

UNIVERSITY OF CINCINNATI

June 1 1939

I hereby recommend that the thesis prepared under my supervision by Earl C. Mirus entitled Gaseous Absorption Phenomena in Packed Towers

be accepted as fulfilling this part of the requirements for the degree of Doctor of Philosophy

Approved by:

W. M. Burgess

W. M. Burgess, Chairman

GASEOUS ABSORPTION PHENOMENA
IN PACKED TOWERS

A Thesis

By

Earl C. Mirus.

Presented to the Faculty
of the
University of Cincinnati

In fulfillment of part of the requirements for the degree of
Doctor of Philosophy

Cincinnati, Ohio

May 1938

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LETTER OF TRANSMITTAL

To the Faculty of the Graduate School of Chemistry
University of Cincinnati
Cincinnati, Ohio

Gentlemen:

I herewith submit, in fulfillment of part of the requirements for the degree of Doctor of Philosophy a thesis entitled "Gaseous Absorption Phenomena in Packed Towers".

The purpose of this thesis is to determine the nature and variation of the constants involved with changes in flow rates, distribution of the liquid phase and various types of packing. As an aid in doing this, tower hold-up, as a function of liquid velocity up to and including tower plugging, was studied.

A summary of results is presented in the body of this thesis.

Respectfully submitted,

Earl C. Mirus

Earl C. Mirus

ACKNOWLEDGEMENTS

The writer wishes to acknowledge the helpful suggestions, encouragement and criticisms of Professor R.S. Tour. To him largely goes the credit for the interpretation of experimental curves and results.

To H.J. Garber and Professor R.S. Tour goes the credit for the derivation of the basic formula which does not include the simplifying assumptions made by previous investigators.

The credit for the design of the absorption cells goes to Clark Rose.

The writer also wishes to thank Mr. Carl Boch and Mr. Walter Scholl of the Chemical Engineering Department for their suggestions and aid in the construction of the experimental tower.

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HISTORICAL

HISTORICAL

"An outstanding example of a unit-process whose apparatus is designed by judgment and experience alone is gas absorption or gas scrubbing. The basic principles of the process were laid down by Hurter, 1 and 2, during the years 1885 to 1893, but their application continued for many years to be qualitative rather than quantitative, partly, it is true, because of lack of experimental data, but undoubtedly also because of the apparent complexity of the events in the apparatus and doubt as to how any pertinent constants could be sorted out of the mass of variables. Lunge's comments on Hurter's work are a good example of the way in which plant designers viewed gas absorption. An article by Heinz, 4, appearing in 1913, was written from the same viewpoint; attention was directed almost exclusively to the design of the packing material, and the only other suggestion that could be made was that 'experience shows' that sixteen meters per minute is the best gas velocity in a tower."*

"The first quantitative study of gas absorption was made by Hurter, 1 and 2, who made a thorough study of absorption towers used in sulphuric acid plants. After trying three methods of absorption, namely, bubbling gas

* W.B. Van Arsdel, 12

through liquid; dropping liquid through soluble gas; passing gas counter-current to liquid in a packed tower, he reached the following conclusions: 1. The slower the liquid passed down through the column, the greater the recovery of soluble gas. 2. The slower the gas velocity, the longer the time of contact and subsequent greater recovery.

Lewis, 5, from his studies of a packed coke column, developed a mathematical expression for both extraction and absorption. He came to the conclusion that the rate of absorption was directly proportional to the driving force. Further than this, the driving force was equivalent to the logarithmic mean of the differences in partial pressures of the soluble gas in liquid and gas phases at top and bottom of column."*

The complicated case of absorption of nitrogen oxides in water in the presence of air to produce nitric acid has been well handled by Partington and Parker, 6, by the use of certain "over-all" factors. They gave the theory substantiating it with data from experimental runs and made calculations for the size of towers using the derived equations and the rule "height equals five times the diameter of the tower".

Zeisberg, 7, gave a table of values of percent free space, surface in square feet per cubic foot and frictional

* J.H. Monaweck and E.M. Baker, 32.

coefficients for a large number of types of packing distributed three ways in the tower, i.e. dumped, stacked and packed. He also made calculations of the pressure necessary to push a certain volume of gas through certain different packings making use of his derived formula.

Baker,⁸ divided the absorption of gases in liquids into three subdivisions. "First, the case where the nature of the gas and liquid is such that a chemical reaction takes place so that the gas will not exert any appreciable vapor pressure after absorption." "Second, the case where the nature of the gas and liquid is such that a chemical reaction takes place, but the compound formed is sufficiently unstable so that the dissolved gas exerts an appreciable vapor pressure." "Third, the case where no chemical reaction takes place between the gas and liquid, and where the liquid exerts a vapor pressure directly dependent on the amount of absorbed gas." He also stated that the force which causes a gas to be absorbed by a liquid is the difference between the partial pressure of the soluble gas in the gas mixture and the vapor pressure exerted by the gas dissolved in the liquid. He further stated that absorption depends also upon the intimacy ~~of~~ of contact which in turn depends upon the design of absorption apparatus.

On the assumptions that temperatures are constant throughout; that the volume changes due to absorption are negligible; that the vapor pressure of the solvent is negligible; that there is uniform distribution of both phases throughout; that the wetted area of the tower sides is negligible compared to the packing wetted area; and that no chemical reactions take place Donnan and Mason,9, derived an equation for absorption and showed how it might aid in tower design.

Van Arsdel,10, reviewed the work of Donnan and Mason and added simplification by the use of heat interchanger formulae.

Jorgensen,11, presented tables showing the Capacity of Tower Packings by Mathematical Analysis. He stated that the flow of gas must be even and equally distributed in all parts of the packing so as to give a perfect balance between contact surfaces and gas flow. He further stated that a weakness of most industrial tower packings is that gas passages are not of equal size.

Van Arsdel,12, extended his work with a detailed discussion of absorption towers by relation to heat interchangers and by building upon the theories proposed by Donnan and Mason. He derived formulae for transfer coefficient, absorption coefficient, absorption factor, percentage removal of solute from gas and percentage

saturation of resulting solution. He made corrections for changes in volume and temperature throughout the tower, showed solute and heat balances and discussed the design of an absorption system.

Whitman and Keats,¹³ presented the theory involved in liquid gas interactions, gave a summary of Lewis's mathematical treatment with modifications, showed the effect of operating variables on the coefficients for various types of apparatus and gave experimental procedure and results verifying the theory. They showed the relation between the general equation for absorption and the equation for heat transfer and stated that the absorption equation could also be expressed in the resistance form given under heat transfer. The general equations showed that the rate of transfer varied directly with the active volume and the driving potential while the effect of other variables is accounted for by changes in the transfer coefficients. They gave a table of these transfer coefficients for various types of equipment.

Haslam, Ryan and Weber,¹⁶ developed a differential equation for absorption where the rate of absorption is proportional to the driving force and the overall volume of the apparatus. They carried out experiments using sulphur dioxide and water with the view of studying the effect of gas velocity and temperature on the rate of ab-

sorption. "They found that the coefficient for the gas film (reciprocal of resistance) varies as the 0.8 power of the gas velocity. The liquid film is independent of gas velocity. Hence, with increase of gas velocity, the overall absorption coefficient rises rapidly at first, but reaches an asymptote owing to the liquid film resistance."*

Van Arsdel,17, reviewed his previous discussion and abandoned the assumptions made in the logarithmic mean formula. He derived a new fundamental equation which he checked by a plant experiment.

Whitman,18, proposed the two film theory of gas absorption i.e. that there are two films, a gas film and a liquid film which offer resistance to absorption. Diffusion through the gas film is determined by the partial pressure gradient of the solute and through the liquid film by a concentration gradient. He then showed the agreement between the formula and experimental absorption of HCl. The work of the subsequent years has been devoted largely to the examination and extension of this theory, and to the determination of constants that are required to permit the use of the theory in engineering calculations.

"Haslem, Hershey and Keen,21, working with an experimental tower of the wetted-wall type, determined the overall absorption coefficients for sulphur dioxide and

* E.M. Baker, 29

ammonia over a range of gas velocities and temperatures."* They found that gas velocity is without appreciable effect on the liquid film, while the gas film coefficient is proportional to the gas velocity to the 0.8 power. The gas film coefficient decreases as the 1.4 power of the absolute temperature, whereas the liquid film coefficient increases as the fourth power of the absolute temperature. Both individual film coefficients are proportional to the two-thirds power of the ratio of density to viscosity of the liquid film.

Lewis and Whitman,22, further developed the two film theory and showed how it could be simplified when using gases of high, low and intermediate solubilities. They concluded that the rate of absorption is controlled by the rate of diffusion of the solute through the surface films of gas and liquid at the gas-liquid boundary.

"Becker,23, studied the absorption of moderately soluble gases by stationary water, and presented a table of data on the initial rates of solution."*

Whitman and Davis,70, studied the absorption of HCl, sulphur dioxide, ammonia and oxygen through a free surface of liquid when the liquid is stirred. Results can be adequately explained by the two film theory. On the assumption

* E.M. Baker,29.

that oxygen absorption is controlled by liquid film diffusion and that ammonia absorption in HCl solution is controlled by gas film diffusion they stated that the absorption rates for these gases can be predicted with an accuracy of fifteen percent or better.

"In 1925 Kowalke, Hougen and Watson,²⁴ published two papers on the absorption of ammonia in towers. They found that experimentally determined values of the absorption coefficient were in agreement with operating conditions in the gas industry. They advanced the theory that the rate of absorption of ammonia and similar gases is controlled by the diffusion factor, and a water distribution factor which is a function of the packing and the rates of water and gas flow. They stated that the total surface of the tower packing is of less importance than the position of the surfaces and the best packing is that which produces the greatest agitation of the gas in direct contact with the water surface."*

"Cantelo,²⁵ developed a series of equations for continuous counter-current absorption."*

Greenwalt,²⁶ presented a method of attack for problems in the design of absorption equipment based on the principles of dimensional homogeneity. He showed that the absorption

* E.M. Baker, 29.

of water vapor in sulphuric acid solutions is limited by gas film diffusion. He established the assumption that the turbulence and velocity effects can be expressed as functions of the resistance to gas flow of an absorption tower. He showed that the gas film coefficient is proportional to the 0.4 power of the pressure drop through the tower and that the entrance turbulence effect is the controlling factor in absorption in wet-walled towers.

"Whitman, Long and Wang, 27, determined rates of absorption into a drop of water falling freely through gas. They found that the coefficients were higher than for flat surfaces, for bubbles rising through a liquid, or in wetted-wall columns. However, the ratio of gas film to liquid film coefficients was about the same."*

"Cantello, Simmons, Giles and Brill, 28, studied the absorption of carbon dioxide and sulphur dioxide in a tower, and reported that the solution coefficient is independent of gas velocity and composition of gas, but does vary as the first power of the rate of flow of absorbing liquid."*

Lewis and McAdams, 30, fully explained the two film theory. They offered curves and showed how to make calculations and designs on the basis of this theory using operating equations and operating lines.

* E.M. Baker, 29.

Hanks and McAdams,³¹ developed equations for two film absorption paying particular attention to the gas film. They gave data on the absorption of ammonia from hydrogen, air and butane by water in a wetted-wall tower. They found that the gas film coefficients for a given mass velocity are greatest through hydrogen, lower through air and lowest through butane.

Monaweck and Baker,³² tabulated coefficients of absorption of ammonia by a still and by a stirred liquid which agree with the Lewis equation for two film absorption.

Colburn,³³ stated that in processes such as absorption and dehumidification, the rate of mass transfer is dependent on the rate of diffusion of molecules through a viscous gas film adjoining the liquid surface and on eddy currents in the turbulent portion of the gas stream. He derived an equation for mass transfer from fluids in both the viscous film and the turbulent core, similar to the method used by Prandtl and by Taylor in obtaining a relation between fluid friction and heat transfer. He showed by experimental data that both absorption and dehumidification are in agreement with the derived equation.

Simmons and Long,³⁴ absorbing benzene by straw oil showed experimental results which indicated the validity of Cantelo's derived equation where the solute obeys Raoult's Law.

Davis and Crandall,³⁵ in their work on absorption involving no irreversible chemical reactions showed how the effective thickness of the liquid stationary film depends upon absorption conditions. They stated that when a pure gas is suddenly brought into contact with a liquid, a gradient of dissolved gas, tending to uniformity, is rapidly built up through the film. In well stirred water the gradient becomes practically uniform in a fraction of a second. They calculated the initial absorption rates per unit area of surface and the liquid film diffusion coefficients from data on gas absorptions by water and a few organic liquids for stirred liquids, gas bubbles and shaken liquids. In their work on absorption involving irreversible chemical reactions they extended the two film theory as proposed by Lewis and Whitman to cases where rapid chemical reactions take place in the solution. The reactions between the dissolved gas and solute appear to occur inside the liquid.

Bennetch and Simmons,³⁶ derived an equation starting with the Lewis concept of two film absorption and verified it by experimental runs on benzene in oil and carbon dioxide in water.

Adams,³⁷ studied the absorption of sulphur dioxide in water in a spiral-tile packed tower with relation to the effect of liquor velocity, gas velocity and temperature on the mechanism of absorption. He obtained data suitable for

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the design of absorption equipment in the practical operating range of these variables.

Davis,38, found that the initial absorption rate of carbon dioxide by sodium carbonate is much higher than that for carbon dioxide by water. He found also that in towers since the area of liquid interface is very great compared to the liquid volume, the laws for batch absorption should be applied only with the utmost caution to tower absorption.

Simmons and Osborn,39, experimented on glass spheres, raschig rings and coke packing to determine the effect of free volume on absorption. Free volume is usually considered as being constant whereas, they found that it seems more logical to assume it to be some function of the extractor rate. They found also that for a given extractor the free volume is an inverse function of the extractor rate, this function being independent of the type of filler, tower size, or gas velocity; that the use of a constant free volume under all operating conditions is shown to be impossible in calculations involving design and operation of absorption systems; that the use of an operating free volume in the Bennetch and Simmons equation gives absorption coefficients which vary linearly with extractor rate. They also gave data for carbon dioxide-water and benzene-oil systems for the three types of packing in the same tower.

Hollings and Silver,40, attempted to restate the two

film theory in a form which permitted of a more practical application.

Chilton and Colburn,⁴¹ proposed that the difficulty of separation in a packed column be expressed, instead of in terms of the "number of theoretical plates", as the number of transfer units. The efficiency of a column would then be expressed, they say, as the "height of a transfer unit" (H. T. U.) instead of the "height equivalent to a theoretical plate" (H. E. T. P.). They showed that for many cases of distillation the H. E. T. P. and H. T. U. are nearly identical but that there may be large differences between them for certain absorption problems.

Hixon and Scott,⁴² determined overall coefficients for the absorption of ammonia and sulphur dioxide into a water spray, and the absorption of benzene vapor into an oil spray for an inner "wall-free" section of a spray type absorption tower. They investigated the effects of variable fluid flows at three tower heights, developed empirical equations relating these variables and compared the results with previous data when possible. They pointed out the use of these equations for practical spray tower design with special consideration of their limitations.

White,⁴³ found that the pressure drop in a tower is substantially independent of tower diameter if the ratio of tower diameter to packing diameter is six or more.

He defined the loading point of a column as the gas velocity at which, for a given liquid rate, the logarithmic pressure velocity curve first deviates from a slope of approximately two. He defined the flooding point as the gas velocity at which the same curve turns abruptly almost vertically upward. He stated that towers should operate just below the loading point and certainly below the flooding point.

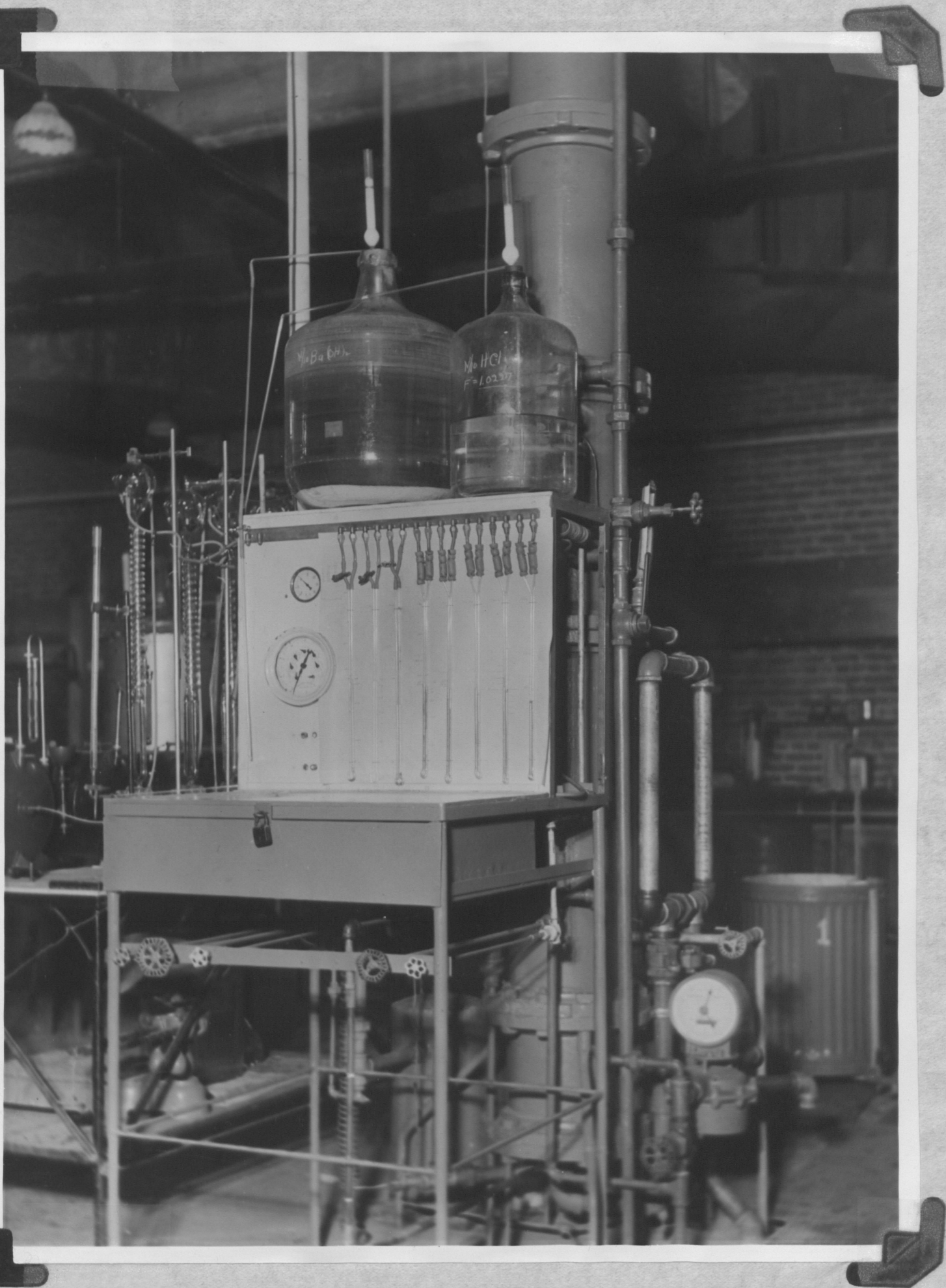
Yushkevich and Zhavoronkov,⁴⁴ found that the absorption coefficient is directly proportional to the intensity of wetting of the tower. They also showed that when the gas rate is decreased or the pressure increased, the rate of increase of the coefficient with intensity of wetting is lessened and that the coefficient itself is increased by decreasing the gas rate or the pressure.

Chilton, Duffey and Vernon,⁴⁵ found that with a ratio of tower diameter to packing diameter of eight to one or greater and adequate initial liquor distribution, there is no substantial effect of tower diameter on final liquor distribution or absorption efficiency.

At the University of Cincinnati work has been carried on for a number of years under the direction of Professor R. S. Tour. However, it remained for Garber,⁴⁷ to develop a theoretically correct equation for absorption based on a material balance over the system. The simplification of Garber's equation for practical use and the determination,

experimentally, of the constants involved, form the nucleus of this research.

