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AN INVESTIGATION OF THE USE AND DEVELOPMENT OF AN ELECTRONIC CALCULATOR FOR DISTILLATION CALCULATIONS OF MULTI-COMPONENT SYSTEMS

Thesis for the Degree of M. S.

MICHIGAN STATE COLLEGE

Howard Jay Cooper

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AN INVESTIGATION OF THE USE AND DEVELOPMENT OF AN ELECTRONIC CALCULATOR FOR DISTILLATION CALCULATIONS OF MULTI-COMPONENT SYSTEMS

by

HOWARD JAY COOPER

A THESIS

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ABSTRACT

In order to economize time and mental effort in mathematical computations of distillation towers, it is proposed to use an electronic calculator for this purpose. In general, most calculating machines do nothing more than solve a series of simultaneous equations. This is essentially the application presented in this work. In industry it is not inconceivable to enounter a fifty plate column being used for the separation of ten components. The solution here would incorporate 1,000 equations with 1,000 unknowns. The basic mathematical processes involved in the solution of these equations are multiplication, and addition.

With the feed composition, feed plate, number of plates, and the desired end products known, the composition at the top is assumed. The calculator is used to make plate to plate calculations going from the top down and from the bottom up until the compositions on the feed plate are obtained. It is desired that these compositions match, but should they be different, a new top composition must be assumed and the calculations done over.

It is further proposed to make this operation automatic.

To perform the aforementioned mathematical processes of multiplication and addition, a series of d.c. amplifiers are employed. As used in the calculator, the d.c. amplifier is essentially a three stage resistance coupled vacuum tube amplifier with negative feedback passing through a feedback resistor. The output voltage from the amplifier is equal to the input voltage multiplied by the ratio of feedback resistance to input resistance.

If a second input voltage is applied, the output voltage of the amplifier is the algebraic sum of the individual input voltages, each multiplied by the ratio of the feedback resistance to its individual input resistance.

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INTRODUCTION

Distillation is the separation of the constituents of a liquid mixture by partial vaporization of the mixture and separate recovery of vapor and residue. The more volatile constituents of the original mixture are obtained in increased concentration in the vapor; the less volatile in greater concentration in the liquid residue. The completeness of separation depends upon certain properties of the components involved and upon the arrangement of the distillation process.

In general distillation is the term applied to vaporization processes in which the vapor evolved is recovered usually by condensation. Evaporation commonly refers to the removal of water from aqueous solutions of non-volatile substances by vaporization. The vapor evolved, i.e., the water, is discarded.

Rectification, the case used in this work, is a distillation carried out in such a way that the vapor rising from a still comes in contact with a condensed portion of vapor previously evolved from the same still. A transfer of material and an interchange of heat result from this contact, thereby securing a greater enrichment of the vapor in the more volatile component than could be secured with a single distillation operation using the same amount of heat. The condensed vapors, returned to accomplish this object, are termed reflux.

Multicomponent mixtures are those containing more than two components in significant amounts. In commercial operations they are encountered more generally than are binary mixtures. As with binary mixtures, they can be treated in batch or continuous operations, in bubble-plate or packed towers. It is the bubble-plate tower that is considered here.

It is assumed that the reader is thoroughly acquainted with the principles and methods used to calculate binary mixtures. It is further assumed that the reader is familiar with the usual simplifying assumptions made in most all rectification calculations. Since these are also used in this work, they will be reviewed briefly here:

1. Sensible-heat changes through the tower are negligible in comparison to the latent heat.

2. The molar latent heats of all components are equal.

3. The heat of mixing of the components is negligible.

4. Heat losses from the tower are negligible.

Fundamentally, the estimation of the number of theoretical plates involved for the continuous separation of a multi-component mixture involves exactly the same principles as those used for binary mixtures. Thus, the operating-line equations for each component in a multi-component mixture are identical in form with those for binary mixtures. And the procedure is exactly the same; i.e., starting with the composition of the liquid at any position in the tower, the vapor in equilibrium with this liquid is calculated; and then by applying the appropriate operating line for the section of the tower in question to each component, the liquid composition on the plate above is determined and the operation repeated from plate to plate up or down the column. However, actually the estimation of the number of theoretical plates required for the separation of a complex mixture is more difficult than for a binary mixture. When considering binary mixtures, fixing the total pressure and one component in either the liquid or vapor immediately fixes the temperature and composition of the other phase, i.e., at a given total pressure, a unique or definite relation between y and x

allows the construction of the y-x curve. In the case of a multi-component mixture of u components, in addition to the pressure it is necessary to fix (u-1) concentrations before the system is completely defined. This means that for a given component in such a mixture the y-x curve is a function not only of the physical characteristics of the other components but also of their relative amounts. Therefore, instead of a single y-x curve for a given component, there are an infinite number of such curves depending on the relative amounts of the other components present. This necessitates a large amount of equilibrium data for each component in the presence of varying proportions of the others, and except in the special cases in which some generalized rule (such as Raoult's Law) applies these are not usually available, and it is very laborious to obtain them. One of the largest uses of multi-component rectification is in the petroleum industry; for a large number of the hydrocarbon mixtures encountered in these rectifications, generalized rules have been developed which give multi-component vapor-liquid equilibriums with precision sufficient for design calculations. Such data are usually present in the form y equals Kx, where K is a function of the pressure temperature, and component. K-charts are given in the appendix. The use of equilibrium data in such a form usually requires a trial-and-error calculation to estimate the vapor in equilibrium with a given liquid at a known pressure. This results from the fact that the temperature is not known so a temperature is assumed and the various equilibrium constants at the known pressure and assumed temperature are used to estimate the vapor composition. If the sum of the mol fractions of all the components in the vapor, so calculated, add up to 1, the assumed temperature was correct. If the sum is not equal to 1, a new temperature must be assumed and the calculation repeated until the sum is unity. Such a procedure is much more laborious than

that involved in a binary mixture where the composition of the liquid and the pressure together with equilibrium data immediately gives the vapor composition without trial and error.

After calculating a great number of multi-component distillation problems, it soon becomes apparent how valuable some kind of calculator would be. Perhaps the need for a calculating machine can be seen better if the problem for which it will be used is presented in a different manner. Take as an example the three component problem used in this work where the separation takes place in a five plate column. Basically the results sought here involve the solution of thirty equations containing thirty unknowns (two equations with two unknowns for each component and each plate). In industry it is not inconceivable to encounter a fifty-plate column being used for the separation of ten components. The solution here would incorporate 1,000 equations with 1,000 unknowns. The first alternative to come into one's mind would be mechanical means. A mechanical differential equation calculator had been used at Massachusetts Institute of Technology at one time, and the navy aimed their guns with mechanical calculators until the recent war. However, these mechanical calculators required new sets of gears for each problem and to compute the sizes, etc. of these gears meant practically working the problem itself. During the recent war the army switched to electronic means for calculating and directing anti-aircraft fire. It has been learned authoritatively that most large oil companies in the United States have been working toward development of an electronic calculator for the same purposes as set forth in this work. The big nemesis to the industries has been the large cost of building an electronic calculator. It is claimed by them that the plate efficiency in a distillation tower could be greatly improved if the maze of calculations involved could be handled in some practical manner. It is to this objective that this work has been devoted.

The reader should not get the impression that the calculator as is can only be applied to distillation. With a few slight modifications the calculator can be utilized for many other unit operations in chemical engineering. Some examples of other application would be absorption towers and heat exchangers. This is further brought out by the fact that the calculator used herein, and in general most calculating machines of this nature, do nothing more than solve a series of simultaneous equations.

HISTORY

The desire to economise time and mental effort in arithmetical computation, and to eliminate human liability to error, is probably as old as the science of arithmetic itself. This desire has led to the design and construction of a variety of aids to computation beginning with "groups of small objects such as pebbles used first loosely, later as 'counters' on ruled boards, and later still as beads mounted on wires fixed in a frame, constituting the abacus". (1,2,4)

The abacus was until the Christian era the only instrument man had developed for the purposes of calculating; it is still used extensively in China, Japan, India, and Russia. During the time after the invention of the abacus, gears and pointers were used in the design of clocks. These machine elements, and more especially a wheel which at the end of a complete revolution gave impetus to a second wheel, paved the way for the development of calculating machinery.

In 1617, John Napier, following his invention of logarithms, published an account of his numbering rods, known as "Napier's bones". (3) Various forms of the bones appeared, some approaching the beginning of mechanical computation. Subsequent to the introduction of logarithms, the slide rule was developed by Oughtred (1630), Evenard (1755), Mannheim (1850) and others. The slide rule is probably the ancestor of all those calculating devices whose operation is based upon an analogy between numbers and physical magnitudes, in which the computed results are obtained by physical measurements. Many such analogy devices have since been constructed. Examples of these are the planimeter, integraph and finally the differential analyser. (5) All analogy devices, like the slide rule, are limited to the accuracy of a physical measurement.

The first real calculating machine employing a mechanical principle did not appear until 1642, when a simple device consisting of geared numbering wheels was invented by Blaise Pascal. (6,7) "The design of Pascal's machine depended upon rotating wheels and provided for carry by mechanically turning the wheel of the next higher order one position when the lower passed from nine to zero". (11)

Mathematicians had realized that multiplication is actually a process of repeated addition, and a machine to carry out this principle was first projected in 1671 by Gottfried Wilhelm Leibnitz, though not successfully completed until 1694. (8) In Pascal's machine the wheels were set and turned individually by hand; in Leibnitz's machine all wheels were set and turned simultaneously by a crank to a previously determined position.

In 1820 Charles Xavier Thomas invented the first calculating machine that was sucessfully manufactured on a commercial scale. It could perform all four elementary arithmetical operations and during the succeeding several years was extensively improved by inventors in Europe and this country.

During the early years of the nineteenth century several more elaborate calculating machines were proposed. These included the so-called difference engines of which several were constructed (engines were to compute and print tables of functions). The most ambitious of all the proposals, however, was the analytical engine designed by Charles Babbage (9,10) in 1833 in which several features of his difference engine were to be embodied. This was a calculator intended for the performance of complete computations according to given instructions. The numbers in the first part of the machine, called the "store", were to be operated upon by the second part of the machine, called the "mill". A succession of selected operations were to be executed mechanically at the command of a "sequence mechanism". (12) The analytical engine was to have been completely general as regards algebraic operations.

As in the difference engines, the analytical engine was to print its own results. Further, a mechanism was to have been added for punching numerical results on blank cards for future use. In this way, the engine could compute the tables required and punch its own cards "entirely free from error". (13)

The plan, too ambitious for engineering and technical facilities of that time, was unfinished when Babbage died. Though his principles were theoretically sound and though he was successful to a limited extent, it remained for the twentieth century and the evolution of advanced mechanical and electrical engineering to bring his ideas into being.

The familiar keyboard type of calculating machine originated in the United States at about the middle of the last century and has been developed, chiefly in this country, for many accounting and commercial computing purposes.

In 1887, Leon Bollée was successful in producing the first machine capable of performing multiplication by a direct method instead of the method of repeated addition. The principle was further developed in later machines.

