

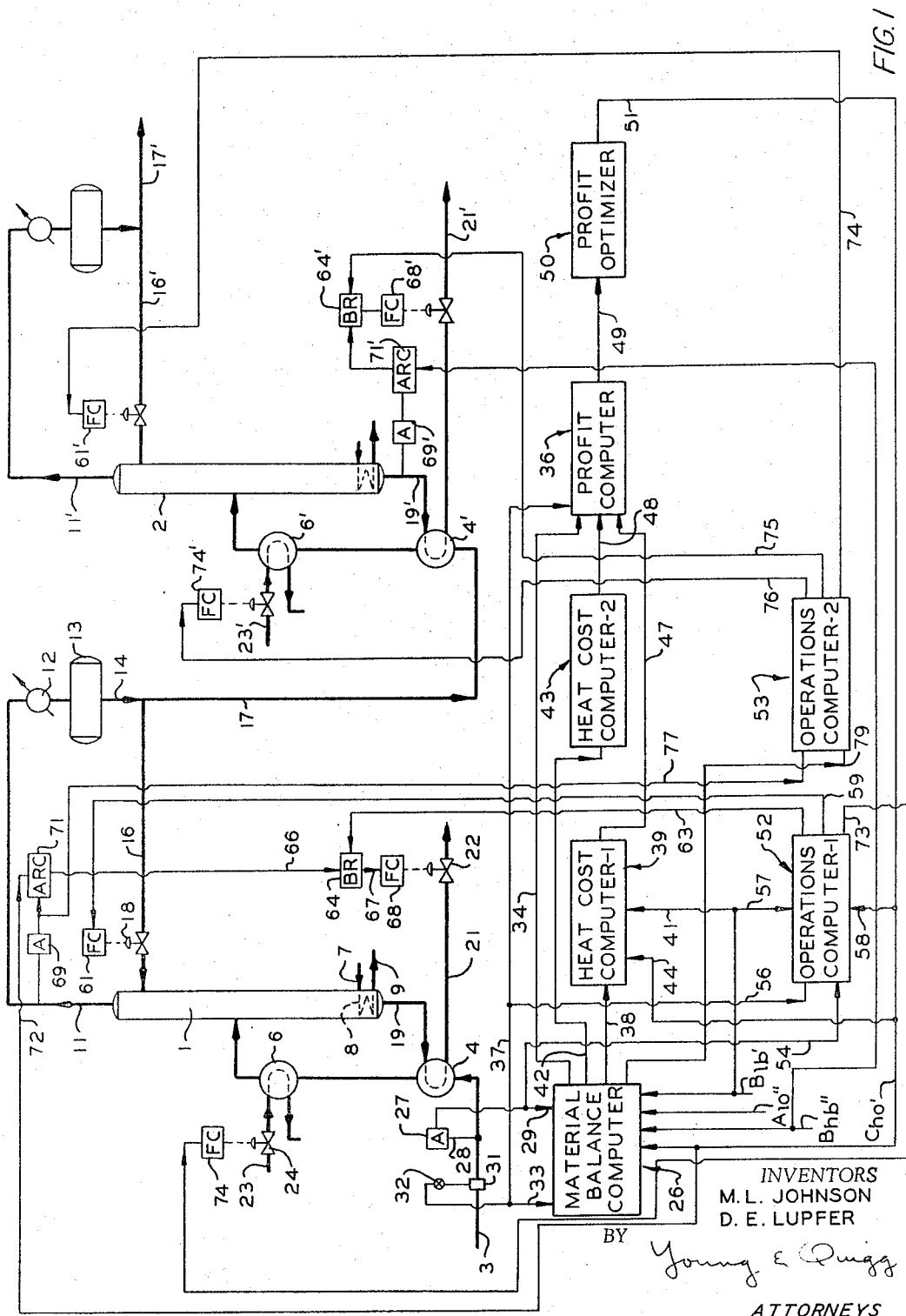
March 7, 1967

M. L. JOHNSON ET AL
CONTROLLING THE OPERATION OF A TRAIN
OF DISTILLATION COLUMNS

3,308,040

Filed March 8, 1963

5 Sheets-Sheet 1



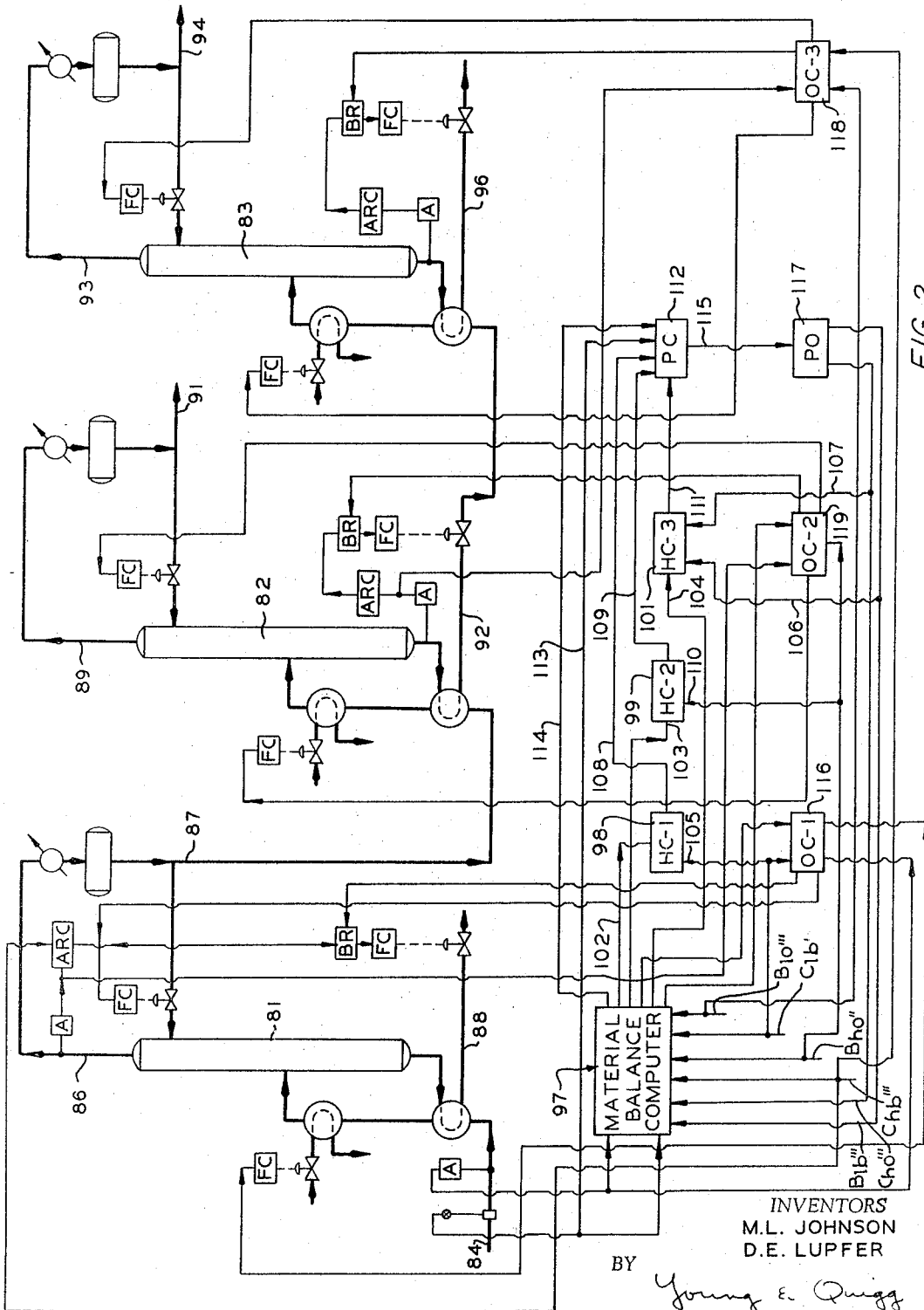
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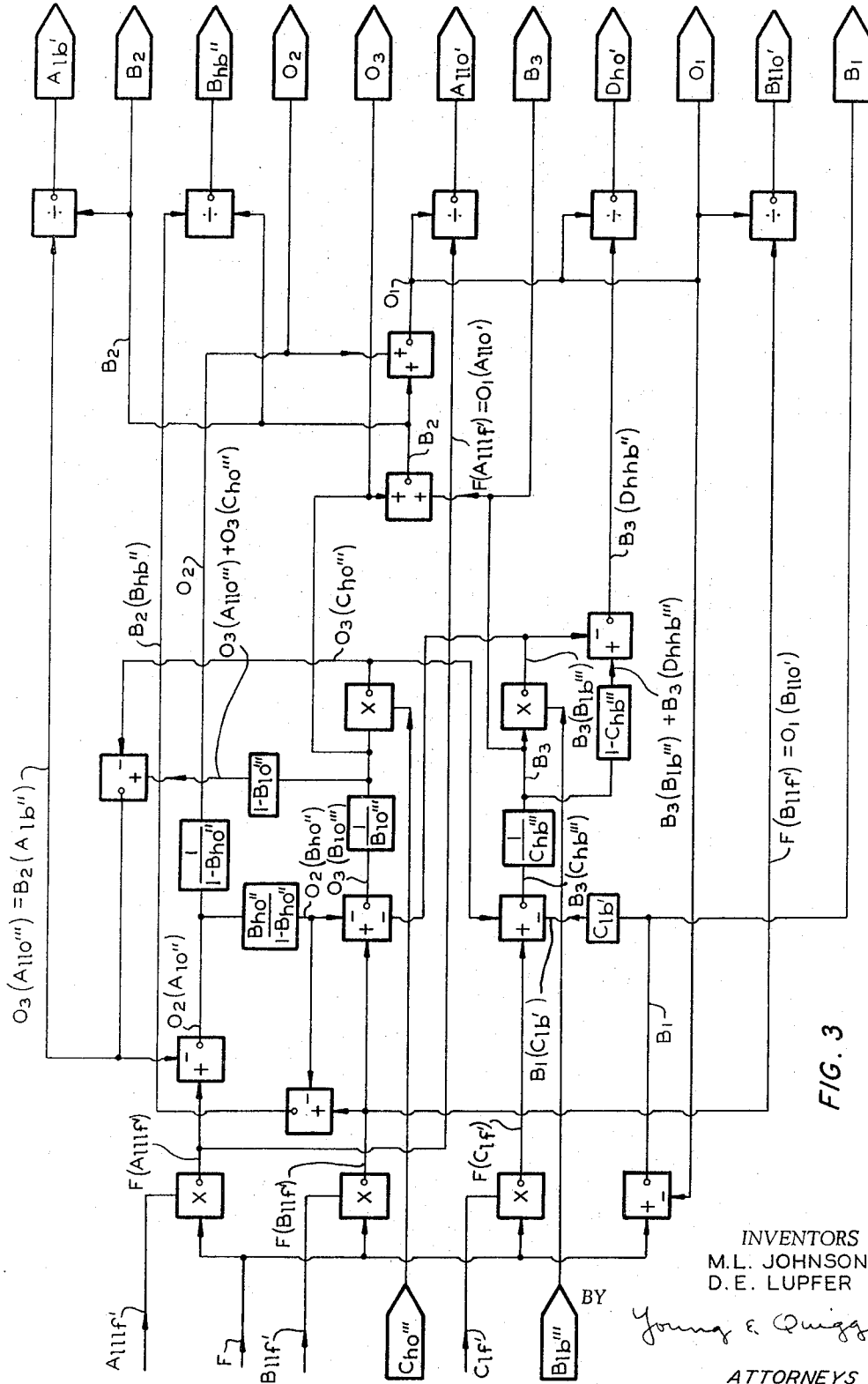
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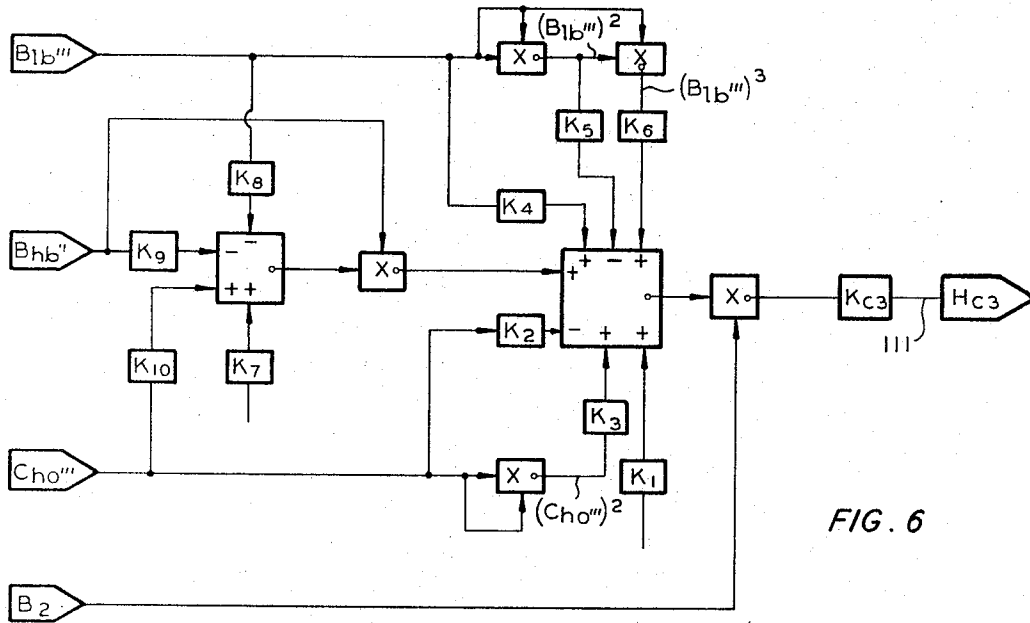
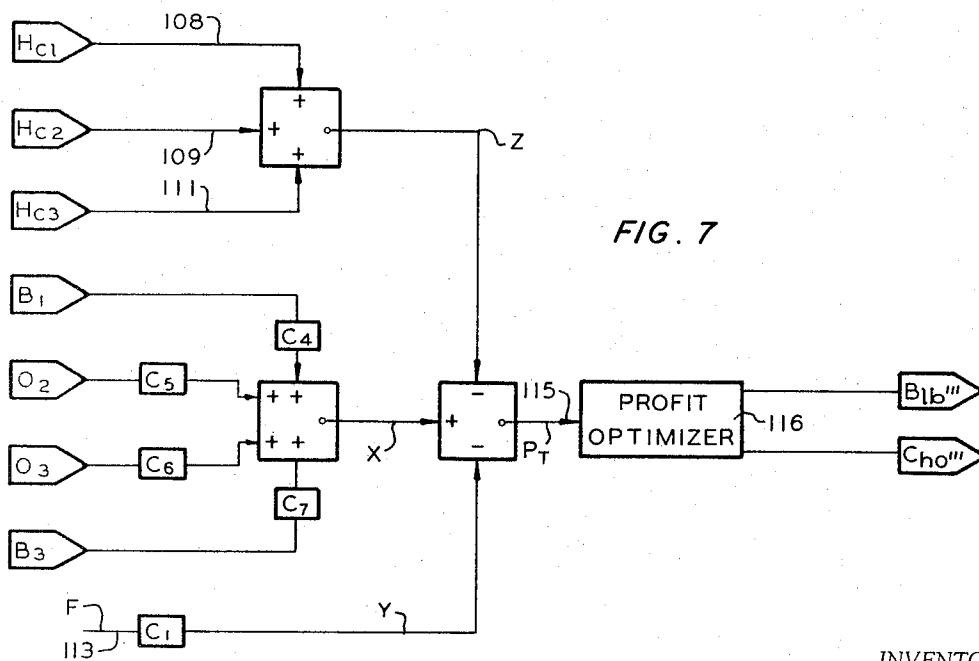
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5 Sheets-Sheet 5



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3,308,040

**CONTROLLING THE OPERATION OF A TRAIN
OF DISTILLATION COLUMNS****Merion L. Johnson and Dale E. Lupfer, Bartlesville,
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4 Claims. (Cl. 203-1)

This invention relates to the operation of a train of distillation columns. In other aspects, it relates to a method and apparatus for controlling the operation of a train of distillation columns in order to produce terminal product streams with desired specifications at optimum conditions to realize maximum profit from the operation.

