GENERAL ENGINEERING LABORATORY

A GRAPHICAL APPROACH TO VACUUM ENGINEERING

by

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GENERAL ELECTRIC

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Copies of the graphs referred to in this report are available from the General Electric Company Interplant Stationery Warehouse, Schenectady, New York.

FN756A - Vacuum Engineering Graph I - for Systems

FN756B - Vacuum Engineering Graph II - for Leaks

CONTENTS

I. INTRODUCTION

In recent years the number of vacuum engineering applications has increased at a very rapid rate. Many new industrial processes require more and better vacuum systems. Vacuum design has left the realm where educated guesses are sufficiently good for a particular system and progressed to where competition has required far greater accuracy and a correspondingly broader understanding of vacuum engineering.

Many of the mathematical equations describing gas flow in vacuum systems have been known for years. The computations required to describe fully the gas flow in the different sized pipes and pumps of a simple vacuum system are laborious to make. To include outgassing, leakage, and permeation adds to the complexity. Far worse are the complex integrations of flow versus pressure, which are required to determine the relation between pressure and time in the evacuation of a vacuum system. The tedious repetition of these gas flow calculations has justified efforts to evolve a simple, reasonably accurate, and speedy method of solution. Many nomograms have been published, generally by vacuum equipment companies These all have the same limitation: They each cover only a small segment of the necessary calculations. One might be for viscous flow in pipes, another for molecular flow, and a third to aid in the selection of the proper pump. The need for the combination of all nomograms into one compact solution which would cover all parts of a vacuum system in all of its ranges of pressure, has led to the nomographic solution presented in this report. This graphical technique of representing these equations has resulted in a great reduction in both the time and effort required to describe and understand a vacuum system. Furthermore, the final answers are presented in a graphical form so that the basic objections or advantages of a particular configuration are readily grasped even by persons not familiar with vacuum theory.

II. SUMMARY

This report explains the basic operations necessary to utilize fully this type of graphical presentation. It explains a superposition approach to the gas flow in vacuum components that allows the solution of each individual component, as well as the graphical combination of any number of components, the net result being that a characteristic curve can be drawn for any point of a vacuum system. This curve, which gives the relation between pressure and thruput, can be

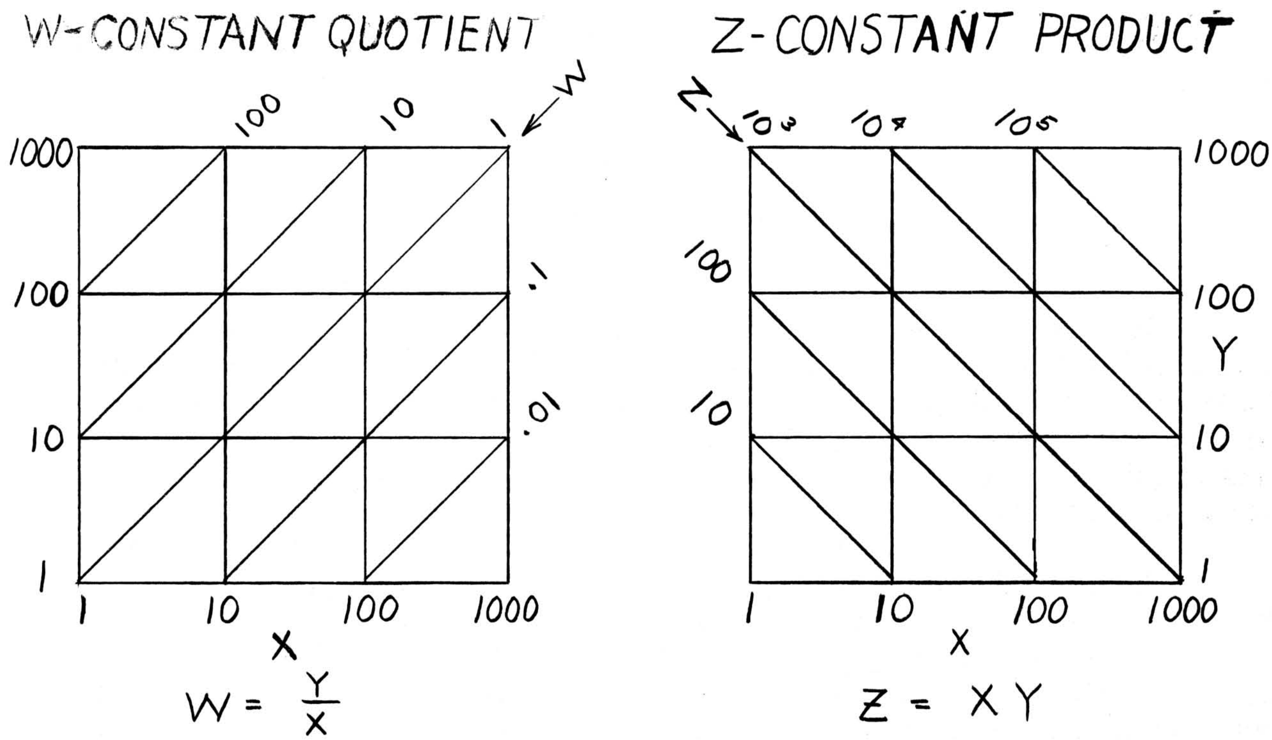


Figure 1

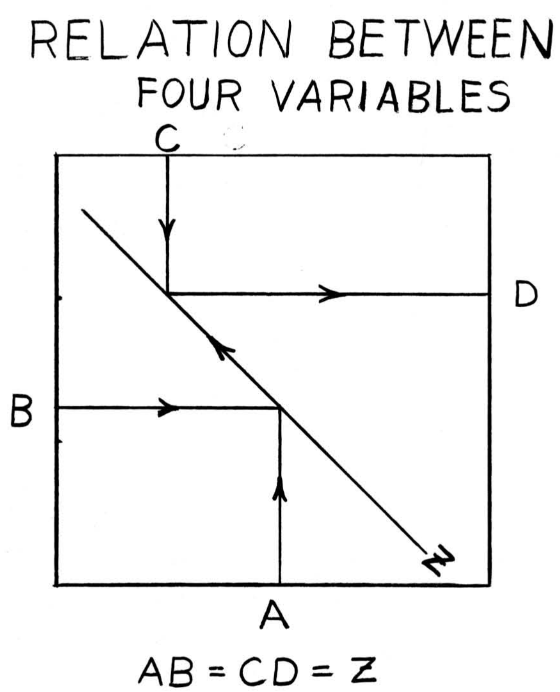


Figure 2

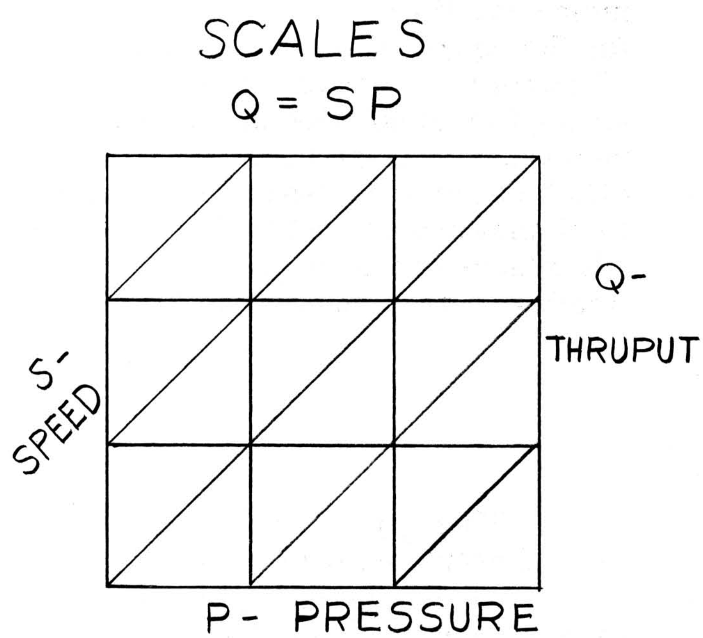


Figure 3

graphically integrated to yield the pressure versus time relationship occurring during pump down. Other applications which are possible with the graph include conversion of leak rates for different gases at different pressures, time response of leak detection, analysis of vacuum processes, and the design of filters and baffles.

III. GENERAL NOMOGRAPHIC SOLUTION

Since this new approach is a graphical one, it seems worth while to review a few of the basic manipulations which are applicable to this type of solution. Let us consider two factors, X and Y. If we scale these on log log coordinates, we observe two relationships (Fig. 1). Any line with a slope of +1 is a constant quotient of Y/X, while any line with a slope of -1 is a constant product of XY. By adding a number of these W or Z lines and properly marking their scales we obtain a direct solution to the relations $W = Y/X$ and $Z = XY$.

