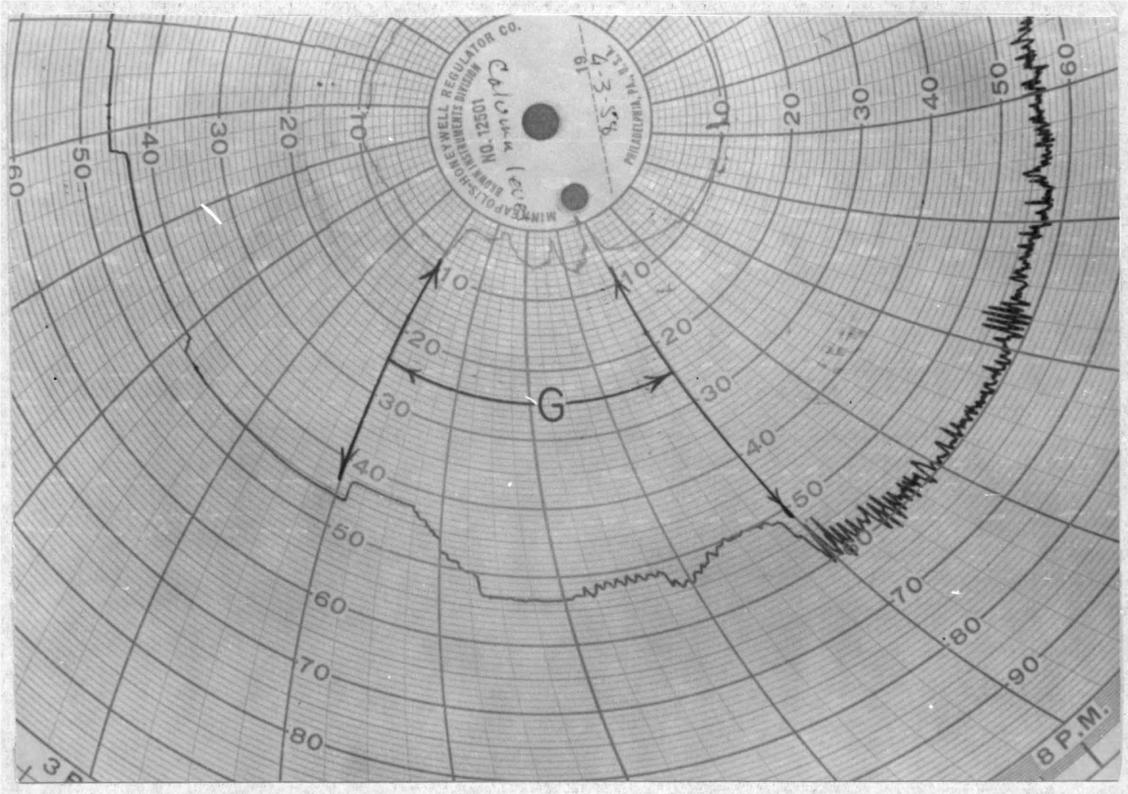


Figure 17. Typical Recorder Chart for Column
Liquid Level and Bottoms Flow Rate

TABLE VI

Control Settings and Responses for the Accumulator Liquid Level Controller

Setting		Observations		Figure ⁽⁴⁾	Cycling Period
Proportional Band	Reset ⁽¹⁾ Rate	Controlled Variable ⁽²⁾	Controlling Medium ⁽³⁾		Cycles per min
Per Cent					
10	0	drifting	cycling	-	0.15
20	0	good	excellent	-	-
40	0	good	excellent	-	-
60	0	good	good	-	-
80	0	good	good	-	-
150	0	drifting	drifting	-	-
150	1/3	drifting	good	<u>T</u>	-
150	2/3	cycling	cycling	<u>U</u>	0.18
150	1	cycling	cycling	<u>V</u>	0.22
80	1	cycling	cycling	<u>W</u>	0.18
80	2/3	cycling	cycling	<u>X</u>	0.22
40	2/3	cycling	good	<u>Y</u>	0.28
40	1	cycling	cycling	-	0.25
20	1	cycling	cycling	-	0.27
20	2/3	cycling	cycling	-	0.33
20	1/3	good	excellent	-	-
40	1/3	good	excellent	-	-
10	1	cycling	cycling	<u>A</u>	0.3