To expedite United States Census compilation work, Herman Hollerith, in 1889, developed the punched card as a means of recording numerical information for automatic computing. At the same time he devised electrically-operated mechanisms which performed adding and counting operations when actuated by punched cards. This method was perfected through a long program of "research and development by the International Business Machines

Corporation to the point where electro-mechanical machines could perform a variety of operations such as reading, adding, printing, sorting, reproducing, multiplying, collating, and summary punching". (14)

By 1934 I.B.M. had perfected electric punch card machines to such an extent that they were capable of handling many of the general calculations of science. An automatic computing laboratory was established in and operated by the Thomas J. Watson Astronomical Computing Bureau, a cooperative project of the American Astronomical Society, Columbia University, and I.B.M.

The first large-scale general-purpose digital calculator was built by I.B.M. Known as the I.B.M. Automatic Sequence Controlled Calculator, it was completed in 1944. It had the greatest internal storage capacity and most elaborate sequencing facilities of any machine prior to the I.B.M. Selective Sequence Electronic Calculator.

Up to this time the adding wheel was utilized as a basic unit in practically all calculating machines. In 1946 the first large electronic calculator was dedicated by the University of Pennsylvania and the first commercial electronic computor was marketed by I.B.M. The "Eniac" was built by the University of Pennsylvania for computing trajectories of shells; it has storage for about 200 digits including those in the multiplication and division units, and is controlled by means of pluggable connections.

The newly developed I.B.M. Selective Sequence Electronic Calculator is the most recent development in the search for a machine more nearly capable of meeting the size and scope of present-day problems. It has a memory capacity of over 400,000 digits.

THEORETICAL CONSIDERATIONS

In the present section it is desired to discuss the theory of amplifiers. Before considering details, certain general remarks concerning the nature of calculating devices should be made. Each such device will have a number of inputs and an output. A pure calculating device can be defined as one which has no source of energy between the input and output. For such a device the outputs must do all the work. In general it is also true that the results will be accurate only when the output does no work. Indeed the order of magnitude of the error is closely associated with the ratio of output work to input work.

It follows therefore that if the mathematical output of such a device is to be used as an input to a similar device, an energy source must be provided.

The ratio of the output energies to input energies of available amplifiers is very important in considering the physical principles upon which a device is to be based. Fortunately this ratio is quite large for electronic amplifiers and the latter are frequently used as part of other amplifiers for this reason.

In the discussion which appears in this section, it is supposed that the reader is familiar with the R.C.A. Receiving Tube Manual, published by the R.C.A. Manufacturing Co. The manual describes the various types of tubes and their uses in radio receiving sets. Many of these uses are immediately applicable to calculating devices, others require a certain amount of reorientation. The manual contains the technical information necessary for the design of circuits and is a remarkable summation of the application of vacuum tubes for radio receiving purposes.

Essentially the two uses of a vacuum tube are (1) rectification, i.e., the process of obtaining a pulsating one directional current from an alternating voltage, and (2) amplification, the control of power by less power.

It is assumed that the reader is familiar with the usual discussion of the action of triodes and multi-electrode vacuum tubes. An excellent summation of the fundamentals of vacuum tubes is also contained in the R.C.A. Manual referred to above. It is also desired herein to point out certain aspects of amplifying ciruits which are important from the point of view of this work. Amplifiers can be roughly divided into two kinds. One type is a voltage multiplier and the other is a power multiplier proper. The voltage multiplier is the one concerned with here.

For electronic amplifiers in general it is necessary to use high voltage direct currents. These are obtained by the use of step-up transformers and diode type rectifying tubes as given in the power-pack circuits in the appendix.

The d.c. amplifier is an electronic device which produces a d.c. output voltage directly proportional to the input voltage, when the input is a d.c. voltage. The amplifiers are used to perform any or all of the following functions:

1. Produce a d.c. voltage proportional to the algebraic sum of two or more d.c. voltages, either with or without weighting of one or more of the input voltages.

2. Reverse the sign of a d.c. voltage, either without changing its value or including multiplying the value by a constant factor.

3. Isolate one circuit element from another.

If d.c. voltages from several sources are connected, each through equal resistance, to a common point from which a resistance is connected to ground, as shown in figure 1, the voltage across the latter resistance

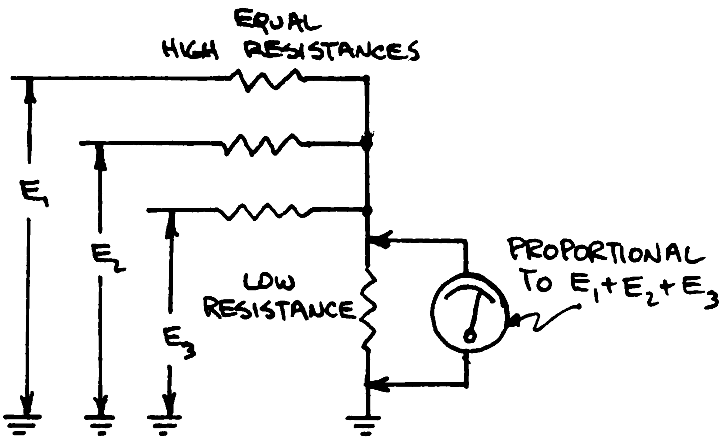


FIGURE 1

is proportional to the algebraic sum of the several voltages. If the latter resistance is very small compared to the input resistances, the factor of proportionality will be very nearly the same for any number of inputs. The voltage measured as in figure 1 would be very small. To obtain a usable voltage, still proportional to the algebraic sum of the input voltages, a vacuum tube amplifier is substituted, in the circuits of the calculator, for the small resistance as indicated in figure 2. This amplifier is so designed that its apparent resistance (input impedance) is only about 25 ohms. By making the input resistance of the order of 1 megohm, the measured voltage is then very nearly proportional to the algebraic sum of the input voltages. The amplifier amplifies the measured voltage about 40,000 times.

If the input resistances are all equal, the voltage across the small resistance of the amplifier and, therefore, the output voltage of the

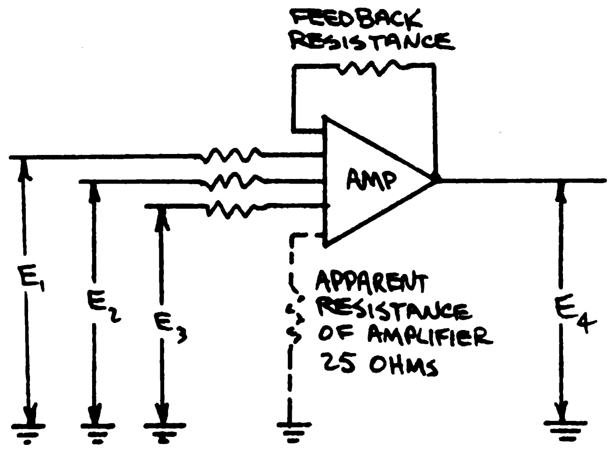


FIGURE 2

amplifier will be directly proportional to the algebraic sum of the input voltages. By suitable arrangement of the circuits, this output voltage may be made (very nearly) equal to the algebraic sum of the input voltages, or it may be multiplied by any factor. If one of the input resistances is made somewhat lower than the others, the input voltage connected through that resistance will be multiplied by a factor or weighted in the summation.

The d.c. amplifier used has three stages. From the fundamentals of vacuum tubes the output voltage of such an amplifier is opposite in sign to the input voltage. The amplifier, therefore, reverses the sign of a voltage applied to it. From the preceding it is apparent that, in this case also, the output voltage may be made equal to the input voltage or to the input voltage multiplied by any factor.

As used in the calculator, the d.c. amplifier is essentially a three stage resistance-coupled vacuum tube amplifier with negative feedback. The following are some of its characteristics:

Number of Stages.................................... 3

Tubes Used:
first stage 6SC7
second stage............................... 6SJ7
third stage................................ 6L6

Supply Voltages.... 350, -350, 300, -190, 75 d.c., and 6.3 a.c.

Net Gain.......................... 30,000 to 40,000

Apparent input impedance............. about 25 ohms

Effective output impedance .... about 1 ohm

In a d.c. amplifier, the connection from the plate of one stage to the grid of the next must be a metallic one, containing no capacitor or transformer which would prevent the transmission of a steady voltage. The plate of the first-stage tube is usually at a considerable voltage above ground, whereas the grid of the second-stage tube must be a few volts negative with respect to its cathode. If this condition were obtained by supplying the cathode with a suitable voltage, the plate supply of the second tube would have to be the sum of the required plate voltage and the cathode voltage. With more than two stages this arrangement is impractical as a very high plate voltage would be required for this last tube.

Figure 3 shows the plan used in the amplifiers of the calculator. The plate voltage is opposed by a second equal voltage of opposite polarity, and the grid of the second tube is connected to a voltage divider to obtain the proper bias potential. This plan involves a loss of part of the amplification as only a part of the voltage change on the plate of the first tube will be transmitted to the second tube. The ratio of resistance ~~BC~~ DC to AC is about 4 to 5, so that about four-fifths of the voltage change is

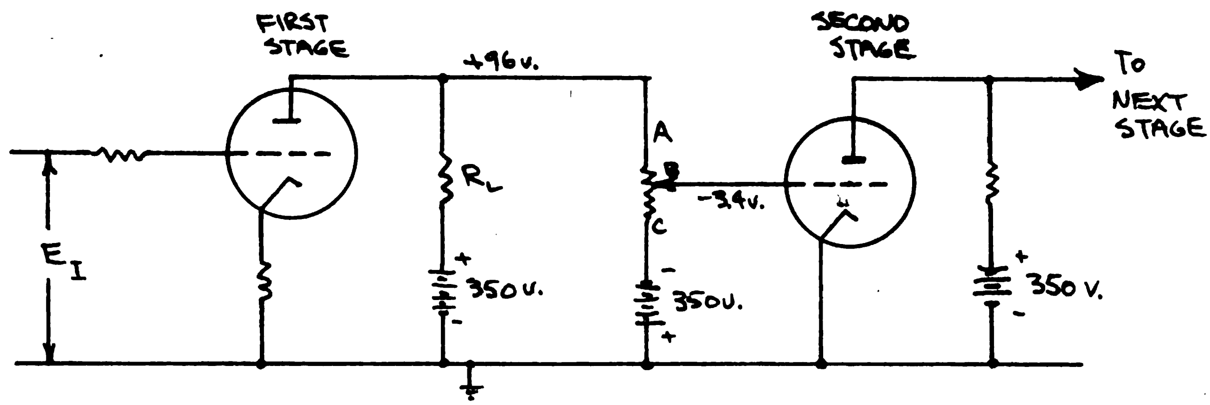


FIGURE 3

transmitted, reducing the gain of the first stage from about 50 to 40.

The amplifier diagram in the appendix shows that a similar arrangement is used for the connection of the plate of the second stage to the grid of the third stage. However, if the output voltage of the amplifier is to be directly proportional to the input voltage, it must be zero when the input voltage is zero. To meet this requirement, the cathode of the third-stage tube is supplied with a negative potential. By applying a suitable negative bias to the grid, the output of the tube is made to balance the plate voltage so that the potential at the plate is normally zero. If now the grid is made more negative with respect to the cathode, the output of the tube will be increased and the potential at the plate will be positive. If the grid is made less negative with respect to the cathode, the output of the tube will be less and the potential at the plate will become negative. With no input voltage, therefore, the output voltage of the amplifier is zero. With a negative input voltage, the output voltage is positive, and with a positive input voltage the output voltage is negative. The amplifier reverses the sign of the input voltage and the value of the output voltage is always directly proportional to the value of the input voltage.