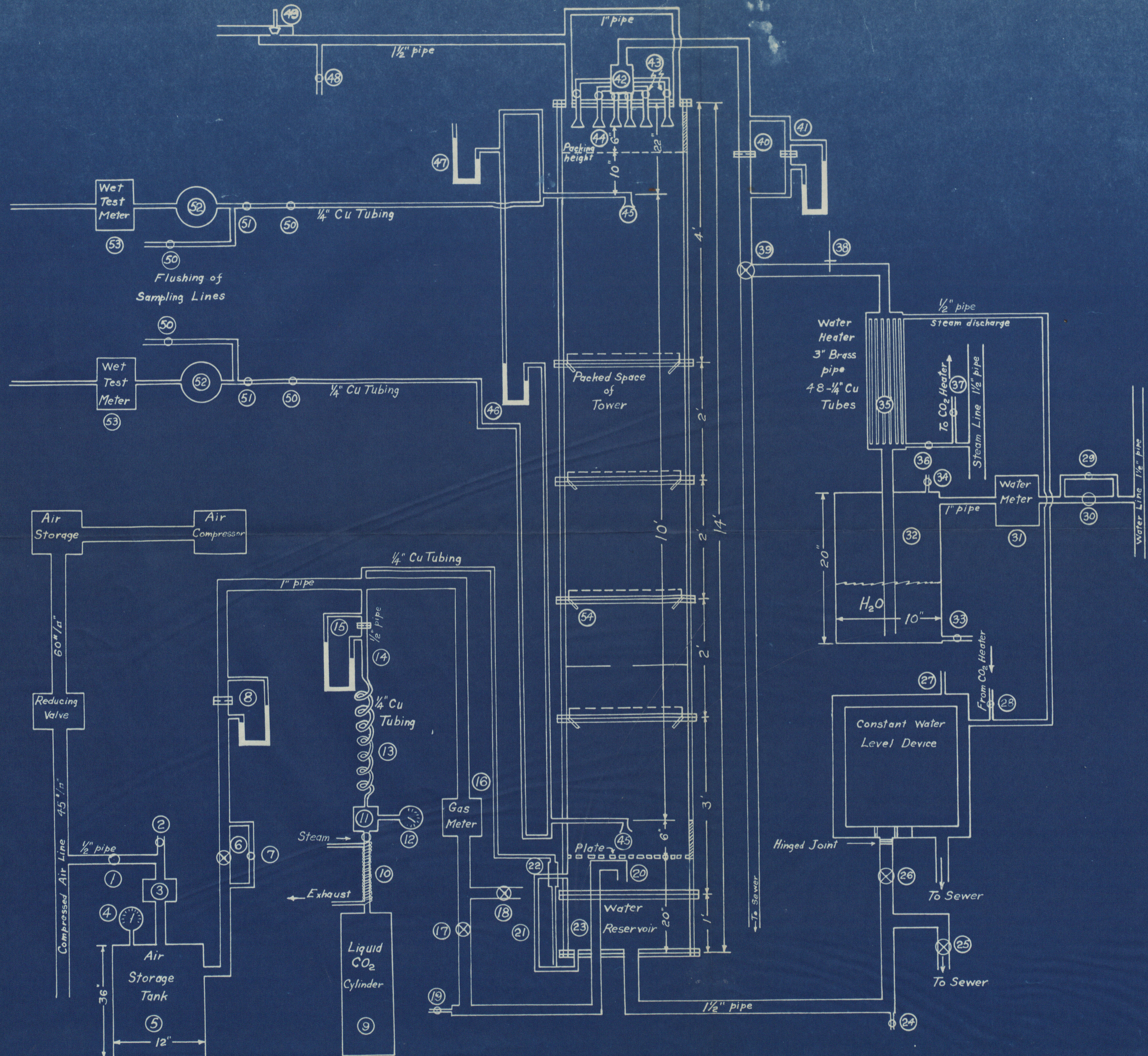
APPARATUS AND PROCEDURE





Tabulation of Units

1. Globe Valve
2. Pressure Release Valve
3. Reducing Valve to 10^{1/2}"
4. 60" Gauge
5. Air Storage Tank 10^{1/2}"
6. Air Control
7. Air Control
8. Calibrated Orifice + Manometer
9. Liquid CO₂ Cylinder
10. Steam Coil Heater
11. Reducing Valve
12. 300" Gauge
13. Constant Temp. Coil (Cooling or Heating)
14. CO₂ Control
15. Calibrated Orifice + Manometer
16. Dry Gas Meter.
17. Quick-Acting Valve
18. Atmospheric Release Valve
19. Pet-Cock
20. L-Bend Gas Inlet
21. Reservoir Gauge Glass
22. Mercury Seal
23. Water Reservoir
24. Pet-Cock
25. Globe Valve
26. Quick Acting Valve
27. Anti-Siphon Tube.
28. Pet-Cock
29. Water Control
30. Water Control
31. Water Meter
32. Hydraulic Equalizer
33. Pet-Cock
34. Pet-Cock
35. Water Heater
36. Steam Control
37. Needle Valve
38. Thermometer.
39. 3-Way Stop Cock
40. Calibrated Orifice + Manometer
41. Calibrated Orifice + Manometer
42. Water Header
43. 6- Stop Cocks
44. 6-Pressure Sprays
45. Sampling Tubes
46. Tower Pressure Drop Manometer
47. Tower Pressure Manometer
48. Discharge to Atmdsphere
49. Discharge to Atmosphere
50. Pet-Cocks
51. Pinch Clamps
52. CO₂ Absorbers
53. Wet Test Meters
54. Redistributing Device



Schematic Diagram
of Apparatus
Figure 3
Not drawn to scale
Earl C. Mirus April 27, 1938

APPARATUS AND PROCEDURE

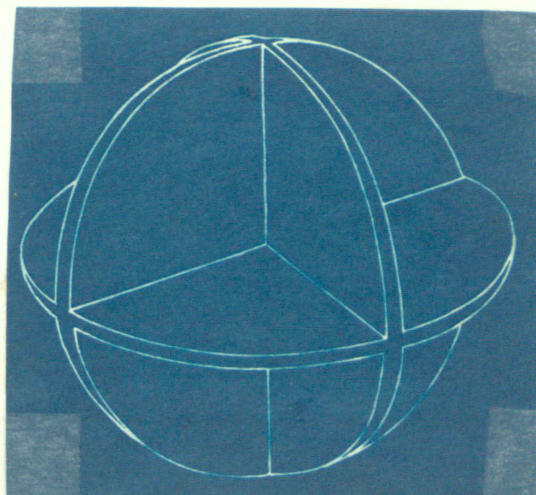
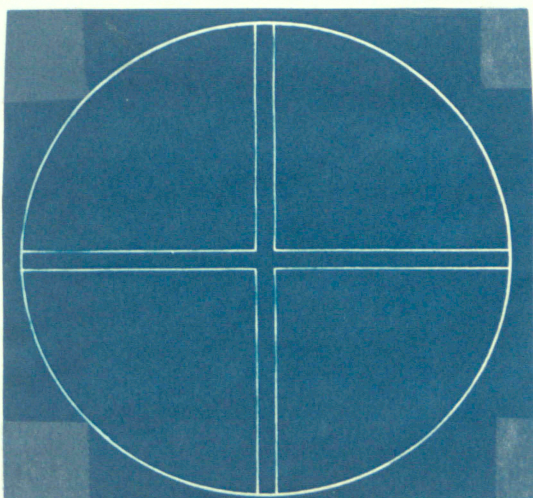
The experimental tower used is a modification of the tower constructed and used in 1932-33 by Rose and Bradt (University of Cincinnati Thesis 1933). Numerous additions to and changes in the previous equipment, however, combine to make the present tower much more complex in construction, and much more precise in operation. Numbers in parenthesis refer to numbered parts on the respective schematic diagrams.

The tower, itself, shown in the photographs (Fig. 1 and 2) and explained schematically in (Fig. 3) consists of six lengths of standard ten inch wrought iron pipe, (See Fig. 3) threaded, flanged and bolted together in the order indicated.

The bottom flange is drilled and tapped for the 1/2 inch gauge-glass, the 1-1/2 inch water discharge pipe and the 1 inch gas inlet pipe. The gas enters through an inverted "L" bend (20) to prevent entrance of water into the gas lines. The top flange is drilled and tapped for the 1 inch gas outlet pipe and the six 1/2 inch pressure sprays (44).

A perforated plate supported on a spider 20 inches above the bottom of the water reservoir, supports the packing which extends upward 10 feet to a level 6 inches below the end of the sprays. The packings used were:

1. 1-1/4 inch cast iron jacks made by the Peerless Foundry, Elmwood, Ohio. They consist essentially of three 1-1/4 inch by 1/8 inch cast iron disks set at right angles to each other. (Fig. 4)



2. 0.008-60 Stainless Steel Textile Knit Tower Packing made by the Metal Textile Corporation, Orange, New Jersey. This packing was made into rolls six inches high and ten inches in diameter so as to fit tightly into the tower and hug the tower walls.

Preliminary data taken on these packings showed the following characteristics:

<u>Type Packing</u>	<u>Weight Lbs./cu.ft.</u>	<u>Surface Sq.ft./cu.ft.</u>	<u>Units Per.Cu.ft.</u>	<u>% Free Volume</u>
Jacks	155	66	1290	56.4
Knit Textile	8.1	291*	3.94	98.3
1 Inch Raschig Rings	40**	58**	1350**	73.0**

* Furnished by Metal Textile Corporation.

** Chemical Engineering Handbook, Perry.

To pack the tower, it was first filled with water and the jack packing was then dumped in through a 8-1/2 by 10 inch hand hole provided at the top.

The packing was removed through a similar hand hole at the bottom. The units of knit textile packing were stacked one on top of the other until the tower was filled.

To provide proper water distribution over the packing the tower was equipped with six Adjusta-Spray Shower Heads, (44) and Fig.5 made by the Speakman Company, Wilmington, Delaware. These six sprays were set at equal distances around the circumference of a seven inch diameter circle as this was thought to give the most even distribution at the top of the tower.

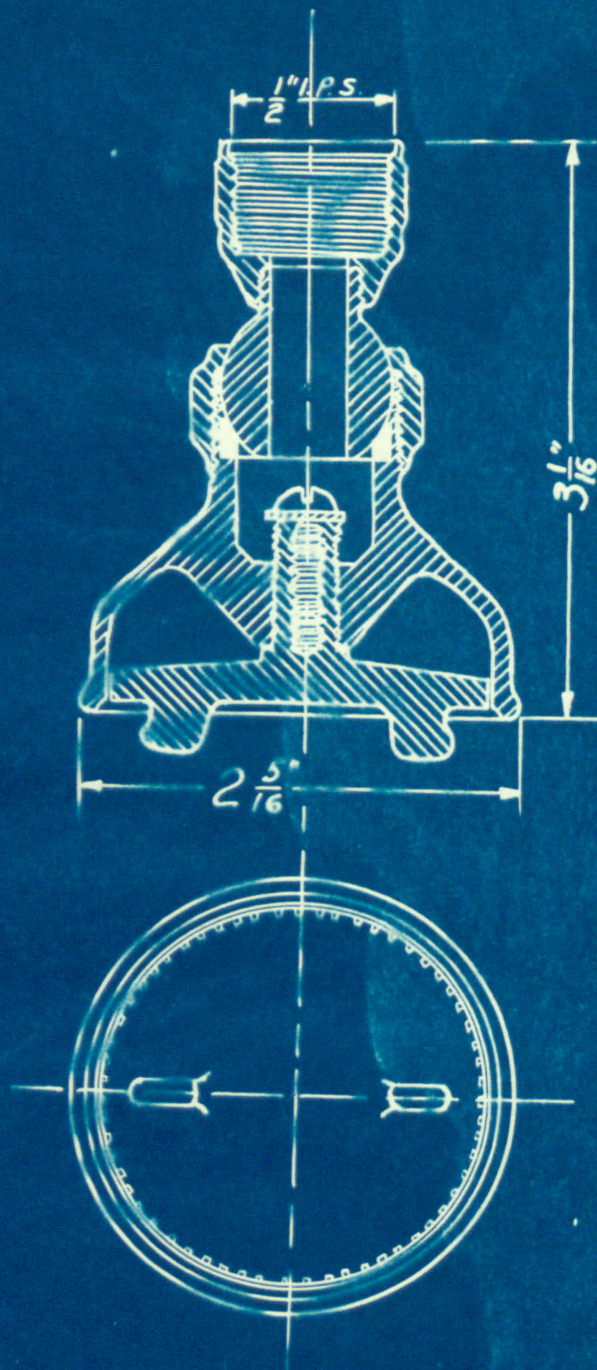
SPEAKMAN ADJUSTA-SPRAY SHOWER HEAD, K-7046

Table showing water discharge at various water pressures with face of head set in different positions.

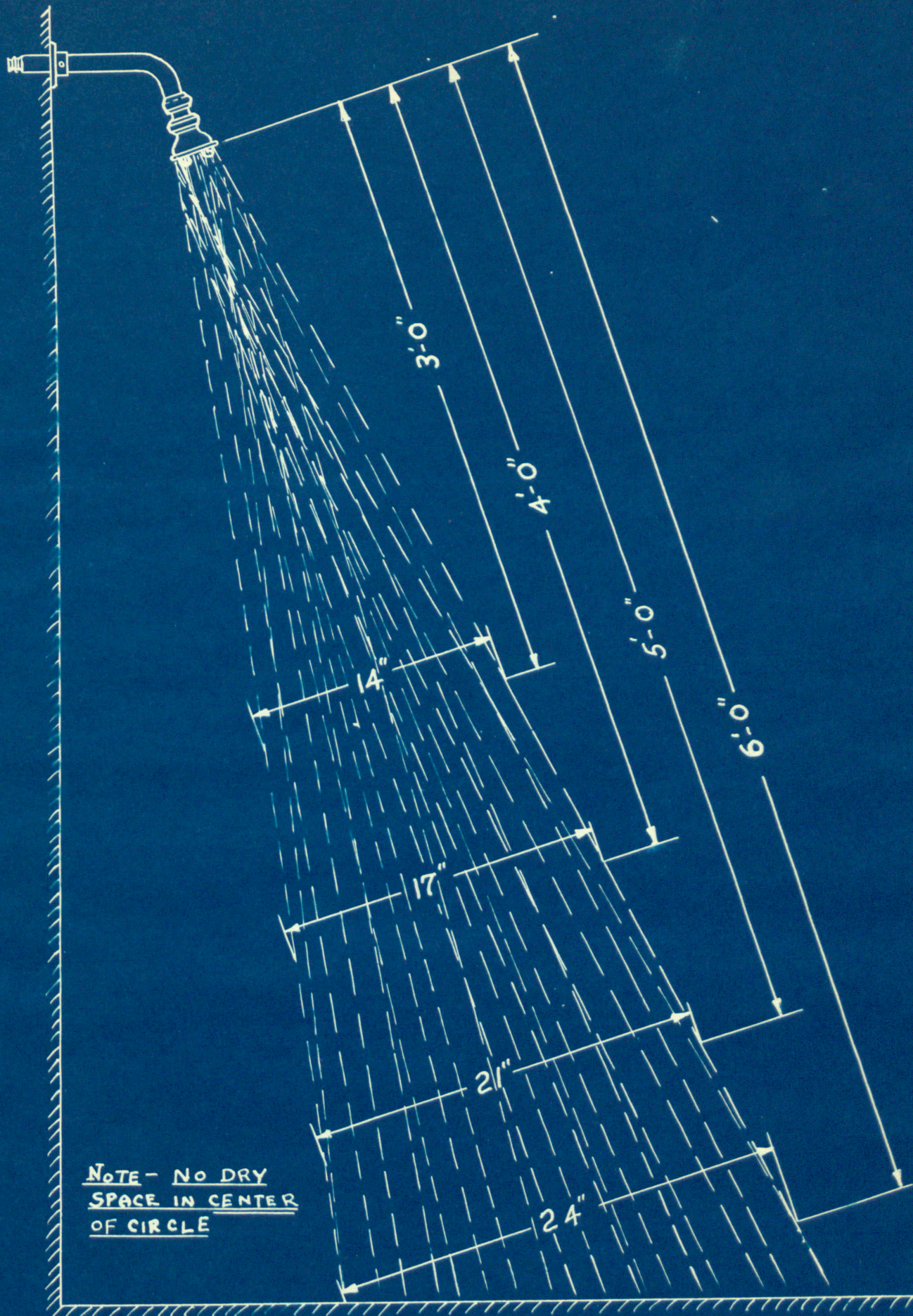
	20	30	40	50	60 Lbs. Pressure	Gal. Per. Min.		
CLOSED	3-1/2	4-3/4	5-1/4	6-1/2	6-3/4			
1/2 TURN OPEN	3-3/4	5	5-3/4	7	7-1/4	"	"	"
1 TURN OPEN	3-7/8	5-1/4	6	7-1/4	7-3/4	"	"	"
1-1/2 TURNS OPEN	4	5-1/2	6-1/4	7-1/2	8	"	"	"
2 TURNS OPEN	4-1/2	5-3/4	6-1/2	7-3/4	8-1/4	"	"	"
2-1/2 TURNS OPEN	4-1/4	6	7	8	8-1/2	"	"	"
OPEN FULL 3-1/2 TURNS	5-1/4	7	8 1/4	10	10-1/2	"	"	"

The distribution obtained with these sprays is shown in Fig. 6.

To insure even distribution of the water throughout the entire length of tower the tower was provided with four redistributing devices (54) spaced at two foot intervals along its length. These redistributors are shown in detail in Fig. 7. They consist of an annular ring of 1/16 inch brass plate fitted between the flanges of the separate pieces of pipe and extending out toward the center of the tower 1/4 inch from the tower wall. Here they are bent upward at right angles so as to parallel the tower wall. Equally spaced around their bottom edges are four pieces of 1/4 inch copper tubing extending toward the center of tower for a distance of 1 inch from the tower wall and making



Detail of Speakman Company's
K-7047 "Adjusta-Spray" Head



K-7047 "ADJUSTA-SPRAY" HEAD AT 40 LBS. PRESSURE

SPEAKMAN COMPANY
WILMINGTON, DELA.

Figure
Copy

an angle of 45° with the tower wall. The distributors catch the water running down the tower wall and return it via the copper tubes to the annular space in the tower. By returning the water to the annular space in the tower where it was thought to be depleted nearly even distribution was probably obtained throughout the entire tower length.

Detail of Redistributing Device

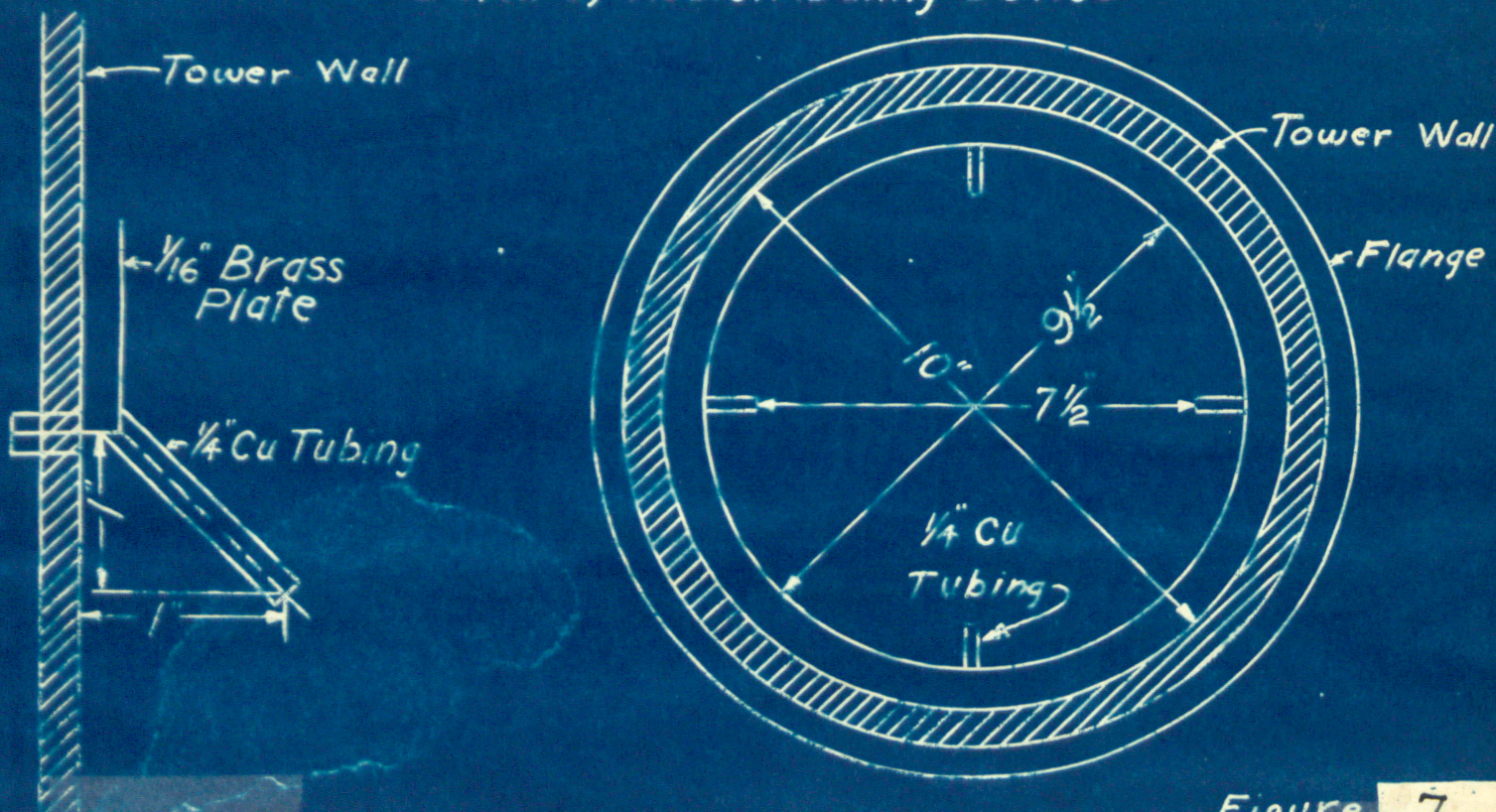


Figure 7

The tower used in 1933 operated at atmospheric pressure. It was decided to remove this variable by operating the tower at a fixed absolute pressure, namely 32 inches of mercury. This was sufficient pressure head above atmospheric pressure for the satisfactory operation of the analytical absorption cells (described later). In order to operate at positive pressure it was necessary to throttle both the discharged gas and discharged water. Ordinary valves were not desirable for several reasons, principally: first, that any fluctuation in flow of the gas and liquid phases caused changes in pressure which could only be relieved by resetting the valves thus necessitating continuous manual control; second, that during any series of runs in which the rate of flow of any one phase was to be kept constant, the change in rate of flow of the other phase necessitated readjusting the exit valves on both gas and water to correspond to the new setting of flow ratio, a tedious adjustment, especially at low flows since the time lag then became very appreciable.

To overcome this difficulty, two automatic self-adjusting controls were designed. To throttle the gas flow a cone seated check valve was disassembled and a plunger attached to the valve (49) see Fig. 8. By adding or removing weights to this plunger, the back pressure

necessary to operate the valve could be changed at will. Any fluctuation in gas flow then only served to increase or decrease the pressure momentarily, which would automatically open or close the valve a little more and thus release more or less gas and correct for the fluctuation. The control obtained with this unit was very satisfactory.

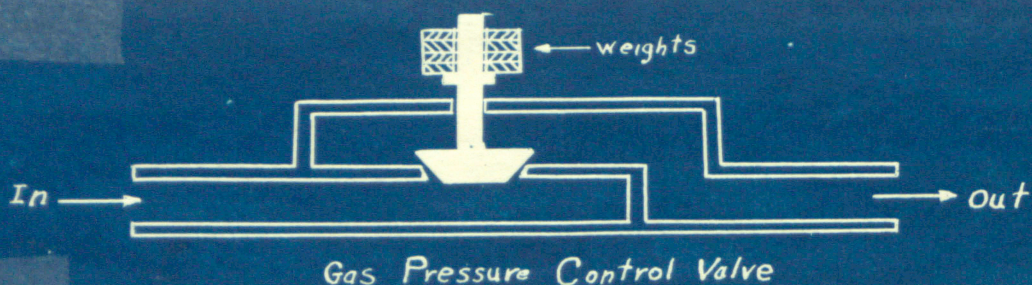


Figure 8

The problem of controlling liquid flow was handled in a different manner. A "water level device" ~~Fig. 9~~ was designed to cause the water to control its own flow and to maintain constant pressure when used in conjunction with the gas valve described above. Assuming that the atmospheric pressure might vary between 720 and 760 m.m. of mercury, it may be shown that the maximum height of water seal required to maintain a pressure of 32 inches of mercury on the tower is about 50 inches and that the minimum is about 29 inches. A trap 52 inches high of 1-1/2 inch pipe, sealed across the lower leg, and provided with an open tee (27) to break any siphoning effect and a hinged joint

to change the level of the upper leg was constructed. The hinged joint consisted of a 1-1/2 inch T fitting with the bottom of the T fixed and the pipe in the cross bar free to swing to raise or lower the whole upper part of the device. The operation is such that for any given water flow, tower pressure, and barometric pressure the "water level device" may be set to give a definite level in the reservoir (23) as indicated on the gauge glass (21).

