# THESIS

submitted to the Faculties of the
College of Engineering
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Graduate School
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by
George Lewis Tuve
Candidate for the Degree
of
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# INTRODUCTORY

This thesis and the investigation which it reports, have been made possible by virtue of a co-operative arrangement between the University of Minnesota, College of Engineering and the Mahr Manufacturing Company of Minneapolis. This work was done largely in the laboratories and shops of the Company under the supervision of Mr. W. E. Johnston, Chief Engineer of the Company, the work being reviewed periodically by Professors J. J. Flather and C. F. Shoop of the Mechanical Engineering Department of the University. From their wide experience all three of these men gave much valuable assistance and many suggestions both as to methods of procedure and interpretation of results, for which I wish to express my thanks. A great many discussions with Mr. Johnston and lessons from his large engineering experience in the field have been invaluable in arriving at an understanding of many of the problems encountered.

The work outlined herein was begun at the Company's plant early in the Summer of 1920. Soon after attacking the problems, it was realized that the work could be made much more effective if by some means the instructional, laboratory, and library facilities of the University could be added to those of the Company.

In an interview with Professor Flather, Head of the Department of Mechanical Engineering at the University, he stated that co-operation in initiating industrial research of the right kind was coming to be recognized as a proper function of Engineering Colleges. I wish to take this opportunity to thank him, as the representative of the University, and Mr. Warner and Mr. Johnston, as officials of the Company, for their efforts by which such co-operation was made possible in this case. It is hoped that all parties concerned, including the Company, and in a less direct way the University, will profit by the arrangement.

# PURPOSE

It is the object of this thesis to present the results of original investigation on the problems which are being met in the development of a line of compressed air atomizing oil burners. Although, as the title indicates, the investigation covers the "burners" in particular, it is not possible, nor would it be desirable, to leave out of consideration the problems of the application of these burners to combustion chambers and heating chambers because many of the "operating characteristics" depend to a greater extent upon the application than upon the design of the burners. The whole problem is therefore taken up in a general way, but most of the detailed matter presented refers to the problems of burner design.

Early in the year it was the intention of the writer to incorporate into this thesis only the results of the investigation on Vacuum Burners. However, the problem of designing and applying burners, the size of which ranged from one pint to twelve gallons per hour oil consumption, to secure the highest efficiency in each case, involved the accurate measurement of compressed air consumption. The orifice was selected as the most practical means of measurement, but unexpected difficulties made necessary a rather extended study of the problem of their calibration. It was intended at one time to use this investigation as a subject for this thesis.

On the advice of Professor Flather, however, it was decided to report on both subjects and an outline was prepared for such a report which included such material as was necessary to connect the two subjects and show their relation to the general problem. Finally, Mr. Johnston suggested that this thesis could be made much more valuable by making it as complete a report as possible on all the problems which have been met by the writer in the development of these oil burners. All the material at hand has therefore been drawn upon, with a special effort to substantiate conclusions by illustrations in the form of experimental facts.

# STATUS OF OIL BURNING EQUIPMENT.

The general adoption of oil fuel, even for those purposes for which it is vastly superior to other fuels, is coming much more slowly than its advantages would seem to justify. Among the reasons for this state of affairs, there are two which are the most outstanding.

The infancy of the oil burner was marked by the pan or drip burners, the "oozing" burner and various gas generating burners. But when the spray or atomizing burner was invented its advantages over the earlier unsatisfactory devices were quickly realized and many modifications of the original burners of Aydon and Spakovsky (1865) were soon in use. Some knowledge of the principles of operation of the atomizing burner became common property and a large number of "home-made" burners were constructed and used. These devices were fairly satisfactory for the simpler heating processes and with the higher grades of fuel. But when such exacting heat requirements as for instance those of the modern steel heat-treating process had to be met, and as the heavier grades of fuel took the place of the lighter grades, such home-made appliances were no longer satisfactory. Instead, there was required a complete heating unit whose design embodied a most careful study and application of the principles both of efficient combustion and of proper heat application.

The "home-made" or "home-assembled" appliances continued to multiply however, to the detriment rather than the encouragement of the general adoption of oil fuel.

In addition to this state of affairs, and intensified by it, stands men's natural prejudice toward innovations. There is a certain inertia which makes men reluctant to substitute new methods and new equipment for those which they have taken as a matter of course ever since they "learned their trade". The~~re~~ir state of mind also makes them quick to draw unfavorable conclusions from single instances or from scant reports of some trial of the innovation even though it may be apparent to an impartial observer that the trial favored the older method or was unsuccessful because of lack of knowledge concerning the new method or appliance.

It is the purpose of this study to outline and discuss the problems which must be solved in the design of satisfactory oil-burning equipment, and to consider in detail some of the methods of attacking these problems.

# OUTLINE AND INDEX

All the material presented in this Thesis is, for clearness of presentation and convenience of reference, arranged in outline form. A summary is given below, with the page numbers referring to the later detailed treatment.

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The extent of satisfaction which is obtained from the service of oil burning equipment of any kind depends, next to intelligent operation, on what may be called the "operating characteristics" of the equipment.

The important operating characteristics are four, and their discussion in these studies is carried out in accordance with the following outline:

I. CONVENIENCE OF HEAT APPLICATION

Consideration of the details of design making for convenience in applying the heat to the work:

1. By torches (page 1)
    - a. Easy control of the flame (p.2)
    - b. Lightness (p.3)
    - c. Portability (p.3)
    - d. Correct capacity (p.3)
2. By forges and furnaces (p.4)

## OUTLINE AND INDEX Page 2.

## OUTLINE AND INDEX Page 3.

# STUDIES IN IMPROVING THE OPERATING CHARACTERISTICS OF OIL BURNERS.

There are several general classes of burners, each of which offers many problems in the improvement of operating characteristics which are peculiar to itself. We shall limit our consideration to those burners which are of the atomizing type and which use high pressure air for atomization. All subsequent material should be studied with this type of burner in mind.

## I. CONVENIENCE OF HEAT APPLICATION:

In order to make the application of heat to the work as convenient an operation as possible, oil burning heating equipment is made in many different forms. We shall divide these into two classes:

### 1. By torches:

Under the classification of "torches" are included the portable burners such as are in common use for various bending jobs, especially in boiler shops and in steel car repairing, for preheating preparatory to welding, for drying molds, lighting cupolas, etc., in the foundry, for thawing, for paint-burning, and for any other work where it is most convenient to take the heat to the work. The most important considerations in securing convenience in the use of torches are:

a. Easy control of the flame:

The correctly designed compressed air torch will light instantly and stay lit, producing a steady, reliable flame which can be controlled with ease by the operator. The valves should if possible be so located and of such a form as to be under the hand of the operator when he is holding the torch in an easy, natural position. The expanding, mixing, and combustion nozzles should be so proportioned that the torch has a reasonable range of capacity, but the maximum amount of compressed air supplied, with valve wide open, should not be so much as to increase the velocity of the mixture at the nozzle outlet beyond the velocity of propagation of any flame which it is desired to maintain. In order to direct the flame of a torch and sometimes to change the shape or size of the area which the flame will cover, it is necessary to attach different forms of combustion nozzles. The means of attachment of these nozzles should be of such design that the nozzles can be changed readily, without the use of special tools.

b. Lightness:

Lightness is a prime consideration in almost every kind of torch. Especially in the case of the larger torches is it advisable to spend considerable time and effort in perfecting the design so that the torch will be light and easy to handle.

c. Portability:

The first reason for a torch is its portability, and in the design of the entire outfit this should be kept in mind. Among the details that are of assistance in the case of the larger capacity torches, (say 3 to 12 gallons per hour, oil burning capacity), might be mentioned: tank mounted on large, roller bearing wheels; brackets for carrying torch on tank; brackets for carrying extra combustion nozzles on tank.

d. Correct capacity:

This is largely a matter of selection from some line of torches which are made in several sizes. In the design of such a line of torches however, care must be taken to keep the matter of proportions in mind throughout, especially as regards the dimensions of the combustion nozzle and their relation to the dimensions of the expanding nozzle as these relations have an important bearing on the "efficiency of air consumption" (which see, below).

2. By forges and furnaces:

The name "Forge" applies to a more or less open fire in a stationary combustion chamber, while the name "furnace" is generally used to designate a heating appliance which has, in addition to the combustion chamber, a refractory heating chamber within which the work is placed, the same generally being closed by a door, although "open front" furnaces are used for certain work, especially for forging.

Many of the considerations treated below under "heat control", "reliability", and "economy", are of prime importance in the convenient application of heat in furnace and forge work. In addition to these, ease of handling the charge and comfort for the operator are of first importance. However, convenience in handling the furnace charge is not a part of the problem of improving the operating characteristics of oil burners, but is a comprehensive engineering problem in itself and one which requires a knowledge not only of the heating problem, but of the entire manufacturing process of which it is a part. Comfort for the operator is also more a problem for the designer of the furnace or forge, than one which should be considered in a study of the design and application of oil burners.

## II. HEAT OR FLAME CONTROL:

The problem of heat or flame control consists in so designing the equipment that it will: (1) Produce the flame best suited to the work, and will (2) Maintain that best flame under the varying conditions of operation.

### 1. Production of the flame best suited to the work:

There are three main factors which are to be considered regarding the character of the flame:

a. The quantity of heat generated:

and

b. The temperature or intensity of the heat:

The size and design of the combustion and heating chambers and the capacity of the burners are of course determined with a view to giving the correct quantity and intensity of heat for the installation. However, the quantity and intensity of <u>useful</u> heat that can be produced by a given installation is also dependent upon how finely the oil is atomized, upon the proportions and the intimacy with which the air and oil are mixed near the burner, and upon the temperature of the mixture. These factors have a decided effect upon the speed of propagation of the flame. The more intimately the air and oil are mixed, the higher will be the flame temperature produced because combustion takes place more rapidly and earlier in the flame travel.

The obtaining of a finely atomized spray, thoroughly mixed with the proper amount of air depends largely on the kind of nozzle in which the air and oil come into contact with each other. An important consideration in the design of this expanding and mixing nozzle is the use of the injector principle for inducing the supply of atmospheric air. In so far as it is consistent with the satisfactory performance of its other functions, the nozzle should be designed to transform as much as possible of the pressure head of the air into velocity head, with the accompaniment of over-expansion. This over-expansion or creation of a vacuum in the jet aids materially in mixing with the atomized oil a proper amount of free air for combustion. It is therefore a factor in the character of flame produced, but its effect is also evident in connection with the study of efficiency of compressed air consumption, under which head it is treated below. (See IV).

c. Establishing the correct atmosphere for the work, whether it be reducing, neutral, or oxidizing, is largely a problem of the proportions of air and oil. However if a flame, or more accurately, the products of combustion, are to be uniformly reducing, neutral, or oxidizing, they must be produced by the combustion of a strictly uniform mixture.

2. Control of the flame:

a. The requirements:

(1) Varying the capacity, or heat output. The heating operations for which any given piece of equipment are used may require varying amounts or intensities of heat, and such changes of heat output of the burner or burners are accomplished by corresponding changes in the quantity of compressed air and of oil supplied to them. Of course the extent of variation which is obtainable, or in other words the "range of capacity", will vary with different installations according to their design.

(2) Maintaining the proper heating conditions in spite of fluctuations in the pressure of the air supplied for atomization. The quantity of air discharged from a nozzle is a function of the supply pressure. (See IV below, for measurement of air consumption.) When, therefore, as often happens in small installations, the supply pressure falls for a short time, due to an overload on the air lines, some manner of control must reduce the oil supply to the burners in proportion to the reduced air supply. Serious damage to the work may otherwise result, because the atmosphere in the

flame is changed. This is especially injurious when the pressure increases and the excess air produces a highly oxidizing atmosphere.

b.Meeting these requirements:

(1) Manual regulation: Most of the compressed air atomizing burners carry pressure on the oil, so that to decrease the amount of heat supplied it is necessary to reduce the air supply by turning down an air valve, and then close down the oil valve to effect a corresponding reduction in oil supply. Similarly, the oil valves must be manually regulated when the air supply pressure fluctuates.

(2) Automatic regulation or control of oil in vacuum burners: A detailed presentation of the experimental work carried out on this problem:

(a) The problem: It is required that variations in the capacity or heat output of the burner shall be effected by the manipulation of a single valve, a needle valve in the air supply line. It is also required that the oil supply shall be regulated automatically when the air pressure fluctuates.

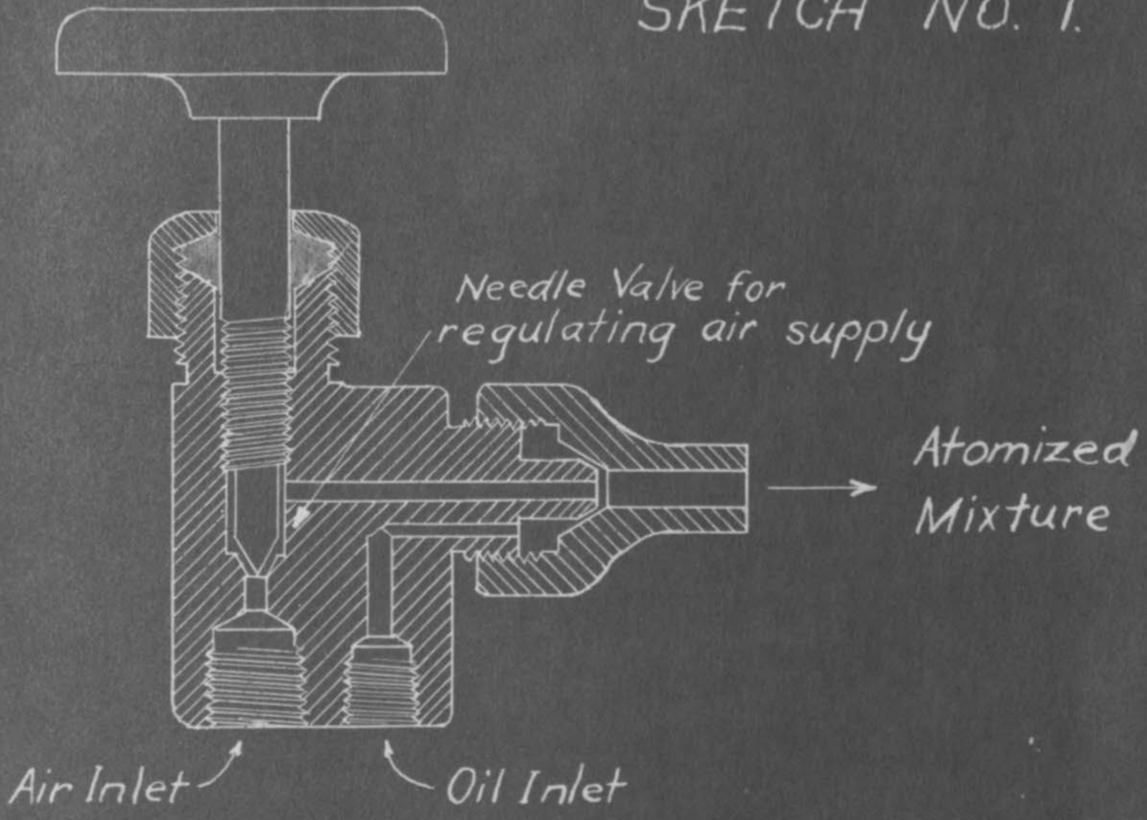
The air nozzle on this burner is proportioned so as to give the over-expansion mentioned above, that is, expansion to a pressure considerably below atmospheric in a certain part of the nozzle. This part of the nozzle is then put in direct communication with the oil supply and the vacuum draws the oil into the air jet, where it is atomized.

The amount of over-expansion, or the magnitude of the vacuum is a function of the air supply pressure, the relation between the two being determined by the proportions of the nozzle. Now if the nozzle can be so proportioned that the quantity of oil induced by the vacuum is directly proportional over a range of operating pressures to the total amount of air, (both high pressure air and free air), then the flame may be varied in size by simply adjusting the air valve since the effect of the valve is to throttle the pressure. That is, if the oil valve is adjusted at any pressure within the operating range to give the required kind of atmosphere, the heat output of the burner may be regulated thereafter, without changing the atmosphere, by simply adjusting a throttle valve in the air line, which of course varies the pressure of the air supplied to the burner and in turn the vacuum, and varies the oil supply in the same proportion as the air. In determining the proportions of the expanding nozzle which shall give these results, several questions at once arise: (1) What is the relation between the magnitude of the vacuum and the quantity of oil induced by the same? (2) What is the relation between the quantity of high pressure air discharged by the nozzle and the pressure of the air supplying the same? (3) What is the relation between the quantity of the high pressure air discharged through the nozzle and the quantity of free air induced by the jet?

(b) Initial assumptions: After some consideration of these questions it was decided that they could not be readily answered by the application of theoretical or available experimental conclusions and that the only satisfactory way to affect their solution would be by careful experimental investigations. Some investigations were undertaken later and reports on the work done to date are given elsewhere. But it was evident before undertaking these investigations that they were a lengthy process and it was accordingly decided to go ahead with the work on the burner nozzles on the assumption that in the case of both air and oil the relations between the pressure causing flow and the quantity flowing are, under the conditions existing in these nozzles, straight line functions. Assuming further that the induced free air is proportional to the quantity of compressed air discharged, the curve between the air supply pressure and the vacuum produced should also be a straight line. These assumptions represent the simplest possible relations, but they have furnished a good working hypothesis as will be shown below.

(c) Status of the burner when the investigation was begun: For manufacturing reasons the form of expanding nozzle was confined to two cylindrical tubes, (See sketch #1.) the first connected to the source of air supply, the other open to the atmosphere. This was the type of nozzle being used on the burners at the time the investigation was begun, which form was not changed. The general plan of the apparatus is also shown in sketch #1. A very substantial amount of business had been built up on the line of burners as they were being manufactured before the initiation of this investigation. Curves showing the relation between pressure and vacuum in these burners are exhibited on Curve Sheet I. The vacuum was measured at five pound pressure increments within the operating range (10# to 90 or 100# gauge). It was decided that in order to determine the relation between the proportions of the nozzle and the character of curve produced, and have such determinations hold for all sizes of air inlet, certain ratios of dimensions should be chosen. Three such ratios were accordingly decided upon and these were designated R, S, and T, respectively, see sketch #2. Values of R, S, and T for the original burners are given on Curve Sheet 1.

## SKETCH NO. 1.



ELEMENTARY BURNER

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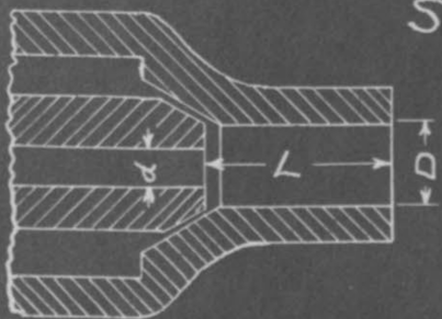
## SKETCH NO. 2.



$$\frac{D^2}{d^2} = \frac{A}{a} = \text{ratio "R"}$$

$$\frac{L}{d} = \text{ratio "S."}$$

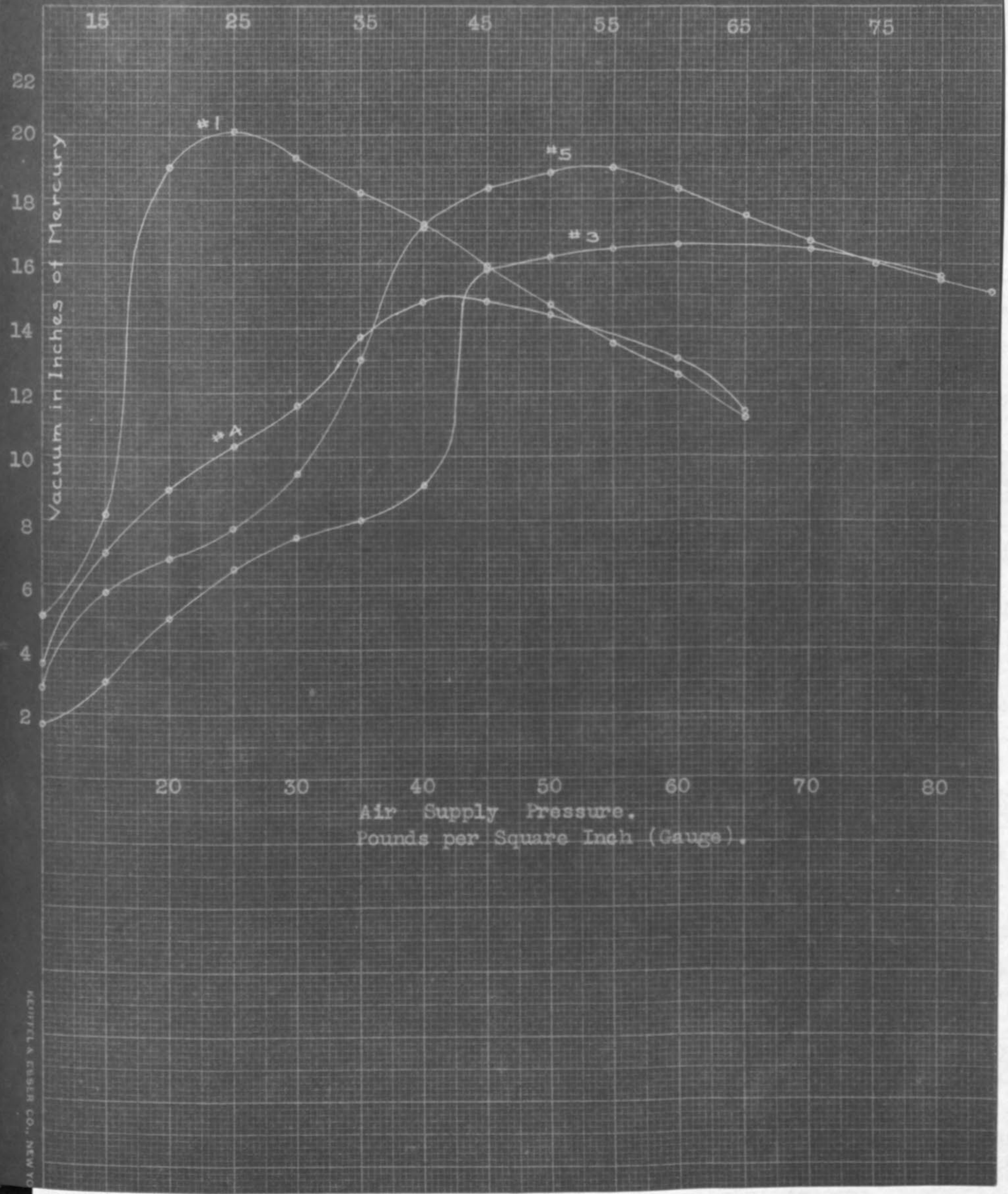
$$\frac{\text{"R"}}{L} = \text{ratio "T."}$$

ENLARGED SECTION of COMBINING NOZZLE.

