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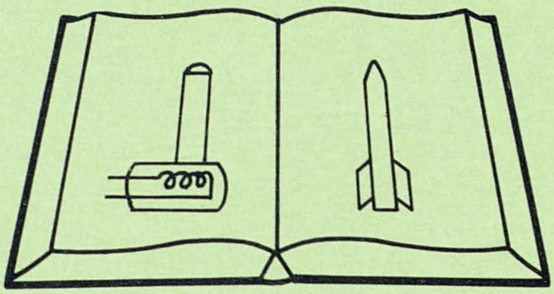
THE JOURNAL OF CHEMICAL ENGINEERING EDUCATION



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WE BOW OUT

As we indicated in our previous issue, this journal has been suffering from an unusual malady — a shortage of publishable material. We have subscribers but we lack a sufficient number of contributors. As a result our issues have become too few and far between. Accordingly, we have regretfully decided to suspend publication.

We do however want to take this final opportunity to thank our subscribers and contributors, our colleagues and friends, and our typists and mimeographers for their support, encouragement, and assistance.

It is our understanding that the Chemical Engineering Division of the American Society for Engineering Education is presently taking steps to revitalize their divisional publication. We wish them success in this endeavor and urge all our readers to support their efforts.

R. L.

ESTIMATION OF RANDOM ERROR IN A DERIVED QUANTITY

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Abstract: The statistical method for determining the variance of an arbitrary function of experimentally measured variables deserves to be more generally employed in undergraduate laboratory courses to assist the student in evaluating the errors in, and the reliability of, experimental data. The statistical method also has an important use in exploratory research studies and in process design. In all cases the method leads to an estimate of the probable error in the derived quantity, whereas an alternative method gives the maximum possible error, which generally represents an overly conservative estimate of the error.

The statistical theory of random errors in a quantity which is derived from primary experimental observations, is useful for the estimation of error in at least three classes of problems:

1) The analysis of experimental error, either in research or in undergraduate student laboratory classes,

2) Exploratory research studies, to ascertain whether the method of measuring a particular variable is of sufficient precision, and

3) Process design, where experimental error creates an uncertainty in the magnitude of the quantity to be designed.

The statistical method for determining the variance of an arbitrary function of experimentally measured variables is given in several textbooks (1, 2, 3, 4) which, although not mentioning chemical engineering specifically in their titles, may come to the attention of chemical engineers. There are, however, at least two leading textbooks, both of which are specifically concerned with applications of mathematical methods to chemical engineering, which do not mention the statistical method. This statistical method, which enables one to construct confidence intervals for the mean value of the derived quantity, deserves to be better known by teachers of chemical engineering, and more generally employed in undergraduate laboratory courses, to assist in evaluating the reliability of the experimental data.

Before presenting the statistical method, it is useful to first present an alternative method of determining the propagated error. This method, given in several textbooks (5, 6) has the weakness that the error it predicts is the maximum possible error, and takes no account of the possibility of compensating or cancelling errors. It is based upon the fact that if

$$U = \phi\ (x_1,\ x_2,\ \ldots\ldots\ ,\ x_n) \tag{1}$$

where x_1, x_2, ..., x_n are several directly measured variables subject to experimental error, then the differential change in the derived quantity U for a differential change in each of the measured x's is

$$dU = \frac{\partial \phi}{\partial x_1}\, dx_1 + \frac{\partial \phi}{\partial x_2}\, dx_2 + \ldots\ldots + \frac{\partial \phi}{\partial x_n}\, dx_n \tag{2}$$

If the errors dx_1, dx_2, ..., dx_n are relatively small, (so that the terms of higher order in the Taylor expansion are negligible), then Equation 2 can be reduced to

$$\Delta U = \frac{\partial \phi}{\partial x_1}\, \Delta x_1 + \frac{\partial \phi}{\partial x_2}\, \Delta x_2 + \ldots\ldots + \frac{\partial \phi}{\partial x_n}\, \Delta x_n \tag{3}$$

Illustrative examples of the use of this formula are given in reference (5), pp. 55-56 and reference (6), pp. 359-360. One important aspect of the use of Equation 3 is that the sign of the partial derivative is so chosen that all terms of Equation 3 have the same sign, that is, the terms add up in such a way that ΔU represents the maximum possible error in the derived variable U. Equation 3 almost certainly overestimates the error involved in the derived quantity, because it considers only the simultaneous occurrence of the most extreme errors and takes no account of the possibility of compensating errors. The probability of operating at the most extreme level of error is always small, and becomes vanishingly small as one increases the number of primary variables subject to error. The concept of maximum possible error is therefore one of limited usefulness.

Statistical techniques lead to a more pertinent measure of the error in a derived quantity by enabling one to calculate the variance of the mean value of the derived quantity. The formula to be used is shown below.

If $Z = f(x_1, x_2, \ldots\ldots, x_n)$, where the x_i are independent random variables with finite means and finite variances, then if the errors in the x_i are not too large (so that the higher order terms of the Taylor expansion can be neglected), then one can write

$$\sigma_z^2 = \left(\frac{\partial f}{\partial x_1}\right)^2 \sigma_{x_1}^2 + \left(\frac{\partial f}{\partial x_2}\right)^2 \sigma_{x_2}^2 + \cdots\cdots + \left(\frac{\partial f}{\partial x_n}\right)^2 \sigma_{x_n}^2 \qquad (4)$$

The partial derivative of the function f with respect to each x_i is taken with all the remaining x's held constant. The quantities $\sigma_{x_1}^2, \sigma_{x_2}^2, \ldots, \sigma_{x_n}^2$ represent the variances of the respective primary variables $x_1, x_2, \ldots\ldots, x_n$. Practical application of Equation 4 depends upon one's ability to determine these variances. The variances are usually determined from random experimental measurements upon the individual variables. Suppose, for example, that in an experiment to determine the flow rate through a pipe, 5 successive weighings of the effluent from the pipe during the same fixed time interval gave values of 97, 102, 99, 104, and 98 pounds respectively. The mean value of the five readings is $\bar{x}_1 = 100$ lbs. and the best estimate of the variance is $\hat{\sigma}_1^2 = \sum_i (x_{1_i} - \bar{x}_1)^2 / (n - 1) = 8.5$. This, together with similar estimates from random samples of the other variables, provide the various variances $\sigma_{x_1}^2, \sigma_{x_2}^2, \ldots\ldots, \sigma_{x_n}^2$ to be used in Equation 4.

Sometimes a reading of a particular quantity on an instrument or measuring device is very steady, but the limiting factor to the precision of the reading is the smallest scale division available on the instrument. Utilizing the fact that practically all of the area (actually 99.73%) under the curve of the normal (Gaussian) distribution is contained within $\pm$ 3 standard deviations of the mean, then one can consider $\pm 3\sigma$ to be synonymous with the range, and thus from a knowledge or a guess of the range, it is possible to obtain a reasonable estimate of the standard deviation. Consider a temperature measurement made with a thermometer in which the smallest scale division is 1°C. It seems reasonable to assume that the maximum error range obtainable (due to human reading error alone) is about 0.5°C (or $\pm$ 0.25°C). Thus an estimate of σ would be $\frac{0.25}{3} = 0.0833$ from which $\sigma^2 = 0.007$. Of course, the range may be considerably greater than 0.5°C, due to large fluctuations or instabilities in the temperature.

Here, one would once again require experimentation to obtain a random sample from which the variance may be estimated. The previous discussion applies only to steady readings where the smallest scale division imposes a limiting factor on the accuracy of the reading.

A special case of Equation 4 occurs when the functional relation is of the form $Z = cx_1^{a_1} x_2^{a_2} \ldots\ldots x_n^{a_n}$, where c, a_1, a_2, ..., a_n are constants. Then it is easy to show, by using Equation 4, that

$$\left(\frac{\sigma_z}{z}\right)^2 = a_1^2 \left(\frac{\sigma_{x_1}}{x_1}\right)^2 + a_2^2 \left(\frac{\sigma_{x_2}}{x_2}\right)^2 + \ldots\ldots + a_n^2 \left(\frac{\sigma_{x_n}}{x_n}\right)^2 \qquad (5)$$

Presented below are two illustrative problems which will indicate the uses to which Equation 4 can be put.

Illustrative Example 1:

Consider an undergraduate laboratory experiment on the unsteady-state heating of water, starting at room temperature, in a steam-jacketted open kettle. The apparent overall heat-transfer coefficient is given by

$$U_a = \frac{Mc_p}{A\Delta t_a} \frac{dt}{d\theta}$$

where

M = weight of water, lb.

c_p = heat capacity of water, BTU/lb (°F)

A = area of kettle in contact with water through which heat transfer can take place, ft²

Δt_a = apparent temperature difference between steam and water at any instant, °F

$dt/d\theta$ = slope, at any instant, of the curve of water temperature versus time.

Suppose it is desired to determine the value of U_a, and its precision, at the condition when $\Delta t_a = 60°F$.

Since this equation is an example of the special case quoted above, the expression for the variance of U_a, obtained with the aid of Equation 5, is

$$\left(\frac{\sigma_{U_a}}{U_a}\right)^2 = \left(\frac{\sigma_M}{M}\right)^2 + \left(\frac{\sigma_{c_p}}{c_p}\right)^2 + \left(\frac{\sigma_A}{A}\right)^2 + \left(\frac{\sigma_{\Delta t_a}}{\Delta t_a}\right)^2 + \left(\frac{\sigma_{dt/d\theta}}{dt/d\theta}\right)^2$$

σ_M: 200 lbs. of water were measured out in 25 lb. batches. Each batch was weighed within maximum error limits of $\pm$ 0.25 lb., i.e. m = 25 $\pm$ 0.25 lb.

Therefore $\hat{\sigma}_m = \frac{0.25}{3} = 0.083$ or let $\hat{\sigma}_m = 0.10$ lb. to take into account the loss of water due to splashing or retention of water in the bucket, etc., when transfer to the kettle is being made.

$$M = m_1 + m_2 + \ldots\ldots + m_8$$

$$\hat{\sigma}_M^2 = 8\,\hat{\sigma}_m^2 = 0.08 \text{ lb}^2,$$ since the variance of a sum is the sum of the individual variances.

σ_{c_p}: The heat capacity of water is so well known that one can assume that there is no uncertainty in the knowledge of c_p, i.e., $\sigma_{c_p}^2 = 0$.

σ_A: As heating continues, expansion of the water takes place, causing the wetted area to increase. However, the term "apparent heat-transfer coefficient" implies in fact that this increase in area has been ignored in favor of using the wetted area at room temperature. From measurement of the liquid depth, and a knowledge of the geometry of the kettle, it is estimated that A = 8.74 ft² with a maximum uncertainty of $\pm$ 0.45 ft².

Therefore $\hat{\sigma}_A = \frac{0.45}{3} = 0.15 \text{ ft}^2$

$$\hat{\sigma}_A^2 = 0.0225 \text{ ft}^2$$

$\sigma_{\Delta t_a}$: The temperature difference $\Delta t_a = t_s - t_w$, where t_s and t_w are the steam and water temperatures, respectively. The temperature of the steam, assumed to be saturated steam, was determined from the steam pressure which was measured using a mercury manometer. The pressure variations were kept within the maximum error limits of $\pm$ 1 inch Hg, i.e., $\pm$ 0.5 p.s.i., about a set value of 5 p.s.i.g. The steam temperature therefore varied between maximum limits of $\pm$ 1.5°F.