An auxiliary drain with a 1-1/2 inch globe valve (25) was provided to permit the collection of the tower hold-up. A 1-1/2 inch quick acting valve (26) in the riser of the "water level device" above the auxiliary drain enabled the drainage to be stopped instantly and thus made tower hold-up data quite accurate.

The water supply was from a 1-1/2 inch feeder at approximately 50 to 60 degrees Fahrenheit and at 60 pounds per square inch pressure. The water flow was set by the globe valve (30) or for low flows and very accurate adjustments by the needle valve (29).

The water was metered by a 1 inch rotary meter (31) manufactured by the National Meter Company, New York City. It could be read directly to 0.01 cubic feet and estimated to 0.0025 cubic feet if necessary.

In order to minimize any pulsations due to the meter in the water flow a "Hydraulic Equalizer" (32) was placed

in the line immediately after the meter. It was constructed of a 20 inch length of 10 inch pipe and provided with petcocks (33) and (34) to drain the water and release the air respectively.

From the "Hydraulic Equalizer" the water passed to a water heater (35) to enable the tower to be kept at constant temperature. The temperature taken as the fixed value for the data obtained was 68 degrees Fahrenheit or 20 degrees Centigrade.

The water heater consisted of 48-1/4 inch copper tubes 29 inches long soldered into headers in a 3 inch brass pipe. The heater was placed in a vertical position and heated by wet steam at 40 pounds per square inch which entered at the bottom parallel to the direction of water flow. Thus the tower water, in the copper tubes, was surrounded by the steam condensate which overflowed at the top of the heater and discharged through the "water level device" to the sewer. Steam feed was controlled by a 1/2 inch globe valve (36). This heater gave excellent control within 1 degree Fahrenheit. The temperature was measured by a thermometer (38) placed just after the water heater.

After leaving the heater the water goes to a 3 way valve (39) where it may be directed either to the tower or may be shunted to the sewer while maintaining the flow of water through the heater. This feature is of especial value

in tower hold-up determinations and in successive runs at the same water velocity because then it is not necessary to readjust the steam setting for the water heater when flow to the tower is stopped.

The constancy and instantaneous value of the water rate was also checked by two orifices in parallel (40) and (41) each of which had a manometer across it. From here the water passed to the top of the tower where it entered the pressure sprays and was sprayed into the tower.

The carrier gas used was compressed air. It was delivered by the compressor to storage at 60 pounds per square inch and reduced to 45 pounds per square inch before delivery at globe valve (1). From here the pressure was again reduced by a 1/2 inch Cash Reducing valve (3) to 10 pounds per square inch. The line then went to a small storage tank (5) to smooth out line pressure fluctuations. The low pressure air was fed to the tower through a 1 inch line passing first to the control valves, a 1 inch globe valve (6) in parallel with a 1/4 inch needle valve for vernier control. The instantaneous air rate and the constancy of flow were measured by an orifice (8) in the line.

The carbon dioxide used was obtained in 50 pound cylinders (9). Immediately after leaving the cylinder it was heated at tank pressure in a seamless steel tube (10)

wrapped with a solder sweated copper steam coil before passing to a 3/8 inch reducing valve (11) where its pressure was reduced to 50 pounds per square inch as indicated on a 300 pound gauge (12). This heater prevented the freezing of the reducing valve and its plugging by dry ice formation. The carbon dioxide was then cooled in a long spiral of 1/4 inch copper tubing, to room temperature, before going to the needle valve (14) for delivery to the tower. The instantaneous carbon dioxide rate and the constancy of flow were measured by an orifice (15) in the line.

The air and carbon dioxide mixture were passed through the gas meter (16). The gas meter was of the bellows type made by the Equitable Meter Company, Pittsburg, Pennsylvania and was capable of being read directly to 0.05 cubic feet and estimated to 0.01 cubic feet. Between the gas meter and the tower was inserted a 1 inch quick acting valve (17) so that gas flow to the tower could be interrupted instantaneously if desired. A pet cock (19) was also provided to allow for water drainage in case the tower should fill up and force water into the gas line.

It was found that when the gas flow to the tower was stopped suddenly by closing the quick acting valve, the increase in pressure which followed emptied the manometer liquids. Also, since carbon dioxide was fed in at 50 pounds

per square inch and air at 15 pounds per square inch, if left statically connected, carbon dioxide would flow back into the air line not only wasting carbon dioxide but contaminating the air supply and effecting subsequent gas compositions. To offset this difficulty a mercury release valve (22) was designed. It consisted of an outer housing made of a 26 inch section of 1/2 inch pipe capped at the lower end and coupled at the upper end to a 6 inch section of 1-1/2 inch pipe which was capped in turn. This housing was filled with mercury, and a 1/4 inch copper tube connected to the gas line ahead of the gas meter was immersed in the mercury so that it would blow off at 15 pounds per square inch. This took care of the pressure increase incident to the closing of the quick acting valve and subsequent leakage through the reducing valves.

The analysis methods which were used necessitated continuous, steady sampling of the gas under a slight positive pressure and free from entrained water vapor. These limitations coupled with the desirability of having a truly representative sample made the problem of a proper sampling installation an important one.

The previous tower used in 1932-33 had sampling tubes inserted in the vapor space a few inches above and below the packing. However, this method introduces the serious question of end effect, and the problem of determining the

amount of this variable is in itself a separate problem in absorption and should, if possible, be avoided. For this reason the tower was equipped with two sampling tubes (45) inserted directly in the packing at suitable distances from the ends as shown on the schematic drawing. They consist of $3/8$ inch pipe passing from the wall to the center of the tower where they expand into $1/2$ inch elbows which are turned down to prevent the entrance of water into the lines. The expansion effect reduces the sampling velocity at the inlet of the sampling tube and minimizes entrainment. The tower was operated at a constant pressure of 32 inches of mercury, providing sufficient pressure head for the sampling. The external connections of the sampling lines were of $1/4$ inch copper tubing connected into pet cocks (50) and thence to the absorption cells. In order to insure that the gas being analyzed was representative of that in the tower and not stagnant gas in the sampling lines which might be of entirely different composition due to the length of the lines, bleeding pet cocks were provided before the absorption cells. These kept the sampling lines well flushed at all times. The pinch clamps (51) were for regulation of the gas sampling velocity to the gas absorption cells. Tower pressure drop was measured by a manometer (46) across the top and bottom sampling connections.

GAS ANALYSIS

In the University of Cincinnati Thesis (1932-33) on "Gaseous Absorption Phenomena" Rose and Bradt pointed out the absolute necessity for accurate gas analysis due to the nature of the theoretical expressions for material transfer through films. It was shown that an error of one percent in the value of the gas analysis might produce an error of 20 to 60 percent in computations for certain ranges of absorption. When the problem was first studied it was found that the various known methods of analyzing for carbon dioxide could be classified as follows:

(1) Gravimetric Methods.

- (a) Carbon dioxide absorbed in strong solutions or solid absorbents of alkali dispersed on asbestos fibers and the increase in weight determined.
- (b) Carbon dioxide absorbed in diluted solutions of sodium hydroxide or potassium hydroxide and weighed as carbonate.
- (c) Carbon dioxide absorbed in strong barium hydroxide and weighed as carbonate or converted to barium sulphate.

(2) Titrimetric Methods.

- (a) Carbon dioxide dissolved in dilute sodium

hydroxide or potassium hydroxide and determined by double titration with phenolphthalein and methyl orange as indicators.

- (b) Carbon dioxide absorbed in barium hydroxide and titrated directly.
- (c) Carbon dioxide absorbed in sodium hydroxide, an excess of barium chloride added and the excess alkali titrated.
- (d) Carbon dioxide absorbed in strong barium hydroxide, the precipitate filtered, washed, dissolved in standard acid and back titrated.

(3) Gasometric Methods.

- (a) Carbon dioxide dissolved in strong alkali and decrease in volume read; or dissolved and regenerated by excess acid and volume of carbon dioxide read.
- (b) By manometric method: carbon dioxide dissolved at constant volume and decrease in pressure noted.

(4) Electrometric Methods.

- (a) Electrolytic resistance: carbon dioxide absorbed in standard alkali and electrolytic conductivity measured.
- (b) Thermal conductivity: resistance of wire heated by a constant current varies with the composition of the enclosing atmosphere due to

variation in thermal conductivity of the gas.

(5) Colorimetric Method.

Carbon dioxide absorbed in a solution of the sodium salt of phenolphthalein and its concentration indicated by the resulting color.

Of all the above methods it seemed that the directly titrated barium hydroxide method was by far the most suitable, accurate and convenient. It is clean cut and rapid and therefore very suitable for work in which a great number of successive determinations must be made. It may also be easily adapted to the problem of taking a continuous composite analysis of a flowing gas stream over a period of time. This type of analysis was necessary because the tower was operated for a 15 minute period at constant values of the variables so that absorption data might be taken.

The details of the unit used are best shown in the diagram (Fig. 10). It is unnecessary to discuss the details involved in the design. The unit was designed for tenth normal barium hydroxide operating continuously at a sampling rate of 150 c.c. per minute of a gas containing approximately ten percent carbon dioxide. The apparatus has been tested for absorption efficiency by connecting two of the cells in series. At 150 c.c. per minute there is no detectable leak of carbon dioxide past the cell until over

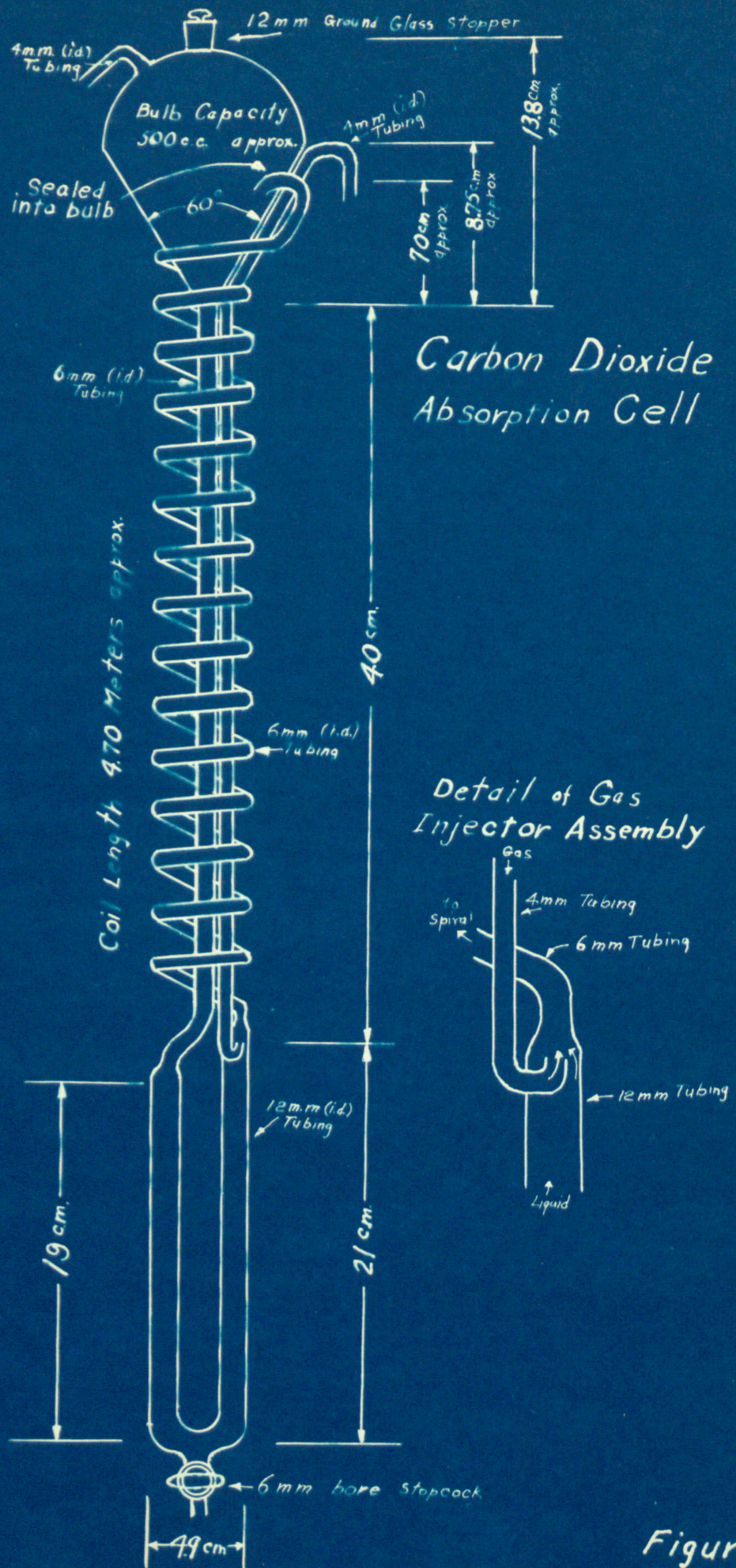


Figure 10

95 percent of the barium hydroxide is used up. The cells were never used past 80 percent of the barium hydroxide used up. The absorbers have a capacity of 200 c.c. of tenth normal barium hydroxide equivalent to an absorption capacity of 224 c.c. of carbon dioxide at S.T.P. The units were fabricated from Pyrex Glass by the Scientific Glass Apparatus Company, Vineland, New Jersey.

The inert gas leaving the absorbers was metered by Sargent Wet Test Meters which could be read directly to 0.001 cubic feet and estimated to 0.00025 cubic feet. The meters were provided with thermometers for recording the temperature at which the gas was being metered.

PROCEDURE

The correct procedure for making an experimental absorption run on the tower is as follows: Adjust the water rate to the desired value by timing it on the water meter with a stop watch. Adjust the steam valve for a temperature of 68 degrees Fahrenheit. Set the gas and carbon dioxide valves to the desired value of gas flow by means of the manometers which have been previously calibrated. Adjust the "water level device" and the exit gas valve so that the total absolute pressure in the tower is 32 inches of mercury and the water in the sight glass shows that its level is somewhere in the water reservoir. Open the bleeding stop cocks on the gas sampling tubes so that a fresh sample of gas is always in the lines. After the tower has attained steady conditions, a minimum of 15 minutes, the run is started and allowed to continue for 15 minutes. The following data are taken: water meter readings before and after 15 minute run, gas meter readings, readings on the wet test meters for both inlet and outlet tower gas, c.c. of HCl used for back titrating the barium hydroxide, pressure drop across the tower and temperature.

The correct procedure for the analysis unit is as follows: Pipette 200 c.c. of the tenth normal barium hydroxide into each absorber and put the stopper in place

tightly. Now take the initial reading on the wet test meters, first making sure that the meter is full of water. Read both volume and temperature to note whether the temperature changes during the run. Next open the bleeding stop cocks to the absorbers and adjust the pinch clamps so that the sampling rate is not over 150 c.c. per minute. Stop the sampling before 80 percent of the barium hydroxide is used up. As soon as sampling is stopped read the wet test meters volume and temperature. Drain the barium hydroxide barium carbonate solution from the absorbers and rinse well with distilled water catching the washings with the rest of the solution. Titrate the excess barium hydroxide with tenth normal HCl using phenolphthalein as indicator. This procedure will give uniform and consistent results capable of an accuracy of about 0.15 percent of the carbon dioxide determined.

The correct procedure for making a run on tower hold-up is as follows: Set the water and gas rates and temperature as in an absorption run. When steady conditions have attained in the tower shut off the inlet and outlet water and inlet gas simultaneously, by means of the quick acting valves, noting at the same time the level of the water in the sight glass. Drain the water off the packing and out of the bottom reservoir until the level in the sight glass is the same as before shutting off the quick acting valves.

After allowing the tower to drain for 5 minutes (this gives consistent results with 98 percent or more of the water drained) the water is weighed to determine tower hold-up.

TABLE OF SYMBOLS

- A Area of cross section of tower.
- C Conductivity of transfer path; defined as the volume of solute, measured at tower conditions, transferred per unit time per unit area of solvent surface per unit concentration driving force.
- c Fractional volume content of soluble constituent in the gas stream at any point in the tower.
- c_1 Fractional volume solute concentration in the inlet gas.
- c_2 Fractional volume solute concentration in the exit gas.
- Ea Absorption efficiency; defined as the ratio of solute absorbed to the total solute introduced into the tower.
- Es Solution or saturation efficiency; defined as the ratio of solute concentration in the exit liquid to the maximum theoretical exit liquid solute concentration.
- e Solute volume concentration of the liquid which is in equilibrium with a gas of solute volume concentration c ; thus $e = cH$.
- F Fraction of free space or voids in the tower.
- f Concentration driving force of the solute which accomplishes absorption.
- G Gas volume velocity at any point in the tower. (cu. ft. per min.)
- G_1 Gas volume velocity of the carrier or inert gas at any point in the tower. (cu. ft. per min.)

TABLE OF SYMBOLS (continued)

- G_1 Gas volume velocity of the gases being fed to the tower.
(cu. ft. per min.)
- G_2 Gas volume velocity of the gases leaving the tower.
(cu. ft. per min.)
- G_{2a} Apparent lineal velocity of the gases leaving the tower;

$$G_{2a} = \frac{G_2}{AF}$$
- H Henry's coefficient; defined as the volume of solute, measured at partial pressure c soluble in a unit volume of liquid in equilibrium with gas of solute partial pressure c .
- J Packing coefficient; defined as the transfer surface presented per unit volume of dry packed tower.
- K Constant depending on the type of materials used.
- L Length of packed tower.
- ΔP Pressure drop per foot length of tower. (inches of Hg)
- r Solute concentration of liquid at any point within the tower; volume of gas, measured at tower conditions at the point in question, dissolved in a unit volume of absorbent.
- S Actual surface presented for solute transfer.
- R Flow ratio (G_1/v); ratio of inert gas volume velocity to the liquid volume velocity.
- R_1 Flow ratio at the tower bottom (G_1/v)

TABLE OF SYMBOLS (continued)

- R_2 Flow ratio at the tower top (G_2/V)
- V Liquid volume velocity through the tower. (cu. ft. per min.)
- V_a Apparent lineal liquid velocity through the tower.
(ft. per min.)
- W Volume of liquid held up per cubic foot of packing.
(cu. ft./cu. ft.)

THEORY

THEORY

The assumptions which were made in the derivation of the fundamental absorption equation are as follows:

(1) "During operation, all factors on any chosen plane within the tower are constant. This assumption embraces several dependent assumptions, viz.,

(a) The temperature and pressure throughout the tower are kept uniform and constant.

(b) The flow rate per unit area and the composition of the two fluids at any area on a given plane remain constant during the period of operation.

(c) The area of interface for solute transfer per unit packed volume of tower is everywhere the same throughout the tower.

(d) The conductivity of the transfer path, defined as the amount of solute transferred per unit time per unit area of solvent surface per unit concentration driving force, is constant throughout the tower."*

(2) "The vapor pressure of the scrubbing liquid is small and is of negligible character."*

(3) "The carrier gas is inert, that is, its solubility in the extractor is zero."*

(4) "The system obeys Henry's Law."*

In an industrial tower operating at constant rates of

* Garber (47)

flow a true steady state is always obtained. In an industrial tower also the temperature and pressure, once constant conditions have obtained, are essentially constant. This does not imply that temperature does not effect absorption but merely that, for a given tower operating at constant conditions, there is a definite fairly constant temperature obtained. Temperature would influence absorption to a marked extent. At higher temperatures there would be less solubility of the gas in the liquid and the vapor pressure of the liquid would also be increased so that the gas would carry with it an appreciable amount of solvent vapor. In opposition to this the viscosities of the fluids are decreased, the thickness of films are decreased and thus the conductivity of the transfer path increases considerably.

Distribution of the liquid phase throughout the tower is a very important item. It has been shown by Kirschbaum, Scott, Lerman and other investigators that the liquid does not distribute itself evenly throughout the tower. They have shown that the liquid tends to build up along the tower walls once it hits there. This gives the same effect as using less water than is actually used or of decreasing the effective volume of the tower. However, the derivation of the equation assumes even distribution of the liquid throughout the cross section of the tower. Since uneven

distribution greatly decreases the efficiency of a tower steps will be taken to make for even distribution in towers in the future.

In the derivation of the general absorption equation C is assumed to be a constant for each specific case. This is true for most industrial towers operating at constant conditions. However, C is not a constant but some unknown function of densities, viscosities, fluid velocities, etc. Since, for a particular tower operating at constant conditions these variables are at the moment constant, C is constant. The conductivity, however, will increase as fluid velocities increase because of the decrease in film thickness and diffusional resistance and the increase in turbulence and intimacy of contact. Because of present ignorance as to how these variables affect the conductivity it cannot be expressed as a function of them and must be treated as a constant during integration of the equation. However, as explained above for industrial towers operating at constant conditions C is a constant and the equation will hold.

The assumption that the vapor pressure of the liquid is small and negligible is justified in the case of absorption where the gases have very low heats of solution. If the heat of solution is high the temperature and consequently vapor pressure of the liquid increases and in this case appreciable

amounts of liquid would be carried out the tower top. However, for gases having low or negligible heats of solution with the tower operating at constant temperature and the gas being saturated with the liquid before entering the tower, there will be negligible amounts of liquid carried out the tower top.

The assumption that the solubility of the carrier or inert gas in the liquid is zero is not a bad one. The error which this assumption introduces is a function of the amount of carrier originally in the liquid. If the liquid is saturated with respect to the carrier gas before it enters the tower the error due to this assumption is negligible.

Henry's law like most of the physical laws of solution is not exact except in very dilute solutions. However, it holds within 3 percent for many gases and it is for these gases that the equation will strictly apply. If Henry's coefficient varies with the concentration of the solute in the solution the assumption may be made that the variation is linear and the average value of the coefficient may be used.

The main steps of Garber's original derivation are as follows:

Starting with a material balance over an infinitesimal area of tower the following equation will hold:

$$(1) \quad -dG = -d(Gc) = KfCdS$$

This states that the change in gas volume, or absorption, is proportional to the conductivity of the transfer path, the surface presented and the concentration driving force causing solute transfer from the gas to the liquid. It is a modified Ohms Law.

The gas volume velocity at any point in the tower is expressed by

$$G = \frac{G_i}{1-c}$$

and

$$(2) \quad dG = \frac{G_i}{(1-c)^2} dc$$

This implies that the inert gas is insoluble in the liquid, assumption (3).

The solute driving force causing absorption may next be evaluated in terms of the variables affecting it. The initial driving force causing solution for pure liquid in contact with gas of concentration c is c . However, as solution of the gas into the liquid takes place this driving force is lessened due to the tendency of the gas to escape from the liquid. This escaping tendency is given by r/H and thus the solute driving force being the difference between solution and escaping tendency is:

$$(3) \quad f = c - \frac{r}{H}$$

For saturated solutions, the equilibrium concentration of gases above the liquid is $\frac{r}{H} = e = c$, and thus $f = 0$.