CURVE SHEET NUMBER 1. Thesis. G.L.Tuve.

Vacuum Burners. Pressure-Vacuum Curves.

## INITIAL STATUS OF VACUUM BURNERS.



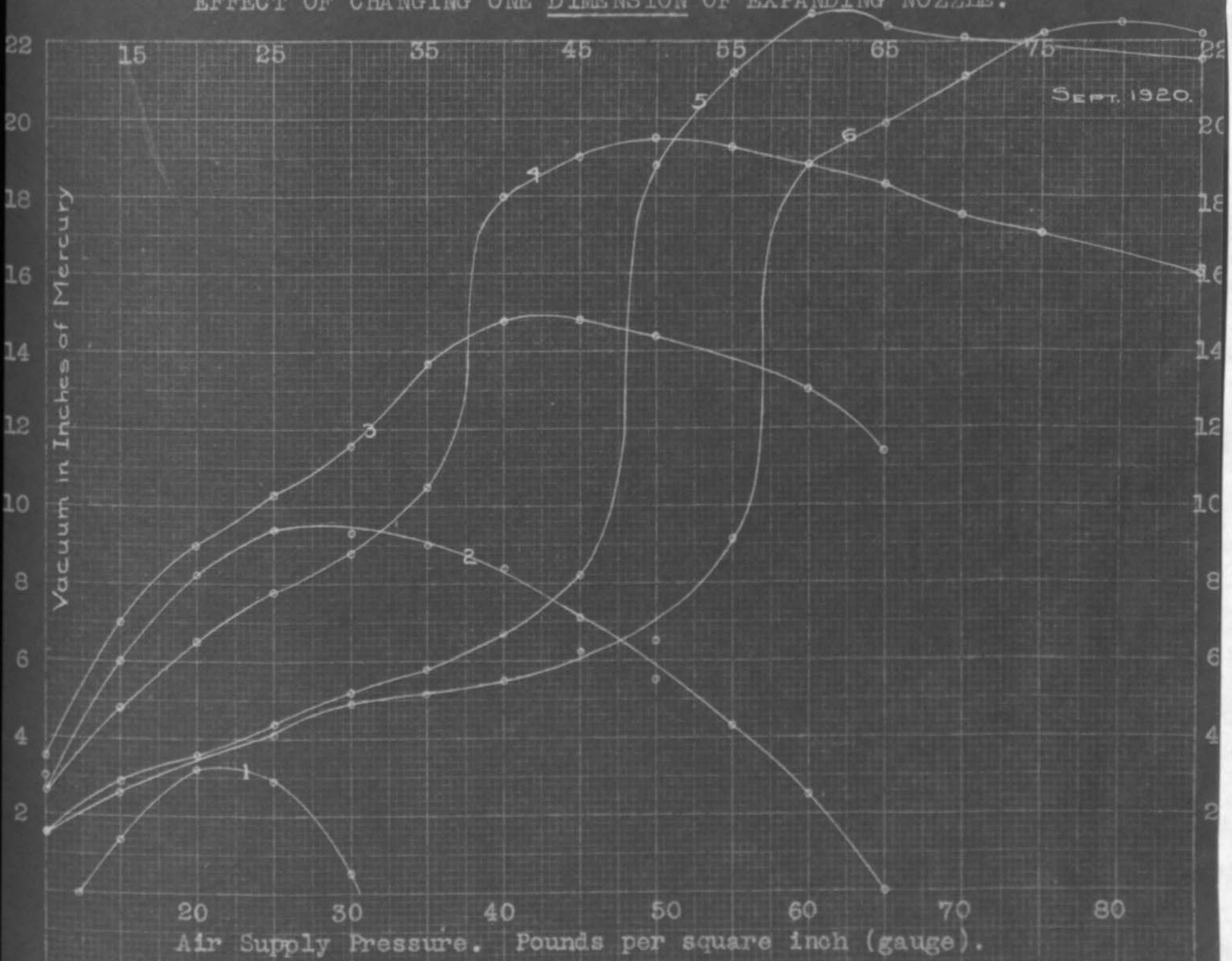
(d) Effect of proportions of the expanding nozzle: The first method of procedure in these experiments was to make up a series of nozzles, identical except for one dimension and to study the variations in the pressure-vacuum curve and in the operation of the burner as this one dimension was varied. However it was found more effective to vary one of the ratios mentioned above, keeping the others constant meanwhile.

Some of the results obtained in these studies are exhibited on curve sheets 3 and 4. Curve sheet 3 shows the effect of changing one dimension of the nozzle, namely the diameter of the larger tube. The curves are numbered in order of the increase in this dimension. Curve sheet 4 shows the greater ease of interpreting the result when one of the ratios is varied. The most striking characteristic of this latter set of curves is the failure of the nozzles to produce a vacuum of any magnitude at lower pressures when the value of the ratio "S" is small. This

CURVE SHEET NUMBER 3 Thesis. G.L.Tuve.

## Vacuum Burners. Pressure-Vacuum Curves.

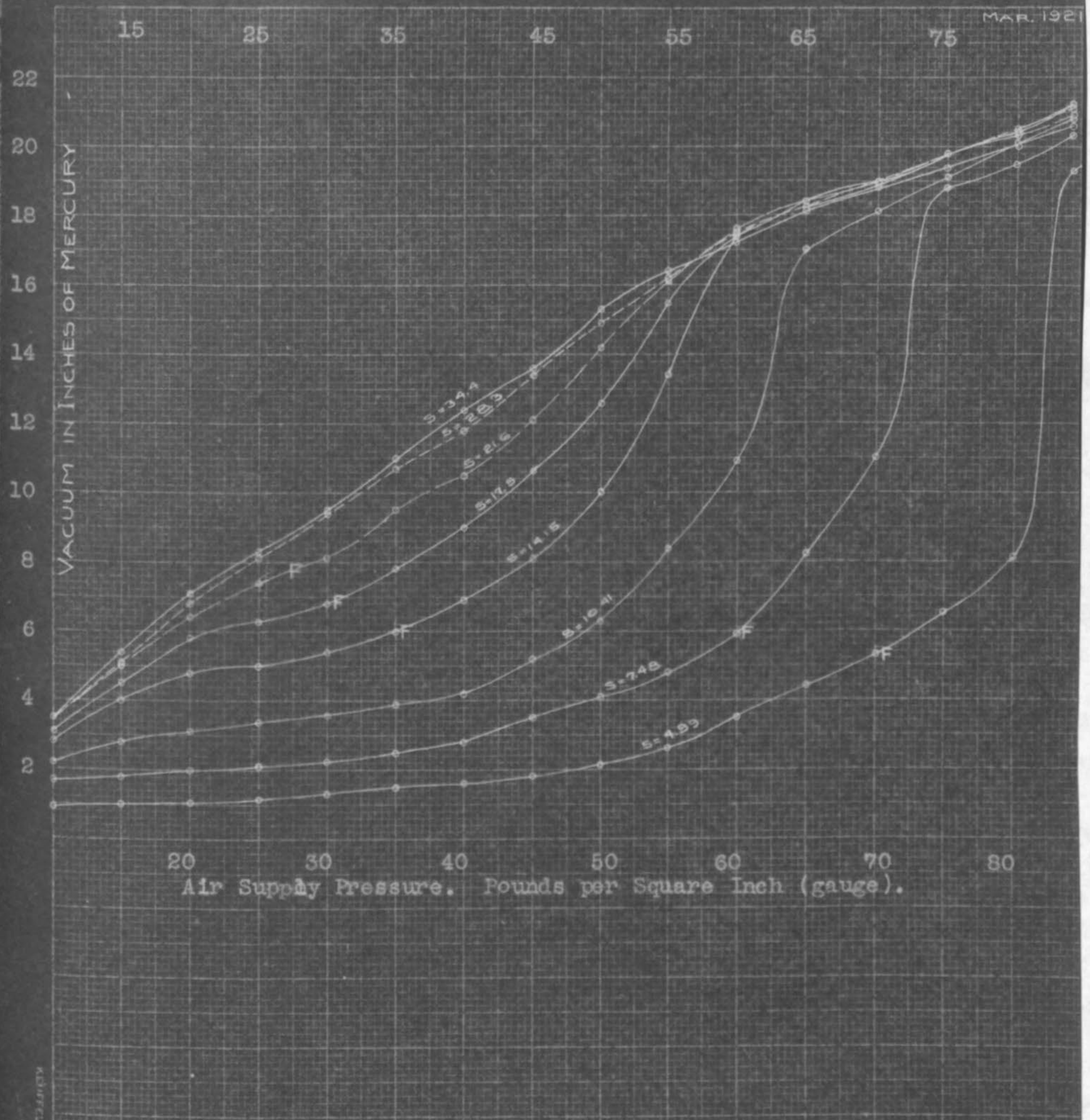
## EFFECT OF CHANGING ONE DIMENSION OF EXPANDING NOZZLE.



CURVE SHEET NUMBER 4  Thesis. G.L.Tuv

## Vacuum Burners. Pressure-Vacuum Curves.

## EFFECT OF CHANGING RATIO OF DIMENSIONS OF EXPANDING NOZZLE.



is evidently due in a large measure to eddies, or severe agitation in the air jet. This conclusion and a number of others are brought out by several observations: (1) As the value of "S" was decreased the noise of the issuing jet increased greatly, but simultaneously there appeared a critical point in the range of supply pressures above which the jet made very little noise. This critical pressure was noted to be that at which the curve "jumps". (2) When a thin steel scale was held in the jet it was caused to vibrate when the supply pressure was below this critical, whereas it was perfectly steady at higher pressures. (3) The pressure at the periphery of the jet where it emerged from the nozzle was negative when the air supply pressure was below this critical and positive when the air supply pressure was above it. (4) When the suction pipe was placed in a pail of water, the jet of atomized mixture was pulsating or "jerky" at certain air supply pressures. (5) The reason for this unsteadiness of flow was evidenced by the behavior of the hand on the vacuum gauge, which fluttered back and forth at these same air supply pressures. As noted at the points "F" on the curves, the curve is smooth and continuous through these points at which the fluctuations of the vacuum were at their worst. (6) No abrupt change in the divergence of the jet could be noted as the pressure was increased through these "fluttering" pressures. (7) All of these disturbing phenomena are absent when the value of S is large, say greater than 25.

A careful comparative study of over a hundred pressure vacuum curves shows that the general form of that part of the curve which approaches a maximum is dependent on the value of S only, the values of the other ratios R and T having no effect on this characteristic. With all of these curves for which the value of S was over 20 or 25 the "disturbing phenomena" mentioned above could not be observed.

No doubt further investigation into the reasons for the phenomena mentioned above would be very interesting, but observation (7) is all that is necessary for our purposes. In the light of results of experiments on steam turbine nozzles, some of the observations would indicate that if the pressure in the jet were plotted against its axial length, an irregular, oscillating curve would result. The "fluttering" and noise suggest that the air jet is in a state of vibration similar to the vibration of the air in sound waves within a tube, and it seems likely that the vibration takes place in segments with nodes between.

Effect of the value of the Dimension-Ratio "R":

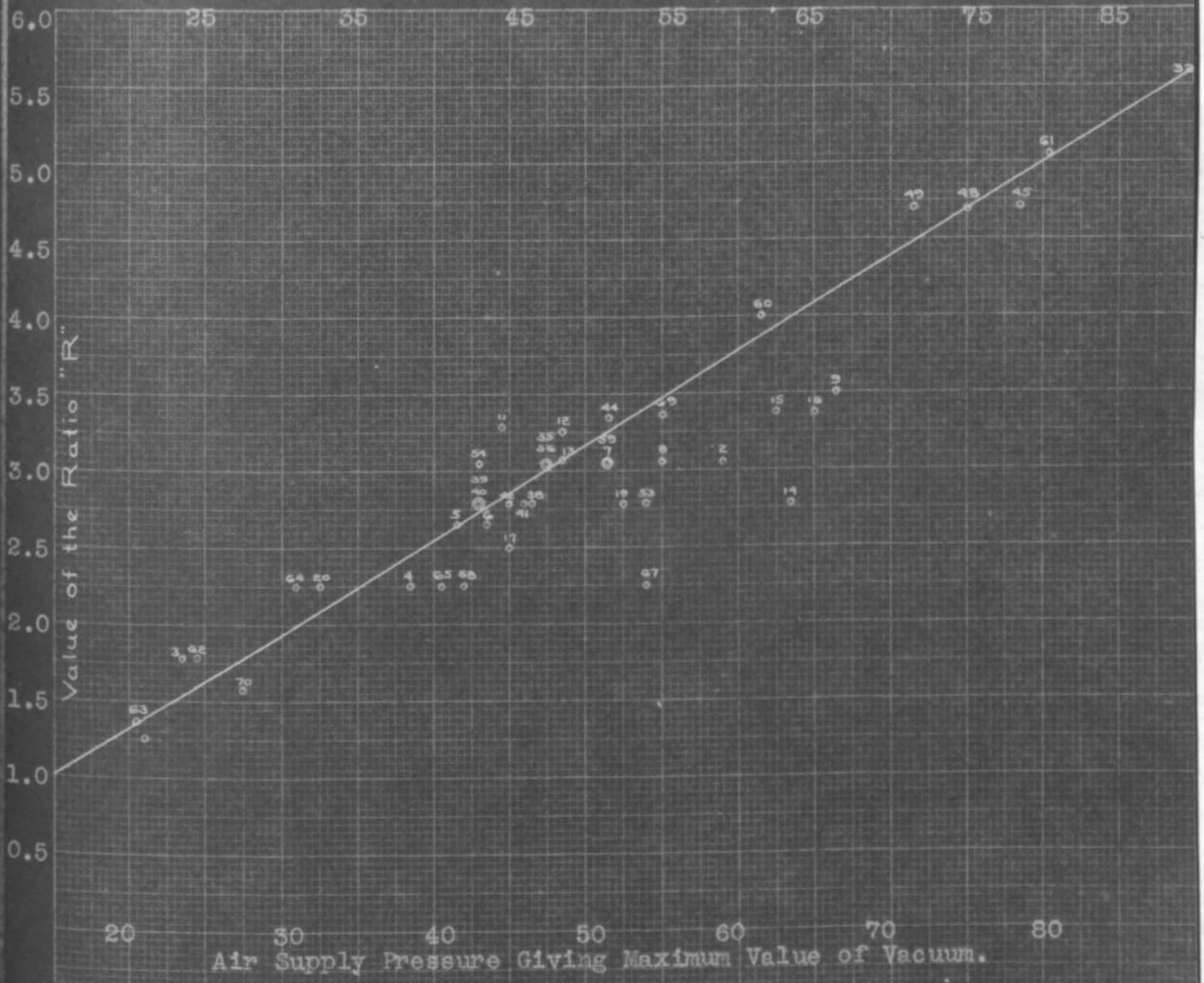
Early in the study of the vacuum burner it was noted that when the value of the ratio R was comparatively large, the maximum vacuum was not reached until the higher pressures were applied (see Curve Sheet 1). A graphical presentation of the relation between the ratio R and the pressure producing the maximum vacuum is presented on curve sheet 5. This plot includes almost all of the curves on record whose maximum value occured at a pressure below 85-90#. It is obvious that inasmuch as it was desired to secure a continuously increasing oil supply, the maximum vacuum

CURVE SHEET NUMBER 5.

Thesis.
G.L.Tuve.

Vacuum Burners. Proportions of Expanding Nozzle.

RELATION BETWEEN VALUE OF "R" AND PRESSURE OF MAX. VACUUM.



must always be above the highest working pressure.
As soon, then, as it was discovered that values of R exceeding 5 or 6 would give a curve whose maximum was beyond 90#, no lesser values of the ratio were used and therefore this plot does not include any of the later curves.

The number adjacent to each point on this sheet is the number of the curve from which it was taken, and it may be seen by referring to Data Sheet~~s~~ 1 ~~and 2~~ that the values of the dimension-ratios S and T do not affect this relation between R and the pressure of maximum vacuum.

The failure of these points to form a smooth curve is due largely to experimental error. As stated above, most of these points represent results obtained early in the investigation, and if the determinations were to be repeated with the more accurate experimental methods since developed, a much more regular curve would no doubt be produced. Another source of error, (which affects slightly some of the other results presented as well as the ones shown

# DATA SHEET NO. 1.

## DEVELOPMENT OF VACUUM BURNERS.

Showing that the supply of pressure at which the vacuum reaches its maximum value is approximately proportional to the value of the ratio "R", but is independent of the values of ratios "S" and "T". See also curve sheet No. 5 and pages 17 and 18 of text.

| | | Values of Ratios | | |
|---|---|---|---|---|
| Curve No. | Pressure of Max. Vacuum | "R" | "S" | "T" |
| 3 | 23.5# | 1.78 | 28.6 | 1.29 |
| 62 | 24.5 | 1.78 | 10.8 | 3.36 |
| 70 | 27.5 | 1.56 | 27.0 | 2.94 |
| 20 | 32.5 | 2.24 | 1.05 | 3.10 |
| 4 | 38.5 | 2.25 | 20.1 | 1.80 |
| 5 | 41.5 | 2.65 | 34.7 | 2.35 |
| 40 | 43.0 | 2.79 | 32.6 | 4.47 |
| 6 | 43.5 | 2.65 | 54.0 | 1.51 |
| 42 | 45.0 | 2.79 | 26.0 | 5.58 |
| 38 | 46.5 | 2.79 | 48.8 | 2.98 |
| 13 | 48.5 | 3.06 | 49.8 | 6.53 |
| 7 | 51.5 | 3.06 | 34.7 | 2.72 |
| 44 | 51.5 | 3.36 | 21.6 | 6.74 |
| 69 | 55.0 | 3.36 | 21.6 | 6.72 |
| 48 | 75.0 | 4.70 | 25.1 | 5.78 |
| 32 | 90.0 | 5.54 | 33.7 | 90.0 |

by this curve), is the drop in air supply pressure in the passage between the gauge and the nozzle. Since the size of this air passage varies in the different burners used, and since its area is only very approximately proportional to the air consumption of the burner, a small relative error in the pressure readings, is introduced also.

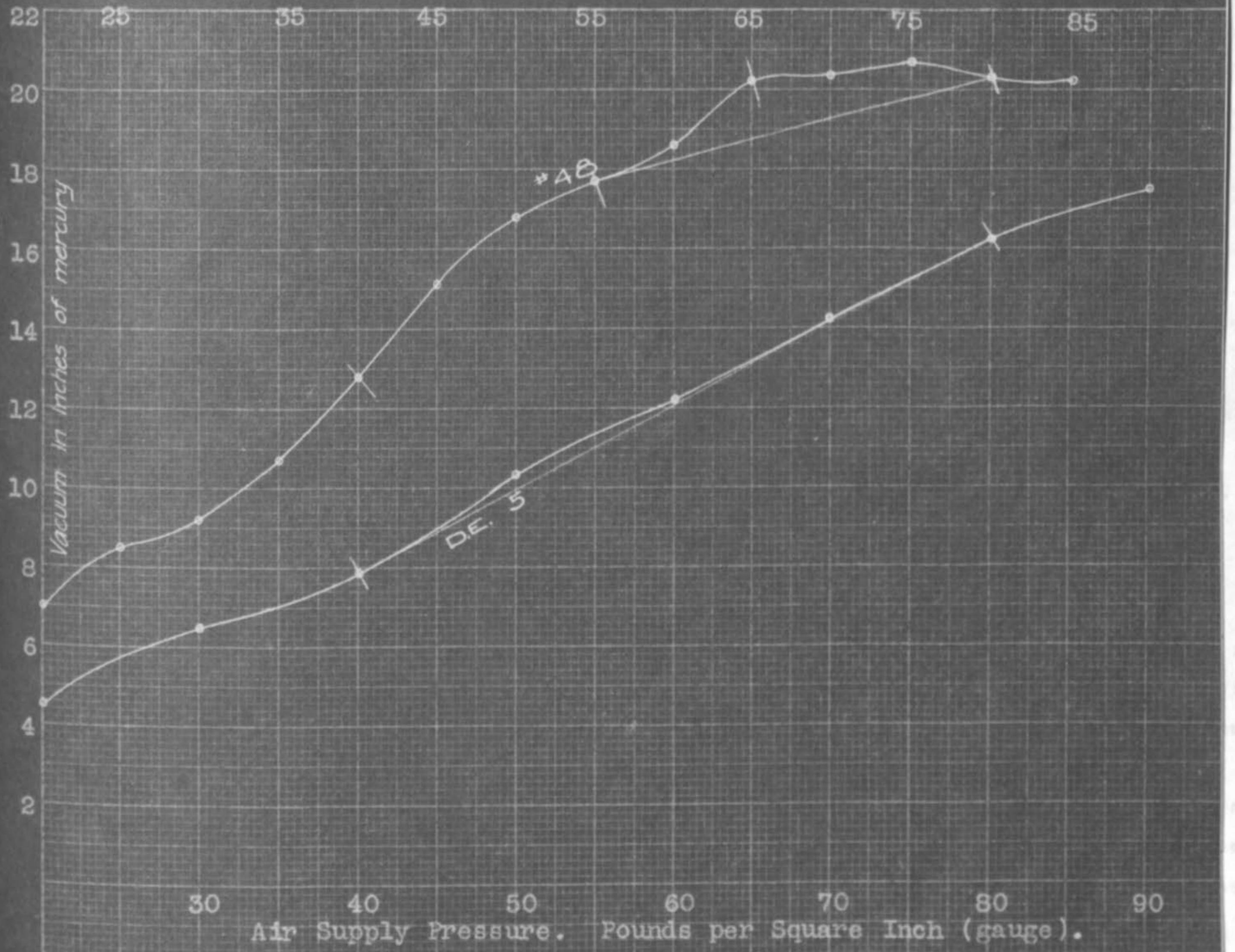
(e) Form of the Ideal Pressure-Vacuum Curve.