Therefore $\widehat{\sigma_{t_s}} = \frac{1.5}{3} = 0.5\,°F \qquad \sigma_{t_s}^2 = 0.25\,(°F)^2$

The water temperature was measured by using the average value of two thermocouples, each thermocouple indicating between error limits of ± 0.5°F.

$$t_w = (1/2)(t_{w_1} + t_{w_2})$$

$$\sigma_{t_w}^2 = (1/4)(\sigma_{t_{w_1}}^2 + \sigma_{t_{w_2}}^2) = (2/4)\left(\frac{0.5}{3}\right)^2$$

$$= 0.0138\ (°F)^2$$

Therefore $\sigma_{\Delta t_a}^2 = 0.25 + 0.01 = 0.26\ (°F)^2$

$\sigma_{dt/d\theta}$: The derivative of temperature with respect to time at the particular time θ where $\Delta t_a = 60°F$ was determined from the tangent drawn to a plot of water temperature versus time. From several trials, considering the various possibilities for drawing a smooth curve through the points, and considering the precision of drawing a tangent to a curve, a reasonable estimate for the derivative $dt/d\theta$ was 3.0 °F/min with variance.

$$\sigma_{dt/d\theta}^2 = 0.048\ (°F/\text{min})^2$$

The average value of the apparent overall heat transfer coefficient, U_a, is obtained to be

$$U_a = \frac{(200)(1)(3.0)(60)}{(8.74)(60)} = 68.6\ \text{BTU}/(\text{hr})(\text{ft}^2)(°F)$$

and the estimated variance to be

$$\sigma_{U_a}^2 = (68.6)^2\left[\frac{0.08}{(200)^2} + \frac{0.0225}{(8.74)^2} + \frac{0.26}{(60)^2} + \frac{0.048}{(3.0)^2}\right]$$

$$= (68.6)^2\left[2 \times 10^{-6} + 2.95 \times 10^{-4} + 7.22 \times 10^{-5} + 0.00533\right]$$

$$= (4706)(0.00570) = 26.82$$

$$\sigma_{U_a} = 5.18$$

Using this value of the standard deviation of U_a, 95% confidence limits upon U_a can be constructed. The limits are $\pm$ 1.96 (5.18) = 10.2, the value 1.96 being taken from a tabulation of the normal distribution function.

Thus U_a = 68.6 $\pm$ 10.2 BTU/hr(ft²)(°F), where $\pm$ 10.2 has the significance of being 95% confidence limits about the mean value 68.6.

The above illustration also shows how Equation 4 can be useful in exploratory research studies, to help the researcher decide if a particular measurement is of sufficient precision. It is seen that by far the biggest contributor to the overall experimental error is that due to $dt/d\theta$, the contribution being 0.00533/0.00570 = 93.5%. Hence, if the purpose of the research project is to determine U_a, then it is of paramount importance to establish the temperature vs. time curve accurately, and also to increase the precision in taking the derivative at a particular point on that curve.

The third use of Equation 4 is in process design. Due to uncertainties in the measured value of certain primary experimental observations, there is going to be an uncertainty in the derived quantity. Since it is necessary that the unit being designed be adequate for its task, this uncertainty must be allowed for in the design. Use of the concept of maximum possible error results in an overly conservative design. However, by using the statistical theory of random error, quantitatively described by Equation 4, one can base the design upon, say, the 95% confidence limit of the derived quantity. This will practically always result in an adequate design without being overly conservative.

Illustrative Example 2:

A countercurrent double-pipe heat exchanger is to be designed to heat 50,000 lb/hr of a liquid from 80 to 150°F. The specific heat of the liquid is not precisely known but its mean value can be taken to be c_p = 0.85 with σ_{c_p} = 0.04 BTU/lb(°F). The overall heat transfer coefficient, U, is estimated to be 73 BTU/hr(ft²)(°F) with σ_U = 4. The heating medium is a liquid of precisely known c_p, which enters at 180°F and leaves at 120°F. Determine the required area of the heat exchanger.

$$A = \frac{wc_p(t_2 - t_1)}{U\Delta t_{lm}} = \frac{50,000(0.85)(70)}{73(34.8)} = 1170 \text{ ft}^2$$

$$\left(\frac{\sigma_A}{A}\right)^2 = \left(\frac{\sigma_{c_p}}{c_p}\right)^2 + \left(\frac{\sigma_U}{U}\right)^2 = \left(\frac{0.04}{0.85}\right)^2 + \left(\frac{4}{73}\right)^2 = 0.00522$$

$$\sigma_A = A(0.00522)^{1/2} = 1170(0.0722) = 84.5 \text{ ft}^2$$

If we wish to be 95% confident that the exchanger will have adequate area (actually the value calculated will represent 97.5% confidence, since in fact a one-tailed test is being considered), then the design area should be

$$A = 1170 + 1.96(84.5) = 1340 \text{ ft}^2$$

Had the concept of maximum possible error been used instead, the design area would have been in the vicinity of 1530 ft^2.

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APPROACH TO STEADY-STATE OF A TWO STAGE MIXER-SETTLER EXTRACTOR*

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Abstract: Under the assumptions of ideal stage behavior, immiscible solvents, constant flow rates, constant interface levels, constant distribution coefficients, instantaneous mass transfer and homogeneous phases, it is possible to solve the appropriate differential equations simultaneously and express the rate of approach of a mixer-settler extractor to steady-state as a function of a dimensionless quantity that involves the elapsed time and a quantity related to the system capacitance. The particular integral, or steady-state solution, is the familiar equation for the concentration of a solute in a stream as a function of the so-called extraction factor. By introducing solvent extraction theory in this manner, the student develops a better understanding of the dynamics of the system and the realization that the steady-state solution is only a somewhat idealized special case of the general solution.

The Differential Equations:

Figure 1 shows a continuous countercurrent two stage mixer-settler extractor with the light solvent L entering from the left and the heavy solvent H with solute entering from the right. Each box represents an ideal stage made up of a mixer where the two phases are contacted and a settler where the two phases are allowed to separate. There are many commercial types of extractors that are designed in this way (1).

Equations 1 and 2 are solute balances made for each stage expressing the rate of accumulation of solute as a function of the rate of solute flowing into and out of the stage.

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* Contribution No. 1445; work was performed in the Ames Laboratory of the U. S. Atomic Energy Commission.

$$\frac{d(V_H x_1 + V_L y_1)}{dt} = L_o y_o + H_2 x_2 - L_1 y_1 - H_1 x_1 \qquad (1)$$

$$\frac{d(V_H x_2 + V_L y_2)}{dt} = L_1 y_1 + H_F x_F - L_2 x_2 - H_2 x_2 \qquad (2)$$

If the flow rates are assumed constant ($L_1 = L_2 = L$ and $H_1 = H_2 = H$), the distribution coefficient m is assumed constant, and the entering solvent contains no solute, Equation 1a and 2a result. The term G is defined as $\frac{V_H + V_L m}{H}$ as will be discussed later.

$$\frac{dx_1}{dt} + \frac{(1 + E)x_1}{G} = \frac{x_2}{G} \qquad (1a)$$

$$\frac{dx_2}{dt} + \frac{(1 + E)x_2}{G} = \frac{Ex_1}{G} + \frac{x_F}{G} \qquad (2a)$$

<u>Solution of the Equations</u>:

The simultaneous solution of Equations 1a and 2a provides a good algebraic work-out and results in Equation 3 for a stepwise change in x_F at $t = 0$. Such a stepwise change may be thought of as suddenly switching from a solute-free aqueous stream to an aqueous feed stream after the extractor has reached a hydraulic balance with no solute in the system.

$$\frac{d^2x_1}{dt^2} + \frac{2(1 + E)}{G}\frac{dx_1}{dt} + \left[\frac{1 + E + E^2}{G^2}\right]x_1 = \frac{x_F}{G^2} \qquad (3)$$

By inspection one can see the steady-state solution because $\frac{d^2x_1}{dt^2}$ and $\frac{dx_1}{dt}$ will both equal zero. This expression can be verified independently by making steady-state material balances about the two stages and solving simultaneously.

$$(x_1)_{SS} = \frac{x_F}{1 + E + E^2} \qquad (4)$$

The complementary function can be found by setting the differential equation equal to zero and solving the resulting equation.

