Title
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Publication Date
1962-01-31

UCRL-9782 Rev.

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Patrick B. Kennedy

January 31, 1962

A HYPOTHESIS CONCERNING LIMITATIONS OF DIFFUSION PUMPS†

By PATRICK B. KENNEDY

An examination is made of the wide discrepancy between theoretical and actual performance of diffusion pumps and of the reasons adduced for this discrepancy. A new hypothesis is offered, according to which the relatively high pressures persisting on the high-vacuum side of diffusion pumps result from the backstreaming of large numbers of molecules carried on compression waves originated by eruptive boiling. This hypothesis accounts for the relative ineffectiveness of baffles and for several other previously unexplained phenomena. Evidence supporting the hypothesis is given, remedial measures are suggested, and implications of many vacuum applications are briefly outlined.

1. Background

The performance of diffusion pumps has improved surprisingly little since their original development 45 years ago. While some improvements in manufacturing and design have resulted in reducing attainable pressures with generally available untrapped pumps from 10^{-4} to 10^{-7} Torr, we are still far from the kind of vacuums which are not only theoretically attainable, but actually very much needed today for several applications.

It has been stated[1, 2, 3] that the vacuums presently being reached by trapped diffusion pumps are about all that can be expected from this type

†This work was done under the auspices of the United States Atomic Energy Commission.

[1]D. ALPERT, "Recent Advances in Ultra-high Vacuum Technology," Advances in Vacuum Science and Technology, Vol. I, pp. 31-38, Ed. E. Thomas, Pergamon Press, London (1958).

[2]I. FARKASS and C. F. VANDERSCHMIDT, "The production of Ultra-high Vacuums in Metal Systems Larger Than One Thousand Liters," Vacuum Symposium Transactions, pp. 42-47, Pergamon Press, Oxford (1959).

[3]H. R. SMITH and P. B. KENNEDY, "Ultra-low Temperature Mechanical Refrigeration Systems for High-vacuum Traps and Baffles," Vacuum Symposium Transactions, pp. 271-277, Pergamon Press, Oxford (1959).

of equipment, and that any further advances[1] must make use of other techniques. Unfortunately, the other techniques being investigated appear to be limited by cost of by small capacities, or both. Meanwhile, the diffusion pump, which is the workhorse of the vacuum field today, is not producing pressures as low by several orders of magnitude as those which theory indicates it should be capable of.[4]

2. Ascribed cause of difficulty

Any vacuum pump will eventually reach a point of equilibrium at which it will not further reduce the pressure in the evacuated vessel by being operated for additional periods of time. This point can be estimated for a given pump, pumping medium and baffle temperature; if the pressure produced by the pump is seriously out of line with the estimated value, it must be assumed that something is wrong. Precisely this phenomenon has been observed by many who have worked with diffusion pumps, and various reasons have been adduced for the discrepancy.

There is no reason to suppose that the theoretical efficiency of the pump itself changes in any way. If the pressure becomes stationary much above the theoretical equilibrium point, it is generally assumed that the cause must be the introduction of molecules into the evacuated chamber at a rate equal to that at which the pump is removing them. The mechanism by which these molecules find their way into the high-vacuum area has not, however, been satisfactorily established.

Alpert[1] has calculated the infiltration of air which could be expected through leaks and permeation of the vessel walls; it is clear from his

[4]F. REINATH, "On the State of the Art of Diffusion Pump Design," LRL Engineering Note 3140-01 M281 (1961).

figures that almost any diffusion pump would be able to handle such permeation easily, and that there is virtually no theoretical lower limit imposed on attainable pressures because of this factor.

Outgassing of the walls is undoubtedly a major source of gas molecules;[5, 6] indeed, it may constitute a barrier to the ultimate vacuum. However, gas molecules from this source will not be a constant source of pressure, unless they are replenished.

There seems to be agreement that an important source of gas maintaining the equilibrium pressure in the high-vacuum area of untrapped systems is backstreaming, or the re-entry of molecules of air or of the pumping medium from the pump itself. The presence of oil on the walls of the evacuated vessel indicates that some molecules do in fact re-enter the vessel from the pump. Five possible mechanisms of such backstreaming have been identified,[7] although none of these has been conclusively measured.

Since at the pressures attained by diffusion pumps conditions of free molecular flow are assumed to exist, it follows that molecules re-entering the evacuated vessel must do so in straight-line paths. On this premise, both isolation traps and low-temperature baffles† have been installed to provide optical opacity between vessel and pump. Despite such traps and

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[5] N. MILLERON, "Some Component Designs Permitting Ultra-high Vacuums with Large Oil Diffusion Pumps," Vacuum Symposium Transactions, pp. 140-147, Pergamon Press, London (1958).

[6] J. C. SIMONS, JR., "An Ultra-high Vacuum Chamber for Space Simulation," Vacuum Symposium Transactions, pp. 48-54, Pergamon Press, Oxford (1959).

