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A HYPOTHESIS CONCERNING LIMITATIONS OF DIFFUSION PUMPS

by

Patrick B. Kennedy

July 6, 1961

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Abstract

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 for many vacuum applications are briefly outlined.

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

A HYPOTHESIS CONCERNING LIMITATIONS OF DIFFUSION PUMPS

1. Background

This paper is based on observations of limitations of some commercially available diffusion pumps. It is concerned with a source of the limitations rather than subsequent remedial use of auxilliary equipment (traps, baking, etc.).

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} mm Hg, 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 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 or 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 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.

D. 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 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. No writers have suggested permeation of this kind as a probable cause of the unsatisfactory performance of the diffusion pumps.

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, since they are not replenished.

There seems to be agreement that an important source of gas maintaining the equilibrium pressure in the high-vacuum area of untrapped system 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 baffles, however, some backstreaming does take place as follows:

a. Light mass molecules pass through both traps and baffles.

b. Heavy mass molecules pass through baffles but not through isolation traps.

The degree of backstreaming is indicated by mass spectrographs of residual gasses. 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 2 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 gasses through the walls. This

*The following are suggested definitions of Norman Milleron:
Isolation traps catch some gasses (particularly the heavy masses moving with free molecular motion) by immobilizing them on the trap surface. 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.

pressure would be on the order of 10-20 mm Hg. 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 should be expected, a 2-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. These waves of molecules move with viscous flow

characteristics—i.e., flow around obstacles instead of being stopped by them. This characteristic of the motion offers a satisfactory explanation for the fact that molecules of the pumping medium are able to penetrate multiple baffles which would be nearly completely impassable for molecules moving under conditions of free molecular motion.

Eruptive 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 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 carried along the bottom of the boiler, it is very rapidly heated to vaporization temperature, having a much higher vapor pressure than the pumping medium, and expands very rapidly as it rises through the boiling medium to the surface. Its initial pressure when the bubble is formed is determined by the liquid head of the medium at the bottom of the boiler (see Figure 1); and on reaching the surface of the liquid, where the pressure is ≈ 0.5 mm Hg, 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.

5. Evidence

The importance of the hypothesis offered above is reflected in the large number of disparate phenomena which it encompasses with a single 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 mercury. 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 $V \propto \sqrt{\frac{T}{M}}$, and this observed velocity implies a molecular weight of

400 AMU; (2) the abrupt disappearance of the pip tail (see Figure 2) indicates that the matter in the vacuum region is a condensable, and a light fraction would indicate a much slower recovery rate.

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.

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 seconds...." 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 $\approx 1.5 \times 10^{-6}$ mm Hg of 20 ms duration were observed with both baffled and unbaffled systems, as shown in Figure 2. Figure 4 shows the sporadic nature of the fluctuations.

These compression waves may be rapidly damped to free molecular flow by surface-adsorption-type[20] traps.

Charmichael and Lange,[21] experimenting with copper foil isolation traps, determined stay-down times (time the system would remain below 10^{-9} mm Hg) for different traps in the same vacuum system. They determined that increasing the length of the trap increased the stay-down time, but that increasing the solid angle for straight-through passage of gas molecules without increasing the effective length of the trap did not. They concluded that the area of copper in the trap was the determining factor. It is equally plausible, however, that the increase of viscous damping provided by increasing the total length of narrow channels through which the backstreaming gas must flow is responsible for the improved performance. If the area exposed were the determining factor, one would expect that cooled finger traps inserted into the vacuum area would, by providing increased area, improve performance. That they do not do so is evidence that some other phenomenon must be at work. The Model C Stellarator vacuum system,[22] may also achieve its ultra-high vacuums when the unique baffles in series degenerate the viscous flow to free molecular flow.

Huber and Trendelenburg[23] 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. 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 encounted 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 material into the evacuated vessel, though some type of muffler may damp out the waves before they reach the chamber.