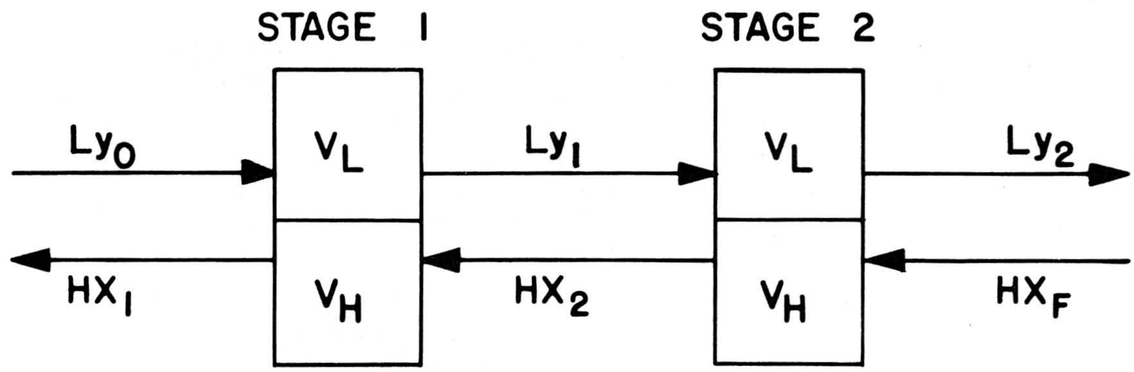


Figure 1

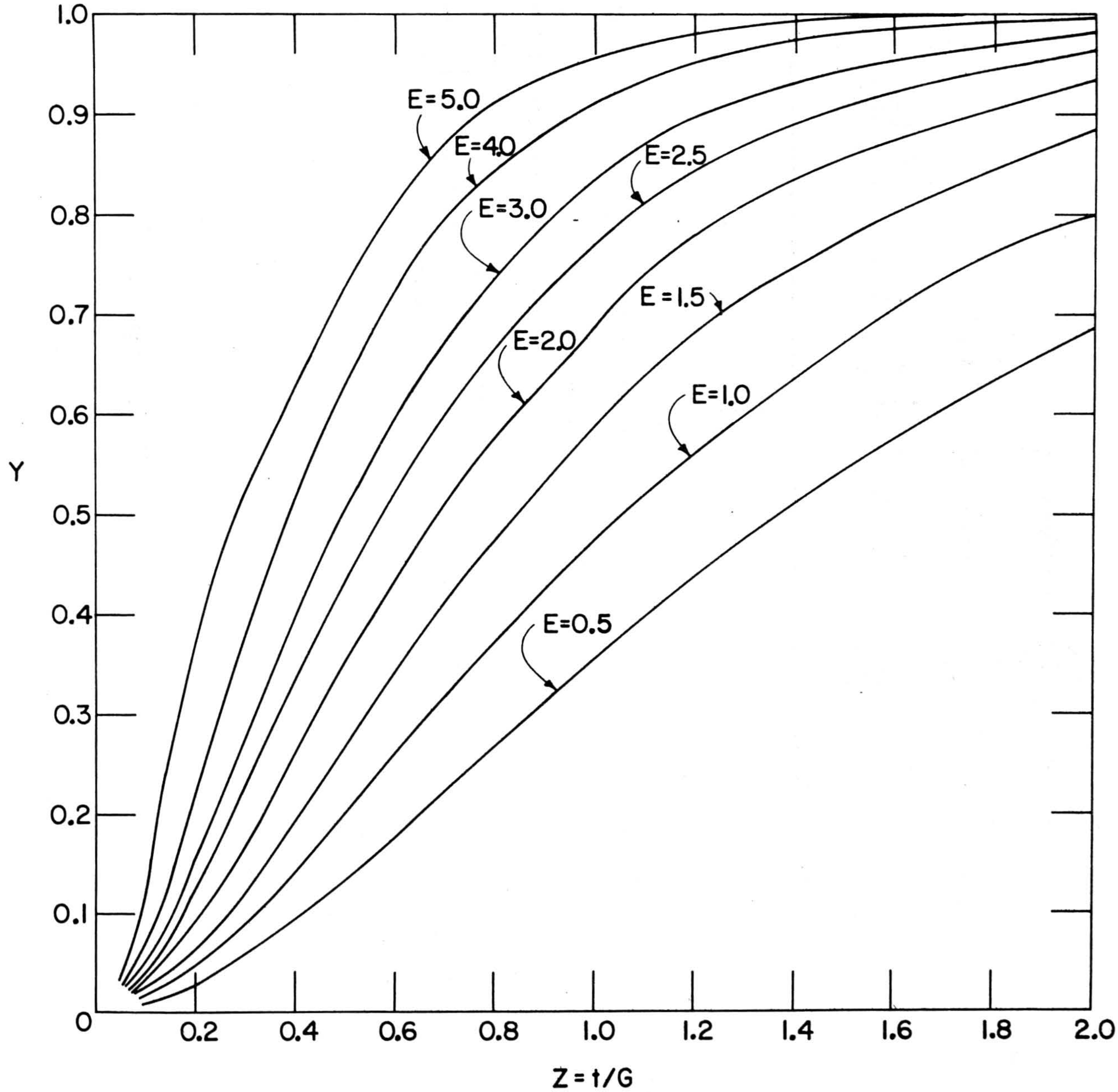
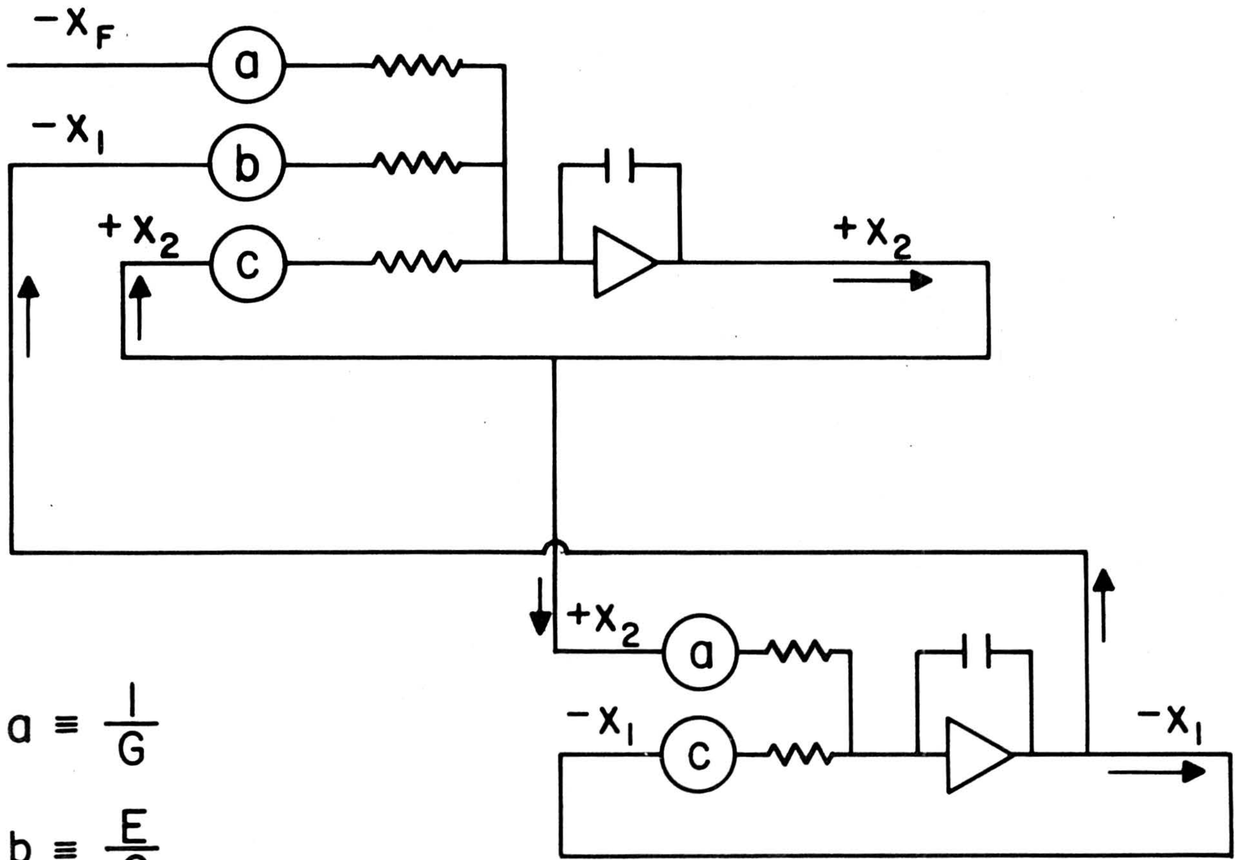


Figure 2



$$a \equiv \frac{1}{G}$$

$$b \equiv \frac{E}{G}$$

$$c \equiv \frac{1+E}{G}$$

Figure 3

$$(x_1)_{CF} = C_1 e^{\frac{-(1+E-E^{\frac{1}{2}})t}{G}} + C_2 e^{\frac{-(1+E+E^{\frac{1}{2}})t}{G}} \tag{5}$$

The complete solution for x_1 is the sum of the expressions in Equations 4 and 5. Boundary conditions assumed were that $t = 0$, $x_1 = 0$, and $dx_1/dt = 0$. After considerable algebra, Equation 6 appears.

$$(x_1)_t = \frac{x_F}{1 + E + E^2}\left[1 - \frac{(1 + E + E^{\frac{1}{2}})e^{\frac{-(1+E-E^{\frac{1}{2}})t}{G}}}{2E^{\frac{1}{2}}} + \frac{(1 + E - E^{\frac{1}{2}})e^{\frac{-(1+E+E^{\frac{1}{2}})t}{G}}}{2E^{\frac{1}{2}}}\right] \tag{6}$$

If both sides of Equation 6 are divided by the steady-state value of x_1, the fractional approach to steady-state Y can be determined as a function of E, G and t.

$$Y = \frac{(x_1)_t}{(x_1)_{ss}} = 1 - \frac{(1 + E + E^{\frac{1}{2}})e^{\frac{-(1+E-E^{\frac{1}{2}})t}{G}}}{2E^{\frac{1}{2}}} + \frac{(1+ E - E^{\frac{1}{2}})e^{\frac{-(1+E+E^{2})t}{G}}}{2E^{\frac{1}{2}}} \tag{7}$$

Significance of G:

Figure 2 shows the solution to Equation 7 as a function of the dimensionless quantity, $Z (Z = t/G)$ with parameters of E.

The significance of G can be seen by multiplying the numerator and denominator of the defining equation by x_i.

$$G = \frac{V_H + V_L m}{H} = \frac{V_H x_i + V_L y_i}{H x_i} \tag{8}$$

The numerator represents the amount of solute in stage i at a given time and the denominator is the amount leaving stage i per unit time in the aqueous stream. In other words, if the numerator is relatively large due to large volumes and a high distribution coefficient, and if the aqueous flow rate is relatively small, then G_L which is related to the system capacitance, will also be large. The fractional approach to steady-state at a given value of E depends on the ratio of t to G, as shown in Figure 2.

Sample Problem:

Suppose that one desires to know the fractional approach to steady-state under the following conditions, choosing any consistent units for the variables.

$t = 1$	$V_H = 1$
$L = 1$	$V_L = 1$
$H = 1$	$m = 1$

For these conditions, E = 1, G = 2 and Z = 0.5. Figure 2 shows that Y would be 20% of its final steady-state value after t = 1. If, however, V_H and V_L were each equal to 0.25 instead of unity, Z would equal 2. Figure 2 shows that Y would equal 80% in this case at t = 1.

Discussion:

The same technique has been used to develop similar expressions for three, four, five and six stage mixer-settlers. These solutions are no more complicated than those described in this paper but there is considerably more algebra to do.

Equation 1a and 2a can be solved simultaneously for x_1 as a function of time, using the analog computer wiring diagram shown in Figure 3, but it is not as much fun and the students learn more electronics and use less of their rusty sophomore mathematics.

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A PROJECTS LABORATORY FOR JUNIOR CHEMICAL ENGINEERS*

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Abstract: This paper describes the operation of an undergraduate chemical engineering laboratory which is in addition to the usual unit operations laboratory but is not a substitute for a research thesis. Small groups of students are assigned different interesting projects and they are required to search the literature, build apparatus, keep a record of their laboratory activities, and present oral and written reports. This laboratory achieves several objectives but best of all, it provides an outlet for the students' creativity and talents.

If God were to prepare an addendum to his ten commandments, this addendum being intended for graduating engineers in general and chemical engineers in particular, it would probably read something like this:

> Thou shalt be well founded in the basic fields of mathematics, physics and chemistry but
>
> Thou shalt perform engineering work and not be a pure scientist.
>
> Thou shalt be creative.
>
> Thou shalt have the basic tools to tackle a new problem and be able to solve it.
>
> Thou shalt have the ability to enlist the help of others who art more knowledgeable than thou art.
>
> Thou shalt have the ability to use other sources and devices such as a library or a computer and if thou shalt find no help, then thou shouldst

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* Presented at the A.I.Ch.E. annual meeting in Boston, December 1964. Publication release was obtained by the author.

proceed on thine own initiative with confidence in thyself, and when thou findest a solution, thou shalt be able to communicate either orally or in writing whatever thou hast found to thy colleagues, supervisors and the public.

According to Mayer (1) and Moulton (2), the chemical industry would say "Amen" to this addendum, and "Hallelujah" if the word "economically" were added to these commandments. And in this spirit, about five years ago, the "Projects Laboratory" was introduced in the normal junior year unit operations course sequence. It had the following objectives:

1. To provide an outlet for the student's creativity and talents.

2. To show the student that textbooks are not all there is to know and thus teach him to use the library and to search the technical literature.

3. To teach the student the methodology of conducting an organized experimental study.

4. To familiarize the student with the basic machine shop practices.

5. To encourage good oral and written presentations.

6. To show the wide variety of interesting problems that a chemical engineer can get involved with because of his versatile wide background.

Before presenting the mechanism and mode of operation of this laboratory and the types of projects pursued, it would be interesting to show where this laboratory falls in our four year undergraduate curriculum at Tufts University.

In order to graduate from Tufts, an engineering student must satisfy the requirements in forty courses of three or four credit hours each. This requires the average student to carry five courses each term.

The Freshman year is the same for all engineers. They take two semesters of chemistry, physics, mathematics, graphics, and English.

Only students desiring to continue in chemical engineering must make up their minds at the end of the first year. During the sophomore year a student takes two semesters of physical chemistry, electric circuits, mathematics, two electives in the humanities or social studies, a third semester of physics and his first course in chemical engineering stoichiometry.

The Junior and Senior year programs are shown below:

Junior Year

*Unit Operations I	4	*Unit Operations II	4
*Thermodynamics I	3	*Thermodynamics II	3
Organic Chemistry	4	Chem. Analysis	4
Applied Mechanics	3	Applied Mechanics	4
Hum. or Soc. Study	3	Hum. or Soc. Study	3

Senior Year

*Chem. Eng. Lab.	3	*Chemical Technology	3
Technical Elective	3	*Plant Design	4
Hum. or Soc. Study	6	Hum. or Soc. Study	6
Free Elective	3	Elective	3

The first projects laboratory is given during the first term of the junior year as part of the unit operations course. It is held one afternoon a week. These afternoons are not solely devoted to laboratory work. Two afternoons are devoted to applied mathematics in chemical engineering. Our students at that point seem to be weak in log-log plotting, graphical integration, trial and error solutions and slide rule manipulations. An afternoon is devoted to a lecture on the chemical engineering literature and report preparation. Mimeographed notes on the literature and sample long form reports (thesis type) are distributed at that time. Another afternoon is devoted to machine shop practice. Occasionally a plant trip or film may be scheduled. About eight afternoons are spent on the project.

During the second term, students perform six experiments in unit operations based on what they have learned during the first term. These experiments are: distillation, extraction, fluid flow, insulation testing, heat exchangers and boiling.

During the first semester of the senior year, a student is given the choice of either doing a B.S. thesis (if he qualifies with a C+ or better average) or taking the regular chemical engineering laboratory course. This laboratory course consists of six weeks of standard experiments in unit operations (humidification, drying, evaporation, filtration, Dorr thickener and flooding of packed beds). The remainder of the course is devoted to more sophisticated group projects. In addition, the students are required to read early in the term a major portion of Wilson's "Introduction to Scientific Research" - McGraw Hill, paperback edition, and they are quizzed on it periodically and are expected to use what they learn

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*Courses taught by the department.

from it in their projects.