Frequently during the investigation of the pressure-vacuum relations the various burners were attached to combustion chambers and the conformity or non-conformity to automatic oil regulation was studied, that is, the atmosphere and flame were observed as the air supply pressure was varied by a throttle valve. These observations were made with different settings of the oil valve. On curve sheets 6 and 7 some of these observations are given, together with the pressure-vacuum curve for the burner under observation. Each of the sets of observations of the flame conditions was made independently of, and in

## CURVE SHEET NUMBER 6.

Vacuum Burners. Pressure-Vacuum Curves.

### IDEAL PRESSURE-VACUUM CURVE AS INDICATED BY BEHAVIOR OF FLAME.



OBSERVATION OF FLAME:

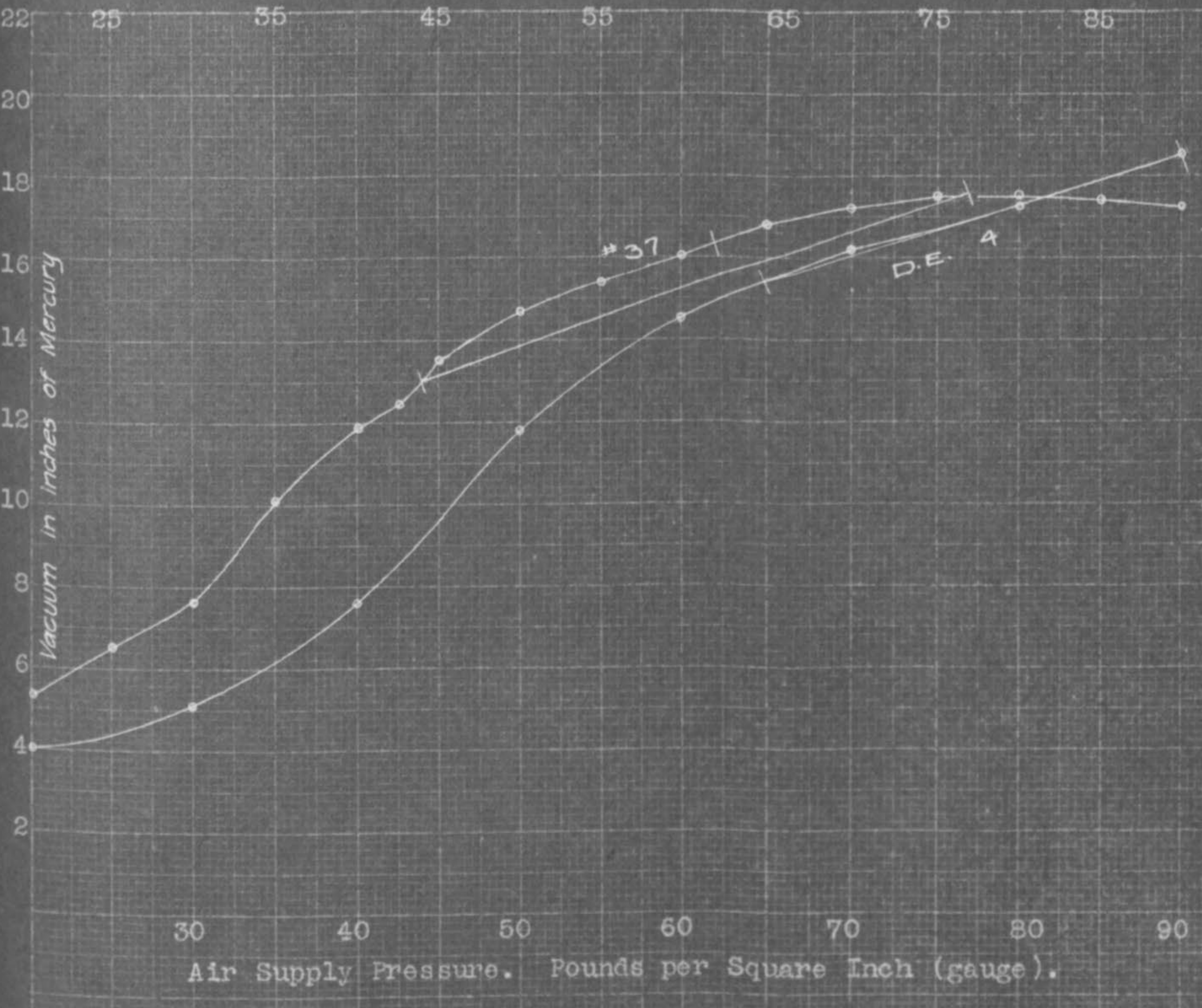
Curve No. 48.
Correct mixture at 80#
Correct mixture at 55#
Fair automatic oil regulation
from 50# to 85#.
Maximum oil feed at 65#
Minimum oil feed at 40#.

Curve No. D.E.5.

Good automatic oil regulation
from 40# to 80#.

Vacuum Burners. Pressure-Vacuum Curves.

IDEAL PRESSURE-VACUUM CURVE AS INDICATED BY BEHAVIOR OF FLAME.



OBSERVATION OF FLAME:

Curve No. 37.
Correct mixture at 44#.
Correct Mixture at 77#
Rather Lean below 44#
Somewhat rich 46#-75#
Maximum oil feed at 62#.

Curve No. D.E.4.
Good automatic oil regulation
from 65# to 90#.
Lean below 65#.

fact before the pressure-vacuum readings were taken. It will be noted that the two agree quite well and a general analysis of the results indicates that the form of the ideal pressure-vacuum curve is not a straight line but rather a curve whose slope decreases with the increase in pressure.

Data Sheet 3 illustrates the basis of this conclusion in the results obtained from ten sets of observations including the four recorded on Curve Sheets 6 and 7. On curve sheet 2 is plotted a characteristic curve obtained from one of the burners as they are now being manufactured. This is representative of the best results obtained to date. Examined in the light of the analysis presented on Data Sheet 3, it is seen that this curve is a fair approximation to what that analysis indicates is the general form of the ideal pressure-vacuum curve for automatic oil regulation. It is then fairly well established that a burner with expanding nozzle having such proportions that R is greater than 5 and S is greater than 30 will give fairly good automatic regulation and that these ratios are all that is necessary to determine the dimensions of such a burner

# DATA SHEET NO. 3.

## DEVELOPMENT OF VACUUM BURNERS.

## FORM OF IDEAL PRESSURE-VACUUM CURVE (See p. 19)
(See also Curve Sheets 6 and 7)

Showing decreasing slope of curve as pressure increases.

| (1) Curve Number | (2) Mixture correct at or within the range of the following pressures: | (3) Average pressure within this range: | (4) Slope of curve. Expressed as increase of vacuum per 10# increase in pressure. |
|---|---|---|---|
| 29 | 75-95# | 85# | 0.87" Hg. |
| 37b | 75-85 | 80 | 1.09 |
| 48 | 55-80 | 70 | 1.08 |
| D.E. 4 | 60-90 | 75 | 1.30 |
| 37a | 44-77 | 60 | 1.35 |
| 100 | 70-85 | 77.5 | 1.47 |
| 36 | 30-70 | 50 | 1.68 |
|  | 40-95 | 67.5 | 1.73 |
| D.E. 5 | 40-80 | 60 | 2.00 |
| 105 | 35-80 | 57.5 | 2.15 |
| 2 | 15-45 | 30 | 2.50 |

EXPLANATION:

Referring to Curve No. 48, Curve Sheet 6: Observation of the flame showed correct mixture at 65# and again at 80#. It was assumed that a straight line represents the correct curve between these points. The average pressure-value of this line is given in column 3 above and its slope in column 4.

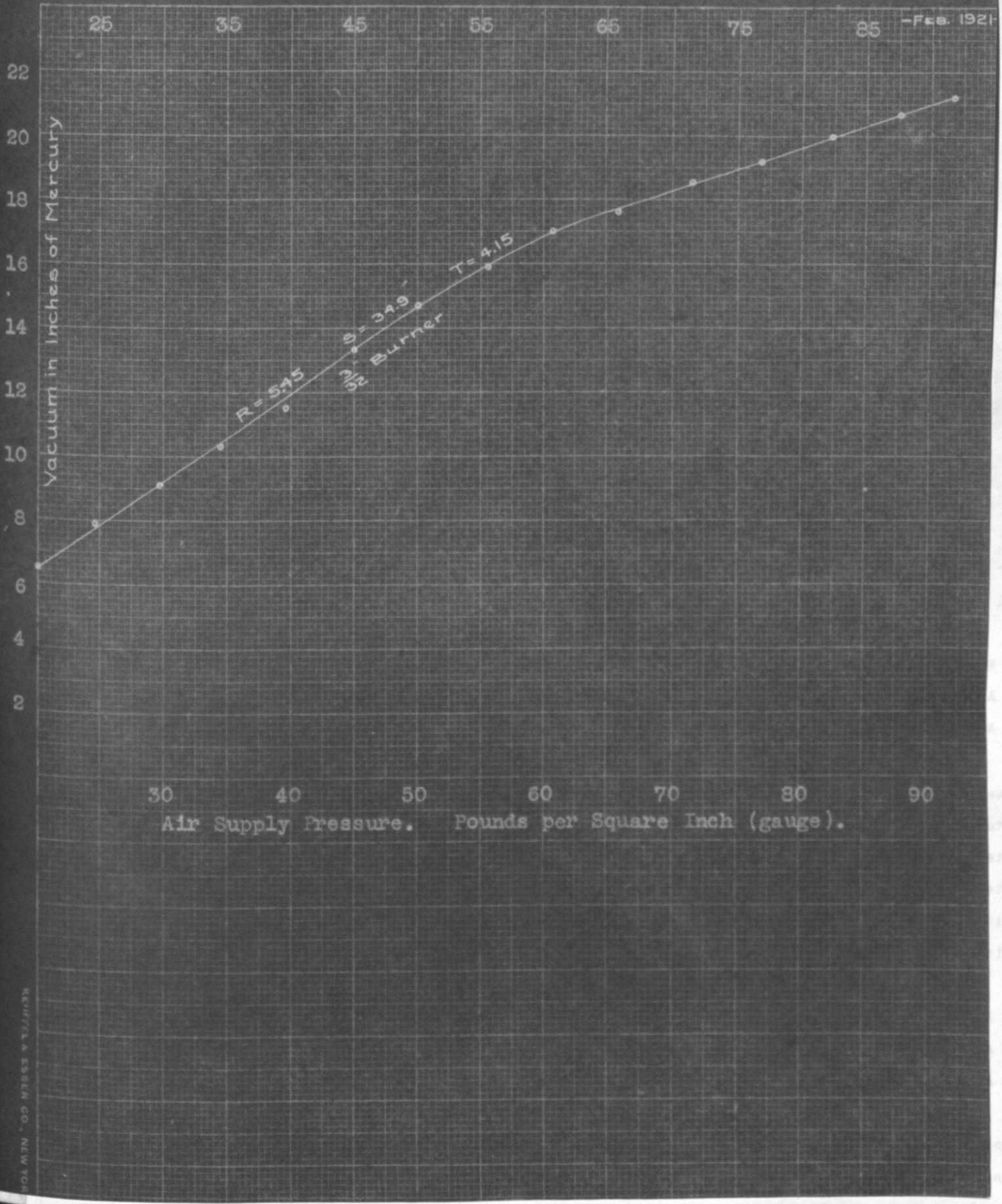
Referring to Curve D.E. 5, Curve sheet 6: Observation of the flame showed correct mixture throughout the range of 40# to 80#. The actual curve between these points is approximately a straight line, the slope of which is such that the vacuum increases 2.00" of mercury for each increase of 10# in the pressure. This fact is given in column 3 above.

All of the results presented in the above tabulation were arrived at by a similar analysis of similar curves, and although there are two or three irregularities it is shown to be a fact that the ideal pressure-vacuum curve for automatic oil regulation has a decreasing slope as the pressure increases.

## CURVE SHEET NUMBER 2.

Vacuum Burners. Pressure-Vacuum Curves.

### PRESENT STATUS OF VACUUM BURNERS.
Characteristic Curve.
V-10 Series.



in any desired size. Up to the present, six different sizes (from .035" to .109" diameter of inlet) have been made up and tested.

(f) Additional investigation desirable:

It would be desirable to carry out somewhat more accurately the determination of the exact proportions of the nozzle necessary for best results. It is quite probable that these proportions vary slightly in the different sizes. It is the intention of the writer to carry out such additional investigation as soon as time permits. Some refinements in experimental procedure are necessary to obtain the desired accuracy of results, the following improvements being the most important: (1) More accurate means of observing changes in atmosphere (flame). (2) More accurate measurement of nozzle dimensions. (3) More frequent calibration of pressure and vacuum gauges.

3. Heat Distribution:

While the problem of heat distribution is a problem of "heat control", which subject we are now discussing, it is to be noted that the various expedients used in effecting equal heat distribution: baffles, checkered and other special forms of arches, etc., are problems of combustion and heating chamber design rather than problems relating to the operating characteristics of the burner, and are therefore not within the scope of this discussion.

## III.RELIABILITY OF FLAME:

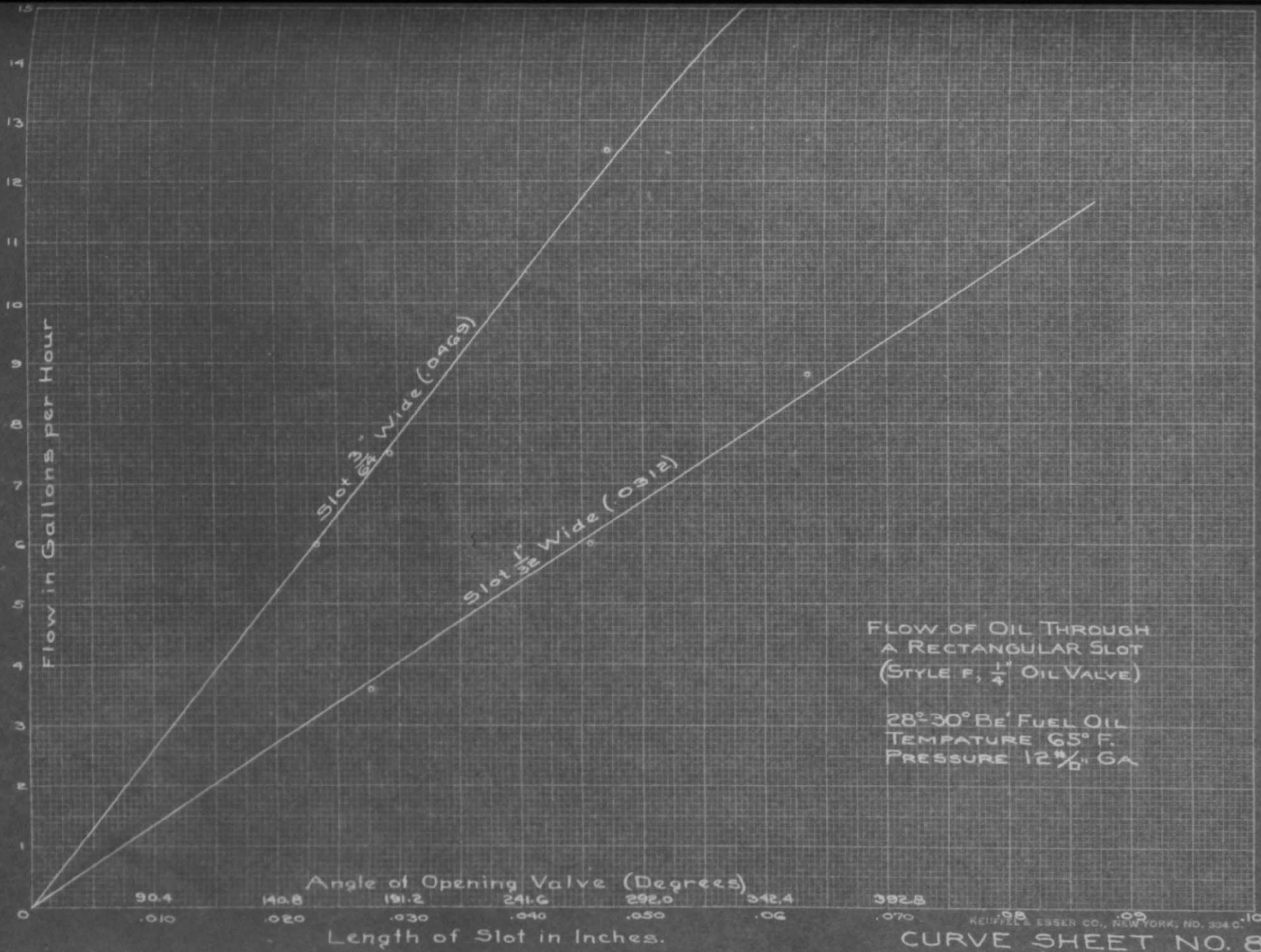
In almost every heating operation the reliability of the fire is a factor of first importance, as it is only in rare instances that the operator can always be at hand to make adjustments. Assuming proper initial adjustment, a change in the character of the fire means not only a lowered efficiency of heat application but often real damage to the work. The factors ordinarily causing interruption or variation in the fire may be discussed under the following headings:

1. Unsteady oil supply, due to

a. Foreign particles in the oil. This is a mechanical problem and is solved without much difficulty when the capacity of the burner is large, say five gallons per burner-hour or more. Smaller burners present problems of varying difficulty, depending on the shape of the aperture through which the oil must pass. It is evident that the difficulty is minimized by making this smallest aperture -- which is always the oil control valve -- either round or square. This will allow the passage of the largest particle for a given area of opening. Some idea of the minuteness of the particles which must be removed from the oil may be secured from a study of Curve Sheet 8, remembering that for certain purposes it is desirable to produce a burner whose oil consumption does not exceed one pint per hour.

*b*. Air "bubbles" in the oil. This is a difficulty which is peculiar to the vacuum type of burner, and the air bubbles enter the oil line as a result of leaks in the same. Such leaks do not announce themselves as is the case with leaks in any pipe carrying a fluid under pressure. Special precautions must therefore be taken when working out burner designs and oil connections to assure *permanent* freedom from this difficulty, as the behavior of the fire when slugs of air are entrained in the oil are both perplexing and exasperating to the uninitiated.

*c*. Water in the oil. This is a result of carelessness



CURVE SHEET NO. 8.

- Nov. 1920 -

in upkeep of equipment rather than of faulty design. A drain-plug should always be located at the lowest point in the bottom of the oil tank and through this the tank should be drained periodically. Water is sometimes carelessly or accidentally poured in with the oil, and if the oil is maintained under compressed air pressure some water will come from that source. Water and sediment will always settle to the bottom of the tank and oil pipes which feed burners should not touch the bottom, but should allow a reasonable space for the accumulation of water and sediment before it is necessary to drain.

d. Oil vapor in heated oil. If the oil is heated to a temperature which is above the vaporizing point of the oil at that pressure, slugs of oil vapor will cause an unsteady fire. This trouble is of course generally experienced in connection with the use of an oil heater, and is due to faulty operation. In the design of torches or burners equipped with nozzles, however, care should be taken not to provide a path for the heat to travel from the nozzle to the burner, lest such vaporizing trouble should arise therefwom. This precaution is expecially applicable when the burner is of the vacuum type since certain fractions of the oil vaporize at comparatively low temperatures under the vacuum maintained in the vacuum burner oil lines.

2. Unsteady air supply, due to

a. Fluctuations in the air pressure. This is not an uncommon annoyance in small installations, and the automatic regulation of oil supply in the vacuum burner, (as described above under "flame control"), furnishes an ideal solution. With other types of burners, if it is not possible to eliminate the fluctuations in main air line pressure, a satisfactory expedient is the installation of a pressure regulating valve on the air line supplying the burners.