In this coupling, about one-half of the gain of the first two stages is lost, but the overall gain of the amplifier is sufficient for the purpose for which it is used.

The amplifier diagram in the appendix shows a resistor connected between the output of the amplifier and the input. Through this feedback resistor a portion of the output voltage is returned to the input. Since the sign of the output voltage is opposite to that of the input voltage, this is a negative feedback.

The effect of negative feedback is illustrated in figure 4 where the amplifier is represented as a single tube. A voltage E, at the input of an amplifier will produce a voltage e at the grid. This will be amplified and appear as a voltage -Ke at the output (K being the gain of the amplifier). A portion of this voltage will be returned to the grid through the feedback resistor R_B and, since it is opposite in sign to the voltage e, will tend to reduce e. This will reduce Ke, allowing e to increase, until a point of stabilization is reached. This stabilization occurs practically instantaneously. Any change in amplification due to variations in the amplifier itself will change the value of K but, due to the feedback this will correspondingly change e and thus tend to maintain E_0 at a constant value. The use of negative feedback gives the amplifier great inherent stability.

If the feedback resistance and the input resistance both have the same value, R, the current through these resistances will be:

$$I = \frac{E + Ke}{2R}$$

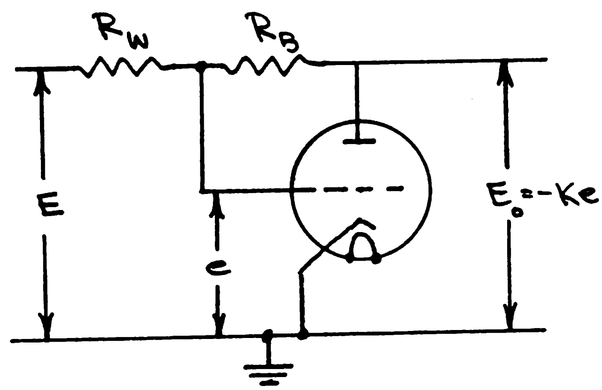


FIGURE 4

since the output voltage E_o, and the input voltage E are in effect aiding. The potential e at the grid will be the input voltage less the voltage drop in the input resistance or:

$$e = E - IR$$

Substituting the value of I in this equation:

$$e = E - \frac{E + Ke}{2}$$

or:

$$e = \frac{E}{K+2}$$

and:

$$E_o = -Ke = -\frac{KE}{K+2}$$

If:

$$K = 40{,}000$$

then:

$$E_o = -0.99995E$$

Thus, if the feedback resistance is made equal to the input resistance, the output voltage of the amplifier will be a negative copy of the input voltage, exact to about 5 parts in 100,000. It will be noted that the larger the gain (K), the greater is the accuracy with which the input voltage is reproduced in the output.

By the same process, it can be shown that if the feedback resistance is not equal to the input resistance, then:

$$E_o = -E\frac{R_B}{R_W} \quad \text{(very nearly)}$$

This makes it possible, by using a suitable ratio of feedback to input resistance, to obtain an output voltage from the amplifier which is always equal to the input voltage multiplied by a constant factor.

In figure 5

$$E_1 = I_1 R_1; \quad E_2 = I_2 R_2; \quad E_3 = I_3 R_3$$

and:

$$I_3 = I_1 + I_2$$

therefore:

$$E_3 = (I_1 + I_2) R_3; \quad E_3 = \frac{R_3}{R_1} E_1 + \frac{R_3}{R_2} E_2$$

The output voltage of the amplifier will, therefore, be the algebraic sum

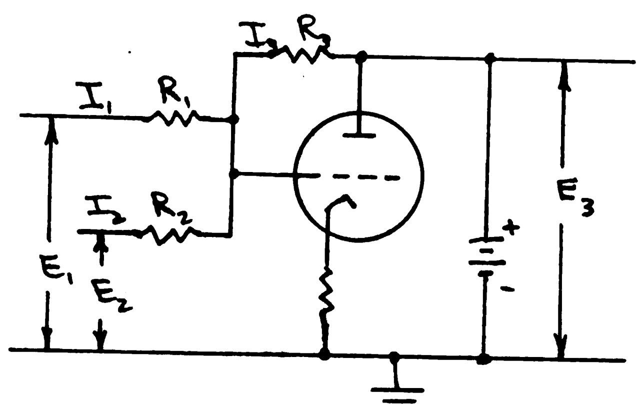


FIGURE 5

of the individual input voltages, each multiplied by the ratio of the feedback resistance to its individual input resistance. This makes it possible, by using suitable values of input resistances, to give each voltage a particular weight in the summation or to emphasize the effect of any one or more voltages. Of course, if the input resistances all have the same value, the input voltages will all have the same weight and the output voltage of the amplifier will be the algebraic sum of the input voltages.

In an ordinary vacuum-tube amplifier, the input impedance is practically infinite. Negative feedback, however, alters this condition. In figure 4 the voltage drop in resistor R_{IN} is E-e. The same result would be obtained if the amplifier were replaced by a resistance. But e is very small compared to E. The resistance which would replace the amplifier will then be very small compared to R_{IN}. Actually the equivalent or apparent resistance of the amplifier with feedback is in the order of 25 ohms. The amplifier with feedback, therefore, satisfies the requirement of low apparent input impedance which was brought out previously to be necessary when the amplifier is used for the addition of several input voltages.

A generator or source of electric power normally has some internal resistance. If an external load is connected to such a generator, the two resistances, R_{INT} and R_{Load} will form a voltage divider and the output voltage will be:

$$E_O = E \times \frac{R_{Load}}{R_{INT.} + R_{Load}}$$

The output voltage E_o will then depend upon the relative values of $R_{INT.}$ and R_{Load}. Changing the load resistance will change the output voltage. If the internal resistance is high compared to the load resistance, the output voltage will vary widely as the load is changed. If the internal resistance is very small, the change in output voltage will be insignificant.

In the d.c. amplifier, an increase in the load resistance would tend to lower the output voltage, but since this change is transmitted through the feedback resistor, it will also tend to increase the voltage e, thereby increasing the output voltage -Ke. Due to this compensating action, the output voltage remains practically constant from no load to the full load which the amplifier can handle. This is the condition that exists with a generator of very low internal resistance or, as it is usually described in connection with vacuum-tube circuits, very low output impedance. The effective output impedance of the amplifiers used in the calculator is in the order of 1 ohm.

Since the effective output impedance of the amplifier is so low, the output voltage is practically uneffected by the load (within the capacity of the amplifier). The amplifier can, therefore, be used to isolate two circuit elements when the load of one element would react unfavorably on the other.

Although negative feedback tends to level out variations in the gain of the amplifier, small changes in gain of the first stage will have an important effect on the output voltage, because such changes in the first stage are greatly amplified by the succeeding stages. For example, if the second stage has a gain of 60 and the third stage a gain of 15, changes in the first stage will be amplified by 60 x 15 or 900 times. Changes in the second stage are not so important as they will be amplified only 15 times, whereas changes in the third stage will not be amplified at all.

The first tube of the amplifier is, therefore, arranged to minimize changes in gain which may be caused by variations in cathode emission. A twin-triode tube with common cathode is used, one section being used as the amplifier and the other section for the stabilization. The cathode is connected to ground through three resistors, one of which is variable.

To be a true negative copy of the input voltage, the output voltage of the amplifier must be zero when the input voltage is zero. Due to manufacturing variations in the vacuum tubes, it is impracticable to make the amplifiers so that they will always give zero output voltage with zero input voltage. They are made, therefore, so that they always give a small positive output voltage with zero input voltage. To compensate for this, each amplifier is provided with a small positive input voltage which may be adjusted. The operation of adjusting this voltage will be called zero-setting. The voltage is derived from the regulated +75-volt supply, and the arrangement is shown schematically in the diagram in the appendix.

By adjusting, the zero-set voltage of each amplifier, the output voltages of all of them are brought to zero before the calculator is operated. This is essential to accurate computation. When zero-setting the amplifiers, there must, of course, be no input voltages other than the zero-set voltage. There must also be no resistance paths to ground at the inputs, which would modify the applied zero-set voltage. Therefore, when zero-setting all amplifier inputs must be grounded.

The complete circuit of the d.c. amplifier is shown in the appendix. The second stage tube is a pentode. The screen grid of this tube is supplied with +75 volts. The third stage tube is a beam-power tube. Since the cathode is supplied with -190 volts, the screen grid is made positive with respect to the cathode by connecting it to ground.

All the tubes have indirectly-heated cathodes, the heaters using 6.3 volts alternating current. In order to prevent a large potential difference between the heater and the cathode of the third tube, two heater supply transformers are used. One, at ground potential, supplies the heaters of the first and second tubes, and the other connected to the -190 volt supply, supplies the heater of the third tube. These two transformers supply all the amplifiers in the calculator.

An amplifier with such high gain is very readily set into oscillation by small disturbances. To prevent oscillation, the control grid of each tube is connected to ground through a filter composed of a resistor and a capacitor. These filters introduce attenuation so that the gain of the amplifier (40,000) is reduced to unity at about 1,000 cycles per second and to a loss at higher frequencies.

METHOD OF PROCEDURE

While the power unit was being built, it was obvious that an actual distillation problem would have to be set up and calculated by trial and error. It was necessary to have a distillation example set up and completely calculated so as to check and develop the calculator when finished. Also, it was needed in order to determine the ratio of feedback resistance to input resistance in the amplifier, which is discussed later. For the purposes here the set up of the distillation problem and subsequent calculations were varied somewhat from the procedure with which the reader is probably most familiar. Two problems, one three-component and one six-component, were set up and calculated as follows:

A fractionating column with a known amount of plates was specified. In this case a five and six plate column plus reboiler. Also specified was the feed composition, feed plate, reflux ratio, pressure, and certain requirements of the end product. To proceed from here, the composition coming from the top or bottom was assumed, and with the top or bottom composition as assumed, and with the feed composition set, the other (top or bottom) composition is automatically set from material balances on the entire column. Using the top and bottom compositions as assumed, a plate to plate calculation was made—working from the top down and from the bottom up. If the compositions so calculated were identical for the feed plate, then the compositions assumed were correct. If the feed plate compositions do not match, a new composition at the top and bottom must be assumed and the calculations repeated until the feed plate compositions match. It was found to be extremely difficult to match these compositions 100 per cent. An alternative is to calculate down from the top and determine the vapor composition from the feed plate, and calculate up from the bottom and determine the liquid composition from the feed plate. Using these values of y and x calculate K for the feed plate. With these values of K, the corresponding values of temperature are obtained from the K-charts, and these temperatures must be identical.

In each of the two problems following, several trials were found necessary by the author. Only the final calculation is given.