Operation of the Projects Laboratory:

In general, the laboratory is conducted in the following manner. The class is divided into groups of two and the projects are assigned to or chosen by these groups. Within three or four weeks a literature survey is made and a written theoretical report is prepared by the group. In addition, one member of the group presents it orally to the class in 8-10 minutes. He is graded by his classmates on: Clarity, knowledge of the subject, information transfer, extemporaneousness, diction and poise. The judging sheets with class comments are returned to the speaker. Th group then spends the remainder of the term building an apparatus, running experiments, obtaining data and correlating results. A final group report (of the thesis type) is handed in at the end of the term at which time the second member of the group presents orally the experimental findings and is judged by the class.

Typical Projects:

The following is a list of projects recently assigned to juniors:

1. Gas Bubbles in Liquids. Study the effect of inlet conditions on the rate and size of bubbles of air in water.

2. Recovery of Chemicals from the Lunar Crust. Attempt to recover the water of crystallization of ores considered to be on the lunar surface.

3. Rocket Fuel Performance. The performance of a hobby rocket solid fuel is studied in static firings. Specific impulse, total impulse, average thrust, mass ratio, etc., are to be found.

4. Desalination with Solar Energy. Construct a flat collector and test its efficiency.

In all these projects, the underlined portion was the title of the initial (theoretical) report. A diagram of the proposed apparatus was prepared and checked by the instructor and machinist for feasibility and economy of construction. Generally, the students assembled the apparatus themselves. Each group was required to maintain a laboratory data book which was checked occasionally. The groups met often with the instructor and sought help from the faculty of other departments.

As one can see from the titles of these projects, they are not equivalent to research theses. They do not contribute new information to human knowledge (although the author must confess that he and other faculty members have occasionally used the projects laboratory to test a few research ideas) but they leave the student with the impression that he is doing research.

There was no problem in searching for project topics. Summers spent in an industrial research laboratory, technical journals, books, other faculty members and the instructor's current research interests have been the usual sources of ideas.

The students' reaction has been gratifying. In a questionaire given at the end of the first year that we started this laboratory, <u>all</u> students indicated that it should be continued. Some felt that they needed more time. Many worked after hours and during vacations. We feel that the projects laboratory encouraged qualified students to choose a B.S. thesis during the senior year and to do a better job on it. We feel that it has contributed to the increase in the number of our students going on to do graduate work (43% over the past five years) and in general we are sure that this laboratory has made better chemical engineers out of our students.

<u>Literature Cited</u>:

1. Mayer, M. W.. "Industries' Views of Current Chemical Enfineering Education", paper delivered at the A.S.E.E. annual meeting, June 1963

2. Moulton, R. W., The Trend, <u>16</u>:No. 4, 4, (Oct. 6, 1964)

UNDERGRADUATE USE OF ANALOG COMPUTERS*

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Abstract: Types of problems that can be solved by undergraduates employing analog computers are examined.

Introduction:

The availability of small electronic analog computers for use by relatively large numbers of students has brought about significant changes in undergraduate education in the Department of Chemical Engineering, Lehigh University. This paper is a brief account of our experiences in the use of analog computers in undergraduate education during the last five years.

Operating Procedure:

Our experience with analog computation began in 1960 with the purchase of an Electronic Associates, Inc. TR-10 20-amplifier computer. The initial use of this computer was somewhat limited because of the lack of programming experience of the faculty and the unavailability of removable patch panels (i.e. it was necessary to patch a problem directly on the face of the computer and then remove it before another problem could be patched). When the manufacturer did finally provide removable patch panels, the demand for the computer increased sharply to the point where it was no longer adequate. The quantity of computing equipment has increased continually to meet the growing demand and it is anticipated that this trend will continue for some time in the future, although our future purchases may be determined to some extent by the recent developments in digital simulation.

At present 32 patch panels are available for use by any student in the University. The analog computer laboratory is open 4 or 5 days a week with supervision and is run on an open-

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*Presented at the annual A.I.Ch.E. meeting in Boston, December 1964. Publication release was obtained by the author.

shop basis. A student may obtain a patch panel, cords, bottle plugs and any other related equipment, patch his problem and run it on a computer without completing any paperwork. Upon completion of the problem, the student returns the panel and components to the central supply area in the laboratory. Patch panels may be retained for further computation for a period of time which is determined primarily by the current demand for additional patch panels to start new problems. When this time during which a patch panel may be retained becomes too short, additional patch panels are purchased.

Undergraduates are encouraged to use the analog computer routinely in the solution of assigned problems. The facilities of the computer laboratory are used extensively in undergraduate and graduate courses in kinetics and reactor design, and process dynamics and control, an undergraduate seminar in mathematical modeling, an introductory sophomore course in analog and digital computation and a senior projects course. The Departments of Mechanical Engineering, Electrical Engineering and Psychology are presently using the analog computer laboratory and it is anticipated that several other departments will do so in the near future.

<u>The Advantages of Analog Computation</u>:

Experience has indicated that the following advantages can be attributed directly to the availability of small analog computers:

1. Undergraduates have an opportunity to gain valuable experience in the mathematical modeling of physical systems. In deriving the system equations, they must make use of the basic principles of physics, chemistry and engineering. It is usually necessary for them to decide which phenomena must be taken into consideration in their analysis in order to arrive at a realistic model and which phenomena can be dismissed as unimportant in contributing to the performance of the system so as to keep the model within manageable proportions. The contribution of the analog computer is, of course, that it enables the student to do something useful and practical with the model after it has been formulated.

2. The programming of an analog computer, in common with all computer programming, requires careful problem formulation and attention to detail. On the other hand, the computer enables the student to essentially by-pass the details of mathematical analysis required to solve the model. He does not become engulfed in complex mathematical manipulations but instead can proceed directly to the solution. The analog computer is, of course, particularly valuable for nonlinear problems for which there are no known analytical methods of solution. The effects of system nonlinearities are easily assess-

ed and the limitations of a linearized analysis are soon apparent.

3. The student can experiment with the modeled system and investigate a large number of alternatives in a short period of time. In a sense he can optimize the system by trial-and-error experimentation on the computer.

It is therefore not surprising to find that most students are analog computer enthusiasts, particularly the better students who are strongly oriented towards the analytical approach to engineering problems.

<u>An Example</u>:

The following simple problem in chemical kinetics illustrates the procedure for programming a problem for analog computer solution

$$A \xrightarrow{k_1} B \xrightarrow{k_2} C$$

Compute the concentration of A, B and C as a function of time when initially, $A = 1$ (mol fraction), $B = 0$, $C = 0$*. Consider three cases: $k_1 = 0.1$, $k_2 = 1$; $k_1 = 0.25$, $k_2 = 0.25$; $k_1 = 1$, $k_2 = 0.1$ (sec^{-1}).

1. State the equations, initial conditions and parameters. The equations should be arranged to give the highest order derivatives explicitly.

1.1 First-order kinetics

$$-dA/dt = k_1 A$$

$$dB/dt = k_1 A - k_2 B$$

$$dC/dt = k_2 B$$

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*We refer to this as the "Piel's Beer" problem

$$\text{Green beer} \xrightarrow{k_1} \text{Piel's Beer} \xrightarrow{k_2} \text{Stale beer}$$

The objective then is to catch the "Piel's Beer at its peak."

1.2 Second-order kinetics

$$-dA/dt = k_1A^2$$

$$dB/dt = k_1A^2 - k_2B^2$$

$$dC/dt = k_2B^2$$

Initial conditions: $A(0) = 1$, $B(0) = 0$, $C(0) = 0$

Parameters: I $k_1 = 0.1$, $k_2 = 1$

II $k_1 = 0.25$, $k_2 = 0.25$

III $k_1 = 1$, $k_2 = 0.1$

2. Magnitude scale the equations. The output of any operational amplifier in the computer should not exceed the reference voltage ($\pm$ 10v in the case of an EAI TR-10 or TR-20) or be so small that the computing accuracy is poor. It is therefore necessary to scale all of the dependent variables of the equations so as to keep the voltages representing these variables in the proper range. In this case scaling is quite easy since the dependent variables are all mol fractions with a maximum value of 1 which immediately suggests a scale factor of 10. If square brackets [ ] are used to represent a scaled variable (i.e. a voltage in the computer), the original equations can be scaled as:

First-order Kinetics

$$-d[10A]/dt = k_1[10A] \quad (1)$$

$$d[10B]/dt = k_1[10A] - k_2[10B] \quad (2)$$

$$d[10C]/dt = k_2[10B] \quad (3)$$

Second-order Kinetics

$$-d[10A]/dt = k_1[10A]^2/10 \quad (4)$$

$$d[10B]/dt = k_1[10A]^2/10 - k_2[10B]^2/10 \quad (5)$$

$$d[10C]/dt = k_2[10B]^2/10 \qquad (6)$$

$$[10A(0)] = 10$$

3. Draw the computer circuit diagram. The circuit for the solution of Equations 1, 2, and 3 is given in Figure 1 and for Equations 4, 5, and 6 in Figure 2.

4. Time scale. In this case the setting of potentiometers 1 and 2 (i.e. the values of k_1 and k_2 respectively) are reasonable and therefore time scaling is not required. Thus problem time and computer time are the same. If the rate constants for Case I had been $k_1 = 0.001$, $k_2 = 0.01$, potentiometers 1 and 2 could still be set to 0.1 and 1 respectively and the computer would run 100 times faster than the physical system. On the other hand if the rate constants had been $k_2 = 100$, $k_2 = 1000$, potentiometers 1 and 2 could be set to 0.1 and 1 respectively and the computer would run 1000 times slower than the physical system. These considerations can be generalized: The inputs to all integrators can be changed by a constant factor in order to arrive at reasonable potentiometer settings and loop gains without changing the solution. The ratio of problem time to computer time equals this constant factor. In a sense then, time scaling takes care of itself quite naturally.

5. Static check. A static check is analogous to a hand calculation used for debugging a digital computer program. It is indispensable for the successful operation of an analog computer, particularly when the amount of time each problem is on the computer is to be minimized. The static check will detect most programming errors and computer components which are not operating properly.

In the present case, the following voltages should appear at the outputs of the indicated amplifiers before the computer is put into operation:

Amplifier	Output
1	+10v
2	0
3	0
4	0

Figure 1. Analog Computer Circuit for Linear Kinetics.

