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TEMPERATURE CONDITIONS EXISTING IN A DIFFUSION
TYPE CLOUD CHAMBER

By

Vance D. Vandervelde

A Thesis Submitted to the Graduate Committee of South
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DIFFUSION TYPE CLOUD CHAMBER

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This thesis is approved as a creditable independent investigation

by a candidate for the degree, Master of Science, and acceptable

as meeting the thesis requirements for this degree, but without

implying that the conclusions reached by the candidate are neces-

sarily the conclusions of the major department.

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INTRODUCTION

There are many types of detectors of radioactive rays, such as Geiger Counters, ionization chambers, photographic emulsions, electroscopes, and cloud chambers. Many of these give only information such as the amount of radiation or the minimum energy of the rays because the information is registered as a change in voltage or a "count".

Outstanding among the different kinds of detectors is the type commonly called "cloud chambers". In a cloud chamber the path of the ray* can actually be seen and photographed, its radius of curvature in an electric or magnetic field can be measured, the amount of ionization can be measured by counting the number of ions per length of path, and the amount of deviation from the predicted normal path can be studied. From this type of information the mass, velocity, and charge of the ray can be determined.

The basic principle utilized in any chamber is that a gas which is supersaturated with a vapor will act as a means of detection of radioactive rays by forming a cloud trail along the path of the ray.

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*The term rays as used here is meant to include particles as well as ultraviolet rays, X-rays, γ-rays, etc.

The most common method of obtaining a gas which is supersaturated with a vapor is by cooling. Gas which has been saturated with vapor can be cooled until a high degree of supersaturation is reached if there are no particles in it to act as nuclei around which droplets can form.

J. Aitken[1] during his investigations (about 1880) indicated that dust particles do act as such nuclei and utilized the fact to count dust particles. In 1896 C. T. R. Wilson[2] showed that ions formed in a supersaturated gas could also act as centers of condensation. This fact led Wilson to the discovery of his famous "expansion" cloud chamber. It is theorized that high energy rays in their motion through matter ionize many atoms along their path. These ions form nuclei for condensation, thus producing a trail of droplets which are visible to the eye and which also can be photographed if desired.

The method used by Wilson for obtaining the super-saturated gas is expansion of a saturated gas by means of a piston on the floor of the chamber. This sudden increase of volume causes a decrease of temperature, thus causing the gas to become supersaturated. The main disadvantage in Wilson's chamber is that it will show tracks for only a very short period of time after expansion and then must be recycled for the next expansion. Therefore, there has been considerable interest in some kind of chamber that would be

continuously sensitive.

The first continuously sensitive cloud chamber was reported by L. G. Hoxton[3] in 1933. This cloud chamber 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 radiation, so this method was not satisfactory.

In 1936 R. E. Vollrath[4] described a continuous cloud chamber that operated by interdiffusion of two vapors such as hydrochloric acid vapor and water vapor, at the interface of which the gas became supersaturated with respect to the mixture (dilute hydrochloric acid).

A. Langsdorf, Jr.[5] reported progress on a continuous diffusion cloud chamber in 1936. The construction[6] of Langsdorf's chamber is essentially a glass cylinder with a refrigerated floor and a heated roof. Through the roof the vapor of a liquid with a high vapor pressure is allowed to diffuse and saturate the gas in the chamber. Then as the saturated gas diffuses downward it becomes cooled and thus supersaturated and within a limited region acts as an ion detector.

Although diffusion chambers have the advantage of being continuous, they frequently have the disadvantage of having diffuse, fuzzy, or distorted tracks which do not

generally present a great problem in a well designed Wilson expansion chamber. There is a definite need to find out more about the conditions that exist in diffusion chambers in order to improve their design. The purpose of this paper is to investigate some of the conditions that exist in a diffusion chamber, similar to the type proposed by Langsdorf.

In order for droplets of any vapor to be formed it is necessary first of all, that there be nuclei to form the beginning of a drop and secondly, that the drops once started, be in a region which is sufficiently supersaturated so that the vapor pressure of the drop is less than the vapor pressure in the region.