It appears more logical, however, to eliminate the waves themselves. One solution might be the use of a flash boiler. With this type of boiler, there is no body of boiling liquid in which bubbles can be generated.[24] Another approach is the ribbon heater reported by Milleron and Levenson.[25] 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 should be 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 process of formation and subsequent rapid expansion of the bubble? How is 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 should be directed to an understanding of the process by which molecules of the pumping medium are carried by the compression wave, and to determining the quantities carried, the velocities of different parts of the wave (see Figure 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.

Acknowledgements

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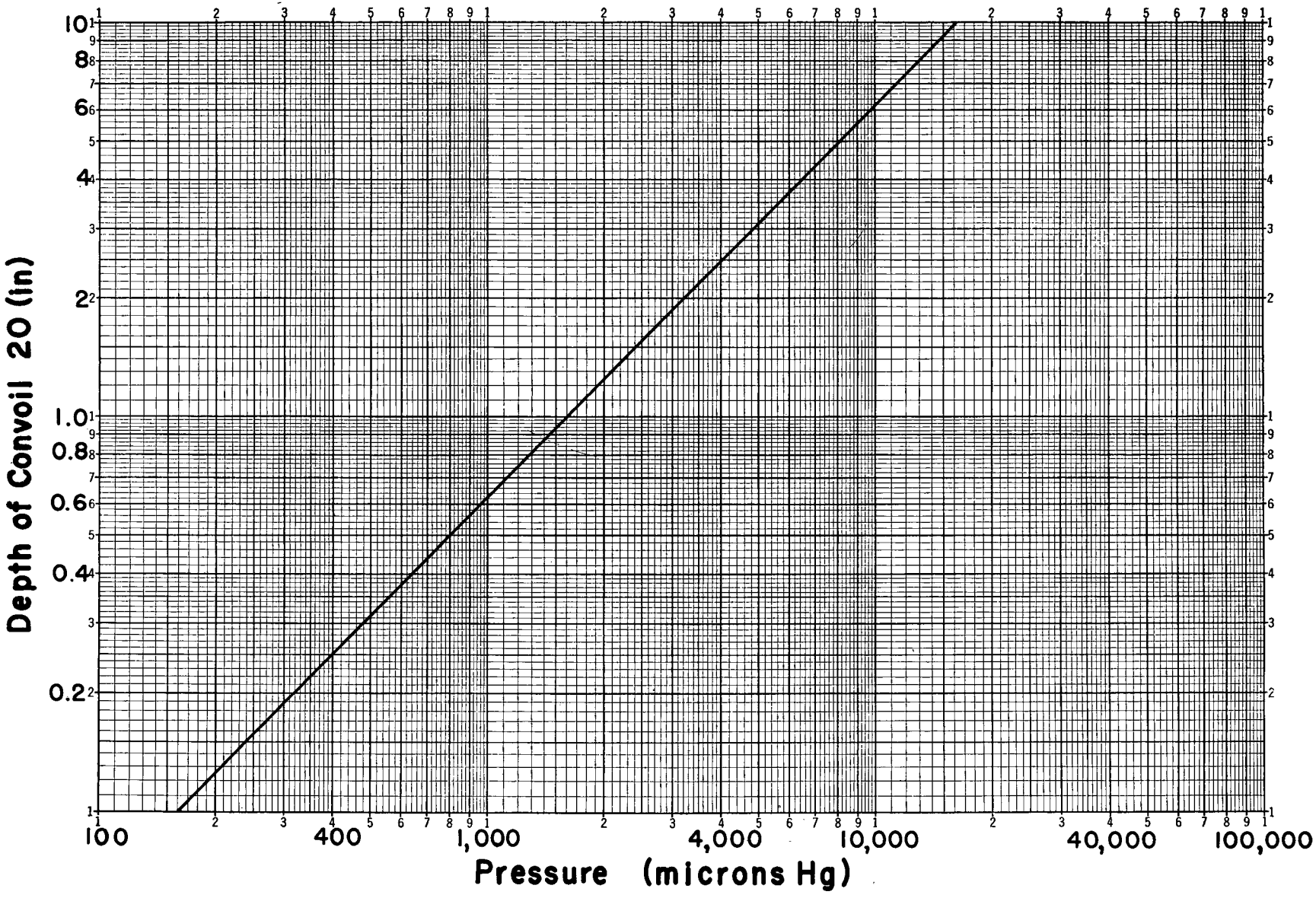