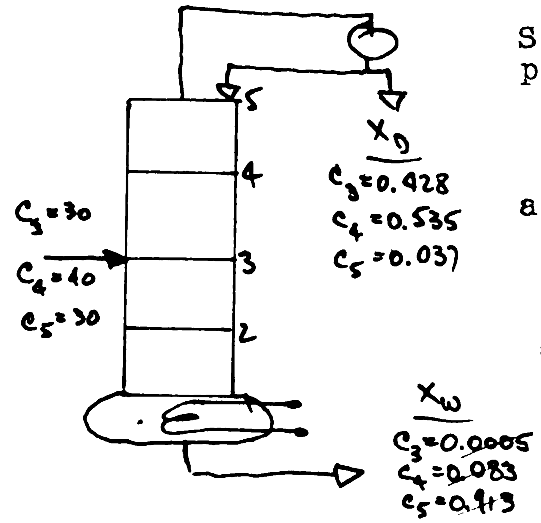
Problem I: Three-component system

A mixture of 30 mol per cent propane, 40 mol per cent butane, and 30 mol per cent pentane is to be fractionated in a five plate column. The feed to the column will enter in such a condition that no net vaporization or condensation will occur on the feed plate ($V_n = V_m$), and the column operates at 100 pounds per square inch absolute. Reflux ratio of O/D = 3. D = 70 W = 30.

Assume:

	x_d
C_3	0.428
C_4	0.5375
C_5	0.037

Using as a basis 100 mols of feed:



Since $O/D = 3$, in the top part of the tower

$$O_n = 3D = 210$$

and $V_n = O_n + D = 280$, and

$$O_m = O_n + F = 310,$$

giving $V_m = 280$

For the part of the column above the feed plate, the operating lines are

for propane:

$$y_n = (O/V)_n x_{n+1} + (D/V)_n x_d = (210/280)x_{n+1} + (70/280)x_D$$

$$= 0.75x_{n+1} + 0.106$$

for butane:

$$y_n = 0.75x_{n+1} + 0.132$$

for pentane:

$$y_n = 0.75x_{n+1} + 0.012$$

For the part of the column below the feed plate, the operating lines are

for propane:

$$y_m = (O/V)_m x_{m+1} - (W/V)_m x_W = (310/280)x_{m+1} - (30/280)x_W$$

$$= 1.10x_{m+1} - 0.00$$

for butane:

$$y_m = 1.10x_{m+1} - 0.011$$

for pentane:

$$y_m = 1.10x_{m+1} - 0.096$$

Beginning with the composition of the vapor at the top and the liquid in the still, a temperature is assumed and the values of K found from the charts. Using these values of K and composition, the composition of vapor or liquid in equilibrium is calculated. If the sum of these mol fractions add up to one, the assumed temperature was correct.

Component	T, °F Assumed	K	$y_5 = x_D$	y/K	$x_5 = \frac{y/K}{\Sigma y/K}$	y_4
C_3	132	2.5	0.428	0.171	0.174	0.238
C_4		0.8	0.535	0.670	0.680	0.644
C_5		0.26	0.037	0.142	0.144	0.117
				$\Sigma y/K = 0.983$	$\Sigma x_5 = 0.998$	
			y_4	y_4/K	x_4	y_3
C_3	156	3.1	0.238	0.077	0.079	0.166
C_4		1.1	0.644	0.585	0.597	0.581
C_5		0.37	0.117	0.316	0.323	0.251
				$\Sigma y/K = 0.978$	$\Sigma x_4 = 0.999$	
			y_3	y_3/K	x_3	
C_3	176	3.7	0.166	0.045	0.045	
C_4		1.3	0.581	0.447	0.450	
C_5		0.50	0.251	0.502	0.505	
				$\Sigma y/K = 0.994$	$\Sigma x_3 = 1.000$	

\- BOTTOM UP -

Component	T, °F Assumed	K	x_w	xK	$y_w = \frac{xK}{\Sigma xK}$	x_1
C_3	224	5.2	0.0005	0.0026	0.00250	0.0023
C_4		2.1	0.083	0.174	0.171	0.163
C_5		0.92	0.913	0.840	0.827	0.843 → 0.835
				$\Sigma xK = 1.017$	$\Sigma y_w = 1.001$	
			x_1	$x_1 K$	y_1	x_2
C_3	212	4.8	0.0023	0.011	0.011	0.011
C_4		1.9	0.163	0.310	0.311	0.290
C_5		0.8	0.843	0.675	0.677	0.707
				$\Sigma xK = 0.996$	$\Sigma y_1 = 0.999$	
			x_2	$x_2 K$	y_2	
C_3	196	4.3	0.011	0.0473	0.0472	0.044 → 0.043
C_4		1.7	0.290	0.493	0.492	0.454 → 0.453
C_5		0.66	0.707	0.466	0.465	0.513 → 0.508
				$\Sigma xK = 1.002$	$\Sigma y_2 = 1.000$	

From the feed plate composition as calculated

Component	y_3	x_3	K	Temperature
C_3	0.166	0.044	3.7	176°F
C_4	0.581	0.454	1.28	176
C_5	0.251	0.513	0.491	176

The maximum operating conditions obtainable with the specified bubble-plate column and under the conditions designated are then

	Feed	Distillate		Residue	
Component	Mols	Mols	Mol fraction	Mols	Mol fraction
Propane..........	30	30.0-	0.428	0.0005	0.0005
Butane...........	40	37.41	0.535	2.49	0.083
Pentane..........	30	2.59	0.037	27.4	0.913
	100	70.00	1.000	29.89	0.9965

Problem II: Six-component system

A natural gasoline of composition given below is to be separated in a six plate column. The column is to operate at 100 pounds per square inch absolute pressure with a reflux ratio, O/D, of 3, and the feed is to enter in such a condition that no net vaporization of condensation occurs on the feed plate ($V_n = V_m$).

assume:

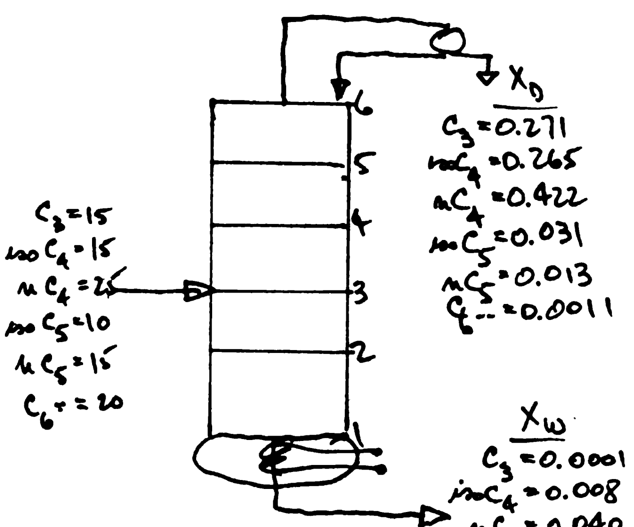
	x_D
propane	0.271
iso-butane	0.265
n-butane	0.422
iso-pentane	0.031
n-pentane	0.013
heavier	0.0011
	1,0031

Feed composition:

propane	15 mol %
iso-butane	15
n-butane	25
iso-pentane	10
n-pentane	15
heavier	20

D = 54.9   W = 45.1

Using as a basis 100 mols of feed:



Since O/D is 3, in the top part of tower

$O_n = 3D = 164.4$

and $V_n = O_n + D = 219.2$,

and $O_m = O_n + F = 264.4$,

giving $V_m = 219.2$

iso C_5 = 0.184
n C_5 = 0.317
C_6... = 0.443

For the part of the column above the feed plate, the operating lines are

for propane:

$$y_n = (O/V)_n x_{n+1} + (D/V)_n x_D = (164.4/219.2)x_{n+1} + (54.9/219.2)x_D$$

$$= 0.75x_{n+1} + 0.0685$$

for butane (iso):

$$y_n = 0.75x_{n+1} + 0.0662$$

for n-butane:

$$y_m = 0.75x_{m+1} + 0.104$$

for iso-pentane:

$$y_m = 0.75x_{m+1} + 0.007$$

for n-pentane:

$$y_m = 0.75x_{m+1} + 0.004$$

for hexanes:

$$y_m = 0.75x_{m+1} + 0.0005$$

For the part of the column below the feed plate, the operating lines are

for propane:

$$y_m = (O/V)_m x_{m+1} - (W/V)_m x_w = (264.4/219.2)x_{m+1} - (45.1/219.2)x_w$$

$$= 1.21x_{m+1} - 0.000$$

for iso-butane:

$$y_m = 1.21x_{m+1} - 0.002$$

for n-butane:

$$y_m = 1.21x_{m+1} - 0.008$$

for iso-pentane:

$$y_m = 1.21x_{m+1} - 0.037$$

for n-pentane:

$$y_m = 1.21x_{m+1} - 0.063$$

for hexanes:

$$y_m = 1.21x_{m+1} - 0.089$$

Component	T, °F assumed	K	$x_6 = y_6$	y/K	$x_6 = \frac{y/K}{\Sigma y/K}$	y_5
C_3	136	2.6	0.271	0.104	0.104	0.148
iso C_4		1.1	0.266	0.241	0.241	0.251
n C_4		0.82	0.422	0.515	0.515	0.490
iso C_5		0.38	0.031	0.0815	0.0815	0.0681
n C_5		0.275	0.013	0.0473	0.0473	0.0395
C_6 ...		0.14	0.0011	0.0078+	0.00785	0.0069
				$\Sigma y/K = 0.998$	$\Sigma x_6 = 0.998$	
			y_5	y_5/K	x_5	y_4
C_3	158	3.1	0.148	0.048	0.050	0.108
iso C_4		1.35	0.251	0.186	0.195	0.216
n C_4		1.1	0.490	0.445	0.465	0.452
iso C_5		0.51	0.068	0.1335	0.140	0.112
n C_5		0.38	0.0395	0.104	0.109	0.0858
C_6 --		0.19	0.0069	0.0337	0.0356	0.0266
				$\Sigma y/K = 0.953$	$\Sigma x_5 = 0.994$	
			y_4	y_4/K	x_4	
C_3	176	3.7	0.108	0.0292	0.0302	
iso C_4		1.6	0.216	0.135	0.140	
n C_4		1.3	0.452	0.349	0.361	
iso C_5		0.65	0.112	0.173	0.179	
n C_5		0.50	0.086	0.172	0.178	
C_6 --		0.26	0.0266	0.102	0.106	
				$\Sigma y/K = 0.967$	$\Sigma x_4 = 0.994$	

— BOTTOM UP —

Component	T, °F assumed	K	x_w	xK	$y_w = \frac{xK}{\Sigma xK}$	x_1
C_3	244	5.9	0.0001	0.00059	0.00060	0.00049
iso C_4		2.88	0.008	0.023	0.0235	0.0215
n C_4		2.40	0.040	0.096	0.098	0.090
iso C_5		1.27	0.184	0.234	0.239	0.230
n C_5		1.13	0.317	0.358	0.366	0.357
C_6 --		0.60	0.443	0.266	0.272	0.301
				$\Sigma xK = 0.978$	$\Sigma y_w = 0.999$	

