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Chemical Engineering Nomographs

BY

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CHEMICAL ENGINEERING NOMOGRAPHS

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PREFACE

The present collection of nomographs derives from two major purposes: (1) to select critically, from the rapidly growing literature, a limited number of alignment and line-coordinate charts of proved practical value to chemical engineers and to analytical, control, and physical chemists and (2) to present these charts suitably grouped and indexed (*a*) in a form large enough to be read easily and (*b*) supplemented with corroboratory material and adequate directions for use. Feasible suggestions as to nomographs for possible subsequent inclusion will be welcomed and given close attention, as will the notification of errors.

The "Bibliography of Chemical Engineering Nomographs" by Myllynen and Davis (American Documentation Institute, *Document* 1599, Washington, D. C.) covering the quarter century ending June, 1941, and an unpublished bibliography covering the period since June, 1941, including in all some 600 titles, have been consulted, and all promising charts have been examined carefully. In most instances, the hundreds of requests for reprints that have been received during the past fourteen years have guided the choice.

Engineers concerned with the design as well as the use of alignment charts will be interested in learning that the charts in this collection, almost without exception, have been or could have been constructed by the simple methods presented in the companion text, "Empirical Equations and Nomography" (1943). Students will discover, with interest and relief, that the present compilation can serve as a fairly complete answer book to both parts of the earlier work through the use of the indexes.

Industrial associates and former students have made many helpful suggestions. Sincere thanks are due the various authors who have permitted use of their charts and whose names appear with their work, particularly Prof. Ernst Berl of the Carnegie Institute of Technology. Grateful acknowledgment is made of the very substantial stimulus accorded industrial nomography over a number of years by J. H. Davis of Renaud et Cie of America, S. D. Kirkpatrick and T. R. Olive, editor and associate editor, respectively, of *Chemical & Metallurgical Engineering;* Walter J. Murphy and F. J. Van Antwerpen, editor and associate editor, respectively, of *Industrial and Engineering Chemistry;* the late Harrison E. Howe, former editor of the latter journal; Harry E. Weston, editorial director of The Fritz Publications; John H. Perry, editor in chief of the well-known "Chemical Engineers' Handbook"; R. G. Macdonald, secretary of the Technical Association of the Pulp and Paper Industry; and the editors of *The Chemist Analyst; Power Plant Engineering*, *The Oil and Gas Journal*, *Food Industries*, *The Melliand Textile Monthly*, *National Petroleum News*, and *The Petroleum Refiner*. Material not credited to others in the footnotes is drawn from the published work of the author.

Marguerite and Margarethe Davis have given generous assistance in proofreading.

DALE S. DAVIS.

DETROIT, MICH.,
March, 1944.

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FOREWORD

Nomography has not yet been recognized as a unit operation or process of chemical engineering, but our profession has come to be one of its most frequent and practical users. The science and art underlying the theory and construction of alignment and line-coordinate charts appeal particularly to chemical engineers in industry who are so often faced with the necessity for making a multiplicity of routine calculations in order to operate a process or design even a simple piece of equipment. Thus it is not surprising that the recent growth and popularity of nomographs have largely coincided with the great engineering advances in the chemical and process industries.

In a recent bibliography of approximately two hundred references to alignment charts, fully 90 per cent were concerned with the chemical engineering problems of the pulp and paper, textile, petroleum, refrigeration, dairy, fuel, and chemical industries. The remainder ran the gamut from medicine to agriculture, from telephones to power plants. Significantly, more than one hundred of these articles were the individual or joint contributions of Dale S. Davis and all were published since this most versatile and productive of our engineering mathematicians completed work for his M.S. thesis in chemical engineering practice at the Massachusetts Institute of Technology in 1924.

The late Dr. Harrison E. Howe was one of the first to suggest that chemists and chemical engineers in industry would welcome a comprehensive collection and reprinting of the Davis nomographs. Members of the editorial staffs of both *Industrial and Engineering Chemistry* and *Chemical & Metallurgical Engineering* have since found it pleasant and stimulating to work with Mr. Davis in assembling the text and charts that are reproduced in this book. Although we may have differed occasionally on our definitions of operations and processes, all agree that these efficient, timesaving tools and methods should now become a part of the permanent literature of chemical engineering.

SIDNEY D. KIRKPATRICK,
Editor, Chemical & Metallurgical Engineering.

NEW YORK CITY,
March, 1944.

CHEMICAL ENGINEERING NOMOGRAPHS

CHAPTER I

ACID NOMOGRAPHS—MISCELLANEOUS

CHARTS FOR SPECIFIC VOLUMES OF MINERAL ACIDS[1]

It is frequently necessary or desirable to know the specific volumes of the more common inorganic acids, sulfuric, nitric, and hydrochloric, as a function of the temperature and the acid concentration, both for laboratory and for larger scale problems. The importance of having such data in an easily usable form is undoubtedly greater in the larger scale problems where extreme accuracy is of secondary importance to availability and moderate accuracy. In the shipment of such acids in a container, such as a drum, carboy, or tank car, it is desirable from an economic standpoint to ship the containers filled as completely as possible. On account of considerations of safety, the danger of excessive expansion by temperature increases, and in order to conform to government regulations, it is necessary to ship less than the container will hold at the temperature obtaining during the filling operation.

To facilitate the determination of these specific volumes, therefore, Figs. 1 to 7 have been prepared.

NOMOGRAPH FOR CALCULATION OF MIXTURES OF OLEUM AND SULFURIC ACID[2]

Determinations of the proportions of oleum and sulfuric acid required for the preparation of a weaker oleum frequently take the form of some adaptation of the familiar Pearson's square, as outlined by Santmyers[3] and Fickenscher.[4] Concentrations of the components are usually expressed on different bases: sulfuric acid as the percentage of total H_2SO_4 and oleum as the percentage of free SO_3. Proper account of this situation must be taken in applying the Pearson's-square method,

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[1] Perry, J. H., and D. S. Davis, *Chem. & Met. Eng.*, **42**, 87 (1935).

[2] *Chem. & Met. Eng.*, **43**, 150 (1936).

[3] Santmyers, G. S., *Chem. & Met. Eng.*, **40**, 657 (1933).

[4] Fickenscher, J. W., *Chem. & Met. Eng.*, **42**, 159 (1935).

and recourse must be made to a conversion calculation before tackling the main problem.

There is evident need for a rapid graphical method where (1) the conversion feature is built into the chart and need not be considered in its use and (2) the desired proportions are given as percentages rather than as numbers of "parts." Figure 8 handles the problem nomographically, and its use is illustrated as follows:

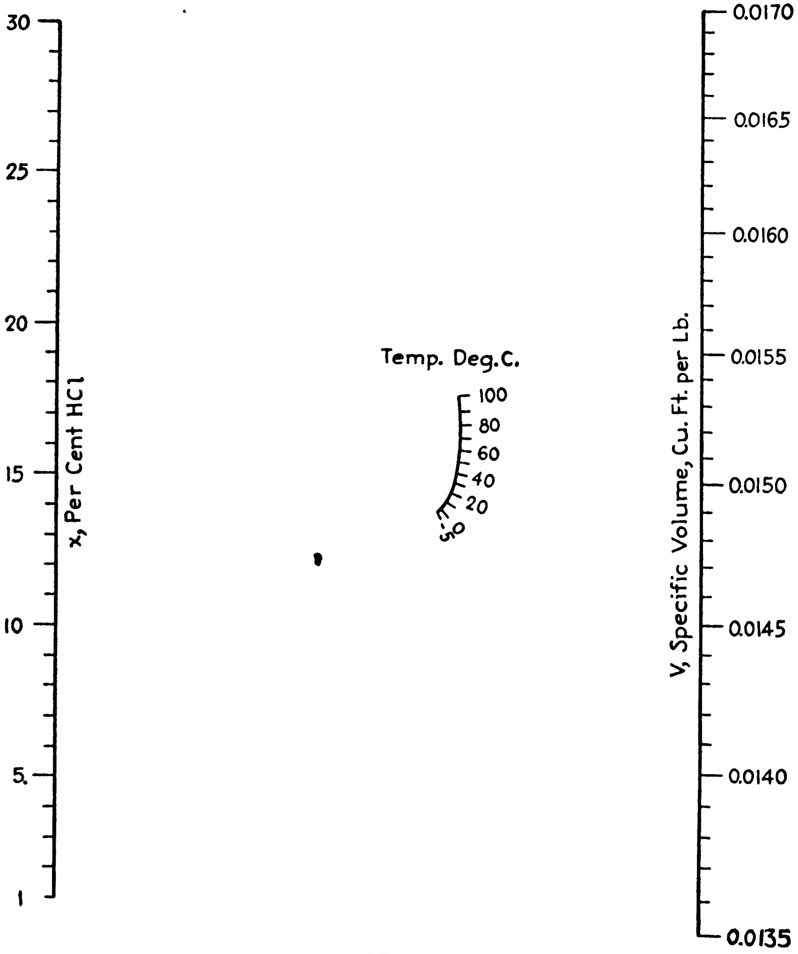

FIG. 1.—Specific volume of hydrochloric acid, 1 to 30 per cent; temperature range, −5 to 100°C. (*From "International Critical Tables."*)

What percentages of sulfuric acid (97.75 per cent total H_2SO_4) and oleum (30 per cent free SO_3) shall be mixed to yield an oleum testing 12 per cent in free SO_3? Following the key, connect 97.75 per cent total H_2SO_4 on the x scale at the left with 12 per cent free SO_3 on the C scale and note the intersection with the A axis. Connect 97.75 per cent total H_2SO_4 on the x scale at the right with 30 per cent free SO_3 on the C_1 scale, and note the intersection with the B axis. Connect the points so found on the A and B axes, and read the desired percentages on the inclined axis as 55 per cent oleum and 45 per cent sulfuric acid. That is, a mixture containing 55 per cent of oleum (30 per cent free SO_3) and 45 per cent of sulfuric acid (97.75 per cent total H_2SO_4) will be an oleum with a content of 12 per cent free SO_3.

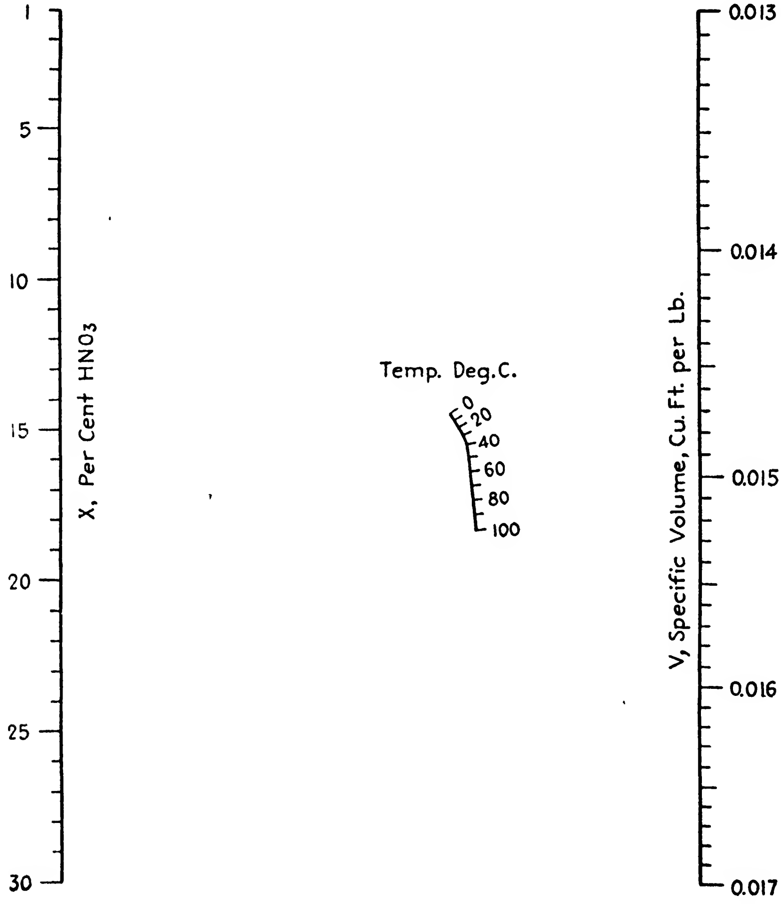

FIG. 2.—Specific volume of nitric acid, 1 to 30 per cent; temperature range, 0 to 100°C. (*From "International Critical Tables."*)

Figure 8 is based upon the relationships

$$P_1 + P_2 = 100$$
$$C_2 = -4.44(100 - x)$$

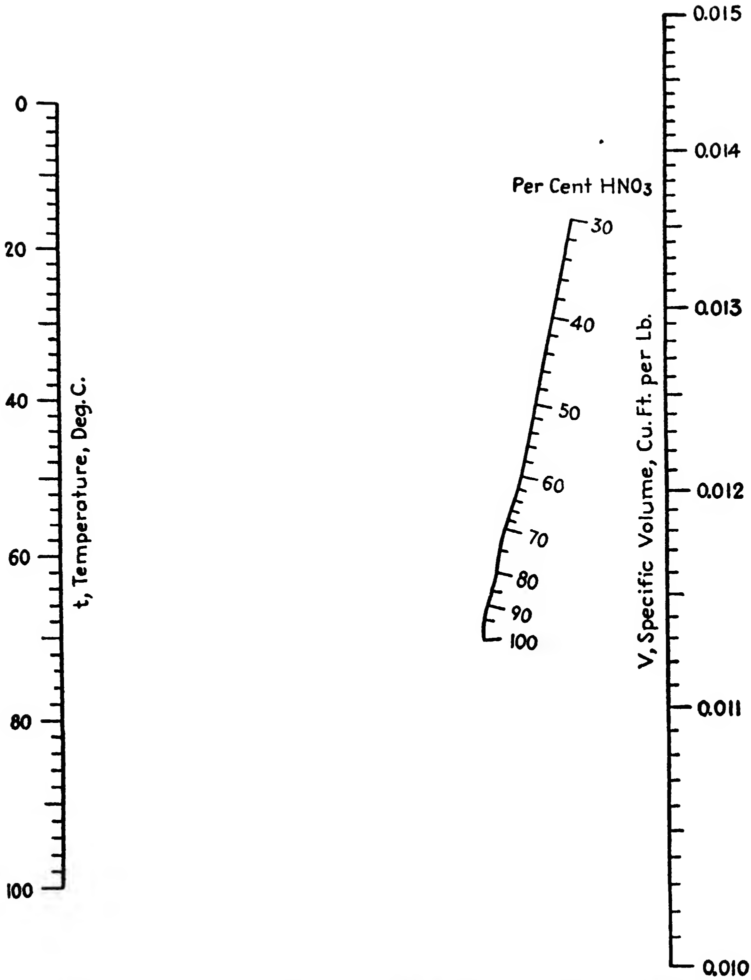

Fig. 3.—Specific volume of nitric acid, 30 to 100 per cent; temperature range, 0 to 100°C. (*From "International Critical Tables."*)

and

$$P_1 = 100\,\frac{C - C_2}{C_1 - C_2}$$
$$= 100\,\frac{C + 4.44(100 - x)}{C_1 + 4.44(100 - x)}$$

where P_1 = percentage of oleum (testing C_1 per cent free SO_3) in the mixture.

P_2 = percentage of sulfuric acid (testing x per cent total H_2SO_4) in the mixture.

C = percentage free SO_3 in the desired oleum.

C_2 = percentage free SO_3 deficiency in the sulfuric acid.
4.44 = the ratio of molecular weights of SO_3 to H_2O.

ENTHALPY-TEMPERATURE NOMOGRAPH FOR THE SYSTEM NITRIC ACID-SULFURIC ACID-WATER[1]

In the preparation of mixed acids for nitration processes, as well as in the nitration reactions themselves, the temperature and, as a result, the heat balance of the system are of prime importance. Recently a correlation of all available heat-content, specific-heat, and heat-of-mixing

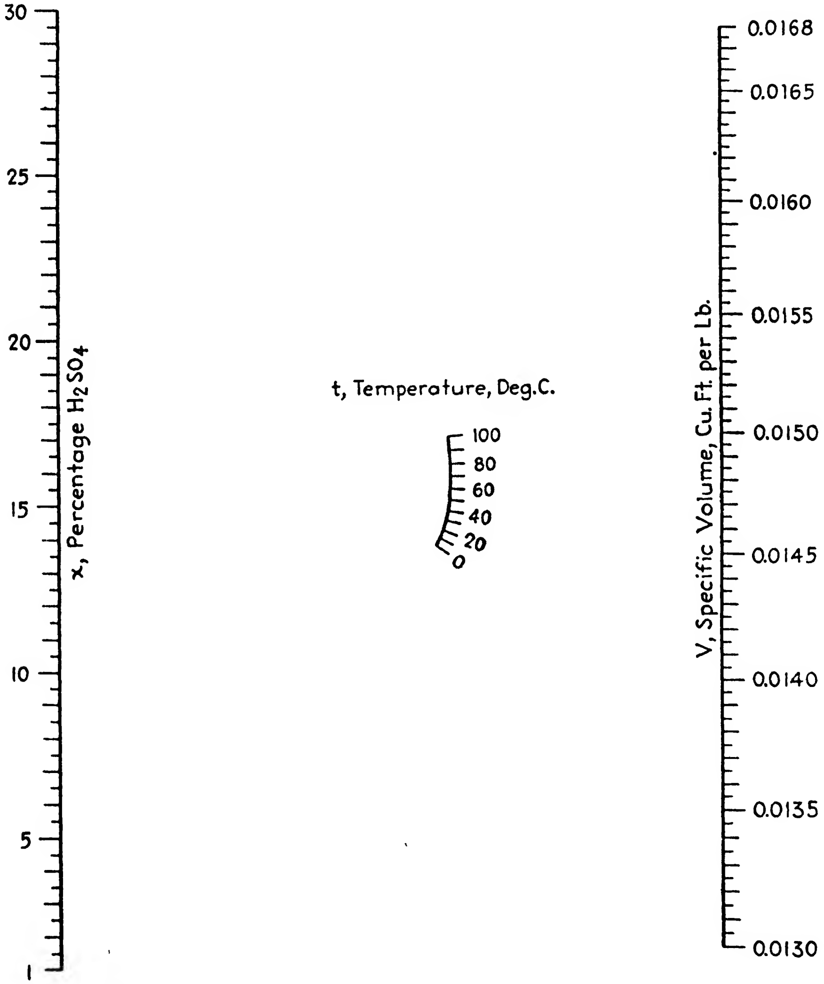

FIG. 4.—Specific volume of sulfuric acid, 1 to 30 per cent; temperature range, 0 to 100°C. (*From "International Critical Tables."*)

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[1] McCurdy, J. L., and Clyde McKinley, *Ind. Eng. Chem.*, **34**, 1002 (1942).

data for the ternary system nitric acid–water–sulfuric acid was presented as a summarized enthalpy and specific-heat plot, with examples for its use in heat-balance calculations.[1]

Owing to the importance of such reactions, it has seemed advisable to present these data in a nomograph to facilitate their use. A solution is presented in Fig. 9 to calculate the change in enthalpy of mixed-acid ternary mixtures with increase or decrease in temperature. Figure 10 shows the relative enthalpy of the ternary system referred to each pure component at 32°F. That is, each component in the pure state has zero enthalpy at 32°F. By the use of Fig. 10 in combination with Fig. 9, it is possible to determine the enthalpy of any acid mixture at any

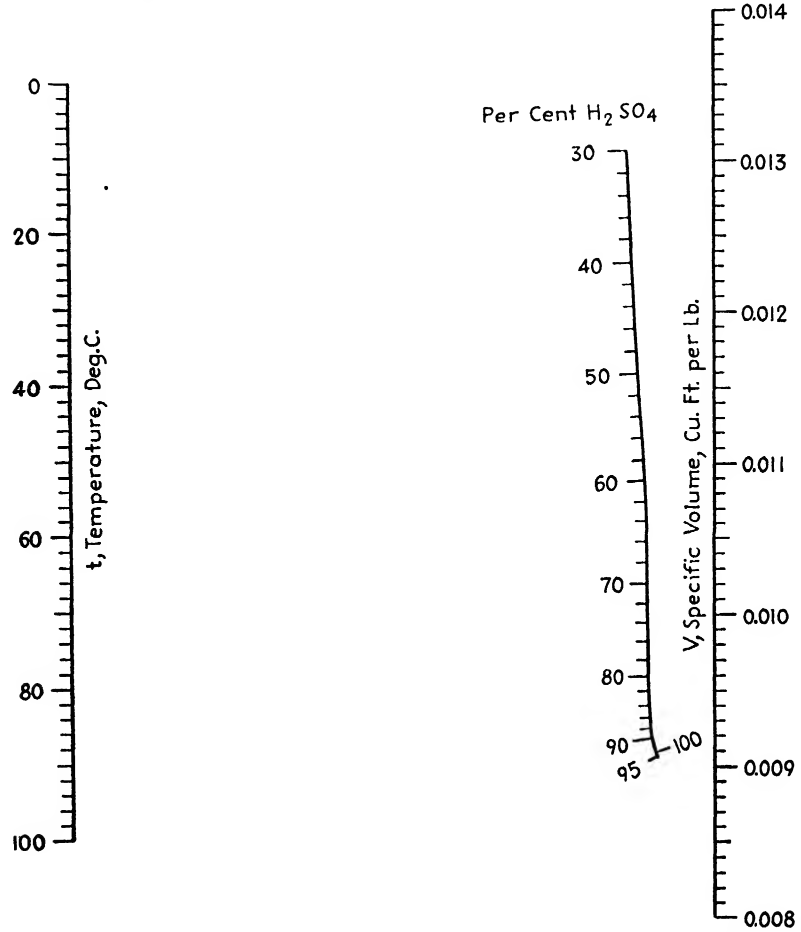

FIG. 5.—Specific volume of sulfuric acid, 30 to 100 per cent, temperature range, 0 to 100°C. (*From "International Critical Tables."*)

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[1] McKinley, C., and G. G. Brown, *Chem. & Met. Eng.*, **49**, 142 (1942).

temperature relative to the above base and the consequent change in enthalpy with change in temperature. With these charts, it is relatively simple to make heat-balance calculations for any system containing these components.

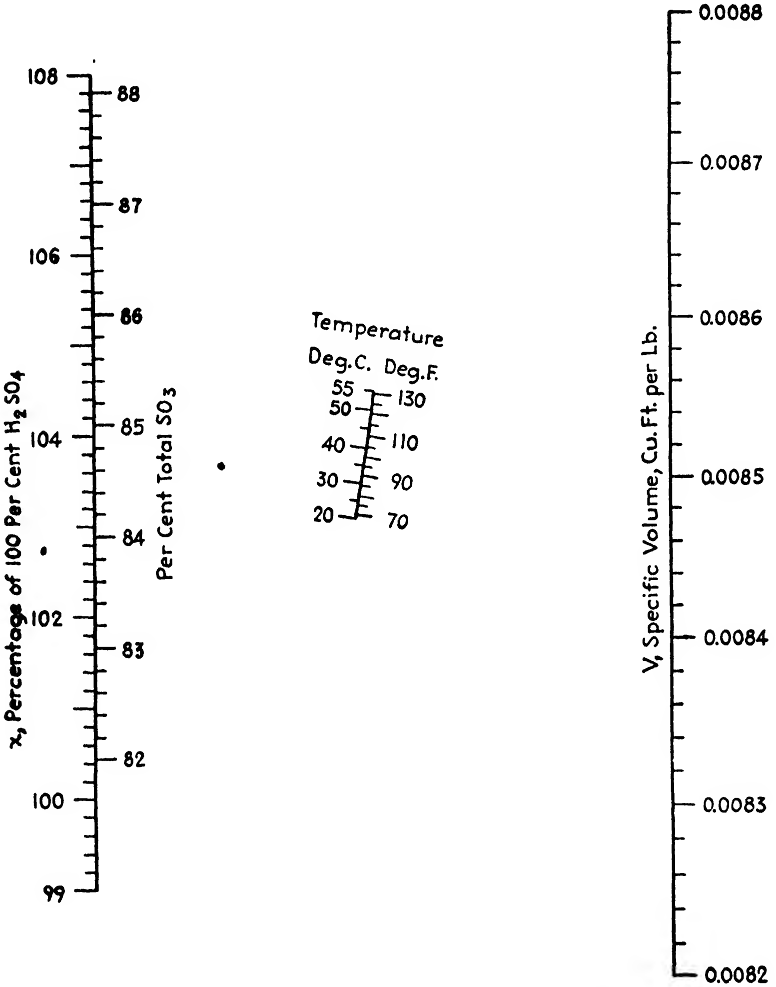

FIG. 6.—Specific volume of fuming sulfuric acid, 99 to 108 per cent, 100 per cent H_2SO_4, 20 to 55°C. (*From "Van Nostrand's Chemical Annual."*)

The nomograph (Fig. 9) solves graphically the relation

$$H = C_p \Delta t \tag{1}$$

where H = change in enthalpy of 1 lb. of mixture.
C_p = specific heat of 1 lb. of mixture.
Δt = change in temperature of 1 lb. of mixture.

Since the specific heat is a function of acid composition, C_p does not appear on the nomograph; instead, acid compositions are plotted in such a way that Eq. (1) is solved.

To find the relative enthalpy of 1 lb. of mixed acid containing 60 per cent sulfuric acid, 20 per cent nitric acid, and 20 per cent water at 100°F., for example, it is necessary to read the relative enthalpy of this mixture at 32°F. from Fig. 10 and then add the change in enthalpy for the temperature change, 32 to 100°F., as given by Fig. 9:

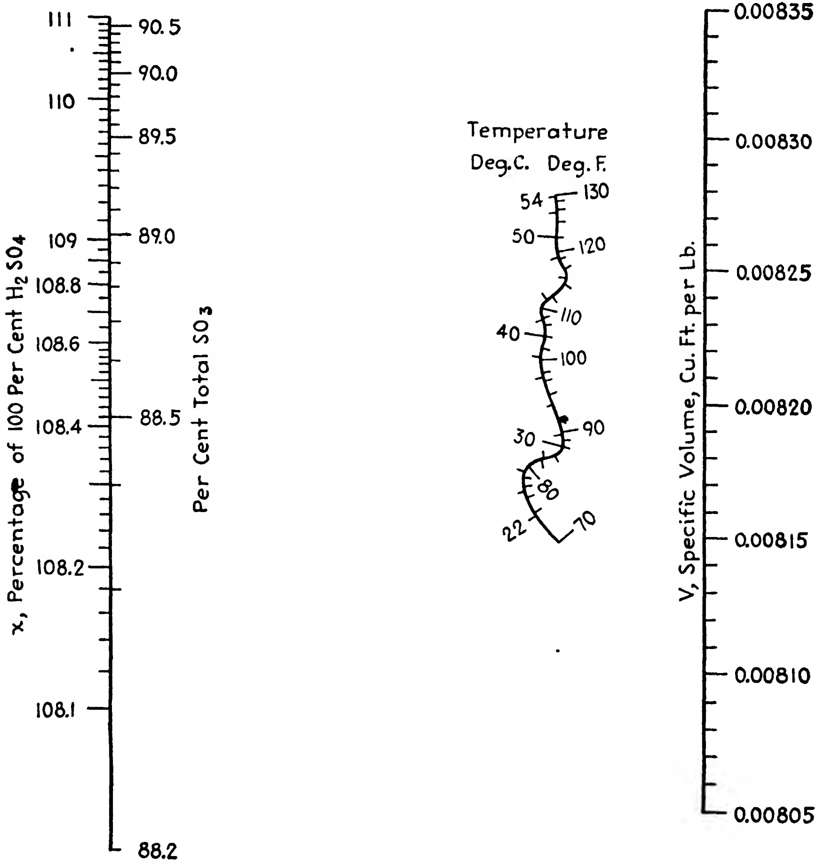

FIG. 7.—Specific volume of fuming sulfuric acid, 108.1 to 111 per cent, 100 per cent H_2SO_4; 22 to 54°C. (*From "Van Nostrand's Chemical Annual."*)

$$\% \ HNO_3 \text{ (anhydrous or water-free basis)} = \tfrac{20}{80} \times 100 = 25\%$$

$$\% \text{ total acid} = 20 + 60 = 80\%.$$

From Fig. 10 for 25 per cent nitric acid (anhydrous basis) and 80 per cent total acid, the relative enthalpy at 32°F. is read as −108 B.t.u./lb. of solution. On Fig. 9 the acid composition is located at 80 per cent total acid, and 25 per cent nitric acid in the anhydrous acid is extended horizontally to reference line *O* and thus locates a point representative of the specific heat of the mixture. Extending a line through this point and a point on temperature scale *N* corresponding to 68°F. (100° − 32°), we read the change in enthalpy on scale *M* as 32 B.t.u./lb. of solution. The relative enthalpy of the mixture, therefore, at 100°F. is −108 + 32 B.t.u., or −76 B.t.u./lb. of solution. The smallest scale possible should be used in reading the temperature difference since this leads to the greatest accuracy in the enthalpy readings.

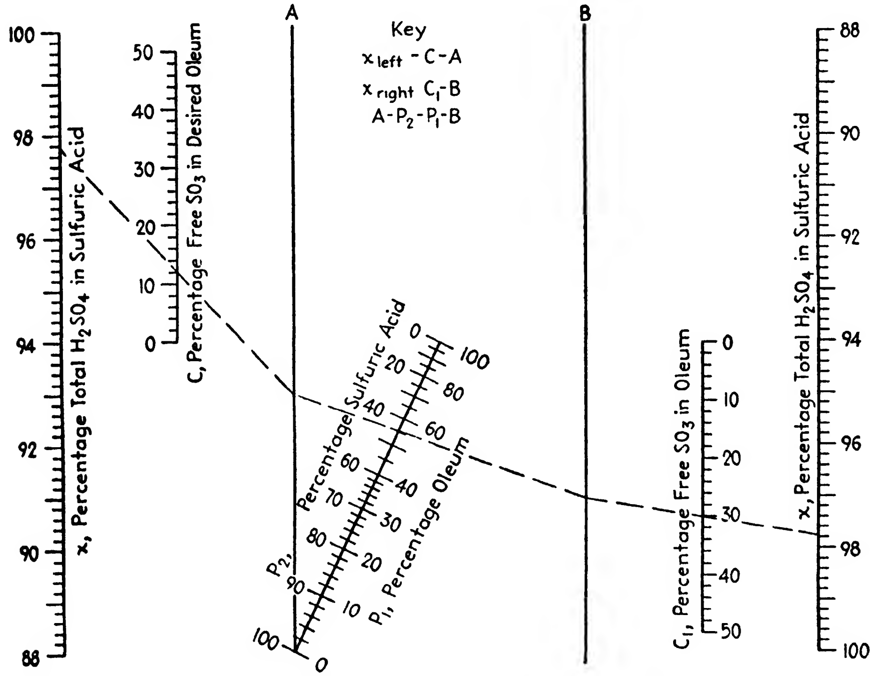

FIG. 8.—Calculation of mixtures of oleum and sulfuric acid.

Following is an example of the use of the charts in the calculation of heat balances commonly encountered in the preparation of mixed acids for nitration: A mixed acid containing 55 per cent sulfuric acid, 10 per cent nitric acid, and 35 per cent water at 90°F. is required for a nitration reaction. This is to be prepared by mixing the requisite amounts of 30 per cent nitric acid at 70°F., 85 per cent sulfuric acid at 70°F., and pure water at 60°F. Heat will be liberated in this mixing, and enough must be removed so that the temperature of the final mixture will not be above 90°F.

The quantity of heat to be removed may be calculated as follows: The total relative enthalpies are obtained by adding the values as read from Figs. 9 and 10:

TABLE I

Mixture	Relative enthalpy at 32°F. (Fig. 10)	Enthalpy change 32° to *T*°F. (Fig. 9)	Total relative enthalpy
30% HNO_3 at 70°F.	− 60	28.1	− 31.9
Water at 60°F.	0	28.0	28.0
85% H_2SO_4 at 70°F.	−100	16 5	− 83.5
Mixed acid at 90°F. .	−131	30 5	−100.5

100 lb. of mixed acid will require 33.3 lb. of 30 per cent nitric acid, 64.7 lb. of 85 per cent sulfuric acid, and 2.0 pounds of water.

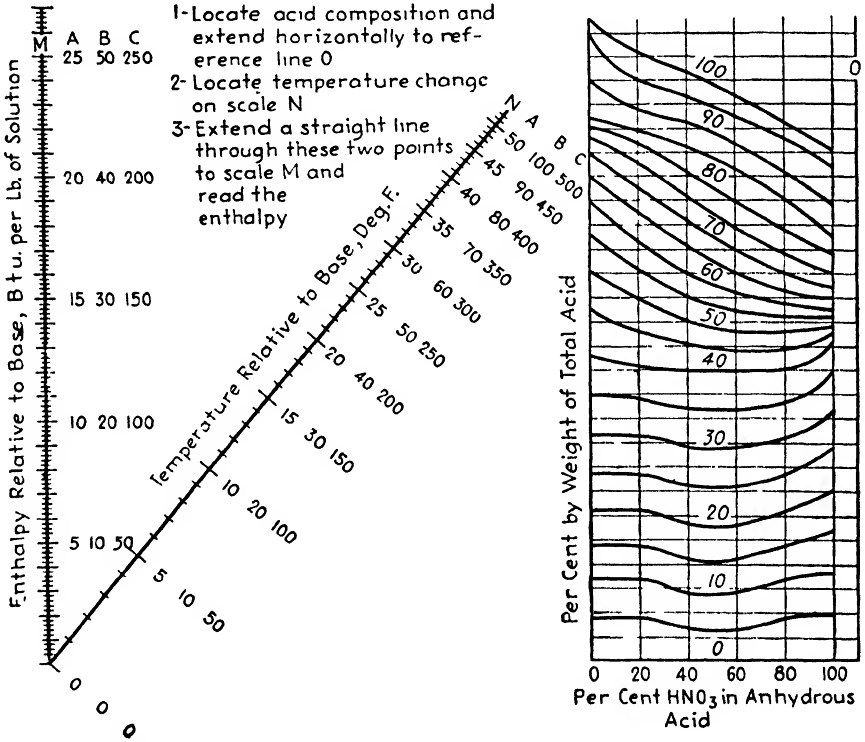
1-Locate acid composition and extend horizontally to reference line O
2- Locate temperature change on scale N
3- Extend a straight line through these two points to scale M and read the enthalpy

FIG. 9.—Enthalpy change with temperature for the system nitric acid–sulfuric acid–water.

The heat balance is as follows:

Enthalpy of entering materials:

30% HNO_3 at 70°F.	33.3 (−31.9) =	−1063 B.t.u.
85% H_2SO_4 at 70°F.	64.7 (−83.5) =	−5400
100% H_2O at 60°F.	2 (28.0) =	56
		−6407 B.t.u.

Enthalpy of mixed acid:

Mixed acid at 90°F............. 100 (−100.5) = −10,050 B.t.u.
Heat to be removed
Per 100 lb. mixed acid.......................... 3643 B.t.u.
Per lb. mixed acid.............................. 36.43 B.t.u.

SULFITE ACID NOMOGRAPH[1]

Figure 11 will be found convenient for use in connection with the determination of sulfur dioxide, total, free, and combined, in sulfite cooking acid.

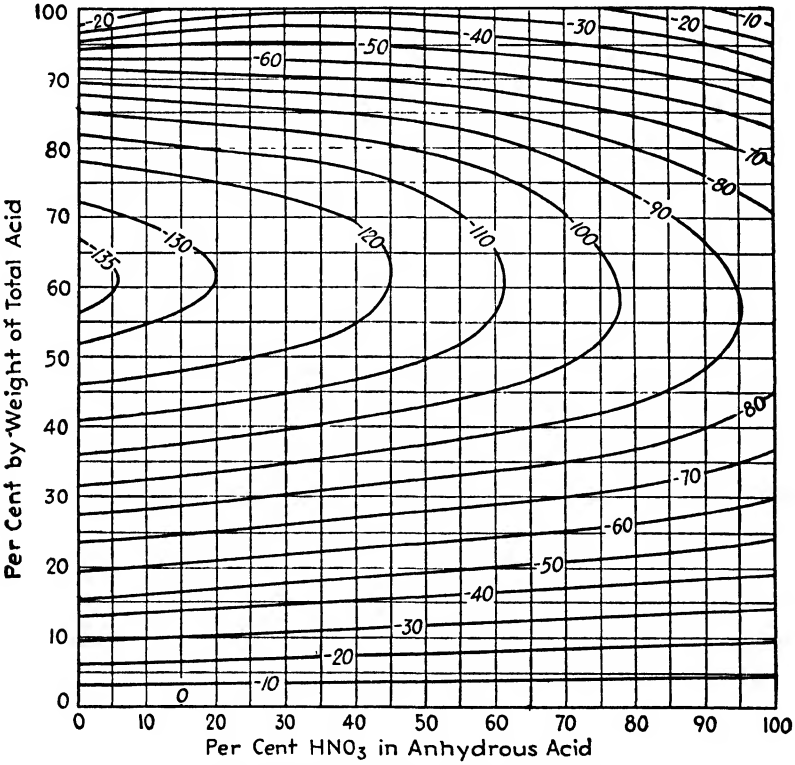

FIG. 10.—Relative enthalpy of nitric acid–sulfuric acid–water mixtures (standard state, pure components at 32°F.).

The procedure adopted in nearly every sulfite mill requires the cook or an assistant to titrate 1-ml. samples of acid with 0.1N iodine and sodium hydroxide. Under such conditions, the percentage total SO_2, T, is given by the equation

$$T = 0.32V_I$$

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[1] *Paper Ind.*, **15**, 449 (1933).

and the percentage free SO_2, F, is given by

$$F = 0.32V_A$$

where V_I and V_A are the volumes of iodine and alkali, in milliliters, respectively. The percentage of combined SO_2, C, is then found from the equation

$$C = T - F.$$

The manner in which the three equations may be quickly solved by Fig. 11 without recourse to multiplication and subtraction is illustrated as follows: In making the titrations, 15 ml. of 0.1N iodine and 10 ml. of 0.1N alkali are used. What are the percentages of total, free, and combined SO_2? Opposite 15 on the V_I scale, read 4.8 per cent total SO_2 on the T scale, and opposite 10 on the V_A scale, read 3.2 per cent free SO_2 on the F scale. The broken line connecting the two points crosses the central axis at C = 1.6 per cent combined SO_2.

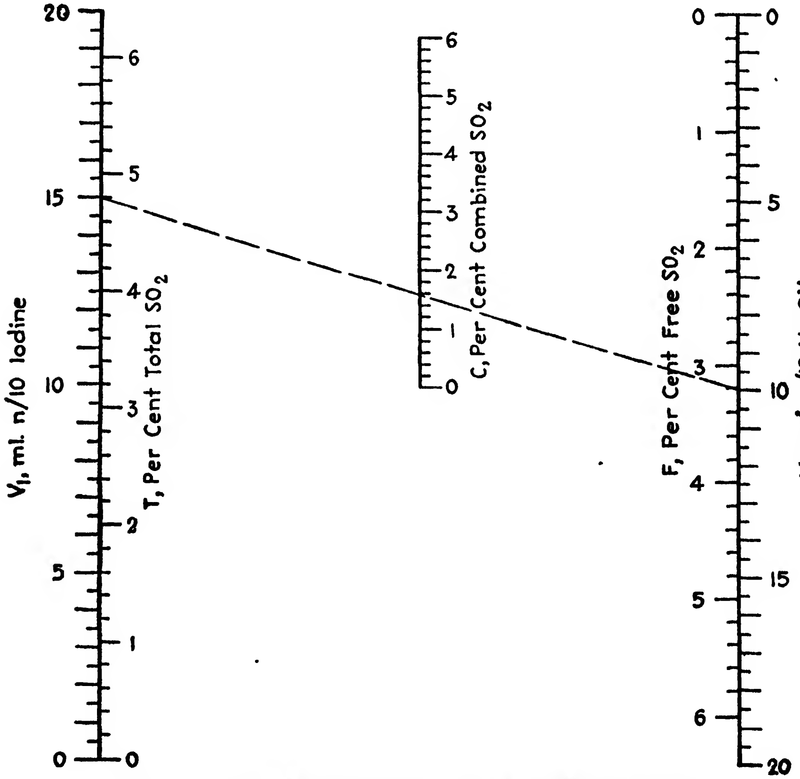

FIG. 11.—Sulfite acid; free, combined, and total SO_2 content.

NOMOGRAPH FOR DETERMINING STRENGTH OF SULFURIC ACID[1]

The Industrial Chemist, p. 508, December, 1930, carries a note on a rapid method of determining the strength of concentrated sulfuric acid,

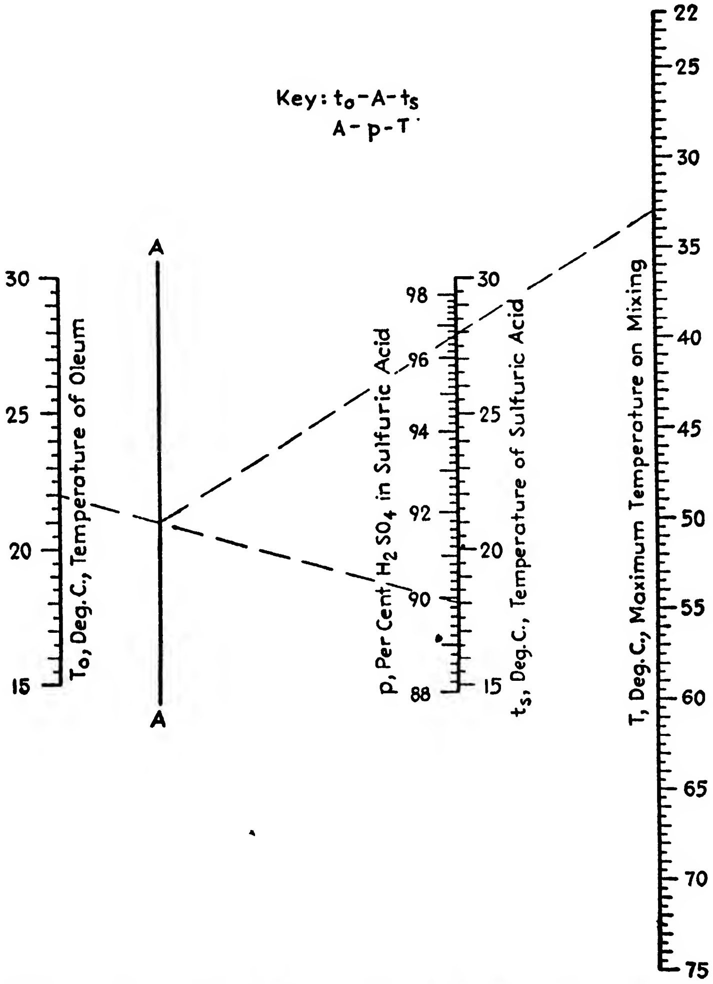

FIG. 12.—Strength of sulfuric acid from temperature rise on mixing with oleum.

utilizing the temperature rise due to heat of reaction on mixing the acid with oleum.

Twenty-five milliliters of the sulfuric acid at a temperature of t_s °C. are mixed with 75 ml. of 20 per cent oleum at a temperature of t_o °C., presumably in a Dewar flask, and the maximum temperature on mixing,

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[1] *Chemist-Analyst*, **23**, (4), 15 (1934).

T °C., is noted. That portion x °C. of the temperature rise due solely to the heat of reaction is given approximately by the expression

$$x = T - 0.75t_o - 0.25t_s. \tag{2}$$

The percentage of sulfuric acid, p, is read from a plot of p against x.

The calculations may be made more conveniently by means of Fig. 12, which incorporates both Eq. (2) and the empirical formula

$$p = 98.73 - 0.240x + 3.37e^{-0.116x}. \tag{3}$$

The use of the nomograph is illustrated as follows: What is the sulfuric acid content when the maximum temperature attained on mixing 25 ml. of the acid at 18°C. with 75 ml. of 20 per cent oleum at 22°C. is 33°C? Connect 18 on the t_s scale with 22 on the t_o scale, and note the intersection with the A axis. Connect this intersection with 33 on the T scale, and read the desired value as 96.7 per cent H_2SO_4 on the p scale.

CHAPTER II

BOILING-POINT CORRECTIONS AND ELEVATIONS

BOILING-POINT NOMOGRAPH[1]

In the literature, boiling points are frequently given at pressures other than atmospheric; hence it is desirable to have some ready means of calculating the approximate boiling point under a pressure of 1 atm. Conversely, given only the boiling point under atmospheric pressure, a rapid method of estimation of vapor pressure at some other temperature is of interest.

Both problems may be solved in an approximate manner by means of Fig. 13. The index line illustrates the case of toluene, which boils at 62°C. under a pressure of 154 mm.[2] and which, according to the chart, boils at 114°C. under atmospheric pressure, the accepted boiling point being 111°C.

The nomograph solves the equation

$$T_{760} = T_p(1.648 - 0.225 \log p) \tag{4}$$

which results from substitution of Trouton's rule

$$L = 20.3T_{760} \tag{5}$$

in the integrated Clausius-Clapeyron equation

$$2.303 \log \frac{p}{760} = \frac{L}{R}\left(\frac{1}{T_{760}} - \frac{1}{T_p}\right) \tag{6}$$

where T_{760} = centigrade-absolute boiling point at 760 mm. pressure.
T_p = centigrade-absolute temperature at p mm. pressure.
L = latent heat of vaporization, g.-cal./mole.
R = 1.985 g.-cal.

as suggested by Adams.[3]

Equation (4) and the nomographs are subject to the same limitations as Trouton's rule but are good approximations for normal organic liquids.

NOMOGRAPH FOR CORRECTION OF BOILING POINTS[4]

For convenience, boiling points are usually determined at atmospheric pressure. Since atmospheric pressure is variable, it is desirable to have a

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[1] *Chemist-Analyst*, **20**, (3), 7 (1931).

[2] BARKER, J. T., *Z. physik. Chem.*, **71**, 235 (1910).

[3] ADAMS, E. Q., *J. Am. Chem. Soc.*, **48**, 870 (1926).

[4] *Chemist-Analyst*, **29**, 57 (1940).

simple and reliable method for correcting boiling points to the standard pressure, 760 mm. mercury.

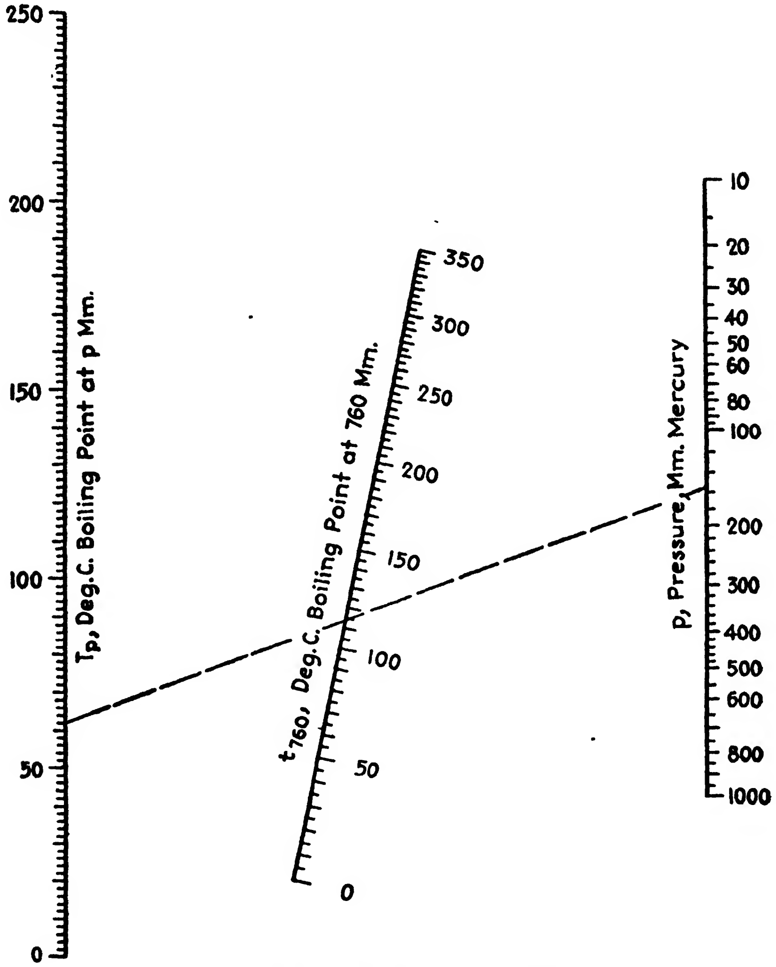

Fig. 13.—Boiling points at pressures of 10 to 1,000 mm. mercury.

In the case of normal organic liquids, recourse may be had to the suggestion made by Adams[1] of substituting Trouton's rule

$$L = 20.3T$$

in the integrated Clausius-Clapeyron equation

$$2.303 \log \frac{p}{760} = \frac{L}{R}\left(\frac{1}{T} - \frac{1}{T_p}\right).$$

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[1] Adams, E. Q., *op. cit.*

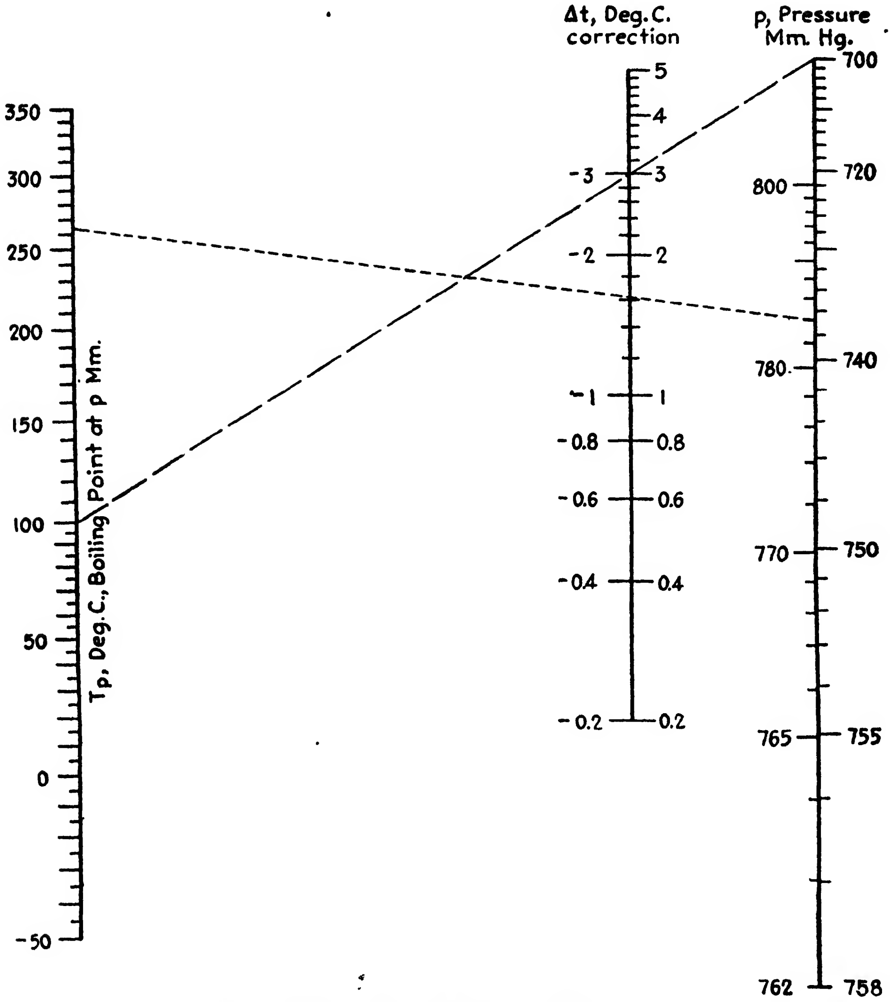

FIG. 14.—Correction of boiling points to 760 mm. mercury.

This gives

$$T = T_p(1.6487 - 0.2252 \log p)$$

where T = absolute boiling point, °C. at pressure of 760 mm. mercury.
T_p = absolute boiling point, °C. at pressure of p mm. mercury.
L = latent heat of vaporization, g.-cal./mole.
R = 1.985.

The amount Δt by which T_p must be corrected is given by

$$\Delta t = T_p(0.6487 - 0.2252 \log p).$$

This correction is readily obtained by means of Fig. 14, the use of which is illustrated as follows:

What is the boiling point of acetal under normal barometric pressure, if it boils at 100.5°C. under a pressure of 700 mm. mercury? Following the dashed line, connect 100.5° with 700 mm. on the *right* side of the pressure scale, and read the boiling point correction on the *right* of the Δ*t* scale as 3.0°C. The corrected boiling point is, then, 100.5 + 3.0, or 103.5°C.

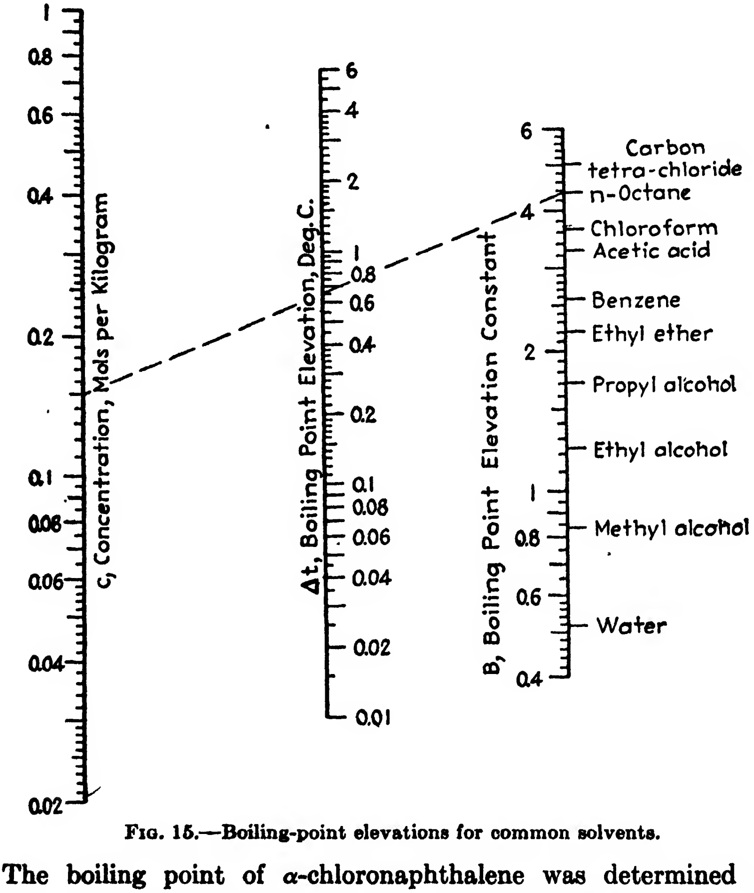

FIG. 15.—Boiling-point elevations for common solvents.

The boiling point of α-chloronaphthalene was determined to be 264.3°C. under a pressure of 784 mm. What is its boiling point under standard pressure? Following the dotted line, connect 264.3° with 784 mm. on the *left* side of the pressure scale, and read the correction as −1.6° on the *left* side of the Δ*t* scale. The corrected boiling point becomes 264.3 − 1.6, or 262.7°C.

The chart can also be used without appreciable error for determining boiling points at pressures other than the normal barometric, when the boiling point at 760 mm. is known. In this case, the boiling-point scale refers to 760 mm., and the signs of the corrections are to be reversed. What is the boiling point of ethylbutyrate under a pressure of 720 mm., when the boiling point at normal barometric pressure is 120°C.? Connect 120° with 720 mm. on the right side of the pressure scale, and read the correction on the right side of the Δt scale as 2.1°. Changing the sign, this becomes $-2.1°$ and the corrected boiling point is $120 - 2.1$, or 117.9°C.

BOILING-POINT ELEVATION NOMOGRAPH[1]

Figure 15 enables convenient calculation of Δt, the boiling-point elevation in degrees centigrade to be expected when the concentration of solute is C moles/kg. of solvent and when 1 mole of solute dissolved in 1 kg. of solvent raises the boiling point B°C. For convenience, values of the boiling-point-elevation constants[2] for 10 common solvents are marked directly on one side of the B scale.

The equation involved is $\Delta t = BC$, which holds for dilute solutions of solutes which do not dissociate in the solvent under consideration. The dashed line indicates that 0.15 mole of, say, a wax, dissolved in 1 kg. of n-octane will raise the boiling point of the solvent 0.65°C.

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[1] *Chemist-Analyst*, **22**, (1), 10 (1933).

[2] ROSANOFF, M. A., and R. A. DUNPHY, *J. Am. Chem. Soc.*, **36**, 1415 (1914).

CHAPTER III

THERMAL CONDUCTIVITIES OF GASES, VAPORS, LIQUIDS, AND WOOD

NOMOGRAPHS FOR THERMAL CONDUCTIVITIES OF GASES AND VAPORS[1]

In connection with the design of heat-transfer equipment, the chemical engineer has frequent need for a convenient and rapid means of estimating the thermal conductivities of gases and vapors at various temperature levels. Gases and vapors fall into three classes, depending upon the manner of the variation of K, the thermal conductivity in (B.t.u.)(ft.)/(hr.)(sq. ft.)(°F.), with t, the temperature, in degrees Fahrenheit. The data upon which the present work is based are from the "International Critical Tables," as reported by McAdams.[2]

Class I:

$$K = K_{32} + a(t - 32)$$

where K_{32} is the conductivity at 32°F. and a is another constant specific to the vapor. This equation holds for methane, ammonia, carbon dioxide, and nitrous oxide. The broken line in Fig. 16 indicates that the thermal conductivity of carbon dioxide at 120°F. is 0.0097 (B.t.u.)-(ft.)/(hr.)(sq. ft.)(°F.). Figure 16 is in exact agreement with the published data.

Class II:

$$K = K_{32}\left(\frac{492 + C}{t + 460 + C}\right)\left(\frac{t + 460}{492}\right)^{\frac{3}{2}}$$

where C is the Sutherland constant, specific for each gas of this class. This equation holds for nitric oxide, carbon monoxide, oxygen, air, nitrogen, and hydrogen. The use of Fig. 17 is illustrated as follows: What is the thermal conductivity of nitric oxide at −40°F.? Following the key, the value of C for nitric oxide is 351. Evaluate $(t + 460 + C)$ as $-40 + 460 + 351$, or 771, and connect this value on the $(t + 460 + C)$ scale with the NO point on the Gas (1) axis noting the intersection with the α axis. Connect this intersection with −40 on the temperature

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[1] *Ind. Eng. Chem.*, **33**, 675 (1941).

[2] McAdams, W. H., "Heat Transmission," McGraw-Hill Book Company, Inc., New York, 1933.

scale, and note the intersection with the β axis. Finally, connect this intersection with NO on the Gas (2) axis, and read the value of K as 0.0103 (B.t.u.)(ft.)/(hr.)(sq. ft.)(°F.). The nomograph agrees exactly with the data upon which it is based.

TABLE II.—CONSTANTS IN THE EQUATIONS

Vapor	Class	10^5K_{32}	10^7a	10^5b	10^4c	10^5m	n	C
Acetone	III	...	...	...	...	524	2.195	
Acetylene	III		..	...	...	1000	1.875	
Air	II	1290	.	...	..	....	.....	225
Ammonia	I	1160	220					
Benzene	III	..	..	..	....	476	2.60	
Carbon dioxide	I	790	204					
Carbon tetrachloride	III	..	.		.	310	1.570	
Chloroform	III	.	.	.	...	352	1.670	
Ethane	III	....	.	...	..	1040	2.300	
Ethyl acetate	III	...	.		.	480	2.375	
Ethyl chloride	III	...	.	.	.	504	2.140	
Ethylene	III	...	.	..	..	947	1.885	
Ethyl ether	III	....	.		...	700	2.115	
n-Hexane	III		.	.		595	1.573	
Hexylene	III	.	.	.		556	2.343	
Hydrogen	II	9170	...	.	...	....	.....	169
H_2-CO_2	.	.		938	578			
H_2-N_2			.	779	1839			
H_2-N_2O	.		.	917	742			
Methane	I	1700	399					.
Methyl acetate	III	.	.	.		543	2.367	
Methyl alcohol	III	.	.	.		763	1.741	
Methyl bromide	III			.		332	2.112	
Methylene chloride	III			.	.	355	1.900	
Methyl iodide	III			.		250	1.950	
Nitric oxide	II	1200	.	..	.	...	....	351
Nitrogen	II	1310	..	...		.	....	205
Nitrous oxide	I	796	59					
Oxygen	II	1340	..	...	.	...	.....	259
n-Pentane	III	...	.	..	....	670	1.890	
Isopentane	III	....	.	..	...	665	2.270	
Water	III	....	...	...	....	864	1.506	

Class III:

$$K = m\left(\frac{t + 600}{632}\right)^n.$$

This equation was developed for the purposes of this topic, where m and n are specific to the vapor, m being identical with K_{32} except for carbon tetrachloride, ethyl acetate, and water, where it is probably only an approximation. This expression is valid for acetone, acetylene, benzene, carbon tetrachloride, chloroform, ethane, ethyl acetate, ethyl chloride, ethylene, ethyl ether, hexane, hexylene, methyl acetate, methyl alcohol, methyl bromide, methyl chloride, methylene chloride, methyl iodide, *n*-pentane, isopentane, and water. The index line in Fig. 18 shows that the thermal conductivity of chloroform at 40°F. is 0.00360 (B.t.u.)(ft.)/(hr.)(sq. ft.)(°F.).

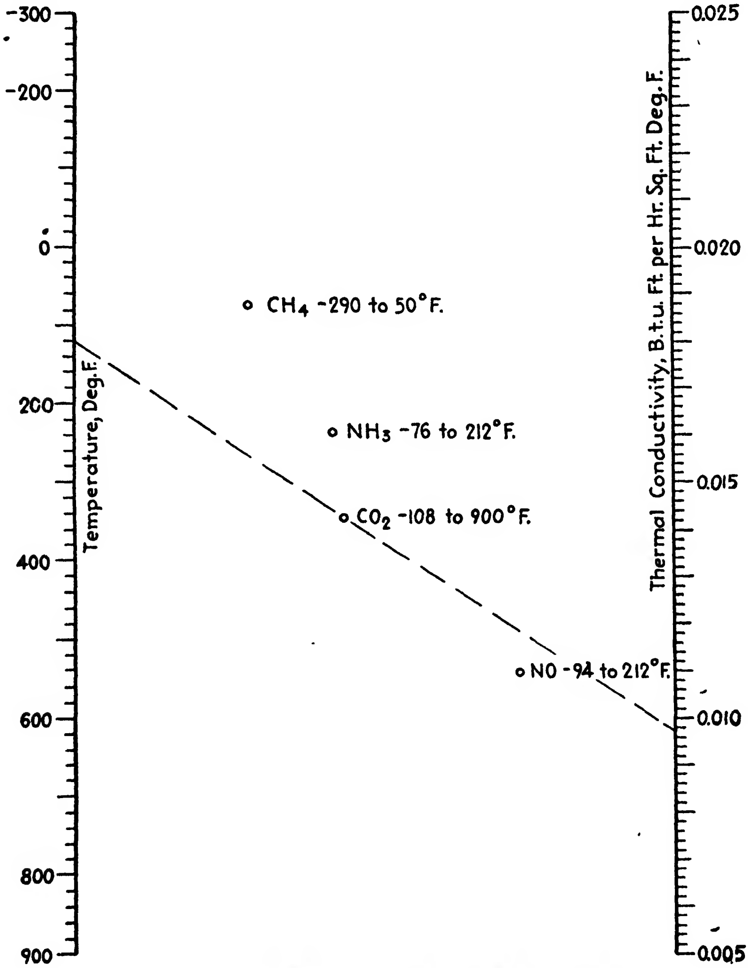
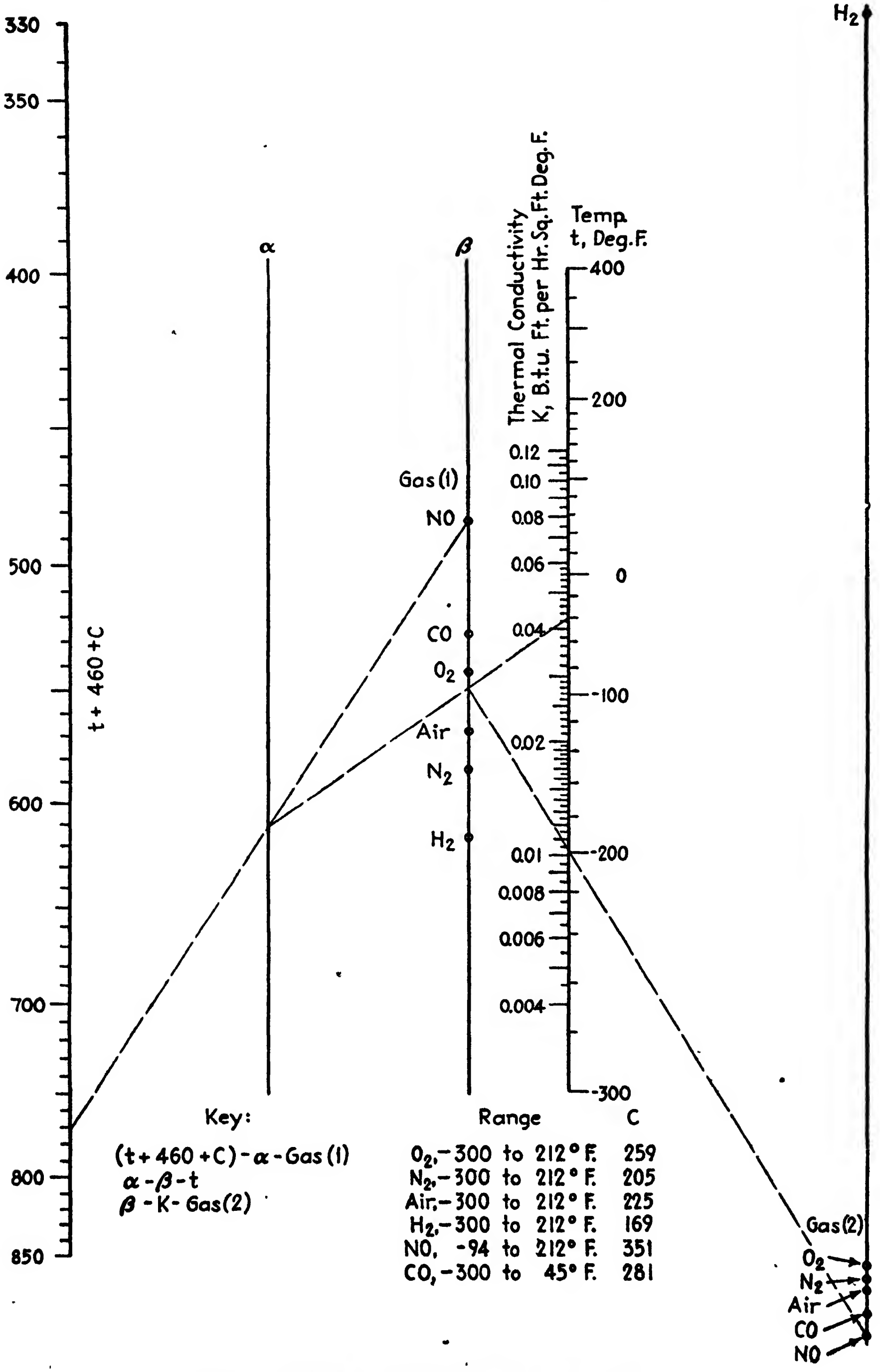


FIG. 16.—Thermal conductivities of gases of Class I.

Although only two pairs of *K*-*t* values have been reported for hexane, hexylene, methyl acetate, methyl alcohol, methyl bromide, the pentanes, and water, it seemed better to apply the Class III equation rather than



Range				C
O_2, -300	to	212° F.		259
N_2, -300	to	212° F.		205
Air, -300	to	212° F.		225
H_2, -300	to	212° F.		169
NO, -94	to	212° F.		351
CO, -300	to	45° F.		281

FIG. 17.—Thermal conductivities of gases of Class II.

a linear form. For these compounds, Fig. 18 is in exact agreement with the data; for the others the average deviation is about 1 per cent.

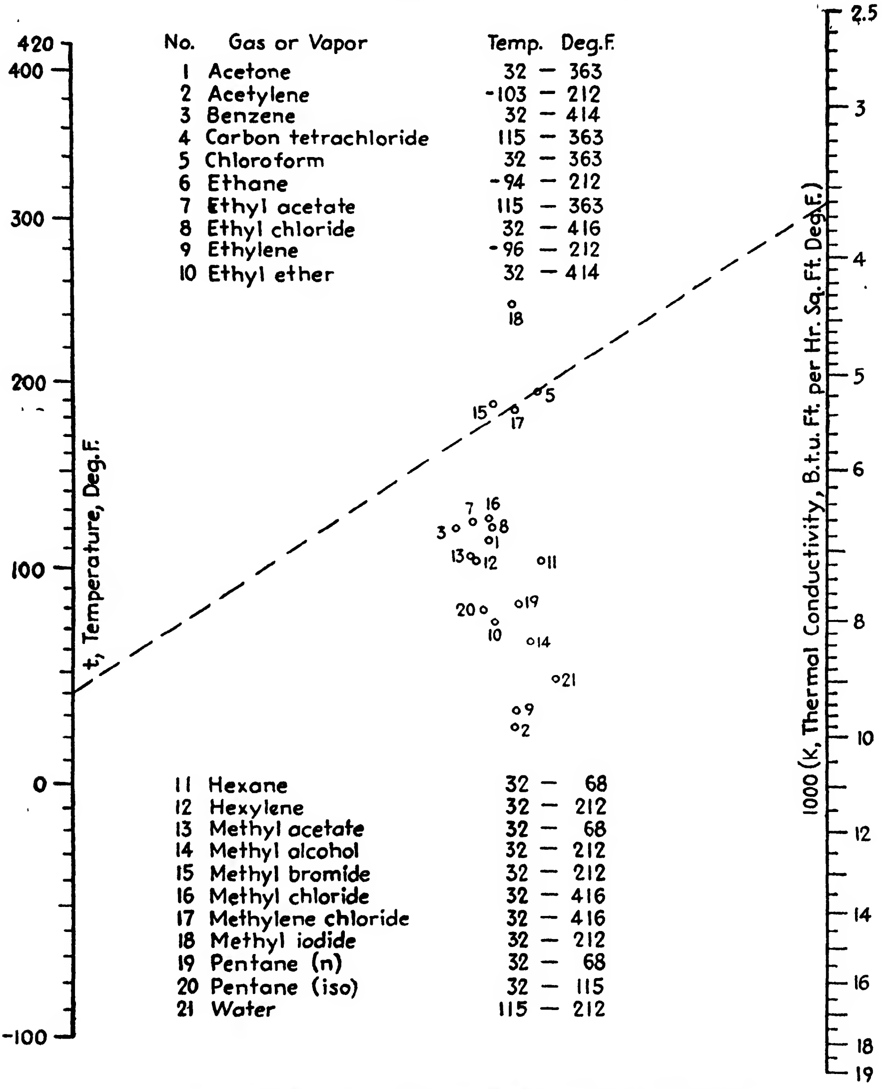


FIG. 18.—Thermal conductivities of gases and vapors of Class III.

The thermal conductivities at 32°F. of mixtures of hydrogen and carbon dioxide, hydrogen and nitrous oxide, and hydrogen and nitrogen are related to the percentage of hydrogen, x, by the expression

$$\log\left(100k + \frac{0.246}{100k}\right) = bx + c$$

where *b* and *c* depend upon the components. The equation was developed in connection with Fig. 19, where the broken line indicates that a mixture of hydrogen and nitrous oxide testing 21 per cent hydrogen has a thermal conductivity of 0.0173 (B.t.u.)(ft.)/(hr.)(sq. ft.)(°F.) at 32°F. Figure 19 yields values correct to about 2 per cent.

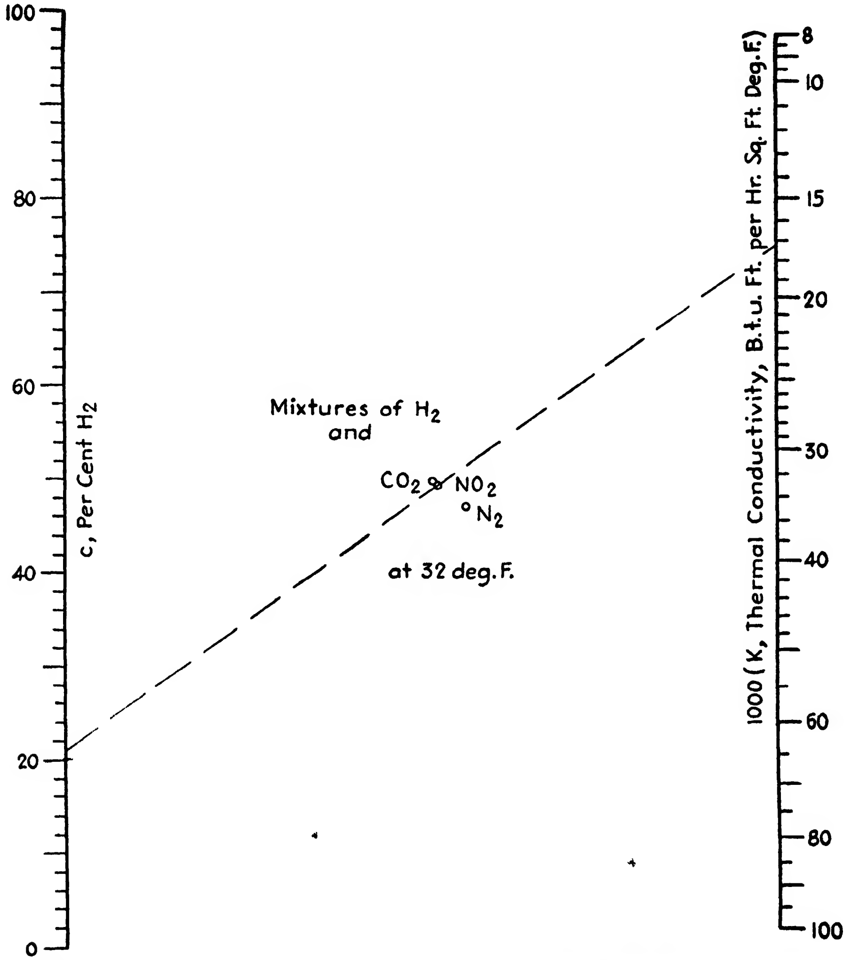


Fig. 19.—Thermal conductivities, at 32°F., of mixtures of gases with hydrogen.

Table II lists the values of the various constants in the four equations and enables construction of full-scale charts. Equations for classes I and II are given by McAdams.[1]

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[1] *Ibid.*, p. 323.

THERMAL CONDUCTIVITY OF LIQUIDS[1]

Few data on the thermal conductivity of liquids at varying temperatures have been known accurately. Data that have appeared have not been presented in the most convenient fashion. New equations have been fitted to these data, and nomographs for covering a considerable temperature range for each of the systems water-methanol, water-ethanol, and water-glycerol have been constructed.

Badger and McCabe[2] state that "the temperature coefficients of thermal conductivity are known with accuracy only for water among the liquids." Excellent data are now beginning to appear, and we are indebted to Bates[3] for a complete investigation of the thermal conductivities of aqueous glycerol solutions between temperatures of 10 and 80°C., and to Bates, Hazzard, and Palmer[4] for similar data covering aqueous methanol and ethanol solutions between 10 and 60°C.

TABLE III.—TABULATION OF a AND b VALUES IN TERMS OF c

Methanol:

$a = 0.3076 - 0.002391c + [3.008c^{1.703} - 0.02204(c - 40)^{2.542}]10^{-5}$

$b = [51{,}130 - 992.2c + 0.689(c - 40)^{2.542}]10^{-8}$

Ethanol:

$a = 0.3081 - 0.002612c + 0.636c^{2.058}10^{-5}$

$c < 62.5$

$b = (49{,}700 - 908c)10^{-8}$

$c > 62.5$

$a = 0.3116 - 0.002668c + 0.636c^{2.058}10^{-5}$

$b = (38{,}810 - 732c)10^{-8}$

Glycerol:

$a = 0.3082 - 0.001736c + 0.00760c^{2.815}10^{-5}$

$$b = \left[49{,}330 - 623.2c + \frac{3{,}495}{e^{3.85-0.14c} + e^{0.14c-3.85}} + 614(c - 67)^{1.524}\right]10^{-8}$$

The data are presented in tabular form and as plots of conductivity against temperature for constant composition and as isotherms on conductivity-concentration plots. Conductivity values are given in (g.-cal.)(cm.)/(sec.)(sq. cm.)(°C.). In view of the importance of the data, it appears worth while to effect a more convenient nomographic presentation yielding conductivities in English engineering units, *viz.*, (B.t.u.)(ft.)/(hr.)(sq. ft.)(°F.).

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[1] *Chem. & Met. Eng.*, **46,** 356 (1939).

[2] BADGER, W. L., and W. L. MCCABE, "Elements of Chemical Engineering," McGraw-Hill Book Company, Inc., New York, 1936.

[3] BATES, O. K., *Ind. Eng. Chem.*, **25,** 431 (1933).

[4] BATES, O. K., G. HAZZARD, and G. PALMER, *Ind. Eng. Chem.*, *Anal. Ed.*, **10,** 314 (1938).

Hyperbolic Sine Equation.—Bates, Hazzard, and Palmer quote the Barratt-Nettleton equation[1] for calculating the thermal conductivity of binary liquid mixtures when the conductivities of the two liquids are known:

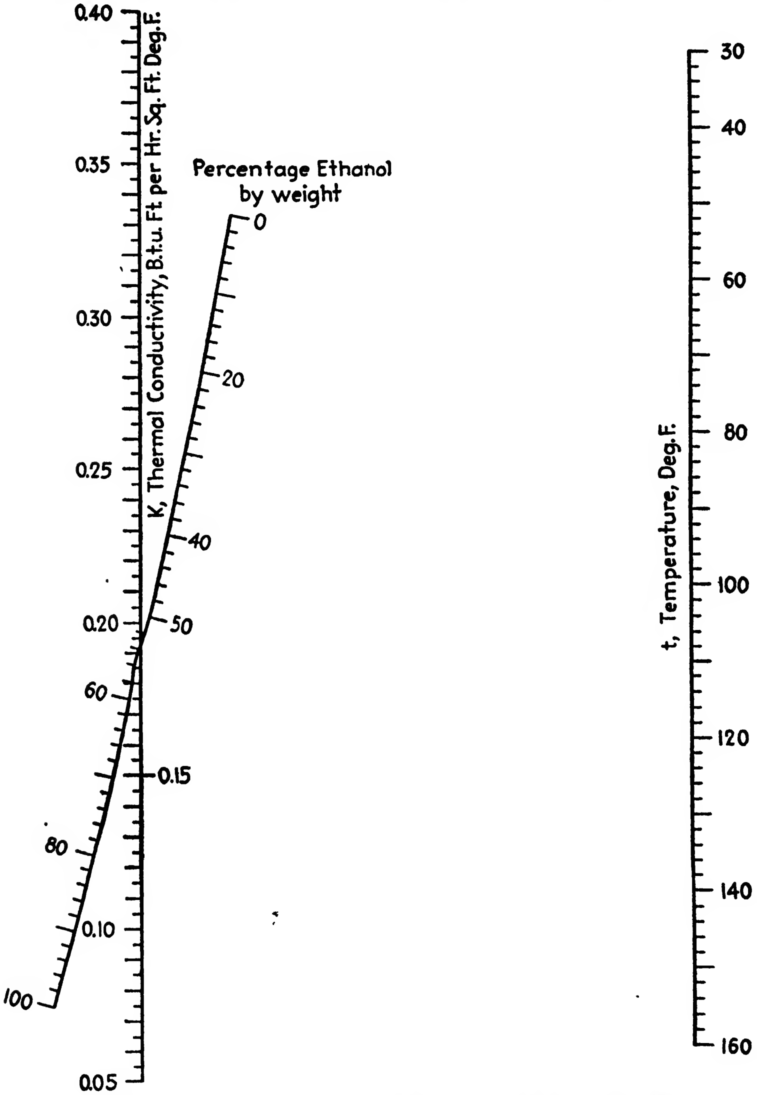

Fig. 20.—Thermal conductivities of ethanol-water mixtures.

$$K \sinh (100\mu) = K_1 \sinh (p_1\mu) + K_2 \sinh (p_2\mu)$$

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[1] "International Critical Tables," Vol. V, p. 227, McGraw-Hill Book Company, Inc., New York, 1929.

where p_1 and p_2 are the percentages by weight of the two constituents and μ is a constant specific to the constituents and independent of temperature in the ranges encountered in the investigation.

Although this is an extremely simple equation, considering the nature of the data, it requires a knowledge of the conductivities of the pure components at the temperature in question and is thus not well adapted to nomographic presentation. For this reason and in the interests of greater precision, new equations correlating the data have been developed. The thermal conductivity K in (B.t.u.)(ft.)/(hr.)(sq. ft.)(°F.) is related to the Fahrenheit temperature t by the expression

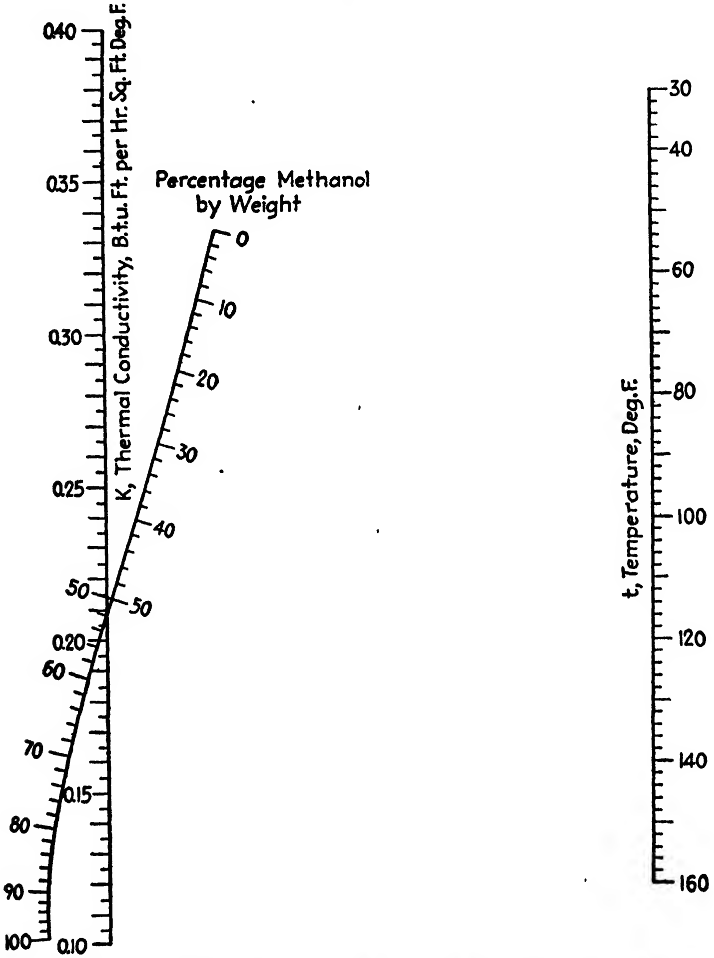

FIG. 21.—Thermal conductivities of methanol-water mixtures.

$$K = a + bt$$

where, for the various binary mixtures, *a* and *b* are defined in terms of *c*, the percentage by weight of the solute, as given in Table III.

Figures 20 to 22, constructed from these equations, afford a rapid and accurate means of calculating the thermal conductivity in terms of the concentration of the solute and the temperature since a straight line will cut the three scales in values physically consistent. It will be noted that for certain concentrations thermal conductivities are independent of temperature, *i.e.*, 52 per cent methanol, 53 per cent ethanol, and 93 per cent glycerol.

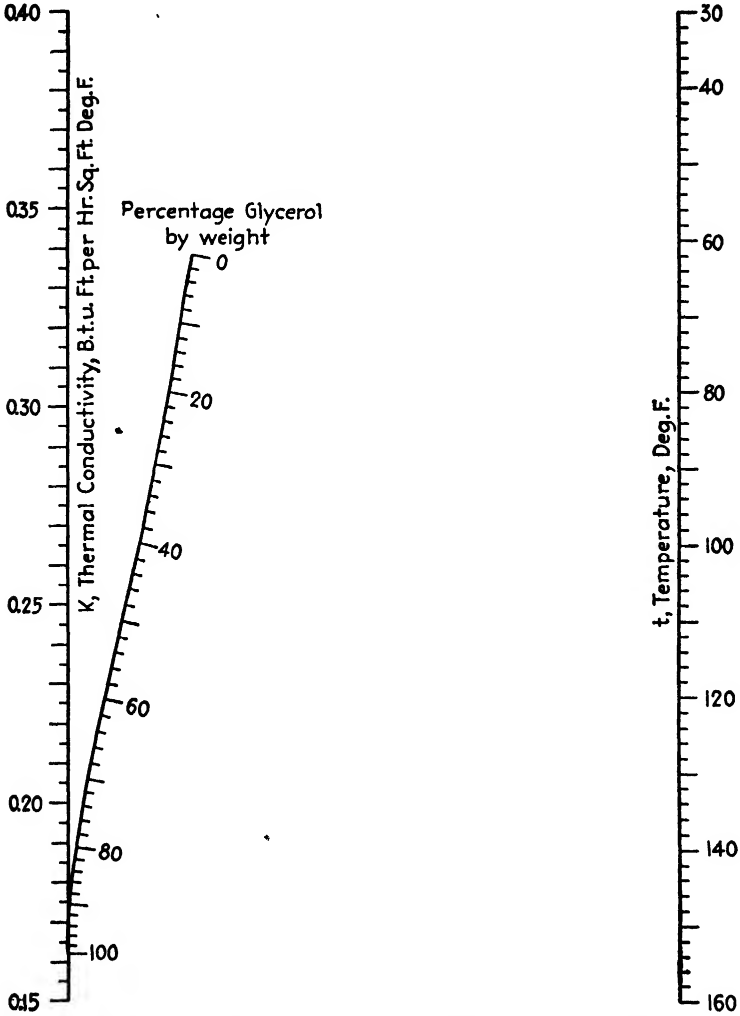

FIG. 22.—Thermal conductivities of glycerol-water mixtures.

TABLE IV.—COMPARATIVE ACCURACY OF HYPERBOLIC SINE EQUATION AND NEW EXPRESSIONS

System	Temperature, °F.	Percentage solute by weight	Percentage deviation of calculated from observed values	
			$B - N$ Eq.*	Present equations
Water-methanol	50	20	0.2	−0.8
		40	0.7	−0.8
		60	0.4	−0.8
		80	0.3	0.3
	86	20	0.3	−0.5
		40	−1.0	−1.5
		60	−1.8	−0.9
		80	−2.6	−0.3
	122	20	0.6	−0.2
		40	−1.7	−1.2
		60	−4.4	−1.0
		80	−4.3	0.8
Water-ethanol	50	20	0.2	−0.5
		40	0.1	−0.2
		60	−1.5	−0.8
		80	−1.7	−0.3
	86	20	1.4	0.8
		40	−1.2	−1.3
		60	−2.6	−1.3
		80	−2.5	−0.5
	140	20	1.3	0.6
		40	−1.3	−1.3
		60	−3.4	−1.3
		80	−2.5	0.2
Water-glycerol	50	20	0.6	0.1
		40	0.2	0.1
		60	−1.3	−0.1
		80	−2.5	−0.4
	104	20	0.1	−0.3
		40	−1.1	−0.4
		60	−3.6	−0.9
		80	−3.7	0.1
	176	20	0.9	0.2
		40	−1.0	0.1
		60	−4.6	−0.3
		80	−5.4	0.5
Average	...	..	1.75	0.60

* For methanol, ethanol, and glycerol values of 100μ are 0.90, 0.94, and 0.65, respectively.

Accuracy of Equations.—Table IV compares the accuracy of the Barratt-Nettleton equation with the present expressions by listing the percentage deviations of the calculated values from the observed values over representative concentration and temperature ranges. The new equations deviate by an average of 0.6 per cent from the observed values as against an average deviation of 1.75 per cent for the hyperbolic sine equation.

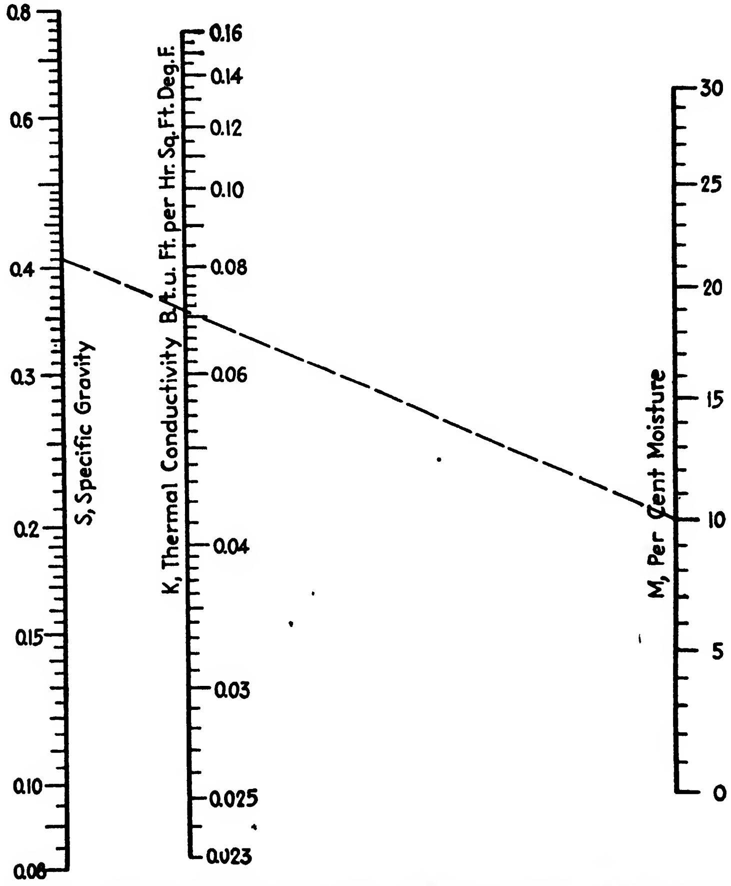

FIG. 23.—Thermal conductivity of wood, based on current moisture content.

THERMAL-CONDUCTIVITY NOMOGRAPHS FOR WOOD[1]

From exhaustive experimental data, MacLean[2] developed two expressions for calculating the thermal conductivity of wood:

$$K = 0.0833S(1.39 + 0.028M) + 0.0138 \qquad (7)$$

---

[1] *Ind. Eng. Chem.*, **35**, 673 (1943).

[2] MacLean, J. D., *Heating, Piping, Air Conditioning*, **13**, 380 (1941).

$$K = \frac{0.0833S_g(1.39 + 0.028M)}{1 - S_g(0.27 - 0.009M)} + 0.0138 \qquad (8)$$

where K = thermal conductivity, (B.t.u.)(ft)./(hr.)(sq. ft.)(°F.).
S = specific gravity at current moisture content and weight when ovendry.
S_g = specific gravity based on volume when green and weight when ovendry.
M = moisture, per cent.

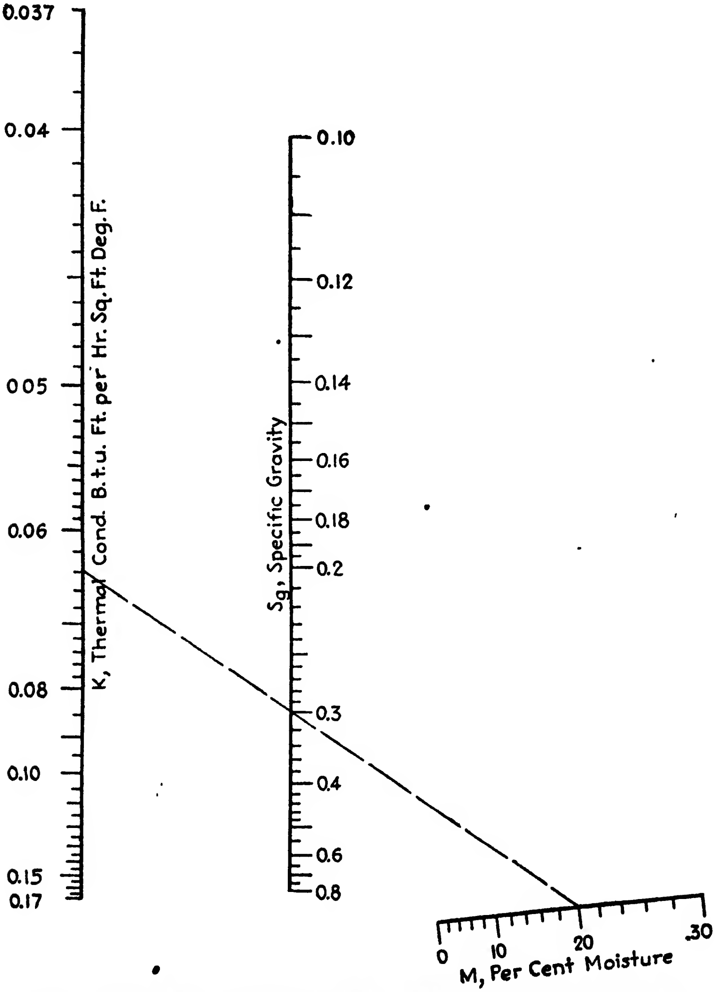

Fig. 24.—Thermal conductivity of wood, based on volume when green.

The use of Fig. 23, which presents a nomographic solution of Eq. (7), is illustrated as follows: What is the thermal conductivity of wood when the specific gravity, based on the current moisture content and the weight when ovendry, is 0.41 and the moisture content is 10 per cent? Connect 0.41 on the S scale with 10 on the M scale, and read the thermal conductivity as 0.071 (B.t.u.)(ft.)/(hr.)(sq. ft.)(°F.) on the K scale.

The use of Fig. 24, which presents a nomographic solution of Eq. (8), is illustrated as follows: What is the thermal conductivity of wood when the specific gravity, based on the volume when green and the weight when ovendry, is 0.30 and the moisture content is 20 per cent? Connect 20 on the M scale with 0.30 on the S_g scale, and read the thermal conductivity as 0.064 (B.t.u.)(ft.)/(hr.)(sq. ft.)(°F.) on the K scale.

CHAPTER IV

DISTILLATION, EVAPORATION, AND EXTRACTION

NOMOGRAPHS FOR THE ABSORPTION-FACTOR EQUATION[1]

In certain methods for the design of multicomponent absorbers and column stills,[2] the following type of equation appears:

$$E = \frac{A^{N+1} - A}{A^{N+1} - 1}$$

where E = "efficiency" of the operation.

$A = L/K_A V$, absorption factor.

N = number of theoretical plates required.

The nomographs for this equation (Figs. 25 and 26) were developed by the use of determinants and transformations as described by Allcock and Jones.[3]

The use of the charts is made clear by the three operations: (1) Make the simple calculation of $A - E$. (2) Extend a line from $A - E$ through A. (3) Find N on the network at the intersection of this line with the proper value of E.

For a given case, the choice of chart may depend on a trial, but in general the higher range chart (Fig. 26) will be found to serve for the higher values of E.

Because of a mathematical quirk, these charts give an infinity of solutions when $A = 1$. However, in this special case the equation simplifies to

$$N = \frac{E}{1 - E} \qquad \text{or} \qquad E = \frac{N}{N + 1}.$$

When either A or E is the unknown, the straightedge should be pivoted around the known point on the chart until it intersects the remaining scales in complementary values.

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[1] CHASE, SHERWIN, *Ind. Eng. Chem.*, **34**, 1499 (1942).

[2] BROWN, G. G., *et al.*, *Trans. Am. Inst. Chem. Eng.*, **30**, 438–545 (1933–1934); SOUDERS, M., and G. G. BROWN, *Ind. Eng. Chem.*, **24**, 519–522 (1932).

[3] ALLCOCK, H. J., and J. R. JONES, "The Nomogram," Sir Isaac Pitman & Sons, Ltd., 1941.

NOMOGRAPHS FOR MINIMUM REFLUX RATIO AND THEORETICAL PLATES FOR SEPARATION OF BINARY MIXTURES[1]

Often distillation problems can be simplified so that the separation to specified purities of only two components, having constant relative volatility and obeying Raoult's law, is necessary. Usually the first step in such problems is the fixing of boundary conditions, *viz.*, (1) the estimation of the minimum number of plates at infinite reflux, and (2) the estimation of the minimum reflux ratio at infinite plates. These can be computed by the following algebraic expressions:

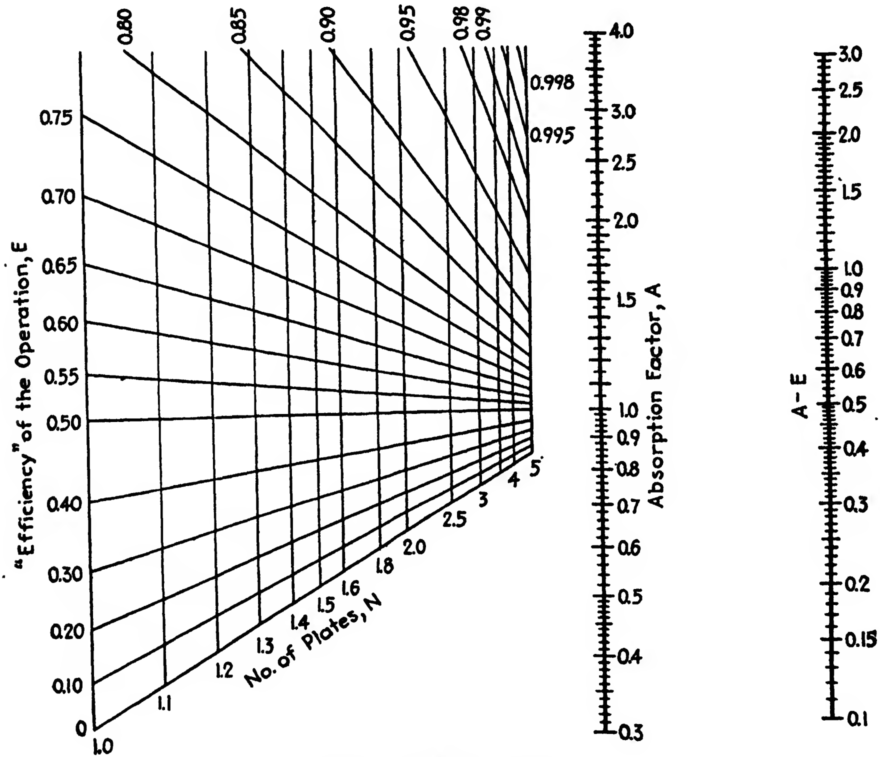

FIG. 25.—Absorption factor.

$$N_{\text{MIN}} = \frac{\log \dfrac{x_O(1 - x_F)}{x_F(1 - x_O)}}{\log \alpha} \tag{9}$$

$$\frac{R_{\text{MIN}}}{1 + R_{\text{MIN}}} = \frac{x_O - \dfrac{\alpha x_F}{1 + (\alpha - 1)x_F}}{x_O - x_F} \tag{10}$$

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[1] SMOKER, E. H., *Ind. Eng. Chem.*, **34**, 509 (1942).

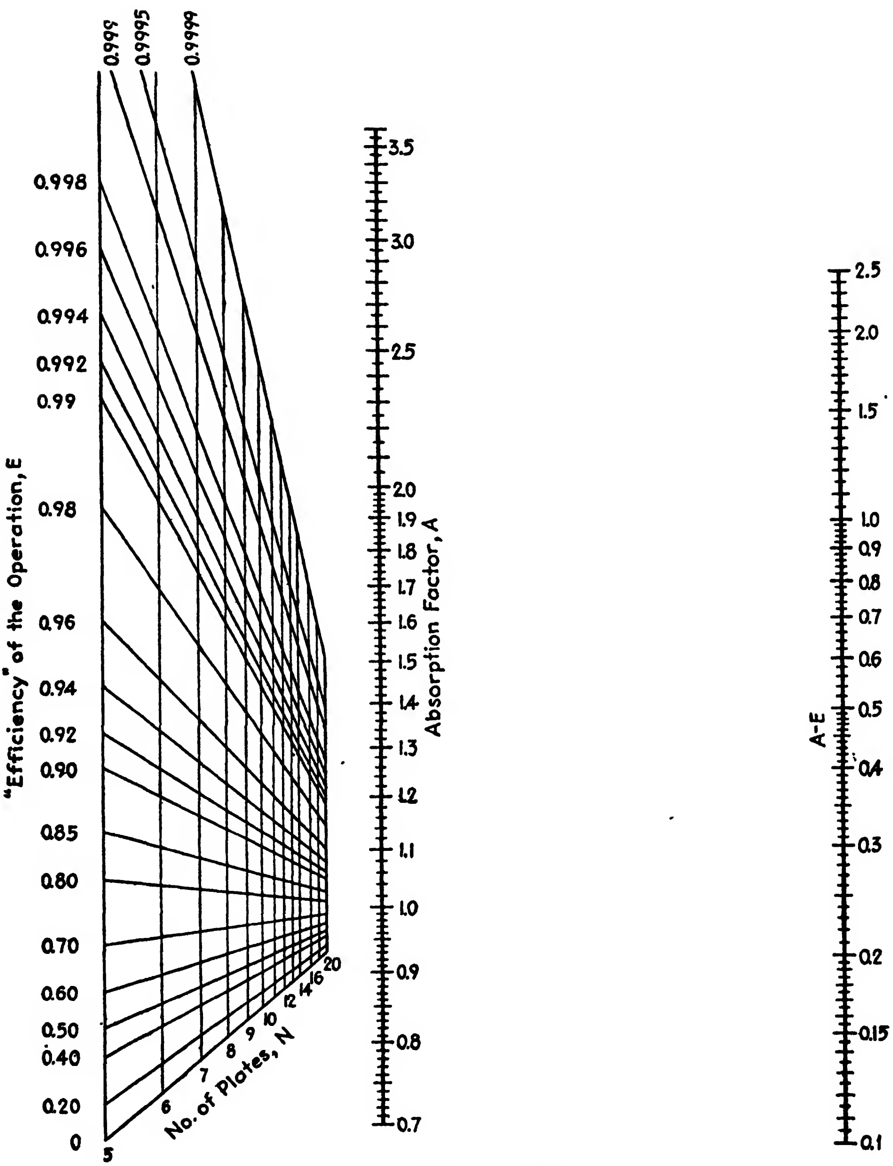

FIG. 26.—Absorption factor.

where N_{MIN} = minimum theoretical plates required at infinite reflux ratio.

R_{MIN} = minimum reflux ratio required at infinite theoretical plates.

x_F = mole fraction of lower boiling component in feed.

x_O = mole fraction of lower boiling component in overhead product.

α = relative volatility of the two components.

The terms x_F and x_O, which normally refer to the feed and overhead compositions, can in Eq. (9) represent any two liquid compositions in the column as long as x_O is greater than x_F.

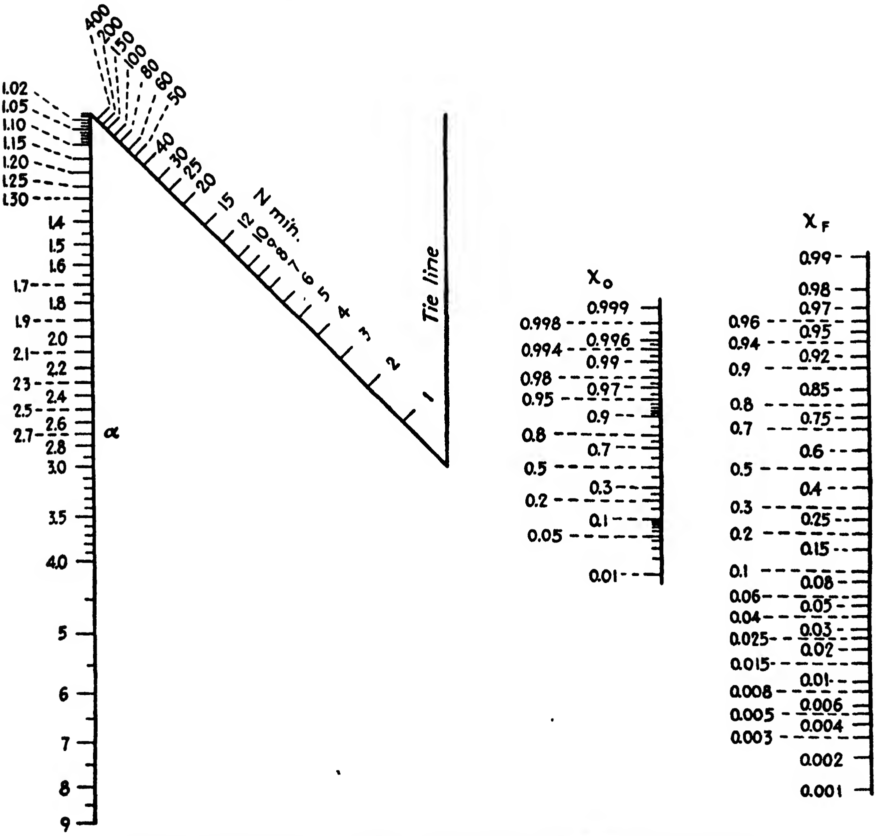

FIG. 27.—Minimum number of theoretical plates at infinite reflux.

Since these two equations are used frequently, nomographs have been constructed for them by well-known mathematical methods.[1] Figure 27 is a common type of nomograph having the four variables expressed along each of four individual straight lines. There are two pairs on either side of the tie line, x_O and x_F on the right, and N_{MIN} and α on the left. From the point where a straight line through the values of the two known

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[1] ALLCOCK, H. J., and J. R. JONES, "The Nomogram—The Theory and Practical Construction of Computation Charts," Pitman Publishing Corporation, New York, 1932.

variables of either pair cuts the tie line, another straight line is drawn through the known value of the third variable to obtain the required value of the fourth.

Figure 28 is a grid-type nomograph in which the values of two of the variables x_F and α are expressed along two intersecting families of curves. A single point within the intersection area represents fixed values for these two. Therefore three points, one within the grid area and the other two on the x_o and R_{MIN} lines, fix the values for all four of the variables. Since the positions of two of the points are always known, the third point, and therefore the fourth variable, can be determined by drawing a straight line through the two known points.