If it is desirable to solve an equation of the form $AB = CD$, we temporarily let each side of the equation equal an unknown factor. We then have $AB = Z$ and $CD = Z$. We prepare our graph to have four scales. From two of the known factors, either A and B or C and D we obtain the constant product line Z. By moving along this line to the third known factor we obtain the solution for the fourth or unknown factor. Multiplication by a constant can be obtained by shifting the scale of any one of the factors. Powers can be introduced by changing the physical scale size. Reciprocal relations can be obtained by scale inversion. Complicated functions can frequently be handled by curved scales. There are the basic manipulations which we will necessarily use frequently. Other manipulations which are required will be explained as they occur.

IV. FUNDAMENTALS

In order to proceed we must define our units and the quantities which are found in vacuum equations. We must also choose their axis on our graph. We begin with the relation $Q = SP$, (Fig. 3) where Q is the thruput or flow in mm. liters per second, S is the speed in liters per second, and P is the absolute pressure in mm. of mercury. Our choice of axes is the same as those used by Dr. Lawrence in his graphical analysis of vacuum pumps.[1,2]

We now take our first departure from standard techniques. We assume that the gas flow through any component of a vacuum system can be divided into two parts, a forward flow and a backward flow. (Fig. 4). Their difference represents the true flow. Furthermore, we demand that the mathematical relation between

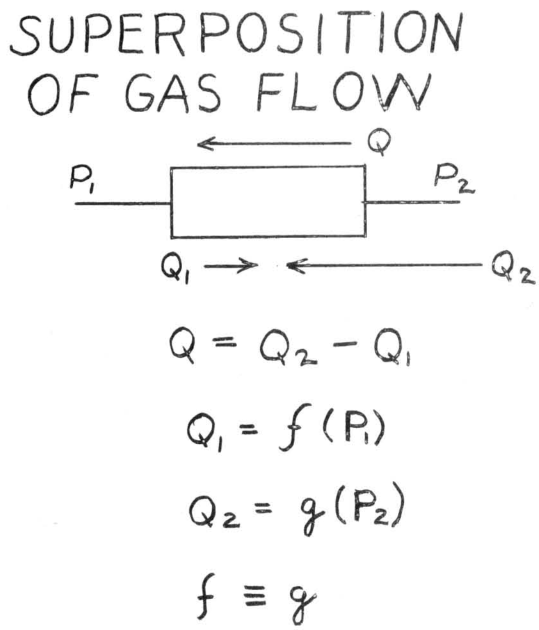


Figure 4

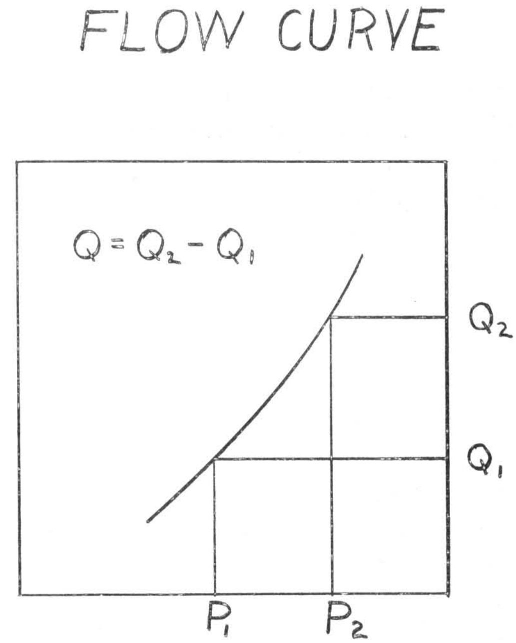


Figure 5

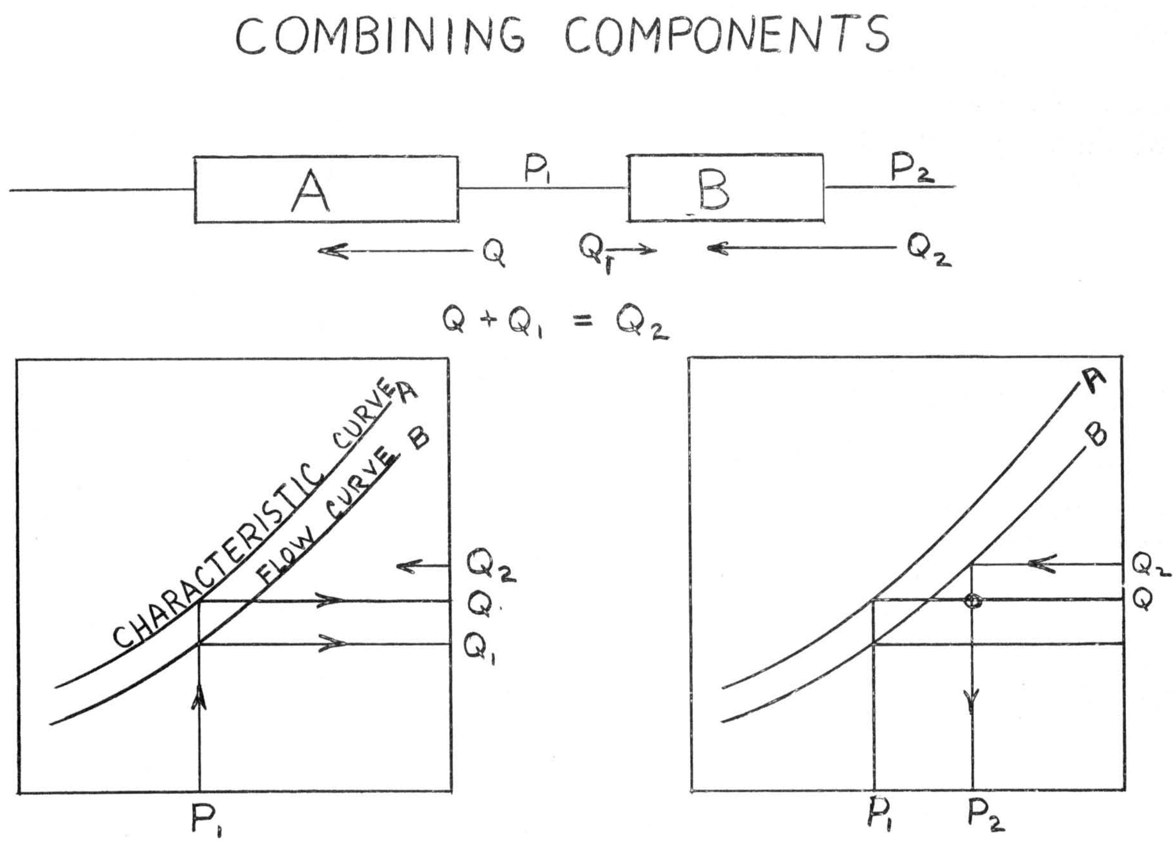


Figure 6

the forward flow and the high side pressure be identical to the relation between the backward flow and the low side pressure. These are necessary conditions which must be imposed on all vacuum equations which are to fit this solution. When we plot on our graph the reduced relation $Q = f(P)$ we obtain what we define as the flow curve of the component. The intersection of any pressure with this line determines the flow. By choosing both a high side and a low side pressure as shown in Fig. 5, we obtain two flows - the forward flow and the backward flow. The numerical difference between these two flows is the true flow for the chosen values of pressure in the graphed component.

We next define a specialized case of the flow curve where the backward flow is equal to zero or where the true mass flow is known as a function of the inlet pressure, that is, independent of the exhaust pressure, at least within certain limits. We define this curve as a characteristic curve.

Our next step is to combine the flow curves of all components of a system into a single characteristic curve representing the entire system. A necessary condition for obtaining a system's characteristic curve is that the flow curve for the component operating at the lowest pressure in the system be a characteristic curve (the backward flow must be zero). Since vacuum pumps are the components operating at lowest pressure, it is of interest to note that the pumping curves given by manufacturers are characteristic curves. The thruput, or speed is always given as a function of the inlet pressure only, the down-stream pressure of a pump being relatively unimportant. The method of combining curves can be illustrated by two components connected in series(Fig. 6). We plot on our graph the characteristic curve of the first component A and the flow curve for the second component B. By arbitrarily choosing a value for their intermediate pressure (P_1) we obtain the two flows indicated: the true flow through the system (Q) and the backward flow through component B (Q_1). The sum of these flows must equal the forward flow through B (Q_2). Where this new thruput intersects curve B, we obtain the inlet pressure (P_2). The intersection of the inlet pressure and the true flow yields one point on the curve which defines the relation between the system's inlet pressure and the true flow. This curve is, therefore, the characteristic curve of the combination. By repeating this process at different values of P_1, the entire curve can be obtained. In the same manner we can add the flow curve for the next component and obtain another characteristic curve of the total; and hence, by repeating the process, we can obtain the characteristic curve of any series system. The flow curves of parallel branches in a vacuum system are easily combined into a net flow curve. A point on this new curve can be obtained by adding the branch thruputs together at constant pressure as in Fig. 7. This new flow curve can then be handled like any other flow curve.

