A Continuously Sensitive Diffusion Cloud Chamber

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Supersaturation necessary for condensation of a vapor upon ions is maintained continuously by the diffusion of an initially warm saturated vapor through a noncondensing gas into a refrigerated region. Convection is avoided by diffusion vertically downward between a horizontal heated roof and refrigerated floor. Calculations show what flux of vapor and what roof and floor temperatures are necessary. Experiment shows that this diffusion cloud chamber operates as expected, and with reasonable precautions it is quite stable against turbulence. Successful operation depends on avoiding production of condensation nuclei which will make a diffuse rain of condensation in the chamber. Vapor from liquid in a glass flask heated by radiation from above has been found to be practically free of aggregates. The chamber cannot produce satisfactory ion tracks in the presence of too great an average ion load. In the steady-state operation of the present apparatus the normal background ionization without shielding loads the chamber so close to its limit that most tracks are diffuse. When first applying refrigeration there is a transient condition in which many more tracks are well defined. There are several possible ways of improving the steady-state ion load capacity of the apparatus.

I. INTRODUCTION

A CONTINUOUSLY sensitive cloud chamber of a sufficiently practical design could be expected to facilitate some types of experiments which hitherto have been performed by means of an expansion cloud chamber. The usefulness of the cloud-chamber technique could thereby be extended. With this purpose in mind, the development of a continuously sensitive cloud chamber was undertaken, and this article reports the design and characteristics of operation of the apparatus.

Modifications of expansion cloud chambers have been described which extend the sensitive period per expansion[1, 2] or increase the frequency with which expansions can be made.[3, 4] However, the expansion cloud chamber is essentially intermittent in its action. For truly continuous sensitivity, the supersaturation required for condensation upon ions must be attained in some other way than by adiabatic expansion in a cylinder.

Descriptions of two continuous cloud chambers have been published,[5, 6, *] as well as brief reports of the one which is the subject of this article.[7] One of the previously reported cloud chambers[5] operated by passing air over water at 70°C and thence into a water-jacketed observing channel at room temperature. Condensation phenomena were produced by electric discharges, but not by radioactive radiations. The other continuously active cloud chamber which has been described by Vollrath[6] operates by the interdiffusion of two vapors such as hydrochloric acid vapor and water vapor, whose mixture becomes supersaturated with respect to both components. In the state of development reported, the apparatus was suitable for visual demonstration but not for photographic recording of the tracks observed in it. The present apparatus maintains supersaturation by the steady diffusion of an initially warm saturated vapor downward through a

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[*] National Research Fellow, 1938.

[†] The original development of the diffusion cloud chamber was carried out in the Physics Department of the Massachusetts Institute of Technology. The developmental work done there is described in a thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy from that institution. The author is greatly indebted to the Massachusetts Institute of Technology for permission to take the apparatus there constructed to the University of California.

[1] F. N. D. Kurie, Phys. Rev. **53**, 215 (1938). Sensitive time 5 seconds in each minute.

[2] J. A. Bearden, Phys. Rev. **45**, 758A (1934). Sensitive time over 1 second per expansion.

[3] H. Brinkman, Proc. Roy. Acad. Amsterdam **39**, 1185 (1936).

[4] T. Shimizu, Proc. Roy. Soc. **99**, 425 (1921).

[5] L. G. Hoxton, "A Continuously Operating Cloud Chamber," Proc. Virginia Acad. Sci., Abst. 9, p. 23 (1933–34).

[6] R. E. Vollrath, Rev. Sci. Inst. **7**, 409 (1936).

[*] *Note added in proof:* Erich Regener, "A Method of Making Visible and Registering the Paths of Corpuscular Rays." (Utilizes a fog of oil drops. Continuous but does not use supersaturation.) *Festschrift der Technischen Hochschule Stuttgart zur Vollendung Ihres Ersten Jahrhunderts, 1829–1929*, pp. 331–338.

[7] A. Langsdorf, Jr., Phys. Rev. **49**, 492 (1936); **51**, 1026 (1937).