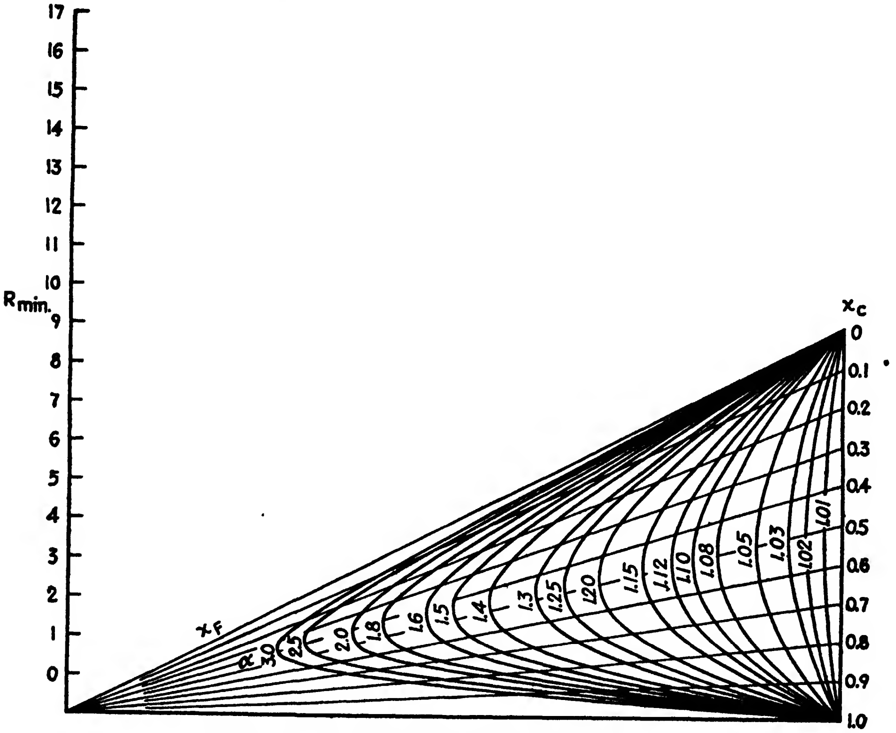

FIG. 28.—Minimum reflux ratio at infinite plates.

EVAPORATION NOMOGRAPH[1]

When dealing with evaporators, it is frequently necessary to calculate the amount of water evaporated per 100 lb. of thin liquor.

Let s = solids in thin liquor, per cent.

S = solids in thick liquor, per cent.

W = lb. water evaporated per 100 lb. thin liquor.

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[1] *Ind. Eng. Chem.*, **33**, 319 (1941).

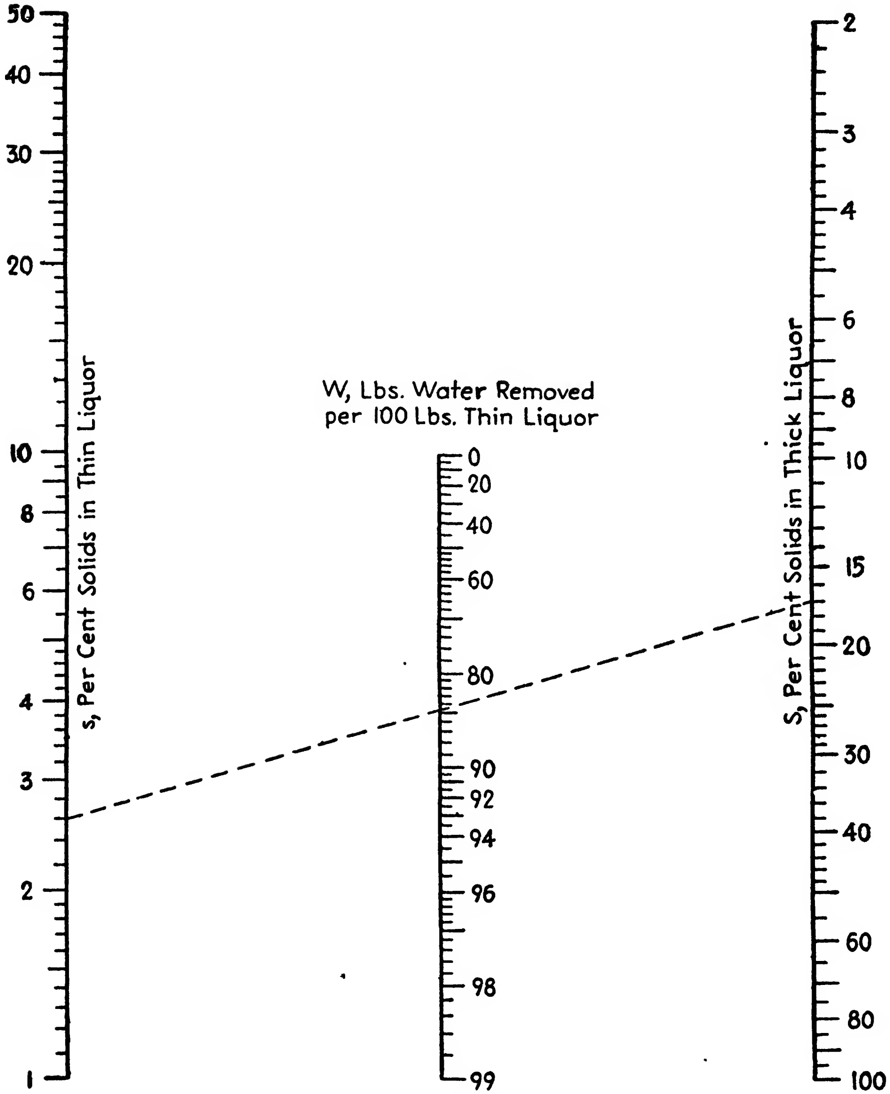

FIG. 29.—Evaporation.

Then $100 - s$ = percentage of water in the thin liquor and

$100 - S$ = percentage of water in the thick liquor.

The number of pounds of water evaporated per pound of solids is

$$\frac{100 - s}{s} - \frac{100 - S}{S},$$

and the number of pounds of water evaporated per 100 lb. of thin liquor is

$$\left(\frac{100-s}{s}-\frac{100-S}{S}\right)s = 100\left(\frac{S-s}{S}\right) = 100\left(1-\frac{s}{S}\right).$$

The expression

$$W = 100\left(1-\frac{s}{S}\right)$$

is solved conveniently by Fig. 29, in which the broken line indicates that 84.7 lb. of water are evaporated from 100 lb. of thin liquor in changing the concentration from 2.60 to 17.0 per cent solids. The chart can be used for values of s and S below the range of the scales by moving the decimal point in these values one place to the left without changing the W scale in any way. Thus the broken line also shows that 84.7 lb. of water are removed from 100 lb. of thin liquor in increasing the concentration from 0.260 to 1.70 per cent solids. What is W for $s = 60$ and $S = 80$? Sixty is beyond the range of the s scale, but W can be found to be 25 by connecting 6 on the s scale with 8 on the S scale.

EXTRACTION NOMOGRAPH FOR SOLUTE-FREE SOLVENTS[1]

In their discussion of the theory of continuous countercurrent extraction under equilibrium conditions, Badger and McCabe[2] quoted Baker's equation[3] for the case of solute-free solvents

$$F = \frac{1}{1 + a_m(1 + a + a^2 + \cdots a^{m-1})} \tag{11}$$

where $F = s_D/s_f$, the ratio of unextracted solute to solute entering with fresh solids.

m = number of cells or units in battery.

$a = S_n/s_n$, which is predicated upon constant retention of liquid by solids within system and is constant for all cells except the last.

n = number of any cell except the last.

a_m = value of a for cell m.

s_D = weight of solute in solution adhering to solids discharged from system, lb./lb. inert solid.

s_f = weight of solute in solution on fresh solids fed to system, lb./lb. inert solid.

S_n = weight of solute in solution overflowing from nth cell, lb./lb. inert solid.

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[1] *Ind. Eng. Chem.*, **34**, 1014 (1942).

[2] BADGER, W. L., and W. L. MCCABE, "Elements of Chemical Engineering," p. 426, McGraw-Hill Book Company, Inc., New York, 1936.

[3] BAKER, E. M., *Chem. & Met. Eng.*, **42**, 669–671 (1935).

s_n = weight of solute in solution in underflow from nth cell, lb./lb. inert solid.

In a form explicit in m, this equation becomes

$$m = \frac{\log \left[\dfrac{1 - (1 - F)(1 - a)}{F a_m} \right]}{\log a}. \tag{12}$$

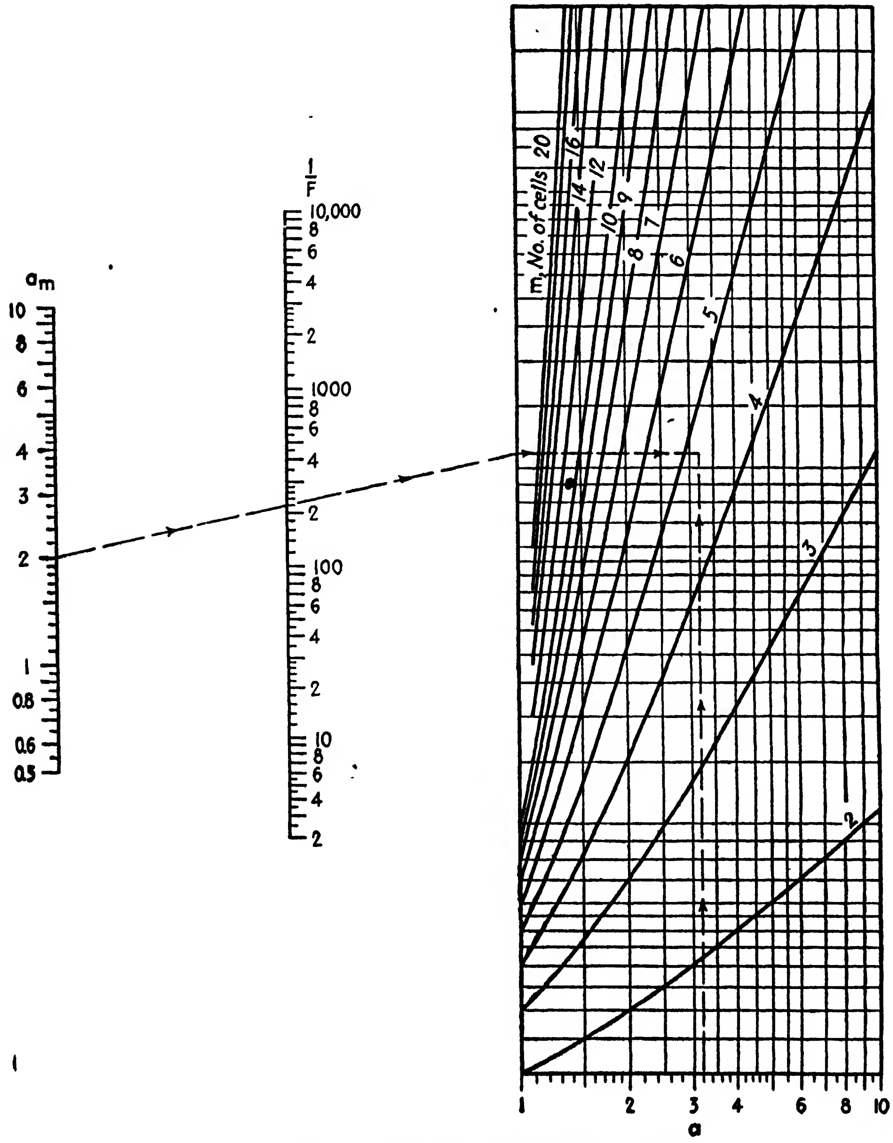

FIG. 30.—Extraction, for solute-free solvents.

The determination of the number of cells, m, required to satisfy given conditions is facilitated by the nomograph which, for convenience, deals with $1/F$ rather than F, although based upon Eq. (11) or (12).

The use of Fig. 30 is illustrated as follows: How many units are needed when $1/F$, the ratio of solute entering with the fresh solids to the unextracted solute, is 220 and a_m and a have the values of 2 and 3.2, respectively? Following the arrows, connect 2 on the a_m scale with 220 on the $1/F$ scale, and project the isopleth to meet the vertical line for $a = 1$. Then proceed horizontally until an intersection with the vertical line for $a = 3.2$ is attained. The intersection is just below the curve for $m = 5$, showing that four cells are insufficient and that five cells provide a little more capacity than is required.

CHAPTER V

FLOW OF FLUIDS AND RELATED NOMOGRAPHS

AIR-LIFT NOMOGRAPH[1]

In connection with air-lift operation, it is frequently necessary to calculate the volume of free air, *i.e.*, air at atmospheric temperature and pressure, required to raise 1 gal. of water through a certain distance when the depth of water above the air inlet is known.

This calculation may be readily made by means of Fig. 31, which solves the equations

$$S = \frac{100H}{h + H}$$

and

$$V = \frac{h}{C \log \dfrac{H + 34}{34}}$$

where h is the total lift in feet or distance from the surface of the water to the discharge outlet; H is the running submergence in feet or depth of water above the air inlet (see Fig. 31); S is the percentage submergence;

TABLE V.—VALUES OF AIR-LIFT CONSTANT

S, percentage submergence	Values of C*	
	Air line outside discharge pipe	Air line inside discharge pipe
35	216	162
37	. . .	171
40	246	185
45	272	204
50	296	228
55	318	262
60	335	285
65	348	306
70	358	322
75	366	330

* Ingersoll-Rand Air Lift Catalog, No. 77, p. 15.

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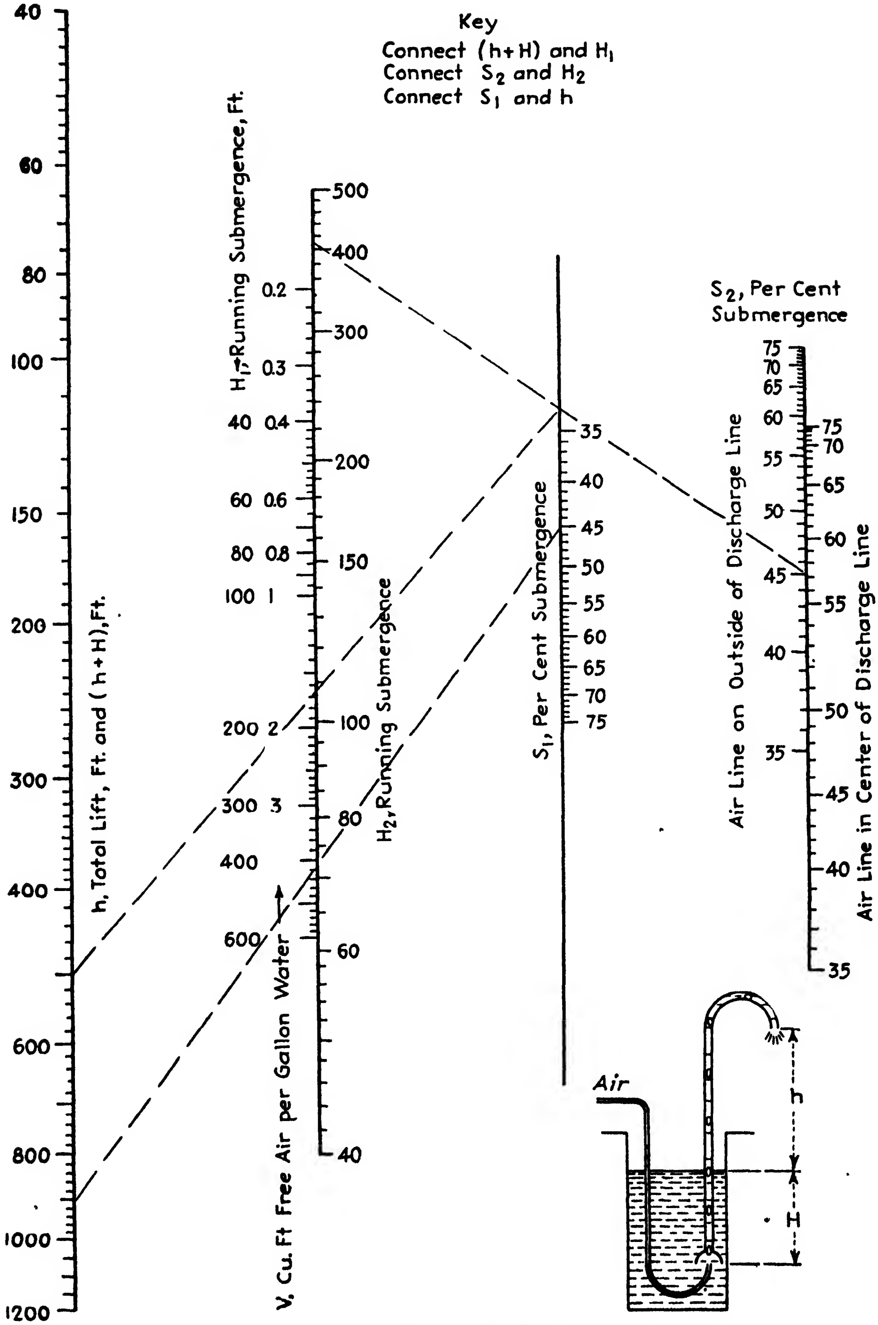
[1] *Chem. & Met. Eng.*, **39**, 101 (1932).



Key
Connect (h+H) and H_1
Connect S_2 and H_2
Connect S_1 and h

FIG. 31.—Air-lift nomograph.

C is a value depending upon the percentage submergence and the position of the air inlet pipe; and V is the volume of free air in cubic feet required for 1 gal. of water. C assumes the values given in Table V.

The broken lines illustrate the use of the chart when the running submergence is $H = 410$ ft., the total lift is $h = 500$ ft., and the air line is outside the discharge pipe. Connect $h + H = 910$ with $H = 410$ on the H_1 scale, and project the line to meet the percentage submergence scale S_1 in the value $S = 45.1$ per cent. Connect 45.1 on the S_2 scale with 410 on the H_2 scale, and note the intersection with the S_1 axis. Connect this latter point with 500 on the h scale, and read V as 1.65 cu. ft. of free air per gallon of water.

ECONOMIC PIPE-DIAMETER NOMOGRAPH[1]

The equation $D_i = 2.2w^{0.45}/\rho^{0.31}$, upon which Fig. 32 is based, gives the economic pipe diameter D_i, inches, in terms of w the weight flow, thousands of pounds mass per hour, and ρ the fluid density, pounds mass per cubic foot. The constant 2.2 also takes proper cognizance of the estimated number of hours operation per year, the cost of electrical energy for pumping, fractional amortization and maintenance, fraction of cost of pipe needed for fittings and erection, the cost of steel pipe, and the estimated average efficiency of motor and pump.

NOMOGRAPH FOR EQUIVALENT DIAMETERS OF ANNULI[2]

The Dittus-Boelter equation[3]

$$h = 0.0225\frac{k}{D}\left(\frac{Du\rho}{\mu}\right)^{0.8}\left(\frac{c\mu}{k}\right)^{0.4}$$

is used in estimating the film coefficient of the fluid flowing in the annular space between standard iron pipes although it was originally developed to cover turbulent flow inside clean round pipes where D is the inner diameter of the pipe in feet. For annuli, D is replaced by the equivalent diameter as given by the expression

$$D = \frac{D_2^2 - D_1^2}{12D_1}$$

where D_1 is the outer diameter of the inner pipe and D_2 is the inner diameter of the outer pipe, both in inches.

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[1] PERRY, J. H., "Chemical Engineers' Handbook," 2d ed., p. 816, McGraw-Hill Book Company, Inc., New York, 1941.

[2] *Chem. & Met. Eng.*, **49**, 148 (1942).

[3] *Univ. Calif. Pub. Eng.*, **2**, 443 (1930); MCADAMS, W. H., "Heat Transmission," p. 169, McGraw-Hill Book Company, Inc., New York, 1933; BADGER, W. L., and W. L. MCCABE, "Elements of Chemical Engineering," p. 134, McGraw-Hill Book Company, Inc., New York, 1936.

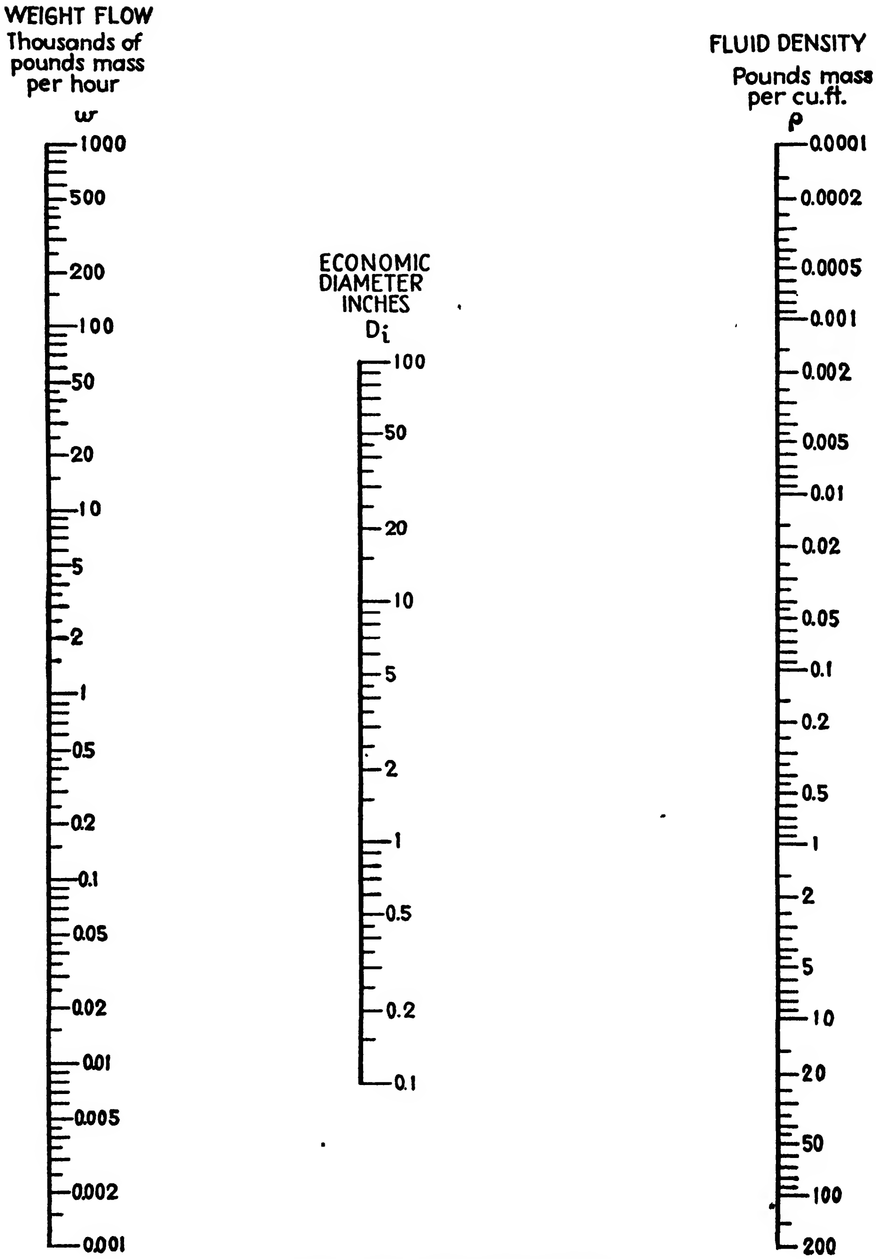

FIG. 32.—Economic pipe diameter.

While actual diameters must be used in the latter equation, Fig. 33 permits convenient calculation of the equivalent diameter in terms of the nominal pipe sizes. The use of the chart is illustrated as follows: What is the equivalent diameter of the annulus between 3½- and 5-in. standard iron pipes? Connect 5 on the D_2 scale with 3½ on the D_1 scale, and read the equivalent diameter as 0.197 ft. on the D scale.

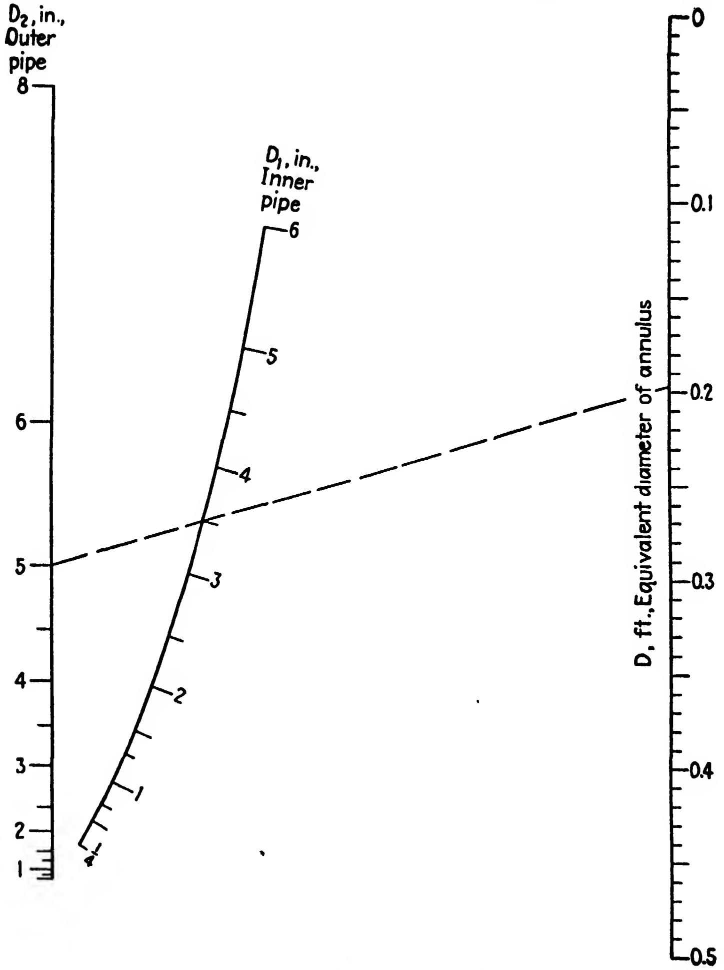

FIG. 33.—Equivalent diameters for annular spaces between concentric pipes.

GAS-DENSITY NOMOGRAPH

The use of Genereaux's chart[1] for gas densities (Fig. 34), based on the equation

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[1] PERRY, J. H., "Chemical Engineers' Handbook," 2d ed., p. 263, McGraw-Hill Book Company, Inc., New York, 1941.

$$\rho = \frac{MP}{1.315T}$$

where ρ = gas density, lb./cu. ft.
M = molecular weight.
P = absolute pressure, atm.
T = absolute temperature, °K.

is illustrated as follows: What is the density of methane at 10 atm. absolute pressure and 300°C.? Connect 300 on the temperature scale with 10 on the pressure scale and note the intersection with the reference line. Connect this point with the point labeled CH_4 on the molecular-weight scale and read the density as 0.21 lb./cu. ft.

PIPE-FLOW NOMOGRAPH[1]

Gas Example.—Air at a pressure of 120 lb. *force*/sq. in. gauge and a temperature of 30°C. is flowing at the rate of 500 lb. *mass*/hr. through a 2-in. standard steel pipe. What is the pressure drop per foot of pipe? The actual inside diameter is 2.067 in. The pressure of the air is (120 + 14.7)/14.7 = 9.16 atm. abs. Connect D_1 = 2.067 with w = 0.5, and extend the line to intersect the reference line at A = 6.15. Connect 30°C. on the gas temperature scale with molecular weight = 29 and inter-

TABLE Va.—MOLECULAR WEIGHTS OF GASES
For use with Fig. 35

Acetylene	26.0	Helium	4.0
Air	29.0	Hexane	86.1
Ammonia	17.0	Hydrogen	2.0
Argon	39.9	Hydrogen bromide	80.9
Bromine vapor	159.8	Hydrogen chloride	36.5
Butane	58.1	Hydrogen cyanide	27.0
Butylene	56.1	Hydrogen fluoride	20.0
Carbon dioxide	44.0	Hydrogen sulfide	34.1
Carbon monoxide	28.0	Methane	16.0
Chlorine	70.9	Methyl chloride	50.5
Cyanogen	52.0	Nitric oxide	30.0
Ethane	30.1	Nitrogen	28.0
Ethylene	28.0	Oxygen	32.0
Fluorine	38.0	Pentane	72.1
"Freon-11"	137.4	Propane	44.1
"Freon-12"	120.9	Propylene	42.1
"Freon-21"	102.9	Sulfur dioxide	64.1
"Freon-22"	86.5	Water	18.0
"Freon-113"	187.4		

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[1] PERRY, J. H., "Chemical Engineers' Handbook," 2d ed., p. 804, McGraw-Hill Book Company, Inc., New York, 1941.

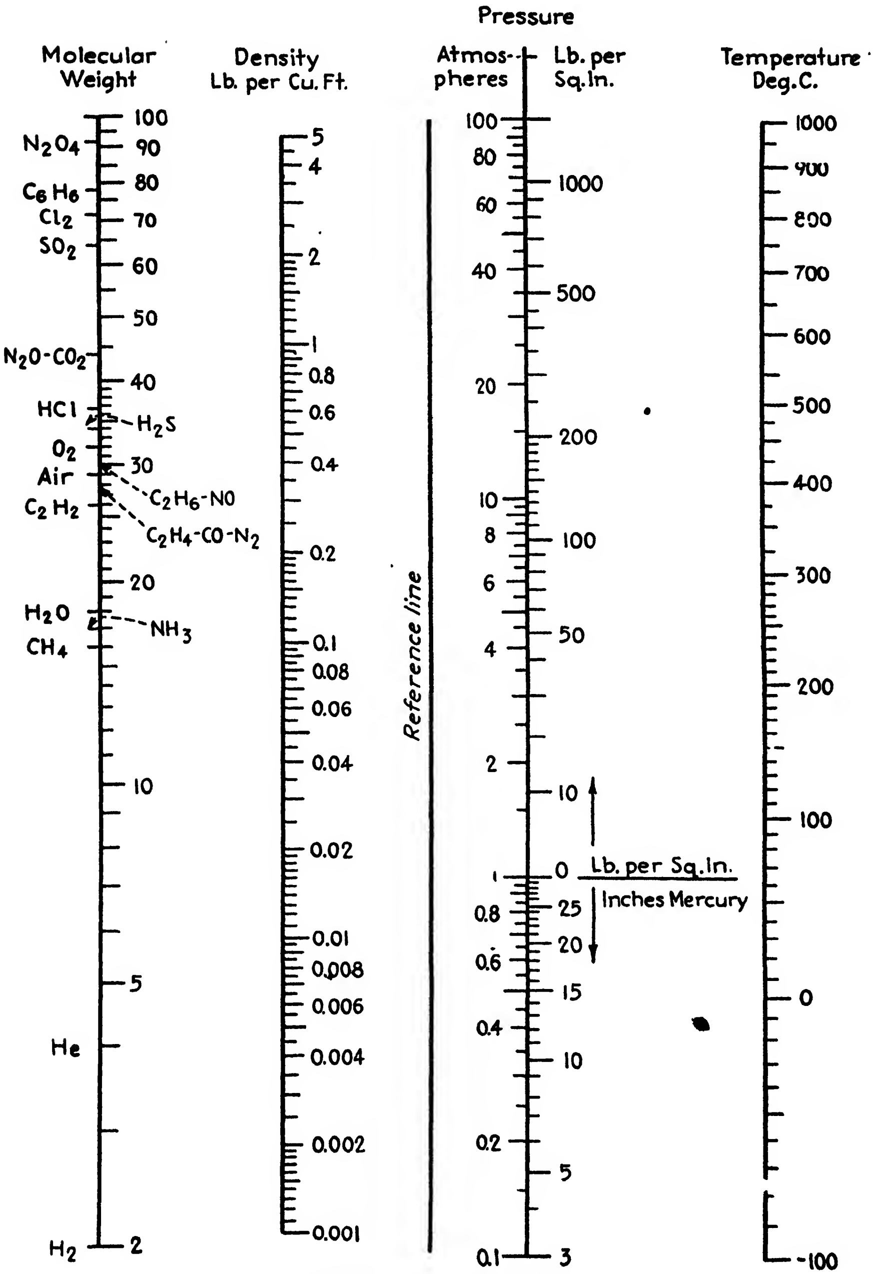

Fig. 34.—Gas-density chart.

sect the $\mu_e^{0.16}/\rho$ line at 7.1. Join this last intersection with point A, intersecting the $\Delta p(P)/L$ line at 0.008. The pressure drop is then

$$\frac{0.008}{9.16} = 0.00087 \text{ lb. } \textit{force}\text{/sq. in./ft. of pipe.}$$

Viscosity and Density Values.—*Gases.*—Temperature and molecular weight scales are given on Fig. 35 in the form of a line-coordinate chart by which values of $\mu_e^{0.16}/\rho$ at atmospheric pressure are determined directly. While it is true that the viscosities of gases and gas mixtures are not exactly proportional to the molecular weights, the error is small when the 0.16 power of the viscosity is used.

TABLE V*b*.—COORDINATES FOR LIQUIDS AND AQUEOUS SOLUTIONS
For use with Fig. 35

	X	*Y*		*X*	*Y*
Acetaldehyde	−0.3	3.7	"Freon 113"	0.9	6.2
Acetic acid, 100%	1.0	4.0	Glycerol, 100%	6.9	1.8
Acetic acid, 77%	2.6	3.8	Glycerol, 50%	3.0	3.7
Acetic anhydride	0.7	4.3	Hydrochloric acid, 31.5%	1.1	4.2
Acetone, 100%	0.9	3.4	Linseed oil, raw	3.4	1.8
Acetone, 35%	2.7	3.7	Mercury	See chart	
Ammonia, anhydrous	0.9	3.6	Methanol, 100%	0.8	3.3
Ammonia, 26%	1.9	3.6	Methanol, 40%	2.8	3.6
Aniline	2.5	3.4	Methyl acetate	0.0	4.2
Benzene	0.6	3.6	Methyl chloride	−0.8	4.3
Butanol	2.6	2.6	Nitric acid, 95%	0.8	5.8
Calcium chloride brine, 25%	2.6	4.2	Nitric acid, 60%	1.5	4.8
Carbon disulfide	0.0	5.6	Nitrobenzene	1.7	4.4
Carbon tetrachloride	0.7	6.0	Octane	0.4	2.7
Chloroform	0.0	6.0	Phenol	2.4	3.4
Chlorosulfonic acid	1.5	5.8	Propionic acid	0.6	3.8
Cyclohexanol	5.3	2.2	Sodium chloride brine, 25%	2.1	4.4
Diphenyl	0.0	3.5	Sodium hydroxide, 50%	5.3	3.7
Ether	−0.3	3.2	Sulfur dioxide	−0.2	6.1
Ethyl acetate	0.2	3.9	Sulfuric acid, 110%	3.7	4.7
Ethyl alcohol, 95%	1.9	3.0	Sulfuric acid, 98%	3.5	4.8
Ethyl alcohol, 45%	3.6	3.4	Sulfuric acid, 78%	3.2	4.8
Ethyl chloride	0.2	4.3	Tetrachlorethylene	0.3	6.2
Ethylene glycol	3.5	2.9	Toluene	0.4	3.6
Formic acid	1.5	4.5	Trichlorethylene	0.1	5.9
"Freon-11"	0.0	6.2	Turpentine	1.1	3.1
"Freon-12"	−1.2	5.9	Vinyl acetate	0.4	4.2
"Freon-21"	−0.4	5.9	Water	2.0	4.2
"Freon-22"	−1.7	5.5			

Liquids.—A separate temperature scale and a grid are given on the chart. Coordinates given in Table V*b* locate the point for a given liquid on the grid; a line through the point and the given temperature determines $\mu_c^{0.16}/\rho$ directly. Coordinates for liquids not given in the table may be determined by calculating values of $\mu_c^{0.16}/\rho$ for two temperatures and noting the intersection of lines connecting corresponding values of $\mu_c^{0.16}/\rho$ and temperature.

Liquid Example.—A 25 per cent calcium chloride brine is to be pumped through a line at 250 gal./min. at a temperature of 0°C. If the allowable pressure drop is 0.006 lb. *force*/sq. in./ft. of pipe, what size of pipe is required? Connect 0°C. on the liquid temperature scale with the intersection of grid values X = 2.6 and Y = 4.2 shown in Table V*b*. Extend the line to $\mu_c^{0.16}/\rho$ = 0.0179 and connect that point to $\Delta p/L$ = 0.006 and extend to the reference line at point B = 11.65. Connect point B through w = 147 (since at density of 73.3 lb. *mass*/cu. ft., 250 gal./min. = 147,000 lb. *mass*/hr.) to intersect at D_i = 5.5 in., indicating a 6-in. pipe.

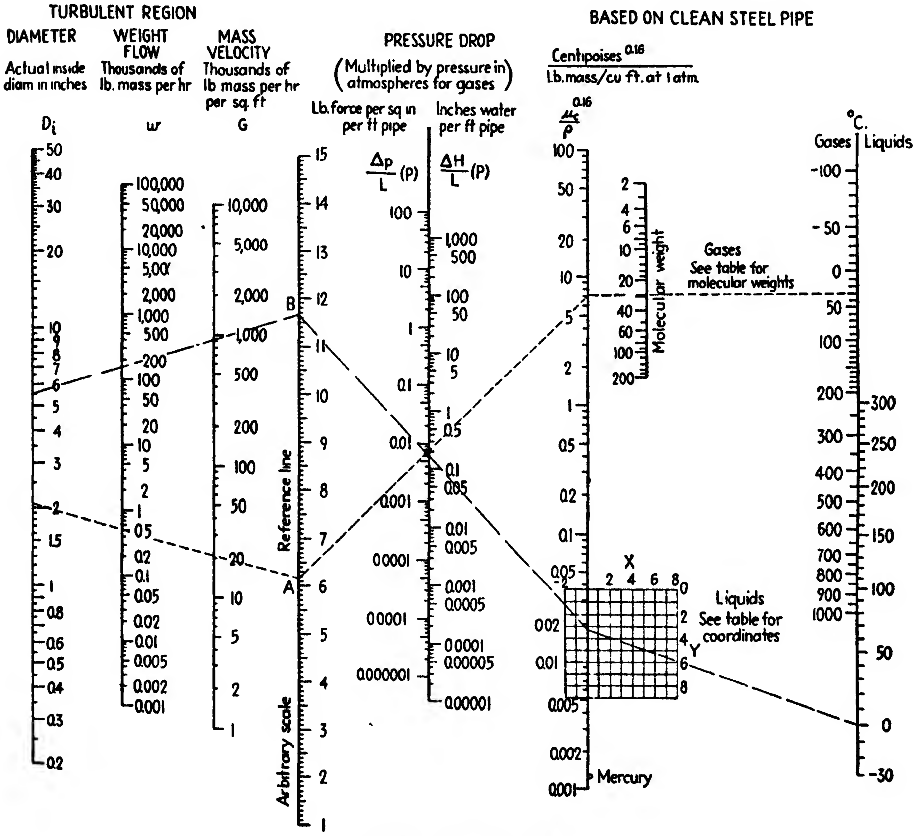

FIG. 35.—Pipe-flow chart.

ORIFICE NOMOGRAPH[1]

Frequently it is necessary to calculate the rate of flow of water through standard orifices, nozzles, and spray pipes. The discharge expression

$$Q = CAV$$

where Q = rate of flow, cu. ft./sec.
C = orifice constant, dependent upon design.
A = area of orifice, sq. ft.
V = velocity of flow, ft./sec.

can be written

$$Q = CA\sqrt{2gh} = 8.02CA\sqrt{h}$$

by substituting $\sqrt{2gh}$ for V, where h is the head of water in feet. To avoid small numerical values, the rate of flow in gallons per minute is more convenient and is given by

$$R = 19.64Cd^2\sqrt{h}$$

where d = diameter of orifice, in.

Figure 36 solves the expression readily and bears several gauge points corresponding to values of C for four commonly used types of orifice: the short or free-running Borda mouthpiece, square and beveled orifices in thin plates, and an orifice in a plate of thickness equal to two to three orifice diameters.[2]

As an illustration of the use of the chart: What is the rate of flow, in gallons of water per minute, through a ¼-in. hole in a wall ⅝ in. thick under a head of 30 ft. of water? The thickness of the wall is 2.5 times the diameter of the hole, corresponding to a coefficient of 0.82. Following the key and the broken lines on the chart, connect 0.82 on the C scale with 30 on the h scale, and note the intersection with the A axis. Connect this intersection with ¼ in. on the d scale, and read the rate of flow on the R scale as 5.52 gal./min.

Conversely, what head is needed to ensure a rate of flow of 20 gal. of water per minute through a standard beveled orifice in a thin plate? Connect ½ in. on the d scale with 20 on the R scale, and note the intersection with the A axis. Connect 0.61, the gauge point for a standard orifice, with this intersection, and produce the line to meet the h scale at 44.8, the required head in feet. Index lines for this solution are not shown on the chart.

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[1] *Ind. Eng. Chem.*, **33**, 420 (1941).

[2] Perry, J. H., "Chemical Engineers' Handbook," 2d ed., pp. 856, 857, McGraw-Hill Book Company, Inc., New York, 1941.

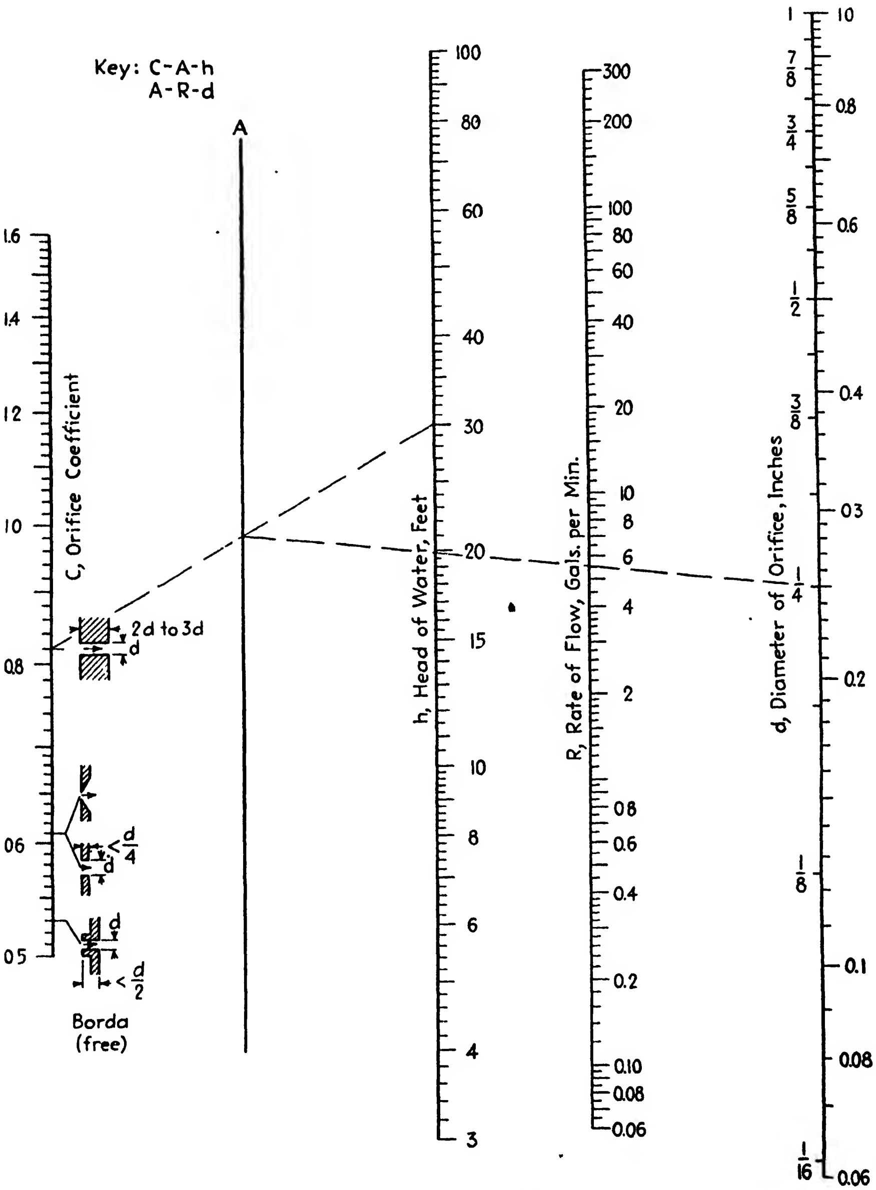

Fig. 36.—Orifice flow.

NOMOGRAPH SOLVES FLOW EQUATIONS FOR THIN-PLATE ORIFICES[1]

For everyday application to problems in flow measurement, no device is more useful than the thin-plate orifice. Only one dimension must be

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[1] Schilling, C. J., *Chem. & Met. Eng.*, **48** (8), 91 (1941).

known accurately, the orifice diameter. Given a pipe through which is flowing the fluid whose rate of flow is to be measured, usually all that is necessary is the insertion of a pipe union, between whose flanges the orifice is placed, and an upstream and a downstream nipple to which the manometer is attached.

As ordinarily derived, the flow formula is

$$V = Cf\left(\frac{\pi}{4}\right) D_2^2 \sqrt{2gH}$$

where V = flow, cu. ft./sec.
H = differential head of flowing fluid, ft.
D_1 = pipe diameter, ft.
D_2 = orifice diameter, ft.
C = coefficient of discharge, and f = the velocity of approach factor $1/\sqrt{1 - (D_2/D_1)^4}$.

If we combine the discharge coefficient with the velocity of approach factor, letting their product be C_f, then

$$V = C_f\left(\frac{\pi}{4}\right) D_2^2 \sqrt{2gH}.$$

In shop practice, we are usually interested in quantity per hour. Orifice diameters are given in decimals of an inch, and the available pressure is approximately just that required for use, so that it is advantageous to employ small loss of pressure. For these small pressure differences, a water manometer is best adapted. To change to these units, let Q = cubic feet per hour of fluid flowing = $3{,}600V$, and $H = \Delta P/\rho$, where ΔP = differential pressure, pounds per square foot and ρ = fluid density, pounds per cubic foot. Also let R = inches of water equivalent to ΔP or $407\Delta P/(14.7)(144)$, because atmospheric pressure equals 407 in. H_2O and there are 144 sq. in. in 1 sq. ft.; and d = orifice diameter, inches = $12D_2$. Then

$$Q = 3{,}600C_f\left(\frac{\pi}{4}\right)\left(\frac{d^2}{144}\right)\sqrt{\frac{64.4(14.7)(144)R}{407\rho}}$$

or

$$Q = 359C_fd^2\sqrt{R/\rho}.$$

When gas flow is measured, and R values are large, an additional coefficient or compressibility factor is usually provided in the flow equation. This may be avoided, however, if it is remembered that ρ changes with pressure and temperature, and if we take the density corresponding to the mean condition.[1] Thus, neglecting temperature change, take the density corresponding to $(P_1 + P_2)/2$ where P_1 = upstream and

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[1] *U. S. Bur. Standards Research Paper* 49.

P_2 = downstream pressure. The flow then represents Q cu. ft./hr. of fluid at this same density. If equivalent standard conditions are wanted,

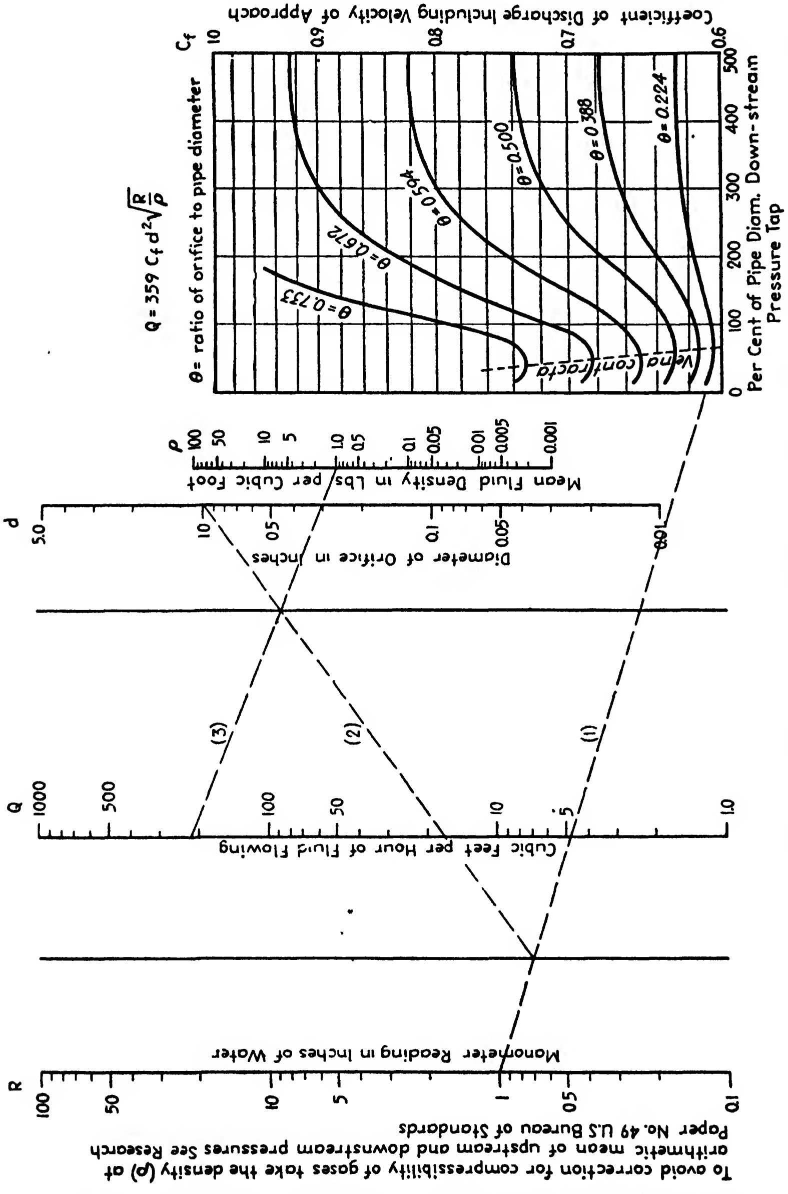

FIG. 37.—Nomograph for determining fluid-flow rate through a thin-plate orifice, for gas or liquid of any density, when manometer reading, density of flowing fluid, diameter of orifice and pipe, and location of downstream pressure tap are known.

the equation must be corrected to standard temperature and pressure, thus:

$$Q_s = Q\left(\frac{P_1 + P_2}{2P_s}\right)\frac{T_s}{T} = \frac{Q\rho_s}{\rho}.$$

If weight rate of flow is wanted, it may be obtained directly by multiplying both sides of the next to the last equation by the density ρ:

$$W = Q\rho = 359C_fd^2\sqrt{R\rho}.$$

Similarly, standard gas volume may be directly translated into weight units or $W = Q_s\rho_s$.

So, either the last two equations may be used for a gas, or the preceding pair.

Next must be considered the value of the coefficient C_f, and since this now includes the velocity of approach, it varies with the ratio of orifice to pipe diameter and also with the position of pressure taps, especially the downstream pressure tap. Assuming an upstream tap one-half pipe diameter or more from the orifice, the coefficient C_f may be obtained from the accompanying graph based on a similar graph in an A.S.M.E., research publication on Fluid Meters. The graph has been plotted so that the vertical scale is logarithmic and thus can become a part of the nomograph (Fig. 37) on which it appears.

To find the flow (liquid or gaseous) through an orifice in a given pipe find: (1) the ratio of orifice to pipe diameter; (2) the location of the downstream tap as percentage of pipe diameter; and (3) the corresponding coefficient of discharge C_f. With this last value as a pivot from the scale at the left edge of the graph, proceed by the straight lines (1), (2), and (3) as illustrated in the example given in Fig. 37. The case shown would correspond to a flow of 219 cu. ft./hr. through a 1-in. orifice in a 4½-in. pipe, the downstream pressure tap being 6 in. from the orifice and the mean fluid density 1 lb./cu. ft. As indicated, the coefficient of discharge for this case is $C_f = 0.61$, and the pressure differential to which it is connected by a straight line is $R = 1$ in. H_2O.

A QUICK WAY TO FIGURE THE FLOW FROM COMPLETELY FILLED PIPES[1]

Many occasions arise in food manufacture when it is desirable to know the velocity or quantity of liquid flowing through a pipe. When more accurate methods are impossible or unnecessary, a rapid approximation can be calculated from the coordinates of a stream as it emerges from a horizontal section.

In the case of small streams of water, actual and calculated values agree within 4 or 5 per cent, although coefficients of discharge and contraction are neglected. Even with more viscous fluids, such as syrups, it is estimated that the results are accurate to well within 10 per cent.

As shown in Fig. 38, the coordinates x and y are measured at any convenient point P in the center of the stream. As pointed out by Hewitt,[2] the equations involved are as follows:

[1] *Food Ind.*, **4**, 65 (1932).

[2] HEWITT, A. C., *Rock Products*, **32**, No. 12, 61, (1929).

$$v = \frac{1.158x}{\sqrt{y}}, \quad \text{and} \quad Q = \frac{3.61Ax}{\sqrt{y}}$$

where v = the linear velocity of the liquid leaving the pipe, feet per second; Q = the rate of flow, gallons per minute; A = the internal cross-sectional area of the pipe, square inches; and x and y are in inches. These equations are solved in Fig. 38, making it a simple matter, by means of a straightedge, to read velocity or rate of flow directly from the chart. A has been replaced by a scale reading the nominal pipe diameter in inches to simplify the problem.

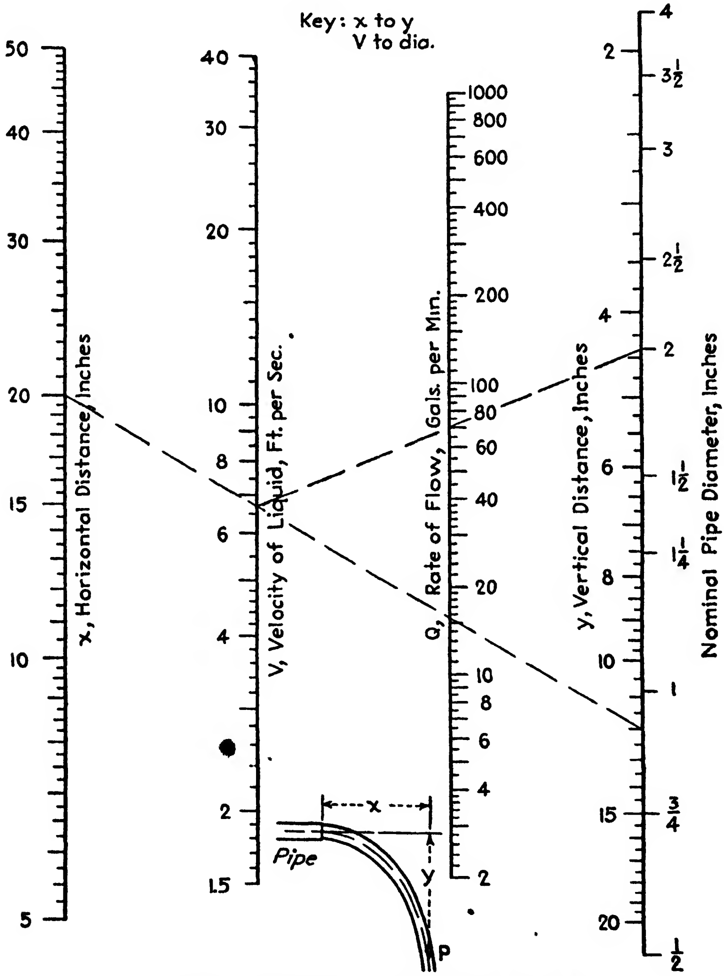

Fig. 38.—Flow from completely filled pipes.

The use of the chart is illustrated as follows: Suppose, for instance, we wish to find the linear velocity and rate of flow from a 2-in. pipe, when x has been found to equal 20 in. and y to equal 12 in. Following the key, connect 20 on the x scale with 12 on the y scale. Then read the velocity where the line crosses the v scale, 6.7 ft./sec. Now connect the latter point (on the v scale) with the pipe-diameter scale at the right of the page, and read on the Q (rate-of-flow) scale, 70 gal./min.

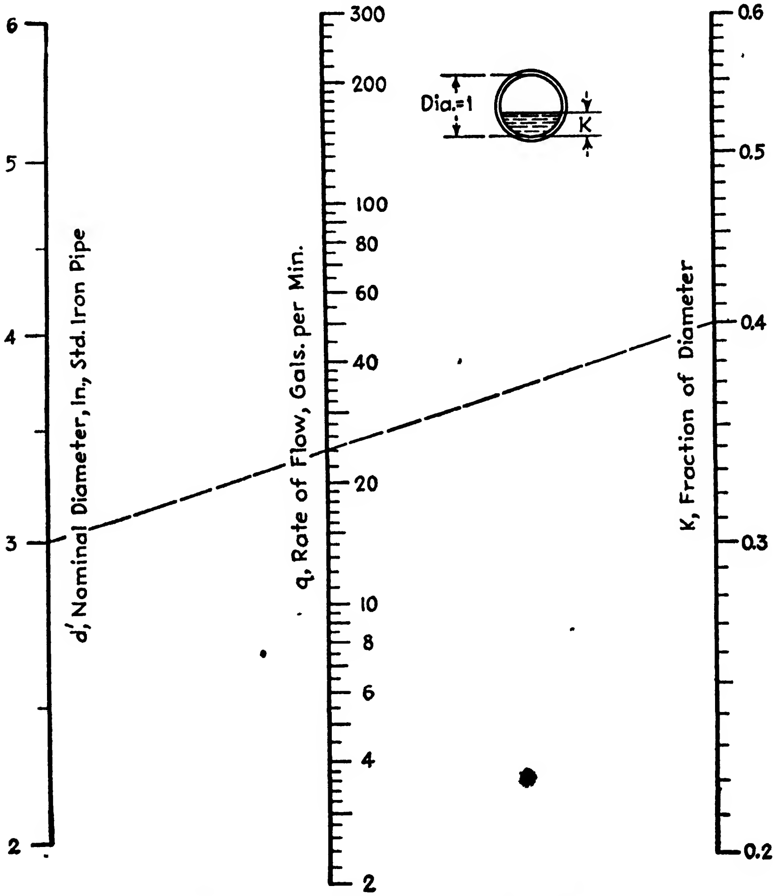

FIG. 39.—Flow from partially filled pipes.

NOMOGRAPH FOR FLOW FROM PARTIALLY FILLED PIPES[1]

Greve[2] proposed an equation for flow in partially filled horizontal pipes

$$Q = 9.43D^{2.56}K^{1.84}$$

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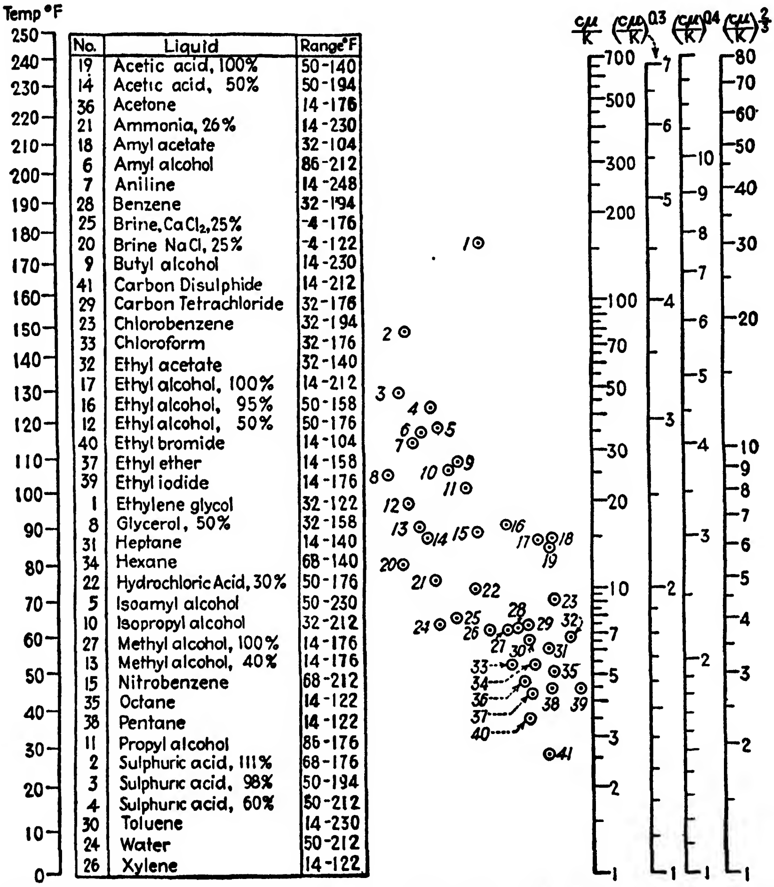
[1] *Ind. Eng. Chem.*, **34**, 52 (1942).

[2] GREVE, F. W., *Bull. Purdue Univ.*, **12**, No. 5 (1928), *Eng. Expt. Sta. Bull.* **32**.

where Q = rate of flow, cu. ft./sec.
D = inner diameter of pipe, ft. (limited to 0.1 to 0.5 ft.).
K = fraction of vertical diameter under fluid (limited to 0.2 to 0.6).

The method of measuring flow is simple, inexpensive, and satisfactory for rough estimations good to about 10 per cent. Figure 39, which facilitates the calculation, is based on the equivalent equation



No.	Liquid	Range°F
19	Acetic acid, 100%	50-140
14	Acetic acid, 50%	50-194
36	Acetone	14-176
21	Ammonia, 26%	14-230
18	Amyl acetate	32-104
6	Amyl alcohol	86-212
7	Aniline	14-248
28	Benzene	32-194
25	Brine, $CaCl_2$, 25%	-4-176
20	Brine NaCl, 25%	-4-122
9	Butyl alcohol	14-230
41	Carbon Disulphide	14-212
29	Carbon Tetrachloride	32-176
23	Chlorobenzene	32-194
33	Chloroform	32-176
32	Ethyl acetate	32-140
17	Ethyl alcohol, 100%	14-212
16	Ethyl alcohol, 95%	50-158
12	Ethyl alcohol, 50%	50-176
40	Ethyl bromide	14-104
37	Ethyl ether	14-158
39	Ethyl iodide	14-176
1	Ethylene glycol	32-122
8	Glycerol, 50%	32-158
31	Heptane	14-140
34	Hexane	68-140
22	Hydrochloric Acid, 30%	50-176
5	Isoamyl alcohol	50-230
10	Isopropyl alcohol	32-212
27	Methyl alcohol, 100%	14-176
13	Methyl alcohol, 40%	14-176
15	Nitrobenzene	68-212
35	Octane	14-122
38	Pentane	14-122
11	Propyl alcohol	86-176
2	Sulphuric acid, 111%	68-176
3	Sulphuric acid, 98%	50-194
4	Sulphuric acid, 60%	50-212
30	Toluene	14-230
24	Water	50-212
26	Xylene	14-122

FIG. 40.—Functions of Prandtl numbers. (*From W. H. McAdams, Heat Transmission, 2d ed., p.* 414.)

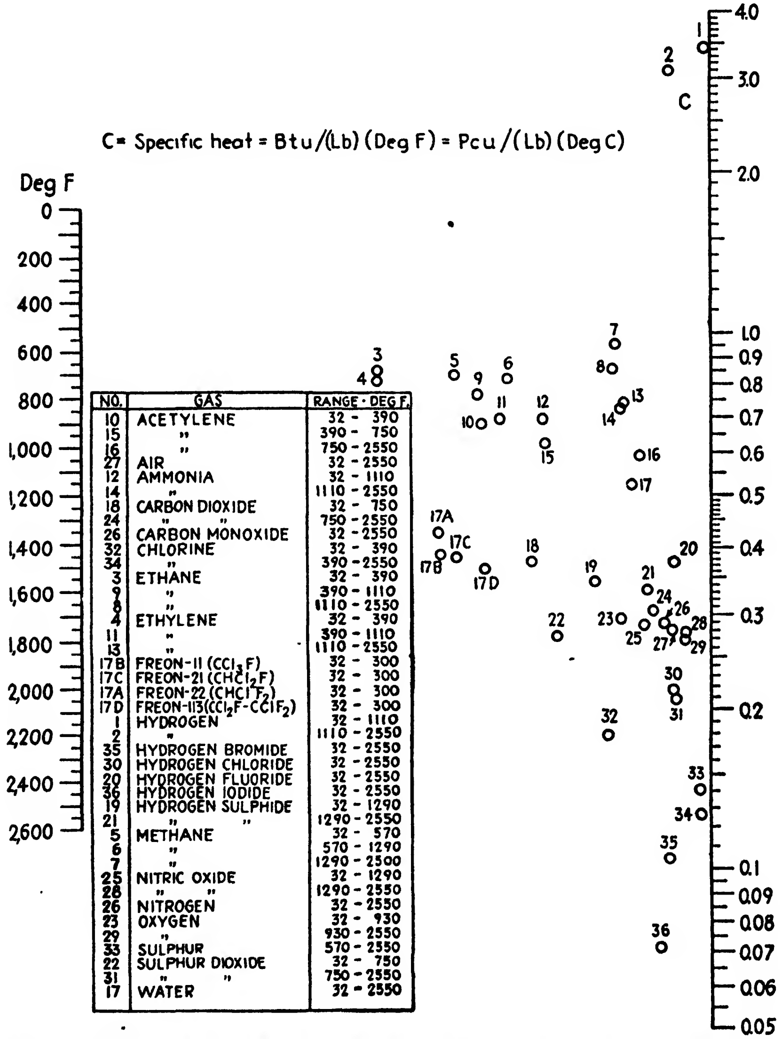
$$q = 7.3d^{2.56}K^{1.84}$$

where q = rate of flow, gal./min.
d = inner diameter of pipe, corresponding to 2- to 6-in. standard iron pipe.

The index line shows that 24 gal./min. flow through a horizontal 3-in. standard iron pipe when 0.4 of the inner vertical diameter is under the fluid.

LINE-COORDINATE CHART FOR FUNCTIONS OF PRANDTL NUMBERS[1]

The use of the Chilton, Colburn, and Vernon line-coordinate chart (Fig. 40) for calculation of several useful functions of Prandtl numbers is illustrated as follows: What is the Prandtl number and its 0.3, 0.4, and $\frac{2}{3}$ powers for aniline at 126°F.? From the table read the point correspond-



NO.	GAS	RANGE · DEG F.
10	ACETYLENE	32 - 390
15	"	390 - 750
16	"	750 - 2550
27	AIR	32 - 2550
12	AMMONIA	32 - 1110
14	"	1110 - 2550
18	CARBON DIOXIDE	32 - 750
24	" "	750 - 2550
26	CARBON MONOXIDE	32 - 2550
32	CHLORINE	32 - 390
34	"	390 - 2550
3	ETHANE	32 - 390
9	"	390 - 1110
8	"	1110 - 2550
4	ETHYLENE	32 - 390
11	"	390 - 1110
13	"	1110 - 2550
17B	FREON-11 (CCl_3F)	32 - 300
17C	FREON-21 ($CHCl_2F$)	32 - 300
17A	FREON-22 ($CHClF_2$)	32 - 300
17D	FREON-113 (CCl_2F-$CClF_2$)	32 - 300
1	HYDROGEN	32 - 1110
2	"	1110 - 2550
35	HYDROGEN BROMIDE	32 - 2550
30	HYDROGEN CHLORIDE	32 - 2550
20	HYDROGEN FLUORIDE	32 - 2550
36	HYDROGEN IODIDE	32 - 2550
19	HYDROGEN SULPHIDE	32 - 1290
21	" "	1290 - 2550
5	METHANE	32 - 570
6	"	570 - 1290
7	"	1290 - 2500
25	NITRIC OXIDE	32 - 1290
28	" "	1290 - 2550
26	NITROGEN	32 - 2550
23	OXYGEN	32 - 930
29	"	930 - 2550
33	SULPHUR	570 - 2550
22	SULPHUR DIOXIDE	32 - 750
31	" "	750 - 2550
17	WATER	32 - 2550

FIG. 41.—Specific heats of gases and vapors. (*From W. H. McAdams, Heat Transmission, 2d ed., p. 406.*)

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[1] McADAMS, W. H., "Heat Transmission," 2d ed., p. 414, McGraw-Hill Book Company, Inc., New York, 1942.

ing to aniline as 7. Connect 126 on the temperature scale with point 7 and read the value of the Prandtl number, $c\mu/k$ as 27. A horizontal line through this point will yield the 0.3, 0.4, and $\frac{2}{3}$ powers of the Prandtl number as 2.69, 3.74, and 9, respectively.

LINE-COORDINATE CHART FOR SPECIFIC HEATS OF GASES AND VAPORS[1] AT ONE ATMOSPHERE

The use of the Chilton, Colburn, and Vernon line-coordinate chart (Fig. 41) for estimation of the specific heats of gases is illustrated as follows: What is the specific heat of methane at 300°F.? Connect 300 on the temperature scale with point 5, obtained from the table, and read the specific heat of methane as 0.63 (B.t.u.)/(lb.)(°F.).

CORRECTING WEIR-FLOW CALCULATIONS FOR VELOCITY OF APPROACH[2]

In connection with the weiring of industrial effluents, it is frequently noted that the stilling-box dimensions do not conform to the best practice, usually because of lack of sufficient space or some other local condition. As a result, the pool above the dam is far from quiet and the velocity of approach before the crest may be considerably too high, causing the calculated rate of flow to be lower than the actual value.

Even a velocity of approach as low as 0.8 ft./sec. can introduce errors up to 8 per cent in the calculated flow, while at higher velocities the discrepancy between the true and apparent rates of flow rises very rapidly. Since an excessive velocity of approach cannot always be avoided, it is evident that a simple and accurate means of determining the proper corrections is needed.

Baker[3] presents data for making such corrections in the case of rectangular weirs. The material, however, is in the form of a family of curves between which interpolation is at once difficult and uncertain. Figure 42 presents the same data in a more convenient form, inasmuch as all interpolation can be accomplished on closely graduated scales.

The velocity of approach, V, in feet per second may be calculated from the apparent rate of flow (which has itself been computed from the head on the weir) by the expression

$$V = \frac{q}{450A}$$

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[1] McAdams, W. H., "Heat Transmission," 2d ed., p. 406, McGraw-Hill Book Company, Inc., New York, 1942.

[2] *Chem. & Met. Eng.*, **40**, 542 (1933).

[3] Baker, C. M., "White Water Surveys," American Paper and Pulp Association, p. 8.

where q is in gallons per minute and A is the sectional area of the channel in square feet.

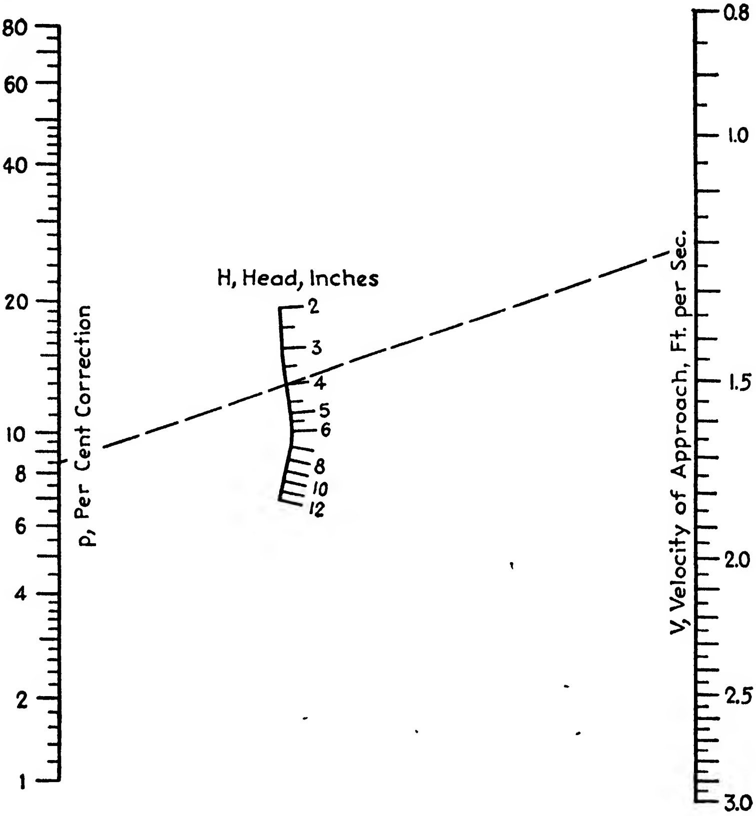

Fig. 42.—Weir-flow corrections for velocity of approach.

The velocity of approach and the percentage correction in rate of flow are related by the empirical equation

$$\log (p + 1) = \frac{a}{173 + 100V} + b$$

where p is the percentage by which the apparent flow is to be increased and where a and b are functions of the head which need not be mathematically defined.

The broken line shows that the apparent rate of flow as calculated by the usual Francis formula must be increased by 8.5 per cent when the head on the weir is 4 in. and the velocity of approach is 1.2 ft./sec.

CHAPTER VI

FREEZING-POINT AND FREEZING-TIME NOMOGRAPHS

SOLIDIFICATION-POINT NOMOGRAPH FOR FATTY ACIDS[1]

In view of the importance of the solidification point of fatty acids as a criterion of purity, Hoerr, Pool, and Ralston[2] presented excellent supplementary data on the effect of water in lowering the freezing points of the normal saturated fatty acids from caproic to stearic. Their results may be correlated by the equation

$$\frac{w}{\Delta t} = a + bw$$

where w is percentage of water, Δt is freezing-point depression (degrees centigrade), and a and b are characteristics of the fatty acid in question and may depend upon n, the number of carbon atoms.

Data are presented conveniently and reliably (±0.02°C.) in the line-coordinate chart (Fig. 43) based upon the equation and the constants given in Table VI.

TABLE VI

No. C atoms	Fatty acid	a	b	Range of w	Freezing point of dry acid, °C.
6	Caproic	0.394	0.289	0.4–2.21	− 3.24
7	Heptylic	0.383	0.357	0.4–2.98	− 6.26
8	Caprylic	0.373	0.414	0.2–3.88	16.30
9	Nonylic	0.351	0.476	0.8–3.45	12.24
10	Capric	0.370	0.535	0.9–3.12	30.92
11	Undecylic	0.479	0.559	0.2–2.72	28.13
12	Lauric	0.467	0.678	0.6–2.35	43.86
13	Tridecylic	0.574	0.713	0.2–2.00	41.76
14	Myristic	0.551	0.880	0.6–1.70	54.01
15	Pentadecylic	0.651	0.924	0.5–1.46	52.49
16	Palmitic	0.743	1.017	0.4–1.25	62.41
17	Heptadecylic	0.820	1.150	0.2–1.06	60.94
18	Stearic	0.912	1.183	0.2–0.92	69.20

The use of Fig. 43 is illustrated as follows: What is the solidification point of capric acid which contains 3.0 per cent water? Connect the

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[1] *Ind. Eng. Chem.*, **35**, 105 (1943).

[2] HOERR, C. W., W. O. POOL, and A. W. RALSTON, *Oil & Soap*, **19**, 126 (1942).

point where $n = 10$, which represents capric acid, with 3.0 on the w scale, and read the lowering of the freezing point as 1.52°C. on the Δt scale; then, using Table VI, the solidification point is 30.92 − 1.52, or 29.40°C.

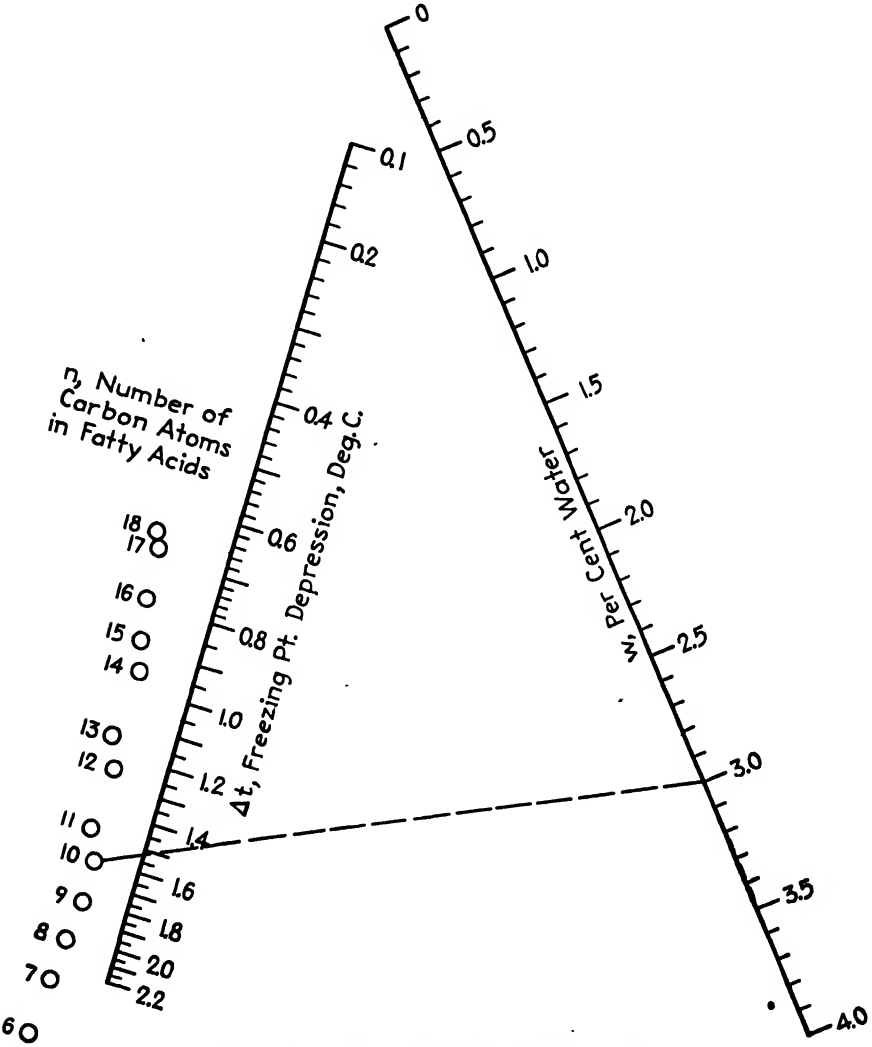

FIG. 43.—Solidification points of fatty acids.

FREEZING POINTS OF TERNARY ALCOHOL MIXTURES[1]

Aldrich and Querfeld[2] have made a thorough study of the freezing points of the ternary system ethanol-methanol-water and have presented'

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[1] *Chem. & Met. Eng.*, **39**, 345 (1932).

[2] ALDRICH, E. W., and D. W. QUERFELD, *Ind. Eng. Chem.*, **23**, 708, 1931.

their data in tabular and graphical forms, plotting freezing points against methanol content for various total alcohol percentages.

Figure 44, which permits more rapid and accurate interpolation of these data than has previously been possible, is based on the following empirical equation determined expressly for this purpose:

$$t = -(0.00001277A^{2.326} + 0.0081)M - 0.01139A^{1.425} - 0.5$$

where t is the freezing point of the ternary system, degrees centigrade; A is the percentage of total alcohol in the aqueous solution, by volume; and M is the methanol content in volume percentage of the total alcohol.

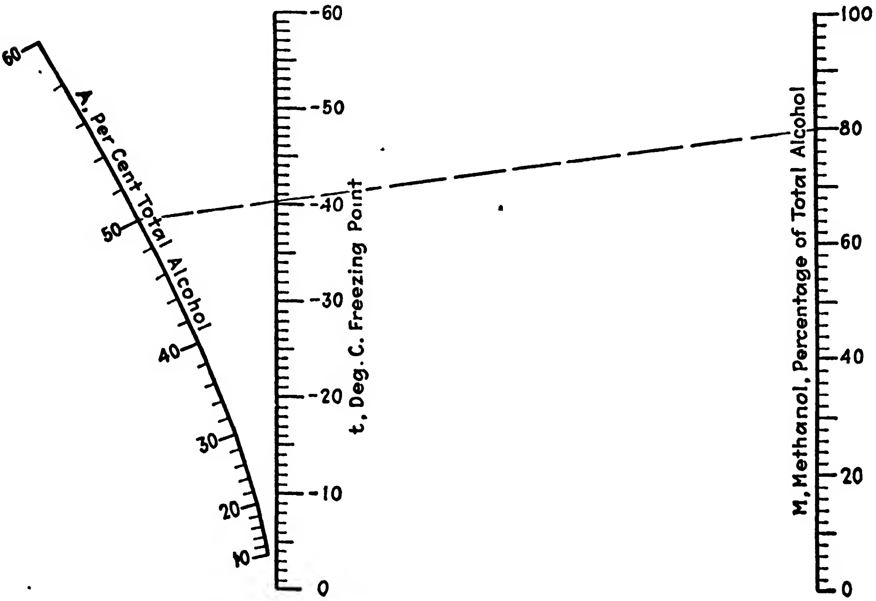

FIG. 44.—Freezing points of ternary alcohol mixtures.

As an illustration of the use of Fig. 44, the broken line indicates that an aqueous solution containing 50 per cent total alcohol, of which 80 per cent is methanol, would freeze at −40.4°C. Both the equation and the nomograph represent the original data within 0.5°C.

FREEZING-POINT LOWERING NOMOGRAPH[1]

Figure 45 enables rapid calculation of Δt, the freezing-point lowering in degrees centigrade to be expected when the concentration of solute is C moles/kg. of solvent and when 1 mole of solute dissolved in 1 kg. of solvent lowers the freezing point F°C. For convenience, values of the

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[1] *Chemist-Analyst*, **22** (1), 8 (1933).

freezing-point lowering constants[1] for 16 common solvents are marked directly on one side of the F scale.

The equation involved is

$$\Delta t = FC$$

which holds for dilute solutions of solutes which do not dissociate in the solvent under consideration. The dashed line indicates that 0.3 mole of,

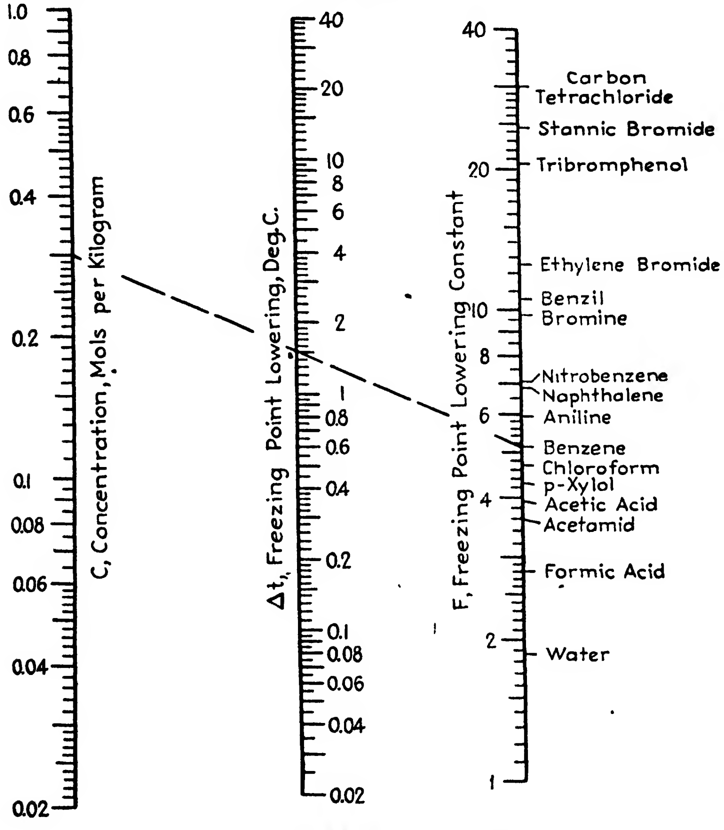

FIG. 45.—Freezing-point lowering.

say, a spindle oil dissolved in 1 kg. of benzene will lower the freezing point of the solvent 1.54°C.

REFRIGERATION NOMOGRAPH[2]

Cranford's interesting and instructive paper,[3] which deals with the calculation of the time required to freeze cakes of ice in commercial

[1] LANDOLT-BORNSTEIN, "Physikalisch-Chemische Tabellen," Vol. II, p. 1424, Julius Springer, Berlin, 1923.

[2] *Power Plant Eng.*, **39**, 133 (1935).

[3] CRANFORD, H. A., *Power Plant Eng.*, **38**, 432 (1934).

installations and with the determination of the number of cans to allow per ton of daily harvest, has prompted the construction of the accompanying nomograph.

Figure 46 enables one to perform graphically, by the simple expedient of drawing two straight lines, the computations which Cranford has explained. The use of the nomograph may be illustrated by the following example in which Cranford's original values are employed. In the case of the standard installation making cakes of an average cross section of 11 by 22 in., how long will it take to freeze the cake if the brine temperature is 14°F.? How many cans per ton of daily harvest will be needed if each cake weighs 300 lb.? Connect 14 on the temperature scale with 11 on the thickness scale, and produce the line to the time scale where the intersection is at 47 hr. Connect this point with 300 on the weight scale, and read the intersection with the N scale as slightly over 13, showing that 14 cans should be provided for every ton of ice expected each day.

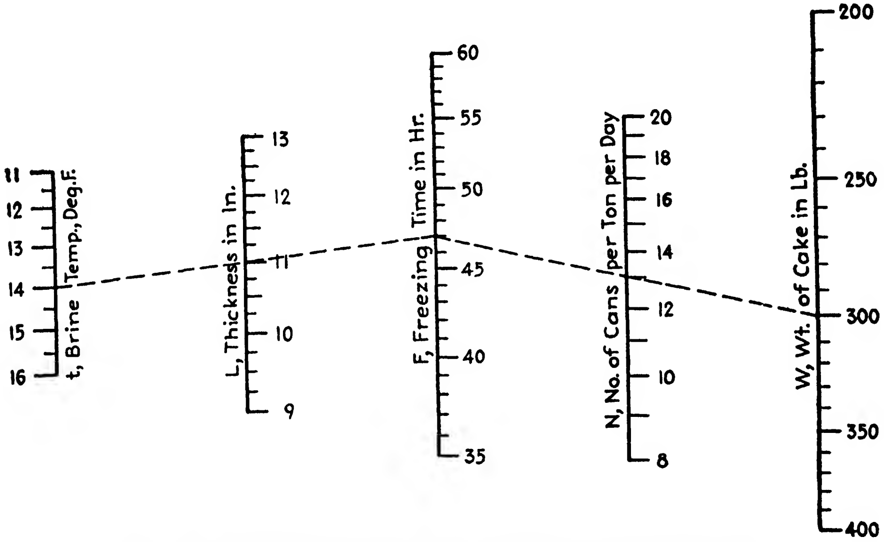

FIG. 46.—Freezing time and daily production for ice manufacture.

The chart solves the equations

$$\theta = \frac{7L^2}{32 - t} \qquad \text{and} \qquad N = 83.3 \frac{\theta}{W}$$

where θ = freezing time, hr.
L = average thickness of cake, in.
t = temperature of the brine, °F.
N = number of cans per ton of daily harvest.
W = weight of each cake, lb.

CHAPTER VII

FUEL-ANALYSIS AND THERMAL-VALUE NOMOGRAPHS

NOMOGRAPH FOR COAL-ANALYSIS CONVERSIONS[1]

Coal analyses and heating values are commonly reported on three bases: the as-received, the dry, and the ash- and moisture-free. For purposes of comparing various coals as to proximate and thermal values, it is essential that all data be expressed on the same basis, requiring, usually, some type of conversion calculation. Alignment charts are admirably adapted to computations of this type, and it is the purpose of this topic to present two such charts and to illustrate their use with typical examples.

Proximate-analysis Chart.—Figure 47 covers conversion of proximate analyses and is arranged so that each scale bears three designations, broken lines connecting the three corresponding legends. The outer axes are doubly graduated, and in any given conversion one works entirely with the scales at the left or at the right of both axes. As an example of the use of Fig. 47, convert the analysis given in Table VII from the as-received basis to the dry basis and to the ash- and moisture-free basis. The last two columns list the results to be obtained from the chart (Fig. 47).

TABLE VII.—ANALYSIS ON THREE BASES OF WEST VIRGINIA SEMIBITUMINOUS COAL

Composition	As-received	Dry	Ash and moisture-free
Moisture	3.0		
Volatile matter	17.0	17.5	19.3
Fixed carbon	71.0	73.2	80.7
Ash	9.0	9.3	
Total	100.0	100.0	100.0

As-received Basis to Dry Basis.—Connect 17.0, the percentage of volatile matter on the as-received basis (found at the left side of the left axis), with 3, the percentage of moisture on the same basis (central scale), and produce the line to meet the right axis at 17.5, the percentage of volatile matter on the dry basis, found at the left side. In the case of the fixed carbon, align 71.0 (left axis, right side) with 3 on the central

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[1] *Chem. & Met. Eng.*, **43**, 331 (1936).

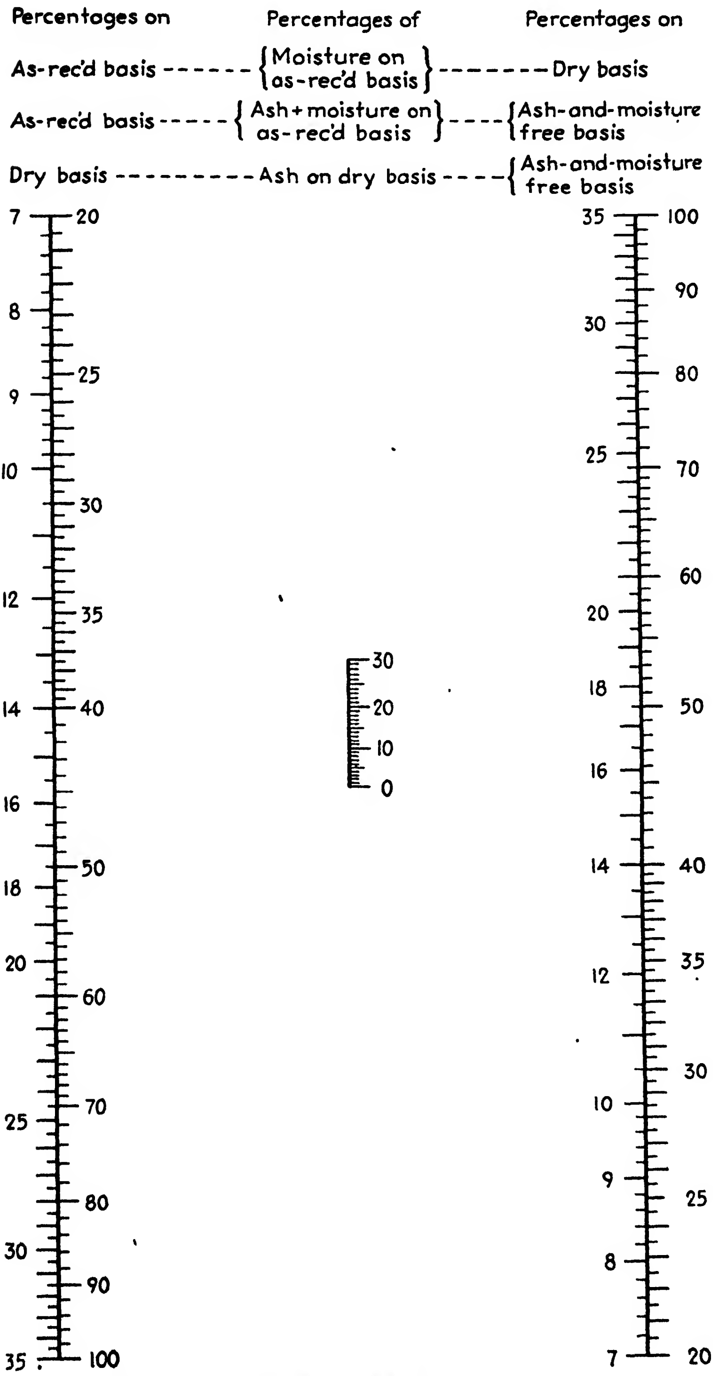

Fig. 47.—Proximate analysis conversions, for coal.

scale and extend the line to 73.2 on the right side of the right axis. Similarly, the percentage ash on the dry basis is found to be 9.3.

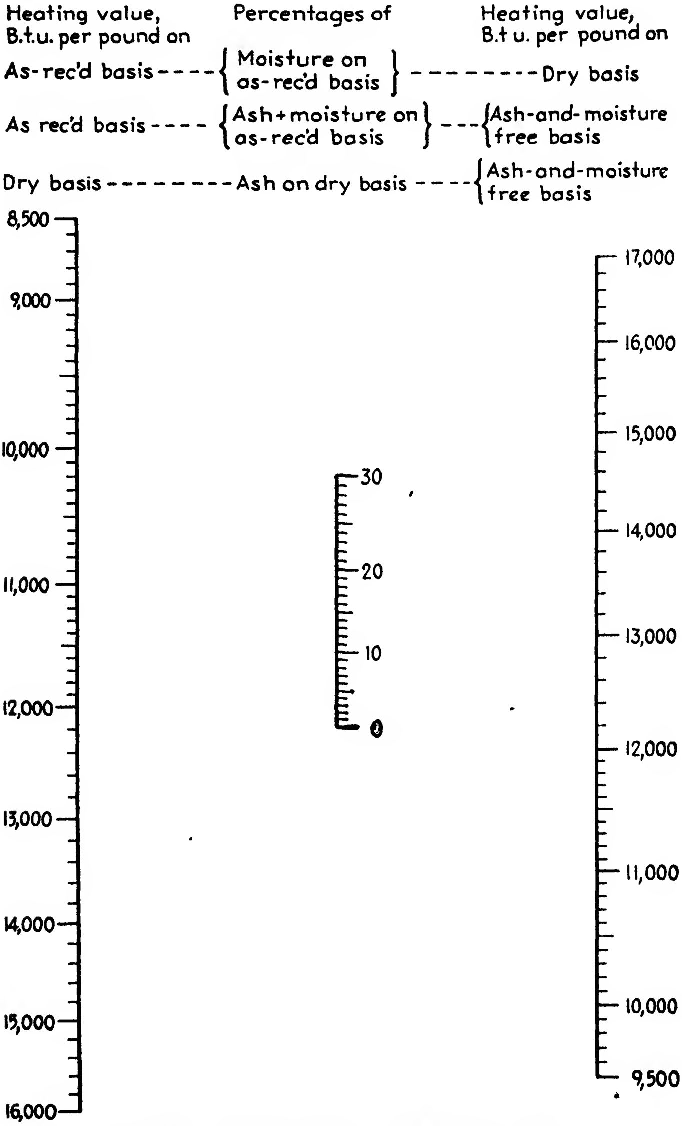

FIG. 48.—Thermal-value conversions, for coal.

As-received Basis to Ash- and Moisture-free Basis.—Following the second line of legends, connect 17.0, the percentage of volatile matter (as-received basis) on the left axis, with 3 + 9, or 12, the sum of the moisture and ash percentages (as-received basis) on the center scale, and produce the line to meet the right axis in 19.3, the percentage of volatile matter on the ash- and moisture-free basis. In a similar manner, but working at the right of both outer axes, the percentage of fixed carbon on the ash- and moisture-free basis is found to be 80.7.

Dry Basis to Ash- and Moisture-free Basis.—Given the percentages of volatile matter, fixed carbon, and ash on the dry basis as 17.5, 73.2, and 9.3, respectively, what is the analysis on the ash- and moisture-free basis? Following the third line of corresponding legends, align 17.5, the percentage of volatile matter on the dry basis (left axis), with 9.3, the percentage of ash on the dry basis (center axis), and extend the line to 19.3 (right axis), which is the percentage of volatile matter on the ash- and moisture-free basis. Similarly, connect the percentage of fixed carbon on the dry basis, 73.2 (left axis), with 9.3 on the center scale, and produce the line to meet the right axis at 80.7, the percentage of fixed carbon on the ash- and moisture-free basis.

In Fig. 47, the outer scales run between 7 and 100 per cent. Values lower than 7 may be handled by first multiplying by 10 and later dividing the result by 10.

Heating-value Chart.—The use of the heating-value chart (Fig. 48) in facilitating conversions may be illustrated as follows: Given a coal with a thermal value of 13,400 B.t.u./lb., a moisture content of 3.0 per cent, and an ash content of 9.0 per cent, all data being on the as-received basis, what is the heating value per pound of dry coal and per pound of combustible, *i.e.*, ash- and moisture-free coal?

As indicated by the first line of legends above the scales, a straightedge connecting 13,400 B.t.u. on the left with 3.0 per cent in the center will cut the scale at the right in the value, 13,800 B.t.u./lb. of dry coal. Following the second line of legends, connect 13,400 B.t.u./lb. of coal on the as-received basis (left) with 3 + 9, or 12, the sum of the moisture and ash percentages (as-received basis) and produce the line to meet the scale at the right in the value, 15,200 B.t.u./lb. of coal, on the ash- and moisture-free basis.

Given the heating value and the percentage of ash, both on the dry basis, as 13,800 B.t.u. and 9.3 per cent, respectively, what is the thermal value on the ash- and moisture-free basis? According to the third line of legends, align 13,800 on the scale at the left with 9.3 per cent on the central scale and extend the line to meet the scale at the right in the value, 15,200 B.t.u./lb. on the ash- and moisture-free basis.

THERMAL-VALUE NOMOGRAPH FOR ANTHRACITE COAL[1]

In connection with their study of the effect of oxidation on the thermal value of anthracites, Scott, Jones, and Cooper[2] correlated data on volatile

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[1] *Ind. Eng. Chem.*, **32**, 1651 (1940).

[2] Scott, G. S., G. W. Jones, and H. M. Cooper, *Ind. Eng. Chem.*, **31**, 1025 (1939).

matter, ash content, and heating value in the equation

$$H = 14{,}803 + 75.8V - 167.4A$$

where H is the heating value, B.t.u. per pound; V is the volatile matter, per cent by weight; A is the ash, per cent by weight; H, V, and A are all on a dry basis.

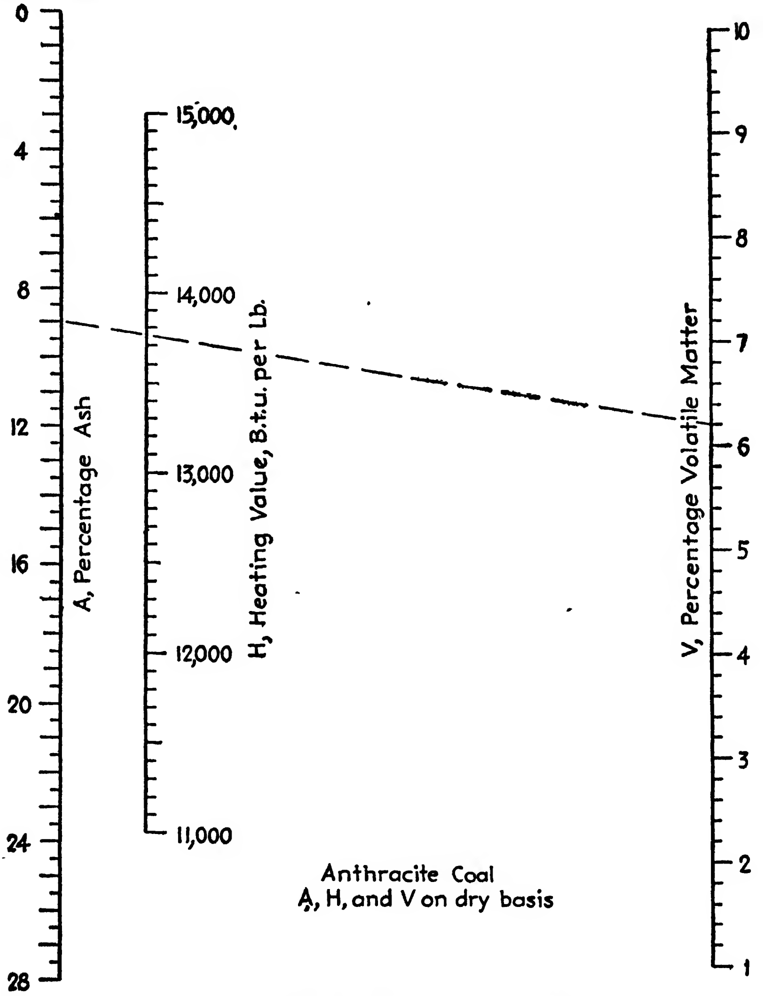

FIG. 49.—Thermal value of anthracite coal.

This relation was based on 1,008 anthracite samples; 76 per cent of them deviated by less than 100 B.t.u. and 96 per cent deviated by less than 200 B.t.u. from the calculated value. The equation represents the average run of anthracites and warrants construction of a nomograph for rapid and convenient solution.

In Fig. 49, the broken line shows that an anthracite containing 9 per cent ash and 6.2 per cent volatile matter will average 13,750 B.t.u./lb. A somewhat similar nomograph covering bituminous coals was given previously.[1]

THERMAL-VALUE NOMOGRAPH FOR BITUMINOUS COAL[2]

Figure 50, based on Mahler's data,[3] enables rapid estimate to be made of the thermal value of bituminous coal when the proximate analysis is known.

The use of the chart is illustrated as follows: Given the analysis, on the as-received basis,

	Per Cent
Volatile combustible matter	33
Fixed carbon	57
Ash	7
Moisture	3

find the heating value in (1) B.t.u. per pound of combustible, (2) B.t.u. per pound of coal as received, and (3) B.t.u. per pound of bone-dry coal.

1. Note that the sum of the ash and moisture percentages is 10. Connect 57 on the fixed-carbon scale with 10 on the horizontal ash-plus-moisture scale, and produce the line to the *A* axis. From this intersection, erect a perpendicular to meet the curve and then proceed horizontally to the scale at the extreme left, reading the heating value as 15,100 B.t.u./lb. of combustible.
2. A line from this point to 10 on the vertical ash-plus-moisture scale will cut the B.t.u. per pound of coal as-received scale at 13,600.
3. Connect this latter intersection with 3 on the vertical moisture scale, and produce the line to meet the scale at the left in the value 14,000, which is the number of B.t.u. per pound of bone-dry coal.

This method of calculation gives results good to within 2 per cent for bituminous and semibituminous coals which run above 55 per cent in fixed carbon and within about 3.5 per cent when the fixed carbon percentages are between 50 and 55.

For most convenient use, the chart can be photostated and the photostat mounted on a light frame bearing raised edges at the bottom and left. The raised edges, together with a draftsman's triangle, facilitate drawing the perpendiculars and horizontals.

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[1] *Chem. & Met. Eng.*, **42**, 158 (1935).

[2] *Chem. & Met. Eng.*, **42**, 158 (1935).

[3] SMALLWOOD, J. C., "Mechanical Laboratory Methods," p. 176, D. Van Nostrand Company, Inc., New York, 1924.

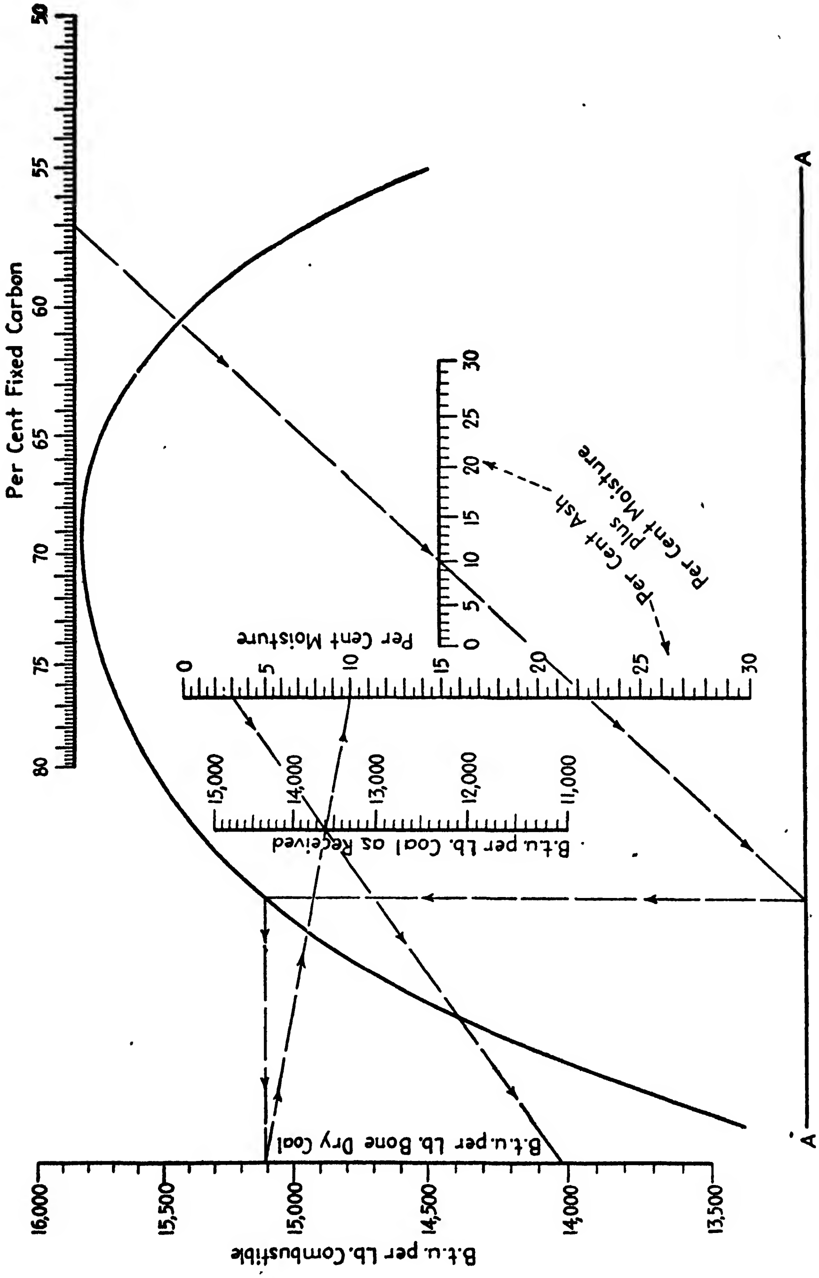

FIG. 50.—Thermal value of bituminous coal.

