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SUPPLEMENTARY REPORT No. 1

December, 1959

C. E. Normand

During the investigation of various vacuum problems observations are occasionally made which have no direct bearing on a particular problem but appear to be of sufficient interest to warrant reporting. A number of such observations made over the past several months, are summarized in this report.

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I. ERRONEOUS IONIZATION GAGES

On a number of occasions ion gages in service, and behaving in an outwardly normally manner, have been found to be in error in their pressure indications by as much as 300 per cent. Failures of this kind have been observed with both VG-1A and RG-75 gages. All failures observed have been on systems pumped by unbaffled (or only slightly baffled) oil diffusion pumps. The insidious feature of these failures is the fact that they may go undetected for a considerable time.

In our work, such gage failures are strikingly revealed whenever a defective gage is used in determining pumping speeds over an extended pressure range. Figure 1 shows two speed curves for the same system taken on successive days. Curve A was taken with a gage which had become defective, and Curve B with a new gage installed in its place. Speed curve C was determined with a third gage which had been previously discarded as defective.

It should be noted that pressures indicated by the defective gages are consistently less than the true pressures; and that the error becomes progressively greater as pressure increases. Also, the two defective gages are in substantial agreement with one another over a considerable pressure range even though both are in error. The mere fact that two gages agree is not, therefore, conclusive evidence of their correctness.

II. EFFECT OF DOME SIZE ON MEASURED PUMP SPEED

Test domes of two general types are commonly used in measuring pump speeds. These are: (a) a small dome[1] having a diameter equal to that of the pump aperture and a length equal to about 1-1/2 times the diameter; and (b) a large dome having all dimensions larger compared with the diameter of the pump aperture.

On using the small dome, the aim is to introduce negligible impedance between the gage and the pump. Thus, the speed measured is essentially the true speed of the pump, not limited by the finite conductance of the pump aperture. Speeds measured by this method provide an excellent basis for comparing one pump with another.

In using a large dome one measures the speed of pumping from a large chamber through the finite (and not negligible) impedance of the pump aperture. This yields a lower value of pumping speed, but one which may be more pertinent to problems of vacuum system performance.

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[1] A dome of this type has been recommended by the Committee on Standards, Am. Vacuum Society, Vac. Symp. Trans. (1955) p. 91-95.

Unless the large dome is very large--and this is difficult to realize except for small pumps--the aperture impedance is only partially effective and the measured speed of pumping from a moderately large dome should be less than the true pump speed but greater than the speed calculated from true pump speed and theoretical aperture conductance.

To check these relations a small dome (10 in. diameter by 16 in. high) was substsitituted for the 20 in. x 20 in. dome used throughout our speed measurements of the MCF-1400 pump. The small dome had its ion gage and gas inlet arranged as recommended by the A.V.S. Committee on Standards.

Typical speed curves as measured with the two domes are shown in Figure 2; and a comparison of average speeds as measured with the two domes at three operating powers is made in Table I.

TABLE I. COMPARISON OF AVERAGE PUMPING SPEEDS AS MEASURED WITH DOMES OF DIFFERENT SIZE

Operating Power (Watts)	S_S Measured Speed With 10"x 16" Dome (L/Sec.)	S_L Measured Speed With 20"x20" Dome (L/Sec.)	S_T^* Theoretical Speed With Large Dome (L/Sec.)	S_T/S_S	S_L/S_S
2070	1767	1539	1359	.769	.871
3150	1666	1473	1298	.779	.884
4125	1531	1360	1215	.794	.888
Average	1655	1457	1291	.781	.881

$^*1/S_T = 1/S_S + 1/C_A$

C_A = Theoretical conductance of pump Aperture

$C_A = 75 \times \Pi^2 = 5888$ L/Sec.

From the last column of Table I it is seen that the speed of this particular pump as measured with a 20 in. x 20 in. dome is about 88 per cent of the small dome speed. The theoretical speed of the pump in series with its aperture conductance should be only 78 per cent of its true speed. Thus speeds determined by the three methods fall in the order expected, and differ by amounts that cannot generally be ignored.

In comparing the speeds of different pumps, or different speed measurements of the same pump, test dome size must be taken into account. Also, in estimating such characteristics of a vacuum system as pump-down time and equilibrium pressure vs. gas in-leakage rate, the appropriate pumping speed may differ significantly from both the speed of the pump and from the pumping speed calculated from theoretical conductance and true pump speed.

III. EFFECT OF LEAK "BEAMING" ON MEASURED PUMPING SPEED

It is well known that pumping speed measurements by the metered leak method may be seriously in error if the admitted leak is beamed toward the pump or the pressure gage. If beaming is toward the pump, the measured speed is too high; if toward the gage, it is too low.

In a recent series of tests of an MCF-1400 pump with a 20 in. x 20 in. test dome, a number of speed measurements were made with the leak inadvertedly admitted into the test dome at a point diametrically opposite the ionization gage. Later, these measurements were repeated with the leak at the 90° position. A comparison of the results in these two cases,

(Figure 3) gives a quantitative measure of the effect of beaming toward the ion gage in this system. Unfortunately, this is not quite the full effect, because the path from leak inlet to ion gage was partially obstructed by the apex of an oil collecting cone. Even so, the error is substantial, especially at the lower pressures where the mean free path is much greater than the dome diameter. At the highest pressure (10^{-4} mm) the mean free path for air at 25° C is about equal to the dome diameter (51 cm vs. 20 in.), and the error due to beaming has decreased from approximately 22 per cent to 6 per cent.

IV. SOME REMARKS ON THE INTERPRETATION OF PUMPING SPEED CURVES

Measurements of pumping speeds by the metered leak method involve:

1. Reducing the pressure in the system to its equilibrium (base) value p_o (microns).
2. Introducing a test gas at a series of measured rates Q_1, Q_2, etc. (liter-microns/sec.).
3. Noting the resulting equilibrium pressures p_1, p_2, etc. (microns).
4. On the basis of continuity of flow, one may then calculate pumping speed.

The speed calculations are made by one of two methods:

1. Total pressure method: This is the method most commonly used.

Speed is defined by the relation:

$$S \times p_n = Q_n$$

and

$$S = \frac{Q_n}{P_n} \quad \text{(at pressure } P_n\text{)} \qquad (1)$$

2. Partial pressure method: It is also reasonable to define speed in terms of the partial pressure due to the measured leak being introduced, i.e.

$$S' \times (P_n - P_o) = Q_n$$

and

$$S' = \frac{Q_n}{P_n - P_o} \quad \text{(at pressure } P_n\text{)} \qquad (2)$$

Speeds calculated by these two methods from the same original data are plotted against pressure in Figure 4. As is obvious from the defining equations, the curves differ insignificantly at pressures much greater than P_o. At pressures near P_o, however, the curves diverge widely, and many people appear to be confused as to just how a pump does perform in this pressure range.