PARALLEL BRANCHES

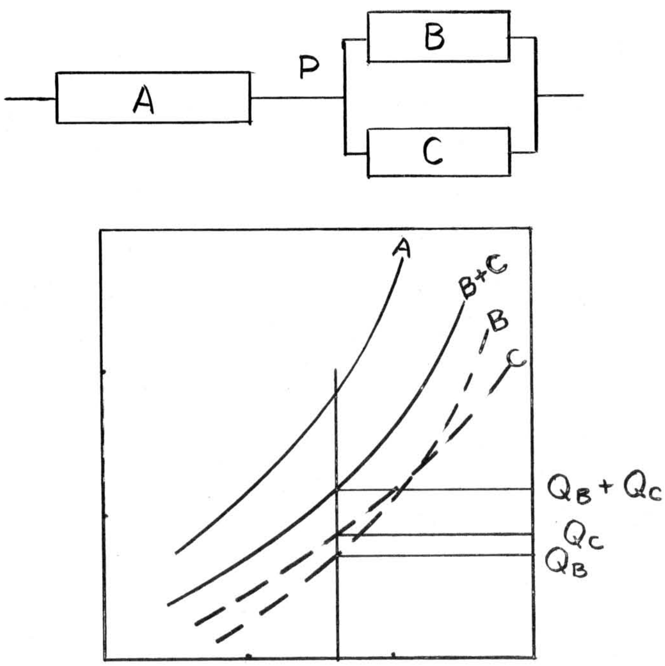


Figure 7

PRESSURE DISTRIBUTION

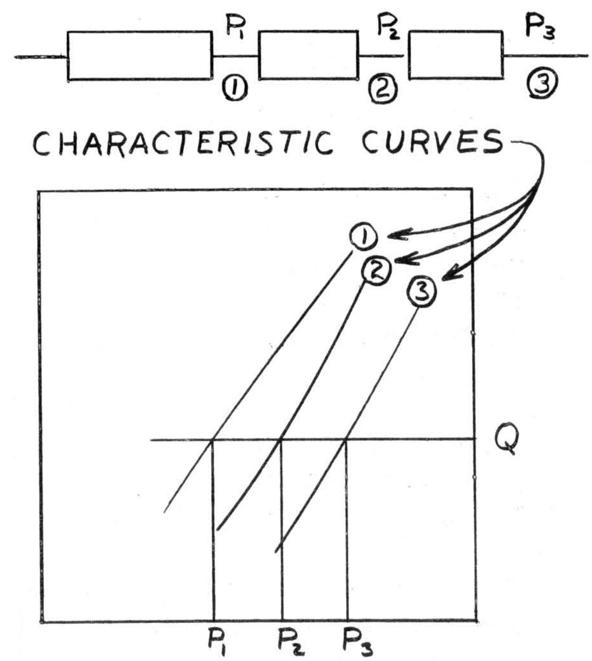
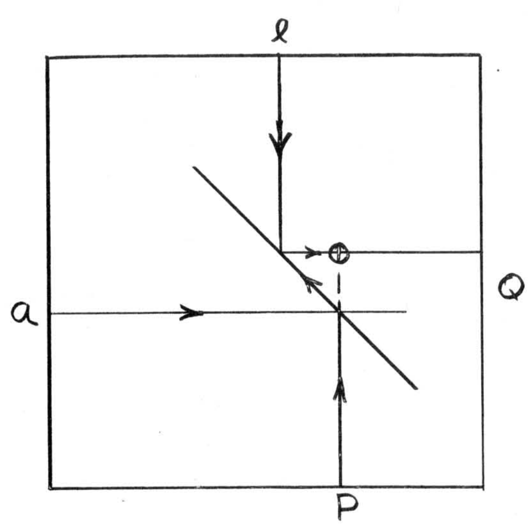


Figure 8

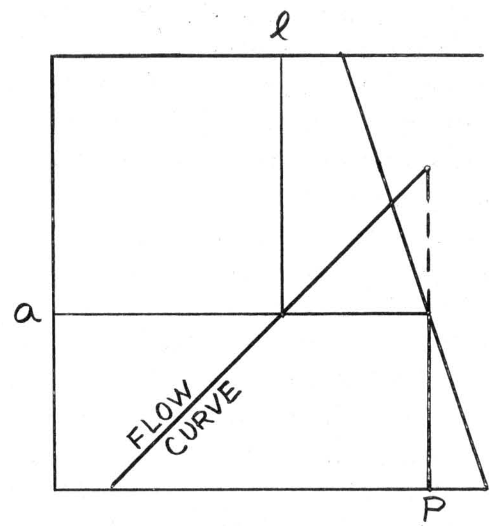
FLOW CURVE CONSTRUCTION IN MOLECULAR FLOW



$$Q\ell = Ka^3P$$

Figure 9

LIMITING PRESSURE IN MOLECULAR FLOW



$$Q\ell = Ka^3P$$

Figure 10

The characteristic curves obtained in the foregoing describe completely the pressure distribution in the system since the total amount of gas flowing must be conserved. A line of constant thruput intersects each characteristic curve and immediately determines the pressure at each point in the system (Fig. 8). Conversely, if the pressure at any point of the system is known, the intersection of that pressure with the corresponding characteristic curve determines the thruput from which all other pressures in a system can be obtained.

V. GRAPHICAL REPRESENTATION OF SPECIFIC VACUUM COMPONENTS

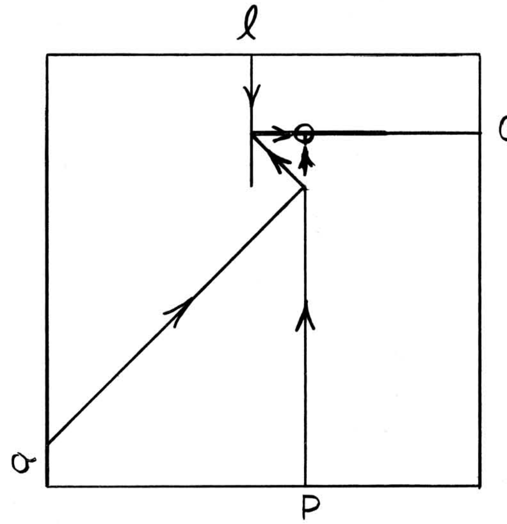
In the development so far, vacuum components have been discussed only in the most general terms. Before we proceed with the application and uses of the characteristic curve, we must direct our attention to the nature of the flow curves or characteristic curves corresponding to specific components.

Let us first consider a piece of tubing of radius "a" and length "ℓ". At very low pressures the flow of gas through this tube is given by Knudsen's equation.[3, 4] For air at 25°C and for our chosen units the equation can be expressed as

$$Q = \frac{97.75a^3}{\ell}(P_2 - P_1)$$

This equation can be broken into two separate opposing flows, which have identical pressure relationships and hence meets our required conditions. The reduced form of the equation becomes $Q\ell = 97.75a^3P$. We already have a P and Q scale on our graph. By adding the ℓ and a scales we can solve this equation graphically (Fig. 9). In order to make the $97.75a^3P$ line of constant product coincide with the $Q\ell$ line of constant product, the a-scale must be displaced by the constant of proportionality and magnified by a factor of 3. If we have known values for a and ℓ, then by choosing a value of the pressure P we obtain the graphical solution for Q, as shown in Fig. 9. That is, the (a, P) intercept gives a line of constant product Z. The intercept of Z and ℓ gives Q. We can then use this value of thruput intersected with the chosen value of P to give one point on the flow curve for our chosen piece of pipe. By repeating this at several values of pressure we can obtain the entire curve. However, the equation points out that $\frac{Q}{P}$ is a constant and hence the curve must be a straight line of constant speed. Therefore, it is only necessary to obtain one point on the curve. By inspection, it will be evident that the intersection of a and ℓ must necessarily lie on this curve (Fig. 10). Therefore, to draw the flow curve for a piece of pipe in molecular flow, it is only necessary to draw a 45° line through the intersection of the radius and the length.