COMPONENT	T, °F ASSUMED	K	X_1	X_1K	$y_1 = \frac{X_1K}{\Sigma X_1K}$	X_2
C_3	220	5.0	0.00049	0.00245	0.00259	0.00215
iso C_4		2.4	0.0215	0.0516	0.0545	0.0472
n C_4		2.0	0.090	0.180	0.190	0.167
iso C_5		1.1	0.230	0.253	0.267	0.254
n C_5		0.90	0.357	0.322	0.340	0.335
C_6...		0.46	0.301	0.138	0.146	0.196
				$\Sigma XK = 0.947$	$\Sigma y_1 = 1.0000$	
			X_2	X_2K	y_2	X_3
C_3	204	4.5	0.00215	0.00968	0.010	0.0083
iso C_4		2.1	0.0472	0.099	0.102	0.0849
n C_4		1.9	0.167	0.317	0.329	0.280
iso C_5		0.90	0.254	0.229	0.236	0.228
n C_5		0.72	0.335	0.241	0.249	0.260
C_6...		0.38	0.196	0.0745	0.077	0.139
				$\Sigma XK = 0.970$	$\Sigma y_2 = 1.001$	
			X_3	X_3K	y_3	X_4
C_3	186	4.0	0.0083	0.0332	0.0342	0.0284
iso C_4		1.8	0.0849	0.153	0.158	0.134
n C_4		1.5	0.280	0.420	0.432	0.367
iso C_5		0.73	0.228	0.167	0.172	0.175
n C_5		0.58	0.260	0.151	0.156	0.182
C_6...		0.30	0.139	0.0417	0.043	0.111
				$\Sigma XK = 0.966$	$\Sigma y_3 = 0.995$	

From the feed plate composition as calculated

Component	y_4	x_4	K	Temperature
C_3	0.108	0.0284	3.80	176°F
isoC_4	0.216	0.134	1.65	172
nC_4	0.452	0.367	1.23	172
isoC_5	0.112	0.175	0.64	174
nC_5	0.0858	0.182	0.47	172
C_6--	0.0265	0.111	0.24	172

The maximum operating conditions obtainable with the specified bubble-plate column and under the conditions designated are then

	Feed	Distillate		Residue	
Component	Mols	Mols	Mol fraction	Mols	Mol fraction
Propane..........	15	14.9	0.271	0.00	0.0001
iso Butane........	15	14.55	0.265	0.36	0.008
n Butane..........	25	23.2	0.422	1.80	0.040
iso Pentane.......	10	1.7	0.031	8.3	0.184
n Pentane.........	15	0.71	0.013	14.3	0.317
Hexanes..........	20	0.06	0.001	20.0	0.443
	100	55.0	1.003	44.8	0.992

DISCUSSION

Upon completion of the power unit and several amplifiers (wiring diagrams shown in appendix) they were tested to make sure each was operating properly. The general scheme was to have one amplifier unit for each component in the system to be calculated. It should be noted that two amplifier units are mounted on each base. As was pointed out in the section on theory, it is the ratio of the feedback resistance to input resistance that determines the multiplication factor. Therefore the first problem to be overcome was setting up these resistances so as to get, exactly, the various multiplication factors needed. It was decided to keep the feedback resistance constant and vary the input resistance to give the multiplication factors. Because of practical limitation neither resistor should be less than 200,000 ohms. An IRC wire-wound precision resistor of 200,000 ohms was selected for the constant feedback resistance, since the accuracy obtainable depends largely on the accuracy of the feedback and input resistors. The next step was to prepare a variable input resistance that would provide the accuracy needed. Using the sample calculations given previously as a basis, it is noted that the first step in the calculations is multiplying by K or 1/K. The ratio of feedback resistance to input resistance (multiplication factor) is therefore used to correspond to K or 1/K. Thus, two sets of resistors are needed for each component; one for the upper part of the column where multiplication is by 1/K, and one set for the lower part of the column where the multiplication is by K.

The "K" charts given in the appendix show that K is definitely not a straight line function of temperature, and also that the range of K values is greatly different for each hydrocarbon. This fact complicates the operation of the calculator. The ideal method of arranging the calculator would be where a series of resistors are ganged on one central shaft, each resistor corresponding to the K curve of a particular hydrocarbon. In that way, setting the shaft to a certain temperature on a calibrated dial automatically sets each resistor to its particular value of K. Actually a value of resistance is set which when divided arithmetically into the resistance value of the fixed feedback resistance gives the particular numerical value of K. In this way the first step of multiplication in the calculation series is accomplished.

Due to factors of time and economy, special variable resistors of this kind could not be ordered from a manufacturer. Thus the main task of this project was undertaken by the author. The first proposal was to wind wire on a thin card of insulating material which can be bent into a circle to save space and better facilitate its use. A brush is arranged to run around one edge of this card making contact with successive turns of the wire. By suitably shaping the width of the card, the resistance of the card at the brush can be made proportional to almost any desired function of the angle of brush displacement. For the problem in this investigation, the card would have to be shaped by computation and trial until a shape is found which gives the desired resistances at every point. Obviously, the shape would approximate the shape of the temperature-K curve for each component.

An investigation was conducted to determine the possibilities of making potentiometers as proposed above, and it was found that the best resistance wire obtainable was one ohm per foot. The highest resistance needed was calculated to be about three million ohms. Because of this, the proposal was considered neither practical nor economical and had to be abandoned.

Another proposal offered was to impregnate a liquid plastic (hardened upon heating) with finely divided carbon. If the right proportion of carbon could be found, sheets of this plastic could be made and then cut into the desired shapes. This proposal was investigated quite extensively and found to be unobtainable. Since the plastic was fairly compressible, any change in pressure due to the moving brush caused a large change in the resistance at the point of contact. This effect was due to the moving of the carbon particles closer together.

Finally, the present set-up had to be adopted. Regular IRC carbon volume control potentiometers are used as the variable input resistors. Two resistors are used with each component, one for calculating the top part of the column and one for calculating the bottom part of the column. For the three-component problem worked out by the author, it can be seen in the pictures of the calculator that there are two panels with three calibrated metal dials on each. One panel for each section of the column, and one dial for each component.

The methods of obtaining a suitable variable input resistance have been discussed in sufficient detail to warrant a discussion of calibration procedure.

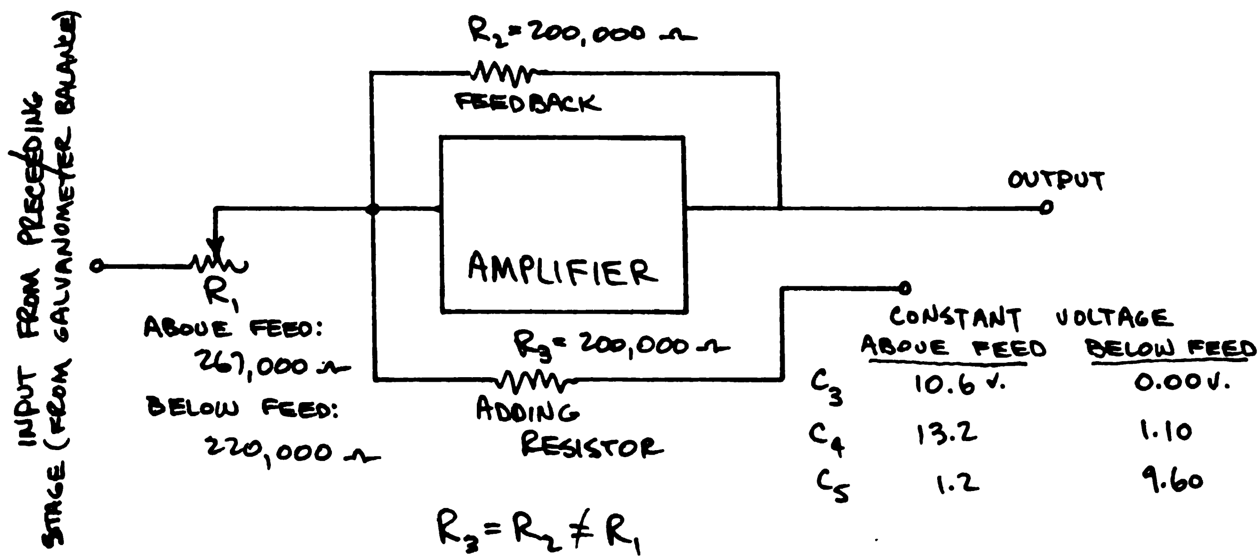
Assuming that the feedback resistor is exactly its rated value of 200,000 ohms, it can be seen that an extremely accurate ohm meter is needed to measure the resistance of the variable input resistor for various portions of the contact slide. Marking these positions accurately would also be quite difficult. Since an accurate numerical ratio of feedback to input resistance is needed, this procedure introduces too many sources of error. To eliminate almost all possible sources of error and also simplify the task of calibration, each amplifier should be calibrated for a particular component, and used only for calculations involving this particular component. By doing the calibration this way it is unnecessary to use an expensive wire-wound precision resistor for the input resistance. Instead, a carbon resistor of approximately the value needed for the constant feedback resistance can be used. The variable input resistor is adjusted until the ratio of feedback to input resistance is such that the output voltage is exactly K times the input voltage (or 1/K times input voltage for top part of the column). This position is then marked and labeled with the temperature corresponding to this value of K. This is continued until the possible range of temperature is marked.

Using the top panel as an example, a temperature is assumed and each pointer set at that temperature. The output voltage of each amplifier, which is X_D expressed in volts multiplied by 1/K, is fed into one amplifier that does nothing but add. If the output voltage of that amplifier is equivalent to one, then the assumed temperature was correct. If the output voltage of the amplifier is not equivalent to one, the pointers must be reset to another temperature value until an output voltage equivalent to one is obtained. Thus the first step in the calculation has been completed. All that remains is to apply the proper operating line equation and repeat the sequence for the next plate. An inspection of the operating line equations shows that to use them involves only multiplying the result of the first operation (X_D multiplied or divided by the proper value of K) by a constant value and then adding a constant value. This operation can be accomplished in the amplifier by merely applying a constant voltage in accordance with the theory presented earlier.

In order to move from plate to plate in the calculations it would seem that a new set of amplifiers is needed for each plate.* If this were the case, a tremendous number of amplifiers would have to be built and tested. The cost of these additional amplifiers would not warrant their use. Instead, just one set of amplifiers is used for the calculations on all plates as follows. Using a galvanometer as the measuring instrument, a balance is struck between the output voltage of the amplifier and the output voltage of a second variable d.c. supply voltage. The two voltages are applied on opposite sides of the galvanometer, so when the galvanometer needle shows no deflection, the voltages balance. The present input supply and the galvanometer are then disconnected, and the voltage that balanced the output voltage is applied as input voltage for the next step.

*The output voltage of each amplifier is really the answer to the mathematical operation performed by that particular amplifier. In other words, if an amplifier is desired to multiply by 3 and the input voltage is 50, the output voltage will be 150. If an amplifier is designed to multiply by 2.5 and then add 40, for an input voltage of 20 volts, the output voltage would be 90 volts. Therefore, in a continuous calculation the output voltage of one amplifier becomes the input voltage of the next one.