[7] S. KOBAYASHI and H. OTATE, "The Experimental Research on the Backstreaming of Oil Vapor of an Oil Diffusion Pump," Advances in Vacuum Science and Technology, pp. 193-195, Pergamon Press, London (1958).

†The following are suggested definitions of N. Milleron: Isolation traps catch some gases (particularly the heavy masses moving with free molecular motion) by immobilizing them on the trap surface. More accurately, the sitting time for a trapped molecule is very long. Baffles, on the other hand, only reduce the rate of flow of gases, either by means of surface temperature or geometrical impedance. The sitting time for molecules in a baffle is short compared to the sitting time in a trap.

baffles, however, some backstreaming does take place.

The degree of backstreaming is indicated by mass spectrographs of residual gases. Oil has been observed on baffled systems in the high vacuum vessel. While the installation of baffles has lowered equilibrium pressures by as much as two orders of magnitude, there is no convincing explanation for the fact that substantial numbers of molecules pass back through the baffles, maintaining the pressure many orders of magnitude above the estimated value.

3. Theoretically attainable pressures

The principle of operation of the diffusion pump is such that it should, in theory, remove all gas molecules from the volume and surfaces being evacuated. The pressure in the evacuated vessel would in that case be the vapor pressure of the material of which the walls were made, plus the pressure resulting from the permeation of gases through the walls. This pressure might be of the order of 10^{-20} Torr. Such a theoretical pressure assumes, of course, no backstreaming or surface migration.

As noted in the previous section, some backstreaming of molecules from the pump is to be expected, and for this reason a baffle is installed upstream of the diffusion pump. If the motion of the molecules is in straight-line paths, as would be expected, a two-bounce baffle should stop the preponderance of molecules. In fact, Farkass and Vanderschmidt note[2] that the addition of complex baffles does not appear to improve pump performance over very simple baffles.

An examination of current results indicates that we are very far from reaching theoretically attainable pressures; likewise, an examination of the literature indicates that no satisfactory explanation has been offered for this very wide discrepancy. A liquid-nitrogen cooled baffle should

prevent re-entry of virtually all working fluid molecules into the evacuated vessel, but this is not in accord with our observations. It appears that there is some element in the situation which is not accounted for.

4. A new hypothesis for backstreaming

On the basis of evidence discussed in the following section, the author has evolved a hypothesis which accounts for the discrepancy between actual and theoretical performance of diffusion pumps and for a number of other unexplained phenomena.

It is suggested that the relatively high pressures persisting on the high-vacuum side of a baffled diffusion pump are the result of the penetration of large numbers of molecules of the pumping medium being carried by randomly occurring compression waves originated by eruptive boiling[7, 8, 9, 10, 11, 14] in the boiler of the pump.

Erruptive boiling is defined here as the eruption of a bubble from a boiling medium into a region of low pressure relative to the pressure at the bottom of the boiling medium. These conditions are exactly fulfilled

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[8] N. BEECHER and N. P. HNILICKA, "High Vacuum Pumping Techniques," Vacuum Symposium Transactions, pp. 94-100, Pergamon Press, London (1958).

[9] H. R. SMITH, "Proposal-Development Program for Improvement of Diffusion Pump Performance," LRL Engineering Note 3140-01 M227 (1959).

[10] H. R. SMITH, "Relationship of Diffusion Pump Performance to the Thermodynamics of the Pumping Fluid," Vacuum Symposium Transactions, pp. 140-145, Pergamon Press, Oxford (1959).

[11] N. MILLERON and L. L. LEVENSON, "Discussion on Optimization of Large Oil Pumped Ultra-high Vacuum Systems," Vacuum Symposium Transactions, pp. 213-218, Pergamon Press, Oxford (1960).

in the boiler of a diffusion pump. The author's present view is that such eruptive boiling is probably the result of the entraining by the circulating medium of small quantities of a contaminant—most likely air, water, or decomposition products, or a combination of these. When the contaminant is heated at the bottom of the boiler, it nucleates a vapor pocket which, when bouyant, rises to the surface. Its initial pressure when formed is determined by the liquid head of the medium at the bottom of the boiler (see Fig. 1); and on reaching the surface of the liquid, where the pressure is ≈ 0.5 Torr, it explodes, setting up a compression wave in the gas above the boiler.

The compression wave propagates through the pumping-fluid vapor, moving readily through the annular jets. When it reaches the high-vacuum region, it carries with it a relatively large mass of the pumping medium in a burst of matter that is much like a projectile leaving a gun, and moves into the high-vacuum region, penetrating to all areas regardless of baffles or contours of the vessel.

