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NYO-6097

PERFORMANCE OF PACKED COLUMNS

II. Wetted Areas, Effective Interfacial Areas, Gas Phase Mass Transfer Rates (k_G) and Liquid Phase Mass Transfer Rates (k_L).

by

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January 8, 1954

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Contract No. AT(30-1)-1463

Issued: January 9, 1954

UNCLASSIFIED

Report Approved: Edward McHugh
Edward McHugh, Director
Division of Research &
Industrial Service

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New York Operations Office - 4 NYO-6097

Submitted for Publication in Chemical Engineering Progress and Presentation at the American Institute of Chemical Engineers meeting, Springfield, Mass., May 1954.

Abstract

A study was made to separate the volumetric mass transfer coefficients, k_Ga and k_La, into their components k_G, k_L, and a so that the effects of variables could be determined separately for each component. Mass transfer rates for four packings, 1/2" and 1 1/2" Raschig rings and 1/2" and 1" Berl saddles, made of naphthalene, were determined by vaporization into air at gas rates from 100 to 1000 lbs./(hr.)(sq.ft.). The data were correlated by

$$\frac{k_G M_M P_{BM}}{G} = 1.195 \left[\frac{D_P G}{\mu_G(1-\epsilon)}\right]^{-0.36} \left[\frac{\mu_G}{\rho_G D_V}\right]^{-2/3}$$

This correlation for k_G was used to determine the wetted areas of these packings when irrigated with water, and to calculate the effective interfacial areas, a, from Fellinger's data for ammonia absorption. These effective areas were then used to evaluate k_L from previously published k_La data, and a correlation was obtained for all packings as follows

$$\frac{k_L D_P}{D_L} = 25.1 \left[\frac{D_P L}{\mu_L}\right]^{0.45} \left[\frac{\mu_L}{\rho_L D_L}\right]^{0.5}$$

The correlations for k_G and k_L and the effective interfacial area data make possible a more rigorous method for the design of packed columns than heretofore available.

Performance of Packed Columns

II. Wetted Areas, Effective Interfacial Areas, Gas Phase Mass Transfer Rates (k_G) and Liquid Phase Mass Transfer Rates (k_L).

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Introduction

To predict the performance of columns employing ring and saddle packings for design purposes reliable data such as that of Fellinger (4) for volumetric gas phase coefficients, k_Ga, and Sherwood and Holloway (8) for volumetric liquid phase coefficients, k_La, are used. Such coefficients can be estimated for aqueous systems from these sources of data and combined by the following relation to give the overall mass transfer coefficients desired for design, for a limited number of packings.

$$\frac{1}{K_Ga} = \frac{1}{k_Ga} + \frac{1}{Hk_La} = \frac{1}{HK_La} \qquad (1)$$

Although these sources of data are considered reliable they are of questionable value for predicting mass transfer rates for non-aqueous systems and for packings other than those for which data are reported. An examination of the data reveals no simple relation between packing size and performance even for one type of packing. For this reason the data must be presented in the form of plots or empirical equations which are of little value in predicting the performance of packings for which data are not available. The work of Surosky and Dodge (11) and Mehta and Parekh (7) on the vaporization of organic liquids and water in packed columns and Shulman, Ullrich, and Wells (10) on total liquid holdup in carbon and porcelain packings indicates the effective interfacial area is a function of the properties of the liquids employed and the nature of the packing surface. Thus it is unlikely that data obtained with aqueous systems and a specific packing material can be used to estimate the performance in non-aqueous systems or even in aqueous systems when packing materials with different surface properties are used.

To overcome the limitations of the methods discussed a more fundamental approach to the problem of mass transfer between phases in packed columns must be employed. As the first and most obvious step in this direction it would be desirable to separate the coefficients, k_G and k_L, from the effective interfacial area, a, in order to determine the effects of variables on each component of the volumetric coefficients, k_Ga and k_La, separately.

Two attempts to separate a and k_G have been reported by Shulman and DeGouff (9) and Weisman and Bonilla (15). The methods used were equivalent to using k_G, obtained by vaporization of naphthalene or water from special Raschig rings of known mass transfer area, and various sources of k_Ga data to evaluate a, the effective interfacial area. As no liquid was used to irrigate the packing no attempt was made to take into account the effect of the liquid flowing through the packing under the conditions packed columns are operated at in practice. The recent work of Shulman, Ullrich, and Wells (10) on total liquid holdup in packings indicates an appreciable portion of the void space in packing may be occupied by liquid, leaving a much smaller free space for gas flow than had been expected previously. In addition the recent work of Gamson (5), Evans and Gerald (3), McCune and Wilhelm (6), and Chu, Kalil and Wetteroth (1) has shown the free space for gas flow, ϵ, is an important variable for correlating mass transfer data.

The present work was undertaken to separate k_G and k_L from a, to overcome the limitations of methods employed previously, and to obtain correlations for k_G and k_L in terms of all pertinent variables in order to make possible the prediction of the performance of packings for which data are not available. The method employed is outlined as follows.

1. Naphthalene packings (0.5-inch and 1.5-inch Raschig rings, and 0.5-inch and 1.0-inch Berl saddles) were used to obtain k_G data which could be combined with previous work to obtain a single k_G correlation, for all ring and saddle packings, which would take into account the effect of liquid in the packing on k_G.

2. The k_G correlation was used in conjunction with Fellinger's (4) extensive k_Ga data for ammonia absorption to calculate the effective interfacial areas, a, for the five packings, 0.5, 1.0, and 1.5-inch Raschig rings and 0.5 and 1.0-inch Berl saddles, for which total holdup data were available.

3. The effective interfacial areas were applied to the k_La data of several investigators to obtain k_L values for the five packings which could be correlated by a single equation.

4. The correlations for k_G and k_L were tested and found satisfactory for extension to larger packings, 2.0-inch rings and 1.5-inch saddles, for which incomplete data were available.

In addition to the studies outlined, work was done on the wetted area in ring and saddle packings to supply data which may be of value in developing a method for predicting the behavior of non-aqueous liquids in packings.

Apparatus and Procedure

A schematic diagram of the apparatus is given in Figure 1. The apparatus has been described in detail by Shulman and DeGouff (9) except for several minor changes which will be discussed. To improve control a water storage tank was installed with a circulating pump and the air orifice meters were replaced by two calibrated rotameters. A new analytical technique was developed to analyze the air for naphthalene. The optical density of air containing naphthalene, as measured in 10-cm. quartz cells in a Beckmann Model DU photoelectric quartz spectrophotometer, was found to be proportional to the naphthalene partial pressure. This provided a very rapid and simple method of analysis for the naphthalene.

The naphthalene Raschig rings were prepared by means of special molds on a fast acting hydraulic press. The rings were held to close tolerances by weighing the feed for each 1.5-inch ring and by the use of a calibrated feed measure for the 0.5-inch rings. The 0.5 and 1.0 inch naphthalene Berl saddles, prepared by Maurice A. Knight, have the same dimensions as that of the porcelain Berl saddles supplied commercially by this company. The characteristics of the naphthalene packings used are tabulated in Table I. The naphthalene used for all the work was crushed refined "Polar" naphthalene obtained from the Barrett Division of Allied Chemical and Dye Corporation.

To determine k_G and wetted areas for a naphthalene packing the 3-foot by 10-inch diameter pyrex column was packed with 6 inches of porcelain packing followed by 3 to 6 inches of naphthalene packing of the same type and another 6 inches of porcelain packing. The porcelain packing above and below the naphthalene provided the gas and liquid distribution which

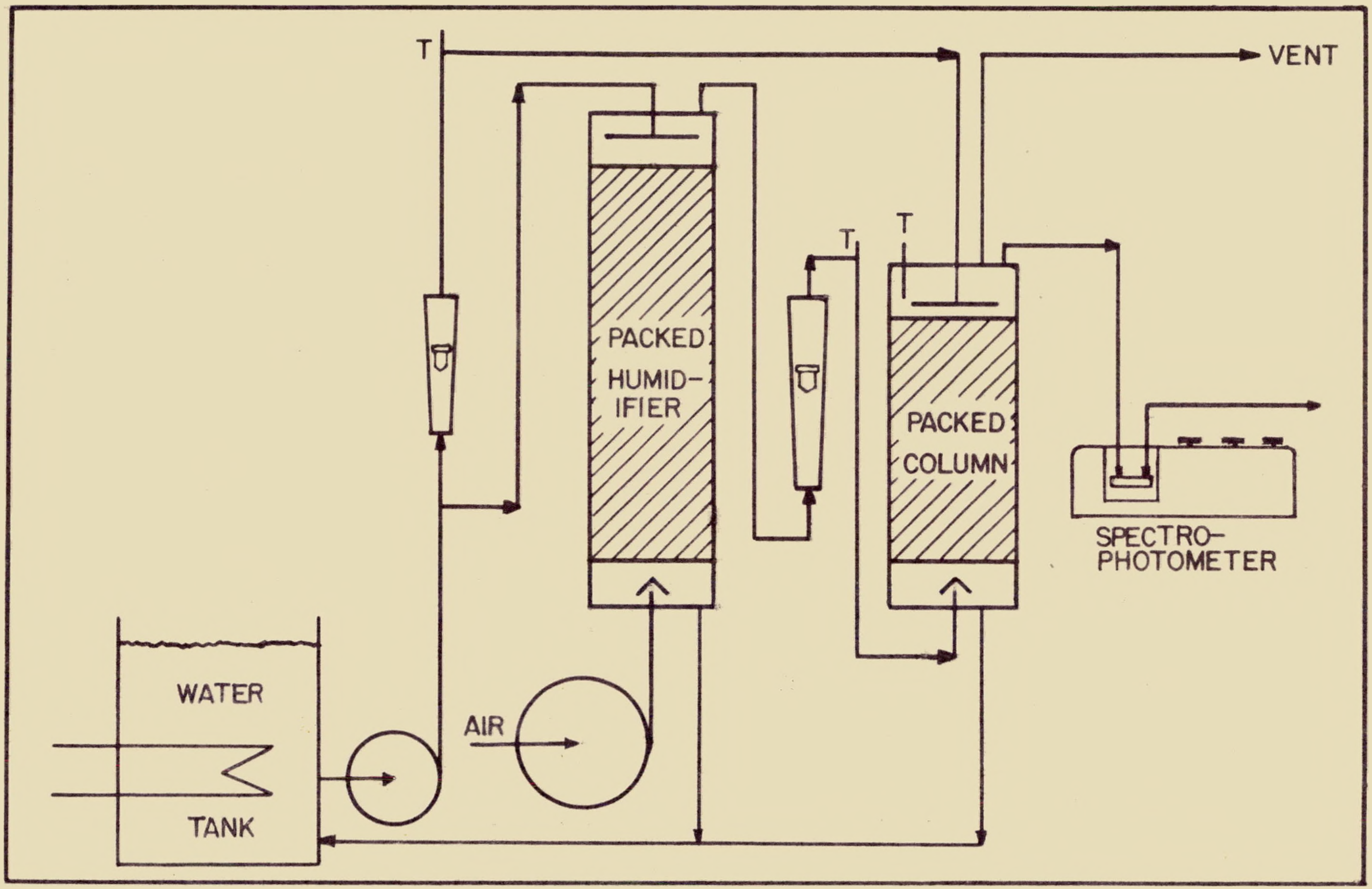

FIG. 1, SCHEMATIC DIAGRAM OF APPARATUS

was characteristic of the packing used. Air and water temperatures were adjusted to the 20 - 23°C range and held constant to within ± 0.1°C for each run. To determine k_G with a dry packing the air rate was set at the desired value and inlet and outlet air temperatures were checked for constancy for a minimum of 10 minutes. When equilibrium was established, a copper air sampling line at the top of the column, which operated at a pressure slightly above atmospheric, was opened and a 10-cm. quartz cell was flushed for about one minute with the outlet air. The cell stopcocks were closed and the cell was placed in the spectrophotometer for analysis. The optical density of the air-naphthalene mixture was determined at three naphthalene ultraviolet absorbtion peaks, 221.75, 258.75, and 268.75 millimicrons. The optical densities of air saturated with naphthalene had been measured previously at these three wavelengths at several temperatures in the 15 - 25°C range. The k_G for the run was calculated by an equation employing these optical densities which was derived as follows. As the inlet air was free of naphthalene and a logarithmic mean driving force is applicable because the partial pressure of naphthalene never exceeds 0.1 mm. Hg., we can write

$$k_G A \frac{\left[(p_s) - (p_s - p_o)\right]}{\ln\left[\frac{p_s}{p_s - p_o}\right]} = \frac{GSp_o}{M_M P} \qquad (2)$$

and since the optical density, α, as measured by the spectrophotometer, is proportional to the partial pressure of naphthalene

$$k_G = \frac{GSp_o}{AM_M P} \frac{\ln\left[\frac{p_s}{p_s - p_o}\right]}{p_o} = \frac{GS \ln\left[\frac{\alpha_s}{\alpha_s - \alpha_o}\right]}{AM_M P} \qquad (3)$$

The term containing the optical densities was evaluated for the readings at the three wavelengths and an average value was used for each run. In addition each run was duplicated and each k_G value reported is the average value for two or more runs at the same conditions. An attempt was made to keep the outlet air naphthalene concentration in the neighborhood of 50 - 60 % saturated. This was not always possible with the smaller packings at lower air rates, and these data scattered as a result. The naphthalene concentrations could be duplicated within two percent.

To determine the wetted area of the naphthalene packings when they were irrigated with water, a similar procedure was used except that Equation 3 was rearranged so that k_GA was evaluated for the dry area. The corresponding k_G was calculated from the correlation of the data obtained with the dry packing so that the dry area, A, could be calculated and the wetted area found by the difference from the total surface area.