THERMAL-VALUE NOMOGRAPH FOR FUEL OILS[1]

Figure 51, based on the data of Faragher, Morrell, and Essex,[2] enables calculation of the thermal value of straight-run fuel oils and normal and flashed residuums when the A.P.I. gravity is known. The relationships involved are

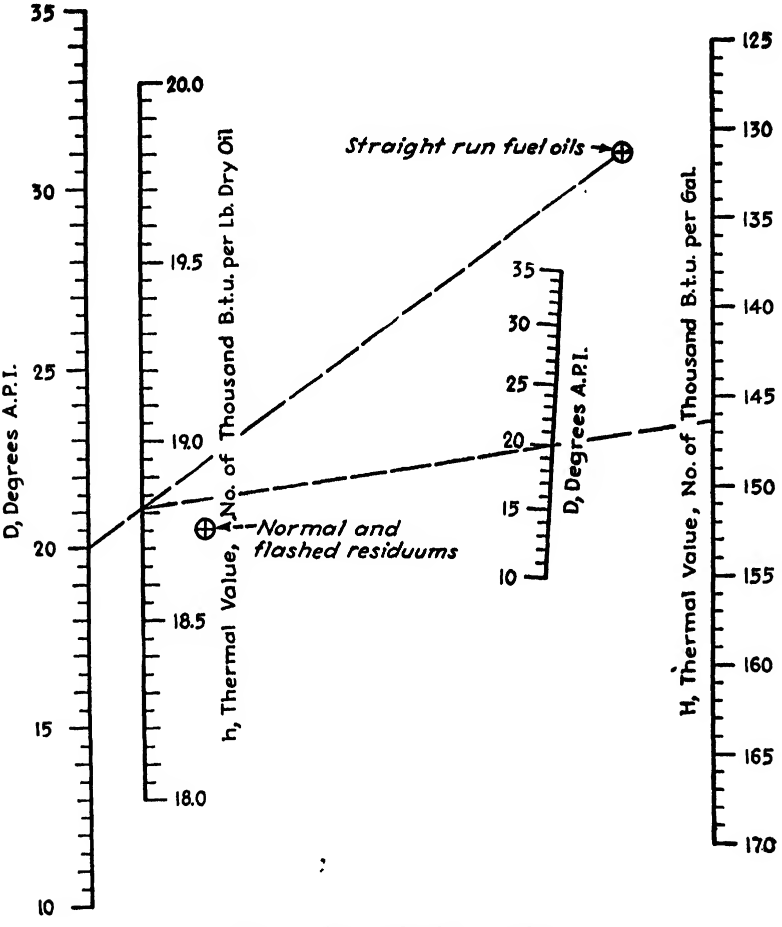

Fig. 51.—Thermal value of fuel oil.

$$h = 17{,}010 + 90D \text{ for straight-run oils}$$
$$h = 17{,}645 + 54D \text{ for normal and flashed residuums}$$
$$H = 8.33\delta h$$

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[1] *Nat. Petroleum News*, **24**, 31 (1932).

[2] Faragher, W. F., J. C. Morrell, and J. L. Essex, *Ind. Eng. Chem.*, **21**, 933 (1929).

and

$$\delta = \frac{141.5}{131.5 + D}$$

where h = thermal value, B.t.u./lb. of dry oil.
H = thermal value, B.t.u./gal. of dry oil.
D = A.P.I. gravity, deg.
δ = density, 60°F./60°F.

The use of the chart is illustrated as follows: What is the thermal value on the pound and gallon basis of a straight-run fuel oil testing 20° A.P.I.? As shown by the upper index line, connect 20 on the D scale at the left with the gauge point marked Straight-run fuel oils, and read the thermal value on the h scale as 18,810 B.t.u./lb. Connect this point with 20 on the slant D scale, and project the line to the H scale where the thermal value is read as 146,300 B.t.u./gal.

CHAPTER VIII

HEAT-TRANSFER COEFFICIENTS

FILM COEFFICIENTS OF HEAT TRANSFER FOR CONDENSATION OF PURE VAPORS[1]

When condensing a single pure vapor, saturated or superheated, the condensate wets the tube, and film-type condensation is obtained. The rate of heat transfer is given by the equation

$$q = h_m A_w (t_v - t_w)_m = h_m A_w (\Delta t)_m$$

where t_v is the saturation temperature of the vapor, t_w is the wall temperature, and h_m is the average coefficient between vapor and wall. So long as the condensate flows in streamline motion [$4\Gamma/\mu_f < 2{,}100$, where Γ is the mass rate of flow from each tube (lb.)/(hr.)(ft.) of wetted periphery measured on a plane normal to direction of fluid flow], the following dimensionless equations of Nusselt may be used:

For horizontal tubes:

$$\frac{h_m D}{k_f} = 0.73 \left(\frac{D^3 \rho_f^2 g_L \lambda}{k_f \mu_f n (\Delta t)_m} \right)^{0.25} = 0.76 \left(\frac{D^3 \rho_f^2 g_L}{\mu_f \Gamma} \right)^{\frac{1}{3}}.$$

For vertical tubes:

$$\frac{h_m L}{k_f} = 0.94 \left(\frac{L^3 \rho_f^2 g_L \lambda}{k_f \mu_f (\Delta t)_m} \right)^{0.25} = 0.93 \left(\frac{L^3 \rho_f^2 g_L}{\mu_f \Gamma} \right)^{\frac{1}{3}}.$$

These equations show that a tube of given dimensions, for the usual case where L/Dn exceeds 2.76, is more effective in a horizontal than in a vertical position. Thus for L/Dn of 100 a horizontal tube gives h_m 2.5 times that for a vertical tube. The values of k_f, ρ_f, and μ_f of the condensate are taken at a special film temperature $t_f = t_v - 0.75(\Delta t)_m$, and t_v is taken at the saturation temperature.

With vertical tubes and values of $4\Gamma/\mu_f$ below 2,100, values of h_m for film-type condensation of steam are 1.2 times those given by the vertical tube equation. Values of h_m on the vapor side of multitubular con-

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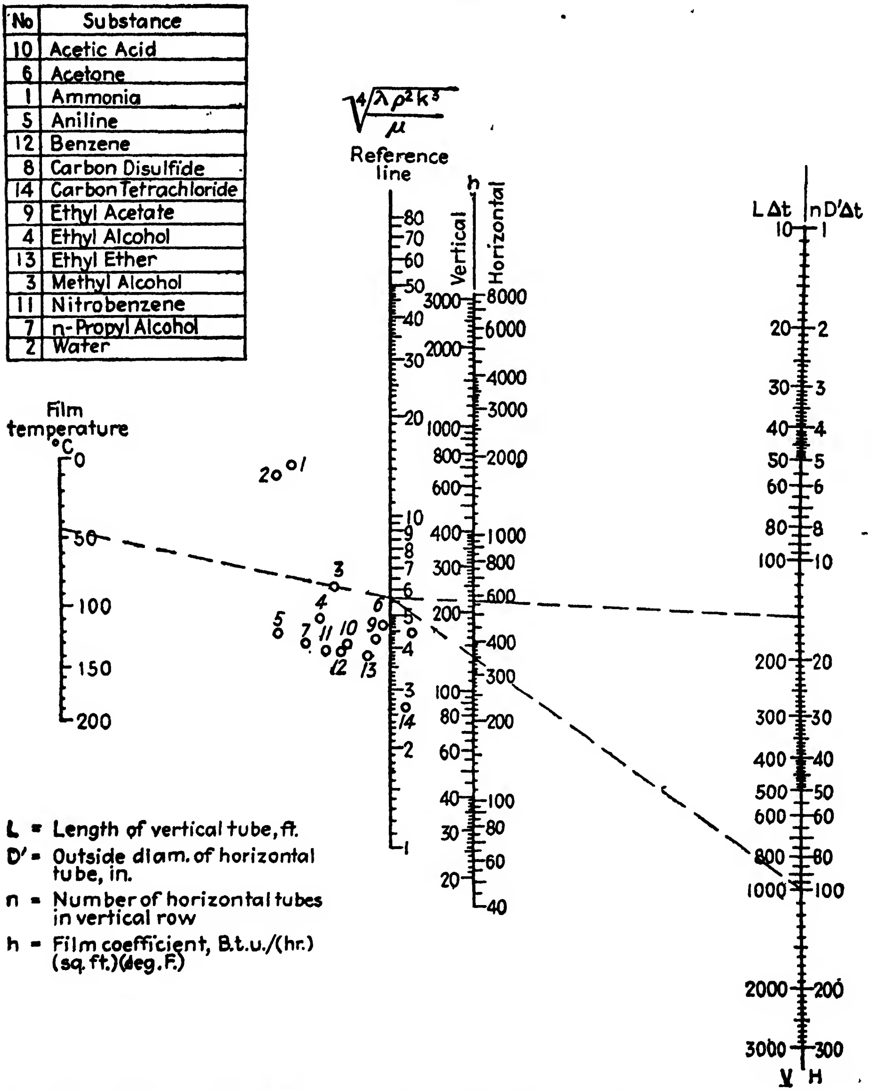
[1] PERRY, J. H., "Chemical Engineers' Handbook," 2d ed., p. 988, McGraw-Hill Book Company, Inc., New York, 1941.

densers with horizontal tubes are not available. The horizontal-tube equation may be used as an approximation.

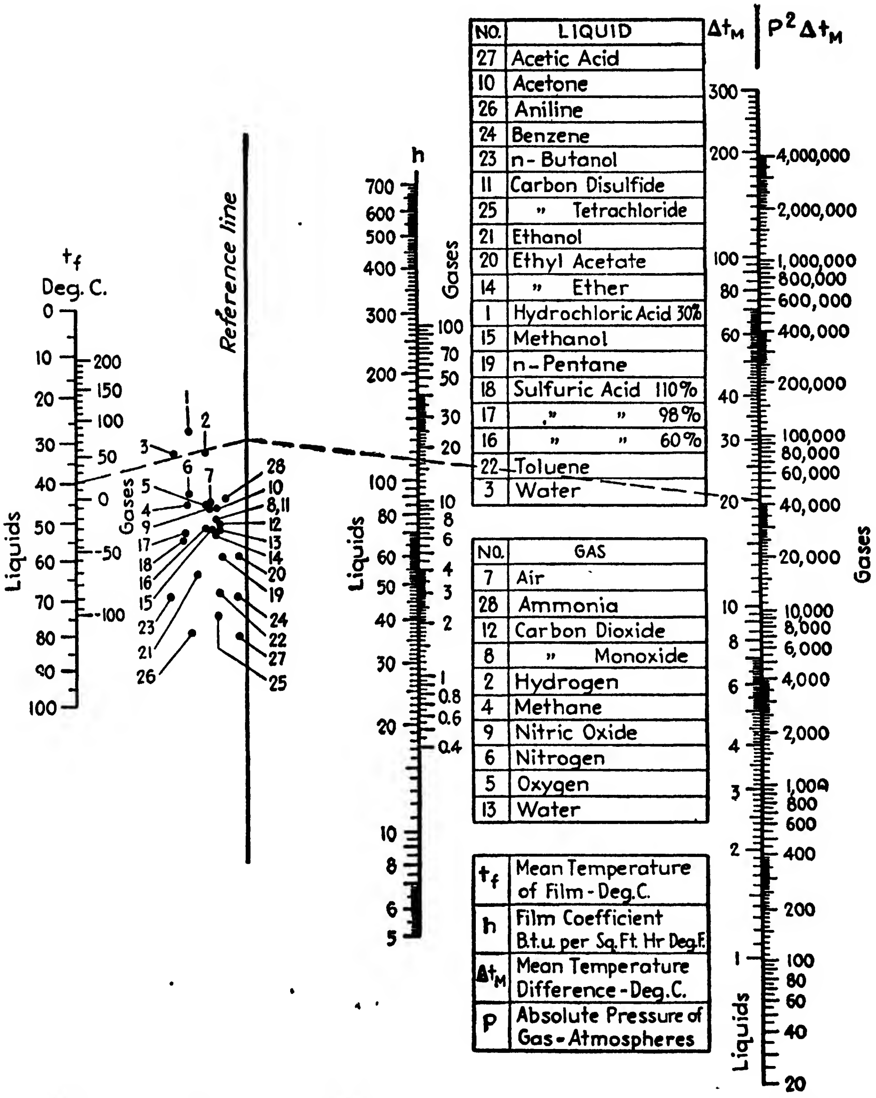


No	Substance
10	Acetic Acid
6	Acetone
1	Ammonia
5	Aniline
12	Benzene
8	Carbon Disulfide
14	Carbon Tetrachloride
9	Ethyl Acetate
4	Ethyl Alcohol
13	Ethyl Ether
3	Methyl Alcohol
11	Nitrobenzene
7	n-Propyl Alcohol
2	Water

L = Length of vertical tube, ft.
D′ = Outside diam. of horizontal tube, in.
n = Number of horizontal tubes in vertical row
h = Film coefficient, B.t.u./(hr.)(sq. ft.)(deg. F.)

FIG. 52.—Film coefficient h_m for film-type condensation of pure vapors. For vertical tubes multiply h_m by 1.2.

Figure 52 is an alignment chart (from Chilton and Drew) based on the horizontal- and vertical-tube equations. For long vertical tubes, $4\Gamma/\mu_f$ may exceed 2,100, in which case turbulence develops in the outer portion of the condensate layer, thus increasing h_m above the values predicted by the equations.



NO.	LIQUID
27	Acetic Acid
10	Acetone
26	Aniline
24	Benzene
23	n-Butanol
11	Carbon Disulfide
25	" Tetrachloride
21	Ethanol
20	Ethyl Acetate
14	" Ether
1	Hydrochloric Acid 30%
15	Methanol
19	n-Pentane
18	Sulfuric Acid 110%
17	" " 98%
16	" " 60%
22	Toluene
3	Water

NO.	GAS
7	Air
28	Ammonia
12	Carbon Dioxide
8	" Monoxide
2	Hydrogen
4	Methane
9	Nitric Oxide
6	Nitrogen
5	Oxygen
13	Water

t_f	Mean Temperature of Film - Deg. C.
h	Film Coefficient B.t.u. per Sq. Ft. Hr Deg. F.
Δt_M	Mean Temperature Difference - Deg. C.
P	Absolute Pressure of Gas - Atmospheres

FIG. 53.—Film coefficients for fluids flowing upward at low velocities inside vertical tubes.

FILM COEFFICIENTS FOR FLUIDS IN VERTICAL PIPES[1]

The following Nusselt-type dimensionless equation correlates the data for fluids flowing upward at low velocities in vertical pipes:

$$\frac{h_m}{[k_f^2\rho_f^2c_pg_L\beta(\Delta t)/\mu_f]^{\frac{1}{3}}} = 0.13$$

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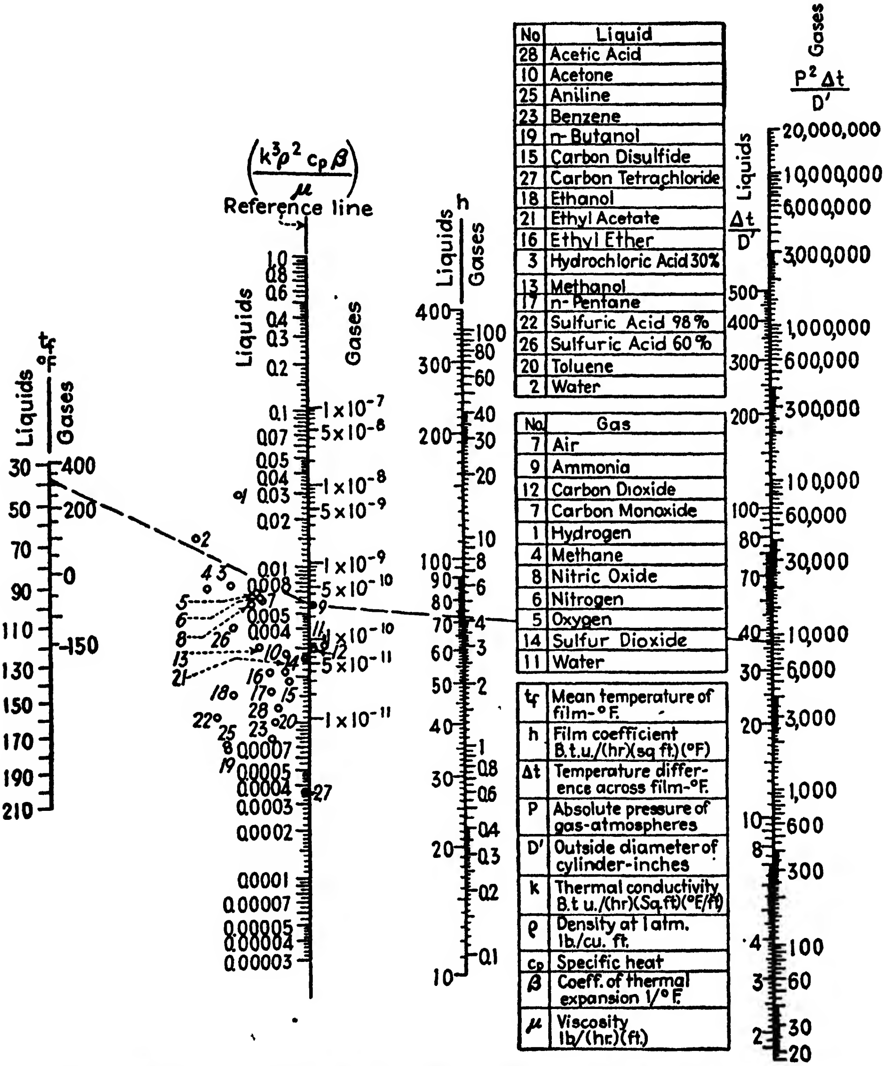
[1] PERRY, *op. cit.*, p. 979.

Although confirmed only for water and air, this equation is the best now available for the warming or cooling of fluids at low velocities in vertical pipes. Figure 53 is based on the above equation and shows the relation



No	Liquid
28	Acetic Acid
10	Acetone
25	Aniline
23	Benzene
19	n-Butanol
15	Carbon Disulfide
27	Carbon Tetrachloride
18	Ethanol
21	Ethyl Acetate
16	Ethyl Ether
3	Hydrochloric Acid 30%
13	Methanol
17	n-Pentane
22	Sulfuric Acid 98%
26	Sulfuric Acid 60%
20	Toluene
2	Water

No.	Gas
7	Air
9	Ammonia
12	Carbon Dioxide
7	Carbon Monoxide
1	Hydrogen
4	Methane
8	Nitric Oxide
6	Nitrogen
5	Oxygen
14	Sulfur Dioxide
11	Water

t_f	Mean temperature of film-°F.
h	Film coefficient B.t.u./(hr)(sq ft)(°F)
Δt	Temperature difference across film-°F.
P	Absolute pressure of gas-atmospheres
D'	Outside diameter of cylinder-inches
k	Thermal conductivity B.t u./(hr)(Sq.ft)(°F/ft)
ρ	Density at 1 atm. lb./cu. ft.
c_p	Specific heat
β	Coeff. of thermal expansion 1/°F.
μ	Viscosity lb/(hr.)(ft.)

FIG. 54.—Heat transfer coefficients h_o for natural convection outside horizontal cylinders.

among the substances involved, the temperature of the film, the temperature difference, and the coefficient h. For use with gases, a pressure term appears on the chart.

HEAT-TRANSFER COEFFICIENTS, FOR NATURAL CONVECTION, OUTSIDE HORIZONTAL CYLINDERS[1]

For the general case of free or natural convection of heat between a solid and a fluid, without change in state, Nusselt, Davis, Rice, and others suggest the dimensionless equation

$$\frac{h_c D}{k_f} = \frac{1}{\alpha}\left(\frac{D^3 \rho_f^2 g_L \beta \Delta t}{\mu_f^2}\right)^n \left(\frac{c_p \mu_f}{k_f}\right)^m.$$

Fluids outside Single Horizontal Cylinders.—For pipes having a large ratio of length to diameter, Rice gives $\alpha = 2.60$, $n = 0.27$, and $m = 0.25$; for approximate results, $\alpha = 2.12$, $n = m = 0.25$. Based on the approximate equation of Rice, Fig. 54 is an alignment chart predicated on the temperature of the film (arithmetic mean of the temperatures of the wall and fluid) expressed in degrees centigrade, the absolute pressure in atmospheres, and the diameter D of the pipe in inches. While based on data for air, hydrogen, carbon dioxide, aniline, carbon tetrachloride, glycerin, olive oil, and toluene, reference points are shown to facilitate the extrapolation of these results to certain fluids other than those tested.

In the equations of this chapter,

q = rate of heat transfer, B.t.u./hr.
h_m and h_c = film coefficients, B.t.u./(hr.)(sq. ft.)(°F.)
A_w = heat transfer area, sq. ft.
$(\Delta t)_m$ = mean temperature difference, °F.
D = inner diameter of pipe, ft.
k = thermal conductivity
c_p = specific heat at constant pressure
ρ = density
μ = viscosity
β = coefficient of expansion
g_L = gravitational constant
λ = latent heat of vaporization, B.t.u./lb.
n = number of tubes in a vertical plane
L = heated length of transfer surface, ft.

All values are to be expressed in consistent units, and k, ρ, β, and μ are to be read at the average temperature of the film.

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[1] Perry, *op. cit.*, p. 985.

CHAPTER IX

MILK AND CREAM NOMOGRAPHS

MILK-SOLIDS NOMOGRAPH[1]

The total solids content of milk can be calculated satisfactorily and with greater ease than it can be determined. In the matter of data, one needs only the percentage of butter fat and the specific gravity, generally known among milk chemists as the *Quevenne lactometer reading.*

The variables are related by the following equation, which is an algebraic rearrangement of a relationship given by Lange:[2]

$$S = \frac{6}{5}F + \frac{L}{4} + 0.14$$

where S = percentage of total milk solids.
F = percentage butter fat.
L = Quevenne lactometer reading, corrected to 60°F., where the lactometer reading is defined as 1,000 (specific gravity − 1).

Figure 55 is designed to solve the equation rapidly and accurately. Its use is illustrated by the broken line which shows that milk testing 3.5 per cent butter fat and with a lactometer reading of 33 at 60°F. (specific gravity of 1.033) contains 12.6 per cent total solids.

SOLIDS-NOT-FAT NOMOGRAPH[3]

Hawley[4] has developed an expression for the percentage of solids-not-fat in milk when the specific gravity of the milk and its percentage of milk fat are known. The equation, in substantially the form in which he gives it, is

$$S.N.F. = 287.2\left(\frac{D - 1}{D}\right) + 0.328F$$

where $S.N.F.$ denotes the percentage of solids-not-fat, D the specific gravity at 85°F./60°F., and F the percentage of milk fat.

Figure 56 has been prepared for the purpose of facilitating the solution of this interesting equation. The broken line indicates that milk, with a

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[1] Davis, D. S., "Empirical Equations and Nomography," pp. 94, 95, McGraw-Hill Book Company, Inc., New York, 1943.

[2] Lange, N. A., "Handbook of Chemistry," p. 526, Handbook Publishing Co., Sandusky, Ohio, 1934.

[3] *Chemist-Analyst*, **30**, 80 (1941).

[4] Hawley, H., *Analyst*, **58**, 272 (1933).

specific gravity of 1.027 and having a fat content of 4.4 per cent, would contain 9.0 per cent of solids not fat.

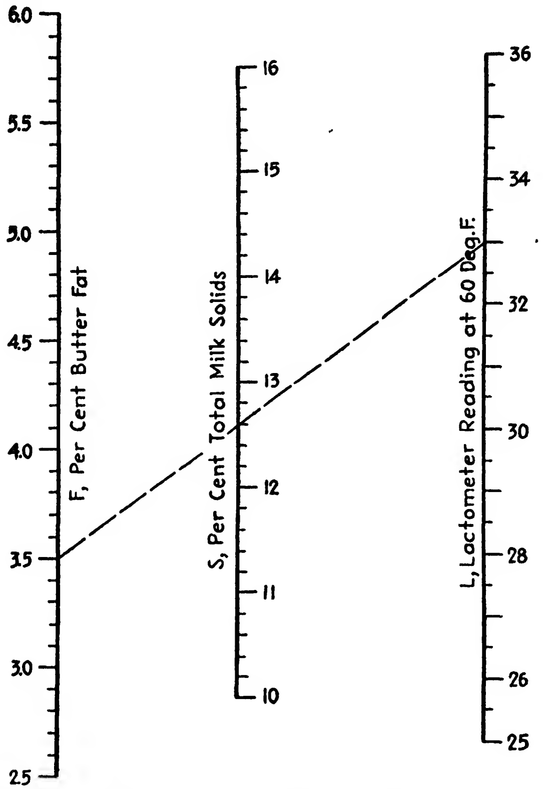

FIG. 55.—Milk-solids content from percentage of butter fat and lactometer reading.

PREPARING CREAM WITH A DESIRED FAT CONTENT[1]

Cream having a predetermined fat content is commonly prepared by diluting high-fat cream with milk. This operation involves a calculation that may be advantageously handled by means of an alignment chart as well as determined mathematically.

In making this mixture, it is evident that the fat contents of the milk and of the cream must be taken into consideration. M lb. of milk with m per cent of fat contains $Mm/100$ lb. of fat, and C lb. of cream with a per cent of fat provides $Ca/100$ lb. of fat. Together they give a total of $(Mm + Ca)/100$ lb. of fat. This is to say, that together, if chosen in the proper proportions, the mixtures give a cream in which the total weight of fat is $[(M + C)d]/100$, in which d is the desired percentage of fat content.

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[1] *Food Ind.*, **4**, 314 (1932).

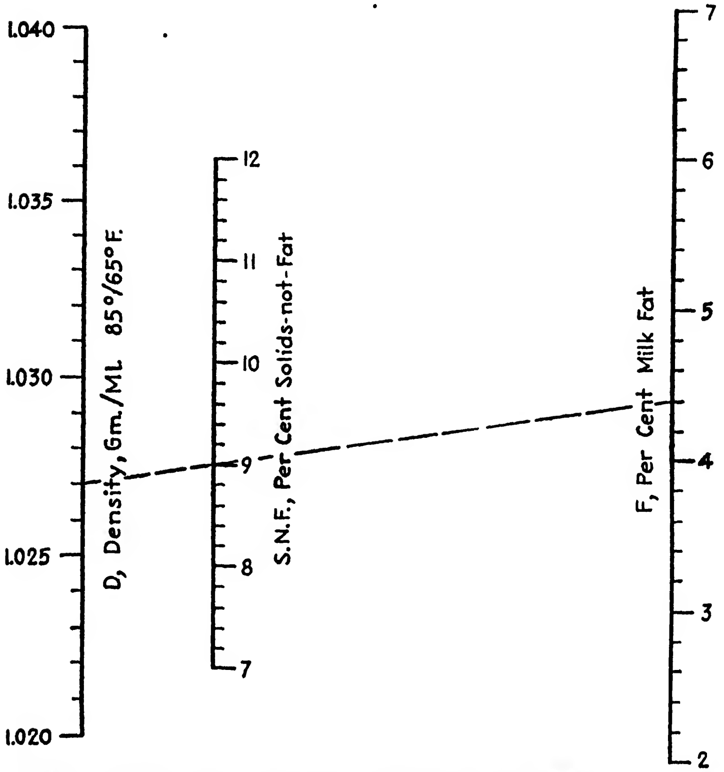

FIG. 56.—Solids-not-fat content from density and percentage fat, for milk.

Equating the two expressions for the total weight of fat, the mathematical statement becomes

$$\frac{Mm + Ca}{100} = \frac{(M + C)d}{100},$$

from which we get

$$M = \frac{a - d}{d - m} C. \tag{13}$$

Substituting the usual value for fat content of milk ($m = 3.5$), Eq. (13) becomes

$$M = \frac{a - d}{d - 3.5} C. \tag{14}$$

Equation (14), which requires two operations of subtraction and one each of division and multiplication, is the step in the calculation which may be solved quickly and accurately by means of Fig. 57. Its use may be illustrated as follows: How much milk with a fat content of 3.5 per cent should be mixed with 2,500 lb. of heavy cream having a fat content of 30.0 per cent to prepare a coffee cream with a fat content of 18 per cent? Following the key, connect 30.0 on the *a* scale with 18 on the *d* scale and produce the broken line to meet the diagonal. Connect this latter intersection with 2,500 on the *C* scale, and produce the second broken line to meet the *M* scale in the desired value, 2,070 lb. of milk.

The chart permits values of *M* to be estimated to the nearest 10 lb. and, though rigorously correct only for values of $m = 3.5$ per cent, it can

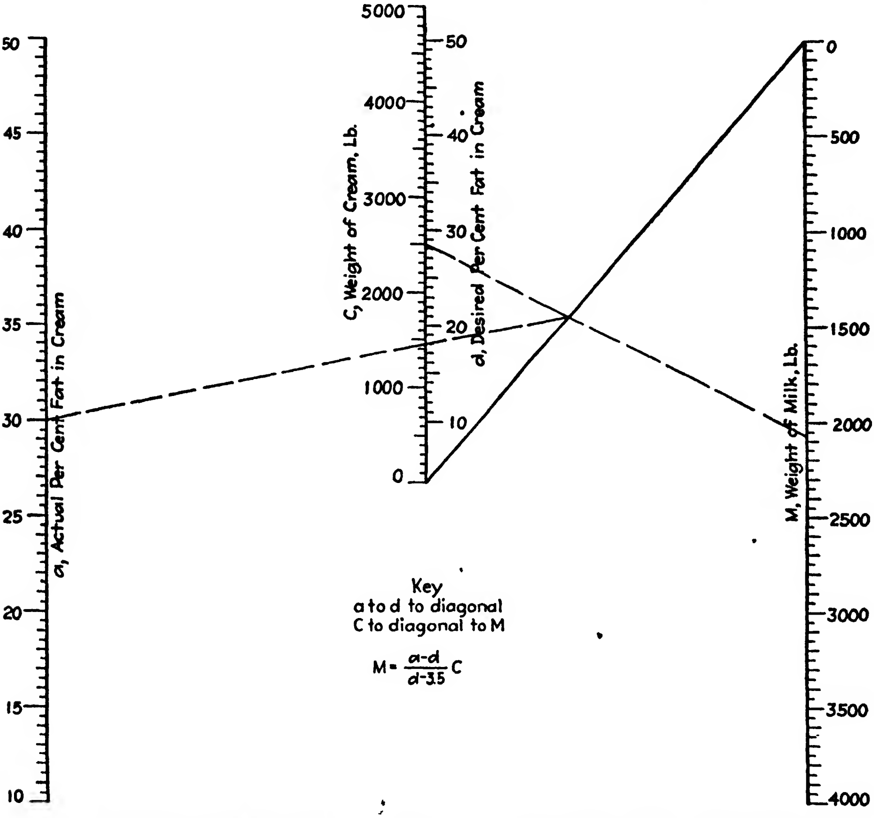

FIG. 57.—Weight of milk required to prepare cream of a desired fat content from a given weight of heavy cream.

be used without serious error when the fat content of the milk varies somewhat from this amount. When the true value of *m* exceeds 3.5 per cent, the use of the chart will result in values of *M* which are slightly low, the percentage discrepancy decreasing with increasing values of *d*. This is shown in the following table, which covers the case of milk with an actual fat content of 3.7 per cent:

d, per cent	15	25	35	45
Percentage error in *M*	−1.7	−0.9	−0.6	−0.5

CHAPTER X

NOMOGRAPHS OF INTEREST TO THE PAPER INDUSTRY

BLEACH-CONSUMPTION NOMOGRAPH[1]

Figure 58 deals with the calculation of bleach requirement V in gallons of bleach liquor per ton of paper pulp when laboratory tests have shown the bleach consumption for the pulp to be p per cent of 35 per cent bleach and the concentration of chlorine in the bleach liquor to be c g./l. The equation is

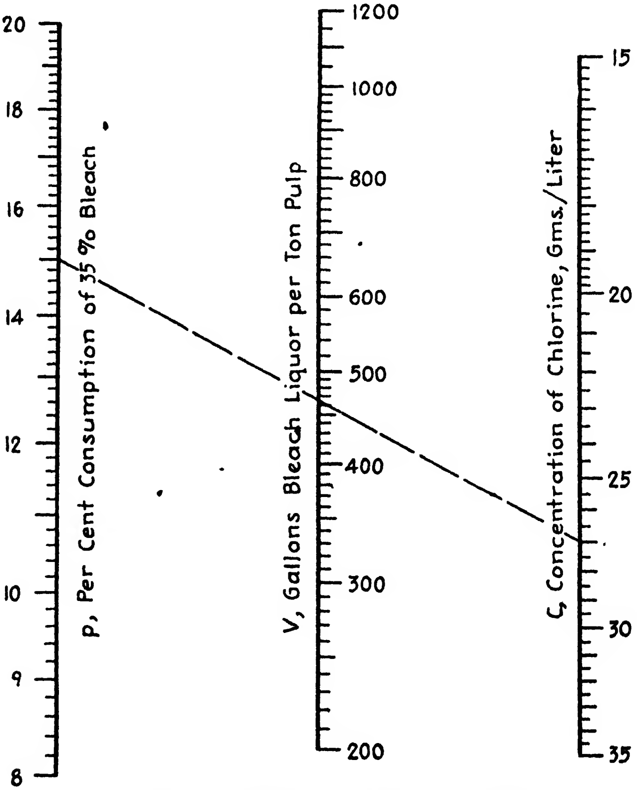

FIG. 58.—Bleach consumption per ton of paper pulp.

$$V = 838.8 \frac{p}{c}.$$

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[1] *Paper Trade J.*, **95** (9), Tappi Sec., p. 106 (1932).

The broken line indicates that 466 gal. of bleach liquor, analyzing 27 g. of chlorine per liter, will be required to bleach 1 ton of pulp when the bleach consumption is 15 per cent, expressed as 35 per cent bleach.

CALENDER-ROLL-WEIGHT NOMOGRAPH[1]

Figure 59 presents calender roll weight data[2] in convenient nomographic form, enabling rapid solution of the equation

$$W = \frac{LD^2}{8{,}000}$$

which gives an approximation of the weight W, in tons, of a calender roll when the length of face L, in inches, and the diameter of the roll D, in inches, are known.

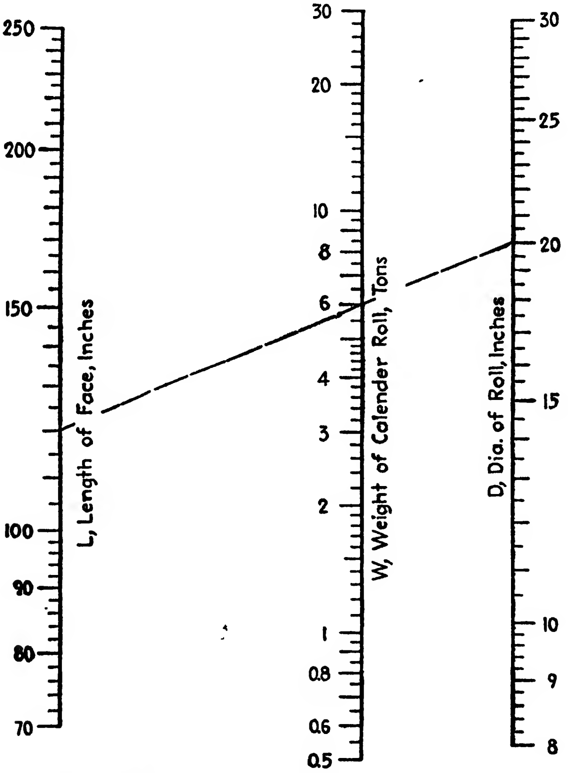

FIG. 59.—Weight of calender rolls from their dimensions.

The dashed line indicates that a 20-in. roll, 120 in. long, weighs 6 tons.

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[1] *Paper Ind.*, **13**, 859 (1931).

[2] Pulp and Paper Mill Catalogue, p. 265, 1930.

CORE-WASTE NOMOGRAPH[1]

In connection with combating losses from various converting operations, it is frequently necessary to determine waste due to paper left upon cores. This can be done by stripping the waste paper from the core and weighing it, but an entirely satisfactory estimate may be made by calculating the weight from the measured depth of paper on the core or, if greater precision is desired, from the measured circumference of the nearly depleted roll.

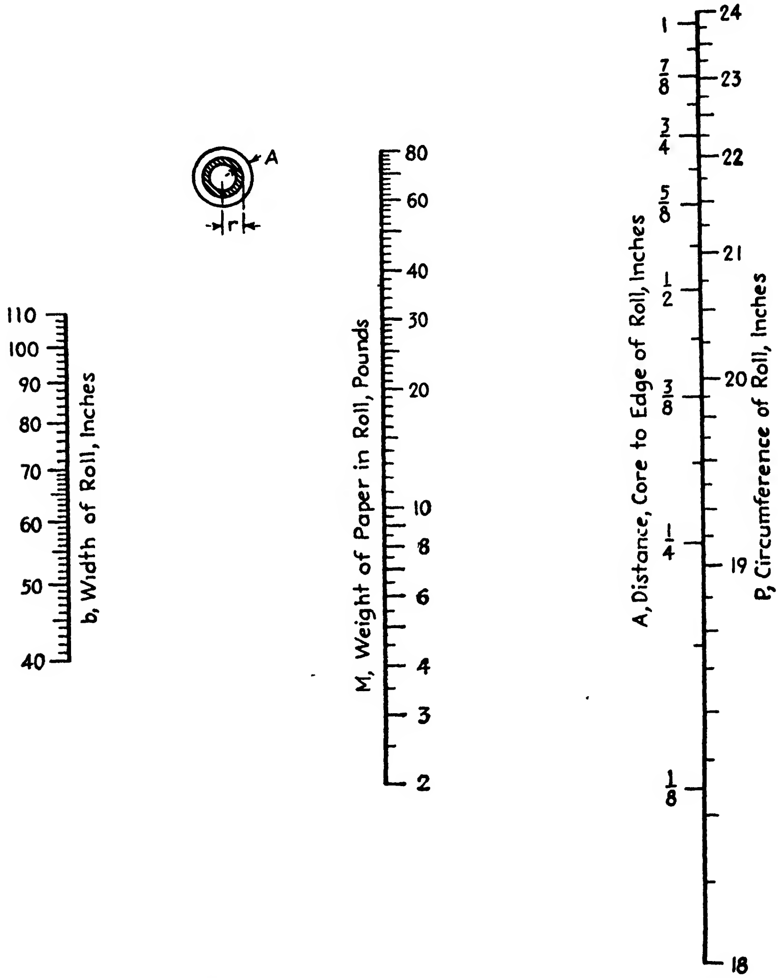

FIG. 60.—Weight of paper left on a core, from the roll dimensions.

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[1] *Paper Ind. & Paper World*, **24**, 373 (1942).

Derivation of Equation.—With reference to the inserted figure on the chart (Fig. 60) let

A = distance, core to edge of roll, in.
r = radius of core, in.
L = unwound length of paper, ft.
c = average caliper, in.

Equating expressions for the area of paper in an end view of the roll and the area of the edge when unwound,

$$\pi[(A + r)^2 - r^2] = 12Lc$$

from which

$$L = \frac{\pi A(A + 2r)}{12c}.$$

Where b = width of roll, in.
R = basis weight, lb., 25 by 38 in., 500
M = weight of roll, lb.

$$L = \frac{M(25)(38)(500)(12)}{R(144)b}$$

from which

$$M = \frac{6.614RbA(A + 5.575)}{c} \times 10^{-6} \qquad (15)$$

where $2r$ = core diameter = 5.575 in.
Let P = circumference of the nearly depleted roll,
p = circumference of the core of diameter, d.

Then

$$2A + d = \frac{P}{\pi}$$

from which

$$A = \frac{\frac{P}{\pi} - d}{2} = \frac{P}{2\pi} - \frac{d}{2}$$

$$A + d = \frac{P}{2\pi} + \frac{d}{2}$$

$$A(A + d) = \left(\frac{P}{2\pi} - \frac{d}{2}\right)\left(\frac{P}{2\pi} + \frac{d}{2}\right) = \frac{P^2 - p^2}{4\pi^2}. \qquad (16)$$

The ratio R/c is fairly constant for a given grade of paper and may be taken as 14,960. When this value and Eq. (16) are substituted in Eq. (15), there results

$$M = \frac{b}{4}(P^2 - 306.95) \times 10^{-2} = 0.0989bA(A + 5.575).$$

For cores other than 5.575 in. in diameter and paper for which R/c is not 14,960, suitable adjustment of the equation must be made.

Use of the Nomograph.—The equation is readily solved by Fig. 60, the use of which is illustrated as follows: What is the waste for an 81-in. roll when $\frac{3}{4}$ in. of paper is left on the core? Connect 81 on the b scale with $\frac{3}{4}$ on the A scale, and read the core waste on the M scale as 38 lb. What is the waste for a 102-in. roll when the circumference of the nearly depleted roll is 22.5 in.? Connect 102 on the b scale with 22.5 on the P scale, and read the core waste as 51 lb. on the M scale.

The Waste-tape Method.—For rolls of the same width, the amount of core waste may be estimated very quickly by using a specially graduated metal or cloth tape reading in pounds directly. Thus, for 100-in. rolls,

$$M = \frac{P^2 - 306.95}{4},$$

and the circumference for any given weight may be calculated by the equation

$$P = \sqrt{4M + 306.95}.$$

Such values are given in Table VIII.

TABLE VIII

M, lb.	P, in.	M, lb.	P, in.	M, lb.	P, in.
4	17.97	18	19.47	44	21.97
6	18.19	20	19.67	48	22.35
8	18.42	24	20.07	52	22.70
10	18.63	28	20.47	56	23.05
12	18.85	32	20.85	60	23.39
14	19.05	36	21.24	64	23.73
16	19.26	40	21.61	68	24.06

NOMOGRAPHIC SOLUTION OF PAPER-DRYING CALCULATIONS[1]

In connection with making a materials balance on a paper machine, the engineer is concerned with the amount of water evaporated per unit weight of paper at dry-end conditions and with the amount of water evaporated per unit weight of bone-dry paper.

The former value may be calculated from the equation

$$w = \frac{M - m}{100 - M} \tag{17}$$

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[1] *Paper Ind.*, **14**, 36 (1932).

where M is the percentage moisture in the sheet as it goes to the driers, m is the percentage moisture in the sheet at the dry end, and w is the number of pounds of water evaporated per pound of paper of moisture content, m. The latter value may be found by solving the equation

$$W = \frac{100(M - m)}{(100 - M)(100 - m)} \tag{18}$$

where W is the number of pounds of water evaporated per pound of bone-dry paper and M and m have the same significance as before.

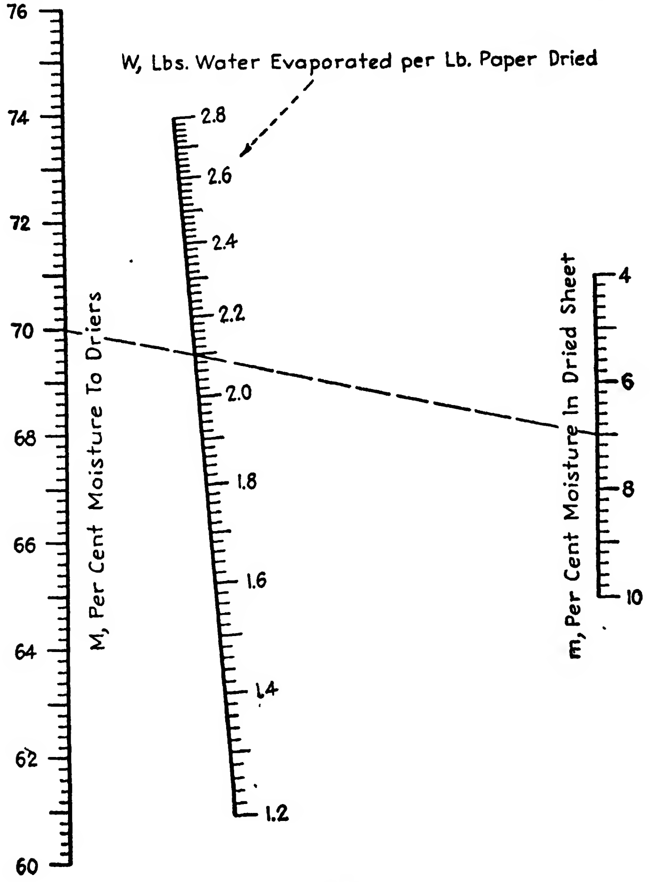

FIG. 61.—Paper drying.

Equations (17) and (18) may be solved most conveniently by means of the alignment charts of Figs. 61 and 62. In Fig. 61, the broken line indicates that 2.10 lb. of water are evaporated per pound of paper dried when the moisture content of the dried paper is 7 per cent and when the sheet as it goes to the driers contains 70 per cent moisture. In Fig. 62, the broken line shows that when the sheet contains 70 per cent moisture as it goes to the driers and 5 per cent moisture when dried, 2.28 lb. of water are evaporated per pound of bone-dry paper produced.

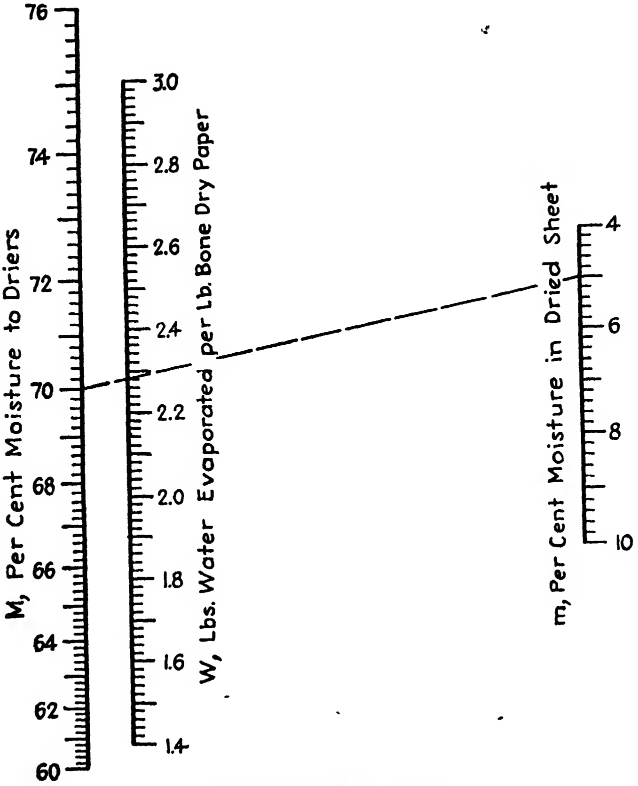

FIG. 62.—Paper drying.

EFFLUENT-LOSS NOMOGRAPH[1]

In determining the amount and cost of paper-mill effluent losses, it is customary to measure the rate of flow of white water by means of a rectangular uncontracted weir, to determine the average consistency of the white water, and to place a valuation on the fiber so lost. The rate of flow Q in gallons per minute is given by the Francis formula

$$Q = 3.00BH^{1.5}$$

where B is the width of the weir and H is the head on the weir, both in inches. The stock loss W in pounds of air-dry pulp per 24 hr. is given by

$$W = 13.33QC = 40BCH^{1.5}$$

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[1] *Paper Trade J.*, **94** (2), 31 (1932).

where *C* is the oven-dry consistency, grams per liter. The value *L* of this lost fiber in dollars per day is given by

$$L = \frac{WP}{2{,}000} = \frac{BCPH^{1.5}}{50}$$

where *P* is the price of the pulp, dollars per ton, air-dry.

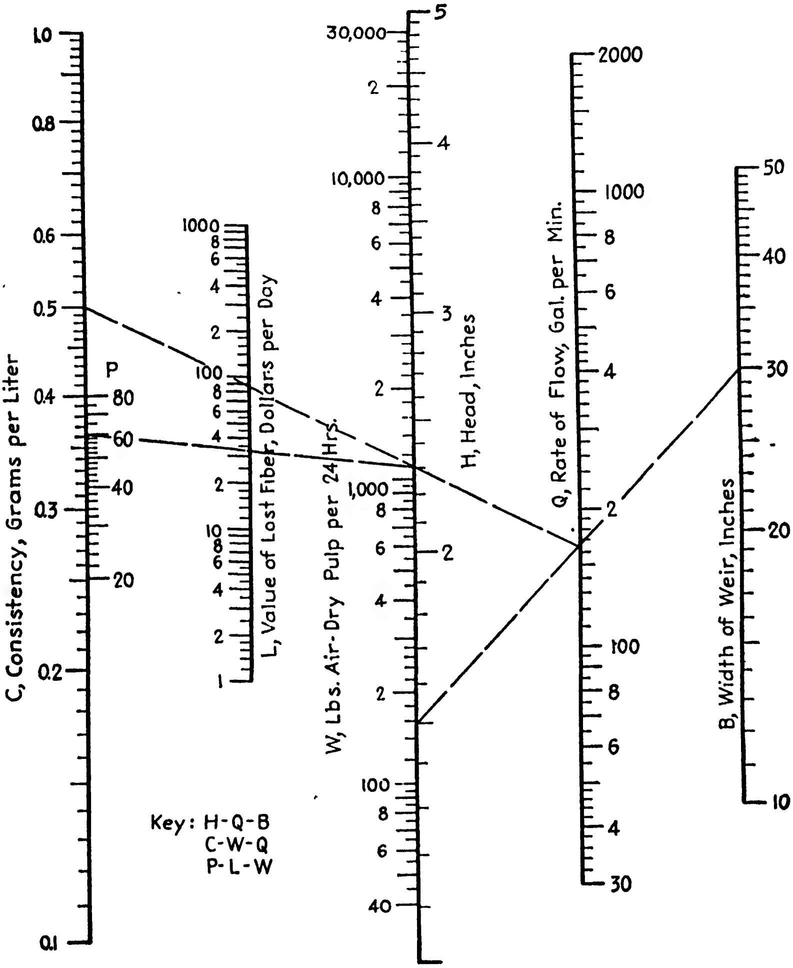

FIG. 63.—Effluent loss.

The use of Fig. 63 is illustrated as follows: Given the average head as 1.5 in. on a 30-in. weir when the average consistency of the white water is 0.5 g./l. and the fiber is valued at $60 per ton, what is the rate of flow, the daily stock loss, and the value of the stock so lost? Connect 1.5 on the *H* scale with 30 on the *B* scale, and read the rate of flow as

165 gal./min. on the Q scale. Connect 165 on the Q scale with 0.5 on the C scale, and read the daily stock loss as 1,100 lb. air-dry. Connect 1,100 on the W scale with 60 on the P scale, and read the value of the daily effluent loss as \$33 on the L scale.

FILLER-RETENTION NOMOGRAPH[1]

Nearly every paper-mill superintendent and chemist is called upon to estimate expected filler retention when changing from one basis weight to another. According to Perekalsky and Tomaschewa,[2] this situation is covered by the expression

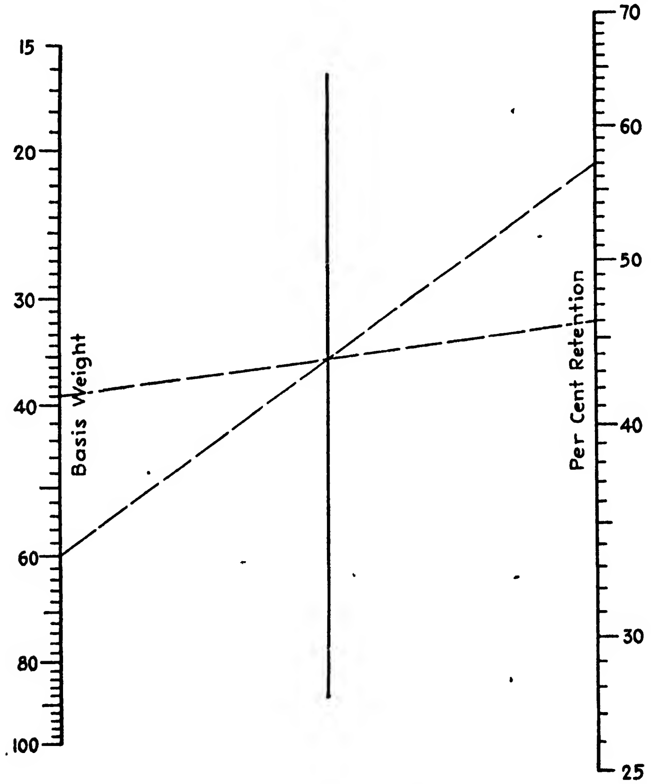

Fig. 64.—Filler retention.

$$R_1 = R_2\sqrt{\frac{W_1}{W_2}}$$

where R_1 and R_2 are percentage filler retentions at basis weights of W_1 and W_2, respectively.

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[1] *Paper Ind.*, **18**, 115 (1936).

[2] Perekalsky, N., and N. Tomaschewa, *Zellstoff u. Papier*, **14** (No. 8), 319 (1934).

Figure 64 will be found to be the most convenient means of handling computations by this equation. Its use is illustrated as follows: Fifty-seven per cent filler retention is experienced with a 60-lb. sheet. What retention may be expected upon decreasing the sheet weight to 39 lb.? Connect 60 on the basis weight scale with 57 on the percentage-retention scale, and note the intersection with the central axis. Connect this point with 39 on the basis-weight scale, and produce the line to the desired value on the retention scale, 46 per cent.

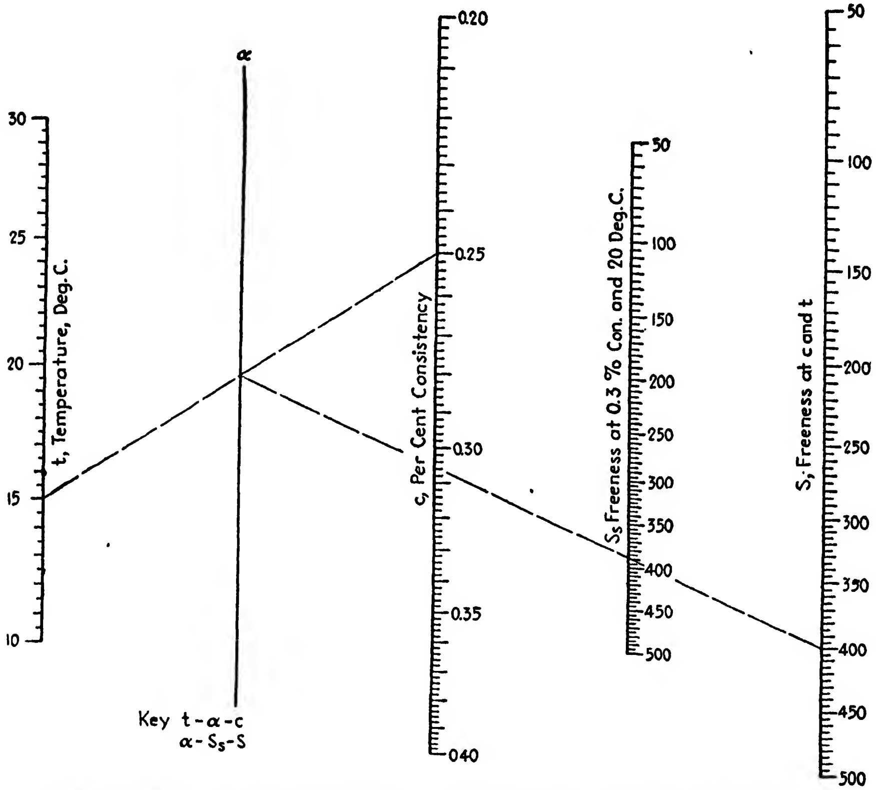

FIG. 65.—Consistency and temperature corrections for the Canadian Standard Freeness tester.

The legend for the basis-weight scale does not specify the units, pounds per ream or grams per square meter, since these are immaterial as long as they are consistent.

NOMOGRAPHIC FREENESS-CORRECTION CHART[1]

The use of Fig. 65, based upon the same theory as the original Canadian Standard temperature and consistency correction charts, is illus-

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[1] *Pulp and Paper Mag. Can.*, **31** (19), 586 (1931).

trated as follows: Given a freeness value of 400 determined at 0.25 per cent bone-dry consistency and 15°C., what is the freeness under standard conditions, *i.e.*, 0.30 per cent consistency and 20°C.? Following the key and the index lines, connect 15 on the t scale with 0.25 on the C scale, and from the point of intersection of this dashed line with the α axis draw a line to 400 on the S scale. The latter dashed line will cut the S_s scale in the desired value, 388. The chart can also be used to convert values to conditions other than the standard as follows: Given a freeness value of 400 determined at 0.25 per cent and 15°C., what is the freeness at 0.35 per cent and 25°C.? Proceed as before, determining 388 as the value under standard conditions. Connect 25 on the t scale with 0.35 on the C scale, and from the intersection of this line with the α axis draw a line to 388 on the S_s scale, producing this latter line to intersect the S scale in the desired value, 382. Index lines for this illustration are not shown.

KRAFT-PRODUCTION NOMOGRAPH[1]

Paper-machine production may be calculated by means of the formula

$$P = KW\theta BV$$

where K is a constant depending upon the units
and where P = production, tons
W = width, in.
θ = operating time, hr.
B = basis weight, pounds per ream (24 by 36 in., 480).
V = machine speed, ft./min.
K = 1/1,152,000.

and the equation is suitable for calculation of kraft production.

The use of Fig. 66 is illustrated as follows: How much 40-lb. kraft can be made on a 170-in. machine operating for 23 hr. at a speed of 500 ft./min.? Following the key, connect 170 on the W scale with 23 on the θ scale, and from the intersection of this line with the P axis draw a line to 40 on the B scale. From the intersection of this latter line with the α axis, draw a line to 500 on the V scale, crossing the P scale at the desired value, 68 tons.

NOMOGRAPHS FOR RIGIDITY, STIFFNESS, AND SOFTNESS OF PAPER[2]

Clark[3] has described very valuable methods for the determination of the rigidity, stiffness, and softness of paper. In this connection, he has defined (1) the *rigidity* of paper as the property of resisting an applied

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[1] *Paper Trade J.*, **94** (2), 31 (1932).

[2] *Paper Ind.*, **17**, 409 (1935).

[3] Clark, James d'A., *Paper Trade J.*, **100** (13) 169, 1935.

force; (2) the *rigidity factor* as a measure of the rigidity of the structure of the sheet and proportional to the modulus of rigidity; (3) the *stiffness* of paper as its ability to support its own weight; and (4) the *softness* of paper as the feeling of softness when the sheet is crumpled in the hand, which property depends upon the ease of crumpling and the absence of sharp edges in the crumpled sheet.

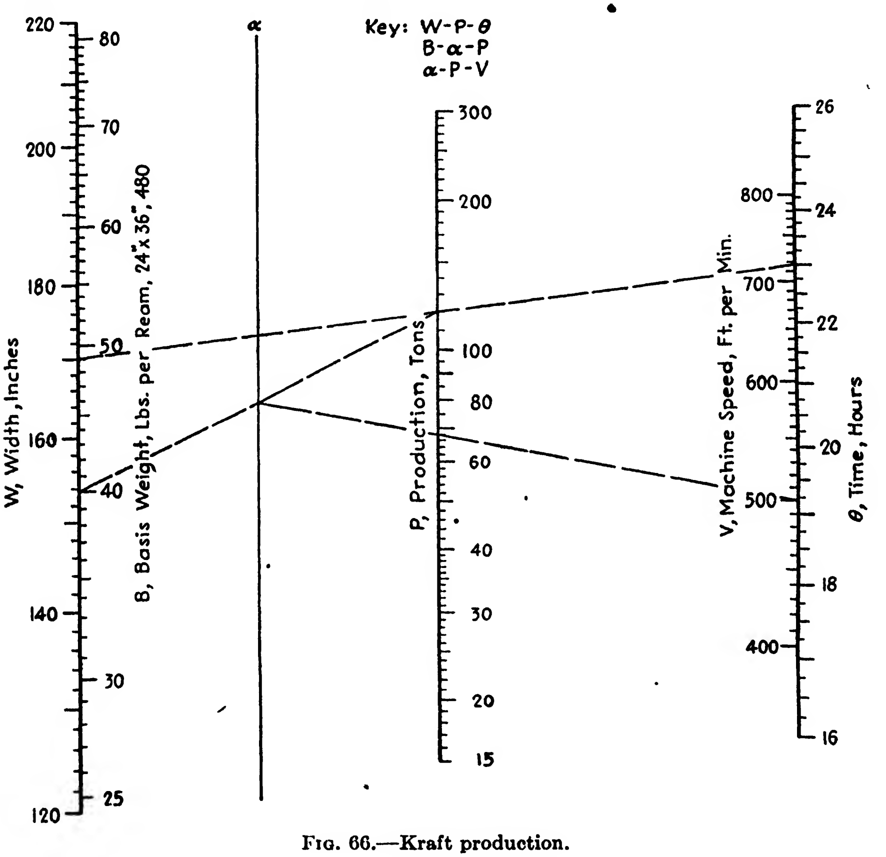

Fig. 66.—Kraft production.

In addition to describing a sturdy mechanical device for performing the tests, Clark presents a simplified field method which brings these extremely practical determinations within the reach of all. The specimen is cut with parallel edges in each principal direction of the paper and is about 50 mm. (2 in.) wide and over 75 mm. (3 in.) long or as long as may be convenient. "For field tests a threefold pocket rule may be used to give fairly accurate results. The test is made by cutting a parallel strip of the paper, inserting it between two of the folded sections of the rule. Using the third section opened at right angles to the other two as a pointer, and the square edge of the remaining paper to indicate when the sweep of the pointer is through a right angle, the folded section carrying the strip is held in a horizontal position on the edge of a table and rotated." The overhanging length of the strip is adjusted until the specimen just falls through the vertical on being rotated through 90 deg. The overhanging length is then measured, and the caliper and basis weight are determined in the usual manner. The basic caliper of creped paper is measured by means of a dial micrometer using strips of paper cut in the machine direction and about 15 mm. ($\frac{5}{8}$ in.) wide. A single strip is placed between the jaws of the micrometer which should have a closing pressure of 1 lb./sq. in., and the paper is stretched with the fingers. The minimum reading just before the strip breaks is recorded as the basic caliper.

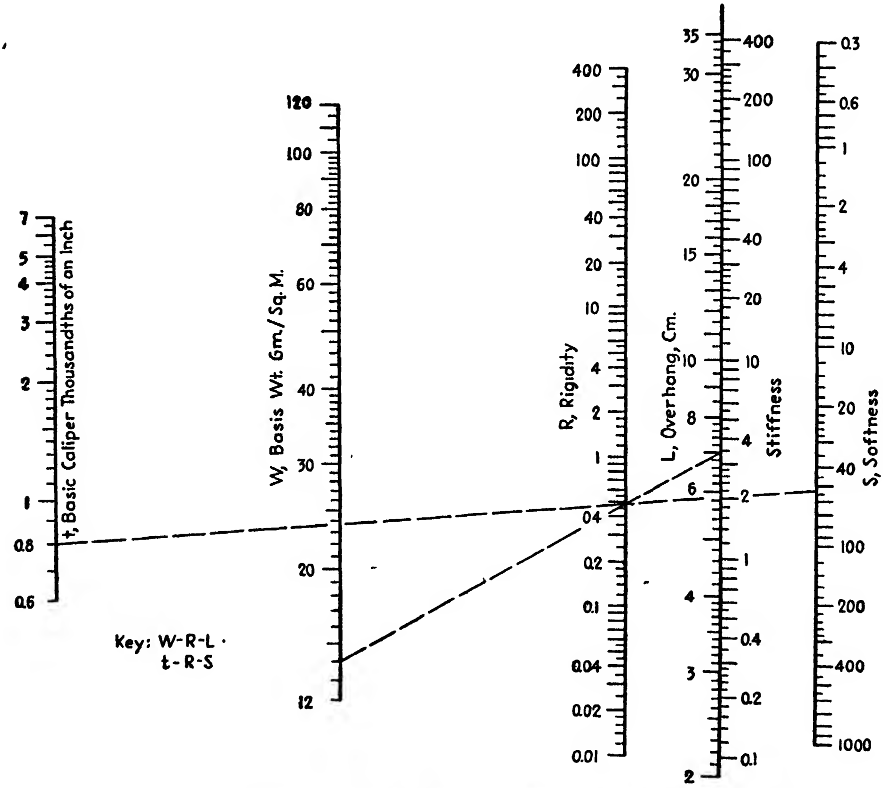

FIG. 67.—Rigidity, stiffness, and softness of paper.

Rigidity, rigidity factor, stiffness, and softness may then be calculated by means of four formulas. It is the purpose of this topic to facilitate these calculations with alignment charts. Figure 67 permits computation of rigidity, stiffness, and softness, while Fig. 68 deals with the determination of the rigidity factor. The use of the charts may be illustrated as follows: a sample of stereo tissue with a basis weight of 14 g./sq. m. and a caliper (and also, in this case, a basic caliper) of 0.8 of one-thousandth of an inch shows an overhanging length of 7.0 cm. for strips cut in the machine direction when tested as described previously. Using Fig. 67, connect 14 on the basis weight scale with 7.0 on the length scale, and read the rigidity as 0.48 on the *R* scale. Connect the basic caliper of 0.8 on the *t* scale with the rigidity so found, and project the line to meet the *S* scale in the value of 53 for the softness. Opposite 7.0 on the length scale, read the stiffness as 3.4.

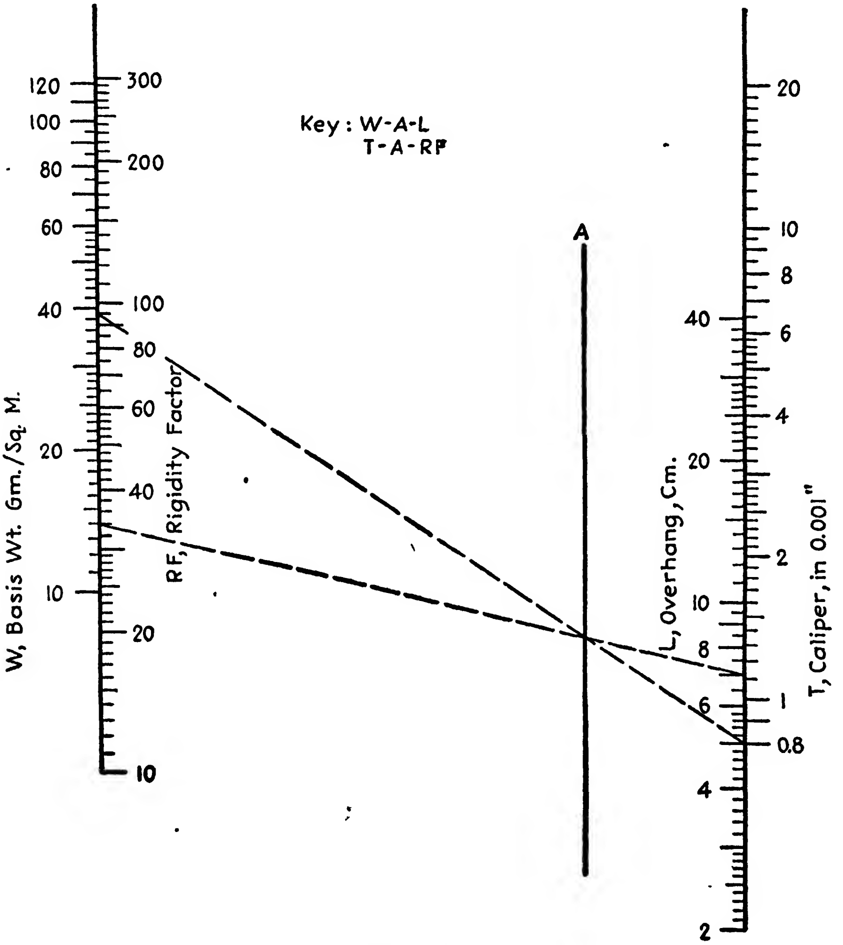

FIG. 68.—Rigidity factor, for paper.

Using Fig. 68, connect 14 on the basis weight scale with 7.0 on the length scale, and note the intersection with the A axis. Connect this intersection with 0.8 on the caliper scale, and project the line to meet the RF scale in the value 94 for the rigidity factor.

The equations involved are

$$\text{Rigidity} = \frac{WL^3}{10{,}000}$$

$$\text{Stiffness} = \frac{L^3}{100}$$

$$\text{Rigidity factor} = \frac{WL^3}{100T^3}$$

$$\text{Softness} = \frac{1{,}000{,}000 \log (t + 1)}{WL^3}$$

where W = basis weight, g./sq. m.
L = overhanging length, cm.
T = caliper, number of thousands of an inch.
t = basic caliper, number of thousandths of an inch.

METHODS OF CALCULATING THE LENGTH OF PAPER IN A ROLL[1]

The calculation of the unwound length of paper in a roll is an important one and is of interest to manufacturers and converters alike. Often, however, the manufacturer and converter, in dealing with the same roll order, will employ widely different methods in determining this value. Inasmuch as the various methods depend upon the measurement of entirely different quantities, which are not capable of determination to the same degree of precision, divergent results are sometimes obtained and these may lead to unfortunate misunderstandings. The three most commonly used length formulas are derived and discussed here, and nomographs for their solution are presented with a view toward relieving the situation.

Nomenclature.—In the ensuing discussion, the symbols have the following significances:

L = unwound length of paper in the roll, ft.
D and R = diameter and radius, respectively, of the roll, in.
d and r = diameter and radius, respectively, of the core, in.
c = caliper of the sheet, in.
n = number of turns in the roll, or number of revolutions of the roll while unwinding between diameters of D and d.
W = net weight of paper in the roll, lb.
R = ream weight of paper, lb.
b = width of the roll, in.

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[1] *Paper Ind.*, **16**, 29 (1934).

Method I.—Given: Diameters of the roll and core, and the caliper.

$$L = \frac{\pi(D^2 - d^2)}{48c}. \tag{19}$$

The area of paper in the end of the roll is the difference between the area of the circle bounded by the outer edge and the gross area of the core, or $\pi(D^2 - d^2)/4$ sq. in. The area of the sheet, unwound, is that of a rectangle L ft. in length and c in. wide, or $12Lc$ sq. in. Equating the expressions for the identical areas,

$$12Lc = \frac{\pi(D^2 - d^2)}{4}$$

where the left side of the equation assumes the caliper to be the true average and the right side assumes the sheet to be wound ideally tight. On solving for the length,

$$L = \frac{\pi(D^2 - d^2)}{48c}.$$

In Fig. 69,[1] which covers the common core diameters of 3½ in. and 6⅝ in., the broken line shows that 3,500 ft. are wound on a 3½-in. core when the diameter of the roll is 40 in. and the caliper of the sheet is 0.030 in.

As suggested by H. F. Cotter, in a private communication, it is interesting to note that the edge of the sheet when wound on the core traces an Archimedean spiral, the radius of which gains c in. during each revolution or $c/2\pi$ in. during each radian swept through. The equation of the spiral, in polar coordinates, is evidently

$$R = r + \frac{c\theta}{2\pi},$$

where θ is the angle in radians, and the length may be found by integrating the expression

$$dL = \frac{\sqrt{dR^2 + R^2 d\theta^2}}{12}$$

between r and R, which gives

$$L = \frac{1}{12}\left[\frac{R}{2}\sqrt{1 + \frac{4\pi^2R^2}{c^2}} + \frac{c}{4\pi}\ln\left(\frac{2\pi R}{c} + \sqrt{1 + \frac{4\pi^2R^2}{c^2}}\right)\right]_r^R.$$

Because of the low value of c, the entire second term in the integrated expression becomes negligible as does 1 under the radical in the first term

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[1] *Paper Ind.*, **12**, 1741, (1931).

in comparison to $4\pi^2R^2/c^2$, so that the equation reduces to

$$L = \frac{1}{12}\left(\frac{R}{2}\cdot\frac{2\pi R}{c}\right)_r^R = \frac{\pi(R^2 - r^2)}{12c}$$
$$= \frac{\pi(D^2 - d^2)}{48c}$$

which is identical with Eq. (19).

Equation (19) is very convenient since only a rule and a micrometer are needed to provide the necessary measurements. However, its disadvantages are that it depends upon caliper, which is often far from uniform, and upon the manner in which the roll has been wound.

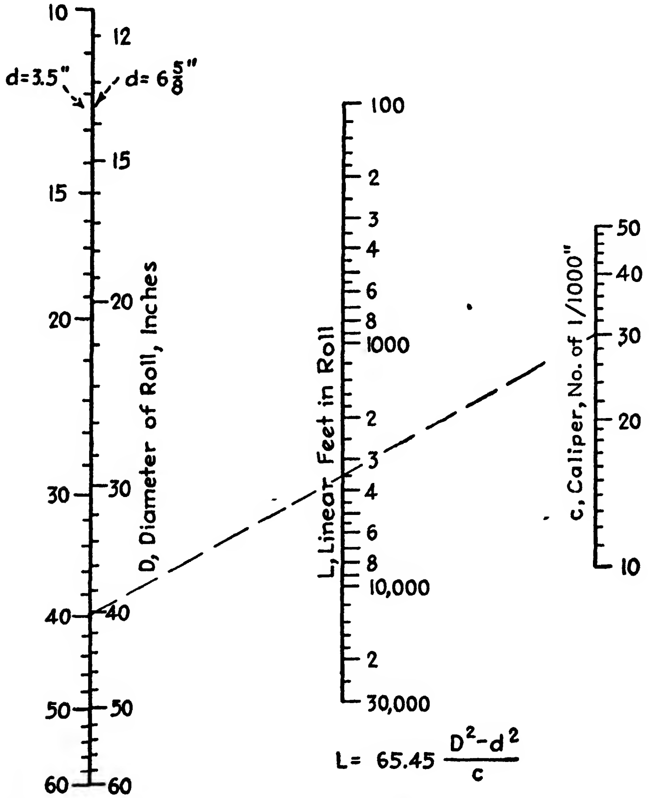

FIG. 69.—Roll length.

Method II.—Given: Diameters of the roll and core and the number of revolutions of the roll while unwinding.

$$L = \frac{\pi n(D + d)}{24}. \tag{20}$$

The addition of the diameters of the roll and core gives Eq. (20) a somewhat anomalous appearance and may lead one to believe that the expression is but a rough approximation. This is far from the case, however, since it is capable of several rigorous derivations, the simplest of which states that, for an ideally wound roll, the difference in radii of the roll and core, $R - r$, must be equal to nc, the thickness of n turns, each of which has a caliper of c in. Equating and solving for c,

$$c = \frac{R - r}{n} = \frac{D - d}{2n}.$$

On substituting this expression in Eq. (19),

$$L = \frac{\pi(D^2 - d^2)2n}{48(D - d)} = \frac{\pi n(D + d)}{24}.$$

The unwound length may also be considered as the sum of the circumference of n nearly perfect circles. The diameters of the first, second, and third turns are, respectively, $d + c$, $d + 3c$, and $d + 5c$. The corresponding cumulative sums of the diameters are $d + c$, $2d + 4c$, and $3d + 9c$, the cumulative sum of the diameters at the nth turn being, by inspection, $nd + n^2c$. The sum of the n circumferences is $\pi n(d + nc)$ in. so that

$$L = \frac{\pi n(d + nc)}{12}.$$

Substitution of $c = (D - d)/2n$ in the length expression leads to

$$L = \frac{\pi n}{12}\left(d + \frac{D - d}{2}\right) = \frac{\pi n(D + d)}{24}.$$

The use of Fig. 70 is illustrated as follows: What length of paper is wound on a 3½-in. core when the diameter of the roll becomes 28.5 in. after 1,100 revolutions? The sum of the roll and core diameters is 32 in. Connect 32 on the $D + d$ scale with 1,100 on the n scale, and read the desired value as 4,600 ft. on the L scale.

Although the diameters of the roll and core are easily measured and the number of turns is conveniently read from a revolution counter, it must be remembered that the results obtained by application of Eq. (20) depend somewhat upon the tension with which the roll has been wound.

Method III.—Given: Net weight of the roll, width of the roll, and the ream weight of the sheet.

$$L = 36{,}000\frac{W}{Rb}. \qquad (21)$$

When the ream dimensions are 24 by 36 in., 500, the ream weight, R, is the weight of $500 \times 2 \times 3$, or 3,000 sq. ft., and the weight of 1 sq. ft. is $R/3000$ lb. The total number of square feet in the roll is the quotient of the net weight of the roll and the weight of 1 sq. ft., or $3{,}000W/R$.

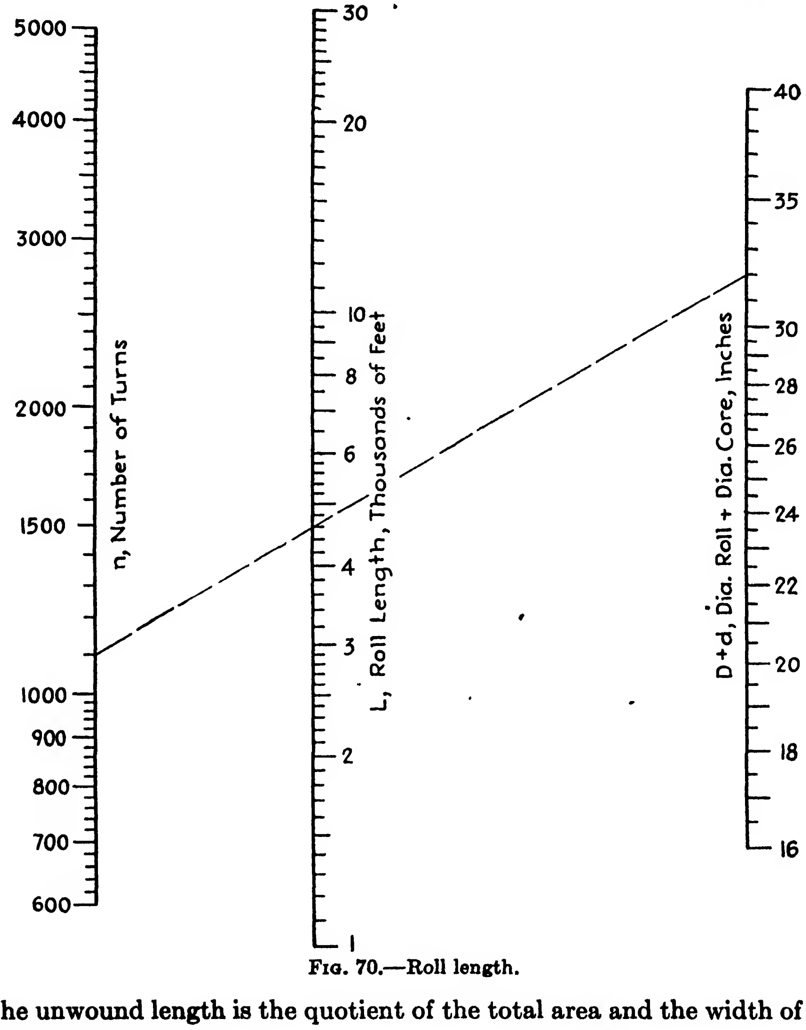

FIG. 70.—Roll length.

The unwound length is the quotient of the total area and the width of the roll in feet, $b/12$, or

$$L = \frac{3{,}000W}{R} \cdot \frac{12}{b} = 36{,}000\frac{W}{Rb}.$$

The constant, of course, depends upon the definition of the ream. When the ream dimensions are 24 by 36 in., 480 and 25 by 38 in., 500 the constants are 34,560 and 39,580, respectively.

The use of Fig. 71[1] is illustrated as follows: What is the length of sheet in a roll 48 in. in width when it weighs 1,500 lb. and when the ream weight is 70 lb. (24 by 36 in., 500)? Following the key, connect 70 on the *R* scale with 48 on the *b* scale, and note the intersection with the α axis. Connect this point with 1,500 on the *W* scale, and read the length of paper in the roll as 16,000 ft. on the *L* scale.

Equation (21) may not always be so convenient to apply as Eqs. (19) and (20) since it requires weighing of the roll and core, determinations of the ream weight, and measurement of the width. However, these data are usually a matter of record, and Eq. (21) is more accurate than Eq. (19) when sufficient ream-weight samples are taken to make sure that they are representative since *R* in Eq. (21) can be determined with greater precision than can *c* in Eq. (19). In addition, Eq. (21) is independent of the tension with which the roll is wound and applies to tightly and loosely wound rolls alike and is thus superior to both Eqs. (19) and (20).

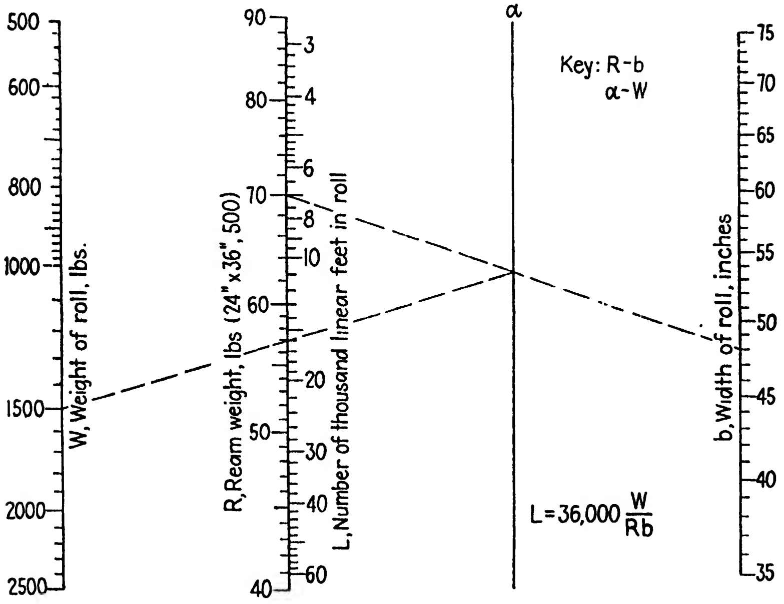

FIG. 71.—Roll length.

SPECIFIC-GRAVITY NOMOGRAPH[2]

Figure 72 enables rapid calculation of the specific gravity δ of test liner or chip board and the weight *W* in pounds per 1,000 sq. ft. when *w*,

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[1] *Paper Ind.*, **13**, 1101 (1931).

[2] *Paper Ind.*, **13** (1), 67 (1931).

the weight in grams of 10 sq. in., and c, the caliper in thousandths of an inch, are known.

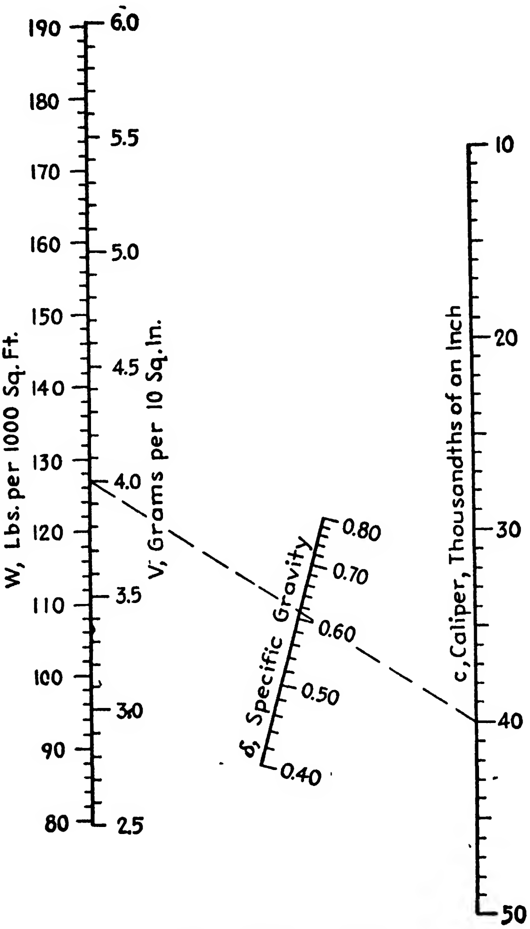

FIG. 72.—Specific gravity.

The relations involved are

$$W = 31.75w$$

$$\delta = 0.1923 \frac{W}{c}$$

$$= 6.105 \frac{w}{c}.$$

SPLIT-SET NOMOGRAPH[1]

In connection with the winding of paper on the reel, winder, and rewinder, it is usual practice to "flag" the close of each day in order to

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[1] *Paper Ind.*, **17**, 953 (1936).

facilitate production accounting. Flagging is accomplished by the insertion of a piece of colored paper or cloth, and it falls to the lot of someone to estimate the distribution of the weight of the paper between the successive days, using the flag as a guide.

It is clear that an inch of paper near the edge of the roll weighs considerably more than an inch at the center and a great deal more than an inch very near the core, so that visual estimation is extremely uncertain at best. There is evident need for a rapid graphical method of set splitting based upon sound geometrical considerations and simple enough to be used by anyone. Figure 73*b* meets these requirements, and it is founded upon the following facts and reasonable assumptions. In Fig. 73*a*, let

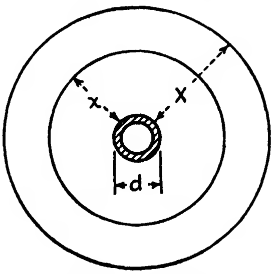

FIG. 73*a*.—Core and roll dimensions.

x = distance, core to any flag point.
X = distance, core to edge of roll.
d = diameter of the core.
w = weight of paper between core and any flag point.
W = weight of paper in the entire roll.

Considering the end of the roll, the area of paper between the core and any flag point is

$$\pi\left[\left(\frac{d}{2}+x\right)^2-\frac{d^2}{4}\right] \quad \text{or} \quad \pi x(d+x).$$

Similarly, the total area between the core and the edge is $\pi X(d + X)$.

Assuming that the moisture content, bulk, and winding tension are uniform throughout, it is seen that the respective ratios of the weights and end areas of the paper in the partial roll and in the entire roll are equal. That is,

$$\frac{w}{W}=\frac{x(d+x)}{X(d+X)},$$

which is the equation upon which the chart is based. The expression holds for any consistent units of weight and length, but the nomograph is built especially for the common core diameters of 3.5, 4.5, and 5.58 in. Note that the chart deals with the easily determined distances out from the core and not with roll diameters which are usually more difficult to measure.

The use of Fig. 73*b* is illustrated as follows: On a rewinder at the close of a day, a flag is found at a point 5.25 in. from the 3.5-in. core. When completed the roll is found to weigh 1,500 lb. and to have attained a depth on the core of 12 in. How much of this paper is between the core and the flag, *i.e.*, how much of this set should be credited to the day just ended? Following the broken lines, connect 1,500 on the central weight scale with 12 on the distance scale at the extreme left, and note the intersection with the *A* axis. Connect this intersection with 5.25 on the same distance scale, and produce the line to meet the weight scale in the desired value, 370. Then, 370 lb. should be credited to the closing day and 1,500 − 370, or 1,130, to the following day.

Twenty-five hundred pounds of paper are wound on a 4.5-in. core to a depth of 14 in. What weight of paper corresponds to the inch of depth between 13 and 14 in., 8 and 9 in., and 2 and 3 in.? Using the chart in the same manner but working with the distance scale marked for 4.5-in. cores, it is possible to obtain the values given in Table IX.

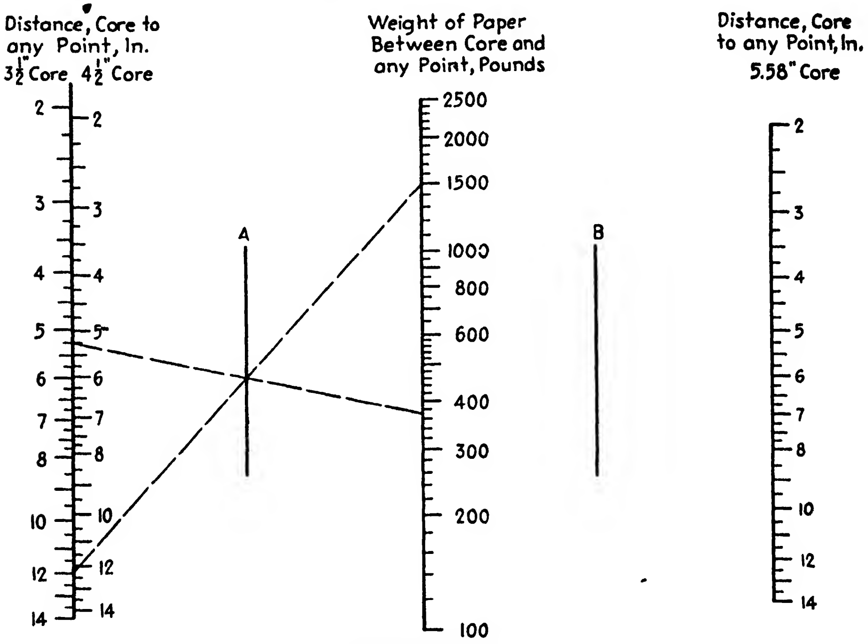

FIG. 73*b*.—Split set.

TABLE IX

Depth on core, in.	Weight at corresponding depth, lb.	Difference in weight, lb.
14 13	2,500 2,200	300
9 8	1,175 965	210
3 2	217 125	92

The close of a day finds paper wound on a 5.58-in. core to a depth of 5 in. At this time the machine reel contains a quantity of paper made during the day just closing. This is marked with a flag, and paper made at the beginning of the new day is wound on top of it. Later, in the new day, this paper is wound from the reel to the winder and flagged properly. When the set on the winder is completed, it exhibits a zone of new-day paper between two zones of old-day paper, flags appearing at distances of 5 and 10 in. from the core, as indicated in Fig. 73*c*. The completed set shows a depth of 14 in. on the core and weighs 2,400 lb. How shall the set be distributed between old and new days?

Working entirely in the right half of the chart (Fig. 73*b*), connect 2,400 on the weight scale with 14 on the distance scale and note the intersection with the *B* axis. Connect this point with 10 on the distance scale, and produce the line to meet the weight scale in the value 1360 lb. Further, connect 5 on the distance scale with the intersection on the *B* axis, and produce the line to meet the weight scale in the value 460 lb. The inner zone between the 5- and 10-in. flags is new-day paper and weighs 1,360 − 460, or 900, lb. The balance of the set, 2,400 − 900, or 1,500, lb. is old-day paper and is the weight of the combined inner and outer zones.

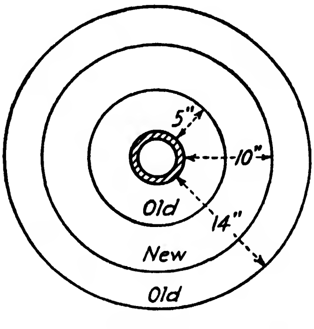

FIG. 73*c*.—Split-set dimensions.

While the chart is designed for core diameters of 3.5, 4.5, and 5.58 in., it can be used without serious error where the diameters of the cores are within ½ in. of these values.

PULP-VISCOSITY NOMOGRAPHS[1]

The growing appreciation of the significance and value of the cuprammonium viscosity test, as applied to bleached and unbleached chemical pulps and to rag stocks, has led to its adoption in many paper and textile control and research laboratories.

The test is known as Cuprammonium Disperse Viscosity of Pulp, T 206 m and is approved by the Technical Association of the Pulp and Paper Industry as an official standard. Briefly, it provides for the following:

1. Dissolving the pulp in a solution containing 200 g. of ammonia (NH_3) and 15 g. of copper per liter in a concentration equivalent to 1 g. of oven-dry pulp to 100 ml.

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[1] *Paper Ind.*, **17**, 101 (1935).

2. Measuring the time required for the level of liquid to fall between two marks in a tube of carefully specified dimensions, the effluent passing through a capillary and the system being maintained at 20°C.

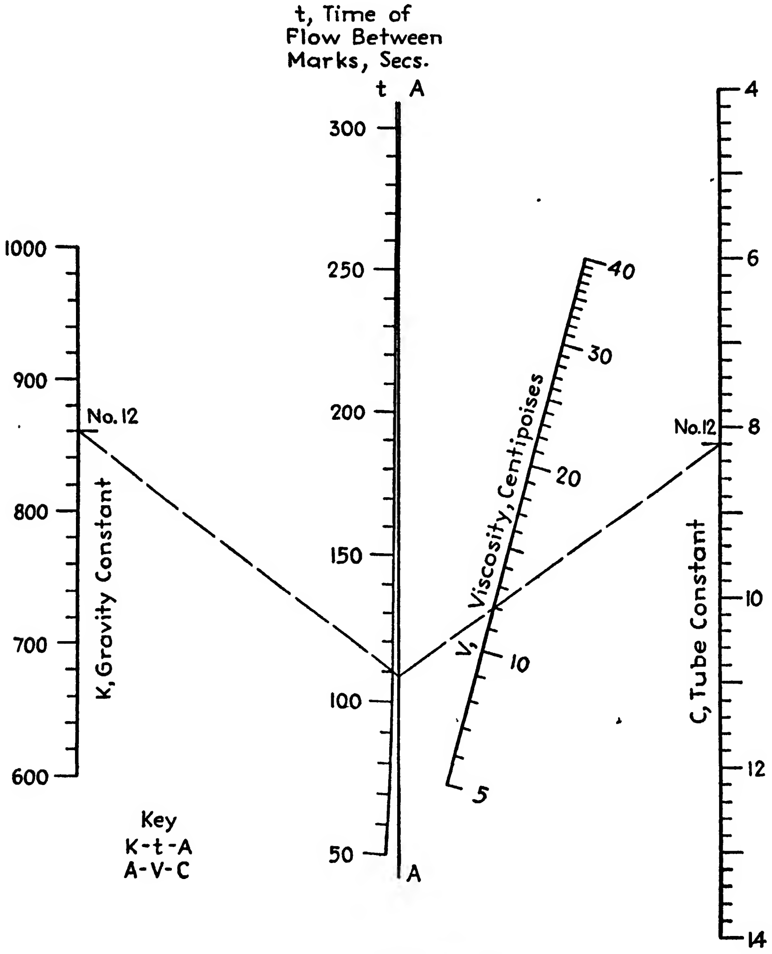

FIG. 74.—Pulp viscosity.

3. Calculation of the viscosity as a function of the measured time, the specific gravity of the solution, and constants specific to the tube.

The general relationship between the variables is

$$V = \frac{0.96}{C}\left(t - \frac{k}{t}\right)$$

where V is the viscosity, centipoises; 0.96 is the specific gravity of the cuprammonium solution of pulp; *t* is the measured time of flow, seconds, and *k* and *C* are the gravity and tube constants, respectively. These differ from tube to tube and are previously determined by tests with glycerin solutions and water of known viscosities, as provided in the official standard procedure.

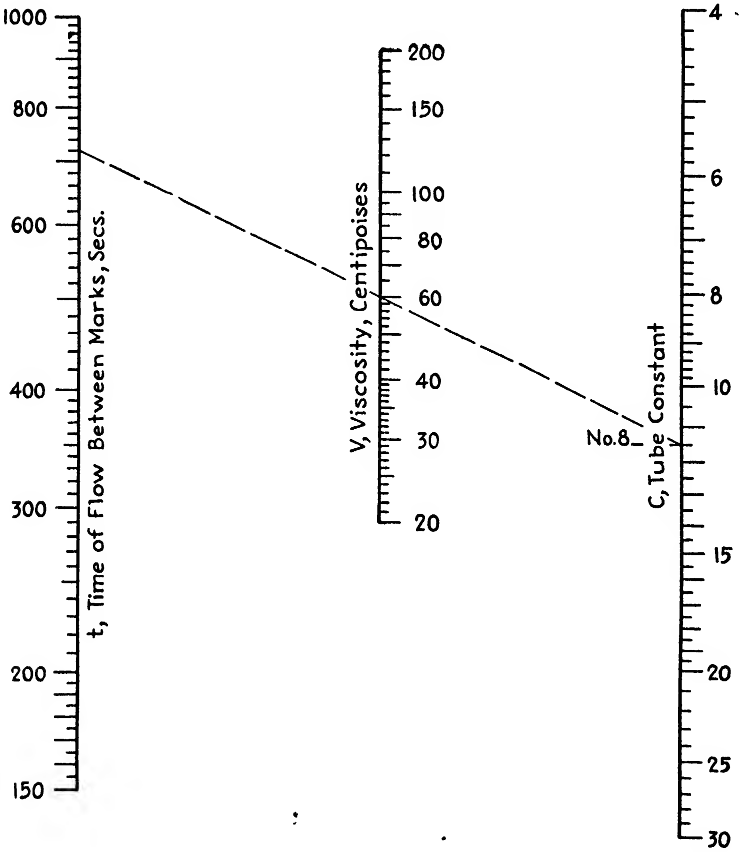

Fig. 75.—Pulp viscosity.

As an illustration of the use of Fig. 74, consider the case of a bleached soda pulp which gave a test of 110 sec. when a viscosity tube was used which had gravity and tube constants of 860 and 8.20, respectively. Following the key, connect 860 on the *k* scale with 110 on the *t* scale and produce the line to the *A* axis. Connect the point so found with 8.20 on the *C* scale, and read the viscosity on the *V* scale as 12.0 centipoises.

In the case of unbleached pulps, such as hard sulfite and kraft, the time of efflux is much larger so that the term k/t is small compared with *t* and may be safely neglected. This simplifies the expression to

$$V = \frac{0.96}{C} t$$

and enables the use of Fig. 75 which permits the calculation to be effected in one operation.

Thus, the broken line in this diagram indicates that an unbleached soda pulp has a viscosity of 60 centipoises when the time of flow is 720 sec. and the tube constant is 11.5.

When adapting the charts for individual use, it is helpful to designate the viscosity tubes by numbers and to mark these numbers opposite the proper values of the gravity and tube constants on the k and C scales as illustrated by No. 12 and No. 8 appearing in Figs. 74 and 75. This is particularly advantageous where a number of tubes are in daily use since it prevents confusion of constants and attendant error.

Acknowledgment is made of several suggestions as to the data used here, particularly those of M. D. Reuben of the York Haven Paper Co., who arranged the testing method for the Technical Association.

CHART FOR CUPRAMMONIUM VISCOSITY OF RAG BLENDS[1]

In connection with their study of rag evaluation, Wennberg and Landt[2] have shown that it is possible to calculate the cuprammonium viscosity of a binary rag blend when the percentage composition of the blend and the viscosities of the components are known.

A rearranged form of the equation connecting the variables is

$$\eta = \eta_1 R^{\frac{100 - \delta}{100}}$$

where η is the viscosity of the blend, η_1 is the viscosity of the less viscous component, R is the ratio of viscosities, higher to lower, δ is the percentage of the less viscous component in the blend, and where all the cuprammonium viscosities are in centipoises determined at 25°C., by the Shirley Institute method.[3]

The equation is somewhat involved and can be handled most readily by means of Fig. 76. The broken lines serve to illustrate the use of the nomograph and answer the question, What will be the cuprammonium viscosity of a blend made up of two rag stocks of viscosities of 63 and 9 centipoises when the percentages of the components are 60 and 40, respectively? The ratio of the viscosities, R, is $\frac{63}{9}$, or 7. Following the key connect 7 on the R scale with 40 on the δ scale and note the intersection with the A axis. Connect this latter point with 9 on the η_1 scale, and read the viscosity of the blend on the η scale as 29 centipoises.

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[1] *Paper Ind.*, **14**, 729 (1933).

[2] *Paper Trade J.*, **93** (18) Tappi Sec., p. 202 (1931).

[3] Birtwell, C., D. A. Clibbens, and A. Geake, *J. Textile Inst.*, **17**, T145 (1926).

LINE-COORDINATE CHART FOR WASTE SULFITE LIQUOR[1]

Figure 77 is a line-coordinate chart dealing with the determination of solids in waste sulfite liquor when the specific gravity δ and the temperature t in degrees Fahrenheit are known and is based upon the data of Moore.[2]

On ordinary cross-section paper, δ and t, for various percentages of solids, can be plotted as a family of curves concave toward the origin, while δ and $(1 + 0.00397t)t$ can be plotted as a family of straight lines. It is these latter functions which are plotted in opposite directions on the parallel δ and t axes of the chart. The scale labeled Per Cent Solids is the locus of the intersections of pairs of lines connecting corresponding specific-gravity and temperature values.

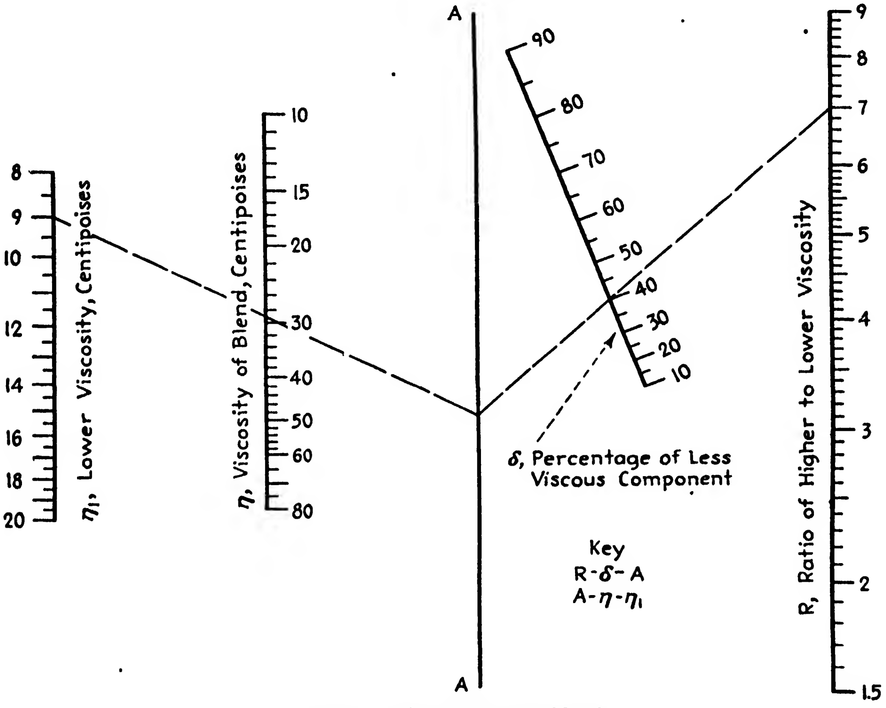

Fig. 76.—Viscosity of rag blends.

The broken line indicates that a sample of waste sulfite liquor concentrated to the point where its specific gravity is 1.105 at 120°F. contains 23.2 per cent solids.

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[1] *Paper Trade J.*, **95** (9), Tappi Sec., p. 106 (1932).

[2] Moore, H. K., *Trans. Am. Inst. Chem. Eng.*, **15** (II), 245 (1923).

PAPER-WINDING NOMOGRAPHS[1]

The winding of paper, whether on the paper machine, supercalenders, and rewinders or in various conversion operations, presents many absorbing calculations which are of never-failing interest to operators and superintendents who will find Figs. 78 and 79 helpful in making them.

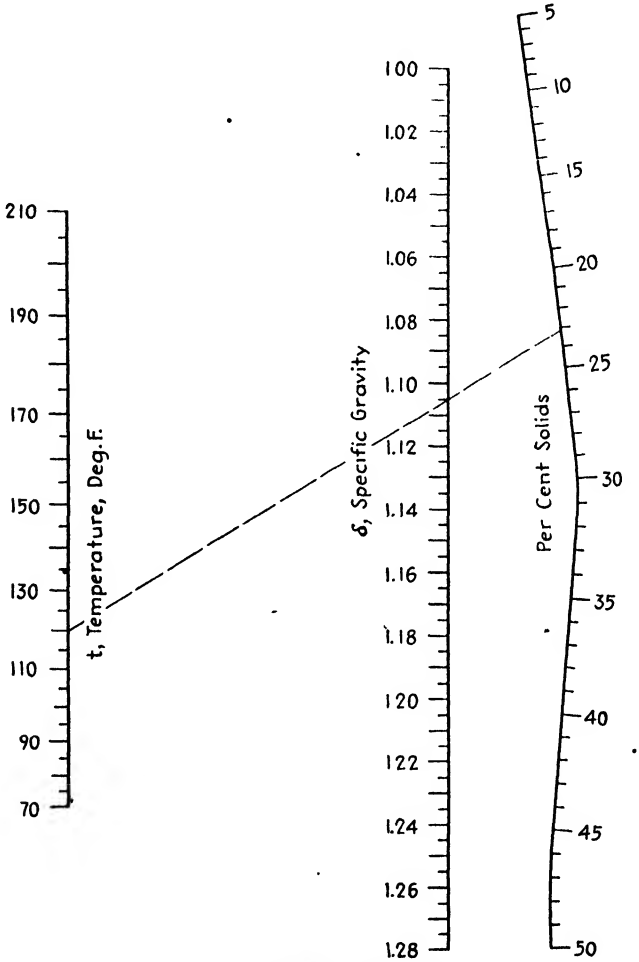

FIG. 77.—Waste sulfite liquor.

Both charts have their origin in the simple geometry of the circle and enable paper-winding calculations to be made without recourse to a slide rule or to the drudgery of pencil and paper work, as shown in the following examples:

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[1] *Paper Ind.*, **16**, 688 (1935).

A roll of paper 20 in. in diameter is to be built up to a diameter of 30 in. at the expense of a 40-in. roll. What will be the final diameter of the diminishing roll? This roll bears splices at diameters of 32 and 34 in. Will they carry over into the new roll? Following the dotted lines in Fig. 78, connect 20 on the "growing" scale at the right with 40 on the "diminishing" scale at the left, noting the intersection with the central axis. Connect this point with 30 on the growing scale, and produce the line to the diminishing scale where it is seen that the final diameter of the diminishing roll will be about 33¼ in. and that the splice at 34 in. will appear in the new roll while the other will not.

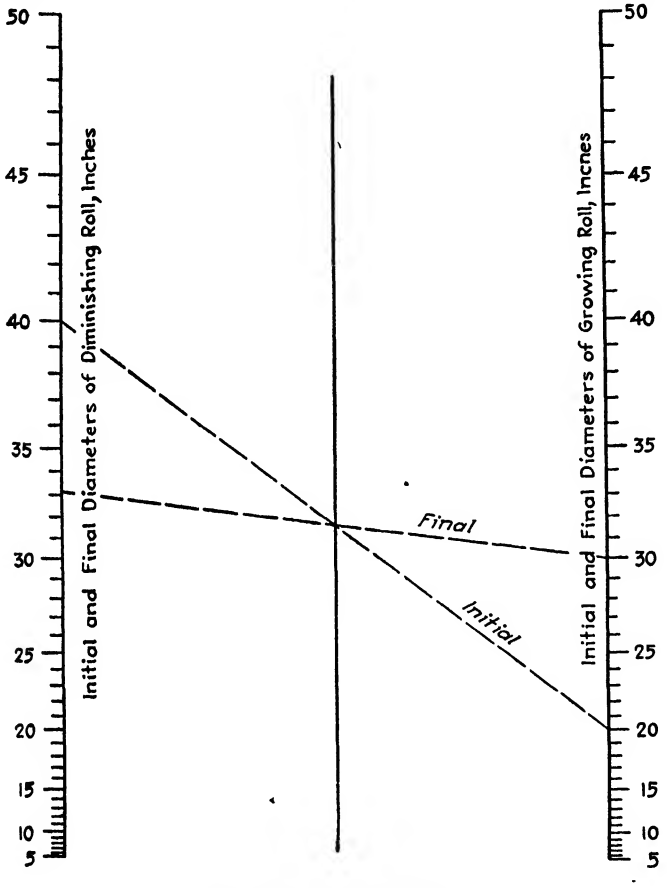

Fig. 78.—Paper winding.

Is there enough paper on a roll 25 in. in diameter wound on a 5½-in. core to increase the diameter of another roll from 30 in. to 40 in.? Using the chart as shown below, connect 30 on the growing scale with 25 on the diminishing scale and note the intersection with the central axis. Produce a line from 40 on the growing scale through this point, and note that it would meet the diminishing scale considerably below the 5-in. mark, showing that there is insufficient paper available. To determine the extent to which the diameter of the growing roll could be increased, connect the intersection on the central axis just found with the core diameter, 5½ in., on the diminishing scale and produce the line to the right where the final diameter of the increasing roll is seen to be about 38¾ in.