The wave is able to transit the cold baffles because the layer coating the baffle surfaces (consisting primarily of condensables) is a poor heat conductor due to its generally spongy character. Molecules of the compression wave are at a relatively high temperature; and those at the front of the wave quickly bring the outer layer of the coating to thermal equilibrium with the wave, so that the remaining molecules of the wave retain their initial velocity and temperature instead of losing it to the baffle surface. The baffle is thus ineffective with relation to a large portion of the molecules in each such compression wave entering the high-vacuum chamber from the pump.

This phenomenon accounts for the relative success of baked systems. The clean, baked walls of the chamber plus the many surfaces of the adsorptive

material or copper foil traps afford a large pumping capacity for condensables entering from the pump.

5. Evidence

The importance of the hypothesis offered above is reflected in the large number of disparate phenomena which it encompasses with a relatively simple explanation. The most important of these has already been outlined in detail; it is the failure of conventional baffled diffusion pumps to produce the vacuums of which they are theoretically capable.

A review of the literature in the light of this hypothesis suggests that compression waves carrying the pumping fluid into the evacuated chamber may be responsible for a number of apparently unrelated phenomena. There is general agreement[8, 12, 13, 14] that the major limitation on vacuums attainable with baffled systems is the backstreaming of molecules of the pump fluid. Use of a mass spectrograph[15] indicated the presence of

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[12] S. P. WOLSKY and E. J. ZDNAK, "The Investigation of Residual Gases in Vacuum Systems," Vacuum, 10, No. 1/2, pp. 12-21 (1960).

[13] H. G. NÖLLER, G. REICH, and W. BÄCHLER, "Diffusion Pump and Baffle Systems of Large Suction Speeds for Pressures Lower than 10^{-8} Torr," Vacuum Symposium Transactions, pp. 72-74, Pergamon Press, Oxford (1959).

[14] B. B. DAYTON, "Vacuum Chamber, Outgassing and Speed Relations," Vacuum Symposium Transactions, pp. 101-119, Pergamon Press, Oxford (1959).

[15] W. TRETNER, "An Electrostatic Mass Spectroscope," Vacuum, 10, No. 1/2, pp. 31-34 (1960).

mercury. Also, masses characteristic of long chain hydrocarbons have been reported,[12, 16, 17, 18] and molecules which could be identified as oil molecules or molecules of light fractions of the oil have been detected in the vacuum region.

It is generally accepted that the molecules which transit the baffle and are found in the vacuum region are those of light fractions of the oil,[11] on the premise that the heavier fractions would condense on the baffle under conditions of free molecular flow. The writer finds it difficult to accept the premise that a significant quantity of light fractions enters the vacuum region for the following reasons: (1) Observed velocities of propagation of the compression wave agree with the formula $V \propto \sqrt{T/M}$, and this observed velocity implies a molecular weight characteristic of the pumping medium; (2) the abrupt disappearance of the pip tail (see Fig. 2) indicates that the matter in the vacuum region is a condensable, as a light fraction should exhibit a much slower recovery rate; and (3) similar waves have been observed in mercury-pumped systems.

It does appear likely however, as previously suggested, that light fractions of the pumping oil may exist in the circulating medium and may be partly or wholly responsible for nucleating the eruptive boiling.

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[16] E. LEYBOLDS NACHFOLGER, Analyses of Ultimate Pressure (1958).

[17] M. RIVERA and R. LeRICHE, "A Differentially Pumped Ultra-high Vacuum System," Vacuum Symposium Transactions, pp. 55-59, Pergamon Press, Oxford (1959).

[18] D. LICHTMAN and A. HEBLING, "Ultra-high Vacuum Demountable System for Mass Spectrometer Gas Analysis," Vacuum Symposium Transactions, pp. 187-195, Pergamon Press, Oxford (1960).

Of particular interest is a report by Martin and Leck[19] describing random fluctuations in pressure on both the high-vacuum and backing sides of a diffusion pump. It is noted that "It was found difficult to describe the pressure fluctuations for any given conditions because of their essentially random nature. In every observation they were found to be made up of random changes occurring at intervals of between 1 and 10 sec...." These writers also noted a dependence of the magnitude of the fluctuations on the heat input to the boiler—a relationship which is not surprising when viewed in the light of our hypothesis. This report suggests that the fluctuations observed may be due to unstable oil-vapor distribution but goes on to acknowledge, "On the backing side the fluctuations are much greater than can be explained by the above simple theory, for because of the short time constant, the variations in gas throughput and therefore backing-side pressures should be negligibly small....This must presumably be caused by some further instability in the jet or boiler."

Our hypothesis suggests the nature of this "further instability" and accounts as well for the random nature of the observed fluctuations.

For example, pressure rises $\approx 1.5 \times 10^{-6}$ Torr of 20-msec. duration were observed for oil with both baffled and unbaffled systems, as shown in Fig. 2. Pressure rises $\approx 3 \times 10^{-5}$ Torr of 60-msec. duration were observed for Hg. The frequency of the fluctuations decreases with time as the pumping fluid cleans up.