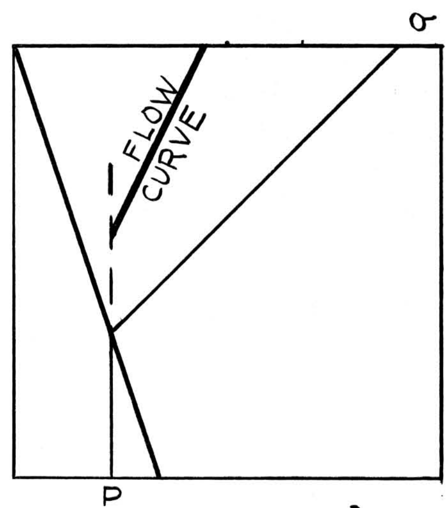
FLOW CURVE CONSTRUCTION IN VISCOUS FLOW



$Q\ell = Ka^4P^2$

Figure 11

LIMITING PRESSURE IN VISCOUS FLOW



$Q\ell = Ka^4P^2$

Figure 12

COMPLETE FLOW CURVE FOR PIPE

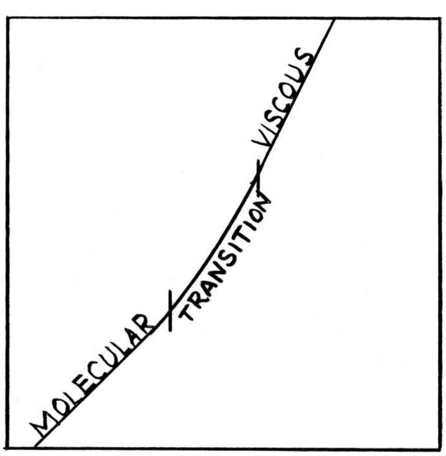


Figure 13

The range of pressures over which this equation applies is limited to where the mean free path of the molecules is large compared to the mean dimensions of the tube. We cut off our graph at this limiting pressure region by drawing a line through the family of points where the pressure is equivalent to a mean free path of $\frac{1}{2}$ the radius. The flow curve is accurate only to that value of pressure where the radius intersects this line.

At substantially higher pressures, we are in the viscous flow region[3] and must deal with a different relation, the well known Poiseuille's equation $Q = 1.42 \times 10^3 \frac{a^4}{\ell} (P_2^2 - P_1^2)$. Now a^3 changes to a^4 and P changes to P^2. In order to avoid adding a new pressure scale, we choose to slope the a scale at 45°. This causes the existing pressure scale to appear as P^2 on our graph. We also spread the vertical height of the a scale to four equivalent decades to account for the a^4 and shift the scale to accommodate our new constant of proportionality. The reduced equation for air at 25°, which applies for this region can be written as: $Q\ell = 1.42 \times 10^3 a^4 P^2$.

The manipulations for solution are the same (Fig. 11). For a given value of a and ℓ we choose a value of P and graphically obtain Q. The intersection of Q and P is one point on the flow curve. This time the equation points out that the curve must have a slope of +2 to accommodate the P^2 factor. Therefore, it is only necessary to obtain a single point through which a straight line with a slope of +2 can be drawn, as in Fig. 12, to solve the viscous flow equation. Again, we must limit the range of the graph with a line whose intersection with a chosen radius defines the lower pressure limit of the viscous flow curve.

To obtain the complete graph as shown in Fig. 13, we combine the two graphs by causing the P and Q scales to coincide. The smooth a-curve which connects the two decade wide pressure region between the two kinds of flow is obtained by an approximate point by point solution of the transition flow equation. It is approximate in the sense that in this region the true equation does not meet our conditions of superposition and hence there is in reality a family of curves connecting the two parts. Also, it will be noted that the normal dip on the left extremity of the transition region is absent. These two approximations were made in the interest of simplicity and are not in sufficient error to be considered in normal calculations. This nomograph now becomes the basic vacuum engineering graph which will be considered in the remainder of this paper.

The next family of vacuum components to be considered are vacuum pumps. Let us first consider a mechanical pump. In the previous section it was stated that the flow curves for vacuum pumps are truly characteristic curves in that the

MECHANICAL PUMP AND FLOW CURVE

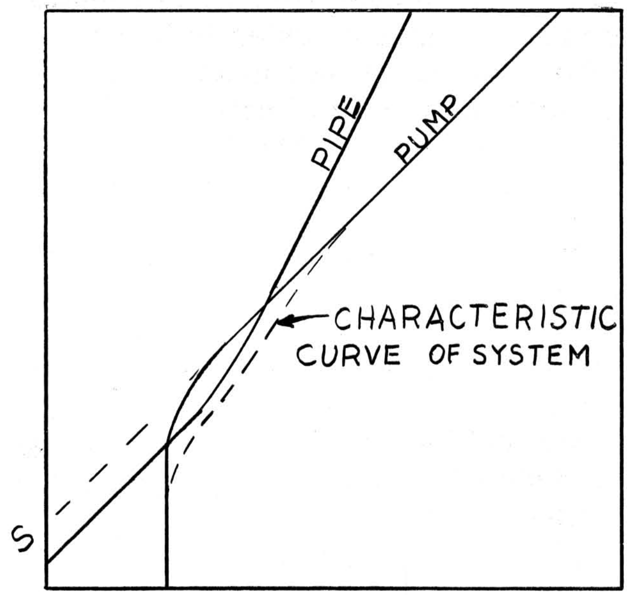


Figure 14

DIFFUSION PUMP CURVE

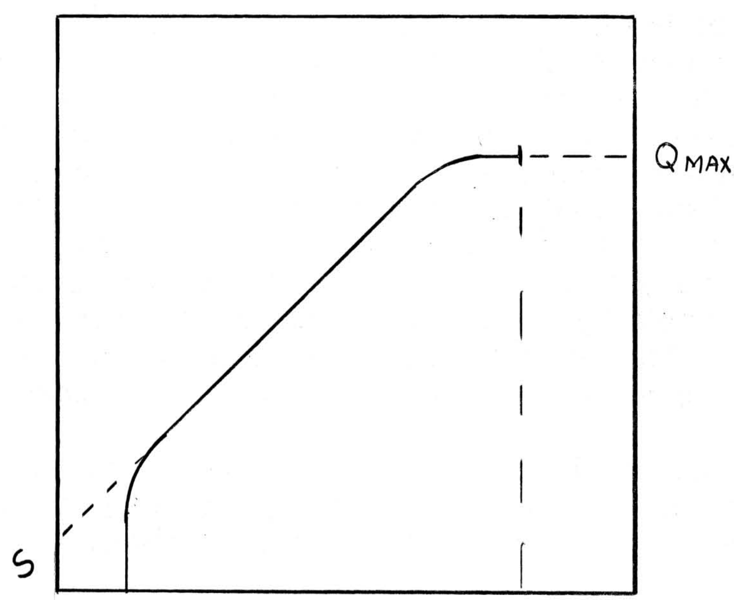


Figure 15

flow through the pump is a function of the inlet pressure only. In studying a number of these curves, we have found that to a first approximation all mechanical pumps can be represented by a similar equation.

$$S = \frac{S_o}{1 + A \log_e \frac{P_o}{P} + \frac{B}{P}}$$

The factor S_o is the speed of the pump at some pressure P_o in the upper end of its operating pressure range. The second term in the denominator containing a pump constant, A, refers to a fixed percent reduction of speed per decade of pressure. For many applications this factor is sufficiently small so that the speed can be considered constant. The last term in the denominator represents a rapid reduction in speed as the pressure approaches its limiting lower value. The rate of curvature in this region is very similar for all vacuum pumps. The factors S_o, P_o, A, and B completely define a particular pump.

We have found it expedient to represent a mechanical pump by two lines, an assigned constant speed and a limiting pressure. Report R55GL333 lists the assigned values of speed and limiting pressure for all mechanical pumps. Fig. 14 shows the characteristic curve for a typical mechanical vacuum pump. A flow curve for a piece of vacuum tubing is also shown as well as the characteristic curve for the combination. Note that in this example the gas flow is limited by the pump at both high and low pressures and is limited by the pipe in the middle pressure region. By plotting these curves, considerable information can be obtained as to the relative size of vacuum lines and pumps required for a given application. From the two characteristic curves the pressure distribution in the system can be obtained as previously indicated.

Let us now consider a diffusion pump. By arguments similar to the case for roughing pumps, we can approximately represent a diffusion pump by three lines: a cutoff pressure, a constant speed, and a constant thruput. A listing of these values for existing diffusion pumps is also available in report R55GL333. Fig. 15 shows the characteristic curve for a diffusion pump. The curved portions connecting the three straight lines can be obtained from the manufacturer's literature; or by experience, they can be directly sketched on the graph.

Traps and baffles can be represented in a similar fashion. The speed of a trap can be considered to be directly proportional to its total area. The theoretical speed of a perfect condensing surface is approximately 11.67 liters per second per square centimeter. The line representing a baffle must also consider the equilibrium vapor pressure of the condensable vapor being pumped and the trap temperature. This represents the backing pressure of the component. In addition all flow restrictions from the baffle to the vacuum system must be included. Generally it is found that the restrictions between the trap and the system are large as compared to the theoretical maximum speed of the condensing surface. Further investigations into the behavior of traps and baffles and their graphical representation will be the subject of a future report.

Previously we have discussed a means of obtaining a flow curve for various vacuum tubing. In some applications it is found that the entrance loss becomes large as compared to the normal restrictions given by the equations.[3] This occurs whenever tubes having a length less than 100 times the radius are used. A good approximation to this correction factor can be made by adding an equivalent length which is equal to 8/3 times the radius.[3] For example a true orifice will have an entrance loss which will cause it to appear the same as a piece of pipe which has the same radius as the orifice, but has a length equal to 8/3 the orifice radius. This is true only in molecular flow. For convenience the line which represents the relation between radius and length of 8/3 is given on the Graph. If the intersection of the radius and length line is well to the right of this line, it is not necessary to consider this entrance loss correction. However, if the intersection is to the left or near the line, then the equivalent length should be obtained from the intersection of the radius and this line. This length should be added to the true length. This only applies in the molecular flow region. In viscous flow a much more complex equation represents the entrance loss correction. We have not as yet developed a simple method of applying this correction. When this information is obtained, it will be published.