The trend in automation in recent years has brought about many proposals for improving the art of controlling the fractional distillation of multi-component mixtures. Many of these proposals have proven useful, but they generally have been limited to improving the control of the operation of a single distillation column. Little has been published or is known about automatically controlling the operation of a train of parallel distillation columns as a unit, where control of each distillation column is integrated into an overall automatic control of the unit to ensure production of fractions or products (usually distillate and bottom products) at optimum conditions to realize maximum profit from the operation.

Although the fractionation or "split" of a feed by a particular distillation column can be improved by certain controls or instruments, notwithstanding some changes in the composition of the feed, there is little taught in the prior art about automatically controlling the composition of the feed passed to different columns in a train of columns to insure optimum production (i.e., maximum profit) of terminal product streams with desired specifications. Rather, it has been the practice heretofore to make each column make the best split possible, i.e., make specification product as close as possible, of whatever the feed composition may be. In other words, the column must "live with" whatever feed is supplied thereto, and where the composition of the feed becomes such as to make it impossible for the column to make specification product, the operator tries to overcome this situation empirically by altering the operation of upstream columns in the train in an effort to insure production of a feed which can be split by downstream columns to produce specification products. Since under such circumstances control over the feed composition is difficult and it is not always possible to make products with desired specifications, especially at maximum profit, resort is often made to further fractionation of the product in yet another column in order to make specification product, with the consequent increase in utilities cost, equipment requirements, etc.

Accordingly, an object of this invention is to improve the operation of a train of distillation columns. Another object is to optimize the operation of a train of distillation columns to produce terminal product streams, particularly distillate and bottom products, of predetermined specifications to realize maximum profit from the operation. Another object is to manipulate the "split" of each column in a series of distillation columns in a train so that terminal product streams can be produced at maxi-

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mum profit for the series, notwithstanding changes in the composition and/or flow rate of the feedstock fractionated by the series of columns. A further object is to control the operation of a series of distillation columns so that intermediate product streams can be produced having compositions such that downstream columns can effectively fractionate such intermediate product streams and make specification products having maximum value or selling price so that the series as a whole is optimized to realize maximum profit.

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

FIGURE 1 is a flow sheet of a two-column train of distillation columns arranged in series, provided with the improved control and optimizing system of this invention;

FIGURE 2 is a flow sheet of a three-column train of distillation columns arranged in series, provided with the improved control and optimizing system of this invention; and

FIGURES 3, 4, 5, 6 and 7 are schematic views of preferred embodiments of mathematical analog computing and controlling instrumentation which can be used in that embodiment shown in FIGURE 2.

According to this invention, a train of distillation columns is operated in a controlled manner to optimize the profit of the operation. In such a train, each column is designed to make a split between known (i.e., predetermined) light and heavy key components in the column feed, and each column is manipulated in accordance with the specification of a light or heavy key component in the column overhead and the specification of a light or heavy key component in the column bottom product. In optimizing the profit rate of a train of such columns, first of all, each terminal product stream produced by the train is specified. (Each such terminal product stream is a product stream which is not further fractionated by the train under consideration.) The specifications for these terminal product streams will be dictated by sales requirements or plant requirements, and thus as used in this invention are predetermined values. Further, such specifications will be that of either a light or heavy key component present in the terminal product stream.

Next, the flow rate of the feedstock supplied to the train is continuously measured (and, thus, the flow rate of the feed stream to the first or upstream column in the train). The feedstock is also continuously analyzed to determine the concentration of components therein. Signals representing said predetermined specifications, feedstock flow rate, and feedstock composition together with signals representing manipulated specifications of certain components in the train's product streams are combined in material balance equations for feedstreams in the train and for components in said feedstreams. Such material balance equations are automatically solved simultaneously for the flow rates of product streams produced in and by the train (i.e., for terminal product streams and for internal feed streams which are further fractionated in the train) and for the concentrations of components in said product streams. Signals representing the said solved-for flow rates of the terminal product streams are each multiplied by a signal representing a predetermined unit value (i.e., selling price) for such stream

to derive the value rate thereof, and signals representing the so-derived value rates of such streams are automatically added to obtain the total value rate of the terminal product streams (i.e., the gross income rate from the operation of the train). For each column in the train, signals representing the column feed flow rate, concentrations of components in the column feed, and the specifications of heavy key component in the column overhead and light key component in the column bottom product are combined to obtain the operating utilities rate or power requirement for each column, and a signal representing such requirement is multiplied by a signal representing a predetermined unit cost for such operating utilities to derive the cost rate thereof for the column. Signals representing the utilities cost rate of each column are automatically added to obtain to total utilities cost rate for the train. A signal representing the flow rate of the feedstock supplied to the train is multiplied by a signal representing the unit cost for such feedstock to obtain the cost rate of the feedstock. The signals representing the utilities cost rate of the train and the feedstock cost rate are automatically added and a signal representing the resulting sum is automatically subtracted from the signal representing the total value rate of the terminal product streams, to obtain the profit rate of the train. A signal representing this profit rate is used to manipulate (vary) signals representing said manipulated specifications (and thus the operation of the train) until said profit rate is maximized. The train is then operated at the so-determined maximum or optimum profit rate, until changes in the composition of the feedstock and/or the flow rate thereof again dictate manipulation of the operation of the train to achieve a new maximum profit rate.

The manipulated specifications mentioned above are specifications of those components in the product streams of the train which can be manipulated (varied) without affecting said predetermined specifications, and which together with the latter serve to "tie-down" (i.e., completely specify) the terminal product streams. The components whose specifications are manipulated will be present in the terminal product streams and/or the internal feed streams. Such manipulated specifications, in addition to providing with the predetermined specifications a knowledge of the complete composition of the terminal product streams, will be those values needed for solution of said material balance equations. The selection of those components whose specifications are to be manipulated according to this invention will become apparent to those skilled in the art in view of the detailed description and examples provided herein.

In determining the operating utilities cost rate requirements for the train, according to this invention, for practical reasons we prefer to consider only the cost of providing the heat necessary to effect the fractionations in the several columns (the cost of other utilities such as cooling water, pumping, etc., can also be considered, but these are relatively constant or relatively insignificant and can be excluded from consideration). Though this heat can include that supplied to the feed preheater of each column as well as that supplied to each column reboiler, we prefer to consider only the reboiler heat requirements since the preheater heat requirements usually will be relatively constant. The computation of reboiler heat requirement and preheater heat requirement can be found according to that disclosed in copending application Ser. No. 246,998, filed Dec. 26, 1962 by M. L. Johnson.

Referring now to the drawing, we have illustrated in FIGURE 1 a two-column distillation train consisting of columns 1 and 2, each of which can be provided with a plurality of the usual vertically-spaced liquid-vapor contact trays (not shown). Feedstock comprising a multicomponent mixture, such as liquefied natural gas liquids and petroleum gases, is supplied to the train via line 3 and introduced onto a feed tray located at an in-

intermediate level in column 1. This feedstock line 3 can be associated with the usual heat exchanger(s) so as to heat, vaporize, or partially vaporize the feedstock. Preferably, this heating of the feedstock is done by an indirect heat exchanger or economizer 4 and an indirect heat exchanger or preheater 6. Heat is supplied to the kettle of column 1, for example by the circulation of steam 7 or other heat exchange medium through reboiler coil 8, the heat exchange medium being withdrawn from the coil 8 via line 9. Vapors are removed from the top of column 1 through an overhead line 11, cooled and condensed by a cooler 12, such as an air-cooled condenser, and the resulting liquid passed to an accumulator 13. Liquid distillate in accumulator 13 is withdrawn via line 14, and a portion of this withdrawn liquid is recycled as external reflux via line 15 to the top of column 1, the flow rate of external reflux being controlled by flow rate control valve 18. The balance of the liquid distillate is passed via line 17 for further fractionation in column 2. Bottom product is withdrawn from the kettle of column 1 via line 19 and, after being used as an indirect heat exchange medium in economizer 4 to heat the feedstock in line 3, it is removed from the system via line 21 as a terminal product stream, its flow rate being controlled by valve 22. An indirect heat exchange medium such as steam is supplied via line 23 to preheater 6, the flow rate of this heat exchange medium being controlled by flow rate control valve 24.