In summary, the three component problem given in the section on procedure will be specifically applied to the calculator. Included in the power unit is a 100-105 volt supply which is used for the starting input. The scale to be used is 100 volts equals 1.0 on a mol fraction basis. Starting at the top of the column of x_D are assumed as given. For propane x_D is 0.428, so the input, voltage to the amplifier for propane is 42.8 volts. Similarly, the input voltage for the other amplifiers is 53.5 volts for butane, and 3.7 volts for pentane. Using the panel for the top section, the three pointers are set at the mark on the calibrated dial corresponding to a temperature of 132 deg. F. The outputs of the three amplifiers are then channeled into the amplifier that does nothing but add. If the output of this amplifier is 100 volts, then the assumed temperature is correct. In this case the pointer settings must be corrected slightly since the output from the addition amplifier will be 98.3 volts. Adjusting the pointers to some position between 132 and 136 deg. F. will give an output voltage of 99.8 volts. It should be stressed that no pointer can be moved to a new position unless all the others are moved to the same reading. This is assumed to be close enough, so the calculation proceeds to the second step. In the second step the output voltages are separated and each connected to a galvanometer. On the other side of each galvanometer is a variable d.c. voltage supply. This voltage is adjusted until it balances the output voltage of the amplifier as shown by the galvanometer. The present input line and the galvanometer are disconnected and the balancing voltage from the variable supply is connected as the input to the same amplifier for the third step. This procedure is followed for each of the three amplifiers. The third step consists of calculating the vapor composition from the plate below by using the proper operating line equation. Applying the operating line equation involves multiplying the input by a constant and then adding a constant. For the top part of the column the multiplication constant is 0.75 and is the same for all components. The addition constant is 0.106 for propane, 0.132 for butane, and 0.012 for pentane. These constants are the same for any plate in the upper part of the column. For the bottom part of the column the multiplication constant is 0.91 and is the same for all the components. The addition constant is 0.000 for propane, 0.011 for butane, and 0.096 for pentane. These constants are the same for any plate in the lower part of the column. The correlation between this and applying the calculator can be seen more clearly in the following diagram.



The feedback resistance, R_2, is a part of the amplifier and is always 200,000 ohms. The adding resistor, R_3, is always 200,000 ohms also. R_1 and R_3 are mounted on panels, and together with the constant voltage shown, are connected to the amplifier when needed.

The output voltage, 23.8 for propane, is the composition of the vapor from the plate below and is recorded as such. The procedure is now repeated for the next plate, using a starting input voltage of 23.8 for propane, 64.4

for butane, and 11.7 volts for pentane.

The calculations are continued in this manner from the top down and from the bottom up until the compositions on the feed plate are obtained. It is desired that these compositions match, but should they be different, a new top composition must be assumed and the calculations done over. This is continued until the compositions match at the feed plate.

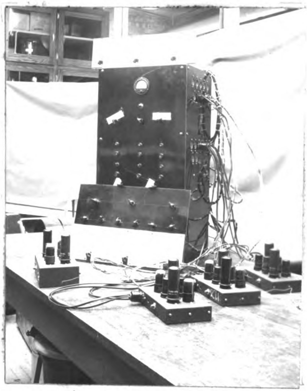


Fig. 6a. Front view of calculator showing power unit, control panels, and amplifiers connected.

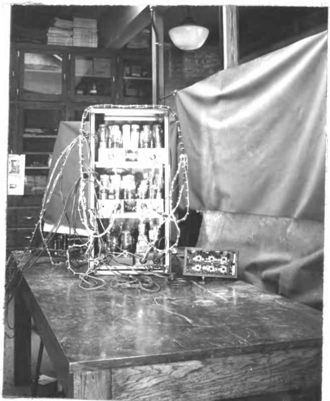


Fig. 6b. Rear view of power unit and amplifier chassis.

CONCLUSIONS AND IMPROVEMENTS

As was stated earlier in the discussion, the power unit and the amplifiers were tested upon their completion and they were found to be operating quite satisfactorily, multiplication and addition proceeding exactly as expected. However, when the calibration was attempted several difficulties were encountered which proved to be the most troublesome of the entire project. As has been pointed out already, the most important physical measurement connected with the calibration is the output voltage. During calibration the output voltage was observed to oscillate in such a manner so as to make an accurate calibration impossible. An analysis of the situation was attempted and the following conclusions arrived at as to the possible causes of this oscillation.

The a.c. line voltage supplying the power unit was tested and found to vary about one or two volts. This may not seem like much of a variation, but it should be remembered that this slight variation is amplified in the amplifier unit with a resulting variation of much larger magnitude. A voltage regulator was put on the line current, but the output oscillation still persisted. Other reasons advanced concerned the possibilities of variation in the carbon resistors due to heating, and the possible effect of heat radiation from the black tubes on the filament temperature of adjoining tubes. Extensive trial and error experiments were tried following this line of thought in an effort to determine the cause of the output oscillation, but nothing concrete was found. Time tests were run on an amplifier in an attempt to learn something of the nature of the output oscillation. The results of the time tests showed the oscillations to be greatest at first with a leveling-off period occuring after several hours. One might infer from this that a "saturation" point is reached wherein the carbon resistor undergoes no further change due to heating.

Two amplifiers built with carbon resistors were selected for further time tests as regards this point of "saturation". One of the amplifiers had been used quite extensively for other miscellaneous tests and therefore, was in effect, run for a considerable length of time. This one shall be designated as amplifier No. 1. The other one had been used hardly at all. This one shall be designated as amplifier No. 2. A log of the observations made is as follows:

10:00 A.M. : Power unit and amplifiers started. Oscillation for zero setting tested (zero input voltage). No. 1 was zero set at 20 volts and stayed constant. No. 2 oscillated from beginning and was not set at any value.

1:30 P.M. : No. 1 amplifier was at 2 volts, but showed no signs of oscillating. No. 2 was still oscillating as before.

5:45 P.M. : No. 1 was constant at 2 volts, but was reset to 20 volts. No. 2 was still oscillating as before.

10:45 A.M. : No. 2 was giving a negative voltage. No. 1 was constant at 52 volts.

2:45 P.M. : No. 2 was still giving a negative voltage. No. 1 was constant at 52 volts.

4:30 P.M. : No. 1 constant at 52 volts. No. 2 gave positive voltage, but was oscillating. Test terminated.

The results of this run tend to bear out this "saturation" theory a little more.

The first improvement that should be attempted would involve the variable input resistors. Efforts should be directed toward ganging the resistors on a central shaft. Perhaps the investigator will be pleasantly surprised at the cost of having resistors made to order by a manufacturer. In any case, it is felt that this improvement can be made in due time. If this suggestion can be accomplished, a second improvement of great importance could be introduced; namely, the use of a servo motor at the point where the input resistances are adjusted until the output voltages of the amplifiers total one. A servo system serves merely to transform electrical data (a voltage) into mechanical data (angular position of a shaft).

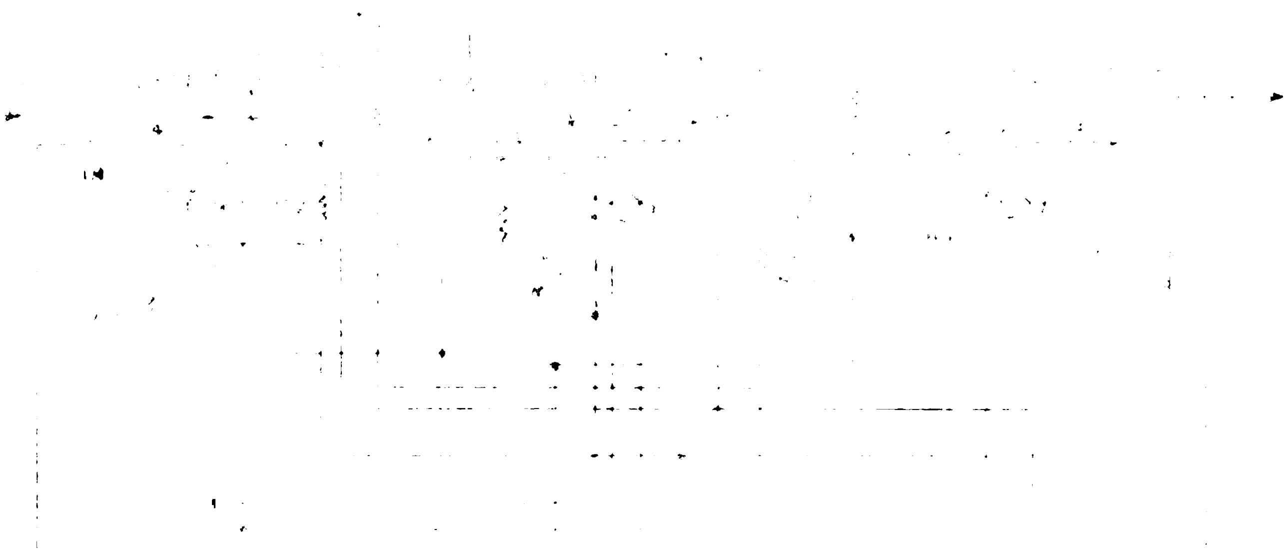
As an example, consider the addition, using a.d.c. amplifier, of two voltages having opposite signs. If the positive voltage is the greater, the output of the amplifier will be a positive voltage. The output voltage of the amplifier will be zero when the values of the two input voltages are equal.

If one of the input voltages is furnished by a potentiometer whose brush is positioned by a reversible motor controlled by the output of the amplifier, the output voltage of the amplifier can be automatically maintained at zero, if the connections to the motor are properly made. If the positive input voltage is greater than the negative input voltage, there will be a negative output from the amplifier which will cause the motor to turn the brush in a direction which increases the negative input voltage. When, by this means, the two input voltages are made equal, there will be zero voltage output from the amplifier and the motor will stop. This is a typical servo system.