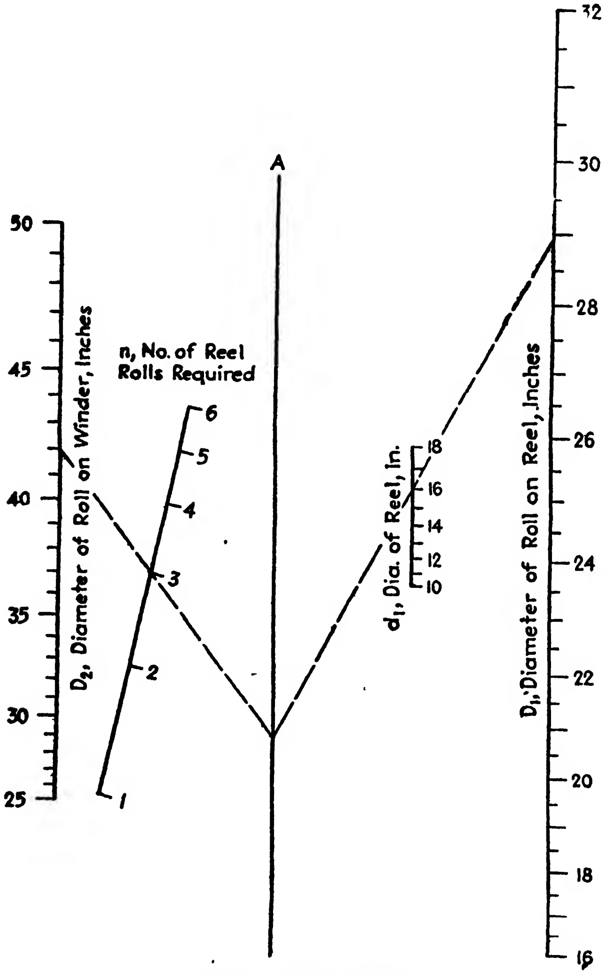

FIG. 79.—Paper winding.

Figure 78 is based upon the relationship

$$d_f = \sqrt{d_i^2 + D_i^2 - D_f^2}$$

where d and D represent the diameters of the diminishing and growing rolls, respectively, and i and f denote initial and final conditions.

In instances where a large roll on the winder is to be built up from several smaller rolls on the reel, it is desirable to know how many such smaller rolls will be needed or, conversely, how large to make the reel rolls in order that a certain convenient number will suffice. For example, how many 30-in. reel rolls are needed to build up a 42-in. roll on the winder if the reel is 16 in. in diameter and 4½-in. winder cores are used? Using Fig. 79, connect 30 on the D_1 scale with 16 on the d_1 scale and produce the line to meet the A axis. A line from this latter intersection to 42 on the D_2 scale will cut the n scale a little below 3, showing that nearly three such reel rolls are required. What should be the exact diameter of the reel rolls so that three will suffice? As shown by the dotted lines in Fig. 79, connect 42 on the D_2 scale with 3 on the n scale and produce the line to meet the A axis. Connect the point so found with 16 on the d_1 scale, and produce the line to meet the D_1 scale at 28.9, showing that the reel rolls need be only 28.9 in. in diameter when three full reel rolls are provided.

While the D_2 scale is built for 4½-in. cores, its use in the case of cores of diameters of 3½ and 5½ in. results in errors of only one-tenth of an inch in the diameter of the roll on the reel when d_1 and D_2 are 14 and 40 in., respectively.

Figure 79 depends upon the relationship

$$n = \frac{D_2^2 - 20}{D_1^2 - d_1^2}$$

where n is the number of reel rolls, having diameters of D_1 in. and wound on d_1-in. reels, required to make up a winder roll D_2 in. in diameter wound on a 4½-in. core.

CHAPTER XI

pH NOMOGRAPHS

NOMOGRAPH FOR EVALUATING ELECTROMETRIC HYDROGEN-ION DETERMINATIONS[1]

Figure 80 facilitates solution of the equation

$$\mathrm{pH} = \frac{V - 0.2458 - 0.0002(t - 25)}{0.0001983(t + 273)}$$

where V = the measured voltage due to the difference in potential between a calomel electrode (mercury in contact with calomel in a saturated solution of KCl) and a hydrogen electrode placed in the test solution; and t = temperature in degrees centigrade. In the example shown, when the voltage is 0.75 and the temperature 20° the pH is found to be 8.7.

The value, 0.2458, is the potential given for the saturated calomel electrode at 25°C.[2], while the temperature coefficient is that given by Fales and Mudge.[3]

NOMOGRAPH FOR ELECTROMETRIC pH DETERMINATIONS[4]

Most electrometric methods for the determination of hydrogen-ion concentration involve the use of either the hydrogen or quinhydrone electrodes together with a saturated KCl-calomel electrode. For careful work, it is necessary to operate at exactly 25°C., using tables or curves to convert from voltage to pH or to note the actual temperature and make the proper corrections when using the graphs and tables.

In the case of the hydrogen-calomel cell, a convenient alignment chart is already available for handling the voltage to pH conversion with the attendant temperature corrections.[5] For use with the quinhydrone-calomel cell, Schollenberger[6] has presented plots similar to those sometimes supplied by potentiometric-equipment manufacturers. It is the purpose of this topic to show how the conversions and corrections for

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[1] *Chem. & Met. Eng.*, **38**, 416 (1931).

[2] Notes on Hydrogen-ion Measurements," Note Book 3, p. 15, Leeds & Northrup Company, Philadelphia, 1930.

[3] Fales, H. A., and W. A. Mudge, *J. Am. Chem. Soc.*, **42**, 2434 (1920).

[4] *Chemist-Analyst*, **26**, 33 (1937).

[5] *Chem. & Met. Eng.*, **38** (7), 416 (1931).

[6] Schollenberger, C. J., *Chemist-Analyst*, **21** (4), 8 (1932).

the quinhydrone cell may be made by means of the more convenient nomographic charts.

At 25°C., the expression

$$pH = 7.67 - 16.92V$$

shows the relation between the pH value and the voltage V. The ordinary slide rule cannot be set so as to permit direct solution of this equation, but recourse may be had to the extremely simple chart, Fig. 81. In Fig. 81, it will be noted that when using the quinhydrone cell at 25°C. a voltage of 0.24 corresponds to a pH of 3.6.

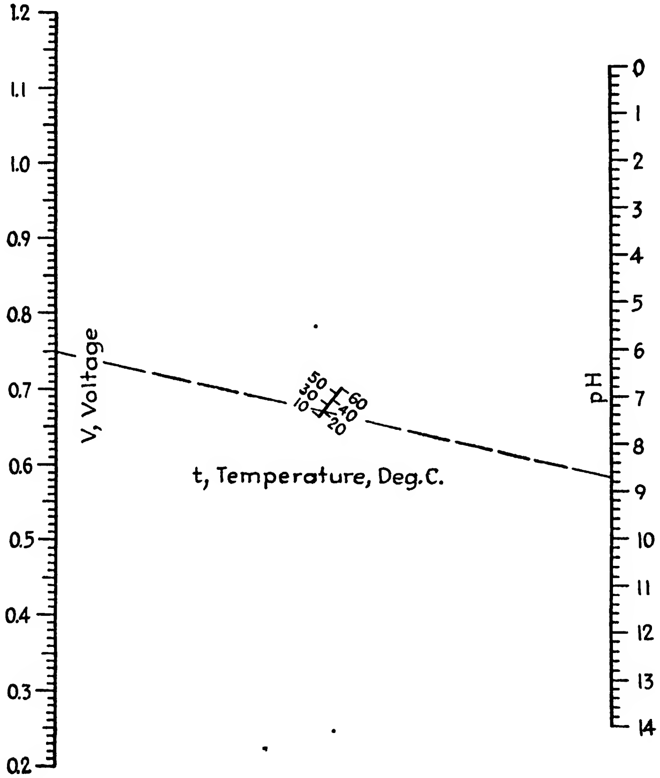

FIG. 80.—pH.

Figure 82 is intended for use when the determinations are carried out at temperatures other than 25°C. It solves the equation

$$pH = \frac{0.4526 - 0.00009(t - 25) - V}{0.0591 + 0.0002(t - 25)}$$

where t is the centigrade temperature. The nomograph is constructed by methods described in Chap. VI of "Empirical Equations and Nomography."[1]

The use of Fig. 82 is illustrated by the broken line which indicates that when the voltage is 0.2 and the temperature is 30°C. the pH value is 4.19. At a temperature of 25°C., Fig. 82 of course gives results identical with Fig. 81. For a temperature of 25°C., Fig. 81 is the preferred chart both on the ground of precision and simplicity of use.. In case determinations are habitually made at any other temperature, say 20°C., it is possible to substitute 20 for t in the general equation and arrive at

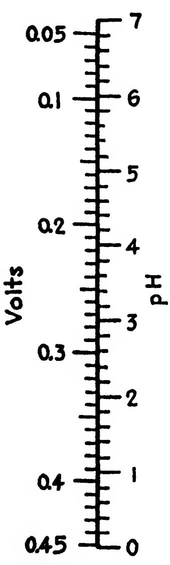

FIG. 81.—pH.

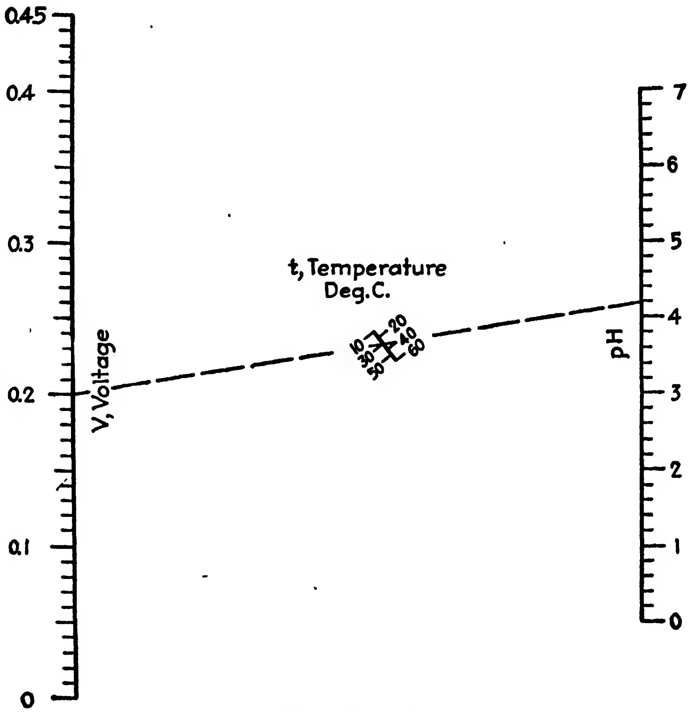

FIG. 82.—pH.

$$\mathrm{pH} = \frac{0.4526 - 0.00009(-5) - V}{0.0591 + 0.0002(-5)}$$
$$= \frac{0.4531 - V}{0.0581} = 7.80 - 17.22V$$

after which a chart similar in form to Fig. 81 may be constructed.

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[1] DAVIS, DALE S., "Empirical Equations and Nomography," McGraw-Hill Book Company, Inc., New York, 1943.

pH NOMOGRAPH FOR INDUSTRIAL ALKALIES[1]

Reliable data covering the pH values of dilute aqueous solutions of the common alkalies are of considerable value in view of the industrial importance of alkalies and in particular their widespread use in the paper industry. Such data are at last available[2] and deal with concentrations of 0.1 to 10 per cent of $Na_2B_4O_7$, Na_2CO_3, Na_3PO_4, Na_4SiO_4, KOH, and NaOH. pH is shown to be linear with the logarithm of concentration for Na_2CO_3 over the entire range and for the others up to about 1 per cent. This relationship and the use of a specially derived concentration scale above 1 per cent enable construction of the line coordinate chart (Fig. 83)

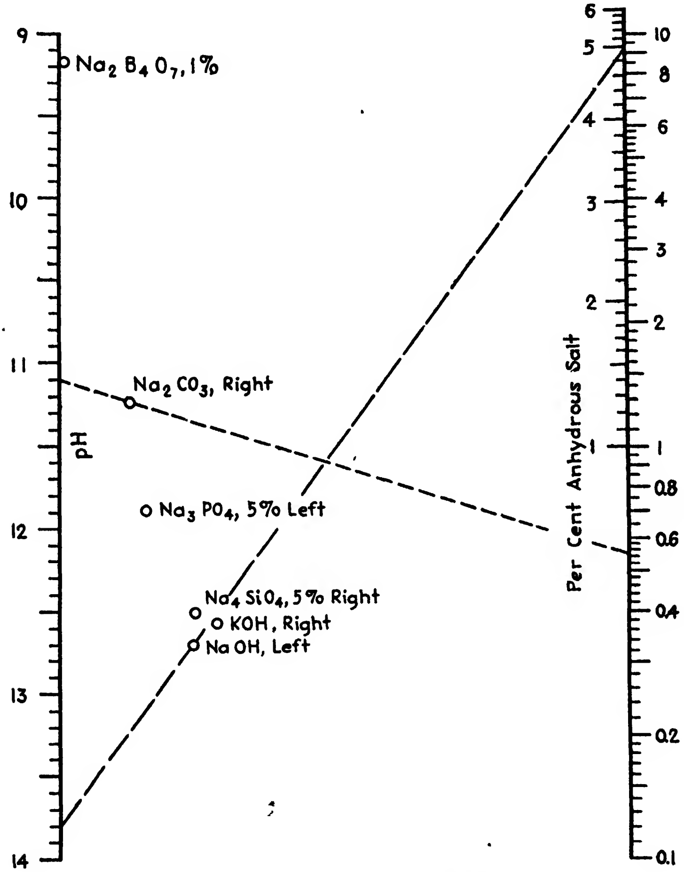

FIG. 83.—pH of industrial alkalies.

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[1] *Paper Ind. & Paper World*, **23**, 802 (1940).

[2] "Wyandotte Caustic Soda," a booklet distributed by the Michigan Alkali Company, Wyandotte, Mich.

which facilitates interpolation. The chart, then, can be said to depend upon the following relationships:

$$\text{pH} = a + b \log C$$

and

$$\text{pH} = a' + b'f(C)$$

where C is percentage concentration and a, b, a', and b' are constants specific to the alkali.

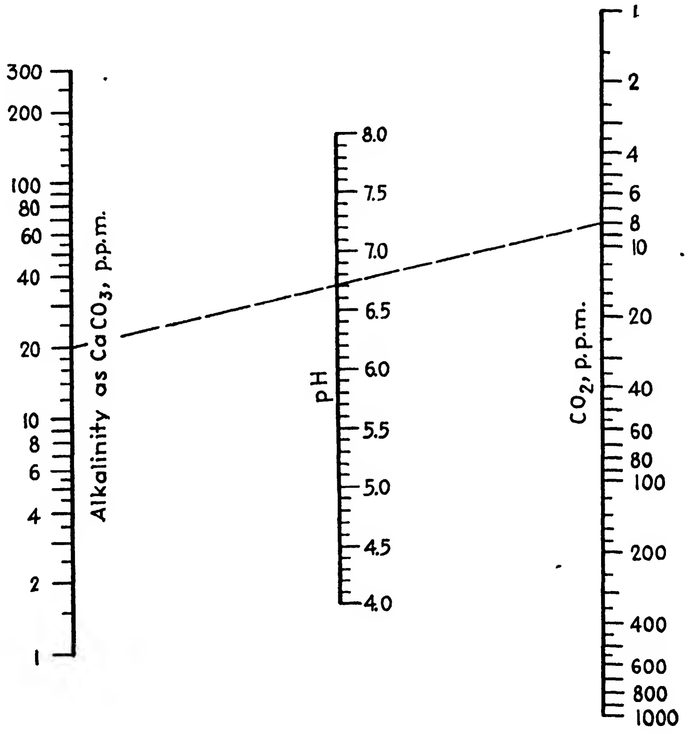

FIG. 84.—pH of natural waters.

In the legends, "left" and "right" refer to the scales at the left and right of the concentration axis. These are identical between 0.1 and 1 per cent, requiring only one to be given, but differ increasingly between 1 and 10 per cent. The dotted line indicates that an aqueous solution containing 0.55 per cent of anhydrous Na_2CO_3 has a pH of 11.11, while the dashed line shows that a 5 per cent solution of NaOH tests 13.80 in pH value. The percentages appearing after some of the formulas indicate the maximum concentrations for which the chart is to be used.

The nature of the agreement between the original data and pH values as read from the nomograph is shown in Table X where parallel columns of observed and calculated pH values for several concentrations of each alkali are listed. As stated in "Wyandotte Caustic Soda," the alkalies used in the original investigation were all of technical grade, and the concentration values are subject to some slight variation depending upon the origin of the material.

TABLE X.—PH OF AQUEOUS SOLUTIONS OF INDUSTRIAL ALKALIES

Percentage concentration	$Na_2B_4O_7$		Na_2CO_3		Na_3PO_4		Na_4SiO_4		KOH		NaOH	
	Data	Chart	Data	Chart	Data	Chart	Data	Chart	Data	Chart	Data	Chart
0.1	9.14	9.14	10.85	10.85	11.50	11.50	12.05	12.05	12.05	12.02	12.29	12.29
0.3	...	...	11.01	11.02	11.71	11.72	12.42	12.41	12.49	12.47	12.66	12.66
0.6	....	....	11.12	11.13	11.85	11.85	12.65	12.65	12.77	12.76	12.90	12.89
1.0	9.15	9.15	11.20	11.20	11.95	11.95	12.82	12.82	12.97	12.97	13.06	13.06
2.0	.	.	11.30	11.30	12.10	12.11	13.05	13.05	13.25	13.26	13.34	13.34
3.0	...	...	11.36	11.36	12.23	12.22	13.20	13.18	13.42	13.43	13.53	13.52
5.0	...	..	11.45	11.45	12.45	12.38	13.42	13.36	13.65	13.64	13.82	13.80
7.0	.	..	11.50	11.50	...	....	....	....	13.82	13.77		
10.0	..	....	11.55	11.55	....	...	.....	...	14.00	13.93		

pH NOMOGRAPH FOR NATURAL WATERS[1]

Joos and Rohlin,[2] state that for natural waters a definite relationship exists among bicarbonate hardness, free carbon dioxide, and pH value as follows:

$$\text{pH} = \log \frac{2{,}000{,}000A}{B}$$

where A is the alkalinity as $CaCO_3$ and B is the CO_2 present, both in parts per million.

The equation can be solved most conveniently and accurately by means of Fig. 84, which covers satisfactorily wide ranges of data and which can be used by many laboratory assistants who might not be able to handle the equation directly.

The broken line indicates that a pH value of 6.7 may be expected from a natural water containing 8 parts per million of free CO_2 when the alkalinity, expressed as parts per million of $CaCO_3$, is 20.

[1] *Chemist-Analyst*, **26**, 14 (1937).

[2] Joos, C. E., and V. A. ROHLIN, *Heating, Piping, and Air Conditioning*, **4** (8), 533 (1932).

CHAPTER XII

VAPOR-PRESSURE–TEMPERATURE-CONCENTRATION NOMOGRAPHS

VAPOR PRESSURES OF NITRIC AND SULFURIC ACIDS[1]

Extensive use of the available data on the vapor pressures, total and partial, of sulfuric and nitric acids makes it desirable for a large number of chemists, physicists, and engineers to have this information in as accurate and convenient a form as possible. Alignment and line-coordinate charts, of course, meet these conditions admirably, and their use, in connection with many types of technical endeavor, has increased markedly during the past few years.

The application of the line-coordinate chart, in particular, to the vapor-pressure data of these two most commonly used heavy chemicals is believed to warrant the presentation of the accompanying diagrams, older forms of which have been profitably used by one of the authors for some time. These charts (Figs. 85 to 90) should be of value to the manufacturers and users of the individual acids and should also prove to be a convenient source of information to laboratory men, to those handling these chemicals, and to those concerned with sulfonations, nitrations, and other operations in which sulfuric and nitric acids play important parts. Similar detailed charts for total vapor pressure of sulfuric acid and for partial pressure of water over strong sulfuric acid solutions have already appeared.[2]

The data used in the construction of the present charts are taken from several sources.[3]

No attempt has been made to determine empirical equations connecting percentage of acid, vapor pressure, and temperature. For the purposes of the line-coordinate charts it is sufficient, in the case of but two of the variables, to choose functions which shall be linear one with the other. These functions are plotted along the parallel axes, while the curved scale represents the third variable.

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[1] PERRY, J. H., and D. S. DAVIS, *Chem. & Met. Eng.*, **41**, 188 (1934).

[2] *Chem. & Met. Eng.*, **41**, 77 (1934).

[3] "International Critical Tables," Vol. III, p. 303, McGraw-Hill Book Company, Inc., New York, 1928; MEYEREN, W. V., *Z. physik. Chem.*, (A), **160**, 272–278 (1932); HEPBURN, J.R.I., *Proc. Phys. Soc.*, **40**, 249–260 (1928).

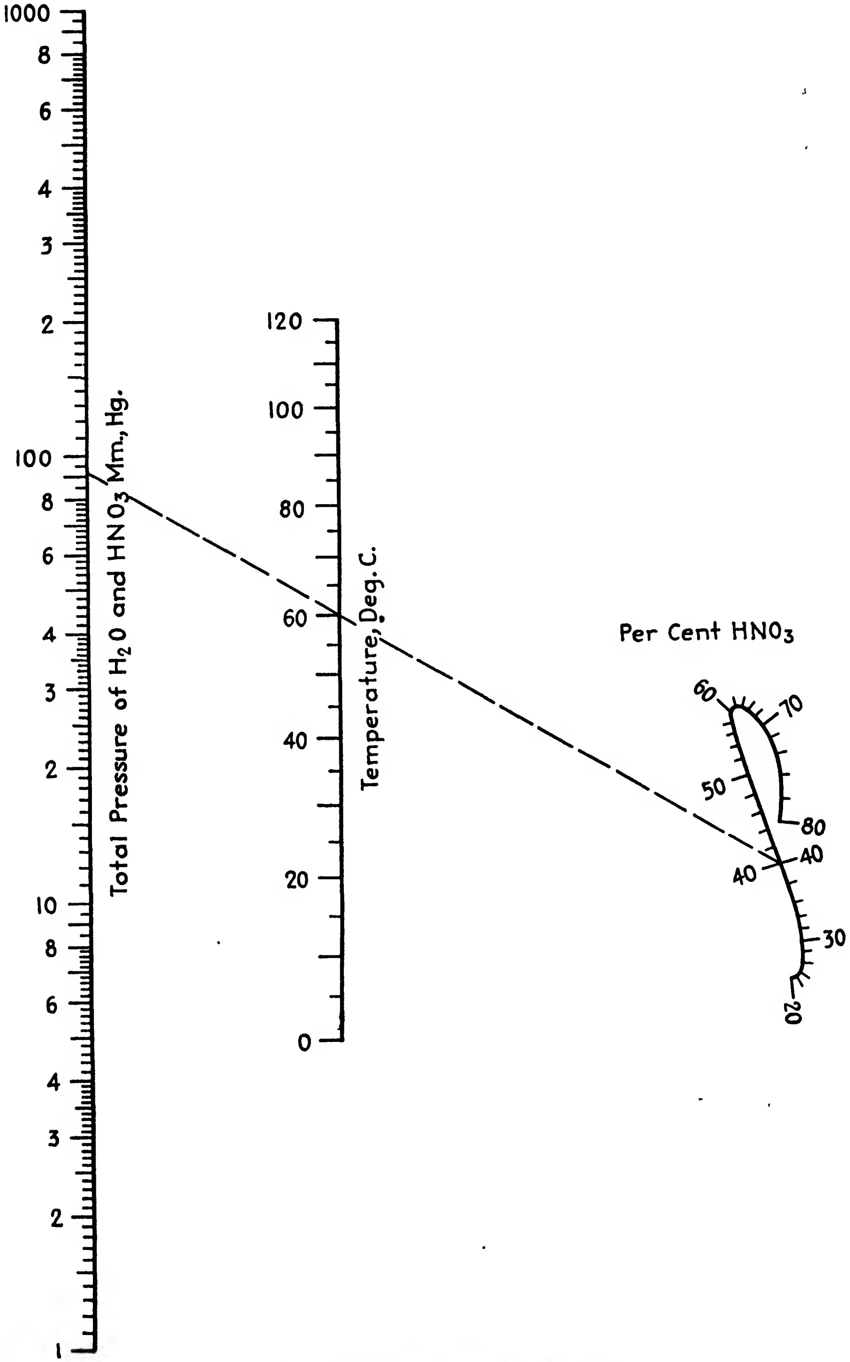

FIG. 85.—Total vapor pressure over HNO_3.

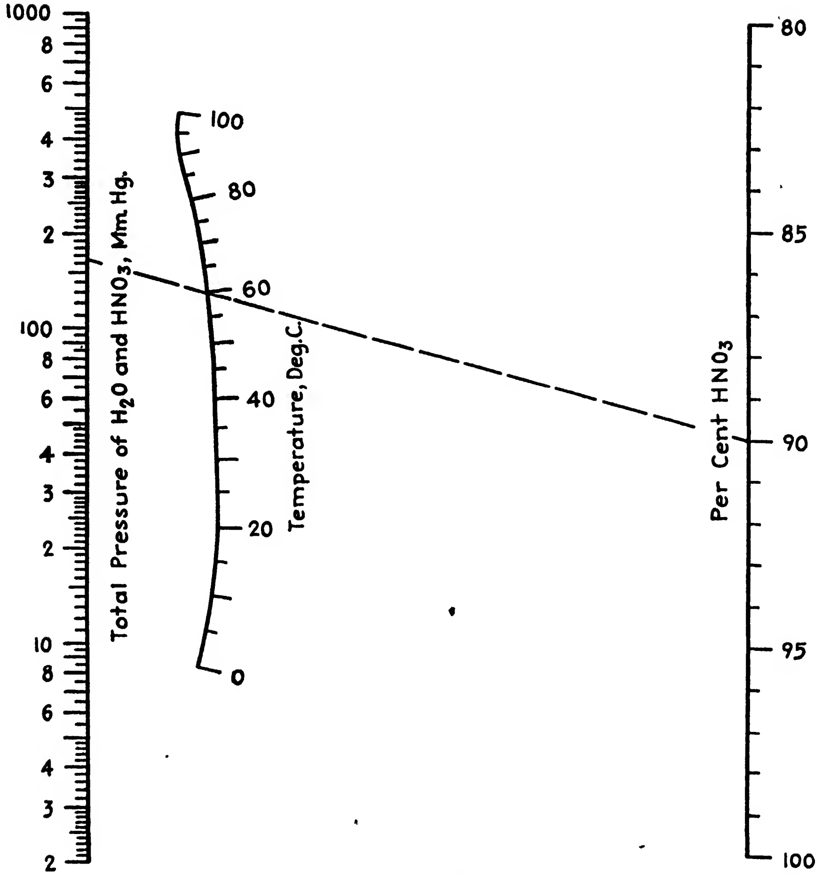

FIG. 86.—Total vapor pressure over HNO_3.

PARTIAL AND TOTAL VAPOR PRESSURE CHARTS FOR SULFURIC AND PHOSPHORIC ACIDS[1]

The equation

$$\log p = A - \frac{B}{T}$$

where p = partial or total pressures of the compounds in question
T = temperature, °K.

serves to correlate sulfuric[2] and phosphoric[3] acid data. The index lines are sufficient illustration of the use of the charts, Figs. 91–94.

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[1] PERRY, J. H., and H. C. DUUS, *Chem. & Met. Eng.*, **41**, 74 (1934).

[2] "International Critical Tables," Vol. III, pp. 303–304.

[3] Private communication from W. H. Woodstock of The Victor Chemical Works to J. H. Perry.

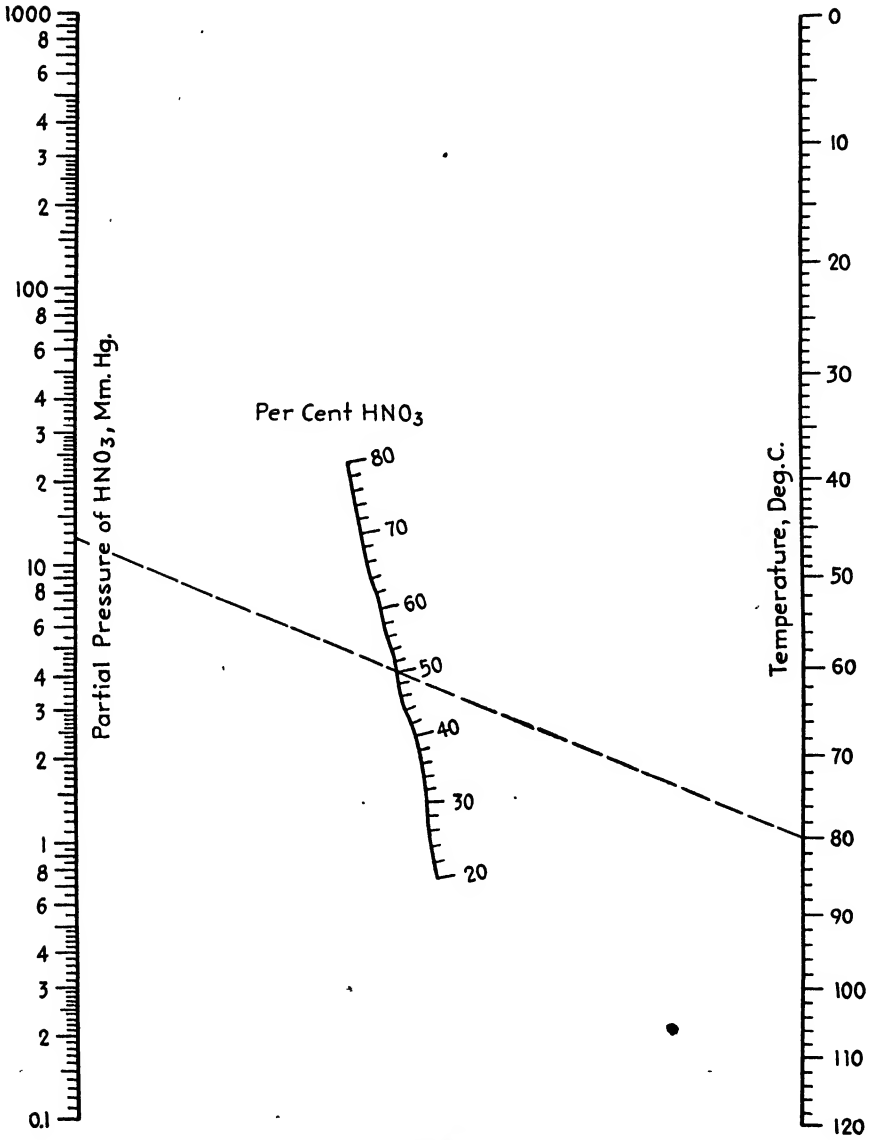

FIG. 87.—Partial pressure of HNO_3.

NOMOGRAPH FOR AMMONIA VAPOR PRESSURE AND COMPOSITION DATA[1]

The use of Fig. 95 is illustrated as follows: What are the partial pressures of ammonia and water vapor in an aqueous solution of ammonia that tests 30 mole per cent NH_3 at 130°F.? Connect 130° on scale *B* with 30 mole per cent on scale *C* and read the partial pressure of NH_3 as 37 lb./in.^{2} on scale *A*. Connect 130° on scale *B* with 30 mole per cent on scale *D* and read the partial pressure of water vapor as 1.6 lb./in.^{2} on scale *A*. What is the vapor composition over this solution? Connect

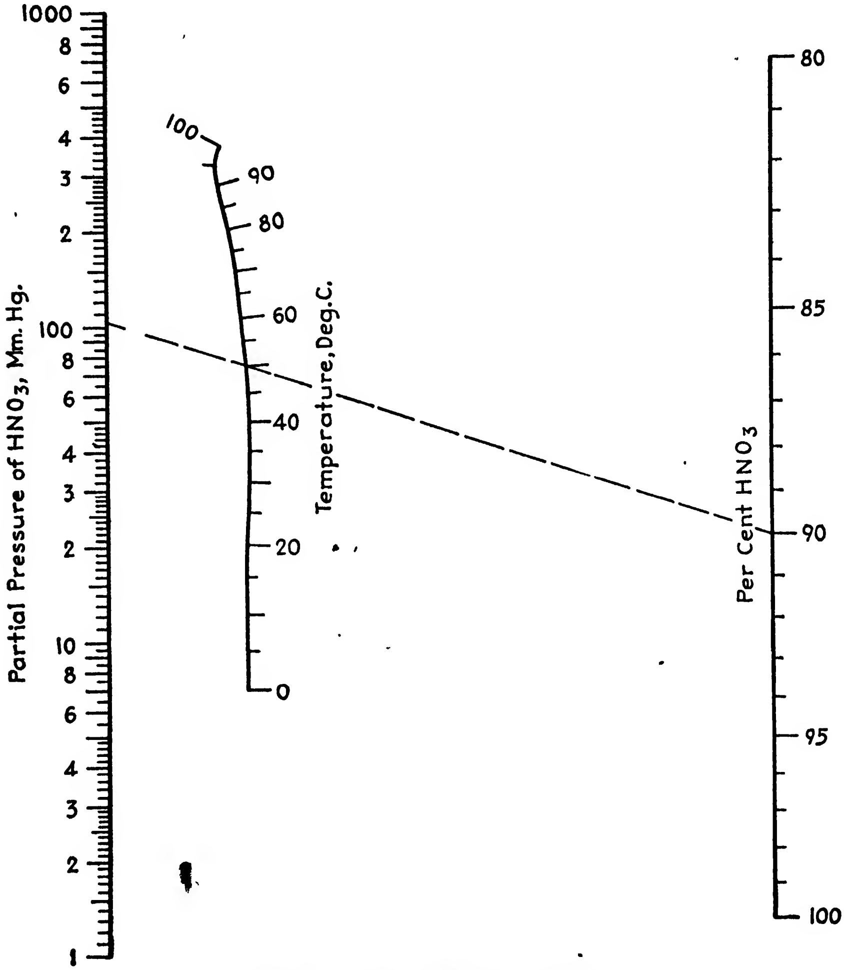

FIG. 88.—Partial pressure of HNO_3.

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[1] OTHMER, D. F., *Chem. & Met. Eng.*, **47**, 631 (1940).

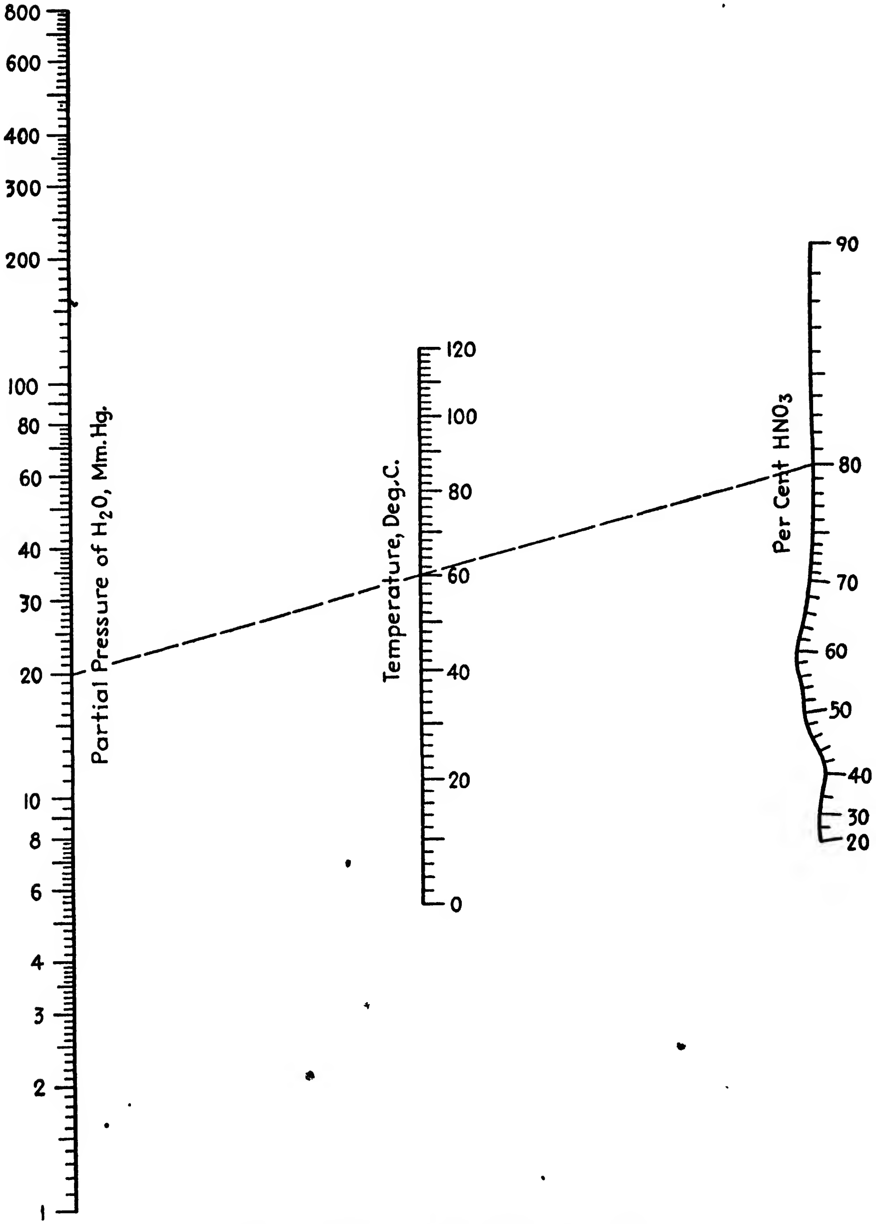

FIG. 89.—Partial pressure of H_2O over HNO_3.

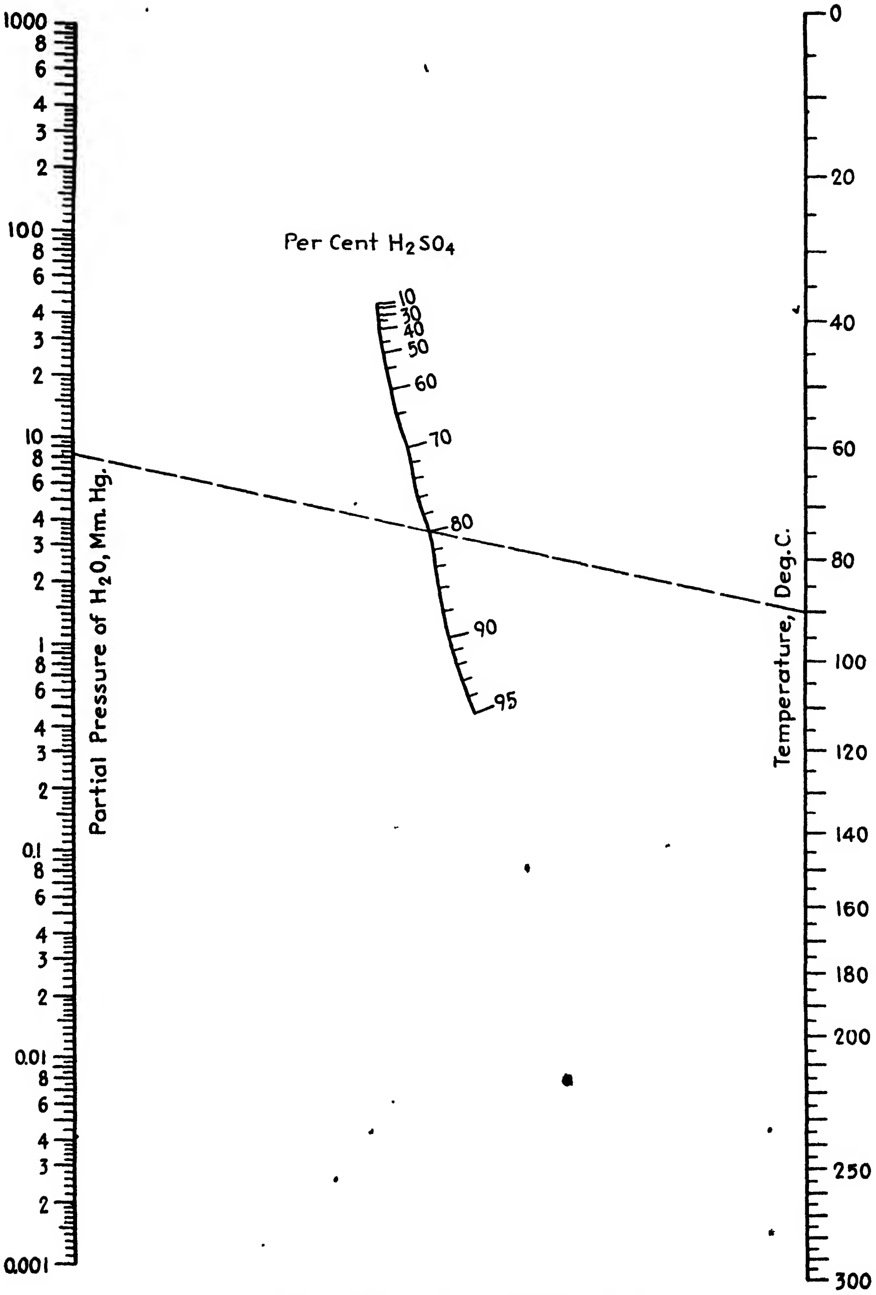

FIG. 90.—Partial pressure of H_2O over H_2SO_4.

130° on scale *B* with 30 mole per cent on scale *E* and read the water-vapor content in the vapor as 4.0 mole per cent.

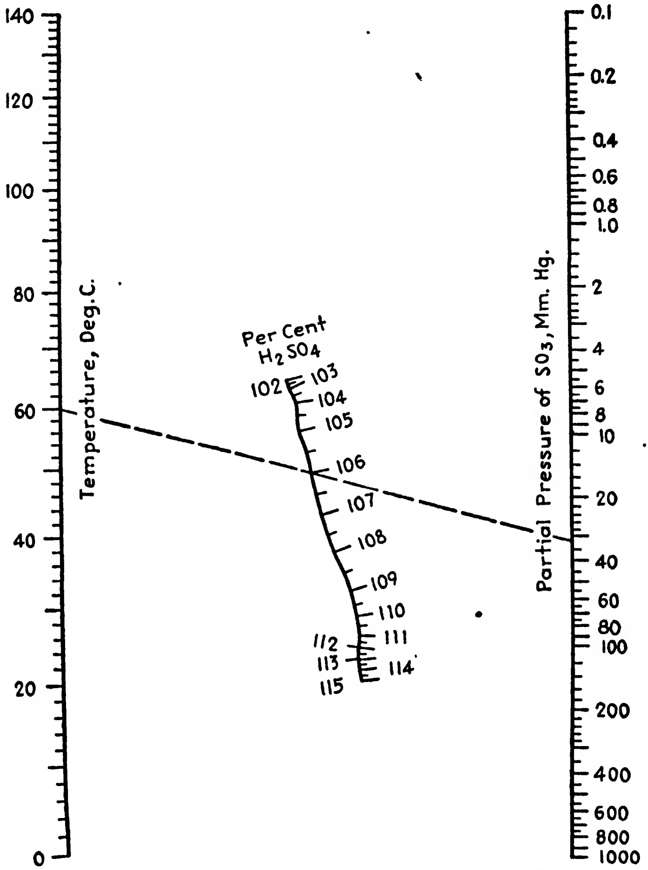

FIG. 91.—Partial pressure of SO_3 over fuming H_2SO_4.

GRAPHICAL DETERMINATION OF AMMONIA SOLUBILITY[1]

Several expressions relating the equilibrium pressures of ammonia over aqueous ammonia solutions, the concentration of dissolved ammonia, and the temperature have been proposed. The equation

$$p = \frac{ac}{b - c}, \tag{22}$$

where *p* is the partial pressure of ammonia in millimeters of mercury over a solution which has a concentration of *c* per cent ammonia and *a* and *b* are constants (Fig. 96*a*) depending upon the temperature, was

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[1] *Chem. & Met. Eng.*, **38**, 576 (1931).

developed by Whitman (private communication, 1924) for use with Perman's data.[1]

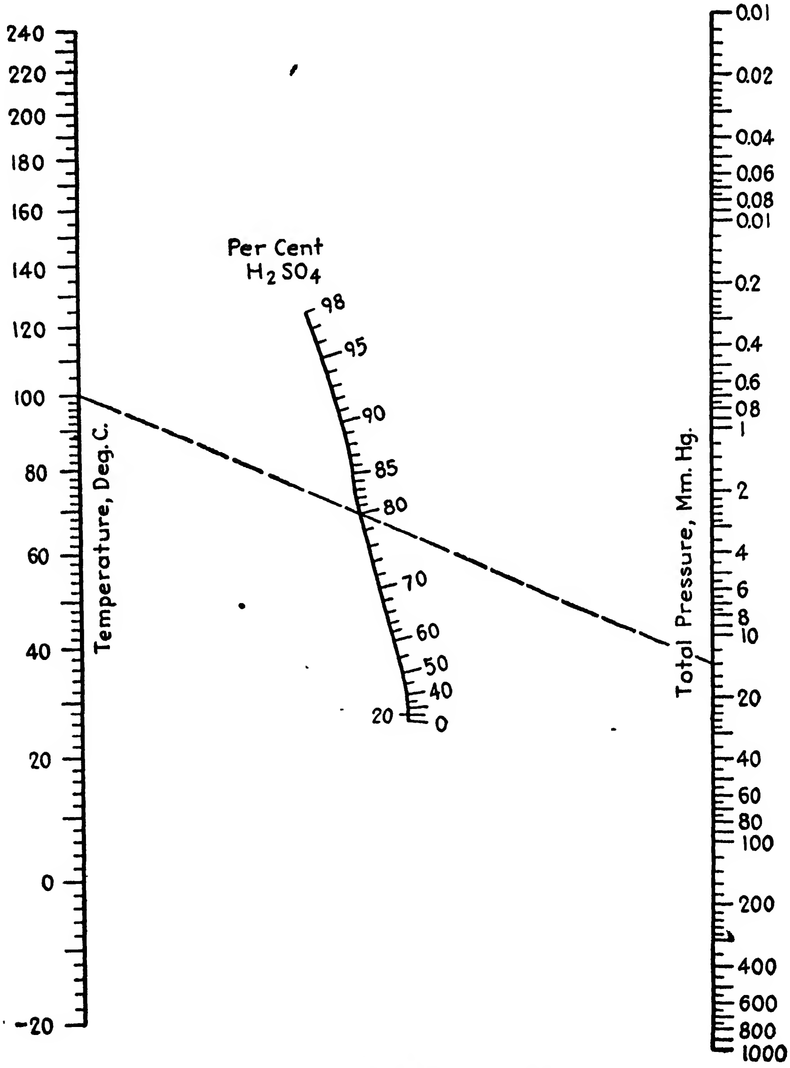

Fig. 92.—Total pressure over H_2SO_4.

From thermodynamic considerations, Kowalke, Hougen, and Watson[2] derived the following equation:

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[1] Perman, E. P., *J. Chem. Soc.*, **83**, 1168 (1903).

[2] Kowalke, O. L., O. A. Hougen, and K. M. Watson, *Chem. & Met. Eng.*, **32**, 443, 704 (1925).

$$\ln \frac{p}{m} = 10.82 - \frac{4{,}425}{T} \tag{23}$$

where p is the partial pressure of ammonia in atmospheres over a solution containing m g. moles of ammonia per 1,000 g. of water at a temperature of T°C. abs.

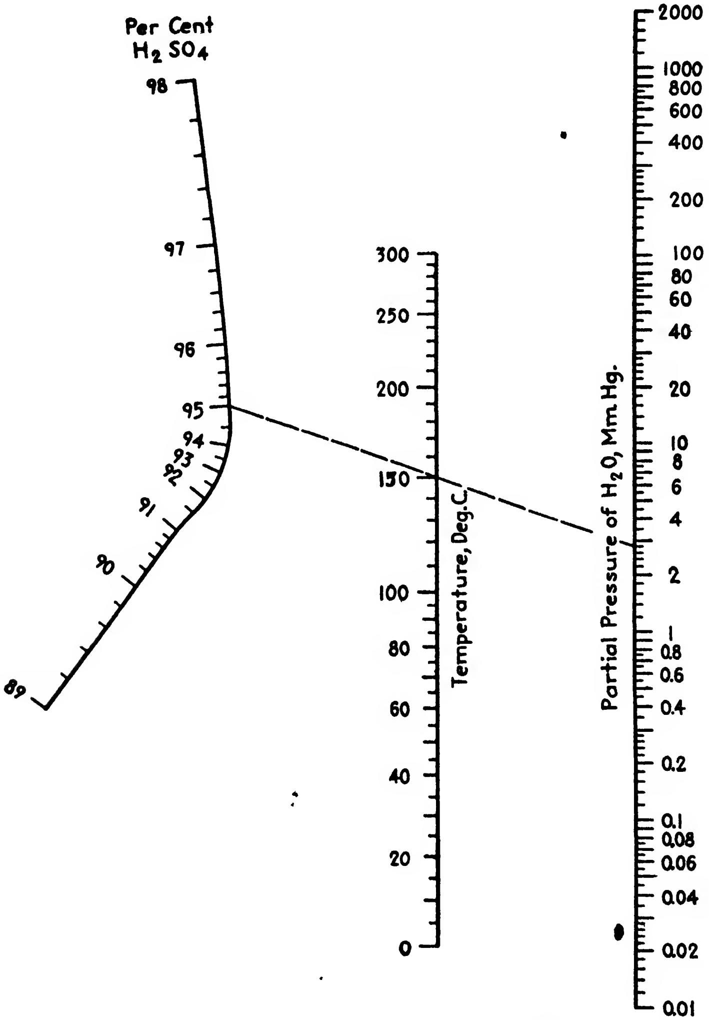

FIG. 93.—Partial pressure of H_2O over H_2SO_4.

In 1925, Sherwood[1] published a critical study of all the best ammonia data, presenting tables and charts of pressure, temperature, and solubility

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[1] SHERWOOD, T. K., *Ind. Eng. Chem.*, **17**, 745 (1925).

values. A little later[1] he proposed the following equation:

$$S = Kp^n - 83 + 1.27t \qquad (24)$$

where p is the partial pressure of ammonia in millimeters of mercury over a solution of S g. of ammonia in 1,000 g. of water at a temperature of t°C. K and n are constants depending on the temperature and must be read, at considerable sacrifice of accuracy, from a plot (Fig. 96a). No attempt was made to express K and n as functions of the temperature.

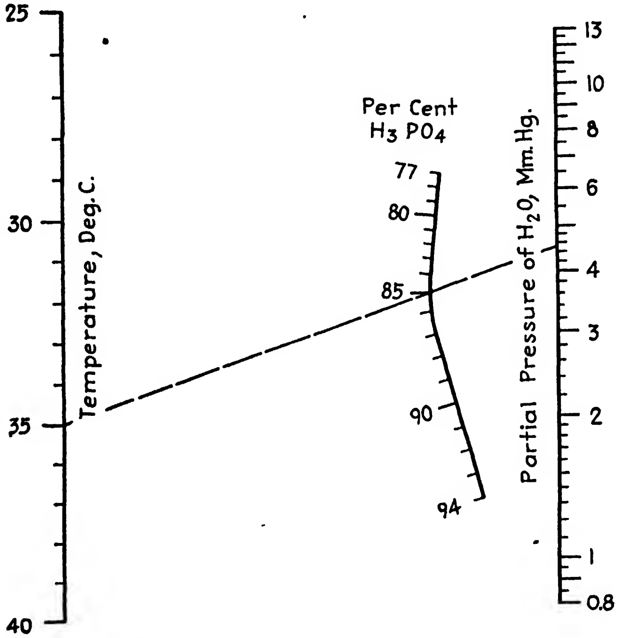

FIG. 94.—Partial pressure of H_2O over H_3PO_4.

Equation (22) is limited to temperatures between 10 and 40°C., to concentrations below 13 molal, and is not independent of the plot of a and b against the temperature. Equation (23), while satisfactory below molalities of 4, is based on the heat of solution of ammonia at 25°C. and is restricted to use near this temperature. Equation (24) must be supplemented by the plot of K and n against t and shows some fairly large deviations from the accepted values. Sherwood's tables and charts give pressures and solubilities at intervals of 10°C. but are difficult to interpolate accurately. Hence there appears to be a need for an equation connecting these variables which can be used with accuracy over wide ranges.

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[1] SHERWOOD, T. K., *Chem. & Met. Eng.*, **32**, 704 (1925).

TABLE XI.—COMPARISON OF ACTUAL SOLUBILITIES OF NH_3 WITH THOSE OBTAINED BY CALCULATION

Temperature °C.	Partial pressure NH_3, mm. Hg.	S = g. NH_3 per 1,000 g. H_2O (Sherwood)	Eqs. (25) and (26)		Eq. (24)		Eq. (23)		Eq. (22)	
			S'	Per cent deviation	S	Per cent deviation	S	Per cent deviation	S	Per cent deviation
0	947.0	1,000	1,003.8	0.4	964.0	−3.6				
	275.0	500	499.5	−0.1	495.0	−1.0				
	89.5	250	246.3	−1.5	254.5	1.8				
	11.2	50	49.8	−0.4						
10	987.0	800	793.4	−0.8	794.2	−0.7				
	439.0	500	501.7	0.3	506.2	1.2				
	190.0	300	302.0	0.7	308.7	2.9	....	.....	293.0	−2.3
	103.5	200	201.3	0.7	209.2	4.6	....	.....	200.0	0.0
	41.8	100	99.1	−0.9	.....	.....	....	.....	98.3	−1.7
	11.3	30	30.0	0.0	.....	.....	....	.....	29.8	−0.7
20	945.0	600	596.8	−0.5	619.4	3.2				
	298.0	300	301.5	0.5	303.9	1.3	....	.....	293.0	−2.3
	50.0	75	74.9	−0.1	.....	.....	81.2	8.3	74.0	−1.3
	24.9	40	39.5	−1.3	.....	.....	40.4	1.0	38.9	−2.8
	12.0	20	19.7	−1.5	.....	.....	19.5	−2.5	19.3	−3.5
30	719.0	400	390.3	−2.4	406.1	1.5				
	260.0	200	205.9	3.0	202.5	1.3	....	.....	201.0	0.5
	79.7	75	75.4	−0.5	.....	.....	78.5	4.7	75.3	0.4
	29.6	30	30.2	0.7	.....	.....	29.2	−2.7	29.8	−0.7
	11.5	12	12.1	0.8	.....	.....	11.3	−5.8	11.9	−0.8
40	692.0	300	289.9	−3.4	287.5	−4.2				
	273.0	150	156.5	4.3	145.8	−2.8	...	.....	150.0	0.0
	120.0	75	74.8	−0.9	73.8	−1.6	....	.....	73.8	−1.6
	45.0	30	30.0	0.0	.....	.....	....	.....	29.4	−2.0
	15.4	10	10.6	6.0	.....	.....	....	.....	10.3	3.0
50	825.0	250	245.5	−1.8	242.1	−3.2				
	405.0	150	152.3	1.5	140.5	−6.3				
	91.1	40	40.2	0.5	37.7	−5.8				
	22.2	10	10.3	3.0						
60	834.0	200	......	.....	190.2	−4.9				
	361.0	100	....	.....	96.5	−3.5				
	94.3	30	....	.....	30.0	0.0				

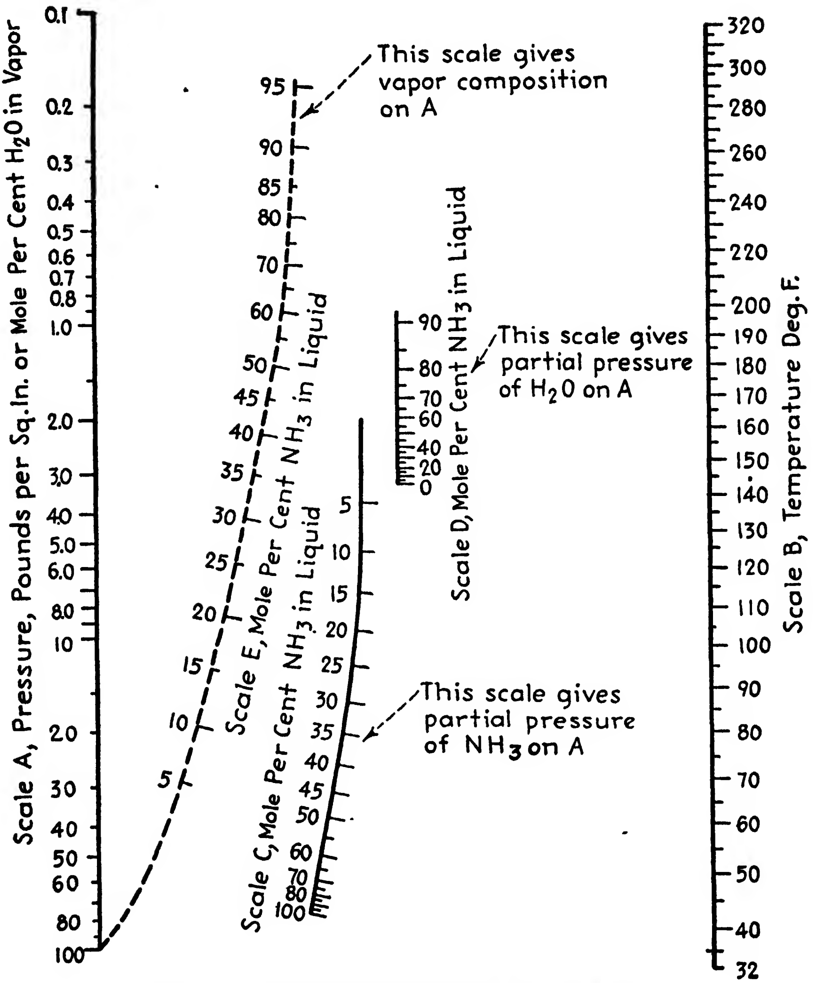

FIG. 95.—Ammonia vapor pressure and composition.

For the ammonia data as compiled by Sherwood, the following two equations are proposed:

$$S = \frac{p}{0.0015p + 6.989(100 + t)^{5.7369} \times 10^{-13}} \qquad (25)$$

for values of S below 100 and

$$S = (e^{-0.02512t+3.542} + 1)\sqrt{p} - 100 \sinh^{-1} \tan [-21.844 \log (t + 25) + 76.264] \qquad (26)$$

for values of S above 100. These equations cover partial pressures p up to 1,000 mm. mercury and temperatures t from 0 to 50°C., S indicating grams of ammonia per 1,000 g. of water. Equations (25) and (26) are not intended for ordinary use, since routine calculations may be handled with greater facility by means of Figs. 96*b* and 97 from which solubilities

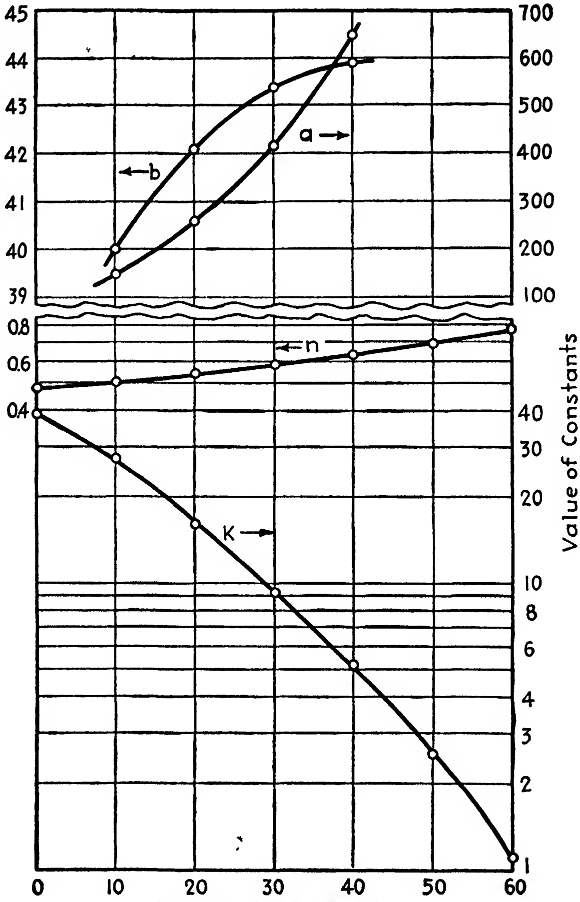

FIG. 96*a*.—Constants for Eqs. (22) and (24).

may be read either on the basis of 1,000 g. of water or 1,000 g. of solution. The solubility σ on the latter basis is related to S by the expression

$$\sigma = \frac{S}{1,000 + S}. \qquad (27)$$

Table XI lists a comparison of actual solubilities with solubilities calculated by the five equations, together with a comparison of percentage deviations. The table covers only four or five pressure-solubility combinations at each temperature.

NOMOGRAPH FOR THE SOLUBILITY OF CHLORINE IN WATER[1]

The most recent data on the solubility of chlorine in water are those of Whitney and Vivian[2] who presented pressure-concentration isotherms in addition to tabular information for the ranges of 10 to 25°C., 0.06 to 1.0 atm. chlorine pressure, and 0.1 to 0.8 g. of chlorine per 100 g. of water. From sound theoretical considerations, they derived a relation

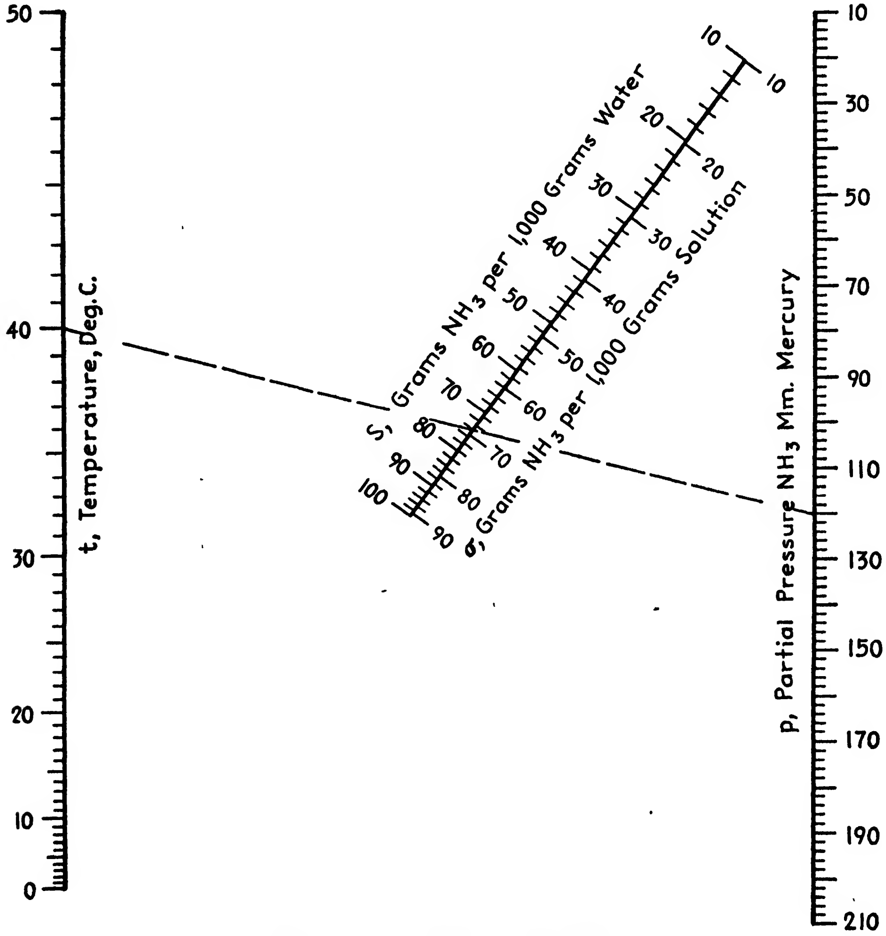

FIG. 96b.—Partial pressure of NH_3.

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[1] *Ind. Eng. Chem.*, **33**, 1202 (1941).

[2] WHITNEY, R. P., and J. E. VIVIAN, *Ind. Eng. Chem.*, **33**, 741 (1941).

between c, the concentration of chlorine (in all forms) as moles per 100 g. of water, and p, the chlorine pressure in atmospheres, equivalent to

$$c = ap + bp^{\frac{1}{3}}$$

where a and b depend upon temperature.

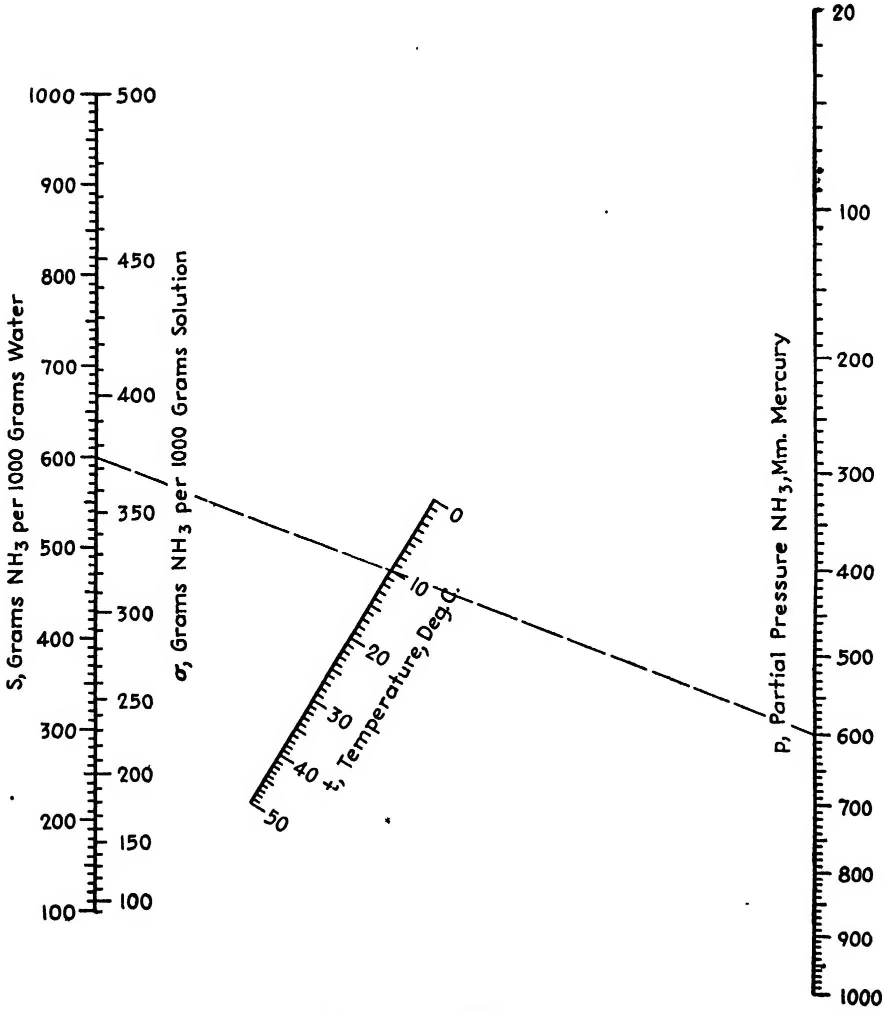

FIG. 97.—Partial pressure of NH_3.

This equation and a table given by Whitney and Vivian[1] enable construction of the nomograph from which solubilities, corresponding to any temperature and pressure in the ranges of the data, can be read

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[1] *Ibid.*

quickly and accurately. The use of Fig. 98 is illustrated as follows: What is the solubility of chlorine in water when the chlorine pressure is 0.6 atm. and the temperature is 20°C.? Following the key, connect 0.6 on the p_1 scale with 20 on the t_1 scale, and produce the line to the vertical axis at the right. Connect 0.6 on the p_2 scale with 20 on the t_2 scale, and produce this line to the vertical axis at the left. A line connecting the intersections at the right and left axes will cut the S scale in the desired value, 4.89 g. of chlorine per 1,000 g. of water.

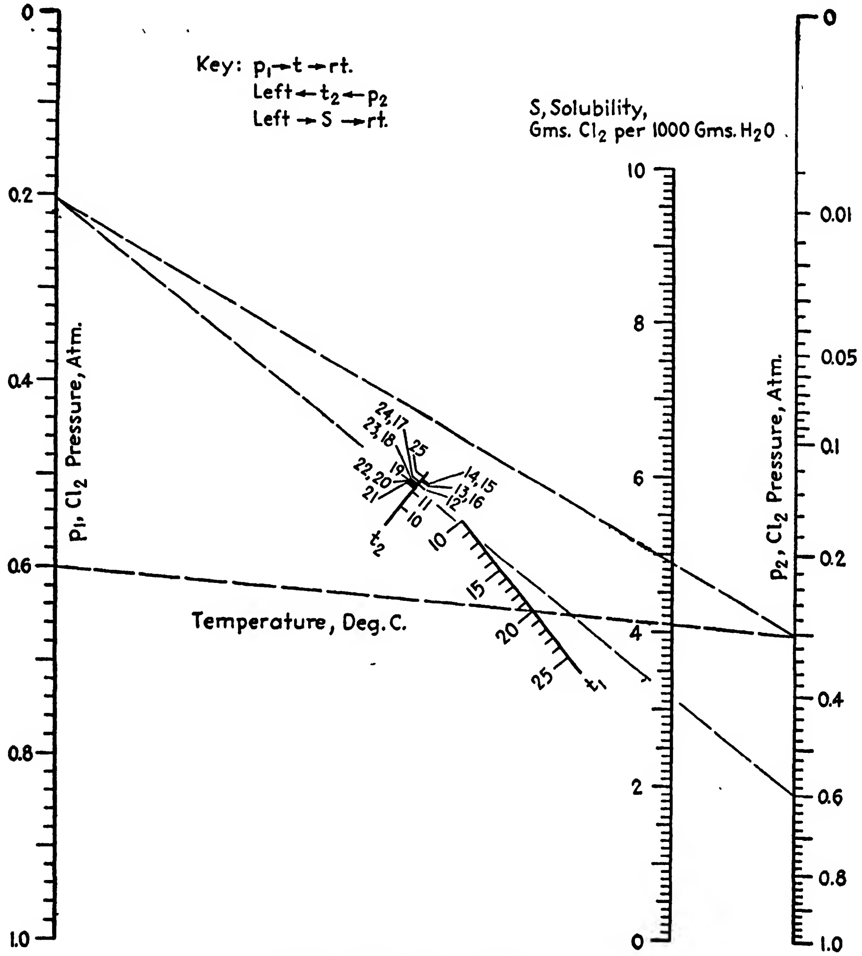

Fig. 98.—Solubility of Cl_2 in water.

Since the molecular weight of chlorine is 70.91, S in grams of chlorine per 1,000 g. of water is equal to 709.1c.

NOMOGRAPH FOR THE SOLUBILITY OF CHLORINE MONOXIDE IN WATER[1]

Secoy and Cady[2] studied the equilibrium

$$2\text{HOCl (aqueous)} \rightleftharpoons \text{Cl}_2\text{O (gas)} + \text{H}_2\text{O (liquid)},$$

which bears directly upon a commercial process for the manufacture of hypochlorous acid, and presented pressure-concentration isotherms for 3.46, 9.92, and 19.98°C., from which they prepared tabular data for 0, 10, and 20°C. Though the data are not regarded as final, their industrial application warrants further correlation and presentation of an alignment chart for convenient interpolation of the solubility S in grams of chlorine monoxide per 100 g. of water at partial pressures p of solute between 1 and 70 mm. mercury, and at temperatures t between 0 and 20°C.

The chart is based on the relation

$$p = aS^b$$

where a and b depend upon temperature as given in Table XII.

TABLE XII

Temperature, °C.	p = 1 to 20 mm.		p = 20 to 70 mm.	
	a	b	a	b
0	0.01757	2.003	0.01231	2.104
2	0.02280	1.958	0.01220	2.146
4	0.02675	1.955	0.01210	2.188
6	0.02955	1.968	0.01225	2.226
8	0.03200	1.982	0.01280	2.259
10	0.03472	1.995	0.01396	2.281
12	0.03830	2.007	0.01745	2.264
14	0.04309	2.020	0.02323	2.228
16	0.04970	2.034	0.03150	2.195
18	0.05921	2.046	0.04373	2.162
20	0.07163	2.060	0.05953	2.127

The use of the chart (Fig. 99) is illustrated in this manner: What is the solubility of chlorine monoxide in water at 10°C. when the partial pressure of the solute is 35 mm. mercury? Following the upper index line, connect 35 on the p scale with 10 on the upper t scale, which is for pressures of 20 mm. or more, and produce the line to the S scale where the solubility is read as 31 g. of chlorine monoxide per 100 g. of water.

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[1] *Ind. Eng. Chem.*, **34**, 624 (1942).

[2] SECOY, C. H., and G. H. CADY, *J. Am. Chem. Soc.*, **63**, 2504 (1941).

What is the partial pressure of chlorine monoxide over an aqueous solution containing 8.2 g. of solute per 100 g. of water at 18°C.? Following the lower dashed line, connect 8.2 on the S scale with 18 on the lower t scale, limited to pressures of 20 mm. or less, and read the partial pressure on the p scale as 4.4 mm. mercury. It is evident in this case that

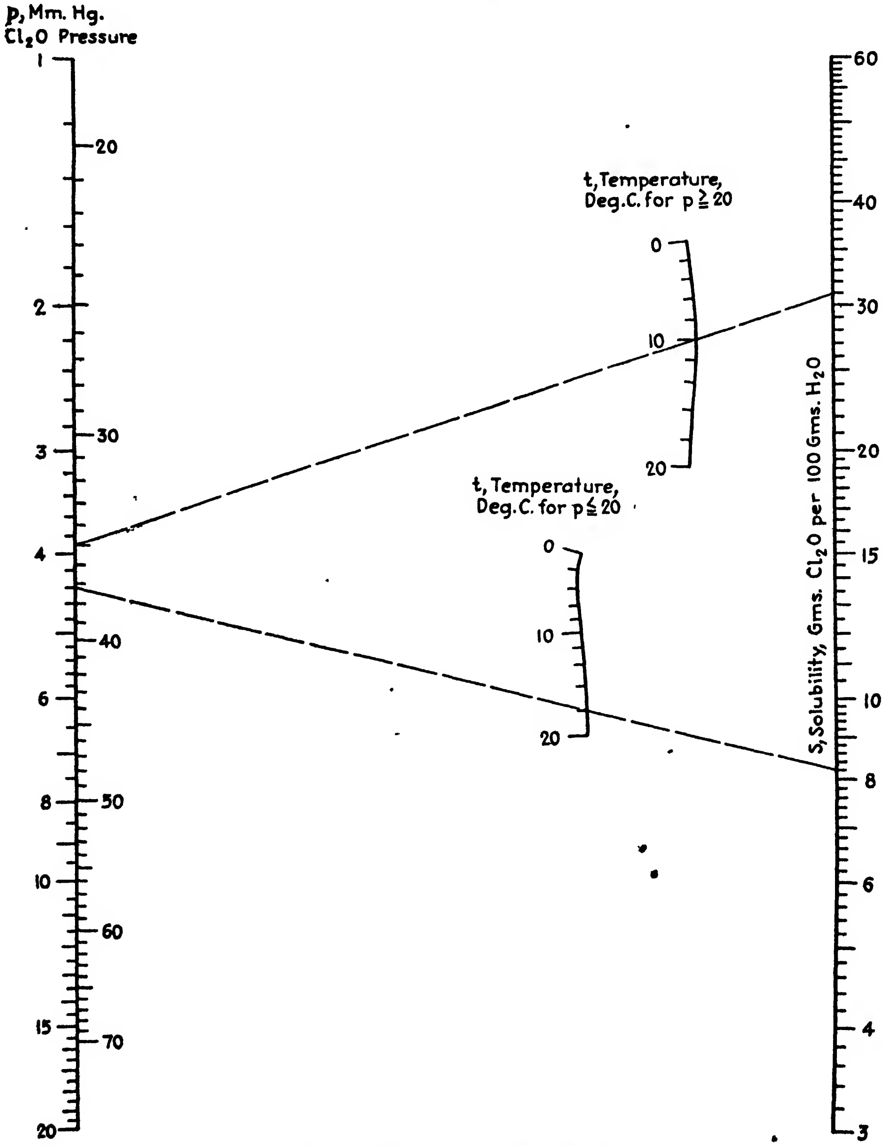

Fig. 99.—Solubility of Cl_2O in water.

the upper t scale is not to be employed since its use would result in an off-scale value for the pressure.

The average deviation of solubilities as read by means of the chart from the original data is 0.7 per cent.

BOILING-POINT NOMOGRAPH FOR GLYCEROL SOLUTIONS[1]

In connection with the study of evaporator design, Carr, Townsend, and Badger[2] have presented data on the boiling points of aqueous glycerol solutions under reduced pressures.

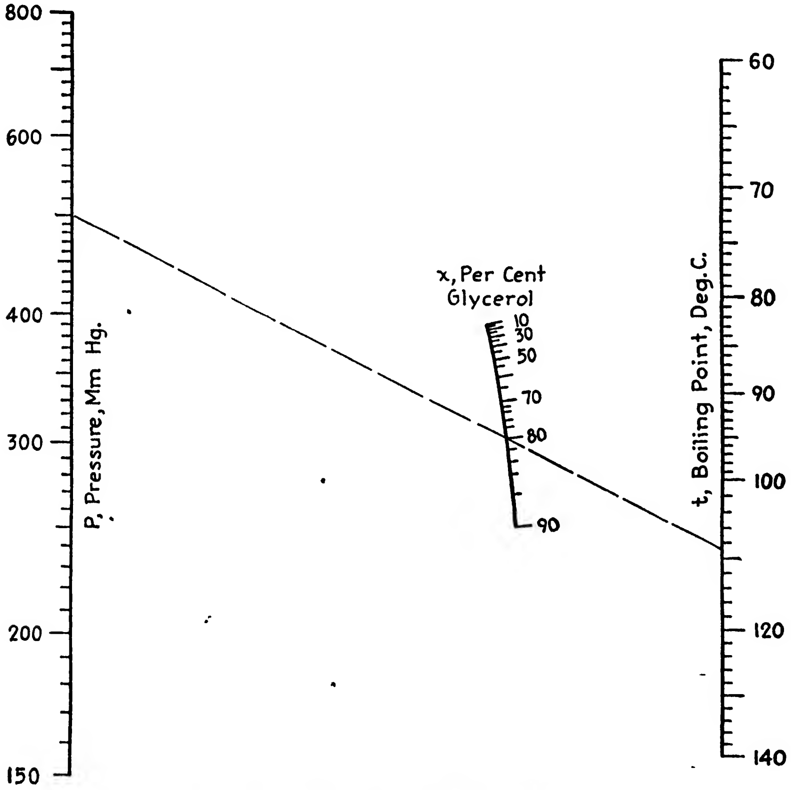

FIG. 100.—Boiling point of glycerol solutions.

In changing from the tabular form of presentation to the nomographic, it was found that the following equation represented the data:

$$P = at^b + 29.1$$

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[1] *Chemist-Analyst*, **22** (4), 8 (1933).

[2] CARR, A. R., R. E. TOWNSEND, and W. L. BADGER, *Ind. Eng. Chem.*, **17**, 643 (1925).

where P is the pressure, millimeters mercury; t is the boiling point of the solution, degrees centigrade, under the pressure P; and where a and b

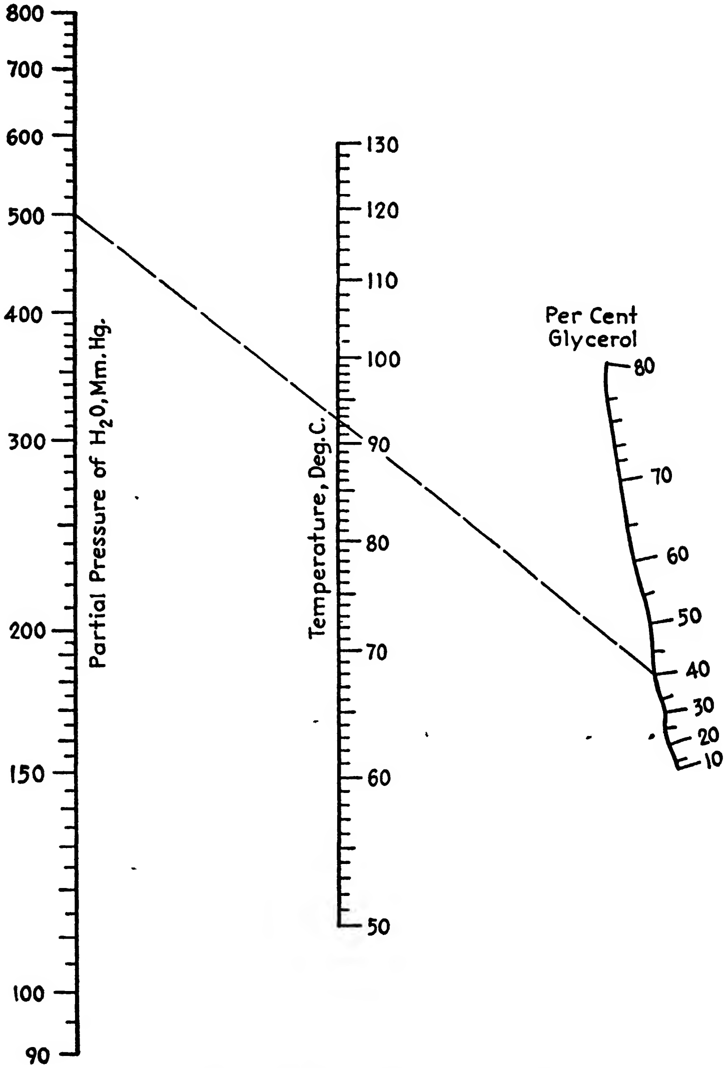

FIG. 101.—Partial pressure of H_2O over glycerol solutions.

are functions of the weight percentage of glycerol, x. For purposes of the line-coordinate chart, a and b need not be defined more exactly.

The broken line in Fig. 100 indicates that an 80 per cent glycerol solution will boil at 109°C. when the pressure is 500 mm. mercury.

PARTIAL PRESSURE OF WATER VAPOR OVER AQUEOUS GLYCEROL SOLUTIONS[1]

In connection with a study of evaporator design, Carr, Townsend, and Badger[2] have presented data on the boiling points of aqueous solutions of glycerol, dealing particularly with temperatures above 50°C. In the course of seeking a relationship between the partial pressure of water vapor, p, over the solutions, and the temperature t in degrees

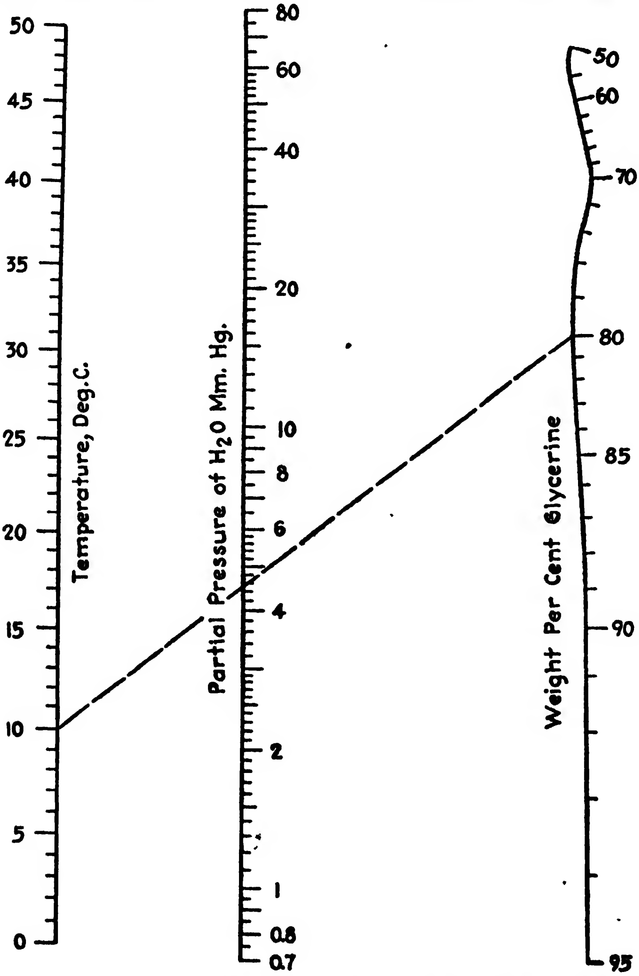

FIG. 102.—Partial pressure of H_2O over glycerol solutions.

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[1] *Chemist-Analyst*, **24** (3), 15 (1935).

[2] CARR, A. R., R. E. TOWNSEND, and W. L. BADGER, *Ind. Eng. Chem.*, **17**, 643 (1925).

centigrade, it was found that the following expression held quite closely:

$$p \doteq at^b + 29.1$$

where a and b are values which depend upon the concentration of glycerol in the solution.

For purposes of Fig. 101, a and b need not be further defined. The chart affords a convenient means of interpolation of the data, and its use is illustrated by the broken line which shows that the partial pressure of water vapor over a 40 per cent glycerol solution at 92.5°C., is 500 mm. mercury.

Figure 102,[1] covering different ranges of the variables, is based on the data of Darke and Lewis[2] and on data from Landolt-Bornstein,[3] which were correlated by the equation

$$\log p = A - \frac{B}{t + 230}$$

where p = partial pressure of water vapor, mm. mercury.
t = degrees centigrade.

The index line in Fig. 102 shows that an aqueous glycerine solution testing 80 per cent glycerin has a water vapor pressure of 4.5 mm. mercury at 10°C.

NOMOGRAPH FOR PARTIAL PRESSURES OF HYDROGEN CHLORIDE IN AQUEOUS SOLUTIONS[4]

Figure 103 permits rapid solution of the Zeisberg equation[5]

$$\log P = 10.9528 - 0.009725W - 0.000868W^2 - \frac{4,557 - 65.3W}{t + 273}$$

where P = partial pressure of HCl, mm. mercury.
W = weight per cent of HCl in aqueous solution.
t = temperature, °C.

Zeisberg has shown this expression to be accurate within 5 per cent for the calculation of partial pressures when working between 0 and 100°C. with solutions of 18 to 32 per cent HCl.

As an illustration of the use of the chart, the broken line indicates that the partial pressure of hydrogen chloride over a 30 per cent solution at 50°C. is 68 mm.

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[1] PERRY, J. H., and H. C. DUUS, *Chem. & Met. Eng.*, **41**, 74 (1934).

[2] DARKE, W. F., and E. LEWIS, *Chemistry and Industry*, **47**, 1073–1092 (1928).

[3] LANDOLT-BORNSTEIN, "Physikalisch-chemische Tabellen," Part 2, p. 1328, Julius Springer, Berlin, 1931.

[4] *Chem. & Met. Eng.*, **37**, 767 (1930).

[5] *Chem. & Met. Eng.*, **32**, 326 (1925).

NOMOGRAPHS FOR THE SOLUBILITIES OF HYDROGEN AND NITROGEN IN LIQUID AMMONIA[1]

In connection with their study of the physical properties of substances bearing upon the production of fertilizers, such as the system ammonia–hydrogen–nitrogen, Wiebe and Tremearne[2] presented data on the solubility of hydrogen in liquid ammonia in tabular form and as isotherms on a solubility-pressure plot in intervals of 25°C. Wiebe and Gaddy[3] added isobars on a solubility-temperature plot in steps of 200 atm. Interpolation for temperatures and pressures other than those specifically covered in these plots can be made quickly and conveniently by means of the line-coordinate chart (Fig. 104) which is based on the expression

$$\log \sin \left(\frac{S - \delta}{10}\right) = a + bt$$

where S is the solubility of H_2 at standard temperature and pressure, cubic centimeters per gram of liquid NH_3; t is the temperature, degrees centigrade; and a and b depend upon the pressure as shown in Table XIII.

TABLE XIII

Pressure, atm.	200	400	600	800	1000
a	−1.58235	−1.36748	−1.22495	−1.13148	−1.06223
$b(10^6)$	5,835	7,467	7,747	7,943	7,993

The quantity $(S - \delta)/10$ is taken to have the units of degrees, circular measure, and δ varies with S as shown in Table XIV.

TABLE XIV

S	δ	S	δ	S	δ
13.11	−2.00	224	16.0	300	29.0
14.00	−0.01	230	16.2	320	35.5
161	0.01	240	16.5	340	42.0
177	0.10	250	17.5	360	48.3
194	1.00	260	19.2	380	53.4
200	2.10	270	21.1	400	57.0
210	6.00	280	23.4		
220	14.0	290	26.0		

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[1] *Ind. Eng. Chem.*, **33**, 1454 (1941).

[2] WIEBE, R., and T. H. TREMEARNE, *J. Am. Chem. Soc.*, **56**, 2357 (1934).

[3] WIEBE, R., and V. L. GADDY, *J. Am. Chem. Soc.*, **59**, 1984 (1937).

The index line in Fig. 104 shows that 66 cc. of H_2 at s.t.p. dissolve in 1 g. of liquid ammonia at 34°C., when the pressure is 640 international atmospheres. The average deviation of solubilities read from the chart from the observed values is about 0.9 per cent.

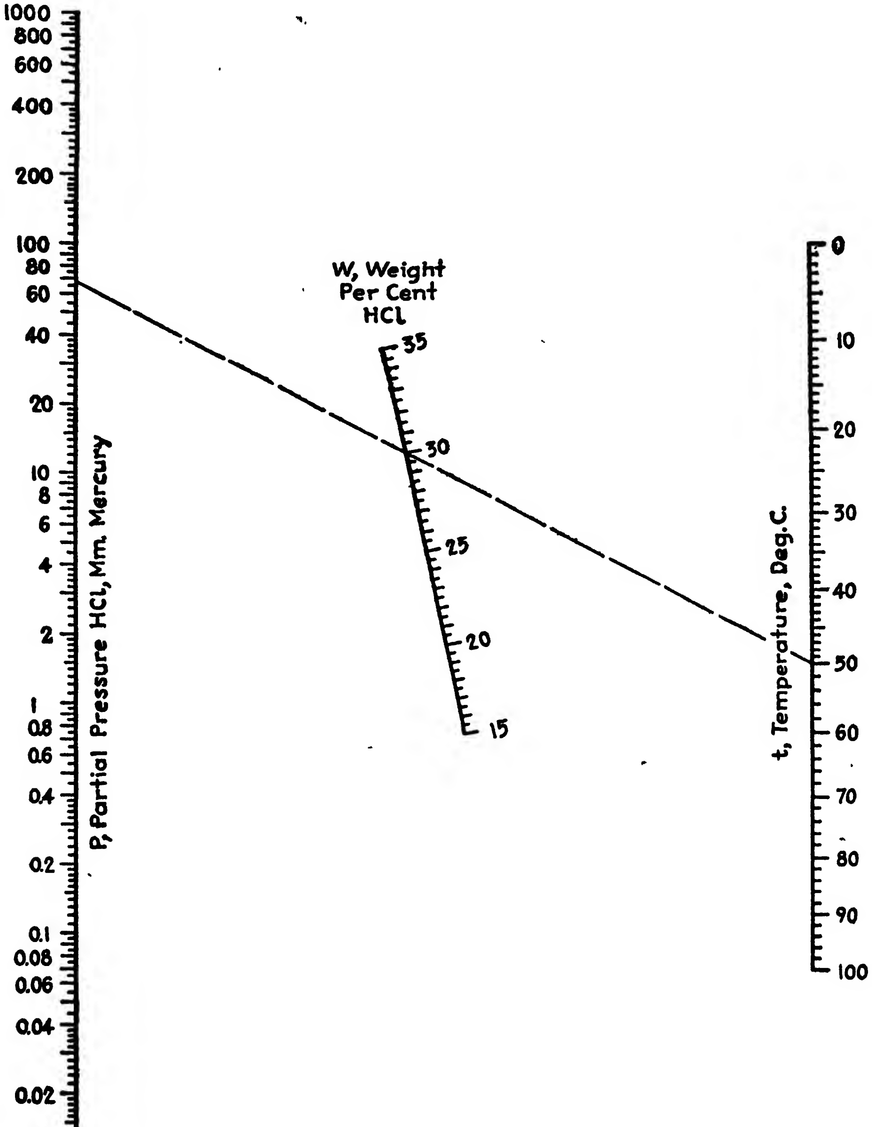

FIG. 103.—Partial pressure of HCl over aqueous solutions.

Wiebe and Gaddy[1] also presented tabular data and similar isotherms and isobars for the solubility of nitrogen in liquid ammonia. Interpolation of these data is facilitated by Fig. 105, a line-coordinate chart based on the expression

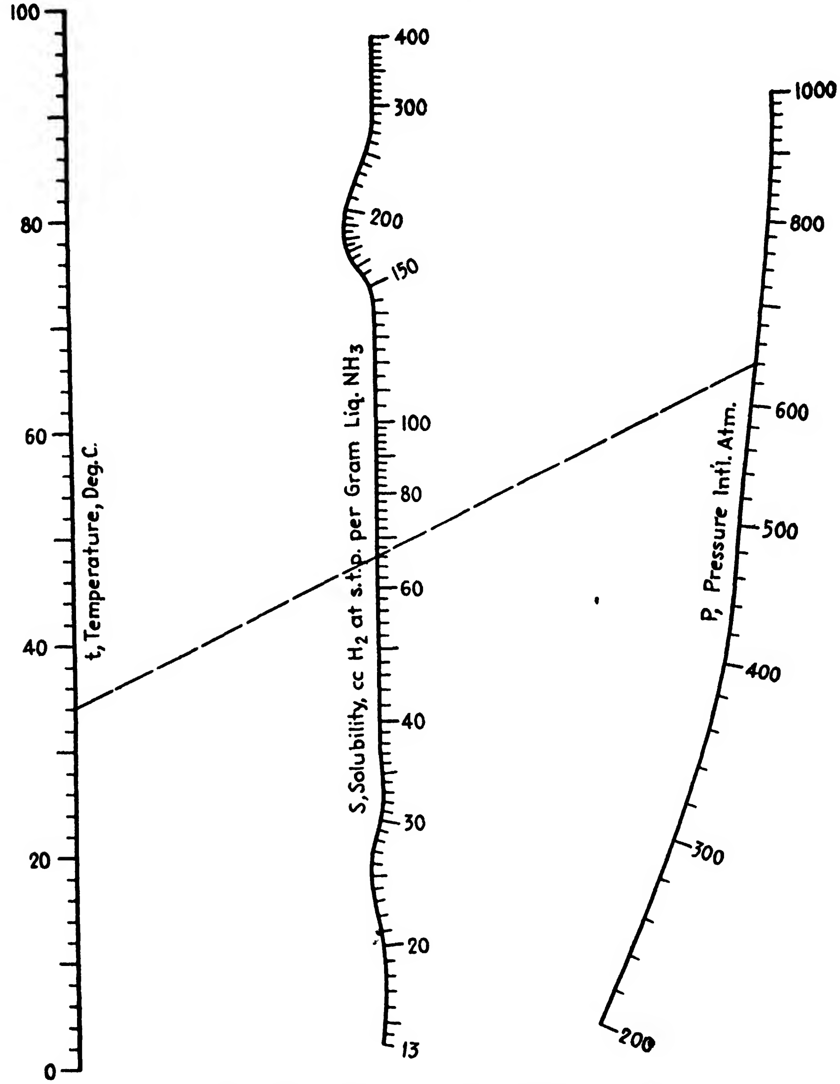

FIG. 104.—Solubility of H_2 in liquid ammonia.

$$\log\left[S - \left(\frac{S}{43}\right)^{\log S} + \delta\right] = a + bt$$

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[1] *Loc. cit.*

where S and t have significances for nitrogen parallel to those for hydrogen and a and b depend on pressure as shown in Table XV.

TABLE XV

Pressure, atm	200	400	600	800	1,000
a	1.1753	1.3092	1.3882	1.4396	1.4640
$b(10^6)$	7,493	9,882	10,650	10,686	10,578

The correction term δ varies with S as shown by Table XVI.

TABLE XVI

S	δ	S	δ	S	δ
35	0.00	75	1.38	94	2.44
40	0.01	80	1.97	96	2.30
45	0.02	82	2.19	98	2.06
50	0.05	84	2.35	100	1.65
55	0.12	86	2.46	102	1.05
60	0.24	88	2.53	104	0.10
65	0.47	90	2.55	106	0.01
70	0.84	92	2.51		

The index line in Fig. 105 shows that 76 cc. of N_2 at s.t.p. dissolve in 1 g. of liquid ammonia at 50°C., when the pressure is 500 international atmospheres. Solubilities read from Fig. 105 deviate, on the average, about 1.0 per cent from the observed values.

VAPOR-PRESSURE NOMOGRAPHS FOR AQUEOUS SODIUM HYDROXIDE SOLUTIONS[1]

The latest data on the vapor pressures of aqueous solutions of sodium hydroxide appear to be those of Åkerlöf and Kegeles,[2] a table of logarithms of vapor pressures for molalities of 0.1, 0.2, 0.4, 0.6, 0.8, 1.0, 1.5, and 2 to 17 in steps of 1 mole for temperatures of 0 to 70°C., in steps of 10°. To devise a convenient method of interpolation for intermediate concentrations and temperatures, it was necessary to effect a correlation suited to the requirements of a line-coordinate chart.

The integrated Clausius-Clapeyron equation, assuming constancy of the latent heat of vaporization, validity of the gas laws for water vapor, and negligibility of solution volume in comparison with vapor volume, yields

$$\log p = a + \frac{b}{T}. \qquad (28)$$

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[1] *Ind. Eng. Chem.*, **34**, 1131 (1942).

[2] ÅKERLÖF, G., and G. KEGELES, *J. Am. Chem. Soc.*, **62**, 620 (1940).

Equation (28) suggests the use of logarithmic pressure and reciprocal absolute temperature axes, but appreciable curvature in the plots is encountered. Satisfactory straight lines result when log $(p - \delta)$ is plotted against $1/(t + 230)$, according to the equation

$$\log (p - \delta) = A + \frac{B}{t + 230} \tag{29}$$

where p is the vapor pressure, millimeters mercury; t is the temperature, degrees centigrade; $\delta = 0.10\ (10)^{-0.10p}$; and A and B depend upon the concentration of sodium hydroxide as shown in Table XVII.

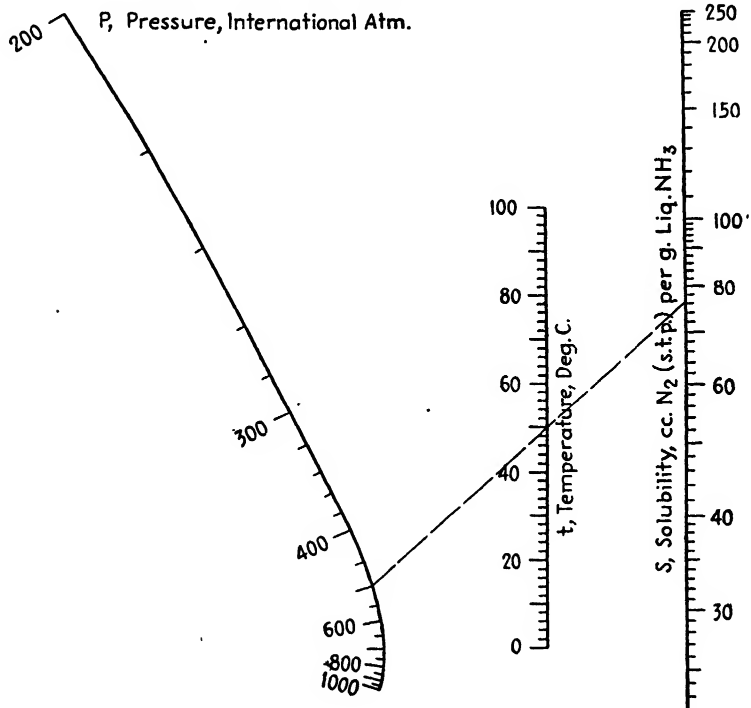

FIG. 105.—Solubility of N_2 in liquid ammonia.

Equation (29) is largely empirical, but this function of temperature has a precedent in the Cox method[1] of plotting vapor-pressure data as shown previously.[2] It has been shown that plots of log p against $1/(t + 230)$ result in straight convergent lines, within the family, for

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[1] Cox, E. R., *Ind. Eng. Chem.*, **15**, 592 (1923).

[2] CALINGAERT, G., and D. S. DAVIS, *Ind. Eng. Chem.*, **17**, 1287 (1925); DAVIS, D. S., *Ind. Eng. Chem.*, **17**, 735 (1925).

TABLE XVII.—VARIATION OF A AND B WITH CONCENTRATION OF SODIUM HYDROXIDE

Molality of NaOH	A	B
0.1	7.98632	−1685.97
0.2	7.98547	−1686.10
0.4	7.98202	−1685.97
0.6	7.97927	−1686.01
0.8	7.97711	−1686.23
1.0	7.97355	−1686.10
1 5	7.96619	−1686.31
2	7.95769	−1686.36
3	7.94304	−1687.70
4	7.93081	−1690.65
5	7.92252	−1695.73
6	7.91801	−1703.07
7	7.92019	−1713.40
8	7.92909	−1726.77
9	7.94692	−1743.56
10	7.97600	−1764.22
11	8.01875	−1789.01
12	8.07724	−1818 00
13	8.10618	−1839.19
14	8.14039	−1862.58
15	8.18029	−1888.23
16	8.22770	−1916.75
17	8.28290	−1948.13

metal, benzene, alcohol, organic acid, and silicon hydride series. Plots of log $(p - \delta)$ against $1/(t + 230)$ for various concentrations of sodium hydroxide exhibit a rough convergence in the neighborhood of 610°C. and 1,200 atm., although this point is not definite enough to be used in a system of correlation.

In Fig. 106, which covers the range of 1 to 17 molal, the index line shows that the vapor pressure of a 10-molal solution of sodium hydroxide is 6.1 mm. mercury at 15°C. Figure 107, confined to concentrations of 0.1 to 7 molal, can be read a little closer than can Fig. 106. The index line shows that the vapor pressure of a 3.6-molal solution of sodium hydroxide is 48 mm. mercury at 40°C.

The average deviation of pressures read from the chart from the original data is about 0.5 per cent.

SOLUBILITY OF SULFUR DIOXIDE IN WATER[1]

Critical study of the solubility of sulfur dioxide by Sherwood[2] has resulted in a compilation of the best concentration, temperature, and

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[1] *Chem. & Met. Eng.*, **39**, 615 (1932).

[2] SHERWOOD, T. K., *Ind. Eng. Chem.*, **17**, 745 (1925).

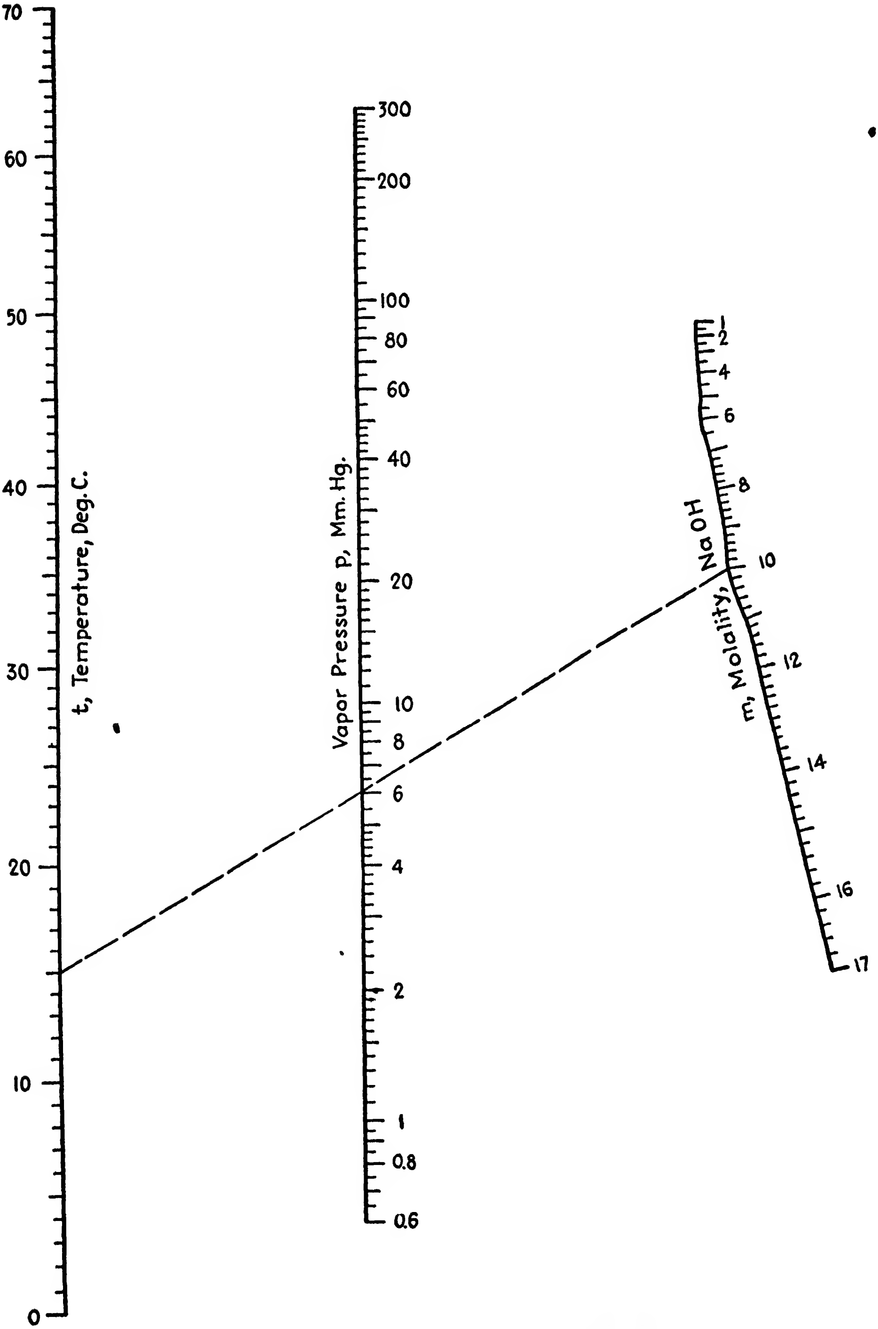


FIG. 106.—Vapor pressure of aqueous NaOH solutions.

