

Dec. 27, 1966

D. E. LUPFER ETAL

3,294,648

CONTROLLING THE OPERATION OF A DISTILLATION COLUMN

Filed Dec. 26, 1962

4 Sheets-Sheet 1

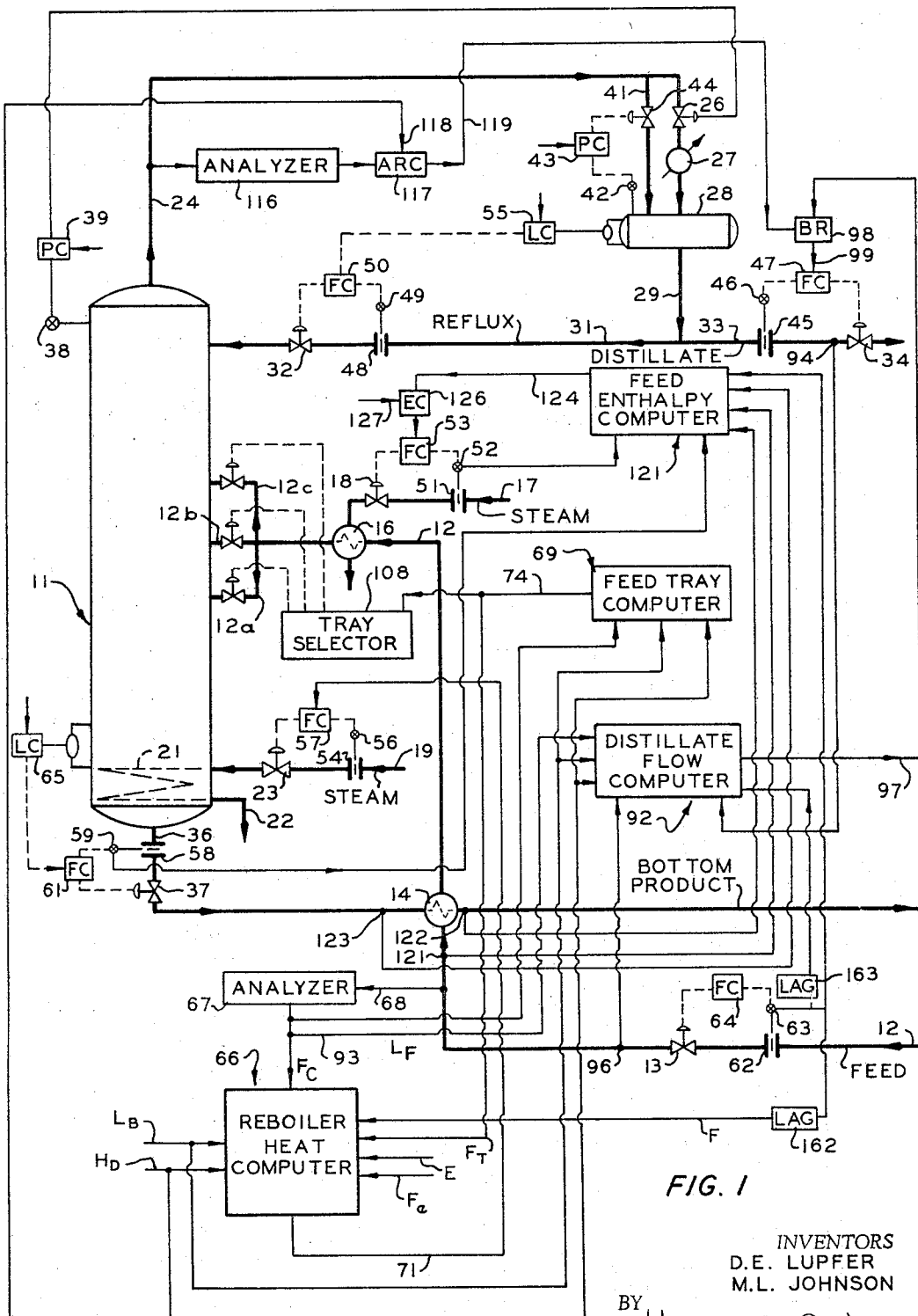


FIG. 1

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4 Sheets-Sheet 2

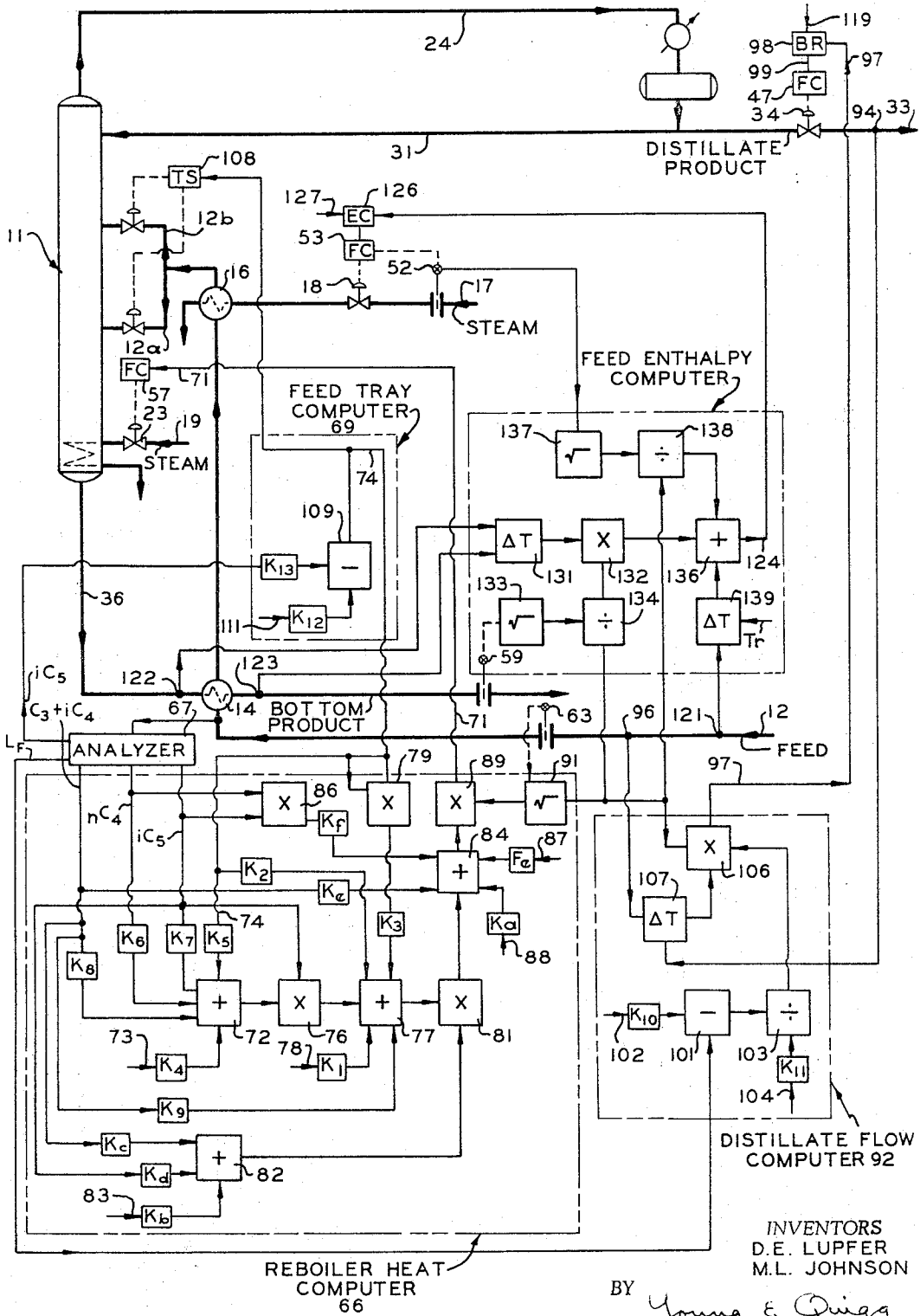


FIG. 2

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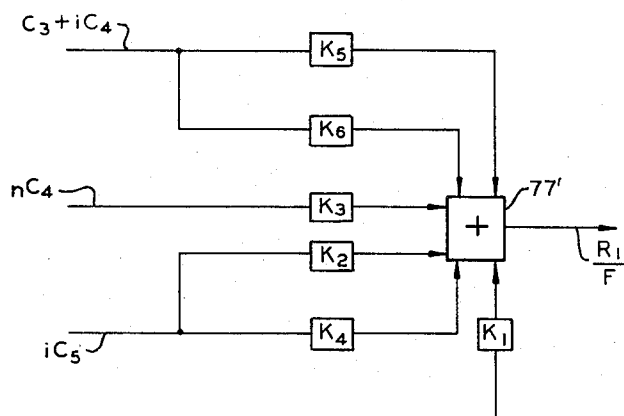