This confusion appears to be resolved if one recognizes the essential difference between the speeds derived from these two treatments. Speed calculated on the basis of total pressure, and falling to zero at the base pressure, is the pertinent speed in all questions regarding the rate of reduction of pressure under non-equilibrium conditions. Speed based on partial pressure, and remaining essentially constant at all pressures above P_o, is the speed to be considered in all questions regarding the relation of equilibrium pressure to rate of gas influx.

Consider, for example, the system represented by the speed curves of Figure 4. If one asks the rate of pump-down (pressure reduction) when the pressure is 2.5×10^{-6} mm, the appropriate speed to use is that given by curve B, ($S_1 = 440$ L/Sec.). If, however, one asks the rate of gas influx required to raise the equilibrium pressure of the system from 1.5×10^{-6} to 2.5×10^{-6} mm, the appropriate speed to use is that given by curve A, $S_s = 1080$ L/Sec.

For simple comparison of one pump or system with another, either representation of speed is satisfactory provided the same representation is used throughout the comparison.

V. EFFECTS OF FRACTIONATION ON ULTIMATE PRESSURE

The principle of fractionation, the practice of providing fractionation in the multi-compartmental boilers of oil-diffusion pumps, and the fact that such fractionation leads to lower ultimate pressures, are all matters of such general knowledge that they need not be gone into here. A little less well known is the fact that the same effect can be attained in some degree by running the lower (rough vacuum) section of the pump at sufficiently high temperature to insure a degree of fractionation external to the boiler. Our interest in the relative effectiveness of these two modes of fractionation stemmed from considerations of pump heaters of non-conventional types, not readily adaptable to multi-compartment boilers.

In order to get some quantitative idea of the dependence of ultimate pressure on fractionation, the test system shown schematically in Figure 5 was used. The pump was a 4 in., three stage MCF-300, operated at 660 watts with Convoil-20 as the pumping fluid.

Variation of the lower pump wall temperature, and, therefore, of the degree of fractionation occurring outside the boiler, was accomplished simply by varying the flow of cooling water to the pump. The temperature of the discharged cooling water was taken as a qualitative indication of external fractionating conditions.

The elimination of fractionation within the boiler, without interrupting operation and possibly altering the distribution of vapor between the various jets, did not appear possible. It was quite easy, however, to reverse the order of fractionation by reversing the direction of flow of oil through the three boiler compartments. This was done by opening a valve in the by-pass line joining the oil seal-ring to the center of the boiler. With oil returned to the central boiler compartments the uppermost (high vacuum) jet was supplied with vapor of the poorest rather than the best quality available, and the effect of vapor quality on ultimate pressure could be observed.

It is realized, of course, that the contrast between "fractionation" and "reverse-fractionation" may be greater than between "fractionation" and "non-fractionation."

The extremes of external fractionation realizable in our tests corresponded to discharge water temperatures of approximately 20°C and 60°C. Operation at these two conditions will be designated "Cool" and "Hot" respectively.

The condition of internal fractionation will be designated "fractionating" and "reverse fractionating". There are then four modes in which the pump was operated. These will be designated and abbreviated as:

1.	Cool & Reverse Fractionation: (CR)	Minimum fractionation both external and internal.
2.	Cool & Fractionating: (CF)	Minimum external fractionation; maximum internal fractionation.
3.	Hot & Reverse Fractionation: (HR)	Maximum external fractionation; minimum internal fractionation.
4.	Hot & Fractionating: (HF)	Maximum fractionation, both external and internal.

If ones interest extends merely to the ultimate pressure attainable at these four modes of operation, it is only necessary to note the pressure attained after operating for a sufficient time in each mode. If, however, one hopes to understand why the different modes of operation lead to different ultimate pressures, it should be helpful to know how the pressure changes in passing from equilibrium under one condition to equilibrium under another. Such information is easily obtained and can be conveniently presented in the form of pressure vs. time curves covering the designated interval. In actual practice, this turns out to be a rather tedious process. First, there are twelve ways in which one may change from one to another of four modes of operation. Second, the time from equilibrium to equilibrium for our system turned out to be greater than eight hours but less than twenty-four. This lead to the adoption of the following schedule: The change from one to another mode of operation was made at the beginning of a work day. For eight hours, the pressure was closely followed by recorder and by readings taken at regular intervals. After an additional sixteen hours, i.e. overnight, the ultimate pressure, characteristic of this mode of operation, was noted and operating conditions were again changed.

For convenient comparison the twelve resulting pressure curves have been plotted in four groups in Figures 6, 7, 8 and 9. All of the curves in each group represent the same mode of operation, but differ from one another in that they start from different initial conditions; i.e. the immediately preceding mode of operation was different.

The point most strikingly displayed by this grouping is that the final pressures attained after 24 hours of operation are quite independent of the initial conditions of the system. These final pressures may, therefore, be taken as characteristic of the different modes of operation. Actually, these pressures after 24 hours are essentially the ultimate pressures at the four modes of operation. This is indicated by the observation of no further pressure change when, on several occasions, runs were extended for an additional 24 to 48 hours.

The indicated ultimate pressures for our test system under different degrees of fractionation are:

Figure 6. Minimum External and Internal Fractionation:
5.5×10^{-6} mm Hg.

Figure 7. Minimum External, Maximum Internal Fractionation:
2.2×10^{-6} mm Hg.

Figure 8. Maximum External, Minimum Internal Fractionation:
2.0×10^{-6} mm Hg.

Figure 9. Maximum External and Internal Fractionation:
1.0×10^{-6} mm Hg.

The fact that internal and external fractionation alone (Figures 7 and 8) result in almost equal ultimate pressures should not be taken as a general relation applicable to other systems, or even to the same system under other operating conditions.

Neither external nor internal fractionation is completely effective; this is shown by the fact that neither alone produces as low an ultimate as the two together (Figure 9).

Pressure variations following a change in mode of operation are consistent, in every case, with the following concepts.

1. The ultimate pressure attained is determined by, and is a measure of, the "quality" of the vapor supplied to the upper-most (high-vacuum)

stage of the diffusion pump. Quality is here used to signify freedom of oil or vapor from high vapor pressure constituents.