Huber and Trendelenburg[20] and others[7] have noted the improvement in vacuums attainable by the use of diffusion pumps in series. This improvement is difficult to account for, although some conjectures have been made.

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[19] V. S. MARTIN and J. H. LECK, Letter to Editor, Vacuum, 4, No. 4, p. 489 (1954).

[20] W. K. HUBER and E. A. TRENDELENBURG, "Recent Development of Ultra-high Vacuum Systems Using Oil Diffusion Pumps," Vacuum Symposium Transactions, pp. 146-149, Pergamon Press, Oxford (1959).

On the basis of the new hypothesis, however, we may assume that putting diffusion pumps in series decreases the quantity of impurities in the pumping fluid, as suggested by Huber and Trendelenburg, and that the improved performance results from a reduction in eruptive boiling nucleated by these impurities.

6. Implications of the hypothesis

It follows from the hypothesis that problems encountered in many high-vacuum applications are readily explained by the intermittent presence of large numbers of molecules.

The occasional early failure of a vacuum tube is possibly explained by assuming that a burst of molecules entered the system during the evacuation of the particular tube in question. Additional evidence is afforded by the experience of users of vacuum tubes, who have found that a tube which has operated satisfactorily for an initial 30 to 60 days has a greater probability of a normal operating life than does a new tube chosen at random. It is evident that a vacuum tube or bulb which has in fact not been evacuated to the degree assumed is likely to fail very early in its operation because of the presence of oil or decomposition products, while if it operates satisfactorily for an initial period, it may be assumed that it was evacuated to the required degree during manufacture.

The vacuum depositing of metal coatings and vacuum melting of metals have also encountered problems, intermittent and unpredictable in nature, which are possibly explainable on the assumption that the evacuated volume is subject to random intrusions of large numbers of oil molecules.

The large numbers of environmental tests conducted in high-vacuum chambers simulating the space environment may also be yielding erroneous results in many cases because of the false reading of pressure indicators and the presence of oil molecules, which are presumably not present in space.

The above suggestions regarding the implications of the new hypothesis are given only to indicate the nature of such implications; workers in the field of high vacuum will readily think of many others which time does not permit mentioning here. An obvious one which has not been mentioned is that more evacuated chambers should be provided with instrumentation capable of detecting the fluctuations in pressure resulting from the creation of compression waves in the diffusion pump.

7. Investigations required for detailed understanding of the phenomenon

It is obvious that the most immediate problem is to find the best means of eliminating the eruptive boiling which is responsible for the compression waves carrying the material into the evacuated vessel. Although some type of muffler may damp out the waves before they reach the chamber, it appears more logical to eliminate the waves themselves. One solution might be the use of a double pressure boiler. Another approach is the ribbon heater reported by Milleron and Levenson.[21] Still other solutions are possible once the nature of the problem is recognized.

In addition to elimination of the difficulties, however, there are a number of investigations which are being made to provide a more complete understanding of the processes involved. One of these is a detailed study of the phenomenon of eruptive boiling itself. What material forms the bubble? How is it carried? Where must it be in the boiler—i.e., on the bottom, over a point source of heat—to form a bubble? What is the

[21] N. MILLERON and L. LEVENSON, "Preliminary Results on Optimization of Diffusion Pumps," No. 2 Le Vide (1961) (forthcoming).

the process of formation and subsequent rapid expansion of the bubble? How are bubble formation and expansion related to the depth and specific gravity of the pumping medium and to the ambient pressure above the liquid? What is the behavior of the compression wave as it passes from the relatively dense gas inside the jets to the high vacuum outside them?

Additional studies are being directed to an understanding of the process by which molecules of the pumping medium are carried by the compression wave, and to determing the quantities carried, the velocities of different parts of the wave (see Fig. 5), the paths followed, and the effects of various obstructions.

More important, perhaps, than the study of the phenomenon itself is a re-evaluation of a vast quantity of experimental results which are possibly based on erroneous assumptions regarding the actual pressures or molecule populations in evacuated vessels.

Acknowledgments

The author wishes to express his appreciation for valuable discussions to R. D. Kennedy, D. T. Scalise, F. S. Reinath, and N. Milleron.