(1) Dial revolutions

(2) Reflux flow rate

(3) Accumulator liquid level

(4) Refers to Figures 20 and 21, pages 90 and 91

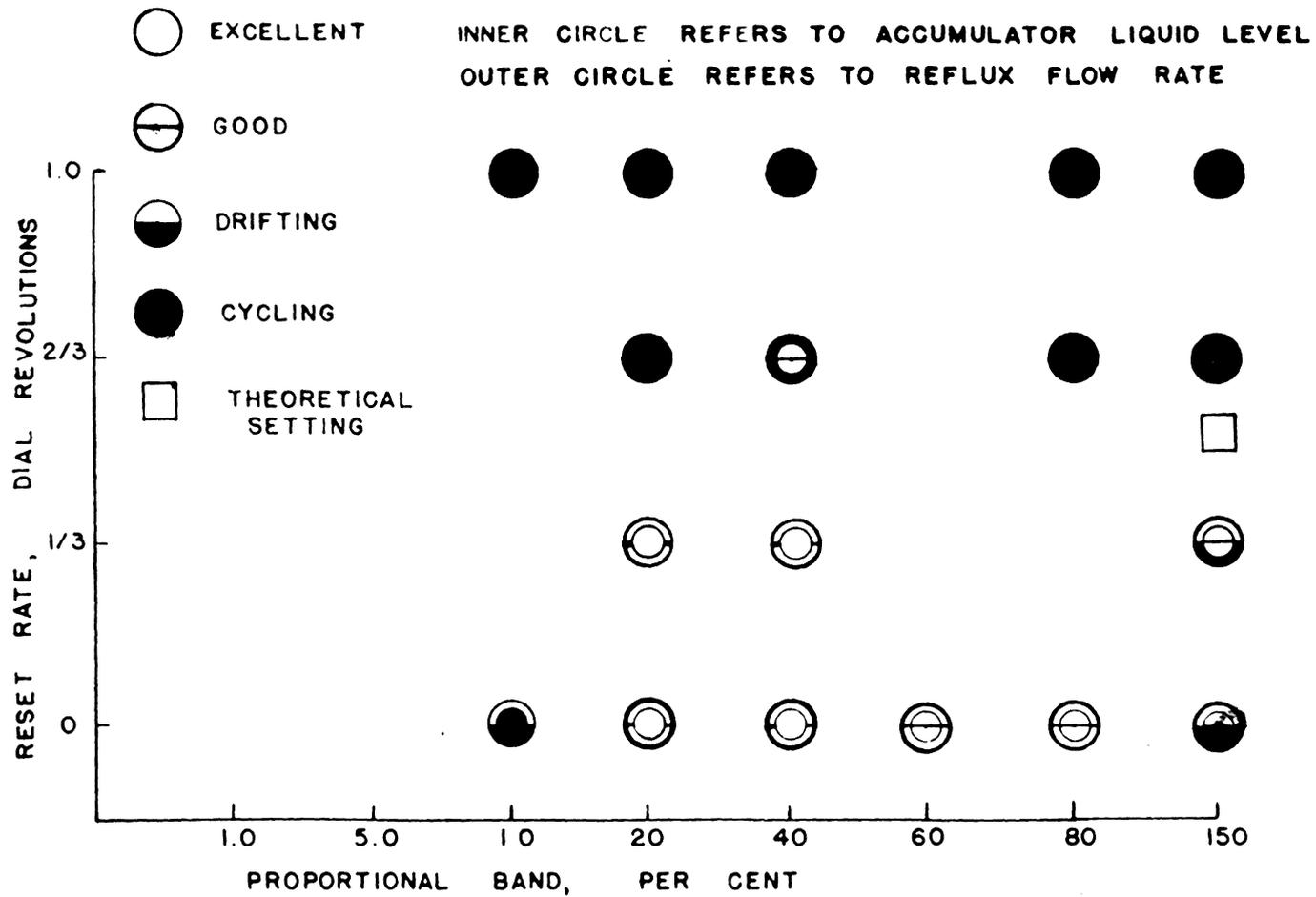


FIGURE 18. ACCUMULATOR LIQUID LEVEL CONTROL SYSTEM RESPONSE

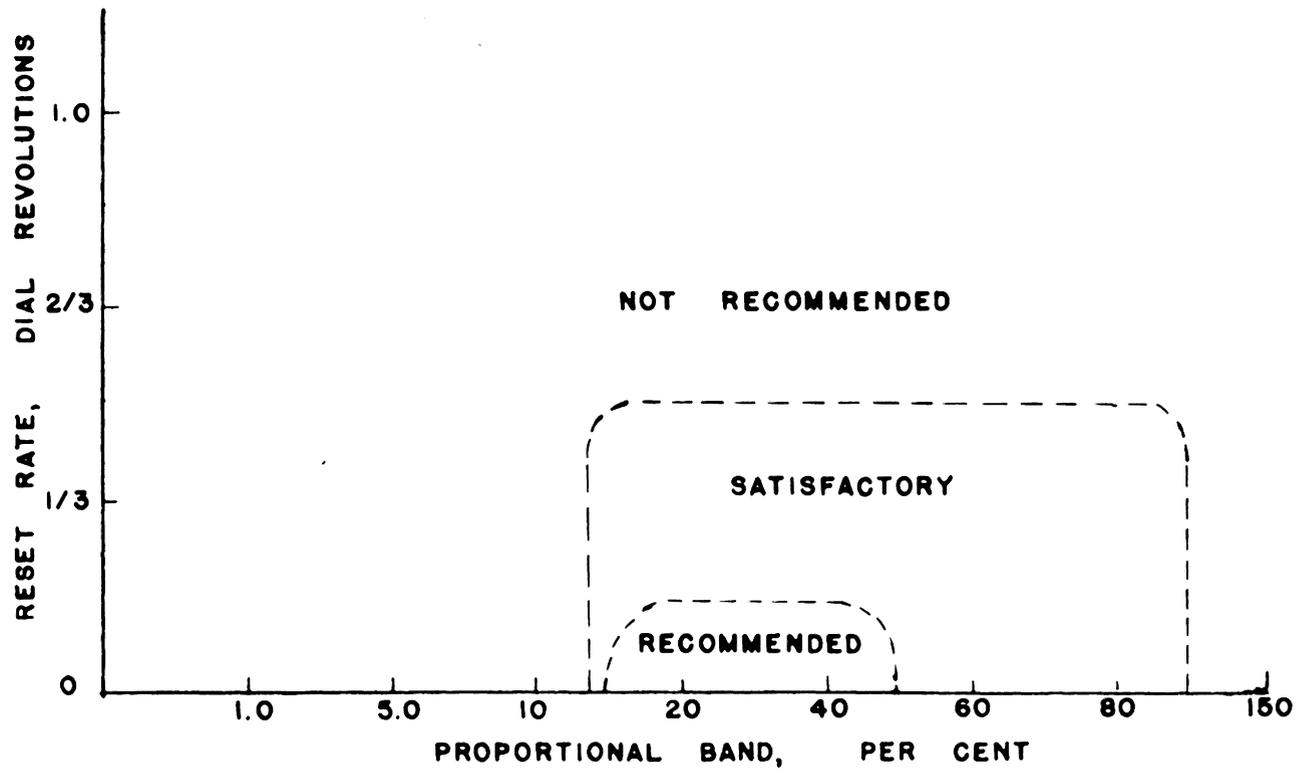


FIGURE 19. RECOMMENDED CONTROLLER SETTINGS FOR ACCUMULATOR LIQUID LEVEL CONTROLLER

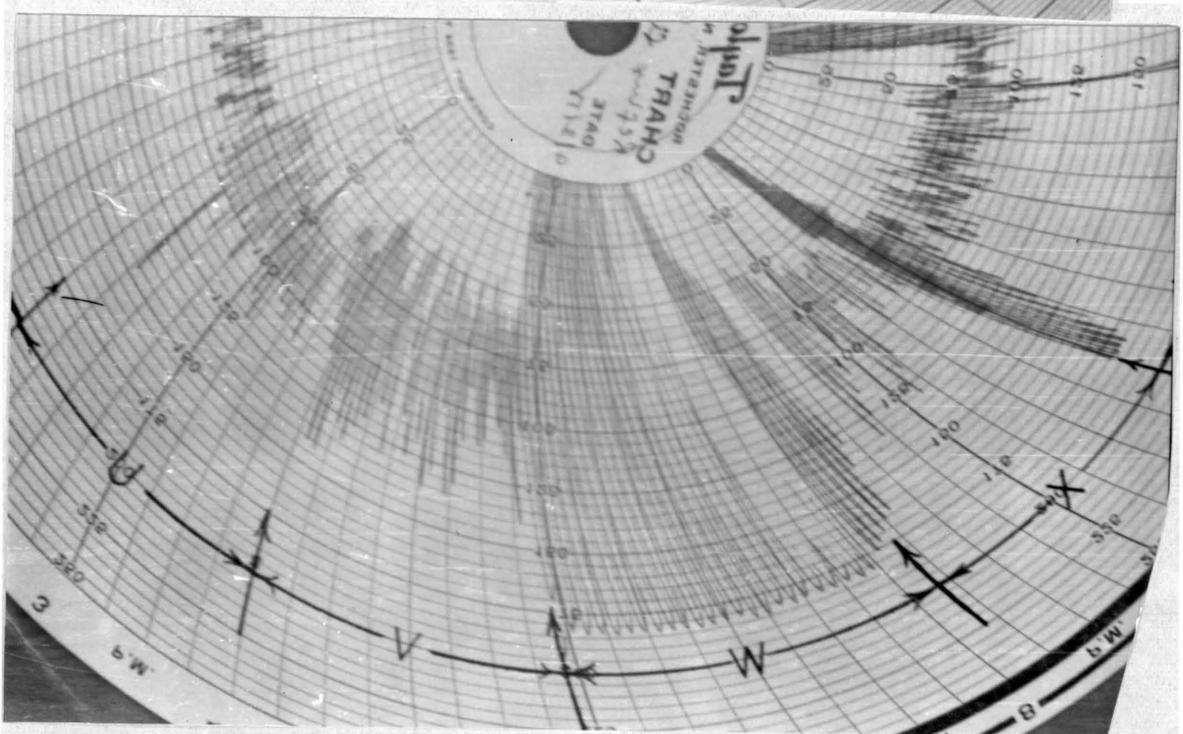
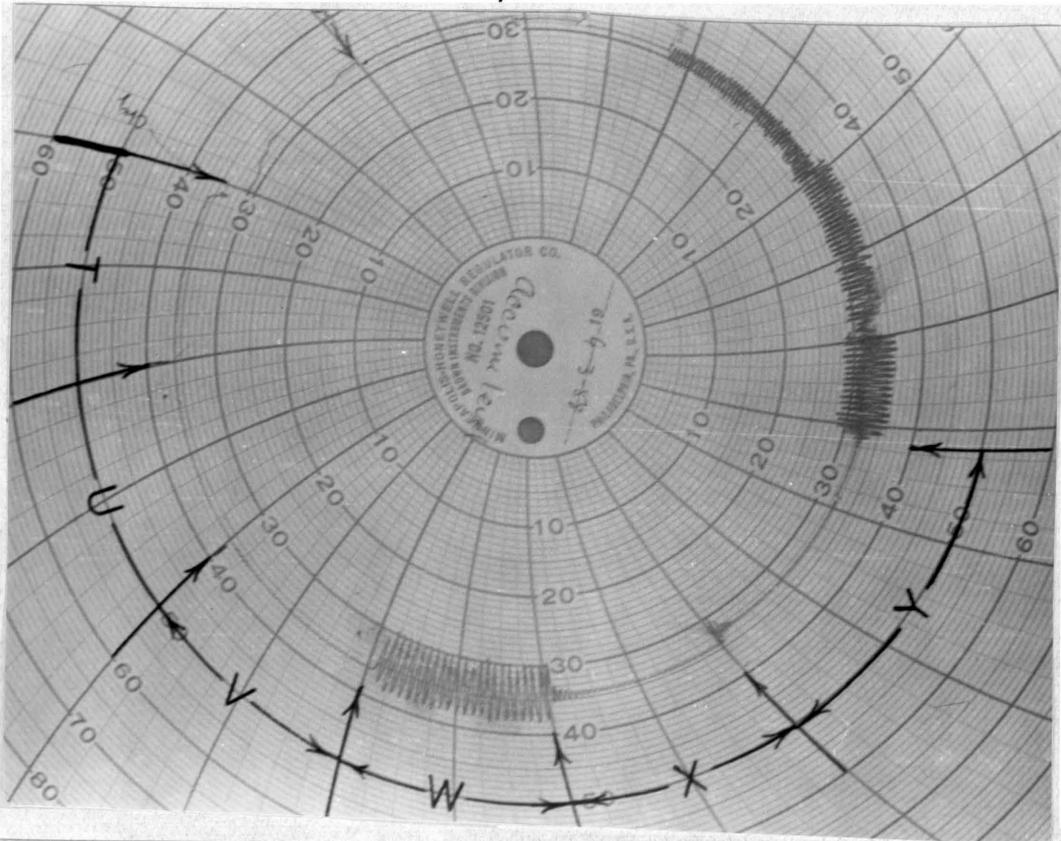