In 1870 Lord Kelvin[9] showed that owing to surface tension, the vapor pressure of a liquid in the form of a drop of radius (r) is greater than the vapor pressure exhibited by the same liquid at a plane surface. The relation is:

Eq. 1

$$\log\left(\frac{P_r}{P_\infty}\right) = \frac{2\theta M}{RT\rho r}$$

Where (θ) is surface tension, (ρ) is the density of the liquid, (M) is the gram molecular weight of the vapor, (R) is the gas constant, (T) is the absolute temperature, and (P_r) and (P_∞) are the saturation vapor pressures over a drop and a plane sheet respectively.

The ratio of (P_r/P_∞) is defined as the _equilibrium supersaturation_ ratio for the given values of (r). Super-saturation ratio (S) is the ratio of the vapor pressure which actually exists to the saturation vapor pressure which would exist if the gas were just saturated with vapor at a given temperature.

The variation of (P_r/P_∞) for different values of (r) is shown by the dotted curve of figure 1. This curve shows that as the drop radius increases, lower supersaturation ratios are needed to hold the drop in equilibrium. A drop formed to the left of the curve will have a saturation vapor pressure greater than the vapor pressure that actually exists, so it will evaporate. A drop formed to the right of the curve will have a saturation vapor pressure less than the vapor pressure that actually exists, so it will grow larger and the larger it grows the faster it grows until its size is finally determined by the amount of vapor available for condensation in the region. A drop formed on the curve will grow if a molecule is added to it or will evaporate if a molecule leaves it. The only requirement for drop formation is the presence of nuclei on which the vapor may first condense.

The air usually contains dust particles whose size may vary from 10^{-4} to 10^{-6} cm. These present very large surfaces of condensation and, from the argument above and the dotted curve of figure 1, it is clear that very little (1.001 to 1.12) supersaturation is needed in order to condense on such nuclei. This explains the phenomenon observed by Aitken that when dusty air is present very little supersaturation is needed to produce fog.

Figure 1

Variation of the saturated vapor pressure over a drop with the radius of the drop.
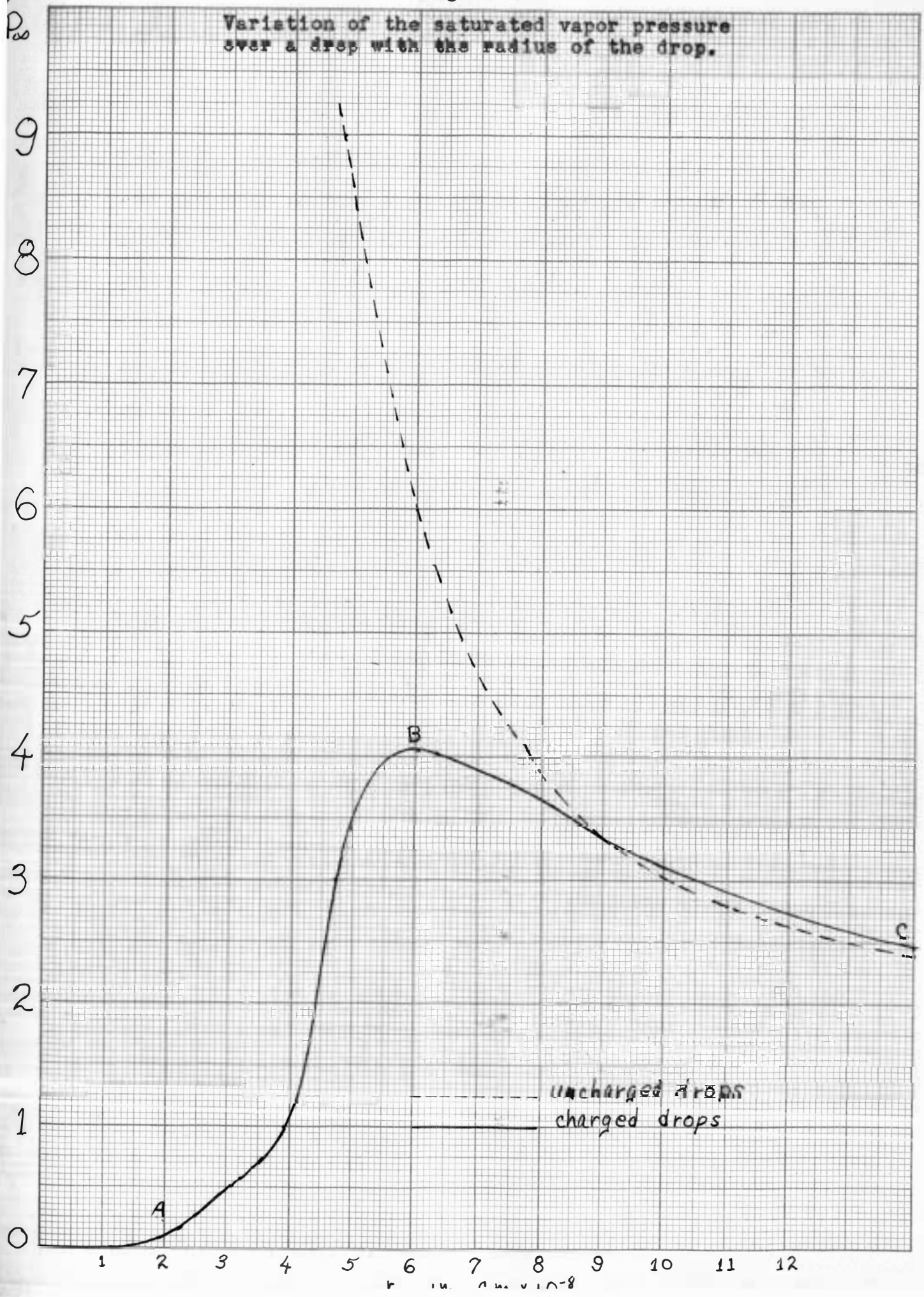
An extension of the dotted curve would show that
the value of (S) needed for the formation of a drop of
radius $2(10)^{-8}$ cm is about 235. Since the largest value
of (S) obtainable is of the order of 8, such small drops
will evaporate at once even if formed.