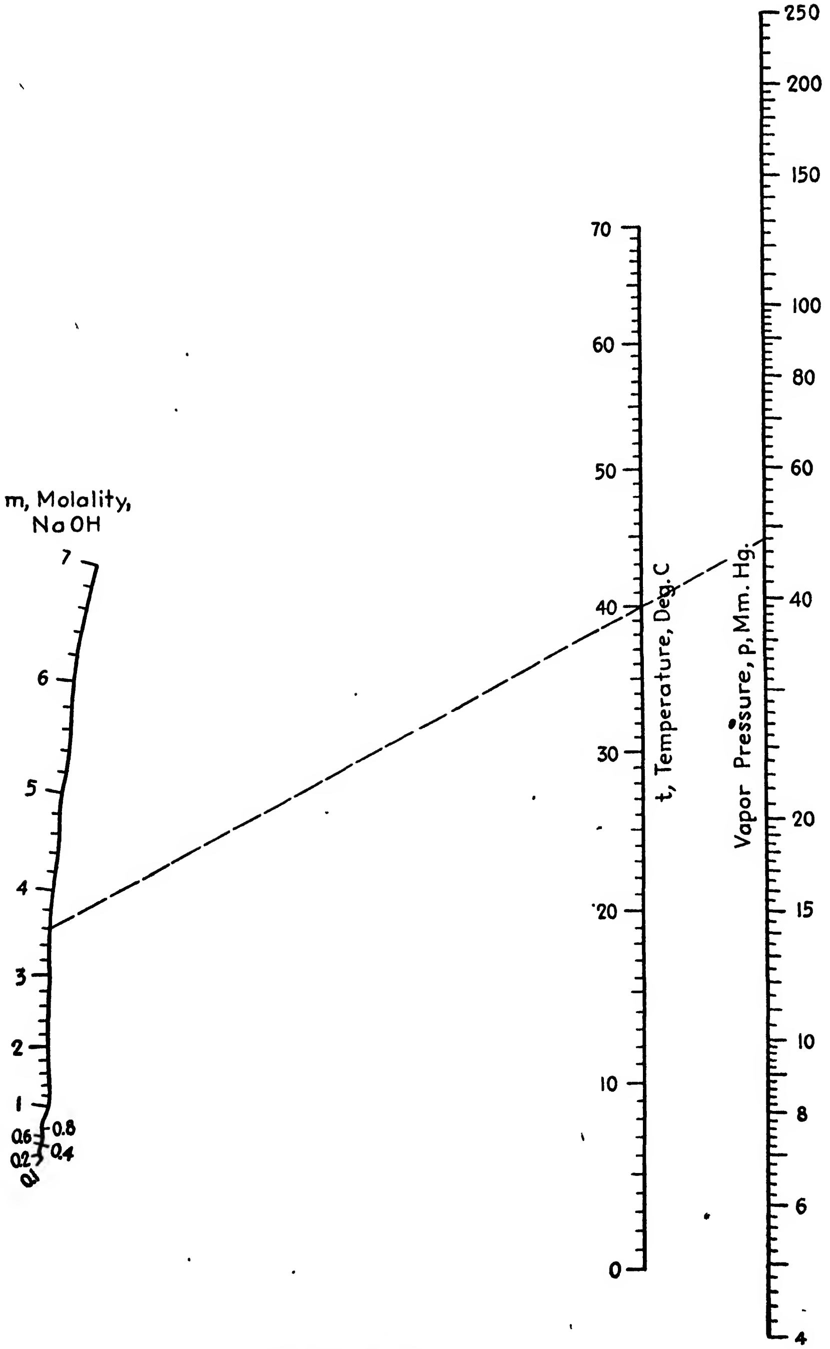


Fig. 107.—Vapor pressure of aqueous NaOH solutions.

partial pressure data presented in tabular form and in the form of isotherms plotted on logarithmic paper. In either form, it is somewhat difficult to interpolate the data rapidly and accurately, and there appears to be need for equations relating the variables and for more convenient means of graphical representation.

It is the purpose of this topic to present such equations together with nomographic charts which enable their rapid and accurate solution and to offer a new method of calculating the approximate dissociation constant of sulfurous acid.

TABLE XVIII.—ACCURACY OF SOLUBILITY CALCULATIONS

Equation	Solubility, S	Temperature, °C.	Percentage deviation, ±
1	1.5–200	0	1.2
1	1.5–150	10	0.7
1	5 – 75	20	2.6
2	5 – 75	20	1.6
2	5 – 50	30	1.4
2	7 – 15	40	5.7

In order to relate p, the partial pressure of SO_2 in millimeters of mercury over an aqueous solution, with c, the concentration of the solution in grams of SO_2 per liter of solution, W. K. Lewis has derived the equation

$$c = Hp + \sqrt{KHp}$$

where H and K are the Henry's law and dissociation constants, respectively.

Sherwood's compilation deals with solubility S on the basis of grams of SO_2 per 1,000 g. of water; and since c and S are nearly equal (differing by but 1 per cent at $S = 10$ and by but 4 per cent at $S = 75$), the relationship between the solubility and partial pressure may be expressed by

$$S = mp + a\sqrt{p} \tag{30}$$

where m and a are functions of the temperature. Between 0 and 20°C., m and a are given by the purely empirical equations

$$m = e^{-0.03876t-1.2825}$$

and

$$a = e^{-0.03872t-0.3054}$$

where e is the base of natural logarithms.

Between 20 and 40°C., the form

$$S = mp + a \tag{31}$$

is more convenient than $S = mp + a\sqrt{p}$, and m and a are defined by the equations $m = 0.13229 + 0.003422t - 0.00013912t^2$ and

$$a = 1.50 - 0.0147t.$$

The agreement between calculated and actual values of the solubility is illustrated by Table XVIII.

Solution of Eqs. (30) and (31) is best accomplished by means of Figs. 108 and 109, which carry two solubility scales, one labeled S, for solubilities in grams of SO_2 per 1,000 g. of water, and the other labeled σ, for solubilities in grams of SO_2 per 1,000 g. of solution. The two scales are related by the equations

$$S = \frac{1{,}000\sigma}{1{,}000 - \sigma} \quad \text{and} \quad \sigma = \frac{1{,}000S}{1{,}000 + S};$$

while the use of the nomographs is illustrated as follows:

Solubility Nomographs.—*Figure* 108, *Eq.* (30): How much sulfur dioxide will dissolve in 1 kg. of water at 10°C. when the partial pressure of SO_2 is 500 mm. mercury? Connect 500 on the left p scale with 10 on the right t scale, and project the line to meet the right p scale at the point A. Connect 500 on the right p scale with 10 on the left t scale, and project the line to meet the left p scale at the point B. A line connecting A and B will cut the S scale at 106 g. SO_2 per kilogram of water and the σ scale at 96 g. SO_2 per kilogram of solution.

Figure 109, *Eq.* (31): The partial pressure of SO_2 over an aqueous solution of sulfur dioxide is 400 mm. mercury at 23°C. What is the concentration of the solution? A line connecting 400 on the p scale with 23 on the t scale cuts the solubility scales in the values S = 56 g. SO_2 per kilogram of water and σ = 53 g. SO_2 per kilogram of solution.

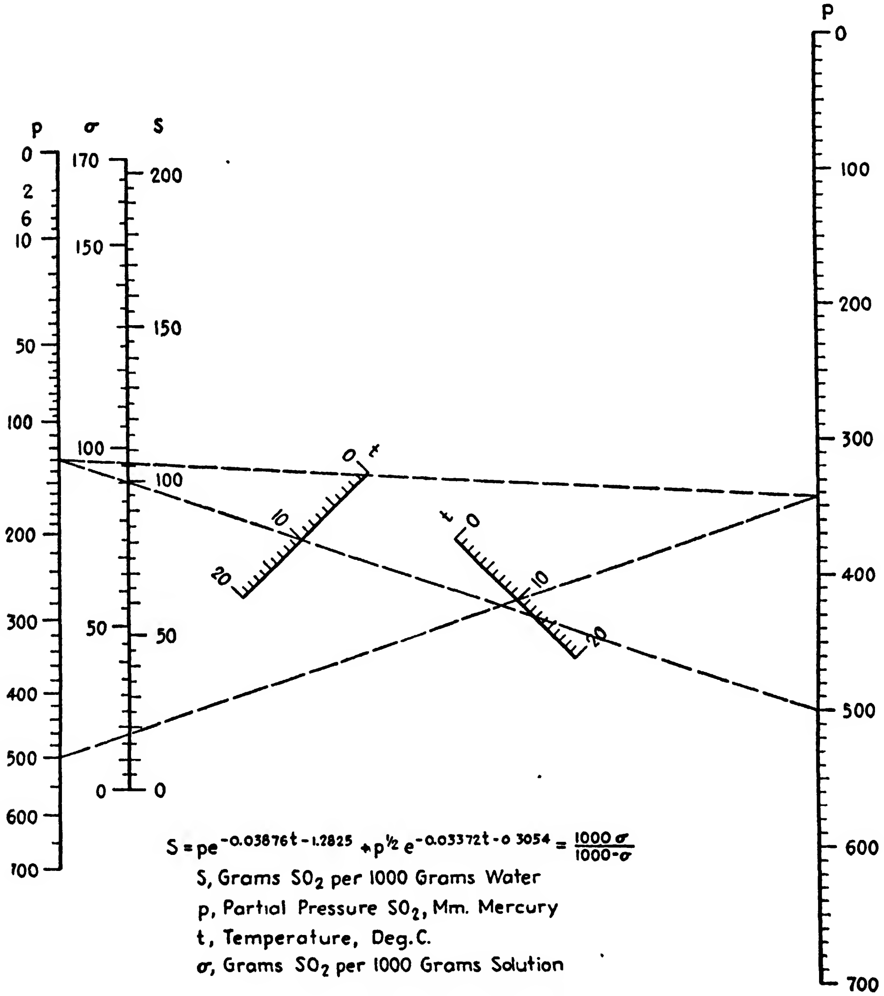
TABLE XIX.—CALCULATED AND RECORDED DISSOCIATION VALUES

Temp., °C	0	5	10	15	20	25
Equation (32)	0.031	0.026	0.023	0.020	0.017	0.015*
Sherrill and Noyes	.....	.....	.....	.....	.....	0.015†
Kerp and Bauer	.....	.....	.....	.....	.....	0.017
Lindner	0.031	.....	.....	.....	0.020	0.017
Campbell and Maas	0.031	.....	.....	.....	0.020	0.017

* Calculated from Eq. (32) although this equation is intended for use only between 0 and 20°C.

† Calculated from the ionization λ and the concentration c by use of the equation $K = \frac{\lambda^2 c}{1 - \lambda}$, not corrected for activation.

Dissociation Constant of H_2SO_3.—Comparison of the Lewis equation and Eq. (30) shows that the Henry's law constant H is approximately equal to m and that $\sqrt{KH}$ is very nearly equal to a so that the dissociation constant of H_2SO_3, K, is practically equal to a^2/m. The dissociation constant is usually calculated from concentration data expressed in moles per liter rather than in grams per liter, making the final approximation $a^2/64m$ since the molecular weight of SO_2 is 64.



$$S = pe^{-0.03876t-1.2825} + p^{1/2}e^{-0.03372t-0.3054} = \frac{1000\sigma}{1000-\sigma}$$

S, Grams SO_2 per 1000 Grams Water
p, Partial Pressure SO_2, Mm. Mercury
t, Temperature, Deg. C.
σ, Grams SO_2 per 1000 Grams Solution

FIG. 108.—Solubility of SO_2 in water.

On substitution of $e^{-0.03372t-0.3054}$ for a and of $e^{-0.03876t-1.2825}$ for m, the dissociation constant may be expressed as a function of the temperature

$$K = \frac{e^{-0.02868t+0.6717}}{64} \tag{32}$$

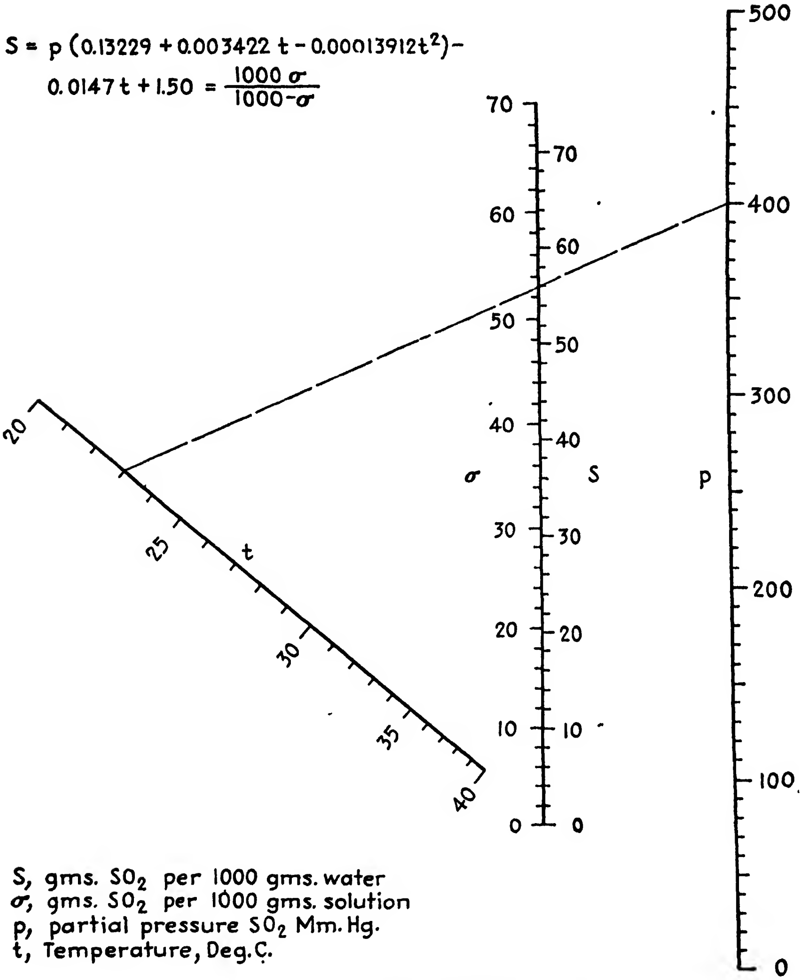


FIG. 109.—Solubility of SO_2 in water.

In Table XIX it is shown that the approximate values of K calculated from Eq. (32) are in line with values given by Sherrill and Noyes,[1] Kerp and Bauer,[2] Lindner,[3] and Campbell and Maas.[4]

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[1] SHERRILL, M. S., and A. A. NOYES, *J. Am. Chem. Soc.*, **48**, 1861 (1926).

[2] KERP, W., and E. BAUER, *Arb. kaiserl. Gesundheitsamt*, **26**, 297 (1907).

[3] LINDNER, J., *Monatsh.*, **33**, 613 (1912).

[4] CAMPBELL, W. B., and O. MAAS, *Pulp & Paper Mag. Can.*, **29**, 599 (1930).

NEW NOMOGRAPHS FOR SOLUBILITY OF SULFUR DIOXIDE IN WATER[1]

Considerable work on the solubility of sulfur dioxide in water has been done since the appearance of Sherwood's compilation[2] and critical study of the results of the earlier investigators. The newer data, for the most part, deal with *total* pressures of sulfur dioxide and water instead of *partial* pressures of SO_2. Higher values of the solubility also are covered, and temperatures up to 120°C. are now included.

Such data covering ranges of industrial importance are those of Maas and Maas[3] and of Campbell and Maas.[4] These investigators have presented their results in tabular form and in the form of pressure-concentration isotherms, spaced, in most cases, at wide temperature intervals. In addition, the isotherms are slightly curved, interpolation between them is somewhat uncertain, and it is difficult to take full advantage of these excellent data.

As in the case of the earlier solubility material for which charts and equations have been prepared,[5] there appears to be need for equations relating pressure, temperature, and solubility and for a more convenient graphical representation. It is the purpose of this topic to offer such correlations together with alignment charts which permit rapid and accurate solution of the equations.

The data of Maas and Maas cover the temperature range 10 to 27°C., while the Campbell and Maas data may be divided, for convenience, into two parts, that between 25 and 90°C. and that between 90 and 120°C. The three ranges are represented by three equations, noted on Figs. 110 to 112, which are all of the form

$$S = mP + a\sqrt{P}$$

where S is the solubility, grams SO_2 per 1,000 g. water; P is the total pressure, SO_2 and H_2O, millimeters of mercury; and m and a are empirical functions of the temperature.

Although the expressions for m and a, shown in Figs. 110 to 112, are of purely empirical origin, the general form of the solubility equations is analogous to that derived by Lewis, quoted by Haslam, Hershey, and Kean,[6] from sound theoretical considerations

$$c = Hp + \sqrt{KHp}$$

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[1] *Chem. & Met. Eng.*, **42**, 492 (1935).

[2] Sherwood, T. K., *Ind. Eng. Chem.*, **17**, 745 (1925).

[3] Maas, C. E., and O. Maas, *J. Am. Chem. Soc.*, **50**, 1352 (1928).

[4] Campbell, W. B., and O. Maas, *Pulp Paper Mag. Can.*, **29**, 599 (1930).

[5] Davis, D. S., *Chem. & Met. Eng.*, **39**, 615 (1932).

[6] Haslam, R. T., R. L. Hershey, and R. H. Kean, *Ind. Eng Chem.*, **16**, 1224 (1924).

where c is the solubility, grams SO_2 per milliliter of solution; p is the partial pressure of SO_2, millimeters of mercury; and H and K are the Henry's law and dissociation constants, respectively.

TABLE XX.—ACCURACY OF SOLUBILITY CALCULATIONS

Equation	t, temperature, °C.	P, total pressure, mm. Hg	S, solubility, grams SO_2 per 1,000 g. H_2O	Average deviation in solubility, per cent ±
1	10	243–1,543	48–300	1.5
	16.5	310–1,884	47–294	0.9
	22	378–1,861	46–287	1.5
	27	448–2,556	45–280	1.1
2	30	232– 845	23– 80	1.5
	40	194–1,165	12– 79	2.6
	50	281–1,536	11– 78	2.2
	60	396–1,977	11– 77	2.1
	70	540–2,494	11– 76	2.1
	80	732–3,083	11– 74	2.6
	90	971–3,290	11– 64	2.3
3	90	971–3,290	10– 64	2.4
	100	1,275–2,801	10– 39	1.5
	110	1,663–3,380	10– 38	2.4
	120	2,130–3,440	10– 29	3.1

Table XX illustrates the agreement, at various temperatures, between calculated and actual values of the solubility over the ranges of data specified.

A nomographic chart has been prepared to solve each of three equations. Each of these charts (Figs. 110 to 112) in addition to the pressure and temperature axes, carries two solubility scales, labeled S and σ, the former for solubilities in grams SO_2 per 1,000 g. of water and the latter for solubilities in grams SO_2 per 1,000 g. of solution. The relation between the two is given by the equation

$$S = \frac{1{,}000\sigma}{1{,}000 - \sigma} \quad \text{or} \quad \sigma = \frac{1{,}000S}{1{,}000 + S}.$$

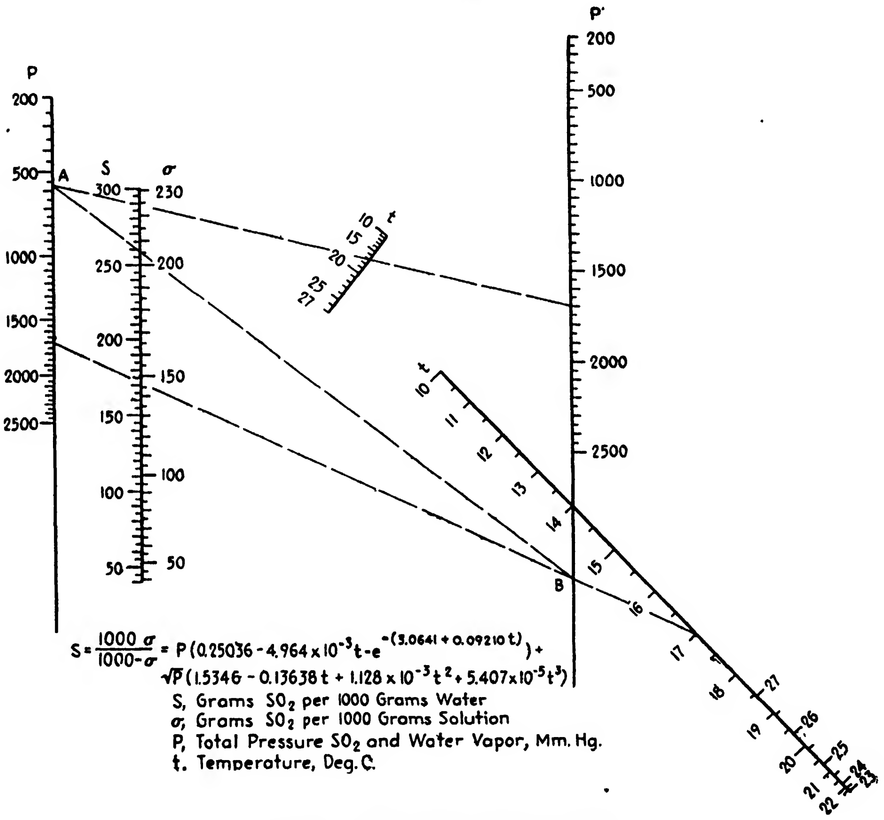
Use of the alignment charts is illustrated as follows:

Figure 110.—What is the solubility of SO_2 at a total pressure of 1,700 mm. mercury and at 17°C.? Connect 1,700 on the right P scale with 17 on the upper t scale, and project the line to the left P scale, calling the latter intersection A. Connect 1,700 on the left P scale with 17 on the lower t scale, and call the intersection with the right P scale B.

A line between *A* and *B* will cut the *S* scale at 258 g. SO_2 per 1,000 g. of water and the σ scale at 205 g. SO_2 per 1,000 g. of solution.

The unique feature of Fig. 110 is the longer temperature axis along which temperatures increase until 22.86°C. is reached, after which the scale, in increasing further, starts back along the axis.

Figure 111.—Given the total pressure as 1,500 mm. mercury and the temperature as 80°C., how much SO_2 will dissolve in 1 kg. of water? How much will be contained in 1 kg. of solution? Draw a line from 1,500 on the right *P* scale through 80 on the upper *t* scale to the left *P* scale, and consider this intersection as point *A*. Draw a line from 1,500 on the left *P* scale to 80 on the lower *t* scale, and consider the intersection of this line with the right *P* scale to be point *B*. A line connecting *A* and *B* will cut the *S* scale in the value of 31.0 g. SO_2 per kilogram of water and the σ scale in the value of 30.0 g. SO_2 per kilogram of solution.



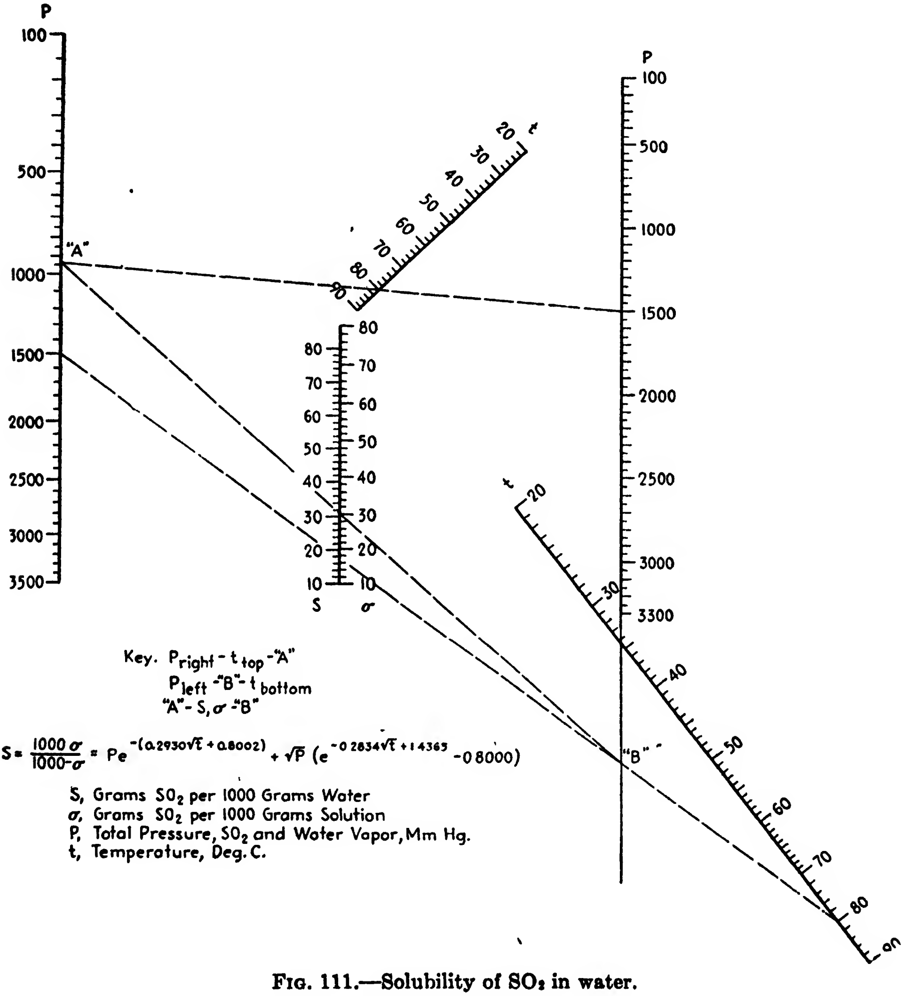
$$S = \frac{1000\,\sigma}{1000-\sigma} = P(0.25036 - 4.964\times10^{-3}t - e^{-(3.0641+0.09210t)}) + \sqrt{P}(1.5346 - 0.13638t + 1.128\times10^{-3}t^2 + 5.407\times10^{-5}t^3)$$

S, Grams SO_2 per 1000 Grams Water
σ, Grams SO_2 per 1000 Grams Solution
P, Total Pressure SO_2 and Water Vapor, Mm. Hg.
t. Temperature, Deg. C.

FIG. 110.—Solubility of SO_2 in water.

Figure 112.—In contrast to Figs. 110 and 111, in which both multiplication and addition operations are performed graphically, Fig. 112

is logarithmic in nature and performs only the operations indicated by mP and $a\sqrt{P}$ requiring supplementary addition to complete the calculation.



Key. P_{right} - t_{top} - "A"
P_{left} - "B" - t_{bottom}
"A" - S, σ - "B"

$$S = \frac{1000\sigma}{1000-\sigma} = Pe^{-(0.2930\sqrt{t}+0.8002)} + \sqrt{P}\left(e^{-0.2834\sqrt{t}+1.4365} - 0.8000\right)$$

S, Grams SO_2 per 1000 Grams Water
σ, Grams SO_2 per 1000 Grams Solution
P, Total Pressure, SO_2 and Water Vapor, Mm Hg.
t, Temperature, Deg. C.

FIG. 111.—Solubility of SO_2 in water.

The original equation

$$S = mP + a\sqrt{P}$$

is split into the equations

$$S_1 = mP \quad \text{and} \quad S_2 = a\sqrt{P}$$

so that $S = S_1 + S_2$. To avoid negative values of S_2, the signs of the terms in the expression for a are changed so that $S = S_1 - S_2$.

On both bases, what is the solubility of SO_2 at a total pressure of 1,700 mm. mercury and a temperature of 95°C.? From 1,700 on the P scale, draw a line to 95 on the t_1 scale and another to 95 on the t_2 scale. The first line cuts the S_1 scale at 47.0, while the second cuts the S_2 scale at 24.8. The difference 22.2 is the value of S in grams SO_2 per 1,000 g. of water and is seen to correspond to 21.7 g. SO_2 per 1,000 g. of solution on the σ scale. To avoid an unduly large chart, conversion between the S and σ scales for values between 10 and 20 is made on the short axis in the right half of the chart.

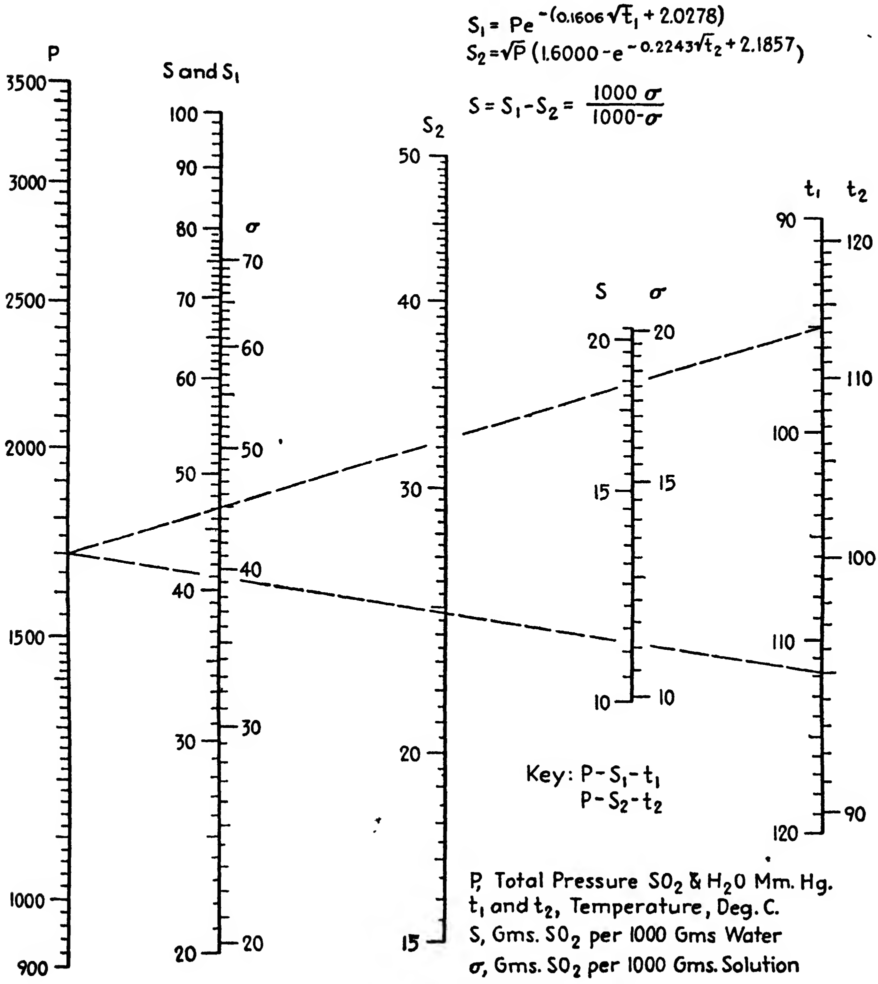


FIG. 112.—Solubility of SO_2 in water.

SULFUR DIOXIDE CHART FOR LOW CONCENTRATIONS[1]

Johnstone and Leppla[2] have presented valuable data on the solubility of sulfur dioxide in water under low partial pressures of the solute.

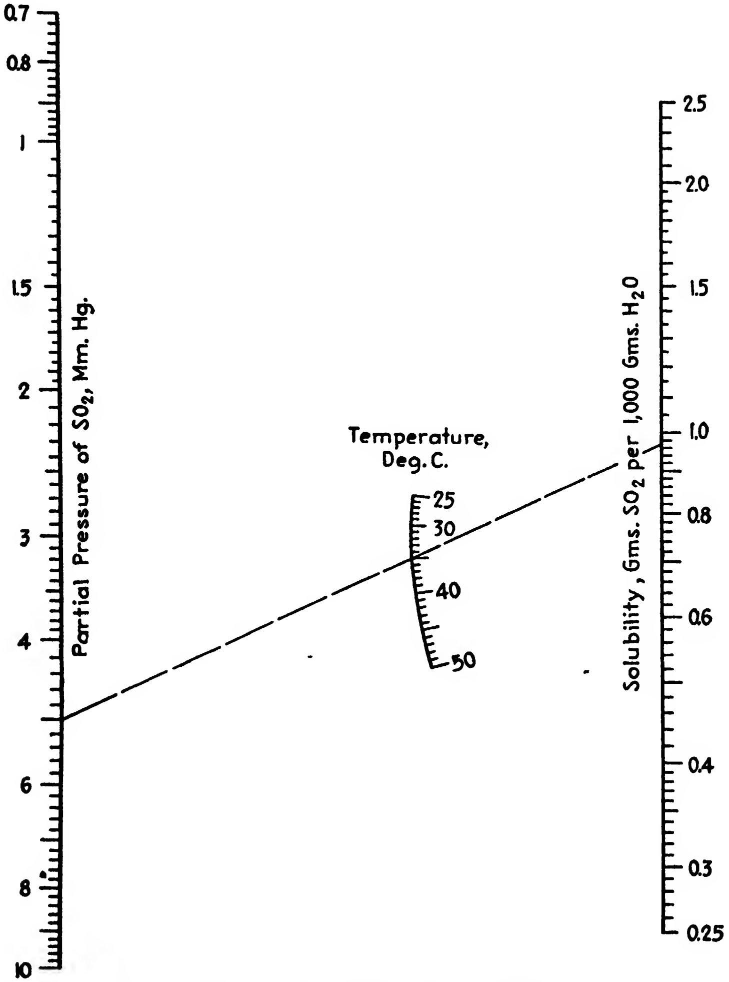


Fig. 113.—Solubility of SO_2 in water.

Their investigation covers a partial pressure range of 0.2 to 10 mm. mercury and a solubility range of 0.2 to 2.1 g. of SO_2 per kilogram of water. These studies were made at 25, 35, and 50°C., so that, except when working at these same temperatures, one who is desirous of using the

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[1] *Chem. & Met. Eng.*, **43**, 433 (1936).

[2] Johnstone, H. F., and P. W. Leppla, *J. Am. Chem. Soc.*, **56**, 2233 (1934).

data is faced with inconvenient interpolation between curved and widely spaced pressure-solubility isotherms.

Figure 113 extends the utility of the studies in question since it permits interpolations to be made along closely graduated scales with rapidity and sufficient accuracy. The use of the chart is illustrated by the broken line which shows that 0.97 g. of sulfur dioxide will dissolve in 1,000 g. of water at a temperature of 35°C., when the partial pressure of SO_2 is 5 mm. mercury.

If it should be desired to express the solubility on the basis of 1,000 g. of solution, this can readily be accomplished with the formula

$$\sigma = \frac{1{,}000S}{1{,}000 + S}$$

where S is solubility per 1,000 g. of water and σ is solubility per 1,000 g. of solution.

TABLE XXI.—DEVIATIONS OF CALCULATED FROM EXPERIMENTAL DATA

Temperature, °C.	Partial pressure of SO_2, mm. Hg	Percentage deviation in solubility, calculated from experimental
25	0.91	−0.8
	1.74	1.3
	2.03	−1.0
	5.10	−0.1
	6.92	−0.7
	10.26	0.5
35	0.78	−1.9
	1.89	2.3
	3.13	8.4
	4.41	1.5
	7.26	−1.7
50	1.75	0.3
	2.91	0.0
	4.09	−6.3
	6.68	0.3

Correlation of Johnstone and Leppla's data has been effected by means of the equations

$$S = mp^n$$
$$m = 0.844 - 0.0212t + 0.000172t^2$$
$$n = 0.482 + 0.0149t - 0.000247t^2.$$

Here S is solubility expressed in grams SO_2 per 1,000 g. of water; p is

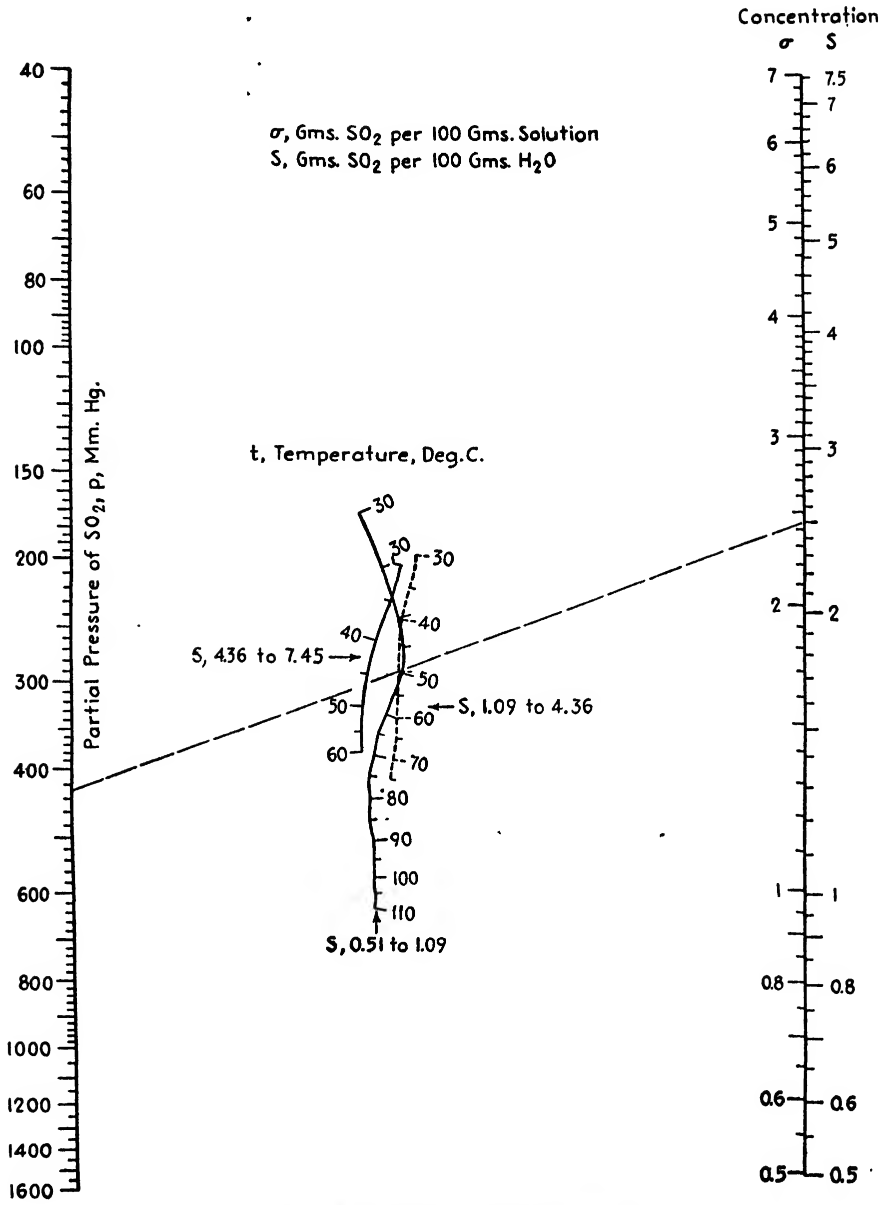

Fig. 114.—Solubility of SO_2 in water.

the partial pressure of SO_2, millimeters of mercury; and t is the temperature, degrees centigrade.

The degree of agreement between the chart and the original data is shown by Table XXI which lists the percentage deviations of the calculated from the experimental values of the solubility at the experimental pressures and temperatures.

It will be seen that the chart agrees with the experimental data within 2.5 per cent except for two instances. Data at these points had been rejected in the correlation procedure as being erratic.

NOMOGRAPH FOR THE SOLUBILITY OF SULFUR DIOXIDE IN WATER[1]

Figure 114 reflects the original data[2] faithfully over the entire ranges of concentration and temperature. Agreement is exact at the experimental concentrations, and elsewhere the chart usually yields values between the Beuschlein and Simenson data and those of the "International Critical Tables,"[3] with which the Beuschlein and Simenson data are in excellent agreement throughout.

Three temperature scales, to be used in three ranges of concentration, appear on the nomograph. The dashed index line shows that a solution testing 2.5 g. of sulfur dioxide per 100 g. of water has a partial pressure of sulfur dioxide of 428 mm. mercury at 50°C.;[4] the dotted temperature scale is used since it is designated as the proper scale for concentrations embracing $S = 2.5$. In the converse use of the chart, to find a concentration corresponding to a given temperature and a given partial pressure, the proper temperature scale is the one that will yield a concentration in the range for which the temperature scale is marked.

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[1] *Ind. Eng. Chem.*, **33**, 1376 (1941).

[2] BEUSCHLEIN, W. L., and L. O. SIMENSON, *J. Am. Chem. Soc.*, **62**, 610 (1940).

[3] Vol. III, p. 302.

[4] BEUSCHLEIN and SIMENSON, *op. cit.*, p. 437; "International Critical Tables," p. 421.

CHAPTER XIII

MOLECULAR-REFRACTION AND MOLECULAR-VOLUME NOMOGRAPHS

MOLECULAR-REFRACTION NOMOGRAPH[1]

An ideal expression for calculating the molecular refraction R of a substance must be independent of temperature, pressure, and changes in the state of aggregation. Such an equation in general use and based upon the Lorentz-Lorenz formula,[2] is

$$R = \frac{M(n^2 - 1)}{d(n^2 + 2)}$$

where M is the molecular weight; n is the refractive index; d is the density, grams per cubic centimeter; and n and d refer to the same state and condition.

Molecular refractions can be computed readily by Fig. 115, the use of which is illustrated as follows: What is the molecular refraction of isopropyl alcohol (C_3H_7OH) when the refractive index at 20°C. is 1.377 and the density at 20°C. is 0.789 g./cc.? Following the key, connect 60.1, the molecular weight, on the M scale with 1.377 on the n scale, and mark the intersection with the α scale. Connect this point with 0.789 on the d scale, and read the molecular refraction as 17.5 on the R scale.

MOLECULAR-REFRACTION–CRITICAL TEMPERATURE NOMOGRAPH[3]

For members of six important organic series Wan[4] showed that the critical temperature is a linear function of the molecular refraction

TABLE XXII

No.	Series	k_1	k_2
1	Acids	4.09	268.5
2	Alcohols	6.74	133.0
3	Esters	4.61	150.8
4	Ethers	5.81	67.1
5	Hydrocarbons	7.02	23.1
6	Nitriles	4.02	228.4

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[1] *Ind. Eng. Chem.*, **34**, 258 (1942).

[2] NERNST, W., "Theoretical Chemistry," 8th–10th ed., Macmillan & Company, Ltd., London, 1923.

[3] *Ind. Eng. Chem.*, **34**, 689 (1942).

[4] WAN, S. W., *J. Phys. Chem.*, **45**, 903 (1941).

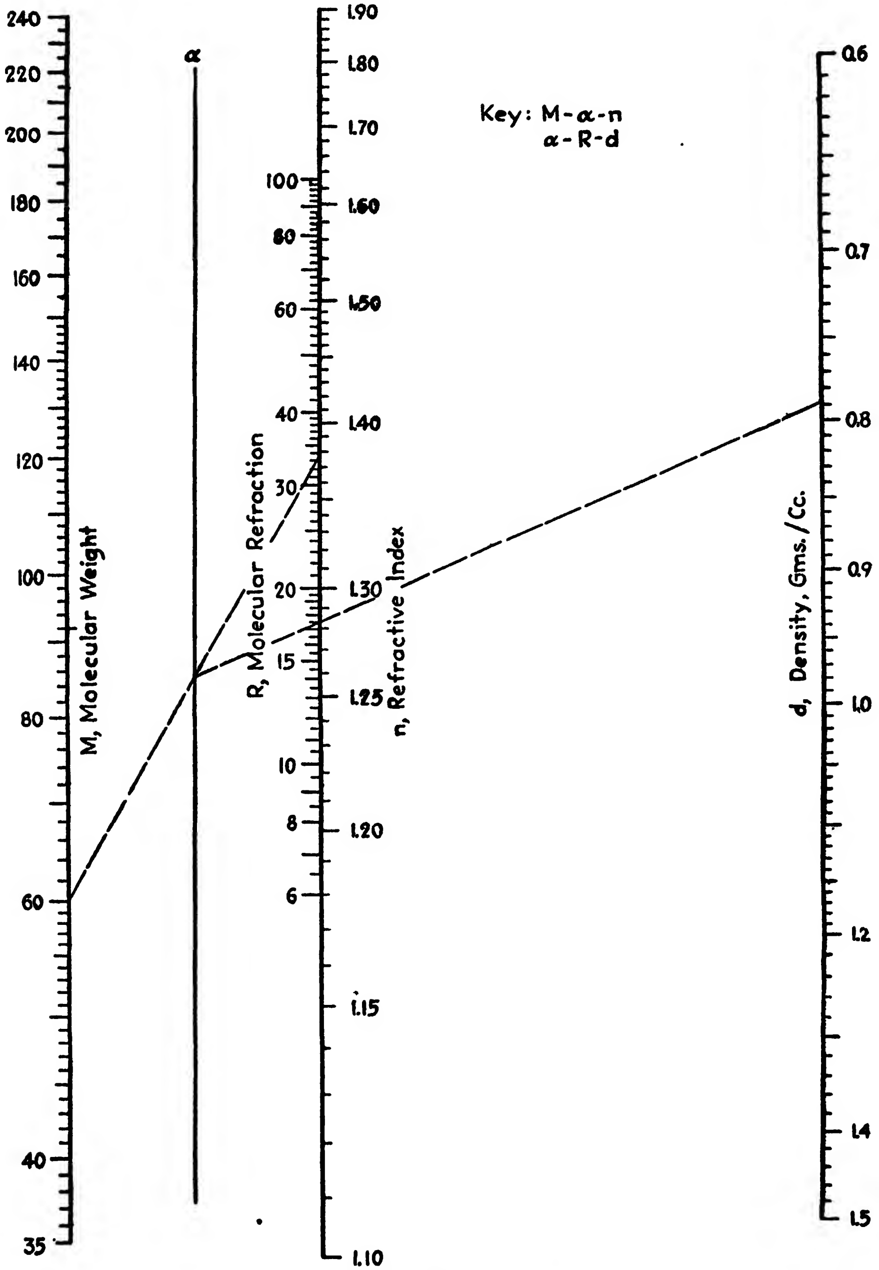

FIG. 115.—Molecular refraction.

according to the equation

$$t_c = k_1R + k_2$$

where t_c is the critical temperature of the member, degrees centigrade; R is the molecular refraction of the member; and k_1 and k_2 depend upon the series given in Table XXII.

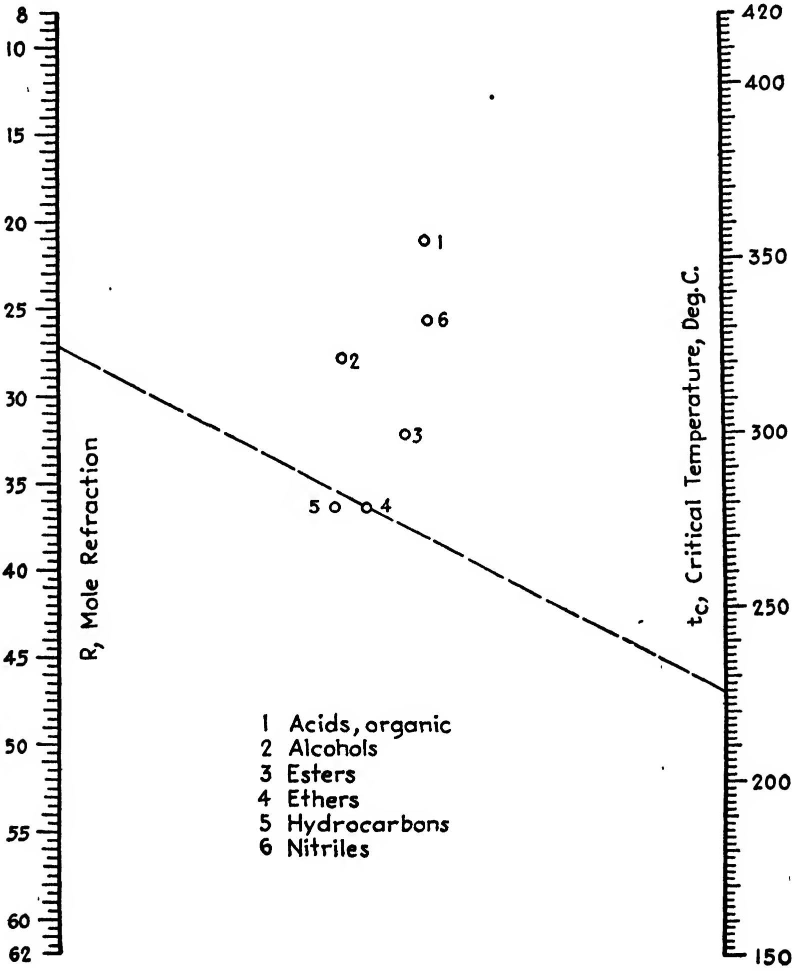

FIG. 116.—Molecular refraction–critical temperature.

Critical temperatures can be read conveniently from Fig. 116, by aligning the molecular refraction of a member with the series number and producing the line to the critical temperature scale. The dashed isopleth shows that ethyl propyl ether, which has a molecular refraction of 27.2 and belongs to series 4, has a critical temperature of 225°C. The observed value from "International Critical Tables" is 227.4°C.

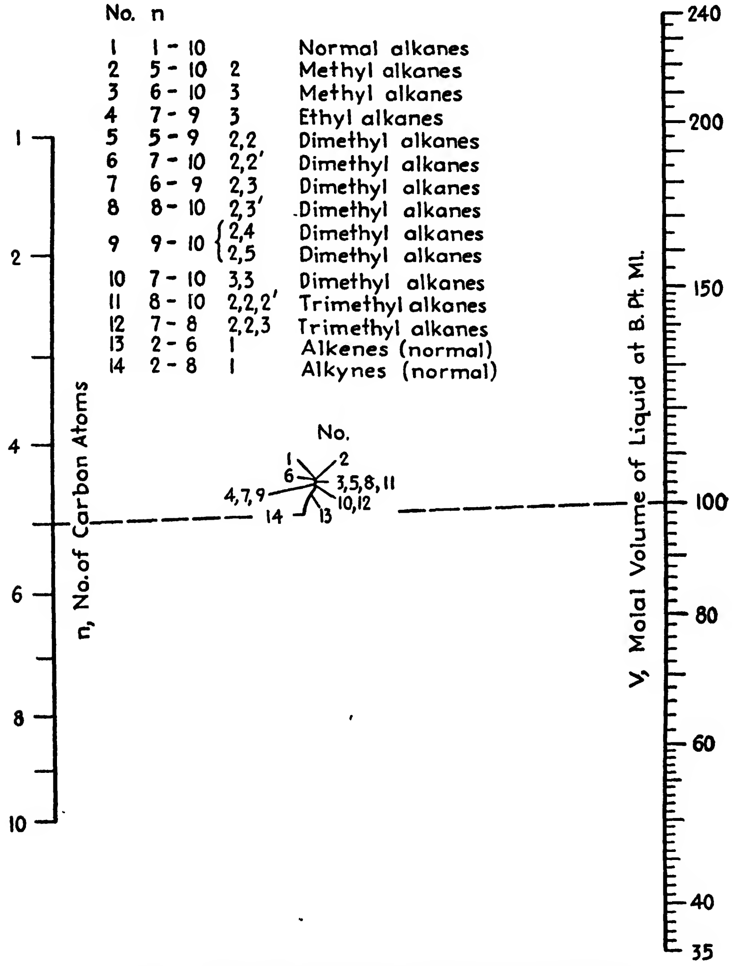

FIG. 117.—Molecular volumes of aliphatic hydrocarbons.

MOLAL VOLUME NOMOGRAPHS FOR ALIPHATIC HYDROCARBONS[1]

Following a study of the molal volume relations of aliphatic hydrocarbons at their boiling points, Egloff and Kuder[2] presented the equations

$$V = a(n + 4.4)^c - 37.00 \qquad (33)$$

$$\log (V + 37.00) = At + B' \qquad (34)$$

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[1] *Ind. Eng. Chem.*, **34**, 351 (1942).

[2] EGLOFF, GUSTAV, and R. C. KUDER, *J. Phys. Chem.*, **45**, 836 (1941).

where V = molal volume of liquid, ml.
n = number of carbon atoms in molecule.
t = temperature at boiling point, °C.

In these equations, a is characteristic of the branching, B' depends upon the series, and c and A are characteristic of the unsaturation.

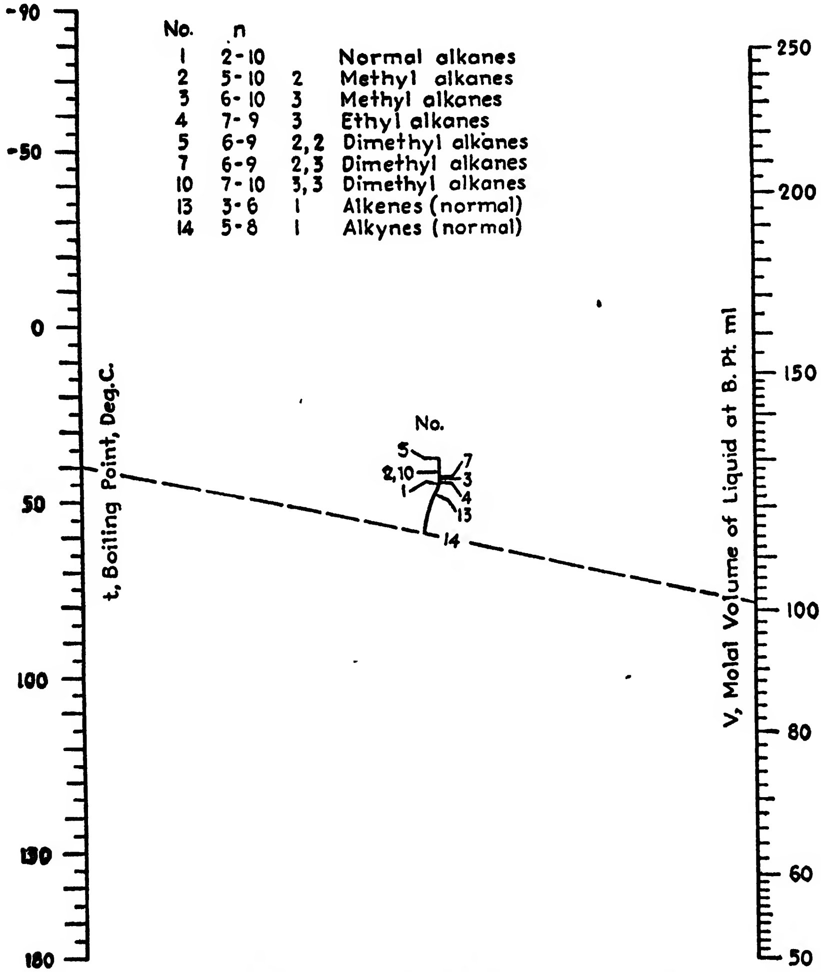

FIG. 118.—Molecular volumes of aliphatic hydrocarbons.

The published values of the constants enabled construction of the two line-coordinate charts. Figure 117, based on Eq. (33), holds closely for 63 aliphatics of the series and ranges of n indicated in the legend; Fig. 118, predicated upon Eq. (34), covers 43 of these compounds reliably.

The index line in Fig. 117 shows that the molal volume of liquid pentyne ($n = 5$) is 100 ml. at the boiling point, while the index line in

Fig. 118 shows that the molal volume of liquid pentyne (boiling point, 40°C.) is 101 ml. at the boiling point. The standard deviations range

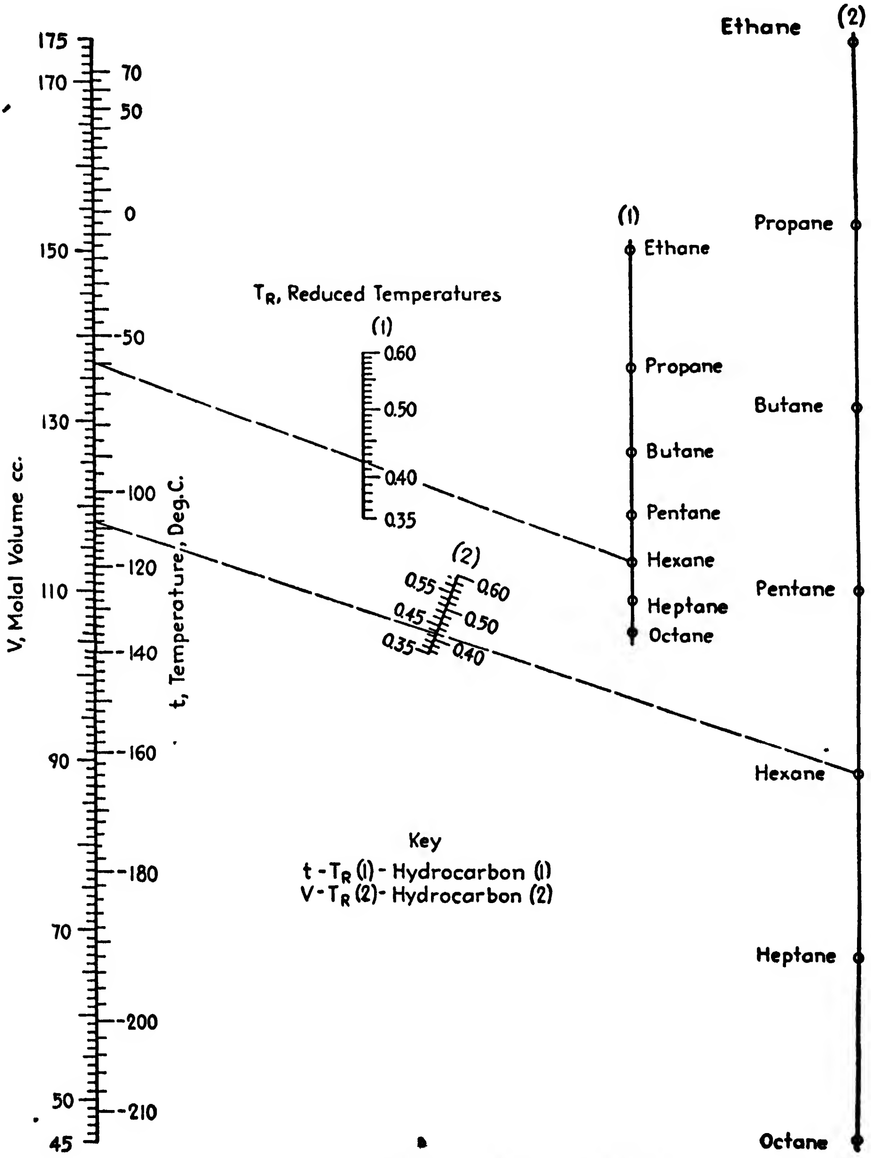

FIG. 119.—Molecular volumes of liquid alkanes.

from 0.2 to 1.1 ml./mole; Fig. 117 yields slightly better values than Fig. 118 since, as pointed out by Egloff and Kuder, Eq. (33) is a function of n, a pure number, while Eq. (34) depends upon experimental boiling points.

MOLECULAR-VOLUME NOMOGRAPH FOR LIQUID ALKANES[1]

Egloff and Kuder[2] showed that the molecular volumes of normal liquid alkanes from methane to octane, inclusive, can be calculated from the equations

$$V = a + bn$$
$$a = 9.43 + 10.24T_R$$
$$b = 14.912 + 1.765T_R + 10.00T_R^2$$

where V = molecular volume, cc.
n = number of carbon atoms.
T_R = reduced temperature, 0.35 to 0.60.

Figure 119, which facilitates this computation, bears two sets of points for the various hydrocarbons and two reduced temperature scales. Its use is illustrated as follows: What is the molecular volume of hexane at −60°C.? Following the key, connect −60 on the t scale with the hexane point in the set marked (1), reading the reduced temperature as 0.42 on the T_R (1) scale. Transfer this value to the T_R (2) scale, connect this point with the hexane point in the set marked (2), and produce the line to the V scale where the molecular volume is read as 118.1 cc.

As reproduced, the chart yields values of the molecular volume good to about 0.4 per cent.

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[1] *Ind. Eng. Chem.*, **34**, 797 (1942).

[2] EGLOFF, GUSTAV, and R. C. KUDER, *Ind. Eng. Chem.*, **34**, 373 (1942).

CHAPTER XIV

SOLUBILITY NOMOGRAPHS (EXCLUSIVE OF VAPOR-PRESSURE DATA)

COUMARIN-SOLUBILITY CHART[1]

The desirability of using solvents other than ethyl alcohol in making up both genuine and imitation vanilla extracts has prompted Hitchens[2] to make a study of the solubility of coumarin in aqueous glycerol solutions. The data have been presented in the form of a graph where the weight, in grams, of coumarin dissolving in 100 ml. of solution is plotted against the weight percentage of glycerol in the solvent with isotherms for 0, 10, 20, 30, 40, and 50°C.

Of necessity, the isotherms are curved and unevenly spaced, rendering interpolation at once difficult and inaccurate. It can be shown empirically, however, that at any temperature t°C. the solubility of coumarin, S, in grams per 100 ml. of solution and x, the weight percentage of glycerol, are related by an expression of the form

$$\log S = ax + b.$$

This relationship has enabled construction of Fig. 120 which permits solubility values between 10 and 50°C. to be read conveniently and accurately. As an illustration of the use of the chart, the broken line indicates that at 40°C. 0.52 g. of coumarin will dissolve in 100 ml. of an aqueous glycerol solution containing 20 per cent glycerol by weight.

NOMOGRAPH FOR PARAFFIN-WAX SOLUBILITY IN PETROLEUM FRACTIONS[3]

Berne-Allen and Work[4] presented excellent data on the solubility of commercially refined paraffin waxes in petroleum distillates. The data take the form of straight-line isotherms when the logarithm of the wax solubility is plotted against the solution equilibrium temperature and quantitative relations between solubilities, paraffin wax melting point, the average boiling point of the solvent, and the solution equilibrium temperature were established. The authors gave their data a

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[1] *Chemist-Analyst*, **26,** 31 (1937).

[2] Hitchens, R. M., *Ind. Eng. Chem.*, **24,** 418 (1932).

[3] *Ind. Eng. Chem.*, **32,** 1293 (1940).

[4] Berne-Allen, A., Jr., and L. T. Work, *Ind. Eng. Chem.*, **30,** 806 (1938).

mathematical treatment adequate from theoretical and empirical standpoints and arrived at the following expression:

$$X = (1120 - 2.97Y)1.1357^{t-m}$$

where X = solubility, grams wax per 100 ml. solvent.

Y = average solvent boiling point, °C. (based on temp. at 10, 30, 50, 70, and 90% points, A.S.T.M. distillation).

m = melting point of wax, °C.

t = solution equilibrium temp., °C.

Berne-Allen and Work also included a rectilinear chart for solution of their equation; the variables are plotted in such a manner that a

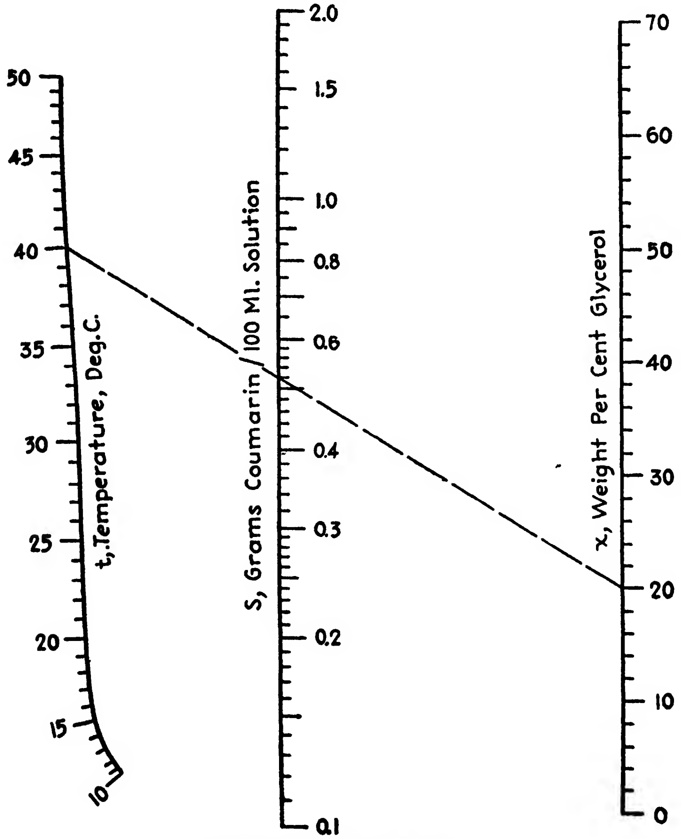

FIG. 120.—Coumarin solubility.

double pencil of intersecting lines results. While obviating considerable slide-rule manipulation, the chart is somewhat difficult to read for high values of the melting point and solution temperature, and interpolation is not convenient. In view of the evident value of the data and their

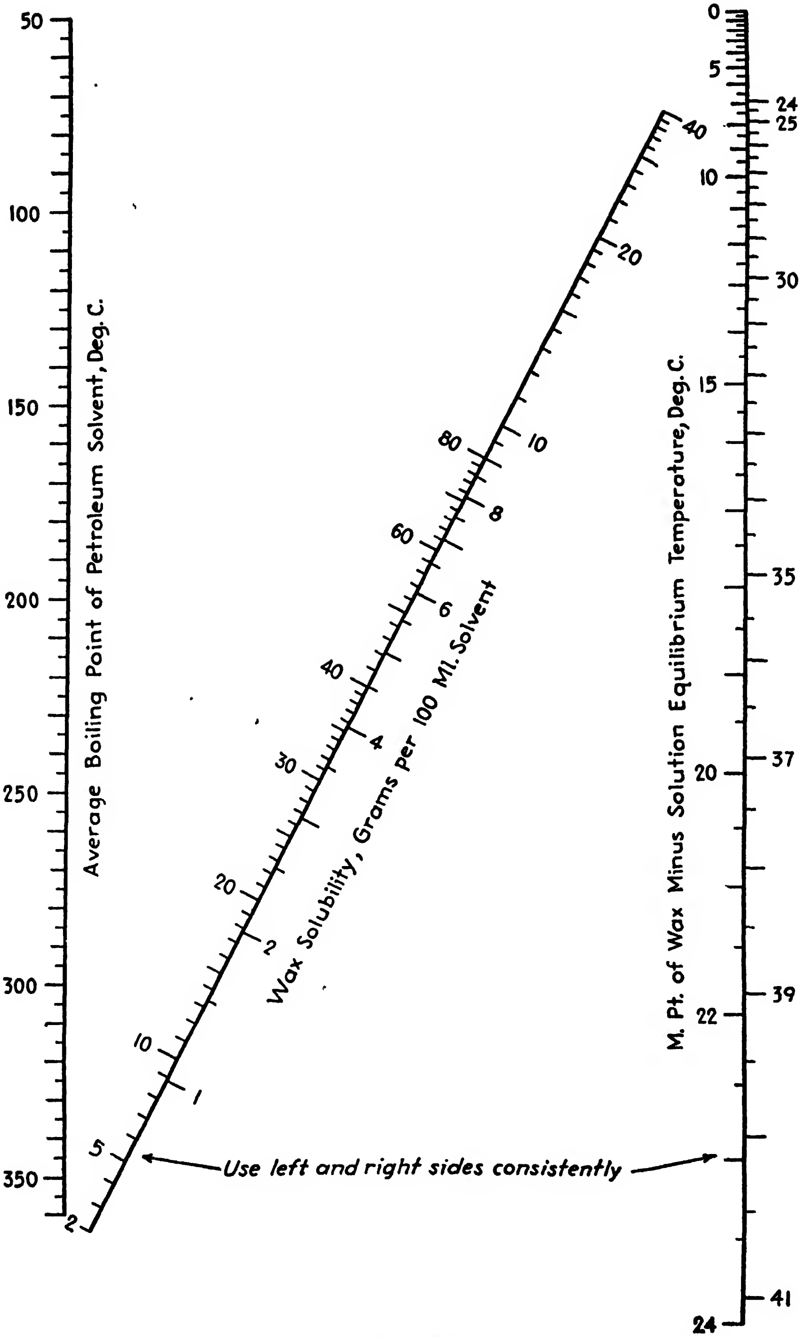

FIG. 121.—Paraffin wax solubility.

industrial application, it appears worth while to offer a nomograph for the solution of the equation. Figure 121 is extremely "open" and permits of easy interpolation along closely graduated scales.

The use of the chart may be illustrated as follows: What is the solubility of paraffin wax in petroleum when the melting point of the wax is 45°C., the temperature of the solution is 26°C., and the average boiling point of the pure distillate is 260°C.? The difference between the melting point and the solution temperature is 45 − 26, or 19°C. Connect 19 on the right-hand scale with 260 on the left-hand scale, and read the solubility on the inclined axis as 31.0 g. of wax per 100 ml. of solvent. Similarly, the chart reveals that 100 ml. of a distillate boiling at 190°C. will dissolve 5 g. of paraffin wax when the melting point of the wax is 60°C. and the temperature of the solution is 23°C. Note that one reads solubilities on the right-hand side of the inclined scale when temperature differences are read on the right-hand side of the temperature difference scale, and conversely.

The same equation could have been handled by the more familiar parallel-scale logarithmic chart, bearing singly graduated axes, with less labor in construction but at the sacrifice of some precision. Area for area, the present Z-type nomograph is more advantageous to the user.

CHAPTER XV

NOMOGRAPHS FOR DENSITY CORRECTIONS AND PHYSICAL DATA ON VARIOUS CHEMICALS[1]

NOMOGRAPHIC CHART FOR TEMPERATURE CORRECTION OF SULFURIC ACID DENSITIES, WITH ADDITIONAL SCALES FOR INTERCONVERSION OF PHYSICAL DATA[2]

Example (Fig. 122): A sample of sulfuric acid is tested with a hydrometer at 46°C. and shows a specific gravity of 1.490 (47.5°Bé.). It is desired to find the specific gravity at the standard temperature of 15°C. (59°F.). Using a straightedge, connect the observed temperature 46° with the density read from the hydrometer, 47.5°Bé., and extend the line to the scale showing density at 15°C., cutting the scale at a specific gravity of 1.516 (49.1°Bé.). To determine the physical properties of the acid corresponding to this density, extend a horizontal line from the point 1.516 on the corrected density scale, to the right, cutting the several scales showing the constants for this acid, corrected to 15°C.

The sample is thus found to contain 50 per cent SO_3, 61.3 per cent H_2SO_4, and the equivalent of 78.5 per cent of 60° and 98.0 per cent of 50°Bé. acid. It contains 758 g. of SO_3 per liter, 928 g. of 100 per cent H_2SO_4, and the equivalent of 1,189 g. of 60° and 1,488 g. of 50°Bé. acid per liter. Its boiling point is 144°C.

NOTE: Interconversion data for acids of 95 to 100 per cent H_2SO_4 will be found in Fig. 123, dealing with oleum. The present chart is too restricted to permit the desired accuracy in this range.

NOMOGRAPHIC CHART FOR CALCULATING OLEUM ANALYSES AND FOR INTERCONVERTING PHYSICAL DATA OF OLEUM[3]

Example (Fig. 123): A sample of oleum is titrated against 0.2*N* NaOH, using 0.360 g. of oleum and requiring 39.61 cc. of NaOH solution. With a straightedge, connect 0.360 on the left scale with 39.61 on the

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[1] These charts belong to a series presented during 1939 in *Chem. & Met. Eng.* They deal with oleum, nitric acid, hydrochloric acid, phosphoric acid, sodium carbonate, sodium hydroxide, potassium carbonate, and ammonia. These charts are translations of a more extended series published in 1930 by Julius Springer of Berlin, under the title of "Nomographic Charts for the Chemical Industry." In their original preparation Dr. Berl had the assistance of Drs. W. Herbert and W. Wahlig.

[2] BERL, ERNST, *Chem. & Met. Eng.*, **46**, 40 (1939).

[3] *Ibid.*, **46**, 174 (1939).

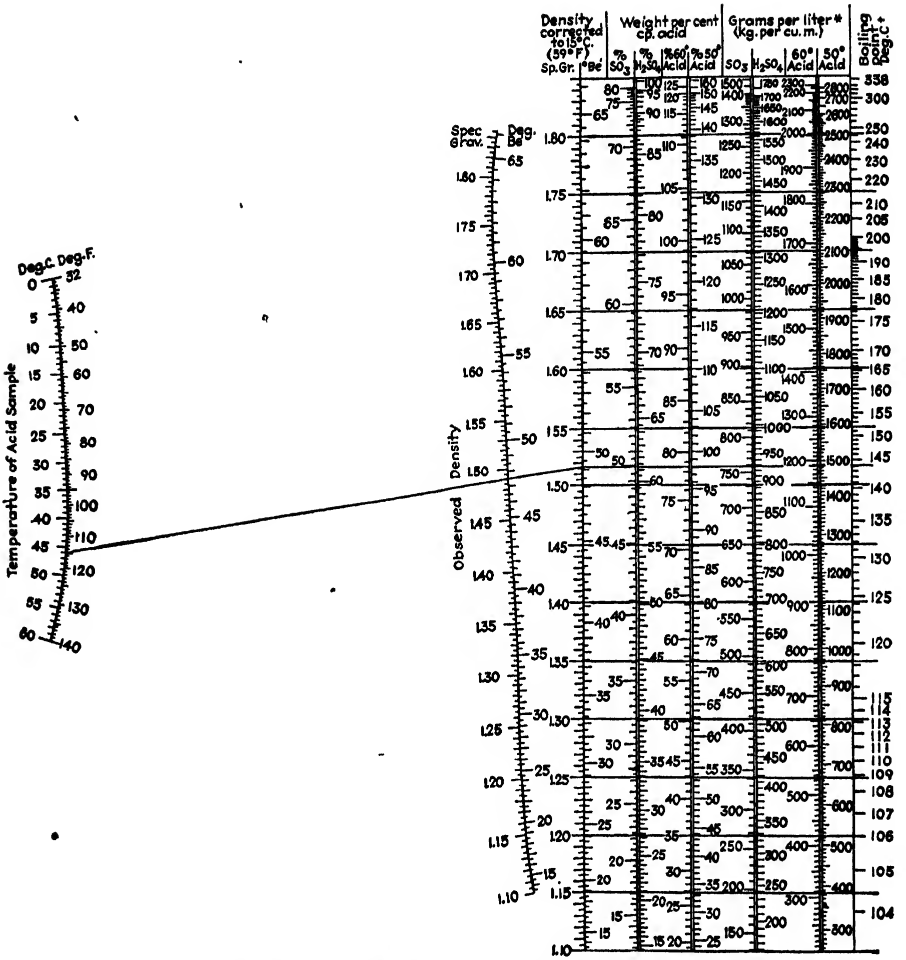

Fig 122.—Temperature correction of sulfuric acid densities and interconversion of physical data.

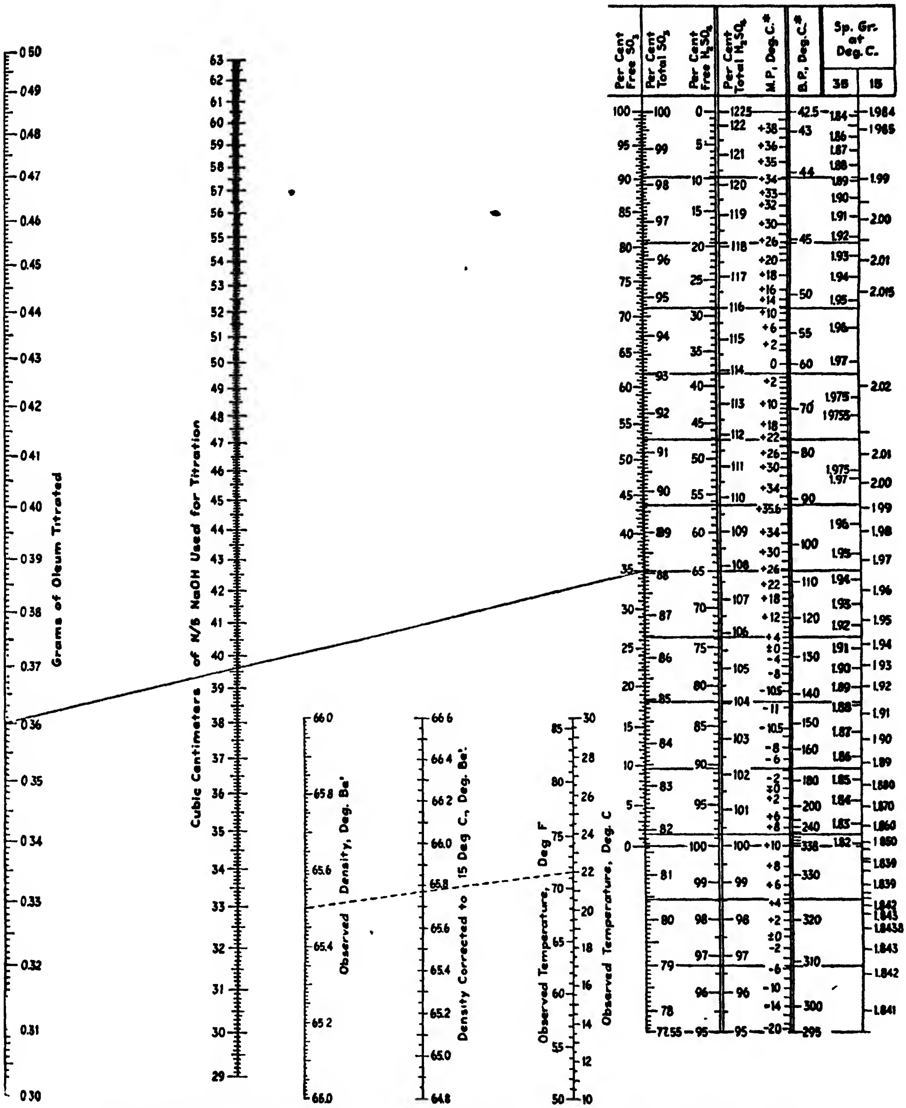

FIG. 123.—Calculation of oleum analyses and interconversion of physical data.

center scale, and extend the line to 35.0 per cent free SO_3 on the first scale at the right. A horizontal line through this point shows that the sample contains 88.06 per cent total SO_3, 65.0 per cent free H_2SO_4, and 107.9 per cent total H_2SO_4. Its melting point is 25.8°C. (78.4°F.), its boiling point about 107°C. (225°F.), and its specific gravity at 15°C. (59°F.) about 1.967. The chart may similarly be used for sulfuric acid of strengths from 95 to 100 per cent.

The small nomograph is useful for making temperature corrections of the Baumé of H_2SO_4 of 65 to 66°. For example, as shown by the dashed line, acid measured as 65.5°Bé. at 22°C. is of 65.77°Bé. when corrected to 15°C.

NOMOGRAPHIC CHART FOR TEMPERATURE CORRECTION OF NITRIC ACID DENSITY AND INTERCONVERSION OF PHYSICAL PROPERTIES[1]

Example (Fig. 124): A sample of nitric acid is tested with a hydrometer at 24°C. and is found to have a specific gravity of 1.255 (29.3°Bé.). It is desired to find the specific gravity at the standard temperature of 15°C. (59°F.). Using a straightedge, connect the observed temperature 24° with the density read from the hydrometer, 29.3°Bé., and extend the line to the scale showing density at 15°C., cutting the scale at a specific gravity of 1.265 (30.2°Bé.). To determine the physical properties of the acid corresponding to this density, extend a horizontal line from the point 1.265 on the corrected density scale to the right, cutting the several scales showing the constants for this acid, corrected to 15°C.

The sample is thus found to contain 42.1 per cent HNO_3, 36.1 per cent N_2O_5, and the equivalent of 79.8 per cent of 36°Bé. acid, 68.1 of 40° acid, and 43.2 per cent of 48½° acid. Each cubic centimeter contains 0.531 g. of HNO_3, 0.457 g. of N_2O_5, and the equivalent of 1.009 g. of 36°Bé. acid, 0.861 g. of 40° acid, and 0.546 g. of 48½° acid. To determine pounds per cubic foot from the equivalent grams per cubic centimeter, multiply the latter by 62.428.

NOMOGRAPHIC CHART FOR TEMPERATURE CORRECTION OF HYDROCHLORIC ACID DENSITIES, WITH SUPPLEMENTAL SCALES FOR THE INTERCONVERSION OF PHYSICAL DATA[2]

Example (Fig. 125): A sample of hydrochloric acid is tested with a hydrometer at 36°C. and shows a specific gravity of 1.135 (17.2°Bé.). It is desired to find the specific gravity at the standard temperature of 15°C. (59°F.). Using a straightedge, connect the observed temperature 36° with the density read from the hydrometer, 17.2°Bé., and extend the line to the scale showing density corrected to 15°C., cutting the scale at

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[1] **Berl, Ernst,** *Chem. & Met. Eng.*, **46,** 234 (1939).

[2] *Ibid.*, **46,** 377 (1939).

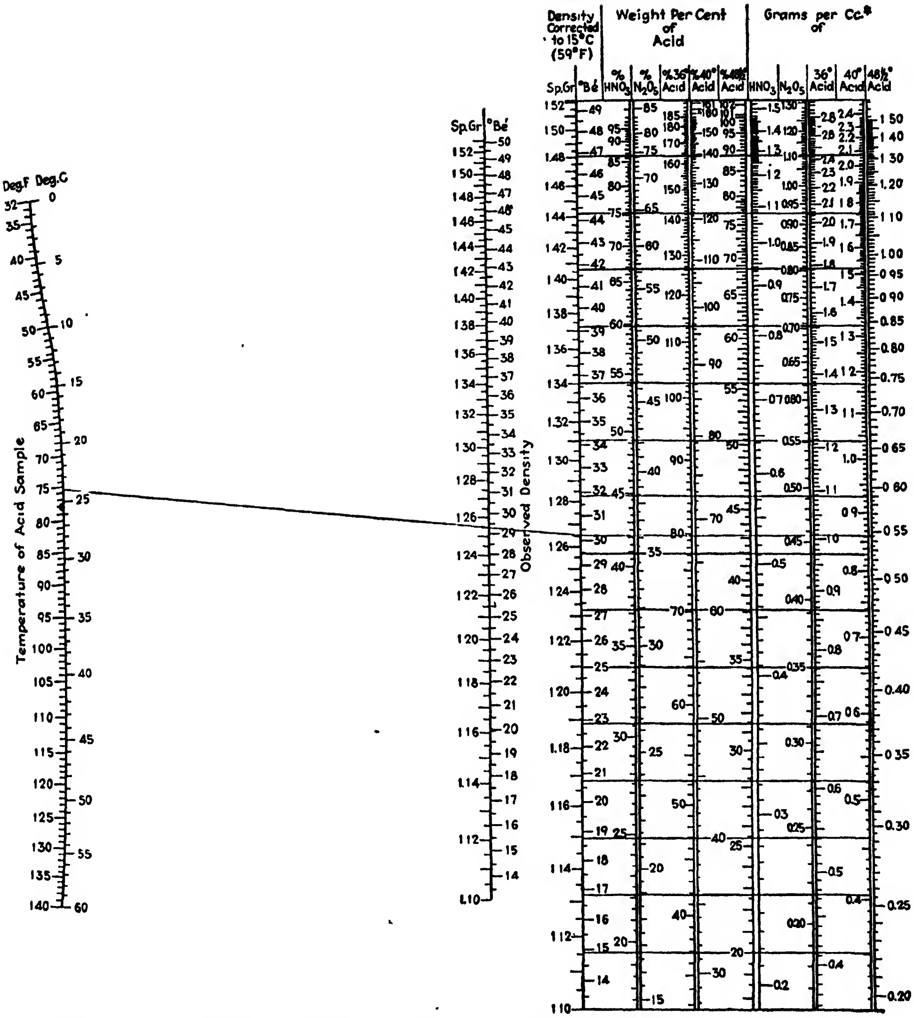

FIG. 124.—Temperature correction of nitric acid densities and interconversion of physical data.

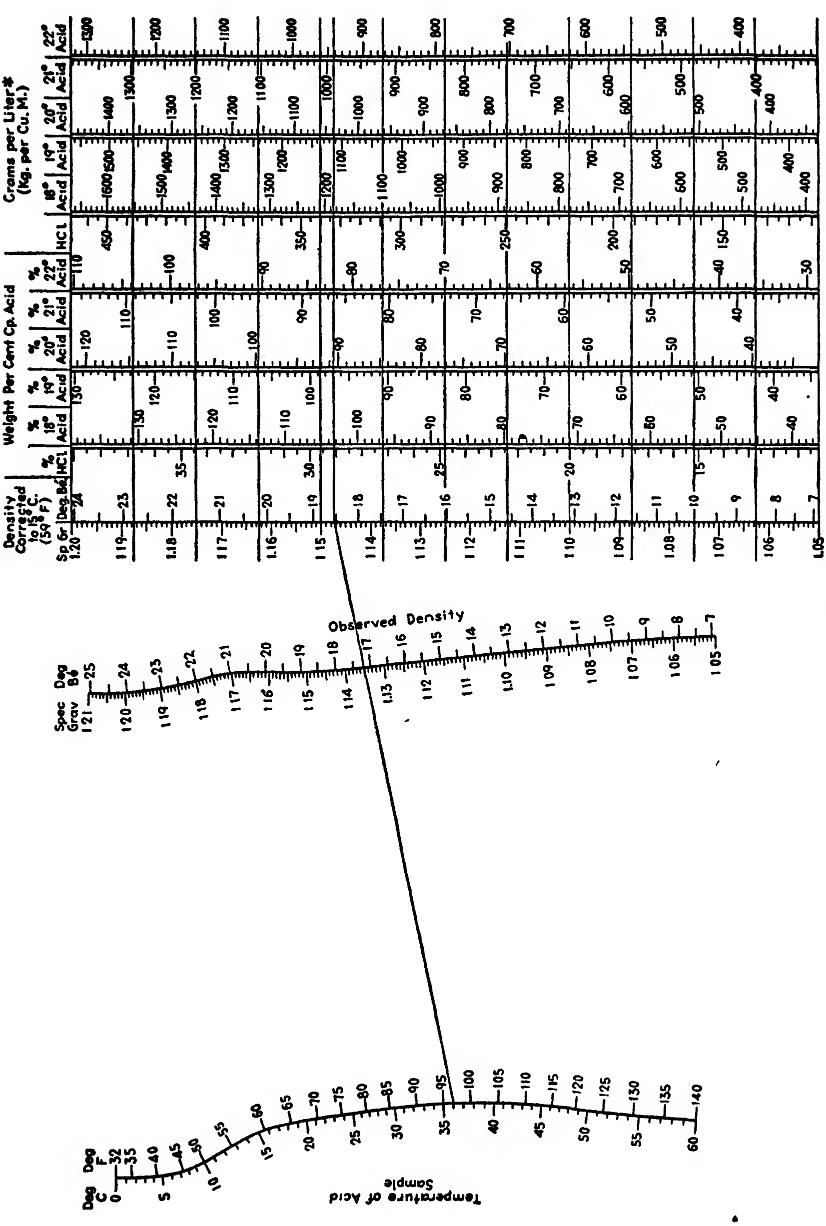

FIG. 125.—Temperature correction of hydrochloric acid densities and interconversion of physical data.

a specific gravity of 1.1473 (18.55°Bé.). To determine the physical properties of the acid corresponding to this density, extend a horizontal line to the right, cutting the several scales showing the constants for this acid.

The sample is thus found to contain 29.1 per cent HCl and the equivalent of 103.3 per cent of 18°, 97 per cent of 19°, 90.6 per cent of 20°, 86.4 per cent of 21°, and 82.1 per cent of 22°Bé. acid. It contains 334 g. of 100 per cent HCl per liter, and the equivalent of 1,185 g. of 18°, 1,113 g. of 19°, 1,039 g. of 20°, 990 g. of 21°, and 941 grams of 22°Bé. acid per liter. For pounds per cubic foot, divide by 16.02.

NOMOGRAPHIC CHART FOR TEMPERATURE CORRECTION OF PHOSPHORIC ACID DENSITIES, WITH ADDITIONAL SCALES FOR INTERCONVERSION OF PHYSICAL DATA[1]

Example (Fig. 126): A sample of phosphoric acid is tested with a hydrometer at 32°C. (89.6°F.) and shows a specific gravity of 1.705 (59.7°Bé.). It is desired to find the specific gravity at the standard temperature of 15°C. (59°F.). With a straightedge, connect the observed temperature 32° with the observed specific gravity 1.705, and extend the line to the corrected density scale, cutting the latter at 1.717 specific gravity (60.3°Bé.). To determine the physical properties of the acid corresponding to this density, extend a horizontal line to the right, cutting the several scales showing the constants for this acid. The acid is thus found to contain 87.2 per cent H_3PO_4 and the equivalent of 63.2 per cent of P_2O_5. In each liter are 1,498 g. of 100 per cent H_3PO_4 and the equivalent of 1,087 g. of P_2O_5. For pounds per cubic foot, divide by 16.02.

NOMOGRAPHIC CHART FOR TEMPERATURE CORRECTION OF SODA ASH SOLUTION DENSITIES, WITH ADDITIONAL SCALES FOR INTERCONVERSION OF PHYSICAL DATA[2]

This chart differs from earlier ones in this series in that the correction scales are in two parts, one for corrections to a standard temperature of 15°C. and the other for corrections to 30°C. The two sections of the chart are separated by the heavy black line which divides the vertical scales at the right. Solutions of more than 1.150 specific gravity become supersaturated above 15°C. Hence, for solutions below 1.150 specific gravity, use the lower scales with a standard temperature of 15°C. For solutions above 1.150 specific gravity, use the upper scales with a standard temperature of 30°C.

Examples (Fig. 127): A solution of soda ash tested with a hydrometer at 40°C. shows a specific gravity of 1.120 (15.45°Bé.) It is desired to

[1] Berl, Ernst, *Chem. & Met. Eng.*, **46**, 435 (1939).

[2] *Ibid.*, **46**, 493 (1939).

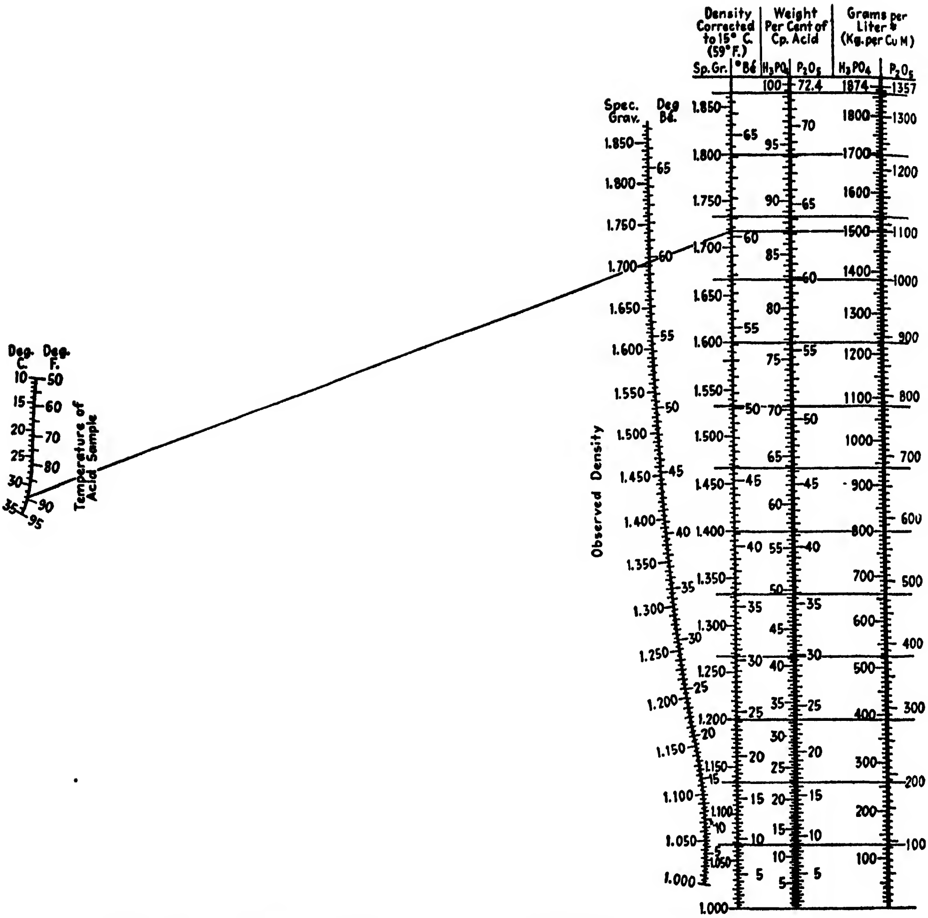

Fig. 126.—Temperature correction of phosphoric acid densities and interconversion of physical data.

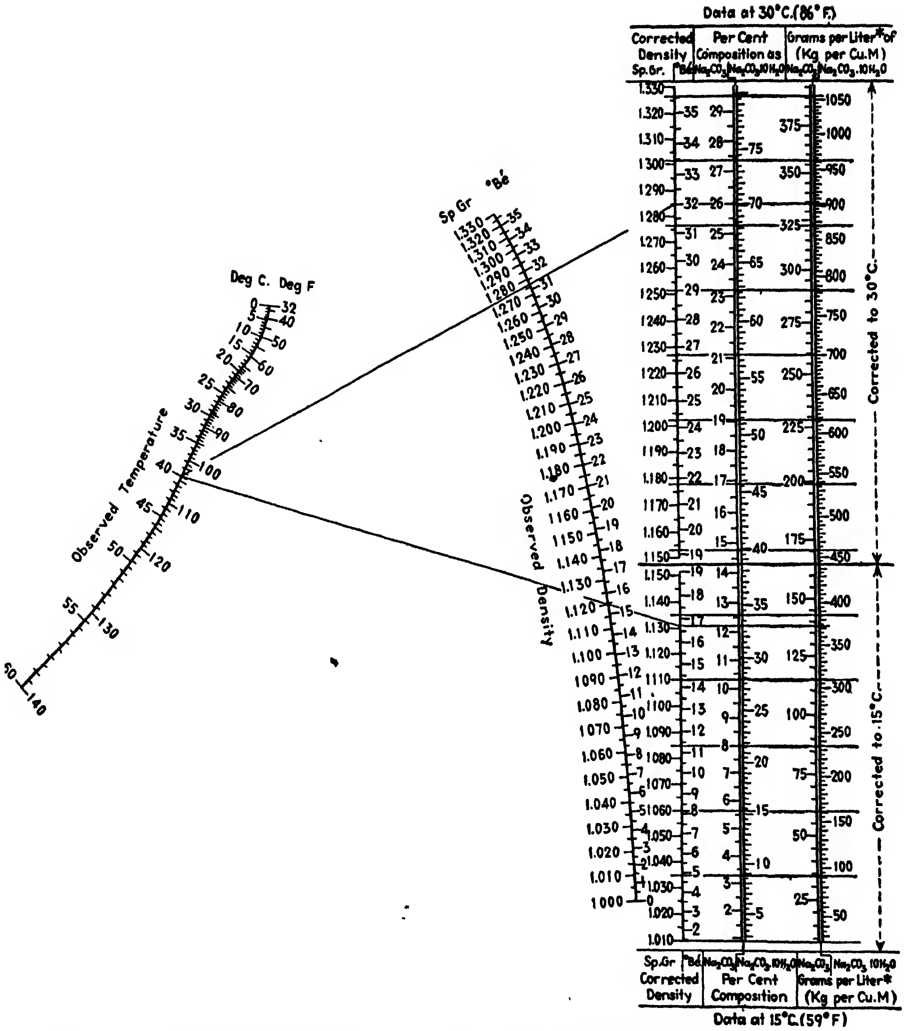

FIG. 127.—Temperature correction of soda ash solution densities and interconversion of physical data.

find the specific gravity corrected to 15°C. (59°F.) and also the composition and the grams per liter (kilograms per cubic meter) in terms of Na_2CO_3 (soda ash) and $Na_2CO_3 \cdot 10\ H_2O$ (sal soda). With a straightedge, connect the observed temperature 40° with the observed density 1.120 specific gravity, and extend the line to the scale for density corrected to 15°C., cutting the latter at 1.131 specific gravity (16.7°Bé.). To determine the physical properties corresponding to this corrected density, extend a horizontal line from 1.131 to the right. The sample is thus found to contain 12.2 per cent Na_2CO_3 and 33.0 per cent $Na_2CO_3 \cdot 10\ H_2O$. It contains 138 g./l. (kg./cu. m.) of Na_2CO_3 and 373 g./l. of $Na_2CO_3 \cdot 10\ H_2O$.

Another sample of soda ash solution tested with a hydrometer at 40°C. shows a specific gravity of 1.277 (31.3°Bé.). By the method shown above, but using the upper section of the vertical scales, the sample corrected to 30°C. is found to have a specific gravity of 1.285 (32.0°Bé.). The solution contains 26.0 per cent Na_2CO_3 and 70.1 per cent $Na_2CO_3 \cdot 10\ H_2O$; and 334 g./l. of Na_2CO_3 and 903 g./l. of $Na_2CO_3 \cdot 10\ H_2O$.

NOMOGRAPHIC CHART FOR THE TEMPERATURE CORRECTION OF CAUSTIC SODA SOLUTION DENSITIES AND INTERCONVERSION OF PHYSICAL DATA[1]

This chart differs from Figs. 122 to 126 and is similar to Fig. 127 of this series in that the correction scales are in two parts, one for correction to a standard temperature of 15°C. (59°F.) and the other for corrections to a standard temperature of 100°C. (212°F.). The two sections of the chart are separated by the heavy lines indicating discontinuity in the scales for corrected density and grams per liter. Caustic soda solutions up to 51 per cent NaOH are liquid at 15°C. (and some percentages considerably below this figure). Solutions of more than 51 per cent NaOH have a rising solubility curve and must be measured at a higher temperature. All concentrations to 70 per cent remain liquid at 64°C. and above. Since the few available data at high concentrations are at 100°C., this temperature has been taken as standard for concentrations of 51 per cent and above.

Example (Fig. 128): A solution of caustic soda is tested with a hydrometer at 46°C. and shows a specific gravity of 1.425 (43°Bé.). It is desired to find the specific gravity and Baumé corrected to 15°C. (59°F.) and also the composition and grams per liter (kilograms per cubic meter) in terms of NaOH and Na_2O and the equivalent percentage composition as sodium carbonate. With a straightedge, connect the observed

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[1] Berl, Ernst, *Chem. & Met. Eng.*, **46**, 527 (1939).

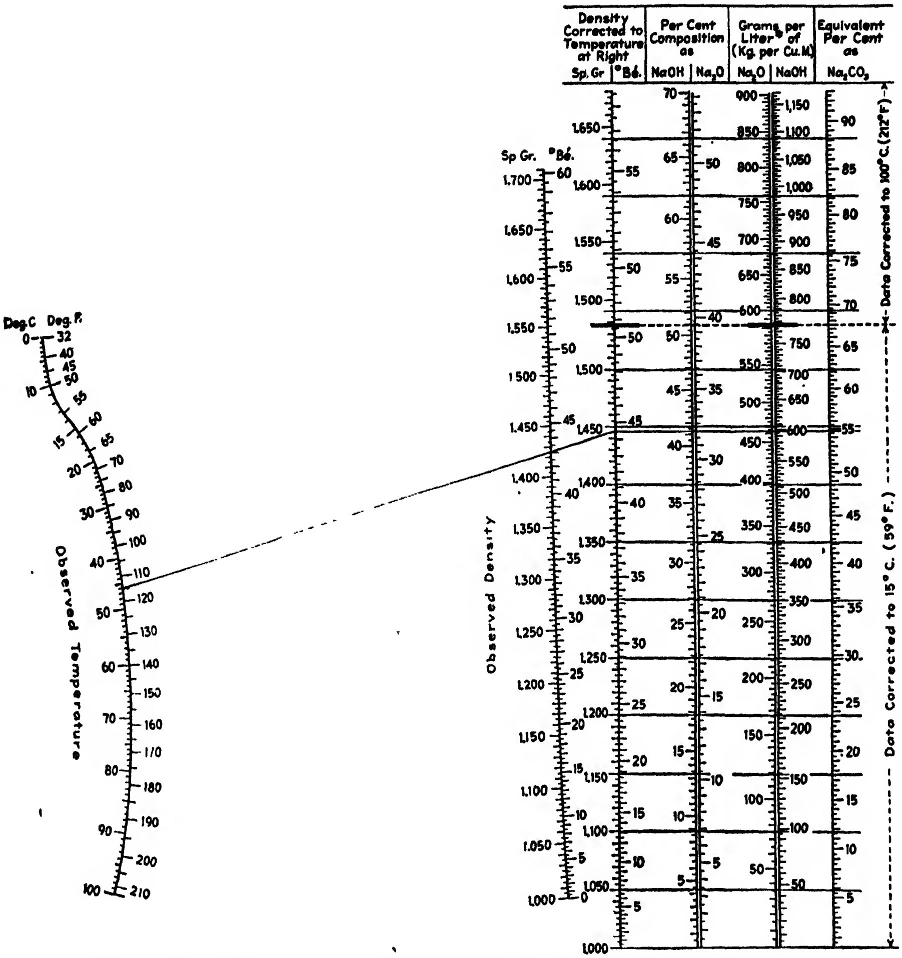

FIG. 128.—Temperature correction of caustic soda solution densities and interconversion of physical data.

temperature 46° with the observed specific gravity 1.425, and extend the line to the corrected density scale for 15°C. standard temperature, cutting the latter at a gravity of 1.446 (44.5°Bé.). To determine the physical properties corresponding to the corrected density, extend a horizontal line to the right, cutting the several scales at the desired quantities.

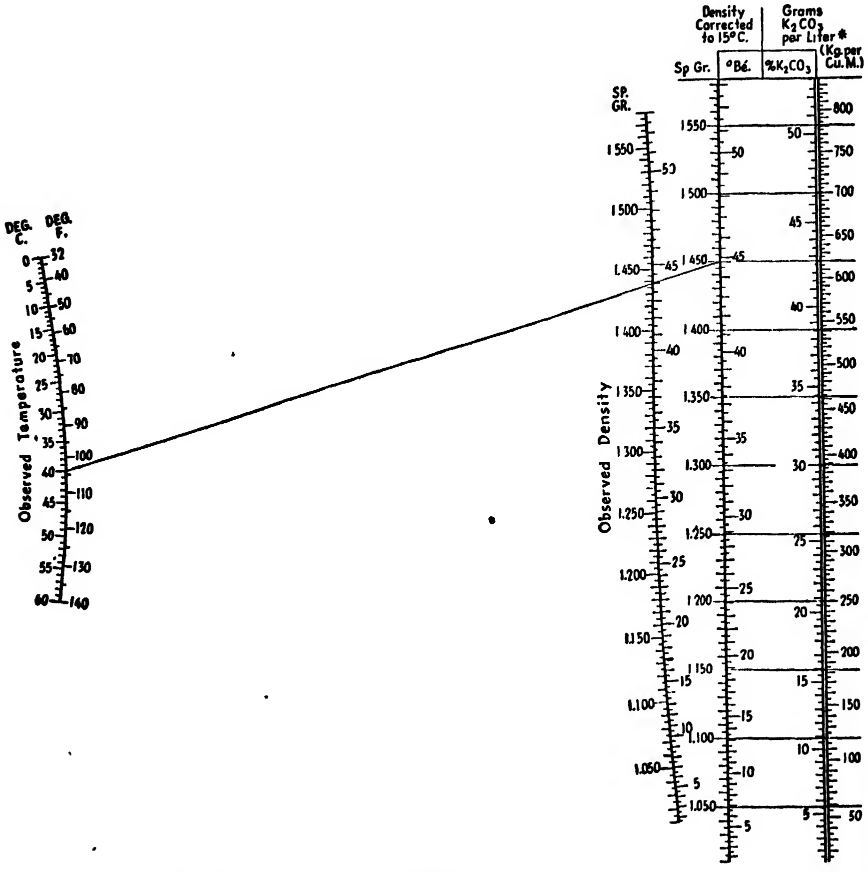

Fig. 129.—Temperature correction of potassium carbonate solution densities and interconversion of physical data.

Thus it is found that the sample contains 41.3 per cent NaOH and 32 per cent Na_2O. It contains 462.5 g./l. (kg./cu. m.) of Na_2O and 597 g./l. of NaOH. The equivalent percentage as Na_2CO_3 is 54.7.

Note: Corrections of solutions containing over 51 per cent of NaOH are handled exactly as above. However, the data for such solutions are not complete, and the completion of the chart above the heavy lines was partly by extrapolation. Consequently accuracy equal to that for solutions of less than 51 per cent cannot be expected.

NOMOGRAPHIC CHART FOR THE TEMPERATURE CORRECTION OF POTASSIUM CARBONATE SOLUTION DENSITIES, WITH ADDITIONAL SCALES FOR INTERCONVERSION OF PHYSICAL DATA[1]

Example (Fig. 129): A sample of K_2CO_3 solution is tested with a hydrometer at 40°C., showing a specific gravity of 1.438 (44°Bé.). It is desired to find the gravity corrected to 15°C., the percentage of K_2CO_3, and the quantity of K_2CO_3 per unit volume of solution. With a straightedge, connect the observed temperature of 40°C. with the observed specific gravity of 1.438, and extend the line to the corrected density scale, cutting the latter at a specific gravity of 1.450 (44.8°Bé.) at 15°C. Extending a horizontal line from this point, note that the sample contains 42.7 per cent K_2CO_3 while each liter contains 620 g. of K_2CO_3 (620 kg./cu. m.).

NOMOGRAPHIC CHART FOR TEMPERATURE CORRECTION OF AQUA AMMONIA DENSITIES, WITH ADDITIONAL SCALES FOR INTERCONVERSION OF PHYSICAL DATA[2]

Example (Fig. 130): A sample of aqua ammonia is tested with a hydrometer at 10.5°C., showing a specific gravity of 0.891 (18.1°Bé.). It is desired to find the specific gravity corrected to 15°C., as well as the Baumé at this temperature and the per cent NH_3 and grams of NH_3 per liter (kilograms per cubic meter). With a straightedge, connect the observed temperature 10.5°C. with the observed specific gravity 0.891, and extend the line to the corrected density scale, cutting the latter at a specific gravity of 0.886 (18.6°Bé.), the density corrected to 15°C. To determine the physical properties corresponding to this density, extend a horizontal line to the right to intersect the scales for composition and grams per liter. Thus it is found that the sample contains 33.0 per cent NH_3 and 293 g. of NH_3 per liter (kg./cu. m.).

HYDROMETRIC NOMOGRAPHS FOR ACETIC ACID SOLUTIONS[3]

Chemical engineers and chemists who find themselves confronted with the problem of designing and maintaining a rapid and reasonably accurate method for the determination of the concentration of acetic acid will naturally turn to hydrometric means. This is particularly true if the test is for control purposes and is to be made at short intervals by an operating man.

Good hydrometers are readily available, and these, together with temperature readings, supply sufficient data from which the desired concentration may be estimated. In place, however, of the somewhat

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[1] Berl, Ernst, *Chem. & Met. Eng.*, **46**, 731 (1939).

[2] Berl, Ernst, *Chem. & Met. Eng.*, **46**, 788 (1939).

[3] *Chem. & Met. Eng.*, **43**, 27 (1936).

cumbersome tables of specific gravities corresponding to various percentage compositions at temperature intervals of 5°C., the accompanying line-coordinate charts will be found to be helpful. They permit the concentration to be read for any temperature between 10 and 30°C. and perform graphically the interpolations that would otherwise have to be handled numerically.