Figure 20. Typical Recorder Charts for Accumulator

Liquid Level and Reflux Flow Rate

Top: Accumulator Liquid Level Controller Recorder

Bottom: Reflux Flow Rate Recorder

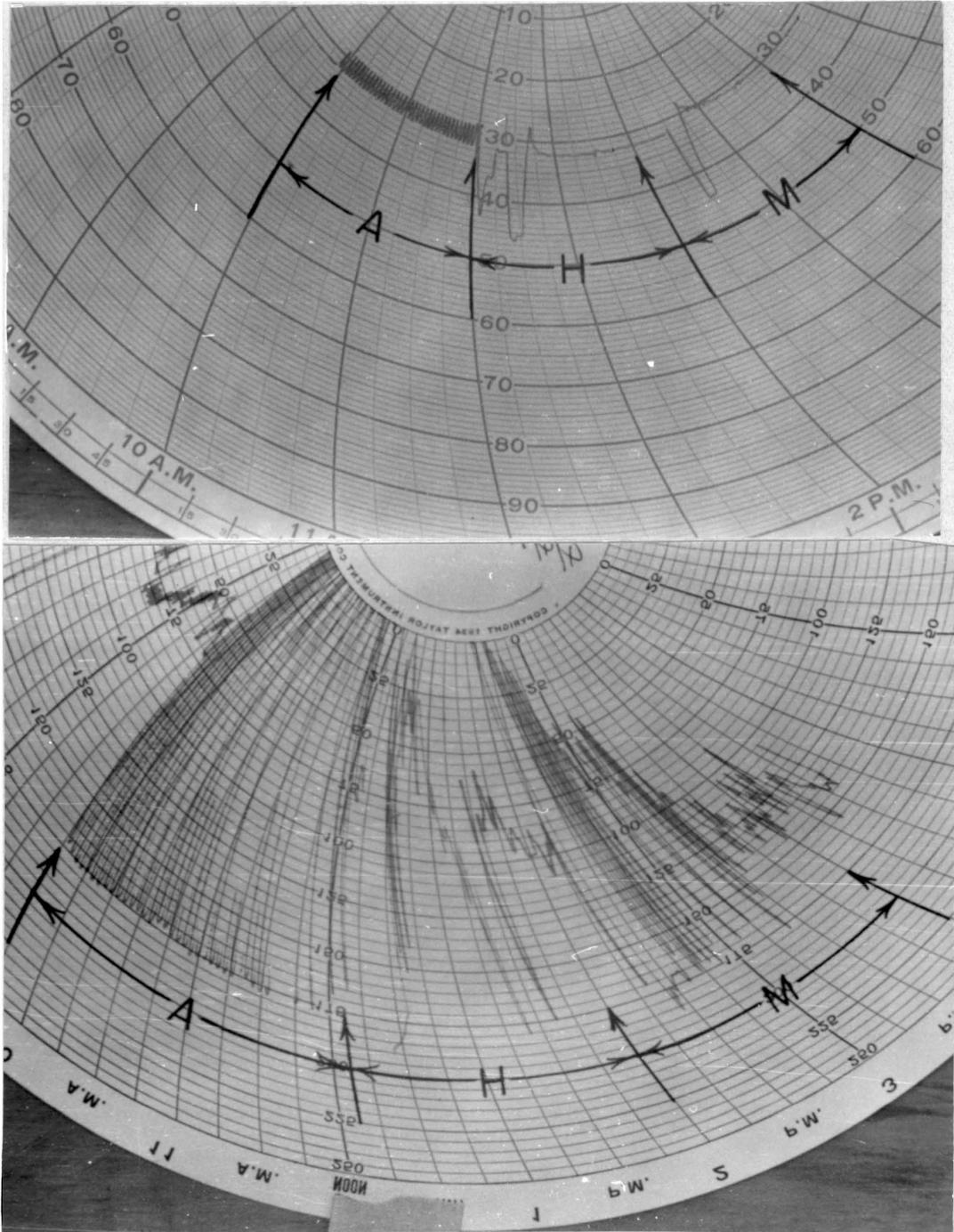


Figure 21. Typical Recorder Charts for Accumulator

Liquid Level and Reflux Flow Rate

Top: Accumulator Liquid Level Response Curve

Bottom: Corresponding Reflux Flow Rate

TABLE VII

Control Settings and Responses for Condensate Temperature Controller

Setting		Observations		Figure ⁽³⁾	Cycling Period
Proportional Band	Reset Rate	Controlled Variable ⁽¹⁾	Controlling Medium ⁽²⁾		
Per Cent	(min) ⁻¹				Cycles per min
1	0	cycling	cycling	<u>T</u>	0.33
5	0	cycling	cycling	<u>U, V</u>	0.15
20	0	excellent	excellent	<u>W</u>	-
40	0	excellent	excellent	<u>Y</u>	-
60	0	excellent	excellent	-	-
60	0.2	excellent	excellent	-	-
80	0.2	good	excellent	-	-
80	0.5	good	excellent	-	-
80	2.0	drifting	good	-	-
80	10.0	drifting	good	-	-
80	50.0	drifting	drifting	-	-
40	2.0	drifting	drifting	-	-
40	0.5	good	excellent	-	-
20	0.5	good	excellent	-	-
10	0.5	cycling	cycling	-	0.15
20	1.0	drifting	good	-	-
20	2.0	drifting	good	-	-
10	2.0	drifting	drifting	-	-
10	10.0	drifting	drifting	-	-