A solute balance from the tower top to any point within the tower gives:

$$V(r-r_2) = G - G_2 = \frac{G_1}{1-\kappa} - \frac{G_2}{1-\kappa_2}$$

For fresh liquid always being fed to the tower $r_2 = 0$ and,

$$r = \frac{G_1(c-\kappa_2)}{V(1-\kappa)(1-\kappa_2)} = \frac{R_2(c-\kappa_2)}{(1-\kappa)}$$

Insertion of this value of r into equation (3) gives:

$$f = \frac{\kappa(1-\kappa) - Z(c-\kappa_2)}{1-\kappa}$$

The transfer surface, dS , may be replaced by its equivalent $dS = JAdL$.

Substitution of the expressions for dG , f , and dS into equation gives:

$$(1) \frac{-dc}{[(1-\kappa)][\kappa(1-\kappa) - Z(c-\kappa_2)]} = \frac{KCJA}{G_1} dL$$

Integration of this equation between $L=L$ and $L=0$ and c_1 and c_2 by means of the standard form found in Pierces Table of Integrals gives the general absorption equation.

$$(4) \frac{-2KCJAL}{G_2} = \frac{H}{R_2} \ln \left[\frac{\kappa_1(1-\kappa_1) - Z(c_1-\kappa_2)}{\kappa_2(1-\kappa_2)} \left(\frac{1-\kappa_2}{1-\kappa_1} \right)^2 \right]$$

$$\left[\frac{2\kappa_1 + (Z-1) - \sqrt{(Z-1)^2 + 4Z\kappa_2}}{2\kappa_2 + (Z-1) - \sqrt{(Z-1)^2 + 4Z\kappa_2}} \times \frac{2\kappa_2 + (Z-1) + \sqrt{(Z-1)^2 + 4Z\kappa_2}}{2\kappa_1 + (Z-1) + \sqrt{(Z-1)^2 + 4Z\kappa_2}} \right]^{\frac{Z+1}{\sqrt{(Z-1)^2 + 4Z\kappa_2}}}$$

It can readily be seen that this equation is too long

and cumbersome to lend itself to engineering calculations so that for practical use some manner of simplification must be found. After trying numerous simplifying assumptions the following was found to involve the least approximations and to give the simplest equation.

Expanding the above equation and writing it as the sum of three log terms gives:

$$(4) \quad -\frac{2KCJAL}{HV} = \ln \left[\frac{c_1(1-c_1) - z(c_1-c_2)}{c_2(1-c_2)} \right] + 2 \ln \left[\frac{1-c_2}{1-c_1} \right] +$$

$$\frac{z+1}{\sqrt{(z-1)^2 + 4zc_2}} \ln \left[\frac{2c_1 + (z-1) - \sqrt{(z-1)^2 + 4zc_2}}{2c_2 + (z-1) - \sqrt{(z-1)^2 + 4zc_2}} \times \frac{2c_2 + (z-1) + \sqrt{(z-1)^2 + 4zc_2}}{2c_1 + (z-1) + \sqrt{(z-1)^2 + 4zc_2}} \right]$$

Since the terms in the second bracket of the third log term are all additive and since they, in order, do not differ much from each other except as c_2 differs from c_1 , the numerator is practically equal to the denominator for all values of c_1 and c_2 actually encountered in operating conditions.

It can be seen by inspecting this term that the numerator will differ from the denominator most for low values of $\frac{R_2}{H}$ and where c_2 and c_1 are as far apart as possible.

Using a set of data where $\frac{R_2}{H}$ is low and where c_2 is far from c_1 and evaluating the $\frac{H}{R_2}$ term will serve to show how close the numerator and denominator actually are.

$$Z=2.13 ; c_1 = 9.83 ; c_2 = 5.98$$

$$\frac{2c_2 + (Z-1) + \sqrt{(Z-1)^2 + 4Zc_2}}{2c_1 + (Z-1) + \sqrt{(Z-1)^2 + 4Zc_2}} = \frac{2.5896}{2.6666} = 0.974$$

When inverted this becomes 1.026

On taking the ln and multiplying by the quantity in front of the ln,

$$\frac{Z+1}{\sqrt{(Z+1)^2 + 4Zc_2}} = 2.34$$

gives for the regular term -0.06

and for the inverted term 0.06

The KCJ for this value is 0.931 and the error in KCJ is $\frac{0.06+0.06}{0.931} = 13\%$ too low

The maximum error, introduced then, by inverting this part of the ln term is 13% and it will tend to make KCJ always too low. Since the numerator and denominator are practically equal, the bracket may be inverted. If now, the two brackets be multiplied together and the results simplified the third term of the absorption equation will be:

$$\frac{Z+1}{\sqrt{(Z-1)^2 + 4Zc_2}} \ln \left[\frac{c_1(1-c_1) - Z(c_1-c_2)}{c_2(1-c_2)} \right]$$

But the expression here within the log is the same as the first log term, so that combining terms gives:

$$(5) \frac{-2KCJAL}{HV} = \left[1 + \frac{Z+1}{\sqrt{(Z-1)^2 + 4Zc_2}} \right] \ln \left[\frac{c_1(1-c_1) - Z(c_1-c_2)}{c_2(1-c_2)} \right] + 2 \ln \left[\frac{1-c_2}{1-c_1} \right]$$

Working on the term, $\frac{\frac{R_2}{H} + 1}{\sqrt{\left(\frac{R_2}{H} - 1\right)^2 + \frac{4R_2 c_2}{H}}}$ in order to simplify

it and letting, $\frac{R_2}{H} = Z$ we have:

$$\frac{Z+1}{\sqrt{(Z-1)^2 + 4Z c_2}}$$

By expanding the term under the radical, adding and subtracting $4Z$, recombining terms, and taking the quantity $(Z+1)$ outside the radical the term becomes:

$$(6) \quad \frac{1}{\sqrt{1 - \frac{4Z(1-c_2)}{(Z+1)^2}}}$$

Since c_2 is always very small compared to 1 it may be neglected in the term $(1-c_2)$ in the denominator of the log term in (5) with very little error.

The error introduced by making this assumption will be shown here. The expression may be written as follows:

$$\ln \frac{c_1(1-c_1) - Z(c_1 - c_2)}{c_2} - \ln(1-c_2)$$

Obviously the greatest error will be introduced when c_2 is large and the expression $\ln \frac{c_1(1-c_1) - Z(c_1 - c_2)}{c_2}$ is small. Taking a set of data where this condition prevails and evaluating the expressions will serve to show the maximum error attained by assuming $(1-c_2) = 1$.

$$Z = 59.0; \quad c_1 = 9.30; \quad c_2 = 9.20$$

$$-\ln(1-c_1) = +0.097$$

$$\ln \frac{c_1(1-c_1) - Z(c_1 - c_2)}{c_2} = -1.28$$

The error then is $\frac{0.097}{1.28} = 7.6\%$ too high.

The maximum error, introduced then by assuming $(1-c_2) = 1$ is 7.6% and it will tend to make KCJ always too high. Also, since c_1 is nearly equal to c_2 in most cases the term $2 \ln \frac{1-c_2}{1-c_1}$ in (5) may be neglected except where c_2 is quite different from c_1 .

In the case of dropping the expression $2 \ln \frac{1-c_2}{1-c_1}$, the largest error will develop when c_2 differs most from c_1 .

Taking a set of data where this condition prevails and evaluating the expression will serve to show the largest error obtained here.

$$c_1 = 8.91; \quad c_2 = 6.47$$

$$2 \ln \frac{1-c_2}{1-c_1} = 0.055$$

The KCJ for this data point is 0.785 and the error in KCJ is $\frac{0.055}{0.785} = 7\%$ too high. Therefore, the error in dropping $2 \ln \frac{1-c_2}{1-c_1}$ will always tend to make KCJ too high.

In order to show ² how these errors cancel two sets of

data for widely separated conditions will be calculated:

(1) Run #2-5-2

(2) Run #1-1-4

$$\frac{R_2}{H} = 2.13, c_1 = 9.83; c_2 = 5.98$$

$$\frac{R_2}{H} = 12.97, c_1 = 10.07, c_2 = 9.58$$

$$KCJ = 0.931$$

$$KCJ = 0.390$$

$$\frac{Z+1}{\sqrt{(Z-1)^2 + 4Zc_2}} \ln \left[\frac{2c_2 + (Z-1) + \sqrt{(Z-1)^2 + 4Zc_2}}{2c_1 + (Z-1) + \sqrt{(Z-1)^2 + 4Zc_2}} \right] =$$

$$2.34 \ln \frac{2.5896}{2.6666} = 0.06$$

$$1.16 \ln \frac{24.1576}{24.1714} = 0$$

$$\text{Error} = \frac{.06 \times 2}{0.931} = \underline{13\% \text{ low}}$$

$$\text{Error} = \frac{0}{0.390} = \underline{0\% \text{ low}}$$

$$- \ln (1-c_2) = 0.094$$

$$- \ln (1-c_2) = 0.099$$

$$\ln \frac{c_1(1-c_1) - Z(c_1-c_2)}{c_2} =$$

$$2.20$$

$$4.44$$

$$\text{Error} = \frac{0.094}{2.20} = \underline{4.3\% \text{ high}}$$

$$\text{Error} = \frac{0.099}{4.44} = \underline{2.2\% \text{ high}}$$

$$2 \ln \frac{1-c_2}{1-c_1} = 0.084$$

$$2 \ln \frac{1-c_2}{1-c_1} = 0.021$$

$$\text{Error} = \frac{0.084}{0.931} = \underline{9.0\% \text{ high}}$$

$$\text{Error} = \frac{0.021}{0.390} = \underline{5.4\% \text{ high}}$$

Total error in KCJ = 0.3% high

Total error in KCJ = 7.6% high

Making these simplifications, substituting in (6) above and inverting the term inside the log to take care of the - sign gives the General Absorption Equation:

$$(7) KCJ = \frac{HV}{2AL} \left[1 \pm \frac{1}{\sqrt{1 - \frac{4Z(1-c_2)}{(Z+1)^2}}} \right] \ln \left[\frac{c_2}{c_1(1-c_1) - Z(c_1-c_2)} \right]$$

The sign before the radical above depends upon the value of Z . If Z is larger than 1 the sign is positive. If Z is less than 1 the sign is negative. This may be proved by going back to Garber's differential equation and finding the part from which the radical originated. Upon extracting the root of this part of the equation the signs of the radical become obvious.

Garber (47) says, "The absorption efficiency of a tower may be defined as the ratio of the amount of solute absorbed in the liquid compared to the amount of total solute entering the tower."

$$(8) \quad E_d = \frac{c_1 - c_2}{c_1(1 - c_2)}$$

He defines saturation efficiency as the ratio of solute concentration in the exit liquid to the maximum theoretical exit liquid solute concentration.

$$(9) \quad E_s = \frac{R_1}{H} E_d = \frac{1 - c_2}{1 - c_1} Z E_d = \frac{c_1 - c_2}{c_1(1 - c_1)} Z$$

These above equations (7), (8), and (9) were used directly in computing all derived absorption data.

In industrial towers where recovery of solute is of prime importance, the more concentrated the exit liquid is with respect to the solute, the more perfect is the operation of the tower. In the perfect tower for securing

saturated exit liquid, the flow rates would be regulated so that the driving force causing solution would become zero just as the liquid reaches the tower bottom. Such a condition is equivalent to requiring the exit liquid to be saturated with solute and in equilibrium with a gas whose solute composition is c_1 . In the actual tower the driving force never vanishes but may be made to approach zero as a limit. In order to make this driving force as low as possible and at the same time make the absorption efficiency as high as possible low flow rates or very long towers must be used.

If the absorption efficiency, E_a , is unimportant, E_s , may be improved by increasing R_2/H to a maximum of infinity. On the other hand, if the saturation efficiency, E_s , is unimportant, E_a may be improved by decreasing R_2/H to a minimum of zero. This is to say that high saturation efficiencies are obtained when the liquid flow is very small as compared to the gas flow, and high absorption efficiencies when the gas flow is small as compared to the liquid flow.

In designing an industrial tower the inlet and outlet gas concentrations are usually known. These fix the absorption efficiency. Then for any desired saturation efficiency the flow ratio, R_2 , may be calculated. However, this does not give the individual values of either the gas or liquid flow.

It will be shown how to calculate these individual flow rates based on experimental data in another section of this thesis.

GENERALIZED RESULTS AND CURVES

TOWER HOLD-UP

"Tower hold-up is defined as the weight of solvent held up, at any instant, on the packing of the tower, under actual operating conditions. It is determined by shutting off all the flows and weighing the liquid which drips from the packing in a specified, sufficient time. It would, therefore, be a function of the viscosity and density of the solvent. Furthermore, due to the effect of temperature on the two properties mentioned, it would also be dependent upon temperature. But for a given tower, with a given solvent flowing over a fixed amount of packing at some fixed temperature, tower hold-up would be merely a function of the rates of flow of the two fluids in the tower. Such were the conditions under which these experiments were ran."*

Tower hold-up is important, because it gives the point of tower loading and flooding. The point of loading will be where the logarithmic tower hold-up vs. liquid velocity begins to deviate from a straight line. The flooding point will be where the same curve turns sharply upward.

The surface presented by the packing under any flow conditions will be given by the dry surface multiplied by some function of the hold-up. Before exact expressions for the packing surface under operating conditions can be developed

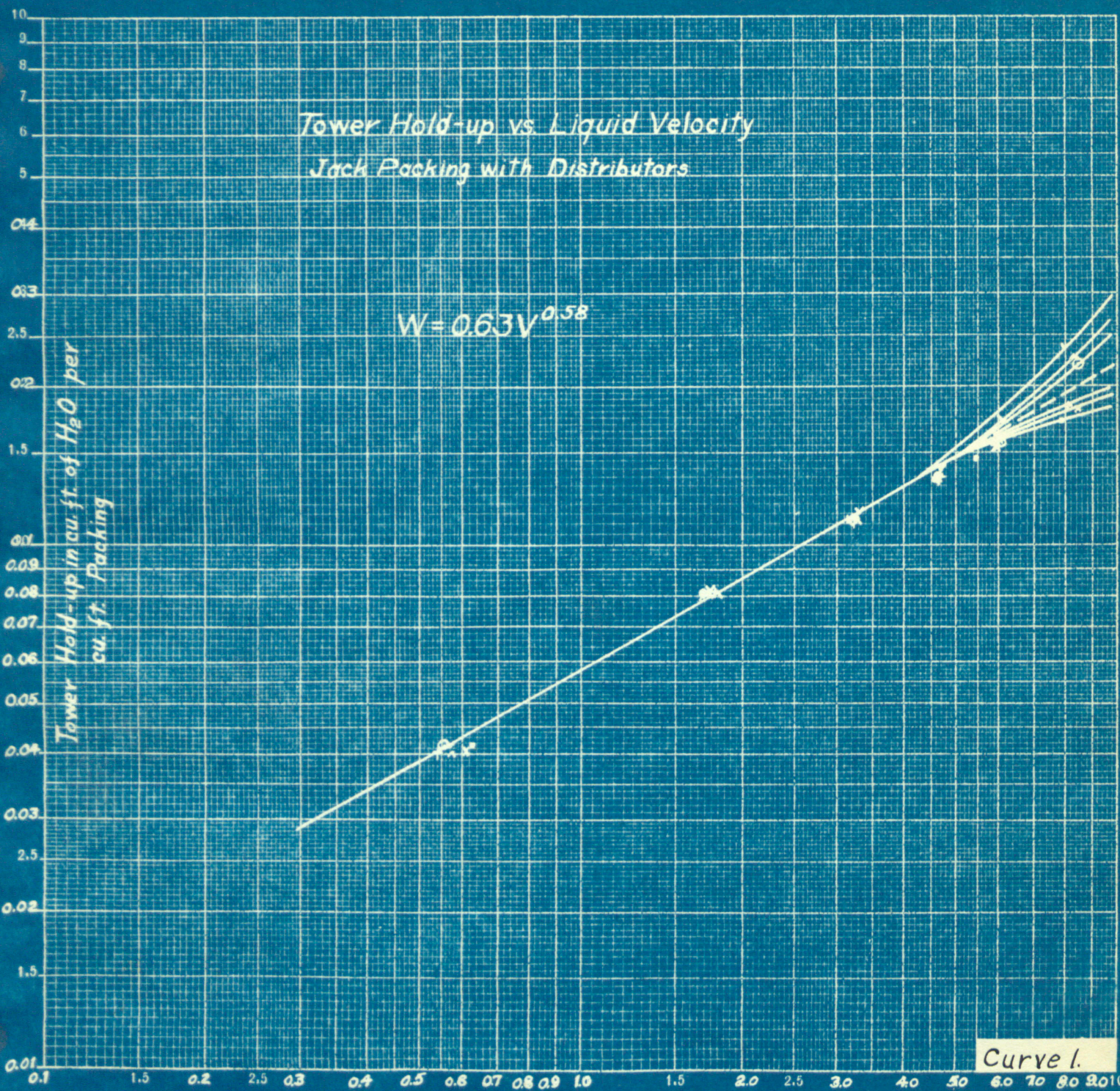
* Bradt and Rose (46)

this function must be determined. Until then the dry packing surface, J , will have to be used and any variation due to hold-up will have to be absorbed by the absorption coefficient, C .

*Tower Hold-up vs. Liquid Velocity
Jack Packing with Distributors*

$$W = 0.63V^{0.58}$$

*Tower Hold-up in cu. ft. of H₂O per
cu. ft. Packing*



Curve I.

Liquid Velocity in ft. per Min.

Logarithmic, 2 x 4 Cycles

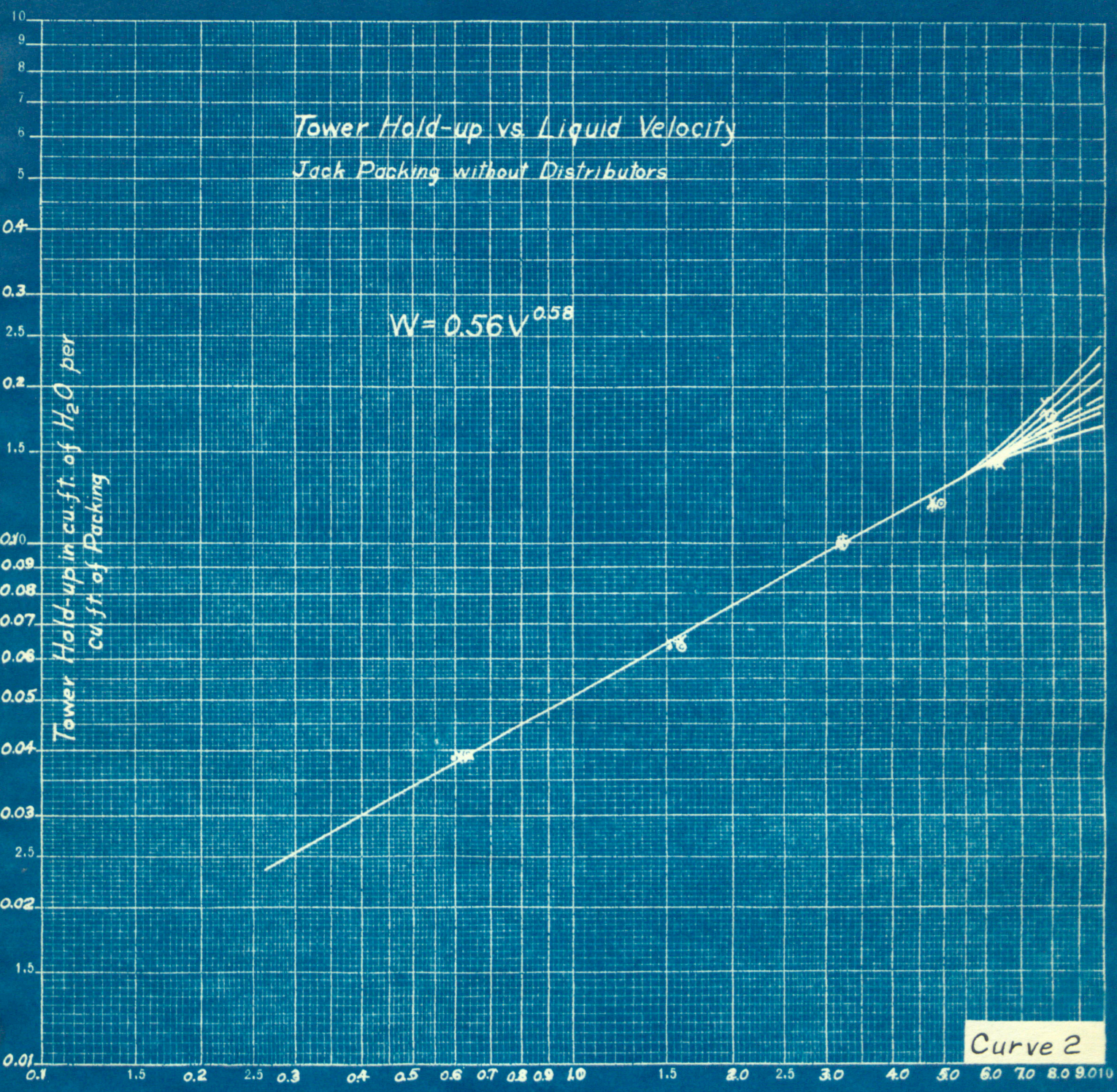
Tower Hold-up vs Liquid Velocity
Jack Packing without Distributors

$$W = 0.56V^{0.58}$$

*Tower Hold-up in cu.-ft. of H₂O per
cu.-ft. of Packing*

Curve 2

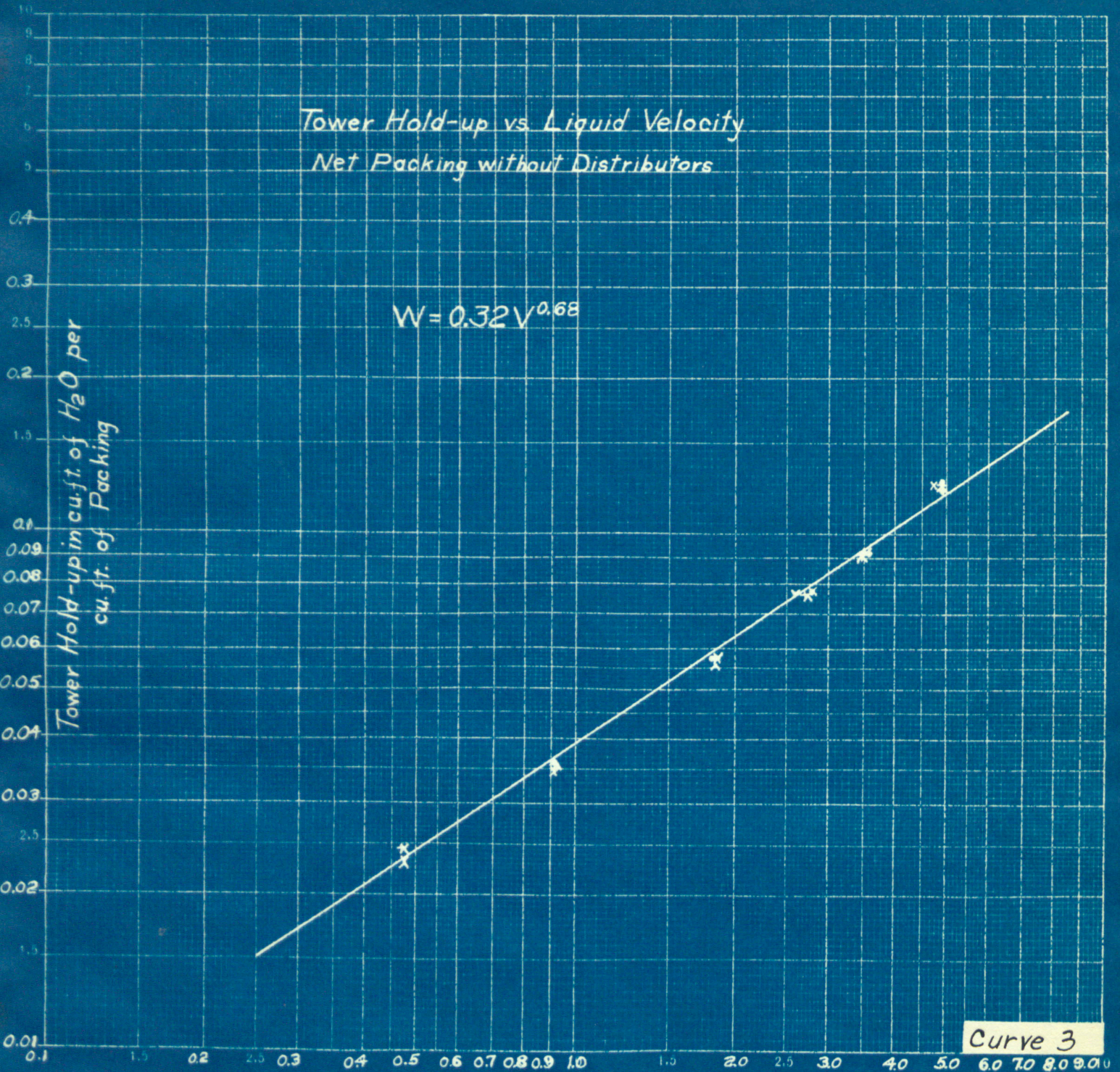
Liquid Velocity in ft. per Min.