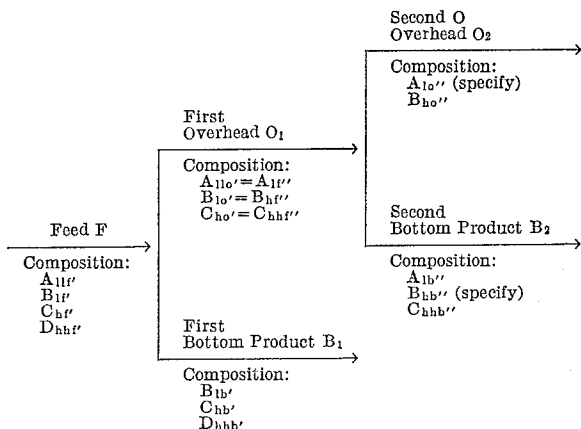
The light components of the feedstock in line 3 introduced into column 1 will appear mainly in the overhead 11 (and thus in the distillate 17) and the heavy components of the feed will appear mainly in the bottom product in line 21. The light components will comprise a light key component and components lighter than the light key component, while the heavy components will comprise a heavy key component and components heavier than the heavy key components. Since perfect separation between the light and heavy key components is impossible, some of the heavy key component will appear as an impurity (H_D) in the overhead 11 (and thus in the distillate 17) and some of the light key component will appear as an impurity (L_B) in the bottom product in line 21. However, the amounts of these impurities can be kept at desired levels by proper operation of the column, preferably by controlling the operation of the column in accordance with predetermined or computed specifications for these impurities.

Column 2 is provided with the usual appurtenances like that of column 1 and like elements have been designated with like primed reference numbers, (see FIGURE 1) this second column producing a distillate product yielded as terminal product stream 17' and a bottom product yielded as a terminal product stream 21'. Other products can be removed from the columns at intermediate points, though this is not shown in the drawing in the interest of brevity. Also not shown are controls which, while necessary in practice, form no part of this invention.

For purposes of illustration, assume that the feedstock passed to the train of FIGURE 1 via line 3 comprises a mixture of components A, B, C and D, that column 1 is designed to make a split between B and C and produce overhead a distillate product 17 comprising components A, B and C, and produce a bottom product 21 (a terminal product stream) comprising components B, C and D; and assume that column 2 is designed to fractionate distillate product 17 of column 1 and make a split between A and B to produce a distillate product 17' (a terminal product stream) comprising components A and B, and produce a bottom product 21' (a terminal product stream) comprising components A, B and C. (It should be understood that the lightest "component" and heaviest "component" of a feed may in fact each comprise a plurality of components, but each such plurality may be considered as one component.) The operation of the train illustrated in FIGURE 1 can be further illustrated

by the following diagram in which the vertical lines represent columns and the horizontal lines represent streams:

DIAGRAM I



where:

F = flow rate of feed to first column
 O_1 = flow rate of overhead from first column
 B_1 = flow rate of bottom product from first column
 O_2 = flow rate of overhead from second column
 B_2 = flow rate of bottom product from second column
 B_{1f} = decimal fraction of light key component B in feed to first column
 A_{1f} = decimal fraction of component A in feed to first column which is lighter than light key component B in feed to first column
 C_{1f} = decimal fraction of heavy key component C in feed to first column
 D_{1f} = decimal fraction of component D in feed to first column which is heavier than heavy key component C in feed to first column
 B_{1o} = decimal fraction of light key component B in first overhead
 B_{1b} = decimal fraction of heavy key component B in feed to second column
 A_{1o} = decimal fraction of component A in overhead from first column which is lighter than light key component B in overhead from first column
 A_{1f} = decimal fraction of light key component A in feed to second column
 C_{1o} = decimal fraction of heavy key component C in overhead from first column
 C_{1b} = decimal fraction of component C in feed to second column which is heavier than heavy key component B in feed to second column
 B_{1b} = decimal fraction of light key component B in bottom product from first column
 C_{1b} = decimal fraction of heavy key component C in bottom product from first column
 D_{1b} = decimal fraction of component D in bottom product from first column which is heavier than heavy key component C in bottom product in first column
 A_{1o} = decimal fraction of light key component A in overhead from second column
 B_{1o} = decimal fraction of heavy key component B in overhead from second column
 A_{1b} = decimal fraction of light key component A in bottom product from second column
 B_{1b} = decimal fraction of heavy key component B of bottom product from second column
 C_{1b} = decimal fraction of component C in bottom product from second column which is heavier than heavy key component B in bottom product from second column

It should be evident from Diagram I that the flow rate of any component in any stream is equal to the product of the flow rate of material in that stream and the decimal fraction of said component; thus, $(F)B_{1f}$ is equal to the

flow rate of the light key component B in the feed passed to the first column.

The operation of each distillation column is preferably controlled in this invention by specifying or computing the amount of the heavy key component in the distillate product (H_D) and the amount of the light key component in the bottom product (L_B), which amounts (or concentrations) must be met if the requirements of selling price or plant requirements for the stream and maximum profit are to be fulfilled. If a component must be present in a major amount, the specified or computed amount is a purity expressed as a minimum value, e.g., 95%; if the component must be present in a minimum amount, the specified or computed amount is an impurity expressed as a maximum value, e.g., 5%. These amounts may be given in terms of percent or in terms of decimal fraction. In this specification and in the appended claims the term "predetermined specification" is meant to cover such specified values or amounts which are known, i.e., those set by sales requirements or plant requirements and unaltered in the operation. These predetermined specifications are distinguished herein and in the appended claims for "manipulated specifications," which are computed values or amounts of components in the stream, which amounts are varied, without affecting the predetermined specification, to achieve maximum profit, notwithstanding changes in feedstock composition and/or feedstock flow rate.

Referring again to Diagram I, the subject invention requires, first of all, that the amounts of the heavy or light key components in the terminal product streams, namely the second overhead and the first and second bottom products, be predetermined and specified. Accordingly, in Diagram I the decimal fractions of components in such streams which are so specified are followed by the term ("specify"), namely decimal fractions A_{1o} (a purity), B_{1b} (an impurity), and B_{2b} (a purity). In determining which of the remaining decimal fractions can be chosen as the manipulated specifications required by this invention, B_{1o} can be excluded from consideration because it cannot be manipulated without affecting A_{1o} , i.e., since A_{1o} is a predetermined specification this means that B_{1o} is consequently fixed, and the complete composition or specification for the second overhead is "tied-down." D_{1b} is also excluded as a possible manipulated specification because all of component D in the feed supplied to the first column appears only in the first bottom product. With B_{1b} as a predetermined specification and D_{1b} being excluded, this of course means that C_{1b} is also excluded from consideration as a possible manipulated specification. C_{1b} can be selected as a manipulated specification because it can be varied (by manipulation of the operation of the first column) without affecting B_{1b} (or the other primary specifications) and together with the latter will tie-down the composition of the second bottom product (the selection of C_{1b} as a manipulated specification causes A_{1b} to be fixed). Selection of C_{1b} as a manipulated specification also means that C_{1o} will be fixed, and together with A_{1b} will be excluded as possible manipulated specifications. However, if C_{1b} is not selected, although it could be, then A_{1b} can be selected as a manipulated specification since it too can be varied (by predetermined specifications and together with B_{1b} will tie-down the composition of the second bottom product; selection of A_{1b} fixes C_{1b}). A_{1o} is excluded from consideration because all of component A in the feed to the first column goes overhead. C_{1o} can be selected as a manipulated specification, but if it is selected this means that A_{1b} and C_{1b} are fixed and thus excluded. Similarly, B_{1o} can be selected as a manipulated specification, but its selection excludes C_{1o} , A_{1b} , and C_{1b} . Thus, in Diagram I, it is possible to select any one of C_{1b} , A_{1b} , C_{1o} and B_{1o} as manipulated specifications. The signal representing the selected manipulated specification is varied by a signal representing the profit rate of the train until said profit rate is optimized. Note that this entails controlling the

composition of the feed to the second column, an internal feed stream.