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Table I

Properties of Naphthalene Packings

	Raschig Rings			Berl Saddles	
Nominal size, inches	0.5	1.0[a]	1.5	0.5	1.0
Height, inches[c]	0.50	1.0	1.5	—	—
Outside diameter, inches[c]	0.50	1.0	1.5	—	—
Wall thickness, inches[c]	0.0938	0.125	0.250	—	—
Void fraction, dry	0.630[d]	0.758[d]	0.688[d]	0.660[c]	0.695[c]
No. of pieces per cu. ft.	10,700[d]	1,220[d]	366[d]	15,000[c]	1,810[c]
Surface area per piece, sq. ft.	0.0105[d]	0.0430[d]	0.0955[d]	0.00888[b]	0.0346[b]
Surface area, (sq.ft.)/cu.ft.)[d]	113	52.5	35.0	133	62.6
Diameter of equivalent sphere, ft.[d]	0.0578	0.1167	0.174	0.0532	0.105

a. From data of Shulman and DeGouff (9)

b. From data of Maurice A. Knight, Akron, Ohio

c. From measurements

d. Calculated

Experimental Results

Mass Transfer in Dry Naphthalene Packings. The data obtained with the dry naphthalene packings are shown in Figure 2 with the data of Shulman and DeGouff (9) for 1.0-inch rings as a plot of the mass transfer factor, j_D, versus a modified Reynolds number. The equation for the best line through the points is

$$j_D = \left[\frac{k_G M_M P_{BM}}{G}\right] \left[\frac{\mu_G}{\rho_G D_V}\right]^{2/3} = 1.195\left[\frac{D_p G}{\mu_G(1-\epsilon)}\right]^{-0.36} \quad (4)$$

Other methods of correlation were tested, such as those suggested by Gamson (5) and Taecker and Hougen (12), but the one used was found to represent the data best. The correlation includes the void fraction, ϵ, which makes it possible to take into account the effect of liquid in the packing when the total holdup is known under operating conditions. In Figure 3 the data are compared with the extensive data of Chu, Kalil, and Wetteroth (1) on fixed and fluidized beds of a variety of particles coated with naphthalene. The agreement is good, with the best line for Chu's data (not shown on Figure 3) lying slightly below the line recommended by the authors. The broken line on Figure 3 represents the equation

$$j_D = 1.77\left[\frac{D_p G}{\mu_G(1-\epsilon)}\right]^{-0.44} \quad (5)$$

which Chu obtained as the best line representing his data and that of numerous previous investigators for fixed and fluidized beds.

Figure 4 compares the authors' line with the data of Taeker and Hougen (12) obtained by vaporizing water from porous packings. There is good agreement for the Berl saddle data, but each series of data for the rings

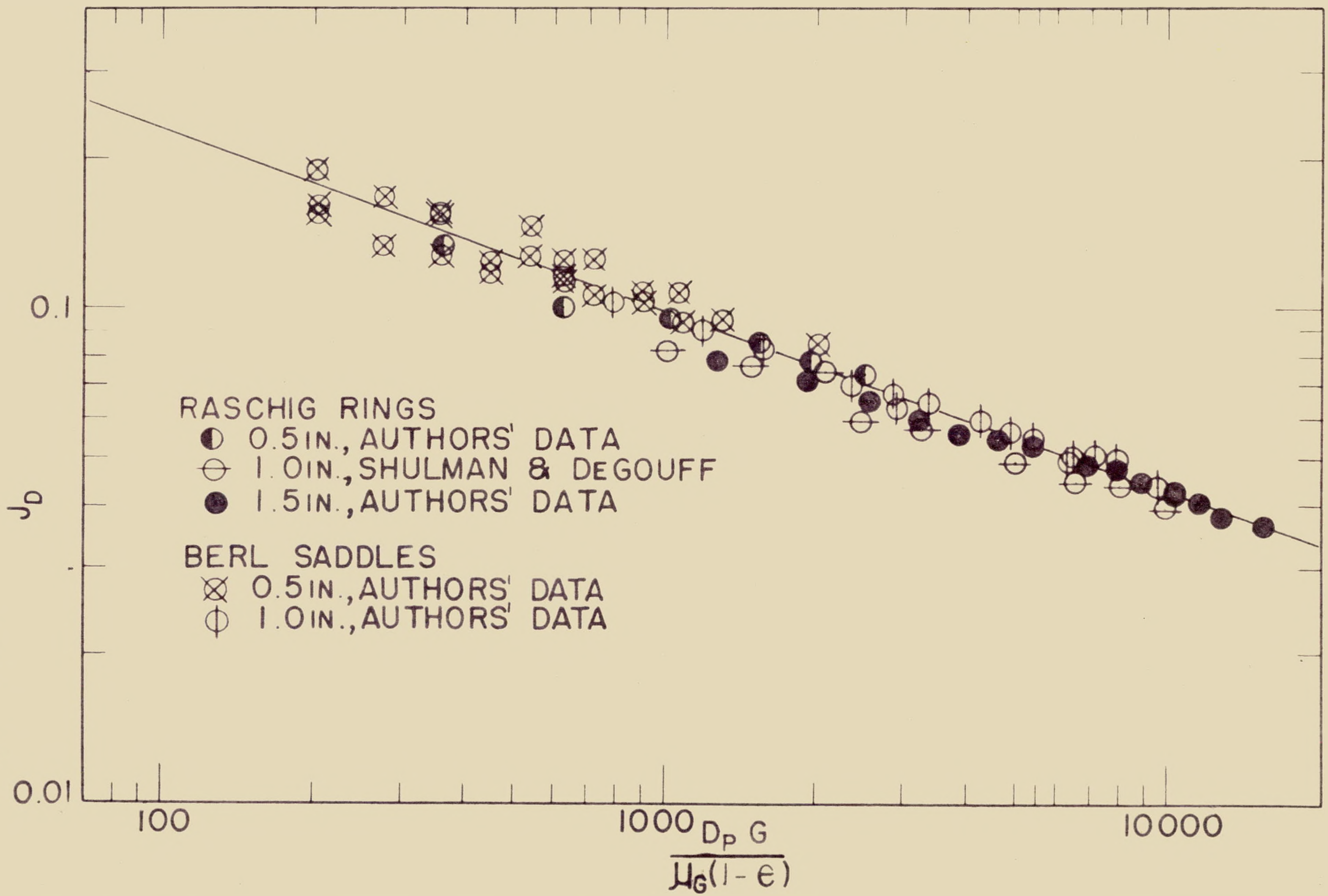

FIG. 2, MASS TRANSFER FACTORS FOR NAPHTHALENE PACKING

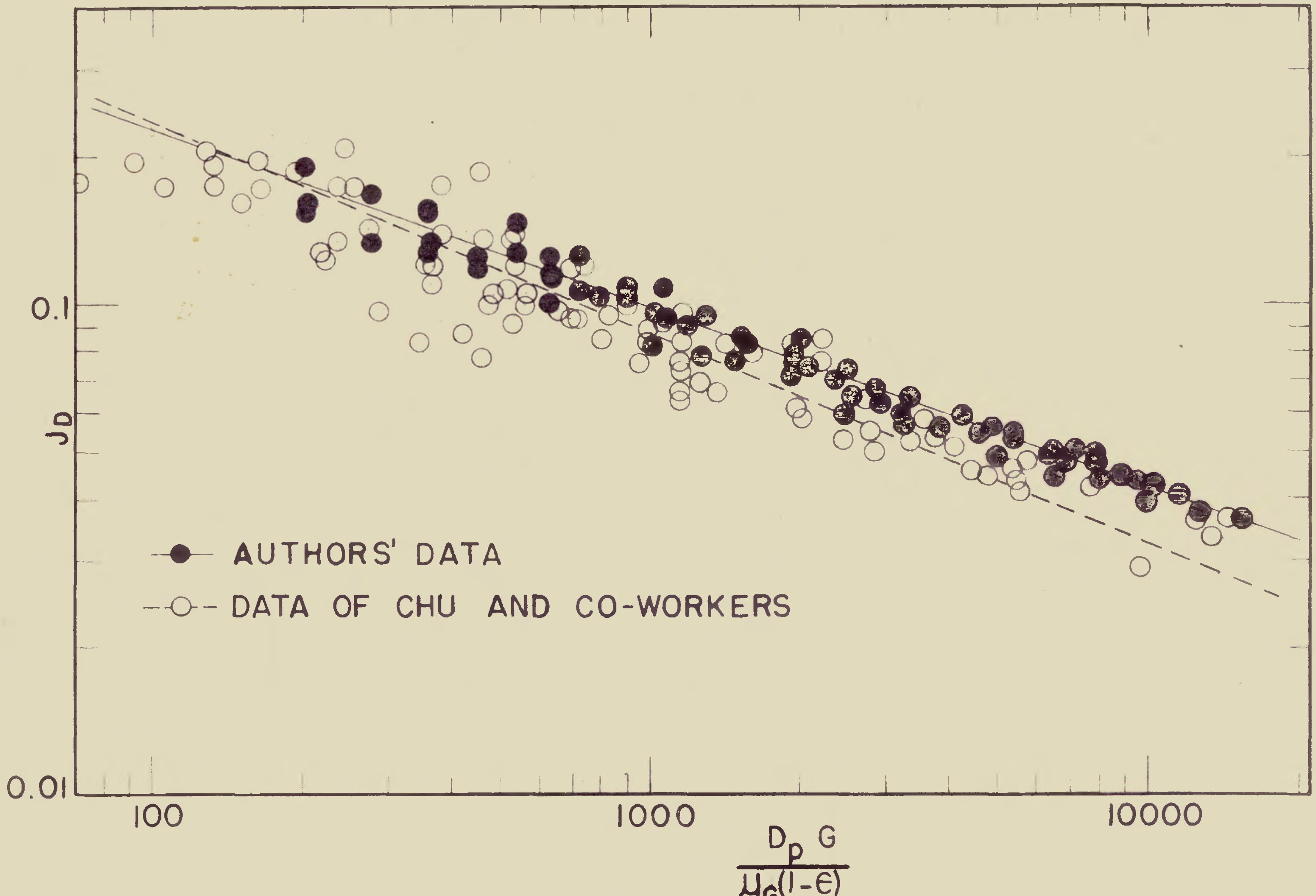

FIG. 3, COMPARISON OF AUTHORS' DATA WITH DATA OF CHU AND CO-WORKERS

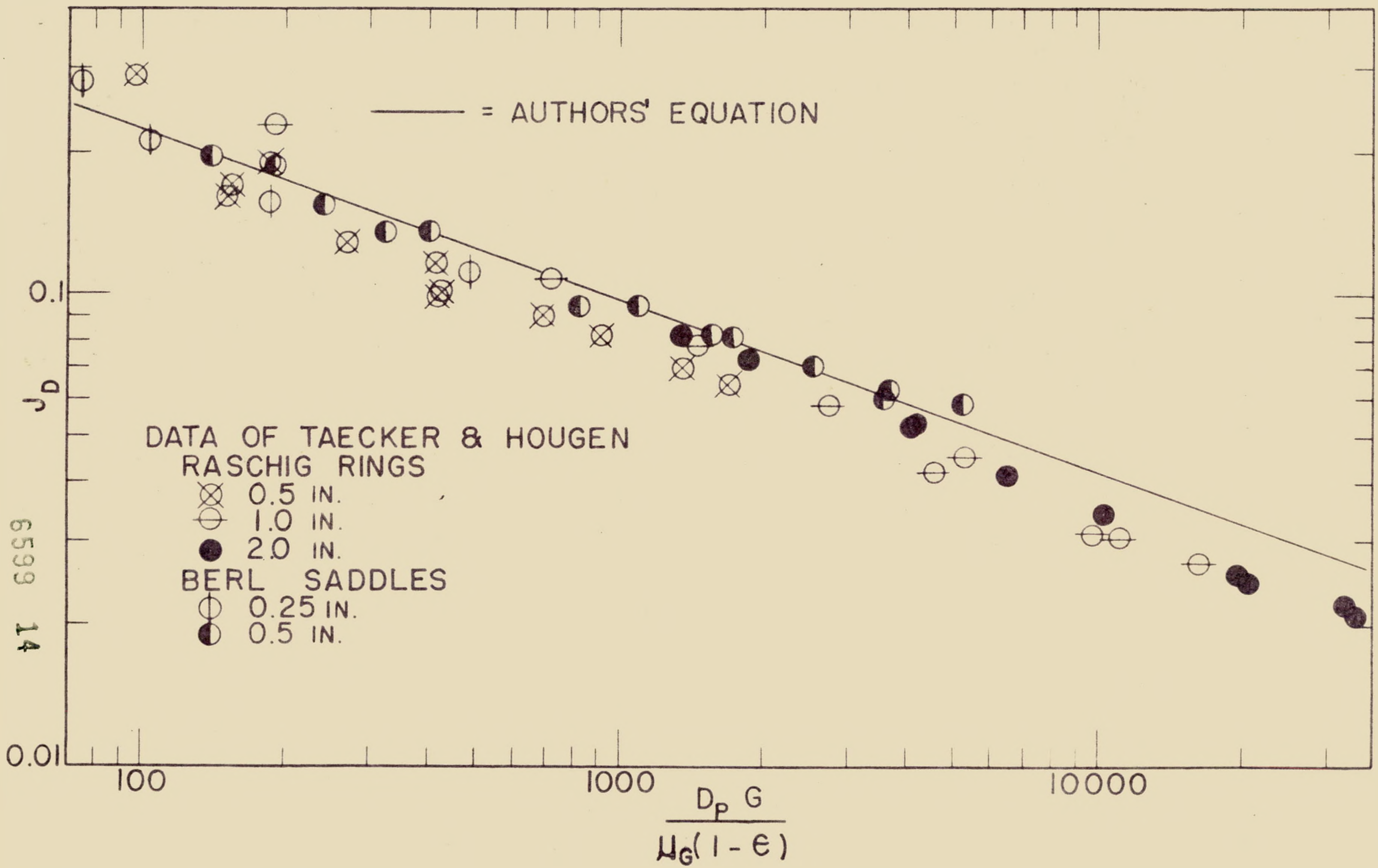

FIG. 4, COMPARISON OF AUTHORS' EQUATION WITH DATA OF TAECKER AND HOUGEN

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shows increasing disagreement at the higher Reynolds numbers corresponding to high gas rates. A possible explanation of this type of behavior for wetted porous rings may be an incompletely wetted surface brought about by the inability of the water to migrate to the surface fast enough to keep the surface completely wetted. It is interesting to note that the Berl saddles used by Taecker and Hougen (12) were prepared by Maurice A. Knight by molding and the Raschig rings were prepared by the authors by extrusion. The differences in preparation may have resulted in porous materials with different properties. The good agreement with the Berl saddle data and the Raschig ring data at the lower gas rates is an indication that the Schmidt number to the 2/3 power is capable of correlating data of different systems.