3. Velocity of the mixture greater than the velocity of propagation of the flame: The atomized mixture has a very high velocity as it leaves the expanding nozzle. Careful observations of the behavior of various kinds of oil burners, especially torches, would indicate that the same principle governs the rate of flame propagation in oil-vapor mixtures as in gas mixtures, namely, that the max-

imum velocity of propagation is attained with a certain mixture and the velocity decreases with both richer and leaner mixtures. Therefore a torch that will satisfactorily deliver a driving flame of approximately a neutral atmosphere, may fail to "hold" a richer or leaner flame because the velocity of the mixture issuing from the nozzle exceeds the velocity of flame propagation. In the case of torches of the larger sizes the correction of this fault consists largely in so proportioning the expansion and combustion nozzles that the total of the compressed air plus the induced air will not be great enough to increase the velocity of the mixture at the nozzle outlet beyond the minimum velocity of flame propagation. Torches fitted with vacuum burners of the type described above are more likely to "go out" than torches fitted with certain pressure burners. In the former the atomized mixture issues in a single jet, while in the latter it issues in a number of smaller jets. It is also probable that the pressure in the jet of the vacuum burner is lower, inasmuch as the nozzle is designed for over-expansion, and when the jet is explored with a very small tube connected to a manometer, or is allowed to draw in smoke from a piece of burning waste, it is shown that the pressure in the jet does not return to atmospheric for some distance beyond the outlet of the expanding nozzle. Now whether the failure of this nozzle-equipped vacuum burner to "hold" fire is due to a higher velocity in the jet, accompanying this lower pressure, or whether it is due to higher velocity or other effect of the single jet as opposed to the multiple jet, is not known.

It has also been the writer's experience that the vacuum torches would not hold fire with as <u>lean</u> a mixture as would the pressure torches, but after experiences with small nozzle-equipped vacuum burners it seems that the most likely reason for this difficulty is that the cast iron nozzle chills the mixture to a temperature below the ignition point. For the purpose of increasing the life of the nozzles under continuous usage, the design of these torches was such that the nozzles did not get as hot as was the case with the pressure torch nozzles and therefore the mixture which constitutes the outside of the jet would not be heated to as high a temperature as is the case in the pressure torches.

In the smaller sizes of torch burners equipped with the usual cast iron nozzles, the flame is very unreliable, and under certain conditions cannot be maintained at all. As the diameter of the jet or flame is decreased, the ratio of circumference to diameter is increased, and all indications are that the iron nozzle is therefore enabled to carry the heat away so rapidly that the flame cannot be maintained except under the most favorable conditions. A refractory nozzle lining which is a poor conductor of heat, when properly designed and applied, makes a reliable piece of equipment out of these small trouble-makers. A considerable amount of time has been spent on the problems of these small torches and they give great promise for such work as starting hot-tube engines, brazing, etc. The refractory lining greatly increases the intensity as well as the reliability of the flame.

The whole difficulty of unreliability is much more pronounced in the case of torches than in the case of burners applied to furnaces and forges. This is no doubt due both to the higher temperature existing in the latter when in operation, (the rate of flame propagation increases with the temperature), and to the decreased velocity of the mixture in a forge or furnace after impact against a flash wall or the walls of the combustion chamber.

4. Carbonization: Deposits of carbon within the expanding and mixing nozzle is a difficulty sometimes encountered, especially in torches, when operating for long periods and using the cheaper oils. This is due to the heating of the mixing nozzle to a temperature which effects the decomposition of the oil. The prevention of this trouble consists in using care in the design of the equipment so that a large amount of heat shall not be carried back to the nozzle.

5. Expansion of the burner parts due to heat: It is thought that this has some bearing on certain difficulties in maintaining the adjustment of the oil supply. In the case of certain styles of burners in which the oil valve is adjacent to the expanding nozzle, it is necessary to increase the oil feed several times during the first minute or two of operation, in order to maintain a suf-

ficiently rich mixture. It seems probable that this is due to temperature changes, the expanding air absorbing heat from, and the flame giving off heat to, the burner. These initial adjustments are of small consequence in burners that are operated for long periods of time, but where the heating job is one that requires but a few minutes it is a considerable annoyance, especially if the same operator has to run several burners at once, as in starting a four-cylinder hot-tube engine. No accurate conclusions can at present be drawn concerning this difficulty, but it is the intention of the writer to make further observations as soon as time permits.

IV. ECONOMY: or cost of operation for a given amount of useful heat:

1. Efficiency in the use of compressed air; air used per gallon of oil burned.

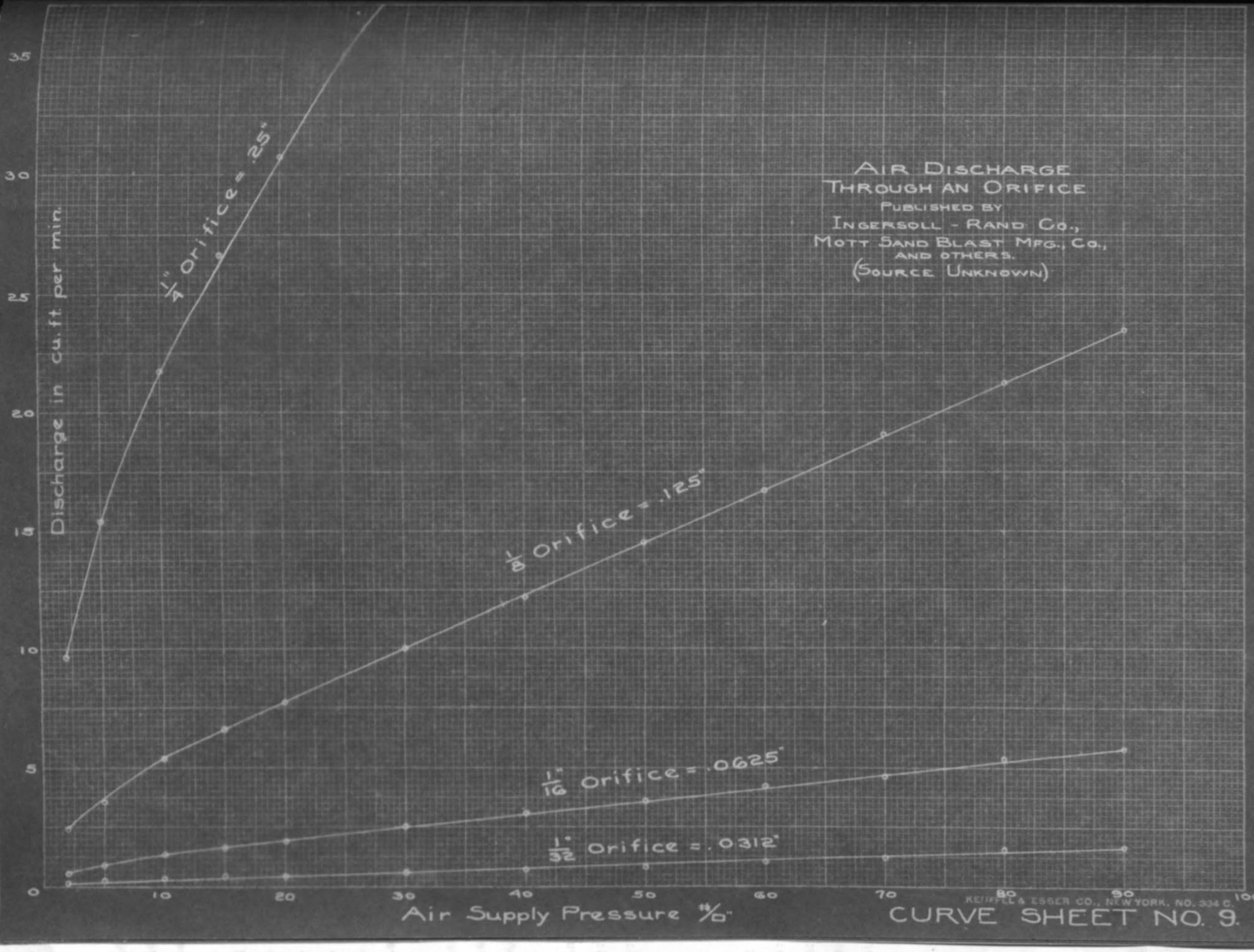
The cost of compressed air is an item whose importance is too often underestimated when considering the cost of operation of oil burning equipment. A few figures will show, however, that the cost of compressed air is an appreciable item. Take as a fair example a forge, small furnace, or large torch, which uses 60 cubic feet per minute. This amounts to 28,800 cubic feet per day of 8 hours. An average figure for the cost of compressed air, used by many large firms, is 35¢ per thousand cubic feet. The air to run this piece of equipment then costs $10.08 per day. A saving of 30% to 40% of this air, effected by increasing the air efficiency of the equipment, would hire another man. As is shown in the studies below, these figures are not at all unlikely.

a. The starting point in efficiency determinations: convenient and accurate methods of measurement of air and oil used. A detailed study of the calibration of orifices for air measurement and the problems met in that connection.

(1) The calibration of orifices:

(a) Available data on compressed air measurements and reasons for undertaking this investigation. A surprisingly small amount of experimental data on the subject is available. Most of the studies reported have been made with lower pressures and the results do not apply when higher pressures are used. This is true of most of the experiments of Fliegener, Weisbach, Zeuner, Durley, Bureau of Standards, American Blower Company, etc. One set of results, published by the Ingersoll-Rand Company (see curve sheet 9), is fairly complete, but an effort to check these aroused suspicion as to their accuracy, and as the demands for accuracy in the investigation of burners increased, it was necessary to give the problem of air measurement more and more attention.

Measurements of air consumption of appliances (or, more accurately, of efflux from nozzles) may be divided into two classes: (1) comparative measurements and (2) absolute measurements. In connection with the design and development of burners, comparative measurements are the more important, the value of a quick but reliable method of obtaining such figures being evident in the discussion of efficiency of air consumption, below.

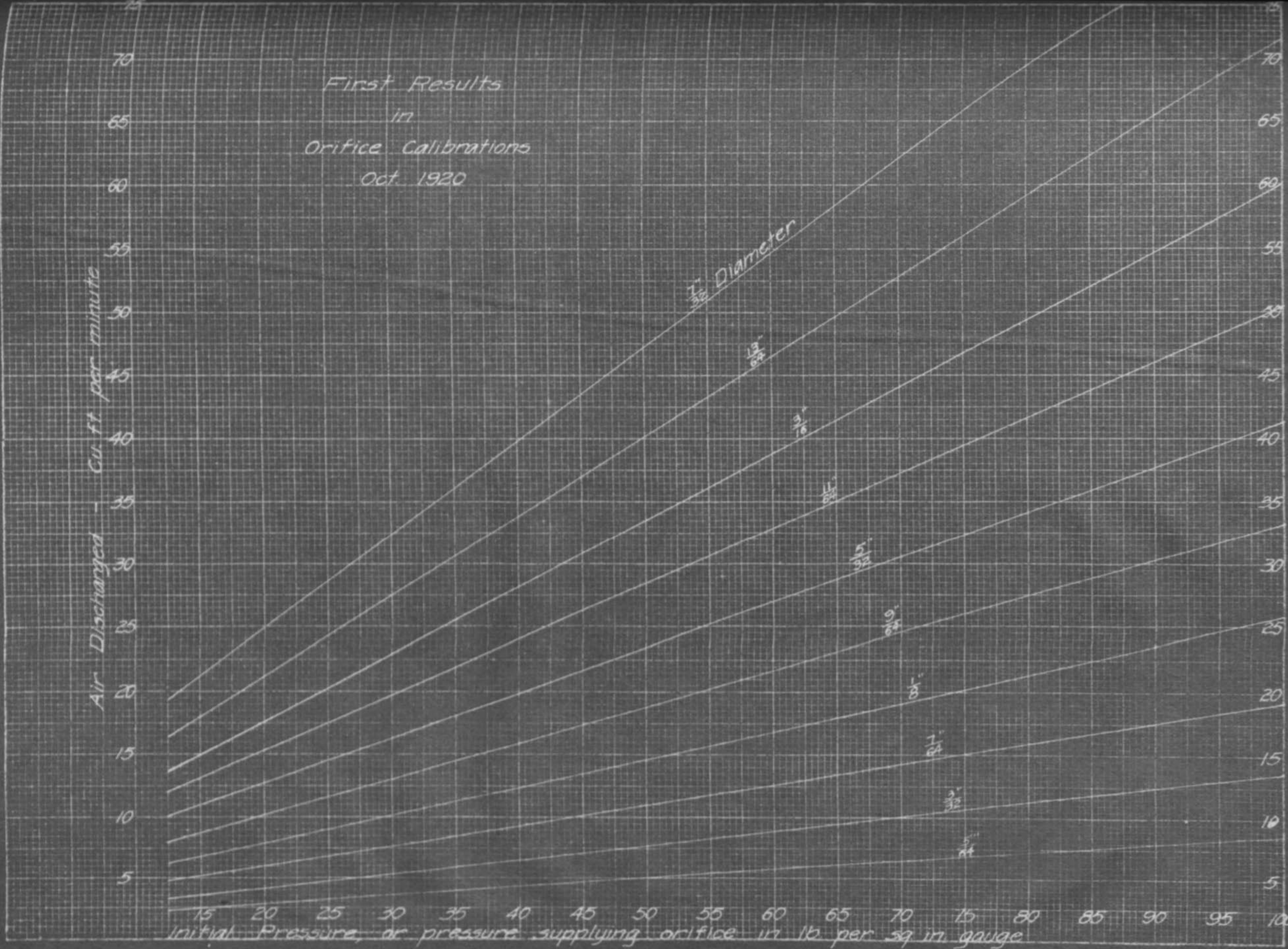


AIR DISCHARGE
THROUGH AN ORIFICE
PUBLISHED BY
INGERSOLL - RAND CO.,
MOTT SAND BLAST MFG. CO.,
AND OTHERS.
(SOURCE UNKNOWN)

CURVE SHEET NO. 9.

For all such measurements and for ordinary absolute measurements of the larger quantities of air, the calibrations given on curve sheet No. 10 were quite satisfactory. Their accuracy in comparative measurements was checked by comparing the discharge of one or two larger orifices with that of two or more smaller ones, both by the method described under "Use of Orifices" (below), and by allowing a receiver to discharge in turn though the larger and through the smaller orifices and taking time-pressure readings. This set of curves was derived by combining the Ingersoll-Rand data with early experimental data obtained by the writer.

As it becomes necessary in the development of the burners to make more accurate measurements, especially of the smaller quantities of air, the work on orifice calibration was extended. It is not felt that the following presentation of the problem is complete, nor is it as complete as it was hoped to make it before incorporating it in this thesis. Much care has been exercised, however, to make it accurate



First Results in Orifice Calibrations Oct. 1920

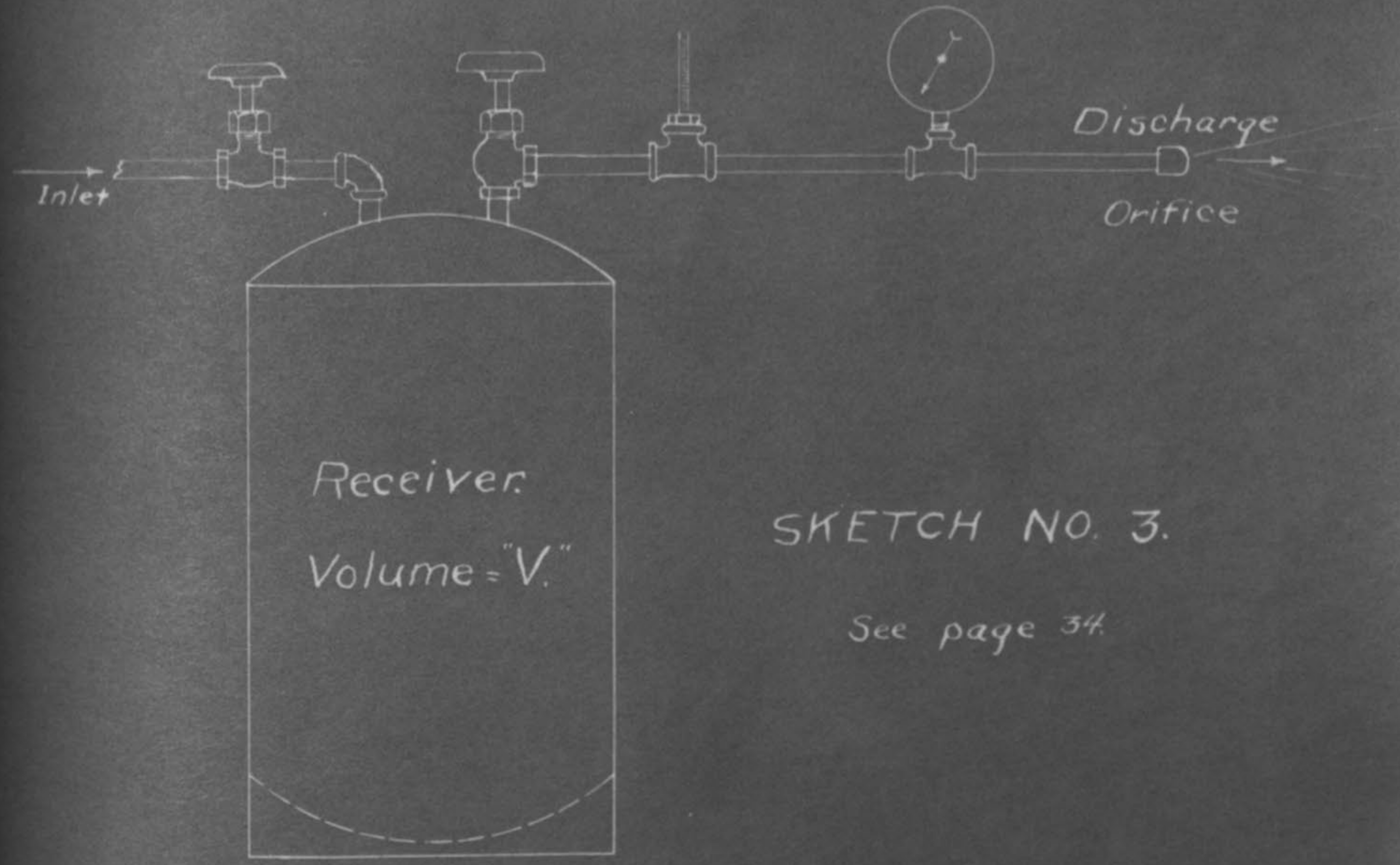
CURVE SHEET NO. 10

as far as it goes. A discussion of its limitations and of the probable error involved in its use is given below.

(b) Experimental procedure: Derivation of a formula for the discharge from any orifice at any pressure within the range.

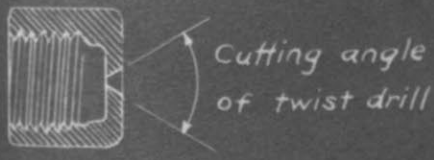
The general method of obtaining the data is as follows: A receiver of volume V is filled with air to a certain pressure, the inlet valve on the receiver closed and the air allowed to discharge through an orifice or nozzle. The orifice or nozzle is placed at the end of a short pipe of large cross section as compared with the area of the nozzle, and in this pipe is a gauge and a thermometer (see sketch #~~2~~3.) During the discharge, pressure and temperature readings are taken at convenient time intervals. From this data, curves of cumulative time against pressure, or differential time against pressure are plotted. Similarly, curves of cumulative or differential time against temperature are plotted.

Use of the data and derivation of the formula for



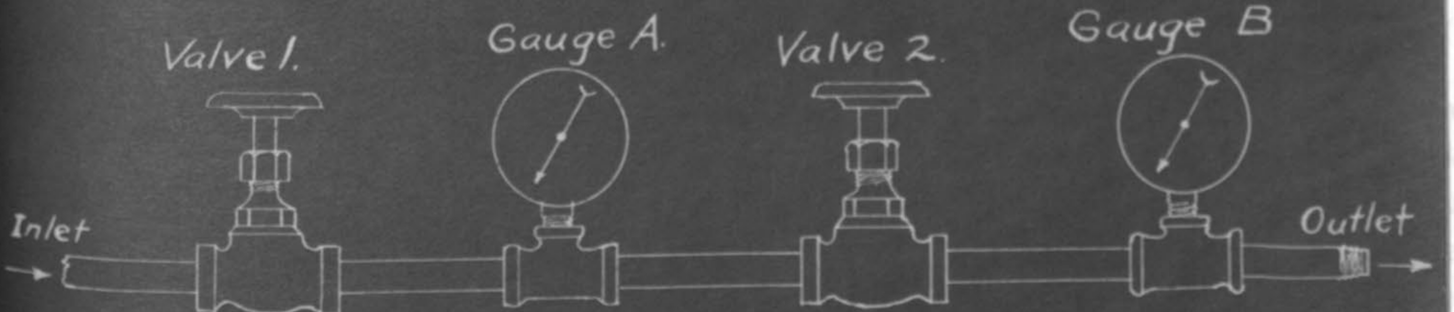
SKETCH NO. 3.

See page 34.



SKETCH NO. 4.

FORM OF ORIFICE in $\frac{1}{4}''$ pipe cap. See p. 42.



Air appliance and standard orifice are alternately attached at outlet. See p. 45.

SKETCH NO. 5.

discharge:

Starting with the fundamental equation for gases:

$$PV = WR\theta$$

Where: $P$ = absolute pressure of the gas in pounds per square foot.