(1) Condensate Cooling Water Flow Rate

(2) Condensate Temperature

(3) Refers to Figures 24 and 25, pages 95 and 96

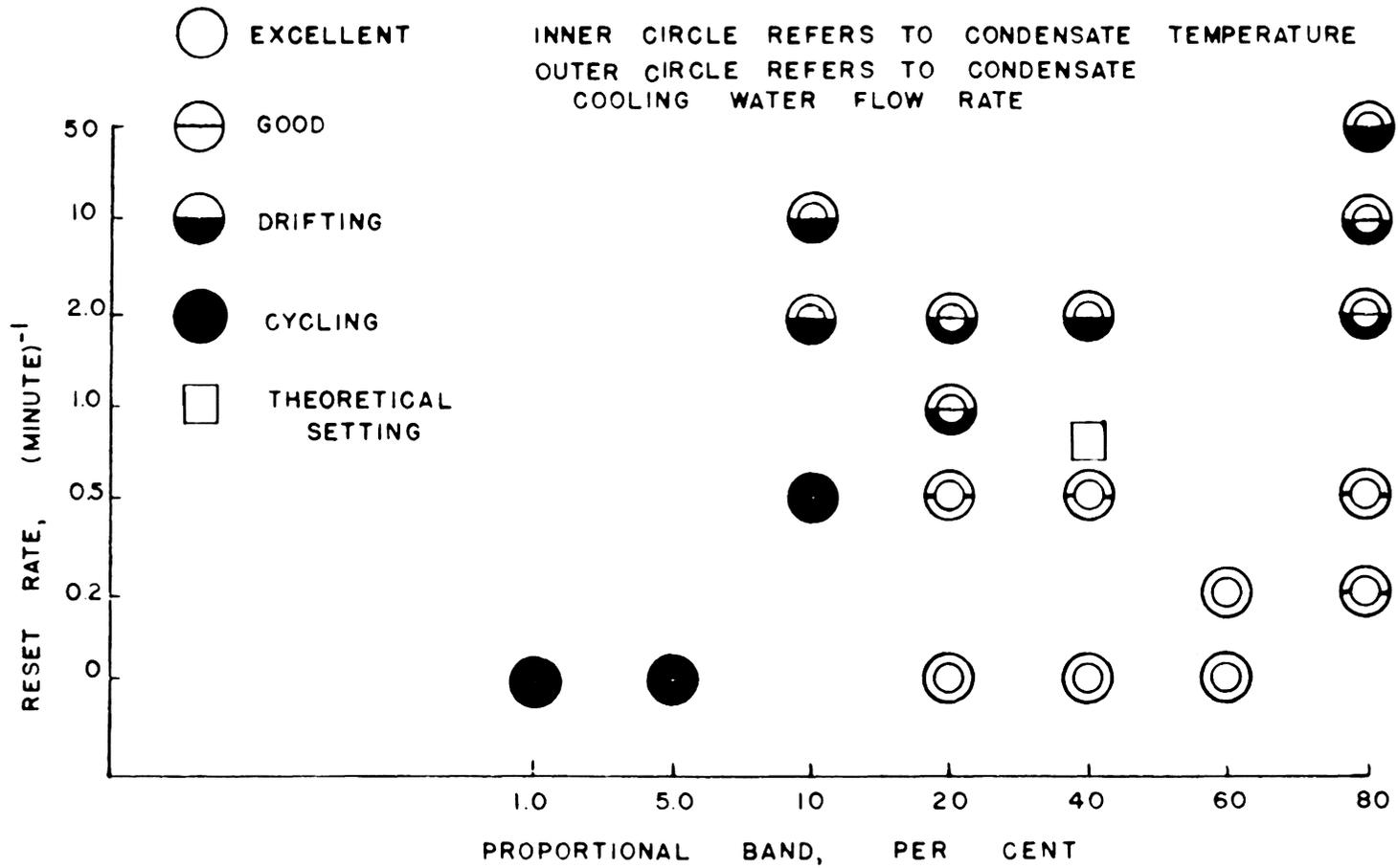


FIGURE 22. CONDENSATE TEMPERATURE CONTROL SYSTEM RESPONSE

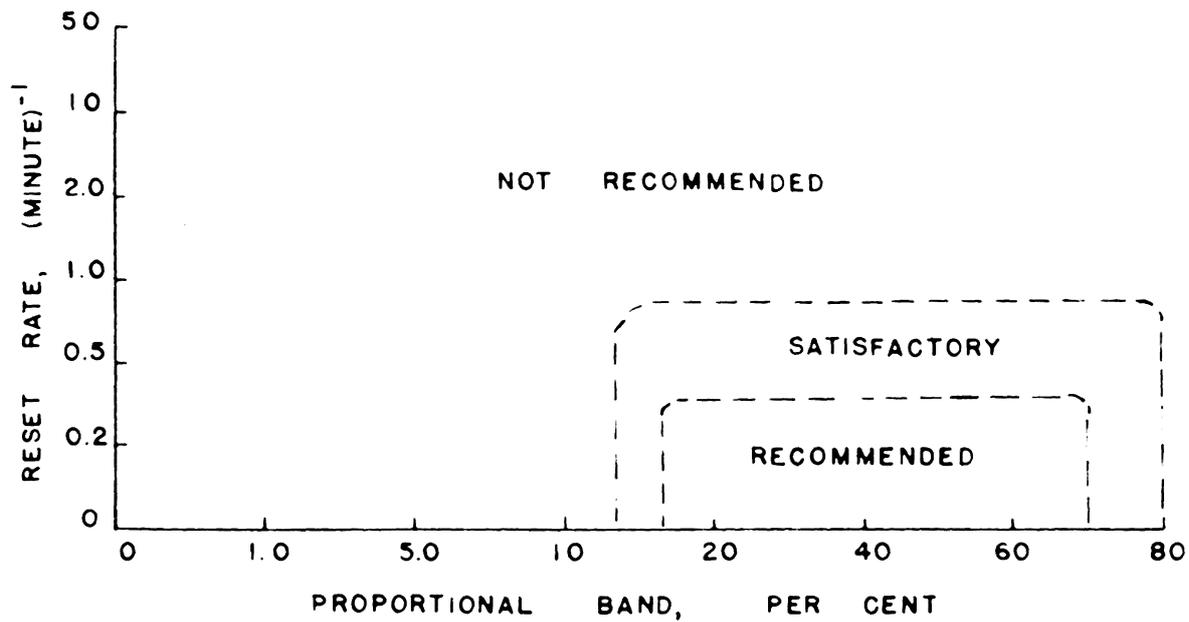


FIGURE 23. RECOMMENDED CONTROLLER SETTINGS FOR CONDENSATE TEMPERATURE CONTROLLER

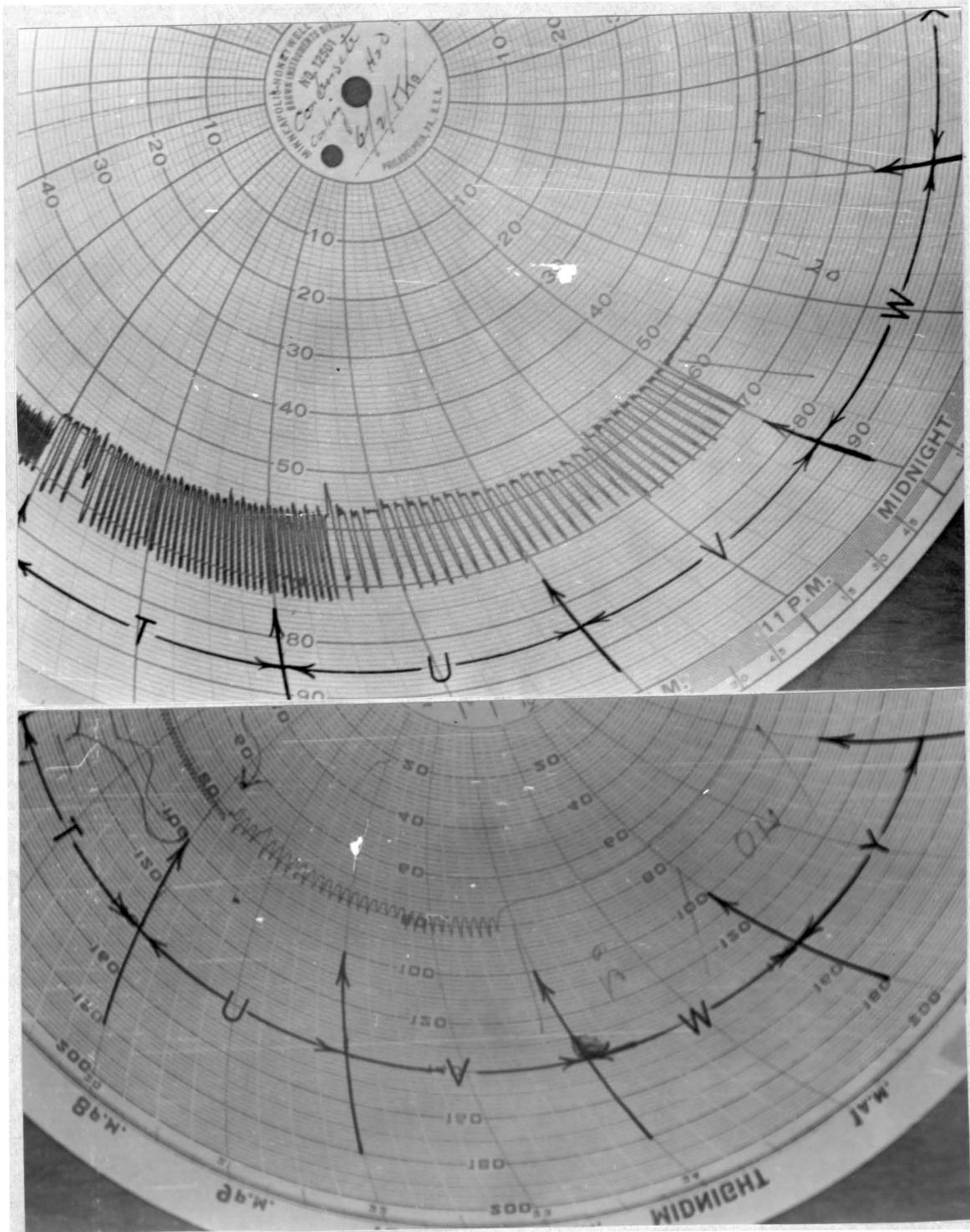


Figure 24. Typical Recorder Charts for Condensate Temperature and Condenser Cooling Water Flow Rate