Wetted Area in Naphthalene Packings. The wetted areas for irrigated naphthalene packings were divided by the total surface areas, listed in Table I, and are presented in Figures 5, 7, 8, and 9 as the fraction of the total area wetted. Figure 6 shows the data of Shulman and DeGouff (9) for 1.0-inch Raschig rings recalculated by means of Equation 4 for k_G and the total holdup data of Shulman, Ullrich, and Wells(10). The loading points shown in these figures are obtained from the work of Tillson (13). For all the packings the wetted areas increase with increasing liquid rate and decrease with increasing gas rate usually until the loading point is reached when the lines tend to become horizontal or even show an increase in wetted area at still higher gas rates. The unusual effect of gas rate was first reported by Shulman and DeGouff (9) and was found again for the four packings used in this work. The explanation of this phenomenon as offered in the earlier work seems to be valid. It will be shown later that the effective interfacial areas also decrease at increasing gas rates for low liquid rates.

The wetted area data obtained in this work can be correlated by a line for each type of packing as shown in Figure 10. For some unknown reason the data of Shulman and DeGouff (9) for the 1.0-inch rings scatter badly on this type of plot. The equations of the two lines in Figure 10 are

$$\frac{a_w}{a_t} = 0.35 \left[\frac{L}{G}\right]^{0.20} \qquad (6)$$

for Berl saddles and

$$\frac{a_w}{a_t} = 0.24 \left[\frac{L}{G}\right]^{0.25} \qquad (7)$$

for Raschig rings.

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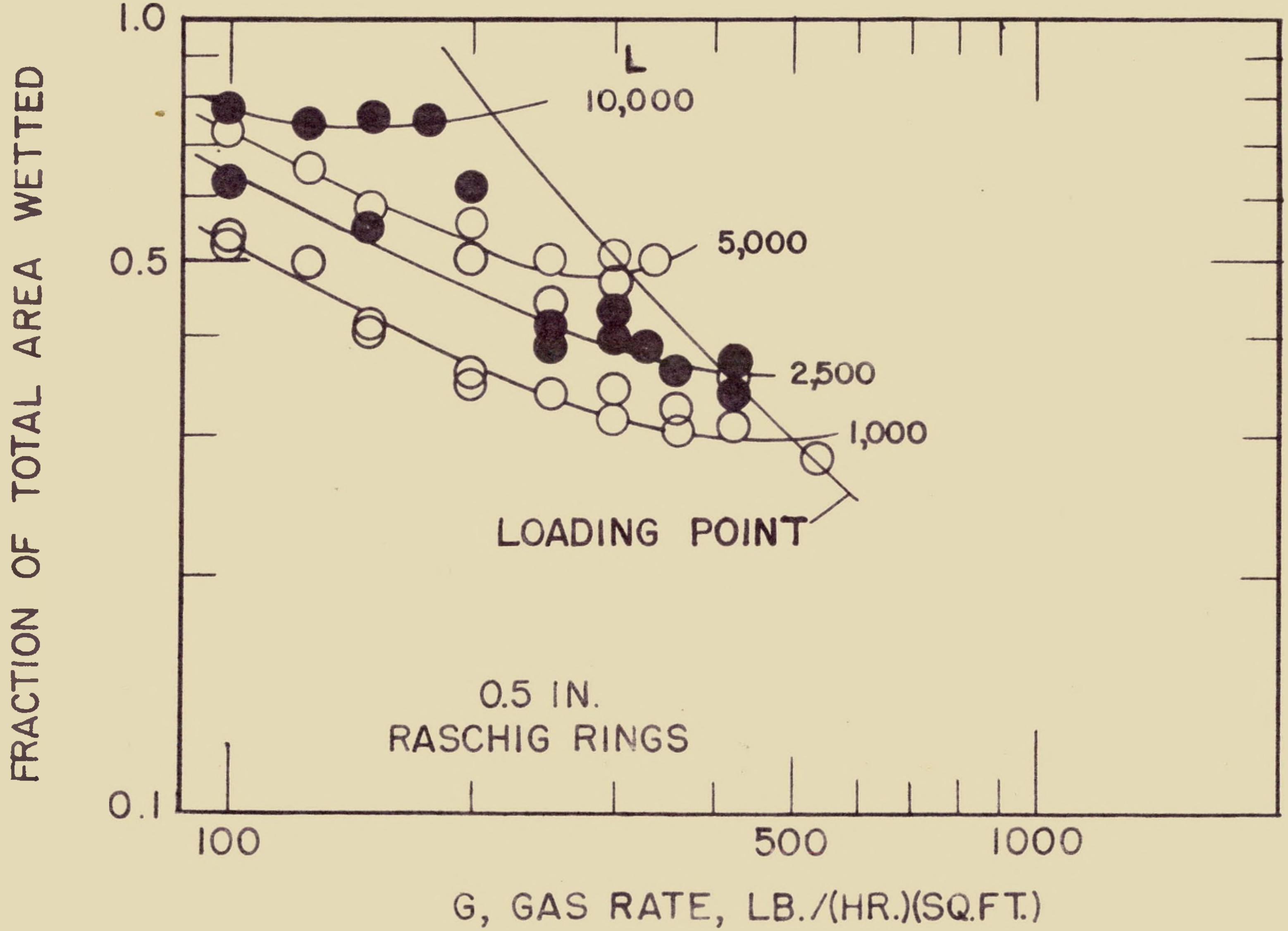

FIG. 5, WETTED AREA FOR 0.5 IN. NAPHTHALENE RASCHIG RINGS

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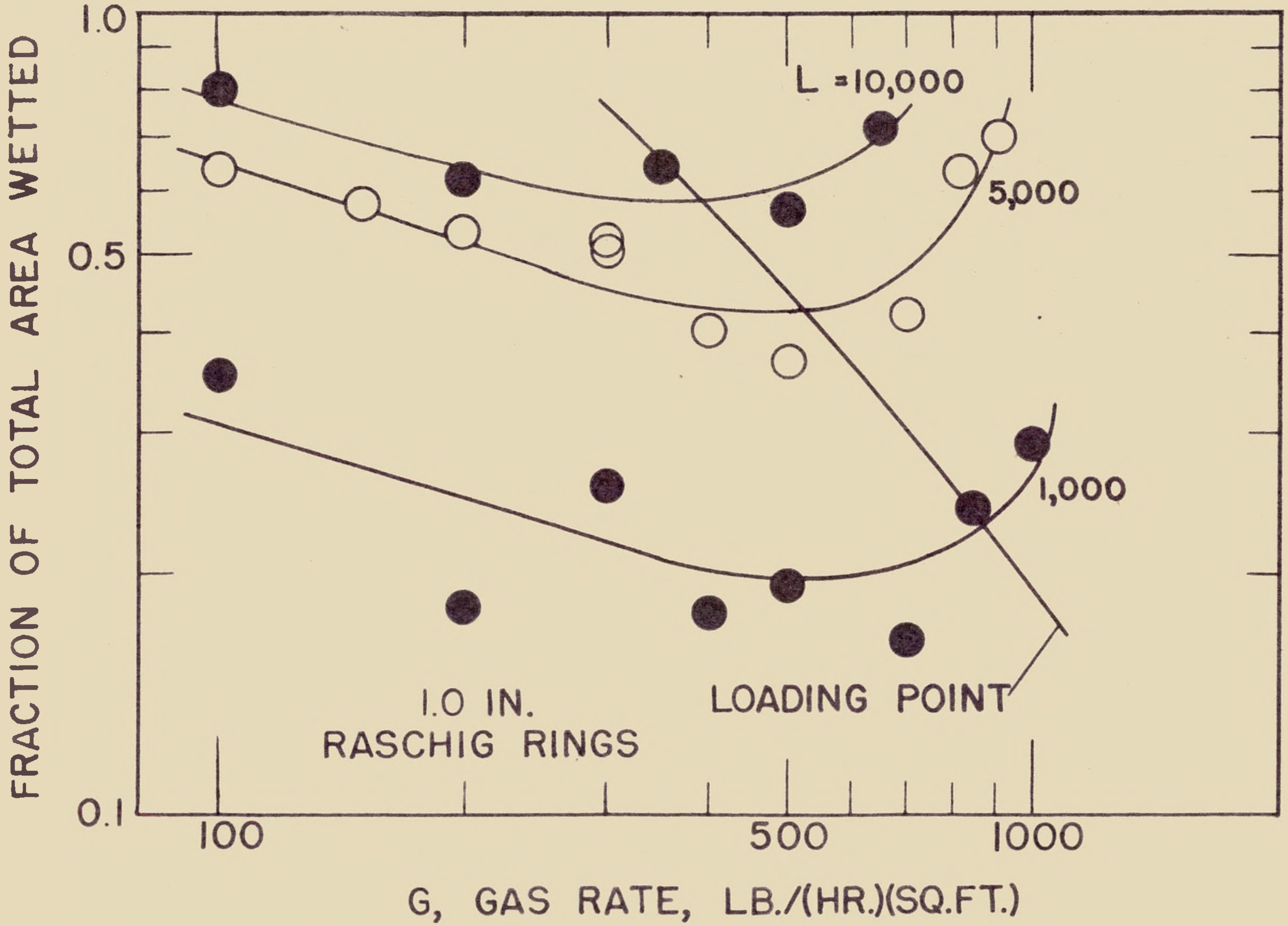