FIGURE 1
LIQUID HEAD VS. PRESSURE

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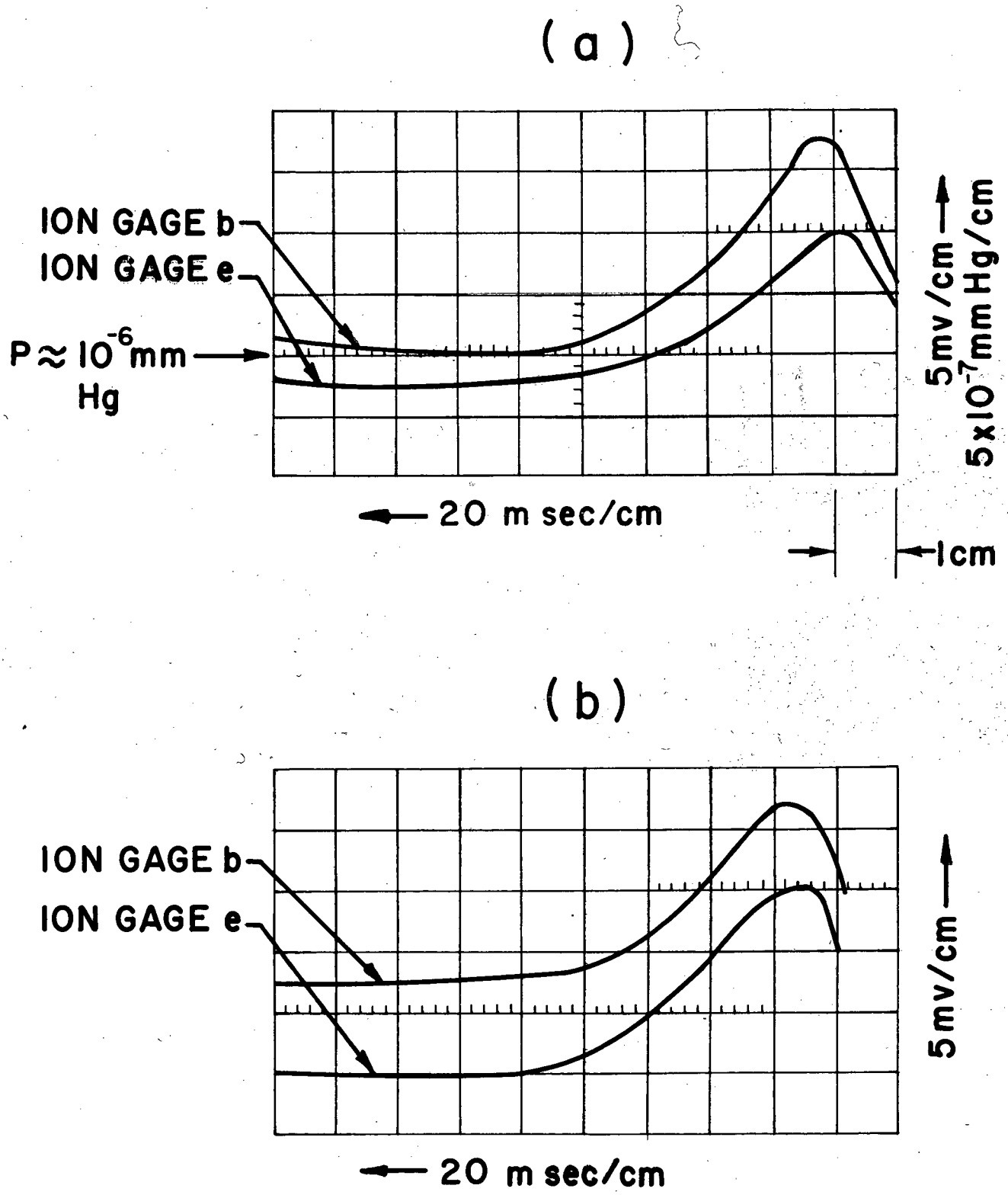