A few more examples will now be described to illustrate the selection of the manipulated specifications required in the operation of this invention.

Assume a feedstock comprising $A_{11f'}$, $B_{1f'}$, $C_{1f'}$ and $D_{11f'}$ is supplied to the first column of a two-column train of distillation columns and that the first column is designed to make a split between components B and C to produce a first overhead (a terminal product stream) comprising $A_{11o'}$, $B_{1o'}$ and $C_{1o'}$, and a first bottom product comprising $B_{1b'}$, $C_{1b'}$ and $D_{11b'}$, which is the feed ($B_{11f'}$, $C_{1f'}$ and $D_{11f'}$) supplied to the second column, and that the latter is designed to make a split between components C and D and produce a second overhead (a terminal product stream) comprising $B_{11o'}$, $C_{1o'}$ and $D_{11o'}$, and a second bottom product (a terminal product stream) comprising $C_{1b'}$ and $D_{11b'}$. If $C_{1o'}$, $C_{1b'}$ and $D_{11b'}$ are selected as predetermined specifications, any one of $C_{1b'}$, $D_{11o'}$, $B_{11o'}$ and $B_{1b'}$ can be selected as manipulated specifications.

As another example, assume a feedstock comprising $A_{11f'}$, $B_{1b'}$, $C_{1f'}$, $D_{11f'}$, and $E_{11f'}$ is supplied to the first column of a three-column train and that the first column is designed to make a split between components B and C to produce a first overhead (a terminal product stream) comprising $A_{11o'}$, $B_{1o'}$ and $C_{1o'}$, and a first bottom product comprising $B_{1b'}$, $C_{1b'}$, $D_{11b'}$ and $E_{11b'}$, which is the feed ($B_{11f'}$, $C_{1f'}$, $D_{11f'}$ and $E_{11f'}$) supplied to the second column; that the latter is designed to make a split between D and E to produce a second bottom product (a terminal product stream) comprising $D_{11b'}$ and $E_{11b'}$, and a second overhead product comprising $B_{11o'}$, $C_{11o'}$, $D_{11o'}$ and $E_{11o'}$, which is the feed ($B_{11f'}$, $C_{11f'}$, $D_{11f'}$ and $E_{11f'}$) supplied to the third column; and that the latter is designed to make a split between C and D to produce a third overhead product (a terminal product stream) comprising $B_{111o'}$, $C_{111o'}$ and $D_{111o'}$, and a third bottom product (a terminal product stream) comprising $C_{111b'}$, $D_{111b'}$ and $E_{111b'}$. If $C_{111o'}$, $D_{111b'}$, $C_{111o'}$ and $D_{111b'}$ are selected as predetermined specifications, any one of $D_{111o'}$, $B_{111o'}$, $B_{111b'}$, $C_{111b'}$ and $B_{11b'}$ and any one of $C_{111b'}$, $E_{111b'}$, $D_{111o'}$, $E_{111o'}$ can be selected as manipulated specifications.

The following material balance equations can be written covering the fractionation system illustrated in FIGURE 1 and Diagram I.

$$F = O_1 + B_1 \quad (1)$$

$$F = B_1 + O_2 + B_2 \quad (2)$$

$$F = (F)A_{11f'} + (F)B_{1f'} + (F)C_{1f'} + (F)D_{11f'} \quad (3)$$

$$(F)A_{11f'} = (O_1)A_{11o'} \quad (4)$$

$$(F)B_{1f'} = (B_1)B_{1b'} + (O_1)B_{1o'} \quad (5)$$

$$(F)C_{1f'} = (B_1)C_{1b'} + (O_1)C_{1o'} \quad (6)$$

$$(F)D_{11f'} = (B_1)D_{11b'} \quad (7)$$

$$O_1 = O_2 + B_2 \quad (8)$$

$$O_1 = (O_1)A_{11o'} + (O_1)B_{1o'} + (O_1)C_{1o'} \quad (9)$$

$$(O_1)A_{11o'} + (O_2)A_{11o'} + (B_2)A_{11b'} \quad (10)$$

$$(O_1)B_{1o'} = (O_2)B_{1o'} + (B_2)B_{1b'} \quad (11)$$

$$(O_1)C_{1o'} = (B_2)C_{11b'} \quad (12)$$

Note that Equations 1, 2, 3, 8 and 9 are material balance equations for column feed streams, and Equations 4, 5, 6, 7, 10, 11 and 12 are material balance equations for components in feed streams.

According to the subject invention, $B_{1b'}$, $A_{11o'}$, and $B_{11b'}$ of terminal product streams 17', 21 and 21' of FIGURE 1 (namely the second overhead and the first and second bottom products of Diagram I, respectively) are fixed by predetermined specifications, and $C_{1o'}$ is selected as a manipulated specification. The first column is manipulated in accordance with $C_{1o'}$ and $B_{1b'}$, and the second column in accordance with $B_{11o'}$ and $A_{11b'}$. Signals representing the predetermined specifications and manipulated specification are combined with signals representing the flow rate F of the feedstock and $A_{11f'}$, $B_{1f'}$, $C_{1f'}$, $D_{11f'}$ in material balance Equations 1 to 12, which equations are

automatically solved simultaneously for the values necessary to compute the operating utilities cost rate and the value rate of the terminal product streams, as well as the product specifications needed for manipulation of the columns.

Referring again to FIGURE 1, there is illustrated a "material balance computer," generally designated 26, which computer can be used to solve said Equations 1 to 12 simultaneously for said values and product specifications. For the purpose of the computation performed by material balance computer 26, the composition of the feedstock in line 3 is analyzed by an analyzer 27 connected to line 3 by sample line 28.

Analyzer 27 comprises any suitable instrument which continuously or substantially continuously (i.e., rapid cycle) analyzes the feedstock in line 3 and determines the relative amounts of components in the feedstock used in the solution of said material balance Equations 1 to 12 and produces signals proportional to the computed values. A suitable analyzer for this purpose is described in The Oil and Gas Journal, vol. 58, No. 12, March 21, 1960, p. 96, and it preferably comprises a high speed chromatographic analyzer having a sample valve, motor, detector, chromatographic column, programmer, and a peak reader, the latter functioning to read the peak height of the measured feed components, giving an equivalent output signal which is suitable for computing and control purposes. In operation sample flows continuously through the analyzers sample handling system. At a signal from the programmer, a measured volume of sample is flushed into the chromatographic column. When the 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 can then be employed as a continuous output signal analogous to the amount of the component present. Signals proportional to the amounts of components can be transmitted to material balance computer 26 by a signal line 29.

In order to perform said material balance computations, it is also necessary to measure the flow rate of feedstock in line 3. For this purpose, a flow measurement device 31 can be disposed in the feedstock line 3 and by means of a suitable transmitter 32 the flow rate can be transmitted to material balance computer 26 by signal line 33.

It is also necessary, as evident from the above material balance Equations 1 to 12, that the predetermined specifications of the terminal product streams and the manipulated specification be employed, and thus signals representing these specifications are also supplied to material balance computer 26 as shown in FIGURE 1.