FIG. 3

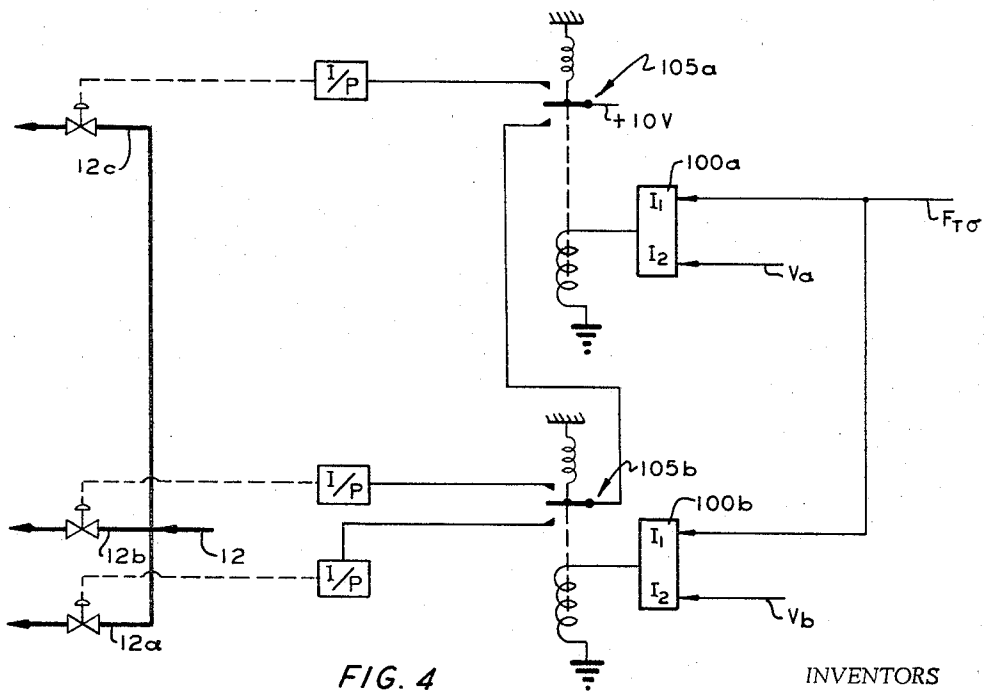


FIG. 4

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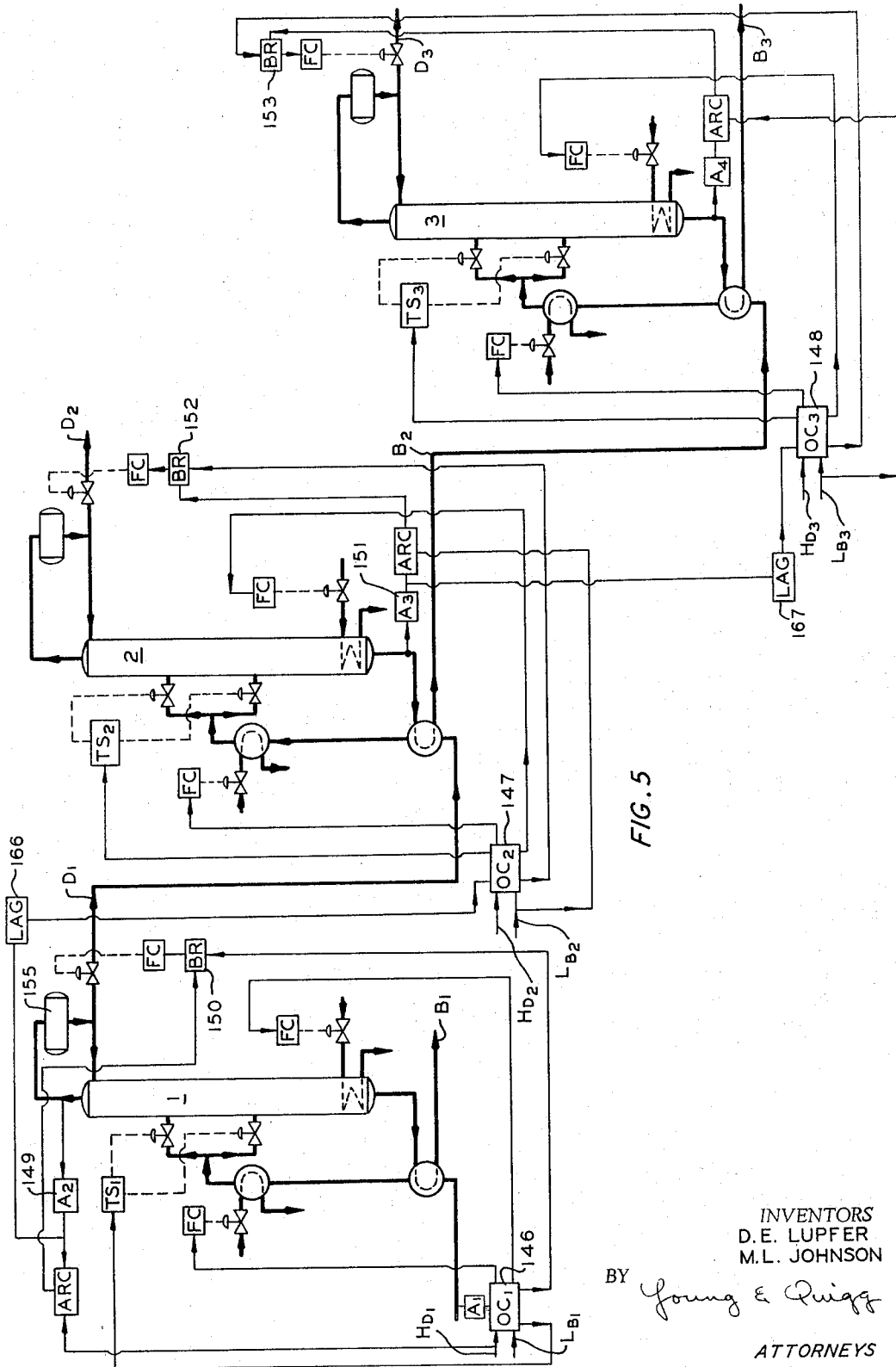
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4 Sheets-Sheet 4



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CONTROLLING THE OPERATION OF A
DISTILLATION COLUMN

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11 Claims. (Cl. 203-2)

This invention relates to controlling the operation of a distillation column. In another aspect, it relates to a method and apparatus for predicting what reboiler heat and/or distillate product flow rate are necessary for a distillation column in order to produce fractions or products, such as distillate and bottom products, of desired specifications from a particular feedstock, and for automatically manipulating these variables in response to such predictions.

There is ever-increasing activity in the art of fractional distillation to optimize the operation of a distillation column so that fractions or products with desired specifications can be produced for minimum operating costs at the column's optimum design value. Optimizing the operation of a distillation column is complicated, difficult and tricky because of the column's numerous degrees of freedom, which are characterized as independent input variables, some of which are controllable (e.g., feed temperature and reboiler heat flow) and others of which are uncontrollable (e.g., ambient temperature and feed composition). Many methods and means have been proposed, patented or used in an effort to reduce the column's degrees of freedom. However, there still remains a need for a suitable automatic method and means for optimizing the control of a distillation column to produce selected product specifications with minimum utilities consumption and maximum utilization of the unit.

One of the important variables of a distillation column is reboiler heat. In striving for optimum operation, this variable may be manipulated, particularly where there occur disturbances in certain uncontrollable input variables, such as feed composition and feed flow rate. The subject invention is particularly concerned with the automatic manipulation of this variable (reboiler heat) as uncontrollable variables fluctuate, to maintain the specified operation of the column at optimum levels. Distillate product flow rate is another important control variable which may be manipulated to compensate for disturbances in such uncontrollable variables, and the subject invention is also concerned with the automatic manipulation of distillate product flow rate, especially in combination with said automatic manipulation of reboiler heat. Another input variable that exists for many columns is that of feed tray location, and this invention provides, in combination with the predictive control of reboiler heater and/or distillate product flow, means for determining which of several trays is the optimum feed tray necessary to use in order to minimize operating costs, and provides for the automatic introduction of the feed-back onto the so-determined feed tray.

Accordingly, an object of this invention is to provide improved control of the operation of a distillation column. Another object is to provide a method and means for predicting what the reboiler heat of a distillation column should be in order to produce products, such as distillate and bottom products, of desired specifications from a particular feedstock. Another object is to provide an improved method and apparatus for predicting what the distillate product flow rate of a distillation column should be in order to produce distillate and bottom products of desired specifications from a particular feedstock. Another object is to provide an improved method and ap-

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paratus for determining, in combination with the predictive control of reboiler heat and/or distillate product flow, which of several trays in a distillation column should be used as the feed tray in order to produce distillate and bottom products of predetermined specifications at minimum operating costs. Another object is to provide an improved method and apparatus for automatically manipulating one or a combination of reboiler heat and distillate product flow rate, together with manipulation of feed tray location, notwithstanding changes in feed composition and feed flow rate, so as to produce distillate and bottom products with minimum specified purities at minimum operating costs and at the optimum design value (i.e. maximum throughput) of the column. Another object is to reduce the degrees of freedom of a distillation column by automatic adjustment of manipulated variables (reboiler heat, distillate product flow rate, and feed tray location) as uncontrolled variables (feed composition and feed flow rate) change, to maintain the specified operation of the column. A further object is to maintain the specified operation of a distillation column at optimum levels by properly regulating reboiler heat as the significant heat input to the column and by a novel predictive or feed-forward control system predict what the reboiler heat and/or distillate product flow rate should be, and automatically employ corrective action to compensate for disturbances in uncontrolled variables such as feed composition and feed flow rate.

Further objects and advantages of this invention will become apparent to those skilled in the art from the following discussion, appended claims and accompanying drawing in which:

FIGURE 1 is a schematic diagram of a distillation column provided with certain features of this invention;

FIGURE 2 is a schematic diagram of a distillation column provided with certain mathematical analog instrumentation of this invention;

FIGURE 3 is a schematic diagram of a modified portion of FIGURE 2;

FIGURE 4 is a schematic view of certain control circuitry which can be used in this invention; and

FIGURE 5 is a schematic diagram of a train of distillation columns with control features of this invention associated therewith.

To provide a setting or background for the subject invention, there will be described in brief fashion a conventional distillation column, illustrated in FIGURE 1.

In FIGURE 1, there is shown a conventional fractional distillation column 11, which can be provided with a plurality of vertically spaced liquid-vapor contact trays (not shown). Feed comprising a multicomponent mixture to be separated is supplied via line 12 and introduced, via one of feed tray supply lines 12a, 12b, 12c, onto a feed tray in column 11 located at an intermediate level therein, the flow rate of the feed supply being controlled by flow control valve 13. Feed line 12 is associated with an indirect heat exchanger or economizer 14 and an indirect heat exchanger or preheater 16. An indirect heat exchange medium such as steam is supplied via line 17 to preheater 16, the flow rate of the heat exchange medium being controlled by valve 18. Heat is supplied to the kettle of column 11 by circulation of steam or other heat exchange medium from supply line 19 through reboiler coil 21, the heat exchange medium being withdrawn from the kettle via line 22. The flow rate of the heat exchange medium in line 19 is controlled by valve 23. Vapors are removed from the top of column 11 through overhead line 24, the flow rate being controlled by valve 26, and passed through a cooler 27 such as an air-cooled condenser, the resulting liquid being passed to an accumulator 28. Liquid distillate in accumulator 28 is with-

drawn via line 29, and a portion of this withdrawn liquid is recycled via line 31 as external reflux to the top of column 11, the flow rate of the external reflux being controlled by valve 32. The balance of the liquid distillate withdrawn from accumulator 29 is removed from the system through line 33 and yielded as distillate product, the flow rate being controlled by valve 34. Bottom product is withdrawn from the kettle of column 11 via line 36 and it is passed in indirect heat exchange relationship through economizer 14 with the feed in line 12, the flow rate of the bottom product being controlled by valve 37.