Top: Condensate Temperature Recorder

Bottom: Condenser Cooling Water Flow Rate

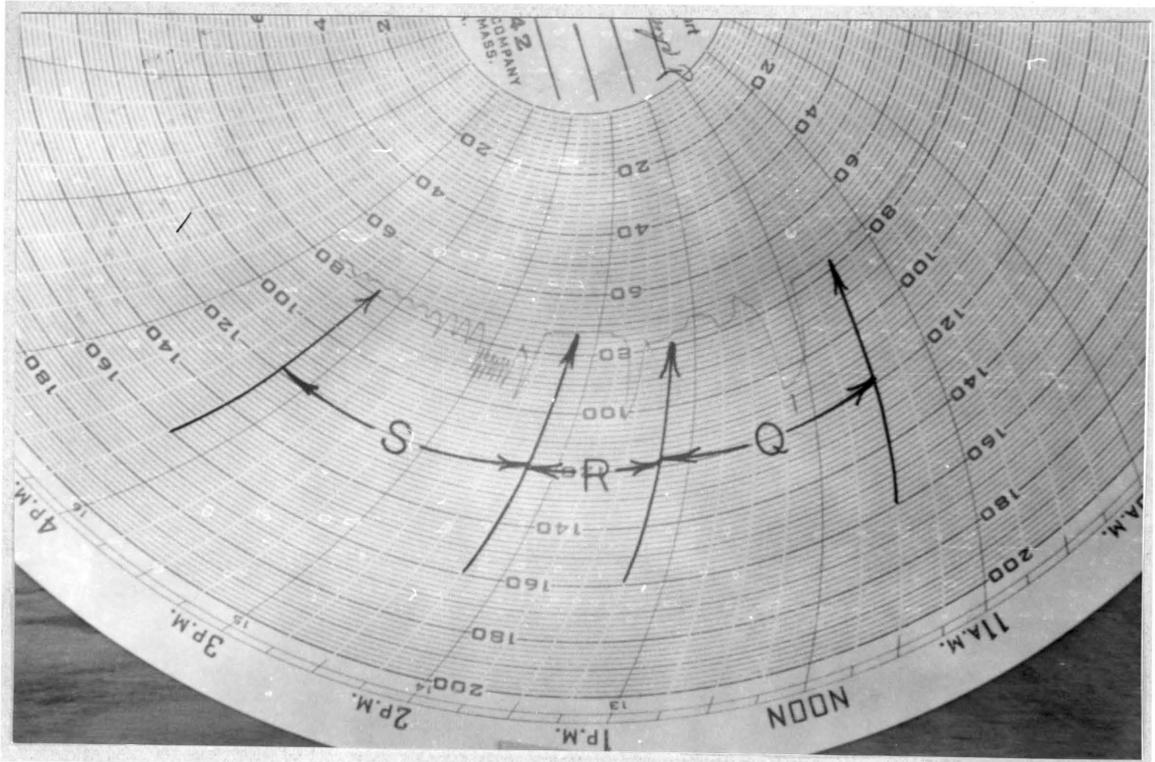


Figure 25. Typical Recorder Chart for Condensate Temperature Showing Response Curve

TABLE VIII

Control Settings and Responses for Feed Rate Controller

Setting		Observation	Cycling Period
Proportional Band	Reset Rate ⁽¹⁾	Feed Flow Rate	
Per Cent			Cycles per min
1	0	cycling	9.5
5	0	cycling	9.1
10	0	cycling	8.1
20	0	cycling	6.4
40	0	drifting	-
40	1/10	drifting	-
40	1/2	drifting	-
40	1.0	cycling	4.0
30	1/4	drifting	-
60	1/4	excellent	-
60	1/2	good	-

(1) Dial revolutions

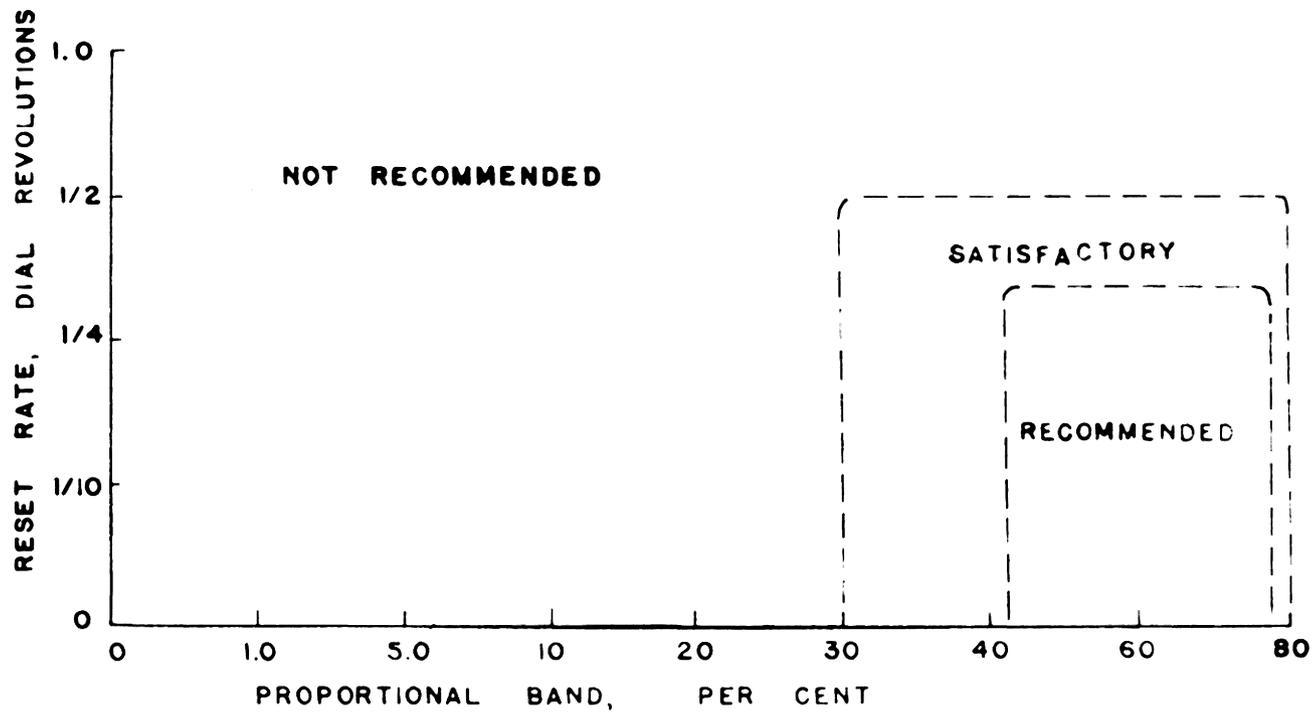


FIGURE 26. RECOMMENDED CONTROLLER SETTINGS FOR FEED FLOW RATE CONTROLLER

TABLE IX

Theoretical and Operational Optimum Control Settings for the
Column Liquid Level, Accumulator Liquid Level, Condensate
Temperature, and Feed Rate Controllers

Controller	Theoretical		Operational	
	Proportional Band	Reset Rate ⁽¹⁾	Proportional Band	Reset Rate ⁽¹⁾
	Per Cent		Per Cent	
Column Liquid Level	80	0.5	10	0
Accumulator Liquid Level	150	0.55	20	0
Condensate Temperature	40	0.65 ⁽²⁾	20	0.20 ⁽²⁾
Feed Rate	100	0.75	60	0.25

(1) Dial revolutions

(2) (Minutes)⁻¹

Sample Calculations

The following paragraphs contain samples of the calculations involved in determining the theoretical control settings for the fractionating column liquid level, accumulator liquid level, condensate temperature, and feed flow rate controllers. The calculations will be illustrated using the column liquid level controller.

Cycling Period. In calculating the theoretical control settings for the column controller the cycling period must be determined first. Following the procedure outlined by Eckman⁽⁵²⁾ the column liquid level controller, which is a proportional-reset mode type of controller, the proportional band is set to a maximum value and the reset rate is set to zero.

The proportional band is reduced from this maximum setting by increments until noticeable instability occurs. During these step changes of the proportional band the column liquid level controller recording chart is observed and the cycles per unit time after cycling commences is recorded. As an example refer to test period G, Figure 17, page 86.

Theoretical Control Settings. The theoretical proportional band is the last setting before noticeable instability commences when the reset rate is at a minimum. The column liquid level controller is a proportional-reset mode type controller and the theoretical reset rate must now be calculated using the formula given by Eckman(52):

$$R = \frac{1}{T}$$

where:

R = reset rate, reciprocal minutes,

T = period of cycling, minutes.

$$R = \frac{1}{0.33}$$

R = 3 per minute

Referring to the chart furnished by the Brown Instrument Company(53) for this instrument it is seen that this reset rate corresponds to about 1 revolution of the controller dial.

IV. DISCUSSION

The following section contains a discussion of the preliminary testing, modifications of equipment, and operation of the hydrocarbon fractionating column in determining the optimum control system settings. A listing of recommendations for equipment improvement and future studies of the fractionating unit, and a listing of the limitations imposed when operating the unit are also presented.

Discussion of Results

The following paragraphs contain the discussion of the preliminary testing, equipment modifications, and operation of the fractionating unit and the tests involved in determining the optimum control settings for the column liquid level, accumulator liquid level, condensate temperature, and feed flow rate controllers.

Preliminary Testing. In order for the author to become better acquainted with the operation of the fractional distillation column and offsite equipment, preliminary tests were performed on the unit. During these tests special attention was placed on studying the operational characteristics of the equipment and the automatic instruments.

Also the feed, bottoms, product, and reflux flow rates were calibrated as well as were the bottoms, product, and feed temperature

recorders. These calibration charts, Figures 7 to 13, pages 73 to 79, are shown in the Data and Results Section. The procedure used in the calibration of the recorders was identical to that performed by Richard⁽³⁷⁾.

Equipment Modifications. The information obtained during these preliminary tests suggested several repairs or modifications of the equipment.

Both the feed and bottoms pumps were found to be damaged because of previous lack of maintenance. Upon inspection it was found that both pumps required a complete overhaul including replacement of all internal parts in the feed pump and all parts except the impeller in the bottoms pump. After rebuilding both pumps with new parts, they were placed back into service, tested, and found to be satisfactory.