The above information is applicable in most instances
to dust particles which may be uncharged. However, if the
particles are charged the situation is affected by this
charge. Assume that a drop is formed on a single ion, that
is, it carries an elementary charge (e). Equation 1 is
then, according to Thompson, modified to

Eq. 2 $$\log\left(\frac{P_r}{P_\infty}\right) = \frac{M}{RT\rho}\left(\frac{2\theta}{r} - \frac{e^2}{8\pi k\, r^4}\right)$$

where k is the dielectric constant.

The two terms on the right hand side of eq. 2 signify
the pressure due to surface tension and electric field. The
two are in opposite sense, for while the potential energy
due to surface tension ($4\pi r^2\theta$) decreases with the decreasing
radius (r), that due to electrification ($e^2/2kr$) decreases
on increasing the drop size. The former tends to decrease
the radius of the drop thereby increasing the vapor pressure,
while the latter tends to increase the radius and decrease
the vapor pressure. A charged drop will therefore always
have less vapor pressure than an uncharged one.

It can be determined from eq. 2 that for

$$r = c = (e^2/16\, k\,)^{\frac{1}{2}}, \quad P_r = P_\infty$$

$$r < c \qquad\qquad , \quad P_r < P_\infty$$

$$r > c \qquad , \quad P_r > P_\infty$$

(c) is the critical radius determining the size of the charged drops when the space is just saturated. Each gaseous ion in saturated vapor will be surrounded by a drop of radius (c).

The variation of (P_r/P_∞) with drop radius (r) for a charged drop is shown by the solid curve of figure 1. For a drop radius $r > 10^{-7}$ cm the effect of charge is negligible and the supersaturation required is the same for charged and uncharged drops. But for smaller radii there are significant differences. Whereas for uncharged drops the equilibrium supersaturation ratio increases rapidly with decrease of (r), with charged drops supersaturation ratio equilibrium reaches a maximum value of 4.1 at $r = 6.05(10)^{-8}$ cm. and for still smaller drops supersaturation ratio required is less. Thus while no uncharged drops can be formed in space for which $(S) < 1$, charged drops do form, but they will have a radius less than $4(10)^{-8}$ cm.