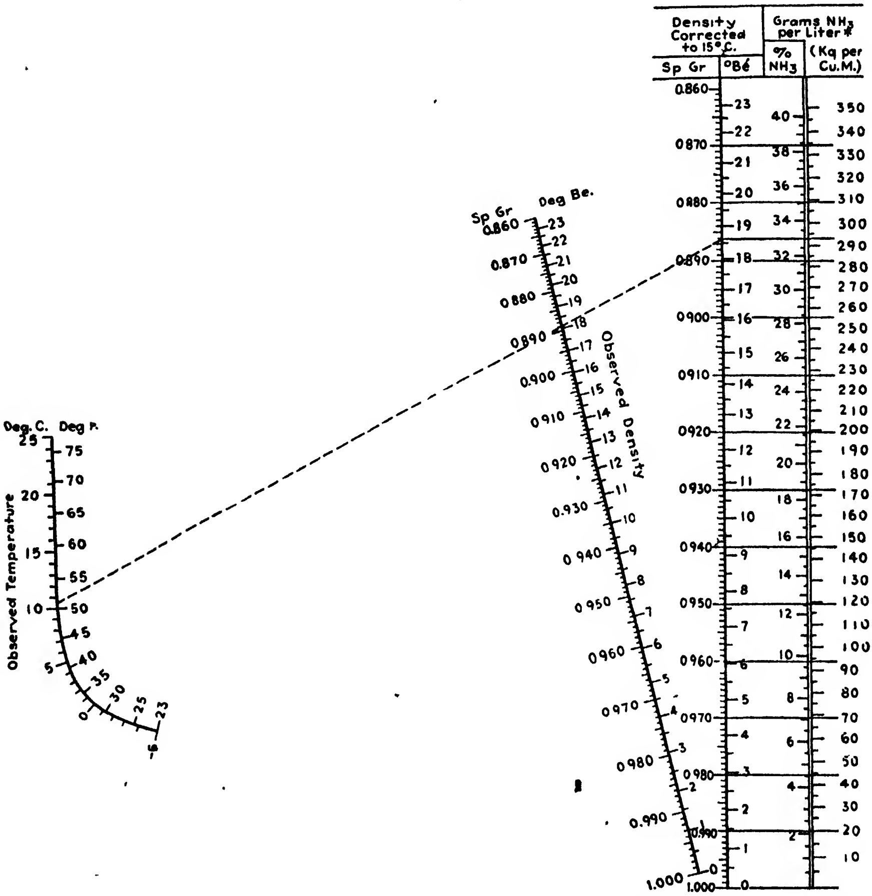

FIG. 130.—Temperature correction of aqua ammonia densities and interconversion of physical data.

Figure 131, which covers the range between 0 and 30 per cent acetic acid, is predicated upon the following relationship between δ, the specific gravity, and t, the centigrade temperature:

$$\delta = a(t + 0.00667t^2) + b$$

where a and b are constants specific for each value of the concentration.

The dashed line indicates that a sample of acetic acid with a specific gravity of 1.034 at 17°C. contains 25.0 per cent CH_3COOH.

Figure 132, covering the range between 30 and 100 per cent acetic acid, depends upon a simpler relationship between specific gravity and temperature

$$\delta = at + b.$$

It is interesting to note in this higher range that a single value of the specific gravity at a given temperature may correspond to *two* concentrations. This ambiguity, inherent in the physical properties of the solution and in no way due to the methods of correlation of the data, need cause no difficulty since one usually knows from experience with the process which value to take. Thus, the broken line shows that a solution testing 1.062 at 16°C. may contain either 52.0 or 96.5 per cent acetic acid.

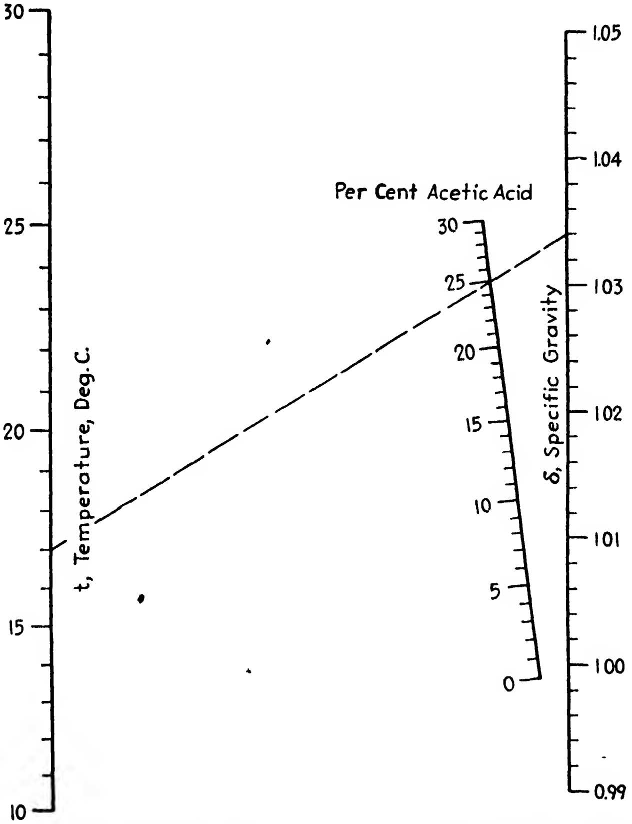

FIG. 131.—Temperature-specific-gravity-concentration relationships for acetic acid. 0 to 30 per cent.

HYDROCYANIC ACID NOMOGRAPH[1]

Walker and Marvin[2] have devised a rapid hydrometric method for the determination of HCN in concentrated hydrocyanic acid, where the only impurity is water, and have presented a table which lists the percentages of HCN corresponding to specific gravities between 0.680 and 0.750 and to temperatures between 0 and 25°C.

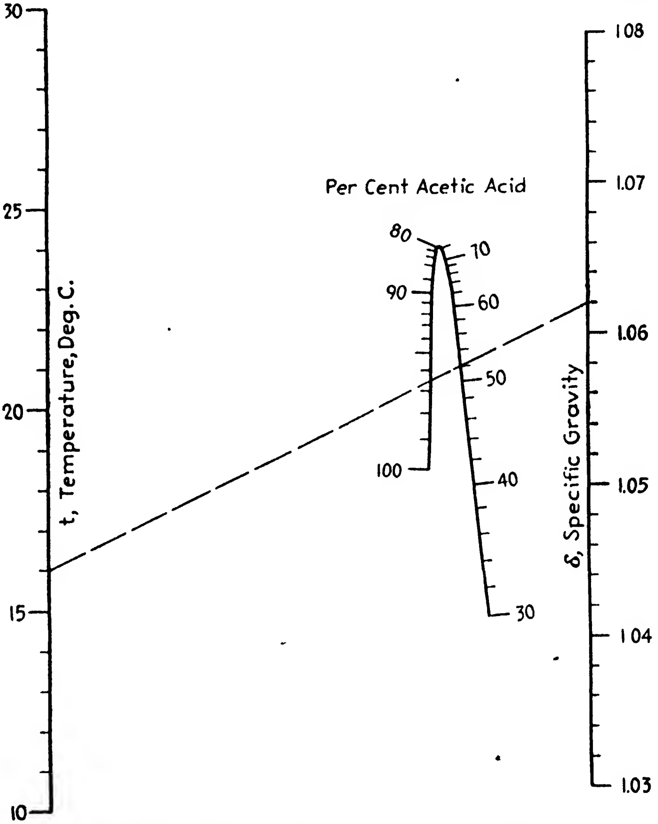

Fig. 132.—Temperature–specific-gravity–concentration relationships for acetic acid. 30 to 100 per cent.

These variables may be related by the expression

$$x = \frac{1.0357 - 0.0003733t - \delta}{0.00001053t + 0.003176}$$

where x = percentage of HCN.

δ = specific gravity of the hydrocyanic acid.

t = temperature, °C.

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[1] *Chemist-Analyst*, **24** (1), 15 (1935).

[2] Walker, M., and C. J. Marvin, *Ind. Eng. Chem.*, **18**, 139 (1926).

The equation is most conveniently solved by means of Fig. 133, the dashed line of which indicates that a sample of hydrocyanic acid that has a specific gravity of 0.710 at 15°C. contains 96.0 per cent HCN.

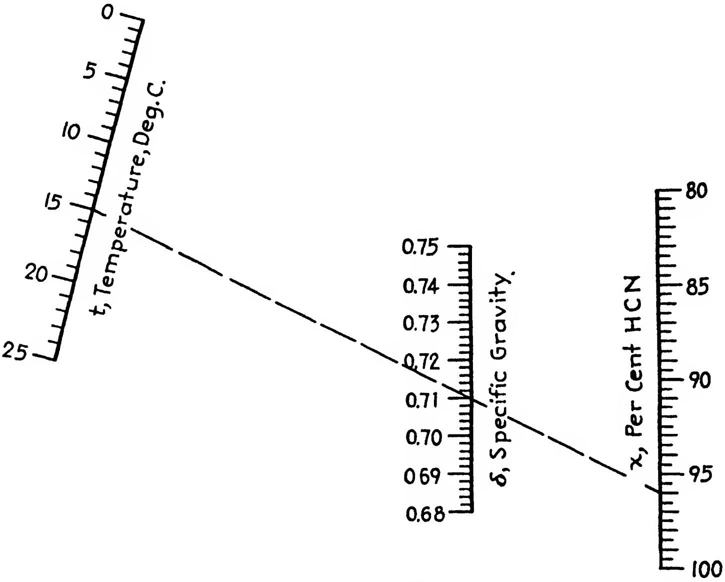

FIG. 133.—Temperature–specific gravity-concentration relationships for aqueous hydrocyanic acid.

The equation and nomograph are reliable to within 0.2 per cent.

HYDROMETRIC LINE-COORDINATE CHARTS FOR NITRIC ACID[1]

The most rapid and foolproof method of determining concentrations is that which makes use of a hydrometer, and even in unskilled hands considerable accuracy can be easily attained. For best results, some little attention must be given to making the measurements at a standard temperature or to applying suitable corrections for temperature deviations from that standard.

The former procedure is often inconvenient and sometimes totally impracticable in plant work, since it would require a means of heating or cooling, or both. The latter plan is the more attractive, but methods of temperature correction usually take the form of bulky tables or complicated families of curves.

It is the purpose of this topic to provide simple and accurate graphical means for calculation of concentration in terms of specific gravity and

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[1] *Chemist-Analyst*, **30**, 35 (1941).

temperature in the case of the industrially important nitric acid. The charts are based upon the table compiled by Beattie.[1,2]

Figure 134 embraces concentrations between 1 and 40 per cent HNO_3. It is predicated upon the fact that, between the convenient temperatures

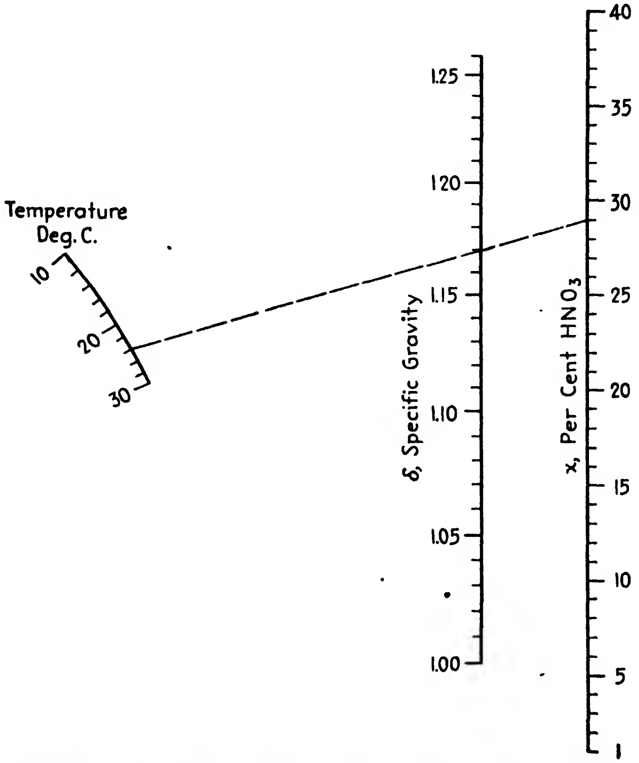

FIG. 134.—Temperature-specific-gravity relationships for 1 to 40 per cent nitric acid.

of 10 and 20°C., the logarithm of the specific gravity is linear with respect to the concentration. That is,

$$\log \delta = ax + b$$

where a and b are constants, δ is the specific gravity, and x is the percentage concentration. The broken line indicates that if nitric acid at 24°C. has a specific gravity of 1.17 (referred to water at 4°C. as 1.000) it contains 29.0 per cent HNO_3.

Figure 135 covers concentrations between 40 and 100 per cent. It derives its form from the linearity of specific gravity and temperature

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[1] BEATTIE, J. A., "International Critical Tables," Vol. III, p. 58, McGraw-Hill Book Company, Inc., New York, 1928.

[2] PERRY, JOHN H., "Chemical Engineers' Handbook," 2d ed., pp. 419–420, McGraw-Hill Book Company, Inc., New York, 1941.

for any given concentration. That is,

$$\delta = ct + d$$

where c and d are constants depending upon the concentration and t is the centigrade temperature. A straight line connecting the temperature and specific-gravity scales will cut the concentration scale in the correct percentage value. Thus the broken line shows that nitric acid with a specific gravity of 1.33 at 23°C. contains 54.0 per cent HNO_3.

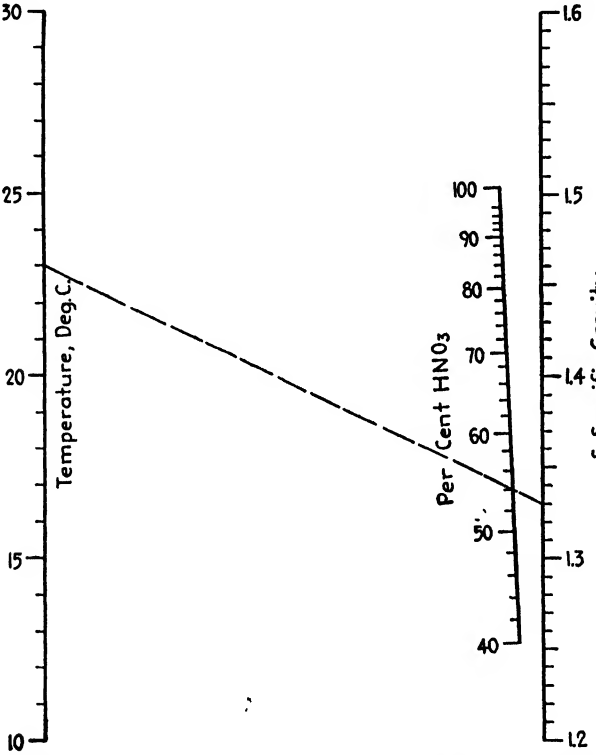

Fig. 135.—Temperature-specific-gravity relationships for 40 to 100 per cent nitric acid.

The use of these self-interpolating charts in place of the more cumbersome tables will obviate many errors and speed up the work considerably.

HYDROMETRIC LINE-COORDINATE CHARTS FOR SULFURIC ACID[1]

The chemist and chemical engineer have frequent need for a rapid and reliable method of determining concentrations of sulfuric acid, as for instance, in the preparation and testing of acids used in maintaining constant humidity.

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[1] *Chemist-Analyst*, **30**, 54 (1941).

The use of the hydrometer at once suggests itself, together with a table of percentage concentrations at various specific gravities and temperatures. Excellent hydrometers are obtainable at low cost, and the reliable table compiled by Beattie[1,2] is readily available. In that extensive table the concentrations range from 1 to 100 per cent in steps of 1 per cent, and the specific gravity of each concentration is given for the temperatures 10, 15, 20, 25, and 30°C. But for intermediate concentrations and temperatures, interpolation is necessary. This usually troublesome interpolation is easily made by using the accompanying line-coordinate charts which have been based upon Beattie's table.

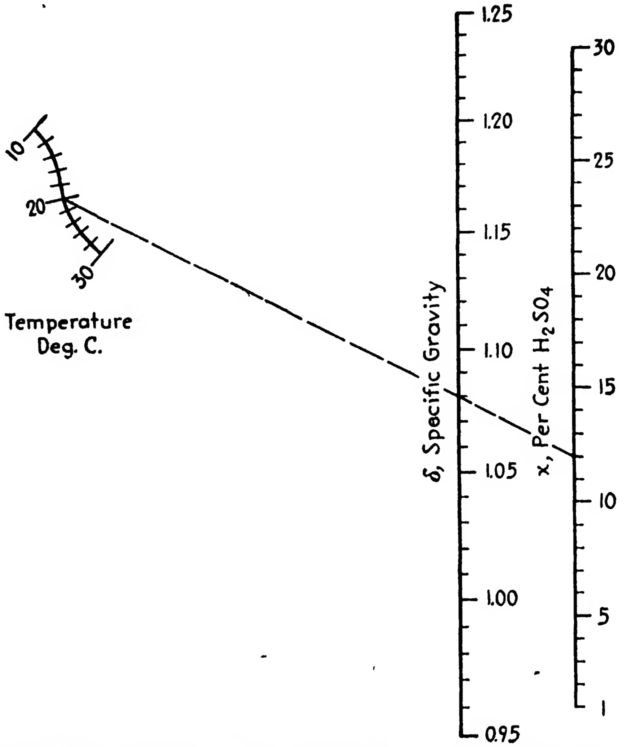

Fig. 136.—Temperature–specific-gravity relationships for 1 to 30 per cent sulfuric acid.

Figure 136 covers concentrations between 1 and 30 per cent. It is predicated upon the fact that, between the temperatures of 10 and 30°C., the logarithm of the specific gravity is linear with respect to the concentration. That is,

$$\log \delta = ax + b$$

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[1] Beattie, *op. cit.*, p. 56.

[2] Perry, *op. cit.*, pp. 372–373.

where *a* and *b* are constants, δ is the specific gravity, and *x* is the percentage concentration. The broken line indicates that if sulfuric acid at 20°C. has a specific gravity of 1.080 it contains 12 per cent H_2SO_4.

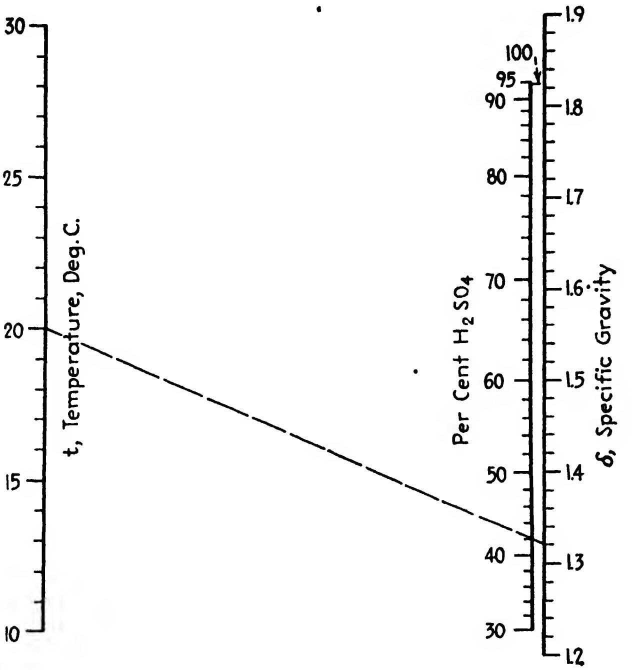

FIG. 137.—Temperature-specific-gravity relationships for 30 to 100 per cent sulfuric acid.

Figure 137 embraces concentrations between 30 and 100 per cent. It derives its form from the linearity of specific gravity and temperature for any given concentration. That is,

$$\delta = ct + d$$

where *c* and *d* are constants and *t* is the centigrade temperature. The broken line shows that a solution having a specific gravity of 1.320 at 20°C. contains 42 per cent H_2SO_4.

Obviously both charts may be used to solve the problem of finding the specific gravity corresponding to any given concentration and temperature.

It should be noted that concentrations higher than 93 per cent H_2SO_4 cannot be accurately measured with a hydrometer. For in the interval extending from 94 to about 97½ per cent, the specific gravity increases more and more slowly, whereas in the interval extending from 97½ to 100 per cent the specific gravity is *decreasing*.

SPECIFIC-GRAVITY—TEMPERATURE RELATIONSHIPS FOR DILUTE ALUM SOLUTIONS[1]

Many paper mills that go in strongly for technical control, as shown by their close attention to qualitative and quantitative analyses of the raw materials and to elaborate physical and chemical testing of the finished product, accord scant attention to the concentration of their alum solutions. This is all the more remarkable in view of the detailed quantitative examination of the solid alum for insoluble matter, total soluble alumina, ferric and ferrous iron, foreign sulfates, and sulfur trioxide and of the daily tests on the concentration of the rosin size milk.

Where testing of the alum solution is undertaken at all, it usually takes the form of a Baumé determination, often without a simultaneous temperature reading. Occasionally someone will attempt to convert the Baumé figure into the relatively more significant percentage value through the use of fragmentary data available in the handbooks and of assumed corrections of Baumé for temperature, which are usually sadly in error.

As a result, few mills using alum solutions have any thoroughly reliable data on the actual amount of alum present in their beater furnishes, and errors in making up the alum solutions may go undetected for days. Because of the importance of the size-alum balance, of the expense of the alum, and of the effect of alum concentration upon freeness and dyes, it would appear that greater attention should be given this item and that there is a need for a testing method that will meet the following requirements:

1. It should be accurate.
2. It should be capable of completion in 5 min.
3. It should yield the concentration in percentage or in pounds per gallon rather than in an arbitrary gravity unit.
4. It should be within the scope of a sample boy.

Experimental Method.—With these points in mind four alum solutions of known concentrations covering the range encountered in the mill were prepared. Each was warmed to slightly over 40°C., and allowed to cool slowly while Baumé and temperature readings were taken. The hydrometers employed were graduated to 0.01° Bé and permitted estimation of 0.001° while the centigrade thermometer allowed estimation of 0.1°. Baumé—temperature ($B - t$) plots of the 85 pairs of values so obtained proved to be concave toward the origin, the curvature increasing with decreasing concentration.

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[1] Simerl, L. E., and D. S. Davis, *Paper Ind. & Paper World*, **18**, 460 (1936).

Mathematical Treatment of the Data.—It was noticed that the curves could be rectified by plotting $B \log B$ vs. t as required by the equation

$$B^B = 10^{mt+a}$$

and that m and a were related to the solids content in pounds per gallon, S, by the expressions

$$m = 0.03243S^{-0.392} - 0.0875$$

and

$$a = (9.386S - 0.758)^{1.053}$$

Use of the Nomograph.—Most hydrometric determinations of solids result in variables connected by means of an involved equation which, however, can be readily solved by an alignment chart wherein the complexity of the relationship is not reflected. Such is the case with the accompanying alum nomograph, Fig. 138, the use of which is illustrated as follows: What is the concentration of an alum solution having a Baumé of 2.200 at 24° C.? Connect 24 on the centigrade temperature scale with 2.200 on the Baumé scale and read the desired value on the curved concentration scale as 0.235 lb./gal.

It will be noted that all the axes are doubly graduated: both centigrade and Fahrenheit scales are used, as well as Baumé and specific-gravity units, and concentrations of alum are in pounds per gallon and in per cent. Percentage concentration is obtained from the expression $100S/8.345\delta$ where δ is the specific gravity at 20° C. Reference to the nomograph will show that an alum solution exhibiting a specific gravity of 1.009 at 83°F., has a concentration of 1.90 per cent.

The four requirements for a satisfactory test method are fully met since any laboratory boy can complete the test in 3 min., reporting a definite concentration value reliable to about 1 per cent.

SPECIFIC-GRAVITY—TEMPERATURE RELATIONSHIPS FOR CONCENTRATED ALUM SOLUTIONS[1]

Alum solutions figure prominently in many beater furnishes and are widely used in water treatment in the paper and other industries; yet a recent survey of the literature has revealed the lack of reliable and usable data covering the relationships among specific gravity, temperature, and concentration. Gerlach[2] and Kullerud[3] have studied fairly wide ranges of concentration but have confined their attention to temperatures of 15 and 18°C., respectively. Reuss[4] presented specific-gravity data for

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[1] Bogart, H. N., and D. S. Davis, *Paper Ind. & Paper World*, **21**, 657 (1939).

[2] Gerlach, G. T., *Zeit. für anal. Chemie*, **28**, 493 (1889).

[3] Kullerud, G., *Paper Trade J.*, **92**, (21), 47 (1931).

[4] Reuss, E. K., *Ber. deutsch. chem. Ges.*, **17**, 2888 (1884).

temperatures between 15 and 45°C., over satisfactory concentration ranges for pure aluminum sulfate and for commercial alum, but the results are somewhat erratic.

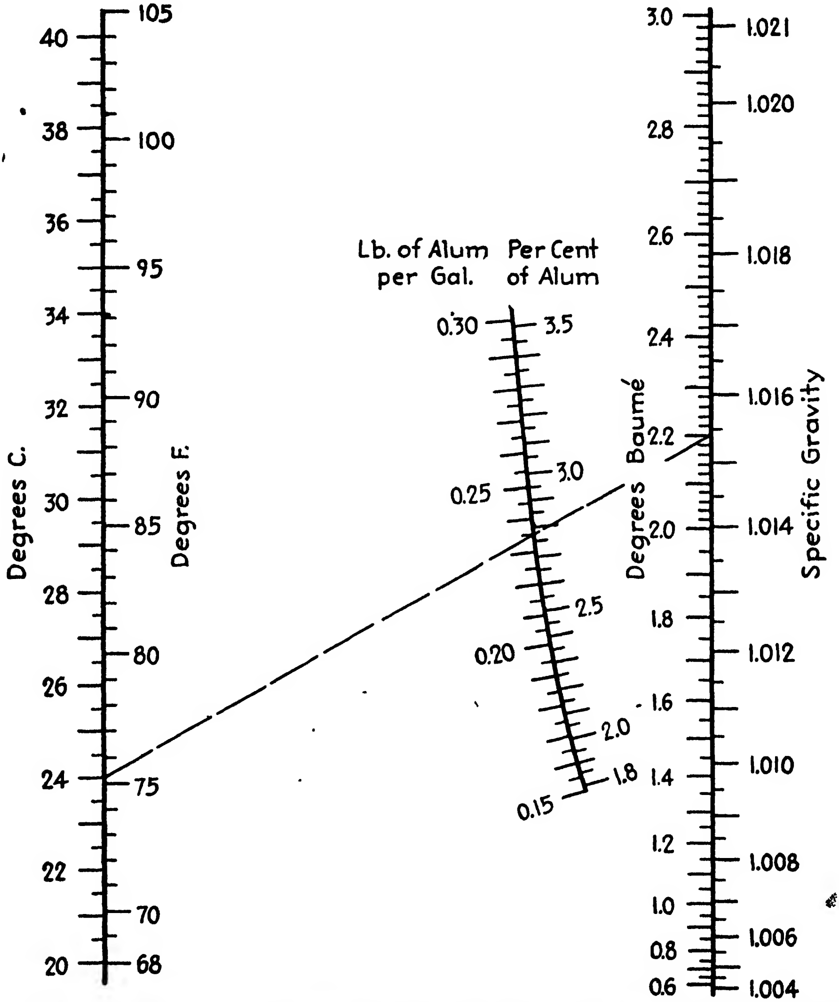

FIG. 138.—Specific-gravity–temperature relationships for aqueous solutions containing 0.15 to 0.30 lb. alum per gallon.

In each case the information is merely in tabular form and is not well adapted to immediate use. The purposes of the present investigation were (1) to determine the specific gravities of a number of alum solutions of known concentrations over the temperature range of 10 to 35°C., (2) to correlate these data by suitable, closely fitting empirical equations, and (3) to present an alignment chart enabling rapid calculation of concentration when specific gravity and temperature are known.

Experimental Method.—Thirteen solutions varying in concentration from about 0.1 to about 2.2 lb./gal. were prepared, using commercial iron-free alum containing 55.2 per cent anhydrous $Al_2(SO_4)_3$. A portion of each, in turn, was placed in a carefully standardized pycnometer of about 30 ml. capacity, equipped with a combination ground-glass stopper and thermometer. The pycnometer and contents were cooled below 10°C. and allowed to warm slowly to 35°C. Weighings were made at 5° intervals, and specific gravities relative to water at 4°C. were calculated. The data are presented in Table XXIII.

TABLE XXIII

Concentration, lb./gal.	Specific gravities (relative to water at 4°C.) at					
	10°C.	15°C.	20°C.	25°C.	30°C.	35°C.
0.0992	1.0065	1.0057	1.0047	1.0035	1.0022	1.0005
0.1973	1.0131	1.0122	1.0113	1.0101	1.0087	1.0066
0 2946	1.0197	1.0188	1.0177	1.0165	1.0150	1.0132
0.3905	1.0259	1.0250	1.0238	1.0226	1.0211	1.0194
0.4855	1.0320	1.0311	1.0299	1.0286	1.0272	1.0253
0.5794	1.0383	1.0368	1.0356	1.0343	1.0332	1.0314
0.7950	1.0519	1.0508	1.0494	1.0477	1.0464	1.0446
1 093	1.0713	1.0701	1.0687	1.0672	......	1.0636
1.380	1.0889	1.0876	1.0862	1.0843	1.0828	1.0808
1.590	1.1028	1.1014	1.1000	1.0986	1.0966	1.0948
1.802	1.1145	1.1133	1.1117	1.1098	1.1081	1.1064
1.989	1.1265	1.1250	1.1234	1.1216	1.1198	1.1177
2.181	1.1379	1.1366	1.1347	1.1331	1.1312	1.1293

Correlation of Data.—For each solution, a linear relationship exists between the specific gravity δ and a certain function of the centigrade temperature t according to the equation

$$\delta = a[t + 0.00032(t - 10)^2] + b.$$

For concentrations C below 1.1 lb./gal.,

$$a = 0.0000594C - 0.0001963$$

and

$$b = 0.06535C + 1.0025;$$

while for concentrations above 1.1 lb./gal.,

$$a = -0.0000324C - 0.0002261$$

and

$$b = 0.06185C + 1.0063.$$

Use of the Nomograph.—Figure 139, a line-coordinate chart based upon the above equations, enables rapid and convenient calculation of the concentration when the specific gravity and temperature are known, enhancing the utility of the experimental data. The broken line on the chart indicates that an alum solution at a temperature of 25°C. (77°F.) with a specific gravity of 1.1030 (relative to water at 4°C.) has a concentration of 1.68 lb. of 55.2 per cent anhydrous alum per gallon. The horizontal scales at the top of the chart effect conversion between pounds per gallon and percentage concentration according to

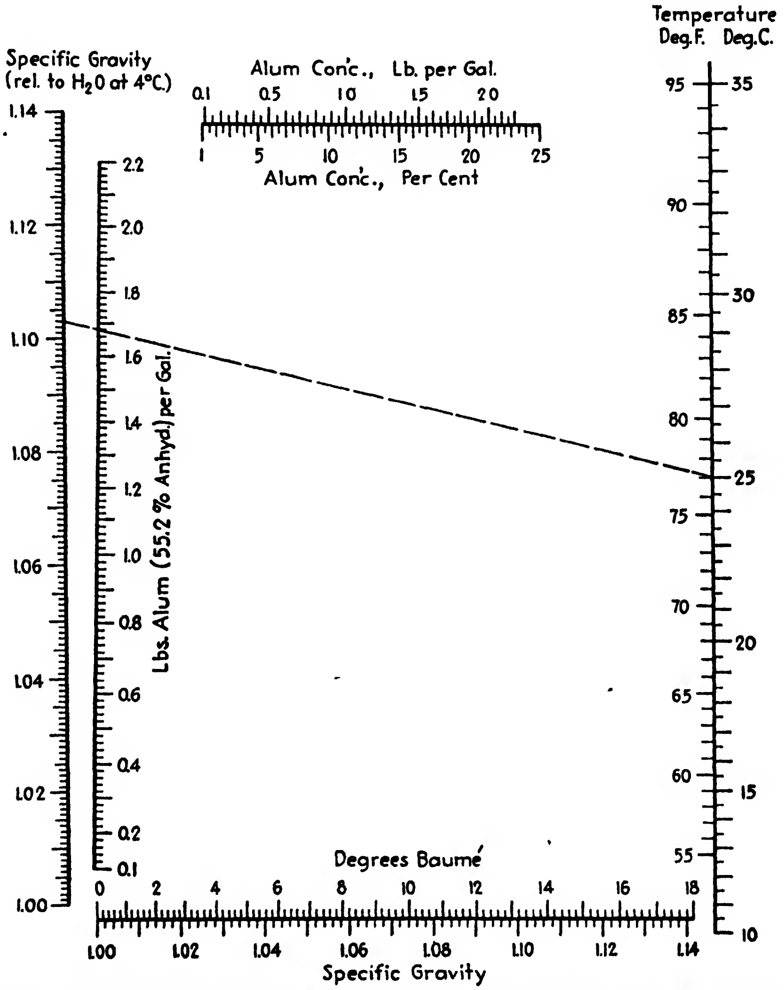

FIG. 139.—Specific-gravity–temperature relationships for aqueous solutions containing 0.1 to 2.2 lb. alum per gallon.

the expression

$$\text{Percentage concentration} = \frac{100C}{8.33\delta'}$$

where δ' is the specific gravity of the same solution at 20°C., relative to water at 4°C.

TABLE XXIV

t, °C.	δ	Pounds per gallon		Percentage deviation
		Known	Chart	
15	1.0122	0.1973	0.194	−1.7
20	1.0113	0.1973	0.198	0.4
25	1.0101	0.1973	0.197	−0.2
30	1.0087	0.1973	0.198	0.4
15	1.0508	0.7950	0.796	0.1
20	1.0494	0.7950	0.795	0.0
25	1 0477	0 7950	0.788	−0.9
30	1.0464	0.7950	0.794	−0.1
15	1.1132	1.802	1.799	−0.2
20	1 1117	1.802	1.798	−0.2
25	1.1098	1.802	1.796	−0.3
30	1.1081	1.802	1.798	−0.2
15	1.0311	0.4155	0.490	0.9
20	1.0299	0.4155	0.491	1.1
25	1.0286	0.4155	0.490	0.9
30	1.0272	0.4155	0.490	0.9
15	1.0876	1.380	1.379	−0.1
20	1.0862	1.380	1.380	0.0
25	1.0843	1.380	1.376	−0.3
30	1.0828	1.380	1.380	0.0
15	1.1366	2.181	2.180	−0.1
20	1.1347	2.181	2.174	−0.3
25	1.1331	2.181	2.176	−0.2
30	1.1312	2.181	2.176	−0.2
Average deviation				0.4

In the present instance, 1.68 lb./gal. is seen to be equivalent to 18.25 per cent of 55.2 per cent anhydrous alum. The horizontal scales at the bottom of the chart enable conversion between degrees Baumé (Bé.) and specific gravity according to the equation

$$\delta = \frac{145}{145 - \text{Bé.}}.$$

Further practice in the use of the chart may be attained by checking through the following illustration: An alum solution testing 8.2°Bé. (specific gravity = 1.060) at 22.5°C. (72.5°F.) contains 0.970 lb. of 55.2 per cent anhydrous alum per gallon, constituting an 11 per cent solution.

Table XXIV shows the nature of the agreement between calculated and experimental values, indicating that the chart yields concentrations deviating, on the average, about 0.4 per cent from the observed data.

Table XXV shows the present work to be in close agreement with the data of Gerlach and of Kullerud but to differ somewhat from the values reported by Reuss.

TABLE XXV

t, °C.	δ	Relative H_2O at °C.	Percentage of 55.2 per cent alum		Percentage of deviation	Earlier data of
			Fig. 139	Earlier data		
15	1.0535	15	9.40	9.31	1.0	Gerlach
15	1.1105	15	18.77	18.62	0.8	Gerlach
18	1.0100	18	1.78	1.81	− 1.7	Kullerud
18	1.0621	18	10.87	10.87	0.0	Kullerud
18	1.1280	18	21.86	21.75	0.5	Kullerud
15	1.0600	4	10.62	9.60	10.6	Reuss*
25	1.0950	4	16.99	16.82	1.0	Reuss*
35	1.1300	4	23.29	24.31	− 4.2	Reuss*
15	1.0600	4	10.62	9.49	11.9	Reuss†
25	1.0950	4	16.99	15.97	6.4	Reuss†
35	1.1300	4	23.29	22.97	1.4	Reuss†

* Pure $Al_2(SO_4)_3$.

† Commercial alum.

CALCIUM CHLORIDE NOMOGRAPHS[1]

Calcium chloride, available in large quantities in flake form, finds industrial application as a general dehydrating agent; in the drying of gases; in the manufacture of liquid carbon dioxide, ammonia, and air; in the curing of Portland cement concrete; in fireproofing paints; in the manufacture of gunpowder, dry colors, and lakes; in automatic sprinkler solutions; and as a refrigerating brine. It is admirably adapted to the latter use; since the specific heats of its aqueous solutions are high enough to

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[1] *Ind. Eng. Chem.*, **34**, 1393 (1942).

ensure the use of moderately small quantities of brine, accidental ammonia leakage does it no harm, it is not particularly corrosive, and its solutions have satisfactorily low freezing points. Large amounts of calcium chloride are used in road treatment for stabilization and dust laying, for ice control on highways, and for the treatment of coal and coke for dustproofing and freezeproofing.

Since many of the uses of calcium chloride require brines, hydrometric methods of analysis for control purposes offer obvious advantages. Excellent specific gravity–temperature–concentration data[1,2,3] are available, but these are in tabular form and require inconvenient interpolation.

For temperatures between 10 and 30°C., the I.C.T. data[3] can be represented closely by the equations

$$\delta = a + b\left(c + \frac{2.36}{10^{0.108c}}\right)$$

for $c = 6$ to 20

$$\delta = a + b\left(c + \frac{0.736}{10^{0.0181c}}\right)$$

for $c = 20$ to 34

where δ = specific gravity, 60°F./60°F.

c = concentration of anhydrous $CaCl_2$ in pure aqueous solutions, per cent.

a, b = functions of temperature resulting from Lagrange interpolation[4] and defined by Table XXVI.

Commercial calcium chloride contains about 1.5 per cent of sodium chloride and thus necessitates adjustment of the quantity c to cover concentrations of anhydrous calcium chloride in the impure brines using the Dow data.[2] The nomographs, based on this correlation, extend the utility of the hydrometric method by permitting reliable graphical interpolations to be made quickly and conveniently.

The use of the charts is illustrated as follows: What is the concentration of calcium chloride in a commercial brine when the hydrometer reading is 1.130 at 22°C.? Using Fig. 140, connect 22 on the temperature with 1.130 on the hydrometer reading scale and read the concentration as 14.8 per cent calcium chloride. What is the freezing point of such a solution? Opposite 14.8 per cent calcium chloride, read the

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[1] Calcium Chloride Assoc., *Bull.* **30, 17** (1942).

[2] The Dow Chemical Company, private communication to Calcium Chloride Assoc.

[3] "International Critical Tables," Vol. II, p. 327, McGraw-Hill Book Company, Inc., New York, 1928.

[4] *Chem. & Met. Eng.*, **45**, 383 (1938).

freezing point as 13.9°F. What is the concentration of calcium chloride in a refrigerating brine when the hydrometer reading is 1.248 at 17°C.?

TABLE XXVI.—FUNCTIONS OF TEMPERATURE

Temperature, °C.	c = 6 to 20		c = 20 to 34	
	a	b	a	b
10	0.9880	0.009723	0.9619	0.010880
12	0.9878	0.009690	0.9616	0.010851
14	0.9875	0.009659	0.9613	0.010826
16	0.9872	0.009632	0.9609	0.010804
18	0.9869	0.009604	0.9605	0.010783
20	0.9865	0.009578	0.9600	0.010765
22	0.9861	0.009554	0.9594	0.010750
24	0.9857	0.009529	0.9588	0.010736
26	0.9852	0.009506	0.9581	0.010724
28	0.9848	0.009484	0.9574	0.010716
30	0.9842	0.009465	0 9565	0.010706

TABLE XXVII.—AGREEMENT BETWEEN TABULAR AND CHART DATA

Hydrometer reading	Temperature, °C.	Percentage $CaCl_2$	
		Nomograph	$CaCl_2$ assoc.
1.071	10	8.15	8.0
1.127	10	14.05	14.0
1.177	10	19.1	19.0
1.231	10	24.15	24.0
1.286	10	29.1	29 0
1.331	10	33.1	33.0
1.068	21.1	8.15	8.0
1.123	21.1	14.35	14.0
1.173	21.1	19.2	19.0
1.226	21.1	24.15	24.0
1.280	21.1	29.1	29.0
1.325	21.1	33.12	33.0
1.066	26.7	8.15	8.0
1.122	26.7	14.4	14.0
1.171	26.7	19.2	19.0
1.223	26.7	24.1	24.0
1.278	26.7	29.2	29.0
1.322	26.7	33.2	33.0

Using Fig. 141, connect 17 on the temperature scale with 1.248 on the hydrometer reading scale and read the concentration of calcium chloride as 26.0 per cent. The freezing point of this brine is read just opposite as −25.8°F.

The line-coordinate charts yield concentrations in good agreement with tabular data from an undisclosed source, given by the Calcium Chloride Association,[1] as shown by Table XXVII.

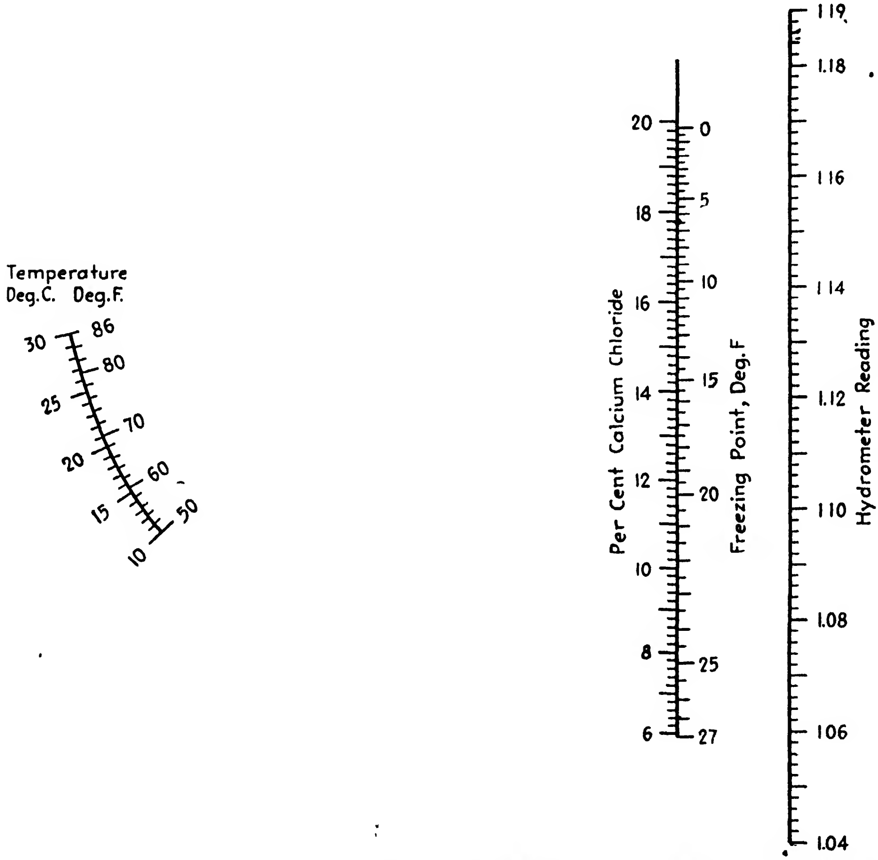

FIG. 140.—Hydrometer-reading–temperature relationships for aqueous solutions containing 6 to 20 per cent calcium chloride.

ETHYLENE GLYCOL NOMOGRAPH[2]

The many industrial applications of ethylene glycol, particularly its growing importance as a solvent and an antifreeze, have directed attention toward a rapid means of determining the glycol content in aqueous solutions. Analysis by hydrometry naturally suggests itself, and Lawrie,[3]

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[1] Calcium Chloride Assoc., *op. cit.*

[2] *Chemist-Analyst*, **24** (2), 8 (1935).

[3] LAWRIE, J. W., "Glycerol and Glycols," p. 377, Reinhold Publishing Corporation, New York, 1928.

presents a plot of specific gravity against percentage glycol, by volume, for temperatures in steps of 10°F.

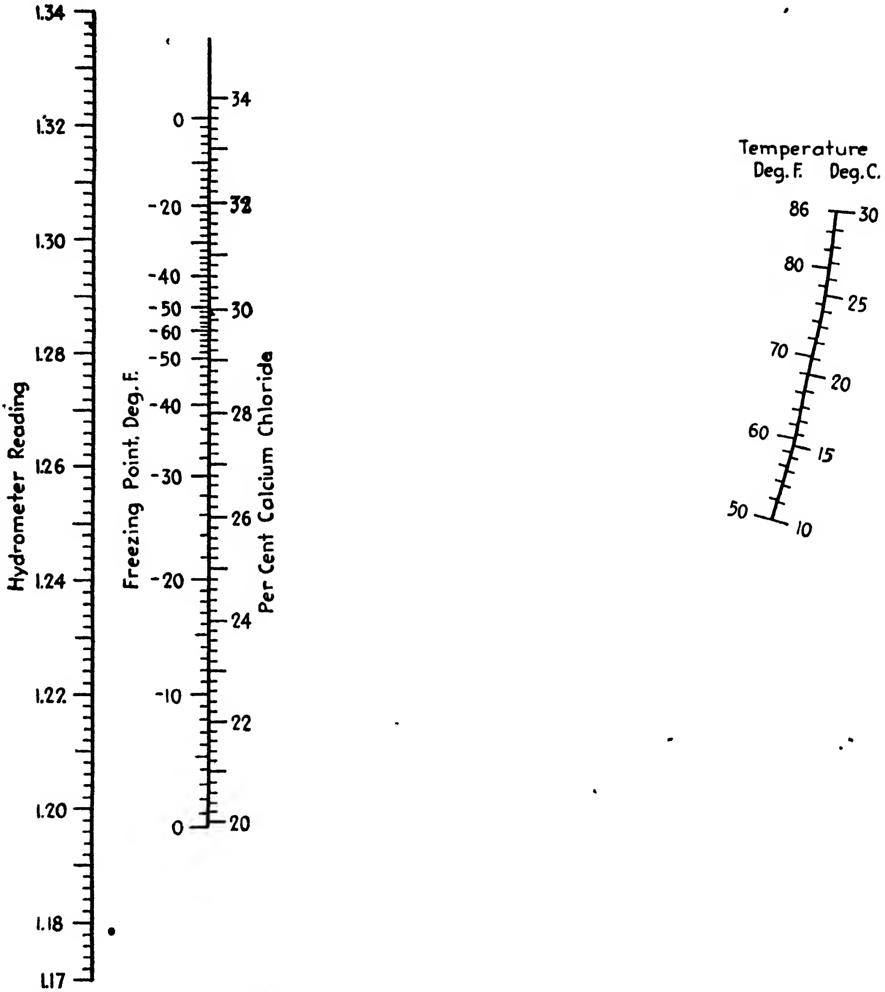

FIG. 141.—Hydrometer-reading–temperature relationships for aqueous solutions containing 20 to 34 per cent calcium chloride.

In connection with converting this plot into the more convenient nomographic form, the following expression relating the variables has been derived:

$$x = \frac{\delta + 4.70t^{2.06} \times 10^{-7} - 1.0015}{0.001516 - 3.40t \times 10^{-6}}$$

where x = percentage glycol by volume.
δ = specific gravity relative to water at 60°F.
t = temperature, °F.

The broken line on Fig. 142 indicates that an aqueous solution of ethylene glycol having a specific gravity of 1.060 at 70°F. contains 48 per cent glycol by volume.

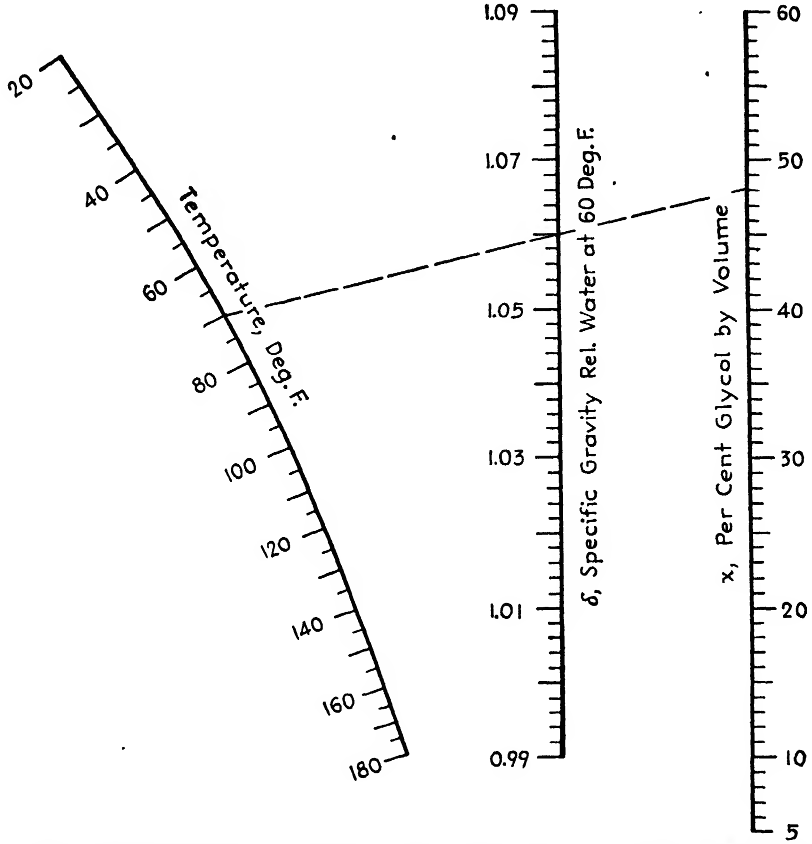

FIG. 142.—Specific-gravity–temperature relationships for aqueous solutions containing 5 to 60 per cent ethylene glycol by volume.

SPECIFIC-GRAVITY–TEMPERATURE RELATIONSHIPS FOR ROSIN SIZE MILK[1]

The determination of solids in rosin size milk has an important place in any program of technical control in the paper industry. It is usually effected by sampling the milk at the beaters or in a storage tank, evaporating a small quantity, and drying the residue at 105°C. Several hours necessarily elapse before a concentration value can be reported so that two or three beaters may be dropped with only an approximately correct charge of rosin.

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[1] BOGART, H. N., and D. S. DAVIS, *Paper Ind. & Paper World*, **22**, 251 (1940).

There is evident need for a rapid and reasonably accurate method for estimation of solids in rosin size milk. Hydrometric means immediately suggest themselves since, in a given mill, rosin is either cooked by a standard procedure or prepared rosin size is in use. It is the purpose of this topic to present (1) specific-gravity data for rosin size milks testing 0.6 to 5.1 per cent solids at temperatures between 10 and 35°C., and (2) a line-coördinate chart enabling convenient calculation of percentage solids when specific gravity and temperature are known.

Experimental Method.—A master milk containing 10 per cent solids was prepared by diluting heavy commercially available rosin size with water, after which six weaker milks were made from the master milk by further dilution. The solids content of each was determined in duplicate by evaporation and drying at 105°C., and a portion of each milk, in turn, was placed in a standardized pycnometer of about 30 ml. capacity, equipped with a combination ground-glass stopper and thermometer. The pycnometer and contents were cooled below 10°C., and allowed to warm slowly to 35°C. Weighings were made at 5-deg. intervals, and specific gravities relative to water at 4°C., were calculated.

TABLE XXVIII

Percentage of solids	Specific gravities (relative to water at 4°C.) at					
	10°C.	15°C.	20°C.	25°C.	30°C.	35°C.
0.617	1.0011	1.0003	0.9995	0.9984	0.9970	0.9952
1.360	1.0025	1.0017	1.0009	0.9998	0.9984	0.9968
2.501	1.0045	1.0038	1.0028	1.0017	1.0004	0.9988
2.869	1.0053	1.0044	1.0035	1.0023	1.0009	0.9993
3.250	1.0058	1.0050	1.0042	1.0030	1.0015	1.0000
4.110	1.0075	1.0066	1.0057	1.0045	1.0031	1.0016
5.073	1.0093	1.0085	1.0074	1.0062	1.0048	1.0032

The data are presented in Table XXVIII.

Correlation of Data.—For each milk, the linear relationship between specific gravity δ and percentage solids C can be written as

$$\delta = aC + b$$

where a and b vary with the centigrade temperature t. A smooth curve through the points enables values of b to be read for temperatures other than 10, 15, 20, 25, 30, and 35°C. In the case of a, values for 12.5, 17.5, 22.5, 28, and 32°C., were calculated by means of the Lagrange interpolation formula[1] enabling a reliable and reproducible curve to be drawn through the points.

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[1] *Chem. & Met. Eng.*, **45**, 383 (1938).

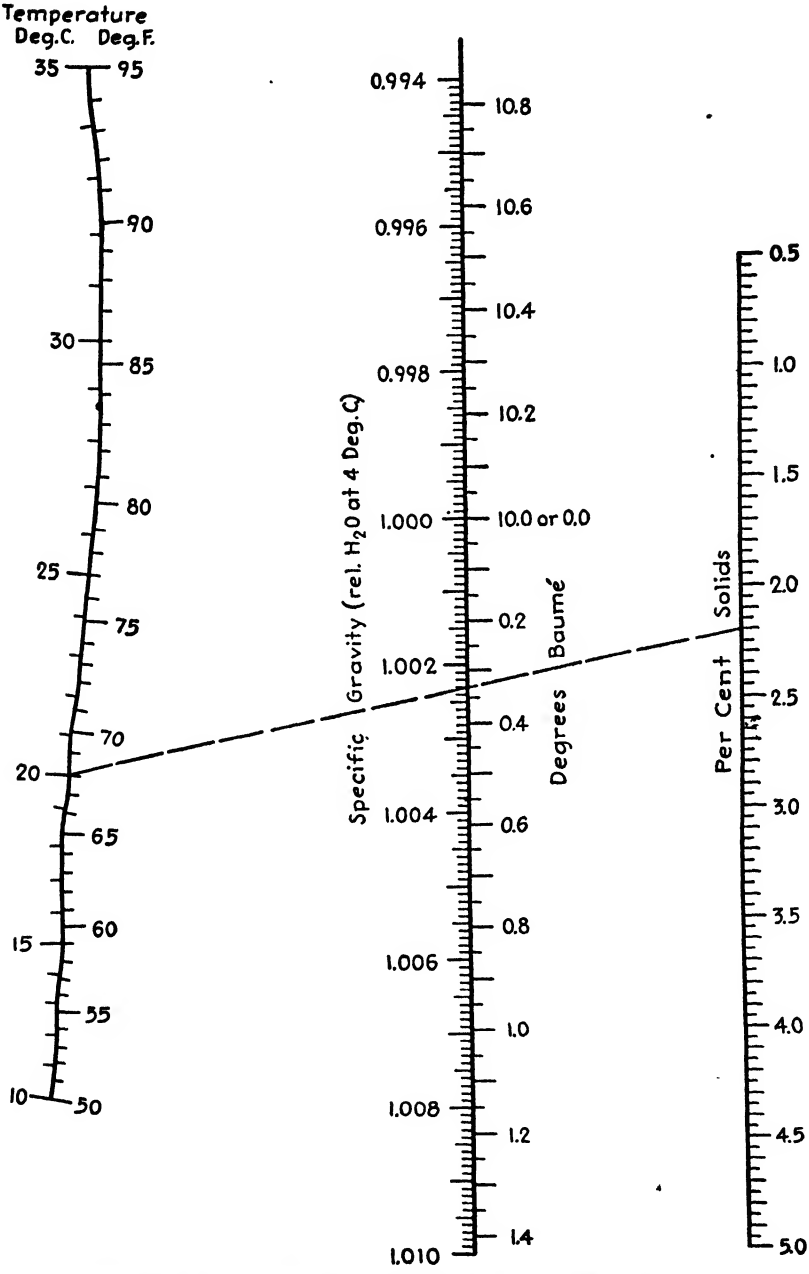

FIG. 143.—Specific-gravity–temperature relationships for milks containing 0.5 to 5.0 per cent rosin size.

Use of the Nomograph.—Figure 143, a line-coordinate chart based upon the above relationships, permits rapid and sufficiently accurate calculation of the percentage solids content when the specific gravity and temperature of the milk are determined. The broken line on the chart indicates that a rosin size milk at 20°C., showing a specific gravity of 1.0023 (relative to water at 4°C.), contains 2.20 per cent solids. For convenience, the temperature axis bears both Fahrenheit and centigrade scales, while the central axis carries a specific-gravity scale and a Baumé scale. In connection with the latter, the relationship for liquids heavier than water is $\delta = 145/(145 - \text{Bé.})$, while for liquids lighter than water it is $\delta = 140/(130 + \text{Bé.})$.

Table XXIX

t, °C.	δ	Percentage of solids		Percentage deviation	t, °C.	δ	Percentage of solids		Percentage deviation
		Chart	Known				Chart	Known	
10	1.0011	0.613	0.617	−0.6	10	1.0024	1.324	1.360	−2.6
20	0.9995	0.623	0.617	1.0	20	1.0008	1.361	1.360	0.1
30	0.9970	0.563	0.617	−8.8	30	0.9984	1.375	1.360	1.1
10	1.0045	2.477	2.501	−1.0	10	1.0053	2.920	2.869	1.8
20	1.0028	2.484	2.501	−0.7	20	1.0035	2.873	2.869	0.1
30	1.0004	2.542	2.501	1.6	30	1.0009	2.842	2.869	−0.9
10	1.0058	3.195	3.250	−1.7	10	1.0075	4.125	4.110	0.4
20	1.0042	3.270	3.250	0.6	20	1.0057	4.110	4.110	0.0
30	1.0015	3.188	3.250	−1.9	30	1.0031	4.120	4.110	0.2

Table XXIX shows the nature of the agreement between calculated and experimental values, indicating that the chart yields percentage solids values deviating, on the average, by about 1.4 per cent from the observed data.

In the case of a rosin size differing widely from that used in this investigation, the user of the nomograph may find it advisable to apply a correction factor. Such a factor can be determined by comparing several observed values with values read from the chart.

TOLUENE-CHLOROFORM NOMOGRAPH[1]

The wide difference between the specific gravities of toluene and chloroform, a matter of some 0.6, enables convenient analysis of mixtures of these commonly used solvents through the use of the Westphal balance, once specific gravity data of various mixtures over a practicable tem-

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[1] *Chemist-Analyst*, **23** (4), 7 (1934).

perature range are available. Such data are reported by Leslie and Geniesse,[1] and are the basis for the following equation:

$$\delta = 1.0025e^{-0.01004x} + (0.00001055x - 0.00179)t + 0.516$$

where δ = specific gravity of the mixture.
x = weight percentage of toluene.
t = temperature, °C.

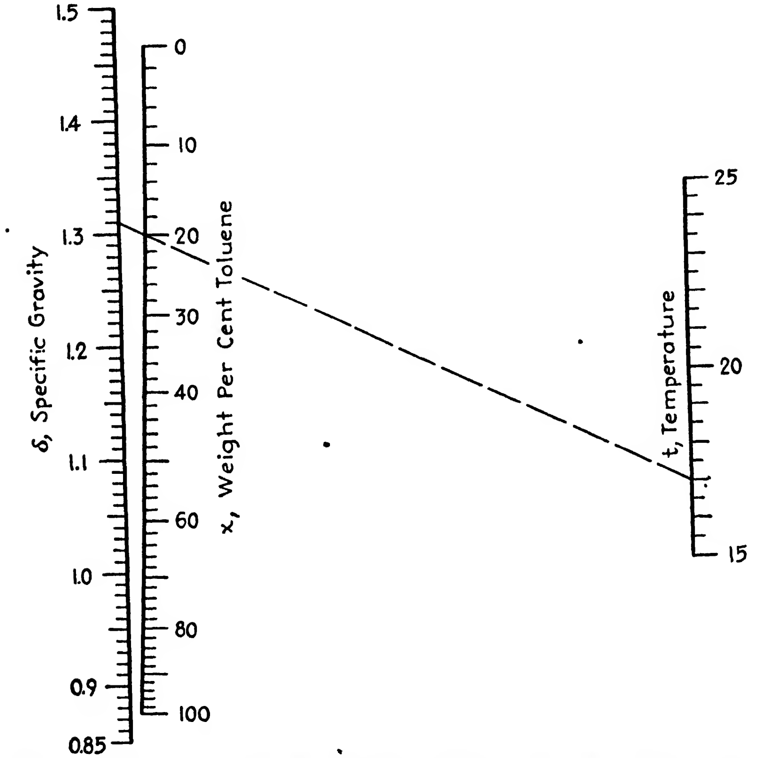

FIG. 144.—Specific-gravity–temperature relationships for the system toluene-chloroform.

Inasmuch as the equation is somewhat involved and does not yield x explicitly, Fig. 144 will be found helpful. The broken line on the chart indicates that a toluene-chloroform mixture having a specific gravity of 1.310 at 17°C. contains 20 per cent toluene.

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[1] LESLIE, E. H., and J. C. GENIESSE, *Ind. Eng. Chem.*, **18**, 590 (1926).

CHAPTER XVI

NOMOGRAPHS FOR CONTENTS OF HORIZONTAL TANKS

NOMOGRAPH FOR CONTENTS OF HORIZONTAL TANKS WITH BULGED ENDS[1]

Calculation of the contents of a partially filled horizontal tank is a bit troublesome, particularly when the tank has bulged ends, which is generally the case. Resort is usually made to a set of two tables, one of which covers the main or cylindrical portion and the other the spherical ends. Tables for the cylindrical portion are given by Perry,[2] while tables for both parts are given by Sullivan.[3] The tables leave something to be desired in the matter of ease of interpolation and in the fact that some of them cover only the bottom half of the tank, requiring additional calculations for tanks more than half filled.

Figure 145, which presents similar data in a more convenient form than do the tables, is based upon the following relationships:

$$V = 0.0408D^2f \qquad (35)$$

where, for the cylindrical portion,

V = contents, gal./ft. of length.
D = inner diameter, in.
f = depth factor.

and

$$v = 0.00866D^3g \qquad (36)$$

where, for the bulged ends which are portions of a sphere the radius of which is equal to the diameter of the tank, v = contents of both ends, gallons; g = depth factor. On the chart, the depth factors f and g are replaced, for convenience, by two scales of depth A and a, which express depth as a percentage of the diameter.

The broken lines illustrate the use of the chart. A cylindrical tank with bulged ends, resting upon its side, is 20 ft. in length, exclusive of the ends, has an inner diameter of 90 in., and is filled to a depth of 27 in. What is the liquid content? A depth of 27 in. represents 30 per cent of the diameter. Connect 30 on the A scale with 90 on the D scale,

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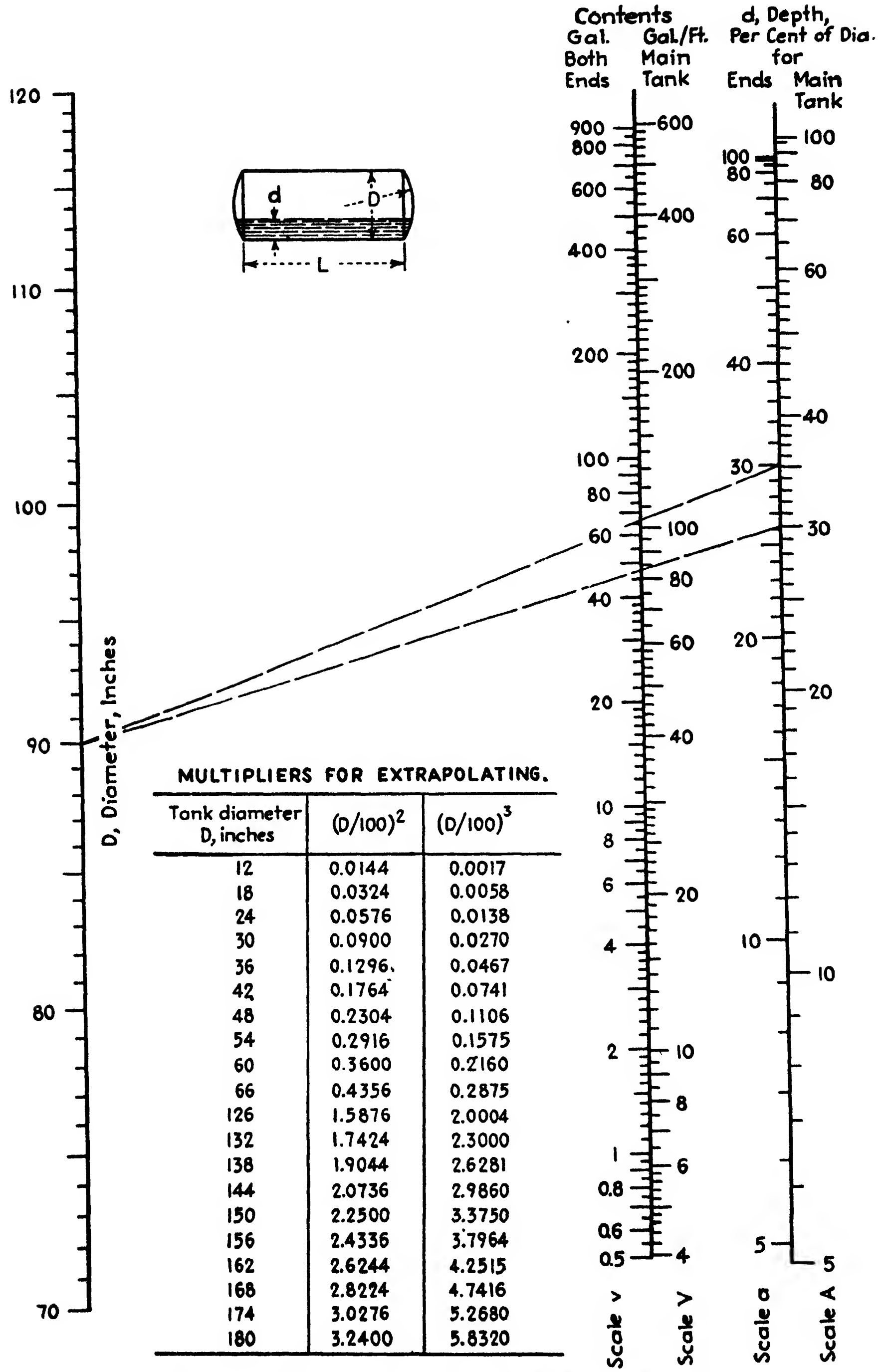
[1] *Chem. & Met. Eng.*, **41**, 602 (1934).

[2] PERRY, JOHN H., "Chemical Engineers' Handbook," 2d ed, pp. 120–122, McGraw-Hill Book Company, Inc., New York, 1941.

[3] SULLIVAN, T. J., "Sulphuric Acid Handbook," pp. 150–154, McGraw-Hill Book Company, Inc., New York, 1918.



MULTIPLIERS FOR EXTRAPOLATING.

Tank diameter D, inches	$(D/100)^2$	$(D/100)^3$
12	0.0144	0.0017
18	0.0324	0.0058
24	0.0576	0.0138
30	0.0900	0.0270
36	0.1296	0.0467
42	0.1764	0.0741
48	0.2304	0.1106
54	0.2916	0.1575
60	0.3600	0.2160
66	0.4356	0.2875
126	1.5876	2.0004
132	1.7424	2.3000
138	1.9044	2.6281
144	2.0736	2.9860
150	2.2500	3.3750
156	2.4336	3.7964
162	2.6244	4.2515
168	2.8224	4.7416
174	3.0276	5.2680
180	3.2400	5.8320

FIG. 145.—Contents of horizontal tanks with bulged ends.

and read the contents of the cylindrical portion on the *V* scale as 83.4 gal./ft. Multiplication by 20 gives 1,668 gal. Connect 30 on the *a* scale with 90 on the *D* scale, and read the sum of the contents of the two bulged ends (on the *v* scale) as 66 gal. The total liquid volume is, then, 1,668 + 66, or 1,734 gal.

The converse problem may be solved by a trial-and-error method as follows: It is desired to pump 900 gal. into a horizontal tank with bulged ends, the diameter of the tank being 80 in. and the length, 16 ft. What will the depth be? The quotient of 900 and 16 is 56.3 gal./ft. Because of the bulged ends, the actual value will be a little less than this, say, 54 gal./ft. Using the chart, connect 80 on the *D* scale with 54 on the *V* scale and read the percentage depth on the *A* scale as 26. Connect 26 on the *a* scale with 80 on the *D* scale, and read the contents of the bulged ends as 33 gal. The product of 54 and 16 or 864 gives the number of gallons in the main tank. This increased by 33 gives 897, which is sufficiently close to the true total, 900. The liquid depth is

$$0.26 \times 80 = 20.8 \text{ in.}$$

In the absence of tables, the chart may readily be used for larger or smaller tanks through a little simple slide-rule calculation. Per foot of length, the volumes of two cylinders are as the squares of their diameters, while the volumes of their bulged ends are as the cubes of their diameters. Therefore, a tank of, say, 48 in. diameter may be calibrated by determining the volumes at each percentage depth of a tank of, say, 100 in. diameter and multiplying each by $(\frac{48}{100})^2$ for the cylindrical portion and by $(\frac{48}{100})^3$ for the bulged ends. The results are the volumes for the 48-in. tank for the corresponding percentages of depth. The table with Fig. 145 gives the values of these multipliers for several tank diameters.

TANK-CONTENT CHART[1]

The chemist, whose work takes him into the plant as well as the laboratory, is frequently called upon to prepare gauges showing the contents, at various depths, of cylindrical tanks resting upon their sides in horizontal positions.

The volume in question is equal to the product of the length of the tank by the area of the "wetted" portion of an end. This area is easily recognized as that of a segment of a circle, and it is given by

$$\frac{R^2(\alpha - \sin \alpha)}{2}$$

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[1] *Chemist-Analyst*, **25**, 87 (1936).

where α, in radians, is equal to $2 \cos^{-1} (R - d)/R$ and where R is the radius of the circle and d is the depth of the segment as shown in Fig. 146.

The computation of contents corresponding to each inch or two of depth in the case of a tank 6 to 10 ft. in diameter would be most laborious. The work may be greatly simplified by reference to Fig. 146, which enables rapid conversion from percentage diameter to percentage volume. Its use may be illustrated as follows: A cylindrical tank 6 ft. 8 in. (80 in.) in diameter and 10 ft. long resting upon its side in a horizontal position contains chemical to a depth of 24 in. What is the volume occupied? The total volume of the tank is $[\pi(\frac{20}{3})^2 \times 10]/4$, or 349 cu. ft. The depth of chemical is $\frac{24}{80}$ or 30 per cent of the diameter. Opposite 30 per cent on the diameter scale, read 25 per cent on the volume scale. The desired volume of chemical is 25 per cent of 349 cu. ft., or 87.3 cu. ft.

The chemical is then to be diluted with water to a volume of 241 cu. ft. To what depth shall the water be added? Two hundred and forty-one cubic feet is $\frac{241}{349}$, or 69.0, per cent of the total capacity of the tank. Reference to the chart shows that 69.0 per cent of the volume corresponds to 65.0 per cent of the diameter, showing that the tank should be filled until the depth is 0.650 × 80, or 52.0 in.

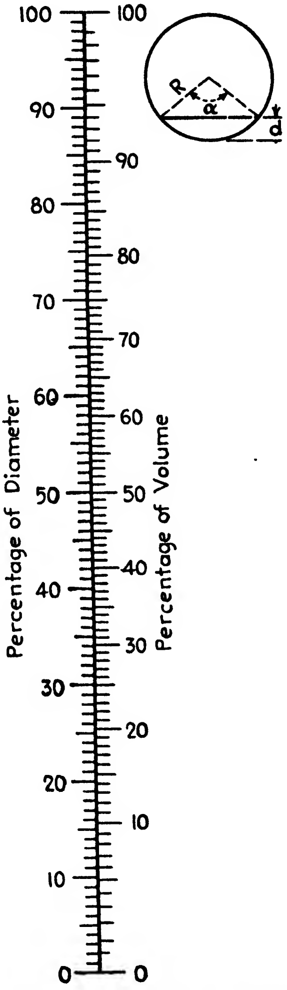

FIG. 146.—Percentage diameter vs. percentage volume for horizontal circular tanks.

TANK-CONTENT NOMOGRAPH[1]

Where vertical space is limited, it is frequently necessary to install long cylindrical tanks so that they rest upon their sides rather than upon their circular bases. While convenient mechanically, this practice makes the calculation of contents for any given depth somewhat difficult, since the volume per unit depth increases with increasing depth for the lower half of the tank and decreases for the upper half.

In the case of a tank with plane ends, the contents at any depth is given by the product of the entire volume of the tank and the ratio of the

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[1] *Ind. Eng. Chem.*, **32**, 1412 (1940).

areas of the wetted segment and an end

$$V = 0.00340D^2Lf$$

where V = contents, gal.
D = inner diameter, in.
L = inner length, in.
f = ratio of areas of the wetted segment and an end.

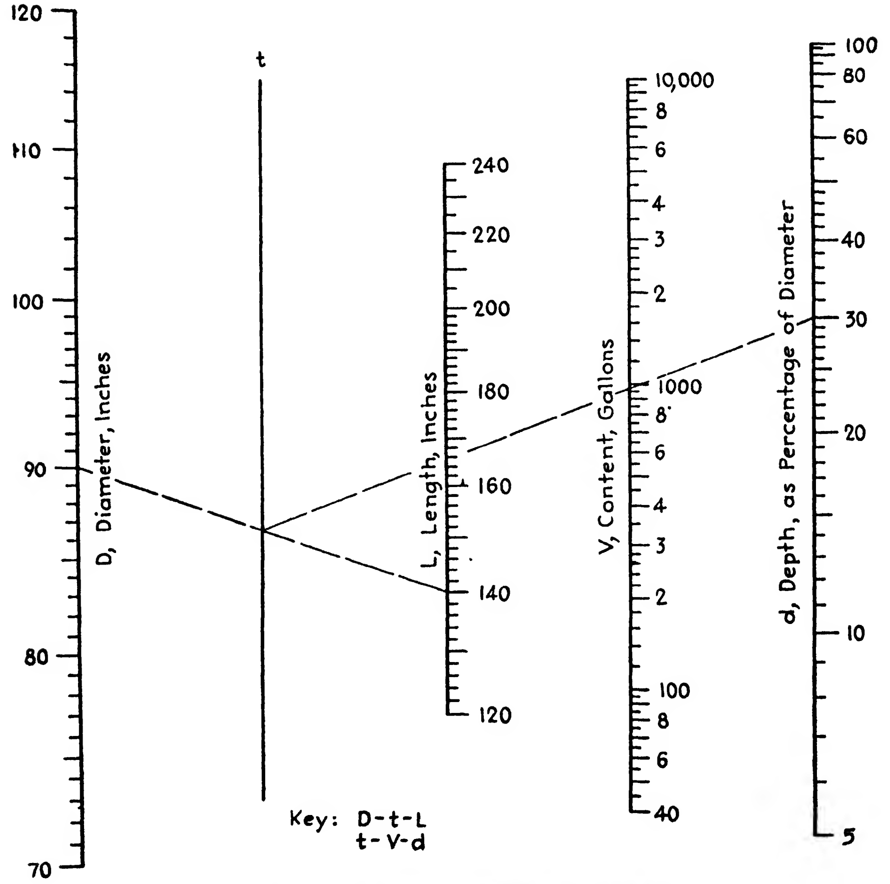

FIG. 147.—Contents of horizontal circular tanks.

The area of the segment is given by $R^2(\alpha - \sin \alpha)/2$ so that f becomes $R^2(\alpha - \sin \alpha)/2\pi R^2$, or $(\alpha - \sin \alpha)/2\pi$, where R is the radius of an end, $\alpha = 2 \cos^{-1} (R - h/R)$, and h is the depth.

Figure 147 performs this confusing computation readily and accurately. The d scale at the right is graduated in units of depth as a percentage of the diameter but is really a scale of f, the ratio of segment to circle. The use of the chart is illustrated as follows: What are the contents of a cylindrical tank resting upon its side when the inner diameter is 90 in., the inside length is 140 in., and the depth is 27 in.? Following the key, connect 90 on the D scale with 140 on the L scale, and mark the intersection with the t axis. Noting that the depth (27 in.) is 30 per cent of the diameter (90 in.), connect the intersection just found with 30 on the d scale, and read the desired value as 964 gal. on the V scale.

A nomograph[1] for calculating the contents of partially filled horizontal tanks with bulged ends was given previously (Fig. 145). A portion of this chart can be used for horizontal tanks with plane ends, but the contents are given per foot of length, requiring outside multiplication for practical use. Figure 147, for the range of lengths given, is more convenient.

[1] *Chem. & Met. Eng.*, **41**, 602 (1934).

CHAPTER XVII

LINE-COORDINATE CHARTS FOR VAPOR-PRESSURE—TEMPERATURE DATA

LINE-COORDINATE CHARTS FOR VAPOR-PRESSURE-TEMPERATURE DATA OF CHAIN AND RING COMPOUNDS[1]

Drawing of Line-coordinate Chart.—There has been a great desire on the part of chemists to find some rapid, accurate method of determining the boiling points of compounds at various atmospheric pressures, such as are encountered in laboratories at various altitudes, as well as to determine the temperatures at which these compounds would boil at various pressures artificially created. Tables are available giving values of the variation in temperature per centimeter variation in pressure for many substances, but, unless the laboratory is located near sea level, these tables are of no value. At the University of Colorado, the barometer averages about 62 cm., so that the above-mentioned tables are useless. It was with the idea of filling this need that the present plots were devised.

Using the integrated form of the Clausius-Clapeyron equation as the basis for the work, the reciprocals of the absolute temperatures were plotted against the logarithms of the pressures, over the range of 500 to 900 mm. mercury. Over this range, the resulting curves were straight lines. The more accurate the data, the more nearly all the points fell on the straight line. A critical review of all existing literature on vapor pressures of organic liquids and some solids resulted in the establishing of such straight lines for 183 organic compounds. In cases where various workers had reported vapor pressures on the same compound, the relative merits of the methods used were studied, and weighted curves were drawn. In all cases, individual variations among the results were greater than the possible error in assuming the lines to be straight. In other words, the straight lines drawn represent improvements over the original data, within the range considered.

These straight lines were then reduced to points on line-coordinate charts (9 × 24 in., or 22.9 × 61 cm.), each point being assigned a number corresponding to a given compound. For convenience, the compounds were separated into chain and ring compounds (Figs. 148 and 149), the only reason for this being to scatter the points over a larger

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[1] GERMANN, F. E. E., and O. S. KNIGHT, *Ind. Eng. Chem.*, **26**, 467 (1934).

TABLE XXX.—ALPHABETICAL INDEX TO BOILING-POINT CHARTS
(A, B, C, and D refer to groups of compounds on the charts; numbers refer to compounds within these groups)

Acenaphthene, D-26
Acetaldehyde, A-13
Acetic acid, A-72
Acetone, A-28
Acetophenone, C-46
n-Amyl alcohol, B-20
n-Amyl *n*-butyrate, B-44
n-Amyl formate, B-13
n-Amyl isobutyrate, B-42
n-Amyl *n*-propionate, B-36
Aniline, C-34
Anthracene, D-35
Anthraquinone, D-37

Benzaldehyde, C-29
Benzene, C-10
Benzoic acid, D-21
Benzonitrile, C-37
Benzophenone, D-32
Benzoyl chloride, C-41
Benzyl alcohol, C-51
Bromobenzene, C-22
α-Bromonaphthalene, D-27
m-Bromotoluene, C-33
o-Bromotoluene, C-30
p-Bromotoluene, C-31
o-Bromo-*p*-xylene, D-10
n-Butyl alcohol, A-73
tert-Butyl alcohol, A-47
sec-Butyl chloroacetate, B-40
n-Butyl formate, A-63
sec-Butyl formate, A-53
n-Butyric acid, B-38

Camphor, C-52
Carbazole, D-36
Carbon disulfide, A-25
Carbon tetrabromide, B-48
Carbon tetrachloride, A-39
m-Chloroaniline, D-15
o-Chloroaniline, C-53
Chlorobenzene, C-15
1,1-Chlorobromoethane, A-44
Chloroform, A-32
α-Chloronaphthalene, D-23
Chloropicrin, A-67
m-Chlorotoluene, C-24
o-Chlorotoluene, C-23
p-Chlorotoluene, C-25

m-Cresol, C-47
o-Cresol, C-38
p-Cresol, C-48
Cyclohexane, C-11
Cymene, C-28

n-Decane, B-35
Dibenzyl ketone, D-33
1,3-Dibromopropane, B-39
2,3-Dibromopropylene, B-26
1,2-Dichloroethane, A-45
Diethylaniline, C-55
Diethyl ether, A-17
Diïsobutyl, A-64
Diïsopropyl, A-31
Dimethylaniline, C-39
Dimethyl-*o*-toluidine, C-35
Dimethyl-*p*-toluidine, C-54
Diphenyl, D-22
Diphenylmethane, D-25
Dipropyl ether, A-50
Durene, C-40

Ethyl acetate, A-40
Ethyl alcohol, A-42
Ethyl aniline, C-50
Ethyl benzene, C-16
Ethyl bromide, A-22
Ethyl *n*-butyrate, B-11
Ethyl chloride, A-12
Ethylchloroacetate, B-28
Ethylene bromide, B-21
Ethylene glycol, B-50
Ethylene oxide, A-11
Ethyl formate, A-27
Ethylidene chloride, A-29
Ethyl iodide, A-37
Ethyl isobutyrate, A-65
Ethyl mercaptan, A-18
Ethyl propionate, A-56
Ethyl sulfide, A-51
Ethyl-*n*-valerate, B-23

Fluorene, D-31
Fluorobenzene, C-12
Formic acid, A-58

Glycol diacetate, B-49

n-Heptane, A-55
n-Heptylic acid, B-52

TABLE XXX.—ALPHABETICAL INDEX TO BOILING-POINT CHARTS.—(*Continued*)

Hexachloroethane, B-46
Hexamethyl benzene, D-24
n-Hexane, A-36
1-Hexene, A-33
Hydrogen cyanide, A-14

Iodobenzene, C-36
Isoamyl alcohol, B-19
Isoamyl formate, B-14
Isobutyl acetate, A-69
Isobutyl alcohol, A-66
Isobutyl benzene, C-26
Isobutyl-*n*-butyrate, B-34
Isobutyl formate, A-54
Isobutyl isobutyrate, B-30
Isobutyl-*n*-propionate, B-24
Isobutyl-*n*-valerate, B-41
Isobutyric acid, B-32
Isocaproic acid, B-51
Isodurene, C-42
Isopentane, A-15
Isopropyl acetate, A-49
Isopropyl alcohol, A-46
Isopropyl benzene, C-19
Isopropyl chloride, A-19
Isopropyl chloroacetate, B-31
Isopropyl formate, A-35
Isopropyl isobutyrate, B-10
Isovaleric acid, B-43

Mesitylene, C-20
Methyl acetate, A-30
Methyl alcohol, A-34
Methyl aniline, C-40
Methyl benzoate, C-43
Methyl butyrate, A-62
Methyl chloroacetate, B-17
Methylene chloride, A-24
Methyl ethyl ether, A-10
Methyl formate, A-16
Methyl isobutyrate, A-52
Methyl *n*-propionate, A-41
Methyl propyl ether, A-25
Methyl salicylate, D-14
Methyl sulfide, A-20
Methyl *n*-valerate, A-70

Naphthalene, C-56
α-Naphthol, D-29
β-Naphthol, D-30
Nitrobenzene, D-12
Nitromethane, A-59
m-Nitrotoluene, D-16
o-Nitrotoluene, D-13
p-Nitrotoluene, D-19
Nitro-*m*-xylene, D-20

n-Octane, B-16

Pentachloroethane, B-37
Pentamethylbenzene, D-17
n-Pentane, A-21
Phenanthrene, D-34
Phenol, C-32
Phthalic anhydride, D-28
Prehnitene, D-11
n-Propionic acid, B-25
n-Propyl acetate, A-60
n-Propyl alcohol, A-57
n-Propyl benzene, C-21
n-Propyl *n*-butyrate, B-27
n-Propyl chloride, A-26
n-Propyl formate, A-43
n-Propyl isobutyrate, B-22
n-Propyl *n*-propionate, B-12
n-Propyl *n*-valerate, B-33
Pseudocumene, C-27
Pyridine, C-14

Quinoline, D-18

1,1,1,2-Tetrachloroethane, B-18
sym-Tetrachloroethane, B-29
Tetrachloroethylene, A-71
Tetranitromethane, B-15
Toluene, C-13
m-Toluidine, C-49
o-Toluidine, C-44
p-Toluidine, C-45
1,1,1-Trichloroethane, A-38
1,1,2-Trichloroethane, A-68
Trichloroethylene, A-48

Urethane, B-45

n-Valeric acid, B-47

Water, A-61

m-Xylene, C-18
o-Xylene, C-18.3
p-Xylene, C-17

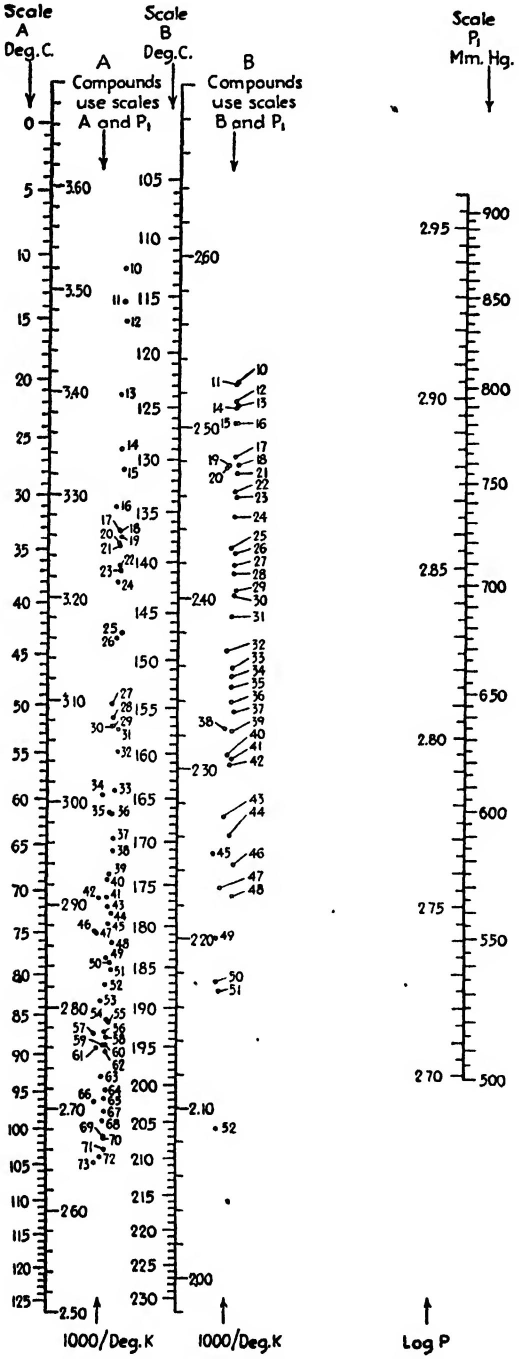

Fig. 148.—Vapor pressures of chain compounds.

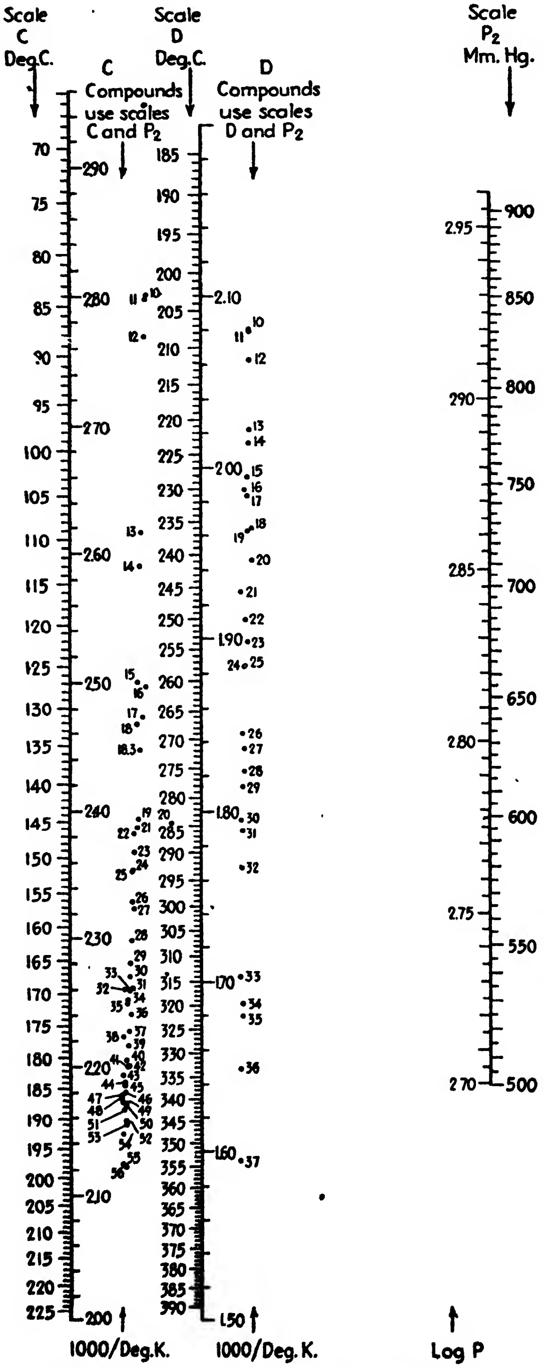

Fig. 149.—Vapor pressures of ring compounds.

area. In order to increase the accuracy of the temperature reading, the chain compounds were separated into compounds *A* with a temperature scale reading from 0 to 125°C. and compounds *B*, with a temperature scale from 105 to 230°C. Similarly, the ring compounds were separated into compounds *C* with a temperature scale from 65 to 225°C. and compounds *D* with a temperature scale from 185 to 390°C. With compounds *A*, scales *A* and P_1 are used; with compounds *B*, scales *B* and P_1; with compounds *C*, scales *C* and P_2; and with compounds *D*, scales *D* and P_2.

On the right-hand side of scales *A*, *B*, *C*, and *D* is the original uniform scale of one-thousand times the reciprocal of the absolute temperature, while on the left of scales P_1 and P_2 is the uniform scale of the common logarithm of the pressure in millimeters. These fundamental scales are then made direct reading in the *A*, *B*, *C*, *D*, P_1, and P_2 scales. Having thus established nonuniform temperature and pressure scales, the uniform scales are no longer necessary.

If, for example, we wish to know the boiling point of water when the barometer reads 620 mm., we note from Table XXX that water is listed as A-61. Therefore, place a straightedge at 620 mm. on P_1 scale (Fig. 148), and pass it through the center of circle 61 under compounds A. On scale *A* we read 94.4°C., which is the value given by the "International Critical Tables" for a pressure of 620.01 mm. mercury. It is safe to state that within the pressure range of 500 to 900 mm. the chart will give boiling points within 0.25°C. and pressures within 2 mm. This accuracy is sufficient for most work in the organic laboratory where temperatures of boiling are used as criteria for the purity of compounds. Where vapor pressures are more accurately known, as in the case of water, more accurate readings are easily possible. In other words, the charts have about the same degree of accuracy as the best vapor-pressure data for the compound in question.

VAPOR-PRESSURE NOMOGRAPH FOR *n*-ALKYL PRIMARY AMINES[1]

Ralston, Selby, Pool, and Potts[2] reported the boiling points of saturated *n*-alkyl primary amines containing 6 to 18 carbon atoms at 11 pressures ranging from 1 to 760 mm. mercury. Figure 150, based on these data, enables estimation of the boiling temperatures at any intermediate pressure and depends on the relation

$$\log p = A - \frac{B}{t + 200 - \alpha}$$

where p is the vapor pressure, millimeters mercury; t is the temperature, degrees centigrade; and α depends upon the temperature, as follows:

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[1] *Ind. Eng. Chem.*, **34**, 1414 (1942).

[2] RALSTON, A. W., W. M. SELBY, W. O. POOL, and R. H. POTTS, *Ind. Eng. Chem.*, **32**, 1093 (1940).

t	200	240	280	300	310
α	0.10	0.54	3.00	6.80	7.90
t	320	330	340	350	
α	8.60	9.12	9.57	10.00	

The values of A and B for various numbers of carbon atoms are given in Table XXXI.

TABLE XXXI

No. C atoms	A	B	No. C atoms	A	B
6	6.878	1331	13	7.716	2287
7	6.981	1462	14	7.833	2416
8	7.099	1602	15	7.929	2535
9	7.162	1726	16	8.024	2658
10	7.373	1887	17	8.220	2814
11	7.365	1976	18	8.341	2944
12	7.477	2105			

The dashed line illustrates the use of the chart (Fig. 150) and shows that the boiling point of the member of the series containing 13 carbon atoms is 168°C. at a pressure of 32 mm. The points marked + on the nomograph should be used rather than the circles for members containing 14, 15, and 16 carbon atoms where the pressures are above 500 mm. Boiling points read from the chart agree with the reported values within 2°C.

LINE-COORDINATE CHART FOR VAPOR PRESSURES OF GLYCOLS[1]

The use of Fig. 151 is illustrated as follows: What is the vapor pressure of ethylene glycol at 100°C.? Connect 100 on the temperature scale with the ethylene glycol point and read the vapor pressure as 14 mm. mercury. What is the boiling point of propylene glycol at atmospheric pressure? Connect 760 mm. on the vapor-pressure scale with the propylene glycol point and read the boiling point as 188°C.

VAPOR-PRESSURE NOMOGRAPH FOR UNSATURATED HYDROCARBONS[2]

In tabular form, Lamb and Roper[3] presented vapor-pressure data for ethene, propene, 2-methylpropene, 1-butene, *trans*-2-butene, *cis*-2-butene, 1,4-pentadiene, and 2-methyl-2-butene, reporting the temperatures in degrees Kelvin. As suggested by the integrated Clausius

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[1] Based on data from "Glycols," p. 10, Carbide and Carbon Chemicals Corporation, 1941.

[2] *Ind. Eng. Chem.*, **33**, 553 (1941).

[3] LAMB, A. B., and E. E. ROPER, *J. Am. Chem. Soc.*, **62**, 806 (1940).

equation, the logarithm of the vapor pressure is (nearly) a linear function of the reciprocal of the absolute temperature according to the expression

$$\log p = A - \frac{B}{T}$$

where A, B = constants specific to the compound.

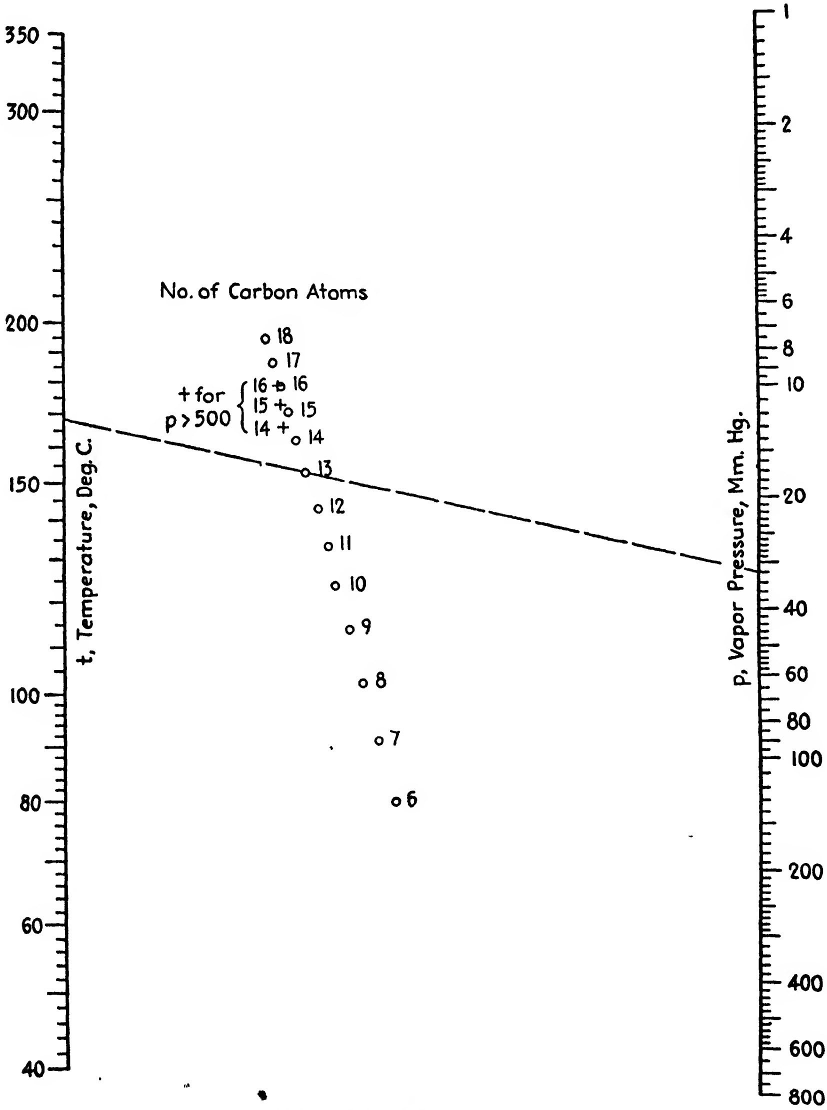

FIG. 150.—Vapor pressures of *n*-alkyl primary amines.

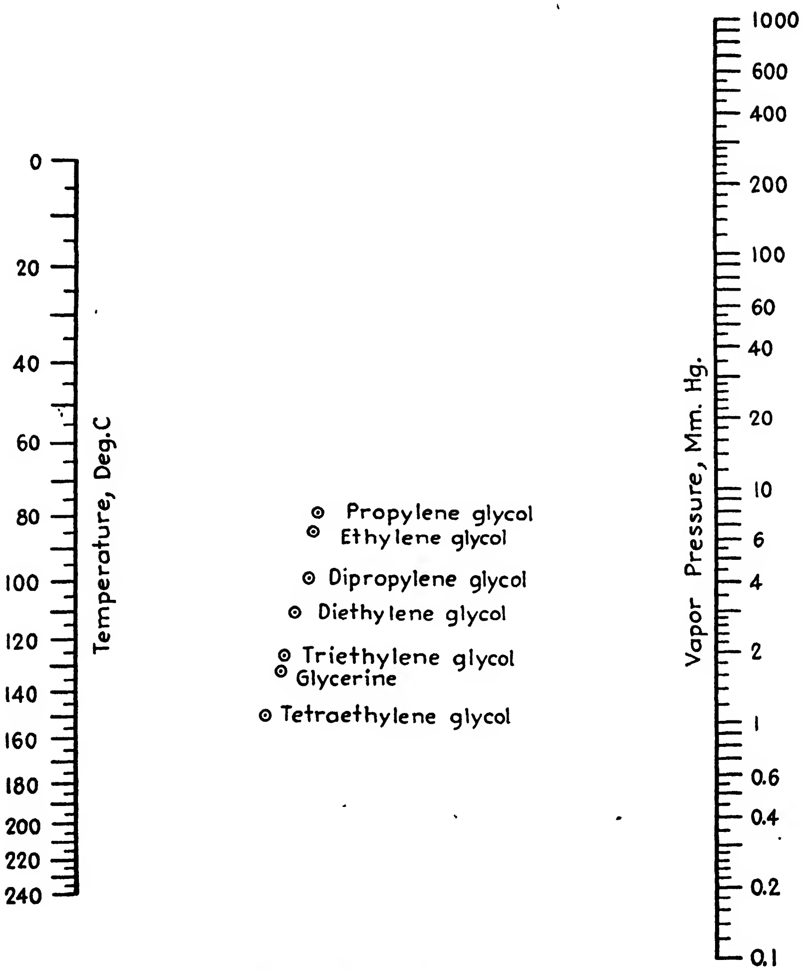

FIG. 151.—Vapor pressures of the common glycols.

TABLE XXXII

Unsaturated hydrocarbon	*A*	*B*
Ethene	7.245	739.1
Propene	7.417	1,023.6
2-Methylpropene	7.341	1,186.8
1-Butene	7.467	1,224.0
trans-2-Butene	7.478	1,260.0
cis-2-Butene	7.649	1,317.9
1,4-Pentadiene	7.752	1,453.0
2-Methyl-2-butene	7.794	1,524.0

This relation enables construction of Fig. 152 which permits convenient interpolation of the original data, thus extending their utility. The index line on the chart shows that the vapor pressure of propene at −60°C. is 410 mm. mercury.

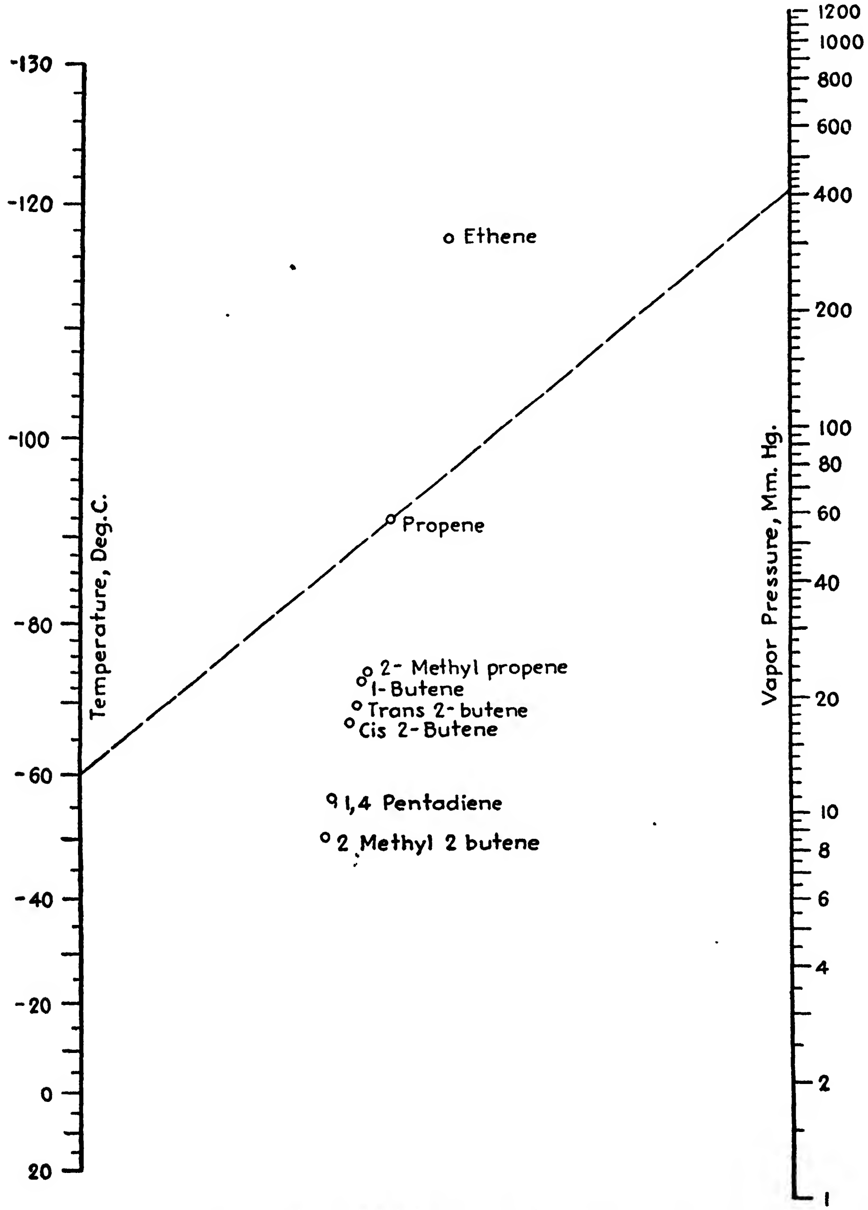

FIG. 152.—Vapor pressures of unsaturated hydrocarbons.

Vapor pressures read from the nomograph agree with the Lamb and Roper data within 2 per cent. Table XXXII lists the specific constants which enable a larger chart to be constructed.

VAPOR PRESSURES FOR SIX ALIPHATIC NITRO COMPOUNDS[1]

Little information is available on the vapor pressures of the aliphatic nitro compounds.[2] Since they show promise of commercial importance, it was believed that such information would be of general interest. Data are given for nitromethane, nitroethane, 1- and 2-nitropropane, and 1- and 2-nitrobutane.

Using semilogarithmic paper, pressures, in millimeters of mercury, were plotted on the logarithmic scale against reciprocals of the absolute temperatures on the linear scale. Smooth curves were drawn through the points, and three points were taken on each curve to evaluate the constants in the equation

$$\log P = A - \frac{B}{T} - C \log T$$

Table XXXIII gives the constants found.

TABLE XXXIII

Compound	A	B	log B	C	log C
Nitromethane	18.0571	2423.7	3.38447	3.3821	0.52918
Nitroethane	32.803	3249.5	3.51181	8.3188	0.92006
2-Nitropropane	29.752	3106.7	3.49230	7.3128	0.86409
1-Nitropropane	28.879	3168.8	3.50089	6.9695	0.84320
2-Nitrobutane	25.591	3048.1	3.48403	5.8579	0.76774
1-Nitrobutane	34.701	3679.3	3.56576	8.817	0.94532

The accuracy to be expected from the equations may be judged by the vapor pressures calculated at the boiling points:

TABLE XXXIV

Compound	Boiling point (760 mm.), °C.	Calculated vapor pressure, mm. Hg
Nitromethane	101.2	758
Nitroethane	114.0	760
2-Nitropropane	120.3	759
1-Nitropropane	131.6	757
2-Nitrobutane	139.6	762
1-Nitrobutane	152.9	759

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[1] HODGE, E. B., *Ind. Eng. Chem.*, **32**, 748 (1940).

[2] THOMPSON, H. W., and C. H. PURKIS, *Trans. Faraday Soc.*, **32**, 674–680 (1936); WILLIAMS, J. W., *J. Am. Chem. Soc.*, **47**, 2644 (1925).

In Fig. 153, values accurate enough for many purposes can be read. This was constructed according to the method of Killeffer,[1] except that the temperature scale was averaged from scales of nitromethane and 2-nitrobutane, which were found to differ somewhat.