Another common restriction which is observed is a bend in tubing. It has been shown by Brown, DiNardo, Chang, and Sherwood[5] that the restriction of a simple right angle bend is approximately equal to 30 pipe diameters at atmospheric pressure. At 0.1 atmosphere this restriction decreases to about 3 pipe diameters and continues to be a linear function of pressure. Since a single bend must already have a length of several pipe diameters plus some entrance loss, it can be seen that at any pressure less than 0.1 atmosphere, a pipe bend can be completely ignored for vacuum calculations. Between 0.1 atmosphere and 1.0 atmosphere, most all vacuum systems are limited by the pump rather than by the pipe; hence it is generally safe to completely ignore all pipe bends.

Vacuum valves are another commonly occurring restriction in vacuum systems. A vacuum valve is made up of three types of restrictions: pipes, bends, and entrance losses. We have indicated that the bends can be ignored;

therefore, if the total physical restriction is plotted on the graph and the entrance loss correction made, a complete flow curve can be obtained for any valve.

As the thruput in a pipe is increased, a point is reached where the viscous flow equation no longer describes the observed facts. This flow region is called turbulent flow and usually commences[3] when the thruput is greater than 490a. This fact is represented on the Vacuum Engineering Graph by the line marked $Q = 490a$. Whenever the intersection of thruput Q and pipe radius a falls above this line, the flow may be turbulent. Turbulent flow is rarely encountered in vacuum systems except perhaps in the initial stage of pump down of a system. Since this time is very short and since the function $Q = f(P_1, P_2)$ is complicated in turbulent flow, no attempt has been made to represent it on the graph.

As was previously mentioned, the scales on the graph have been constructed for air at 25°C. Frequently we are concerned with other gases and other temperatures. The correction for the flow of different gases through pipes in both the viscous and molecular region in given in the Appendix. The corrections to the characteristic curves of pumps for different gases have not been completely established and will be the subject of a future report. Temperature corrections are generally negligible, however, when extreme cases are considered a correction can be made to the radius lines in a manner analogous to the procedure used for different gases. Since the amount of the temperature correction is gas dependent, no attempt has been made to include it on the graph which is already sufficiently complex.

VI. STEADY STATE FLOW ANALYSIS

Before we proceed with the solution of transient flow problems it would be well to demonstrate the analysis of a vacuum system in steady state flow. Let us assume that we desire to design a new system. Generally the outgassing plus leakage load on the pump is the hardest information to obtain. However this can be obtained for a different reference system which has a similar load and then extrapolated to the new system. The pressure versus time for the reference system is first measured and plotted. By differentiating this curve we can obtain a pressure versus thruput relationship which has been modified by actual pump performance, outgassing, and leakage. This curve is then plotted on the Vacuum Engineering Graph. It has been previously shown that the restrictions of all parts of the vacuum system can be sketched on the graph and a complete characteristic curve of the system can be constructed. This theoretical curve which does not contain outgassing or leakage is also plotted on the graph. Figure 16 represents a typical system employing a mechanical pump, a diffusion pump, and vacuum piping.

CHARACTERISTIC CURVES FOR A VACUUM SYSTEM

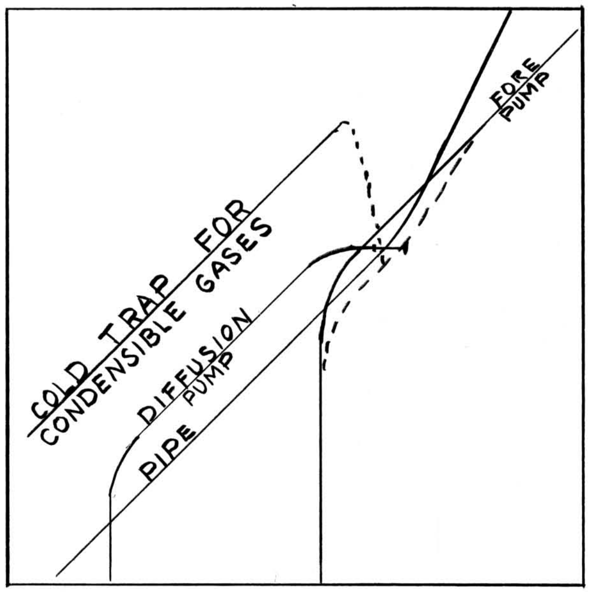


Figure 16

MODIFIED CHARACTERISTIC CURVES DUE TO PUMP SIZE AND OUTGASSING

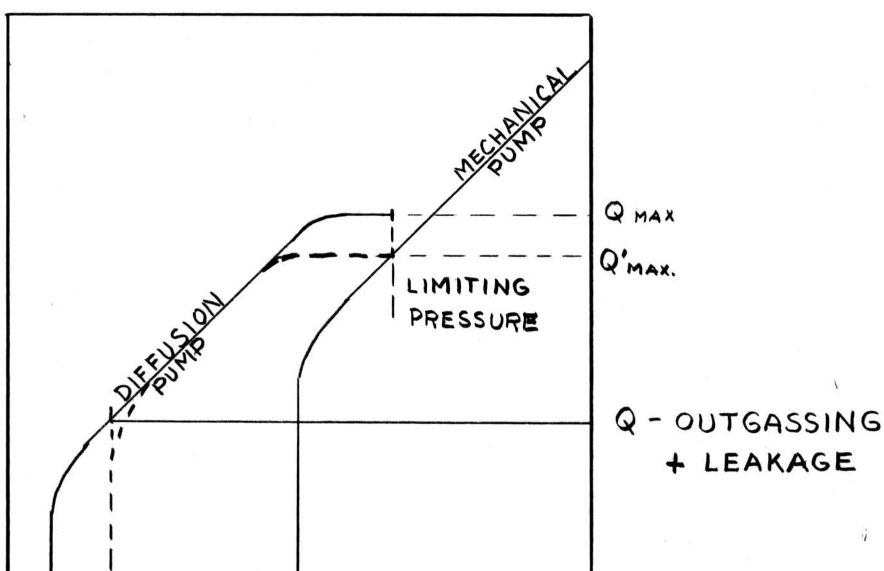


Figure 17

The comparison of these two curves immediately gives us an indication of what is occurring. The vertical distance between the two curves is a direct measure of the outgassing plus leakage or total gas load on the vacuum system at all pressures. The presence of water vapor in the system can be determined. Failures of the pump will also be indicated by this comparison. The major piece of information which one obtains is the total outgassing load at different pressures. From this information it is generally possible to design a vacuum system which has a high thruput in the ranges where it is really needed. Frequently bad design features will become apparent from the theoretical curve. For example, it may indicate the pressure range where a pipe restriction limits the speed of the system.

In designing a new vacuum system we take the measured outgassing rate obtained from the foregoing and allow this thruput to intersect the ultimate pressure required. This intersection gives the speed required of the vacuum system at that pressure. The pumping speed of the pump and flow restrictions must be greater than this speed. We can therefore choose a pump and line to perform in this region and draw their characteristic curve. From this curve we subtract the expected outgassing and leakage to obtain a modified curve of the system. (Fig. 17). If the outgassing is highly time dependent, this must also be taken into consideration. The modified curve represents the relation between the pressure and the thruput available for evacuation. If the required pressure was sufficiently low so as to require a diffusion pump, then it is also necessary to choose a backing pump and a roughing pump.

Let us first consider the backing pump. For best operation it is desirable for the characteristic curve of the backing pump to intersect the diffusion pump characteristic curve. If this does not occur, then either the diffusion pump will bump or there will be a reduction in its maximum thruput. This depends upon system size and flow restrictions. Bumping is caused by the diffusion pump's building up the foreline pressure to where the diffusion pump operation breaks down. This allows the gas to flow back into the rest of the system and thus reduce the pressure to where the diffusion pump will begin pumping again. If the small size backing pump limits the thruput for the diffusion pump, then the diffusion pump curve must be modified as in Fig. 17. That is, where the upper limiting diffusion pump pressure intersects the rough pump characteristic curve we obtain the maximum thruput of the system. This value of thruput represents the modified constant thruput part of the diffusion pump characteristic curve. If the backing pump is a vapor pump then the foregoing must be repeated for its backing pump.