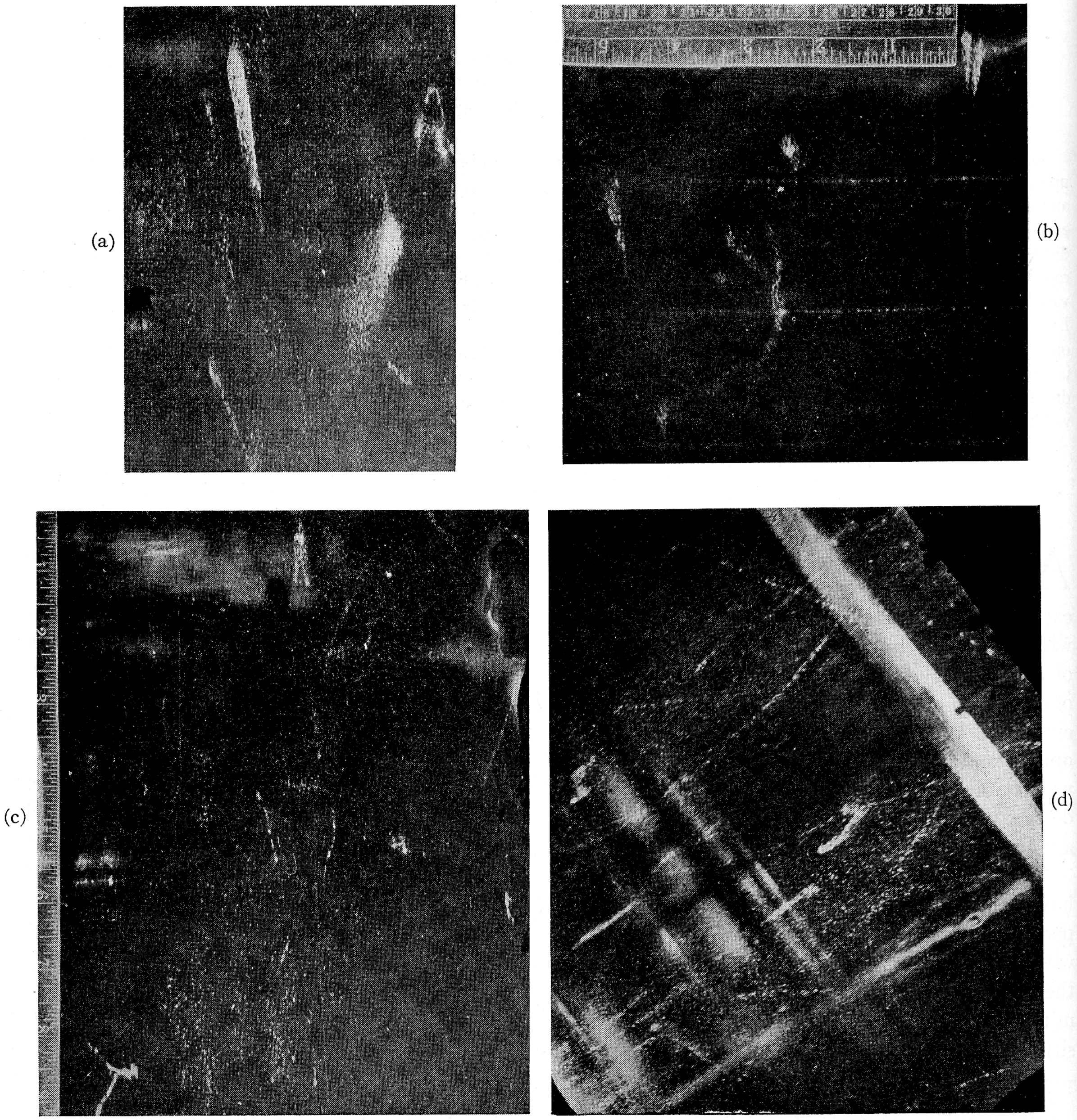

Fig. 1. Diffusion cloud chamber phenomena photographed from below as indicated in Fig. 2. Scales indicate true size of objects. (a) Curtaining effect. (b) Typical diffuse tracks. (c) Typical sharp tracks. (d) Moderately sharp tracks. The diffusely lighted regions are a result of reflections from the top of the chamber.

noncondensing gas to a horizontal refrigerated plate. A cloud chamber operating in such a manner will be called a *diffusion cloud chamber* for the remainder of this article. Fig. 1 shows photographs of tracks as they are now obtainable in this type of cloud chamber. Such tracks as these, which are continually being produced by the cosmic radiations, radioactive contamination, and secondaries from local gamma-radiation, make it unnecessary to supply any special source for tracks in order to make observations as recorded in this article (except where specific reference to special sources is made).

The apparatus built to operate on the principle just described is shown schematically in Fig. 2. The diffusion chamber itself is the volume *B* inside a box whose sides are of sheet glass, *D*. The top of the chamber is a metal sheet, *K*, which has many small holes communicating into space *A*. Vapor is introduced from a boiler *F* into space *A* where it is distributed so it flows uniformly through the holes, *K*, into chamber *B*. The space *A* and plate *K* are kept hot by electric heaters, *M*. The floor of the cloud chamber, *C*, is made of two sheets of glass between which a refrigerating liquid is pumped. This liquid is circulated by pump, *E*, and is cooled by passing through a coil, *H*, immersed in liquid cooled by ice or solid carbon dioxide, as desired. The vapor which has diffused through space *B* condenses on the chamber floor and is drained into a reservoir, *S*. The gas float tank, *N*, maintains the pressure in the chamber near to atmospheric pressure in order to avoid breaking the glass floor plates, *C*.

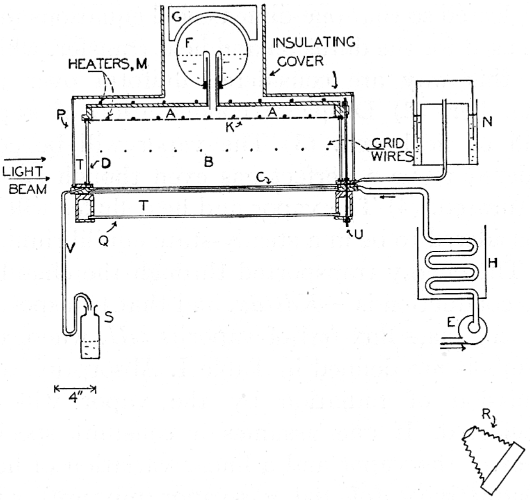

FIG. 2. A. Vapor distributor space. B. Region of chamber where tracks form. C. Chamber floor of two glass sheets. D. Chamber walls of glass. E. Refrigerating system pump. Its inlet connects to outlet from left side of chamber floor, not shown. F. Glass vaporizer. G. Radiant heater. H. Refrigerating system cooling coil. K. Chamber roof with vapor inlet holes. M. Heaters for plate K and top of space A. N. Gas float reservoir. P. Outer insulating glass side plate. Q. Outer insulating glass bottom plate. R. Camera focused on horizontal plane through B. S, V. Condensed vapor reservoir and drain tube. T. Sealed spaces containing dry gas. U. Tie rod holding chamber top and bottom together. Upper end electrically insulated from top frame.

TABLE I.

SYMBOL	VALUE USED IN CALCULATION	DEFINITION
(1)	Methanol	Subscript (1) refers to vapor.
(2)	Carbon dioxide	Subscript (2) refers to gas.
α	1	Temperature coefficient of diffusivity, k (in general $0.75<\alpha<1$).
b	0.0048	Temperature coefficient of heat conductivity, K.
c_1	Table II	Flux of vapor in g cm^{-2} sec.$^{-1}$.
c_2	0	Flux of gas.
C_pt	0.25	Specific heat of vapor in cal./g/degree (assumed constant).
D_1	M_1p_1/RT†	Concentration of vapor.
D_2	M_2p_2/RT	Concentration of gas.
f	Table II	Energy flux through chamber, cal. cm^{-2} sec.$^{-1}$.
h	40	Height of chamber in cm.
H	C_pt	Enthalpy of vapor in cal./g.
k	$(k_0/P_0)(T/T_0)^{1+\alpha}$	Diffusion constant.
k_0	0.0641	Diffusion constant at one atmos. and T°K.
K	$K_0(1+bt)$	Heat conductivity of gas-vapor mixture.*
K_0	2.86×10^{-5}	Heat conductivity of mixture at T°K.
M_1	32	Molecular weight vapor.
M_2	44	Molecular weight gas.
$p_1(t)$	$P_0-p_2(t)$	Pressure of vapor in chamber where temperature is t.
$p_{1s}(t)$	Reference a	Saturation pressure of vapor at temperature t.
$p_2(t)$	Eq. (6)	Pressure of gas in chamber where temperature is t.
P_0	1	Total pressure in chamber in atmos.
R	1.986	The gas constant, cal./°C/mol.
r	$f/c_1C_pt_1$	A parameter. See Table II.
S	p_1/p_{1s}	Supersaturation of vapor.
$T(x)$		Temperature in degrees absolute at height x.
T_0	233°K	Temperature of surface of liquid film on the floor of chamber, $x=0$.
T_1	343°K	Temperature of chamber top, $x=h$.
$t(x)$	Eq. (2)	By definition, $t(x)=T(x)-T_0$.
t_1	110	By definition, $t_1=t(h)=T_1-T_0$.
v_1	RT/M_1P_0†	Partial volume of vapor per gram (equivalent to partial molal volume for molal quantities).
v_2	RT/M_2P_0	Partial volume of gas.
w	c_1v_1	Convective flux associated with diffusion.
x	Eq. (2)	Position in chamber measured up from floor.