The solid curve of Fig. 1 shows that the radius of the drops formed around ions diminishes very slowly as the quantity of vapor in air diminishes. Since there are always present in air some ions and some vapor, very fine droplets are also always present. But these drops cannot grow to visible size because, as seen from the curve, for the ascending part AB, the saturation vapor pressure must also

increase as the drop radius increases. This is not physically possible. The drop merely grows until radius is equal to such a value that (Pr/P_∞) is equal to the existing value of (S).

Once the drop has crossed B, the saturation vapor pressure decreases as the drop gets bigger, so that vapor will condense on the drops and the drops increase in size. But the bigger a drop gets, the smaller the saturation pressure and the faster it grows. In fact the region between B and C is unstable and when once the drop has passed the stage B, the drop soon becomes visible. Hence in the presence of ions if the supersaturation ratio increases to 4.1 drops will grow on ions as nuclei.

Above a value of S=8 a dense cloud appears even in the absence of an ionizing source. The reason for this fog has not been clearly shown but J. J. Thompson[9] has postulated that it could be due to the fact that small droplets are being continually formed and instantaneously evaporate away. Some of these may be caught by pure chance and act as nuclei of condensation. This seems to be supported by the fact that the density of the fog increases with an increase of supersaturation in this range.
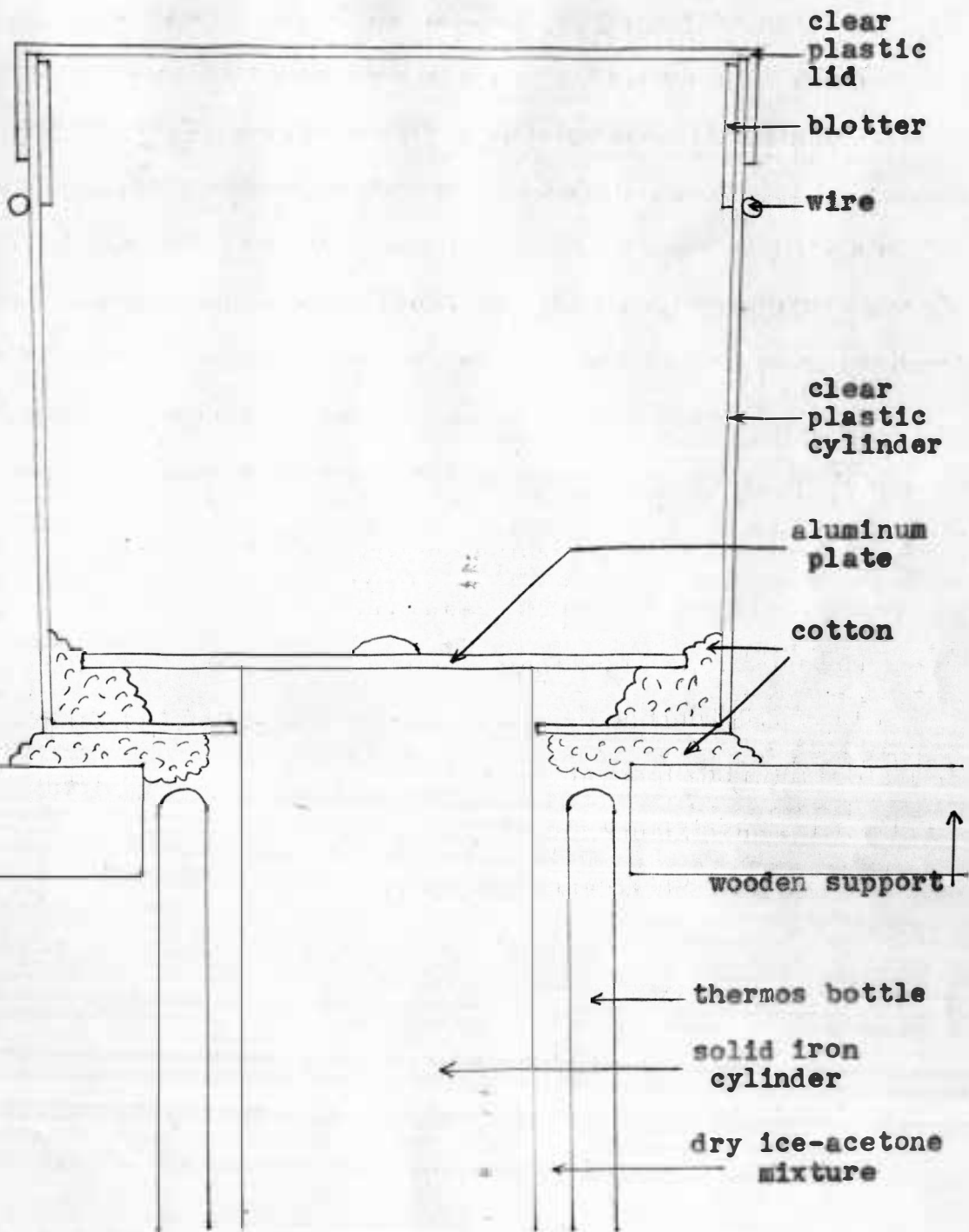
THE DIFFUSION CLOUD CHAMBER