Thus far, there has been described a conventional distillation column, which by itself does not constitute the subject invention. The object of the distillation column, of course, is to separate the multicomponent feed into at least two fractions, such as an overhead and a bottom product. The light components of the feed will appear mainly in the overhead and the heavy components of the feed will appear mainly in the bottom product. The light components will comprise a light component and components lighter than the light component, while the heavy components will comprise a heavy component and components heavier than the heavy component. Since perfect separation between the light component and the heavy component is impossible, some of the heavy feed component will appear as an impurity in the overhead (and thus in the distillate product) and some of the light feed component will appear as an impurity in the bottom product. However, the amounts of these impurities (called key components) can be maintained at desired levels by proper operation of the column. The operation of a distillation column can be specified by specifying the fraction (H_D) of the heavy key component desired in the overhead (or distillate product) and the fraction (L_B) of the light key component desired in the bottom product. If these specifications are to be met at minimum operating costs and at maximum utilization of the column, corrective actions must be taken at the proper time and rate to minimize the effects of disturbances on product compositions and flows.

The operation of such a distillation column is affected by disturbances in independent input variables, (i.e., the variables which can change or be changed independently without any effect of one upon the other). Such independent variables can either be manipulated or are uncontrolled. Feed composition and feed flow are examples of independent input variables which cannot be altered or controlled (within the limits of the process in question). Reboiler steam flow and distillate product flow are examples of manipulated or controlled independent input variables. Then there are dependent output variables, such as the purities of the distillate and bottom products, which are a function or result of the independent variables. As should be evident, a distillation column has numerous degrees of freedom and any significant step in the control of the operation of a distillation column must reduce these degrees of freedom.

The degrees of freedom of the distillation column of FIGURE 1 can be reduced by providing it with minimum controls well known in the art. For example, referring now to the drawing, a constant pressure in the top of column 11 can be maintained by an assembly comprising a pressure transducer 38 and pressure controller 39 in conjunction with control valve 26. A constant pressure can be maintained in accumulator 28 by passing a small amount of overhead from line 24 to accumulator 28 via by-pass line 41 and providing an assembly comprising pressure transducer 42, pressure controller 43 and flow control valve 44. The flow rate in distillate product line 33 can be regulated by an assembly comprising orifice plate 45, differential pressure transducer 46 and flow controller 47 in conjunction with control valve 34. The flow rate in reflux line 31 can be regulated by an assembly comprising orifice plate 48, differential pressure transducer 49

and flow controller 50 in conjunction with flow control valve 32, flow controller 50 being manipulated by a liquid level controller 55 associated with accumulator 28, so as to maintain a constant liquid level in the accumulator. The volume flow rate of steam in line 17 can be regulated by an assembly comprising orifice plate 51, differential pressure transducer 52 and flow controller 53 in conjunction with flow control valve 18. The volume flow rate of steam in line 19 can be regulated by an assembly comprising orifice plate 54, differential pressure transducer 56 and flow controller 57 in conjunction with flow control valve 23. The flow rate of bottom product in line 36 can be regulated by an assembly comprising orifice plate 58, differential pressure transducer 59 and flow controller 61 in conjunction with control valve 37. Similarly, the flow rate of feed in line 12 can be regulated by an assembly comprising orifice plate 62, differential pressure transducer 63 and flow controller 64 in conjunction with flow control valve 13, the setpoint of the controller usually being adjusted to satisfy the inventory of upstream processes. Further reduction in the degrees of freedom in the column can be accomplished by using the level of liquid in the reboiler of column 11 to manipulate by means of liquid level controller 65 the setpoint of flow controller 61 on the bottom product line 36. The use of these minimum control features of the prior art reduces the number of degrees of freedom of the column and their use is preferred in the practice of this invention. However, many input variables can still affect the operation.

An input variable of primary concern in this invention is reboiler heat. Uncontrolled fluctuations in this variable can affect purity and operation cost. Thus, for efficient operation this reboiler heat must be maintained at the optimum value.

There will be now described, how, according to the subject invention, the reboiler heat of a distillation column can be predicted and how the heat (e.g., steam flow rate) supplied to the reboiler can be accordingly manipulated to maintain the reboiler heat at the desired predicted value, so that distillate and bottom products with specified purities can be produced.

Briefly, measurements are made of the feed flow rate and the volume fractions of the components in the feed-stock, signals are produced proportional to such variables and these signals are combined with other signals proportional to the certain constants in a statistically-derived equation for reboiler heat based on the expression:

$$H_R = f(F, F_c, E, F_e, F_T, H_D, L_B) \quad (1)$$

where:

H_R = heat supplied to column by reboiler (B.t.u.'s/lb. of feed)

F = feed flow rate (vol./unit time)

F_c = generic symbol for components in feed, each expressed as a liquid volume fraction of feed

E = average column tray efficiency

F_e = feed enthalpy (B.t.u.'s/lb.)

F_T = feed tray (numbering trays from top of column)

H_D = specified liquid volume fraction of heavy key in distillate product

L_B = specified liquid volume fraction of light key in bottom product

For practical reasons, we prefer to develop expression (1) for the ratio of reboiler heat-to-feed flow rate, i.e., H_R/F .

A signal proportional to the reboiler heat can be recorded by a recorder (not shown) and used for monitoring purposes, only, but preferably such signal is fed forward as a setpoint-adjusting signal to trim the setpoint of the flow rate controller used to manipulate reboiler heat. This predictive corrective action compensates for changes in feed composition and feed flow rate and the corrective action is taken at the proper rate and time to minimize the effect of such changes on the desired product purities. The system used to make this corrective

action is called a predictive or feed-forward control system.

The exact equation used to predict what the reboiler heat, or the ratio of reboiler heat to feed flow rate, of the distillation column should be to obtain a specified separation will vary and be dependent upon the nature of the feedstock, products desired, and column used. But, having determined what independent variables are significantly related to reboiler heat, it is possible by straight-forward, well-known statistical methodology to determine how these significant variables can be combined in an equation to predict reboiler heat with specified limits of accuracy to compensate for changes in feed composition and feed flow. One means of developing such an equation is the response surface experiment or empirical surface study, wherein the approximate value of reboiler heat is found on the basis of the independent variables. The empirical study of reboiler heat will be adequate when the ranges of the independent variables are predetermined, and when the effects of other factors are known to be insignificant or constant. The procedure for determining the response surface is straight-forward. For this purpose, the Box-Wilson central composite designs will be quite useful since they will determine the curvature in the response surface in the region of interest. These designs provide data estimating linear, quadratic, and two-factor interaction effects by measuring each variable at five different levels, and, where plant data is used rather than theoretical data, repeating a single observation several times in order to estimate the non-reproducibility of the measurements. When the functional rela-

(2) Design and carry out screening experiments to test for the significant effects of the independent variables;

(3) Perform a correlation analysis to identify variables which should be represented in a predictive equation;

(4) Perform a surface response experiment either on the actual operation column or by tray-to-tray calculations (e.g., on a digital computer) to obtain data, using a suitable experimental design for data gathering, such as the Box-Wilson composition design; and

(5) Using regression analysis, determine the best set of coefficients for an assumed form of the predictive equation and determine the precision of the equation in terms of Coefficient of Determination and Standard Error of Estimate.

Those skilled in the art of statistics will be able to determine the predictive equation for reboiler heat for any distillation column, in view of the foregoing discussion.

As an example, a distillation column 11 like that of FIGURE 1 was used as a debutanizer to separate a mixture of hydrocarbons to produce a distillate product comprising isopentane (iC_5), normal butane (nC_4), isobutane (iC_4), and propane (C_3), and a bottom product comprising normal butane (nC_4), isopentane (iC_5), normal pentane (nC_5) and some components heavier than nC_5 designated C_6^+ . Isopentane (iC_5) was the heavy key component and appeared as an impurity in the distillate product, while normal butane (nC_4) was the light key component and appeared as an impurity in the bottom product. The data of Table I is representative of the statistical designed experiment that was necessary to describe the surface response of debutanizer column 11.

TABLE I

Run	Feed components (liquid volume percent)		iC_5	Product specifications (liquid volume percent)		E	F_e^1	F_T^2	R_T/F^3	H_R
	C_3+iC_4	nC_4		L_B	H_D					
1.....	37.0	30.5	13.0	1.0	0.2	74	11	19	1.028	125.3
2.....	26.0	25.5	13.0	1.0	0.4	74	25	31	0.844	120.7
3.....	37.0	25.5	9.0	1.0	0.4	74	11	19	0.724	103.7
4.....	26.0	30.5	13.0	0.4	0.4	60	25	31	1.454	182.3
5.....	26.0	25.5	9.0	1.0	0.4	60	25	31	0.825	131.5
6.....	37.0	25.5	13.0	0.4	0.4	74	25	19	0.884	97.5
7.....	26.0	30.5	9.0	0.4	0.4	74	25	31	0.861	131.3
8.....	37.0	30.5	9.0	0.4	0.4	60	11	19	0.906	122.2
9.....	31.5	23.0	11.0	0.7	0.3	67	18	25	0.759	111.8
10.....	20.5	28.0	11.0	0.7	0.3	67	18	25	0.827	143.8
11.....	42.5	28.0	11.0	0.7	0.3	67	18	25	0.864	90
12.....	31.5	28.0	11.0	0.7	0.3	67	4	25	0.816	128.3
13.....	31.5	28.0	11.0	0.7	0.3	67	32	25	0.875	107.4
14.....	31.5	28.0	11.0	0.2	0.3	67	18	25	1.036	142.5

¹ Reference temp., 151° F.

² Trays numbered from top of column.

³ Internal reflux flow-to-feed flow.

tionship between reboiler heat and the independent variables has thus been determined, it then is necessary to determine the coefficients in the predictive equation. One common method of analysis can be used to determine these coefficients is called regression analysis. Regression analysis assumes a relationship between the dependent variable (reboiler heat) and each term in the proposed equation, and determines the best set of coefficients for the predictive equation. The criterion for calculating the best set of constants for the equation is Gauss' familiar Principle of Least Squares, and it determines the percent of the variation in reboiler heat that is explained by the equation, and establishes the precision of the equation in terms of Standard Error of Estimate.