$V$ = Volume of the gas in cubic feet.

$W$ = Weight in pounds of the quantity of gas under consideration.

$\theta$ = Absolute temperature of the gas in Fahrenheit degrees.

$R$ = the gas constant = 53.34 for air.

But it is desired to express P in pounds per square <u>inch</u>. If this value is called P' and 144P' is substituted for its equivalent P, the fundamental equation becomes:

$$W = \frac{144\ P'V}{R\theta} \qquad \text{(Equation "A")}$$

For the gas in the receiver or tank, V and R are constant, but P', W, and θ are variable and it is with the <u>rate</u> <u>of</u> <u>change</u> of these variables that we are especially concerned. The rate of change of the weight of the air contained in the tanks, $\left(\frac{dw}{dt}\right)$, is equal to the rate of discharge of the orifice. Evidently the relations between the rates of change of these variables may be obtained by differentiating the fundamental equation (Equation "A" above". The differentiation of two forms of this equation is therefore given on "Math. Sheet 1", (q.v.) Equation (1) is the ~~most~~ more convenient for our use since V and R are known directly from the data, while W of equation (2) would have to be calculated.

Now if tangents to the curves of cumulative time-pressure and cumulative time-temperature are drawn at any given value of the time "t", the slope of these tangents will represent respectively $\frac{dP'}{dt}$ and $\frac{d\theta}{dt}$. Corresponding values of $\theta$ and P' may be read from the curves at the points to which the tangents were drawn, and equation (1) can then be solved for $\frac{dW}{dt}$, which is the rate of discharge of air from the nozzle, in pounds per second.

Equations of Discharge:

# Math Sheet No. 1.

Solution I: $PV = WR\theta$

$144\,P'V = WR\theta \qquad W = \frac{144\,P'V}{R\theta}$

For the gas in the tank, V and R are constant.

Then, differentiating with respect to t (time)

$$\frac{dW}{dt} = \frac{144\,V}{R}\left(\frac{\theta\frac{dP'}{dt} - P'\frac{d\theta}{dt}}{\theta^2}\right)$$

$$\frac{dW}{dt} = \frac{144\,V}{R}\left(\frac{1}{\theta}\frac{dP'}{dt} - \frac{P'}{\theta^2}\frac{d\theta}{dt}\right) \qquad \text{(Equation 1.)}$$

Solution II: $P'V = WR\theta$

Differentiating:

$$\frac{dP'}{dt}V = R\left(W\frac{d\theta}{dt} + \theta\frac{dW}{dt}\right).$$

Solving for $\frac{dW}{dt}$:

$$\frac{dW}{dt} = \frac{1}{\theta}\left(V\frac{dP'}{dt} - W\frac{d\theta}{dt}\right) \qquad \text{(Equation 2)}$$

Equation 1 is the most convenient since V and R are known directly from the data, while W of equation 2 would have to be calculated.

$$\frac{dP'}{dt} = \frac{5}{MP' + T} \qquad \text{(Equation 3) (See page 39.)}$$

But M = slope of "differential-time pressure curve" $= -K\left(\frac{V}{A}\right)$

and T = t-intercept of curve = $-120.6\ m$

$$\therefore \frac{dP'}{dt} = \frac{5}{-K\frac{V}{A}P' + 120.6\,K\frac{V}{A}} = \frac{5A}{KV(120.6 - P')} \qquad \text{(Equation 4)}$$

Equation 1:

$$\frac{dW}{dt} = 144\frac{V}{R}\left(\frac{1}{\theta}\frac{dP'}{dt} - \frac{P'}{\theta^2}\frac{d\theta}{dt}\right)$$

The $\frac{d\theta}{dt}$ term is so small in comparison with the $\frac{dP'}{dt}$ term that the former may be left out of consideration entirely. (See page 40.)

Then:

$$\frac{dW}{dt} = 144\frac{V}{R\theta}\frac{dP'}{dt}$$

Substituting from equation 4:

$$\frac{dW}{dt} = 144\frac{V}{R\theta} \times \frac{5A}{KV(120.6 - P')}$$

$$= \frac{144 \times 5}{53.34}\,\frac{A}{\theta K(120.6 - P')}$$

$$= \frac{13.5\,A}{\theta K(120.6 - P')}$$

$\frac{dW}{dt}$ = lb. of air per second

A = Area of orifice in sq. in.

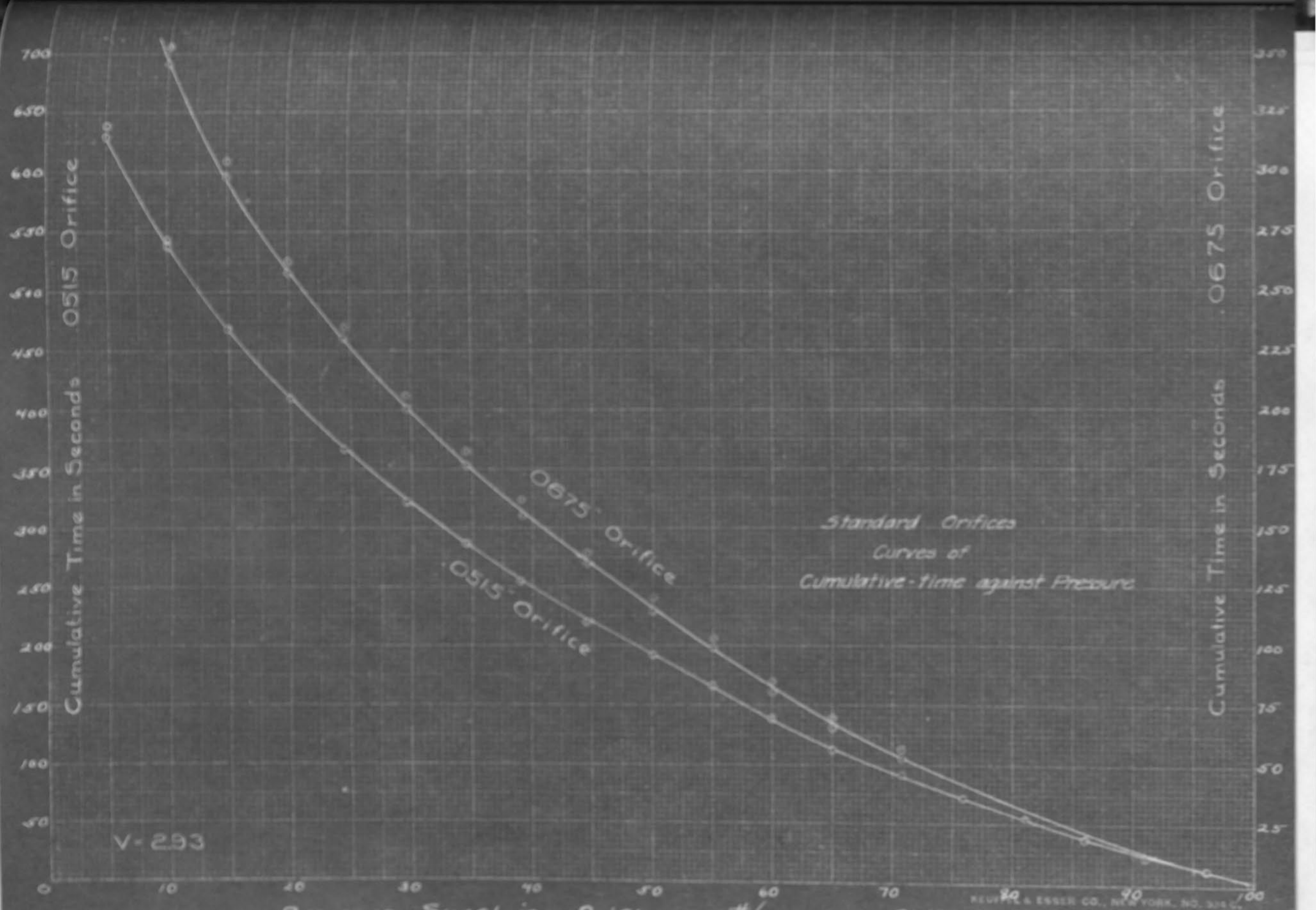
$\theta$ = Absolute temp. in degrees Fahr.

P' = Upstream pressure in lb. per sq. in

K = A constant proportional to "A" See curve sheet No. 18 for values.

*First method:* By obtaining for any given nozzle several values of $\frac{dW}{dt}$, with corresponding values of P' and θ, and substituting these values in Fliegener's equation $\frac{dW}{dt} = C\sqrt{\frac{P'}{\theta}}$, a series of values, or a mean value of "C" may be obtained. As a result of a long series of experiments, it seems evident to the writer that a *mean* value of the orifice coefficient will *not* serve to give accurately the discharge at pressures above about 75#. That is, the writer has found that the pressure-discharge curve does not even approximate a straight line above that pressure. It has, therefore, been necessary to derive an equation which will more accurately represent the experimental results obtained. The derivation follows:

*Second method:* If *general* values for $\frac{dP'}{dt}$ and $\frac{d\theta}{dt}$, (the slopes of the tangents to the cumulative time-pressure and cumulative time-temperature curves) could be derived in terms of P' and A (area of orifice), then the variation of the coefficient of discharge with pressure would be taken care of.



CURVE SHEET NO. 18
-MAR. 1921-

Such values of these slopes could be arrived at by finding the equations of the cumulative time-pressure and cumulative time-temperature curves and differentiating these equations. Some simpler method is necessary, however, and it was found experimentally that within the range of ordinary compressed air pressures, the curve representing all the values of $\frac{dP}{dt}$, (which is much more important than $\frac{d\theta}{dt}$), is approximately a straight line. Before the above mathematical treatment was developed, a large number of sets of readings had been taken on the rate of change of pressure. (No temperature readings were taken). Time was noted for every 5# pressure drop and this differential time was plotted against the <u>average</u> pressure (assuming straight line pressure drop) during the time interval. That is, if $P''$ = initial pressure for any time interval, and $P = 5$, then $P'' - \frac{P}{2}$ was plotted against T, which was the time required for the pressure to drop from P" to ($P''$ - 5). (The above pressures are expressed in pounds per square inch gauge).

With differential time plotted as ordinates, and pressure as abscissae, the equation of the time would be $t = mP' + T$, where m is the slope of the line, P', a variable, is the pressure corresponding on the curve to the value of t, and T is the intercept on the T-axis. $mP' + T$ is then equal to the time required for the pressure to drop 5# at an average pressure P', (that is, from P' + 2 1/2# to P' - 2 1/2#). Then, since the curve is a straight line, $\frac{mP' + T}{5}$ is the time required for the pressure to drop 1# at the same average pressure P'. Since seconds per pound drop = $\frac{mP' + T}{5}$, then pounds drop per second is equal to: $\frac{5}{mP' + T} = \frac{dP'}{dt}$. - Equation (3).

By plotting the above described curve (pressure against differential time) for a large number of orifices of different sizes, it was found that the curves all had approximately the same intercept on the P-axis, in which case the T-intercept on the line is a direct function of the slope. (This relation is: $T = -120.6m$. See below, Data Sheet #4. It was found

## DATA SHEET NO. 4.

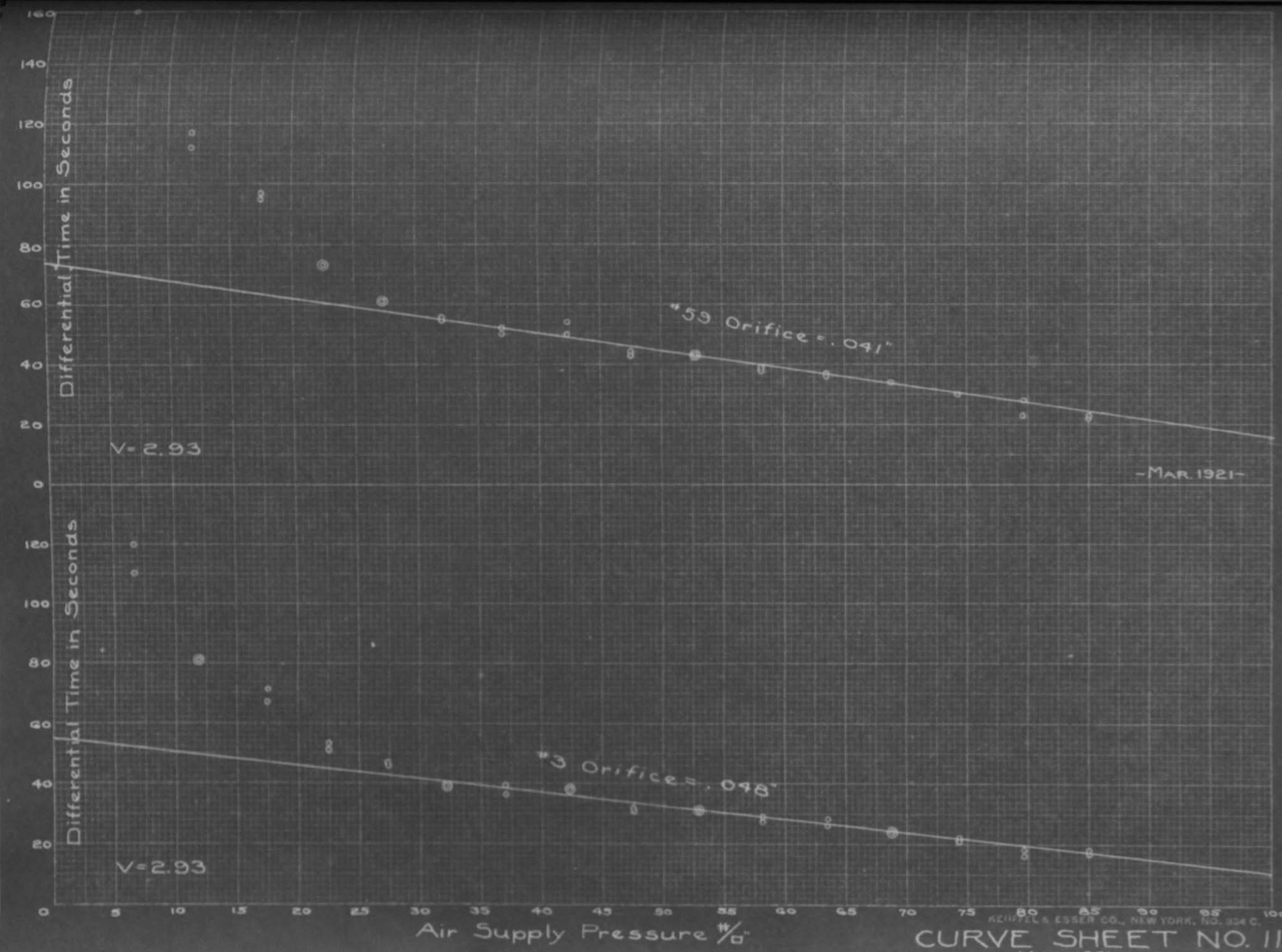
## CALIBRATION OF ORIFICES.

Analysis of the curves of differential time against pressure given on Curve Sheets 11 to 17.

| Designation and diam. of Orifice | | A=Area of Orifice sq. in. | T= T intercept. | M= Slope | V= Vol. of tank | $\frac{V}{A}$ | $\frac{M}{\frac{V}{A}}$ | $\frac{T}{M}$ |
|---|---|---|---|---|---|---|---|---|
| #59 | .041" | .00132 | 74.0 | .59 | 2.93 | 2200 | .000266 | 125.4 |
| #3 | .048 | .00181 | 55.0 | .45 | 2.93 | 1620 | .000266 | 122.0 |
| #55 | .051 | .00208 | 47.5 | .38 | 2.93 | 1405 | .000270 | 125.0 |
| $\frac{5}{64}$ | .078 | .00479 | 20.7 | .173 | 2.93 | 618 | .000283 | 119.6 |
| $\frac{3}{32}$ | .094 | .00690 | 14.5 | .12 | 2.93 | 425 | .000282 | 120.8 |
| $\frac{3}{32}$ | .094 | .00690 | 58.0 | .645 | 11.713 | 1700 | .000274 | 124.6 |
| $\frac{7}{64}$ | .109 | .00940 | 42.5 | .365 | 11.713 | 1249 | .000292 | 116.6 |
| $\frac{1}{8}$ | .125 | .01227 | 35.0 | .288 | 11.713 | 955 | .000301 | 121.4 |
| $\frac{9}{64}$ | .141 | .01553 | 28.0 | .23 | 11.713 | 755 | .000312 | 119.0 |
| $\frac{5}{32}$ | .156 | .01917 | 23.0 | .20 | 11.713 | 612 | .000327 | 115.0 |
| $\frac{11}{64}$ | .172 | .02320 | 20.0 | .175 | 11.713 | 505 | .000346 | 117.7 |

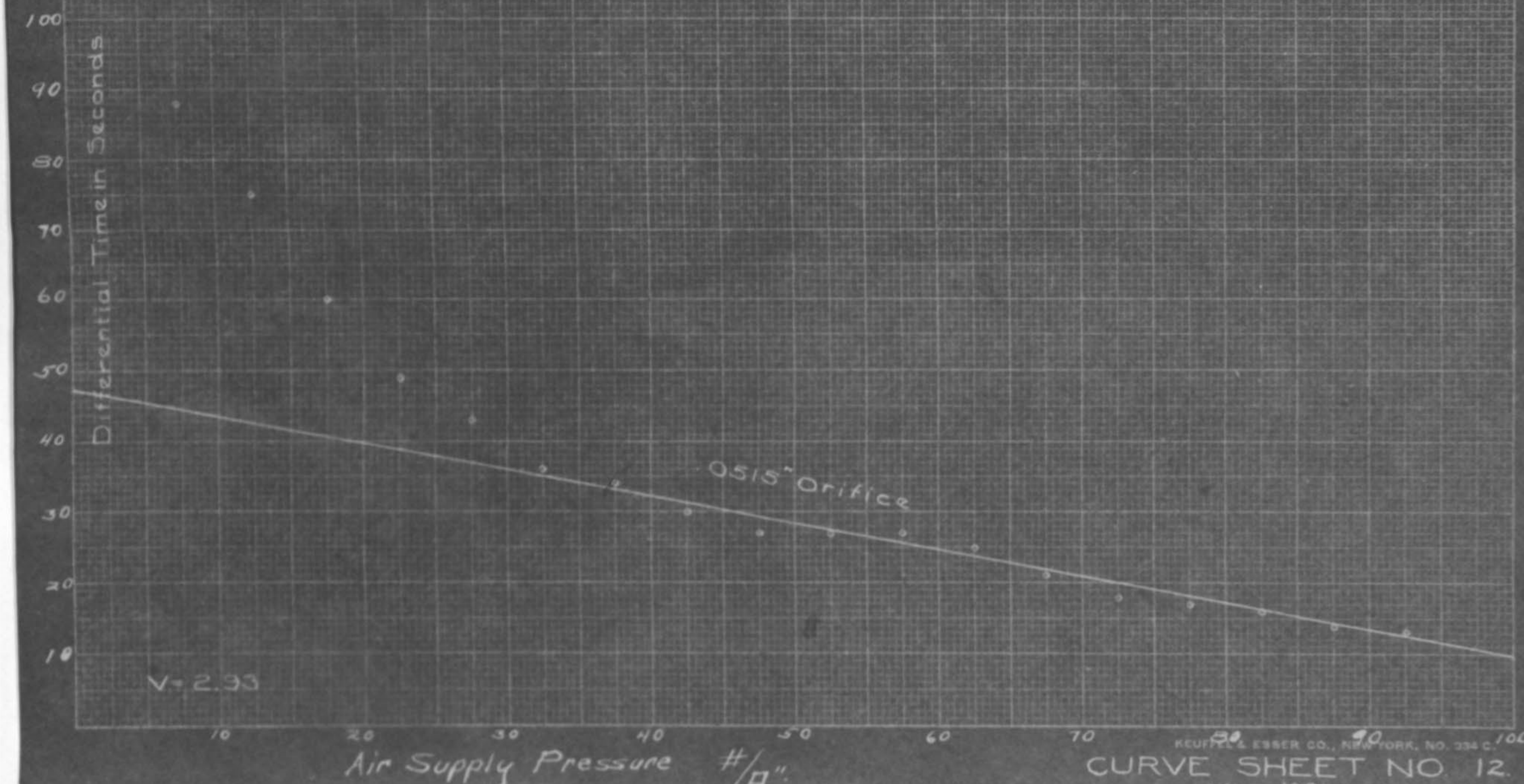
The value $\frac{T}{M}$ represents the constant of proportionality between the slope of the line and its intercept on the T-axis. The average of the values given is 120.6. Then T = 120.6M. The variation of this constant is no doubt due to experimental error.

The variations of the value of $\frac{M}{V/A}$, on the other hand, evidently increase in some regular fashion with the size of the orifice. This relation is illustrated graphically on Curve Sheet No. 20, and it is seen that there is very little irregularity in this set of values.