2. A change of fractionation within the boiler (direct to reverse fractionation or vice versa) leads to a change between two extremes in the quality of vapor to the top stage. Such changes occur quite quickly, and result in a prompt (1/2 hour) rise (or drop) in pressure. These prompt pressure changes are large or small depending on the over-all quality of the oil returning to the boiler. A larger pressure change results from oil of poorer quality. There is no indication that the quality of the oil is altered by reversal of fractionation within the boiler.

3. Increasing or decreasing the degree of external fractionation does result in a significant improvement or degradation in the quality of the oil. Both of these changes occur slowly over a long (8 hours or more) period of time.

4. When both internal and external fractionation are changed simultaneously, the effects of the two changes are simply super-imposed.

Qualitatively, it appears that all of these observations should be generally applicable. Quantitatively, however, these results apply only to the particular test system and operating conditions used in making these tests.

VI. A PECULIAR EFFECT IN INTERCONNECTED VACUUM SYSTEMS

The following observations were made in the course of current investigations of the performance of a C.E.C. type E.I.-2000 Evapor-Ion pump. In the test assembly used, the 20 x 20 inch test dome above the Evapor-Ion pump was connected by a 4 inch line and valve (total length

2 feet) to a similar dome pumped by an MCF-1400 oil diffusion pump. Except during initial pump down and start up of the Evapor-Ion pump, the cross-tie valve was normally closed.

After continuous operation for a number of days the two systems attain their respective base pressures. For a typical case, illustrated in Figure 10, the indicated base pressures as ready from VG-1A ionization gages on the two test domes are:

$$P_D = 1.07 \times 10^{-6} \text{ mm Hg for the diffusion pump}$$

$$P_e = 1.4 \times 10^{-7} \text{ mm Hg for the Evapor-Ion pump}$$

If now the cross-tie valve is opened, both pressures change but not toward equalization as might be expected. Actually, the pressure above the Evapor-Ion pump drops from 1.4×10^{-7} to 9×10^{-8} mm while pressure above the diffusion pump rises slightly and then returns slowly to about its initial value.

When the feeding of titanium wire is stopped, pressure above the Evapor-Ion pump is further reduced. At the same time, pressure variations arising from the periodic liberation of gas from the Ti wire as it is fed onto the post are eliminated.

With the elimination of these pressure variations, the periodic pressure "pips" which are characteristic of this particular diffusion pump system are seen reflected in the Evapor-Ion chamber. (Pressure pips of this type are frequently observed, and have been traced, in a number of cases, to air leaks past oily O-rings).

Half an hour after opening the cross-tie valve, pressures in the two systems are essentially steady at:

$P_D = 1.06 \times 10^{-6}$ mm Hg for the diffusion pump

and

$P_e = 6.5 \times 10^{-8}$ mm Hg for the Evapor-Ion pump.

Reduction of the pressure in one system by connecting it to another system having higher pressure is peculiar to say the least. Until further measurements have been made, however, one can only speculate as to the causes of this effect. Three factors are suggested as possibly pertinent and subject to further investigation.

First, there is the possibility that one or both of the ionization gages may be seriously in error in spite of their outwardly normal behavior. Independent checks of the gages can be made.

Second, the difference in ion gage sensitivity to different gases has not been taken into account; nor can it be until we have some knowledge of the composition of the gases involved. (In this connection it should be emphasized that all pressures quoted are direct gage readings, uncorrected for gage sensitivity). It is quite probable that gage sensitivity contributes to the effect observed. It is even conceivable but unlikely, that the difference in pressures initially observed in the two systems could be due wholly to gage sensitivity. Certainly, there is every reason to expect residual gases of different compositions in these two systems. After the cross-tie valve is opened, however, mixing of gases from the two systems must occur with a resulting decrease in gage differences due to sensitivity effect. Actually, this difference becomes more pronounced.

A third factor, and possibly the most important, is the very great difference in pumping speed of the Evapor-Ion pump for different gases. For example, the rated pumping speed for hydrogen is about 300 times that for the inert gases. This being the case, it is conceivable that a reduction in pressure above the Evapor-Ion pump could result from opening the cross-tie valve, even though this results in a net flow of gas into the system. For this to be true, one must assume that the gas flowing into the Evapor-Ion system is one for which the pumping speed is very high while the smaller quantity of gas flowing out is one for which the pumping speed is very low.

If the true explanation of this phenomenon is something of the sort just suggested, the possible advantage of using Evapor-Ion and diffusion pumps in combination appears to be greater than might be expected. However, further measurements, including mass analyses of the gases involved, are needed before any real evaluation can be made.

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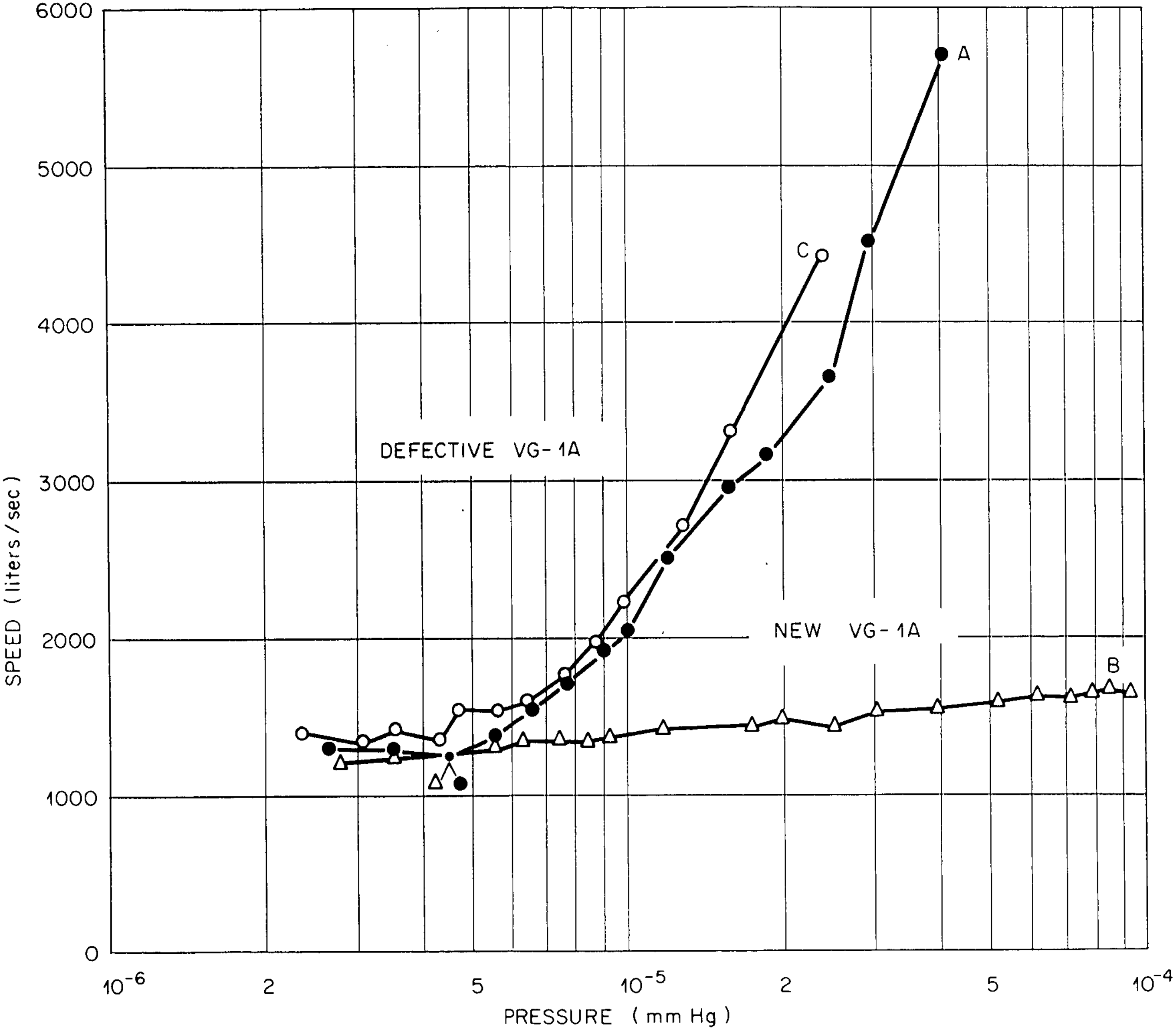