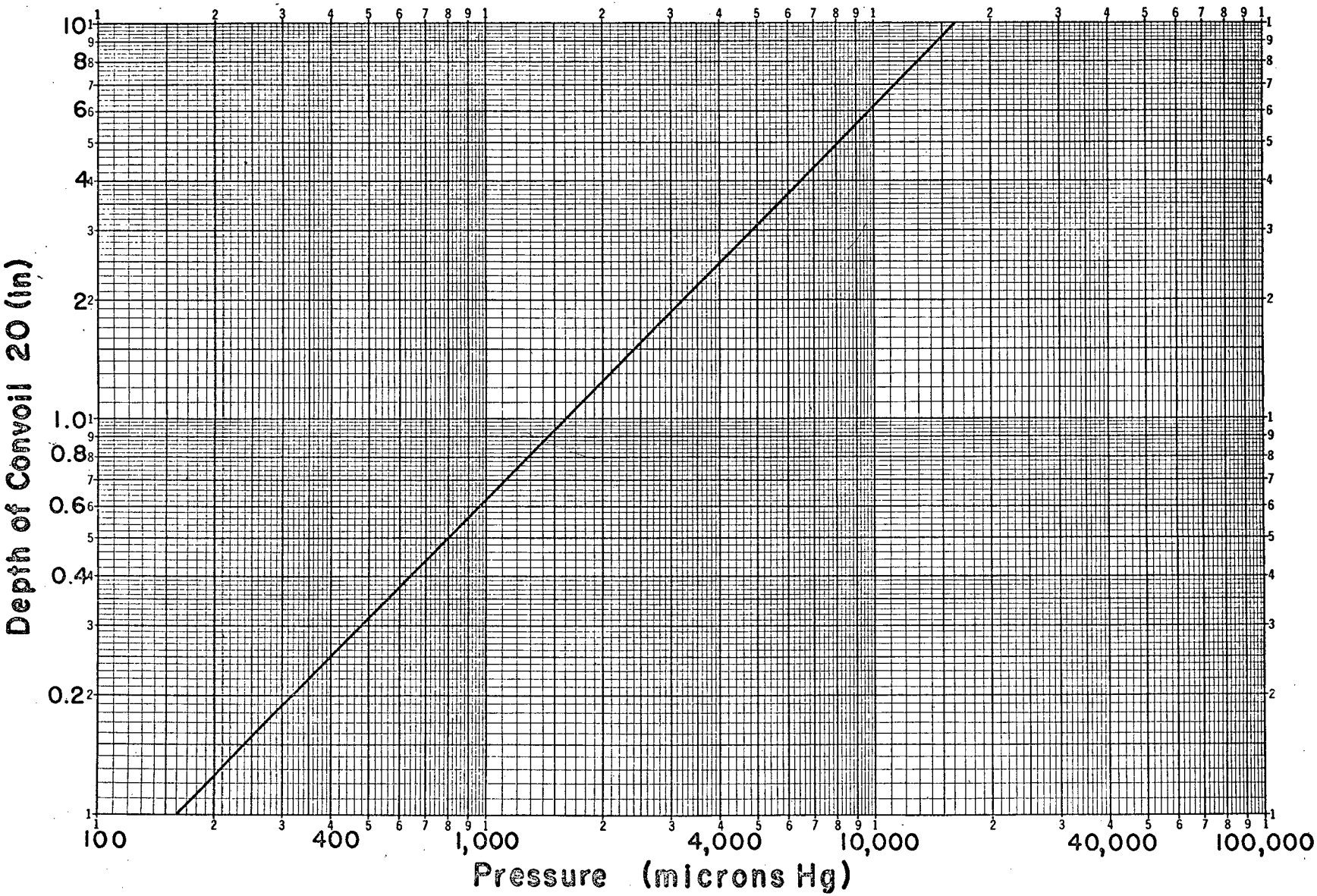

FIGURE 1

LIQUID HEAD VS. PRESSURE

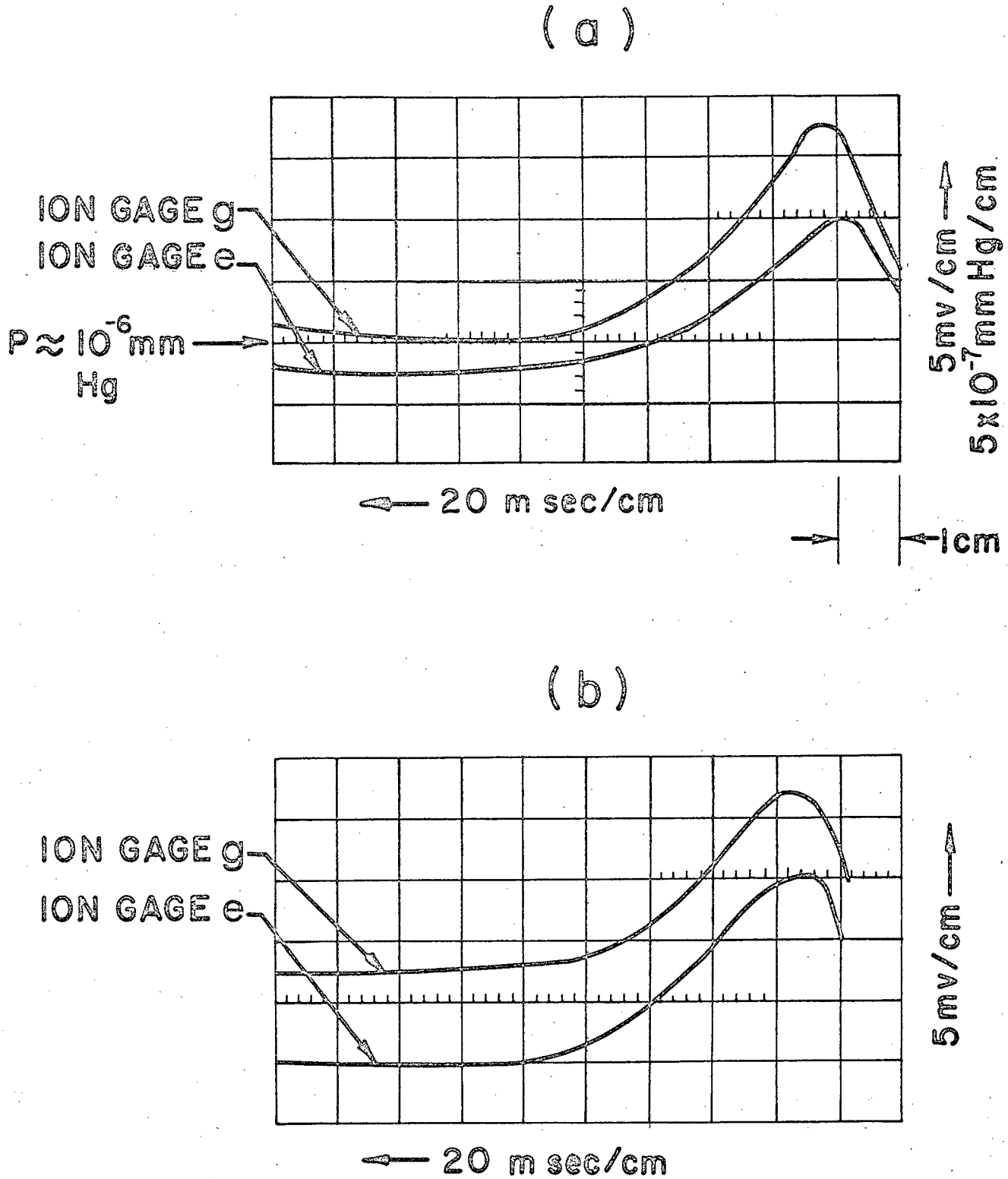

FIGURE 2
OSCILLOSCOPE TRACES
(a) WITHOUT COPPER FOIL TRAP (b) WITH COPPER FOIL TRAP
(for location of ion gauges, see Figure 3)