TIME CONSTANT CONSTRUCTION

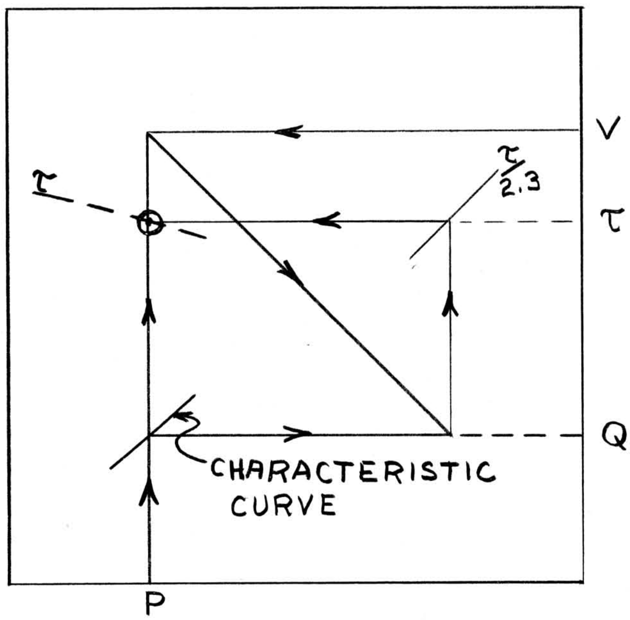


Figure 18

TIME CONSTANT CURVE AND CHARACTERISTIC CURVE

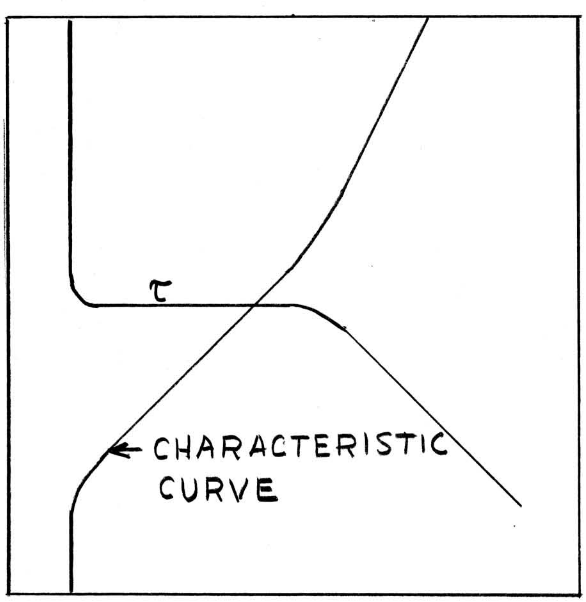


Figure 19

The choice of a roughing pump for the initial pump down is generally contingent on the time allowed for evacuation. This involves transient flow which is the next subject for consideration. It should be pointed out that the pressure at which the roughing pump characteristic curve crosses the modified diffusion pump characteristic curve is the optimum point for switching over to the diffusion pump.

VII. TRANSIENT FLOW ANALYSIS

Up to this point, we have only considered steady state flow. What happens to the pressure in a vessel during evacuation? How long will it take to evacuate from a higher pressure to a lower pressure in a given system? To answer these questions in our proposed approach, we must set up the mechanism for the solution of transient flow conditions. Time is introduced by the following differential equation for the pressure decrease with time as a function of the flow rate.

$$-VdP = Qdt$$

In order to integrate this equation, it is necessary to know the relation between the flow Q and pressure P at all pressures under consideration. A glance at a few characteristic curves indicates that this relation generally is quite complex. We therefore propose to do a simple graphical integration of the characteristic curves which will give us the pressure versus time relationship.

We note that at any fixed value of pressure a particular speed exists for the system, such that $Q = SP$. Using this value for Q, we integrate and obtain.

$$\Delta T = \frac{V}{S} \log \frac{P}{P'}$$

A time constant τ is defined as the time required to reduce the pressure by one decade at the existing speed.[3] This eliminates the log relation and we obtain,

$$\tau = 2.3 \frac{V}{S} = 2.3 \frac{VP}{Q}$$

or

$$Q\tau = 2.3\, VP$$

TIME CONSTANT ON SEMI-LOG PLOT

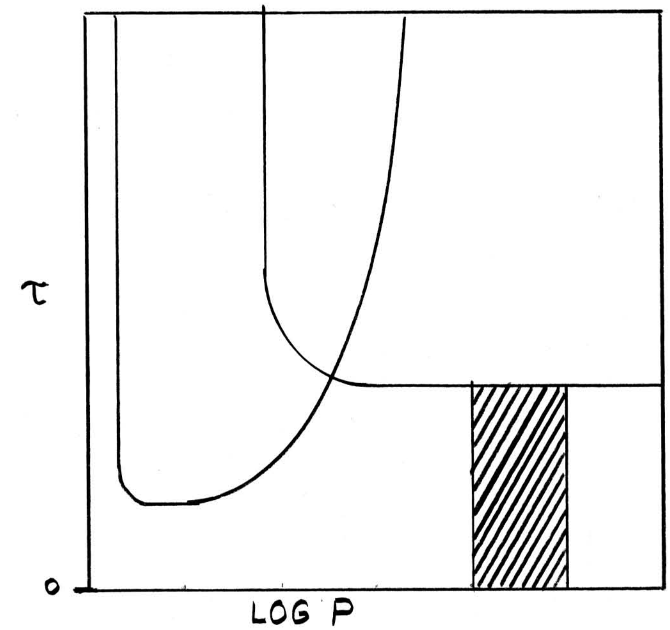


Figure 20

COMPARISON OF PUMPS ON A GIVEN SYSTEM

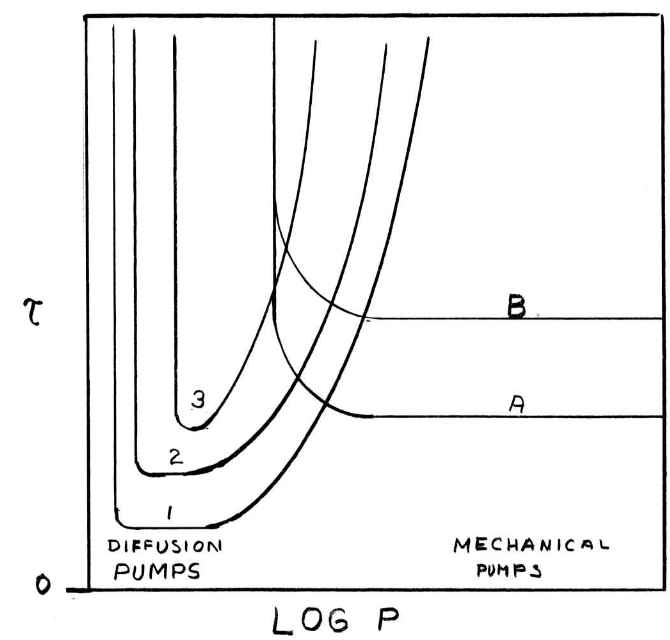


Figure 21

The S, P, and Q scales are already on the graph. The volume scale in liters and the time constant scale in seconds per decade of pressure are chosen to coincide with the units of the thruput scale. With these scales and the characteristic curve of the steady state system one can construct the time constant at every pressure using manipulations similar to those developed earlier. Fig. 18. Any arbitrary pressure determines immediately two things on the Graph: first, the thruput (Q) of the system and second, a V P constant product line. Their intersection then determines $\tau/2.3$ on the pressure scale. By reflecting the value of $\tau/2.3$ around a particular 45^{o} line on the graph, the value of τ is obtained for the pressure originally chosen. From this manipulation we obtain one point on the curve which relates pressure and time constant. By repeating this process we can construct the entire time constant curve. This is not as much work as it might first appear, for many short cuts are available (Fig. 19). Note that wherever the speed is constant, the time constant curve is horizontal. Where we are in viscous flow or a 2:1 slope, the time constant is a line with slope -1. Only a few points are required to obtain the entire curve. In order to integrate the τ function, the time constant curve is transferred to semi-log paper. By defining the time constant as we did, the area under the new curve and between two pressure limits is proportional to the time required to evacuate between the two pressures. The time constant curves typical of mechanical and diffusion pumps are shown in Fig. 20. Several time constant curves for a given volume but for different sized pumps can be plotted on one graph (Fig. 21). From this a comparison can be made to evaluate evacuation time versus equipment size and cost.

The foregoing analysis applies only to those systems which contain a single volume or a parallel group of volumes of the same size and at the same pressure. If a vacuum system contains two volumes of different size with different connecting lines, the analysis becomes much more complex. Another limiting condition is that the volume of the pumping line must be small as compared to the volume to be evacuated. If the vacuum line is the volume being pumped out, the solution involves a non-linear second degree differential equation which has not as yet been solved. However, empirical data suggests that a simplified approximation can be used for this case. The graphical techniques for solving these more complex problems will be presented in future reports.

VIII. OTHER USES OF THE VACUUM ENGINEERING WORK SHEET

As the vacuum engineer becomes more familiar with the work sheet, many other applications will suggest themselves. Several of these applications will be listed and discussed briefly: however a detailed analysis of each will furnish an abundance of material for future reports.