Fig. 1. Example of Erroneous Speed As Measured With Defective VG-1A Gages. MCF-1400 Pump at 2050 Watts.

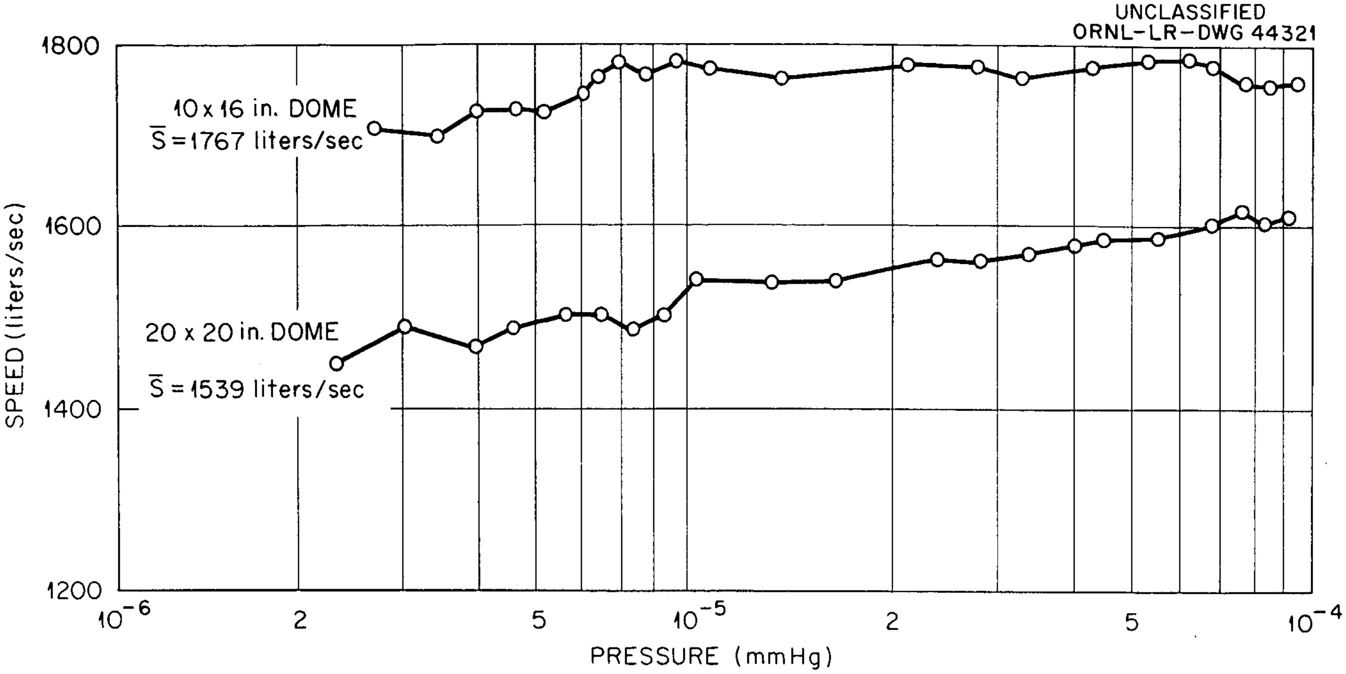

Fig. 2. Effect of Dome Size on Pumping Speed. MCF-1400 Pump at 2070 watts.