The following summarizes the statistical approach in deriving a predictive equation for reboiler heat:

(1) Select all independent variables believed to exert a significant effect upon reboiler heat;

Eighty-one runs were actually used to describe the surface and the runs in Table I are typical. The data for this experiment were obtained by tray-to-tray calculations on an I.B.M. 7090 digital computer. It is also possible to obtain the data from an actual operating column. However, this presents many problems, chief among which is that the variables usually do not change or cannot be changed over the range necessary to complete the statistically designed experiment.

Based on the data such as shown in Table I, expression (1) was developed for the ratio of reboiler heat-to-feed flow rate to give the following predictive statistically-derived second order equation:

$$\frac{H_R}{F} = K_a + \{K_1 + K_2(F_T) + K_3(F_T)^2 + iC_5 [K_4 + K_5(F_T) + K_6(nC_4) + K_7(iC_5) + K_8(C_3 + iC_4)] + K_9(C_3 + iC_4)\} \{K_b + K_c(C_3 + iC_4) + K_d(iC_5)\} + K_e(C_3 + iC_4) + K_f(nC_4)(iC_5) - F_e \quad (2)$$

where:

$\frac{H_R}{F}$ = reboiler heat-to-feed flow rate ratio (B.t.u./lb. of feed)

$$K_1 = A_1 + A_3(E) + A_4(E)^2 + A_{23}(F_e)^2 + H_D[A_9 + A_{10}(H_D) + A_{11}(L_B) + A_{12}(E)] + L_B[A_5(L_B) + A_7 + A_6(E)]$$

$$K_2 = A_8(L_B)$$

$$K_3 = A_2$$

$$K_4 = A_{13}(L_B) + A_{14}(E)(H_D) + A_{15}(E) + A_{17}(H_D)$$

$$K_5 = A_{16}(E)$$

$$K_6 = A_{18} + A_{19}(E)$$

$$K_7 = A_{20}$$

$$K_8 = A_{21}(E)$$

$$K_9 = A_{22}(F_e)$$

$$K_a \text{ through } K_f = \text{constants}$$

$$A_1 \text{ through } A_{23} = \text{constants}$$

In the event that the particular column being controlled does not have more than one tray which can function as a feed tray, or in the event that this variable is assumed to be a constant, Equation 2 can be rewritten as follows:

$$\frac{H_R}{F} = K_a + \frac{R_1}{F} [K_b + K_c (C_3 + iC_4) + K_d (iC_5)] + K_e (C_3 + iC_4) + K_f (nC_4)(iC_4) - F_e \quad (3)$$

where:

$\frac{H_R}{F}$ = reboiler heat-to-feed flow ratio (B.t.u./lb. of feed)

$$\frac{R_1}{F} = K_1 + iC_5 (K_2) + K_3 (nC_4) + K_4 (iC_5) +$$

$$K_5 (C_3 + iC_4) + K_6 (C_3 + iC_4)$$

$$K_1 = A_1 + A_2(F_T)^2 + A_3(E) + A_4(E)^2 + A_{23}(F_e)^2 + H_D[A_9 + A_{10}(H_D) + A_{11}(L_B) + A_{12}(E)] + L_B[A_5(L_B) + A_7 + A_6(F_T) + A_6(E)]$$

$$K_2 = A_{13}(L_B) + A_{14}(E)(H_D) + A_{15}(E) + A_{17}(H_D) + A_{16}(E)(F_T)$$

$$K_3 = A_{18} + A_{19}(E)$$

$$K_4 = A_{20}$$

$$K_5 = A_{21}(E)$$

$$K_6 = A_{22}(F_e)$$

$$K_a \text{ through } K_f = \text{constants}$$

$$A_1 \text{ through } A_{23} = \text{constants}$$

Where Equations 2 and 3 are developed for H_R rather than H_R/F , the right-hand side of the equations can be multiplied by F .

Examination of Equations 2 and 3 show that it is necessary to measure the feed flow rate F and the liquid volume fractions of C_3 , iC_4 , nC_4 and iC_5 in the feedstock, and in the case of Equation 2 to determine the feed tray location F_T . Feed enthalpy F_e , tray efficiency E , and in the case of Equation 3, feed tray F_T , are inserted as constants. E is adjusted when necessary to update the equations due to changes in column efficiency because of deposition of coke, etc.

Referring again to FIGURE 1, reference number 66 designates a computer which can be used to automatically solve Equation 2 for a predictive value of reboiler heat. Computer 66 is associated with an analyzer 67, the latter being in communication with feed line 12 by reason of a sampling line 68. Analyzer 67 comprises any suitable instrument which continuously or substantially continuously (i.e., rapid cycle) analyzes the feed and determines the relative amounts, e.g., liquid volume percent, of the components in the feed which function as independent variables in the predictive equation, and produces signals proportional thereto. Analyzer 67, such as described in I.S.A. Journal, Vol. 5, No. 10, p. 28, October 1958, preferably comprises a high speed chromatographic analyzer having a sampling valve, motor, detector, chromatographic column, programmer, and a peak reader, the latter functioning to read the peak height of the components, giving an equivalent output signal which is

suitable for control purposes. In operation, sample flows continuously through the analyzer. At a signal from the programmer, a measured volume of sample is flushed into the chromatographic column. When a sample component arrives at the detector, the resulting signal is measured, amplified, and stored until the next signal when the sequence is repeated. The stored signal is a continuous output signal analogous to the amount of the component present. Such an analyzer and the operation thereof are well known in the art.

Specifications L_B and H_D for the column operation as well as the other constants E and F_e can be dialed into computer 66. The feed tray location F_T can be determined by feed tray computer 69 and the signal proportional thereto is also transmitted to computer 66. The predicted reboiler heat H_R computed in computer 66 is transmitted as an output signal via signal line 71 to the flow controller 57 on the steam line 19, signal 71 serving as a setpoint adjusting signal for controller 57. In controller 57, the setpoint signal 71 is compared with the actual or measured heat supplied to the reboiler by steam line 19. If the predicted reboiler heat is larger than the measured reboiler heat, controller 57 will accordingly increase the flow rate of the steam in line 19 by increasing the opening of flow control valve 23. Conversely, if the predicted reboiler heat is less than the measured reboiler heat, flow controller 57 will accordingly decrease the opening of flow control valve 23. Accordingly, reboiler heat is manipulated. Thus, fluctuations in feed composition and feed flow rate are compensated for by changing the reboiler heat indirectly.

In FIGURE 2, we have schematically illustrated a novel combination of analog instruments which can be used in the solution of Equation 2 for the prediction of reboiler heat, H_R , such instrumentation being illustrated in association with an abbreviated version of column 11 of FIGURE 1. (Other computers such as digital computers can also be used.) Referring to FIGURE 2 in detail, analyzer 67 produces an output signal proportional to the sum of C_3 and iC_4 in the feedstock, which signal is necessary in the solution of Equation 2. This signal is transmitted to a potentiometer K_8 and the resulting product signal $K_8(C_3 + iC_4)$ is transmitted to a summing amplifier 72. Similarly, analyzer 67 produces signals proportional to nC_4 and iC_5 and these signals are applied across potentiometers K_6 and K_7 , respectively, and the resulting product signals $K_6(nC_4)$ and $K_7(iC_5)$ are also transmitted to summing amplifier 72. A reference potential 73 is applied across potentiometer K_4 and the output signal therefrom is also transmitted to summing amplifier 72. A signal 74 proportional to F_T is applied across potentiometer K_5 and the resulting product signal $K_5(F_T)$ is also transmitted to summing amplifier 72. The latter produces an output sum signal which is transmitted to multiplier 76 where it is multiplied by a signal proportional to iC_5 . The resulting product signal

$$iC_5[K_4 + K_5(F_T) + K_6(nC_4) + K_7(iC_5) + K_8(C_3 + iC_4)]$$

is then transmitted to summing amplifier 77. The signal from analyzer 67 proportional to the sum of C_3 and iC_4 is also applied across a potentiometer K_9 and the resulting product signal $K_9(C_3 + iC_4)$ is transmitted to summing amplifier 77. A reference potential 78 is applied across potentiometer K_1 and the output signal therefrom is also transmitted to summing amplifier 77. Signal 74 proportional to F_T is applied across potentiometer K_2 and the resulting product signal $K_2(F_T)$ is also transmitted to summing amplifier 77. Signal 74 is multiplied by itself by means of multiplier 79 and the resulting product signal $(F_T)^2$ is applied across potentiometer K_3 and the resulting product signal $K_3(F_T)^2$ is also transmitted to summing amplifier 77. The output sum signal from the latter is transmitted to a multiplier 81. The signal proportional to the sum of $C_3 + iC_4$ from analyzer 67 is also applied across a potentiometer K_e and the resulting product signal

$K_6(C_3+iC_4)$ is transmitted to summing amplifier 82. Signal iC_5 from analyzer 67 is also applied across potentiometer K_4 and the resulting product signal K_4iC_5 is also transmitted to summing amplifier 82. A reference potential 82 is applied across potentiometer K_b and the output therefrom is also transmitted to summing amplifier 82. The resulting sum signal from relay 82 is transmitted to multiplier 81, which produces an output signal proportional to

$$\{K_1+K_2(F_T)+K_3(F_T)^2+iC_5[K_4+K_5(F_T)+K_6(nC_4)+K_7(iC_5)+K_8(C_3+iC_4)]+K_9(C_3+iC_4)\}\{K_b+K_c(C_3+iC_4)+K_d(iC_5)\}$$

This latter signal is transmitted to summing amplifier 84. The signal from analyzer 67 proportional to the sum of C_3 and iC_4 is also applied across a potentiometer K_e and the resulting product signal $K_e(C_3+iC_4)$ is also transmitted to summing amplifier 84. Signals proportional to nC_4 and iC_5 are transmitted from analyzer 67 to multiplier 86 where they are multiplied and the output product signal therefrom is applied across a potentiometer K_f and the resulting product signal proportional to $K_f(nC_4)(iC_5)$ is also transmitted to summing amplifier 84. A reference potential 87 is applied across a potentiometer F_e and the output signal therefrom is also transmitted to summing amplifier 84. Another reference potential 88 is applied across a potentiometer K_a and the output signal therefrom is also transmitted to summing amplifier 84. The output sum signal from summing amplifier 84 is then transmitted to a multiplier 89 where it is multiplied by a signal proportional to F , the output signal proportional to H_R from multiplier 89 being transmitted via signal line 71 to the flow controller 57 controlling the flow of steam 19 to the reboiler. The signal F which is transmitted to multiplier 89 is supplied from a square root extractor 91, to which there is transmitted from differential pressure transducer 63 a signal proportional to the square of the flow rate of the feed in line 12.