The petroleum feed stock used in this study dries the pump packing causing it to become very brittle when the pumps are allowed to stand idle. The dried packing will not act as a satisfactory seal and leakage around the shaft occurs regardless of how tight the packing gland is tightened. Prior to any actual testing of the unit it was necessary for the pumps to be repacked. The pumps as repaired worked satisfactorily during all the actual experimental tests performed. It can be safely assumed that the pumps added no load to the control systems. This point is important in a negative sense, only. If the pumps do not operate

satisfactorily, control of any kind is impossible. If the pumps operate satisfactorily they lose any importance as far as the control systems are concerned.

The column and the condensate accumulator liquid level controllers were observed to be operating unsatisfactorily during preliminary testing. Both of these depend upon a differential pressure measurement to indicate the actual level. In installing the controllers it was assumed that they operate with the seal pot on the upper manometer leg filled with fluid. This is necessary when measuring the level of an easily vaporizable fluid, because that leg will eventually fill with condensed vapor. Upon examination both seal pots were found to be dry at the start of each test and presumably filled up during the test. Thus the differential pressure bore no relation to the actual level during the early part of the test. Therefore incorrect corrective action was taken by the level controllers and the unit could never reach steady state.

Each of these seal pots could have been filled by hand prior to commencing a test run, laborious and somewhat dangerous procedure. It was decided that it would be best to install a permanent method of filling the seal pots. Copper tubing was connected from the feed line to each of the seal pots. The pots can be filled before each test or whenever desired if the feed pump is operating. This simple change corrected all the troubles

originally encountered with both liquid level controllers. During actual tests the vapor condensing in the relatively colder tubing leading to the manometers kept the upper line full.

It is possible to check to make sure the level is actually in the controlled zone easily with this modification. Opening the manometer leg connecting valve puts the same differential pressure on both legs, the unit full condition. After determining the full portion the upper seal pot can be easily refilled without opening the seal pots to the atmosphere.

It was observed while operating the fractionating unit in preliminary tests that there was no way of knowing the temperature of the feed entering the preheater, steam condensate leaving the column or the preheater, bottoms entering the bottoms cooler, and entering and exit cooling water streams for the bottoms and tops condenser. Although the indication of these temperatures do not effect the control systems in anyway, these temperatures give a better picture of the overall operation. These temperatures, furthermore, give an added degree of comfort that all controls are operating satisfactorily.

With the installation of thermocouples to indicate these temperatures at the potentiometer on the panel board, Figure 3, page 59, the complete operation of the hydrocarbon unit could be better understood. A heat balance was not attempted in this work and probably could not be determined because the quality of the

steam is not well known and also because there is a large loss of heat from the column and the heat exchangers.

Feed System. The fractionating column was designed for a petroleum system similar to one used in this investigation. When using a gas-liquid partition chromatograph for analyzing a feed sample approximately 28 components were noted. Since no particular components were found to be in large concentrations especially in the heavy virgin naphtha, Table I, page 67, multicomponent distillation calculations would probably be based on boiling ranges and would be very difficult.

A crude method of calculation using refractive indices and a McCabe-Thiele calculation method⁽⁴⁴⁾ for binary mixtures was used in calculating the overall column efficiency in previous work with this column. For the calculations the two components in the system were assumed to be hexane and heavy virgin naphtha. The poor results obtained seemed to indicate and an examination of chromatograph charts showed that the assumptions made in the two component calculations were incorrect. The chromatograph charts indicated that the heavy virgin naphtha did not keep its identity as was assumed, but was itself partially fractionated.

In this work no attempt was made to determine the plate efficiency for the distillation tower.

Optimum Controller Settings. During preliminary tests it was noted that the column liquid level, accumulator liquid level,

condensate temperature, and feed flow rate controllers were either cycling or drifting, reducing the possibility of the unit ever reaching a steady state.

Since the equipment governed by these controllers appeared to be rather easy to control, it was decided to use the simple method given by Eckman⁽⁵²⁾ for obtaining the theoretical control settings. After ensuring that all of the controllers were in good mechanical condition, tests to determine the required information were commenced. The procedure used in these tests are covered in detail by Eckman⁽⁵²⁾ and in the procedure of this report, page 63. - An explanation of the calculations made is given in the Sample Calculations, page 100.

The feed flow rate controller was the easiest of the four controllers to study since there was little, if any, time lag. The condensate accumulator liquid level controller was more difficult to control because of a definite time lag of approximately 5 minutes, while the column liquid level and condensate temperature were very difficult to control because of extreme time lags present in the system.

For each of the four controllers studied in this investigation the theoretical control settings were greater than those found by actual observation to be satisfactory. The reason for this was probably because of the relatively large time lag resulting from the large size of the equipment compared to the average throughput.

The feed flow rate was 18 pounds per minute while the product and bottoms flow rates were 9 pounds per minute each during these tests. About 20 minutes of flow were required to fill the accumulator tank and approximately four hours to fill the column reboiler. When using the formula Eckman(52) found by empirical methods:

$$R = \frac{1}{\pi}$$

where:

R = reset rate, reciprocal minutes

π = period of cycling, minutes,

the value of the reset rate calculated was consistently high. This formula was developed as a rough approximation for what could be called average industrial units. The flow rate to throughput ratio would in general be much greater in industrial use than those used in this experiment. The flow rate to throughput for the accumulator tank was 1.25 : 50 and for the column reboiler 1.25 : 250 per minute. This accounts for some of the considerable lag found in this system. Also the tops condenser and feed preheater were originally designed for greater capacity than is presently required for this unit. Equipment being used at lower than normal rates is a common cause of lags in control systems.

Consequently it was thought advisable to modify Eckman's equation(52) for this fractional distillation unit to the following form:

$$R = \frac{k}{\pi}$$

where:

k = system constant, dimensionless.

When using a value of k = 0.75, the theoretical reset rates were closer to the optimum reset rates found experimentally. If when using this equation for finding the reset rate of an average industrial controller, k is set equal to 1, the equation becomes identical to Eckman's equation(52).

The larger the reset rate the more cycling that will occur in a system with large time lags during startups. Smaller reset rates than predicted by the method described above were found to be the actual optimum control settings for the feed flow rate, column liquid level, accumulator liquid level, and condensate temperature controllers, as are discussed in the following paragraphs.

Feed Flow Rate Controller. If the feed flow rate varied during the operation of the fractionating unit the throughput of the distillation column would be varying and consequently the other controllers would not be able to steady out the unit easily. For this reason the feed flow

rate controller is very important. Therefore the feed flow rate controller was tested prior to the other controllers in the hope that good feed control could be maintained while testing the other controllers. The feed control system, itself, is independent of any of the control systems that were to be studied. Thus, final adjustments of these other systems should not effect the feed system. However the other systems were expected to be a function of the feed at least to some extent.

The feed flow rate controller regulates flow of feed to the column directly by means of an air controlled diaphragm valve located in the feed line, which receives an air signal from the controller and responds with no appreciable time lag. Consequently no specific duration for the tests was necessary for each set of proportional band and reset rate controller settings.

After obtaining the theoretical control settings the complete fractionating unit was operated and the feed rate recorder was observed. Some slight cycling was noted. The theoretical control settings were not the optimum control settings and the feed flow rate controller had to be re-adjusted. Better controller settings were determined by essentially a trial and error procedure.

Since the controller was cycling it was thought that by decreasing the reset rate the cycling would stop. The lower reset rate allowed a smaller proportional band to be used. Table VIII, page 96, shows the controller settings and responses for the feed rate controller when using various combinations of proportional band and reset rate. Figure 26, page 97, graphically represents the recommended operational control settings. Even within the recommended region control could not be called excellent. The trouble, however, seemed to lie in the controller and probably resulted from non-precise positioning of the pneumatic parts caused by age and a poor overall condition of the controller.

It was noted that when the feed temperature was raised to approximately 150 °F, the approximate bubble point for the feed mixture, the feed controller was no longer able to control the feed rate. A definite and uniform cycling was noticed even at the widest proportional band setting of the controller. This condition arose from the relative positions of the control valve and preheater. Since the feed control valve was on the exit side of feed preheater the more volatile components of the feed stock vaporized in the lower pressure of the discharge side and were "flashing" through the control valve and the orifice used to measure the feed flow rate. Because of this "flashing" of the feed the control system evidently acquired

decidedly non-linear characteristics. Over the entire range of possible controller settings an oscillatory state was stable. The controller was unable to compensate for "flashing" and considerable cycling was evident. Various control settings were attempted to eliminate this cycling when the feed temperature to the column was 150 °F or higher. However the controller action was unsatisfactory in all cases, therefore, the feed temperature was maintained in all future tests at 141 °F using the feed control system settings found to be satisfactory for this lower temperature.