Tower Hold-up vs. Liquid Velocity Net Packing without Distributors

$$W = 0.32V^{0.68}$$

Tower Hold-up in cu.ft. of H_2O per
cu.ft. of Packing

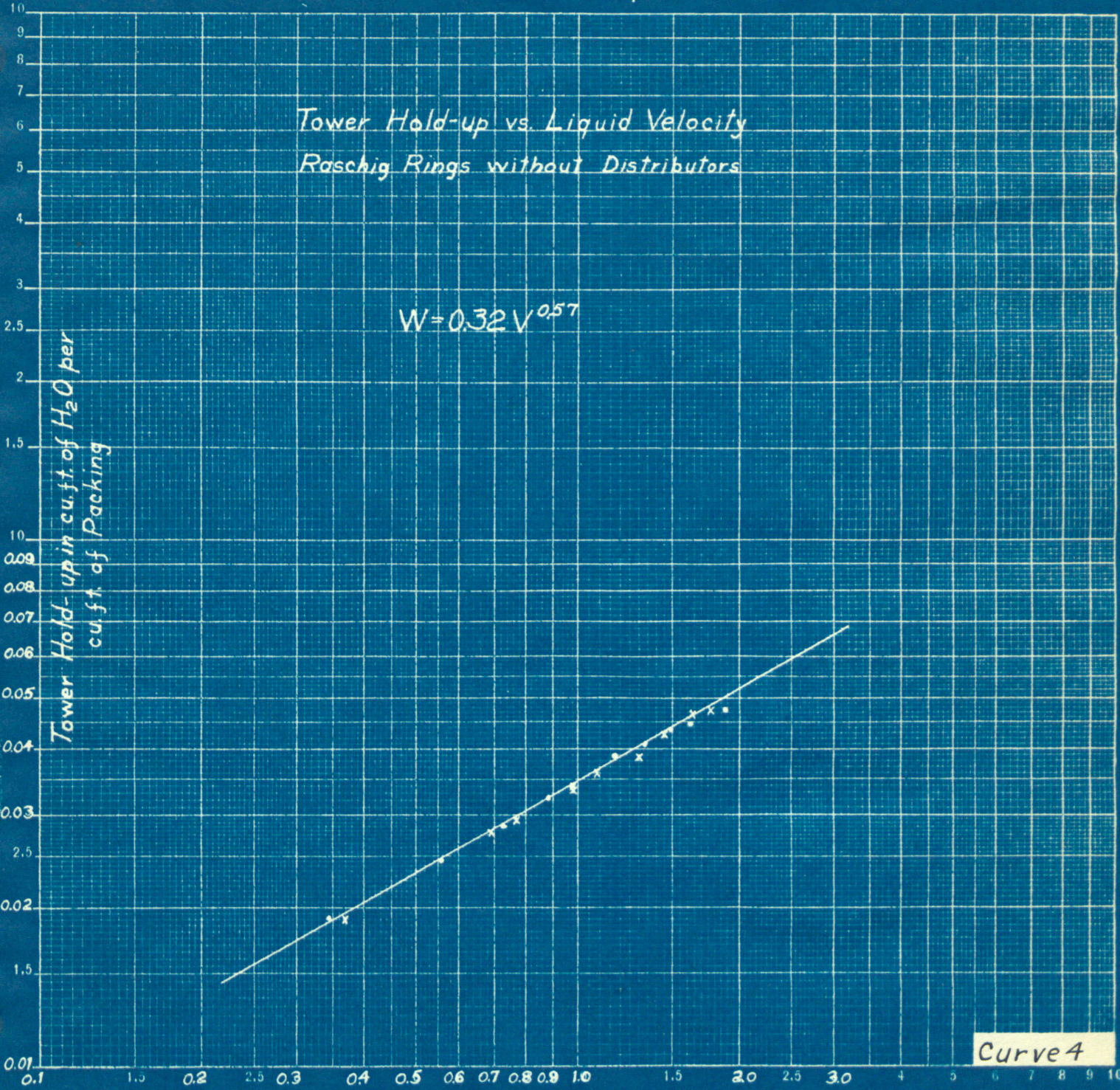


Curve 3

Liquid Velocity in ft. per Min.

Tower Hold-up vs. Liquid Velocity
Raschig Rings without Distributors

$$W = 0.32 V^{0.57}$$



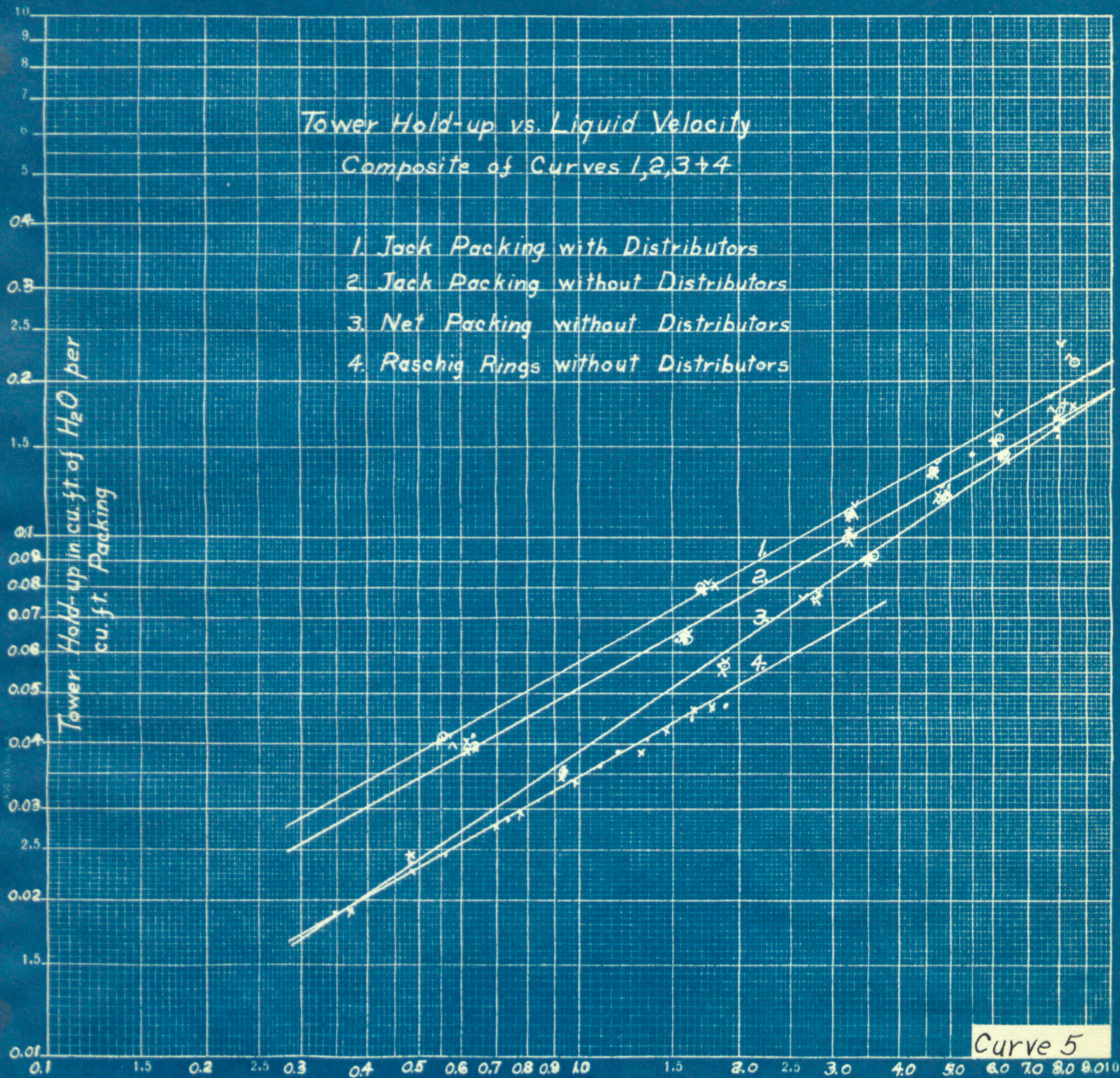
Curve 4

Liquid Velocity in ft. per Min.

Tower Hold-up vs. Liquid Velocity
Composite of Curves 1,2,3+4

- 1. Jack Packing with Distributors*
- 2. Jack Packing without Distributors*
- 3. Net Packing without Distributors*
- 4. Raschig Rings without Distributors*

*Tower Hold-up in cu. ft. of H₂O per
cu. ft. Packing*



Curve 5

Liquid Velocity in ft. per Min.

TOWER HOLD-UP vs. APPARENT VELOCITY

Curves 1 and 2 show that tower hold-up is independent of gas velocity and dependent only on liquid velocity up to tower loading. At or above loading more water than is theoretically called for is held up due to the gas actually holding back some of the water in the form of ripples which adhere to the packing. The points of loading are where the curves for the given higher gas velocities begin to deviate from the curve for very low gas velocity. For the Jack Packing both with and without distributors, the tower begins to load at a liquid velocity of 4 to 5 ft. per min. and the highest attainable gas velocity.

Curve 3 shows that loading did not occur with the Net Packing at the highest gas and liquid velocities attainable. Here again the tower hold-up was independent of gas velocity and dependent only on liquid velocity.

Curve 4 shows that loading did not occur with the Raschig Rings. Here however, the gas and liquid velocities used were small as compared to those used for the Jack and Net Packing so that the curve for Raschig Rings is not directly comparable to the others mentioned. Again however, tower hold-up was independent of gas velocity and dependent only on liquid velocity.

These curves show that for Jack Packing with and without

distributors and for Raschig Rings the tower hold-up is proportional to the 0.57 to 0.58 power of the liquid velocity. This is interesting because it checks with the value $7/12=0.583$ which Professor Tour found to be the power to which the quantity of water flowing must be raised to give the thickness of a turbulent film flowing down an inclined plane. Since the tower hold-up is directly proportional to the thickness of film, the checking of these two values proves that the liquid is in turbulent flow over the packing in the case of Jack Packing and Raschig Rings. However, in the case of the Net Packing, (curve 3), the tower hold-up was found to be proportional to the 0.68 power of the liquid velocity.

The equations for tower hold-up for the various packings used are as follows:

Jack Packing with Distributors

$$W = 0.63 V^{0.58} = 0.058 V_a^{0.58}$$

Jack Packing without Distributors

$$W = 0.56 V^{0.58} = 0.051 V_a^{0.58}$$

Net Packing without Distributors

$$W = 0.32 V^{0.68} = 0.039 V_a^{0.68}$$

Raschig Ring without Distributors

$$W = 0.32 V^{0.57} = 0.035 V_a^{0.57}$$

The higher value of the tower hold-up for Jack Packing with distributors over Jack Packing without dis-

tributors proves that the distributors did replenish the packing with the water that ran to the tower walls and stayed there until it was redistributed.

Gas vs. ΔP
Jack Packing
with
Distributors

ΔP in in. of Hg

V_g = 7.6

V_g = 6.4

V_g = 4.8

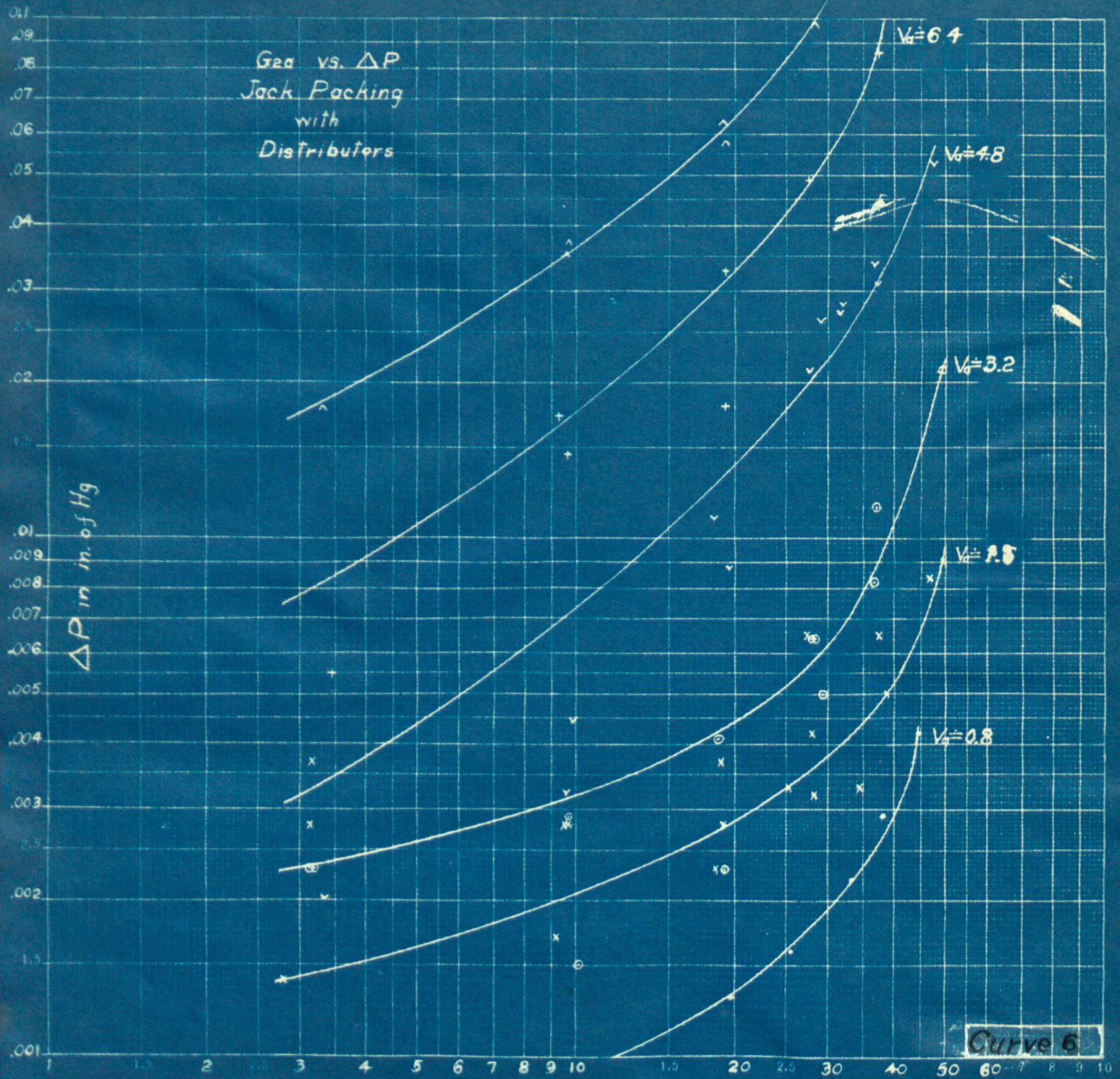
V_g = 3.2

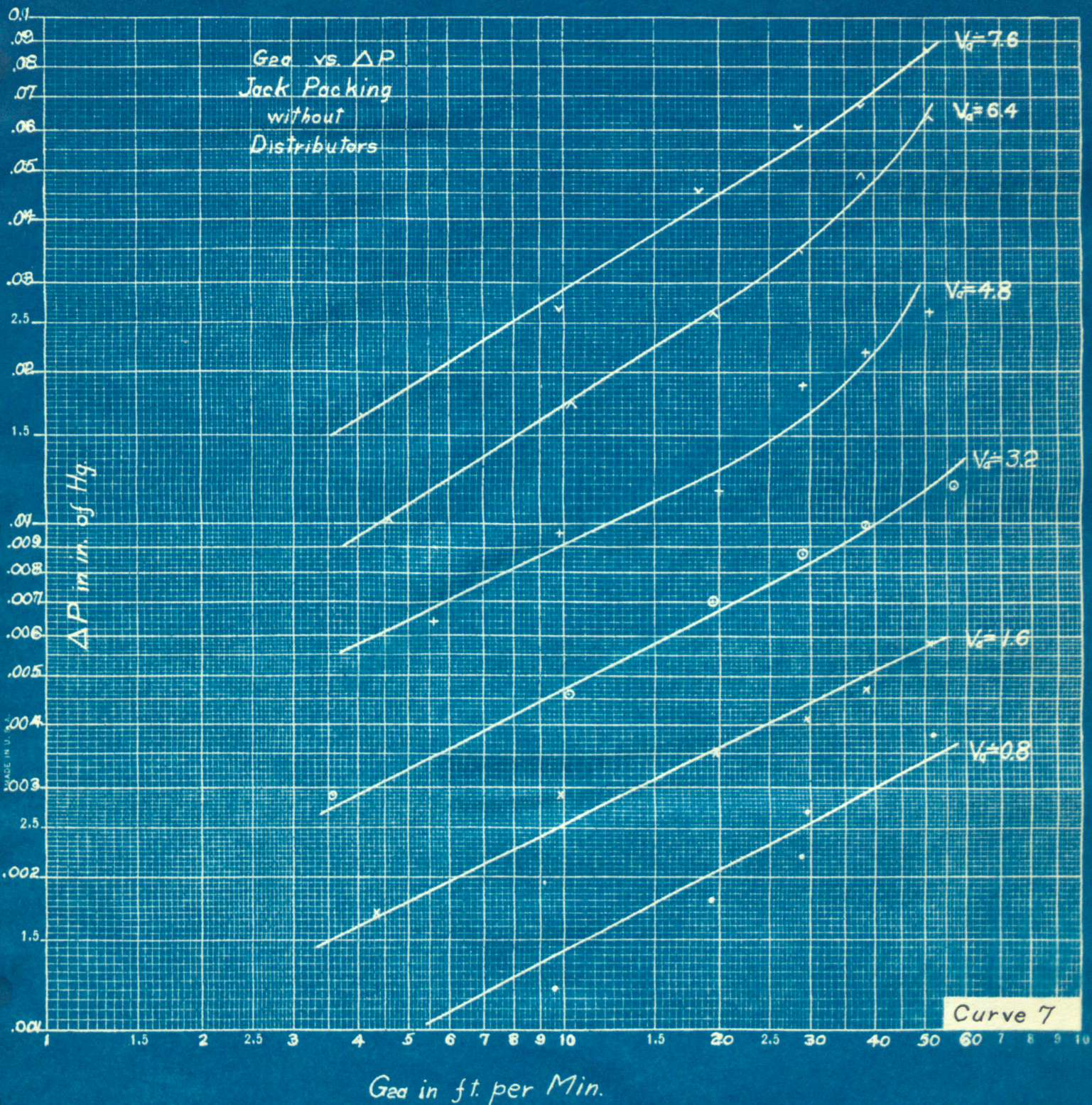
V_g = 1.8

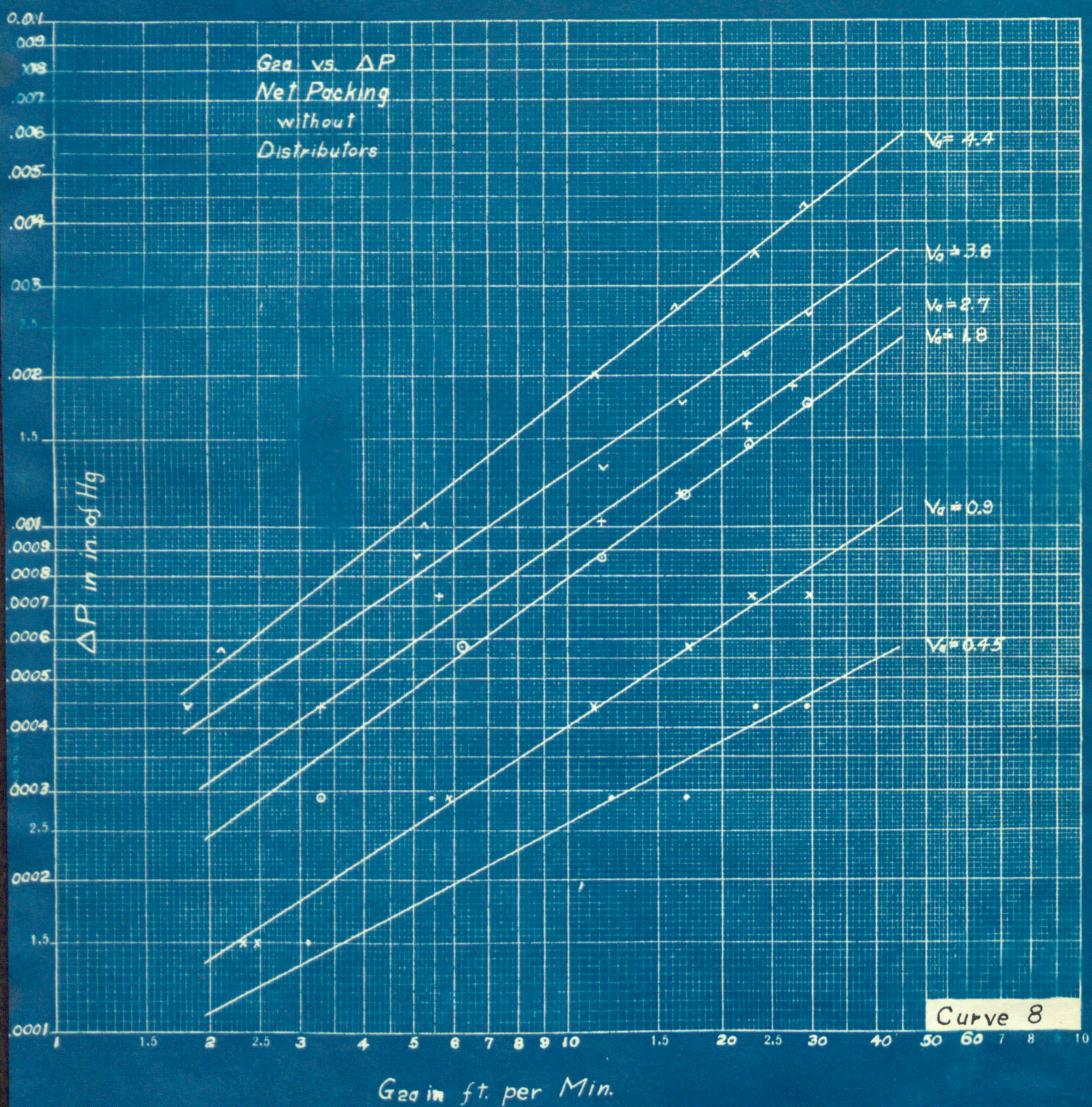
V_g = 0.8

Curve 6

Gas in ft. per Min.