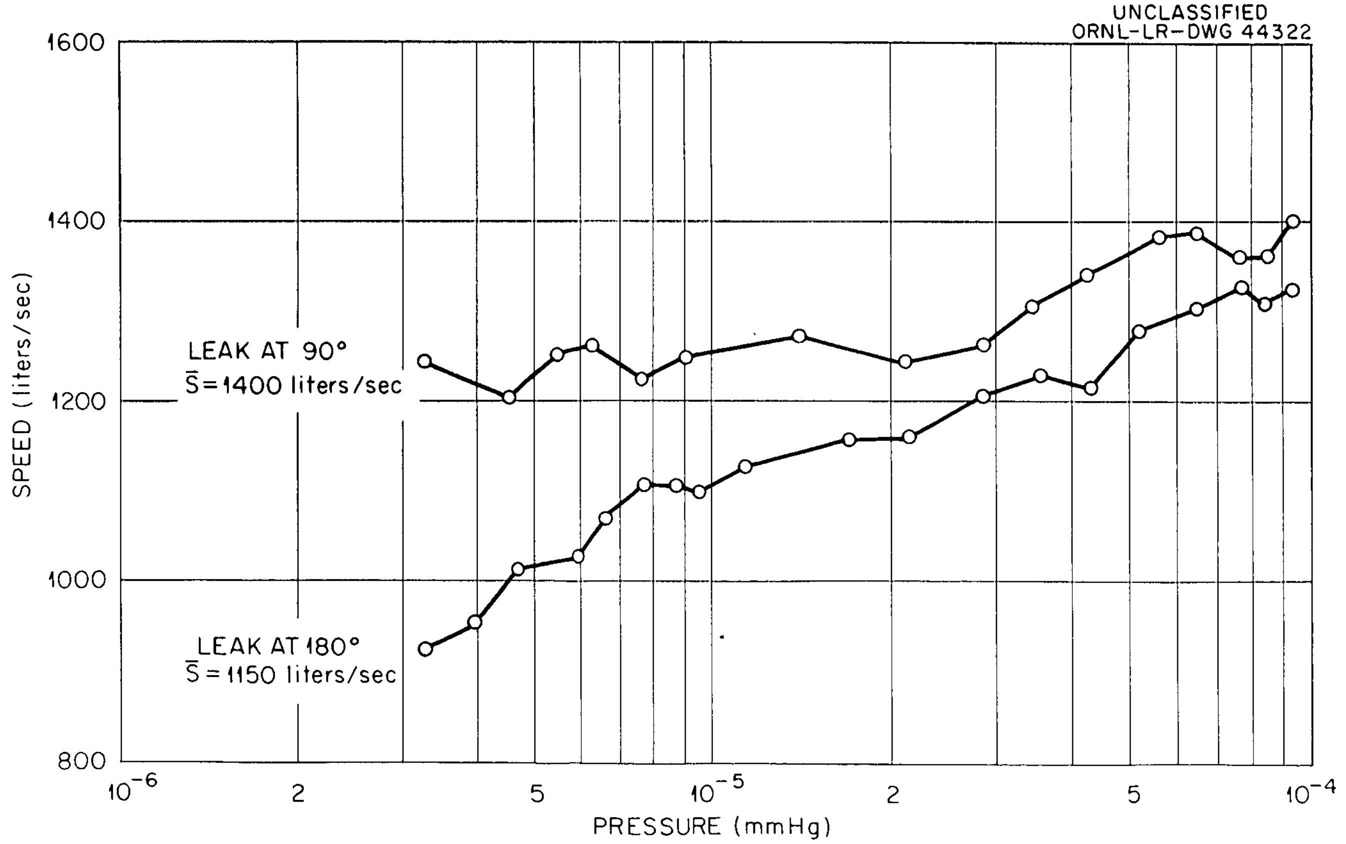

Fig. 3. Effect of Leak Beaming on Apparent Dumping Speed. MCF-1400 Pump at 3150 watts.

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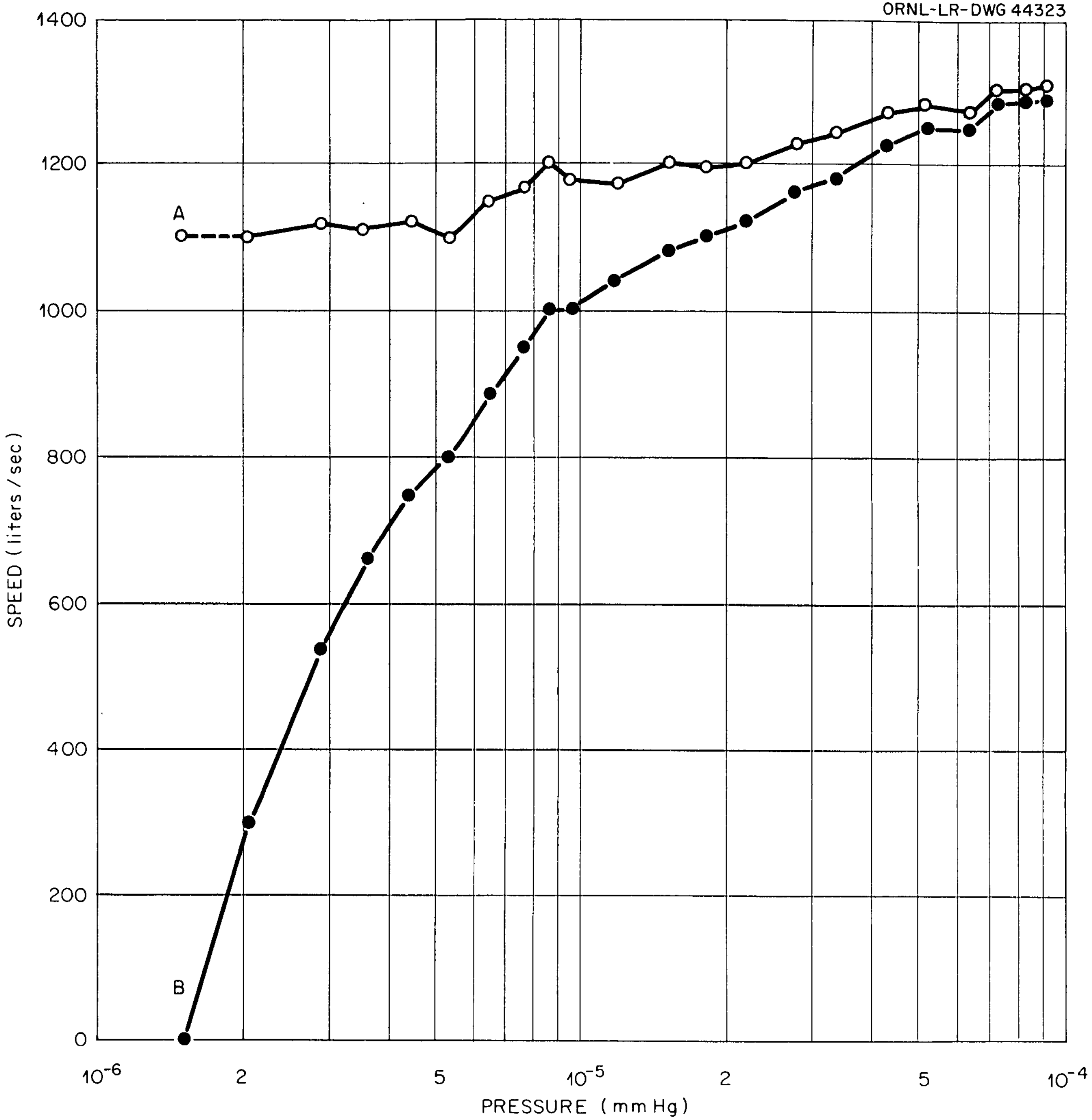

Fig. 4. Comparison of Speeds Calculated by Two Methods,

A. Partial Pressure Method: $S = \frac{Q}{P-P_0}$.

B. Total Pressure Method: $S = \frac{Q}{P}$.

MCF-1400 Pump at 2100 Watts.