A comparison of Equations 2 and 3 reveals that the term

$$\{K_1+K_2F_T+K_3(F_T)^2+iC_5[K_4+K_5F_T+K_6nC_4+K_7iC_5+K_8(C_3+iC_4)]+K_9(C_3+iC_4)\}$$

in Equation 2 is replaced by the term R_T/F in Equation 3. The computers which can be used to compute reboiler heat according to these equations can be the same except for this difference, and the fact that the term F_T can be dialed into the reboiler heat computer as a constant. In FIGURE 3 we have illustrated analog instrumentation which can be used to compute R_T/F . Referring to FIGURE 3, signals proportional to the designated feed components (as determined by analyzer 67 of FIGURE 2) are applied across various potentiometers (K_2 through K_8) and the output signals therefrom together with a signal proportional to K_1 are transmitted to summing amplifier 77', which produces an output signal proportional to R_T/F . This latter signal can be transmitted to multiplier 81 of FIGURE 2 in place of the output signal from amplifier 77.

As mentioned hereinabove, the distillate product flow rate is another important control variable which may be manipulated to compensate for disturbances in such variables as feed composition and feed flow, and the automatic manipulation of distillate product flow rate, particularly in combination with the automatic manipulation of reboiler heat as discussed hereinbefore, further reduces the effects of disturbances on column performance. The distillate product flow can be determined from the expression:

$$D=f(L_F, F, H_D, L_B) \quad (4)$$

where:

D =predicted volume flow rate of distillate product if flow is measured at temperature equal to feed temperature

L_F =generic symbol for the sum of the light key component and components lighter than the light key, each expressed as a liquid volume fraction of feed

F =feed flow rate (volume/unit time)

H_D =specified fraction of heavy key in distillate (liquid volume decimal fraction)

L_B =specified fraction of light key in bottoms product (liquid volume decimal fraction)

In the example where column 11 of FIGURE 1 is used as a debutanizer, Expression 4 becomes:

$$D=f(C_3, iC_4, nC_4, F, H_D, L_B) \quad (5)$$

where:

H_D =specified fraction of isopentane in distillate (liquid volume decimal fraction)

L_B =specified fraction of normal butane in bottom product (liquid volume decimal fraction)

The exact distillate product flow rate predictive equation can be derived from a material balance, and this equation (for the debutanizer example) is expressed as:

$$D=F\left(\frac{L_F-K_{10}}{K_{11}}\right) \quad (6)$$

where:

$K_{10}=L_B$

$K_{11}=1-L_B-H_D$

Equation 6 shows that the distillate product flow rate can be computed if H_D and L_B are specified and if the feed flow F and feed components L_F are known. Computer 92 of FIGURE 1 is applied to manipulate D as a function of these variables. When the feed composition and/or feed flow changes, a new value of distillate product flow is computed by computer 92 and the computed value of distillate product flow rate is gradually forced upon the column in a predictive manner.

There is one practical consideration which must be made when applying Equation 6 to an operating column. This consideration arises when feed flow F and distillate product flow D are measured in volume per unit time. Equation 6 assumes the volume flows D and F are at the same temperature. If they are not at the same temperature, compensation is necessary. One method of compensating requires that distillate product flow D be referred to feed temperature by multiplying the right side of Equation 6 by the quantity:

$$1+K_D\Delta T$$

where:

K_D =coefficient of thermal expansion (change in vol./unit vol./° F.)

$T=T_{D2}-T_{F1}$

T_{D2} =temperature of distillate product at point where distillate flow is measured (° F.)

T_{F1} =temperature of feed at point where feed flow is measured (° F.)

Equation 7 with necessary compensation becomes:

$$D=F(1+K_D\Delta T)\left(\frac{L_F-K_{10}}{K_{11}}\right) \quad (8)$$

where:

D =volume flow rate of distillate product at existing temperature

Referring now to FIGURE 1, the feed composition information needed in the solution of Equation 8 can be supplied from analyzer 67 to distillate flow computer 92 by signal line 93. The temperature T_{D1} of the distillate and temperature T_{F1} of the feed are detected by thermocouples 94 and 96, respectively, and transmitted to distillate flow computer 92, as is the feed signal from flow transducer 63 associated with feed flow line 12. In addition, the product specifications H_D and L_B are dialed into the computer 92. The computed distillate product flow rate D is transmitted as an output signal 97 from

computer 92 to a biasing device 98 such as a conventional summing relay. The biasing device 98 accordingly produces an output signal 99 which serves as the setpoint for flow controller 47 of the distillate product line 33. Flow controller 47 compares the predicted distillate flow rate with the measured distillate flow rate; if the predicted value is the larger of the two, the flow controller proportionately increases the opening of valve 34, and, conversely, if the predicted value is smaller than the measured value, valve 34 is proportionately closed down.

A suitable embodiment of a distillate flow computer is shown in more detail in FIGURE 2. In FIGURE 2, a signal proportional to L_F is transmitted from analyzer 67 to a summing relay 101. A reference potential 102 is applied across a potentiometer K_{10} and the resulting signal therefrom also transmitted to summing relay 101. The sum from relay 101 proportional to $(L_F - K_{10})$ is transmitted to a divider 103. A reference potential 104 is applied across a potentiometer K_{11} and the signal therefrom also transmitted to divider 103. The quotient $(L_F - K_{10})/K_{11}$ from divider 103 is transmitted to a multiplier 106. The temperatures T_{D2} and T_{F1} , measured by thermocouples 94 and 96, respectively, are supplied to a differential temperature transducer 107 to determine ΔT of Equation 8. Transducer 107 is calibrated to provide an output signal proportional to $(1 + K_D \Delta T)$, the constant 1 being added by adjustment of the transducer's zero point and the constant K_D being taken care of by adjustment of the span of the transducer. The signal from transducer 107 is transmitted to multiplier 106, as is a signal proportional to F from square root extractor 91. The resulting product signal from multiplier 106 is proportional to D of Equation 8, which signal is transmitted to biasing relay 98. The output of biasing device 98 is transmitted by signal line 99 for manipulation of control valve 34 by distillate product flow controller 47 as described in the preceding paragraph.

In another aspect of this invention, the predictive control of reboiler heat and/or distillate product flow can be combined with the predictive control of feed tray location. The optimum feed tray location can be found by taking the partial derivative of the reboiler heat Equation 2 with respect to feed tray location F_T , setting this partial derivative equal to zero, and solving for the optimum feed tray. For example, the partial derivative of Equation 2 is:

$$\frac{\partial H_R}{\partial F_T} = A_8(L_B) + 2A_2(F_T) + A_{16}(E) (iC_5) \quad (9)$$

By setting Equation 9 equal to zero, and solving for the optimum feed tray location, F_{T0} , the following equation is developed:

$$F_{T0} = K_{12} + K_{13} (iC_5) \quad (10)$$

where:

$$K_{12} = -\frac{A_8(L_B)}{2A_2}$$

$$K_{13} = -\frac{A_{16}(E)}{2A_2}$$

In FIGURE 1 a computer which can be used to solve for the optimum feed tray location F_{T0} is identified by reference numeral 69. Its output signal F_{T0} , designated by reference numeral 74, can be used by the reboiler heat computer 66, as described hereinbefore, and in addition can be used to manipulate a tray selector controller 108, which in turn manipulates the valves in feed input lines 12a, 12b and 12c (only two of which are shown in FIGURE 2 for purposes of brevity).

One embodiment of a suitable tray selector is shown in FIGURE 4, and it comprises voltage comparators 100a, 100b, and relay switches 105a, 105b. Feed tray supply lines 12a, 12b, and 12c are shown, each having

flow control valves therein, such valves preferably being normally closed air operated diaphragm valves, the operation of which are controlled by the tray selector, which in turn is responsive to the optimum feed tray signal F_{T0} from computer 69 of FIGURE 1.

V_a is a voltage representing the tray number midway between the trays supplied by supply lines 12c and 12b, and V_b is a voltage representing the tray number midway between the trays supplied by supply lines 12b and 12a. Each of the voltage comparators 100a, 100b, have two inputs, I_1 and I_2 , as shown. These voltage comparators are energized when I_1 (viz., F_{T0}) is greater than I_2 (viz., V_a or V_b). Relays 105a, 105b each comprise a pivotal contact normally biased in an "up" position by a spring, and a rod connected to the contact at one end and surrounded by an electrical coil at the other end, said coil being energizable by its adjacent voltage comparator. The boxes containing "I/P" in FIGURE 4 are conventional current-to-pressure converters.

In operation, when F_{T0} is less than either of V_a and V_b , the voltage comparators will not be energized, and the contacts of both relays will be in their biased "up" positions, and the valve in supply line 12c will be opened, while the valves in supply lines 12b and 12a will be closed. When F_{T0} is greater than V_a but less than V_b , only voltage comparator 100a will be energized, and relay 105a will be in its "down" position and relay 105b will be in its "up" position, and consequently only the valve in supply line 12b will be opened. When F_{T0} is greater than either V_a or V_b , both voltage comparators will be energized, and both relays will be in their "down" positions, and consequently only the valve in supply line 12a will be opened.

Similar tray selectors can be designed for any other combination of possible feed trays.

An embodiment of a suitable analog computer which can be used as the feed tray computer 69 is shown in FIGURE 2. In the latter, a signal iC_5 is applied across potentiometer K_{13} and the resulting $K_{13}(iC_5)$ is transmitted to a summing relay 109. A reference potential 111 is applied across a potentiometer K_{12} , and the resulting signal also transmitted to relay 109. The resulting quotient signal 74 is proportional to F_{T0} .