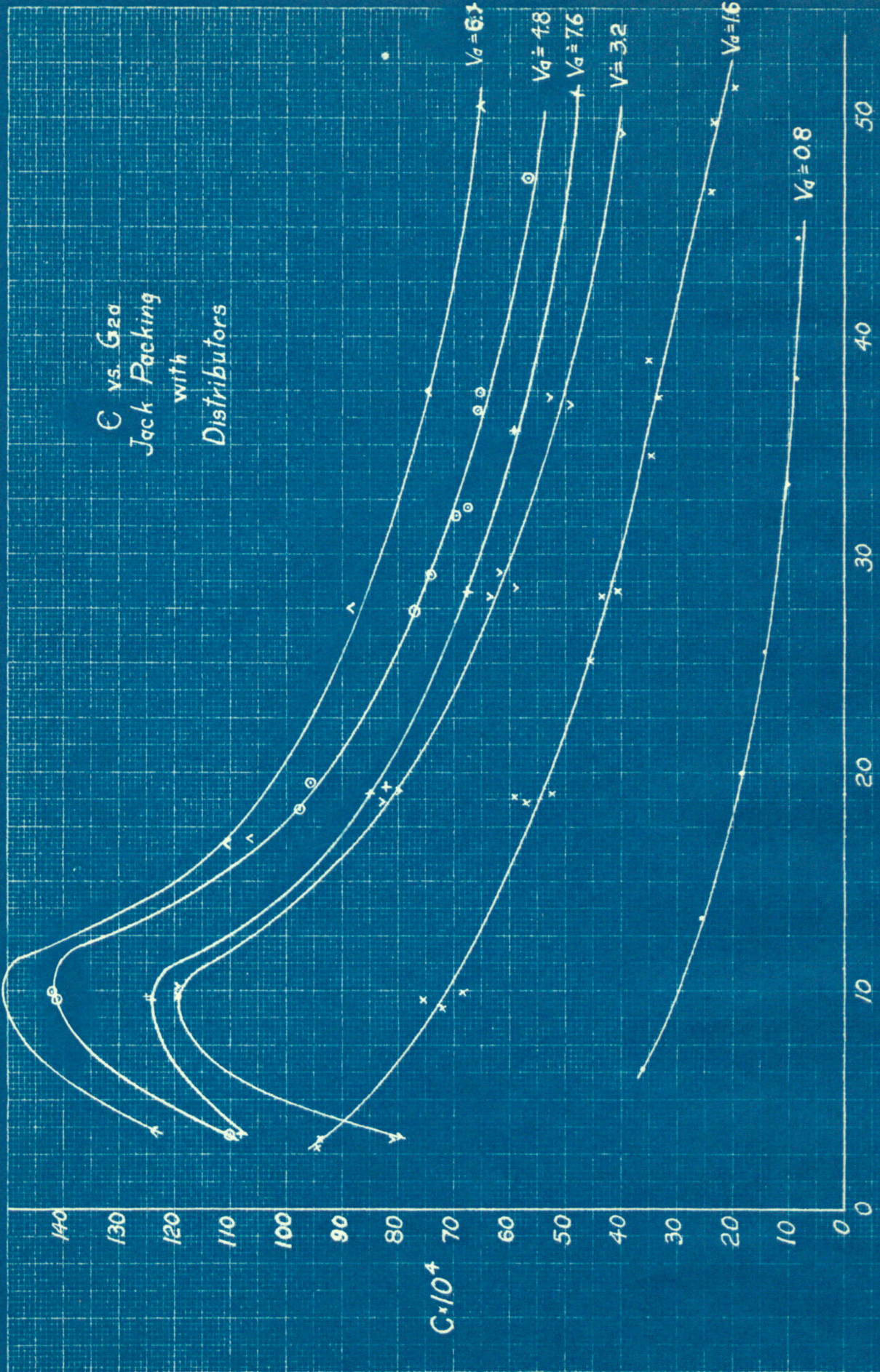
PRESSURE DROP vs. APPARENT GAS VELOCITY

Curves 6, 7, and 8 show pressure drop along the tower length plotted against gas velocity. White (43) found that the pressure drop in a tower is substantially independent of tower diameter if the ratio of tower diameter to packing diameter is six or more. (In the tower used with the Jack Packing this ratio was 8 to 1.) He defined the loading point of a column as the gas velocity at which, for a given liquid rate, the logarithmic pressure velocity curve first deviates from a slope of approximately two. He defined the flooding point as the gas velocity at which the same curve turns abruptly almost vertically upward. He stated that towers should operate just below the loading point and certainly below the flooding point.

In the curves shown the tower packed with Jacks with distributors shows a loading point at a gas velocity of 20 to 25 ft. per min. while the tower packed with Jacks without distributors has not reached the loading point at a gas velocity of 50 ft. per min. This is because in the former case there is more water on the packing and it is more evenly distributed thus cutting down the chances of channeling. In the Jack filled tower without distributors the water runs to the walls and most of it remains there thus depleting the supply on the packing. With less water on the packing there

is more free space and consequently less resistance to the gas flow. This condition was also noticed under tower hold-up when it was shown that the Jack filled tower with distributors held up more water than the Jack filled tower without distributors. Of course, the Net Packed tower with its large percentage of free volume is not near the loading point at the gas and liquid velocities attainable. The Jack filled tower with distributors should then according to White run most efficiently at a gas velocity somewhere below 2000 ft. per min. The Jack filled tower without distributors is uncertain but will probably run most efficiently somewhere below 50 ft. per min. (The pressure drop vs. gas velocity curves at the highest water velocities show signs of changing slope at about 50 ft. of gas per min.) The Net packed tower shows no sign of loading so it probably has not reached a point of maximum efficiency.

Note: All gas velocities plotted are apparent gas velocities i.e. $G_{2a} = \frac{G_2}{AF}$ and that all water velocities are apparent water velocities i.e. $V_a = \frac{V}{AF}$.



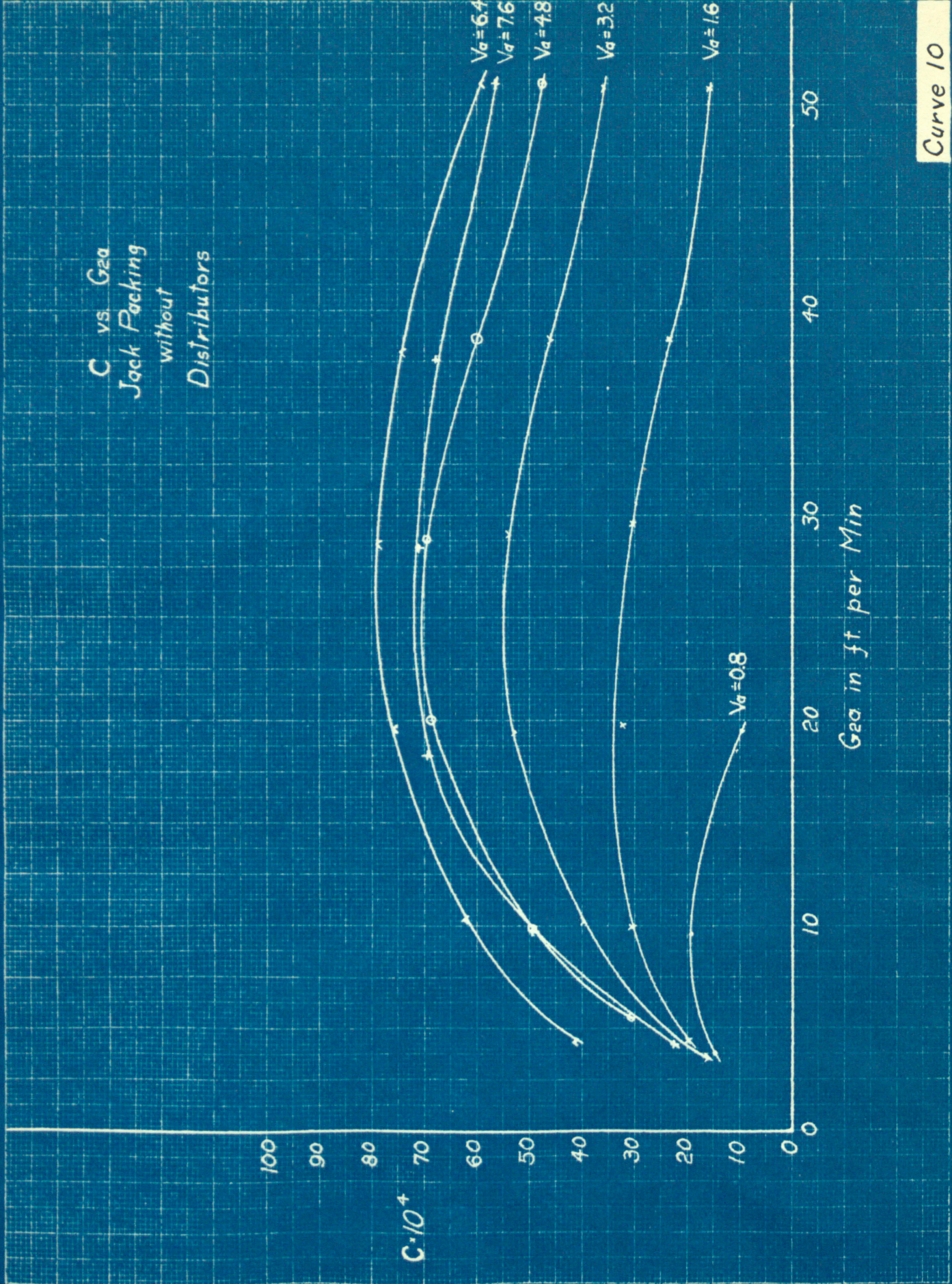
C vs. G_{2d}
Jack Packing
with
Distributors

$C \times 10^4$

G_{2d} in ft. per Min.

Curve 9

Curve 10



C vs G_{2a}
Jack Packing
without
Distributors

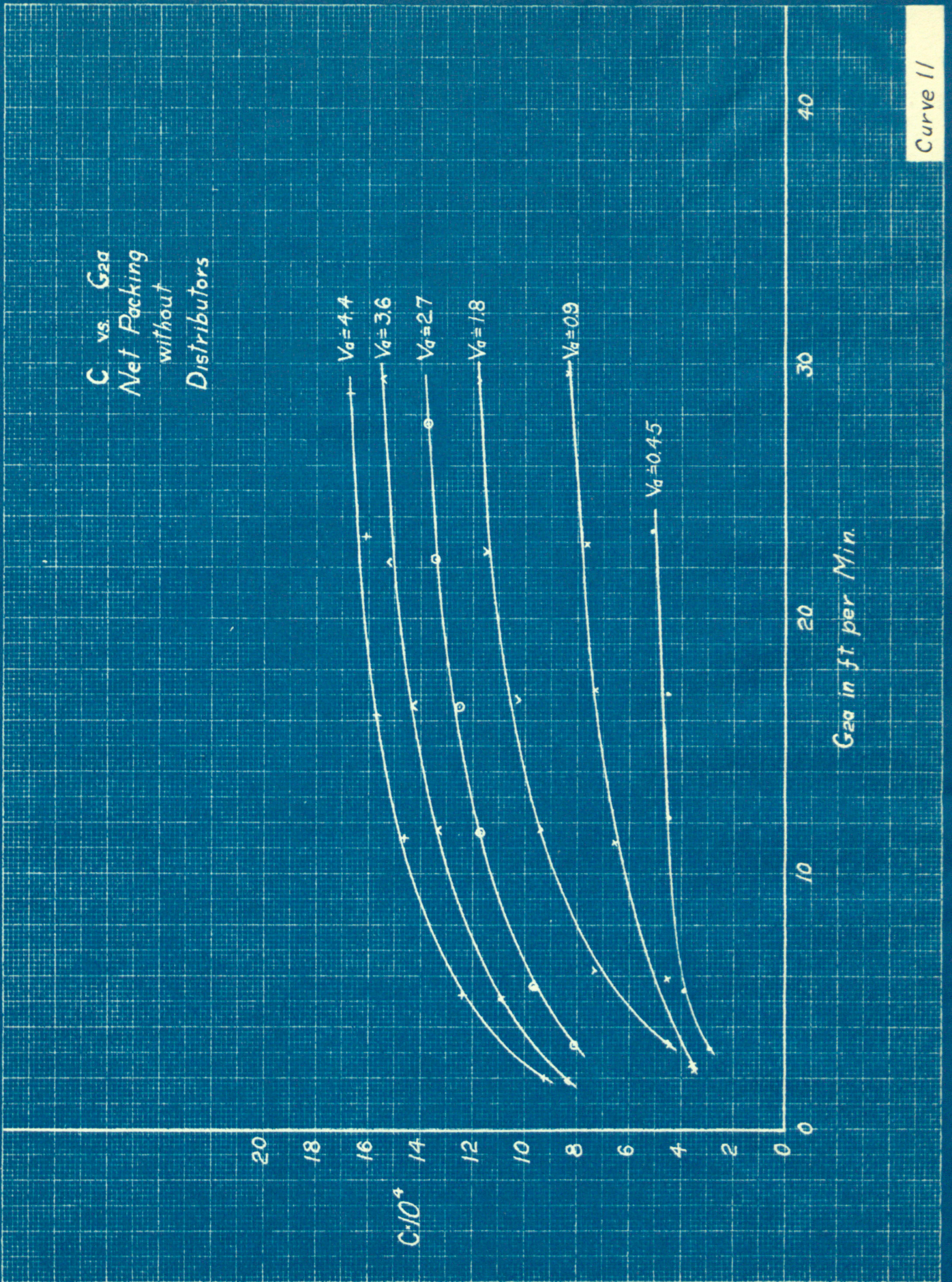
$C \cdot 10^4$

G_{2a} in ft. per Min

$V_d = 6.4$
 $V_d = 7.6$
 $V_d = 4.8$
 $V_d = 3.2$
 $V_d = 1.6$

$V_d = 0.8$

Millimeters, Jobb Lines Power
MADE IN U. S. A



Curve 11

ABSORPTION COEFFICIENT vs. APPARENT GAS VELOCITY

Curves 9, 10 and 11 show C (absorption coefficient) plotted against gas velocity. It may be seen that as the gas velocity increases there is an increase in C to a maximum and then a gradual decrease in C . In the case of the Jack filled tower with distributors this maximum occurs at a low gas velocity, i.e. 7 to 9 ft. per min. whereas in the Jack filled tower without distributors the maximum occurs at a gas velocity of about 22 to 28 ft. per min. The reason for the early maximum in the former case is that the distributors keep most of the water on the packing and there is thus a very intimate contact between gas and liquid. This would seem to indicate that towers using distributors should be of greater cross section and of lesser height than towers of the same volume not using distributors. The data indicates that for maximum efficiency the tower using distributors should be about 3 times the cross section and $1/3$ the height of a tower of the same volume operating without distributors. In other words the tower using distributors should have been about 18 inches in diameter and 3 feet high in order to handle the same volume of gas as the 10 inch diameter and 10 feet high tower operating without distributors. These dimensions are not meant to be quantitative but are given so that the reader may get an idea quantitatively of a qualitative generalization.

The Net packed tower (curve 11) shows no maximum HC_1 but the shape of the curves indicate that it is to be expected at a gas velocity of about 36 ft. per min. Qualitatively everything that was predicted in the discussion of pressure drop vs. gas velocity (curves 6, 7 and 8 has been borne out here. The Net Packing shows no sign of loading and no maximum C for the gas rate used. The Jack Packing with distributors shows a loading velocity of 7 to 9 ft. per min. The Jack Packing without distributors loads at a velocity of 50 ft. of gas per min. and has a maximum C at a gas velocity of 22 to 28 ft. per min.

The value of C was obtained from the general absorption equation (7) by substituting experimental values of c_1 , c_2 , Z , H , V , A , L and assuming $K=1$ and J constant.

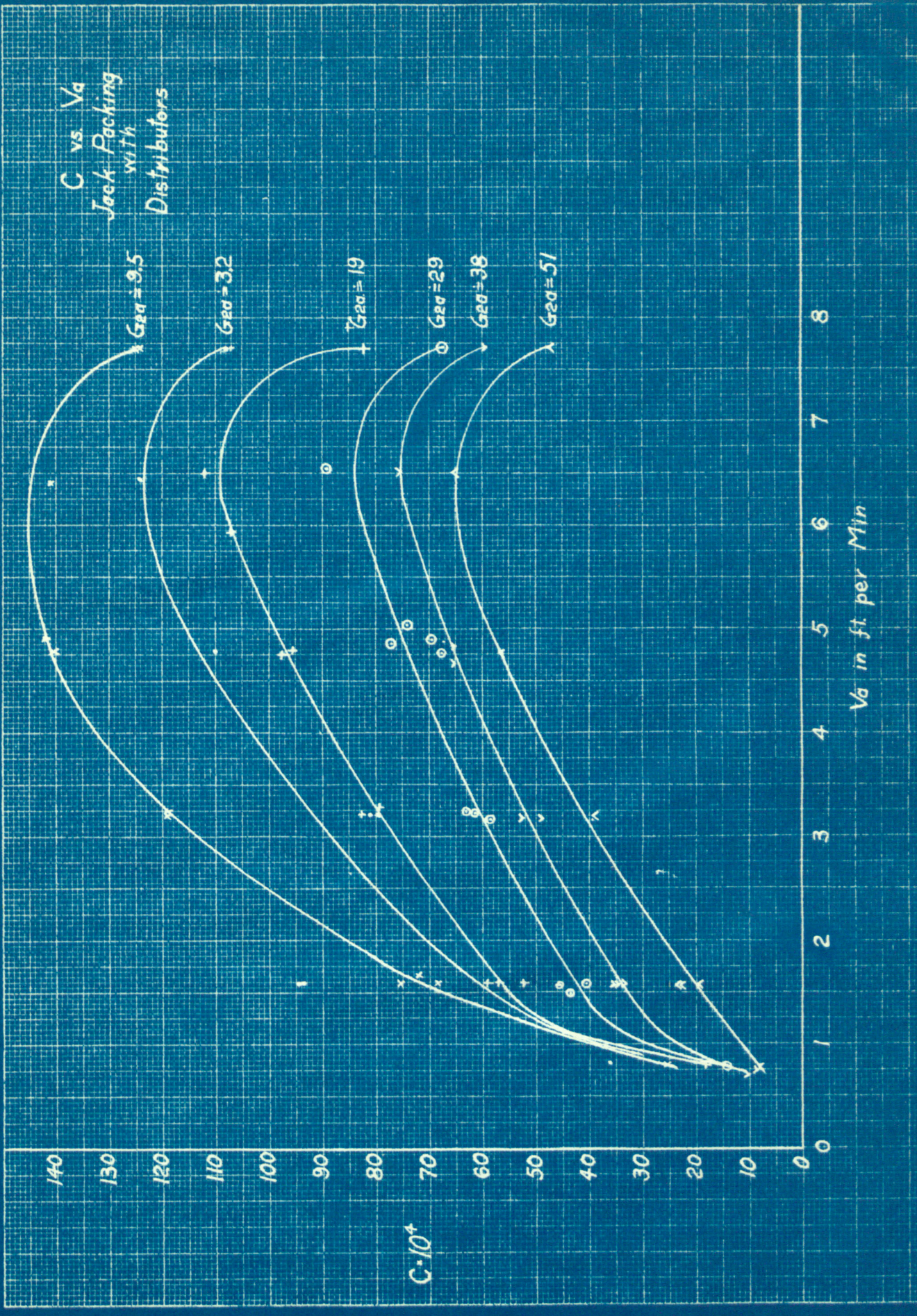
K , may be assumed equal to 1 because it is a constant depending on the type of system used. Since, throughout this work the system was carbon dioxide water the constant, K , will be assumed to be 1 and any variation will thus be thrown upon C .

J , is assumed constant and equal to the dry surface presented by the packing. This is not strictly true because with liquid flowing in turbulent flow over the packing the actual surface presented may be more or less than the dry surface. However, for a maximum operating value of C and Jack Packing the maximum amount of water hold-up by

the packing is 15% of the total volume of the tower. How much this will effect the transfer surface is not known and cannot be easily determined. As a first approximation then it will be assumed in this work that the transfer surface is constant and equal to the dry surface presented by the packing.