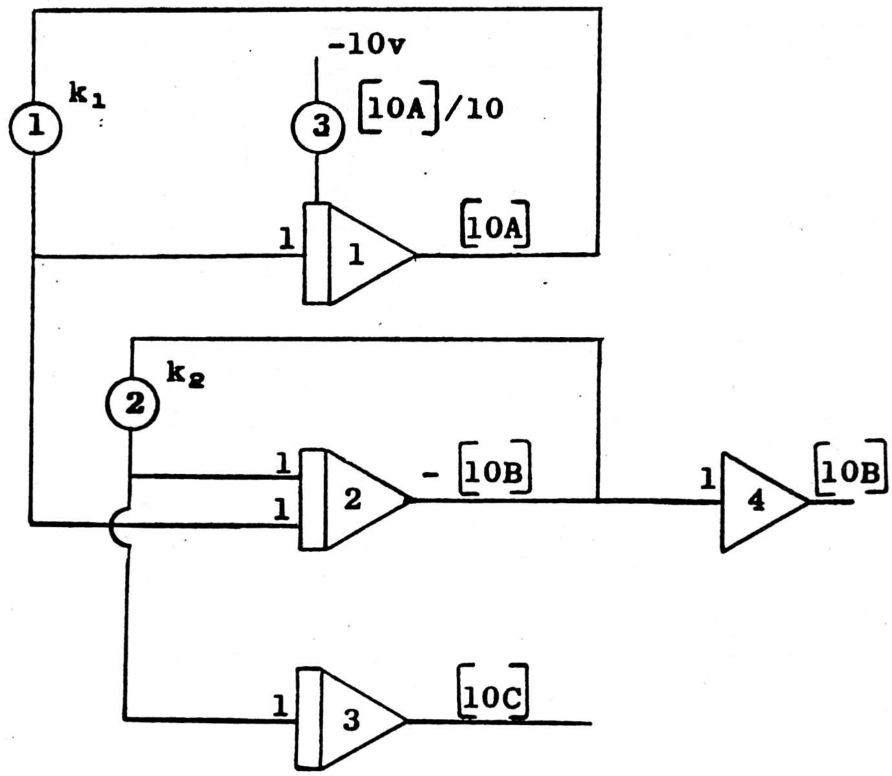
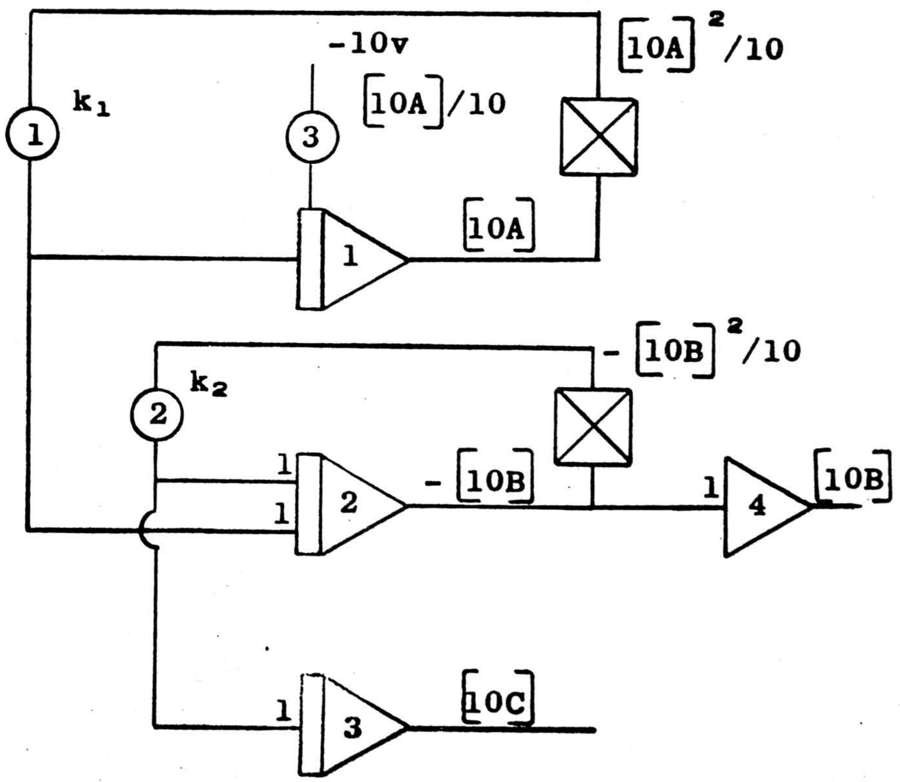


Figure 2. Analog Computer Circuit for Nonlinear Kinetics.



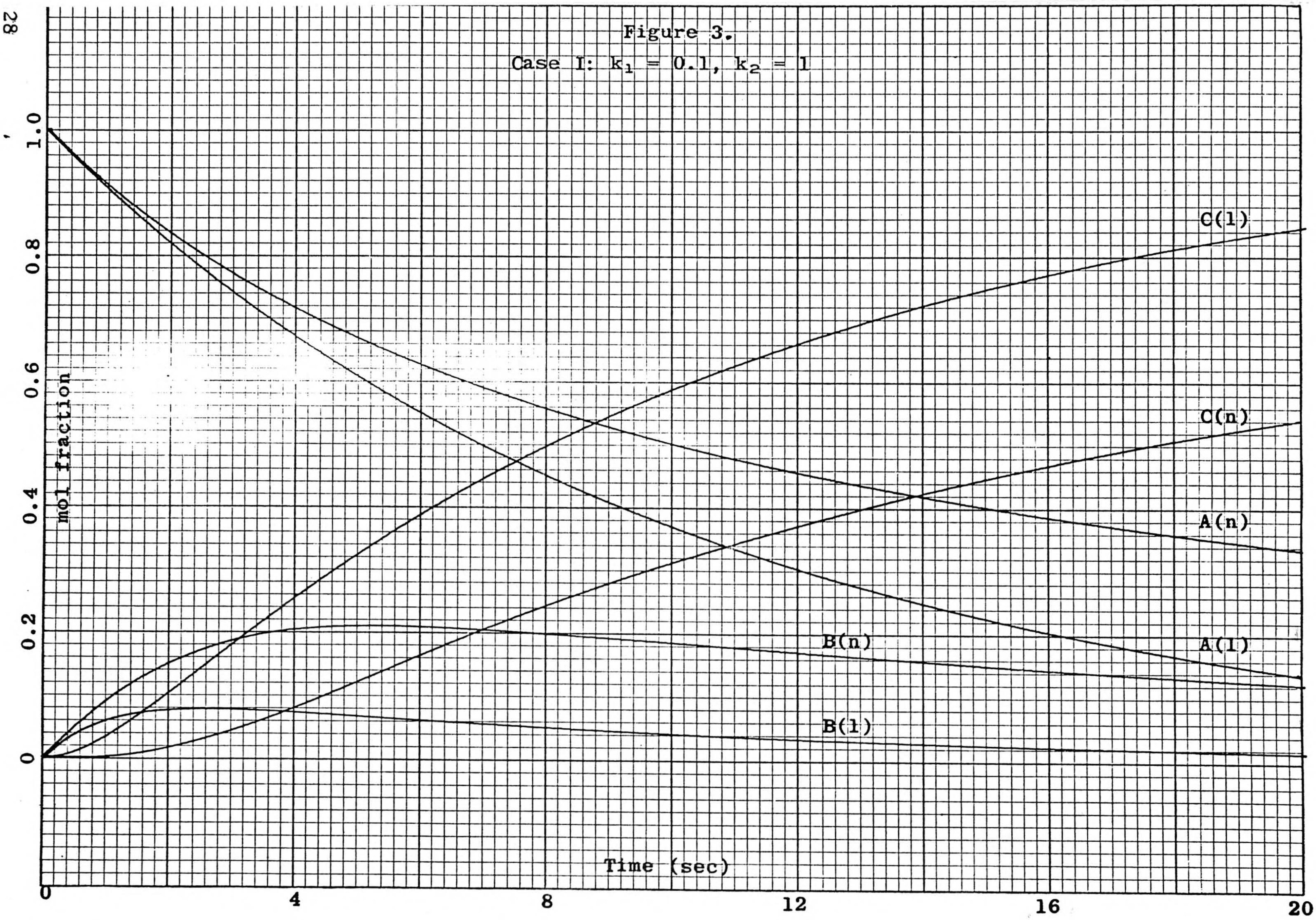


Figure 3.

Case I: $k_1 = 0.1$, $k_2 = 1$

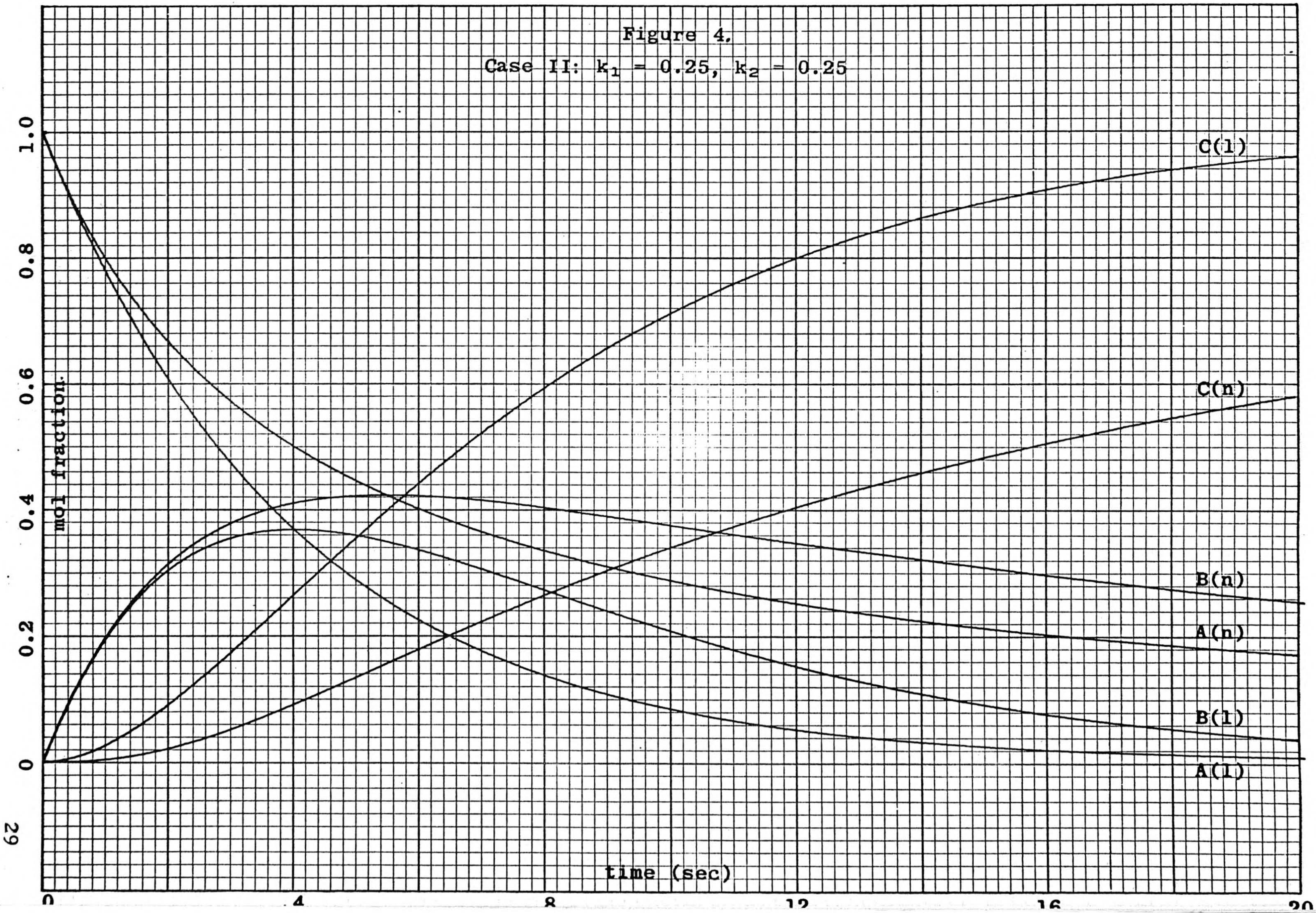


Figure 4.
Case II: $k_1 = 0.25$, $k_2 = 0.25$
mol fraction
1.0
0.8
0.6
0.4
0.2
0
C(1)
C(n)
B(n)
A(n)
B(1)
A(1)
time (sec)
0
4
8
12
16
20