As described hereinbefore, the reboiler heat computer is utilized in a predictive manner to control the reboiler heat. Since predictive controls as such may often only be approximate and not exact, we prefer to override the control operation with feedback control. To achieve this feedback control, referring again to FIGURE 1, we prefer to analyze the overhead in line 24 (if this is the more important product) by means of an analyzer 116 to determine the concentration of the heavy key component, e.g., isopentane. Analyzer 116 can be a chromatographic, infrared, or ultraviolet analyzer, or the like, or a mass spectrometer, or any other suitable analyzer which will measure the concentration of the component and provide a signal representative thereof. Analyzer 116 produces an output signal corresponding to the concentration of the heavy key in overhead line 24 and it is transmitted to a controller 117, such as an analyzer recorder controller, where it is compared with a setpoint signal 118 proportional to H_D . Any difference in the actual (or measured) heavy key concentration in the overhead and H_D is transmitted as a signal to bias relay 98. For example, if the key component in the bottom product is on specification, but the key component in the overhead is less than the specified concentration H_D , this means that the overhead (and consequently the distillate) has a purity better than that necessary, i.e., that the column is being operated at operating costs greater than minimum. Accordingly, the analyzer controller 117 produces a signal 119 which can add to or subtract from the computed distillate flow signal 97. If computed distillate flow signal 97 is exactly that required to give the product purity specified, signal 99 will equal

97. Due to errors in measurements and computing, signal 97 will be slightly altered by signal 119 to always produce the exact distillate flow setpoint 99 required.

Where the bottom product purity is of more importance than the distillate purity, analyzer means can analyze instead the bottom product to determine the concentration of the light key component therein, and the difference between this measurement and L_B can be used to bias the computed distillate flow signal 97.

Although the predictive control systems for reboiler heat and distillate product flow discussed above significantly reduce the degrees of freedom of a distillation column so that improved control of the distillation operation is effected and practical profits obtained, we prefer in another aspect of this invention to also regulate the feed enthalpy (heat content), since this will improve operation of the column. Where the feed rate changes, or where the feed must be heated to its bubble point or must be partially vaporized, any variations in feed flow, initial feed enthalpy, steam, steam supply conditions, or bottom product flow, may give rise to substantial changes in feed enthalpy with very little or no change in feed temperature. So, we prefer in combination with the above-described control of reboiler heat and distillate product to compute the enthalpy of the feed and regulate it notwithstanding a wide range of feed flow rates, changes in the physical state of the feed, and flow disturbances in the heat exchange medium. The system we prefer to use to accomplish this is that disclosed in co-pending application Serial No. 125,025 filed July 3, 1961 by M. W. Oglesby and D. E. Lupfer.

Where the feed heated in the economizer is not vaporized but remains in the liquid state, and the heated liquid feed is then passed to a preheater, and is then introduced into the column, the enthalpy of the feed can be computed from the following equation:

$$F_e = C_{pF}(T_f - T_r) + (S/F)h_s$$

where:

F_e = total enthalpy of feed leaving preheater above reference temperature T_r , (B.t.u.'s/lb.)

C_{pF} = average specific heat of feed (B.t.u.'s/lb. $\times$ $^{\circ}$ F.)

T_f = temperature of feed at exit of economizer exchanger ($^{\circ}$ F.)

T_r = reference temperature ($^{\circ}$ F.)

S = steam flow (lb./hr.)

F = feed flow (lb./hr.)

h_s = difference in enthalpy of steam entering preheater and the condensate T_o , (B.t.u.'s/lb.)

However, in many cases the feed at the exit of the economizer will be partially vaporized, and so we prefer in such event to compute the feed enthalpy by the following equation:

$$F_e = C_{pF}(T_f - T_r) + (S/F)h_s + (B/F)(C_{pB})(T_{b1} - T_{b2})$$

where:

T_f = temperature of feed before entering economizer exchanger ($^{\circ}$ F.)

C_{pB} = average specific heat of bottoms product (B.t.u.'s/lb. $\times$ $^{\circ}$ F.)

B = bottom flow (lb./hr.)

T_{b1} = temperature of bottom product (B.t.u.'s/lb. $\times$ $^{\circ}$ F.)

T_{b2} = temperature of bottom product leaving economizer exchanger ($^{\circ}$ F.)

A feed enthalpy computer which can be used in the solution of Equation 12 is generally designated 121 in FIGURE 1. The temperature T_f , T_{b1} and T_{b2} are detected by thermocouples 121, 122 and 123 respectively, and transmitted to feed enthalpy computer 121, together with a flow rate signal F from transmitter 63, a flow rate signal B from transmitter 59, and a flow rate signal S from transmitter 52. The output signal 124 from enthalpy computer 121 is proportional to the enthalpy F_e of the feed above the reference temperature. This output signal

124 can be recorded by a recorder (not shown) and used for monitoring purposes only, or this output can be conveyed to a suitable enthalpy controller recorder 126 to which is supplied the desired enthalpy value as setpoint 127, the latter being proportional to a value that will result in the least operating costs for the column. The output of enthalpy controller 126 then manipulates the setpoint of steam flow controller 53 so as to maintain the enthalpy of the feed introduced into column 11 at a constant value. Although this particular arrangement assumes constant steam supply conditions, variations can be taken into account by proper measurements of the steam. Computer 121 would be modified to take this into account.

In FIGURE 2 we have illustrated in detail the feed enthalpy computer 121 of FIGURE 1. Referring now to FIGURE 2, differential temperature transducer 131 compares temperature signals T_{b1} and T_{b2} , detected by thermocouples 122 and 123, respectively. Transducer 131 is calibrated to provide an output signal proportional to $C_{pB}(T_{b1} - T_{b2})$, the constant C_{pB} taken care of by adjustment of the span. The output signal from transducer 131 is supplied to a multiplier 132. Signals proportional to the squares of the flow rates of bottom product and feed, as established by differential pressure transducers 59 and 63 respectively, are transmitted to square root extractors 133 and 91, respectively, and outputs from these extractors are transmitted to a divider 134. The output signal from the latter, proportional to B/F , is then transmitted to multiplier 132, where it is multiplied by $C_{pB}(T_{b1} - T_{b2})$, and the product signal therefrom is transmitted to an adder 136. Signals proportional to the squares of the flow rates of steam and feed, as established by differential pressure transducers 52 and 63, respectively, are transmitted to square root extractors 137 and 91, respectively. The outputs from these extractors are transmitted to a divider 138, and the output from the latter proportional to $(S/F)h_s$ is transmitted to adder 136, the constant h_s being handled by adjusting the span of divider 138. The temperature T_r , detected by thermocouple 121 of feed line 12, and temperature T_f are compared in a temperature transmitter 139, which produces an output signal proportional to $C_{pF}(T_f - T_r)$, is also transmitted to adder 136, the constant C_{pF} being added by adjustment of the span of transducer 139. Adder 136 adds the three input signals supplied thereto and produces an output signal 124 proportional to F_e , the total enthalpy of the feed with reference to T_r .

As shown in FIGURE 1, a single distillation column can be instrumented with a feed analyzer 67 and an overhead (or bottom product) analyzer 116 to achieve a predictable operation of that column. If column 11 is one column in a train of distillation columns, such as illustrated in FIGURE 5, each of such columns 1, 2, and 3 would have to be provided with two such analyzers. However, to avoid such costly installation and expense, we prefer to utilize that analyzer analyzing the product of more importance of one column for the dual purpose of analyzing the feed composition necessary to control the operation of the subsequent column which employs as feed a product from the preceding column; thus, where the bottom product (or distillate) of one column serves as feed to a subsequent column in the train, we prefer to use that analyzer which analyzes the bottom product (or distillate) for purposes of feedback control to serve the dual purpose of analyzing such product for the necessary feed components used in the predictive control of the subsequent column which uses said product as feed. Referring to FIGURE 5, each of columns 1, 2, and 3 are provided with an operations computer 146, 147 and 148, respectively. Each of such operations computers can comprise in one unit the above-described combination of the reboiler heat computer 66 with the distillate computer 92, or the above-described combination of such computers with feed tray computer 69 and the feed enthalpy com-

puter 121. Column 1 is provided with an overhead analyzer 149, for the purpose of determining in one phase of operation the concentration of the heavy key component in the overhead, so as to bias the computed distillate product flow of that column. In addition, analyzer 149 of column 1, in another phase of operation, analyzes the overhead to determine the concentration of components of interest, and this composition information is transmitted to the operations computer 147 of column 2, since the feed to this latter column will consist of the distillate D_1 from column 1. In the case of column 2, the product of interest here is the bottom product B_2 and the analyzer 151, in one phase of its operation, determines the concentration of the light key component in the bottom product B_2 , and sends a corrective signal to bias relay 152 for purposes of feedback control. In another phase of its operation, analyzer 151 analyzes the bottom product B_2 to determine the concentration of those components necessary in the solution of the predictive equation solved by operations computer 148 of column 3, which column employs as feed the bottom product B_2 of column 2. In the train of fractionators illustrated in FIGURE 5, the total number of analyzers required for predictive and feedback control would be four.

In describing the various aspects of this invention thus far, no attention has been given to column dynamics, and the predictions of reboiler heat, reflux and distillate product flow are accurate and satisfactory where changes in feed flow and feed composition are relatively small. The equations for prediction of reboiler heat and distillate product flow are in fact steady-state equations. However, where there are relatively large, material and frequent changes in feed flow or feed composition, we propose to take into account the dynamics of the column and modify the predictive control systems. Material changes in these variables of feed composition and feed flow necessitates compensation for the process dynamics of dead-time and exponential response in making the reboiler heat and distillate flow adjustments to minimize changes in product composition.

Dead-time is the time elapsing between the initiation of a process change and the detection (or manifestation) of the effect of the change at another point in the process system. Exponential response is the gradual change in a variable resulting from a step change in input.

To illustrate the problem when there is a material change in feed flow, the following happens when the column depicted in FIGURE 1 is operated without compensation for dead-time and exponential response. Assume that column 11 has 1200 units of feed, that the split is such that 850 units of overhead and 350 units of bottom product result, that the internal reflux is 1050 units, and that reboiler heat H_R is 1900 units. An abrupt change in feed flow to 1300 units will immediately increase the distillate product to 921 units by action of the distillate product flow computer 92, the internal reflux will decrease to 979 by action of the accumulator level controller 55, and the reboiler heat will increase to 2060 units. The increase in distillate product flow will decrease the reflux flow by 71 units and the increase in reboiler heat will decrease the bottom product flow by 160 units because of the reboiler level controller action. Both reflux flow and bottom product flow have responded in the wrong direction. Eventually bottom product flow will increase when the increased feed flow reaches the reboiler and reflux flow will increase when increased vapor reaches the overhead accumulator. All variables will return to their proper values in time but during the transient period reboiler heat and reflux flow respond in the wrong directions. These responses may in turn be transmitted to succeeding columns in the train.