FIG. 6, **WETTED AREA FOR 1.0 IN. NAPHTHALENE RASCHIG RINGS**
CALCULATED FROM DATA OF SHULMAN AND DeGOUFF

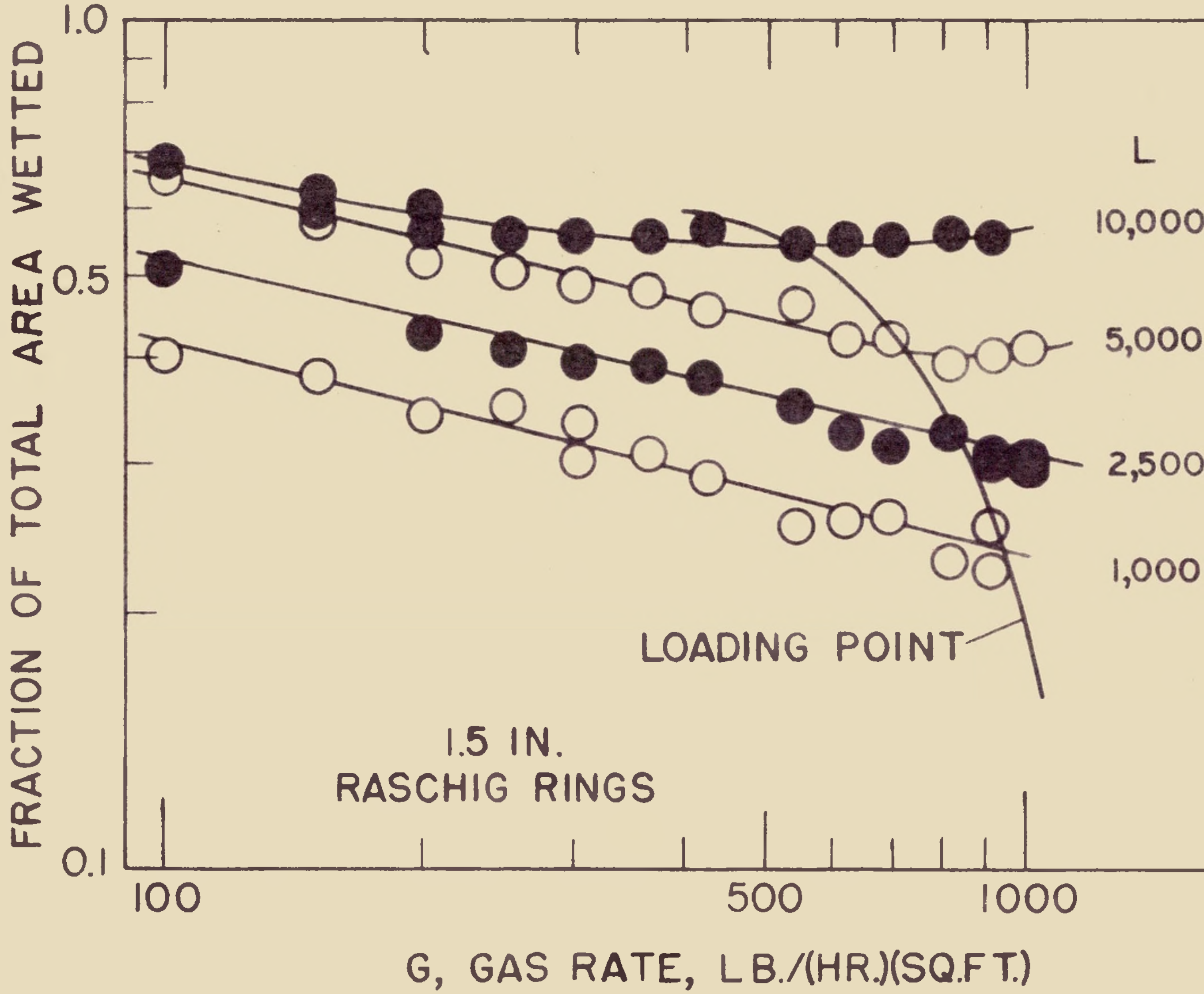

FIG. 7, WETTED AREA FOR 1.5 IN. NAPHTHALENE RASCHIG RINGS

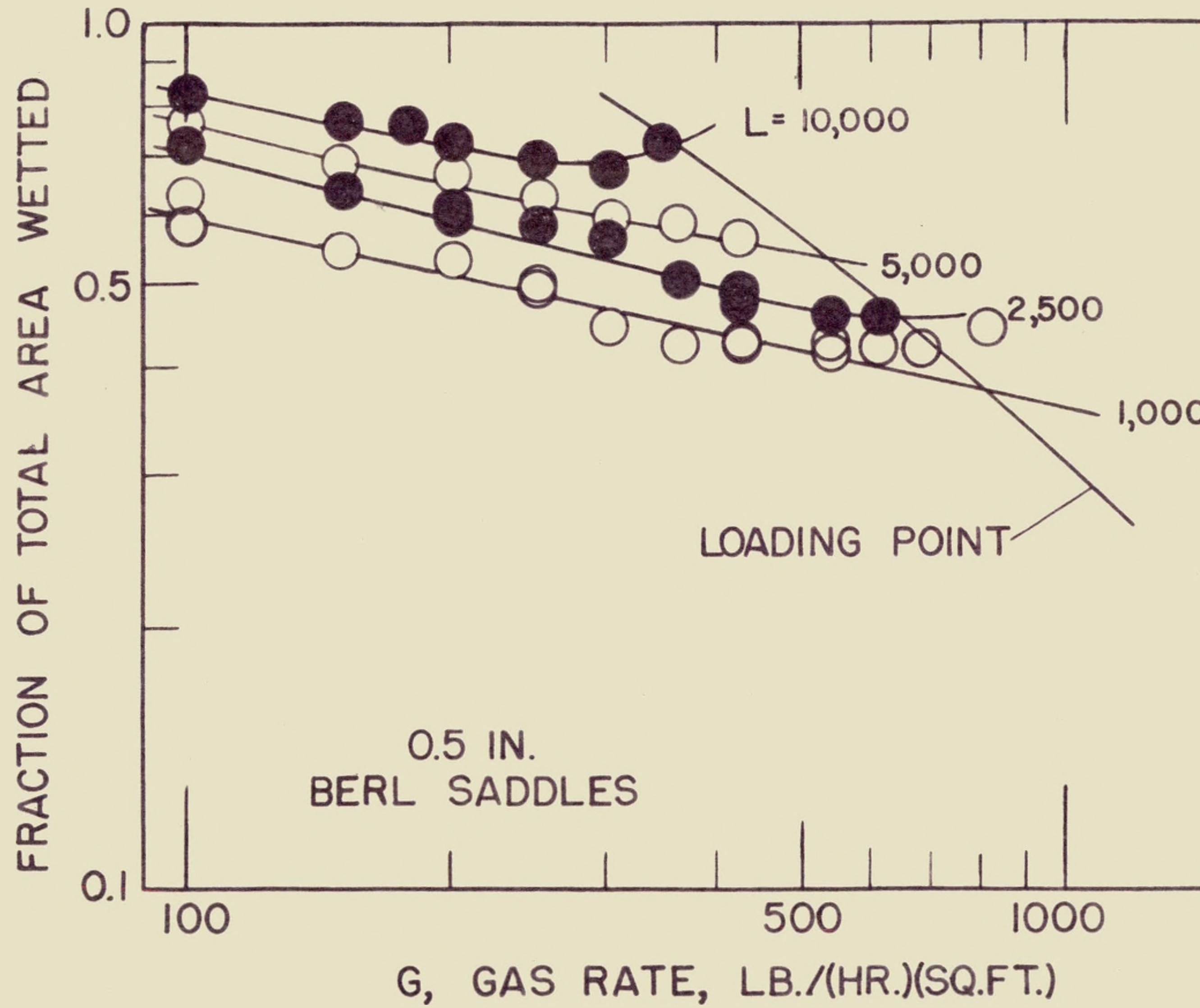

FIG. 8, WETTED AREA FOR 0.5 IN. NAPHTHALENE BERL SADDLES

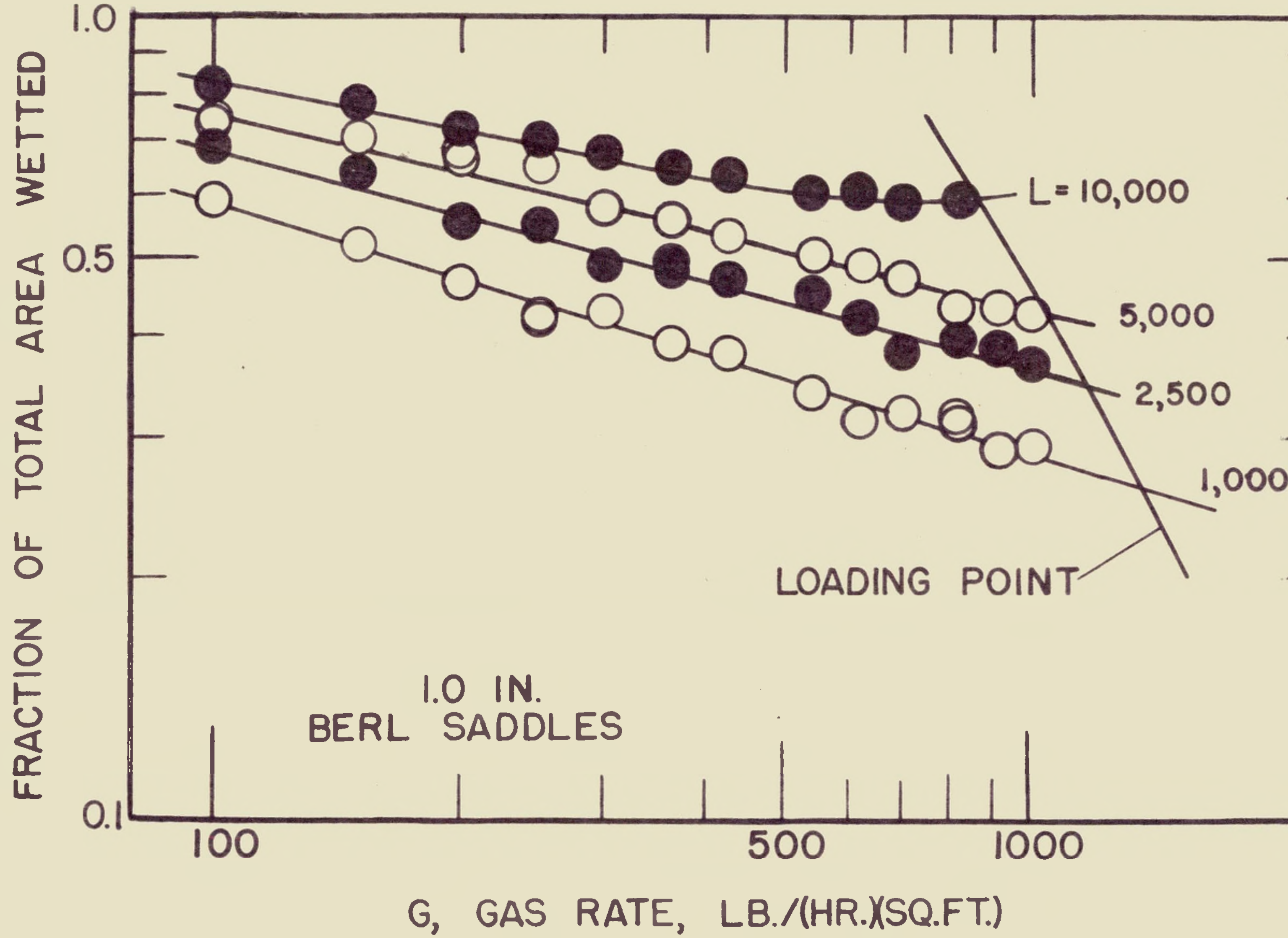

FIG. 9, WETTED AREA FOR 1.0 IN. NAPHTHALENE BERL SADDLES

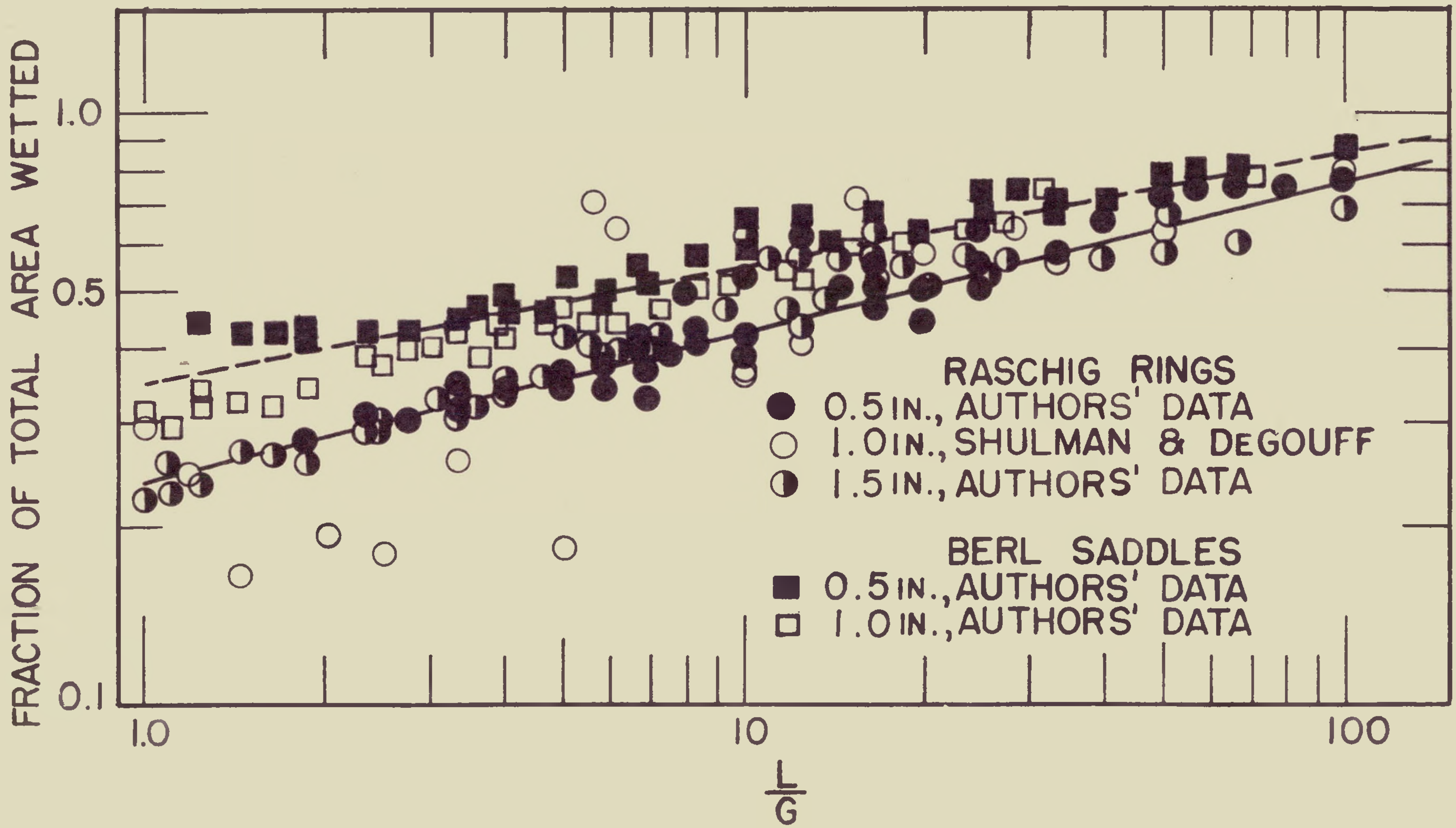

FIG. 10, CORRELATION OF FRACTION WETTED FOR NAPHTHALENE PACKINGS

Effective Interfacial Area

A correlation for k_G, such as given by Equation 4, makes it possible to calculate the effective interfacial area, a, from reliable sources of k_Ga data. The data of Fellinger (4) for ammonia absorption in water employing nine ceramic packings seems to be the most complete and reliable source of data. Shulman, Ullrich, and Wells (10) have been able to explain the reason for the large differences between k_Ga obtained by vaporization and absorption techniques on the basis of total and operating holdups. On the basis of their explanation it should be emphasized that the effective interfacial areas reported here are valid for absorption work. For vaporization of water the effective area is greater by a factor equal to 0.85 times the ratio of total to operating holdup at the liquid and gas rates employed.

Fellinger's (4) data were corrected for liquid phase resistance by means of the Sherwood and Holloway (8) correlation and divided by the corresponding k_G obtained from Equation 4 and the holdup data of Shulman, Ullrich, and Wells (10). Figures 11, 12, 13, 15, and 16 present the effective interfacial areas for the packings for which both absorption and holdup data are available. Figures 14 and 17 present these areas for 2.0-inch rings and 1.5-inch saddles employing holdups estimated by means of correlating equations given by Shulman, Ullrich, and Wells (10). The loading point line on each figure was obtained from the data of Tillson (13).

An examination of these plots shows the effective interfacial area increases with increasing liquid rate and is fairly independent of gas rate although in general it increases with gas rate at high liquid rates, decreases at the lower liquid rates and is independent at the intermediate liquid rates. The behavior at low liquid rates is similar to that of the wetted area. A comparison of wetted and effective areas reveals some important differences. Wetted areas increase as packing size decreases. The effective area, however, is smallest for the smallest packings in spite of the fact that they possess the largest total surface and wetted area. The effective area seems to go through a maximum for the 1.0-inch rings and saddles although the larger packings have almost as much effective area. It may be possible to explain these results with the holdup studies mentioned previously (10). The small packings were found to have very large static holdups which exist in the packing as pockets of almost stagnant water. This water can account for the large wetted area, but it is practically useless for absorption because it comes to equilibrium with the gas very rapidly. The water which runs through the packing, corresponding to the operating holdup, flows through the numerous crevices at the points of contact in the small packing, exposing a relatively small surface area. In the larger packings there are fewer points of contact and resulting crevices so that the water must spread out over the surface, and the effective area is more closely related to the wetted area.