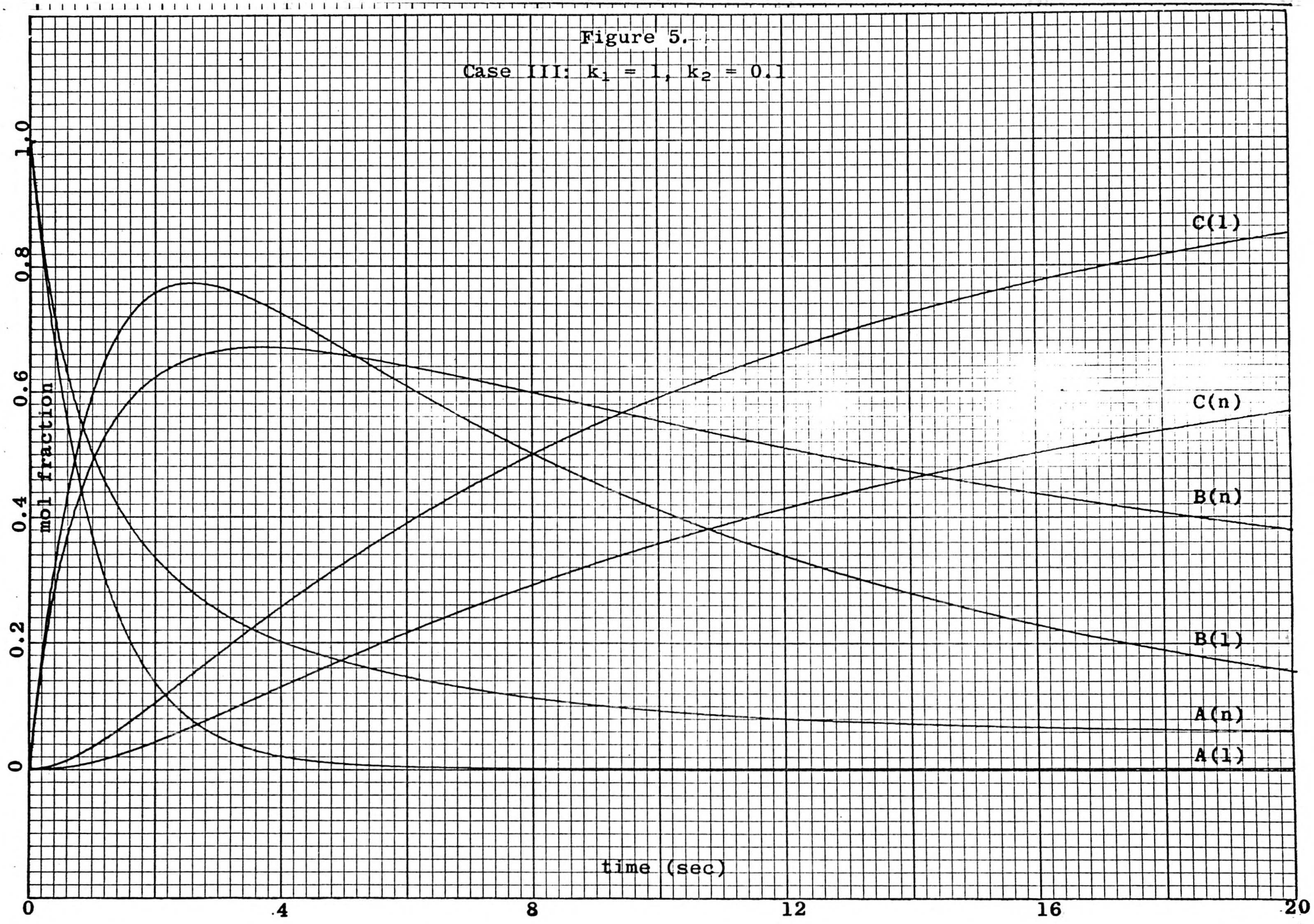


Figure 5.
Case III: $k_1 = 1$, $k_2 = 0.1$

A more complete check can be made by artifically introducing an initial condition into each integrator and by summing the inputs used to form the highest-order derivative in each equation (the inputs to amplifiers 1 and 2 in this case). This sum can then be checked against the values of the highest-order derivatives computed directly from the system equations.

6. Run the problem and document the results. Since it is possible to rapidly generate a large number of solutions in a short period of time, it is essential to document these solutions as they are obtained. The solutions to the present problem as they appeared on the xy plotter are given in Figures 3, 4 and 5.

This kinetics problem is especially simple from the point of view of magnitude and time scaling. The author has put together several small linear and nonlinear problems with detailed solutions which illustrate the more typical complexities of scaling. These problems are available upon request.

DEPARTMENTALIZED CURRICULUM BASED ON CHEMICAL CHANGE *

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Abstract: Departmentalized curriculum based on chemical change is defined. Then, better building upon high-school preparation to keep a 4-year undergraduate program in chemical engineering is discussed. Emphasis is placed upon the need to prevent proliferation of courses and work in the presence of the continual acceleration in the growth of knowledge. Argument is given in favor of teaching principles and developing abilities to think, with the belief that the best type of men will agressively and successfully continue to treat their own technological gaps. The need for continual analysis of curricula is reviewed. Suggestions are given for improved teaching of chemical principles in the early part of the chemical engineering program and for a new attack to chemical engineering design in the senior year.

In a discussion of a departmentalized curriculum in chemical engineering, or any branch of engineering, the first thing to consider is what is meant by departmentalized curriculum relative to a general engineering curriculum. There could be many definitions, but one choice would distinguish between the two by noting that the departmentalized curriculum would provide the opportunity for the B.S. graduate to be prepared properly for specialized or semi-specialized employment after four years of undergraduate education. A departmentalized curriculum based on chemical change would have 15 to 20 per cent of the program devoted to appropriate courses in chemistry. The generalized curriculum would not give significant specialized preparation, and at least another year of study would be required to provide the student with the necessary professional tools to begin specialized employment.

After one has considered the meaning of departmentalized curriculum, the next act could logically be the asking of why be concerned about that curriculum when a generalized four-

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year program with one or two years of graduate study in professional subjects would certainly give a sound training for the first professional degree. The response is threefold:

1. We are less stimulated to significant changes in curricula if we are just allowed to extend course work. The four-year program for the first professional degree demands significant and continuous revision in order to provide the most up-to-date training and education in a restricted time schedule.

2. Tuition charges in at least the private schools continue to rise. For example, in 1965-66, the yearly tuition at the California Institute of Technology will be $1800. The increase of one or two years in the program for the first professional degree adds significant educational expenses for tuition and other charges.

3. Space needs are always critical in universities. The addition of 25 to 50 per cent in curriculum time means increased facilities. Should money be put into that area or should it be put into efforts on improved teaching, better linking of research and teaching, and related fields?

The professional training of a chemical engineer is probably less tractable in the framework of a generalized curriculum for preparatory work than for other engineering professions. The chemical engineer is marked by his particular concern with the economic control of chemical reactions for the benefit of mankind in either defense or non-defense work. As a chemical engineer, and not just as an engineer, he must know about the subtleties of chemical reactions that are not just simply handled by writing chemical rate equations in combinations with transport equations to design chemical reactors. For example, if he is to maximize his ability to program the best type of knowledge into a computer, it is now desirable and becoming necessary that he have some understanding of the movements of electrons in the framework of chemical reactions. He cannot afford to wait too long in his college work to get the background that will allow him to think in chemical terms. That background would include a significant amount of training in physical chemistry, chemical kinetics, inorganic chemistry, and organic chemistry. If that work were left in the main to the latter professional part of a training program, more than a year of work after a four-year program would be necessary for the chemical engineer. The man would be well trained, no doubt, but in consideration of time and money would the gain be necessary relative to the needs of the employer or to those of the man himself in any subsequent graduate work?

A departmentalized curriculum to prepare a man for specialized professional performance after four years of undergraduate work appears to be a continuing possibility. The possibility seems very desirable in these days of increasing tuition and of increasing ability of entering freshmen. Rather than to think that we must increase our training at the undergraduate level and move toward a generalized engineering program in that period of development, we should look closely at our educational techniques and be willing to make significant changes in our teaching program in order to provide an education in a specialized way in four years. There is a tendency today to believe that as progress adds to our armamentarium of technical ideas and methods at a high rate we must communicate a large portion of this fund of knowledge to the student before he receives even his first degree. Instead of that concern we should emphasize the development of the thinking abilities of the student. We should be more selective in our teaching and spend more time on principles and less time on technological details. The principles can certainly be taught in the framework of technology, but the technology really should serve mainly as a matrix for the development of the analytical abilities of the students. As a student develops his thinking powers and interest in his own self-education, he should experience no particular difficulty in continually filling in the crevices in his knowledge with technical details that are evolving day by day.

We have not really exploited the abilities of freshmen entering from the many excellent high schools in the United States. Even though the students have been exposed to improved courses in mathematics, physics, and chemistry in the high school, we have not done enough in providing those courses with an engineering flavor to exploit fully the opportunity to optimize the preparation of the man who is to become a freshman in an engineering college. The lack of integrated effort between engineering educators and high-school departments of science and mathematics is a challenge that is especially directed to us who favor the concept of a departmentalized curriculum based upon chemical change.

The simplest way to focus thoughts on curriculum is to be specific, and so a four-year program for the near future is proposed which would continue to provide the high level of education we have today, would accommodate for the increasingly exciting additions to knowledge and methods, and would allow the graduate from that program to work for any chemical industry and perform well in operations and possibly development work or enter graduate work in chemical engineering in the best schools in the United States. Humanities training would be about 20 per cent of the curriculum and electives about 10 per cent.

Table 1 shows the proposed curriculum. The data are shown for a quarter system with three terms in the academic year of 9 months. The units noted in the table represent the total number of class and home hours per week assigned to the different subjects. Conversion of units to semester hours is accomplished by multiplying by 2/9. Over-all percentages of time devoted to a given area of effort are more meaningful, and are shown in the summary Table 2. Table 3 gives the current program at the California Institute of Technology, and in Table 4 there is a summary of the details in Table 3.

A comparison of the proposed and current curricula shows two major changes. First, the new proposal calls for a new course in chemistry for the first and second years. It would be a systematized integration of physical chemistry, inorganic chemistry, and organic chemistry in place of the current separate courses in quantitative chemistry, organic chemistry, and physical chemistry. Sufficient progress has been made in the development of quantitative organic chemistry that such integration seems possible. Not only would the course be taught to chemical engineers, but strong consideration should be given to its inclusion in all engineering and science courses to improve the scientific literacy of the undergraduate. The second major change is the proposed senior course in chemical engineering design. In the suggested curriculum, the student at the end of his junior year would be well trained in many aspects of applied mathematics and able to move more rapidly in the parts of design work concerned with applied mechanics than if the applied mechanics had been taken at a lower level of training. Therefore there is some logic in suggesting a significant course in chemical engineering design which would bring together stoichiometry, industrial chemistry, economics, applied mechanics, and strength of materials with the student's knowledge of transport phenomena at a given time in the senior year.

Electives would be available for the senior year in areas such as electrical engineering, applied mechanics, and other technical fields. The electives courses would be selected according to the developing interest of the student relative to graduate school or industrial work. In the suggested curriculum, significant education in principles of chemistry, physics, mathematics, and engineering would be allowed. Only parts of current technology would be presented to the chemical engineer in his first four years, and they would be more concerned with explaining principles than with just technological knowledge for its own sake. The student would be expected to have prepared himself, however, to think clearly in the attack of new problems and to have the courage to work on these problems even in the face of failure. His technological development would be a continuing part of his graduate and subsequent professional study or of his professional work alone.

In summary, a seven-point program is suggested for insuring a high-quality departmentalized curriculum in chemical engineering to be given in four years and to have chemical change as the main basis for its differentiation from general engineering. The seven points are:

1. Continue with a strong effort to teach why. Worry less about all technology and focus more on use of new technology to illustrate old and new principles.

2. Build more carefully upon the greatly improved education in high school.

3. Work to introduce more engineering thinking into the problems and laboratory assignments in high-school science and mathematics.

4. Introduce more engineering problems and attitudes into the lower-division college courses in mathematics, physics, and chemistry, and integrate that effort with the upper-division engineering courses.

5. Introduce a new two-year chemistry course in which physical chemistry, inorganic chemistry, and organic chemistry have been systematically combined in place of the often-used three-year program of separate general and quantitative chemistry, organic chemistry, and physical chemistry.

6. Introduce a third-year course in quantum mechanics and statistical mechanics with carefully prepared applications in the gaseous, liquid, and solid states.

7. Build more carefully in the fourth year on the advanced principles developed in the first three years. Use fewer units to cover work more intensively. Specifically, introduce a new senior course in chemical engineering design to encompass work in stoichiometry, industrial chemistry, economics, applied mechanics, and strength of materials.

The above steps as they pertain to college work are achievable even in the presence of 20 per cent of the curriculum devoted to Humanities and 10 per cent to electives.