Curve 12

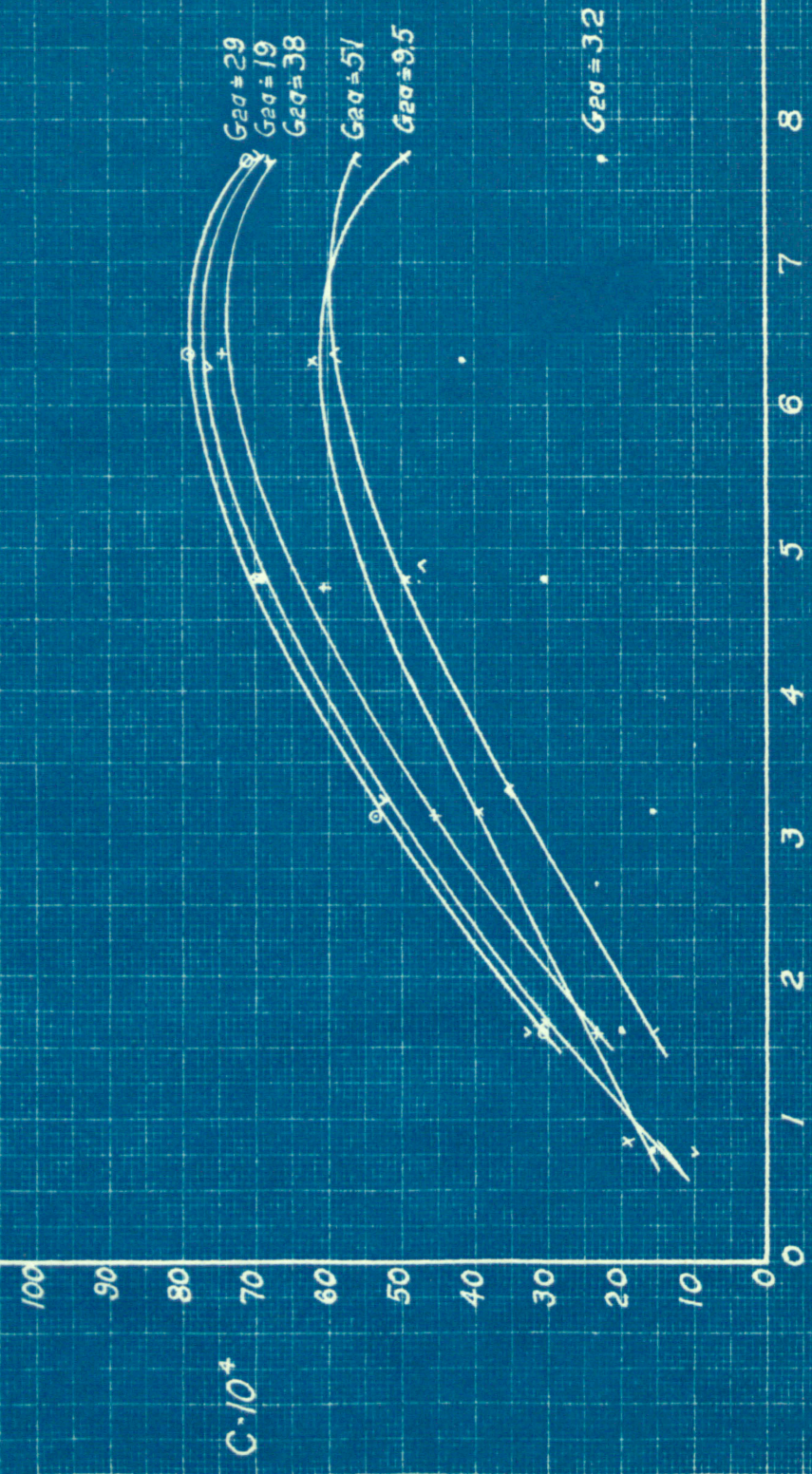
C vs. Va
Jack Packing
with
Distributors



Summers, Ithaca Inc. - heavy.

MADE IN U. S. A.

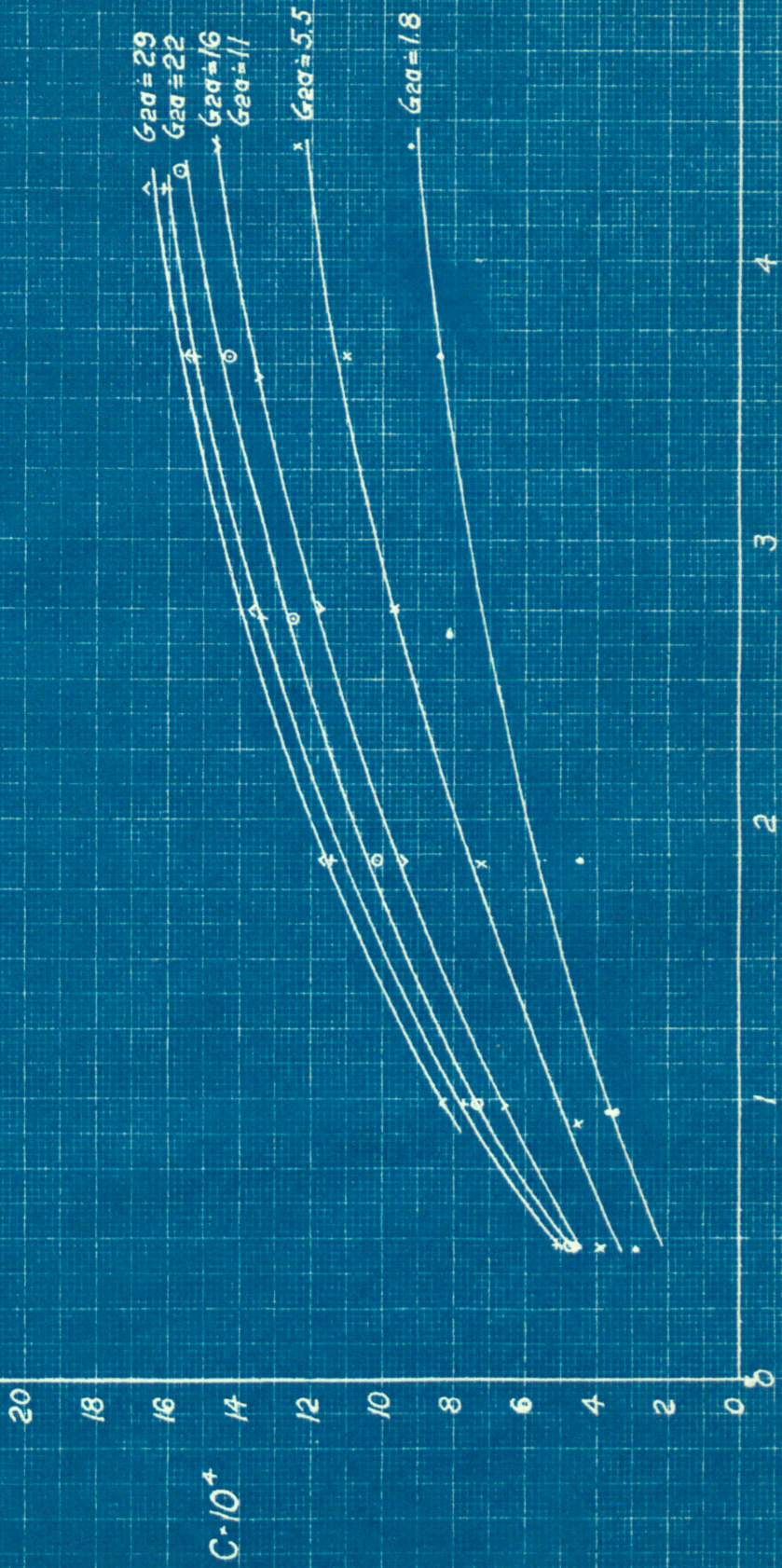
C vs. Va
Jack Racking
without
Distributors



Muller, Inc. 10000, 10000, 10000
MADE IN U.S.A.

WILMINGTON, DEL. PIPE-PLANT
MADE IN U.S.A.

*C vs. Va
Net Packing
without
Distributors*



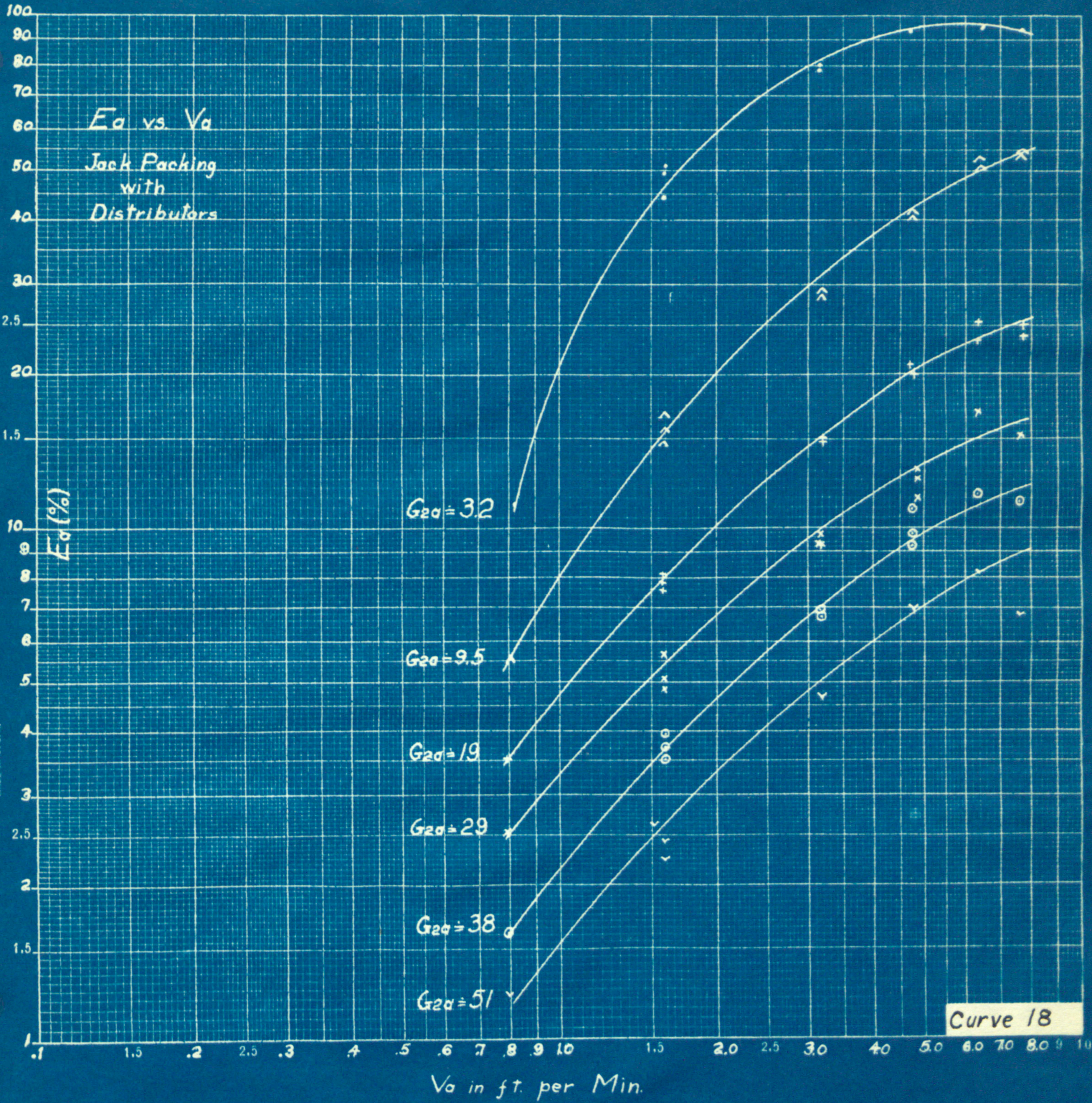
Curve 14

ABSORPTION COEFFICIENT vs. APPARENT LIQUID VELOCITY

Curves 12, 13, and 14 show C plotted against liquid velocity. The curves for Jack Packing with and without distributors show a maximum at a velocity of about 6 ft. of water per min. However, the data for low gas velocity on the Jack Packing without distributors is so scattered that no attempt was made to draw a curve through it. This irregularity is probably due to channeling of the gas since the same thing does not hold true with distributors where there is even liquid distribution and thus little chance for channeling. The Net Packing shows that absorption has not reached a maximum with the flow rates attainable but indications are that such a maximum may be reached at a liquid velocity of about 6 to 7 ft. per min. As may be seen, especially with the Jack Packing without distributors, the data for very low and very high liquid velocities is out of line with the rest of the data. This is because of channeling at the low liquid velocities and partial plugging at the high liquid velocities.

ABSORPTION EFFICIENCY vs. APPARENT RECIPROCAL GAS VELOCITY

Curves 15, 16 and 17 show the relationship between absorption efficiency and reciprocal gas velocity. It will be noted that in the case of Jack Packing with distributors and Net Packing the curves are approximately straight lines throughout the range studied, with absorption efficiency increasing with a decreasing gas velocity. In the case of Jack Packing without distributors where the liquid is not evenly distributed the curves are no longer straight lines and the efficiency is considerably less at lower gas velocities than where there is even distribution. This is due to channeling of the gas at low velocities. It will be noted also that where there is uneven distribution of the liquid phase the data for low liquid velocities is somewhat irregular.



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ABSORPTION EFFICIENCY vs. APPARENT LIQUID VELOCITY

Curves 18, 19 and 20 show the relationship between absorption efficiency and liquid velocity. In the two cases of Jack Packing, the efficiency reaches a maximum at a liquid velocity of approximately 10 ft. per min. The efficiency of the Net Packing did not reach a maximum but indications are that a maximum would have been reached at a liquid velocity of 8 to 10 ft. per min. also.

ABSORPTION EFFICIENCY vs. FLOW RATIOS

Curves 21, 22 and 23 show the relationship between absorption efficiency and ratio of liquid to gas velocity. These plots show that absorption efficiency is a function of V/G_2 up to tower plugging.

This function of absorption efficiency and V/G_2 is stated approximately as follows:

Jack Packing with distributors:

$$(IIa) \quad E_a = 76 \left(\frac{V}{G_2} \right)$$

Jack Packing without distributors:

$$(IIb) \quad E_a = 50 \left(\frac{V}{G_2} \right)^{0.88}$$

Net Packing without distributors:

$$(IIc) \quad E_a = 48 \left(\frac{V}{G_2} \right)^{0.81}$$

The values for $V_a = 7.7$ ft. per min. do not fall on the curves for either case of Jack Packing, because at this liquid velocity there is partial plugging of the tower. However, for Net Packing all points fall on the curve because the tower has not as yet approached plugged conditions.

SUMMARY

SUMMARY

Tower hold-up was investigated from very low liquid flows up to partial tower plugging. For all values of liquid flow the hold-up was found to be proportional to some power of the liquid velocity. Where the flow is turbulent, this power was found to be 0.57 to 0.58 and where viscous, 0.68. These values agree within 2% of the values found mathematically by Professor Tour for flow of fluids down an inclined plane. For Jacks and Raschig Rings, the flow was shown to be turbulent and for Net Packing, viscous.

Tower hold-up was found to be independent of gas velocity up to the loading point of the tower at which point the liquid began to be held back by the gas. After the loading point is reached hold-up increases greatly with increased gas rate.

For the same packing with and without distributors, the hold-up was found to be more with the distributors present because they kept the water from running down the walls in a sheet by putting it back on the packing at regular intervals.

A simple engineering equation for absorption was obtained from Garbers more complex equation making use of certain approximations and simplifications. The absorption coefficient, C , was calculated from the experimental data by means of this equation and the values of C plotted against gas and liquid velocities. Also values of absorption efficiency

were calculated and plotted against various functions of gas and liquid velocities.

The C curves indicated that there is a maximum gas and a maximum liquid velocity above which it is not feasible to operate. These values of gas and liquid velocity are dependent on the type of packing and the distribution of the liquid phase, other things being constant. The experiments show that when the liquid phase is evenly distributed the maximum HCF is obtained with a lesser value of gas velocity than when the liquid phase is unevenly distributed. This shows in a qualitative way that shorter towers of greater cross section may be used where the liquid phase is evenly distributed than where it is not.

Distributors were shown to have most effect at low gas and liquid velocities because it is here that channeling is most likely to occur. This may be seen by observing how erratic the data is for low gas and liquid flows without distributors. At higher flow rates distributors are not so essential because the packing begins to get flooded with liquid and the rapid gas flow keeps it well mixed and distributed fairly uniformly.

APPLICATIONS

APPLICATIONS

In designing a tower for industrial use certain information is usually known. This may be:

Case 1. The volume of gas to be handled per unit time and its inlet and outlet concentrations.

Case 2. The volume of gas to be handled per unit time and its initial concentration and the desired concentration of the exit liquid.

In case 1, the absorption efficiency is important and is specified by equation (8). $E_a = \frac{c_1 - c_2}{c_1(1 - c_2)}$ The most economical gas velocity will be found by referring to the curves of absorption coefficient vs. apparent gas velocity. The gas velocity at which the absorption coefficient is a maximum is the most economical gas velocity because a maximum absorption coefficient means a minimum volume of tower and thus minimum initial cost. The free cross-sectional area of the tower is given by dividing the total volume of gas to be handled per minute by the gas velocity obtained from the C vs. G_2a curves. The true cross section of the tower is then equal to this free cross sectional area divided by the fractional free volume of the packing. The diameter of the tower, in feet, will be given by:

$$(12) \quad D = 2 \sqrt{\frac{V}{\pi G_{2a} F}} = 1.13 \sqrt{\frac{V}{G_{2a} F}}$$

Where G_{2a} is the most economical gas velocity as obtained from the maximum of the C vs. G_{2a} curves.

The flow ratio will be found by reference to the E_a vs. Va/G_{2a} curves or empirical equations (11a), (b), or (c).

Jack Packing with Distributors

$$(11a) \quad E_a = 76 \left(\frac{V}{G_{2a}} \right)$$

Jack Packing without Distributors

$$(11b) \quad E_a = 50 \left(\frac{V}{G_{2a}} \right)^{0.88}$$

Net Packing without Distributors

$$(11c) \quad E_a = 48 \left(\frac{V}{G_{2a}} \right)^{0.81}$$

Knowing E_a the corresponding value of Va/G_{2a} can be found and since G_{2a} is known Va is readily calculated. The value of J , the surface presented by the dry packing per cubic foot, will usually be available from handbooks or may be easily approximated from the geometry of the packing. Also Henry's coefficient is usually found in handbooks. All the variables in equation (7), the general absorption equation, are now known except L , the length of tower, which may be solved for directly.

$$(7) \quad KCJ = \frac{HV}{2AL} \left[1 \pm \frac{1}{\sqrt{1 - \frac{4Z(1-C_2)}{Z+0^2}}} \right] \ln \left[\frac{C_2}{C_1(1-C_1) - Z(C_1-C_2)} \right]$$

In case 2, the saturation efficiency is important and is given by the ratio of the solute concentration desired in the exit liquid and the maximum theoretical exit liquid solute concentration.

The theoretical exit liquid solute concentration is merely the concentration of the liquid when saturated when the concentration of the solute in the vapor phase above the liquid is c_1 . Its value can be found in handbooks or can be computed from the value of Henry's coefficient for the solvent and solute.

The values of R_2/H and E_a can be found by solving equation (9) and empirical equation (11a), (b), or (c) simultaneously.

$$(9) \quad E_s = \frac{R_1}{H} E_a = \frac{1-c_2}{1-c_1} z E_a = \frac{c_1-c_2}{c_1(1-c_1)} z$$

Substituting the value of E_a in equation (8), gives the exit gas concentration directly.

The diameter of the tower is found as before by obtaining the most economical gas velocity from the C vs. G_{2a} curves and substituting this value in equation (12). The length of tower is found by means of equation (7) as before.

Similarly any problem of absorption tower design may be solved by means of equations (7), (8), (9), (12), and (11a), (b), or (c) depending upon the type of packing used.

The type of packing aside from distributional effects changes the design of a tower in two ways. It changes first the value of J , the dry packing surface per cubic foot of tower, and thus the total tower volume and second the value of the most economical gas velocity and thus the tower diameter.

The distributors increase the absorption coefficient greatly at low gas and liquid flows where there is a good chance of channeling but have very little effect at higher flow rates. Distributors also shift the value of the maximum C , and thus the most economical gas velocity is changed. Other things being the same distributors will cause the maximum C , to be shifted to a lower gas velocity and the diameter of the tower will thus be increased. This increased diameter will serve to decrease the length in order to keep the same tower volume and thus the same packing surface. However, it is more economical both from the standpoint of initial cost and of operating cost to build a short fat tower than a long thin one. The initial cost of a short tower is less than a long one because less wall material is used and because of its greater stability, ease of construction and the need of fewer supports. Also smaller blowers, pumps and other auxiliary equipment may be used because of the smaller overall pressure drops due both to

decreased lineal velocities and to decreased tower height. Also the liquid does not need to be pumped to as great a height. Operating costs are cut down also because of the smaller equipment used.

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APPENDIX

Tower Hold-Up Data

Jack packing with distributors. Temperature 68° F.

<u>Gas velocity</u> <u>ft./min.</u>	<u>Water velocity</u> <u>ft./min.</u>	<u>Hold-up</u> <u>cu.ft. water</u> <u>per cu.ft. packing</u>
3.12	0.623	0.0415
3.08	1.723	0.0803
3.05	3.250	0.113
3.02	4.550	0.133
2.92	5.435	0.146
3.05	7.850	0.172

10.95	0.604	0.0401
10.93	1.686	0.0803
10.93	3.190	0.112
10.97	4.650	0.135
10.81	5.955	0.155
10.75	8.430	0.181

21.8	0.540	0.0401
21.7	1.782	0.0820
21.6	3.240	0.113
21.5	4.692	0.135
21.7	5.940	0.155
21.6	8.010	0.184

Jack packing with distributors continued. Temperature 68° F.

<u>Gas velocity</u> <u>ft./min.</u>	<u>Water velocity</u> <u>ft./min.</u>	<u>Hold-up</u> <u>cu.ft. water</u> <u>per cu.ft. packing</u>
34.9	0.553	0.0415
34.9	1.693	0.0803
35.0	3.210	0.112
34.8	4.630	0.135
34.7	6.030	0.156
34.5	8.453	0.220

52.3	0.585	0.0401
52.3	1.810	0.0820
52.3	3.250	0.113
52.0	4.655	0.135
52.3	5.900	0.155
50.3	8.270	0.229

60.3	0.566	0.0415
60.4	1.739	0.0820
60.3	3.276	0.115
60.3	4.710	0.138
60.6	6.130	0.172
58.6	7.980	0.235

Jack packing without distributors. Temperature 68° F.