When changes in feed flow occur, it is necessary to lag the adjustments to reboiler heat and distillate product flow so that both the overhead and bottom products flows will respond in the proper direction without overshoot

in the least time. Such adjustments will result in establishing the proper liquid to vapor flow ratios within the column in minimum time, thereby the smallest possible deviation in terminal product compositions will result. The lags necessary to accomplish this are determined by the column material flow dynamics.

Compensation for dead-time can be made by first, second, third, fourth and nth order dead-time simulators, depending upon process dynamics of the system. Such dead-time simulators are described in said copending application Serial No. 125,025. Compensation for exponential response can be made by the use of first, second, third and nth order interacting or non-interacting lags, depending upon the process dynamics of the system. Such exponential response compensators are also disclosed in said copending application Serial No. 125,025.

When a change in feed flow occurs, the flow from the feed tray down the column will be lagged by each tray. If there are 25 trays from the feed tray to the column bottom, the dynamic character of the flow process can be approximated by a 25th order non-interacting lag. Each tray is essentially a first order lag. It is necessary to lag the reboiler heat adjustment at least the same amount or bottom product flow will respond in the wrong direction due to action of the bottom level controller. The use of equipment necessary to simulate a 25th order lag for a lag device 162 would be expensive. Therefore, the desired lag is approximated with an approximate dead-time device and a low order lag system. Such devices are described in said copending application Serial No. 125,025. The parameters (time constants and gains) for the approximate lag devices are usually determined experimentally when installed on the column.

Device 163 required to lag the distillate product flow adjustment as a function of feed flow changes is basically the same as device 162. The parameters of device 162 are usually adjusted to give slightly longer lags than are used for lag 163. The requirements for lag 162 are the same as lag 163 except for that fact that lag 162 must also include the lags necessary to simulate the vapor flow from the bottom of the column to the reflux accumulator.

Changes in feed composition may be of such a nature to require dynamic compensation similar to that required for feed flow changes. This is seldom the case. Sudden changes in feed composition to distillation columns is rare. When the changes are slow, no dynamic compensation is required. Straight, steady-state corrections are satisfactory. Of course, whenever sudden changes in feed composition can occur, lags will need to be introduced in each of the feed component measurement signals.

In general, the lags required are multiorder in nature. Approximation would also be used for these as an economic measure.

Wherein that aspect of the invention illustrated in FIGURE 5 the analyzer 149 is used in determining the concentration of stream components for purpose of reboiler heat prediction by computer 147, it will also be necessary to delay the transmission of this composition information to computer 147. This is because there will be a definite lag between the time such analysis is made and the time that the liquid in accumulator 155 is introduced as feed into column 2. To accomplish the lag of this signal, we prefer to interpose a lag means 166 between computer 147 and analyzer 149, such lag means having dynamics equivalent to accumulator 155. An example of such lag means is the combination of a 3rd order exponential lag and a 2nd order dead-time model.

Similarly, the composition information fed by analyzer 151 to reflux computer 148 must be delayed to compensate for the difference in time between that time when the analysis of the bottom product of column 2 is made by analyzer 151 and that time when such bottom product is introduced as feed into column 3. For this purpose we can interpose an appropriate lag means 167 which

will have dynamics equivalent to this part of the process.

In one form of the invention, the described control system is operated by air pressure. For example, transmitters 52, 59 and 63 can all supply air pressure proportional to the measured properties and the adding relays and force bridges, in turn, modify and supply air pressure signals. If air pressures are used, it is necessary to provide supply air to the various components but it has not been thought necessary to show such an air supply system since such systems are well known in the art and to show such a system here would simply complicate the drawing unnecessarily.

All of the various components, that is, the sensing elements, transmitters, adding relays, dividers, multipliers, square root extractors, bias relays, flow controller valves, etc., are well known in the art and, therefore, details of their construction have not been shown here. For example, Taylor Transmitter No. 317 RG, described in Taylor Instrument Company Brochure 2B100 of December 1952 may be used for temperature transmitters. Adding relays may consist of the Foxboro Model 56 Computing Relay, described in Catalog 37-A-57a, September 12, 1956, of the Foxboro Company. The Sorteberg Force Bridge, described in Catalog C80-1-5M, December 1956, of the Minneapolis-Honeywell Company, may be used for dividers, square root extractors, multipliers, etc. Foxboro Model M/40 Controller, described in Bulletin 5A-10A, November 1955, of the Foxboro Company, may be used for flow rate controllers. All electronic components can be employed. These are also well known in the art.

Various modifications and alterations of this invention will become apparent to those skilled in the art without departing from the scope and spirit of this invention, and it should be understood that the foregoing description and accompanying drawing should not be construed to limit unduly this invention.

We claim:

1. In a process wherein a multicomponent feed stream is separated in a fractional distillation column into an overhead vapor stream and a liquid bottom product stream each having a specified purity, said overhead stream is condensed, some of the condensed overhead is recycled to said column as an external reflux stream, some of said condensed overhead is yielded as a distillate product stream having a specified purity, and heat is supplied to the reboiler of said column, a control method for said process comprising the steps of measuring the amounts of feed components in said feed stream; producing signals proportional to said measurements; combining said signals together with signals proportional to constants in a statistically-derived equation based on the expression:

$$\frac{H_R}{F} = f(F_c, E, F_T, F_e, H_D, L_B)$$

where

$$\frac{H_R}{F} = f(F_c, E, F_T, F_e, H_D, L_B)$$

F_c =generic symbol for components in feed, each expressed as a liquid volume fraction of the feed in said feed stream

E =average column tray efficiency

F_T =the number feed tray at which the feed stream enters into the column, wherein the trays are numbered from the top of said column

F_e =feed enthalpy of said feed stream (B.t.u.'s per pound)

H_D =specified liquid volume fraction of heavy key in distillate product

L_B =specified liquid volume fraction of light key in said bottom product stream,

producing a signal in a reboiler heat computer proportional to said H_R/F ; measuring process variables indicative of the feed flow rate to said column; producing a signal responsive thereto proportional to said feed flow rate; multiplying the H_R/F signal by said signal propor-

tional to the feed flow rate; producing a signal proportional to H_R ; measuring a process variable indicative of the supply of heat to the reboiler of said column; producing a signal in response thereto; comparing the latter signal with said H_R ; controlling the supply of heat to said reboiler in accordance with said comparison to produce at an optimum said distillate and bottom product streams with said purities H_p and L_B , respectively; measuring the amounts of light key feed component and feed components lighter than the said light key feed; producing signals responsive to said measurements proportional to the amounts of said key components; combining the former signals with the aforesaid feed flow rate signal in a predictive equation derived from a material balance around said column; combining the latter signals in a distillate flow computer based on the expression:

$$D = f(L_F, F, H_D, L_B)$$

where:

D =predicted volume flow rate of distillate product when flow is measured at temperature equal to feed temperature

L_F =generic symbol for the sum of the light key component and components lighter than light key, each expressed as a liquid volume fraction of said feed

F =feed flow rate (volume per unit time)

H_D =specified liquid volume decimal fraction of heavy key in distillate

L_B =specified liquid volume decimal fraction of light key in bottoms product;

producing a signal proportional to D ; analyzing one of said overhead and bottom product streams to determine the concentration of a specified key component thereof; producing a feedback signal responsive to said analysis proportional to said concentration; comparing said signal D with said feedback signal and biasing the predicted flow rate D of said distillate product stream with said feedback signal.

2. In the process according to claim 1, wherein said feedback signal is obtained from a measurement of the heavy key component in said overhead stream.

3. In the process according to claim 1 wherein said feedback signal is obtained from a measurement of the light key component in said bottom product stream.

4. In a process wherein a multicomponent feed stream is separated in a fractional distillation column into an overhead vapor stream and a liquid bottom product stream each having a specified purity, said overhead stream is condensed, some of the condensed overhead is recycled to said column as an external reflux stream, some of said condensed overhead is yielded as a distillate product stream having a specified purity, and heat is supplied to the reboiler of said column, a control method for said process comprising the steps of measuring the amounts of feed components in said feed stream; producing signals proportional to said measurements; combining said signals together with signals proportional to constants in a statistically-derived equation based on the expression:

$$\frac{H_R}{F} = f(F_c, E, F_T, F_e, H_D, L_B)$$

where:

$\frac{H_R}{F}$ =ratio of predicted reboiler heat-to-feed flow rate for said column

F_c =generic symbol for components in feed, each expressed as a liquid volume fraction of the feed in said feed stream

E =average column tray efficiency

F_T =the number feed tray at which the feed stream enters into the column, wherein the trays are numbered from the top of said column

F_e =feed enthalpy of said feed stream (B.t.u.'s per pound)

H_D =specified liquid volume fraction of heavy key in distillate product

L_B =specified liquid volume fraction of light key in said bottom product stream,

producing a signal in a reboiler heat computer proportional to said H_R/F , measuring process variables indicative of the feed flow rate to said column; producing a signal responsive thereto proportional to said feed flow rate; multiplying the H_R/F signal by said signal proportional to said feed flow rate; producing a signal proportional to H_R , measuring a process variable indicative of the supply of heat to the reboiler of said column; producing a signal in response thereto; comparing the latter signal with said H_R signal; controlling the supply heat to said reboiler in accordance with said comparison to produce at an optimum said distillate and bottom product streams with said purities H_D and L_B , respectively.

5. In the process according to claim 4 wherein said column is a debutanizer column and said feed stream comprises a mixture of propane, isobutane, normal butane, isopentane, normal pentane, and hexane, and wherein the heavy key component in said distillate product stream is isopentane and the light key component in said bottom product stream is normal butane.