Material balance computer 26 produces output signals proportional to the flow rates B_1 , O_2 , and B_2 of the terminal product streams 17', 21 and 21' (respectively), and these are transmitted by signal line 34 to a "profit computer" generally designated 36, where each of these flow rates are multiplied by a unit value (or unit selling price), so that the value rate of each terminal product stream is obtained. The value rates of the terminal product streams are summed in computer 36, to obtain a total value rate for the terminal products.

Thus:

$$X = v_1 B_1 + v_2 O_2 + v_3 B_2 \quad (13)$$

where:

X = total value rate of terminal product streams (\$/hr.)

v_1 , v_2 , v_3 = unit value of terminal product streams 17', 21, 21', respectively (\$/lb.)

B_1 , O_2 , B_2 = flow rates of terminal product streams 17', 21, 21', respectively (lbs./hr.)

In addition to computing the total value rate of the terminal product streams, profit computer 36 computes the cost rate of the feedstock. This can be accomplished by transmitting via signal line 37 to computer 36 a signal proportional to the flow rate of the feedstock in line 3,

said signal being multiplied by the unit cost of the feedstock. Thus:

$$Y = c_1 F \quad (14)$$

where:

Y = the total cost rate of the feedstock (\$/hr.)

c_1 = unit cost of feedstock (\$/lb.)

F = flow rate of feedstock (lbs./hr.)

In determining total profit rate, it is also necessary according to this invention to determine the cost rate of the operating utilities (preferably only reboiler heat) required by the train of distillation columns.

To determine the cost rate of reboiler heat required by each column to effect a specified separation, signals representing the concentration of heavy key component in the distillate and light key component in the bottom product are produced, and signals proportional to the concentration of components in the column's feed stream are produced, and these signals together with the signals proportional to certain constants, including constants assigned to unmanipulated values, such as feed tray location, tray efficiency, and feed enthalpy (though in some cases these variables can be manipulated, in which case the signals representing these variables can be produced from measurements) are combined in a predictive, statistically-derived equation for reboiler heat required by the column based on the expression:

$$H_R = f(F, F_c, E, F_T, F_e, H_D, L_B) \quad (15)$$

where:

H_R = predicted heat supplied to column by reboiler (B.t.u./lb. of feed)

F = feed flow rate (lb./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./lb. of feed)

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

H_D = liquid volume fraction of heavy key component desired in distillate product

L_B = liquid volume fraction of light key component desired in bottom product

The equations for reboiler heat for the first and second columns of Diagram I, respectively, are based on the following expressions:

$$H_{R1} = f(F, A_{11f}, B_{1f}, C_{1f}, E_1, F_{T1}, F_{e1}, C_{ho'}, B_{1b'}) \quad (16)$$

$$H_{R2} = f(O_1, A_{11o'}, B_{1o'}, E_2, F_{T2}, F_{e2}, A_{1o'}, B_{1b''}) \quad (17)$$

The signals representing the latter-mentioned feed flow rate and amounts of components in feed streams can be obtained as output signals from material balance computer 26 of FIGURE 1. Also, the signals representing H_D and L_B can also be obtained from material balance computer 26, although if any of these values are predetermined or manipulated specifications they can be obtained as shown. In FIGURE 1 the signals obtained from a material balance computer 26 necessary for computing the reboiler heat required by the first column are transmitted from computer 26 via signal line 38 to "heat cost computer" 39. The signals necessary for computing the reboiler heat required by the second column are transmitted from computer 26 via signal line 42 to "heat cost computer" 43. Each of heat cost computers 39 and 43 produces output signals 47 and 48, respectively, proportional to the heat cost rate of columns 1 and 2, respectively, and these signals are transmitted to profit computer 36. In profit computer 36, the heat cost rate signals 47, 48 are added to obtain a signal representing the total heat requirement of the train. Thus:

$$Z = c_2 H_{R1} + c_3 H_{R2} \quad (18)$$

where:

Z = total reboiler heat cost rate of train (\$/hr.)

c_2 = unit cost of heat (\$/B.t.u.)

H_{R1} = computed heat rate required for operation of first column (B.t.u./hr.)

H_{R2} = computed heat rate required for operation of second column (B.t.u./hr.)

In the event that the unit costs of heat for the two columns are different, for example where the heating medium (e.g., steam) used by the first column comes from one source and has a different unit value than the heating medium (e.g., steam) used by the second column and obtained from another source, then equation 18 can be expressed as:

$$Z = c_2 H_{R1} + c_3 H_{R2} \quad (19)$$

where:

c_2 = unit cost of heat for first column (\$/B.t.u.)

c_3 = unit cost of heat for second column (\$/B.t.u.)

The so-determined total reboiler heat cost rate Z is added in profit computer 36 to the total cost rate Y of the feedstock, and the sum is subtracted from the computer total value rate X of the terminal product streams, thus:

$$P_T = X - Y - Z \quad (20)$$

where:

P_T = the total profit rate obtained by the operation (\$/hr.)

Computer 36 produces an output signal 49 representing P_T and this signal is transmitted to a "profit optimizer," generally designated 50 in FIGURE 1. Profit optimizer 50 manipulates (i.e., varies) specification $C_{ho'}$ until profit rate P_T is maximized; in other words, profit optimizer 50 determines that value of $C_{ho'}$ which will maximize total profit. Manipulated specification $C_{ho'}$ (in the form of output signal 51) is fed forward in a predictive manner to material balance computer 26 for purposes described earlier. In addition, as will be pointed out, the manipulation of this specification by profit optimizer 50 affects the operation of each of the columns in the train, altering such operations until total profit is maximized.

Profit optimizer 50 can be any one of several optimizing controllers known in the art and commercially available. For example, profit optimizer 50 can be a Quarie Maximizer Model 760 Zero-Slope Controller, manufactured by Quarie Controllers, Sharon, Massachusetts. Or, the profit optimizer can be a Westinghouse Electrical Company Opcon Unit.

The split performed by each of the columns in the train can be controlled by any conventional means; for example, each of the columns can be controlled by manipulation of reboiler heat and distillate product flow, but preferably by manipulating reflux flow and bottom product flow with the distillate product flow being regulated by a liquid level controller on the accumulator cascaded with a flow controller on the distillate product flow and the reboiler heat being manipulated by liquid level controller on the kettle cascaded with the flow controller on the reboiler heat. An improved distillation column control method and apparatus of the latter type which we prefer to use in controlling the operation of each distillation column is that disclosed and claimed in copending application Serial No. 189,375 filed April 23, 1962 by D. E. Lupfer, such control of each column being integrated and dependent upon the material balance computer and profit optimization of this invention. The control system disclosed in said copending application Serial No. 189,375 is termed therein as an "operations computer" and this term is used in this application. In FIGURE 1, such operations computer for column 1 is generally designated 52, and such operations computer for column 2 is generally designated 53.

As described in said copending application Serial No. 189,375, each column can be controlled by measuring the flow rate of feed to the column and concentrations of components in the feed, signals are produced representing said measurements, and these signals are combined with signals proportional to constants in a statistically-derived

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equation to predict the internal reflux flow rate of the column; a signal is produced representing said predicted internal reflux flow rate and the external flow rate is controlled in accordance therewith to be sure that the column produces products of desired specifications. In FIGURE 1, feed composition information necessary for the function of operation computer 52, associated with column 1, is transmitted from analyzer 27 (or a similar analyzer associated with feed stream 3) via signal line 54 to operations computer 52. (Alternatively, this information can be obtained through material balance computer 26.) Feed flow rate information is transmitted from flow transducer 32 via signal line 56 to operations computer 52 (although this information can likewise be transmitted through material balance computer 26). Product specifications B_{1b} (fraction of light key component in bottom product) and C_{ho} (fraction of heavy key component in distillate) are transmitted to operations computer 52 via signal lines 57 and 58, respectively, which signals are preferably lagged in their transmission to compensate for the process dynamics of dead-time and exponential response. Operations computer 52 produces an output signal 59 representing the predicted internal reflux flow rate for column 1, and this signal serves to adjust the setpoint of a flow controller 61, so as to manipulate valve 18 in the external reflux line 16 of column 1.