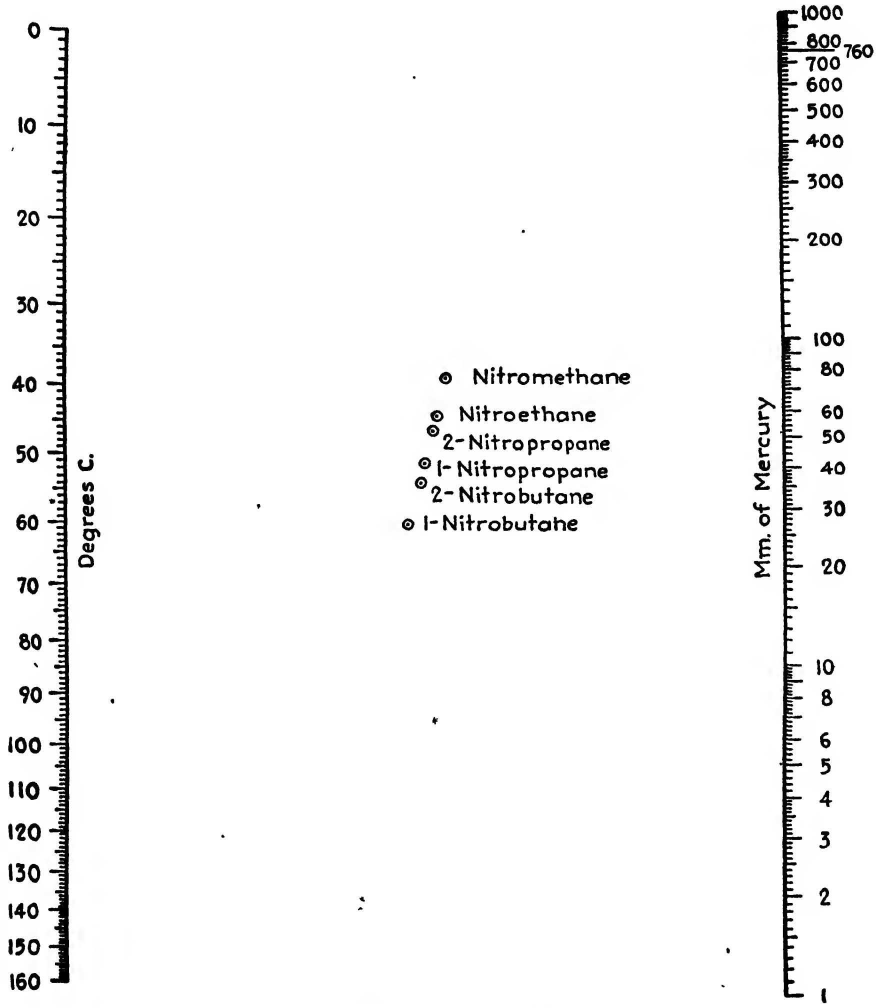

FIG. 153.—Vapor pressures of six aliphatic nitro compounds.

Over most of the range, pressures for a given temperature can be read within about 2 per cent of the value calculated from the corresponding equation.

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[1] KILLEFFER, D. H., *Ind. Eng. Chem.*, **30**, 477 (1938).

VAPOR-PRESSURE NOMOGRAPH FOR ISOMERIC OCTANOLS[1]

Recent vapor-pressure data[2] covering 22 isomeric octanols appeared as a table of boiling points for pressures of 20, 100, 300, and 760 mm. mercury, supplemented by pressure-temperature curves for 12 of the series. Figure 154 enables convenient estimation of boiling points at other pressures or vapor pressures at any temperature in the range of the data. It is based upon the expression

$$\log p = A - \frac{B}{t + \alpha}$$

where p is the vapor pressure, millimeters mercury; t is the temperature, degrees centigrade; and A, B, and α have values, depending upon the compound, as given in Table XXXV.

TABLE XXXV

Key No.	A	B	α	Key No.	A	B	α
41	8.040	2340	*	61	6.599	1144	120
42	6.586	1155	140	62	7.726	1802	200
43	8.190	2258	270	63	6.417	1126	160
44	6.638	1130	140	64	6.990	1341	160
51	6.383	1074	120	65	6.961	1335	160
52	7.393	1678	200	66	7.885	1782	200
53	7.078	1483	200	67	6.385	1105	140
54	7.214	1580	200	71	6.596	1170	120
55	7.032	1326	160	72	6.434	1066	120
56	7.197	1580	200	73	6.089	940	120
57	7.500	1782	200	74	6.229	992	120

* $\alpha = 270 - 10^{5.034 - 0.00047t}$.

With respect to the key numbers which appear on the chart and in Table XXXV the original investigators stated, "The first digit locates the methyl group and the second the hydroxyl group: thus 72 is 7-methyl-2-heptanol, *i. e.*, 2-octanol, and 53 is 5-methyl-3-heptanol. Sometimes the key numbers depart, for convenience, from official nomenclature."

The temperature scales on the chart bear symbols or numbers that must correspond with those of the gauge points for the various compounds. The circled points, for instance, are employed with the temperature scale headed by a circle.

The use of Fig. 154 is illustrated as follows: What is the vapor pressure of 5-methyl-3-heptanol at 85°C.? The key number for this compound

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[1] *Ind. Eng. Chem.*, **35**, 232 (1943).

[2] DOROUGH, G. L., H. B. GLASS, T. L. GRESHAM, G. B. MALONE, and E. E. REID, *J. Am. Chem. Soc.*, **63**, 3100 (1941).

is 53 which appears as a circled point on the chart. Connect this point with 85 on the *t* scale topped by a circle, and produce the line to the *p* scale where the vapor pressure is read as 75 mm. mercury. Vapor pressures read from the chart deviate from the original data by an average of about 0.8 per cent.

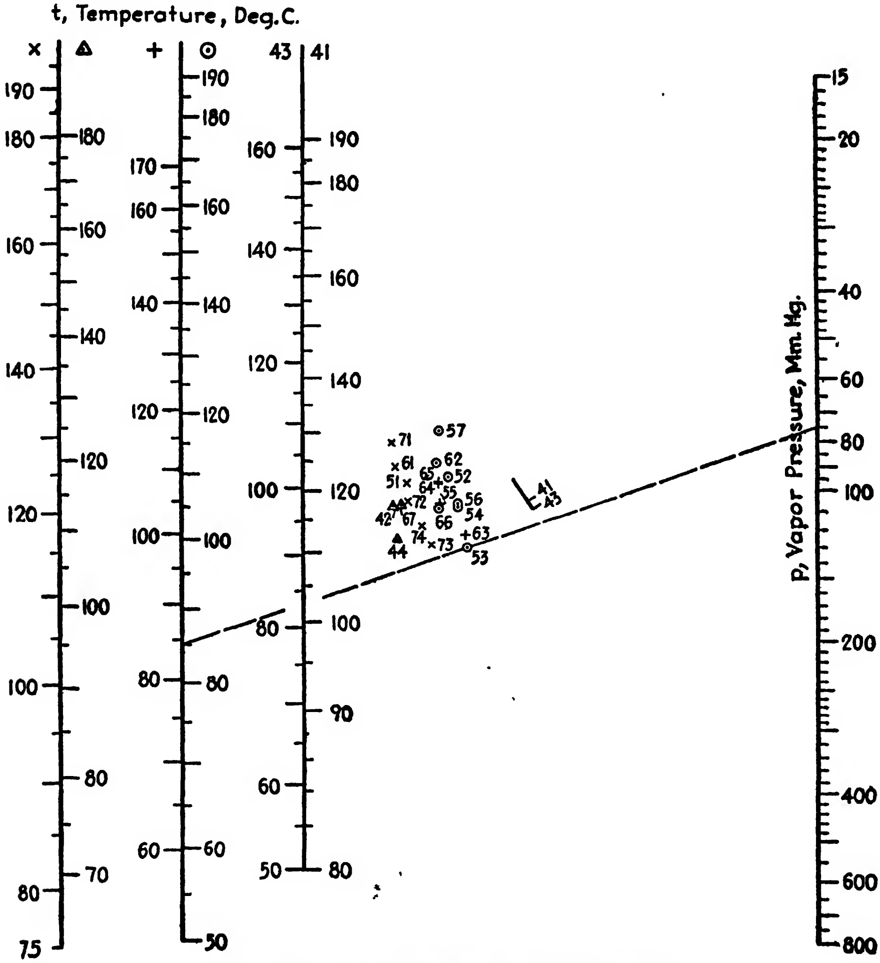

Fig. 154.—Vapor pressures of isomeric octanols.

LINE-COORDINATE CHART FOR VAPOR PRESSURES OF SATURATED AQUEOUS SOLUTIONS[1]

For saturated aqueous solutions of potassium and sodium sulfates and of potassium, sodium, and cesium chloride, Foote, Saxton, and Dixon[2]

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[1] *Ind. Eng. Chem.*, **33**, 1278 (1941).

[2] Foote, H. W., B. Saxton, and J. K. Dixon, *J. Am. Chem. Soc.*, **54**, 563 (1932).

presented equations connecting the vapor pressure p in millimeters of mercury, with the temperature T in degrees Kelvin. The equations for the sodium and potassium chloride solutions are, respectively,

$$\log p = -\frac{2890.7}{T} - 4.715 \log T + 22.612 \qquad (37)$$

$$\log p = -\frac{2995.5}{T} - 6.680 \log T + 0.001024T + 27.569. \qquad (38)$$

The equations for the other solutions are of the form

$$\log p = A - \frac{B}{T}. \qquad (39)$$

Figure 155 facilitates calculation of vapor pressures, once equations of the form of Eq. (39) are determined for solutions of sodium and potassium chlorides. Values of A and B are given in Table XXXVI.

TABLE XXXVI

Saturated solution	A	B
K_2SO_4	9.1881	2332.5
KCl	8.8750	2258.0
NaCl	8.9850	2306.0
CsCl	8.5621	2198.5
Na_2SO_4	10.3630	2696.6

The index line on the chart shows that the vapor pressure of a saturated aqueous solution of sodium sulfate is 10 mm. mercury at 15°C.

LINE-COORDINATE CHART FOR VAPOR PRESSURES OF 11 ORGANIC SOLVENTS[1]

Gardner and Brewer[2] presented valuable data on the vapor pressures of 11 commercial high-boiling organic solvents. The samples represented technical products in actual use and were not specially purified. Their values are in agreement with fragmentary data which exist in the literature, and it appears worth while to present the new data in a compact and readily usable line-coordinate chart.

As required by the integrated Clausius-Clapeyron equation, the data can be plotted as straight lines on paper ruled log P *vs.* $1/T$ so that the equation for each set is of the form

$$\log P = A - \frac{B}{T},$$

suggesting the diagram shown in Fig. 156.

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[1] *Ind. Eng. Chem.*, **30**, 320 (1938).

[2] GARDNER, G. S., and J. E. BREWER, *Ind. Eng. Chem.*, **29**, 179 (1937).

Values of constants *A* and *B* were determined by the method of averages, discarding occasional pairs of values which appeared to be in error. The constants are listed in Table XXXVII.

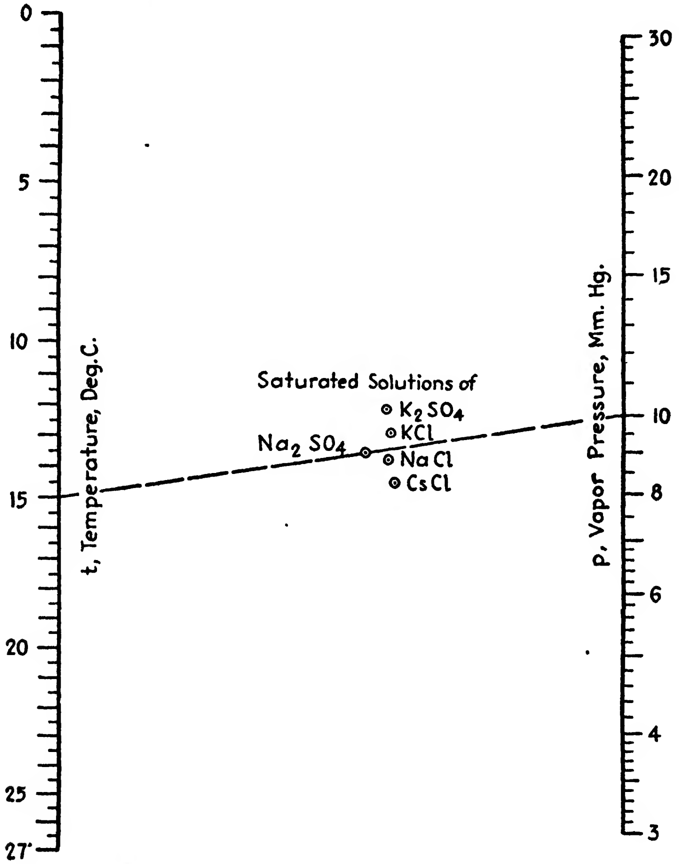
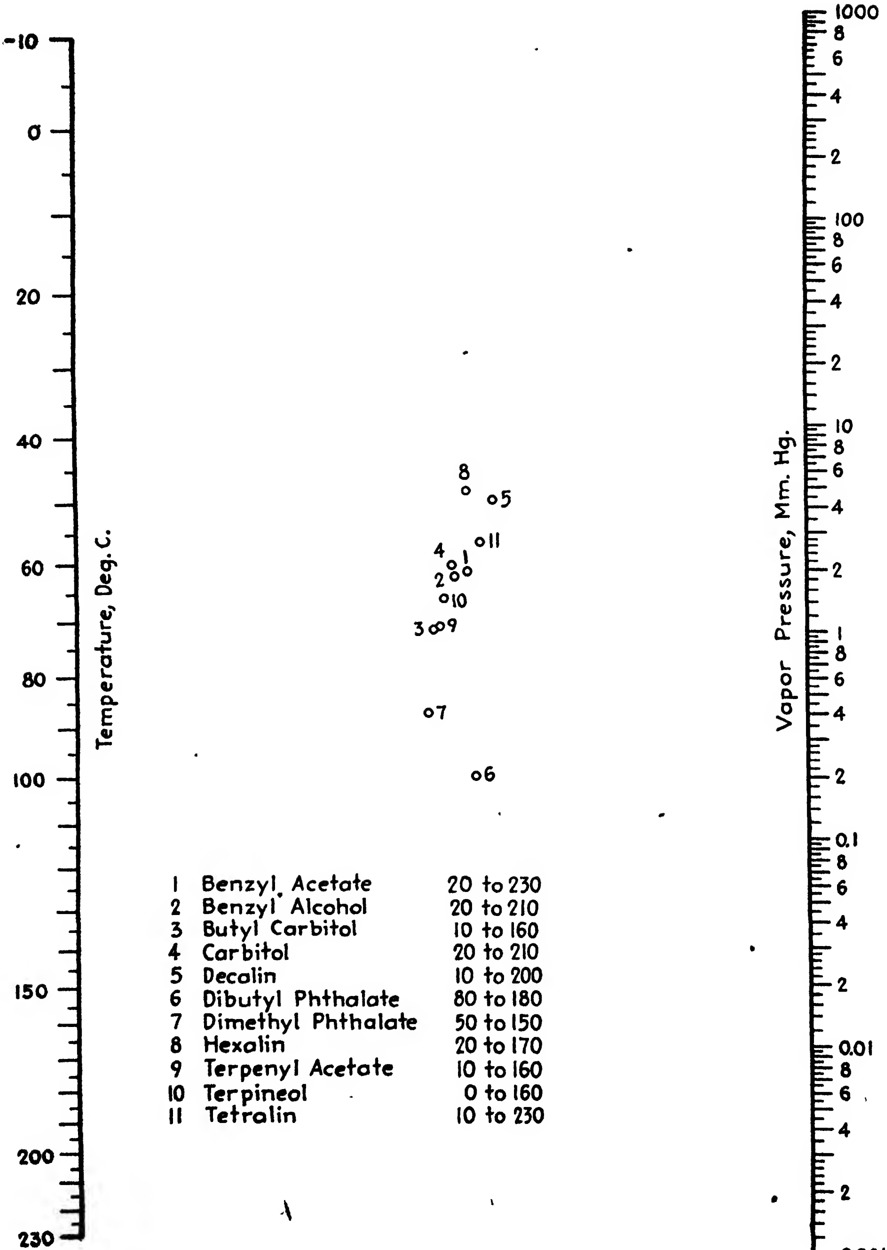


Fig. 155.—Vapor pressures of saturated aqueous solutions.

Table XXXVII

Organic solvent	*A*	*B*	Organic solvent	*A*	*B*
Benzyl acetate	8.587	2,770	Dibutyl phthalate	6.455	2,662
Benzyl alcohol	9.133	2,965	Dimethyl phthalate	9.209	3,452
Butyl carbitol	9.684	3,328	Hexalin	9.337	2,779
Carbitol	9.336	3,001	Terpenyl acetate	9.408	3,224
Decalin	8.049	2,389	Terpineol	9.432	3,137
			Tetralin	8.235	2,567

Figure 156 was prepared from these constants, and its use is illustrated as follows: What is the vapor pressure of benzyl acetate at 90°C.? Con-



1	Benzyl Acetate	20 to 230
2	Benzyl Alcohol	20 to 210
3	Butyl Carbitol	10 to 160
4	Carbitol	20 to 210
5	Decalin	10 to 200
6	Dibutyl Phthalate	80 to 180
7	Dimethyl Phthalate	50 to 150
8	Hexalin	20 to 170
9	Terpenyl Acetate	10 to 160
10	Terpineol	0 to 160
11	Tetralin	10 to 230

FIG. 156.—Vapor pressure of 11 organic solvents.

nect 90 on the temperature scale with point 1, and note the intersection with the pressure scale at 9.2 mm., the desired value. Similarly, what is the boiling point of hexalin? Connect 760 on the pressure scale with hexalin point 8, and note the intersection with the temperature scale at 157°C.

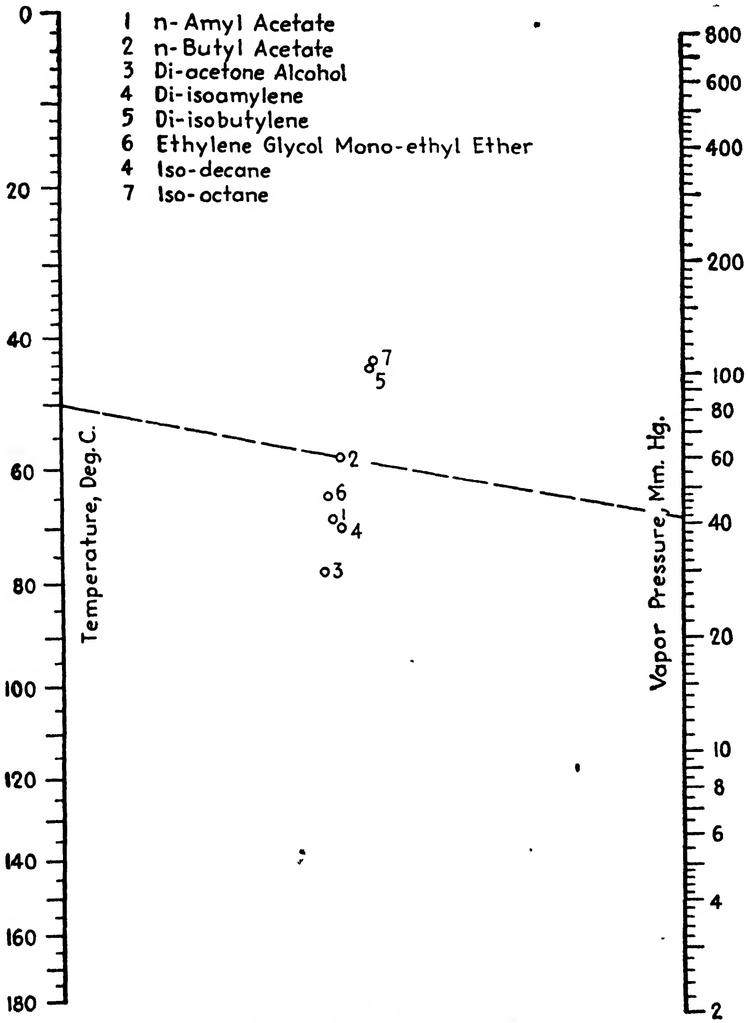


Fig. 157.—Vapor pressures of eight organic solvents.

The legend at the bottom of Fig. 156 lists the solvents, their identification numbers, and the limits of the temperature ranges.

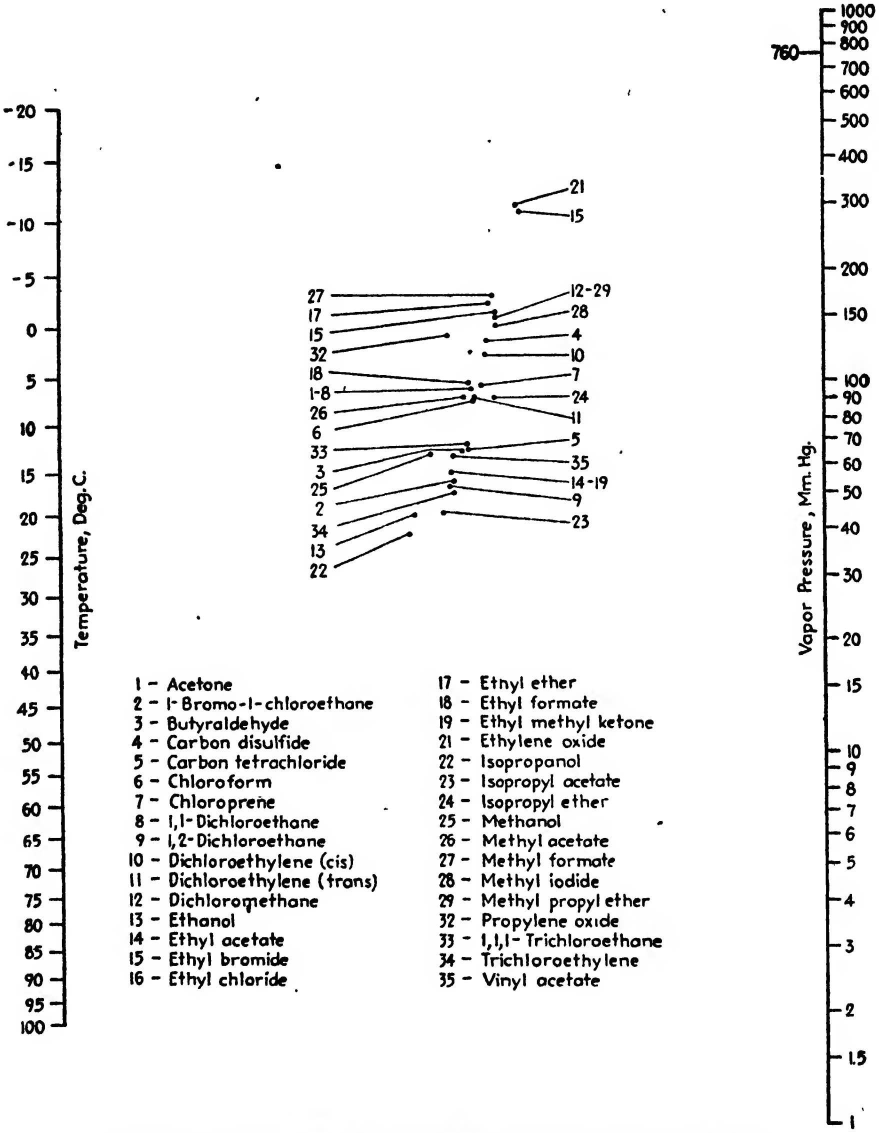


FIG. 158.—Vapor pressures of 32 organic solvents boiling below 90°C.

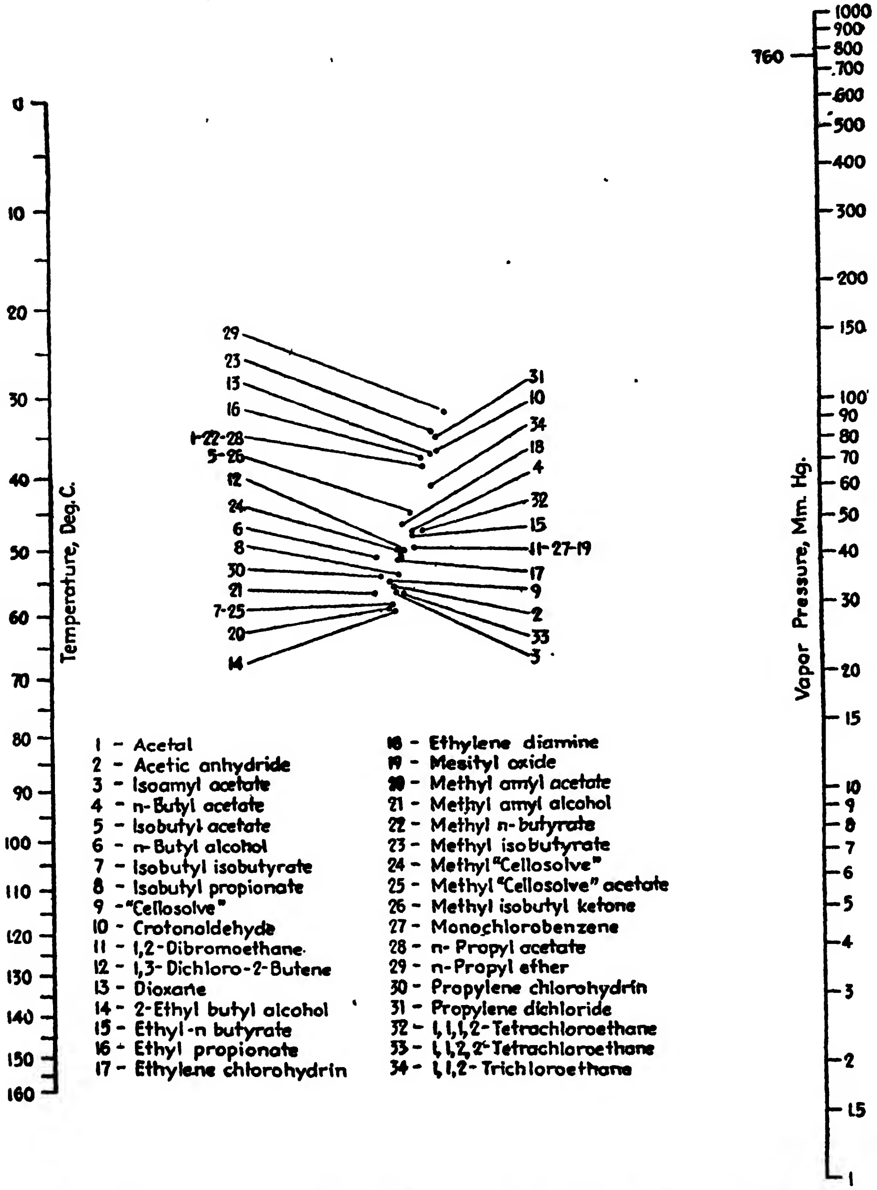


FIG. 159.—Vapor pressures of 34 organic solvents boiling between 90 and 150°C.

LINE-COORDINATE CHART FOR VAPOR PRESSURES OF EIGHT ORGANIC SOLVENTS[1]

In connection with his study of evaporative index, Gardner[2] presented vapor-pressure–temperature data for eight organic solvents. From the actual coordinates of the plotted points given in a private communication, it is possible to show that the relationship between p, the vapor pressure in millimeters of mercury, and t, the centigrade temperature, is given by

$$\log p = A - \frac{B}{t + 253}$$

where A and B are constants specific to the compound.

The linearity of $\log p$ and $1/(t + 253)$ enables construction of Fig. 157; which presents the data in a compact and convenient form. The broken line indicates that the vapor pressure of *n*-butyl acetate is 41 mm. at 50°C.

The nature of the agreement between values read from the chart and the actual data is shown in Table XXXVIII, which includes values of A and B for each material.

TABLE XXXVIII

Compound	Temperature, °C.	Pressure, mm. Hg		A	B
		Data	Chart		
n-Amyl acetate	56.9 106.6	23.9 204	24.0 200	8.078	2,077
n-Butyl acetate	49.2 93.5	43.2 274	39.7 270	8.099	1,964
Diacetone alcohol	66.5 139.3	17.8 324	17.6 324	8.091	2,188
Diisoamylene	58.0 110.7	21.6 188	23.0 188	7.641	1,953
Diisobutylene	35.8 72.0	72.3 303	72.0 304	7.474	1,623
Ethylene glycol monoethyl ether	49.9 94.0	23.2 180	23.0 180	8.416	2,139
Isodecane	59.8 120.3	24.5 254	25.0 258	7.620	1,948
Isooctane	31.0 63.5	65.1 243	64.0 240	7.413	1,592

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[1] *Ind. Eng. Chem.*, **33**, 401 (1941).

[2] GARDNER, G. S., *Ind. Eng. Chem.*, **32**, 226 (1940).

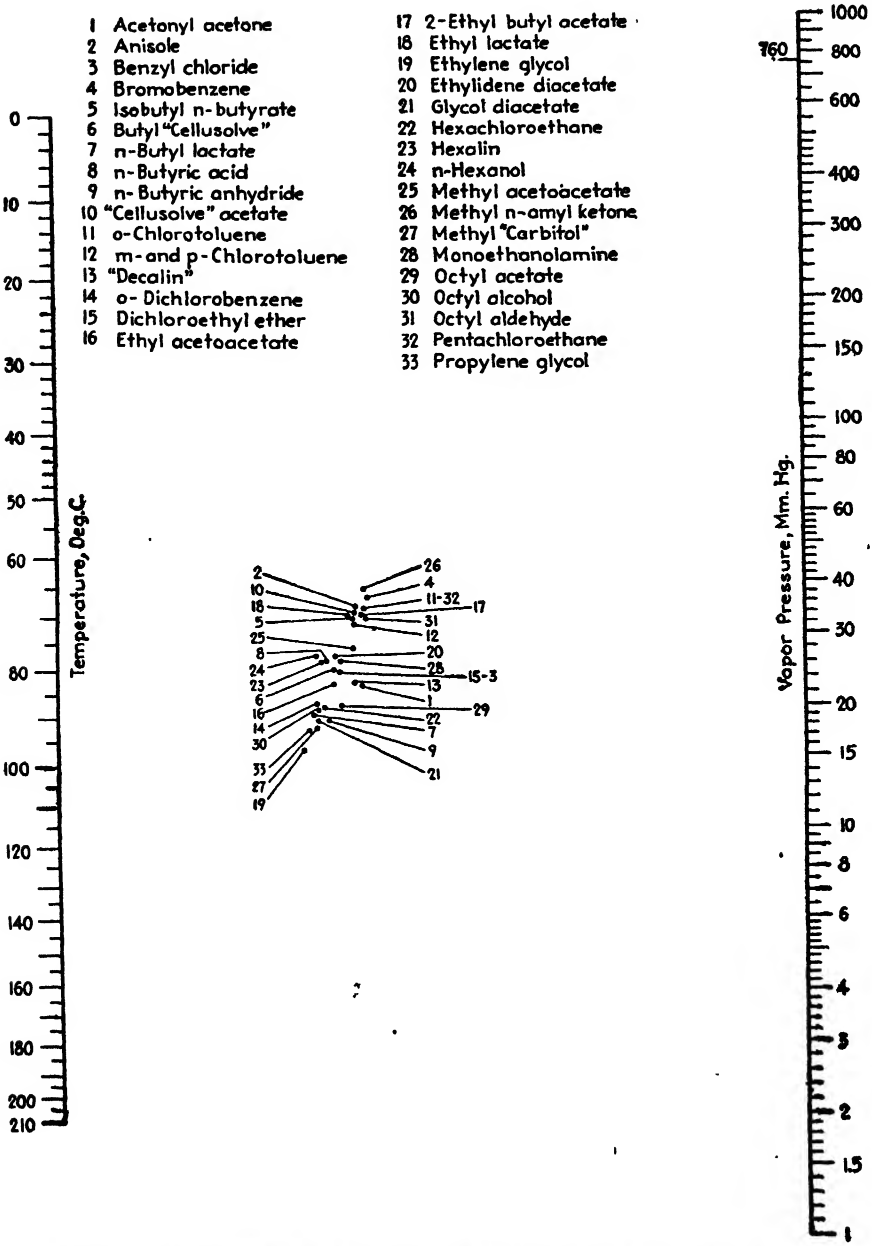

Fig. 160.—Vapor pressures of 33 organic solvents boiling between 150 and 200°C.

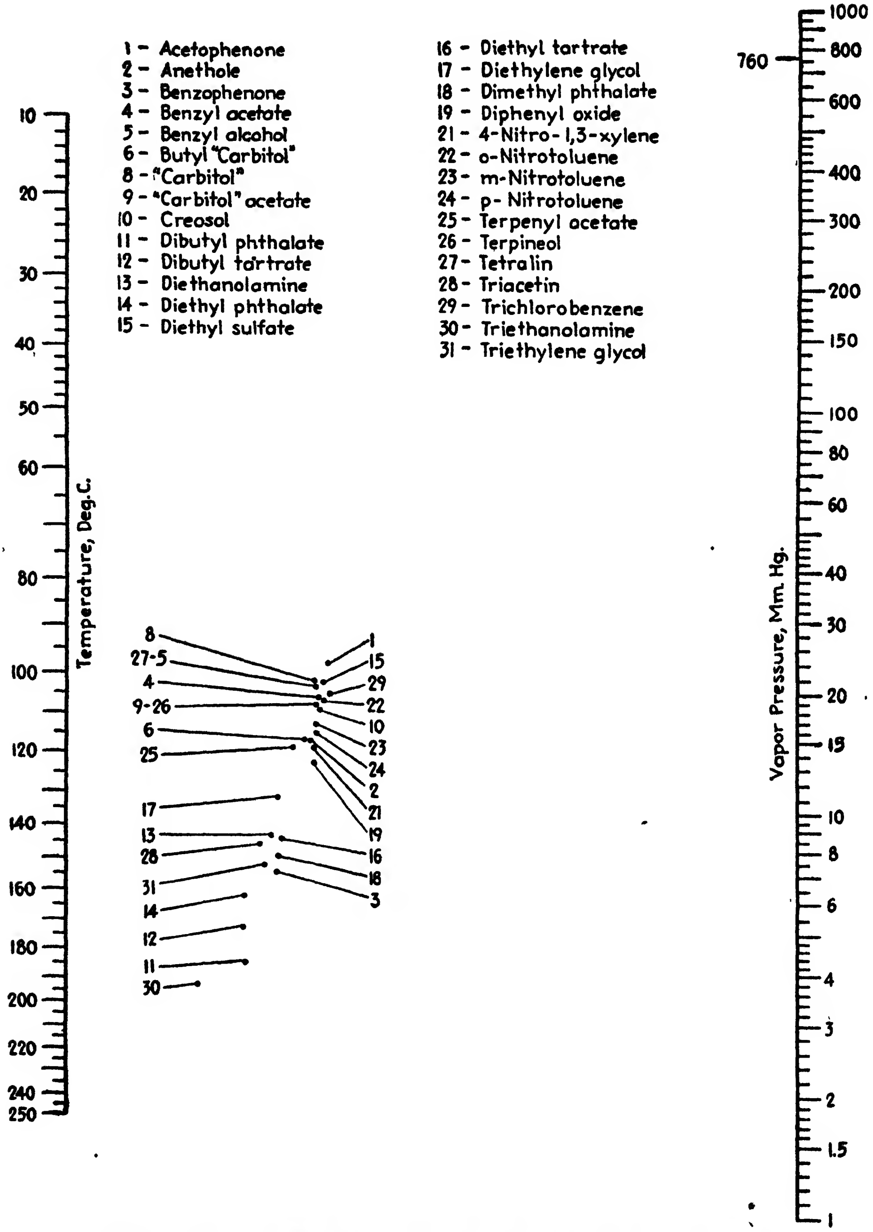

FIG. 161.—Vapor pressures of 29 organic solvents boiling above 200°C.

LINE-COORDINATE CHARTS FOR VAPOR PRESSURES OF 128 ORGANIC SOLVENTS[1]

Figures 158 to 161, which present vapor-pressure data in convenient line-coordinate form, are modifications of an earlier Davis chart and depend upon linearity of the logarithm of the vapor pressure and an arbitrary function of the temperature as defined by the pressure-temperature curve of a single compound in a manner similar to that suggested previously.[2,3] The charts were constructed by methods described by Davis.[4]

For convenience the 128 solvents were divided into four groups according to their boiling points at atmospheric pressure as follows: <90°C. (Fig. 158), 90 to 150°C. (Fig. 159), 150 to 200°C (Fig. 160), and >200°C. (Fig. 161). In each chart a straight line through any numbered gauge point will cut the temperature and vapor-pressure scales in consistent values.

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[1] KILLEFFER, D. H., *Ind. Eng. Chem.*, **30**, 477, 565 (1938).

[2] COX, E. R., *Ind. Eng. Chem.*, **15**, 592 (1923).

[3] DAVIS, D. S., *Ind. Eng. Chem.*, **17**, 735 (1925).

[4] DAVIS, D. S., "Empirical Equations and Nomography," p. 140, McGraw-Hill Book Company, Inc., New York, 1943.

CHAPTER XVIII

VISCOSITY NOMOGRAPHS

LINE-COORDINATE CHART FOR VISCOSITIES OF LIQUIDS[1]

Based upon a linear relation between the logarithm of viscosity and an arbitrary function of temperature, Fig. 162 enables estimation of the

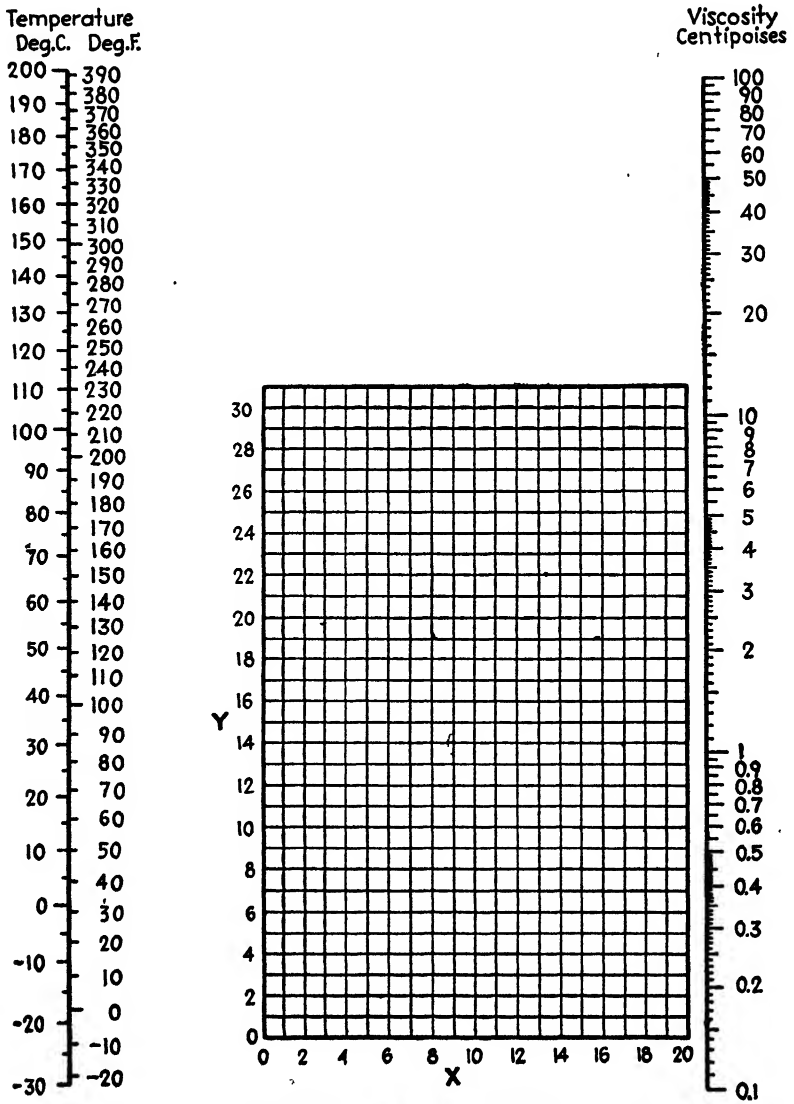

Fig. 162.—Viscosities of liquids.

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[1] Perry, J. H., "Chemical Engineers' Handbook," 2d ed., p. 794, McGraw-Hill Book Company, Inc., New York, 1941.

TABLE XXXIX.—VISCOSITIES OF LIQUIDS*
Coordinates for Fig. 162

No.	Liquid	X	Y	No.	Liquid	X	Y
1	Acetaldehyde	15.2	4.8	56	Freon-22	17.2	4.7
2	Acetic acid, 100%	12.1	14.2	57	Freon-113	12.5	11.4
3	Acetic acid, 70%	9.5	17.0	58	Glycerol, 100%	2.0	30.0
4	Acetic anhydride	12.7	12.8	59	Glycerol, 50%	6.9	19.6
5	Acetone, 100%	14.5	7.2	60	Heptene	14.1	8.4
6	Acetone, 35%	7.9	15.0	61	Hexane	14.7	7.0
7	Allyl alcohol	10.2	14.3	62	Hydrochloric acid, 31.5%	13.0	16.6
8	Ammonia, 100%	12.6	2.0	63	Isobutyl alcohol	7.1	18.0
9	Ammonia, 26%	10.1	13.9	64	Isobutyric acid	12.2	14.4
10	Amyl acetate	11 8	12.5	65	Isopropyl alcohol	8.2	16.0
11	Amyl alcohol	7.5	18.4	66	Kerosene	10.2	16.9
12	Aniline	8.1	18.7	67	Linseed oil, raw	7.5	27.2
13	Anisole	12.3	13.5	68	Mercury	18.4	16.4
14	Arsenic trichloride	13.9	14.5	69	Methanol, 100%	12.4	10.5
15	Benzene	12.5	10.9	70	Methanol, 90%	12.3	11.8
16	Brine, $CaCl_2$, 25%	6.6	15.9	71	Methanol, 40%	7.8	15.5
17	Brine, NaCl, 25%	10.2	16.6	72	Methyl acetate	14.2	8.2
18	Bromine	14.2	13 2	73	Methyl chloride	15.0	3.8
19	Bromotoluene	20.0	15.9	74	Methyl ethyl ketone	13.9	8.6
20	Butyl acetate	12.3	11.0	75	Naphthalene	7.9	18.1
21	Butyl alcohol	8.6	17.2	76	Nitric acid, 95%	12.8	13.8
22	Butyric acid	12.1	15.3	77	Nitric acid, 60%	10.8	17.0
23	Carbon dioxide	11 6	0.3	78	Nitrobenzene	10.6	16.2
24	Carbon disulphide	16.1	7.5	79	Nitrotoluene	11.0	17.0
25	Carbon tetrachloride	12.7	13.1	80	Octane	13.7	10.0
26	Chlorobenzene	12.3	12.4	81	Octyl alcohol	6.6	21.1
27	Chloroform	14 4	10.2	82	Pentachloroethane	10.9	17.3
28	Chlorosulfonic acid	11 2	18.1	83	Pentane	14.9	5.2
29	Chlorotoluene, ortho	13.0	13.3	84	Phenol	6.9	20.8
30	Chlorotoluene, meta	13.3	12.5	85	Phosphorus tribromide	13.8	16.7
31	Chlorotoluene para	13.3	12.5	86	Phosphorus trichloride	16.2	10.9
32	Cresol, meta	2.5	20.8	87	Propionic acid	12.8	13.8
33	Cyclohexanol	2.9	24.3	88	Propyl alcohol	9 1	16.5
34	Dibromoethane	12 7	15.8	89	Propyl bromide	14.5	9.6
35	Dichloroethane	13 2	12.2	90	Propyl chloride	14.4	7.5
36	Dichloromethane	14.6	8.9	91	Propyl iodide	14 1	11.6
37	Diethyl oxalate	11 0	16.4	92	Sodium	16.4	13.9
38	Dimethyl oxalate	12.3	15.8	93	Sodium hydroxide, 50%	3.2	25.8
39	Diphenyl	12.0	18.3	94	Stannic chloride	13.5	12.8
40	Dipropyl oxalate	10.3	17.7	95	Sulphur dioxide	15.2	7.1
41	Ethyl acetate	13.7	9.1	96	Sulphuric acid, 110%	7.2	27.4
42	Ethyl alcohol, 100%	10.5	13.8	97	Sulphuric acid, 98%	7.0	24.8
43	Ethyl alcohol, 95%	9.8	14.3	98	Sulphuric acid, 60%	10.2	21.3
44	Ethyl alcohol, 40%	6.5	16.6	99	Sulphuryl chloride	15.2	12.4
45	Ethyl benzene	13.2	11.5	100	Tetrachloroethane	11.9	15.7
46	Ethyl bromide	14 5	8.1	101	Tetrachloroethylene	14.2	12.7
47	Ethyl chloride	14.8	6.0	102	Titanium tetrachloride	14.4	12.3
48	Ethyl ether	14.5	5.3	103	Toluene	13.7	10.4
49	Ethyl formate	14.2	8.4	104	Trichloroethylene	14.8	10.5
50	Ethyl iodide	14.7	10.3	105	Turpentine	11.5	14.9
51	Ethylene glycol	6.0	23.6	106	Vinyl acetate	14.0	8.8
52	Formic acid	10.7	15.8	107	Water	10.2	13.0
53	Freon-11	14.4	9.0	108	Xylene, ortho	13.5	12.1
54	Freon-12	16.8	5.6	109	Xylene, meta	13.9	10.6
55	Freon-21	15.7	7.5	110	Xylene, para	13.9	10.9

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* From J. H. Perry, "Chemical Engineers' Handbook," 2d ed., p. 794, McGraw-Hill Book Company, Inc., New York, 1941.

viscosity of 110 pure liquids and aqueous solutions over a wide temperature range and is particularly useful in designing heat transfer and fluid-flow equipment. Table XXXIX lists the liquids and solutions and the coordinates of their gauge points to be plotted on Fig. 162 when the chart is used.

TABLE XL.—VISCOSITIES OF GASES*
Coordinates for use with Fig. 163

No.	Gas	X	Y	No.	Gas	X	Y
1	Acetic acid	7.7	14.3	29	Freon-113	11.3	14.0
2	Acetone	8.9	13.0	30	Helium	10.9	20.5
3	Acetylene	9.8	14.9	31	Hexane	8.6	11.8
4	Air	11.0	20.0	32	Hydrogen	11.2	12.4
5	Ammonia	8.4	16.0	33	$3H_2 + 1N_2$	11.2	17.2
6	Argon	10.5	22.4	34	Hydrogen bromide	8.8	20.9
7	Benzene	8.5	13.2	35	Hydrogen chloride	8.8	18.7
8	Bromine	8.9	19.2	36	Hydrogen cyanide	9.8	14.9
9	Butene	9.2	13.7	37	Hydrogen iodide	9.0	21.3
10	Butylene	8.9	13.0	38	Hydrogen sulphide	8.6	18.0
11	Carbon dioxide	9.5	18.7	39	Iodine	9.0	18.4
12	Carbon disulphide	8.0	16.0	40	Mercury	5.3	22.9
13	Carbon monoxide	11.0	20.0	41	Methane	9.9	15.5
14	Chlorine	9.0	18.4	42	Methyl alcohol	8.5	15.6
15	Chloroform	8.9	15.7	43	Nitric oxide	10.9	20.5
16	Cyanogen	9.2	15.2	44	Nitrogen	10.6	20.0
17	Cyclohexane	9.2	12.0	45	Nitrosyl chloride	8.0	17.6
18	Ethane	9.1	14.5	46	Nitrous oxide	8.8	19.0
19	Ethyl acetate	8.5	13.2	47	Oxygen	11.0	21.3
20	Ethyl alcohol	9.2	14.2	48	Pentane	7.0	12.8
21	Ethyl chloride	8.5	15.6	49	Propane	9.7	12.9
22	Ethyl ether	8.9	13.0	50	Propyl alcohol	8.4	13.4
23	Ethylene	9.5	15.1	51	Propylene	9.0	13.8
24	Fluorine	7.3	23.8	52	Sulphur dioxide	9.6	17.0
25	Freon-11	10.6	15.1	53	Toluene	8.6	12.4
26	Freon-12	11.1	16.0	54	2, 3, 3-trimethylbutane	9.5	10.5
27	Freon-21	10.8	15.3	55	Water	8.0	16.0
28	Freon-22	10.1	17.0	56	Xenon	9.3	23.0

* From J. H. Perry, "Chemical Engineers' Handbook," 2d ed., p. 790, McGraw-Hill Book Company, Inc., New York, 1941.

LINE-COORDINATE CHART FOR VISCOSITIES OF GASES[1]

Table XL lists 56 gases and the coordinates of their gauge points to be plotted on Fig. 163 when the chart is used to estimate vis-

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[1] PERRY, J. H., "Chemical Engineers' Handbook," 2d ed., p. 790, McGraw-Hill Book Company, Inc., New York, 1941.

cosites over wide temperature ranges. The nomograph facilitates the design of heat transfer and fluid-flow equipment.

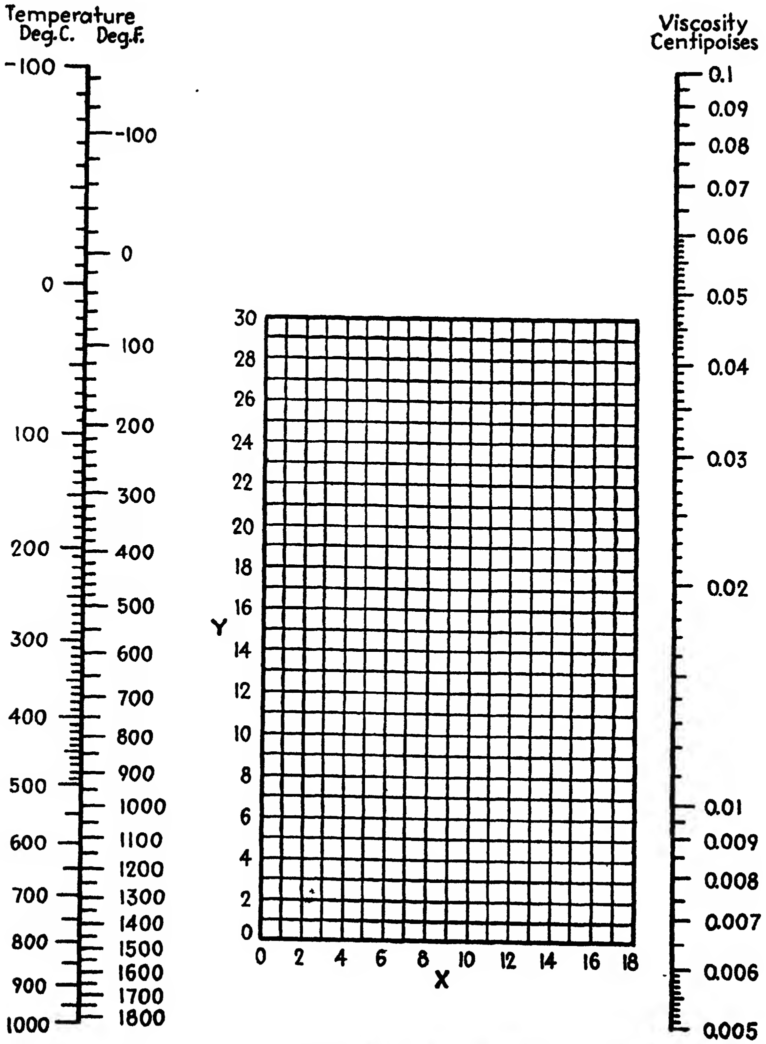

FIG. 163.—Viscosities of gases.

VISCOSITY OF STRONG PHOSPHORIC ACIDS[1]

As a part of their study of the characteristics of strong phosphoric acids Lum, Malowan, and Durgin[2] have presented excellent data covering

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[1] *Chem. & Met. Eng.*, **47**, 155 (1940).

[2] LUM, J. H., J. E. MALOWAN, and C. B. DURGIN, *Chem. & Met. Eng.*, **44**, 721–725 (1937).

the viscosity-temperature relationships for several acids of known P_2O_5 content. The data can be plotted as straight lines on special coordinate paper[1] but interpolation is somewhat difficult since the lines are not parallel and do not represent equal intervals in P_2O_5 content.

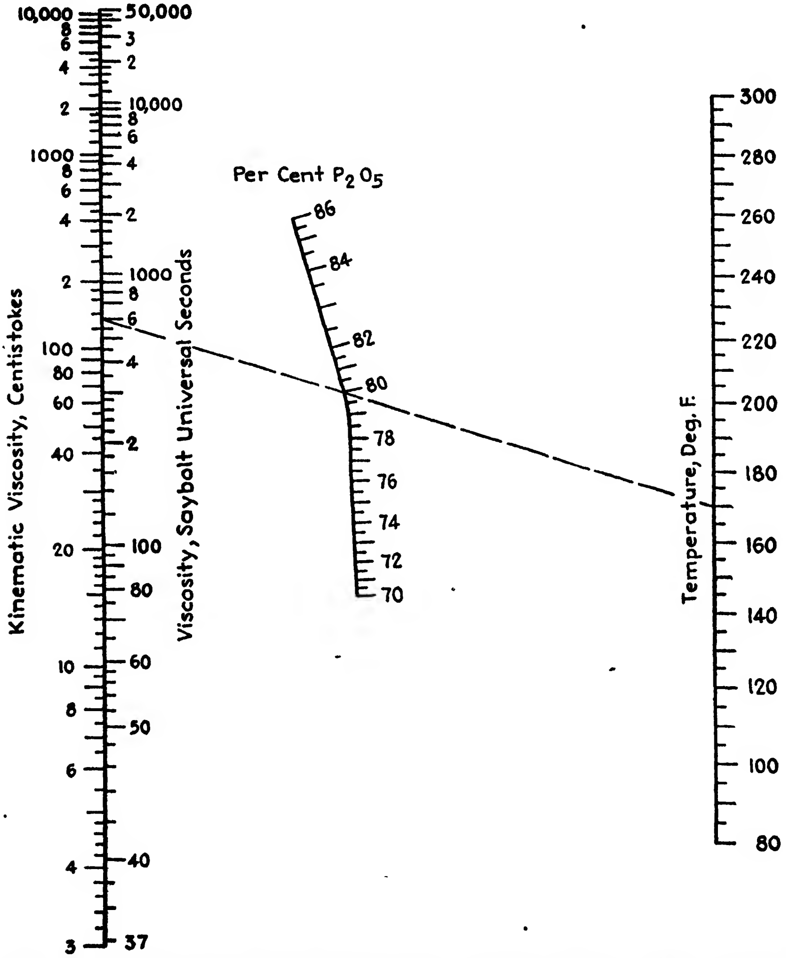

FIG. 164.—Viscosity-temperature-concentration relationships for phosphoric acids.

Figure 164 extends the utility of the original data through the inclusion of (1) a definitely graduated scale for percentages of P_2O_5 and (2) a more closely graduated temperature scale. As an illustration of the use of the chart, the broken line indicates that phosphoric acid testing 80.0 per cent P_2O_5 will exhibit a kinematic viscosity of 132 centistokes or a Saybolt viscosity of 600 sec. at 170°F.

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[1] A.S.T.M. Tentative Standards, 1936, p. 666.

SPECIFIC-HEAT AND VISCOSITY NOMOGRAPHS FOR CALCIUM CHLORIDE BRINES[1]

Since calcium chloride solutions find wide application as refrigerating brines, reliable specific heat[2] and viscosity[3] data are necessary in connection with the design of cooling systems. The purpose of this topic is to present such data in convenient nomographic form.

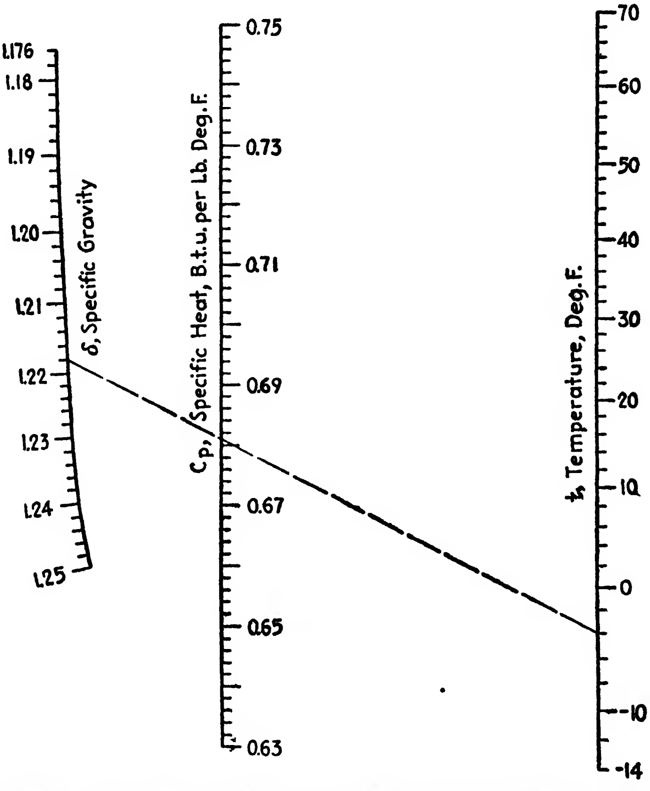

FIG. 165.—Specific heat–specific gravity–temperature relationships for calcium chloride brines.

Specific Heats.—The line-coordinate specific-heat chart (Fig. 165) is based on the correlation equation

$$c_p = a + b[t - 6.9(10)^{-0.028t}]$$

where c_p is the specific heat, B.t.u./(lb.) (°F.); t is the temperature,

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[1] *Ind. Eng. Chem.*, **34**, 1532 (1942).

[2] Calcium Chloride Assoc., *Bull.* **30**, 19 (1942).

[3] Am. Soc. Refrig. Eng. Data Book, 1939–1940.

degrees Fahrenheit; and a and b depend upon the specific gravity of the brine, δ, as given in Table XLI.

TABLE XLI

δ	1.250	1.225	1.200	1.175
a	0.6604	0.6794	0.7040	0.7278
$b(10^7)$	3225	3575	3743	3821

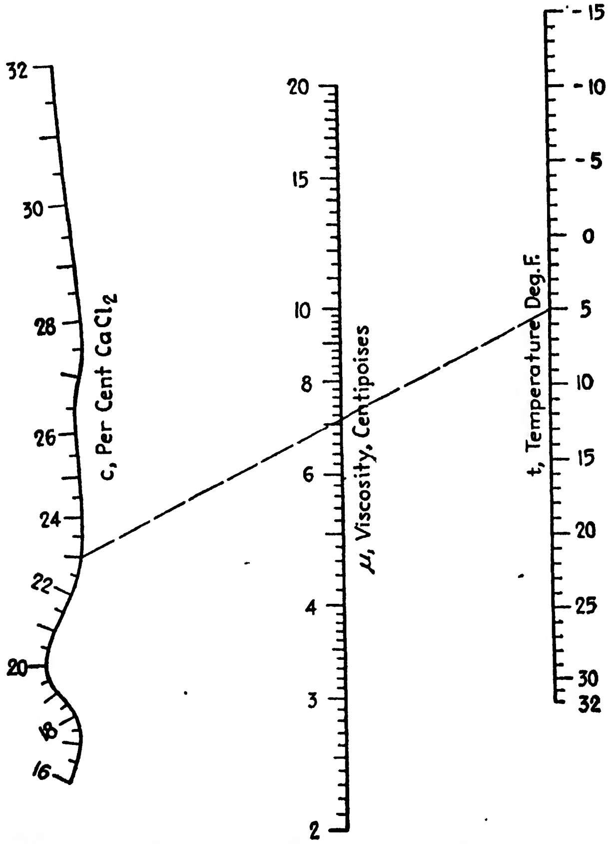

FIG. 166.—Viscosity-temperature-concentration relationships for calcium chloride brines.*

The use of the chart is illustrated as follows: What is the specific heat of a calcium chloride brine at −4°F. which has a specific gravity of 1.218? Connect 1.218 on the δ scale with −4 on the t scale, and read the specific heat as 0.681 B.t.u./(lb.) (°F.) on the c_p scale.

Viscosities.—The line-coordinate viscosity chart (Fig. 166) is based on the correlation equation

$$\log \mu = a + b(t - 10^{0.154t-5.075})$$

where μ is the viscosity of the brine in centiposes, and a and b depend upon the percentage of anhydrous calcium chloride, c, as given in Table XLII.

TABLE XLII

c	a	b	c	a	b
16	0.785	−0.0114	26	0.983	−0.0111
18	0.817	−0.0113	28	1.048	−0.0111
20	0.861	−0.0118	30	1.118	−0.0113
22	0.891	−0.0113	32	1.196	−0.0116
24	0.930	−0.0111			

The use of the chart is illustrated as follows: What is the viscosity of a calcium chloride brine at 5°F. when the concentration is 23 per cent? Connect 23 on the c scale with 5 on the t scale, and read the viscosity as 7.1 centipoises on the μ scale.

For all design purposes, values read from the charts are in sufficient agreement with the original data.

VISCOSITY NOMOGRAPHS FOR ORGANIC LIQUIDS[1]

Souders[2] showed that for a wide range of organic liquids the logarithm of the logarithm of the viscosity in millipoises is linear with the density in grams per cubic centimeter according to the expression

$$\log(\log \eta) = md - 2.9 \tag{40}$$

where m is a constant characteristic of each liquid. He calculated the viscosity-density constant m by the equation

$$m = \frac{I}{M} \tag{41}$$

where M = molecular weight.
I = viscosity-constitutional constant.

The two equations may be combined to give

$$\log(\log \eta) = \frac{Id}{M} - 2.9. \tag{42}$$

The viscosity-constitutional constant I may be evaluated from the summation of general atomic and structural constants given in Table XLIII. For example, the value of I for ethyl iodide is

$$2(50.2) + 5(2.7) + 110 = 223.9.$$

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[1] *Ind. Eng. Chem.*, **33**, 1537 (1941).

[2] SOUDERS, MOTT, JR., *J. Am. Chem. Soc.*, **60**, 154 (1938).

The use of Fig. 167, designed to solve Eq. (42) quickly and accurately, is illustrated as follows: What is the viscosity of ethyl iodide when the density is 1.925 g./cc.? Connect 224 on the *I* scale with 156, the molecular weight, on the *M* scale, and note the intersection with the α axis. Connect this intersection with 1.925 on the *d* scale, and produce the line to the η scale where the viscosity is read as 5.5 millipoises.

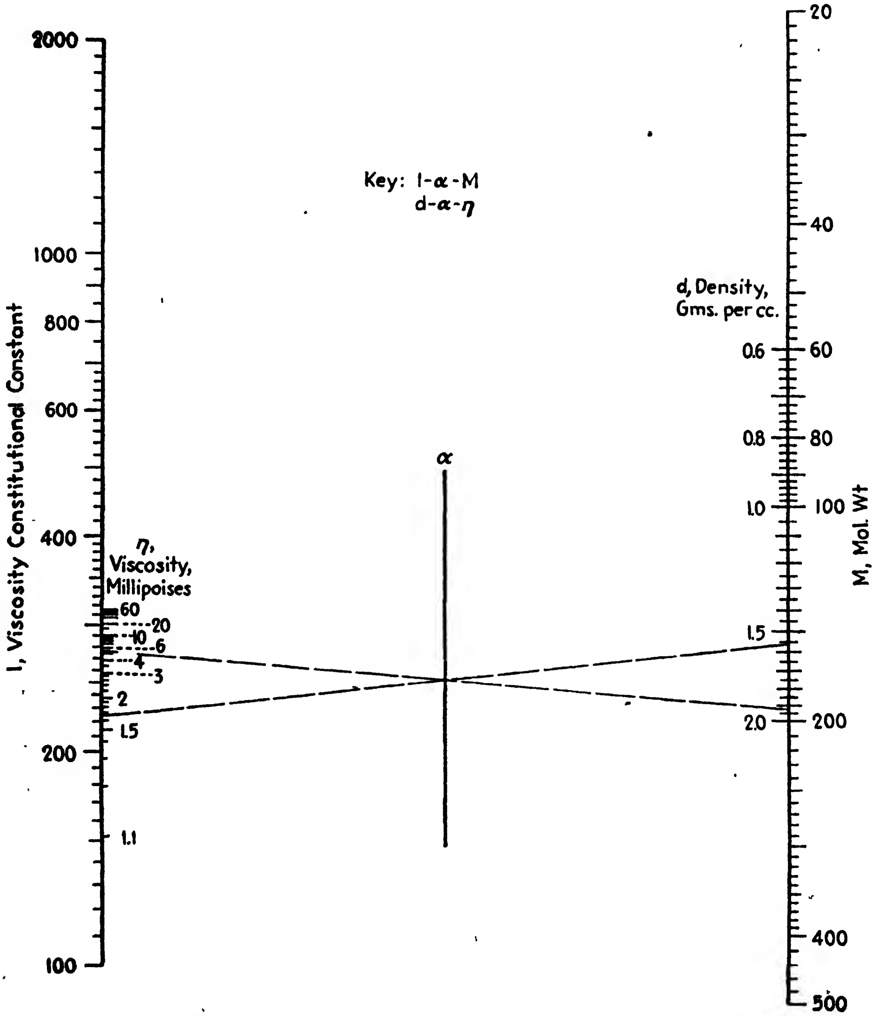


FIG. 167.—Viscosities of organic liquids from the constitutional constants, densities, and molecular weights.

Figure 167 is a general chart for organic liquids and covers wide ranges, but the viscosity scale is necessarily short and crowded owing to the nature of Eq. (42). Figures 168 and 169 are less general but permit closer estimation of viscosity and require reference to Table XLIV

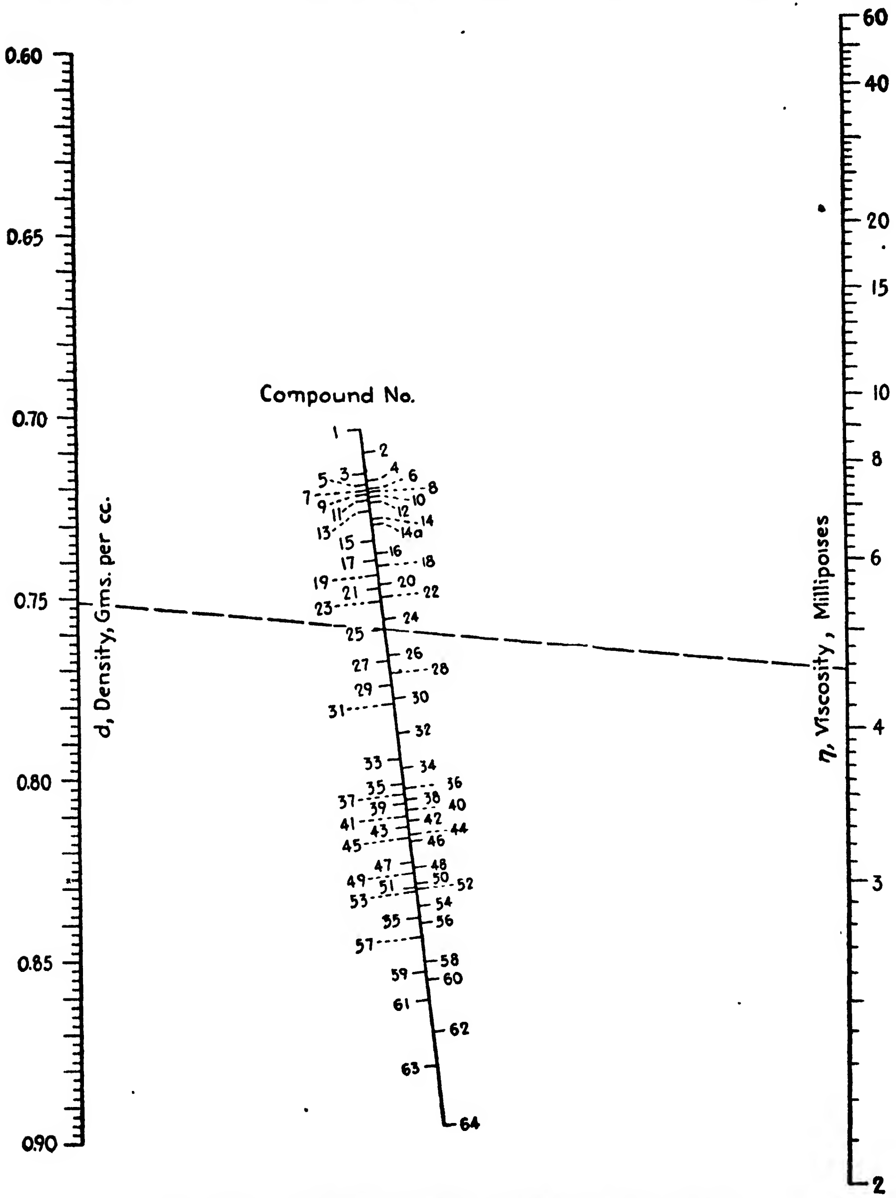


Fig. 168.—Viscosities of organic liquids from their densities.

which lists compound numbers against the names of the compounds in question.

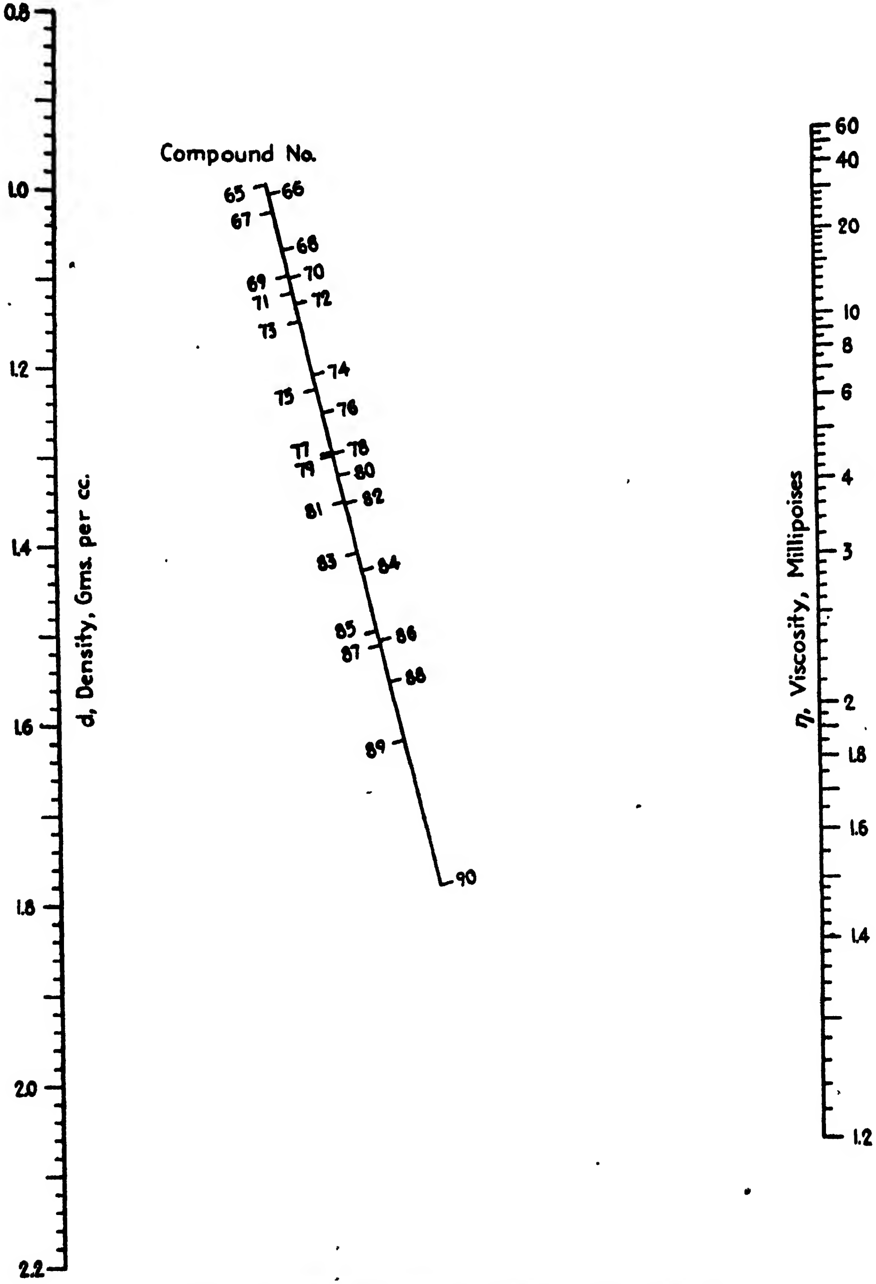


Fig. 169.—Viscosities of organic liquids from their densities.

The index line in Fig. 168 shows that the viscosity of cyclopentane (compound 25) is 4.54 millipoises when the density is 0.751 g./cc., and the index line in Fig. 169 indicates that isobutyl iodide (compound 84) with a density of 1.614 has a viscosity of 9.5 millipoises.

A comparison between results as read from the specific and general charts may be effected by noting that the viscosity of ethyl iodide (compound 89) at a density of 1.925 g./cc. is 5.6 when read from Fig. 169 as against 5.5 reported in a previous illustration. A small variation in density or in the constitutional constant will result in a considerable change in viscosity due to the log-log function. This condition is faithfully reflected in the charts.

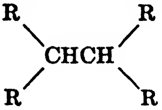
TABLE XLIII.—ATOMIC AND STRUCTURAL CONSTANTS

Atomic and Group Values

CH_2	55.6	OH	57.1	N	37
H	2.7	COO	90	Cl	60
C	50.2	COOH	104.4	Br	79
O	29.7	NO_2	80	I	110

Structural Values

Double bond −15.5

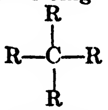

R_2CHCHR_2 8

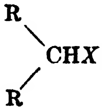
$-CH = CHCH_2X$ 4

where X is a negative group

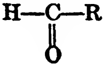
5—C ring −24
6—C ring −21

Side group on 6—C ring


$R—C(R)_2—R$ 13

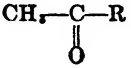

R_2CHX 6

Mol. wt. < 17, −9


$H—C(=O)—R$ 16

Mol. wt. > 16, −17

Ortho and para = 3; meta = 1


$CH_3—C(=O)—R$ 5

SURFACE TENSION-VISCOSITY NOMOGRAPH FOR ORGANIC LIQUIDS[1]

For 32 organic compounds, Buehler[2] drew attention to an important relation between surface tension and viscosity:

$$\gamma^{\frac{1}{4}} = \frac{\log (\log \eta) + 2.9}{I/P}$$

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[1] *Ind. Eng. Chem.*, **34**, 1231 (1942).

[2] BUEHLER, C. A., *J. Phys. Chem.*, **42**, 1207 (1938).

where γ = surface tension, dynes/cm.
η = viscosity, millipoises, at same temperature as γ.
I = viscosity-constitutional constant.
P = parachor.

TABLE XLIV.—COMPOUND NUMBERS LISTED ON FIGS. 168 AND 169

49	Acetaldehyde
57	Acetate, ethyl
23	Acetate, ethyl tetradecyl
22	Acetate, 2-heptyl nonyl
62	Acetate, methyl
48	Acetate, *n*-propyl
35	Acetone
63	Acid, acetic
51	Acid, *n*-butyric
34	Acid, *n*-caproic
50	Acid, isobutyric
60	Acid, propionic
42	Acid, *n*-valeric
31	Alcohol, allyl
16	Alcohol, butyl
20	Alcohol, ethyl
14a	Alcohol, isobutyl
14	Alcohol, isopropyl
28	Alcohol, methyl
17	Alcohol, *n*-propyl
55	Aniline
45	Benzene
55	Benzylamine
81	Bromide, allyl
83	Bromide, ethyl
76	Bromide, isobutyl
77	Bromide, isopropyl
80	Bromide, *n*-propyl
82	Bromobenzene
79	*m*-Bromotoluene
77	*o*-Bromotoluene
77	*p*-Bromotoluene
53	*n*-Butyrate, methyl
68	Chloride, allyl
75	Chloride, ethylene
65	Chloride, isobutyl
66	Chloride, isopropyl
67	Chloride, *n*-propyl
72	Chlorobenzene
70	*m*-Chlorotoluene
70	*o*-Chlorotoluene
69	*p*-Chlorotoluene
20	Cyclohexane
29	Cyclohexanol
44	Cyclohexanone
80	Dichloromethane
20	Diisopropenyl (diallyl)
2	Diisopropyl
1	Dimethylbutane
46	Dimethylaniline
19	5-Docosene, phenyl
15	Docosylbenzene
11	Docosylcyclohexane
21	β-Docosylnaphthalene
5	Dodecane
31	Ether, ethyl
24	Ether, ethyl isobutyl
27	Ether, ethyl propyl
30	Ether, methyl propyl
25	Ether, propyl
47	Ethylaniline
40	Ethylbenzene
6	Ethyltetradecanol
61	Formate, ethyl
64	Formate, methyl
56	Formate, propyl
3	Hepatadecane
8	Heptane
4	Heptylnonanol
16	5-Hexacosene, phenyl
5	Hexane
36	Hexylnaphthalene
88	Iodide, allyl
89	Iodide, ethyl
84	Iodide, isobutyl
85	Iodide, isopropyl
90	Iodide, methyl
87	Iodide, propyl
86	Iodobenzene
53	Isobutyrate, methyl
10	Isoheptane
6	Isohexane
6	Isopentane
26	Isoprene
33	Ketone, diethyl
33	Ketone, methyl ethyl
32	Ketone, methyl propyl
54	Methylaniline
22	Methylcyclohexane
10	Methylpentane

TABLE XLIV.—COMPOUND NUMBERS LISTED ON FIGS. 168 AND 169.—(*Continued*)

12	Cyclohexyldocosane	73	Nitrobenzene
4	Cyclohexylhexacosane	71	Nitrotoluene
25	Cyclopentane	6	Nonane
6	Decane	18	Octadecylbenzene
74	Dichloroethane	13	Octadecylcyclohexane
24	β-Octadecylnaphthalene	58	Propionate, methyl
6	Octane	43	Toluene
9	Pentane	52	*o*-Toluidine
59	Phenol	50	*p*-Toluidine
15	Phenyldocosane	5	Undecane
14	Phenylhexacosane	41	*m*-Xylene
37	Propionaldehyde	38	*o*-Xylene
51	Propionate, ethyl	39	*p*-Xylene

Table XLV lists compound numbers and values of I/P[1,2] for the organic liquids in question.

TABLE XLV

No.	I/P	Compound	No.	I/P	Compound
15	1.226	Acetate, ethyl	12	1.212	Formate, ethyl
6	1.195	Acetate, methyl	18	1.266	Heptane
17	1.253	Acetate, propyl	17	1.253	Hexane
3	1.186	Acetone	10	1.205	Iodide, ethyl
10	1.205	Benzene	1	1.163	Iodide, methyl
11	1.208	Benzene, ethyl	14	1.222	Iodide, propyl
7	1.198	Bromide, ethyl	14	1.222	Ketone, diethyl
16	1.243	Bromide, isobutyl	12	1.212	Ketone, methyl ethyl
17	1.253	Bromide, isopropyl	10	1.205	Naphthalene
13	1.217	Bromide, propyl	2	1.172	Nitrobenzene
5	1.192	Bromobenzene	19	1.280	Octane
17	1.253	Chloride, isobutyl	9	1.202	Toluene
13	1.217	Chloride, propyl	8	1.201	*m*-Toluene
4	1.190	Chlorobenzene	11	1.208	*m*-Xylene
20	1.303	Decane	15	1.226	*o*-Xylene
12	1.212	Ether, ethyl	13	1.217	*p*-Xylene

The use of Fig. 170, constructed to solve the equation conveniently and accurately, is illustrated as follows: What is the surface tension of ethyl iodide at 16°C. when its viscosity is 6.2 millipoises[3] at this temperature? The compound number for ethyl iodide, read from Table XLV, is 10. Connect 6.2 on the η scale with 10 on the compound number scale, and produce the line to the γ scale where the surface tension is read

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[1] BUEHLER, C. A., *J. Phys. Chem.*, **42**, 1207 (1938).

[2] SOUDERS, MOTT, JR., *J. Am. Chem. Soc.*, **60**, 154 (1938).

[3] PERRY, J. H., "Chemical Engineers' Handbook," 2d ed., p. 794, McGraw-Hill Book Company, Inc., New York, 1941.

as 29.1 dynes/cm. The experimental value reported in the "International Critical Tables"[1] is 29.9.

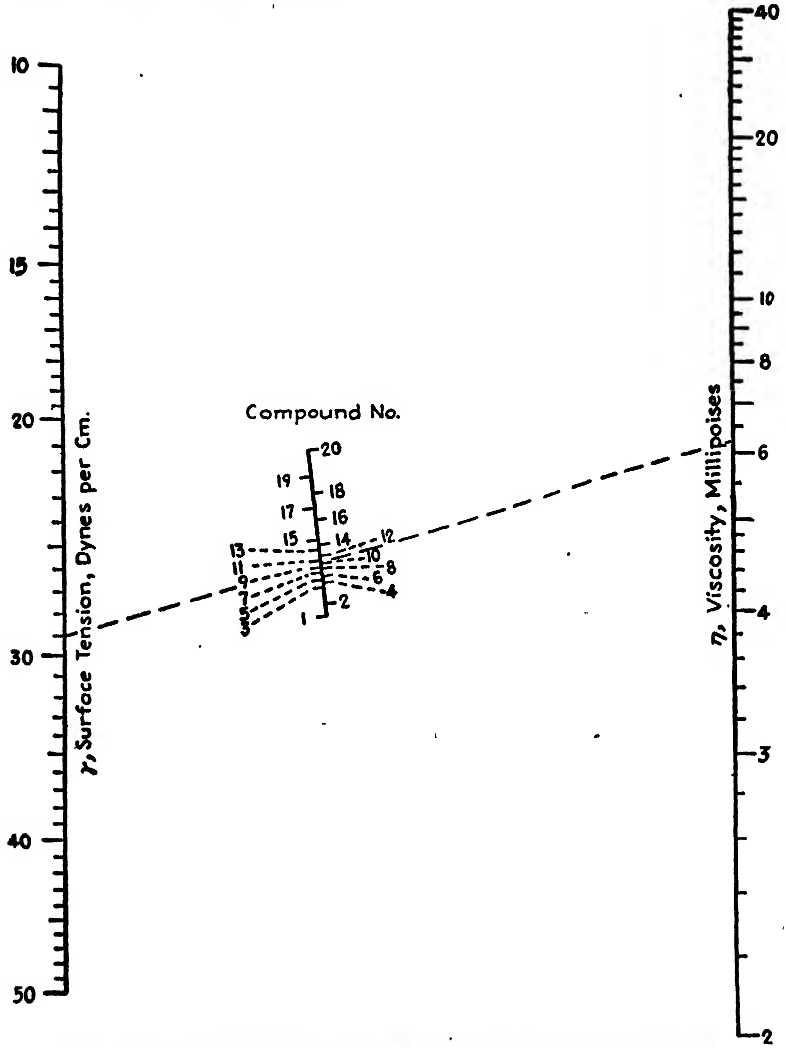

FIG. 170.—Surface tensions of organic liquids from their viscosities.

VISCOSITY NOMOGRAPHS FOR ALKALINE SOLUTIONS[2]

Original Data.—Hitchcock and McIlhenny[3] presented the first extensive data on the viscosities of aqueous solutions of sodium hydroxide,

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[1] "International Critical Tables," Vol. IV, p. 436, McGraw-Hill Book Company, Inc., New York, 1928.

[2] *Ind. Eng. Chem.*, **28**, 953 (1936).

[3] HITCHCOCK, L. B., and J. S. MCILHENNY, *Ind. Eng. Chem.*, **27**, 461 (1935).

sodium carbonate, potassium hydroxide, and potassium carbonate, together with a study of the viscosities of mixtures of solutions of sodium hydroxide and sodium carbonate and of potassium hydroxide and potassium carbonate. Their investigation merits particular attention in view of the industrial importance of these alkalies and because of the need for reliable viscosity data in connection with the design of equipment where calculation of gas absorption rates and heat and fluid flow must be made.

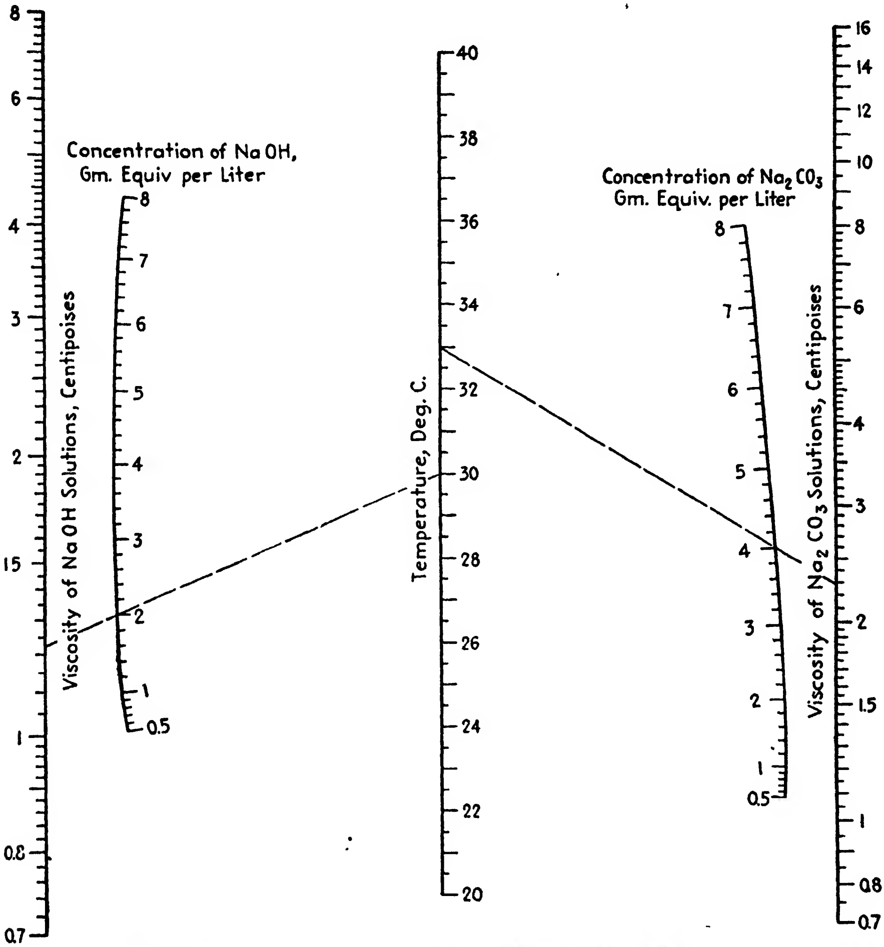

FIG. 171.—Viscosity-temperature-concentration relationships for sodium hydroxide and sodium carbonate solutions.

Their studies were conducted at temperatures of 20, 30, and 40°C., and viscosities are given for concentrations of 0.5, 1, 2, 3, 4, 5, 6, 7, and

8 gram-equivalents per liter of solution. In the case of mixtures of sodium hydroxide and sodium carbonate solutions, the volume percentages of the latter are 26.5, 50.5, and 74.7; for mixtures of potassium hydroxide and potassium carbonate solutions, the volume percentages of the latter component are 27.7, 53.7, and 75.9.

There is evident need for convenient interpolation means which shall be rapid and accurate. It is the purpose of this topic to present line-coordinate and nomographic charts that meet these requirements and thus extend the usefulness of the original data.

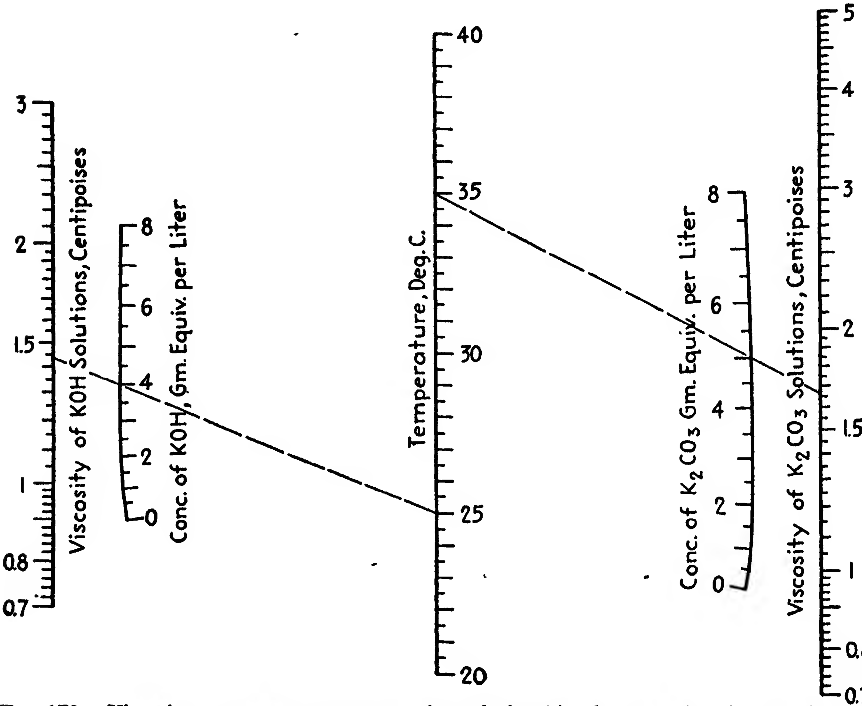

FIG. 172.—Viscosity-temperature-concentration relationships for potassium hydroxide and potassium carbonate solutions.

Primary Alkaline Solutions.—In the case of sodium hydroxide solutions, log ($\mu + 0.4$) is linear with temperature over the narrow range between 20 and 40°C.; for the other pure alkaline solutions, log μ is linear with temperature, where μ is the viscosity of the solution in centipoises. These relationships form the basis of Figs. 171 and 172. For convenience, the data for sodium hydroxide and sodium carbonate are combined in Fig. 171, and Fig. 172 presents the potassium hydroxide and potassium carbonate data in compact form.

In Fig. 171, the broken line at the left shows that a sodium hydroxide solution containing 2 gram-equivalents of solute per liter has a viscosity of 1.225 centipoises at 30°C. The dashed line at the right indicates that the viscosity of a 4 N solution of sodium carbonate is 2.29 centipoises at 33°C. In Fig. 172, the broken lines at the left and right, respectively, show that the viscosity of a 4 N potassium hydroxide solution is 1.43 centipoises at 25°C., and that the viscosity of a 5 N solution of potassium carbonate is 1.66 centipoises at 35°C.

At 20°C., Figs. 171 and 172 agree exactly with the original data; above this temperature the discrepancies average no more than about 1 per cent. The convenience of interpolation along closely graduated scales more than compensates for the slight loss in accuracy.

As pointed out by Hitchcock and McIlhenny, no ideal law has been proposed to enable calculation of the viscosity of mixtures of alkaline solutions from the viscosities of their components and the percentage composition. The assumption of additivity of viscosities according to the expression

$$\mu = \mu_1(1 - y) + \mu_2 y$$

where μ = viscosity of mixture
μ_1, μ_2 = viscosities of hydroxide and carbonate solutions, respectively, at same concentration
y = volume fraction of carbonate solution

leads to errors of as much as 10 per cent in the case of concentrated solutions and must be rejected as unsatisfactory.

The equation

$$\sqrt[3]{\mu} = (1 - y)\sqrt[3]{\mu_1} + y\sqrt[3]{\mu_2}$$

suggested by Kendall and Monroe's expression,[1] which holds for a wide variety of binary liquid mixtures including lubricating oils, is somewhat better but not entirely adequate.

Mixtures of Sodium Hydroxide and Sodium Carbonate Solutions.—For mixtures of sodium hydroxide and sodium carbonate solutions, the equation

$$\mu = \mu_1\left(\frac{\mu_2}{\mu_1}\right)^y \tag{43}$$

holds very closely, as indicated by Table XLVI which lists deviations of the calculated values from the original data for total normalities of 0.5 to 8 [Eq. (43)]:

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[1] Kendall, J., and K. P. Monroe, *J. Am. Chem. Soc.*, **39**, 1787 (1917).

TABLE XLVI

y	Average deviation in viscosity, per cent		
	20°C.	30°C.	40°C.
0.265	1.1	2.1	0.7
0.505	0.8	1.5	0.4
0.747	0.1	0.9	0.3

The expression is admittedly empirical but has a precedent in an identical equation proposed by Wennberg and Landt[1] for the cuprammonium viscosity of binary rag blends.

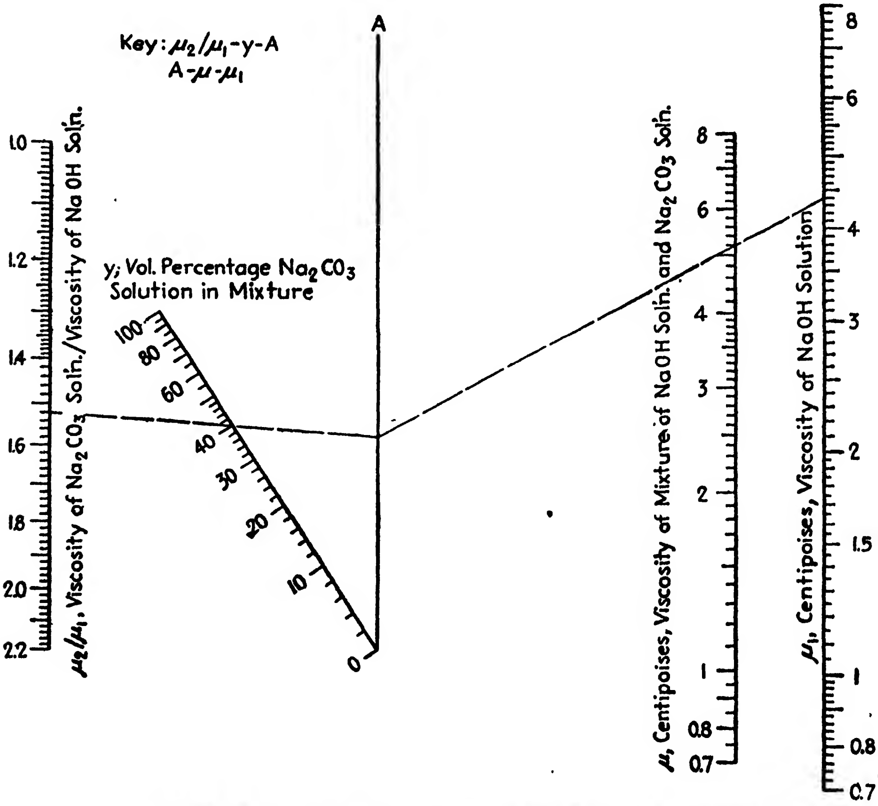

FIG. 173.—Viscosities of mixed sodium hydroxide and sodium carbonate solutions.

The equation can be handled most conveniently by means of Fig. 173, the use of which is illustrated as follows: What is the viscosity of a mixture of sodium hydroxide and sodium carbonate solutions of the same concentration when their viscosities are 4.40 and 6.69 centipoises, respec-

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[1] WENNBERG, E. N., and G. E. LANDT, *Paper Trade J.*, 93, 202 (1931).

tively, and the composition of the mixture is 60 per cent sodium hydroxide solution by volume and 40 per cent sodium carbonate solution? The ratio of the two viscosities is (6.69/4.40) or 1.52. Connect this value on the scale at the left with 40 per cent on the y scale, and note the intersection with the A axis. Connect this latter point with 4.40 on the μ_1 scale, and read the desired value as 5.20 on the μ scale.

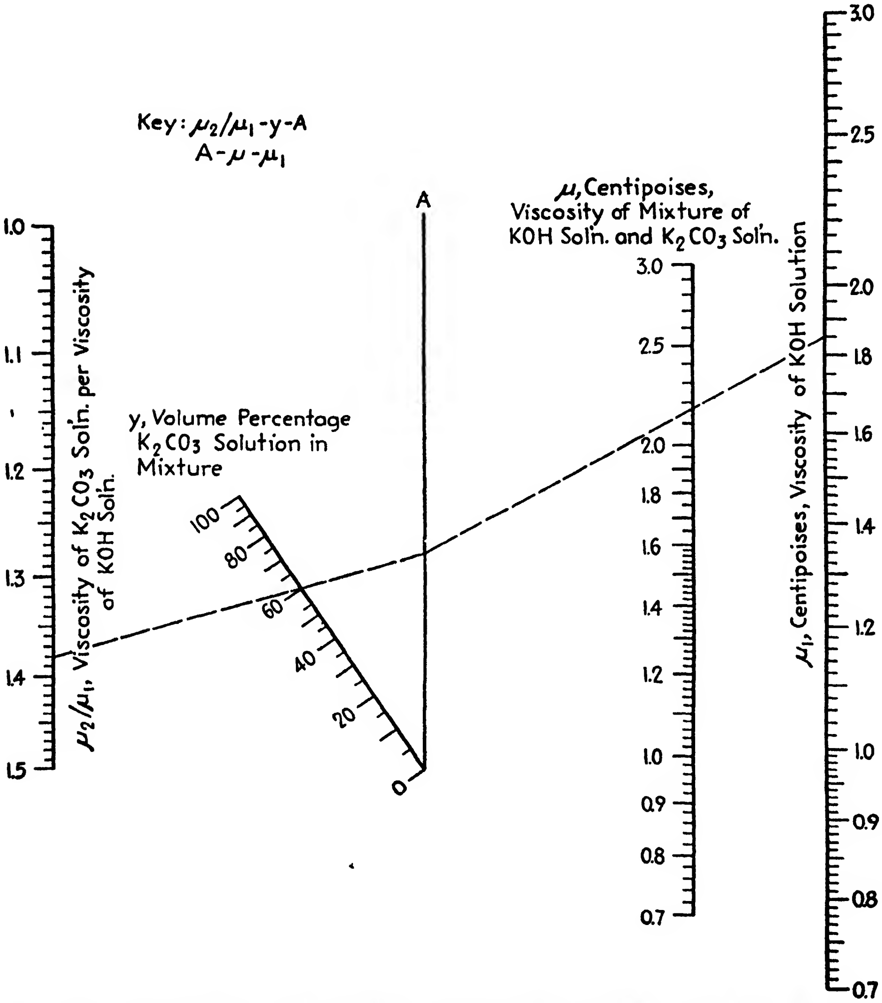

FIG. 174.—Viscosities of mixed potassium hydroxide and potassium carbonate solutions.

Mixtures of Potassium Hydroxide and Potassium Carbonate Solutions.—The expression

$$\mu = \mu_1 \left(\frac{\mu_2}{\mu_1}\right)^n. \qquad (44)$$

correlates the data for mixtures of potassium hydroxide and potassium carbonate solutions at the same concentration. In this case, n is defined as $0.791\,y$ between $y = 0$ and $y = 0.55$ and as $(1.2556y - 0.2556)$ between $y = 0.55$ and $y = 1.00$, although no cognizance need be taken of the varying definition of n in using Fig. 174, designed to solve the equation rapidly and accurately.

Table XLVII indicates the nature of the agreement between the empirical expression and the original data for total normalities of 0.5 to 8 [Eq. (44)].

TABLE XLVII

y	Average deviation in viscosity, per cent		
	20°C.	30°C.	40°C.
0.277	0.2	0 8	0.3
0.537	−0.8	−0.3	−0.8
0.759	−0.8	−0.2	−0.5

The use of Fig. 174 is illustrated by the following example: A solution of potassium hydroxide with a viscosity of 1.850 centipoises is mixed with a solution of potassium carbonate having a viscosity of 2.553 centipoises. The solutions have the same concentration, and the mixture contains 40 per cent potassium hydroxide solution by volume and 60 per cent potassium carbonate solution. What is the viscosity of the mixture? The ratio of the viscosities μ_2/μ_1 is (2.553/1.850), or 1.380. Following the key, connect 1.380 on the scale at the left with 60 per cent on the y scale, and note the intersection with the A axis. Connect this point with 1.850 on the μ_1 scale, and read the desired value on the μ scale as 2.17 centipoises.

VISCOSITY NOMOGRAPH FOR SALT SOLUTIONS[1]

In designing chemical-engineering equipment where the flow of salt solutions has to be considered, it is frequently necessary to estimate viscosities at various concentrations. Figure 175 facilitates such estimation in the case of aqueous solutions of 40 industrially important salts and 4 common acids and is based on data given by Perry.[2] This originated with Reyher[3] and with Wagner.[4] As tabulated in the literature, the data cover concentrations of ⅛, ¼, ½, and 1 normal, while the chart

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[1] *Chem. & Met. Eng.*, **43**, 485 (1936).

[2] PERRY, JOHN H., "Chemical Engineers' Handbook," 2d ed., p. 679, McGraw-Hill Book Company, Inc., New York, 1934.

[3] REYHER, R., *Z. physik. Chem.*, **2**, 749 (1888).

[4] WAGNER, J., *Z. physik. Chem.*, **5**, 31 (1890).

embraces all normalities between 0.1 and 1. At the same time, it retains a conveniently compact form.

The mechanism of the chart is predicated upon Arrhenius's relationship[1]

$$\mu = \mu_1^n$$

where μ is the specific viscosity (referred to water at the same temperature) of a solution of normality n, and μ_1 is the specific viscosity of a normal solution.

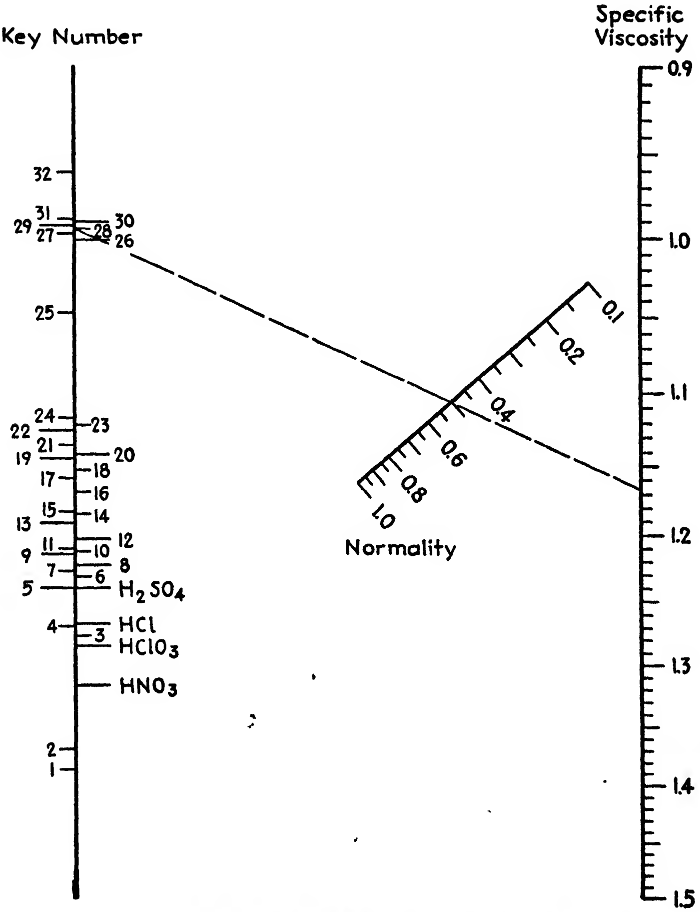

FIG. 175.—Viscosities of salt solutions between 0.1 and 1 *N*.

For ready reference and to avoid overcrowding of the chart, one of the parallel axes bears a scale of key numbers each corresponding to one

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[1] ARRHENIUS, S. A., *Z. physik. Chem.*, 1, 285 (1887).

or more salts. The key numbers may be identified by means of Table XLVIII.

In using the chart, find the key number from the table and connect the point so numbered on the axis at the left with the normality of the solution, producing the line to meet the specific-viscosity scale in the desired value. Thus, to find the specific viscosity of a 0.5 *N* aqueous solution of copper sulphate at 25°C., connect 28 (key number) on the key number scale with 0.5 on the normality scale and produce the line to meet the specific-viscosity scale in the value 1.165.

TABLE XLVIII.—KEY NUMBERS IDENTIFYING POINTS ON SPECIFIC-VISCOSITY CHART

	Chloride	Nitrate	Sulfate	Chromate
Aluminum			32	
Barium	12	5		
Cadmium	13	17	26	
Calcium	16	11		
Cobalt	23	17	27	
Copper	23	19	28	
Lead		7		
Lithium	15		25	
Magnesium	22	18	31	
Manganese	24	20	30	
Nickel	23	19	29	
Potassium	2	1	8	9
Silver		3		
Sodium*	6	4		
Strontium	14	10		
Zinc	21	17	31	

* Sodium bromide and chlorate, respectively, 4 and 5.

SPECIFIC GRAVITY AND VISCOSITY OF SODIUM CARBONATE SOLUTIONS[1]

Roberts and Mangold[2] have presented excellent data covering the specific gravities and viscosities of sodium carbonate solutions over the temperature range 22.5 to 98°C. and the concentration range 1 to 6 normal. The data appear in tabular form and as specific gravity-normality isotherms for 22.5, 40, 50, 60, 70, 75, 85, and 98°C., and as viscosity-normality isotherms for 22.5, 50, 75, and 98°C.

In view of the industrial importance of sodium carbonate and the desirability of readily usable specific-gravity and viscosity data in connection with equipment design, it has appeared worth while to correlate the data by means of empirical equations and to construct nomographic charts based upon these relationships. Such charts enable

[1] *Chem. & Met. Eng.*, **47**, 690 (1940).

[2] ROBERTS, L. D., and G. B. MANGOLD, *Ind. Eng. Chem.*, **31**, 1293 (1939).