* K for methanol and carbon dioxide are so nearly the same that K for mixture is nearly independent of the composition.

† Assuming vapor is perfect gas.

[a] E. F. Fiock, D. C. Ginnings and W. B. Holton, Nat. Bur. Stand. J. Research **6**, 881 (1931).

This cloud chamber was operated with methanol vapor diffusing through carbon dioxide gas. In its original condition the chamber showed ion tracks in a region about one inch deep near the chamber floor. The total chamber depth was about six inches. The operation was accompanied by a considerable "rain" of condensation which seemingly was not dependent on the presence of ions. More recently it has been found possible to obtain tracks in a region three inches deep and with much less general "rain."

II. AN ANALYSIS OF THE PHYSICAL CONDITIONS IN THE DIFFUSION CLOUD CHAMBER

Before describing the construction and operation of the apparatus, it will be useful to illustrate by analysis what distributions of temperature, vapor density, and supersaturation may be expected within this cloud chamber. Quantitative calculations will be simplified by a number of assumptions: (1) Side wall effects will be neglected so that one-dimensional equations may be used for the diffusion and heat transfer, which in this way are considered uniform over the chamber. (2) Dropwise condensation of vapor will be neglected. (3) The vapor will be considered to be a perfect gas even though supersaturated. (4) The vapor and heat fluxes will be considered to be in a steady-state equilibrium.

The energy transported through the chamber by conduction is $-Kdt/dx$, and that transported by the mass flux (c_1) of vapor is c_1H, where the symbols are defined in Table I. Absorption and emission of radiation by the vapor will be neglected. If one assumes a constant specific heat of the vapor and a linear variation of heat conductivity (of the gas-vapor mixture) with temperature, the total energy flux becomes

$$f=c_1H-Kdt/dx=c_1C_pt-K_0(1+bt)dt/dx. \tag{1}$$

With initial conditions $x=0$, $t=0$ and final conditions $x=h$, $t=t_1$, one obtains an integral of Eq. (1),

$$\frac{x}{h}=\frac{bt+(1+rbt_1)\ln(1-t/rt_1)}{bt_1+(1+rbt_1)\ln(1-1/r)}, \tag{2}$$

where r is a convenient parameter defined as $r=f/c_1C_pt_1$. By the use of r, c_1 and f can be determined from

$$c_1C_ph/K_0=bt_1+(1+rbt_1)\ln(1-1/r). \tag{3}$$

Fig. 3 is a plot showing temperature distributions in the cloud chamber as determined from Eq. (2). The necessary numerical data are given in Tables I and II for methanol and carbon dioxide.

The distribution of vapor has been calculated on the assumption that the isothermal diffusion equations can be extended to a system involving a temperature gradient. For one dimensional isothermal diffusion Kuusinen[8] gives equations

$$c_1=wD_1-k\partial D_1/\partial x, \tag{4a}$$

$$c_2=wD_2-k\partial D_2/\partial x, \tag{4b}$$

$$w=c_1v_1+c_2v_2. \tag{4c}$$

The symbols are defined in Table I. With variable temperature, the substitution of $(M_1/RT)\partial p_1/\partial x$ for $\partial D_1/\partial x$ and $(M_2/RT)\partial p_2/\partial x$ for $\partial D_2/\partial x$ appears to be adequate. With this substitution and the others indicated in Table I, Eq. (4b) may be put into the form

$$(c_1RT_0/M_1k_0)p_2=(1+t/T_0)^\alpha dp_2/dx. \tag{5}$$

Since Eq. (2) gives x as a function of t, it is simplest to change the independent variable in Eq. (5)

$$\frac{dp_2}{p_2}=\frac{c_1RT_0K_0(1+bt)dt}{M_1k_0(1+t/T_0)^\alpha(c_1C_pt-f)}. \tag{5a}$$

If $\alpha=1$ as it does for methanol and carbon dioxide, one obtains the integral

$$\ln\frac{p_2(t)}{p_2(0)}=\frac{T_0}{T_0+rt_1}\cdot\frac{RT_0K_0}{M_1k_0C_p}[(1+brt_1)\ln(1-t/rt_1)-(1-bT_0)\ln(1+t/T_0)]. \tag{6}$$

Figure 4 is a plot showing the distribution of vapor, $p(x)$, for three values of vapor flux, as

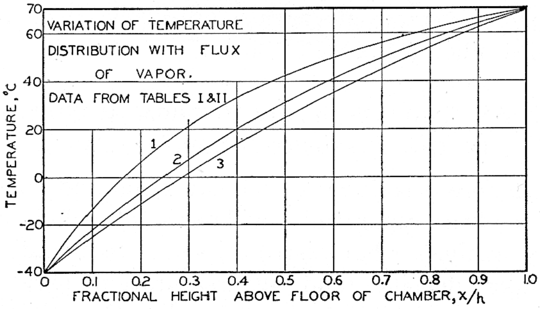

FIG. 3.

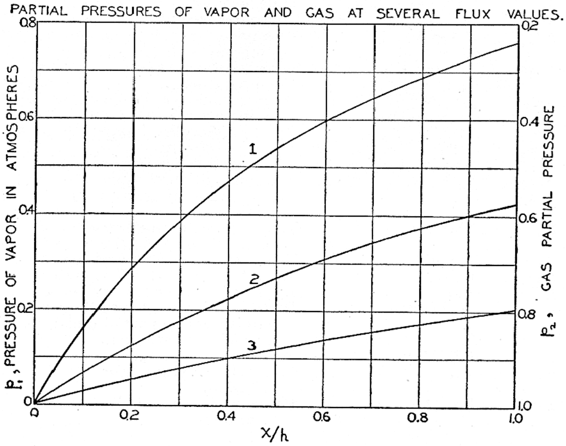

FIG. 4.