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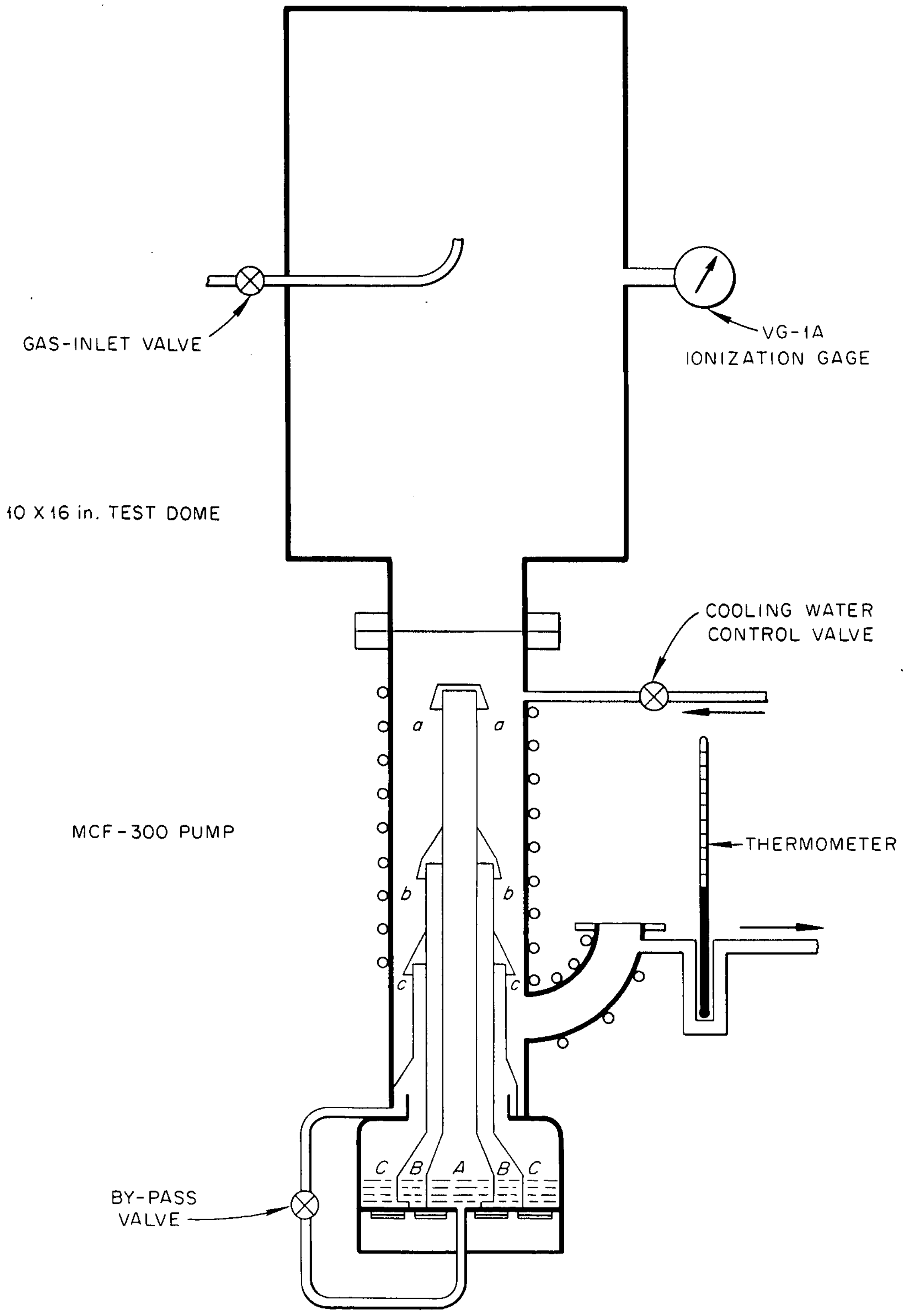

Fig. 5. Fractionation Test Assembly Schematic.

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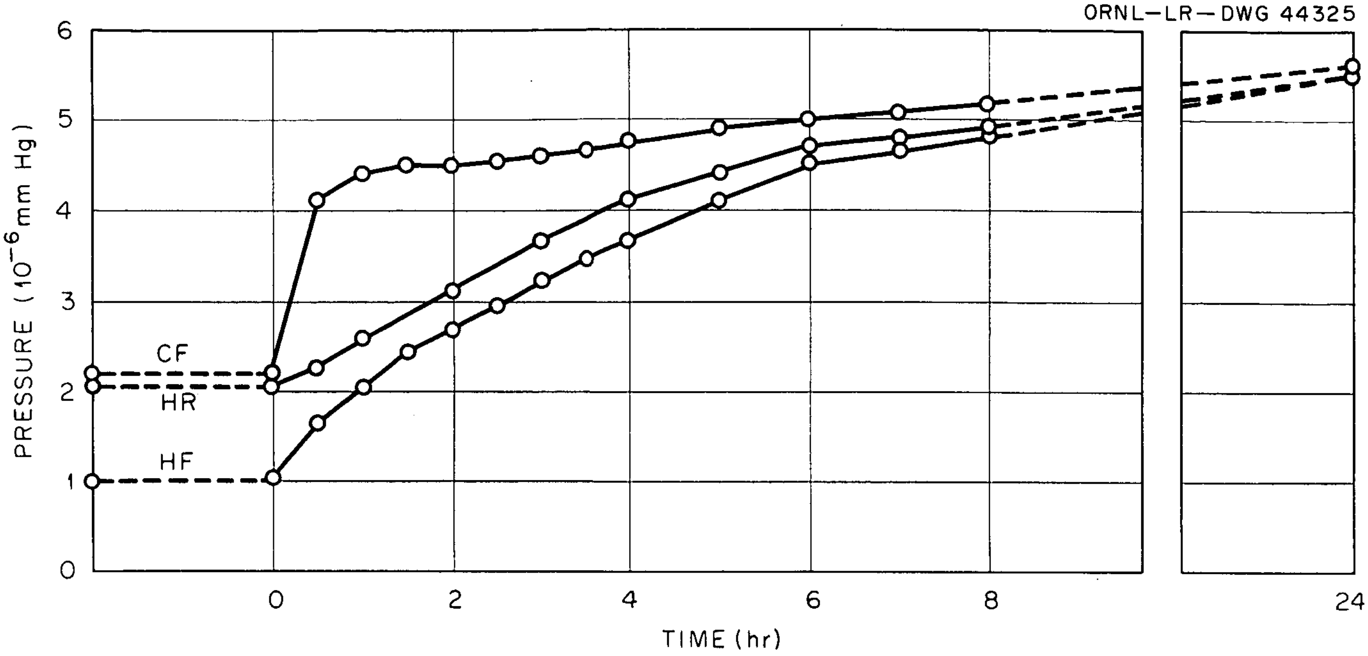