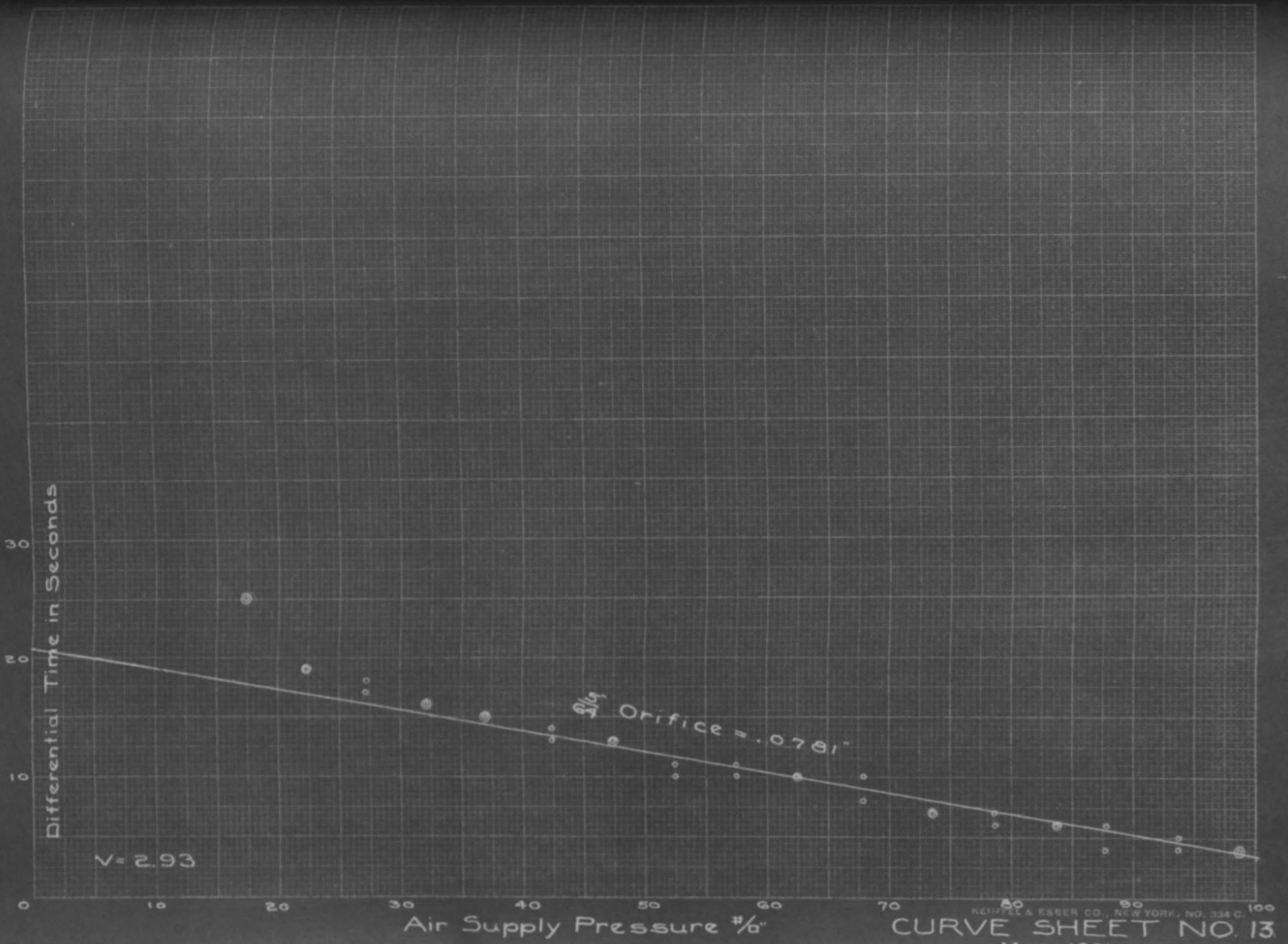


CURVE SHEET NO. 11.

-MAR. 1921-

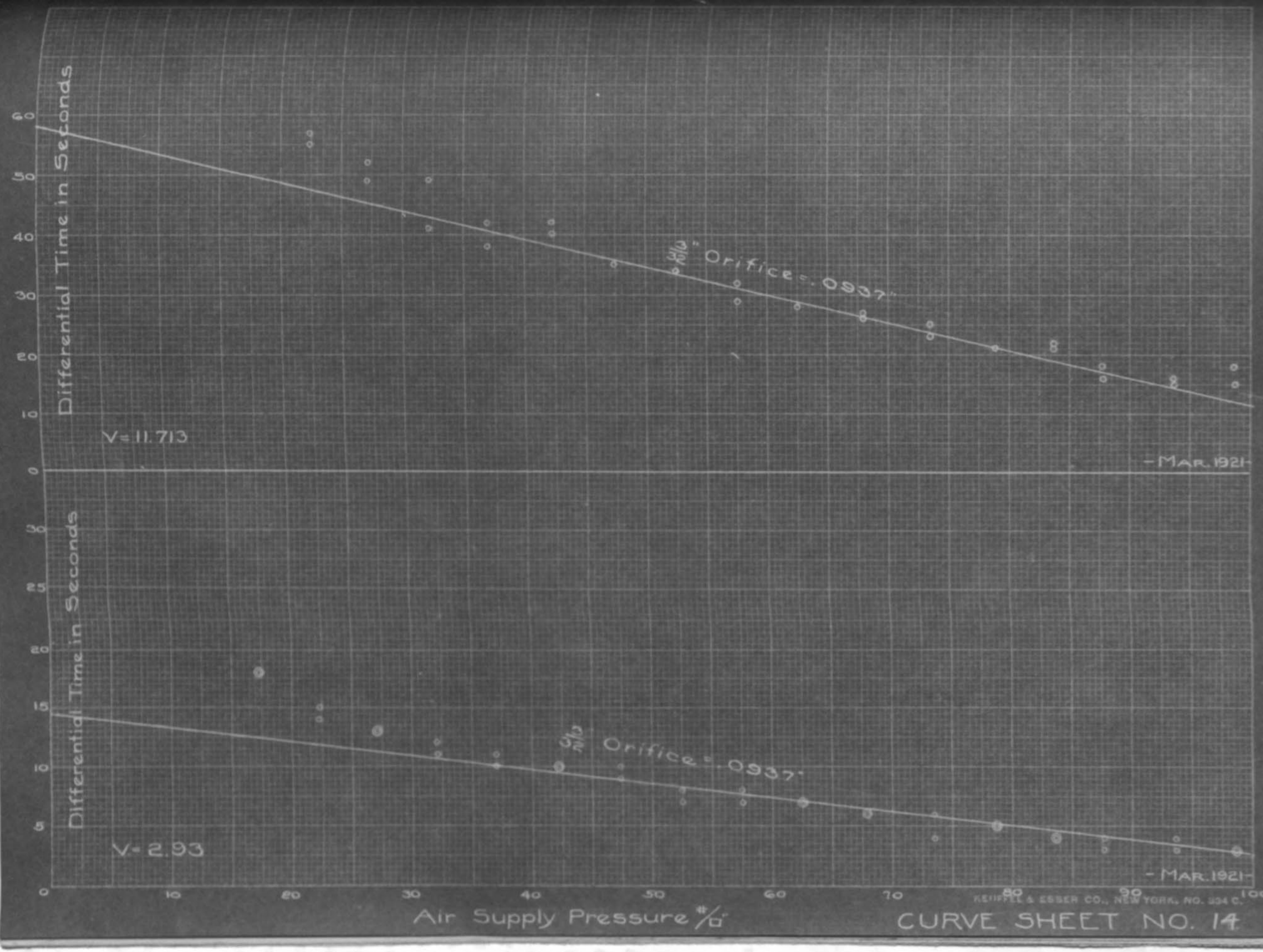


CURVE SHEET NO. 12.
-MAR. 1921-

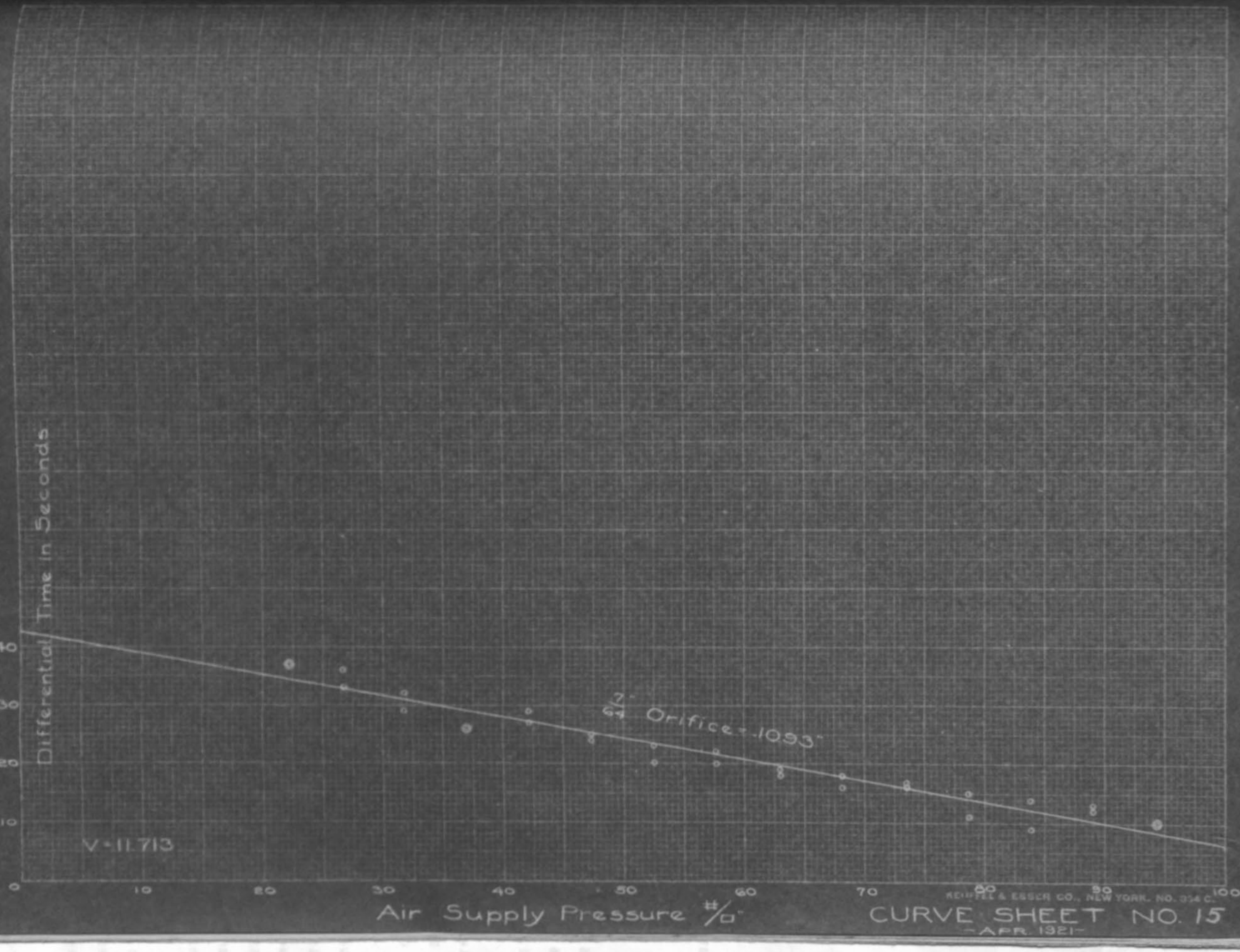


CURVE SHEET NO. 13

-MAR. 1921-

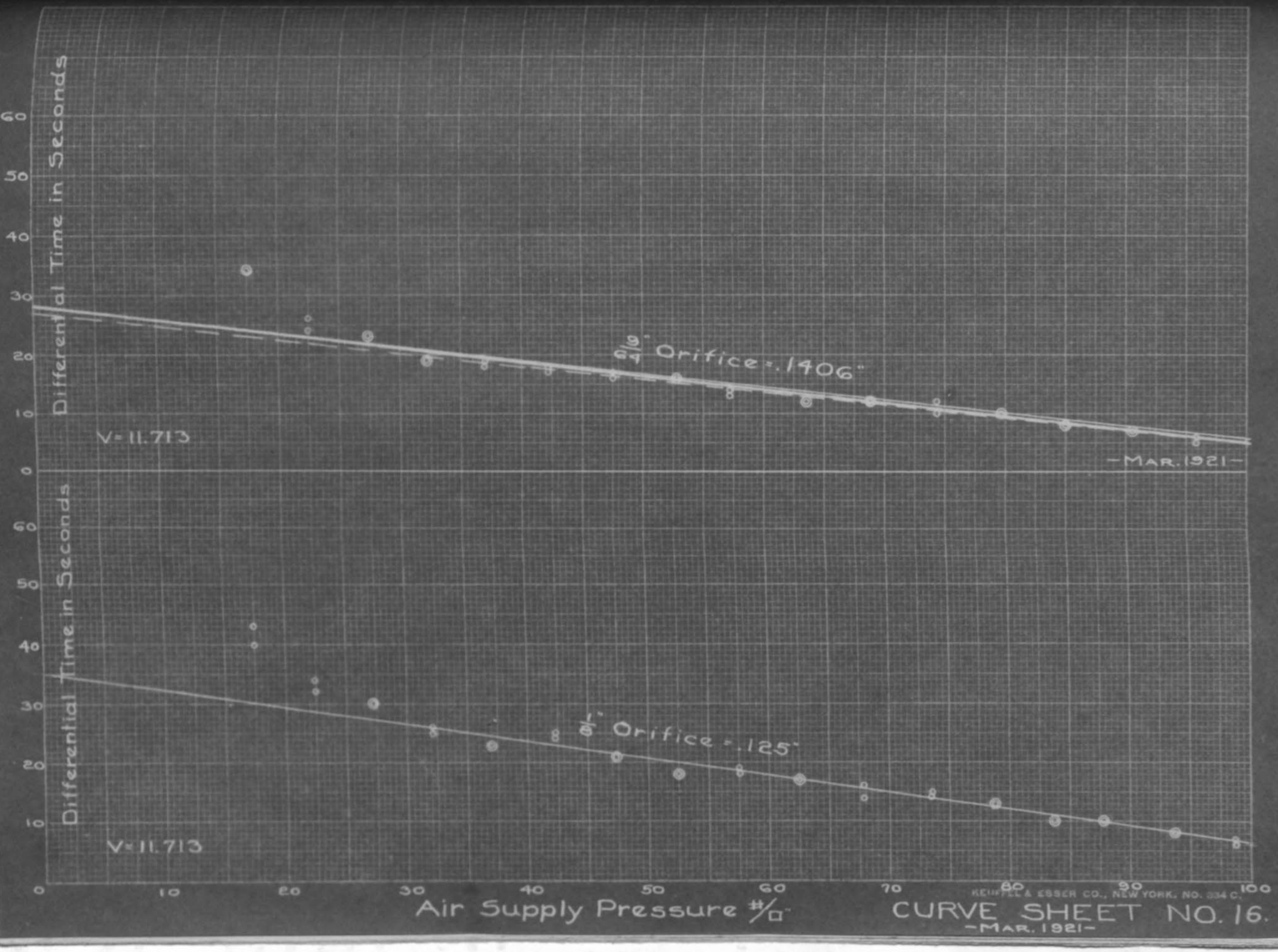


CURVE SHEET NO. 14



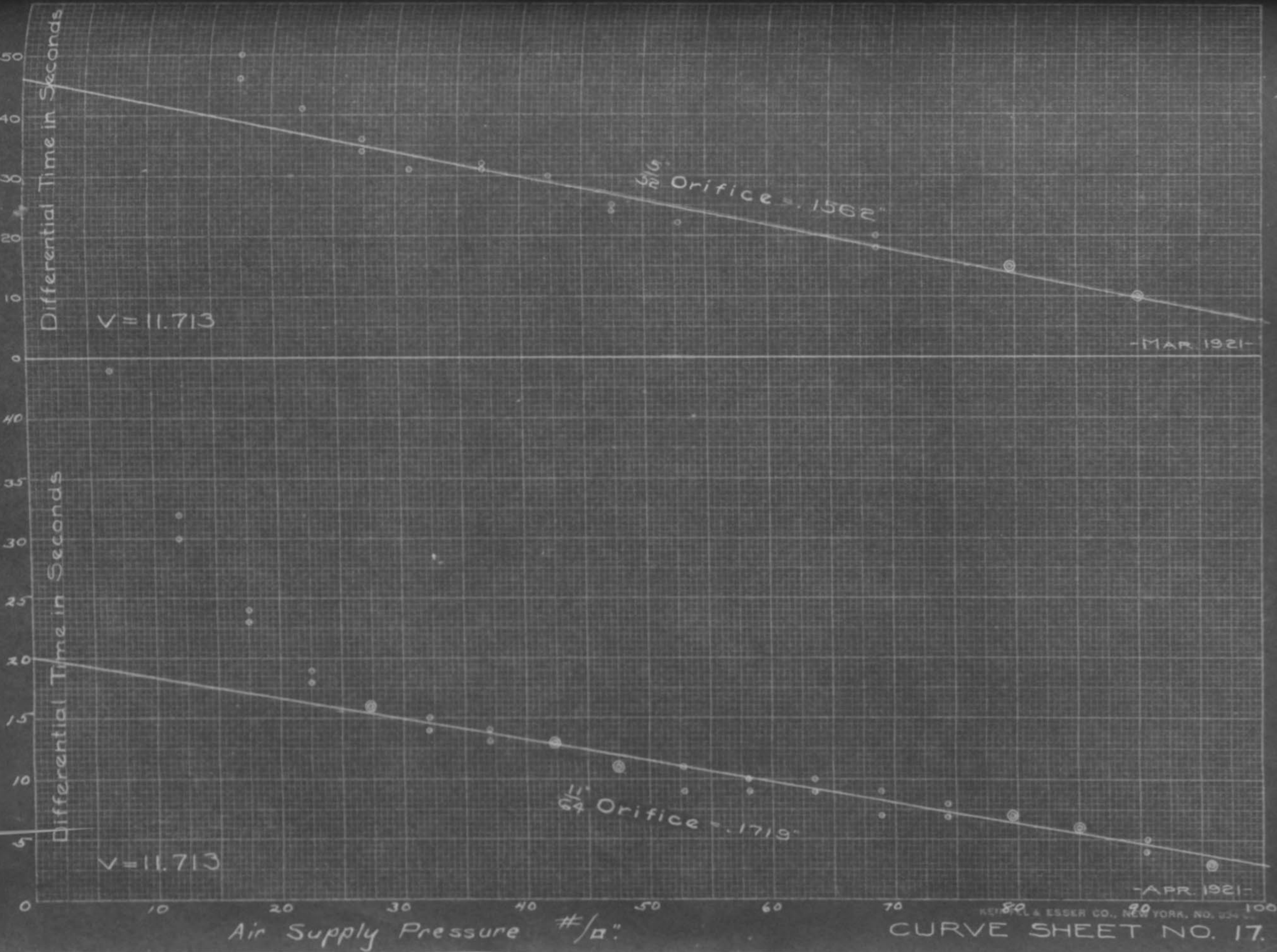
CURVE SHEET NO. 15

-APR. 1921-



CURVE SHEET NO. 16.

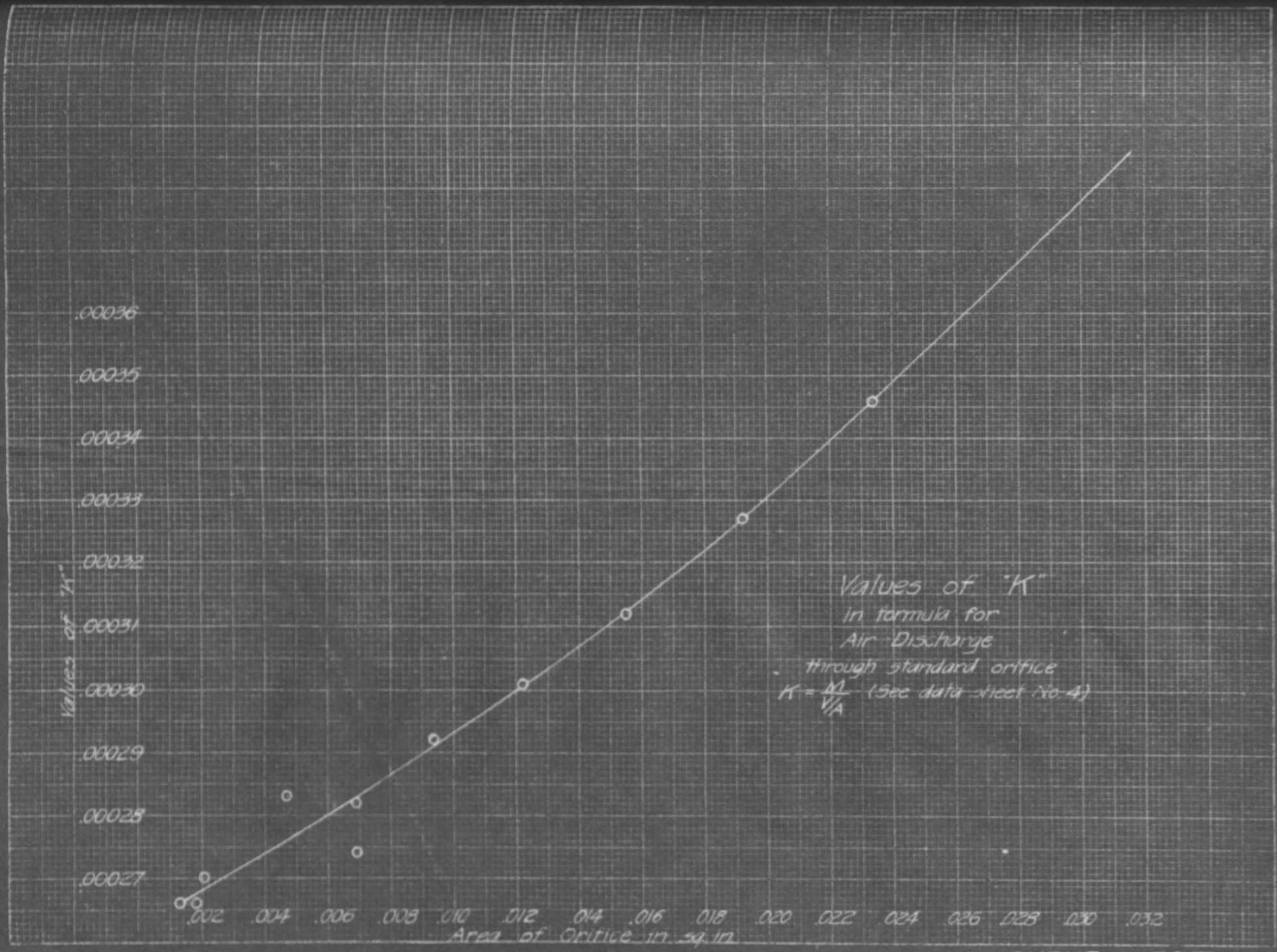
-MAR. 1921-



CURVE SHEET NO. 17.

further that the slope of the line is a function of the area of the orifice and of the volume of the receiver or tank. (This relation is: $m = -K\frac{V}{A}$. See below, Data Sheet #4, and Curve Sheet #~~20~~ 19 for values of K). These relations enable us to solve Equation (3) for $\frac{dP'}{dt}$, in terms of the area of the orifice, the volume of the receiver, and the variable P'. (See Math. Sheet (1.) for this solution).