FIGURE 2
OSCILLOSCOPE TRACES
(a) WITHOUT COPPER FOIL TRAP (b) WITH COPPER FOIL TRAP
(for location of ion gauges, see Figure 3)

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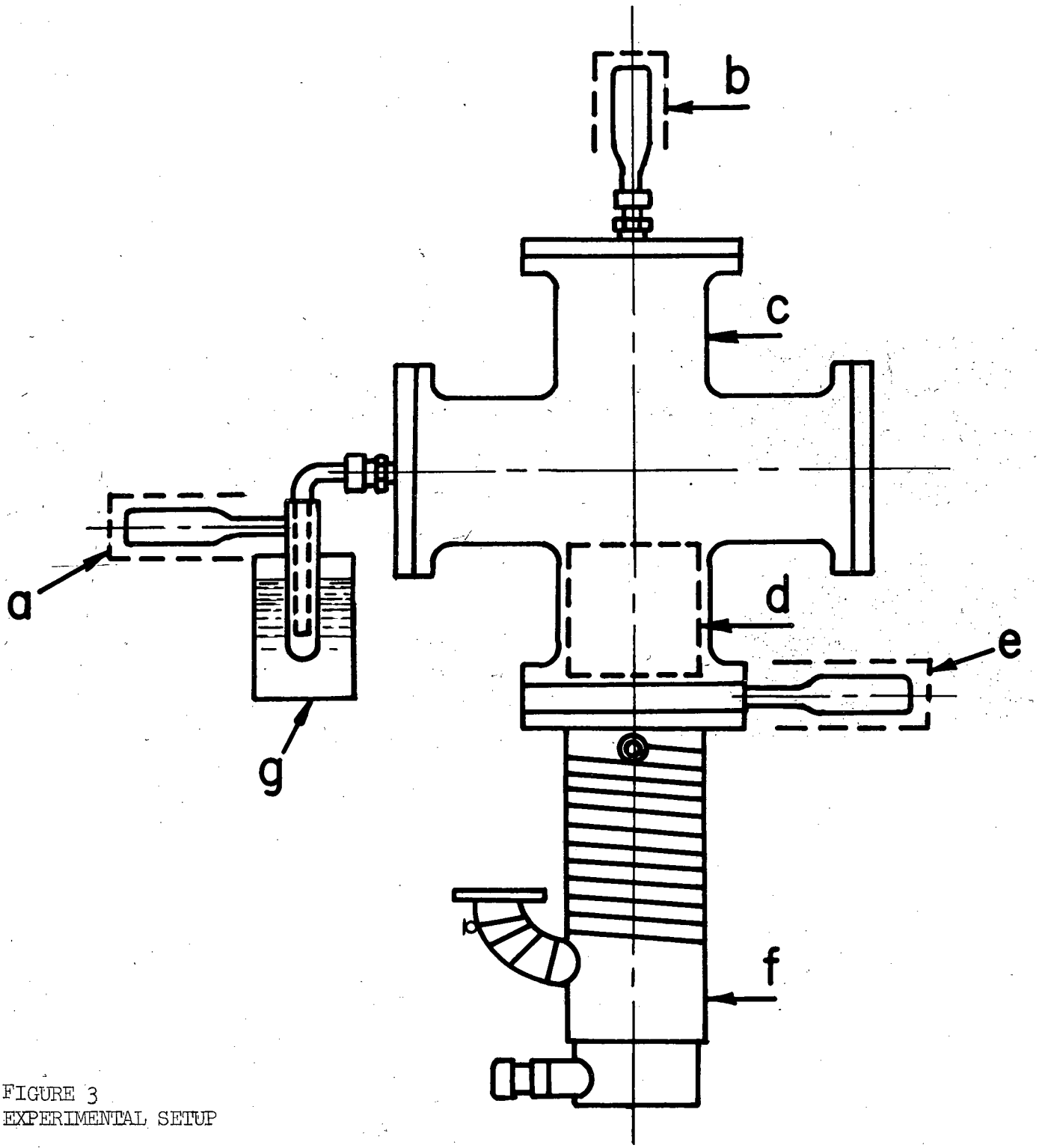