Fig. 6. Minimum External and Internal Fractionation. (CR)

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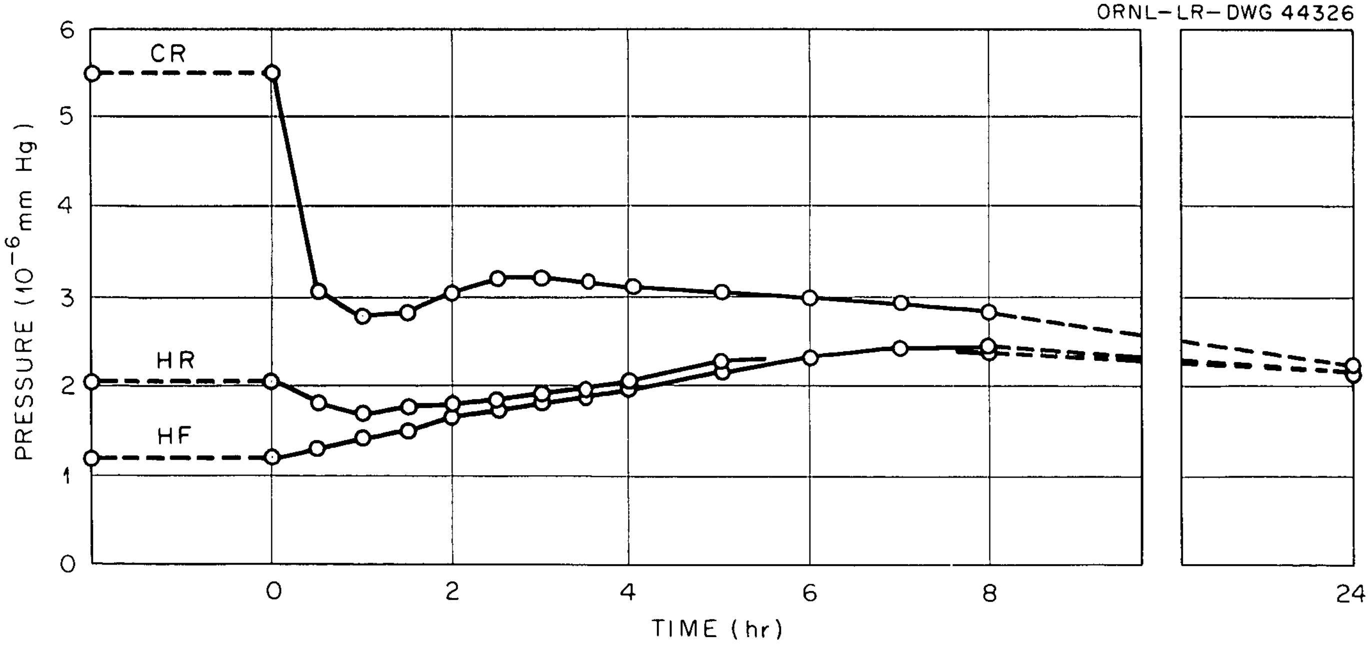

Fig. 7. Minimum External, Maximum Internal Fractionation. (CF)

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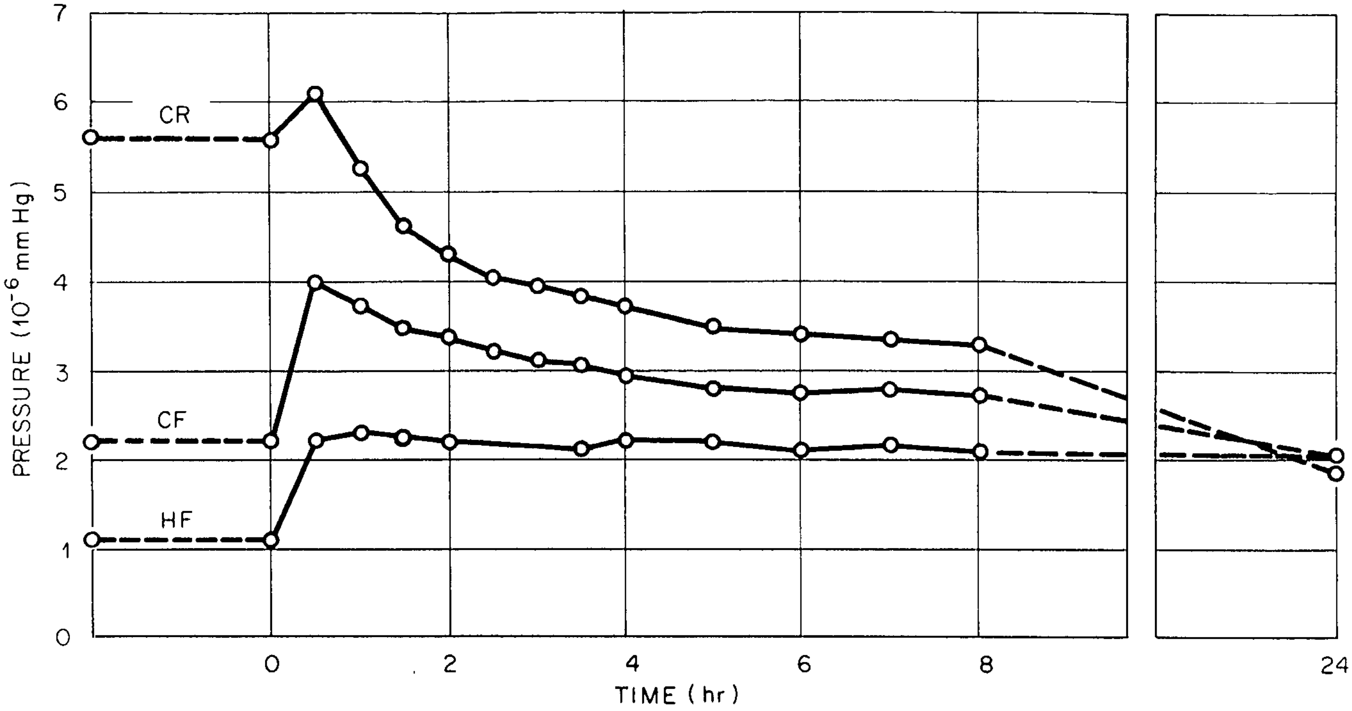

Fig. 8. Maximum External, Minimum Internal Fractionation. (HR)