Further work is planned on the relations between wetted area, holdup, and effective area, and the effects of liquid and packing properties. It is hoped that a method can be devised to predict the effective interfacial area for non-aqueous systems and various packing materials.

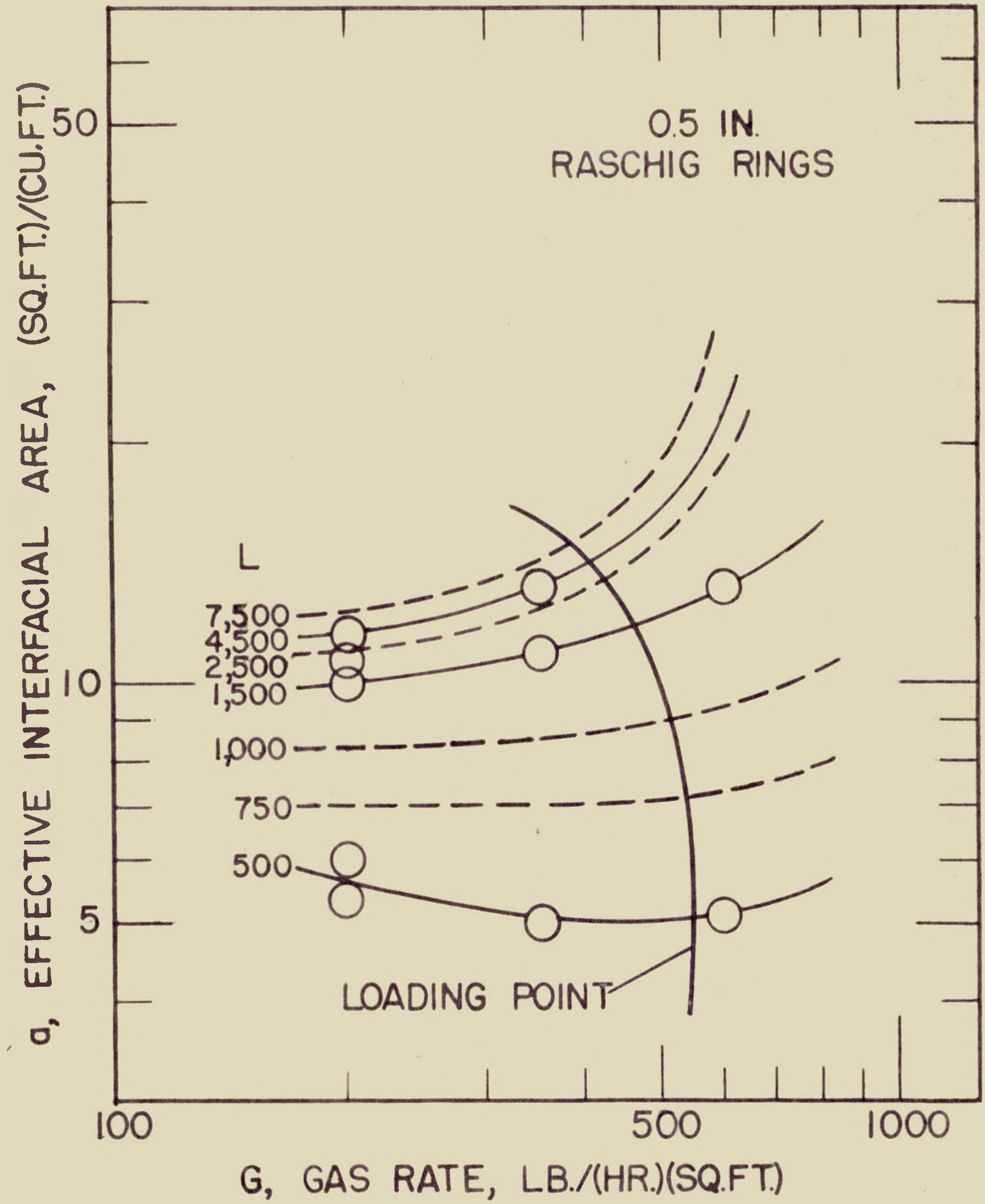

FIG. 11, EFFECTIVE INTERFACIAL AREA FOR 0.5 IN. RASCHIG RINGS BASED ON DATA OF FELLINGER

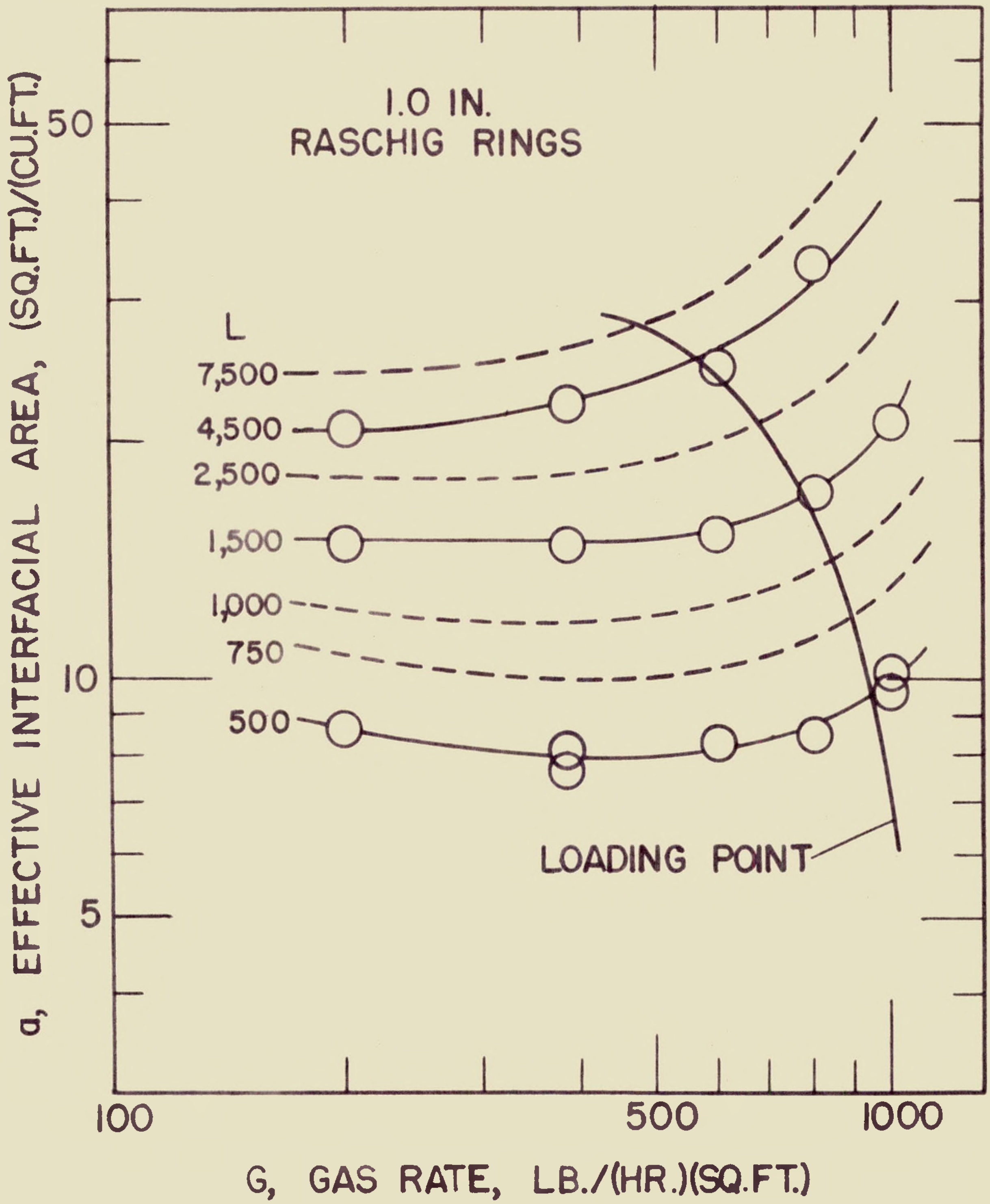

FIG. 12, EFFECTIVE INTERFACIAL AREA FOR 1.0 IN. RASCHIG RINGS BASED ON DATA OF FELLINGER

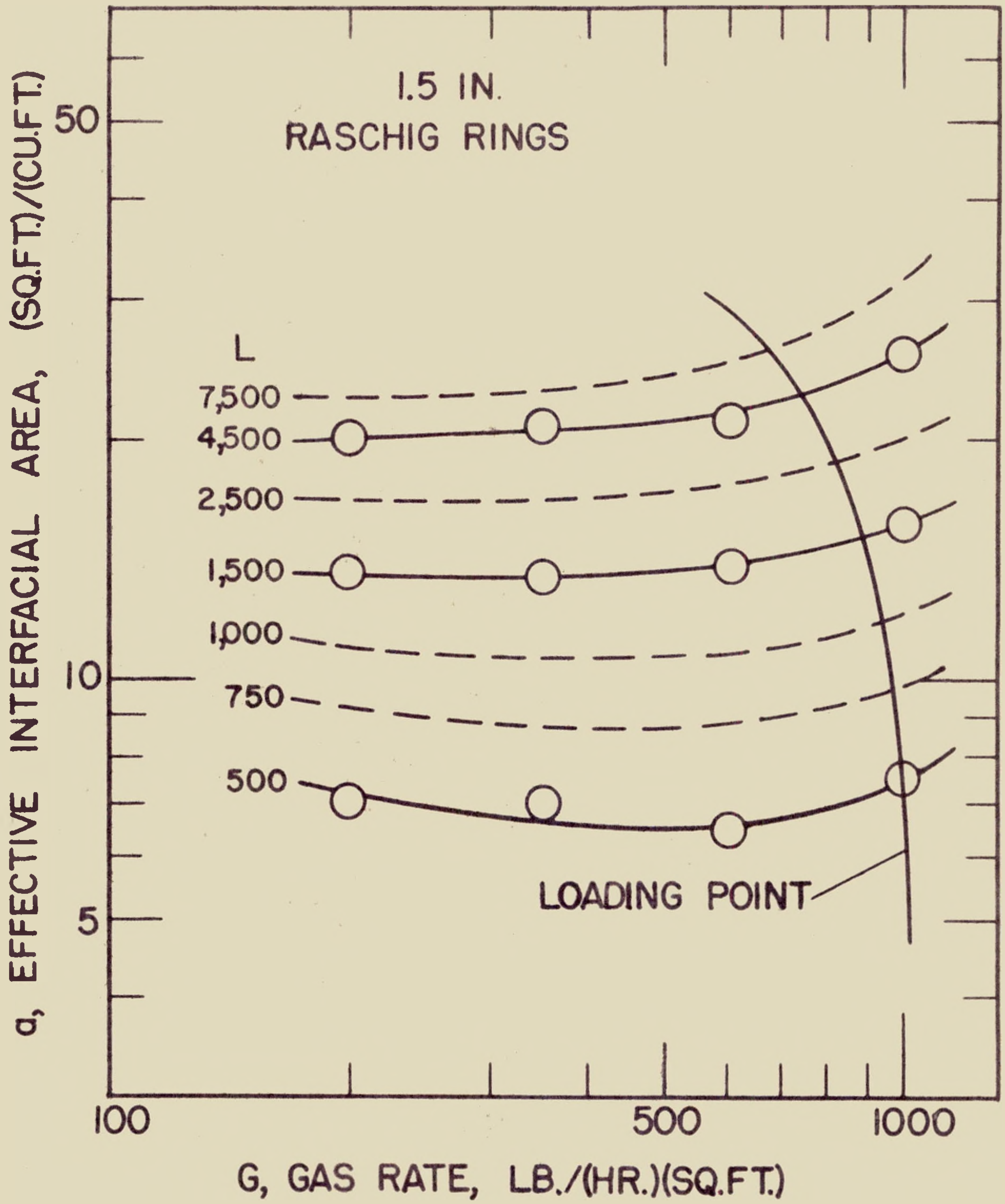

FIG. 13, EFFECTIVE INTERFACIAL AREA FOR 1.5 IN. RASCHIG RINGS BASED ON DATA OF FELLINGER

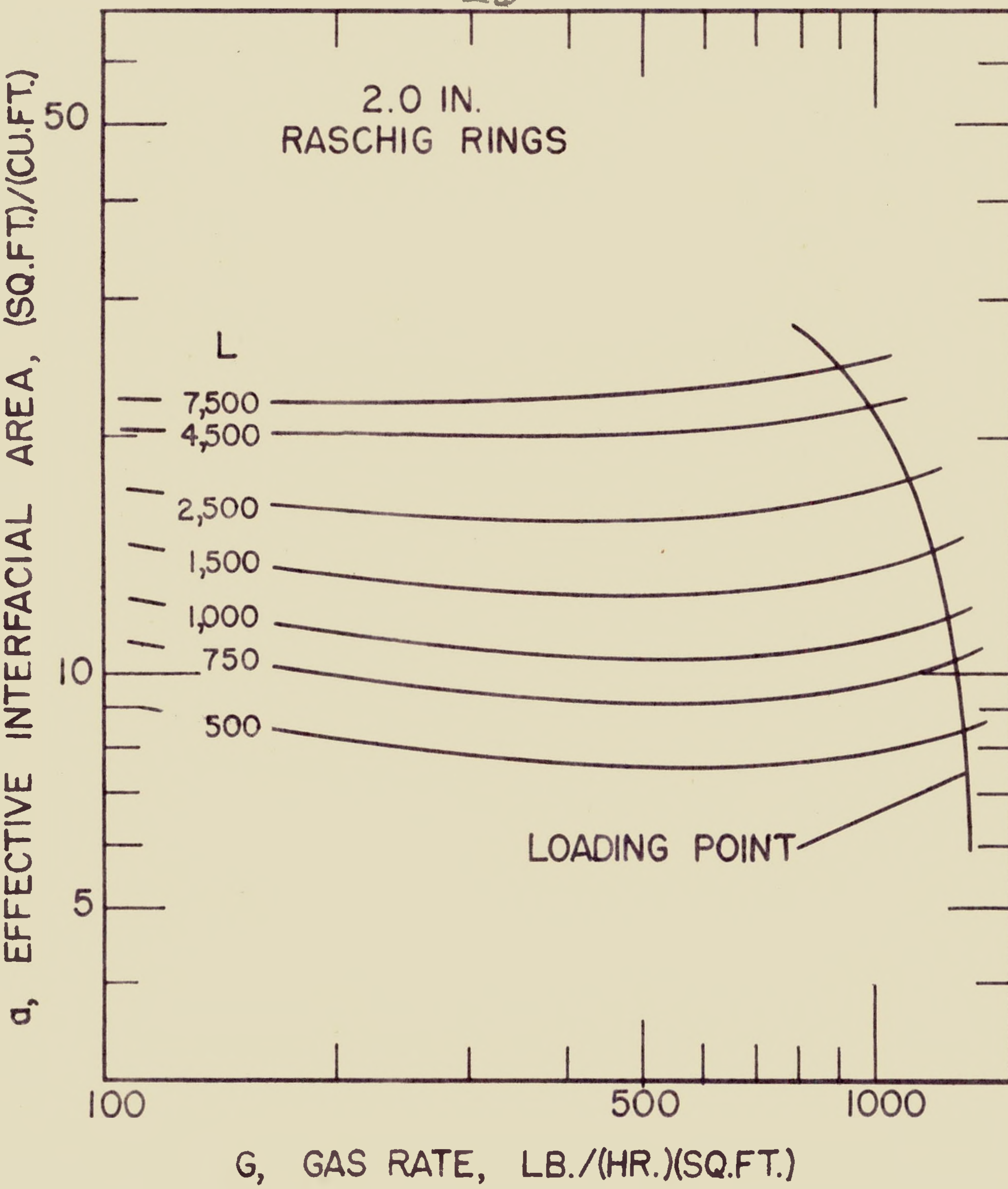

FIG. 14, EFFECTIVE INTERFACIAL AREA FOR 2.0 IN. RASCHIG RINGS BASED ON DATA OF FELLINGER USING ESTIMATED HOLDUPS

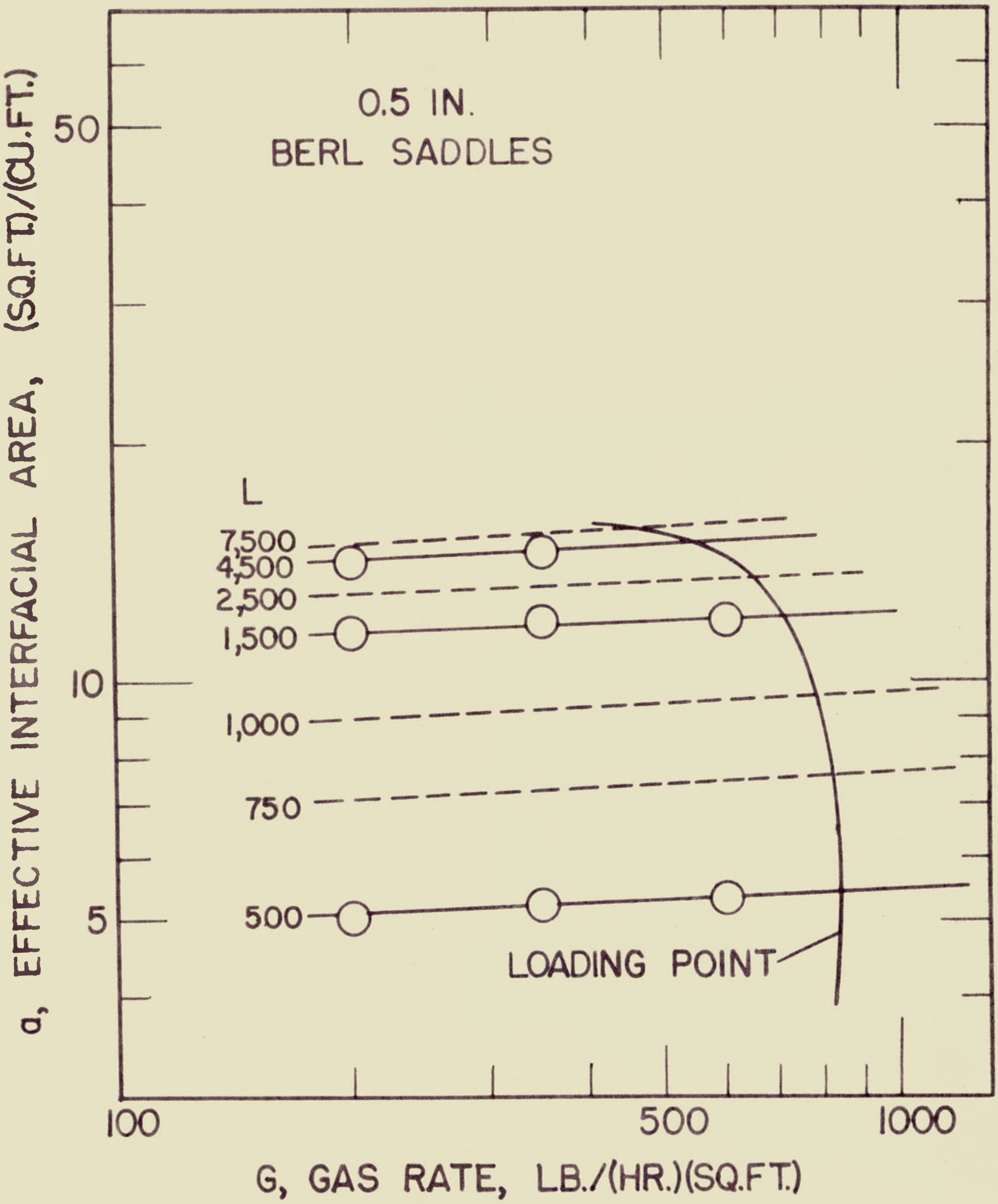

FIG. 15, EFFECTIVE INTERFACIAL AREA FOR 0.5 IN. BERL SADDLES BASED ON DATA OF FELLINGER

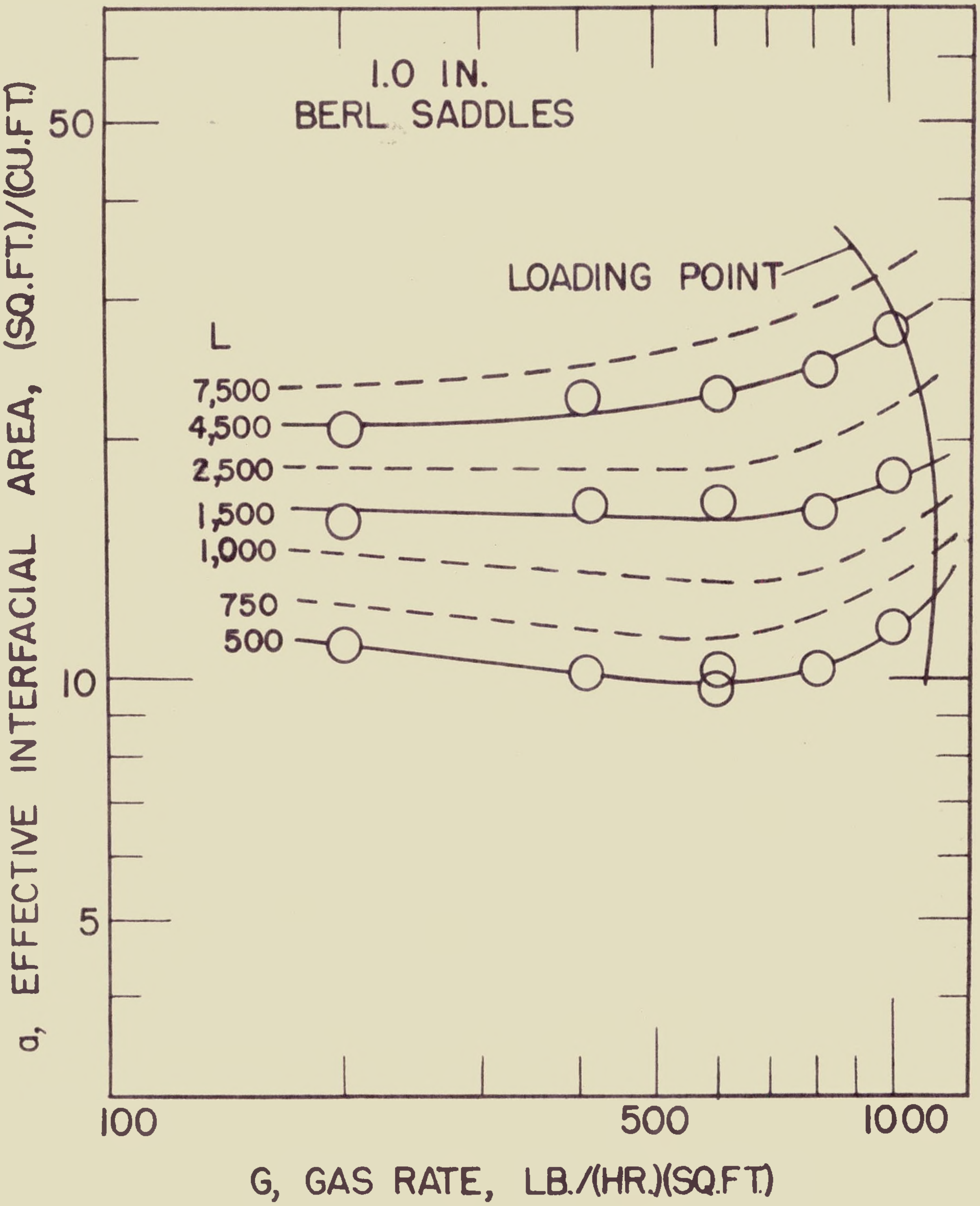

FIG. 16, EFFECTIVE INTERFACIAL AREA FOR 1.0 IN. BERL SADDLES BASED ON DATA OF FELLINGER

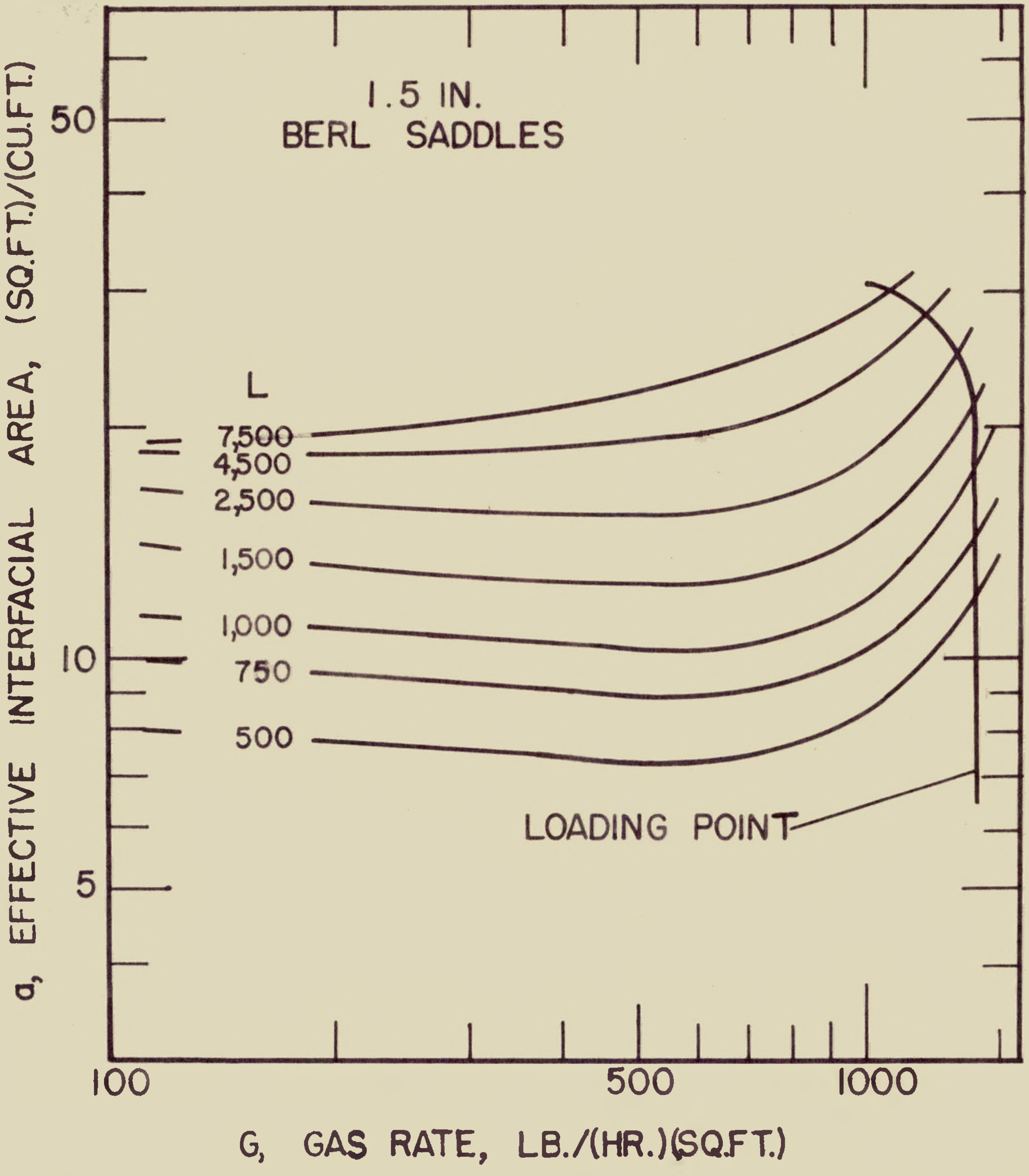

FIG. 17, EFFECTIVE INTERFACIAL AREA FOR 1.5 IN. BERL SADDLES BASED ON DATA OF FELLINGER USING ESTIMATED HOLDUPS

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Correlation of k_L for Rings and Saddles

Sherwood and Holloway (8) have obtained k_La data for nine ceramic packings by desorption of slightly soluble gases from water. Some of this work has been checked by other investigators such as Deed, Schutz, and Drew (2) and Vivian and Whitney (14, 16) with good agreement. As was pointed out earlier there is no way to correlate the k_La data for the different packings.. With the effective interfacial areas for absorption as shown in Figures 11 to 17 inclusive, it is a simple matter to extract k_L and attempt a generalized correlation. Figure 18 shows the best correlation that could be obtained from the three sources of data cited above. For some of the packings it was possible to extrapolate with confidence the effective interfacial areas to liquid rates well above those shown in Figures 11 to 17. The line drawn in Figure 18 is the best line through the points for 0.5, 1.0, and 1.5-inch rings and 0.5 and 1.0-inch saddles. The points for 2.0-inch rings and 1.5-inch saddles, which are based on effective interfacial areas calculated from Fellinger's (4) data, Equation 4 for k_G, and estimated holdups, are also in good agreement with this line. This is an indication that the correlations for k_G, k_L, and holdup can be used to predict the performance of packings for which complete data are not available.