Frequently it is necessary to convert leakage rates for one gas at one pressure condition to a different gas at a different pressure condition. This conversion sometimes will be such that at one condition molecular flow will be prevalent while at another condition viscous flow will exist. An example occurs in the refrigeration industry where the problem is one of determining how much Freon will leak from a refrigeration unit in a given period of time as a result of a leak which is found on a helium mass spectrometer leak detector. The technique of this solution is a reversal of the previous analyses; that is, generally the pressure and flow are known and it becomes a problem of assuming a value of ℓ to determine a value of the radius. This radius is then corrected for the different gas and a new radius line is constructed. By using this new radius line and the new pressure condition, the flow under this new set of conditions can be determined as before. Frequently the choice of ℓ will determine whether flow is occurring in the viscous or in the molecular region. For this reason it is sometimes advantageous to choose several different values of ℓ , thus obtaining several different values of the prevalent radius, from which several different values of flow under the new conditions will be obtained. It is then possible to plot the expected flow as a function of the different assumed lengths. In this manner we can determine what worst possible condition might exist for the largest fea sible length.

Another application of the work sheet involves defining leak detector time consta nts. The expression

$$R = R_o (1 - e^{-St/V})$$

defines the relation between leak detector signal versus time when a volume is being tested for leaks by any vacuum method. This is a standard exponential function from which we can define a 63% response time constant.

$$T' = \frac{V}{S} = \frac{VP}{Q}$$

Here, again, we see that most of the scales are available. The Q, P, S, and V scales are already on the graph. By letting the time scale be coincident with the pressure scale, we can solve directly for the time required to obtain 63% response when leak checking any volume of a known size. You will observe that it is necessary to know the thruput or the speed at the leak detector connection. The time scale is already added to the work sheet.

Since Applications of the Vacuum Engineering Graph cover such a wide range of pressures, flows, and radii it has been necessary to provide two different graphs. One is titled "Vacuum Engineering Graph I - for Systems" and covers the normal ranges used in vacuum system design. This is available as FN-756A. The second, FN-756B is titled "Vacuum Engineering Graph II - for Leaks." This graph has flow rates down to 10^{-16} mml./sec. and radii down to 10^{-5} cm. There is sufficient overlap between the two such that one or the other should be adequate for any vacuum application. Fig. 22 and 23 are copies of the completed Vacuum Engineering Graphs in the back cover.

The complete analysis of a vacuum system results in many lines on the Vacuum Engineering Graph. We have found that the use of colored pencils following a consistent color code adds clarity. For reasons of construction and contrast we have found the following code satisfactory.

Black	-	Construction lines
Green	-	Flow curves
Red	-	Characteristic curve
Blue	-	Time constant curves

The degree of accuracy obtainable with the engineering graph is determined by the care with which the constructions are made. The agreement between experimental data and predicted evacuation time has been excellent; the error being less than 5%. One great advantage of this technique is that this method is a graphical method. Any error in plotting one point is quickly detected by deviation from other points which fall into a pattern.

The development of this graphical method of handling vacuum problems has great value for those who are faced continually with the problems of vacuum design. You will note the similarity between this solution and the slide rule. There are some simple scales which can be frequently and rapidly applied to yield the desired solution. There are other more complex scales and manipulations. While the average engineer can use the simple scales, it requires a good understanding of vacuum to apply the more complex ones and to make a proper analysis of a given vacuum system.

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APPENDIX A

Definition of Symbols

Symbol	Name	Unit
P	Pressure	Millimeters of mercury
Q	Thruput	$\frac{\text{Millimeter Liters}}{\text{Second}}$
S	Speed	$\frac{\text{Liters}}{\text{Second}}$
t	Time	Seconds
τ	Time Constant	Time in seconds to reduce pressure one decade at existing value of speed.
a	Radius	Centimeters
ℓ	Length	Centimeters
V	Volume	Liters

APPENDIX B

Correction for Change in Type of Gas

The flow curve or the restriction of a piece of pipe for a gas other than air can be determined by shifting one scale. For obvious reasons we choose to shift the radius scale. Rather than changing the entire scale, it is only necessary to change the radius being used. This change is not only a different amount for viscous and molecular flow but frequently is in opposite directions. The mean free path is also different for different gases and hence the lines limiting the molecular and viscous flow regions must also be shifted. The figure below illustrates the method of correction. Table I lists the values of the correction factors for a number of common gases.

Example - Helium flowing in a one cm. radius pipe. From Table: A = 1.39, B = .98, C = 2.88.

In molecular region use radius of 1.39 cm.
In viscous region use radius of .982 cm.
Move mean free path lines to a reading of 2.88 on the pressure scale.