FIGURE 3
EXPERIMENTAL SETUP

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

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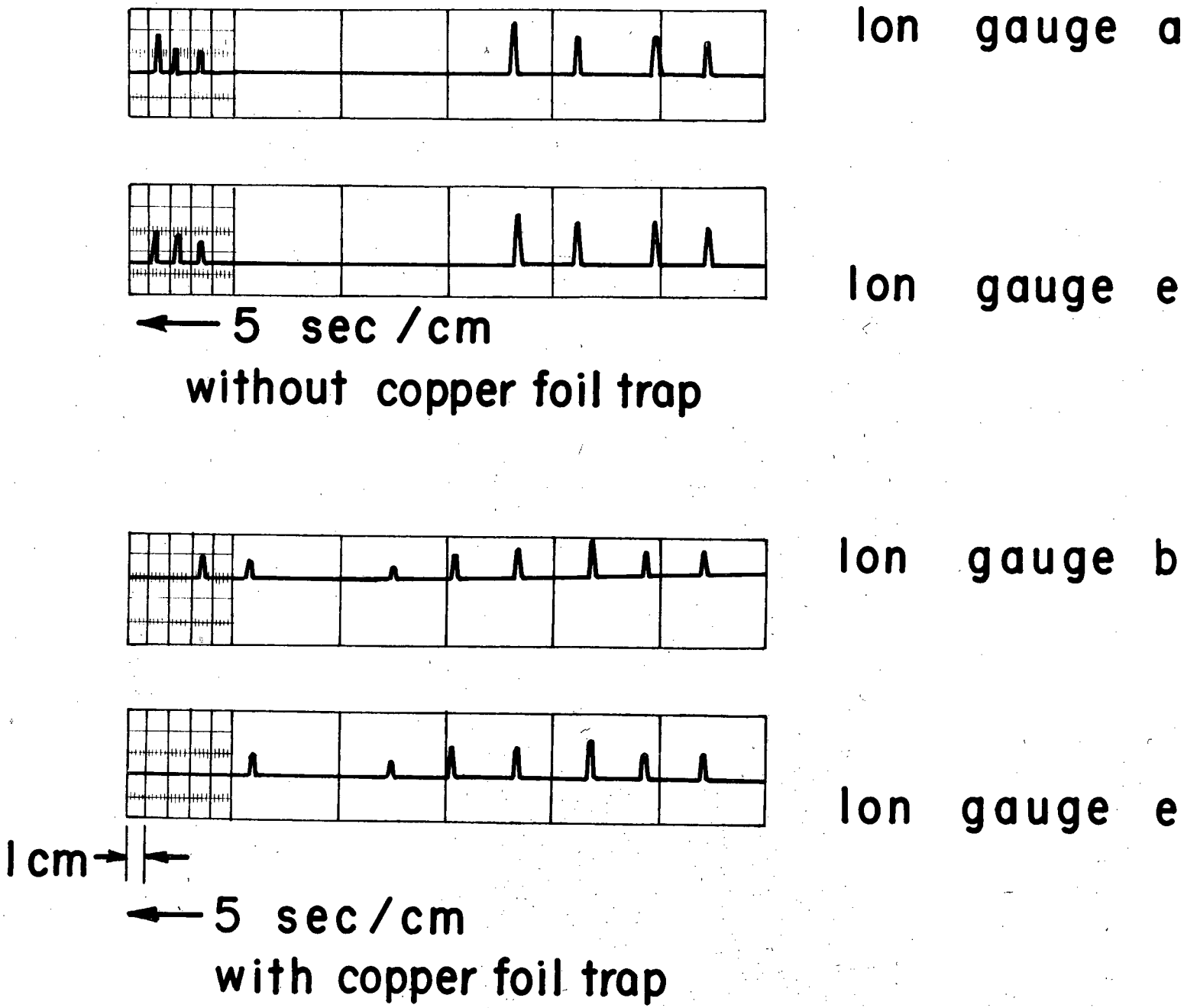