FIG. 3 and FIG. 4. In both figures, flux values are: Curve 1, 6.86×10^{-6} g/cm²/sec.; Curve 2, 2.56×10^{-6}; Curve 3, 1.05×10^{-6}.

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[8] K. Kuusinen, Ann. d. Physik **24**, 445, 447 (1935).

determined by the use of Eq. (6) and the data in Tables I and II.

From Eq. (6) the supersaturation may be determined readily by

$$S=p_1/p_{1S}=(P_0-p_2)/p_{1S}$$
$$=[P_0-(p_2/p_2(0))(P_0-p_1(0))]/p_{1S}. \quad (7)$$

As long as $p_1(0)$ is small compared with P_0, the approximation

$$S=P_0(1-p_2/p_2(0))/p_{1S} \quad (7a)$$

may be used except very near to $t=0$. It appears immediately that for a given flux of vapor the supersaturation will be nearly proportional to the total operating pressure.

The depth of the cloud chamber, h, does not appear explicitly in the Eq. (6) for pressure nor in the right-hand side of Eq. (2) for the distribution of temperature in terms of (x/h). Therefore if the ratio r is held constant the *form* of the supersaturation curve remains unchanged when h is changed. But Eq. (3) shows that the flux of vapor, c_1 (consequently the energy flux, f, also), decreases in proportion as h increases. This consideration is important because the amount of vapor removed by condensation to form drops tends to increase proportionately as the chamber is made deeper, while these calculations show that the supply of vapor grows smaller. As a result, a chamber can be too deep to operate satisfactorily. There will be an optimum chamber depth to be determined experimentally for any given conditions of use of the apparatus.

TABLE II.

r	$c_1\times10^6$	$f\times10^4$	CURVE NO., FIGS. 3 AND 4
1.2	6.86	2.26	1
2	2.56	1.41	2
4	1.05	1.16	3

Figure 5 shows typical curves relating S and x calculated from Eq. (7a) and the information plotted in Figs. 3 and 4. The effect upon S of variation in vapor flux is illustrated by curves 2, 3, and 5 in Fig. 5, which correspond to the three curves of Figs. 3 and 4. The effect of a small change in floor temperature, T_0, is illustrated by curves 1, 3, and 4 in Fig. 5. For this small change in T_0 (holding $t_1=T_1-T_0$ constant) the physical constants entering into Eqs. (2) and (6) change negligibly, so that with the previously calculated data of Figs. 3 and 4 it is simple to calculate the supersaturations for curves 1 and 4, Fig. 5, by considering just the change in saturation pressure, p_{1S}, with temperature.

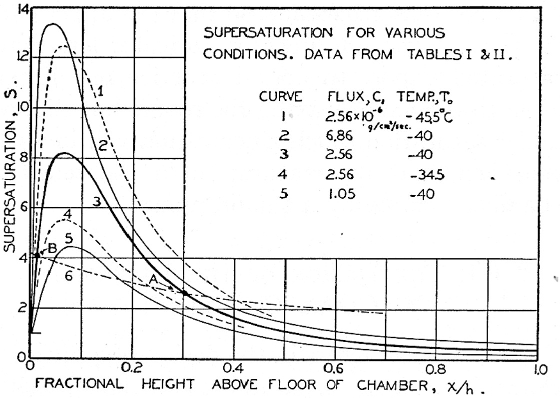

FIG. 5.

The dot-dashed curve, No. 6, in Fig. 5 represents a rough estimate[9] of the minimum supersaturation, S_{cr}, which will permit methanol vapor to condense upon ions to form tracks for the temperature distribution corresponding to curve 3. Regarding curve 6 as correct, the intersection points, A and B, represent the limits of the region in which ion tracks should be produced for the conditions corresponding to curve 3. For the other curves, 1 through 5, there will be corresponding S_{cr} curves, displaced somewhat from curve 6. However, their mutual displacements will be small compared to the displacement of the curves 1 through 5. Obviously, if the supersaturation is lowered, the ion sensitive region will become narrower and eventually disappear completely. One may conclude that the necessary vapor flow is of the order of 10^{-6} to 10^{-5} g/cm²/sec. and, what is perhaps more important, that the operation of the chamber is very temperature sensitive. A change of 5 to 10 degrees may easily make the difference between operation and nonoperation of the chamber.

The previous calculations were simplified by assuming a value of the roof temperature, T_1, a

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[9] The curve is calculated by the equation $\ln S_{cr}=k(M/d)(\sigma^{4/3}/T)$ as suggested by calculations of Powell in the Proc. Roy. Soc. **119**, 553 (1928). Taking $S_{cr}=2.9$ at -6°C evaluates the constant k, where M is the molecular weight of methanol, d its density, σ its surface tension, and T the absolute temperature.

bit higher than necessary, so that the upper ends of the curves in Fig. 5 indicate less-than-saturated vapor. In actual practice one lowers T_1 until the vapor leaving the roof is but slightly under saturation. Such a correction will increase the calculated supersaturation in the sensitive chamber volume by a small amount.

III. The Design of the Diffusion Cloud Chamber

The various factors in the design of a diffusion cloud chamber are separated as much as possible in order to systematize the following discussion:

The choice of vapors and gases is limited by the necessity that the vapor density should not be greater than the gas density to maintain an absolutely stable system. Experiments have shown that methanol (mol. wt. 32) diffusing through nitrogen (mol. wt. 28) is not completely stable against convection. Water vapor might be used with nitrogen, but freezes before the floor temperature, T_0, can be lowered enough to reach the best operating conditions. The only satisfactory vapors that have been used are methanol and ethanol (containing 5 percent water), in each case diffusing through carbon dioxide gas. Argon should be very satisfactory to use with methanol, but has not been tried as yet.

In an attempt to find a vapor-gas combination which would need less severe refrigeration for the chamber floor, the heavy gas dichloro-difluoromethane has been used with butyl alcohol vapor. A few tracks were observed, but for various reasons the chamber was not satisfactory and the tests were discontinued. A particular disadvantage of these dense materials is that their slow rate of interdiffusion cuts down the supply of vapor available for track formation, as compared to that available with lighter materials.