<u>Gas velocity</u> <u>ft./min.</u>	<u>Water velocity</u> <u>ft./min.</u>	<u>Hold-up</u> <u>cu.ft.water</u> <u>per cu.ft. packing</u>
2.74	0.598	0.0387
2.86	1.502	0.0629
2.93	3.180	0.100
2.99	4.720	0.119
2.99	6.070	0.142
3.02	7.960	0.156

9.79	0.610	0.0387
9.22	1.508	0.0645
9.15	3.200	0.100
8.39	4.730	0.120
8.26	6.300	0.144
8.26	7.85	0.161

21.6	0.626	0.0387
21.7	1.566	0.0645
21.7	3.220	0.102
21.7	4.720	0.119
21.7	6.100	0.142
21.5	8.030	0.166

Jack packing without distributors continued. Temperature 68° F.

<u>Gas velocity</u> <u>ft./min.</u>	<u>Water velocity</u> <u>ft./min.</u>	<u>Hold-up</u> <u>cu.ft. water</u> <u>per cu.ft. packing</u>
35.0	0.636	0.0386
34.8	1.598	0.0629
34.8	3.242	0.0992
34.3	4.860	0.119
34.8	6.320	0.143
34.8	7.890	0.175

52.2	0.637	0.0387
52.2	1.598	0.0645
52.4	3.200	0.100
52.5	4.740	0.120
53.0	6.380	0.143
51.5	7.730	0.179

60.4	0.605	0.0387
60.5	1.598	0.0645
60.0	3.260	0.0992
60.2	4.750	0.120
60.3	6.350	0.142
60.3	7.700	0.186

Net packing without distributors. Temperature 68° F.

<u>Gas velocity</u> <u>ft./min.</u>	<u>Water velocity</u> <u>ft./min.</u>	<u>Hold-up</u> <u>cu.ft. water</u> <u>per cu.ft. packing</u>
5.75	0.473	0.0244
5.28	0.910	0.0358
5.35	1.820	0.0575
5.90	2.780	0.0775
5.72	3.540	0.0919
5.13	4.900	0.126

11.0	0.474	0.0244
11.2	0.917	0.0346
11.4	1.840	0.0575
10.7	2.770	0.0775
10.6	3.478	0.0919
11.1	4.706	0.125

15.2	0.470	0.0244
16.7	0.915	0.0358
16.4	1.827	0.0575
16.9	2.700	0.0761
16.2	3.460	0.0919
16.3	4.890	0.125

Net packing without distributors continued. Temperature 68° F.

<u>Gas velocity</u> <u>ft./min.</u>	<u>Water velocity</u> <u>ft./min.</u>	<u>Hold-up</u> <u>cu.ft. water</u> <u>per cu.ft. packing</u>
22.9	0.477	0.0229
22.2	0.921	0.0358
23.4	1.841	0.0560
22.6	2.745	0.0761
22.2	3.440	0.0919
22.6	4.900	0.125

30.1	0.474	0.0229
28.7	0.921	0.0346
31.1	1.835	0.0575
30.1	2.680	0.0761
30.2	3.505	0.0919
29.4	4.900	0.125

39.5	0.474	0.0229
42.4	0.926	0.0346
42.8	1.838	0.0560
42.6	2.600	0.0761
41.3	3.538	0.0919
40.6	4.890	0.121

Data of Bradt and Rose (46), taken on 7'-7" of 10" pipe, using 1" Rashig Rings. Temperature 68° F.

<u>Gas velocity</u> <u>ft./min.</u>	<u>Water velocity</u> <u>ft./min.</u>	<u>Hold-up</u> <u>cu.ft. water</u> <u>per cu.ft. packing</u>
0.00	0.343	0.0190
0.00	0.557	0.0245
0.00	0.726	0.0285
0.00	0.888	0.0322
0.00	1.160	0.0388
0.00	1.331	0.0408
0.00	1.486	0.0435
0.00	1.613	0.0446
0.00	1.785	0.0475

7.35	0.370	0.0190
7.35	0.692	0.0278
7.35	0.770	0.0294
7.35	1.080	0.0360
7.35	1.453	0.0426
7.35	1.638	0.0464
7.35	1.764	0.0475
7.35	1.311	0.0388

7.37	0.982	0.0340
5.49	0.982	0.0340
10.9	0.982	0.0333

Jack Packing with distributors. Temperature 68°F

Run #	V_a	G_{2a}	$c_1(\%)$	$c_2(\%)$	ΔP	$1/G_{2a}$	V_a/G_{2a}	$Cx10^4$	$Ea(\%)$
A-1- 1	0.820	6.36	10.86	9.77	0.0009	0.1570	0.129	36.4	11.10
2	0.805	13.3	10.42	9.90	0.0007	0.0755	0.061	25.3	5.50
3	0.798	19.9	10.13	9.81	0.0013	0.0503	0.040	18.2	3.50
4	0.791	25.5	10.09	9.86	0.0016	0.0390	0.031	14.1	2.50
5	0.728	33.2	10.91	10.75	0.0022	0.0302	0.022	10.0	1.60
6	0.805	38.0	9.50	9.38	0.0029	0.0264	0.021	8.50	1.40
7	0.801	44.5	9.30	9.20	0.0042	0.0223	0.018	8.34	1.20

A-2- 1	1.583	3.15	11.95	7.02	0.0028	0.3180	0.501	93.8	44.40
2	1.572	9.83	11.75	10.20	0.0028	0.1020	0.160	68.8	14.70
3	1.655	19.0	9.43	8.74	0.0028	0.0525	0.087	52.1	8.00
4	1.563	25.2	9.15	8.68	0.0033	0.0396	0.062	45.5	5.60

Jack Packing with distributors continued. Temperature 68°F

Run #	V_a	G_{2a}	$c_1(\%)$	$c_2(\%)$	ΔP	$1/G_{2a}$	V_a/G_{2a}	$Cx10^4$	$E_a(\%)$
A-2-5	1.538	34.5	9.06	8.74	0.0033	0.0289	0.044	34.4	3.90
6	1.512	46.6	8.53	8.33	0.0084	0.0214	0.032	23.9	2.60
7	1.594	3.18	13.05	7.00	0.0037	0.3140	0.500	1	50.00
8	1.610	9.47	10.44	8.96	0.0028	0.1056	0.169	75.2	15.60
9	1.552	18.9	10.07	9.38	0.0037	0.0528	0.082	59.1	7.60
10	1.483	28.1	9.14	8.74	0.0042	0.0355	0.053	43.5	4.80
11	1.598	37.2	8.95	8.65	0.0065	0.0267	0.043	33.2	3.70
12	1.587	51.3	7.75	7.59	0.0079	0.0195	0.031	19.8	2.20
13	1.549	2.80	8.73	4.64	0.0014	0.3570	0.550	94.4	49.20
14	1.678	9.20	8.71	7.36	0.0017	0.1087	0.177	72.0	16.70
15	1.598	18.6	9.12	8.46	0.0023	0.0537	0.086	57.1	7.90

Jack Packing with distributors continued. Temperature 68°F.

Run#	V_a	G_{2a}	$C_1(\%)$	$C_2(\%)$	ΔP	$1/G_{2a}$	V_a/G_{2a}	$C \times 10^4$	$E_a(\%)$
A-2-16	1.598	28.2	8.92	8.51	0.0032	0.0352	0.057	40.5	5.00
17	1.587	38.9	8.95	8.66	0.0050	0.0258	0.041	35.0	3.50
18	1.570	49.8	9.02	8.82	0.0090	0.0201	0.032	23.3	2.40

A-3-1	3.179	3.12	9.85	2.31	0.0023	0.3210	1.020	80.4	78.30
2	3.165	3.21	8.52	2.14	0.0023	0.3110	0.985	79.5	76.60
3	3.180	9.71	8.91	6.47	0.0029	0.1030	0.328	119	29.30
4	3.260	10.1	8.81	6.44	0.0015	0.0988	0.322	119	28.70
5	3.170	18.6	8.88	7.66	0.0041	0.0537	0.170	82.5	14.90
6	3.280	19.1	9.41	8.13	0.0023	0.0527	0.172	79.5	14.80
7	3.158	28.4	8.20	7.51	0.0064	0.0352	0.111	58.6	9.10
8	3.230	28.0	8.36	7.62	0.0064	0.0358	0.116	63.0	9.60

Jack Packing with distributors continued. Temperature 68°F.

Run #	V_a	G_{2a}	$c_1(\%)$	$c_2(\%)$	ΔP	$1/G_{2a}$	V_a/G_{2a}	$Cx10^4$	$E_a(\%)$
A-3- 9	3.230	29.1	8.80	8.06	0.0050	0.0343	0.111	61.4	9.20
10	3.190	37.2	9.42	8.84	0.0115	0.0267	0.085	52.5	6.60
11	3.195	36.8	8.97	8.42	0.0082	0.0273	0.087	48.8	6.70
12	3.218	49.3	9.38	8.99	0.0212	0.0204	0.065	39.3	4.60

A-4- 1	4.775	3.34	9.35	0.61	0.0020	0.3000	1.300	110	94.00
2	4.773	9.60	9.83	5.98	0.0032	0.1040	0.497	141	41.70
3	4.900	9.95	11.24	6.97	0.0044	0.1000	0.492	142	40.80
4	4.722	18.3	9.17	7.41	0.0108	0.0547	0.253	97.5	20.70
5	4.820	19.5	10.50	8.59	0.0087	0.0513	0.248	95.6	19.90
6	4.855	27.3	9.46	8.33	0.0210	0.0368	0.178	77.0	13.00
7	4.885	31.7	8.15	7.29	0.0271	0.0314	0.154	69.7	11.40

Jack Packing with distributors continued. Temperature 68°F.

Run #	V_a	G_{2a}	$C_1(\%)$	$C_2(\%)$	ΔP	$1/G_{2a}$	V_a/G_{2a}	$C \times 10^4$	$E_a(\%)$
A-4- 8	5.055	29.0	9.28	8.18	0.0262	0.0346	0.174	74.0	12.90
9	4.760	32.1	8.73	7.85	0.0282	0.0311	0.149	67.5	10.90
10	4.820	36.6	9.39	8.57	0.0335	0.0273	0.132	65.2	9.60
11	4.652	37.3	8.86	8.11	0.0309	0.0267	0.125	65.2	9.20
12	4.750	47.2	9.37	8.78	0.0524	0.0210	0.100	56.7	6.90

A-5- 1	6.440	3.47	8.86	0.49	0.0055	0.2970	1.910	124	95.00
2	6.390	9.30	8.85	4.36	0.0172	0.1072	0.685	155	53.00
3	6.400	9.64	9.17	4.76	0.0145	0.1038	0.663	141	50.50
4	6.480	19.2	9.31	7.11	0.0329	0.0522	0.338	111	25.40
5	5.920	19.4	10.38	8.15	0.0180	0.0512	0.304	107	23.40
6	6.530	27.5	8.82	7.45	0.0495	0.0365	0.237	89.0	16.80

Jack Packing with distributors continued. Temperature 68°F.

Run #	V_a	G_{2a}	$c_1(\%)$	$c_2(\%)$	ΔP	$1/G_{2a}$	V_a/G_{2a}	$C \times 10^4$	$E_a(\%)$
A-5-7	6.510	37.4	7.90	7.05	0.0860	0.0267	0.174	75.1	11.60
8	6.520	50.5	9.36	8.67	0.1540	0.0198	0.129	65.7	8.10

A-6-1	7.690	3.31	6.52	0.40	0.0180	0.3020	2.320	108	94.20
2	7.700	9.60	8.80	4.18	0.0355	0.1040	0.802	124	54.80
3	7.780	9.66	10.50	5.08	0.0325	0.1050	0.800	125	54.40
4	7.690	19.3	8.70	6.75	0.0582	0.0519	0.397	82.0	24.00
5	7.900	19.0	9.84	7.58	0.0640	0.0525	0.415	85.0	24.90
6	7.700	28.2	8.79	7.56	0.0990	0.0355	0.275	67.5	15.10
7	7.695	35.6	8.18	7.33	0.1810	0.0280	0.216	59.1	11.20
8	7.695	51.0	8.95	8.40	0.4360	0.0195	0.151	47.6	6.70

Jack Packing without distributors. Temperature 68°F.

Run #	V_a	G_{2a}	$c_1(\%)$	$c_2(\%)$	ΔP	$1/G_{2a}$	V_a/G_{2a}	$C \times 10^4$	$E_a(\%)$
B-1- 1	0.783	3.82	6.15	5.18	0.0006	0.2620	0.205	14.8	16.60
2	0.846	9.61	7.01	6.50	0.0012	0.1040	0.088	19.3	7.80
3	0.770	19.4	9.21	8.97	0.0018	0.0513	0.040	9.8	2.90
4	0.840	28.9	9.29	9.02	0.0022	0.0346	0.029	1	3.20
5	0.742	29.5	8.65	8.42	0.0027	0.0251	0.019	1	2.90
6	0.830	51.9	9.60	9.36	0.0038	0.0192	0.016	1	2.80

B-2- 1	1.620	4.33	6.68	5.12	0.0017	0.2310	0.374	20.0	24.60
2	1.667	9.93	8.75	7.66	0.0029	0.1005	0.168	30.6	13.50
3	1.610	19.7	8.22	7.70	0.0035	0.0506	0.082	32.3	6.90
4	1.618	29.6	8.64	8.28	0.0041	0.0336	0.055	30.4	4.60
5	1.600	38.6	9.43	9.16	0.0047	0.0258	0.041	23.2	3.20
6	1.602	50.7	9.38	9.21	0.0058	0.0198	0.031	15.9	2.00

Jack Packing without distributors continued. Temperature 68°F.

Run #	V_a	G_{2a}	$c_1(\%)$	$c_2(\%)$	ΔP	$1/G_{2a}$	V_a/G_{2a}	$C \times 10^4$	$E_a(\%)$
B-3-1	3.160	3.59	5.95	3.93	0.0029	0.2780	0.882	15.9	35.40
2	3.180	10.2	7.30	5.86	0.0046	0.0982	0.313	39.7	21.00
3	3.230	19.4	7.01	6.16	0.0070	0.0515	0.166	52.4	12.90
4	3.125	29.0	8.74	8.05	0.0087	0.0346	0.108	53.8	8.60
5	3.141	38.6	8.90	8.40	0.0099	0.0258	0.081	45.6	6.10
6	3.285	50.7	9.82	9.44	0.0119	0.0198	0.065	35.6	4.30

B-4-1	4.770	5.63	7.00	4.40	0.0006	0.1775	0.848	30.2	38.90
2	4.775	9.86	8.96	6.60	0.0012	0.1010	0.485	49.4	28.20
3	4.715	20.0	8.74	7.34	0.0018	0.0500	0.239	68.7	17.30
4	4.770	28.8	9.44	8.38	0.0022	0.0346	0.165	69.7	12.30
5	4.735	38.5	8.95	8.24	0.0027	0.0258	0.122	60.3	8.70
6	4.860	51.0	9.35	8.85	0.0038	0.0195	0.095	47.5	5.90

Jack Packing without distributors continued. Temperature 68°F.

Run #	V_a	G_{2a}	$C_1(\%)$	$C_2(\%)$	ΔP	$1/G_{2a}$	V_a/G_{2a}	$CX10^4$	$E_a(\%)$
B-5-1	6.310	4.61	7.22	3.98	0.0102	0.2170	1.370	41.8	46.70
2	6.318	10.3	8.15	5.50	0.0175	0.0970	0.615	62.1	34.40
3	6.260	19.6	8.24	6.62	0.0262	0.0510	0.319	76.0	21.10
4	6.350	28.6	8.33	7.16	0.0350	0.0349	0.222	79.0	15.10
5	6.350	37.9	8.70	7.80	0.0495	0.0264	0.168	74.3	11.20
6	6.345	51.0	8.62	8.03	0.0640	0.0195	0.124	59.4	7.50

B-6-1	7.710	4.10	10.72	4.13	0.0163	0.2440	1.880	22.4	64.10
2	7.735	9.80	8.76	5.90	0.0265	0.1020	0.790	49.5	34.70
3	7.720	18.2	8.55	6.72	0.0451	0.0547	0.413	69.5	23.00
4	7.690	28.4	8.48	7.26	0.0600	0.0352	0.271	71.0	15.50
5	7.680	37.7	8.78	7.85	0.0670	0.0264	0.203	67.7	11.50
6	7.708	51.0	9.02	8.39	0.0858	0.0195	0.151	56.5	7.60

Net Packing without distributors. Temperature 68°F.

Run #	V_a	G_{2a}	$C_1(\%)$	$C_2(\%)$	ΔP	$1/G_{2a}$	V/G_{2a}	$C \times 10^4$	$E_a(\%)$
C-1-1	0.452	3.10	3.65	3.24	0.00015	0.3230	0.146	2.96	11.20
2	0.454	5.43	5.75	5.35	0.00029	0.1870	0.085	3.95	7.40
3	0.452	12.2	7.53	7.30	0.00029	0.0819	0.037	4.50	3.30
4	0.452	17.0	8.28	8.10	0.00029	0.0588	0.027	4.54	2.40
5	0.454	23.4	8.04	7.91	0.00044	0.0428	0.019	5.12	1.80
6	0.452	29.4	9.17	9.04	0.00044	0.0340	0.015	1	1.60

C-2-1	0.942	2.31	7.46	5.85	0.00015	0.4320	0.407	3.47	22.90
2	0.920	2.46	7.14	5.66	0.00015	0.4070	0.374	3.61	22.00
3	0.867	5.86	7.64	6.88	0.00029	0.1700	0.148	4.57	10.70
4	0.920	11.2	7.88	7.39	0.00044	0.0890	0.082	6.55	6.70
5	0.914	17.2	8.19	7.85	0.00058	0.0582	0.053	7.35	4.50
6	0.916	22.9	7.55	7.31	0.00073	0.0434	0.040	7.63	3.40
7	0.932	29.6	8.72	8.50	0.00073	0.0340	0.032	8.35	2.80

Net Packing without distributors continued. Temperature 68°F.

Run #	V_a	G_{2a}	$c_1(\%)$	$c_2(\%)$	ΔP	$1/G_{2a}$	V/G_{2a}	$C \times 10^4$	$E_a(\%)$
C-3- 1	1.841	3.30	8.05	5.91	0.00029	0.3040	0.560	4.47	28.20
2	1.838	6.21	7.67	6.40	0.00058	0.1610	0.295	7.29	17.70
3	1.810	11.7	6.79	6.25	0.00087	0.0851	0.154	9.35	11.00
4	1.843	16.8	8.40	7.77	0.00116	0.0593	0.110	10.2	8.10
5	1.760	22.6	8.45	7.97	0.00145	0.0445	0.078	11.4	6.20
6	1.798	29.3	9.24	8.83	0.00175	0.0340	0.061	11.7	4.90

C-4- 1	2.670	3.29	8.36	5.17	0.00044	0.3040	0.811	8.05	40.20
2	2.735	5.61	8.34	6.30	0.00073	0.1780	0.488	9.66	26.10
3	2.740	11.6	8.49	7.32	0.00102	0.0862	0.236	11.7	14.90
4	2.712	16.5	8.82	7.92	0.00116	0.0605	0.165	12.5	11.10
5	2.730	22.3	8.79	8.10	0.00160	0.0450	0.122	13.4	8.60
6	2.730	27.6	9.19	8.60	0.00190	0.0363	0.099	13.7	7.90

Net Packing without distributors continued. Temperature 680F.

Run #	V_a	G_{2a}	$\frac{C_1(\%)}{C_2(\%)}$	ΔP	$\frac{1}{G_{2a}}$	$\frac{V}{G_{2a}}$	$C \times 10^4$	$\frac{E_a(\%)}{E_b(\%)}$	
C-5-1	3.640	1.81	8.51	3.24	0.00044	0.5570	2.030	8.42	64.00
2	3.640	5.03	7.30	4.85	0.00087	0.1980	0.725	11.0	35.30
3	3.580	11.7	7.98	6.65	0.00130	0.0855	0.307	13.4	17.80
4	3.605	16.6	8.62	7.57	0.00175	0.0598	0.216	14.3	13.20
5	3.620	22.2	8.50	7.68	0.00218	0.0450	0.163	15.3	10.40
6	3.600	29.4	9.33	8.65	0.00262	0.0341	0.123	15.5	8.00

C-6-1	4.405	2.11	8.42	3.20	0.00058	0.4740	2.090	9.25	64.00
2	4.430	5.26	7.39	4.46	0.00102	0.1900	0.842	12.4	41.50
3	4.380	11.4	7.85	6.36	0.00204	0.0873	0.383	14.6	20.30
4	4.330	16.2	8.71	7.48	0.00276	0.0615	0.268	15.7	15.30
5	4.240	23.2	8.22	7.38	0.00349	0.0428	0.183	16.1	11.00
6	4.290	28.8	9.32	8.54	0.00436	0.0346	0.149	16.7	9.20

Data on Rashig Rings from Thesis by Bradt and Rose (46). Taken on 7'-7" of 10" pipe

Temperature 68°F.

<u>Run #</u>	<u>Va</u>	<u>G2a</u>	<u>c1(%)</u>	<u>c2(%)</u>	<u>ΔP</u>	<u>l/G2a</u>	<u>V/G2a</u>	<u>cx10⁴</u>	<u>Ea(%)</u>
D-1- 1	7.35	8.94	8.1	6.7	0.0007	0.112	0.822	34.5	18.60
2	7.35	7.77	8.4	7.3	0.0007	0.129	0.947	21.4	14.10
3	7.35	1.96	10.5	6.4	0.0007	0.510	3.750	7.25	41.60
4	7.35	3.26	11.0	7.9	0.0007	0.307	2.253	2.93	30.60
5	7.35	5.00	9.7	7.9	0.0007	0.200	1.470	-5.35	20.10
6	7.35	6.30	9.4	8.0	0.0007	0.159	1.166	-10.5	16.20
7	7.35	10.4	10.2	9.2	0.0007	0.096	0.704	30.2	10.80
8	7.35	15.9	9.9	9.4	0.0007	0.063	0.461	25.5	5.60
9	7.35	13.2	9.0	8.7	0.0007	0.076	0.558	19.3	3.70
10	7.35	13.3	10.3	9.6	0.0007	0.075	0.552	27.8	7.50

D-2- 1	7.31	1.56	10.7	4.6	0.0007	0.640	4.670	4.14	59.80
2	7.31	1.21	11.0	3.6	0.0007	0.826	6.040	14.5	69.80
3	7.31	0.858	10.6	1.8	0.0007	1.160	8.510	18.1	84.50
4	7.31	0.647	10.5	0.9	0.0007	1.546	11.350	21.4	92.20
5	7.31	0.211	10.0	0.2	0.0007	4.740	34.620	9.83	98.20