6. In a process wherein a multicomponent feed stream is separated in a fractional distillation column into an overhead vapor stream and a liquid bottom product stream having a specified purity, said overhead stream is condensed, some of the condensed overhead is recycled to said column as an external reflux stream, and some of said condensed overhead is yielded as a distillate product stream having a specified purity, a control method comprising the steps of measuring the amounts of light key feed component and feed components lighter than the said light key feed; producing signals responsive to said measurements proportional to the amount of said key components; measuring a process variable indicative of the flow rate of feed to the column; producing a signal in response thereto proportional to the feed flow rate; combining the former signals with said feed flow rate signal in a predictive equation derived from a material balance around said column; combining the latter signals in a distillate flow computer based on the expression:

$$D=f(L_F, F, H_D, L_B)$$

where:

D =predicted volume flow rate of distillate product when flow is measured at temperature equal to feed temperature

L_F =generic symbol for the sum of the light key component and components lighter than light key, each expressed as a liquid volume fraction of said feed

F =feed flow rate (volume per unit time)

H_D =specified liquid volume decimal fraction of heavy key in distillate

L_B =specified liquid volume decimal fraction of light key in bottoms product;

producing a signal proportional to D ; analyzing one of said overhead and bottom product streams to determine the concentration of a specified key component thereof; producing a feedback signal responsive to said analysis proportional to said concentration; comparing said signal D with said feedback signal and biasing the predicted flow rate D of said distillate product stream with said feedback signal.

7. In a process wherein a multicomponent feed stream is separated into fractions in a train of fractional distillation columns, wherein each of said columns separates a common feed stream into an overhead vapor stream and a liquid bottom product stream having a specified purity, said overhead is condensed, some of the condensed overhead is recycled to said column as an external reflux stream, some of said condensed overhead is yielded as a distillate product stream having a specified purity, steam is supplied to the reboiler of said column, wherein one of said distillate and bottom products streams of one of said columns comprises the column feed of a subsequent

column in said train, a control method for ensuring the flow rates of the steam and distillate product streams of each of said columns is controlled to ensure that each of said columns produces at an optimum distillate and bottom product stream of specified purities, said control method with respect to each of said columns comprising the steps of measuring the amounts of feed components in a first feed stream to a first column; producing signals responsive thereto; combining said signals together with signals proportional to constants in a statistically-derived equation based on the expression:

$$\frac{H_R}{F}=f(F_c, E, F_T, F_e, H_D, L_B)$$

where:

$\frac{H_R}{F}$ =ratio of predicted reboiler heat-to-feed flow rate for said first column

F_c =generic symbol for components in feed, each expressed as a liquid volume fraction of feed

F =feed flow rate (volume per unit time)

E =average column tray efficiency of said first column

F_T =the feed tray on the first column on which the feed enters (numbering trays from top of column)

F_e =feed enthalpy (B.t.u.'s per pound)

H_D =specified liquid volume fraction of heavy key in distillate product

L_B =specified liquid volume fraction of light key in said bottom stream of said first column

producing a signal proportional to H_R/F ; measuring process variables indicative of the feed flow rate to said column; producing a signal responsive thereto proportional to said feed flow rate; multiplying the H_R/F signal by said feed flow rate signal; producing a signal proportional to H_R ; measuring a process variable indicative of the flow rate of steam supplied to the reboiler of said first column; producing a signal responsive thereto proportional to said steam flow rate; comparing the latter signal with H_R ; controlling the flow rate of said steam to said first column in accordance with said comparison; measuring the amounts of light key feed component and feed components lighter than the light key feed component in said first feed stream; producing signals responsive thereto proportional to said amount of key components; combining the latter signals in a distillate flow computer with said flow rate signal of said first feed stream in a predictive equation derived from a material balance around said first column and based on the expression:

$$D=(L_F, F, H_D, L_B)$$

where:

D =predicted volume flow rate of distillate product when flow is measured at temperature equal to feed temperature

L_F =generic symbol for the sum of the light key component and components lighter than light key, each expressed as a liquid volume fraction of feed

F =feed flow rate (volume per unit time)

H_D =specified liquid volume decimal fraction of heavy key in distillate

L_B =specified liquid volume decimal fraction of light key in bottoms product

producing a signal proportional to D ; analyzing one of said overhead and bottom product streams to determine the concentration of a specified key component thereof; producing a feedback signal responsive to said analysis proportional to said concentration; comparing said signal D with said feedback signal and biasing the predicted flow rate D of said distillate product stream of said first column in accordance therewith; and repeating said control method for each of said columns in said train.

8. In the process according to claim 7, wherein said feedback signal used in the control of the flow rate of said distillate product stream is obtained by analysis of a product stream employed as feed in a subsequent column in said train.

9. In a fractionation system wherein a multicomponent feed stream is passed into a fractional distillation column, an overhead vapor stream is withdrawn from the top of said column and condensed, some of the condensed overhead is recycled to said column as an external reflux stream, some of said condensed overhead is yielded as a distillate product stream having a specified purity, a liquid bottom product stream having a specified purity is withdrawn from the bottom of said column, and steam is supplied to the reboiler of said column, a control system comprising means to measure a process variable indicative of the flow rate of said feed stream; means responsive to said flow rate measurement for establishing a signal proportional to the flow rate of said feed stream; means to measure the amounts of feed components in said feed stream; means responsive to said feed measurements to establish signals proportional to the amounts of feed components in said feed stream; means to combine said component measurement signals in a statistically-derived equation to establish a signal H_R proportional to a predicted value for the reboiler heat of said column, said equation being based on the expression:

$$H_R = f(F, F_c, E, E_T, F_e, H_D, L_B)$$

where:

H_R = heat supplied to column by reboiler (B.t.u.'s per pound of feed)

F = feed flow rate (volume per unit time)

F_c = generic symbol for components in feed, each expressed as a liquid volume fraction of said feed

E = average column tray efficiency

F_T = the number of tray on which the feed enters the column (numbering trays from top of column)

F_e = feed enthalpy (B.t.u.'s per pound)

H_D = specified liquid volume fraction of heavy key in distillate product

L_B = specified liquid volume fraction of light key in bottom product

means to measure a process variable indicative of the flow rate of steam to the reboiler of said column; means responsive to said steam flow rate to establish a signal proportional to the flow rate of said steam; means to compare the latter signal with said H_R ; means to establish a signal proportional to said comparison; means responsive to said latter signal to regulate the flow rate of said steam whereby said column is operated to produce at an optimum distillate and bottom products stream having specified purities; means for measuring the amount of light key feed component and feed components lighter than the said light key feed; means for producing signals responsive to said measurements proportional to the amounts of said key components; means to combine the latter signals to establish a signal D in a distillate flow computer which is proportional to a predicted value for the flow rate of said distillate product stream, said signal D being established from a predicted equation derived from a material balance around said column and based on the expression:

$$D = f(L_F, F, H_D, L_B)$$

where:

D = predicted volume flow rate of distillate product when flow is measured at temperature equal to feed temperature

L_F = generic symbol for the sum of the light key component and components lighter than light key, each expressed as a liquid volume fraction of feed

F = feed flow rate (volume per unit time)

H_D = specified liquid volume decimal fraction of heavy key in, distillate

L_B = specified liquid volume decimal fraction of light key in bottoms product

means for analyzing one of said overhead and bottom product streams to determine the concentration of a specified key component thereof; means responsive to said

analyzation for producing a feedback signal proportional to said concentration; means for comparing said signal D with said feedback signal and means for biasing the predicted flow rate D of said distillate product stream with said feedback signal.

10. In a fractionation system wherein a multicomponent feed stream is passed into a fractional distillation column, an overhead vapor stream is withdrawn from the top of said column and condensed, some of the condensed overhead is recycled to said column as an external reflux stream, some of said condensed overhead is yielded as a distillate product stream having a specified purity, a liquid bottom product stream having a specified purity is withdrawn from the bottom of said column, and steam is supplied to the reboiler of said column, a control system comprising means to measure process variables indicative of the flow rate of said feed stream; means to establish a signal proportional to said measurement; means to measure the amounts of feed components in said feed stream; means in response to said feed component measurements to establish signals proportional to the amounts of feed components in said feed streams; means to combine in a reboiler heat computer said signals in a statistically-derived equation to establish a signal H_R proportional to a predicted value for the reboiler heat of said column, said equation being based on the expression:

$$\frac{H_R}{F} = f(F_c, E, F_T, F_e, H_D, L_B)$$

where:

$\frac{H_R}{F}$ = ratio of predicted reboiler heat-to-feed flow rate for said first column

F_c = generic symbol for components in feed, each expressed as a liquid volume fraction of feed

F = feed flow rate (volume per unit time)

E = average column tray efficiency of said first column

F_T = the feed tray on the first column on which the feed enters (numbering trays from top of column)

F_e = feed enthalpy (B.t.u.'s per pound)

H_D = specified liquid volume fraction of heavy key in distillate product

L_B = specified liquid volume fraction of light key in said bottom stream of said first column

means to establish a signal proportional to the flow rate of steam to the reboiler of said column; means to compare the latter signal with said signal H_R ; means to establish a signal proportional to said comparison; means responsive to said latter signal to regulate to flow rate of said steam to said reboiler whereby said column is operated to produce at an optimum distillate and bottom product streams having specified purities.

11. In a fractionation system wherein a multicomponent feed stream is passed into a fractional distillation column, an overhead vapor stream is withdrawn from the top of said column and condensed, some of the condensed overhead is recycled to said column as an external reflux stream, some of said condensed overhead is yielded as a distillate product stream having a specified purity and a liquid bottom product stream having a specified purity is withdrawn from the bottom of said column, a control system comprising means to measure the process variables indicative of the amounts of the light key feed component and feed components lighter than the same in said feed stream, means to establish responsive thereto signals proportional to the amounts of the light key feed component and feed components lighter than same in said feed stream; means to combine the latter signals and to establish a signal D in a distillate flow computer proportional to a predicted value for the flow rate of said distillate product stream, said signal D being established from a predictive equation derived from a material balance around said column and based on the expression:

$$D=f(L_F, F, H_D, L_B)$$

where:

D =predicted volume flow rate of distillate product when flow is measured at temperature equal to feed temperature

L_F =generic symbol for the sum of the light key component and components lighter than light key, each expressed as a liquid volume fraction of feed

F =feed flow rate (volume per unit time)

H_D =specified liquid volume decimal fraction of heavy key in distillate

L_B =specified liquid volume decimal fraction of light key in bottoms product

means for analyzing one of said overhead and bottom product streams to determine the concentration of a specified key component thereof; means for producing responsive thereto a feedback signal proportional to said

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concentration; means for comparing said signal D with said feedback signal and means for biasing the predicted flow rate D of said distillate product stream with said feedback signal.

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