Said copending application Serial No. 189,375, in one of its other aspects, employs such operations computer to also manipulate the flow rate of bottom product from the column, and FIGURE 1 of this application illustrates the same. For example, operations computer 52 produces another output signal 63 representing the predicted bottom product flow rate for the bottom product in line 21, and transmits this signal to a biasing device 64, such as a summing relay, where it is added to signal 66. The biasing device 64 accordingly produces an output signal 67 which serves as the setpoint for flow controller 68, the latter manipulating valve 22 in bottom product line 21. The predicted bottom product flow is preferably overridden by a feedback control. To accomplish this feedback control, the overhead 11 of column 1 is analyzed by a multi-component analyzer 69 to determine the concentration of the heavy key component C in the distillate product line 17. The output signal from analyzer 69 is transmitted to an analyzer recorder controller 71 where it is compared with a setpoint signal 72 representing the predicted manipulated specification C_{ho} for component C in the distillate product 17 (used as feed by column 2). Any difference in the actual (or measured) concentration of component C in the distillate product and the predicted concentration of component C is transmitted as signal 66 to biasing relay 64.

Said copending application Serial No. 189,375 also discloses that the operations computer can compute the desired feed enthalpy (heat content) of the feed to a column and manipulate the heating of the feed to maintain the desired feed enthalpy. Accordingly, as shown in FIGURE 1, operations computer 52 produces a third output signal 73 which is used as the setpoint of a flow controller 74, which serves to manipulate valve 24 in steam line 23.

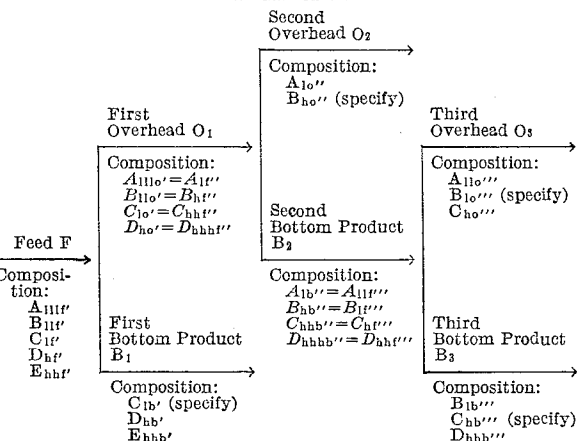
Operations computer 53 of FIGURE 1 similarly manipulates reflux flow, bottom product flow, and feed preheat by means of output signals 74, 75 and 76, respectively. The feed stream composition information needed by operations computer 53 can be supplied thereto by signal line 77. This composition information can be transmitted from analyzer 69 since the composition of the feed stream 17 to column 2 will be the same as the overhead 11 of column 1. Also, the product specification information needed by operations computer 53 can be supplied by signal line 79 from material balance computer 26, the transmission of such information to computer 53 preferably being lagged to compensate for the process dynamics (both dead-time and exponential response). In addition,

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over the latter signal line 79 the necessary feed stream flow rate information for column 2 can be transmitted.

In FIGURE 2 there is illustrated a three-column distillation train comprising columns 81, 82 and 83, each column being provided with appurtenances similar to that provided for each of the columns in FIGURE 1. In FIGURE 2, assume that the feedstock in line 84, supplied to the train and introduced to the first column 81, comprises components A, B, C, D and E. Further, assume that the first column 81 makes a separation between components C and D and produces an overhead 86 (and distillate product 87) containing components A, B, C and D and a bottom product 88 (a terminal product stream) comprising components C, D and E, that the second column 82 uses as feed the distillate product 87 produced by the first column 81 and splits the same between A and B to produce an overhead 89 (and distillate product 91, a terminal product stream) comprising components A and B and a bottom product 92 comprising components A, B, C and D, and that the bottom product stream 92 is split between components B and C by the third column 83 to produce an overhead 93 (and distillate product 94, a terminal product stream) comprising components A, B and C and a bottom product 96 (a terminal product stream) comprising components B, C and D. The operation of the train of distillation columns illustrated in FIGURE 2 can be diagrammed as follows:

DIAGRAM II



From the foregoing discussion relative in Diagram I, the meaning of the symbols used in Diagram II should be readily understood. For example, F is the flow rate of the feed stream split by the first column, O_1 is the flow rate of the feed stream split by the second column, $A_{111'}$ is the decimal fraction of component A in the feed stream split by the first column, $C_{10'}$ is the decimal fraction of the component C in the overhead of the first column (which is the feed stream to the second column), etc. Predetermined specifications for the terminal product streams can be C_{1b} , $B_{10''}$, $B_{10'''}$, and $C_{1b''}$. Manipulated specifications can be any one of $D_{10'}$, $C_{10'}$, $C_{1b''}$, $D_{1b''}$, $B_{1b''}$ and $D_{1b''}$, and any one of $A_{1b''}$, $B_{1b''}$, $A_{10''}$, and $C_{10''}$. For purpose of illustration, the manipulated specifications chosen are $B_{1b''}$ and $C_{10''}$.

It is not necessary to write out the material balance equations for each particular train of distillation columns such as that shown in FIGURE 2 and illustrated in Diagram II, since the particular material balance computer necessary to compute the values used in controlling the operation of the train to realize maximum profit can be arrived at implicitly. The material balance equations for any train of distillation columns can be expressed by a general set of simultaneous equations of the form:

$$\sum_{j=1}^n (a_{ij}x_j + b_{ij}x_j) = k_i \quad (i=l \text{ to } m, \text{ where } m \text{ and } n \text{ are positive integers}) \quad (21)$$

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In the equation of the form (21), x_i is a material flow, e.g., F of Equation 1, and x_i is the decimal fraction of a component in the feed, e.g., B_{1r} of Equation 9. In all equations which contain only material flow, b_{ij} will be equal to zero.

The material balance computers 26 of FIGURE 1 and 97 of FIGURE 2 are adapted to solve sets of simultaneous equations of the form (21). In addition, any of the other computers known in the art for solving non-linear simultaneous equations can be used, for example those disclosed in U.S. Patent Nos. 2,827,113, 2,742,227, and 2,808,989. Suitable mathematical analog instrumentation used by material balance computer 97 of FIGURE 2 is shown schematically in FIGURE 3, the circuitry of which will not be described in the interest of brevity, since it will be readily understood by those skilled in the art. In such circuitry, the values shown inside of pentagons are those obtained from or supplied to other instrumentation, the boxes are analog multipliers, adders, etc., depending on the sign within the box, and the other boxes are potentiometers or the like. All of the various components, that is, the sensing elements, transmitters, adding relays, dividers, multipliers, square root extractors, bias relays, flow controllers, 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.

In FIGURE 2, it is necessary according to this invention to compute the cost rate of the reboiler heat required by each of the columns, and thus it is necessary to provide heat cost computers 98, 99 and 101 to compute the heat cost rate required by columns 81, 82 and 83, respectively. (The illustration of these heat cost computers in FIGURE 2 is simplified and each appears as a rectangle containing the designation HC-1, HC-2 or HC-3.) Each of these heat cost computers receives certain information, in the form of signals from material balance computer 97. Heat computer 98 receives from material balance computer 97 via signal line 102 values representing A_{11r} , B_{11r} , D_{11r} , F and $D_{ho'}$ (the latter being the concentration of the heavy key component D in overhead line 86) and receives a signal 105 representing $C_{1b'}$ (a predetermined specification representing the concentration of the light key component C in bottom product line 88), and solves the predictive heat cost rate requirement equation for column 81, namely:

$$H_{c1} = K_{c1} F \{ K_1 - K_2 (D_{ho'})^2 + K_3 (D_{ho'}) - K_4 (A_{11r} + B_{11r}) + D_{11r} [K_5 - K_6 (A_{11r} + B_{11r}) - K_7 (D_{11r}) - K_8 (C_{1r}) - K_9 (D_{ho'})] \} \quad (22)$$

where:

H_{c1} = cost rate of reboiler heat required for operation of column 1 (\$/hr.)