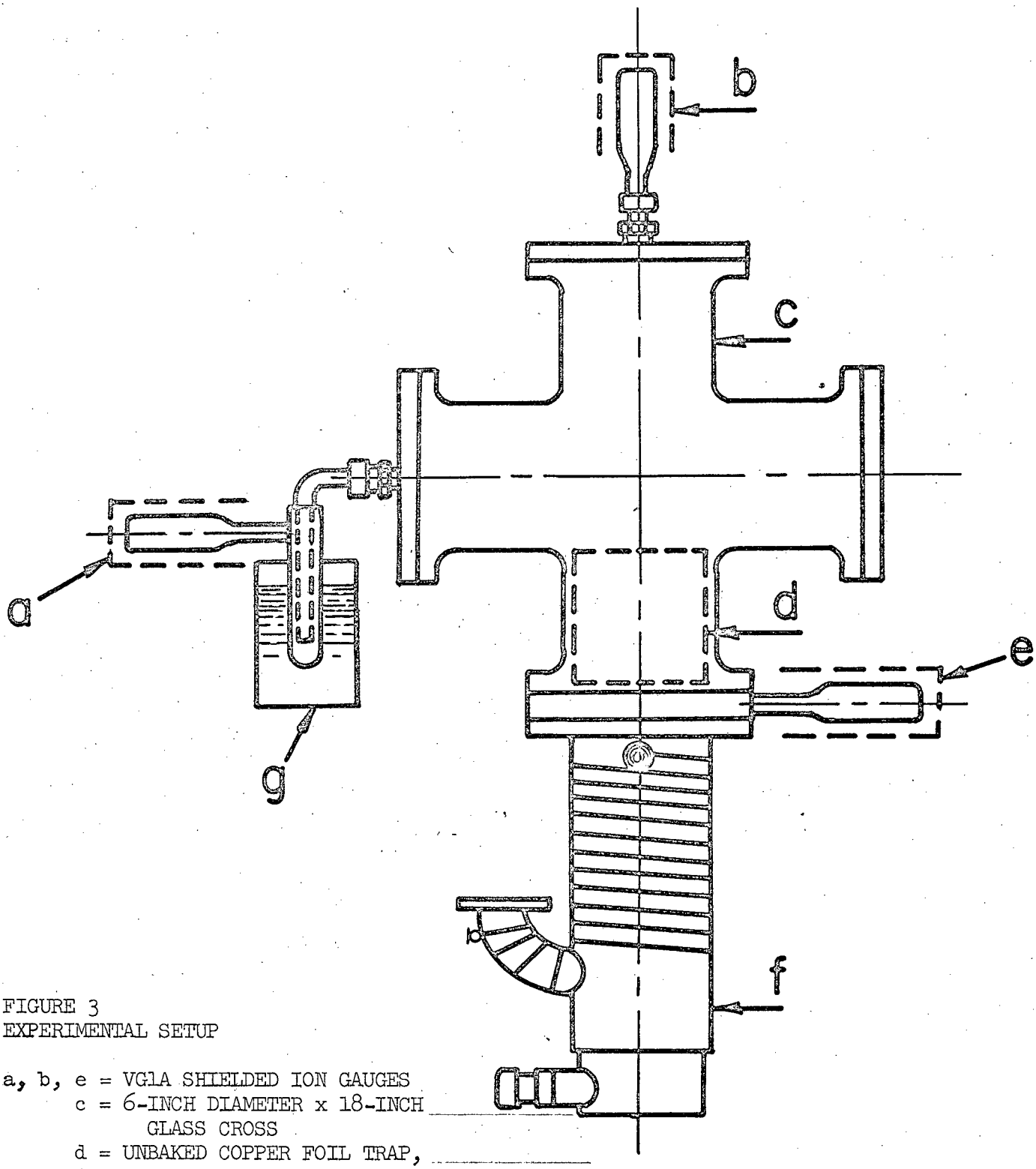

FIGURE 3
EXPERIMENTAL SETUP

a, b, e = VG1A SHIELDED ION GAUGES
c = 6-INCH DIAMETER x 18-INCH GLASS CROSS
d = UNBAKED COPPER FOIL TRAP,
f = DIFFUSION PUMP, CVC, PMC720
g = LIQUID NITROGEN TRAP