Turning next to Equation (1), it is seen that the solution of this equation for $\frac{dW}{dt}$, the rate of discharge of the orifice, in terms of the area of the orifice and the pressure of the air supply, is not yet possible because $\frac{d\theta}{dt}$ is unknown. From several sets of time-temperature readings, however, the maximum value of $\frac{d\theta}{dt}$ at any pressure was .04 degrees per second, while the corresponding value of $\frac{dP}{dt}$ was almost 2.0 pounds per second. Also, the term containing $\frac{d\theta}{dt}$ has the second power of $\theta$ in the denominator while the term containing $\frac{dP}{dt}$ has only the first power of $\theta$. At $P = 100$ pounds per square inch gauge, the value of the latter term would be over 250 times as great as the



CURVE SHEET No. 19

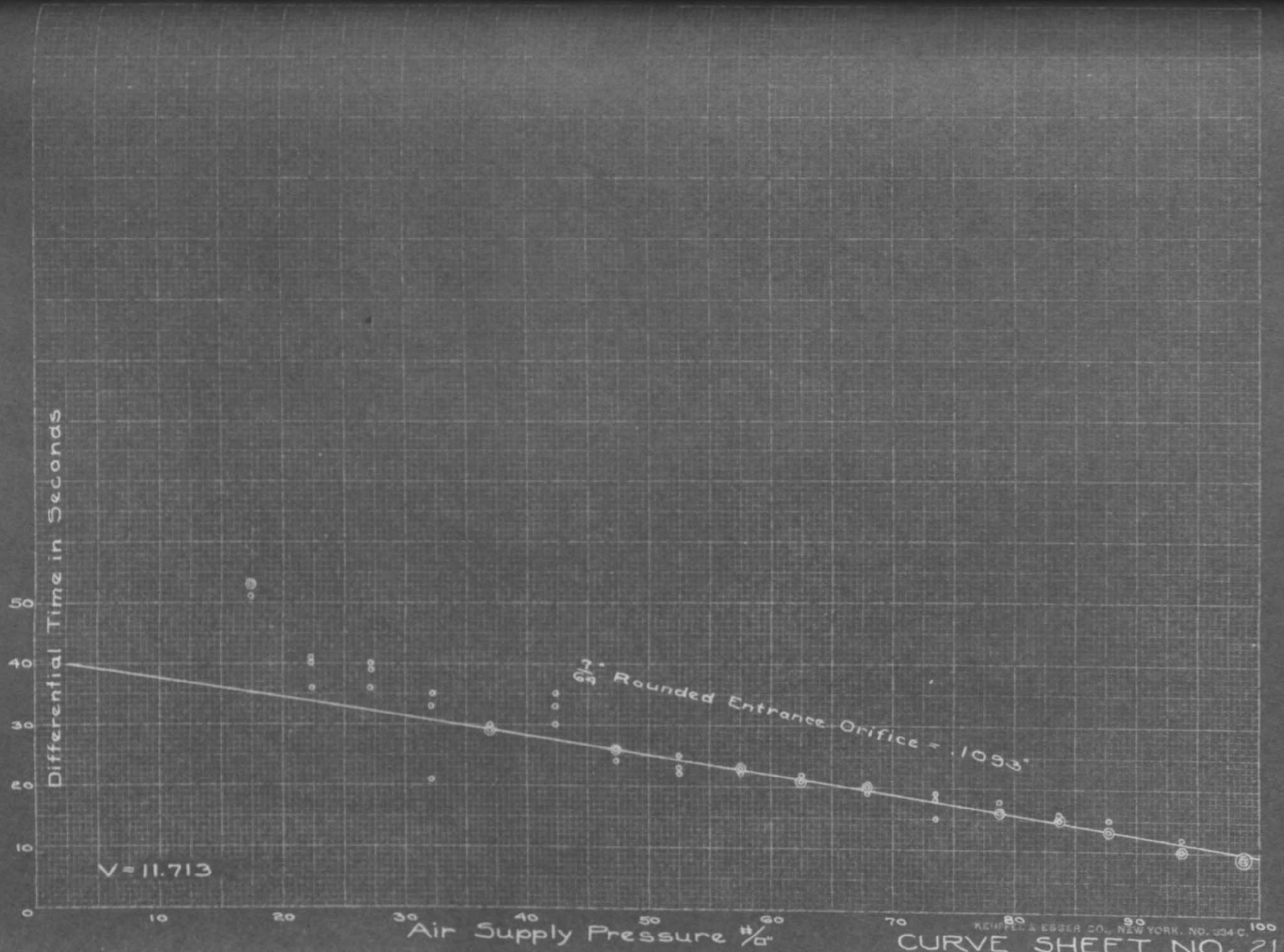
value of the former. In most instances, however, the value of the $\frac{dP}{dt}$ term will be well over 500 times as great as the value of the $\frac{d\theta}{dt}$ term. Inasmuch as the accuracy of the values of $\frac{dP}{dt}$ probably do not approach this figure of one-fifth of one percent, the term containing $\frac{d\theta}{dt}$ is left out of consideration entirely. This leaves us a formula for the rate of discharge of the orifice, in terms of the area of the orifice, the pressure of the air supply, and the temperature of the air. For the simplification of this formula, see Math. Sheet (1).

(c) Analysis of results and probable error:

Ordinary malleable pipe caps were used in making up all orifices, most of the caps being 1/4" pipe size. These were first drilled through with an ordinary twist drill of the desired final size, after which a large drill was used as a countersink to produce a "knife-edged" orifice, as shown by Sketch No. 4. This form was adopted because it can be duplicated easily, at any time and place, with materials readily available. A rounded entrance orifice was checked against the sharp-edged form, with less difference in results than might be expected, -- see Curve Sheet No. 21.

Atmospheric pressure did not enter directly into the derivation, since all results are calculated on the basis of gage pressure, which in this case is the differential pressure on the two sides of the orifice.

The various measurements were made as follows:
Diameter of orifice: Twist drill sizes. Carefully checked with new drills. Numbered drills for smaller sizes than one-sixteenth inch. Probable error not to exceed .002"



CURVE SHEET NO. 21
-MAR. 1921-

or .003". Pressures: Six new Ashcroft Bourdon gages were used. Calibrations by Crosby and American Dead-Weight Gage Testers. Time: Actual readings were cumulative time, as read on the second-hand of a watch. Differential time was obtained by subtraction. Temperatures: Read from a new S. & B. calibrated test thermometer, inserted directly into discharge line through a stuffing box.

The working temperature was about constant at 65° Fahrenheit. Probably 200 feet of pipe intervened between compressor and receiver.

A glance at the orifice formula, as derived above, shows that it gives the rate of discharge equal to infinity when the air supply pressure equals 120.6 pounds per square inch. This, of course, is an absurdity. It would be very desirable to make observations similar to the ones already made, starting with a pressure in the receiver of 130# to 150#. Attempts at such observations have been made, but results were not satisfactory because no suitable equipment was available for producing these high pressures. It is intended to make such observations as soon as possible, however. In the meantime, considering the regularity of the constants determined with different sizes of orifices and under different conditions, and the remarkably consistent straight-line character of all "differential-time-pressure" curves, there seems to be ample reason for depending on the results of this investigation within the limited range which it covers, say from 30 pounds gage to 85 pounds gage. The pressure-discharge curve for the orifices is evidently an exponential curve of some kind, a portion of which corresponds very closely to the equilateral hyperbola obtained from the straight line "differential-time-pressure" curves derived in this investigation.

It is felt that this investigation is only a good start toward the establishment of a simple and accurate direct method of measuring high pressure air. The writer was forced by the pressing of other matters to be satisfied for the time being with the progress here recorded, but hopes to turn his attention to the problem again at some future date.

## (2) The use of orifices in air flow measurements:

### (a) Method of using orifices.

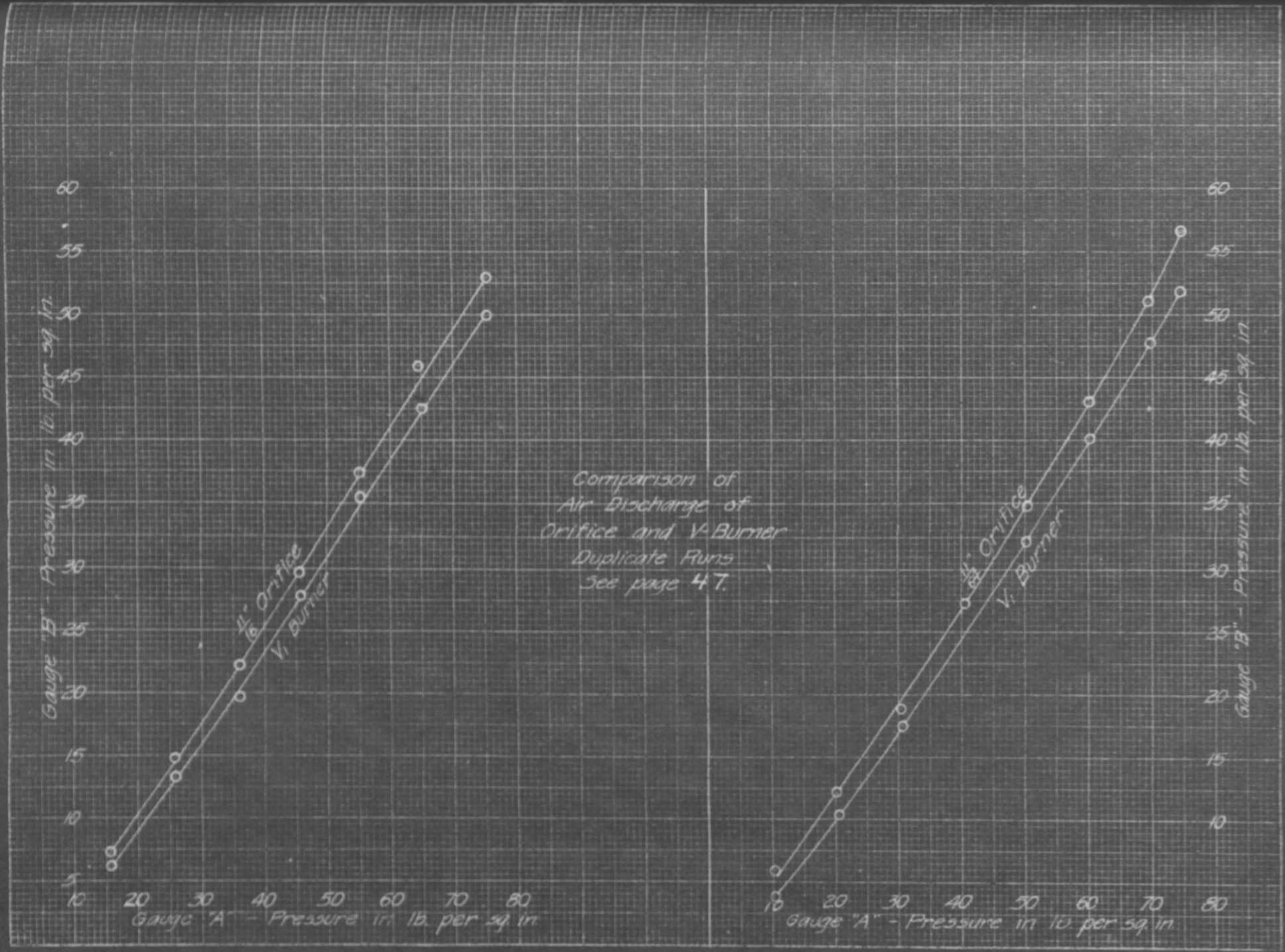
Sketch No. 5 shows the method used in measuring the air consumption of an appliance by means of the orifices described above. Valve 1 is used to vary the pressure, while valve 2 acts merely as a constant resistance in the line. The appliance is attached as shown and the amount of pressure drop between A and B caused by the resistance of valve 2, is read on the gauges, for several values of the initial pressure at A. By trial, an orifice is selected from the series which causes the same pressure drop at corresponding initial pressures as was caused by the appliance the air consumption of which is being measured. The air flow must be the same in both cases, since the pressure drop is proportional to the resistance and to the quantity of air flowing, and the resistance is constant. (Analagous to Ohm's Law: E = IR). This is a very simple method of measurement, especially since all the orifices are drilled in 1/4" pipe caps. The only apparatus then required being two 1/4" valves and two pressure gauges.

It is recognized of course, that this method of measurement has its disadvantages for certain other kinds of work, but for the burner tests here described, it served the purpose very well. It is probable that an "orifice meter" method, (large orifice in supply pipe line), could have been devised which would have been just as satisfactory as the comparison method above described. The latter method was considered first however, and after some work had been done on the same it was considered inadvisable to change. Moreover, the pipe cap orifice is somewhat more easily calibrated than the flange type orifice meter ~~flange type~~ and the apparatus for the comparison method can be readily assembled in the field, no special instruments being required.

(b) In order to determine how closely the discharge from various appliances corresponds with the discharge from a standard orifice, two methods were used:

First: With the set-up described above (sketch No. ~~4~~ 5), a series of initial pressures (Gauge A) were used and corresponding final pressures (Gauge B) taken, using first the appliance to be checked against and then the nearest corresponding standard orifice. Several sets of observations at various times and with various appliances show no appreciable difference in the characteristic pressure-discharge curve of a standard orifice and that of any nozzle or combination of nozzles whose outlets are circular in section. One of these studies is exhibited on Curve Sheet No. 22, the two sets of curves being duplicate determinations.

Second: A differential time-pressure curve was obtained for the appliance under observation, by the method used in calibrating the orifices, the appliance being substituted for the orifice (Sketch No. 3). The size of orifice equivalent to the appliance was then determined by the method described under "the use of orifices", above, Sketch No. 5. Using this equivalent area, the constants $\frac{T}{M}$ and $\frac{M}{V/A}$, discussed on Data Sheet 4, were determined from the curve and were found to approximate very closely the corresponding constants for the equivalent standard orifice. The differential time-pressure curves for these



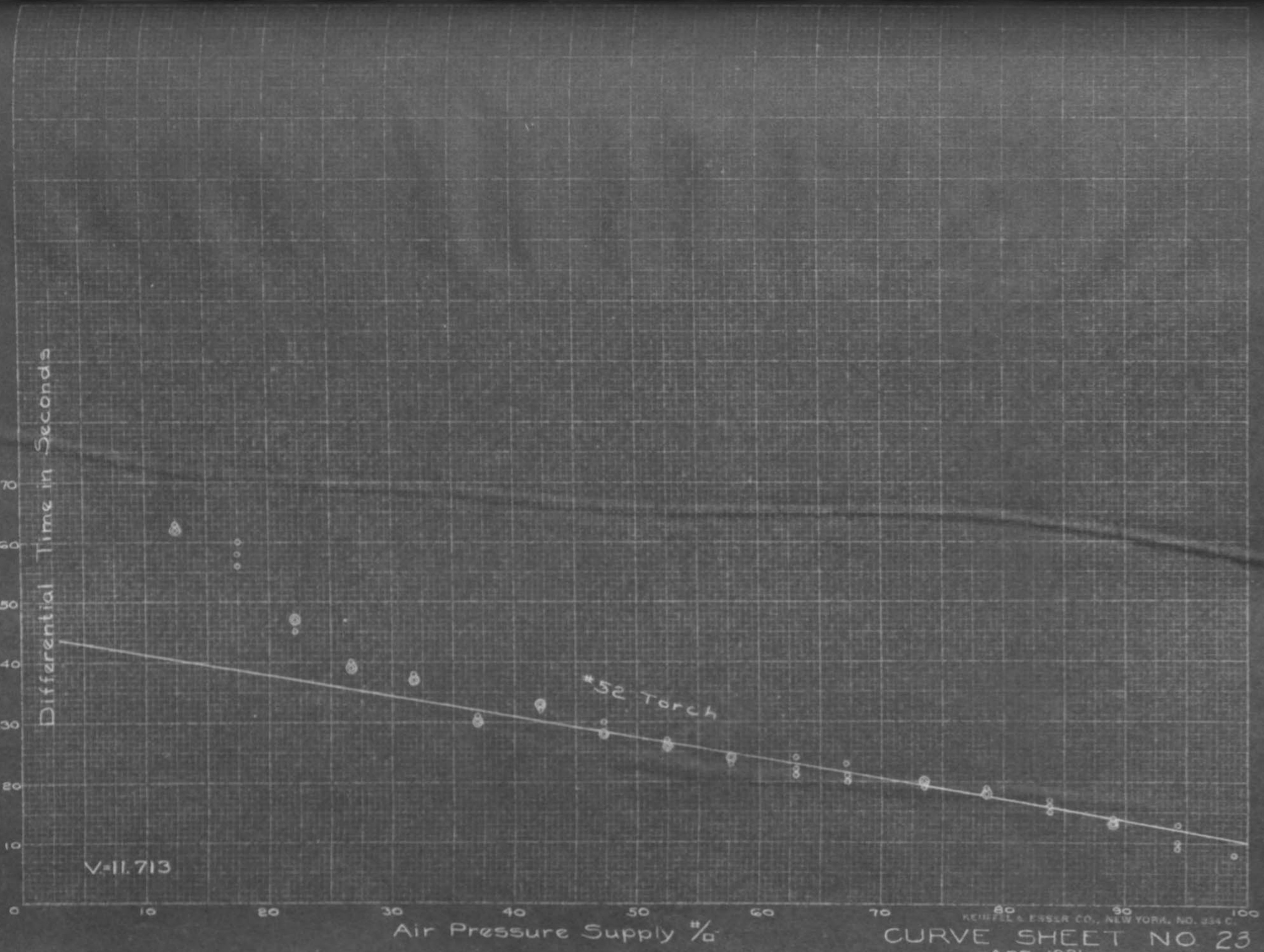
Comparison of
Air Discharge of
Orifice and V1 Burner
Duplicate Runs
See page 47.

CURVE SHEET NO 22

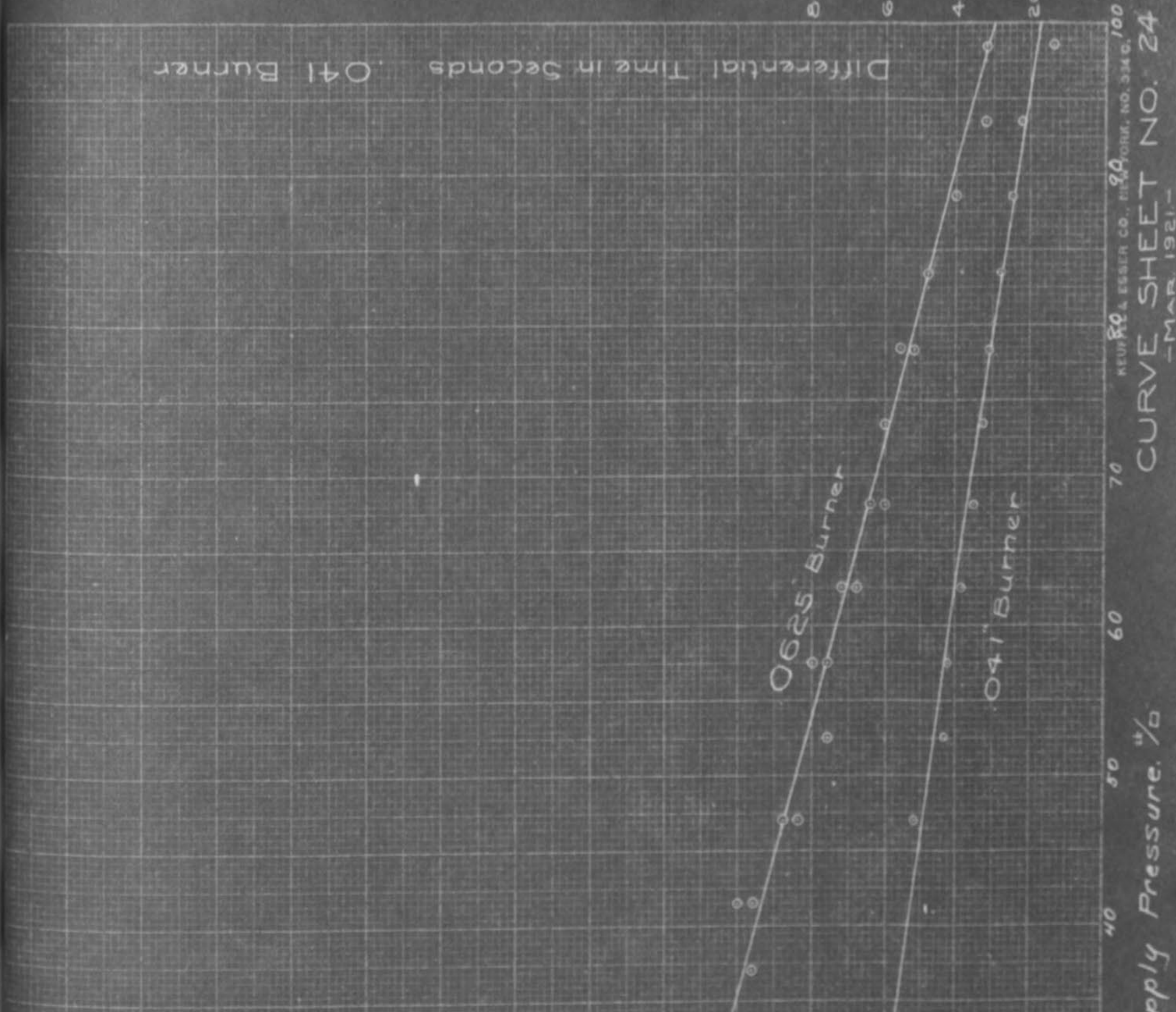
determinations are shown on Curve Sheets 23, 24, and 25.

b. A study of the factors which affect the efficiency of compressed air consumption.