Visibility of the interior of the cloud chamber must be such that one can see and photograph what goes on within it. Tracks may be observed with ease through the sides of the chamber, just off the line of sight toward an incandescent lamp. But the whole cloud chamber, and consequently the sensitive region within it, must have great breadth compared to its depth in order to minimize detrimental effects of the side walls. Therefore, it is only by a view through the top or bottom, as illustrated by camera R in Fig. 2, that the object focal plane of a camera may be made to remain within the part of the chamber where tracks are formed. The necessary transparent floor has been built into the most recent chamber. This floor must at the same time be refrigerated, drained free of excess condensed vapor, and kept free of frost on the under side exposed to air, as will be described in more detail later. Illumination of the condensation phenomena inside the chamber may be provided through the glass sides.

The *light source* that has been used for photography is a high intensity type of arc with a 9-mm positive carbon drawing sixty amperes. The arrangement of light source and camera is illustrated in Fig. 2. The photographs in Fig. 1 were taken with the arrangement illustrated. No doubt there are other more satisfactory light sources: A condensed discharge would stop the motion of the falling drops of liquid; a capillary source would produce a broad horizontal beam more efficiently than a disk-shaped source like an arc. If the high intensity illumination is allowed to fall on the chamber for an appreciable length of time important precautions must be taken if steady operation of the chamber is to be maintained. The light beam should pass out of the chamber through the glass sides, for heat liberated by its absorption at an opaque wall will produce a steady convection current which interferes with operation of the chamber. A copper chloride solution is desirable to remove infra-red radiation, but of greater importance is removal of certain violet and ultraviolet radiations. For example, when the chamber was operated with ethanol vapor and carbon dioxide gas, a Jena glass filter cutting off radiation below 4750A permitted satisfactory operation of the chamber with continuous intense illumination, but when the filter was changed to one cutting off below 4500A, a diffuse rain was produced which prevented further formation of tracks upon ions. With transmission of shorter wave-lengths the fogging became more pronounced. Presumably light induces some photochemical action which creates condensation nuclei.

The method of production of vapor is of utmost importance. Heating liquid in a clean glass flask

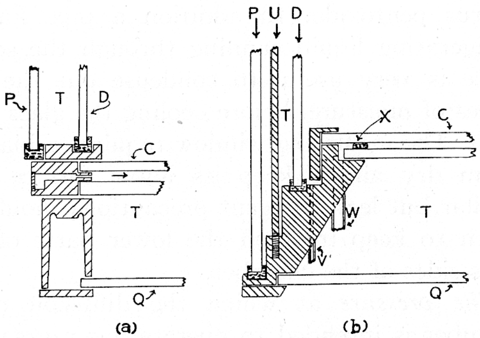

FIG. 6. (a) Detail of chamber floor assembly of cloud chamber shown in Fig. 2. (b) Suggested variation of floor assembly. *X*. Spacers between glass plates. Gaps between adjacent spacer pieces permit liquid flow. *W*. Refrigerating liquid inlet or outlet. Other lettering follows Fig. 2.

by radiation downward from above is the only method that can be recommended on the basis of experience. In the earlier work, the chambers obtained vapor produced by other methods, and were troubled by continuous rainy condensation not dependent upon presence of ions. In recent work the chamber obtained vapor produced by the method just described and was nearly free of condensation other than upon ions. In this chamber, an input to the radiant heater of sixty watts gives a sufficient supply of vapor. (A considerable part of this heat is wasted.) Experiments have not yet been performed which would show definitely what mechanisms have been responsible for the undesirable condensation in the previous chambers, but aggregates produced in the vapor source are very likely to have been involved. Until further investigation the following possible sources of aggregates should be avoided in production of vapor for any continuous cloud chamber: *Bubbling* of boiling liquid (heated from below), contact of boiling liquid and a *metal* surface, contact of vapor with a *chilled* (wet) surface or with an *overheated* surface.

The chamber roof acts as a vapor flow distributor. It must be heated so no vapor condenses at the top of the cloud chamber. No attempt has been made to design a chamber with a transparent roof, because it would be difficult (though perhaps is possible) to distribute vapor uniformly, keep all parts heated, and at the same time maintain a clear view into the sensitive region. The roof of the chamber is a box-like space (*A*, Fig. 2). The under side of this box is a sheet of brass (*K*, Fig. 2) $\frac{1}{32}''$ thick and two feet square in which are 0.015″-diameter holes spaced $\frac{1}{2}''$ apart. On the upper side of the brass sheet is an electric heater, *M*, in a copper sheath which is soldered onto the brass between the rows of holes. The lower side of the brass sheet is chrome plated to minimize radiation loss of heat.[10] About seventy watts heating current keeps the plate warm enough under normal operating conditions. Outside the roof of the distributor box (*A*) there is another heater to warm the remainder of the box. Once heated, about 25 watts is sufficient to keep it hot when properly insulated. The remarks in the preceding paragraph concerning sources of aggregates apply here also: Neither condensation nor overheating should be allowed in any part of the vapor distributing system. In either case nuclei may be created, which will produce a diffuse rain of condensation in the cloud chamber.

The design of the chamber floor and its auxiliaries can vary in complexity. Chambers can, for example, be built with simple metal floors, but at present the most useful design embodies a double glass floor with a clean liquid such as methanol or acetone circulating between the plates at −40°C to −50°C. Fig. 6 (a) illustrates the method of floor assembly that has been used, and Fig. 6(b) illustrates a suggested modification of the assembly.

The refrigerating system must be designed to maintain adequate flow with moderate pressure at the necessary low temperature, where the viscosity of the liquid used is much greater than at room temperature. In particular the pressure must be kept low between the glass floor plates to avoid bursting them. In order that the glass floor may be transparent, the whole refrigerating system must be scrupulously clean and free of iron or steel which may cause corrosion. A filter is useful to help keep the system clean, and a specially designed centrifugal pump has been another valuable aid to cleanliness. Fig. 7 illustrates its construction. The rotor is supported within but not touching its housing, by a vertical shaft whose bearings are all above the free surface of the liquid, while the rotor and its housing are submerged.

A drain should be provided to remove con-

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[10] Experiments have not been performed to determine the real necessity of a polished reflecting top.