FIGURE 4

SPORADIC NATURE OF THE PRESSURE FLUCTUATION

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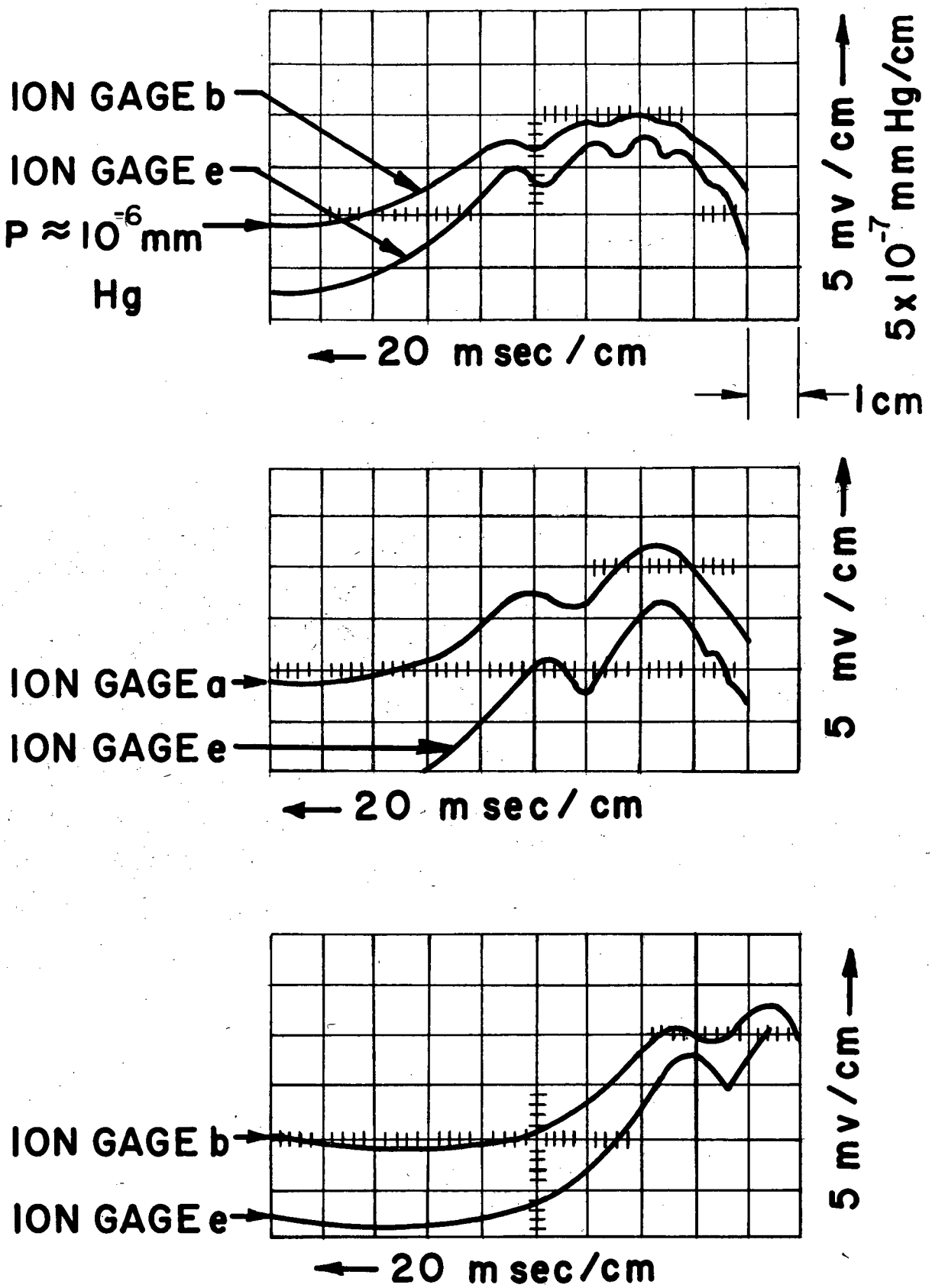