K_{c1} = unit cost of steam used by reboiler of first column (\$/B.t.u.)

K_1 to K_9 = constants (some of which include the predetermined specifications)

The mathematical analog instrumentation used by heat cost computer 98 is illustrated in FIGURE 4, which circuitry will not be described in the interest of brevity since it is readily understood by those skilled in the art.

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Heat cost computer 99 receives from material balance computer 97 via signal line 103 values representing $A_{1b'}$, $B_{11o'}$, $A_{11o'}$ and O_1 , and receives a signal 110 representing $B_{ho'}$, a fixed value since $B_{ho'}$ is a predetermined specification, and solves the predictive heat cost rate requirement equation for column 82, namely:

$$H_{c2} = K_{c2} O_1 \{ K_1 + K_2 (A_{1b'})^2 - K_3 (A_{1b'}) + K_5 (A_{11o'}) - K_4 (A_{11o'})^2 + B_{11o'} [K_6 - K_7 (A_{1b'}) + K_8 (A_{11o'})] \} \quad (23)$$

10 where:

H_{c2} = cost rate of reboiler heat required for operation of second column (\$/hr.)

K_{c2} = unit cost of steam used by reboiler of second column (\$/B.t.u.)

K_1 to K_8 = constants (some of which include the predetermined specifications)

The mathematical analog instrumentation used by heat computer 99 is shown in FIGURE 5, the circuitry of which will be readily understood by those skilled in the art.

Heat cost computer 101 receives from material balance computer 97 via signal line 104 values representing $B_{1b'}$ and B_2 , and receives by signal lines 106 and 107 values representing $B_{1b''}$ and $C_{ho''}$, respectively, and solves the predictive heat cost requirement equation for column 83, namely:

$$H_{c3} = K_{c3} B_2 \{ K_1 - K_2 (C_{ho''}) + K_3 (C_{ho''})^2 + K_4 (B_{1b''}) - K_5 (B_{1b''})^2 + K_6 (B_{1b''})^3 + B_{1b'} [K_7 - K_8 (B_{1b''}) - K_9 (B_{1b''}) + K_{10} (C_{ho''})] \} \quad (24)$$

where:

H_{c3} = cost rate of reboiler heat required for operation of third column (\$/hr.)

K_{c3} = unit cost of steam used by reboiler of second column (\$/B.t.u.)

K_1 to K_{10} = constants

FIGURE 6 schematically illustrates the mathematical analog instrumentation used by heat computer 101. Heat cost computers 98, 99 and 101 transmit via signal lines 108, 109 and 111, respectively, the heat cost values H_{c1} , H_{c2} and H_{c3} for columns 81, 82 and 83, respectively, to profit computer 112, where these values are added to obtain the total cost rate of reboiler heat.

Profit computer 112 also receives a signal via line 113 representing the flow rate of feedstock 84, and, as shown in FIGURE 7 this signal is multiplied by the unit cost (c_1) of feedstock to obtain the cost rate Y of the feedstock. Profit computer 112 also receives from material balance computer 97 via signal line 114 the flow rates of the various terminal product streams 88, 91, 94 and 96 (B_1 , O_2 , O_3 and B_3 of Diagram II) and, as shown in FIGURE 7, these values are multiplied by their respective unit values (c_4 , c_5 , c_6 and c_7 , respectively), the latter being added to obtain a total value rate X for the terminal product streams. Profit computer 112 then adds the total cost rate of reboiler heat required by the train and the total cost rate of the feedstock, and subtracts the sum thereof from the total value rate of the terminal product streams to produce a signal P_T representing the total profit rate. The latter signal is transmitted via signal line 115 to the profit optimizer 117, which accordingly manipulates $B_{11b''}$ and $C_{ho''}$, the manipulated specifications of the components B and C in terminal product streams 94 and 96, respectively, so as to maximize the profit rate of the operation. Manipulation of $B_{11b''}$ and $C_{ho''}$, of course, alters the operation of each of the distillation columns, such alteration being impressed on columns 81, 82 and 83 by operations computers 116, 119 and 118, respectively.

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 this invention is not

to be limited unduly to that set forth herein for illustrative purposes.

We claim:

1. In a process wherein a multicomponent feedstock is separated in a train of fractional distillation columns to produce a plurality of terminal product streams wherein the control of each of said columns is manipulated in accordance with signals representative of desired products necessary to realize maximum profit from the production of terminal products in each of said columns in said train, the process comprising the steps of measuring a process variable indicative of the flow rate of said feedstock to the first of said columns in the train; producing in response thereto a signal representative of the feed flow rate; analyzing said feedstock to determine the concentration of key components contained in said feedstock; producing in response thereto signals representative of said concentrations of said key components; combining the feed flow rate signals and the feed composition signals together with signals representative of predetermined product specifications desired in the said plurality of terminal product streams and signals representative of manipulated purity of intermediate product streams desired in said train of columns in a material balance computer; transmitting from said material balance computer said feed composition signals and said feed flow rate signals to a heat cost computer for said first column in said train of columns; transmitting signals representative of predetermined or manipulated product specifications associated with said heat cost computer; combining said feed flow rate signals and feed composition signals together with said first column from said material balance computer with said signals representative of predetermined or manipulated product specifications associated with said first column in a heat cost computer according to the following expression:

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

wherein:

H_R = predicted heat supplied to column by reboiler

F = flow rate of feed stream to column

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

E = average column tray efficiency

F_e = enthalpy of feed stream

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

H_D = liquid volume fraction of heavy key component desired in distillate product of column

L_B = liquid volume fraction of light key component desired in bottom product of column

producing in said heat cost computer a signal proportional to H_R ; multiplying in said heat cost computer said H_R signal by a signal representative of the rate cost of heat (dollars per B.t.u.) for said first column; producing a signal representative of the cost rate in dollars per unit time for said first column in said train of columns; repeating each of said aforementioned steps for each of said columns in said train in order to produce a signal representative of the cost rate for each of said columns; totaling

each of said cost rate signals per unit of time in a profit computer to produce a signal representative of the cost rate per unit of time for the train of columns; combining in a profit computer for said train of columns signals representative of the cost rate per unit of time for the train of columns, signals representative of the terminal flow rates of each of said columns in said train, signals representative of the feed flow rates to each of said columns, signals representative of the unit cost of the terminal products and signals representative of the unit cost of feed to the first column; producing a signal representative of the profit for said train of columns in said profit computer; comparing the profit signal with an optimum profit signal in said profit optimizer; changing the manipulated purities of the intermediate product streams in response to the difference between the optimum profit signal and the profit signal produced in the material balance computer; combining said signal representative of said manipulated purities of the intermediate product stream in an operations computer for each of said columns with signals representative of the flow rates and compositions of the streams entering and leaving each of said columns respectively to produce signals representative of desired terminal product purities for each of said columns in said train; controlling in response to said combined signals the flow rate of a stream selected from the group consisting of bottoms product stream, distillate product stream, external reflux stream, reboiler steam stream, and feed preheater steam stream for each of said columns in said train thereby assuring the operation of the columns in said train at optimum profit conditions.

2. The process according to claim 1 wherein the separation made by each column is manipulated by controlling the internal reflux flow rate.

3. The process according to claim 1 wherein the separation made by each said column is manipulated by controlling the bottom product flow rate.

4. The process according to claim 1 wherein the separation made by each said column is manipulated by controlling the enthalpy of the feed streams supplied to the column.

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WILBUR L. BASCOMB, Jr., *Examiner*.

UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,308,040

March 7, 1967

Merion L. Johnson et al.

It is hereby certified that error appears in the above numbered patent requiring correction and that the said Letters Patent should read as corrected below.

Column 15, line 29, after " associated" insert -- with said first column from said material balance computer --; line 30, strike out "puted"; line 32, strike out "with said first column from said material balance com-".

Signed and sealed this 7th day of November 1967.

(SEAL)

Attest:

Edward M. Fletcher, Jr.

Attesting Officer

EDWARD J. BRENNER

Commissioner of Patents