Table 1

Proposed Four-Year Undergraduate Course in Chemical Engineering

First Year
(Same for all Science and Engineering Students)

		Units per term 1st	2nd	3rd
Mathematics	Calculus, Vector Algebra, Analytic Geometry, Infinite series	12	12	12
Physics	Kinematics, Particle Mechanics, and Electric Forces	12	12	12
Chemistry	Physical Chemistry, Inorganic Chemistry, and Organic Chemistry	12	12	12
English	English Literature	6	6	6
History	History of European Civilization	5	5	5
Graphics	Basic Graphics	3	-	-
		50	47	47

Second Year

History	History and Government of the United States	6	6	6
Mathematics	Calculus (functions of several variables), Probability, Vector Analysis, Group Theory, Differential Equations, Numerical Analysis	12	12	12
Physics	Electricity, Fields, and Atomic Structure	12	12	12
Chemistry	Physical Chemistry, Inorganic Chemistry, Organic Chemistry .	12	12	12
	Electives in Science and/or Engineering	9	9	9
		51	51	51

Table 1 (Continued)

Third Year

		Units per term 1st	2nd	3rd
English	Advanced Literature	8	8	8
Economics	Economic Principles and Problems .	–	6	6
Electrical Engineering	Electronics and Circuit Theory ...	10	–	–
Advanced Physical Chemistry	Quantum Mechanics, Statistical Mechanics, Applications to solids, liquids, and gases (solid state theory, plasmas, etc.)	10	10	10
Chemical Engineering	Computer programming as applied to chemical engineering problems	–	3	3
Chemical Engineering	Chemical Engineering Thermodynamics, Applied Chemical Thermodynamics ...	10	10	10
Mathematics	Engineering Mathematics, Mathematical treatment of problems in Engineering Chemistry and Physics, Complex Variables, Series, Partial Differential Equations, Boundary Value of Problems, Integral Transforms	12	12	12
		50	49	49

Fourth Year

		1st	2nd	3rd
Humanities	Humanities Electives	9	9	9
History	Public Affairs	2	2	2
Chemical Engineering	Transport Phenomena	12	12	–
Chemical Engineering	Unit Operations	–	–	12
Chemical Engineering	Kinetics	9	–	–
Chemical Engineering	Chemical Engineering Laboratory ..	–	9	9
Chemical Engineering	Chemical Engineering Design (Process design and study of strength of materials and elasticity applied to process components in framework of industrial chemistry and economics)	10	10	10
Electives	Free Electives	10	10	10
		52	52	52

Table 2

Percentage Distribution of Time in Proposed Four-Year Undergraduate Program in Chemical Engineering

Area	Per Cent of Time
Mathematics	18.0
Physics	12.0
Chemistry	16.9
Chemical Engineering	21.4
Free Electives	5.0
Electrical Engineering	1.7
Science and Engineering Electives	4.5
Graphics	0.5
Humanities	20.0

Table 3

Current Undergraduate Course in Chemical Engineering
at the California Institute of Technology

First Year
(Common to all Curricula)

			Units per term 1st	2nd	3rd
Ma	1 abc	Calculus, Vector Algebra, Analytic Geometry	12	12	12
Ph	1 abc	Kinematics, Particle Mechanics, and Electric Forces	12	12	12
Ch	1 abc	General and Quantitative Chemistry .	12	12	12
En	1 abc	English Literature	6	6	6
H	1 abc	History of European Civilization ...	5	5	5
Gr	1	Basic Graphics	3	–	–
			50	47	47

Second Year

			1st	2nd	3rd
H	2 abc	History and Government of the United States	6	6	6
Ma	2 abc	Sophomore Mathematics	12	12	12
Ph	2 abc	Electricity, Fields, and Atomic Structure	12	12	12
Ch	41 abc	Basic Organic Chemistry	10	4	4
Ch	46 ab	Basic Organic Chemistry Laboratory .	–	6	6
		Electives in Science and/or Engineering*	9	9	9
			49	49	49

Table 3 (Cont.)

Third Year

			Units per term 1st	2nd	3rd
En	7abc	Advanced Literature	8	8	8
Ec	4ab	Economic Principles and Problems ...	–	6	6
Ch	14	Quantitative Analysis	10	–	–
Ch	21abc	Physical Chemistry	9	9	9
Ch	26ab	Physical Chemistry Laboratory	–	8	8
ChE	63ab	Chemical Engineering Thermodynamics.	9	6	–
AM	95abc	Engineering Mathematics	12	12	12
			48	49	43

Fourth Year

			1st	2nd	3rd
		Humanities Electives	9	9	9
H	5abc	Public Affairs	2	2	2
ME	55	Adaptive Design	9	–	–
ChE	61ab	Industrial Chemistry	9	9	–
ChE	64	Applied Chemical Thermodynamics	–	–	9
ChE	66ab	Transport Phenomena	12	12	–
ChE	67ab	Chemical Engineering Laboratory	–	9	9
ChE	73	Unit Operations	–	–	12
		Electives*..........................	6–10	6–10	6–10
			47–51	47–51	47–51

*If an electrical engineering course in electronics and circuit theory is not elected in the sophomore year, the adviser will strongly recommend its inclusion in the senior year.

Table 4

Percentage Distribution of Time in Current Undergraduate Program in Chemical Engineering at the California Institute of Technology

Area	Per Cent of Time
Mathematics	18.5
Physics	12.3
Chemistry	20.3
Chemical Engineering	16.4
Free Electives	5.1
Mechanical Engineering Design	1.5
Science or Engineering Electives	4.6
Graphics	0.51
Humanities	20.5

A COMMON STUDIES CURRICULUM IN ENGINEERING*

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Abstract: The common studies program in engineering at Washington University is discussed from the viewpoint of the chemical engineering curriculum. The courses in engineering science and applied mathematics taken by all engineering undergraduates are discussed first. The three courses specifically oriented toward chemical engineering are described and special emphasis is given to a new senior course which has the objective of acquainting the students with process design problems.

The Common Studies Program was put into effect in our Engineering School at Washington University in the fall of 1962. The program is based on the belief that there is a basic body of knowledge — in science, mathematics, and the engineering sciences — which anyone in engineering should possess — regardless of their specialty.

The program consists of 79 units (or credits, a unit being 1 semester hour of a course, or 2½ lab hours) of courses. Of the 79, 52 are taken in the Arts and Sciences College, — the ones listed as "General" in Table 1. The other 27 are taken in the field of Engineering Sciences.

As can be seen from Table 2, the curriculum for Chemical Engineering in the first two years consist solely of common studies courses. The one exception for Chemical Engineering students is that they must take a more comprehensive second semester of general chemistry as a prerequisite to the additional chemistry they have to take later on. This permits a choice of a specific engineering field to be put off until the student is well into his second year. We feel this to be desirable, since the average incoming freshman usually has no basis for making an intelligent choice in this matter.

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One of the fields in which we thought all engineering students should obtain a comparable background was applied mathematics. The details of the common studies program in mathematics courses can be seen in Table 2. After three semesters of Calculus given by the Mathematics Department, the students begin their applied math sequence in the Engineering School.

Two semesters of classical applied mathematics (called Analysis I and II to appease the mathematicians) present ordinary and partial differential equations, vectors, complex variables, operational methods, Fourier series, etc. The techniques of "setting up" problems for mathematical solution are heavily emphasized, especially in the first semester. The course entitled "Numerical Methods" in the junior year is entirely computer oriented. The students become acquainted with computer techniques and simple programming. They are encouraged in all their subsequent courses to make use of the computer whenever it might be of help to them. They punch their own programs and batches are run off three times a day on Washington University's IBM 7072 computer. The Statistics course completes the sequence.

Among the other engineering science common studies courses, the Thermodynamics course is probably of special interest to Chemical Engineers. It is, of course, not possible nor desirable perhaps, to cover some of the specifically chemical engineering aspects of thermodynamics in the core course. These are taken up in the subsequent Elements of Chemical Engineering Course.

This brings us to the specialized Chemical Engineering part of the program. First of all, there are, of course, additional chemistry courses. I might say here that the position of these courses is not the optimum from our viewpoint. This is especially so with respect to Physical Chemistry. We would like to see this in the curriculum somewhere before the senior year. However, we are constrained by the fact that the Chemistry Department teaches it definitely on a senior level. Consequently some of the physical chemistry topics which Chemical Engineering students need for their senior design course have to be taught by us.

There are actually only three undergraduate courses taught by the Chemical Engineering Department. The first is a Transport Phenomena course and its associated laboratory. This is a full year course. The text by Bird, Stewart, and Lightfoot is used in the lectures and the laboratory manual by Crosby is followed to a large extent in the Lab. The next Chemical Engineering course is the Elements of Chemical Engineering course. This course is a very intensive one semester presentation of basic stoichiometry, some of the chemical engineering aspects of thermodynamics, and the fundamentals of kinetics. To do all this in one semester, we have allotted 4 lecture hours and a $2\frac{1}{2}$ hour problem working session per week to the course.

The course listed as Process Analysis and Design in the fourth year of the Chemical Engineering curriculum is being taught for the first time during the 1964-65 academic year. The objective of this course is to acquaint the student with and give him some practice in the various aspects of chemical process design. You must keep in mind that up to this point the student has not been brought into contact with the traditional unit operations, reactor design, economics, or design problems. The senior Process Analysis course must, therefore, cover some of the important aspects of all of these topics. We have also found it necessary to include some additional material on vapor-liquid equilibria, estimation of properties and mass and energy balances.

The design aspect of the course is being handled by taking up a series of "case studies". The present plan is to have about half-a-dozen of these. The problems presented to the students will be progressively more sophisticated and difficult. As an example I might cite the first case study which was handed out to our seniors. It is a project to produce a "Preliminary Design and Economics Evaluation of Processes for Producing Cyclohexane from Benzene". Both gas and liquid phase processes are to be explored. The students, paired in teams of two and three, have been given about four weeks to come up with a Tentative Process Report. For this first project they are being given a great deal of assistance in locating sources of property data, outlining of process flow sheets, etc. In the later studies they will be expected to do more of this themselves. We are planning case studies to cover some of the newer aspects of chemical engineering, such as biochemical and aerothermochemical engineering, as well as the more traditional processes.

Concurrently with work on their case studies, the students are attending lectures on continuous and stagewise processes, reactor design, and process economics. One of the four units assigned to the course is for one laboratory period or problem working session per week. This period will be utilized during the second semester for a ten week series of sessions on process control (both lecture and lab) and also some additional laboratory work with equipment such as distillation columns, which were not encountered in the Transport Phenomena Laboratory.

The big problem in this course is to present the material in such a way that it ties in meaningfully with the material in the basic and engineering sciences which the students have had in their first three years. I think, on the basis of our present limited experience, that so far we are succeeding.

In conclusion, I would say that I believe that we have achieved as good a balance as is possible of analysis and synthesis in our curriculum of chemical engineering courses tied in with a common studies program. I feel that this curriculum will be suitable both for the terminal Bachelors man as well as the prospective graduate student.

Table 1

Washington University

School of Engineering and Applied Science

Common Studies Program

General	
English Composition	6
Chemistry	8
Physics	8
Mathematics	12
Electives*	18
	52
Engineering Sciences	
Mechanics	6
Electrical Sciences	7
Thermodynamics	3
Engineering Analysis**	11
	27

* Recommended courses include languages, literature, economics, history, sociology, psychology, philosophy, and political science.

** Includes statistics and an introduction to digital computers.

Table 2

Washington University

Curriculum in Chemical Engineering

FIRST YEAR

FALL SEMESTER	Units	SPRING SEMESTER	Units
Phys. 117 Gen. Physics	4	Phys. 118 Gen. Physics	4
Math. 116 Calculus I	4	Math. 215 Calculus II	4
ECMP 101 Eng. Comp.	3	ECMP 102 Eng. Comp.	3
Humanity Electives	3–6	Humanity Electives	3–6
Phys. Ed., ROTC or Band	(1)	Phys. Ed., ROTC or Band	(1)
	14–17		14–17

SECOND YEAR

Math. 216 Calculus III	4	Engr. 211 Analysis I	3
Chem. 111 Gen. Chem.	5	Chem. 112 Gen. Chem.	5
Engr. 213 Networks I	3	Engr. 214 Networks II	3
		Engr. 219 Networks Lab.	1
Engr. 231 Mechanics I	3	Engr. 232 Mechanics II	3
Humanity Elective	3	Humanity Elective	3
Phys. Ed., ROTC or Band	(1)	Phys. Ed., ROTC or Band	(1)
	18		18

THIRD YEAR

Engr. 365 Num. Methods	2	Engr. 325 Statistics	3
Engr. 320 Thermodynamics	3		
Engr. 312 Analysis II	3	Engr. 358 Elems. of Ch.E.	5
Engr. 367 Transport Phen.	3	Engr. 368 Transport Phen.	3
Engr. 373 Trans. Phen. Lab	2	Engr. 374 Trans. Phen. Lab	2
Chem. 241 Quantitative	4	Chem. 254 Organic	5
	17		18

FOURTH YEAR

Engr. 477 Proc. Anal. and Design	4	Engr. 478 Proc. Anal. and Design	4
Chem. 421 Physical	3	Chem. 422 Physical	3
Chem. 431 Physical Lab.	1	Chem. 432 Physical Lab.	1
Humanity Elective	0–3	Humanity Elective	0–3
Technical Electives	6	Technical Electives	6
	14–17		14–17

Total number of units: 133

THE UNDERGRADUATE CURRICULUM IN CHEMICAL ENGINEERING AT YALE*

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In a reorganization in July 1962, the Department of Engineering and Applied Science was created at Yale to replace to a large extent the School of Engineering. The degree of Bachelor of Science is offered by the Department as a part of Yale College and degrees of Master of Science and Doctor of Philosophy are offered through the Yale Graduate School.