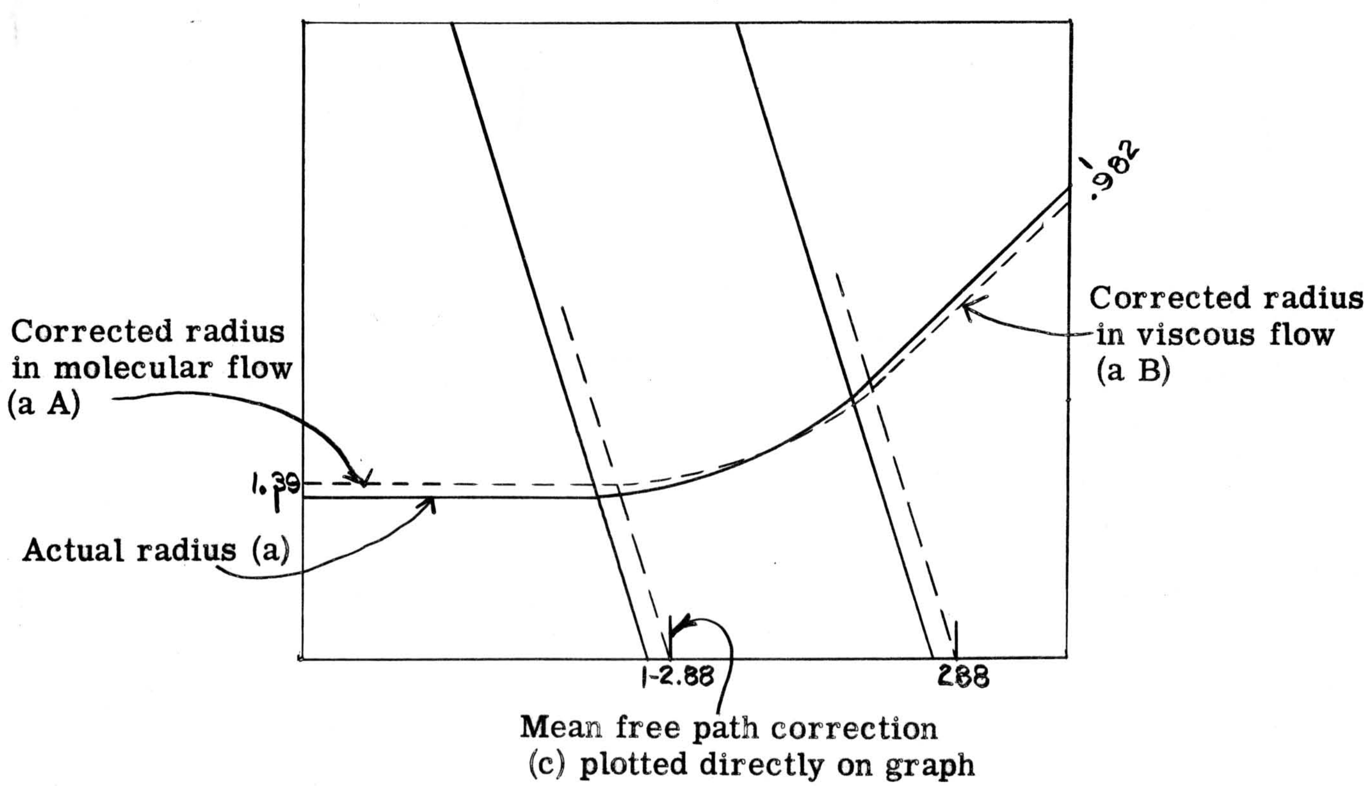


TABLE I

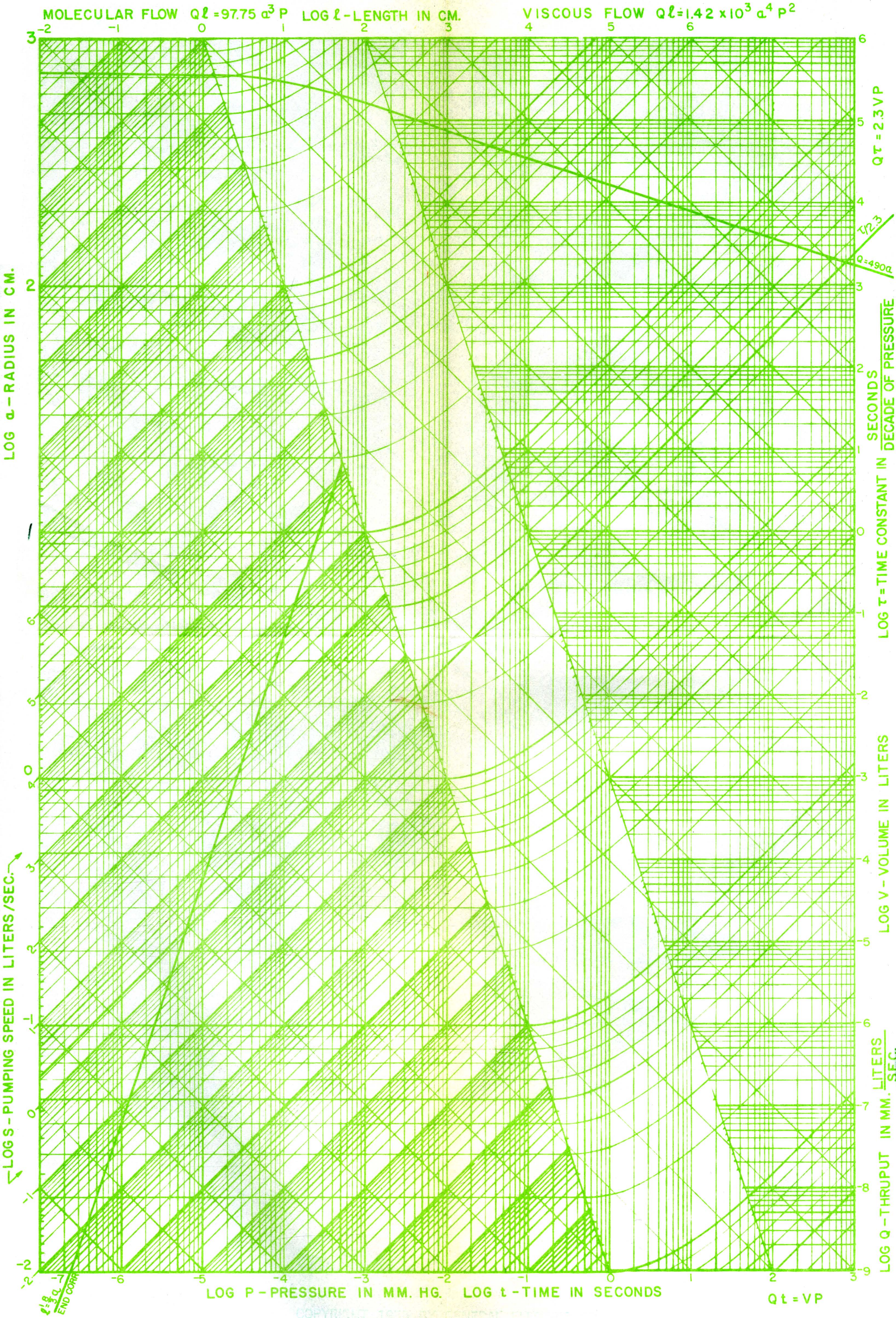
Radius Conversion Factors for Gases Other Than Air

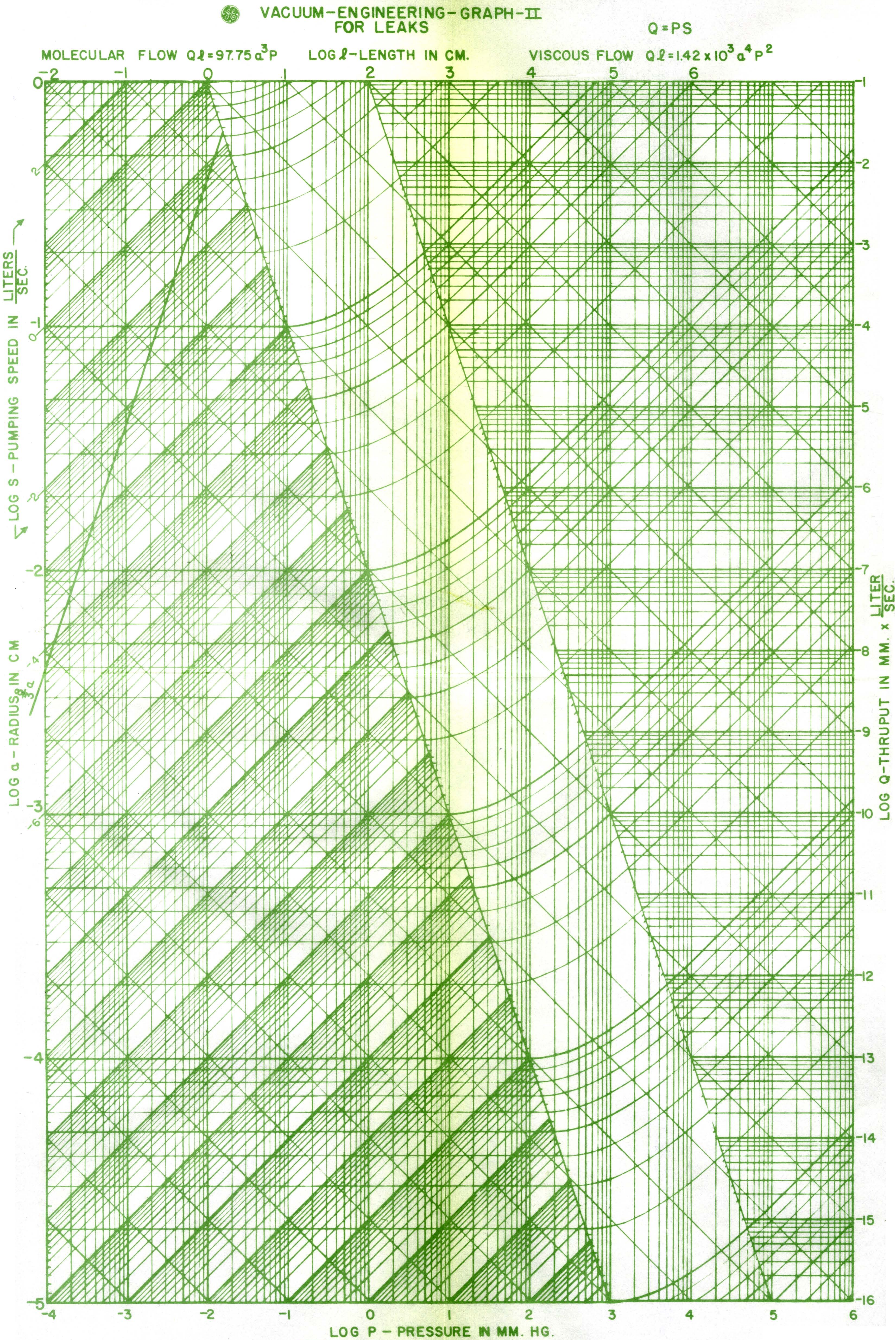
Gas	A Molecular Region	B Viscous Region	C Mean Free Path
Argon	.95	.95	1.04
Carbon Dioxide	.93	1.05	.66
Helium	1.39	.98	2.88
Hydrogen	1.56	1.20	1.83
* Freon 11	.78	1.14	.28
Freon 12	.78	1.10	.30
Freon 21	.81	1.13	.33
Freon 22	.84	1.09	.37
Mercury	.73	.92	.52
Neon	1.06	.87	2.05
Sulphur Dioxide	.90	1.09	.45
Water	1.08	1.18	.66

* "FREON" is DuPont's registered Trade Mark for its fluorinated hydrocarbon refrigerants.

VACUUM ENGINEERING GRAPH-I FOR SYSTEMS

Q = PS





VACUUM-ENGINEERING-GRAPH-II
FOR LEAKS
Q=PS
MOLECULAR FLOW Qℓ=97.75 a³P
LOG ℓ-LENGTH IN CM.
VISCOUS FLOW Qℓ=1.42 x 10³ a⁴ P²
LOG S - PUMPING SPEED IN LITERS/SEC.
LOG a - RADIUS IN CM
LOG Q-THRUPUT IN MM. x LITER/SEC.
LOG P - PRESSURE IN MM. HG.

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AUTHOR	SUBJECT CLASSIFICATION	NO. / DATE
D. J. Santeler J. F. Norton	Vacuum	R55GL332 DATE Sept. 29, 1955

TITLE

A Graphical Approach to Vacuum Engineering

ABSTRACT

A "Vacuum Engineering Graph" and the methods of using it to obtain simple and rapid solutions to vacuum engineering problems are explained.

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CONCLUSIONS

Steady state thruput of a system can be obtained. Time of evacuation of a volume between two pressures can be obtained including the effects of outgassing and leakage. Other applications are also discussed.

For list of contents—drawings, photos, etc. and for distribution see next page (FN-610-2).

INFORMATION PREPARED FOR Mechanical Engineering Laboratory

TESTS MADE BY

AUTHOR D. J. Santeler, J. F. Norton D J Santeler James F Norton 5 Oct. 1955

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