The equation for the line in Figure 18 is

$$\frac{k_L D_P}{D_L} = 25.1 \left[\frac{D_P L}{\mu_L}\right]^{0.45} \left[\frac{\mu_L}{\rho_L D_L}\right]^{0.5} \qquad (8)$$

It can be seen that k_L is indeoendent of gas rate so k_La can be exoected to vary with gas rate as a does as shown in Figures 11 to 17, inclusive.

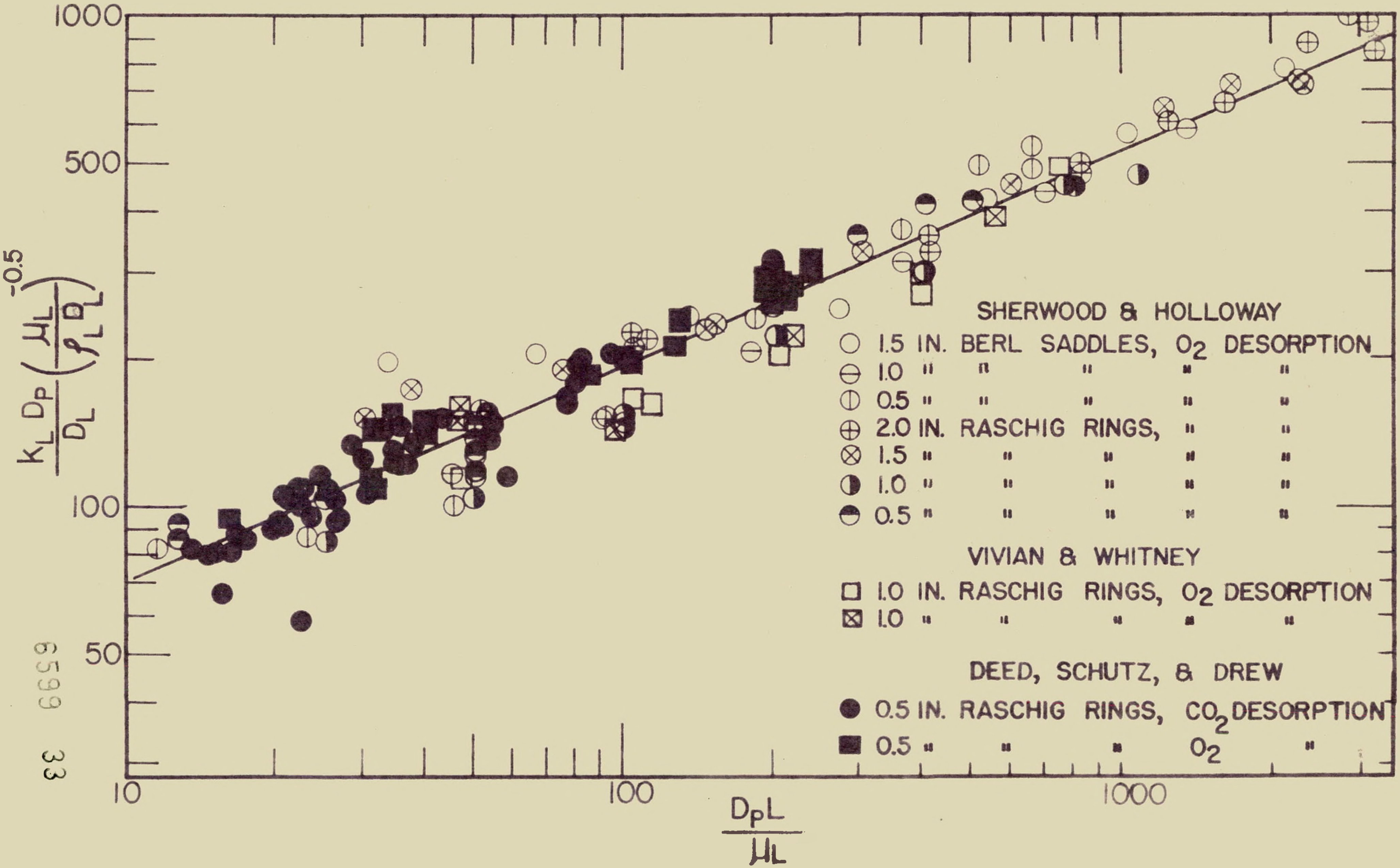

FIG. 18, CORRELATION OF LIQUID PHASE DATA

This observation seems to contradict that of Sherwood and Holloway (8) who found $k_L a$ to be independent of gas rate up to loading. Their statement, however, seems to be based on data obtained with 1.5-inch rings at a liquid rate of 2000 (lbs.)/(hr.)(sq.ft.). An examination of Figure 13 shows a to be just about independent of gas rate at this liquid rate so $k_L a$ should also be independent. It should be noted that it would not be serious to neglect the effect of gas rate with large packings but some of the small packings do show an appreciable effect at the high and low liquid rates.

Equation 8 will predict the effects of temperature and diffusivity as found by Sherwood and Holloway (8). If further work on effective interfacial areas makes possible predictions for non-aqueous systems it will be possible to use Equations 4 and 8 to predict the performance of ring and saddle packing for all systems.

Summary of Results and Conclusions

For Raschig ring and Berl Saddle packings mass transfer rates can be predicted for the gas phase by

$$j_D = \left[\frac{k_G M_M P_{BM}}{G}\right]\left[\frac{\mu_G}{\rho_G D_V}\right]^{2/3} = 1.195\left[\frac{D_P G}{\mu_G(1-\epsilon)}\right]^{-0.36} \qquad (4)$$

and for the liquid phase by

$$\frac{k_L D_P}{D_L} = 25.1\left[\frac{D_P L}{\mu_L}\right]^{0.45}\left[\frac{\mu_L}{\rho_L D_L}\right]^{0.5} \qquad (8)$$

The effective interfacial areas, a, for absorption and desorption are given for seven packings in Figures 11 to 17, inclusive, and those for vaporization can be estimated from these by applying a factor equal to 0.85 times the ratio of total holdup to operating holdup.

The wetted areas for five packings, Figures 5 to 9, inclusive, are not related in any simple manner to the effective interfacial areas.

Acknowledgement

The authors wish to acknowledge support of this work under Grant G-200 of the National Science Foundation and Contract No. AT(30-1)-1463 of the Atomic Energy Commission.

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Notation

A = total dry surface area, sq. ft.

a = effective interfacial area, (sq.ft.)/(cu.ft.)

a_w = wetted area, (sq.ft.)/(cu.ft.)

a_t = total surface area, (sq.ft.)/(cu.ft.)

D_L = diffusivity of solute in liquid, (sq.ft.)/(hr.)

D_P = diameter of sphere possessing the same surface area as a piece of packing, ft.

D_V = diffusivity of solute in gas, (sq.ft.)/(hr.)

G = superficial gas rate, lbs./(hr.)(sq.ft.)

H = Henry's law constant, lb. moles/(cu.ft.)(atm.)

j_D = mass transfer factor

K_G = overall mass transfer coefficient, lb. moles/(hr.)(sq.ft.)(atm.)

k_G = gas phase mass transfer coefficient, lb. moles/(hr.)(sq.ft.)(atm.)

K_L = overall mass transfer coefficient, lb. moles/(hr.)(sq.ft.)(lb. moles/cu.ft.)

k_L = liquid phase mass transfer coefficient, lb. moles/(hr.)(sq.ft.)(lb. moles/cu.ft.)

L = superficial liquid rate, lbs./(hr.)(sq.ft.)

M_M = mean molecular weight of gas, lb./(lb. mole)

P = total pressure, atm

p_{BM} = mean partial pressure of inert gas in the gas phase, atm.

p_o = partial pressure of naphthalene in outlet air, atm.

p_s = vapor pressure of naphthalene, atm.

S = column cross-sectional area, sq. ft.

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Notation (continued) 36

Greek Letters:

α = optical density

α_o = optical density of outlet air

α_s = optical density of air saturated with naphthalene

ϵ = void fraction, cu.ft./(cu.ft.)

μ_G = gas viscosity, lb./(hr.)(ft.)

μ_L = liquid viscosity, lb./(hr.)(ft.)

ρ_G = gas density, lb./(cu.ft.)

ρ_L = liquid density, lb./(cu.ft.)

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Table II

Packing: 0.5-inch naphthalene Raschig rings

Air Temperature: 21.0 - 22.5°C

Void Fraction, Dry: 0.630

Number of Pieces of Packing Used: 1450

Total Area, Dry: 15.3 sq. ft.

Total Pressure: 1.06 atm.

G	$\left[\ln \frac{\alpha_s}{\alpha_s - \alpha_o}\right]_{AV}$	k_G	j_D	$\frac{D_p G}{\mu_G (1 - \epsilon)}$
100	2.08	0.231	0.1332	362
200	1.599	0.356	0.1015	724
300	1.51	0.504	0.0963	1082
425	1.348	0.634	0.0857	1528
540	1.228	0.735	0.0783	1947
696	1.16	0.894	0.0738	2510
910	0.936	0.941	0.0596	3270

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Table III

Packing: 1.5-inch naphthalene Raschig rings

Air Temperature: 21.3 - 21.8°C

Void Fraction, Dry: 0.688

Number of Pieces of Packing Used: 160

Total Area, Dry: 15.25 sq. ft.

Total Pressure: 1.06 atm.

G	$\left[\ln \frac{\alpha_s}{\alpha_s - \alpha_o}\right]_{AV}$	k_G	j_D	$\frac{D_p G}{\mu_G (1 - \epsilon)}$
251	0.936	0.260	0.0597	3200
301	0.875	0.291	0.0558	3830
425	0.833	0.391	0.0530	5410
619	0.747	0.510	0.0475	7880
696	0.702	0.540	0.0447	8870
813	0.673	0.603	0.0427	10340
909	0.640	0.641	0.0407	11560
1003	0.593	0.658	0.0378	12790
1200	0.570	0.755	0.0363	15280
201	1.02	0.226	0.0649	2560
540	0.755	0.451	0.0482	6880
813	0.652	0.585	0.0415	10340
151	1.129	0.188	0.0716	1912
363	0.855	0.343	0.0545	4620
100	1.232	0.137	0.0785	1279

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Table IV

Packing: 0.5-inch naphthalene Berl saddles

Air Temperature: 21.1 - 22.5°C

Void Fraction, Dry: 0.660

Number of Pieces of Packing: 1720

Total Area, Dry: 15.15 sq. ft.

Total Pressure: 1.06 atm.

G	$\left[\ln\frac{\alpha_s}{\alpha_s-\alpha_o}\right]_{AV}$	k_G	j_D	$\frac{D_p G}{\mu_G(1-\epsilon)}$
100	2.44	0.272	0.1568	359
151	2.29	0.383	0.147	540
201	1.96	0.438	0.126	719
251	1.688	0.470	0.108	898
301	1.675	0.561	0.1075	1079
363	1.488	0.600	0.0954	1300
58	2.405	0.1545	0.154	206
178	1.798	0.354	0.1152	636
178	1.785	0.352	0.1146	636
126	1.865	0.259	0.119	451
77	2.075	0.1775	0.1335	276
58	2.10	0.135	0.161	206
100	2.015	0.224	0.129	359

Table IV (continued)

G	$\left[\ln \frac{\alpha_s}{\alpha_s - \alpha_o}\right]_{AV}$	k_G	j_D	$\frac{D_p G}{\mu_G(1-\epsilon)}$
	Number of Pieces of Packing: 1420			
	Total Area, Dry: 12.5 sq. ft.			
301	1.208	0.490	0.0939	1079
251	1.332	0.452	0.104	898
201	1.373	0.372	0.1069	719
178	1.623	0.389	0.126	636
126	1.61	0.273	0.125	451
	Number of Pieces of Packing: 1100			
	Total Area, Dry: 9.7 sq. ft.			
151	1.282	0.336	0.1282	540
100	1.538	0.268	0.154	359
77	1.672	0.225	0.1682	276
58	1.91	0.192	0.191	206
562	0.850	0.826	0.0848	2015
77	1.69	0.227	0.1692	276

Table V

Packing: 1.0-inch naphthalene Berl saddles

Air Temperature: 21.2 - 21.8°C

Void Fraction, Dry: 0.695

Number of Pieces of Packing Used: 450

Total Area, Dry: 15.45 sq. ft.