In making the transition from a School to a Department it was necessary to adopt the general requirements of Yale College for the bachelor's degree. These requirements include as one feature a program for distribution of studies. This program of distribution requires every student to elect a full-year course or two term courses in each of the following fields: (1) English; (2) a foreign language at the second-year level; (3) history; (4) social studies; (5) the natural sciences; (6) philosophy; (7) a second course in natural science or mathematics at the second-year level or a course in literature in a foreign language. Since requirements (5) and (7) are met automatically by students in Engineering and Applied Science programs, this means that at least five year courses of the twenty normally taken must be in fields other than science, mathematics and engineering. The curriculum is so arranged that as many as eight courses may be taken outside those fields.

Other features of the Yale scene should be borne in mind in considering the curriculum pattern for chemical engineering. One of the most important of these is the fact that most of the students graduating from Yale College receive the degree of Bachelor of Arts in the humanities. The Class of 1965, for example, includes about 800 candidates for degrees in the humanities, 110 for degrees in the natural sciences and 50 for degrees in engineering and applied science. Our students thus carry on their engineering studies in a community in

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which the humanities are dominant and this has both advantages and disadvantages. Our students benefit from the high quality of teaching in the humanities and acquit themselves well in competition with students in other majors. However, as Astin [Science, 141, 334-8 (1963)] has pointed out, such an environment, characteristic of several of the Northeastern men's colleges, has a decidedly negative effect on the student's decision to pursue a career in science and his conclusions probably also apply to engineering students. That is to say, it is a characteristic of Yale and other schools in this group that a Freshman planning to enter the field of science is more likely to be dissuaded from this choice than he would in other schools.

A second factor which should be borne in mind is the orientation of Yale students after graduation. Over two-thirds of Yale graduates enter graduate or professional schools. For example, 649 of the 956 members of the Class of 1964 entered into advanced study and a sizeable number (280) of these chose law and business schools. This trend of graduates to the enterprising professions is also seen among graduates from programs offered by the Department of Engineering and Applied Science. Of the graduates of this Department in 1964, more than one-fourth entered law schools and business schools; the others were evenly divided between graduate school in engineering and science and industrial positions.

In terms of size, the Department of Engineering and Applied Science with fifty-three faculty members is somewhat smaller than the Department of English or the Department of History and is about the same size as the Department of Physics. In addition to the 50-70 undergraduate students per year receiving degrees, this Department also has in residence about 30 candidates for the degree of Master of Science and 120 candidates for the degree of Doctor of Philosophy.

This, then, is the framework within which the program in chemical engineering is planned and administrated. It is a program characterized by flexibility, a feature which is considered to be essential in view of the factors discussed above.

The Department of Engineering and Applied Science is not formally broken into subgroups representing the traditional fields of engineering nor into subgroups according to other patterns such as the engineering sciences. The Department of some 50 faculty members is small enough that subgroups may not be as necessary as they would be in schools which have many more faculty members. This is not to say that subgroups do not exist. They form naturally according to common interests but they no longer have formal status. There is, for example, a natural subgroup of faculty members with primary interests in chemical engineering and the members of this subgroup are responsible for activities in our field. Administratively, we make recommendations regarding our curriculum and research programs to the larger group. In this regard, we have the usual problems of communicating with our colleagues whose work is based in physics rather than in chemistry.

The Department offers some 50 term courses at the undergraduate level in the fields of applied mathematics, chemical engineering, electronics, mechanics of solids and structures, mechanics of fluids, control systems, communications, solid state science, etc. These courses are listed by level in Table 1 in a manner similar to that used in the catalog. Each student is required to build a four-year program on the following general scheme:

- 3 terms of physics
- 3 terms of mathematics
- 2 terms of chemistry
- 16 terms of courses in engineering, applied science, science
- 10 terms of distributional requirements
- 6 terms of electives

The selection of courses in engineering and science must be on a basis to form some coherent pattern but a high degree of flexibility is allowed. Such a system requires close consultation between the student and his faculty advisors in order to insure that the course plan is in fact a coherent one and that the student is aware of requirements for admission to graduate schools and of the requirements of industry and government for various kinds of positions.

Turning now to the specific case of chemical engineering, it is expected that the majority of students interested in this field will plan a curriculum in accord with the pattern shown in Figure 1. However, we expect that some students will vary this pattern by substitution within the block of E. and A. S. courses. For example, a student with strong interests in applied mathematics or control systems or physics of fluids could replace some of the suggested courses with others if he has a strong reason for doing so.

The greatest degree of flexibility comes about, however, with the eight terms of electives, two of which must be in engineering or science. The student planning to enter graduate school would be urged to elect courses in mathematics, computers, physics of fluids, or a senior project in chemical engineering. Those planning to enter industry directly might find it advisable to elect courses in economics or data processing or personnel administration.

Thus we feel that we have a core curriculum which can be tailored to the requirements of students with a variety of interests. It will be recognized, of course, that other institutions have similar programs. Hence we present this program not as something new and different but simply as a curriculum in chemical engineering which seems to us to fit the requirements of the Yale students of today.

Many aspects of this approach are present in the interim programs developed for the Classes of 1966 to 1968; the elective flexibility has applied to all classes from 1962 on since it was adopted for undergraduate engineers in 1959. However, as the Class of 1969 will be the first to follow this program for all four years, it is not possible to attempt an overall evaluation of this curriculum now.

Figure 1

A Suggested Pattern in Chemical Engineering

Term

<table>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th></tr>
<tr><td colspan="3">Mathematics</td><td>Applied Mathematics</td><td>Momentum and Mass Transport</td><td>Separation Processes</td><td>Heat Transfer</td><td>Reaction Kinetics</td></tr>
<tr><td colspan="3">Physics</td><td>Digital Computation</td><td colspan="2">Thermodynamics</td><td colspan="2">Design</td></tr>
<tr><td colspan="2">General Chemistry</td><td colspan="2">Organic Chemistry</td><td colspan="2">Physical Chemistry</td><td>EAS elective</td><td>EAS elective</td></tr>
<tr><td colspan="2">English</td><td colspan="2">History</td><td colspan="2">Philosophy</td><td colspan="2">Elective</td></tr>
<tr><td colspan="2">Foreign Language</td><td colspan="2">Social Science</td><td colspan="2">Elective</td><td colspan="2">Elective</td></tr>
</table>

Table 1

Term Courses Offered by the Department of Engineering and Applied Science

Number	Sophomore or Junior Level
10a	Digital Computation
22a	Thermodynamics
23b	Mechanics of Deformable Bodies
26a,27b	Linear Systems
29b	Physical Electronics
30a	Engineering Analysis
30b	Applications of Ordinary Differential Equations
31b	Applications of Partial Differential Equations
32a	Applications of the Complex Variable
35a	Electronic Circuits
38a	Advanced Networks
39b	Advanced Mechanics
42a	Momentum and Mass Transport
43b	Chemical Thermodynamics
45	Communications, Language, and Machines
48a	Physical Metallurgy
49b	Solid State Science

Number	Senior Level
50a,51b	Case Studies in the Interaction of Engineering and Society
56a	Probability and Stochastic Processes
47b	Numerical Analysis
58a	Applied Discrete Mathematics
59b	Digital Systems
60b	Quantum Mechanics
61a,62b	Fluid Mechanics
64a	Heat Transfer
65b	Energy Conversion
68a	Structural Mechanics
69b	Elasticity
70a	Electric and Magnetic Fields
72a	Nonlinear Magnetics
74a	Communication Theory
76a,77b	Control Theory
81b	Separation Theory
83b	Reaction Kinetics
86a,87b	Engineering Design
88a,89b	Modern Experimental Techniques
99a,91b	Special Projects

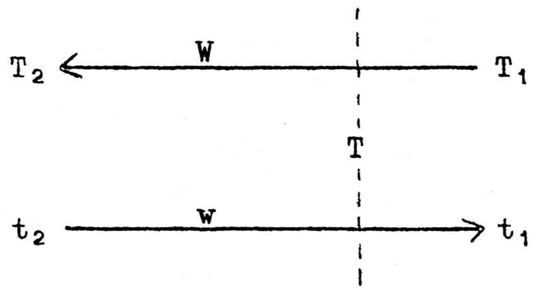
SOLUTION TO THE PREVIOUS PROBLEM

which appeared in 3: No.1, 33 (1964)

Restatement of Problem:

Consider an infinitely long, counterflow, water to water, heat exchanger. Making appropriate assumptions, prove that the temperature pinch must occur at the inlet of the stream with the larger flow rate, and nowhere else along the exchanger.

Solution:



Let us say for the moment that the pinch can occur at some other location such as shown at the dotted line in the diagram. Call this pinch temperature T. For convenience, let all temperatures be absolute (so that they will all be positive). Finally, let W be the larger flow rate, and w the smaller, so that $W > w$.

Since each stream consists of water, it is reasonable to equate the two heat capacities. An energy balance to the right of the pinch point then gives

$$W(T_1 - T) = w(t_1 - T) \tag{1}$$

or

$$\frac{T_1 - T}{t_1 - T} = \frac{w}{W} \tag{2}$$

But $0 < \frac{w}{W} < 1$. Combining with Equation 2 yields

$$0 < \frac{T_1 - T}{t_1 - T} = \frac{T - T_1}{T - t_1} < 1 \tag{3}$$

From this last relationship, either $(T_1 - T) < (t_1 - T)$ and both $(T_1 - T)$ and $(t_1 - T)$ are positive, or $(T - T_1) < (T - t_1)$ and both $(T - T_1)$ and $(T - t_1)$ are positive.

Consider the first alternative. Since $(T_1 - T)$ is positive, $T_1 > T$. This means W cools down as it passes through the exchanger, and so W must be for the hot stream. (To accept the contrary would obviously violate the Second Law by having a cold stream cool down further by thermal contact with a hot stream.) However, canceling T from the aformentioned inequality which is $(T_1 - T) < (t_1 - T)$ yields $T_1 < t_1$. This means W is for the cold stream. Obviously, W cannot represent both the hot stream and the cold stream. Therefore this first alternative is impossible.

Consider now the second alternative. Here $(T - T_1)$ is positive, so $T > T_1$. This means W warms up as it passes through the exchanger, and so W must be for the cold stream. (Again, accepting the contrary would violate the Second Law.) However, subtracting T from $(T - T_1) < (T - t_1)$ which is the inequality for this alternative, yields $-T_1 < -t_1$ or $T_1 > t_1$. This means W is for the hot stream. Again, W obviously cannot represent both the cold stream and the hot stream. Therefore this second alternative is also impossible.

Since there are only two alternatives, and both are impossible, the entire situation is impossible. In other words we cannot say the pinch occurs at some location along the exchanger. In fact, it cannot even occur at the left-hand extremity of the exchanger since we could always write Equation 1 for an energy balance to the right of the pinch.

The pinch must therefore occur at a location to the right of which we are unable to write an energy balance. Only the right-hand extremity of the exchanger qualifies. In other words, the pinch must occur at the inlet of the stream with the larger flow rate.

R. L.

TRANSLATION OF TITLES

Spanish - S. Botero

German - H. Zimmer

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