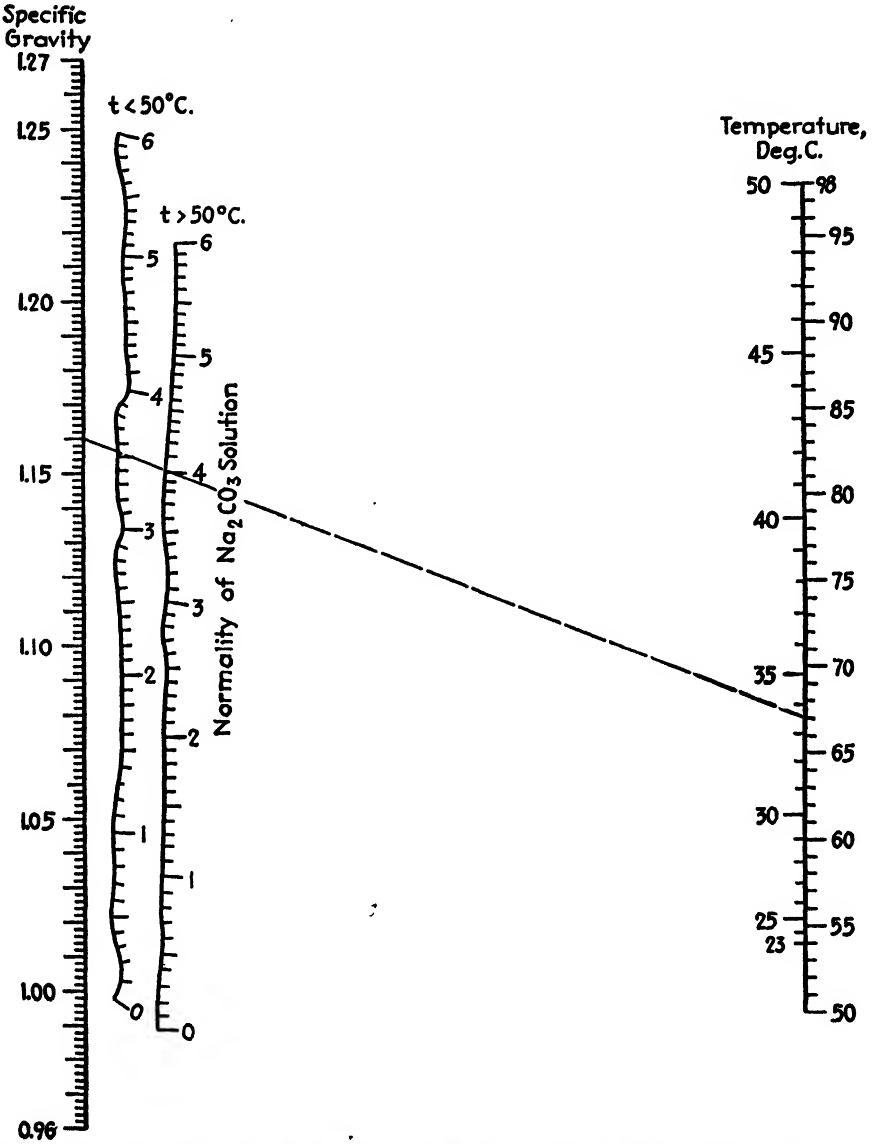

FIG. 176.—Specific gravity–temperature–concentration relationships for sodium carbonate solutions.

rapid and reliable interpolation and greatly extend the utility of the original data.

Specific-Gravity-Temperature-Concentration Relationships.—Above 50°C., the specific gravity δ and the centigrade temperature t are related by the expression

$$\delta = at + b,$$

while below 50°C., the relationship is given by

$$\delta = a\left(t + \frac{214.8}{(20 - t)^4}\right) + b$$

where a and b depend upon the normality as shown by Table XLIX.

The broken line in Fig. 176 indicates that a sodium carbonate solution having a specific gravity of 1.160 at 33.5°C. has a concentration of 3.54 N and that a solution having the same specific gravity at 67°C. would test 4.01 normal. Table L illustrates the nature of the agreement between experimental values of the normality N and values read from Fig. 176, the average deviation being slightly under 0.4 per cent.

Viscosity-Temperature-Concentration Relationships.—Correlation of the viscosity μ, in centipoises, with normality N may be effected by the expression

$$\log \sin 10\mu = aN + b$$

TABLE XLIX

Normality	Above 50°C.		Below 50°C.	
	$a \times 10^6$	b	$a \times 10^6$	b
0	−563	1.0168	−399	1.0087
1	−600	1.0680	−434	1.0600
2	−629	1.1154	−539	1.1109
3	−653	1.1612	−570	1.1570
4	−633	1.2020	−672	1.2040
5	−722	1.2481	−634	1.2427
6	−735	1.2864	−526	1.2760

where 10 μ is considered to be degrees circular measure and where a and b are defined by the equations

$$a = 0.15037 - 0.00063430t - e^{-2.8754-0.062725t}$$

$$b = -0.66694 - 0.0063237t - \frac{0.1059}{e^{0.07525(73.5-t)} + e^{0.07525(t-73.5)}}.$$

TABLE L

Observed normality	1.00			2.00			3.00			4.00			5.00			6.00		
t, °C.	δ	N	Percentage deviation	δ	N	Percentage deviation	δ	N	Percentage deviation	δ	N	Percentage deviation	δ	N	Percentage deviation	δ	N	Percentage deviation
22.5..........	1.047	0.98	−2.0	1.095	1.97	−1.5	1.141	3.00	0.0	1.185	4.00	0.0	1.225	5.00	0.0	1.262	6.02	0.3
40............	1.043	1.02	2.0	1.090	2.02	1.0	1.134	3.00	0.0	1.177	4.01	0.3	1.217	4.99	−0.2	1.254	5.98	−0.3
60............	1.032	1.00	0.0	1.077	1.98	−1.0	1.122	3.00	0.0	1.164	3.99	−0.3	1.205	5.00	0.0	1.243	6.02	0.3
80............	1.020	1.00	0.0	1.065	2.00	0.0	1.109	3.00	0.0	1.152	4.02	0.5	1.190	4.99	−0.2	1.228	6.01	0.2
98............	1.009	1.00	0.0	1.054	2.00	0.0	1.098	3.02	0.7	1.140	4.01	0.3	1.177	4.99	−0.2	1.214	5.99	−0.2

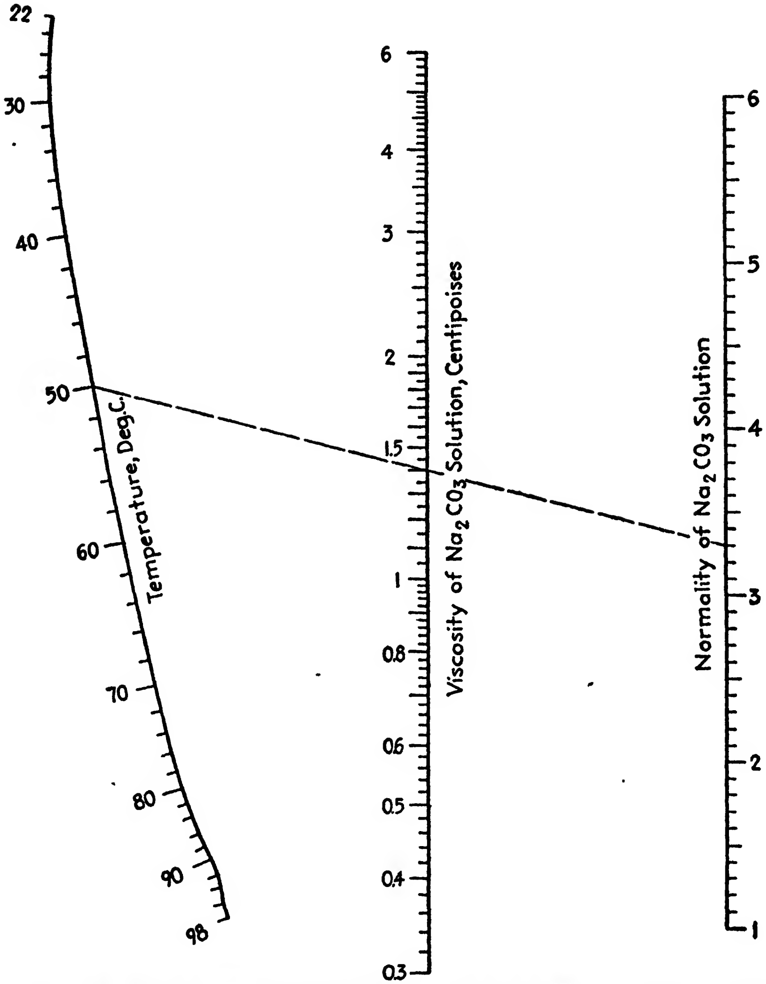

Fig. 177.—Viscosity-temperature-concentration relationships for sodium carbonate solutions.

The broken line in Fig. 177 indicates that the viscosity of a 3.30 *N* solution of sodium carbonate is 1.40 centipoises at 50°C. Table LI lists observed and calculated values of the viscosity and their percentage deviations, the average discrepancy being about 0.5 per cent.

TABLE LI

t, °C.	22.5			50		
N	Viscosity, centipoises		Percentage deviation	Viscosity, centipoises		Percentage deviation
	Obs.	Chart		Obs.	Chart	
1	1.201	1.180	−1.7	0.756	0.750	−0.8
2	1.564	1.573	0.6	0.976	0.980	0.4
3	2.116	2.110	−0.3	1.283	1.285	0.2
4	2.863	2.845	−0.6	1.678	1.690	0.7
5	3.980	3.920	−1.5	2.246	2.245	0.0
6	5.650	5.690	0.7	2.994	2.981	−0.4

t, °C.	75			98		
N	Viscosity, centipoises		Percentage deviation	Viscosity, centipoises		Percentage deviation
	Obs.	Chart		Obs.	Chart	
1	0.468	0.465	−0.6	0.347	0.349	0.6
2	0.584	0.589	0.9	0.428	0.429	0.2
3	0.746	0.746	0.0	0.530	0.526	−0.8
4	0.950	0.945	−0.5	0.647	0.646	−0.2
5	1.198	1.200	0.2	0.794	0.793	−0.1
6	1.521	1.524	0.2	0.960	0.967	0.7

NOMOGRAPH FOR CALCULATING VISCOSITY OF ROSINS[1]

Using the data of Peterson and Pragoff[2] on the viscosity-temperature relationships of rosins, Nash[3] has shown that the viscosity of many rosins may be approximated, for any desired elevated temperature, from the melting point through use of the formula

$$\log \eta = \frac{6.05t_m - 54}{t - 20} - 3.50$$

where η is the viscosity, in poises, at a temperature of t°C. when the melting point, by the thermometer drop method, is t_m°C.

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[1] *Chemist-Analyst*, **22** (4), 11 (1933).

[2] PETERSON, J. M., and E. PRAGOFF, Jr., *Ind. Eng. Chem.*, **24**, 173 (1932).

[3] NASH, H. E., *Ind. Eng. Chem.*, **24** 177 (1932).

In order to extend this useful equation to many who might not otherwise be able to solve it and to provide a rapid and accurate means of solution in any case, Fig. 178, has been prepared. Its use is illustrated

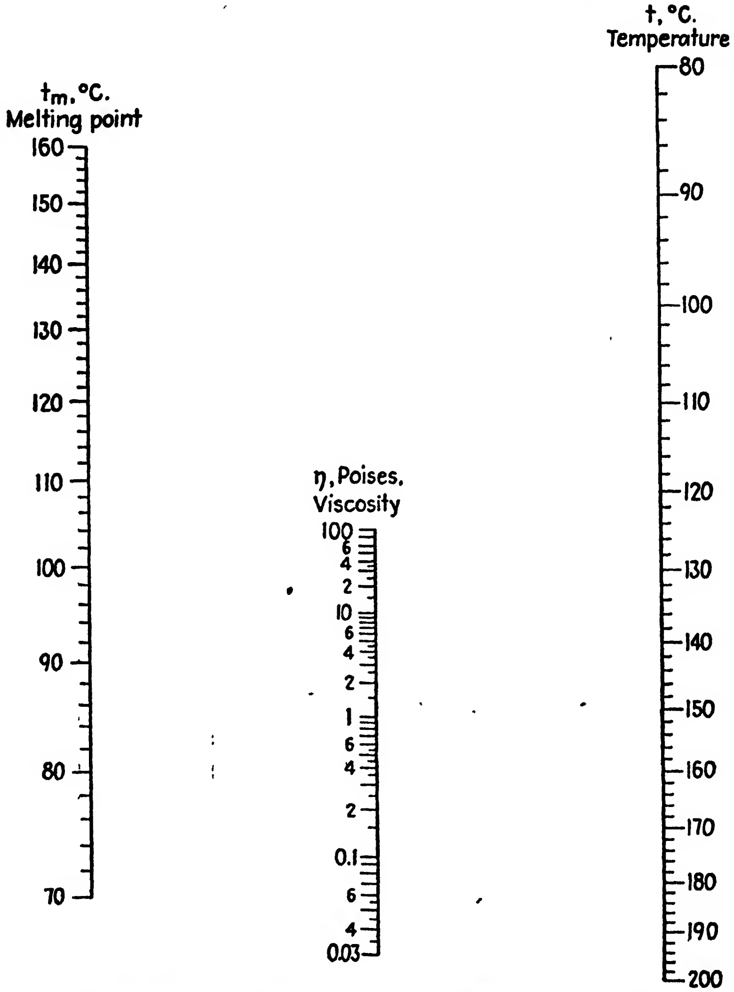

FIG. 178.—Viscosities of rosins when the temperatures and melting points are known.

as follows: At 160°C., what is the viscosity of a certain limed rosin which shows a melting point of 114°C.? Connect 114 on the t_m scale with 160 on the t scale, and read the desired value as 11 poises on the η scale.

CHAPTER XIX

MISCELLANEOUS NOMOGRAPHS

ALIQUOT PORTION NOMOGRAPH[1]

The analytical chemist frequently encounters procedures that read somewhat as follows: "Pipet v' ml. of a stock solution containing C g. of solute per liter into a V-ml. volumetric flask. Dilute to the mark with water, mix thoroughly, and pipet out v ml. for each determination." In other instances, he may desire to introduce a certain weight W (W being quite a small amount) of a solute into a determination from a concentrated stock solution and is confronted with the choice of pipets and flasks.

Under such conditions, the weight in grams, W, of solute finally delivered may be found by solving the equation

$$W = \frac{vCv'}{1{,}000V}$$

which is most readily accomplished by means of a nomograph.

Such an alignment chart (Fig. 179) is illustrated here and is constructed quite simply. Use is made of the auxiliary equations

$$A = \frac{C}{V} \qquad \text{and} \qquad B = vA$$

so that

$$W = \frac{v'B}{1{,}000}.$$

By choosing a modulus of 12.5 cm. for the V, v, and v' axes, it is possible to use a modulus of 25 cm. for the A, B, C, and W axes. The smaller modulus is sufficient for the V, v, and v' axes which are scaled in very few values, leaving the larger modulus for the more closely graduated C and W scales. Although this arrangement requires seven axes, it is to be preferred to another design requiring but five axes, two of which must serve a double purpose since such a plan would necessitate much smaller moduli with attendant loss of accuracy. For laboratory use, it is suggested that adjacent axes be spaced at intervals of 5 cm., making the chart measure about 28 by 34 cm.

The use of Fig. 179 is illustrated as follows: What weight of solute is delivered when 50 ml. of a solution containing 20 g. of solute per liter

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[1] *Chemist-Analyst*, **27** (2), 35 (1938).

is diluted to 500 ml. and 25 ml. are pipetted out? Following the key, connect 20 on the *C* scale with 500 on the *V* scale, and produce the broken line to meet the *A* axis. From this point, draw a line to 25 on the *v* scale, and produce the broken line to meet the *B* axis. From this point, draw a line to 50 on the *v′* axis, and produce the broken line to meet the *W* scale in the desired value, 0.05 g.

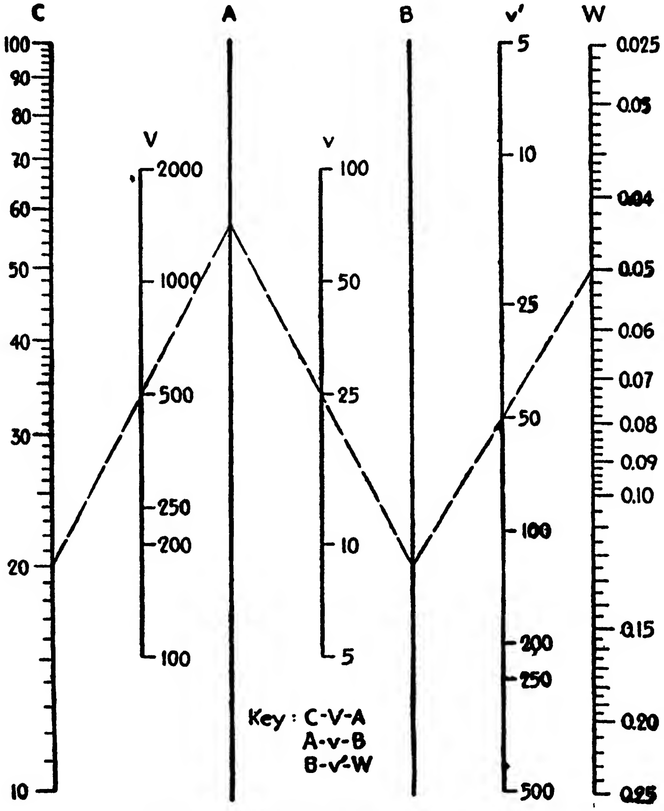

FIG. 179.—Aliquot portion nomograph.

Both *C* and *W*, of course, may represent the concentration and weight, respectively, of a certain anion or cathion, as Cu^{++} or SO_4^{--}, in place of the total concentration of solute, $CuSO_4$.

BOILING POINT-MOLECULAR WEIGHT CHART FOR HIGHER HYDROCARBONS[1]

Studies of the molecular weights and boiling points (at 1 mm. mercury) of a number of higher hydrocarbon oils by Mair and Willingham

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[1] *Ind. Eng. Chem.*, **32**, 1148 (1940).

and by Lucy[1] resulted in the expressions

$$T = 111.3n^{0.4895}$$

$$M = \left(\frac{T}{35}\right)^{2.276}$$

where T = uncorrected distilling temp. at 1 mm. mercury, °K.
n = number of carbon atoms per molecule.
M = molecular weight.

From them may be derived a third equation relating the number of carbon atoms and the molecular weight:

$$M = 13.91n.$$

All three expressions can be solved readily by Fig. 180, in which horizontal lines cut the three scales in consistent values. Thus, reading from right to left, a higher hydrocarbon exhibiting a boiling point of 231°C. under a pressure of 1 mm. mercury would have an approximate molecular weight of 432 and contain 31 carbon atoms per molecule.

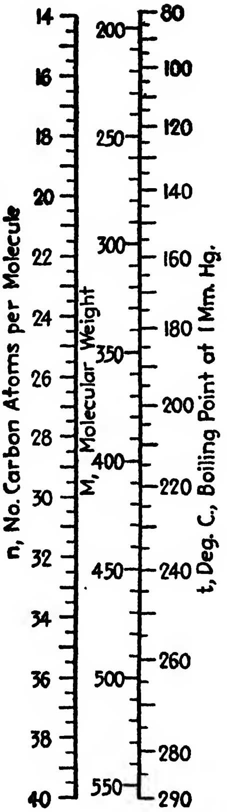

FIG. 180.—Boiling points of higher hydrocarbons when the numbers of carbon atoms or molecular weights are known.

NOMOGRAPH FOR HANDLING CONCENTRATION CONVERSIONS[2]

Solubilities and many other data involving the concentration of solutions, whether aqueous or otherwise, are reported in a wide variety of units. Usually these are grams per liter of solution, grams per 1,000 g. of solvent, grams per 1,000 g. of solution, or percentages. The need for a rapid and convenient method of converting from one basis to another is met by Fig. 181, which is based on the following relationships:

$$S = \frac{1{,}000\sigma}{1{,}000 - \sigma} \quad \text{or} \quad \sigma = \frac{1{,}000S}{1{,}000 + S}$$

$$s = \delta\sigma = \frac{1{,}000S\delta}{1{,}000 + S}$$

$$S = \frac{1{,}000s}{1{,}000\delta - s}$$

where S = concentration, g. per 1,000 g. solvent.
σ = concentration, g. per 1,000 g. solution.
s = concentration, g. per liter solution.
δ = specific gravity of the solution.

---

[1] MAIR, B. J., and C. B. WILLINGHAM, *Ind. Eng. Chem.*, **28**, 1457 (1936); F. A. LUCY, *ibid.*, **30**, 959 (1938).

[2] *Chemist-Analyst*, **23** (2), 7 (1934).

The chart also enables conversion between Baumé (B) and specific-gravity values according to the equations

$$\delta = \frac{145}{145 - B} \qquad \text{where } \delta > 1$$

and

$$\delta = \frac{140}{130 + B} \qquad \text{where } \delta < 1$$

and performs the calculations indicated by $s = \dfrac{145\sigma}{145 - B}$ for solutions heavier than water and by $s = \dfrac{140\sigma}{130 + B}$ for solutions lighter than water.

Direct conversion may be made between S and σ, using the double scale at the right, and between B and δ, using the double scale at the left. Note that at $\delta = 1$, $B = 0$°Bé. on the scale for solutions heavier than water and that $B = 10$°Bé. on the scale for solutions lighter than water.

The use of Fig. 181 may be illustrated as follows: A solution has a concentration of 26 per cent and a Baumé value of 24°. What is the concentration in grams per 1,000 g. of solution, grams per 1,000 g. of solvent, and in grams per liter of solution? What is the specific gravity of the solution? Twenty-six per cent, or 26 g. per 100 g. of solution, is the same as $\sigma = 260$ g. per 1,000 g. of solution. Opposite $\sigma = 260$, read $S = 351$ g. per 1,000 g. of solvent. Connect 260 on the σ axis with 24 on the B scale, and read s as 312 g./l. on the s scale. Opposite 24 on the B scale, read δ as 1.20.

DESIGN CHART TO CALCULATE FLASH POINT OF LUBRICANTS OF KNOWN COMPONENTS[1]

Figure 182 enables convenient calculation of the flash point of a mixture of lubricating oils, when the composition of the mixture and the flash points of the components are known, and is based on an equation given by Thiele,[2]

$$F_m = -100 \log [x(10^{-0.01F}) + x'(10^{-0.01F'})]$$

where F_m is the flash point of a mixture of two oils, A and B, in degrees Fahrenheit; F and F' are the flash points of oils A and B, respectively; and x and x' are the respective fractions, by volume, of A and B present in the blend.

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[1] *Oil Gas. J.*, **31**, 38 (1932).

[2] THIELE, E. W., *Ind. Eng. Chem.*, **19**, 259 (1927).

The use of Fig. 182 in the case of a two-component mixture is illustrated as follows: A lubricating oil consists of 40 per cent oil *A* having a flash point of 250°F. and 60 per cent oil *B* having a flash point of 350°F. What is the flash point of the mixture? Connect 40 on the x scale with 250 on the F scale, and produce the line to the x' axis. Connect 60 on the x' scale with 350 on the F' scale, and produce the line to the x axis. Connect the points so determined, and note the intersection of the connecting line with the F_m scale at the desired value, 284°F.

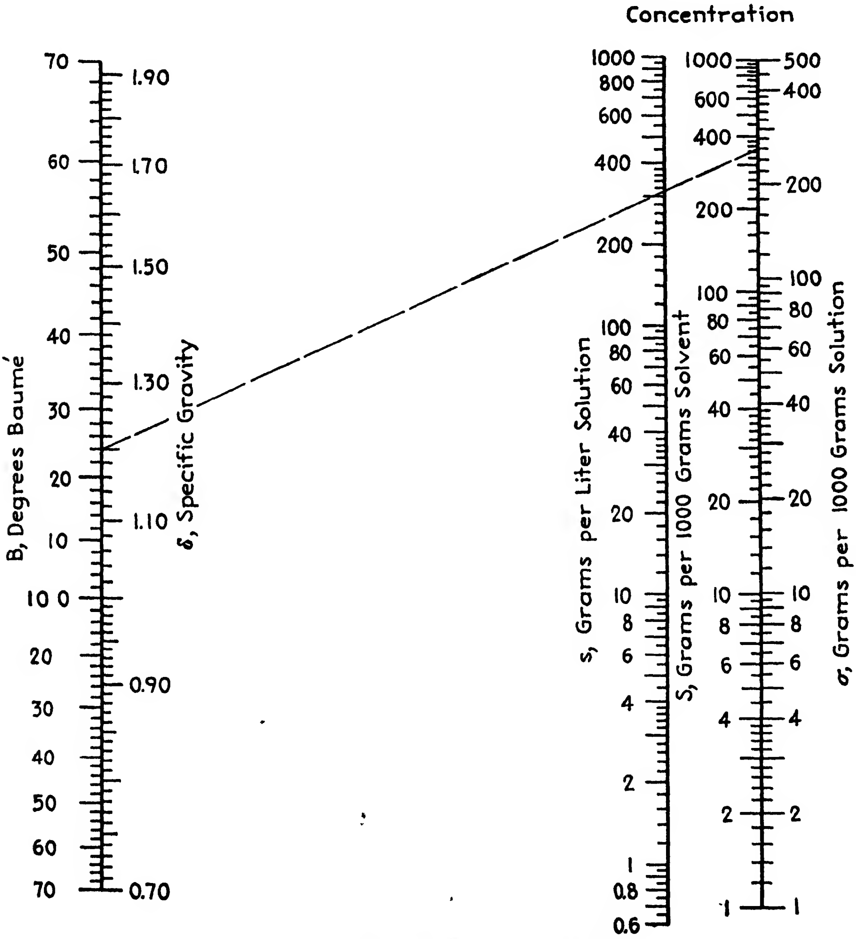

FIG. 181.—Concentration conversions.

The flash point of a mixture of three oils can be calculated in a similar manner by finding first the flash point of the oil resulting from a mixture of any two components and then calculating the flash point of the oil resulting from combination of the mixture with the third oil. As an illustration of such a case, consider Table LII.

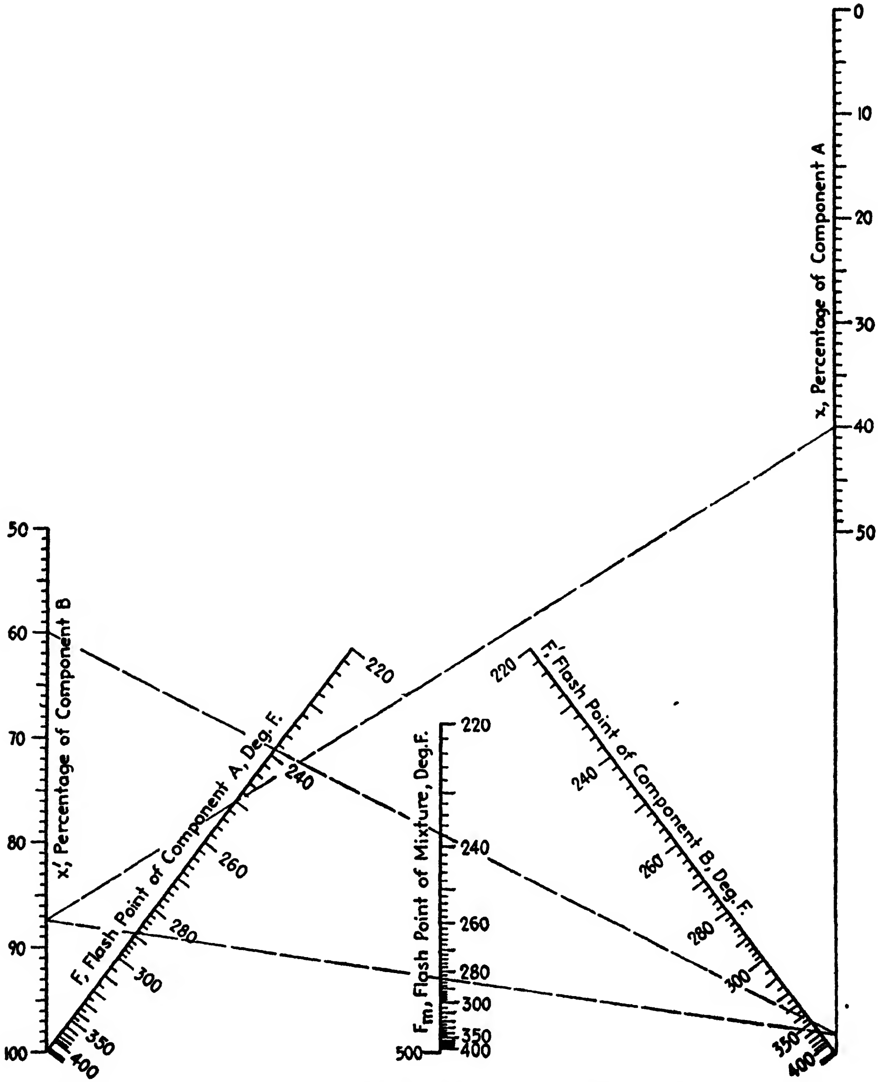

FIG. 182.—Estimation of the flash point of a mixture of oils from the flash points and percentages of the components.

The flash point of the blend of *A* and *B* is 284°F. since the percentages 30 and 45 are in the ratio of 40:60 as in the previous example. The problem then becomes that of calculating the flash point of a blend of

75 per cent of an oil having a flash point of 284°F. with 25 per cent of an oil having a flash point of 400°F. This will be found to be 296°F.

TABLE LII

Oil	Percentage	Flash point
A	30	250
B	45	350
C	25	400

NOMOGRAPHIC CHARTS FOR VOLUME RELATIONS OF GASES AT HIGH PRESSURES[1]

With the advent of high-pressure processes, attention has focused on the failure of the ideal gas laws to serve the purposes of the engineer in an adequate manner, as delineated so clearly by the 1936 Perkin Medallist, Prof. Lewis.[2] For instance, the use of the perfect gas laws in calculating the volumes of hydrogen, nitrogen, and carbon monoxide when compressed at 0°C. from atmospheric pressure to 800 atm. results in values which are, respectively, 36, 44, and 45 per cent too low, the discrepancies growing with increasing pressure.

Compressibility Factors Determined.—The ideal gas laws can be corrected through the use of experimentally determined compressibility factors which depend upon temperature and pressure and are found to vary from gas to gas.

These compressibility factors have been reported by the Fixed Nitrogen Research Laboratory, U. S. Department of Agriculture, and cover the industrially important carbon monoxide, hydrogen, nitrogen, and a 3:1 (by volume) mixture of hydrogen and nitrogen.[3]

For temperature conditions corresponding to the subscripts 1 and 2, the corrected gas law becomes

$$V_2 = V_1 \frac{P_1}{P_2} \frac{c_2}{c_1} \tag{45}$$

where V and P are volumes and pressures, respectively, and c is the compressibility constant for a given temperature and pressure.

Dilley[4] has made the excellent compressibility data more readily usable through the preparation of charts for each of the four gases. In these, for various temperatures, the quotient of P and c, designated as

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[1] *Chem. & Met. Eng.*, **44**, 384 (1937).

[2] LEWIS, W. K., *Chem. & Met. Eng.*, **43**, 32 (1936); *Ind. Eng. Chem.*, **28**, 257 (1936).

[3] BARTLETT, E. P., *J. Am. Chem. Soc.*, **49**, 1955 (1927); BARTLETT, E. P., H. L. CUPPLES, and T. H. TREMEARNE, *ibid.*, **50**, 1275 (1928); BARTLETT, E. P., H. C. HETHERINGTON, H. M. KVALNES, and T. H. TREMEARNE, *ibid.*, **52**, 1363, 1374 (1930).

[4] DILLEY, J. R., *Chem. & Met. Eng.*, **38**, 280 (1931).

the volume relation factor f, is plotted against the pressure. Since $f_1 = P_1/c_1$ and $f_2 = P_2/c_2$, Eq. (45) becomes

$$V_2 = V_1 \frac{f_1}{f_2}. \tag{46}$$

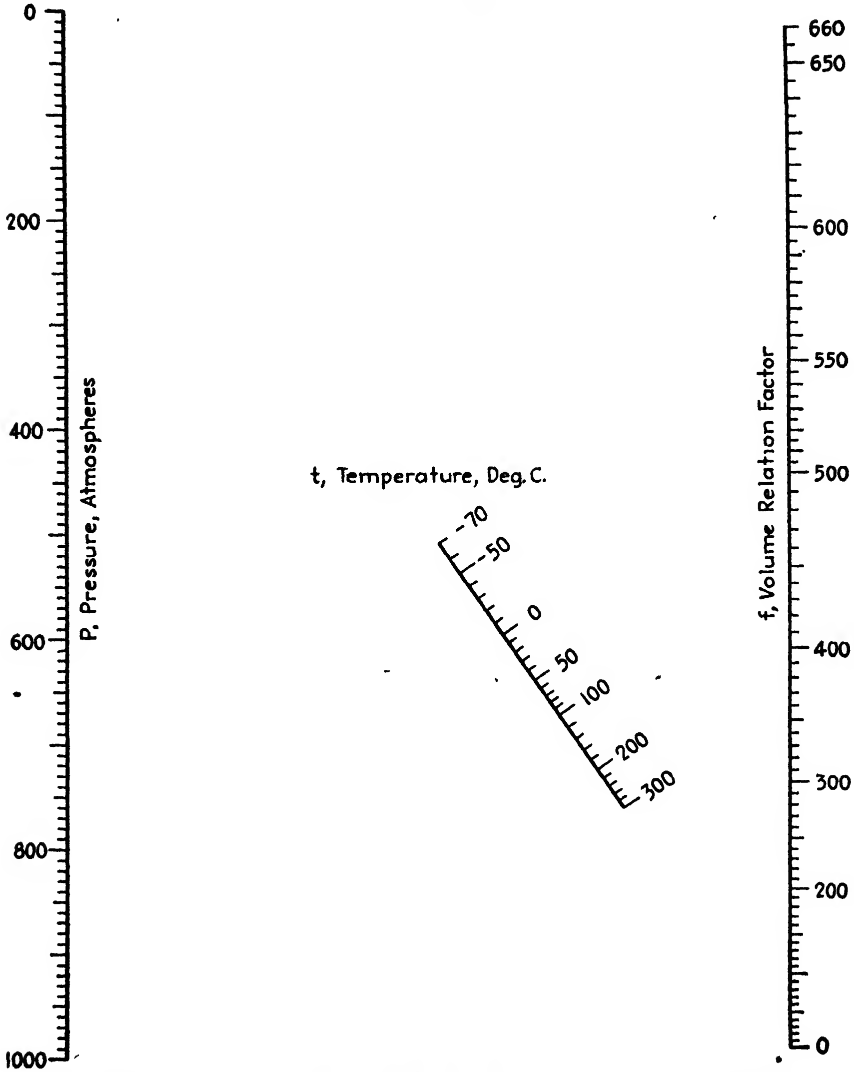


FIG. 183.—Volume-relation factors for 3:1 mixtures (by volume) of hydrogen and nitrogen when the pressures and temperatures are known.

The plots are a distinct improvement, but they still leave much to be desired from the standpoint of interpolation. The factor-pressure isotherms are nearly linear up to about 150 atm. but show considerable curvature between 150 and 1,000 atm. In addition, the temperatures covered increase in uneven steps, as −70, −50, −25, 0, 20, 50, 100, 200,

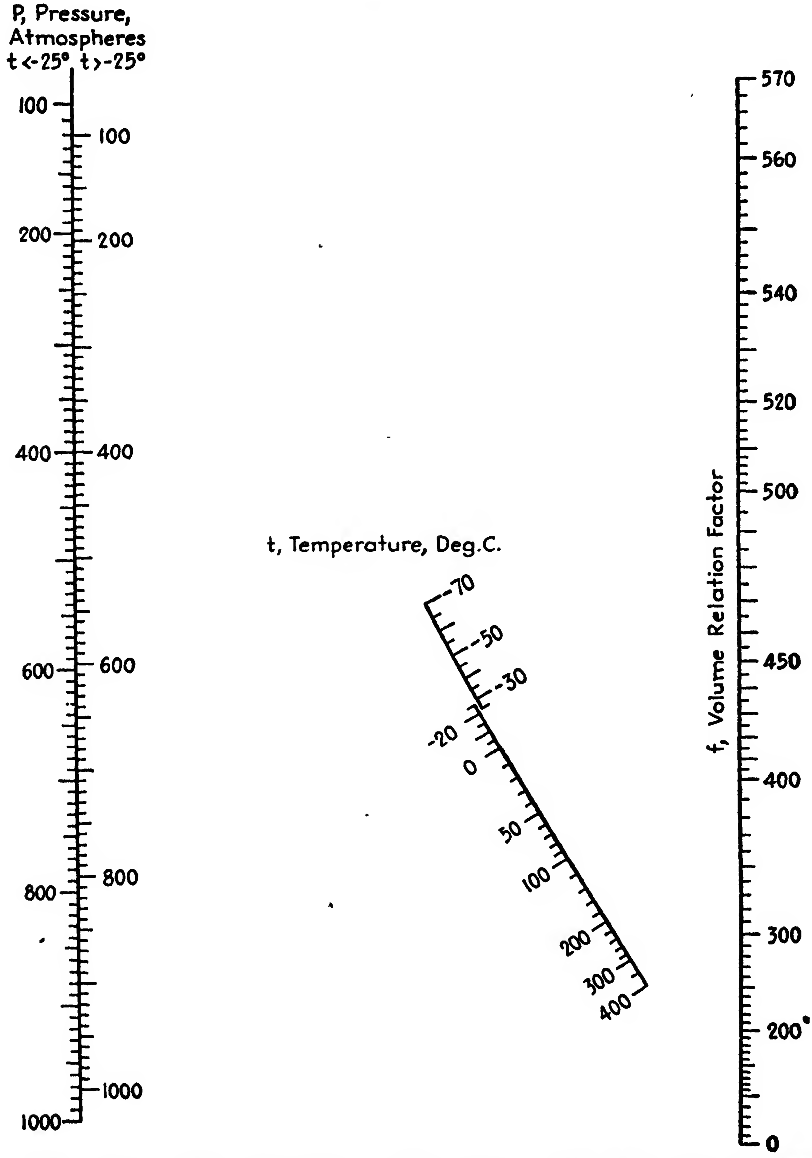
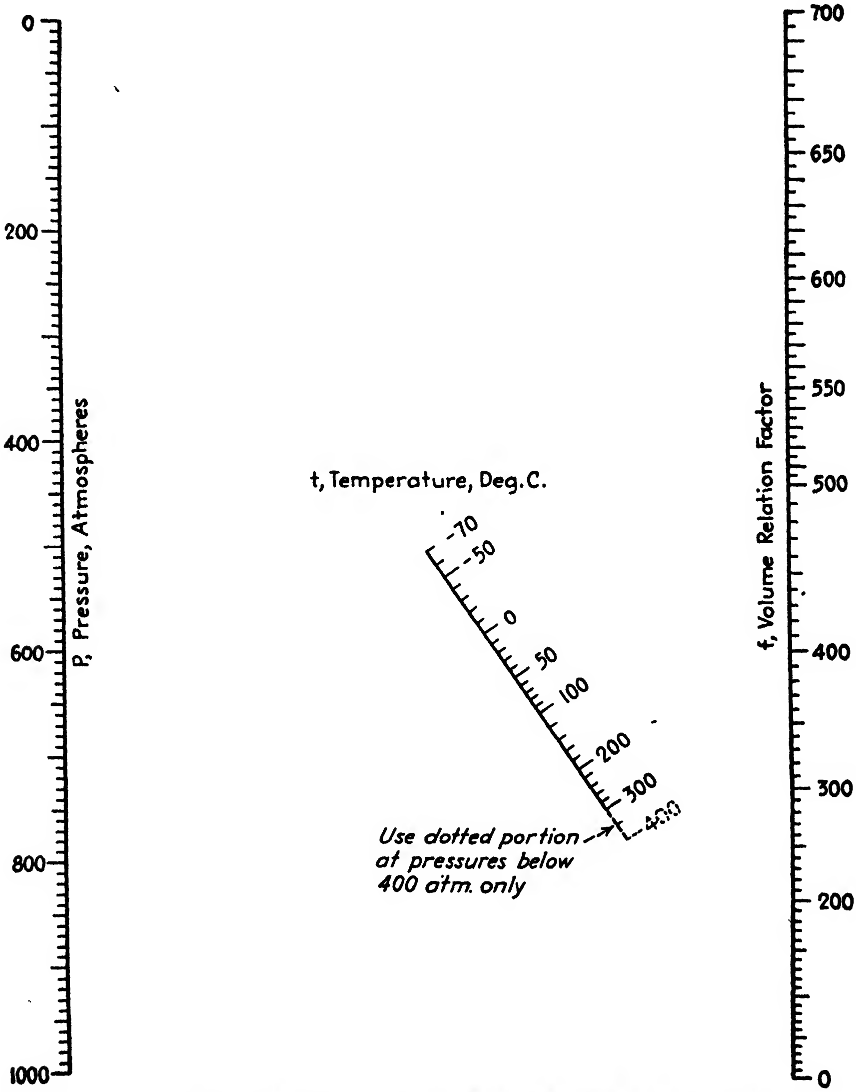


FIG. 184.—Volume-relation factors for nitrogen when the pressures and temperatures are known.

and 300°C., for hydrogen; and the scales are graduated to only 50 units in volume relation factor and to only 100 atm. Thus, while it is fairly easy, in the case of hydrogen, to read the factor corresponding to exactly 600 atm. and exactly 100°C., it is difficult to interpolate *f* for, say, 640 atm. and 160°C.



Use dotted portion at pressures below 400 atm. only

FIG. 185.—Volume-relation factors for hydrogen when the pressures and temperatures are known.

There is evident need for a different sort of graphical representation of pressure, temperature, and volume relation factor data such that interpolations can be made along closely graduated scales with greater accuracy and facility. These requirements are met by Figs. 183 to 187, where, in each case, it is sufficient to connect values on the pressure and temperature scales with a straightedge in order to read the volume-relation factor with gratifying ease and accuracy. The charts are based directly upon the original data of the Fixed Nitrogen Research Laboratory and have resulted from close studies of the relationships between the pressures and factors at the various temperatures.

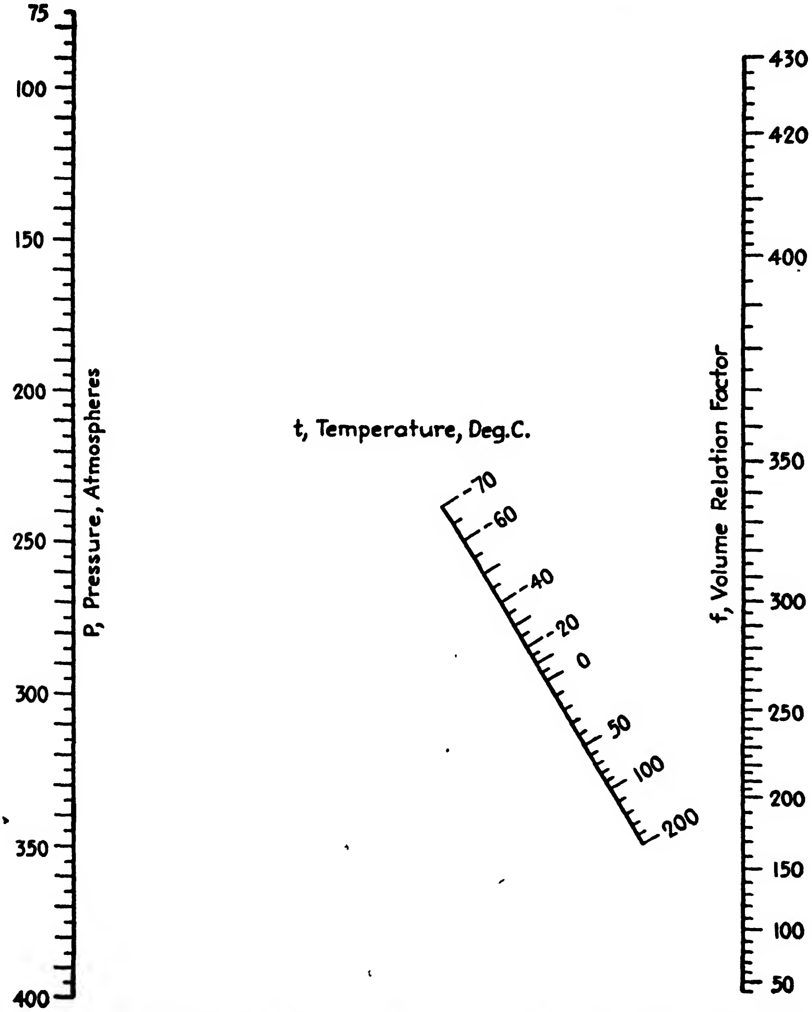


FIG. 186.—Volume-relation factors for carbon monoxide (below 400 atm.) when the pressures and temperatures are known.

The use of the charts is illustrated as follows: Given 100 cu. ft. of a 3:1 mixture (by volume) of hydrogen and nitrogen at 750 atm. and 30°C., what is the volume at 250 atm. and 260°C.? One reads the volume relation factors f_1 and f_2 corresponding to the initial and final conditions and substitutes them in Eq. (46). In Fig. 183, a line connecting $P = 750$ with $t = 30$ crosses the f scale at 442, the value of f_1.

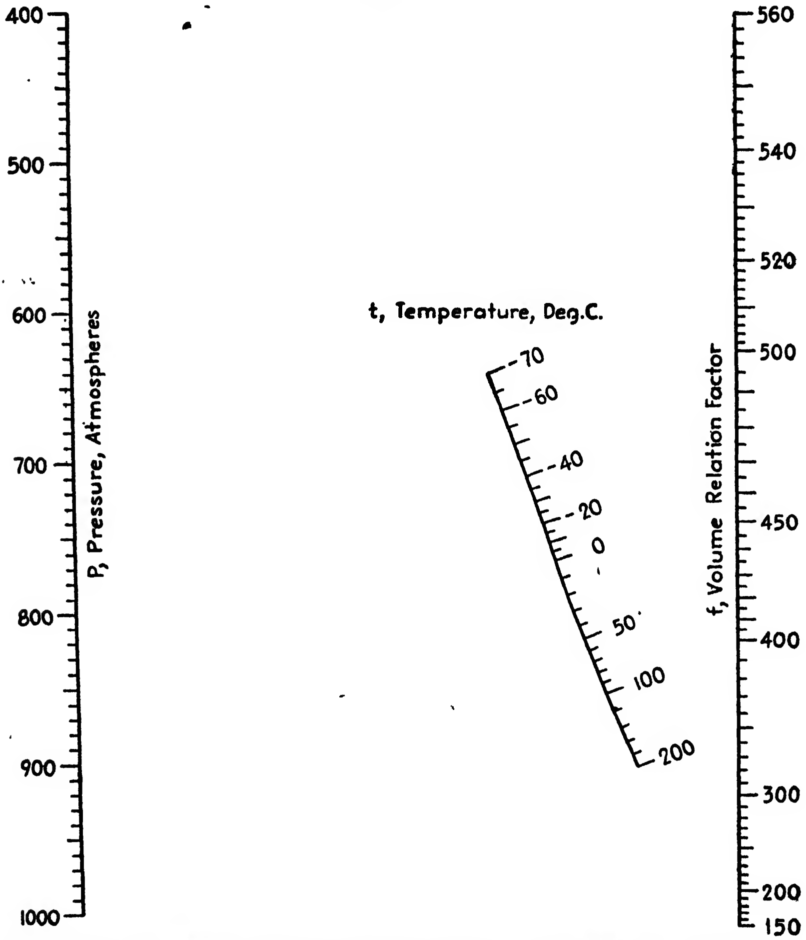


FIG. 187.—Volume-relation factors for carbon monoxide (above 400 atm.) when the pressures and temperatures are known.

Similarly, a line connecting $P = 250$ with $t = 260$ indicates a value of 114 for f_2. The volume under the final conditions is then

$$V_2 = 100(\tfrac{442}{114}) = 388 \text{ cu. ft.}$$

When the volume at a given pressure and temperature is known, the charts can also be used to determine either the pressure or temperature required to yield a new volume. The value of f_1 is first found and f_2 is calculated by transposing Eq. (1) into the form, $f_2 = (V_1/V_2)f_1$. Then the unknown pressure or temperature value is read from the chart. Thus, if 25 cu. ft. of nitrogen at 720 atm. and 80°C. is expanded to 32 cu. ft. at 380 atm., what final temperature will be required? Reference to Fig. 184 shows that the volume relation factor is 353 when $P = 720$ and $t = 80$. Hence $f_2 = (\frac{25}{32})353 = 276$. A line connecting 276 on the volume relation scale with 380 on the pressure scale crosses the temperature scale at the desired value, 31°C. In using the nitrogen chart, note that there are two pressure scales, one for use at temperatures below −25°C., the other for temperatures above this point.

Two Charts Cover Carbon Monoxide.—The following example will serve to illustrate the use of the carbon monoxide charts (Figs. 186 and 187), the former covering pressures between 75 and 400 atm. and the latter pressures between 400 and 1,000 atm. If 200 cu. ft. of carbon monoxide at 310 atm. and 10°C. is compressed to 110 cu. ft. at a temperature of −40°C., what pressure is required? Reference to the low-pressure chart (Fig. 186) yields a volume relation factor of 262.5 under the initial conditions. The final factor is given by $(\frac{200}{110})262.5 = 477$. Aligning $f = 477$ with $t = -40$ on the high-pressure chart (Fig. 187), results in a pressure value of 762 atm.

At atmospheric pressure, the volume-relation factors for all four gases are nearly identical with values obtained from the expression $273/(273 + t)$, where t is the temperature in degrees centigrade. For convenience, they can be read from Fig. 188, the use of which is shown as follows: 2,500 cu. ft. of hydrogen at 1 atm. and 40°C. is put under a pressure of 550 atm. at 120°C. What is the final volume? Opposite 40°, the value of f_1 is read to be 0.872 in Fig. 188, while f_2 is found to be 298 through aligning $P = 550$ with $t = 120$ in Fig. 185. The final volume is $2{,}500(0.872/298) = 7.32$ cu. ft. In connection with the hydrogen chart (Fig. 185), it should be mentioned that the dotted portion of the temperature scale between 300 and 400°C. is restricted to use with pressures below 400 atm., the highest pressure covered by the original data at 400°C.

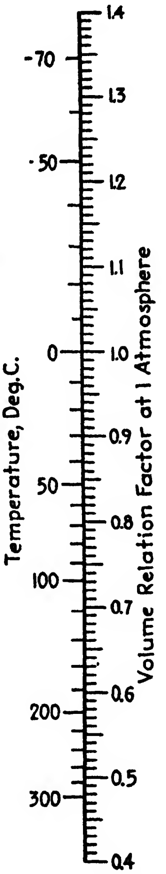


FIG. 188.—Volume-relation factors for nitrogen, hydrogen, their mixtures, and carbon monoxide at a pressure of 1 atm.

Calculation Shows Chart Accuracy.—Table LIII shows the nature of the agreement between volume-relation factors as read from the charts and those calculated directly from the data upon which the charts are based. With almost every combination of temperature and pressure values, the charts are good to well within 1 per cent.

Table LIII.—Calculated Volume Relation Factors Compared with Chart Factors

Gas	Temperature, °C.	Pressure, atm.	Volume relation factors		Percentage deviation
			Original data	Chart	
75% H_2—25% N_2	− 70	100	128	130	1.6
	− 50	200	216	218	0.9
	− 25	300	272	272	0.0
	0	400	310	310	0.0
	25	400	290	290	0.0
	50	600	362	363	0.3
	100	600	326	325	−0.3
	199	800	334	335	0.3
	300	1,000	339	340	0.3
H_2	− 70	100	125	125	0.0
	− 50	200	213	212	−0.5
	− 25	300	270	270	0.0
	0	400	312	312	0.0
	50	400	272	272	0.0
	100	600	333	334	0.3
	199	800	345	345	0.0
	299	1,000	356	355	−0.3
	400	400	145	145	0.0
N_2	− 70	100	157	168	7.0
	− 70	600	487	487	0.0
	− 50	200	255	260	2.0
	− 25	300	295	294	−0.3
	0	400	318	316	−0.6
	50	400	269	270	0.4
	100	600	305	306	0.3
	199	800	302	302	0.0
	300	1,000	301	300	−0.3
	400	1,000	269	268	−0.4
CO	− 70	100	163	164	0.6
	− 50	200	261	259	−0.8
	− 25	300	297	297	0.0
	0	400	320	320	0.0
	25	400	294	293	−0.3
	50	600	345	347	0.6
	100	600	307	306	−0.3
	150	800	327	328	0.3
	200	1,000	342	342	0.0

NOMOGRAPH FOR DETERMINATION OF MOISTURE IN HONEY[1]

Chataway[2] has shown that the viscosity of honey, as measured by the falling-sphere method, bears a close relationship to the moisture content.

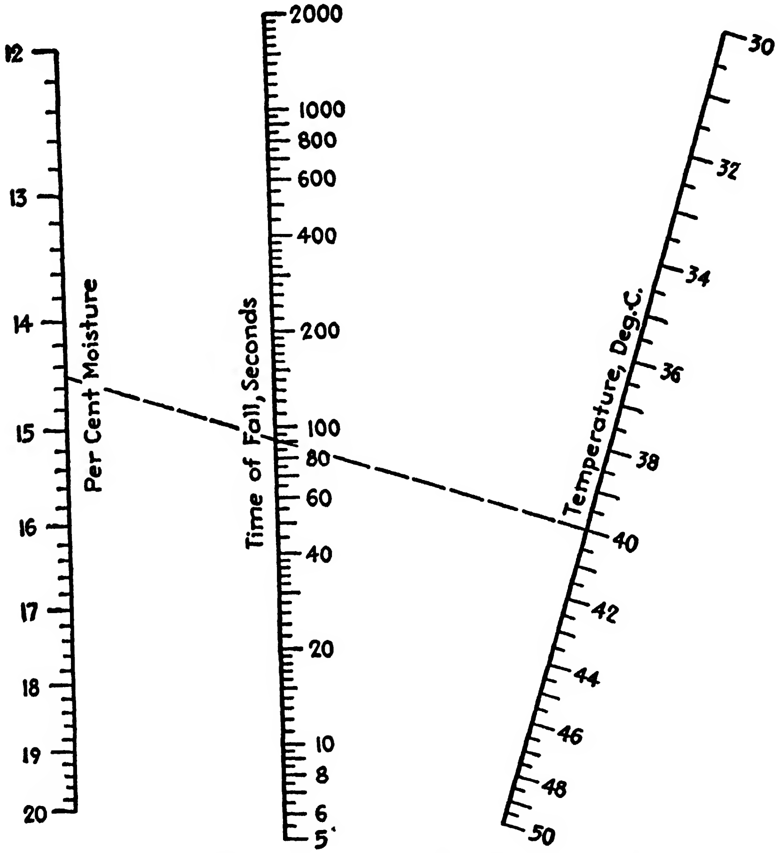


Fig. 189.—Percentage moisture in honey determined from the viscosity and temperature.

Oppen and Schuette,[3] using a modified viscometer of the Gibson-Jacobs type,[4] have presented excellent data showing the effect of temperature and moisture content upon viscosity and have developed an empirical expression connecting these variables. Their equation is

$$w = \frac{62{,}500 - 156.7T}{T(\log V + 1) - 2.287(313 - T)}$$

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[1] *Chemist-Analyst*, **29**, 87 (1940).

[2] Chataway, H. D., *Can. J. Research*, **6**, 532 (1932).

[3] Oppen, F. C., and H. A. Schuette, *Ind. Eng. Chem., Anal. Ed.*, **11**, 130–133 (1939).

[4] Gibson, W. H., and L. M. Jacobs, *J. Chem. Soc.*, **117**, 473 (1920).

where w is the percentage moisture in the honey; T is the centigrade-absolute temperature; and V is the viscosity or time in seconds required for a 0.16-cm. (0.06-in.) steel ball to fall through 15 cm. of honey in a standard-wall Pyrex tube of 21.2 mm. internal diameter.

The viscometric method for moisture determination, giving results in close agreement with the official drying method,[1] suggests the need for a convenient and accurate means of solving the above equation. In Fig. 189, designed to meet these requirements, the dashed line indicates that a honey showing a viscosity or time of fall of 92 sec. at 40°C. contains 14.5 per cent moisture.

NOMOGRAPHIC SOLUTION OF HUMIDITY CONVERSIONS[2]

A need for a method of handling conversions between percentage relative and percentage absolute humidities is evident and has prompted the development of several conversion charts, notably that of Lavine and Sutherland[3] and that of Monack.[4] Both, however, are subject to two disadvantages: (1) in their construction they require the careful plotting of a number of curves which are parabolic or hyperbolic in nature and (2) in their use they necessitate the interpolation of values between lines of rapidly changing curvature.

There is need for a conversion chart that will be simpler to prepare and easier to read. A nomograph will meet these requirements satisfactorily since it is a familiar property of the nomographic chart that curves are reduced to straight lines, or to a single curve, and that all interpolations are made along graduated axes. It is the purpose of this topic to present such a nomograph and to illustrate its use.

The equation connecting percentage absolute humidity H with percentage relative humidity R is

$$H = \frac{B - p}{B - Rp/100} R \tag{47}$$

where B is the barometric pressure and p is the vapor tension of water at the temperature in question. Equation (47) may be written as

$$\frac{HB}{R} - \frac{Hp}{100} = B - p,$$

and if S is made equal to HB/R so that

$$\frac{R}{B} = \frac{H}{S} \tag{48}$$

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[1] Association Official Agricultural Chemistry, "Official and Tentative Methods," 4th ed., p. 462, 1935.

[2] *Chem. & Met. Eng.*, **39**, 256 (1932).

[3] Lavine, I., and R. L. Sutherland, *Chem. & Met. Eng.*, **36**, 425 (1929).

[4] Monack, A. J., *Chem. & Met. Eng.*, **38**, 718 (1931).

the original equation becomes

$$S - \frac{Hp}{100} = B - p,$$

which, in turn, may be written as

$$\frac{p}{100} = \frac{B - S}{100 - H}. \tag{49}$$

Equations (48) and (49) are seen to be of the form

$$f(x) = \frac{F(y)}{\phi(z)},$$

and each can be charted in the form of an N-type nomograph, a discussion of which has been given elsewhere.[1]

Suffice it to say here that when B and p are expressed in millimeters of mercury a chart of a convenient size results from the use of unit representations or moduli of 0.3 and 0.05 cm. for the H and S axes, respectively, in the case of both Eqs. (48) and (49), superimposing the charts for the individual equations and finally discarding the S axis, which is of interest only during construction of the chart. The diagonal R scale results from Eq. (48), while the diagonal t scale arises from Eq. (49) where the scaled values of p, the vapor pressure, are replaced by the corresponding Fahrenheit temperatures.

Use of Fig. 190 is illustrated as follows: What is the percentage relative humidity of air when the percentage absolute humidity at 140°F. is 40? Connect 40 on the H scale with 140 on the t scale, and read the percentage relative humidity as 45.4 on the R scale.

As stated by Monack, inspection of Eq. (47) shows that H is indeterminate when $t = 212$°F. and $R = 100$, that for any value of R except 100, H is zero at 212°F., and that when solved for R as in

$$R = \frac{BH}{B - (1 - H/100)p}$$

Eq. (48) indicates that $R = 100$ for all values of H at 212°F. These points are all brought out very nicely by the nomograph: the t and R axes intersect at $t = 212$°F. and $R = 100$, so there is nothing to give direction to an index line when t and R have these values, making H indeterminate. For any value of R except 100, the R axis becomes the index line when $t = 212$°F., making $H = 0$. Further, all indices drawn

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[1] DAVIS, D. S., "Empirical Equations and Nomography," p. 122, McGraw-Hill Book Company, Inc., New York, 1943.

from any point on the H scale to the point $t = 212$ intersect the R axis only in the point $R = 100$.

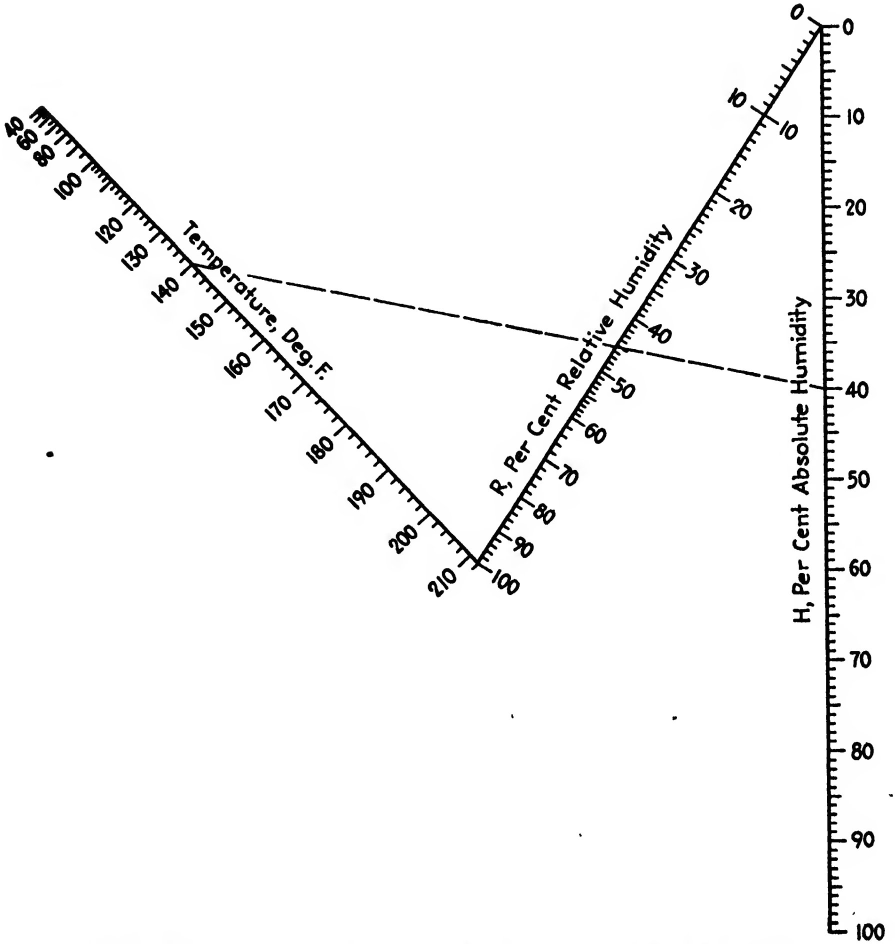

FIG. 190.—Interconversion: percentages of relative and absolute humidity.

STEAM-LEAK NOMOGRAPH[1]

In connection with heat and material balances, chemical engineers have frequent occasion to estimate the extent of steam losses due to leakage to the atmosphere from both high- and low-pressure lines. It is the purpose of this topic (1) to present a convenient alignment chart that enables rapid calculation of the rates of steam losses to the atmosphere and (2) to show how the well-known Napier and Rankine steam-flow equations can be rearranged to deal with gage pressures in place of

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[1] *Paper Ind.*, **17**, 571 (1935).

absolute pressures. The use of gage pressures results in considerable simplification in the case of the Rankine expression when applied to flow to the atmosphere.

The use of Fig. 191 may be illustrated as follows: Assuming orifice flow, how much steam will be lost in 1 min. through an aperture having an area of 0.046 sq. in. when the pressure of the steam is 100 lb./sq. in. gage? Connect 0.046 on the *A* scale (center) with 100 on the *P* scale at the left, and read the rate of leakage on the *W* scale in the left half of the chart as 4.5 lb./min.

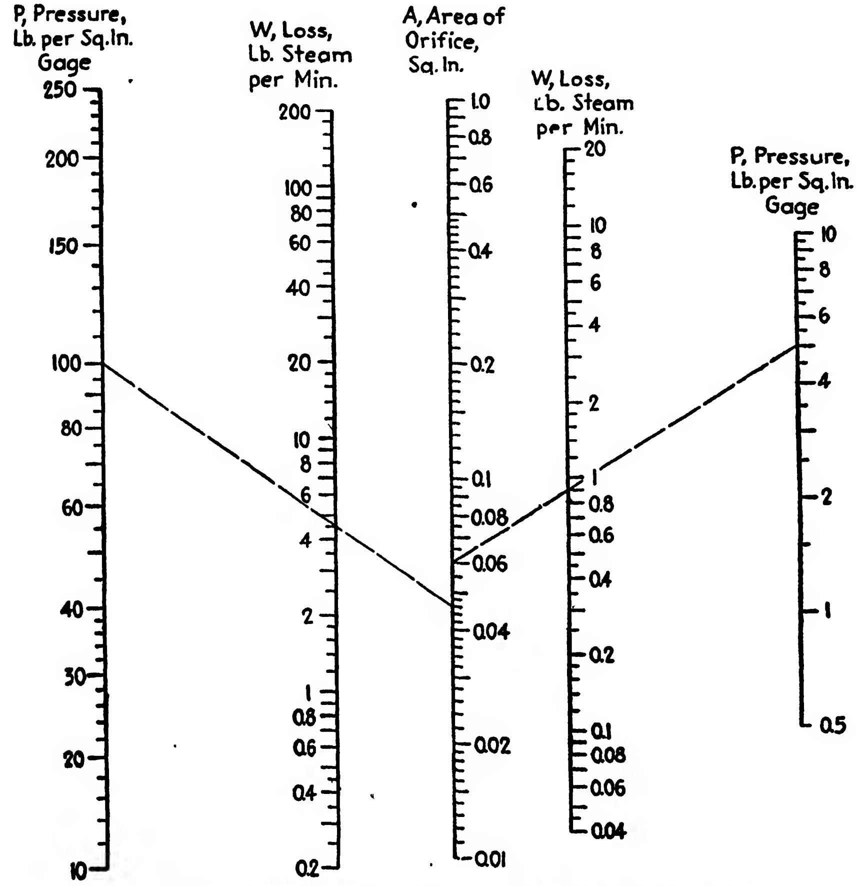

FIG. 191.—Steam loss estimated from pressure and orifice area.

Exhaust steam at a gage pressure of 5 lb./sq. in. is leaking around a worn fitting. What will be the rate of loss of steam if the area of the opening is 0.06 sq. in.? As indicated by the broken line in the right half of the chart, connect 0.06 on the *A* scale with 5 on the *P* scale at the right, and read the desired value on the W scale in the right half of the chart as 0.90 lb. of steam per minute.

The nomograph is based upon the Napier and Rankine formulas for the flow of steam and takes proper cognizance of the ranges of applicability of each. The left half of the chart has its origin in Napier's equation which may be written as

$$W = \tfrac{6}{7}A(P + 14.7)$$

where W = rate of flow of steam, lb./min.
A = area of the orifice, sq. in.
P = gage pressure, lb./sq. in.

This expression is applicable for orifice flow whenever the upstream absolute pressure is equal to or greater than five-thirds the downstream absolute pressure, or in the case of flow of steam to the atmosphere, when the absolute pressure in the line is equal to or greater than $\tfrac{5}{3} \times 14.7$, or 24.5 lb./sq. in., or about 10 lb./sq. in., gauge.

The right half of the chart is predicated upon Rankine's equation

$$W = 1.74A\sqrt{P_2(P_1 - P_2)}$$

where P_1 and P_2 are the upstream and downstream absolute pressures, respectively, in pounds per square inch, and W and A have the same significances as before. In the case of leakage to the atmosphere,

$$P_2 = 14.7,$$

and substituting this value in the Rankine expression we have

$$W = 6.67A\sqrt{P_1 - 14.7}.$$

Now, $P_1 - 14.7$ is equal to the gage pressure P of the steam so that

$$W = 6.67A\sqrt{P},$$

which is a simplified Rankine expression specific for flow of steam to the atmosphere.

NOMOGRAPH FOR THE ANGLES OF LIQUID LENSES[1]

In some instances when a drop of a liquid b is placed on the surface of a substrate liquid a and the two liquids exhibit low mutual solubility, a single liquid lens or a number of liquid lenses may form. Miller[2] investigated the tension mechanisms responsible for lens phenomena and devised a new method for measuring the angles of such lenses. He calculated the total volume of the lens from its weight and density and dis-

[1] *Ind. Eng. Chem.*, **34**, 442 (1942).

[2] MILLER, N. F., *J. Phys. Chem.*, **45**, 1025 (1941).

tributed the volume between the upper and lower portions, assumed to be spherical segments, according to the relation

$$\frac{V_\alpha}{V_\alpha + V_\beta} \cong \frac{S_{23}}{S_2' + S_{23}} \tag{50}$$

where V_α, V_β = volumes of upper and lower segments of lens, respectively, cc.

S_{23} = interfacial tension between liquids a and b.

S_2' = surface tension of liquid b saturated with liquid a.

Miller measured the width of lens w, in centimeters, and computed angle α, in degrees, from the equation

$$\frac{\sin \alpha(2 + \cos \alpha)}{(1 + \cos \alpha)^2} = \frac{24V_\alpha}{\pi w^3} \tag{51}$$

derived from the geometry of the sphere, using a similar equation for β and V_β. The density of liquid b should be only a little greater than that of liquid a, and the total lens angle $\alpha + \beta$ should not be much larger than 45 deg.

The nomograph (Fig. 192) was constructed to provide a rapid and accurate means of solving Eq. (51) which does not yield α explicitly. For convenience in graphing, volumes V_α given in the chart are expressed in thousandths of a cubic centimeter. A straight line connecting values of w and V_α can be produced to intersect the α scale in the value required by the equation. There are two scales for V_α, one for $\alpha > 10°$ and one for $\alpha < 10°$.

The use of the chart is illustrated as follows: For isoamyl phthalate, with water as the substrate liquid, the total volume of a liquid lens 0.46 cm. wide is 0.00460 cc., distributed so that $V_\alpha = 1.97$ and $V_\beta = 2.63$ as required by values of S_{23} and S_2' of 23.5 and 31.3 dynes/cm., respectively. The lower index line connecting $w = 0.46$ with $V_\alpha = 1.97$ is produced to the α axis where α is read as 11.7°. The index line for $w = 0.46$ and $V_\beta = 2.63$ is not shown but would result in a value of β of 15.6°. The total lens angle of 11.7° + 15.6°, or 27.3°, can be compared with the approximate value obtained by aligning $w = 0.46$ with 4.6 on the volume scale, resulting in 26.5°. The left-hand V_α scale and the left side of the α axis are used throughout.

Similarly, for carbon tetrachloride and water, the total volume of a liquid lens 0.60 cm. in width is 0.00466 cc.; the volumes of the upper and lower segments are 0.00290 and 0.00176 cc., respectively, corresponding to tension values of $S_{23} = 43.7$ and $S_2' = 26.5$ dynes/cm. The upper index line connecting $w = 0.60$ with $V_\alpha = 2.90$ is produced to the α axis where α is read as 7.8°. The index line for β is not shown, but alignment of $w = 0.60$ with $V_\beta = 1.76$ results in $\beta = 4.8°$. The total lens angle is

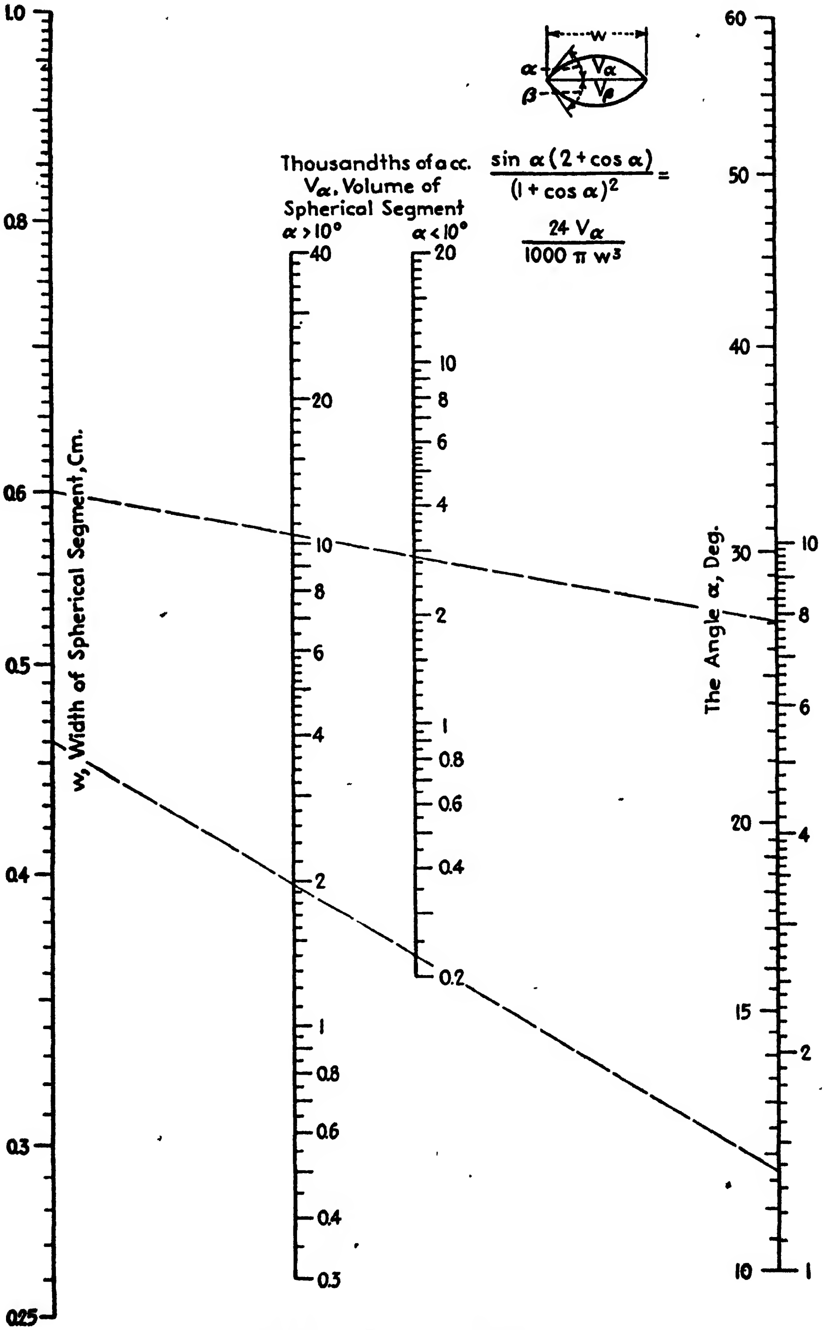

FIG. 192.—The angles of a liquid lens.

7.8° + 4.8°, or 12.6°. The right-hand V_α and α scales are used throughout. The approximate value of the total angle, which is found by aligning $w = 0.60$ with the total volume of the lens, 0.00466 cc., proves to be 12.4°, in excellent agreement with the sum of α and β since the latter are so small.

NOMOGRAPH FOR CALORIMETRIC DETERMINATION OF LIME[1]

The alignment chart (Fig. 193) is for use in connection with a calorimetric method, said to be reliable within 0.5 per cent, for the determination of lime in cement, concrete, and mortar as described by Bessey.[2]

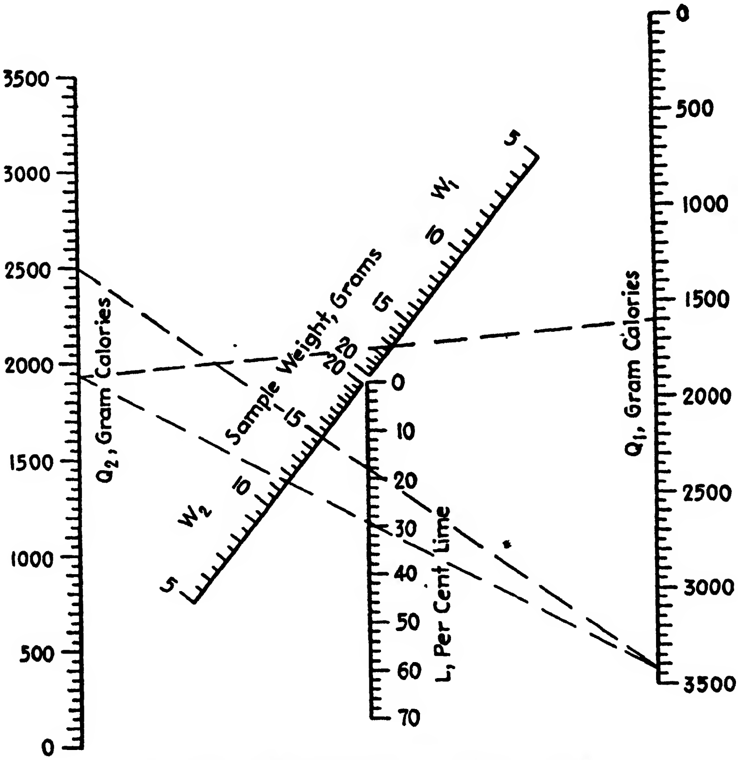

FIG. 193.—Calorimetric determination of lime.

Two samples of the crushed material are weighed out. One is ignited at a temperature of 350°C. and the other at 550°C. Each is hydrated in a suitable calorimeter, and the heat evolved in each case

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[1] *Chemist-Analyst*, **20** (6), 10 (1931).

[2] BESSEY, G. E., *Dept. Sci. Ind. Research, London, Tech. Paper* 9; see also *Rock Products*, **33** (25), 61 (1930).

is measured. The percentage of CaO may then be calculated by means of the chart which is built on the equation

$$L = \left(\frac{Q_2}{W_2} - \frac{Q_1}{W_1}\right)\frac{100}{273}fk$$

where L is the percentage of CaO; Q_1 and Q_2 are quantities of heat, in gram-calories, evolved from samples ignited at 350° and 550°C., respectively; W_1 and W_2 are sample weights, in grams, for the 350 and 550°C. ignitions, respectively; 273 is the heat of hydration of CaO, calories per gram; f is a correction factor for incomplete decomposition of $CaCO_3$ and carbonization of the sample, about 1.075; k is a correction factor for combination of lime with other materials during ignition. For Portland cement, $k = 1.04$.

Substituting, the above equation becomes

$$L = 0.409\left(\frac{Q_2}{W_2} - \frac{Q_1}{W_1}\right).$$

The use of the chart (Fig. 193) is illustrated as follows. The heat of hydration of 15.0 g. of Portland cement which has been ignited at 550°C. is 2,500 g.-cal., while that for 17.0 g. ignited at 350°C. is 1,600 g.-cal. What is the lime content? Connect 2,500 on the Q_2 scale with 15.0 on the W_2 scale, and produce the line to the Q_1 scale, calling the intersection A. Connect 1,600 on the Q_1 scale with 17.0 on the W_1 scale, and produce the line to the Q_2 scale, calling this intersection B. A line between A and B will cut the L scale in the desired value, 29.7 per cent.

NOMOGRAPHIC CHART FOR NONTANNIN DETERMINATION[1]

The alignment chart (Fig. 194) is for the purpose of calculating nontannin content of commercial tanning extracts and is intended for use in connection with the official analytical procedure[2] of the American Leather Chemists' Association.

About 17 g. of the tanning extract is dissolved in 1 l. of water, and 200 cc. of this solution is shaken with 46.3 g. of wet chrome-treated and washed hide powder after which the liquor is filtered and 100 cc. of the filtered liquor is evaporated to dryness.

The percentage nontannins, R is given by the equation

$$R = 1{,}000(1 + 0.002315W)\left(\frac{N}{S}\right)$$

where N = grams nontannins per 100 cc. filtered liquor.
S = grams tanning extract sample.
W = percentage moisture in the wet hide powder.

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[1] *Chemist-Analyst*, 18 (4), 8 (1929).

[2] *J. Am. Leather Chemists' Assoc.*, (May, 1930), p. 48.

The use of the chart is illustrated as follows: 100 cc. of the filtered liquor yielded 0.420 g. nontannins when the hide powder contained 75.0 per cent moisture and the weight of tanning extract was 17.8 g. To find the percentage nontannins, follow the key and connect 17.8 on the *S* scale with 0.420 on the *N* scale, and from the intersection with the

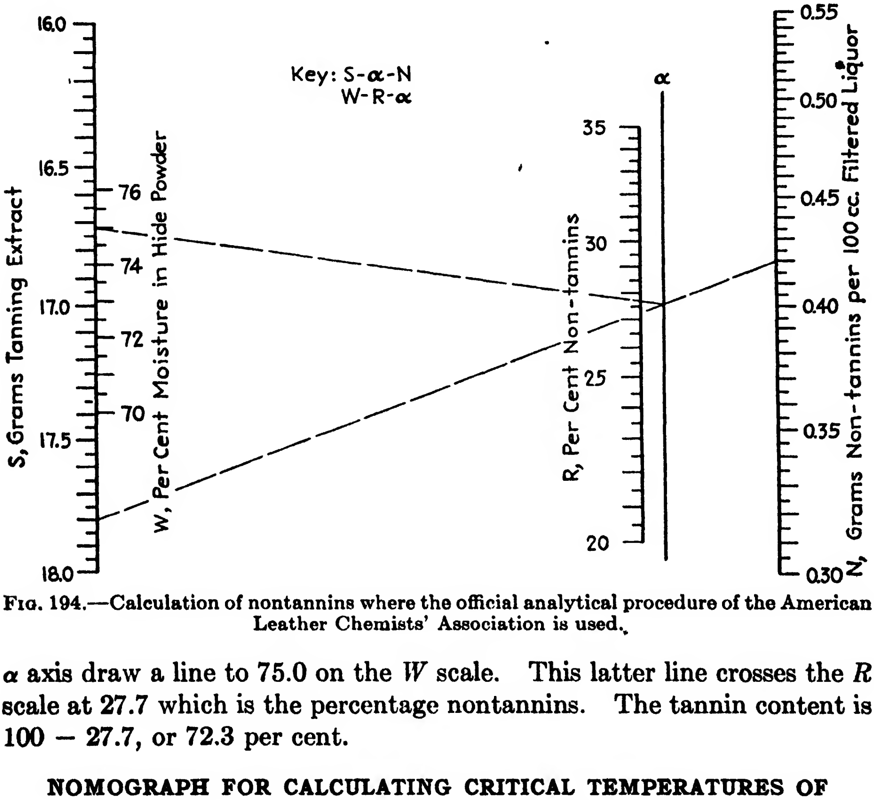

FIG. 194.—Calculation of nontannins where the official analytical procedure of the American Leather Chemists' Association is used.

α axis draw a line to 75.0 on the *W* scale. This latter line crosses the *R* scale at 27.7 which is the percentage nontannins. The tannin content is 100 − 27.7, or 72.3 per cent.

NOMOGRAPH FOR CALCULATING CRITICAL TEMPERATURES OF PETROLEUM OILS[1]

Eaton and Porter[2] have proposed the following empirical relationship between t_c, the critical temperature of a petroleum oil, in degrees Fahrenheit; and a, a function of the 50 per cent boiling point and of the specific gravity of the oil:

$$t_c = 180 + 1.75a - 0.00088a^2 \tag{52}$$

$$a = (t_b + 100)S \tag{53}$$

where t_b = 50 per cent boiling point (A.S.T.M. distillation).
S = specific gravity at 60°F.

---

[1] *Chemist-Analyst*, **25**, 55 (1936).

[2] EATON, G. L., and C. A. PORTER, *Ind. Eng. Chem.*, **24**, 819 (1932).

Inasmuch as the equations have been shown to hold for many pure paraffins, olefins, naphthenes, and aromatics as well as for a wide variety of petroleums it appears that a rapid and accurate method of solution is desirable. A plot of t_c vs. a obviates algebraic solution of Eq. (52) but requires outside solution of Eq. (53), while a plot of t_c vs. t_b for various values of S requires interpolation between curves.

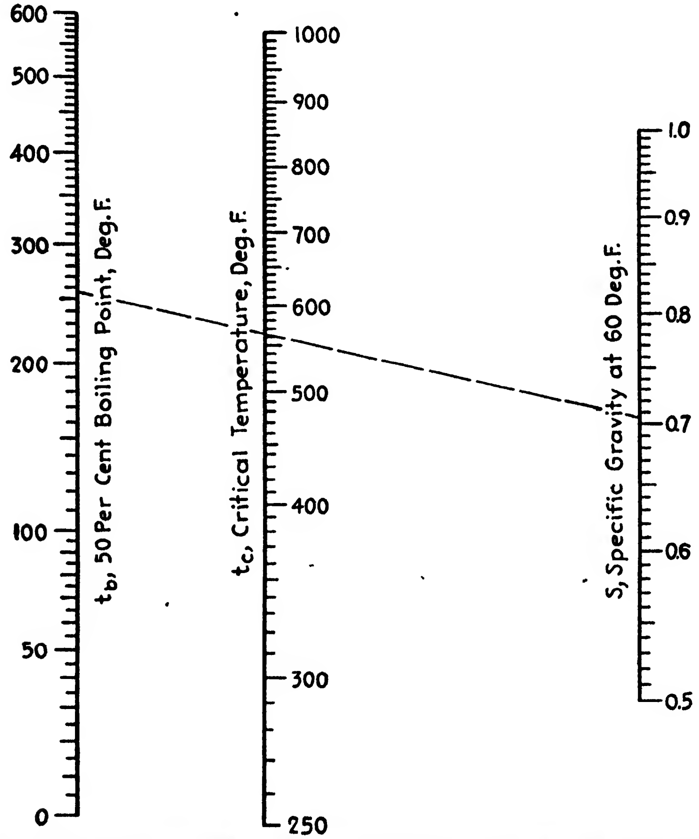

FIG. 195.—Critical temperatures of petroleum oils from the 50 per cent boiling point and the specific gravity.

The equations can be solved most conveniently by means of Fig. 195, the use of which involves no algebraic solutions or interpolations except along closely graduated scales. Thus, to find the critical temperature of normal octane, connect its boiling point 256°F. on the t_b scale with its specific gravity 0.706 on the S scale and read the critical temperature as 564°F. on the t_c scale.

The chart is essentially of the familiar logarithmic type: the left axis is logarithmic in $t_b + 100$ but the scale is marked in values of t_b,

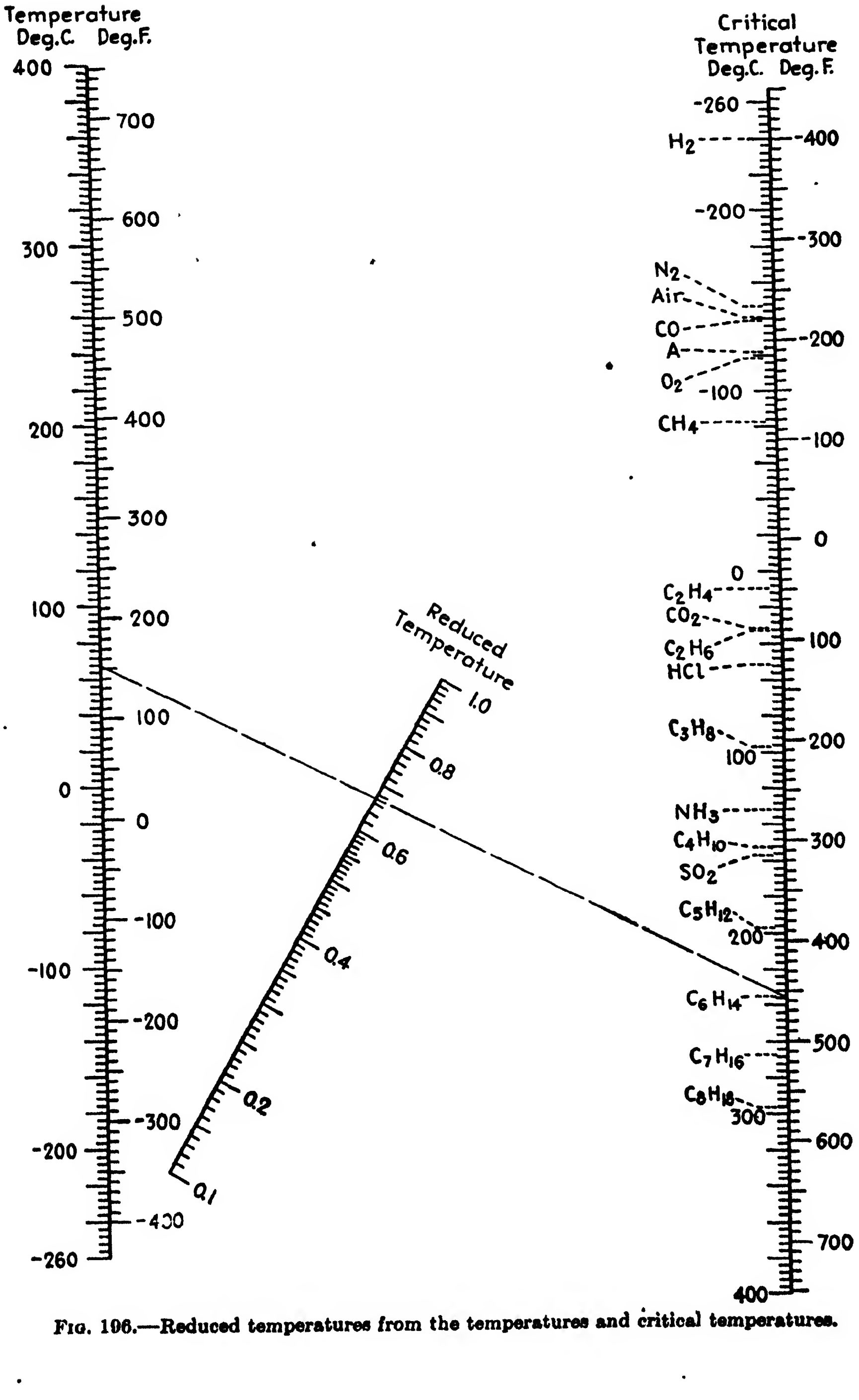

FIG. 106.—Reduced temperatures from the temperatures and critical temperatures.

the right axis is logarithmic in S and is marked in values of S, while the central axis is logarithmic in a but is marked in values of t_c.

NOMOGRAPH FOR CALCULATING REDUCED TEMPERATURES[1]

Reduced temperature, the ratio of the absolute temperature of a substance to its absolute critical temperature, has sufficient thermodynamic application to warrant the construction and use of a nomograph for its calculation. Figure 196 covers temperatures, critical and otherwise, in centigrade and Fahrenheit units and indicates the critical temperatures for 18 pure gases and air.

The index line shows that the value of the reduced temperature for hexane at 68°C. is 0.67.

NOMOGRAPH FOR SURFACE TENSION OF ETHYL ALCOHOL–WATER MIXTURES[2]

Bonnell, Byman, and Keyes[3] presented excellent data covering the surface tension of ethyl alcohol–water mixtures. The solutions studied had concentrations of 2.33, 5.94, 15.93, 29.67, 43.64, 61.10, 75.68, and 92.72 per cent ethyl alcohol by weight, while the temperatures were at uneven intervals between 20°C. and the atmospheric boiling points.

In view of the importance of the data, it seems worth while to provide a convenient and accurate means of interpolation. Surface tension γ can be plotted linearly with temperature t according to the expression

$$\gamma = a + bt$$

where a and b are specific for each concentration. A close study of the variation of a and b with concentration, using the Lagrange interpolation formula[4] where necessary, enables construction of a line-coordinate chart (Fig. 197).

The chart permits ready percentage and temperature interpolation, a straight line cutting the three axes in values consistent with the original data. As an illustration, a solution containing 10 per cent ethyl alcohol by weight has a surface tension of 44.0 dynes/cm. at 59°C.

Surface tension data for pure water are from the "International Critical Tables."[5]

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[1] *Ind. Eng. Chem.*, **34**, 1174 (1942).

[2] *Ind. End. Chem.*, **32**, 1587 (1940).

[3] BONNELL, W. S., L. BYMAN, and D. B. KEYES, *Ind. Eng. Chem.*, **32**, 532 (1940).

[4] *Chem. & Met. Eng.*, **45**, 383 (1938).

[5] "International Critical Tables," Vol. IV, p. 447, McGraw-Hill Book Company, Inc., New York, 1928.

ROVING-TWIST NOMOGRAPH[1]

The alignment chart (Fig. 198) enables rapid and accurate solution of Bissonette's equation[2]

$$N = \frac{1.20H^{0.57735}}{L}$$

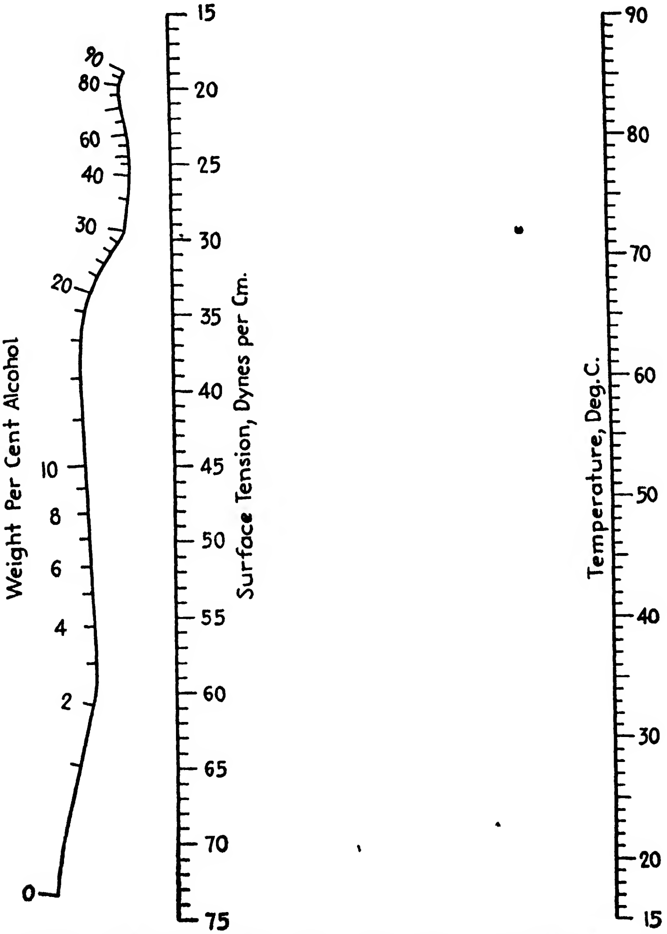

FIG. 197.—Surface tension of aqueous ethyl alcohol when the analysis and temperature are known.

where N = the number of turns per inch.
H = hank roving.
L = average length of staple, in.

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[1] *The Melliand Textile Monthly*, **2**, 1577 (1931).
[2] *Ibid.*, **2** (10), 1924 (1931).

The broken line indicates that three turns per inch corresponds to a hank roving of six and a staple *length* of $1\frac{1}{8}$ in.

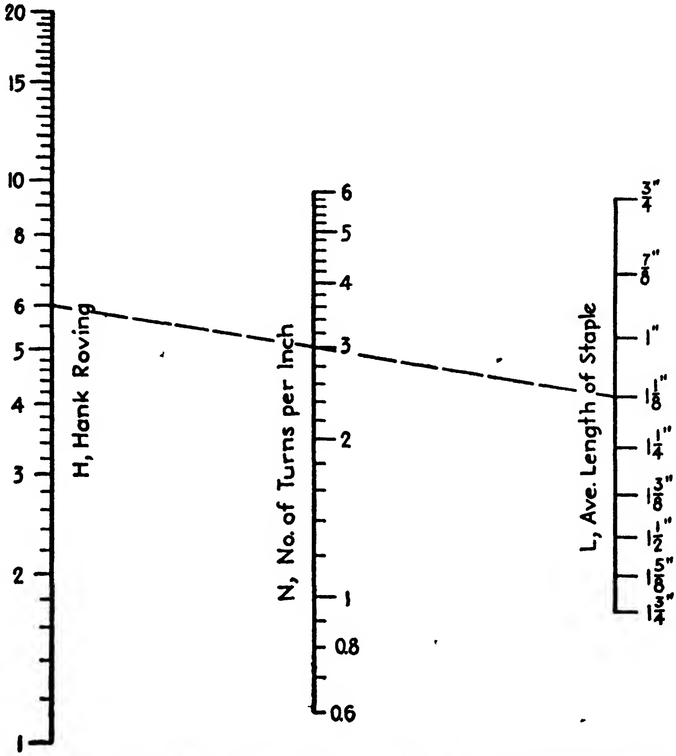

FIG. 198.—Number of turns when the hank roving and staple length are known, for weaving textiles.

NOMOGRAPHIC SOLUTION OF SLUDGE WASHING[1]

Methods of essentially a decantation nature are frequently employed both in the plant and in the laboratory for the washing of sludges and precipitates. In either case, efficient control involves a somewhat troublesome calculation which can be best performed by means of the alignment chart (Fig. 199), based upon the following considerations.

Let C_0 = the concentration of the original supernatant liquor.
r = the percentage of the total volume which is decanted each time.

Then $100 - r$ = the percentage of the total volume remaining each time.

C_1, the concentration after the first washing, is evidently equal to $\left(\frac{100 - r}{100}\right) C_0$ and C_2, the concentration after the second washing

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[1] *Chem. & Met. Eng.*, **40**, 94 (1933).

$= \left(\frac{100 - r}{100}\right) C_1 = \left(\frac{100 - r}{100}\right)^2 C_0$. The concentration after n washings, C_n, will then equal $\left(\frac{100 - r}{100}\right)^n C_0$.

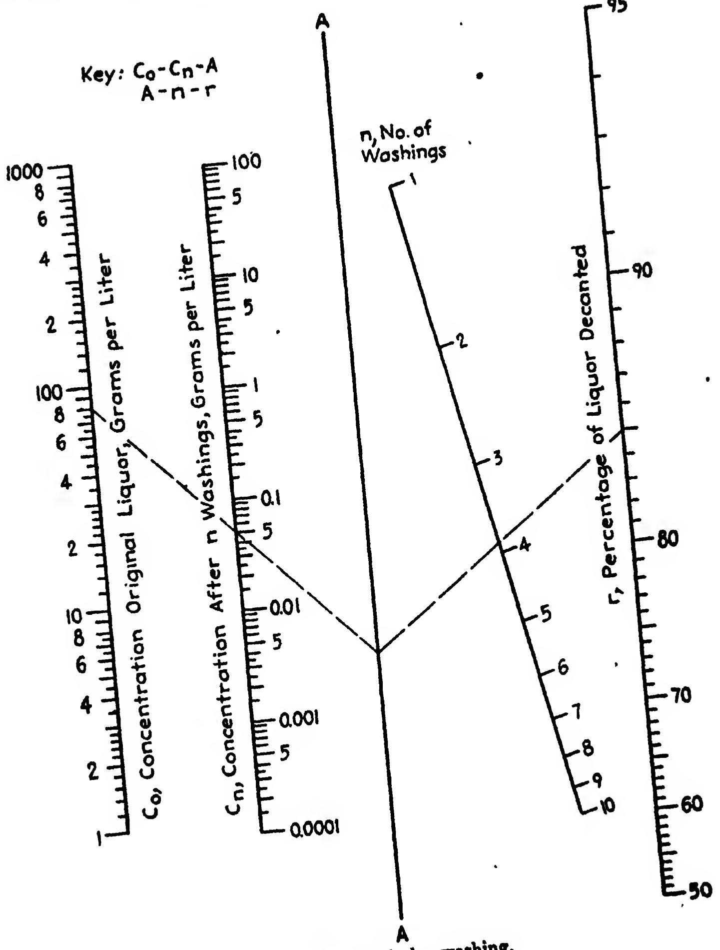

FIG. 199.—Sludge washing.

The use of Fig. 199 is illustrated as follows:

Example 1.—How many washings are required in order to reduce the concentration of liquor from 80 g./l. to less than 0.05 g./l. if it is possible to decant 85 per cent of the liquor each time? As shown by the key, connect 80 on the C_0 scale with 0.05 on the C_n scale and continue the line to the A axis. Connect the latter intersection with 85 on the r scale and note that the latter index line crosses the n scale between values of 3 and 4, indicating the need for four washings.

Example 2.—A sludge is washed five times with volumes of water equal to 70 per cent of the volume of the original liquor and sludge. If the initial concentration of dissolved matter was 62 g./l., what will be the concentration in the final wash water? Connect 70 on the r scale with 5 on the n scale, and continue the line to the A axis. Connect this latter intersection with 62 on the C_0 scale, and read the desired value as 0.15 g./l. on the C_n scale. The index lines for Example 2 are not shown on the chart.

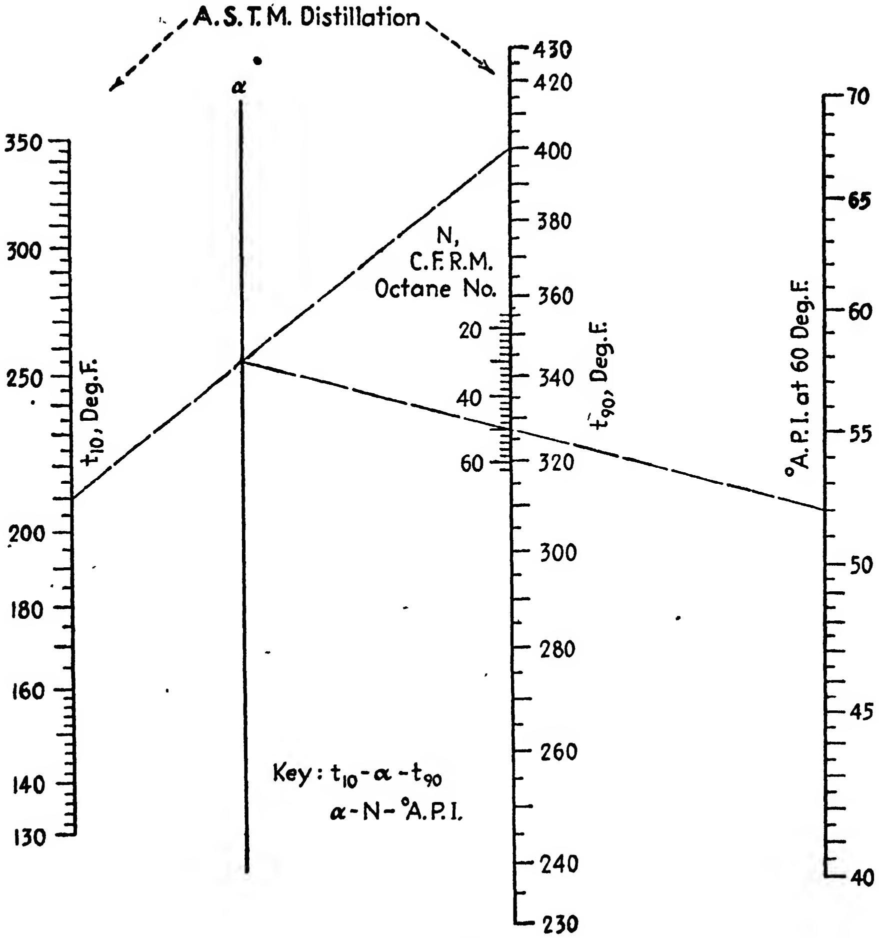

FIG. 200.

OCTANE NUMBER NOMOGRAPHS[1]

As shown previously, the octane number of gasoline can be calculated from the A.P.I. gravity and the 10 and 90 per cent points of the A.S.T.M. distillation. Plots of the octane number against functions of these variables have been presented. The relationships in question, for the second method of calculation[2] are

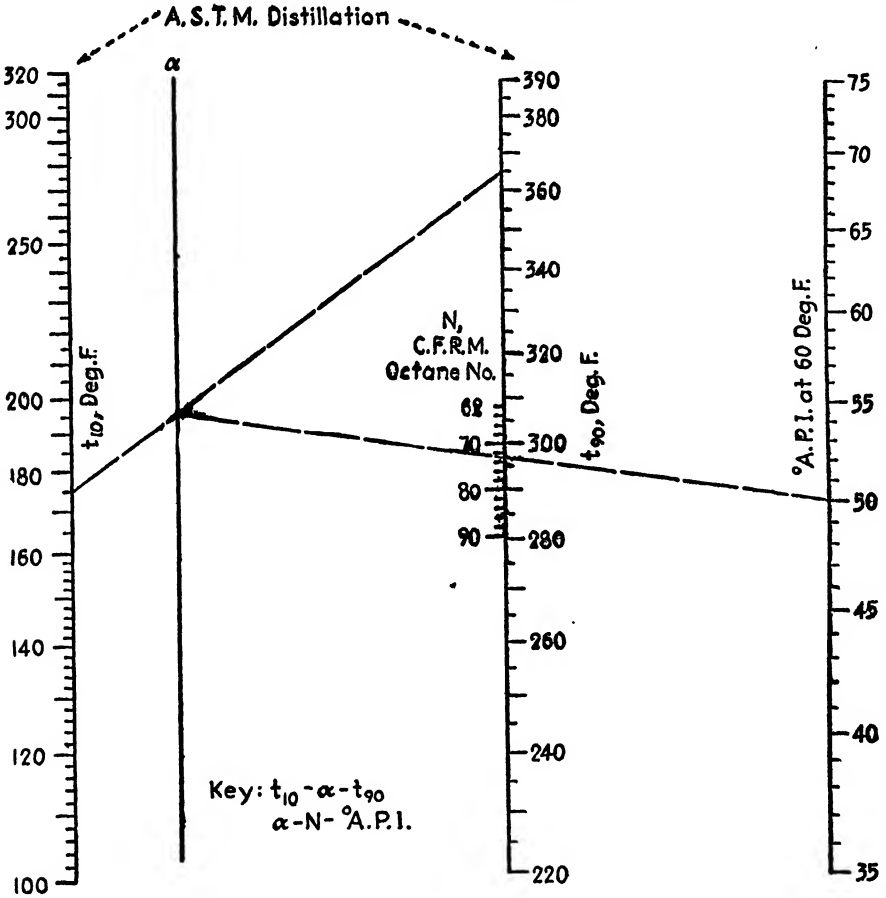

Fig. 201.

$$N = 1698.7 - 126.11\ (3.5 \log \text{degrees A.P.I.} + 2 \log t_{10} + 1.3 \log t_{90})$$

for gasolines with octane numbers between 16 and 62, and

$$N = 1020.7 - 64.86\ (4 \log \text{degrees A.P.I.} + 2 \log t_{10} + 1.3 \log t_{90})$$

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[1] Cox, R. B., and D. S. Davis, *Petroleum Refiner*, **22**, 350 (1943).

[2] Cox, R. B., *Refiner and Natural Gasoline Manufacturer*, **19**, 31 (1940).

for gasolines with octane numbers that are between 62 and 90, where N = C.F.R.M. octane number, degrees A.P.I. = gravity corrected to 60°F., A.P.I. scale; and t_{10} and t_{90} = 10 and 90 per cent points, respectively, of the A.S.T.M. distillation, degrees Fahrenheit.

The former charts require a somewhat tedious computation of the functions in the parentheses before they can be used. The accompanying nomographs, however, greatly facilitate the accurate calculation of octane numbers. Their use is illustrated as follows: What is the octane number when the 10 and 90 per cent points of the A.S.T.M. distillation are 210 and 400°F., respectively, and the corrected A.P.I. gravity is 52°? Using Fig. 200 and following the key, connect 210 on the t_{10} scale with 400 on the t_{90} scale and mark the intersection with the α axis. Connect this point with 52 and the A.P.I. scale and read the octane number on the N scale as 50. Figure 200 is used rather than Fig. 201 since 400°F. does not appear on the t_{90} scale of the latter figure.

What is the octane number of a gasoline when the 10 and 90 per cent points determined by an A.S.T.M. distillation are 175 and 365°F., respectively, and the A.P.I. gravity is 50°? An attempt to use Fig. 200 results in an intersection with the N axis which is beyond the scale, indicating that Fig. 201, for higher values, should be used. As shown by the index lines on Fig. 201 the octane number is 73.

The nomographs, constructed by methods previously described,[1] yield octane numbers in satisfactory agreement with values read from the charts of the earlier paper and with experimental values.

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[1] Davis, D. S., "Empirical Equations and Nomography," Chaps. IV and V, McGraw-Hill Book Company, Inc., New York, 1943.

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