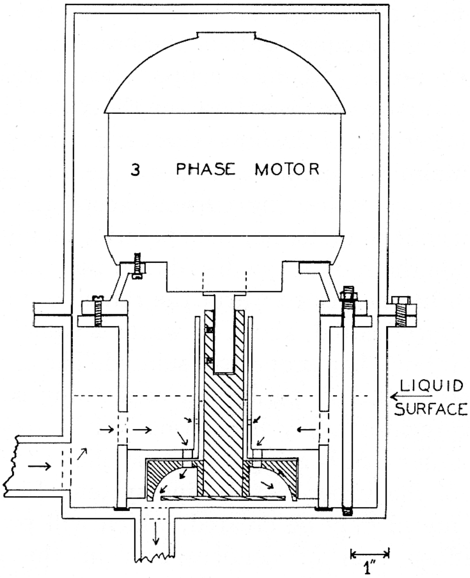

FIG. 7. Centrifugal pump. Rotor, shown cross-hatched, is entirely supported by motor shaft bearings. The interior of the rotor contains a diaphragm to assure rotation of contained liquid.

densed vapor from the chamber floor. Although the apparatus can be run for hours without needing to be drained, it is preferable that the pool of liquid be kept shallow to make the refrigeration most efficient and to decrease rippling from vibrations. It is most practical to drain the liquid by gravity through a hole in the main floor frame. The metal frame which holds the upper glass floor plate down should have a gap large enough to let liquid drain over the edge of the glass and into the hole. Otherwise the liquid would have to collect to a depth equal to the thickness of this frame and its gasket. As a consequence of this design for floor draining, the refrigerating liquid system must be sealed by a gasket to the under surface of the upper glass plate, as illustrated by Figs. 6a and b.

Prevention of frosting on the outside of the lower glass floor plate by moisture in the air requires real precautions at −40°C and lower temperatures. It is practically essential to have a sealed space[11] (*T*, Figs. 2 and 6) between the floor and an insulating window below it, and to fill this space with nitrogen[12] dried with phosphorus pentoxide. In addition a pipe line of refrigerating liquid running through the sealed space is very useful to condense out the last traces of moisture, before cooling the glass floor itself. The insulating window requires a blast of warm dry air to keep its lower surface dry. Similar but less stringent precautions should be taken to keep frost off the lower parts of the glass sides of the chamber.

The pressure at which the diffusion cloud chamber is intended to operate has a great influence upon its design, and vice versa. For example, large glass plates such as are illustrated in Fig. 2 cannot be subjected to appreciable pressure. Therefore a float reservoir (*N*, Fig. 2) has had to be provided to equalize pressure changes that would otherwise be produced when putting the apparatus into or out of operation. When the floor temperature of the chamber decreases, gas from the reservoir flows into the cloud chamber and produces some turbulence and condensation phenomena. This undesirable effect could be avoided in a smaller, stronger chamber which could withstand pressures of the order imposed by the heating and cooling of the chamber, so that it could be sealed without a float reservoir. There are, however, definite advantages in operating a chamber maintained close to atmospheric pressure: Small leaks become negligible, very thin large windows can be used to admit alpha-, beta-, and soft x-rays, and radioactive samples can be introduced into the chamber through a tube or door opened and shut again with moderate rapidity.

The large temperature gradient in a diffusion cloud chamber gives it a natural stability against *convection* and *turbulence*.[13] Observation of small drops suspended in the chamber shows that motion of the gas dies out quickly when the cause of the motion ceases to act. Latent heat liberated by heavy localized condensation such

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[11] In a chamber as large as *D* this sealed space must aspirate so pressure changes from cooling and warming will not break the glass.

[12] Air can be used. Nitrogen decreases fire hazard.

[13] Another type of system capable of being free of convection may be worth mentioning in passing, as illustrated by the specific combination of materials that was used. Butyl alcohol vapor was diffused upward through hydrogen from a warm surface to a refrigerated plate. The gas volume appeared to be free of convection. However, there was a great deal of condensation which started so very close to the top refrigerated plate that one might conclude that the liquid surface on this top plate acted as a source of condensation nuclei. This observation should be of value in an investigation of processes of aggregate formation.

as occurs along an alpha-ray track can be observed to produce a slight convection effect, but the disturbance remains localized and equilibrium is restored rapidly. In the chemical cloud chamber,[6] Vollrath observed convection from heat liberated by condensation along beta-ray tracks; the diffusion cloud chamber is not that sensitive to convection. Several causes of large scale convection effects have been mentioned previously: incorrect gas and vapor combination, heating by the light beam, and introduction of gas. In addition, a chamber with metal walls is more subject to convection as a result of incorrect wall temperatures than one with glass walls, and a chamber with height to breadth ratio of one to two is much more subject to convection than a chamber with a one to four ratio.

An *electric field* has been applied within chamber *D* in two different ways. The vapor distributor box (*A*, Fig. 2) was insulated by using insulating bushings on the tie rods holding it in place and an insulating transformer in the power line supplying the electric heater currents. With the floor of the chamber grounded, the top could be raised 2000 volts from ground, thus supplying a vertical electric field of gradient up to 130 volts per cm. The other arrangement consisted of a grid of wires strung across the chamber, alternately positive and negative in potential, also shown in Fig. 2.

It is clear that cosmic rays and gamma-rays produce nearly as many ions per unit of volume in the upper part of the cloud chamber where tracks are not formed as in the lower part where tracks are formed. The ions in the upper part will diffuse downward until they are condensed upon to form a diffuse rain, unless they are removed by an electric sweep field. A simple vertical electric field draws half the ions to the roof of the chamber, but the other half is drawn down into the ion sensitive region. This action can be observed in several ways. When the field is suddenly switched on there is a sudden "shower" of condensation which would seem to be a result of suddenly drawing downward the ions (of one sign) which have collected to a relatively high concentration under no-field conditions. Thereafter as long as the field is left on, and if it is sufficiently strong, the diffuse rain is not completely diffuse but contains "puffs" of condensation which, one may guess, come from clusters of ions which have not had time to diffuse very much before being drawn into the ion-sensitive region of the cloud chamber.

The grid wire system was tried in an attempt to prevent any of the diffused ions from above from getting down into the region where tracks form. The results (with 30 B & S gauge wire, 2″ apart, 2½″ from top of chamber) were not clear cut. The grid seemed to remove some but not all ions when the wires were at about 500 volts, alternately positive and negative. The grid wires became covered with condensation. Also at a potential near 1000 volts faint traces of discharge phenomena set in, as evidenced by streamers of condensation starting at certain spots on the wires. A grid wire system might operate better made of larger wires and placed higher up in the chamber. Results to date favor the use of some sort of electric ion-sweep field, but do not permit definite recommendation of any one system for providing this field. It should be emphasized that the field is intended only to remove ions from the nonsensitive part of the cloud chamber. Where tracks form, ions will be condensed upon and removed by gravity. However, an electric field still can have visible effects in this region. For example, if the supersaturation is just barely great enough to produce tracks, an electric field will destroy track formation entirely, for in this case the ions remain mobile long enough to move under the influence of the field, and they move so far that when they do condense they no longer form a track. This characteristic allows a crude test for the degree of supersaturation existing in the chamber.