FIGURE 5
RANDOM WAVES PER SWEEP

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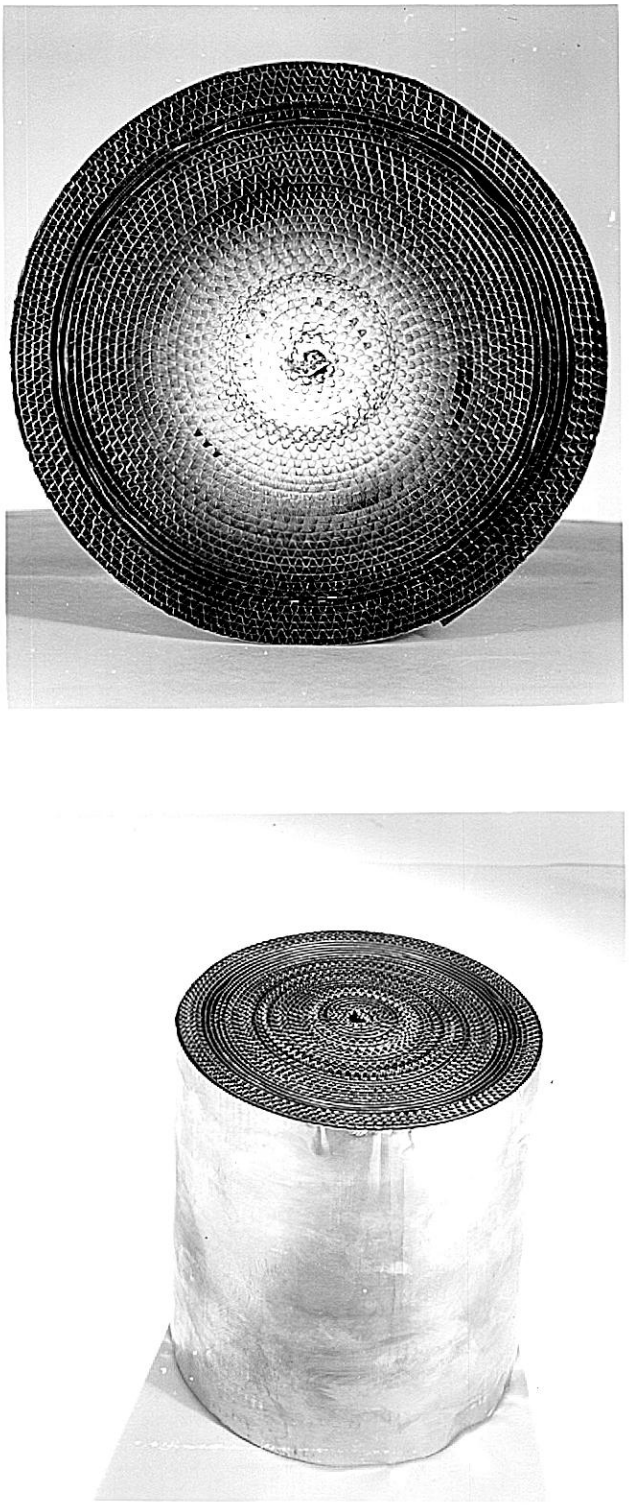

FIGURE 6
COPPER FOIL TRAP, 6-INCH DIAMETER, 5 3/4 INCHES LONG

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