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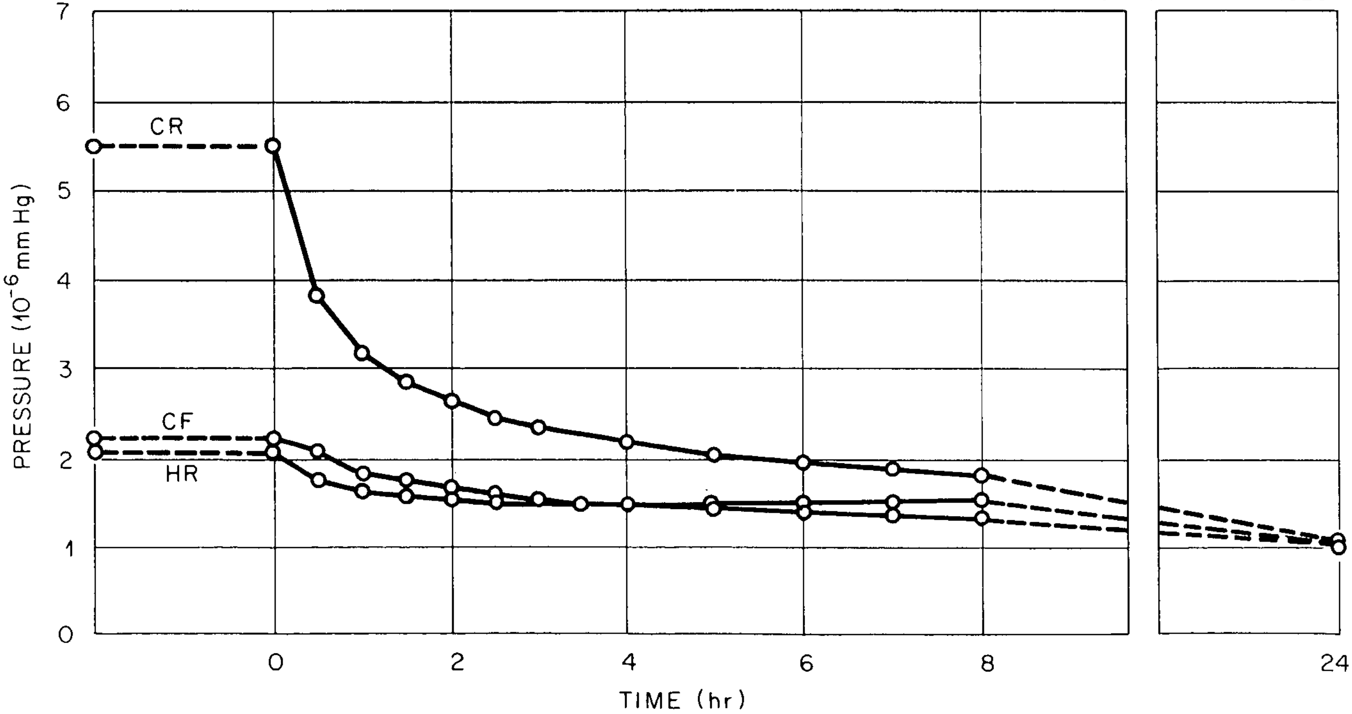

Fig. 9. Maximum External and Internal Fractionation. (HF)

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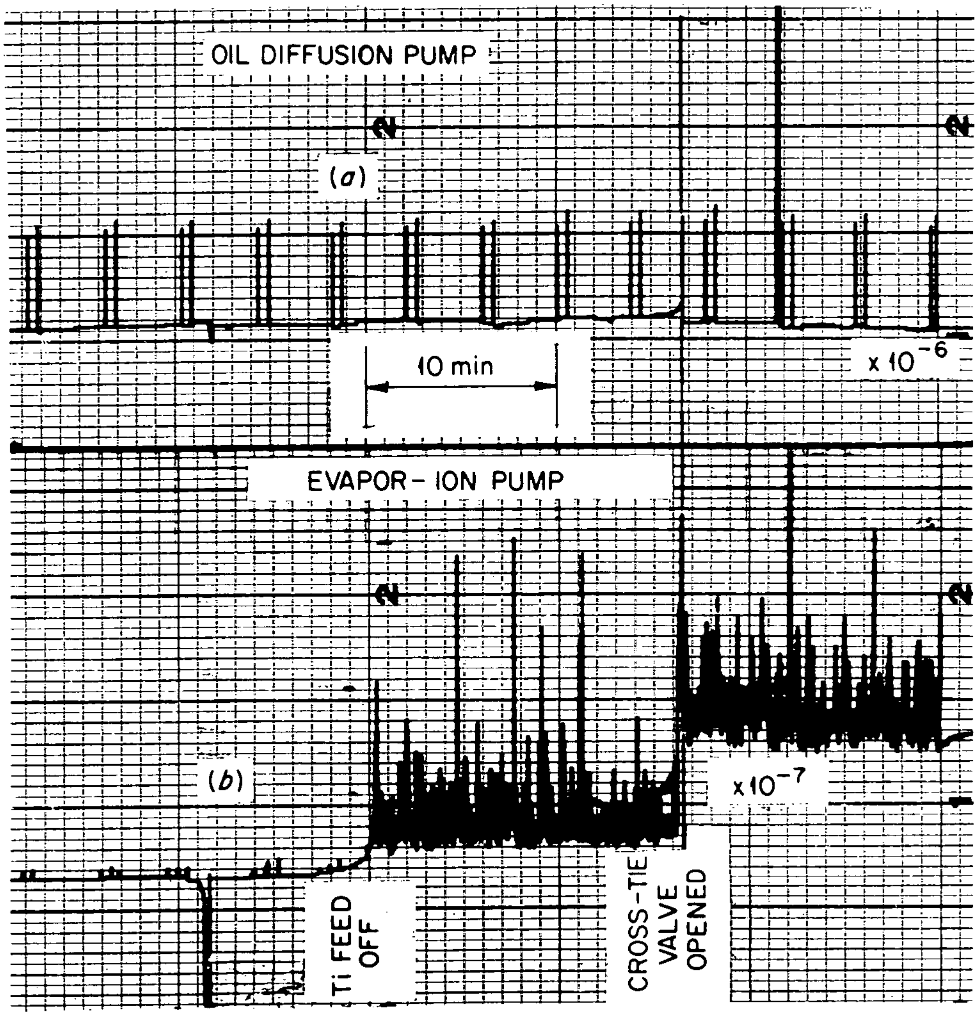

Fig. 10. Pressure Changes on Interconnecting Evacuates Systems:
(*a*) System Pumped by Oil Diffusion Pump
(*b*) System Pumped by Evapor-Ion Pump

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