The present cloud chamber is a rectangular box. It is not improbable that a cylindrical chamber, by eliminating certain stress concentrations and decreasing the number of joints, would avoid sources of troublesome leaks and also permit the chamber to withstand more pressure difference between its interior and the atmosphere. When the present chamber was constructed there was some difficulty in obtaining glass cylinders of the size desired. Since then a source of large glass cylinders has been located. The problem of distributing refrigerant flow between circular glass floor plates has also been found not difficult to solve.

IV. THE OPERATION OF THE DIFFUSION CLOUD CHAMBER

The air initially present in the chamber is displaced by carbon dioxide, and the vaporizer is filled with alcohol preparatory to its operation. The several electric heaters are turned on and set to about double their normal heating rates until the chamber reaches operating temperature. As the vapor flow is being established, some fog forms in the chamber, but within an hour the gas is cleared of aggregates and the chamber free of dropwise condensation.[14] Finally the chamber floor becomes covered with condensed vapor. As this time the refrigerating system pump it started and solid carbon dioxide is placed in the cooler tank. The circulating system valves are adjusted so there is a large flow through the pipe line in the dead air space (*T*, Fig. 2). When all moisture in this space has condensed on the cold pipe, the flow through the chamber floor itself is started and gradually increased to the maximum pressure the glass plates can safely stand. Finally a potential of several hundred volts is applied to the top of the chamber and between the alternate grid wires.

For visual observation, an incandescent lamp gives enough light. Just before beginning refrigeration, no dropwise condensation can be seen. As the floor temperature decreases, one may observe just off the floor of the chamber a diffuse rain of condensation in a thin region, which gradually becomes deeper. The rain first appears on the side where the refrigerating liquid enters the floor, but after a short time, when the refrigerant flow has been made large, the effects become uniform from one side of the chamber to the other. When the region of diffuse condensation is about one-half inch thick, one may observe within it concentrated "puffs" of condensation. These "puffs" may be interpreted to consist of a short length of visible track, on the upper end of which there is a piling up of condensation on ions liberated above the sensitive region and drawn down into the sensitive region in the form of a somewhat diffuse cluster. The largest of these "puffs" will rise up like a miniature geyser. Obviously the latent heat of condensation produces the convection by a localized warming of the gas, and the convection is exaggerated because the gas just above the thin region of condensation is still in a nearly isothermal state. When the temperature gradient has been established throughout the chamber, such striking convection is no longer observed.

About fifteen minutes to one-half hour after the strong refrigeration is applied, clear sharp tracks of the types associated with cosmic rays and the normal gamma-ray background may be observed in a region about two inches thick just off the chamber floor. There are also "fuzzy" tracks which form higher in the chamber where the supersaturation is lower. The general rain is less dense than at first because much condensation which previously occurred on diffused ions is resolved into sharp tracks. Illumination by a strong light source gives the observer a vivid impression of their appearance. It is at this stage in the operation of the chamber that photographs like those in Fig. 1(c) have been obtained.

The drops in a track are not all of the same size, so as they fall an initially sharp track becomes somewhat diffuse when viewed horizontally. Viewed vertically it remains sharp. A track takes the order of one to three seconds to fall to the floor of the chamber. Sometimes, if the surface tension conditions of the liquid on the chamber floor are just right, the drops of condensate float on its surface an appreciable length of time, so that one can see a pattern of old tracks laid out in an horizontal projection upon the liquid surface on the floor.

As the chamber operation continues the ion-sensitive region will gradually extend upward until it may reach an upper limit of four inches above the floor of the chamber. However, the tracks observed are no longer sharp, and are not very satisfactory for detailed study. With the chamber in this condition one may observe an increase in the number of visible tracks for a short period after suddenly removing the electric ion sweeping field, but after the field has been off about a minute, fewer tracks can be seen than when the field was on. It would seem that the chamber reaches a condition where the supersaturation is just sufficient to permit condensation on ions, and as a result the time an ion

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[14] If condensation persists without the chamber floor being cooled, there is strong reason to presume aggregates are present in the vapor supply before it reaches the chamber.

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remains in the vapor before it forms a visible drop may be quite appreciable. Thus an electric field can move the ions so far that they form no track at all. Removing the field, the ions remain in a smaller region and form a diffuse but recognizable "fuzzy" track. However, the lack of an ion sweep-field increases the ion load, so the supersaturation decreases further to a point where distinct tracks are no longer formed. It is probable that the best sharp tracks are formed in the earlier period of operation because at that time the supersaturation is actually greater than in the steady-state condition. (Reversed procedure of cooling the chamber floor and then starting vapor flow would not give this transient maximum of chamber sensitivity.)

A ten-microgram radium sample brought near the chamber increases sharply both the number of tracks and the diffuse rain. Apparently many of the tracks are incomplete, because they appear to be only a few inches long except when the exposure to the gamma-rays is a brief one made just after removing the electric field. In this case some tracks appear much longer. A milligram sample of radium twenty feet from the apparatus produces a noticeable number of tracks. Close by, it creates at first a very strong shower of diffuse condensation, which soon decreases in intensity again so that the equilibrium amount of condensation is not strikingly greater than when no ion source is nearby. In the presence of this excessive number of ions, the droplets formed appear to fall at nearly the same rate as previously. It seems to be characteristic of the chamber in the presence of an increasing number of ions to tend toward the production of a fixed maximum number of large drops rather than more and smaller drops. The excess of ions must be removed by the electric field, diffusion to the walls, and recombination. If the strong source is removed, it takes several minutes to build up supersaturation again to a point where tracks can be seen.

One might suggest increasing the flux of vapor above the rate previously used as a means of increasing the supply of vapor for track formation. However, experiments show that a flux appreciably greater than that which has been used makes the chamber operation less satisfactory.