Column Liquid Level Controller. The liquid level in the fractionating column is maintained at the desired level by varying the flow rate of the exiting bottoms stream. If because of increased feed rate or decreased boilup the level in the column should rise as shown by the column liquid level recorder, Figure 3, page 59, the liquid level controller will tend to correct this condition by opening the bottoms flow rate control valve, increasing the bottoms flow rate.

As the feed line is 1/2-inch piping but the bottoms line only 1/4-inch, the maximum bottoms flow rate is relatively limited compared to the feed flow rate. This has two undesirable effects. It is possible to feed at rates which will fill up the column even at the maximum bottoms rate. Also the control valve has relatively less control because of

the abnormally high resistance of the bottoms line. For proper liquid level control a feed rate of about 20 pounds per minute is the maximum that can be handled. At feed rates greater than this the bottoms control valve would be completely open and the liquid level in the column would still be rising. For the tests a feed rate of about 18 pounds per minute was used.

However because of the small feed compared to the column inventory any variation of the preselected feed flow rate will not cause an appreciable change in the liquid level of the column immediately. The control action taken by the column liquid level controller will be tardy. Because of this large time lag, when testing the controller settings and responses, test periods of four hours duration were used.

During the preliminary testing of the fractionating unit it was observed that the theoretical control settings were not satisfactory and also that lower reset rates increased the stability. During the extended test of the unit a minimum reset rate and a proportional band of 10 per cent were found to be the optimum operational control settings. Figure 14, page 82, graphically represents the control system and responses for the liquid level controller.

Recorder charts are presented photographically in Figures 16 and 17, pages 84 and 85. Test period A shows the bottoms flow rate cycling while the column liquid level recorder indicates good control. The bottoms flow rate is a much more sensitive indication of stability, since it records a variable with a very low time lag, and is very useful for studying the level control system. Also, the level recorder utilizes only one-fifth of the recorder chart making small irregularities harder to observe. On this basis it was decided that the control settings for test period A were unsatisfactory. Test periods B and C show excellent control while period G demonstrates drifting.

Accumulator Liquid Level Controller. As the more volatile vapors leave the fractionating unit and pass through the tops condenser, the vapor condenses and collects in the accumulator tank from where it is pumped either back to the column as reflux or to the feed storage tank as product. The temperature controller that was originally installed to control the product rate was damaged and could not be used. It was necessary to operate, during this study, with the product valve on manual control. The product control valve was set at 13 pounds per square inch, gage, and remained constant throughout the testing. Therefore any sudden surge of condensate would be returned to the column as reflux in preference to product.

The purpose of the accumulator is to act both as a feed unit for the condensate pump and as a surge tank for evening out the reflux ratio. The condensate accumulator liquid level controller controls the level in the accumulator tank, a relatively unimportant variable, as well as the reflux flow rate, a very important variable.

During preliminary testing it was found that the theoretical settings were once again high. The reflux flow rate recorder being very sensitive compared to the recorded level was taken as an indication of control stability. During the extended testing a minimum reset rate was used and a small proportional band. Even though the time lag for the accumulator level control is not as great as for the column level control there is still an appreciable lag which effects control.

If a larger reset rate was used as was indicated by the theoretical control settings, Table IX, page 98, then the unit would not settle out because the fluid flow in a fractional distillation unit varies constantly and the reset control incurrecting for this would tend to overcorrect. If the proportional band was too large then the level control would allow the liquid level in the accumulator or the fractionating column to go to extremes prior to taking significant corrective action. Also large proportional bands

and high reset rates tend to cause trouble in startups. Figure 18, page 87, graphically represents the accumulator liquid level control system responses.

Test periods A, U, V, W, and X, Figures 20 and 21, pages 89 and 90, show different cycling periods for various control settings listed in Table VI, page 86. Test periods T and Y show that the flow recorder is much more sensitive than the liquid level recorders. For this reason the reflux flow rate recorder was used primarily to select the proper operational control settings. All test periods for the accumulator liquid level controller were of two hour duration.

Condensate Temperature Controller. The temperature of the condensate leaving the tops condenser is controlled at the desired value by controlling the amount of cooling water available to this heat exchanger. The condensate temperature controller measures the temperature of the condensate leaving the condenser, compares it with the preselected temperature desired and the difference or error signal regulates the cooling water control valve. This change in the amount of cooling water regulates the amount the condensate is cooled. It would be expected that the relation between condensate temperature and cooling water is quite non-linear and might cause considerable trouble. Again this process has a relatively long time lag caused by the low vapor rate used

for the condenser size installed. Test periods of two hour duration were used when studying the control settings and responses for this controller are seen in Table VII, page 91.

Figure 24, page 94, are photographs of typical recorder charts for the condensate temperature and condensate cooling water flow rate recorders. Test periods T, U, and V show both recorders cycling, but test periods W and Y show excellent control.

While observing the recorder charts several control settings gave excellent responses and these were noted. It was planned to upset the system when using these excellent settings and to observe which control settings gave the desired response curve. The condensate temperature controller was switched from automatic to manual and the cooling water was cut off in order to upset the system. The controller was switched back to automatic control and the response curves were obtained as seen in Figure 25, page 95. Test period R gave a more satisfactory response curve and was selected as the best values for the operational control settings.

Recommendations

The following paragraphs contain a discussion of possible recommendations that may be utilized in future studies and modifications of the fractionating column.

Multicomponent Calculations. In order that multicomponent calculations may be solved accurately it is recommended that a system of less chemical complexity, such as benzene-toluene-xylene be substituted for the now existing system of commercial grade hexane and heavy virgin naphtha. This present feed stock contains approximately 28 components of significantly high compositions. Using a ternary system, overall column efficiency and Murphree plate efficiency may be calculated readily for the hydrocarbon fractionating column from a gas-liquid partition chromatograph analysis or some other suitable analysis.

Other problems that could be solved using this ternary system would be calculating the gain in efficiency of the column when the automatic instruments are at their optimum control settings compared to just barely satisfactory control settings. The ideal feed plate, feed and reflux flow rates, liquid level in the column, the effect of a vapor feed as compared with a cold feed, and the optimum reflux ratio could be calculated for this system.

Bottoms Flow Rate. While operating the fractionating column it was noted that if the feed flow rate exceeded 20 pounds per minute the liquid level in the column could not be controlled

properly because of the small maximum bottoms flow rate possible. The maximum bottoms rate is limited by the bottoms line which is only 1/4-inch in diameter. It is recommended that 1/2-inch pipe be substituted throughout for the present smaller bottoms line diameter piping. If this is done the feed rate may be increased and the liquid level controller will still be able to control the column level.

Chart Range. During the operation of the hydrocarbon unit it was noticed that the complete range over which the column and the accumulator liquid level controllers operated was only about one-fifth of the total chart scale. Because the scales were so narrow it was difficult to judge whether the controllers were actually well adjusted or if the liquid level controllers were actually drifting or cycling, but because of the small scale could not be observed and therefore assumed to be controlling ideally. The reflux and bottoms streams, which depend upon the action of the two liquid level controllers, present a better overall picture of the action of these two controllers than the liquid level recorders themselves. Nevertheless it is advisable that both level controllers be changed so as to take advantage of the full recorder range available thus enabling the operator to follow the operation of the controllers more closely. This larger scale would enable the operator to see sooner if any adjustments were required for the two controllers.

Plate Pressure Drop. It is recommended that the pressure drop across the plates be used to control the steam flow rate and the tops temperature be used to control the product flow rate. Presently the product is controlled manually and reflux is controlled by the accumulator level. Since any sudden increase of vapor goes back as added reflux, the reflux ratio varies considerably. Any multicomponent distillation calculations made would be inaccurate because of the varying reflux ratio.

Knowing the pressure drop across each plate would also enable the operator to determine the liquid seal on each of the plates which is an important factor in analyzing the operating efficiency of the distillation unit. A differential pressure measuring device should be connected to taps through the column wall at the two ends of the column in the vapor space. It would also be desirable to indicate or record the pressure drop for each plate.

Automatic Steam Cut-Off Valve. In the operation of the fractional distillation unit there is always the possibility that a motor relay will trip out when one of the pump motors is overloaded or a pump might fail in some other way. If the accumulator pump stops a potentially dangerous situation arises.

If the accumulator pump stops and steam continues to heat the distillation column, the more volatile components in the feed stock will continue to come over as product and this vapor and condensate will collect in the accumulator, filling it up and

eventually covering the condenser tubes. Any further vapor which cannot condense will be vented to the atmosphere through the feed storage tank vent. This results in a potential fire hazard as well as an economic loss of feed material.

It is therefore advisable that an automatically controlled valve be installed on the steam line leading to the calandria section and the feed preheater of the fractionating unit which would stop the steam flow whenever the accumulator pump stops.