Total Pressure: 1.06 atm.

G	$\left[\ln \frac{\alpha_s}{\alpha_s - \alpha_o}\right]_{AV}$	k_G	j_D	$\frac{D_p G}{\mu_G(1-\epsilon)}$
1003	0.779	0.853	0.0490	7910
909	0.806	0.797	0.0507	7160
813	0.784	0.694	0.0492	6400
696	0.863	0.654	0.0542	5480
619	0.895	0.603	0.0563	4870
540	0.935	0.552	0.0590	4250
425	1.022	0.474	0.0644	3340
363	0.995	0.394	0.0627	2855
301	1.109	0.364	0.0698	2370
251	1.198	0.328	0.0754	1970
201	1.295	0.284	0.0815	1585
151	1.443	0.237	0.0907	1187
100	1.645	0.180	0.1035	791
363	1.071	0.424	0.0675	2855
813	0.806	0.712	0.0506	6400
1200	0.694	0.905	0.0436	9450

Table VI

Packing: 0.5-inch naphthalene Raschig rings

Air Temperature: 21.3 - 21.7°C

Water Temperature: 21.2 - 21.5°C

Void Fraction, Dry: 0.630

Number of Pieces of Packing Used: 1450

Total Area, Dry: 15.3 sq. ft.

Total Pressure: 1.05 atm.

G	$\left[\ln\frac{a_s}{a_s - a_e}\right]_{AV}$	$(k_G A)$ dry	A dry	Fraction Wetted
		L = 1000		
100	1.092	1.84	7.12	0.534
201	1.175	3.95	9.78	0.361
301	1.033	5.21	10.00	0.346
363	1.028	6.25	10.62	0.306
425	0.970	6.90	10.55	0.311
540	0.925	8.375	10.97	0.283
151	1.148	2.99	8.90	0.418
201	1.198	4.03	9.98	0.348
251	1.112	4.68	10.06	0.342
100	1.121	1.89	7.29	0.524
301	1.082	5.47	10.5	0.314
151	1.204	3.04	9.05	0.408
126	1.100	2.32	7.73	0.495

Table VI (continued)

G	$\left[\ln \frac{\alpha_s}{\alpha_s - \alpha_o}\right]_{AV}$	$(k_G A)$ dry	A dry	Fraction Wetted
		L = 2500		
201	0.912	3.08	5.83	0.619
301	0.920	4.65	8.70	0.431
425	0.944	6.74	10.09	0.341
363	1.009	6.15	10.30	0.327
251	1.048	4.43	9.37	0.388
100	0.887	1.49	5.68	0.629
151	0.932	2.36	6.88	0.551
251	1.002	4.24	8.95	0.415
330	0.960	5.30	9.37	0.388
301	0.971	4.90	9.16	0.401
363	0.952	5.79	9.71	0.365
425	0.896	6.38	9.56	0.375
		L = 5000		
100	0.708	1.195	4.18	0.726
151	0.874	2.210	6.39	0.582
201	0.964	3.25	7.63	0.501
251	0.978	4.13	8.46	0.446
301	0.900	4.56	8.12	0.469
339	0.815	4.63	7.72	0.502
126	0.775	1.64	5.23	0.657
251	0.884	3.73	7.61	0.502
301	0.832	4.22	7.51	0.509
201	0.855	2.88	6.77	0.557

Table VI (continued)

G	$\left[\ln \frac{a_s}{a_s - a_o}\right]_{AV}$	$(k_G A)$ dry	A dry	Fraction Wetted
		L = 10,000		
100	0.565	0.954	3.41	0.777
126	0.606	1.28	3.96	0.742
151	0.624	1.58	3.73	0.756
178	0.545	1.628	3.93	0.743
126	0.604	1.275	3.96	0.742

Table VII

Packing: 1.5-inch naphthalene Raschig rings

Air Temperature: 21.2 - 21.5°C

Water Temperature: 20.8 - 21.6°C

Void Fraction, Dry: 0.688

Number of Pieces of Packing Used: 160

Total Area, Dry: 12.25 sq. ft.

Total Pressure: 1.06 atm.

G	$\left[\ln \frac{\alpha_s}{\alpha_s - \alpha_o}\right]_{AV}$	$(k_G A)$ dry	A dry	Fraction Wetted
		L = 1000		
100	0.850	1.435	9.06	0.406
151	0.760	1.925	9.36	0.386
201	0.722	2.44	9.97	0.346
251	0.668	2.82	9.87	0.353
301	0.620	3.14	10.10	0.338
363	0.620	3.78	10.50	0.311
425	0.599	4.27	10.80	0.292
540	0.576	5.24	11.35	0.256
619	0.548	5.70	11.27	0.261
696	0.521	6.10	11.22	0.264
813	0.515	7.03	11.70	0.233
909	0.501	7.64	11.78	0.227
1003	0.485	8.20	11.85	0.223
301	0.668	3.38	10.58	0.306
909	0.482	7.36	11.35	0.256

Table VII (continued)

G	$\left[\ln \frac{\alpha_s}{\alpha_s - \alpha_o}\right]_{AV}$	$(k_G A)$ dry	A Dry	Fraction Wetted
		L = 2500		
100	0.742	1.182	7.41	0.514
151	0.672	1.161	5.58	0.634
201	0.642	2.17	8.66	0.432
251	0.609	2.58	8.94	0.414
301	0.582	2.96	9.12	0.402
363	0.548	3.36	9.20	0.397
425	0.532	3.80	9.41	0.383
540	0.507	4.61	9.82	0.356
619	0.501	5.22	10.20	0.331
696	0.489	5.73	10.38	0.319
813	0.457	6.24	10.21	0.330
909	0.457	7.00	10.62	0.304
1003	0.438	7.42	10.55	0.308
909	0.454	6.93	10.50	0.311
1003	0.442	7.46	10.60	0.305
		L = 5000		
100	0.585	0.936	5.77	0.654
151	0.604	1.453	6.88	0.588
201	0.606	2.05	7.98	0.522
251	0.565	2.38	8.16	0.511
301	0.548	2.77	8.44	0.495
363	0.525	3.20	8.64	0.483
425	0.515	3.68	9.00	0.461
540	0.466	4.24	8.88	0.468

Table VII (continued)

G	$\left[\ln\frac{\alpha_s}{\alpha_s - \alpha_o}\right]_{AV}$	(k_GA) dry	A dry	Fraction Wetted
		L = 5000		
619	0.482	5.01	9.62	0.424
696	0.460	5.38	9.56	0.423
813	0.464	6.32	10.07	0.397
909	0.438	6.68	9.87	0.409
1003	0.418	7.06	9.72	0.418
		L = 10,000		
100	0.533	0.911	5.27	0.684
151	0.579	1.465	6.75	0.596
201	0.554	1.870	7.19	0.570
251	0.512	2.16	7.24	0.566
301	0.482	2.44	7.28	0.564
363	0.452	2.75	7.25	0.566
425	0.412	2.98	7.08	0.576
540	0.398	3.67	7.50	0.551
619	0.375	3.95	7.32	0.562
696	0.361	4.27	7.30	0.562
813	0.350	4.75	7.22	0.568
909	0.343	5.31	7.32	0.562
201	0.500	1.71	6.58	0.606

Table VIII

Packing: 0.5-inch naphthalene Berl saddles

Air Temperature: 21.1 - 23.2°C

Water Temperature: 21.0 - 23.0°C

Void Fraction, Dry: 0.660

Number of Pieces of Packing Used: 1400

Total Area, Dry: 12.34 sq. ft.

Total Pressure: 1.06 atm.

G	$\left[\ln \frac{\alpha_s}{\alpha_s - \alpha_o}\right]_{AV}$	$(k_G A)$ dry	A dry	Fraction Wetted
		L = 1000		
100	0.810	1.363	5.11	0.586
363	0.704	4.31	7.11	0.424
425	0.663	4.72	7.08	0.426
540	0.610	5.53	7.08	0.426
619	0.590	6.11	7.16	0.420
696	0.565	6.59	7.14	0.421
813	0.531	7.21	6.86	0.444
1003	0.479	8.06	—	—
251	0.718	3.02	6.28	0.491
909	0.507	7.70	—	—
301	0.718	3.68	6.85	0.445
251	0.718	3.03	6.28	0.491
425	0.663	4.73	7.08	0.426
540	0.615	5.59	7.15	0.421
100	0.733	1.24	4.54	0.632
151	0.756	1.921	5.58	0.548
201	0.708	2.40	5.78	0.532

Table VIII (continued)

G	$\left[\ln \frac{\alpha_s}{\alpha_s - \alpha_o}\right]_{AV}$	$(k_G A)$ dry	A dry	Fraction Wetted
		L = 2500		
100	0.554	0.931	3.45	0.720
151	0.604	1.545	4.41	0.642
201	0.604	2.03	4.82	0.610
251	0.594	2.495	5.14	0.584
301	0.582	2.94	5.38	0.564
425	0.615	4.39	6.44	0.478
619	0.565	5.87	6.70	0.457
696	0.536	6.27	6.52	0.472
813	0.501	6.82	—	—
425	0.604	4.32	6.34	0.486
540	0.588	5.34	6.69	0.458
363	0.615	3.76	6.10	0.506
201	0.636	2.15	4.97	0.597
696	0.548	6.41	—	—
		L = 5000		
100	0.482	0.816	2.94	0.762
151	0.548	1.392	3.85	0.688
201	0.530	1.796	4.14	0.664
251	0.548	2.320	4.60	0.627
301	0.554	2.816	5.02	0.593
363	0.530	3.245	5.10	0.587
425	0.530	3.80	5.40	0.562
540	0.530	4.84	—	—
580	0.513	5.02	—	—

Table VIII (continued)

G	$\left[\ln \frac{a_s}{a_s - a_e}\right]_{AV}$	$(k_G A)$ dry	A dry	Fraction Wetted
		L = 10,000		
100	0.364	0.618	2.15	0.826
151	0.425	1.079	2.89	0.766
178	0.422	1.262	3.03	0.754
201	0.438	1.485	3.29	0.733
251	0.464	1.962	3.75	0.696
301	0.467	2.375	4.00	0.676
348	0.419	2.155	3.26	0.736

Table IX

Packing: 1.0-inch naphthalene Berl saddles

Air Temperature: 21.7 - 22.7°C

Water Temperature: 21.5 - 22.6°C

Void Fraction, Dry: 0.695

Number of Pieces of Packing Used: 475

Total Area, Dry: 16.32 sq. ft.

Total Pressure: 1.06 atm.

G	$\left[\ln \frac{\alpha_s}{\alpha_s - \alpha_o}\right]_{AV}$	$(k_G A)$ dry	A dry	Fraction Wetted
		L = 1000		
100	0.752	1.264	6.54	0.599
151	0.770	1.944	7.76	0.524
201	0.770	2.59	8.66	0.469
251	0.770	3.24	9.36	0.426
301	0.713	3.57	9.22	0.435
363	0.708	4.31	9.88	0.395
425	0.683	4.88	10.04	0.384
251	0.775	3.28	9.47	0.420
619	0.658	6.86	11.15	0.316
696	0.628	7.32	11.08	0.322
813	0.594	8.12	11.15	0.316
909	0.594	9.08	11.59	0.290
1003	0.565	9.575	11.49	0.296
813	0.590	8.08	11.09	0.321
540	0.668	6.09	10.79	0.340

Table IX (continued)

G	$\left[\ln \frac{\alpha_s}{\alpha_s - \alpha_o}\right]_{AV}$	(k_GA) dry	A dry	Fraction Wetted
		L = 2500		
100	0.582	0.986	5.06	0.690
151	0.596	1.515	5.85	0.642
201	0.631	2.19	7.21	0.558
251	0.610	2.58	7.35	0.549
301	0.636	3.235	8.24	0.494
363	0.594	3.635	8.23	0.494
425	0.591	4.24	8.63	0.471
540	0.554	5.05	8.87	0.456
619	0.560	5.84	9.38	0.425
696	0.571	6.74	10.05	0.384
813	0.531	7.31	9.82	0.398
909	0.519	7.99	9.94	0.390
1003	0.513	8.75	10.29	0.370
363	0.605	3.73	8.43	0.484
		L = 5000		
100	0.470	0.802	4.03	0.753
151	0.476	1.218	4.76	0.708
201	0.464	1.581	5.09	0.688
301	0.534	2.73	6.84	0.581
363	0.525	3.234	7.14	0.562
425	0.525	3.78	7.56	0.537
540	0.507	4.65	8.03	0.508
619	0.507	5.32	8.34	0.489

Table IX (continued)

G	$\left[\ln\frac{\alpha_s}{\alpha_s - \alpha_o}\right]_{AV}$	$(k_G A)$ dry	A dry	Fraction Wetted
		L = 5000		
696	0.501	5.91	8.57	0.475
813	0.507	6.98	9.20	0.436
909	0.489	7.52	9.19	0.437
1003	0.476	8.12	9.31	0.430
251	0.507	2.16	6.08	0.628
201	0.489	1.67	5.38	0.670
100	0.464	0.790	3.97	0.756
		L = 10,000		
100	0.372	0.634	3.11	0.810
151	0.406	1.04	3.93	0.759
201	0.415	1.405	4.44	0.728
251	0.412	1.76	4.82	0.704
301	0.425	2.174	5.24	0.679
363	0.432	2.66	5.74	0.648
425	0.419	3.02	5.91	0.638
540	0.425	3.90	6.49	0.602
619	0.402	4.22	6.13	0.606
696	0.406	4.78	6.70	0.590
813	0.385	5.30	6.68	0.591
909	0.344	5.29	—	—
968	0.296	4.86	—	—
100	0.336	0.574	2.94	0.818
151	0.365	0.933	3.60	0.780
100	0.336	0.574	2.94	0.818