The diffusion cloud chamber can show tracks when exposed to moderately strong ionization for a short period, but its supply of vapor available for track formation rapidly becomes depleted. In the presence of a uniform amount of ionization over a period of several minutes or more, the load limit for track formation appears to be of the same order of magnitude as the normal background of ionization to be expected in an unshielded chamber. Such a conclusion is not inconsistent with a rough calculation employing Stokes law to determine the mass of the droplets, and making use of the simple fact that the average mass flux of drops at the floor of the chamber cannot be greater than the mass of vapor diffusing in at the top of the chamber. The mass of one drop of density ρ is $(4/3)\pi a^3\rho$, where its radius a is given in terms of its velocity of fall, v, by $v=2ga^2/9\eta\rho$. The viscosity of the gas is η, and g is the acceleration of gravity. For the particular system being considered here, the mass of one drop becomes $3.6\times 10^{-9}v^{\frac{3}{2}}$ in grams, where v is measured in cm/sec. Then in a horizontal section of the chamber of area 1 cm^2, with a flux c_1 of the order of 10^{-5} g/sec., the total flux of drops cannot average more than $(10^{-5}/3.6\times 10^{-9}v^{\frac{3}{2}})$ drops per second. Let I be the average number of ions liberated per cubic centimeter per second, then in a chamber 15 cm deep, if each ion is to form a drop, $15I$ cannot be greater than $(10^{-5}/3.6\times 10^{-9}v^{\frac{3}{2}})$, or $I \leqslant 185v^{-\frac{3}{2}}$. Without shielding I will be about 30, from which $v \leqslant 3.4$ cm/sec. Actually, v is of about this order and is never much smaller than this. Thus one is confirmed in the conclusion that the ion load-limit is of the order of the normal background ionization. One may conclude as follows: (1) It should be advantageous to shield the chamber from local gamma-radiation and thereby cut down the steady ion-load by 50 percent to 90 percent. (2) It should be desirable to find a vapor-gas combination of higher diffusivity and heat conductivity than methanol and carbon dioxide,[15] and thereby increase the vapor supply.

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[15] The most promising materials appear to be some combination of water, ammonia, methane, and nitrogen. Ammonia and water are particularly interesting because of the large reduction of the saturation vapor pressure of water by dissolved ammonia, so that a cloud chamber operating with these materials would combine the operating principles of the diffusion cloud chamber and Vollrath's chemical cloud chamber.

Alpha-ray tracks have not been discussed up to this point because alpha-ray ionization has had little influence upon the general conditions in the cloud chamber in the experiments performed so far. The normal background of alpha-ray emitting radioactive contamination of the chamber walls is unimportant in the large volume of this cloud chamber, and radon contamination of the gas itself is small. However, alpha-ray tracks have been observed to originate within the gas volume, at the electric grid wires, and at the floor of the chamber. With a few exceptions, these dense tracks are always accompanied by "curtaining" effects.[16] An explanation is that there is insufficient vapor near the initial ionized path to form drops on all the ions immediately. In the absence of an electric field the first drops formed start to fall, and the remaining small ions are condensed upon gradually as they diffuse out toward a region of higher supersaturation and as fresh vapor diffuses in toward the region depleted of vapor. In the presence of a strong electric field the curtaining appears to be somewhat different. In this case it seems that the small ions move in the gradient of field much more rapidly than the large drops fall, so that condensation quickly forms a thin "sheet" between the original track position and the chamber floor. In either case, a noticeable mass convection of vapor is produced in the vicinity of the heavy localized condensation by the latent heat liberated.

The best alpha-ray tracks appeared during the initial transient period of cooling, just as did the best beta-ray tracks. A polonium sample emitting an average of about one alpha-ray per minute was placed on a wire about two inches above the chamber floor. Just after the cooling produced supersaturation at this level, a few tracks were formed that were sharp and free of curtaining.

A few other phenomena may be mentioned in passing: (1) A corona discharge from a bit of lint on one of the grid wires, at about 1000 volts negative potential, produced a continuous stream of very small drops which would flow approximately along the lines of force toward the adjacent grid wire of opposite polarity. Just before reaching this grid wire the stream would turn down and flow to the chamber floor. (2) If the chamber top was allowed to cool too much, vapor condensed there and dripped down onto the floor. The splash produced a small vortex ring of very fine mist just above the chamber floor, and the paths of secondary drops of splattered cold liquid from the floor could be followed by the line of fine mist produced along such a path. These fine paths often distorted into a sort of helix. This effect suggests the possible use of this cloud chamber to study motions in gases in the wake of a moving object. (3) Dusty or smoky air introduced into the chamber produced condensation as it does in expansion cloud chambers.

V. DISCUSSION

At the present stage in the development of the diffusion cloud chamber it is not possible to make positive statements as to just how useful the apparatus should become for nuclear physics research. It is clear that its special field of usefulness should be in problems for which a combination of extreme sensitivity and detail of information concerning a single event is of the greatest importance. For any particular problem, the balance of the advantages and limitations of the diffusion cloud chamber compared to expansion chambers and electrical apparatus will determine its usefulness. In some cases it may be a desirable supplement to the more usual types of apparatus.

Satisfactory use of the diffusion cloud chamber will depend on an understanding of its limitations, including especially the following: (1) The chamber floor and roof must be horizontal. This restriction is unfortunate in the study of cosmic rays, because it makes it difficult if not impossible to obtain as long vertical cosmic ray tracks as horizontal ones. The large horizontal dimensions of the chamber also interfere with efficient application of a strong horizontal magnetic field for deflection of vertical cosmic rays. (2) The limited supply of vapor prohibits use of the apparatus in the presence of strong ionization by x-rays, gamma-rays, neutrons, etc. (3) The continuous supersaturation will produce condensation on the surface of a source of radioactivity placed in the supersaturated region. Some technique for preventing such condensation may be developed, but at present none is known.

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[16] A similar effect has been observed in expansion cloud chambers. See reference 1.

Efficient photography with this apparatus requires the development of a new technique for taking pictures. Random photographs or Geiger counter tripped photographs would give no advantages to this apparatus compared to the expansion cloud chamber. Continuous motion pictures would be expensive and impossibly tedious to study. Visual observation, combined with the snapping of a photograph as quickly as possible after observing an interesting phenomenon, may be a possible technique. The logical development from this method is the use of a photoelectric trigger arrangement. Such a device has not been tried as yet, but the prospects for its successful operation are good.

In the study of phenomena outside the field of nuclear physics the diffusion cloud chamber should have distinct uses for which it will be superior to the expansion cloud chamber. It should be usable in the study of atmospheric nucleation, electric discharges, and any other processes which create aggregates which act as centers of condensation. It should also be useful in the study of the kinetics of condensation itself.

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