Repacking Pumps. It was found that whenever the feed, bottoms, or accumulator pumps were allowed to remain idle for extended periods of time the pump packing became very dry and brittle. When the pumps were started there was considerable leaking around the pump shaft which could not be stopped by tightening the packing gland. It is recommended that the pumps be repacked prior to commencing any experimentation. Also, a study should be made to find a packing that is not affected by the hydrocarbon components in the feed stock and to investigate the possibility of using mechanical seals on these pumps.

Continuous Operation. When operating the fractionating unit for less than six hours it appeared that the automatic control system never completely reached steady state conditions. However when operating the column continuously for periods of 24 to 36 hours the automatic instruments appeared to control the unit appreciably better than during shorter tests. Tests may then be

performed on the control systems by changing the set point of the variables and studying the response of the instruments without upsetting this improved steady state appreciably. Therefore it is recommended when the fractionating unit is being operated to study either control or distillation that the entire unit should be run continuously for 24 to 36 hours or longer by several groups in shifts.

Steam Pressure. It is recommended that studies be made on the fractionating unit to increase the capacity of the unit. This could consist of higher pressure steam, say of at least 80 pounds per square inch, gage, or of an external reboiler. At present the 65 to 70 pounds per square inch, gage, steam pressure is not sufficient to heat the bottoms in the still pot above 235 °F, especially in cool weather even though the steam valve is completely open. The boiling range for the heavy virgin naphtha component in the bottoms is 225-315 °F.

Steam and Cooling Water Flow Rate Control Valves. While examining the offsite equipment it was found that the air controlled diaphragm valve that regulates the steam flow rate to the calandria section was an air to close valve while the bottoms and tops cooling water flow rate controller valves were air to open. Consequently if for some reason the air supply to the unit failed the steam flow rate control valve would open completely and the bottoms and tops cooling water flow rates would close.

Temperatures throughout the unit would increase and probably much of the more volatile components of the feed stock would be vaporized and vented to the atmosphere through the feed tank vent.

It is recommended that these valves be replaced with valves having a reverse action. Then the steam flow rate control valve would be an air to open valve while the bottoms and tops cooling water flow rate control valves would be of the air to close type.

Steam Calorimeter. An accurate knowledge of the quality of steam would enable the operator to evaluate the heat passing into the calandria section of the column and the feed preheater. A throttling type steam calorimeter would permit the determination of the quality of steam during the operation of the unit if installed to the main steam line.

Application of Thermal Insulation. While operating the hydrocarbon fractionating unit it was quite evident that considerable amount of heat was being lost through the walls of the fractionating tower, feed preheater, and piping between various pieces of major equipment. Because of this heat loss an accurate heat balance is very difficult to calculate.

It seems advisable that outdoor type thermal insulation be applied to the distillation column, feed preheater, and other piping so as to prevent this great heat loss and also to protect any individual from a serious burn who might accidentally touch the hot equipment.

Installation of Glass Ports. Except for the recording instruments the operator has no way of knowing what is actually happening on the column plates. Since this column is being used as an Unit Operations Laboratory Experiment it is recommended that glass ports be installed for several of the plates. This would aid the operator in determining column operation and dumping or blowing could visually be observed on the plates if it occurs.

Limitations

The following paragraphs contain a listing of the limitations imposed upon the operation of the fractionating column.

Distillation Column. The fractionating column used in the distillation process contained ten plates, spaced one foot apart, was 25 feet high, two feet in diameter, and contained twenty-two 2-inch bubble caps per plate. The heating coils in the column were constructed of extra heavy one inch pipe and had a total heating area of 60 square feet.

Bottoms Cooler. The bottoms cooler in the fractionating unit was a four-pass shell and tube type exchanger having a contact surface of thirty-seven $3/4$ -inch tubes 70 inches long.

Tops Condenser. The tops condenser used in the fractionating unit was a single pass shell and tube type exchanger having a contact surface of eighty-nine $3/4$ -inch admiralty metal tubes 69 inches long.

Feed Preheater. The feed preheater used in the fractionating unit was a single pass shell and tube type exchanger having a contact surface of nineteen $5/8$ -inch copper tubes $45-1/2$ inches long.

Pumps. The two centrifugal pumps used to pump the feed and the overhead vapor condensate stream had a capacity of 38 gallons per minute against a 40 pound head. The centrifugal pump used to pump the bottoms stream had a capacity of 30 gallons per minute against a 40 pound head.

Control Valves. All control valves were diaphragm motor valves with throttling action.

Steam Supply. Steam at 70 pounds per square inch, gage, was used to supply heat to the calandria and feed preheater.

Feed Rate Control. The feed rate was maintained at a rate of 18 pounds per minute during all the tests with the use of a flow rate controller.

Feed Temperature. The feed to the distillation column was maintained at a constant temperature of 141 °F, controlled by means of a temperature controller on the feed preheater except during those tests in which the effect of feed temperature were studied.

Feed Mixture. The feed was approximately a 50 to 50 weight per cent mixture of commercial grade hexane, boiling in the range from 145 to 158 °F, and heavy virgin naphtha, boiling in a range from 225 to 315 °F.

Calandria Section Temperature Control. The temperature of the calandria section was controlled at the preset temperature of 235 °F, by use of a temperature controller, controlling the steam flow rate to the calandria section of the distillation column.

Product Valve Pressure. The product control valve opening was controlled by the air pressure exerted on the diaphragm of the valve. The pressure used was 13 pounds per square inch, gage.

Reflux Temperature. The reflux temperature was maintained at a temperature of 146 °F by using a temperature controller on the tops condenser to control the cooling water rate to this condenser except in those tests in which the effect of reflux temperature was studied.

Atmospheric Pressure. The atmospheric pressure for the tests on the fractionating column was between 710 and 720 millimeters mercury for all tests.

Water. The cooling water for the bottoms cooler, and condensing water for the tops condenser was at a temperature of approximately 45 to 50 °F.

Column Liquid Level. The liquid level in the distillation column was maintained at a setting of 8, 60 per cent full, by using the column liquid level control valve to control the bottoms flow rate from the fractionating column.

Accumulator Liquid Level. The liquid level in the accumulator tank was maintained at a setting of 32 on the accumulator liquid level controller, 60 per cent full, by using the accumulator liquid level control valve to regulate the flow of condensate from the accumulator.

V. CONCLUSIONS

An automatically controlled hydrocarbon fractionating unit two feet in diameter, 25 feet high, having 10 plates spaced one foot apart, each containing twenty-two 2-inch bubble-caps, with an intergal calandria section was operated to study the response of the control systems. A feed mixture of about 50 weight per cent commercial grade hexane and 50 per cent heavy virgin naphtha was used. The column liquid level, accumulator liquid level, condensate temperature, and feed flow rate controllers were tested for optimum control settings when operated with a constant feed rate of 18 pounds per minute, calandria section temperature of 235 °F, and a product valve pressure of 13 pounds per square inch, gage. The feed and reflux temperatures were 141 °F and 146 °F, respectively, and the reflux ratio was about 1 : 1.

From the investigation the following conclusions may be drawn:

1. The best proportional band and reset rate control settings for the column liquid level controller were 10 and 0.
2. The best proportional band and reset rate control settings for the accumulator liquid level controller were 20 and 0.

3. The best proportional band and reset rate control settings for the condensate temperature controller were 20 and 0.2.

4. The best proportional band and reset rate control settings for the feed flow rate controller were 60 and 0.25.

VI. SUMMARY

The automatic control system of an industrial type bubble-cap fractional distillation column was studied in this investigation in order to determine the optimum control settings for the column liquid level, accumulator liquid level, condensate temperature, and feed rate controllers.

The column itself was 25 feet high, two feet in diameter, with an intergal calandria section, and contained ten bubble-cap trays spaced one foot apart with each tray having twenty-two 2-inch bubble-caps. The system used consists of commercial grade hexane and heavy virgin naphtha.

During the testing of the controllers the feed flow rate was maintained at 18 pounds per minute, the product valve pressure 13 pounds per square inch, gage, and the calandria temperature 235 °F. The reflux ratio was about 1 : 1, the feed and reflux temperature was 141 °F and 146 °F.

Preliminary tests were run on the hydrocarbon fractionating unit in order to become familiar with the actual operation of the unit, calibrate the recorders, repair or modify any unsatisfactory equipment, and to study the response of the controllers used in this investigation.

With the completion of preliminary testing and repair of equipment one continuous test was run for several days. The best

control settings found from the preliminary testing were used when commencing this test and after twelve hours steady state existed throughout the unit. Next, various combinations of proportional band and reset rate control settings were tested. The entire unit was observed during this testing of the controllers for satisfactory control or for any irregularities. The degree of control and control settings were recorded.

After studying the recorder charts the optimum control settings for each controller were selected. Using these control settings the entire fractionating column was started up cold and steady state existed throughout the unit in less than three hours.

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