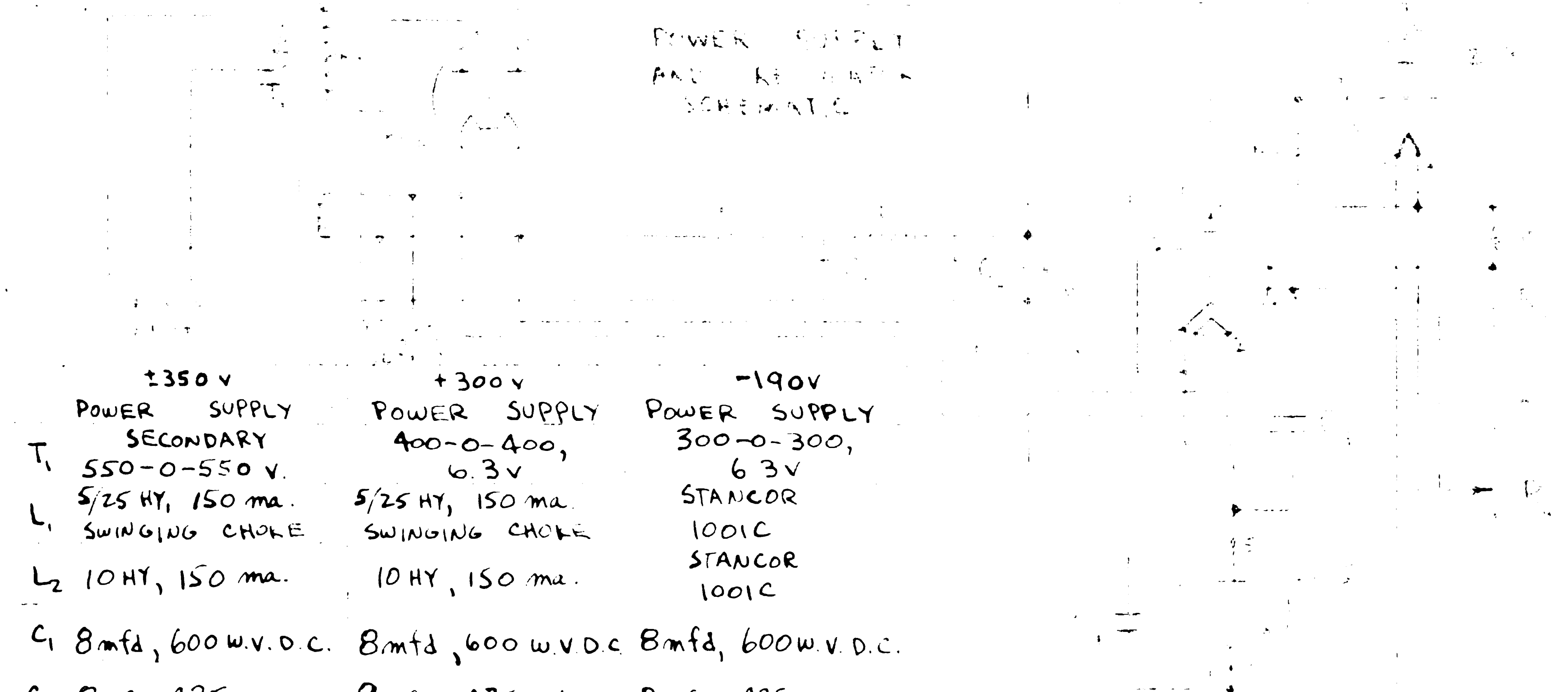
It is not entirely inconceivable that the calculator could be made fully automatic in its application to the problem. To do this a servo motor would be used at the point where the input resistances are adjusted until the output voltages of the amplifiers total one. A storage or memory capacity, consisting of a revolving bank of potentiometers, would also be used, and in conjunction with this could go a servo system for balancing with the galvanometer. This balanced voltage would be stored, and a relay might then switch the amplifier for applying the operating line equation into the system and withdraw the balanced voltage from the memory unit for use as the input to this amplifier. This output is then stored until used as input for the first step in repeating the calculations over the next plate. Another servo system would be utilised at the feed plate where the compositions as calculated down from the top are supposed to match those obtained calculating up from the bottom. In this way the amplifiers would first be set-up to meet the conditions of the problem (reflux ratio, simplifying assumptions, constants in operating line equations, etc). Then the assumed composition of vapor off the top and liquid composition off the bottom are introduced. The machine would be started and the calculations would proceed simultaneously from the top down and from the bottom up. If the composition at the feed plate does not match, the servo system would throw the unit back to the beginning, and repeat the process with different assumed end conditions. Thus the calculations would go up and down the column until the correct end conditions are assumed, at which time the servo motor at the feed plate would stop the calculator.

Throughout this work the calculator has been applied to problems wherein the usual simplifying assumptions could be made without introducing appreciable errors. However, in many petroleum problems these assumptions of equal molar latent heats and negligible heat capacity changes cannot be made. It is felt that the calculator could be applied equally well to these problems for here the sectional heat balance equations are used in conjunction with material balance equations on a trial and error basis. A liquid composition on a plate is always a starting point in plate calculations. In this case, the variable input resistances would be correlated with heat contents and molecular weights together with K-charts.

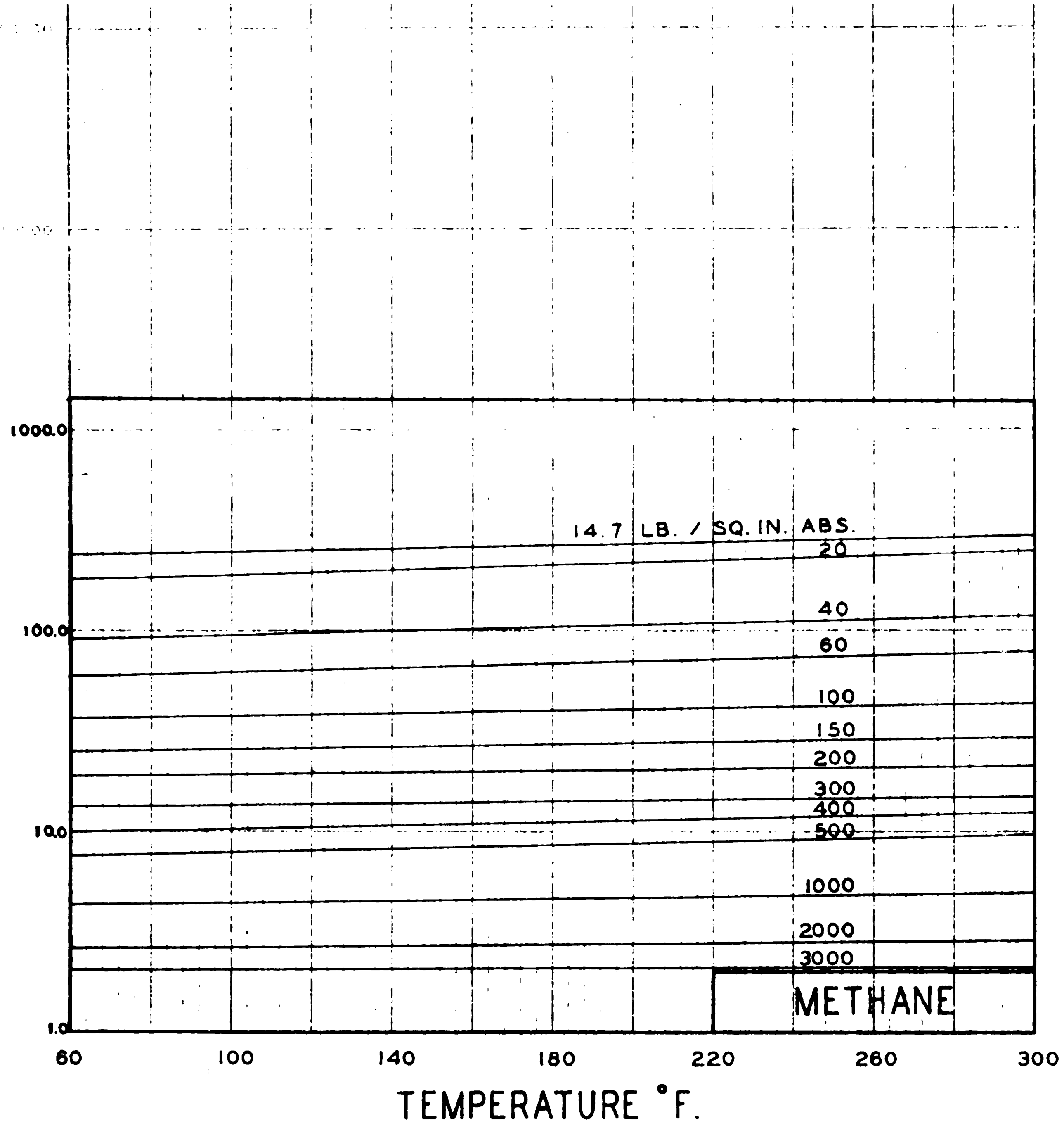
As pointed out previously, there are many applications of the calculator to chemical engineering problems besides distillation. An example of another application of the calculator to a chemical engineering problem would be calculating flow of fluids (pressure drop) in a pipe still. Due to vaporization of the oil, the viscosity changes through the equipment, and this has the effect of changing the value of Reynolds number. To avoid this in the analytical calculations the pipe still is divided into sections over which the change in Reynolds number is not great. In this case the resistors would be correlated with f, friction factor, and flash vaporization curves instead of K-charts. The desired pressure drop at the end is known, so a large pressure is assumed at the other end. Then the pressure drop is calculated over the several sections of the pipe still and if the end pressure is that desired, the assumed large pressure value was correct. If not, the assumed pressure value is altered and the calculations repeated until the desired pressure is obtained at the other end. Again the calculator could be made automatic so as to repeat the calculations over and over until the correct pressure is assumed.