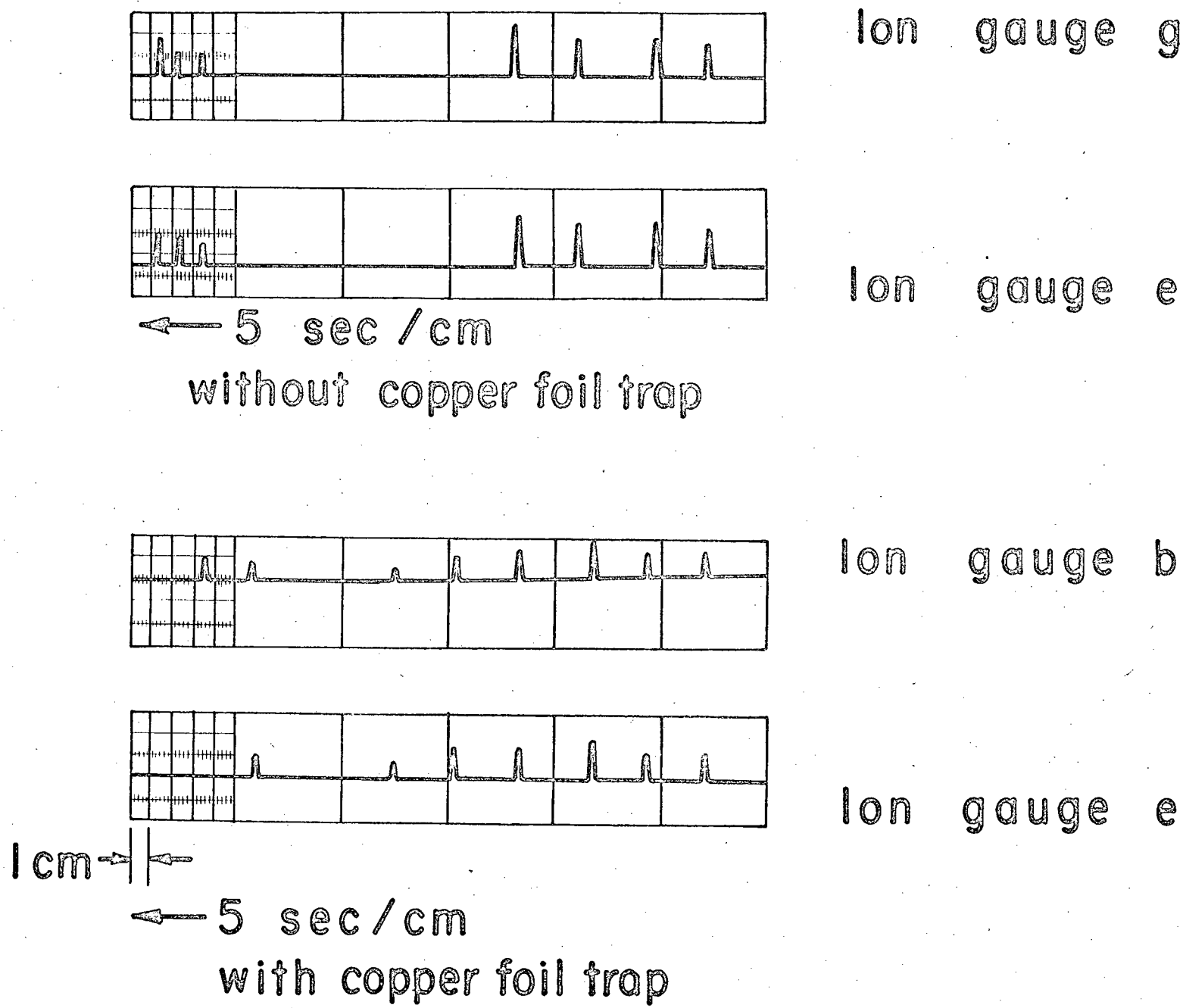

FIGURE 4
SPORADIC NATURE OF THE PRESSURE FLUCTUATION

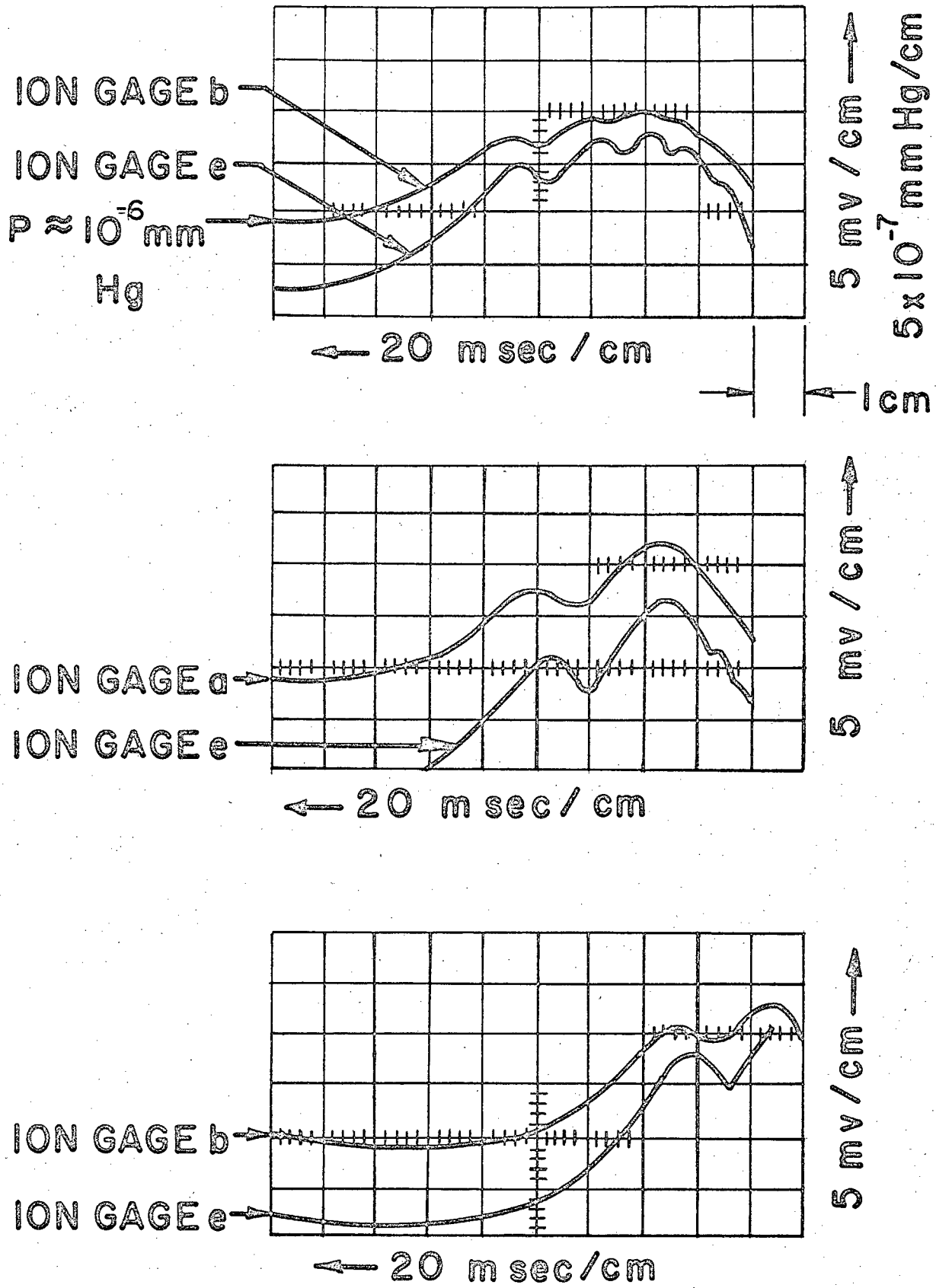

FIGURE 5
RANDOM WAVES PER SWEEP