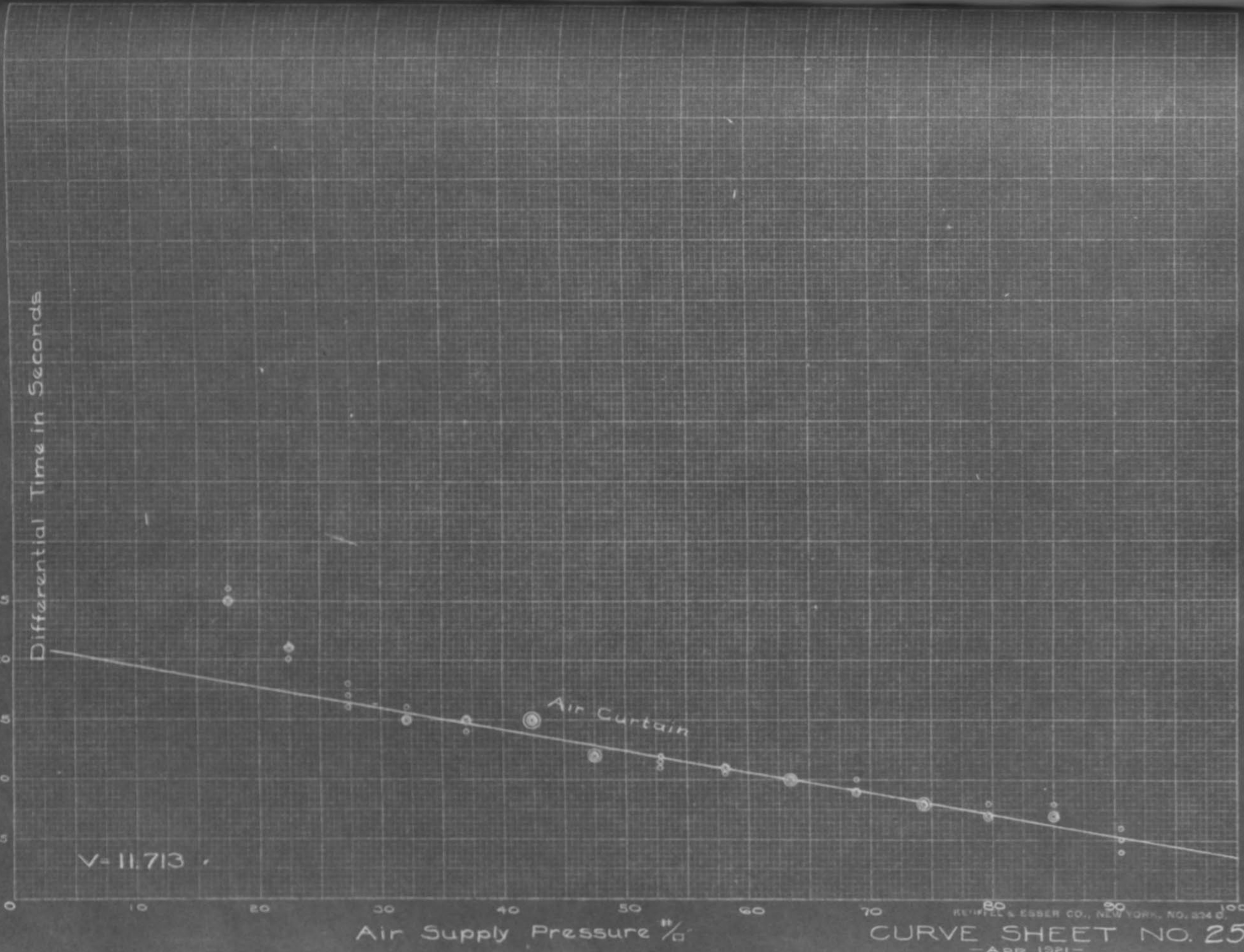
(1) Design of the expanding nozzle. It would seem reasonable to expect that a nozzle in which the air is greatly over-expanded, (as is the case in the vacuum burners), will be more efficient in the use of compressed air than one in which there is little over-expansion, for this negative pressure induces a large quantity of atmospheric air into the jet. (As mentioned above, the vacuum zone extends for some distance beyond the outlet of the nozzle.) The V-10 series of burners shows a higher air efficiency than the original V-1 series, but an analysis has not yet been made which will determine how much, if any, of this improvement is due to the greater vacuum which is produced by the V-10 type. Moreover, it has been noted that when high pressure air expands from almost <u>any</u> form of nozzle or orifice into the atmosphere, the jet induces a considerable amount of free air. The value of overexpansion and the effect of the



CURVE SHEET NO 23
-APR. 1921-



CURVE SHEET NO. 24
-MAR. 1921-



CURVE SHEET NO. 25

—APR. 1921—

form of nozzle upon the amount of air induced would form an interesting study.

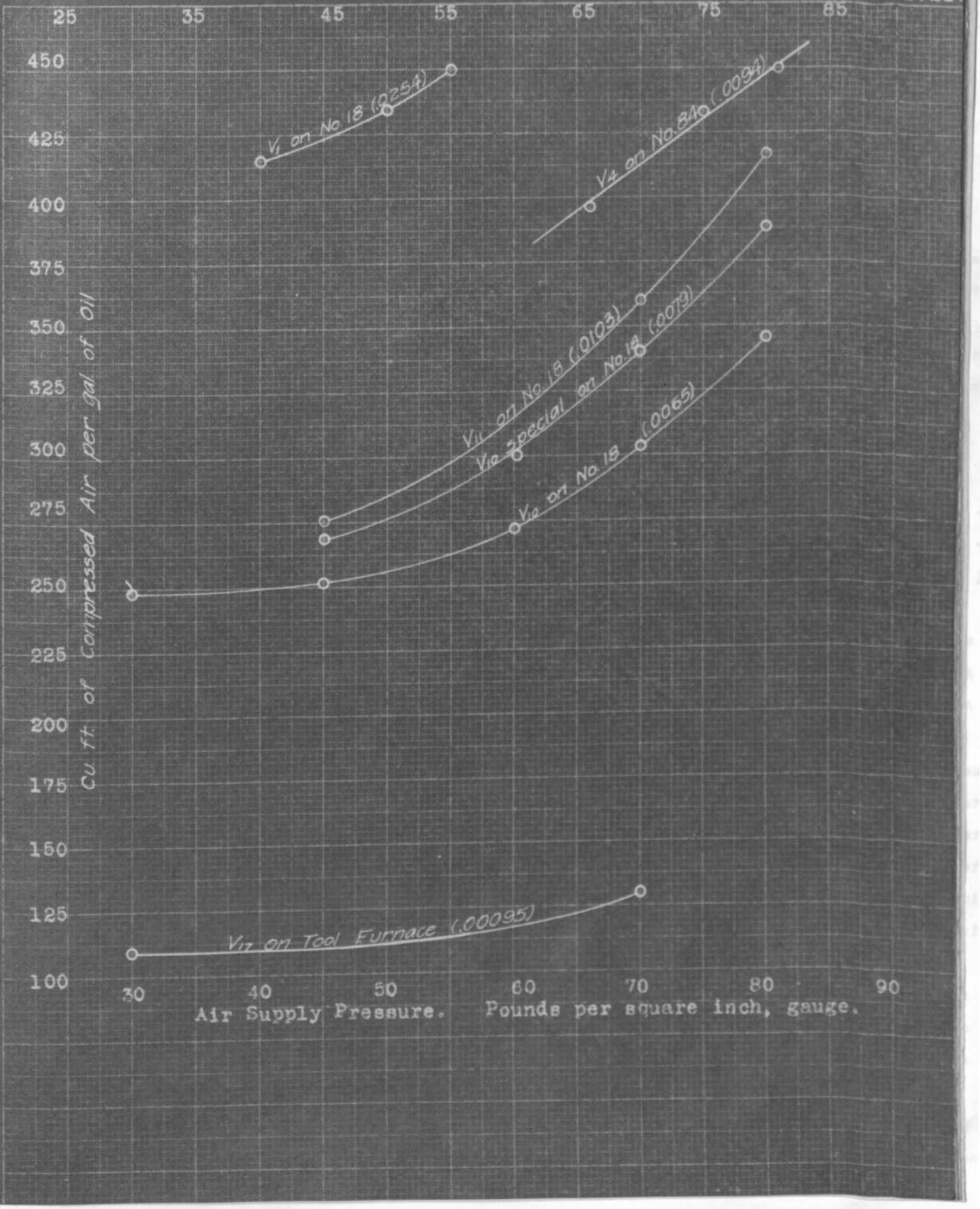
(2)-(3) Air supply pressure and diameter of air jet. Curve Sheet No. 26 is very illuminating on the effect of air supply pressure and size of jet on the amount of compressed air used per gallon of oil, and these curves represent sufficient data for reliable conclusions. (The data upon which these curves is based is given on Data Sheet No. 5.) It is seen that more compressed air is required in burning a gallon of oil when the air is supplied at higher pressures and that the curve which represents this relation assumes a fairly definite form. The curves of the V-1, V-10, V-10 special, and V-11 are especially comparable because although made at different times the same forge was used in all tests. The same size of inlet and position of burner was used, and it is evident that, under these conditions, the efficiency is a function of the size of the jet. This is probably due to the larger ratio of circumference to area in the case of a small jet. (The figures in parenthesis on the curve

## CURVE SHEET NUMBER 26.

Vacuum Burners. Compressed Air Required per Gallon of Oil.

EFFECT OF AIR SUPPLY PRESSURE AND DIAMETER OF AIR JET.

Completed
June 1921.



## DATA SHEET NO. 5.

## DEVELOPMENT OF VACUUM BURNERS.

Compressed air required per gallon of oil. Showing the effect of air supply pressure and diameter of the air jet.

| Burner and Application | Air Pressure | Air Used c.f.m. | Oil Used Gal.per hr. | Efficiency Cu.ft.air/gal.oil |
|---|---|---|---|---|
| $V_1$ on #18 Forge | 40 | 19.7 | 2.85 | 415 |
| | 50 | 22.4 | 3.10 | 434 |
| | 55 | 24.2 | 3.22 | 450 |
| $V_{11}$ on same #18 | 45 | 9.86 | 2.15 | 276 |
| | 70 | 14.75 | 2.46 | 360 |
| | 80 | 18.4 | 2.65 | 417 |
| $V_{10}$ special on same #18 | 45 | 7.78 | 1.74 | 269 |
| | 70 | 11.6 | 2.05 | 340 |
| | 80 | 14.5 | 2.24 | 388 |
| $V_{10}$ on same #18 Forge | 30 | 5.61 | 1.35 | 249 |
| | 45 | 6.72 | 1.60 | 252 |
| | 60 | 8.40 | 1.85 | 272 |
| | 70 | 10.1 | 2.00 | 303 |
| | 80 | 12.5 | 2.17 | 346 |
| $V_4$ on #84 | 66 | 12.6 | 1.90 | 398 |
| | 75 | 15.1 | 2;09 | 433 |
| | 81 | 17.4 | 2.32 | 450 |

Kerosene oil was used as fuel on all the above tests. All figures on oil consumption were checked by duplicate runs.

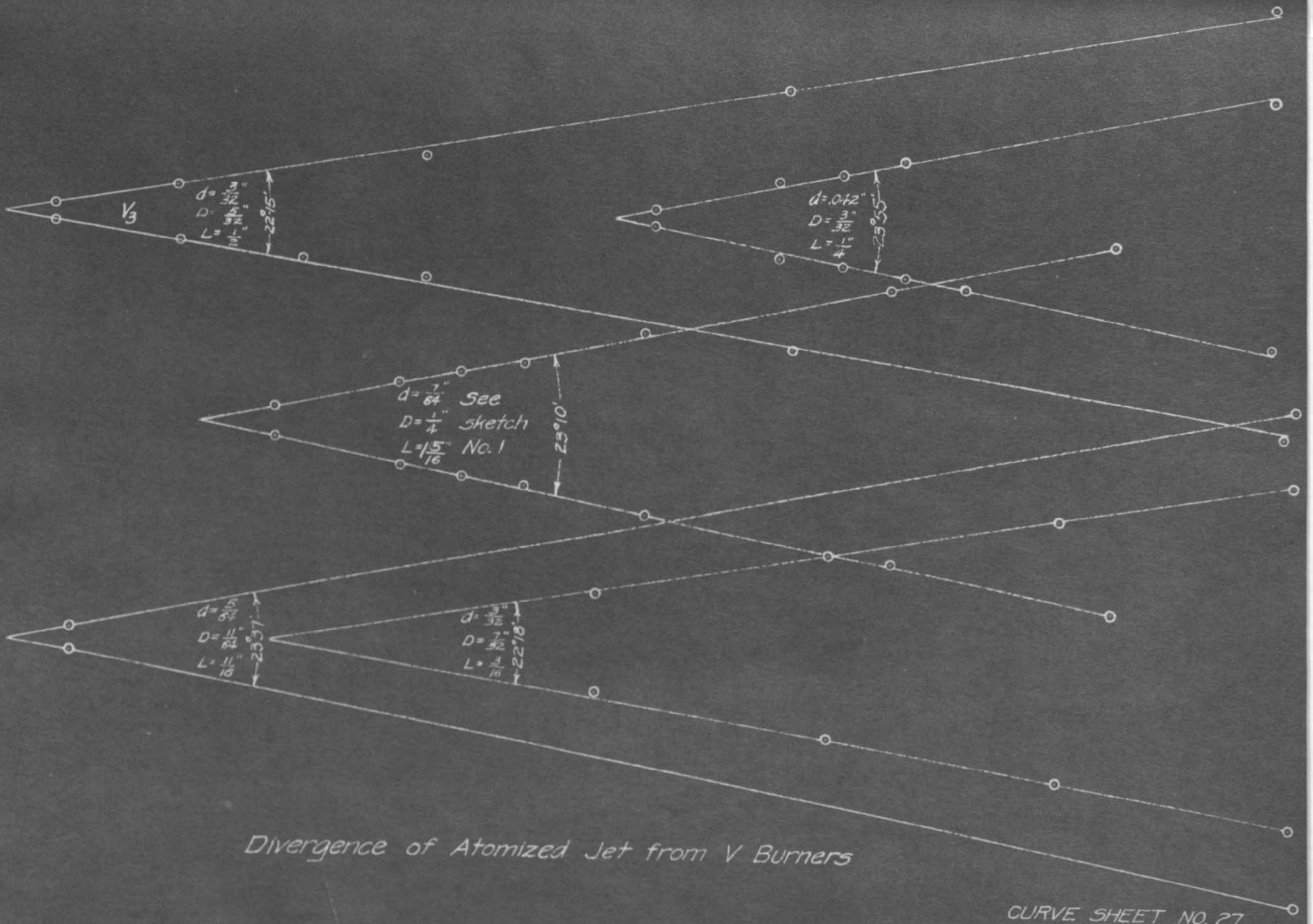
sheet represent equivalent orifice area in square inches). It might seem reasonable to expect that if the proportions of the inlet and position of the burner had been varied in accordance with the size of jet, the same efficiency might have been maintained. A large number of experiments, however, on several kinds of burners applied to various kinds of combustion chambers, indicate that even with the best proportions of inlet and combustion chamber the air efficiency is higher with the smaller jet burners. With the present type of vacuum burner this means that the smaller the capacity of the burner, the higher the efficiency. Hence the high cost of operation of high-pressure single-jet burners on large installations and the consequent advantage of using low pressure air in such installations. However, the multiple-jet type of burner (such as the Mahr pressure torch burner) can be made very efficient in the large sizes. The higher efficiency of the small jet in inducing atmospheric air is also very evident in this type of burner, witness the recent improvement in the No. 3 size torch, when the air consumption was reduced to less than 50% of its former value by reducing the size and changing the arrangement of the jets. No doubt there are possibilities in the multiple-jet burner which have not yet been realized.

(4) Inlet of the combustion chamber. The size and shape of inlet surrounding the jet, and the relative position of the burner, have an important bearing on the amount of free air induced by the jet. There is no doubt a definite value of each of these factors for each size of jet, and probably also for each pressure, if highest efficiency is to be secured. Other considerations play a large part in determining these dimensions however, and these generally make it necessary to use a smaller inlet and to place the burner closer than would give the highest efficiency. If a strictly uniform neutral or reducing atmosphere is important the inlet must be small enough so that it is well filled with flame and the burner close enough so that the velocity in the jet (with lowest operating pressure) is well above the velocity of propagation of the flame so that the flame shall not "backfire". Limited space and

interference by wind are other reasons for placing the burner close and making the inlet small. Cylindrical inlets, or even "any kind of a hole in the furnace" are often used, with resulting low efficiency. A number of studies in the subject have been made but it is not felt that the best combination has been arrived at and it is intended to continue the studies. Although the divergence of the jet changes slightly with increase in pressure, the change is not great and, as is shown on Curve Sheet No. 27, the angle of divergence is about 23° for nozzles of widely differing proportions.

(5) Design of combustion and heating chambers. This is of great importance in securing a high efficiency in the use of compressed air. The design should be such as will offer the least resistance to the passage of the gases which is consistent with other requirements. In a refractory combustion chamber it is generally necessary to use a flash wall with a high pressure burner. Care should be taken that this flash wall does not introduce more resistance than is necessary, and the arrangement

Divergence of Atomized Jet from V Burners.



Divergence of Atomized Jet from V Burners

CURVE SHEET NO. 27.

should be such that the jet or flame is not required to turn sharp corners. A case in point is illustrated by the material presented on Data Sheet No. 6 . Other similar cases have given results even more striking. Another resistance which frequently cuts the efficiency is that of small and insufficient vents.

(6) Burner capacity. A considerable number of the burners in use (especially those used for intermittent heating, as in rivet forges, torches, etc.), are over-capacity. From the standpoint of a lazy workman this is a good thing, for it means that the work will heat more rapidly and hence less care needs be used in keeping the correct number of pieces charged. But the cost per unit product is increased not only by the additional oil and air used, but also because the excessive temperatures produced necessitate frequent renewals of the combustion chamber (or its lining). As a concrete example of the savings which can be effected by a study of capacity requirements, the Mahr #18 Rivet Forge was formerly equipped with a burner and air curtain the air consumption of which was 71.3 cu.

ft. per minute at 80 pounds per sq. in. pressure. The oil used was about 3.8 gal. per hour. Careful tests showed that both burner and air curtain were over-capacity and the new burner and air curtain adopted as ample for this forge showed an air consumption of 26.1 cu. ft. per minute and used 2.8 gal. of oil per hour. With air at 35 cents per M and oil at 10 cents per gallon, this means a saving of $1.05 during every hour of operation as compared with the old equipment.

2. Efficiency of Heat Application.

Lack of time has made it impossible to do more than indicate the nature of this part of the problem.

Highest efficiency of heat application may be defined as the securing of correct quantity and intensity of heat and the application of this heat where it is most effective. The obtaining of this result is largely the problem of correct design of combustion and heating chambers.

The heat losses must be reduced to a minimum. These losses are of two kinds. (1) Heat lost in the gases issuing from vents or outlets and (2) Heat lost by radiation. The first loss may be greatly reduced by so designing the combustion and heating chambers that the high temperatures are produced where they are utilized and by arranging the gas passages and vents such that the most possible heat will be abstracted from the gases before they leave the unit. In most refractory chambers the radiation loss may be made negligible by the proper thickness of wall, and proper use of insulating materials. For forging, welding, and certain other work requiring extremely high temperatures, however, a certain amount of heat loss by radiation is unavoidable as present day refractories will not withstand these high temperatures. For this reason, insulation for the purpose of retaining the heat, cannot be used on such installations.