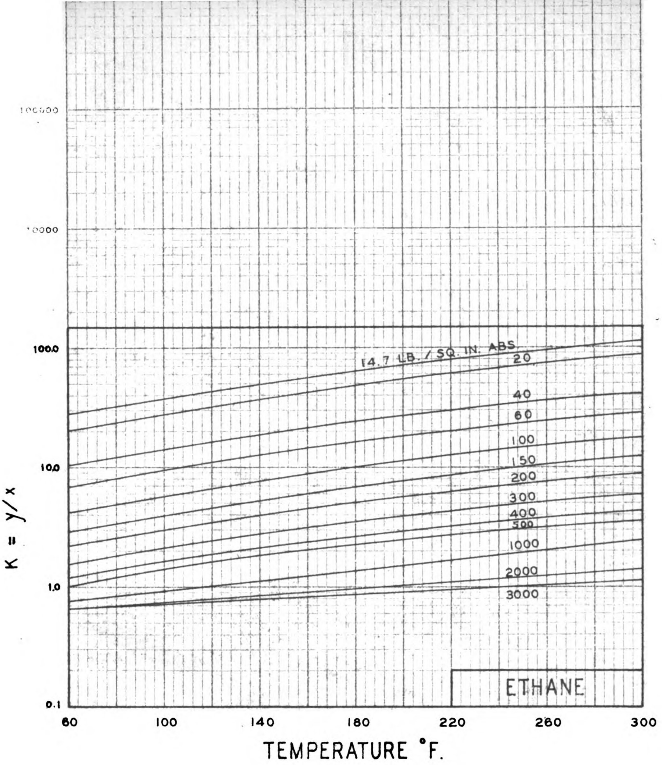


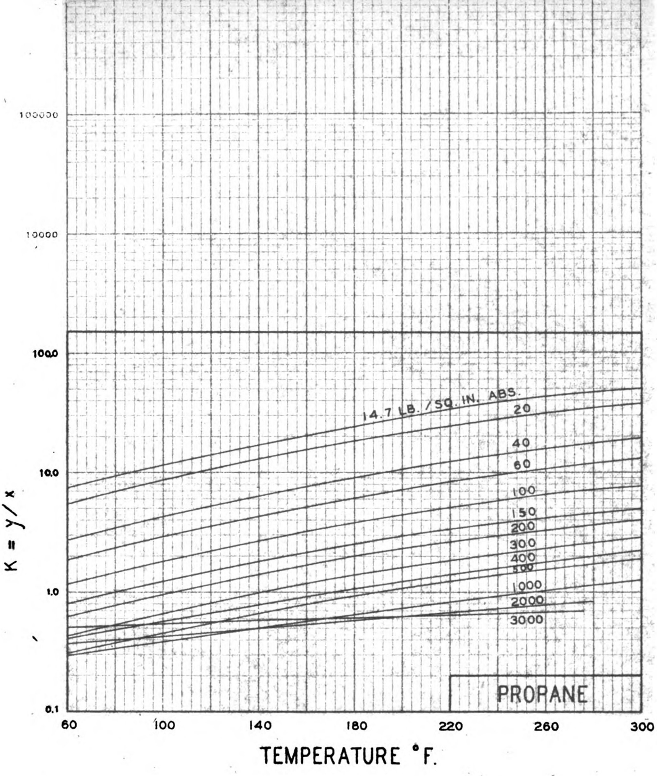
POWER [illegible]
[illegible]
SCHEMATIC

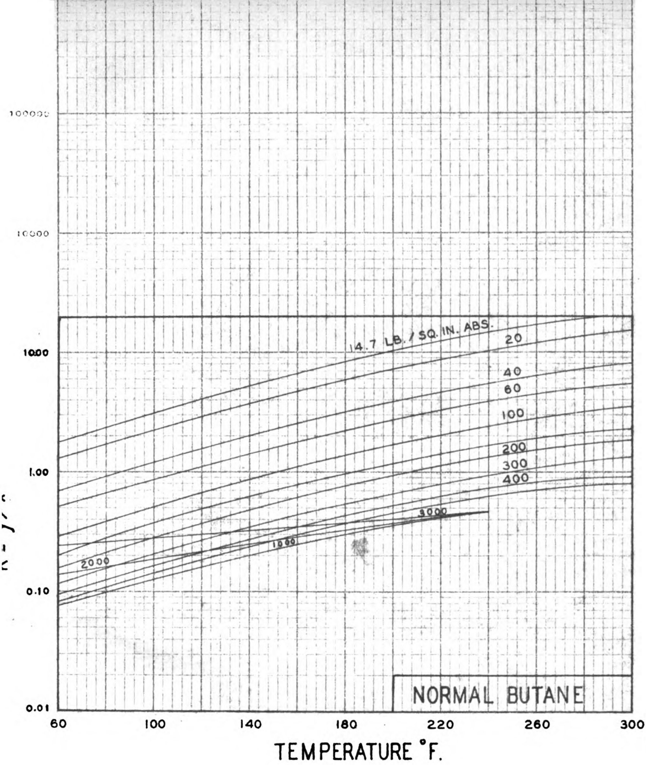


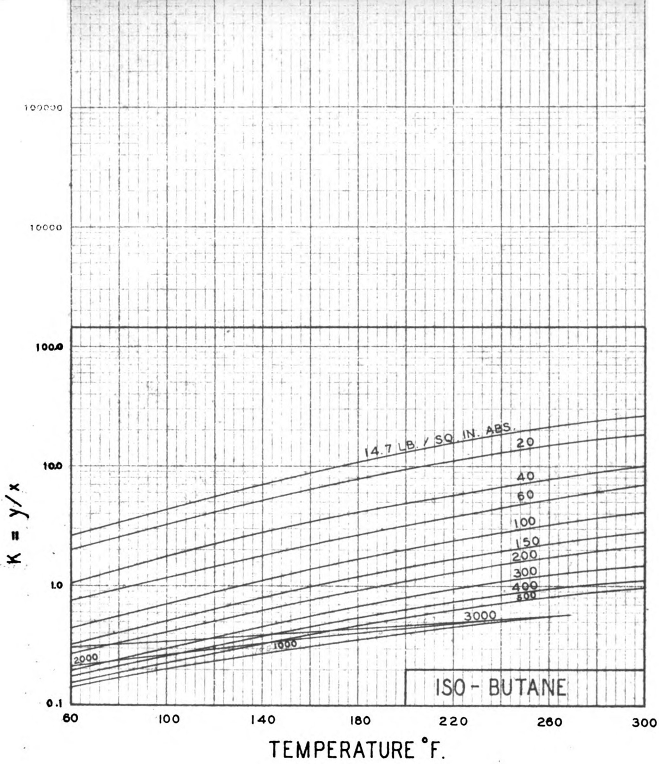
	±350 V	+300 V	−190 V
T_1	POWER SUPPLY SECONDARY 550-0-550 V.	POWER SUPPLY 400-0-400, 6.3 V	POWER SUPPLY 300-0-300, 6.3 V
L_1	5/25 HY, 150 ma. SWINGING CHOKE	5/25 HY, 150 ma. SWINGING CHOKE	STANCOR 1001C
L_2	10 HY, 150 ma.	10 HY, 150 ma.	STANCOR 1001C
C_1	8 mfd, 600 W.V.D.C.	8 mfd, 600 W.V.D.C.	8 mfd, 600 W.V.D.C.
C_2	8 mfd, 475 W.V.D.C.	8 mfd, 475 W.V.D.C.	8 mfd, 475 W.V.D.C.
C_3 C_4	0.1 mfd.	0.1 mfd	0.1 mfd
R_1	23,000 Ω	23,000 Ω	23,000 Ω
R_2	10,000	10,000	10,000
R_3	10,000	10,000	10,000
R_4	6,800	6,800	6,800
R_5	10,000	10,000	10,000
R_6	500,000	500,000	500,000

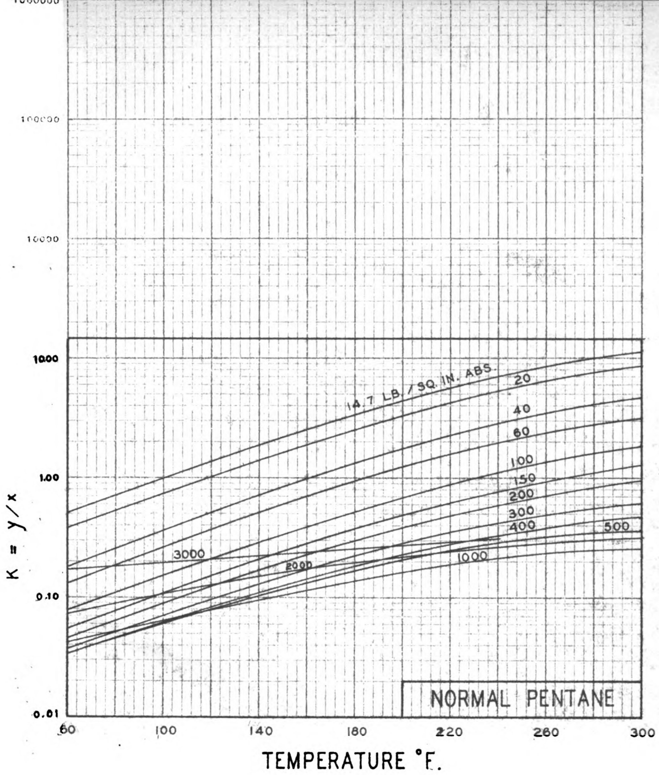

1000.0
100.0
10.0
1.0
14.7 LB. / SQ. IN. ABS.
20
40
60
100
150
200
300
400
500
1000
2000
3000
METHANE
60
100
140
180
220
260
300
TEMPERATURE °F.

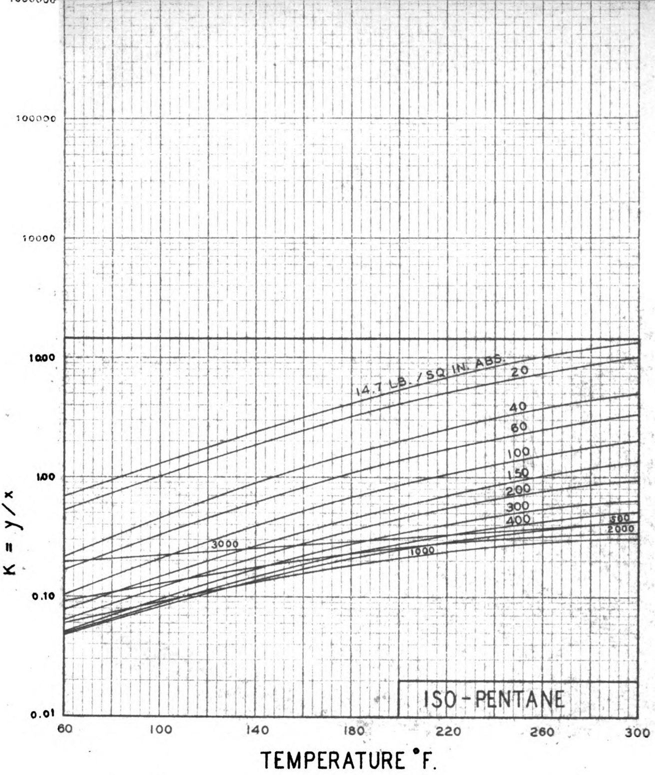

100000
10000
100.0
10.0
1.0
0.1
K = y/x
14.7 LB. / SQ. IN. ABS.
20
40
60
100
150
200
300
400
500
1000
2000
3000
ETHANE
60
100
140
180
220
260
300
TEMPERATURE °F.


100000
10000
100.0
10.0
1.0
0.1
K = y/x
14.7 LB./SQ. IN. ABS.
20
40
60
100
150
200
300
400
500
1000
2000
3000
PROPANE
60
100
140
180
220
260
300
TEMPERATURE °F.

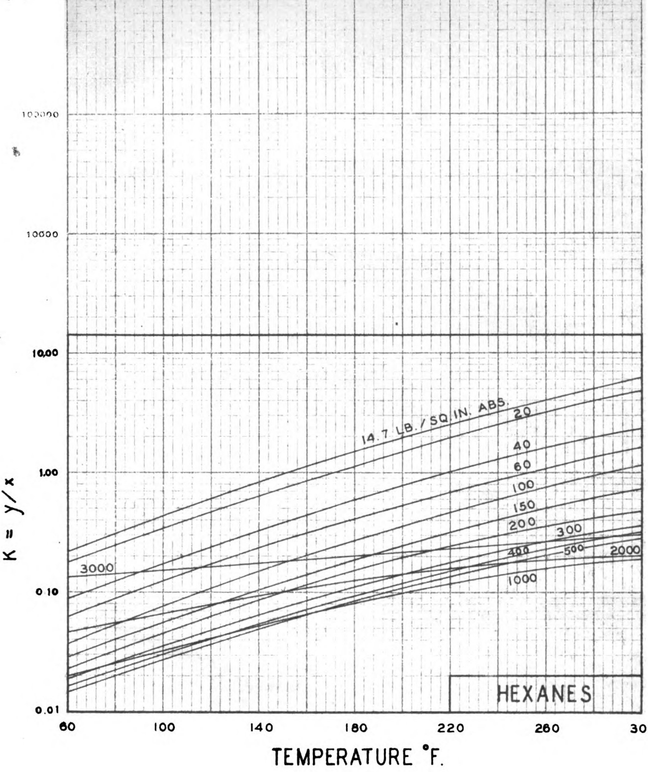

100000
10000
10.00
1.00
0.10
0.01
14.7 LB. / SQ. IN. ABS.
20
40
60
100
200
300
400
1000
2000
3000
60
100
140
180
220
260
300
TEMPERATURE °F.
NORMAL BUTANE


100000
10000
100.0
10.0
1.0
0.1
K = y/x
14.7 LB. / SQ. IN. ABS.
20
40
60
100
150
200
300
400
500
3000
1000
2000
ISO - BUTANE
60
100
140
180
220
260
300
TEMPERATURE °F.


NORMAL PENTANE
14.7 LB / SQ. IN. ABS.
20
40
60
100
150
200
300
400
500
1000
2000
3000
K = y/x
TEMPERATURE °F.
0.01
0.10
1.00
10.00
10000
100000
60
100
140
180
220
260
300



100000
10000
10.00
1.00
0.10
0.01
K = y/x
14.7 LB. / SQ. IN. ABS.
20
40
60
100
150
200
300
400
500
2000
3000
1000
ISO-PENTANE
60
100
140
180
220
260
300
TEMPERATURE °F.


100000
10000
10.00
1.00
0.10
0.01
K = y/x
14.7 LB./SQ.IN. ABS.
20
40
60
100
150
200
300
400
500
2000
1000
3000
HEXANES
60
100
140
180
220
260
300
TEMPERATURE °F.

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