The cloud chamber used for the experimental work in this paper is a diffusion chamber the design of which is essentially that of Snyder and Heilemann[10]. It was chosen because it has been tried and tested and is especially adaptable to experimental work.

Figure 2 is a sectional view of the diffusion chamber drawn to scale. The chamber is a clear plastic cylinder with a one-sixteenth inch wall provided with a removable lid of the same material and fitted as shown. A ring of blotting paper, supported on small plastic blocks, when moistened with ethyl alcohol serves as the source of the vapor. An aluminum plate painted a dull black is the cold surface on which the alcohol vapor condenses. This plate is cooled by an acetone-dry ice mixture contained in a thermos bottle. Thermal connection between the aluminum plate and the cooling mixture is made by a solid iron cylinder which passes through a hole in the bottom of the chamber. Cotton is packed around the bottom of the aluminum plate to help seal the chamber and cut down the flow velocity of the vapor near the cold surface. A circle of wire held in place by friction is one electrode of a continuous sweep voltage of about 1000 volts; the other electrode is the aluminum plate. The purpose of the sweep voltage is to clear the sensitive region of unwanted ions that were formed either above the region or by previous

Figure 2

Sectional view of a diffusion type
cloud chamber drawn to scale

clear
plastic
lid

blotter

wire

clear
plastic
cylinder

aluminum
plate

cotton

wooden support

thermos bottle

solid iron
cylinder

dry ice-acetone
mixture

scale: 2 cm = 1 inch

tracks in the region and tend to deplete the supply of vapor and cause a background fog.

The chamber is supported by a board with a hole large enough to permit the thermos to be raised around the iron cylinder and against the bottom of the plastic cylinder. A matting of cotton is placed between the chamber and the support for extra insulation to help conserve the dry ice.

The lid of the chamber has three one-quarter inch holes to allow a thermocouple to be placed in the chamber. One hole is in the center, one hole is 2.3 cm from the center, and the third hole is 4.8 cm from the center. These holes were used to study the change of temperature with distance along the radius.

Because of condensation there is a flow of vapor downward. It "falls off" the aluminum plate and because of the flow velocity there is a tendency for the tracks to become distorted. To prevent this, a cardboard strip about an inch high was glued around the aluminum plate. In fact, a number of measurements were taken with the strip in place and were found to agree with those taken with the cotton around the bottom of the plate. The cotton was substituted for the cardboard strip because the cardboard blocked the light from the slide projector which was used to illuminate the tracks. The cotton substitute seems actually to serve better than the cardboard strip as a preventative measure

against the flow of vapor.

For an alpha particle source, both radioactive lead chloride and thorium were used. The tip of a wire or a sliver of wood was covered with glue, then dipped into the radioactive material to make sure the alpha particles would be emitted from the radioactive material on the surface and therefore would not be stopped before they could enter the cloud chamber.

The alpha rays were emitted radially from the small source and could be seen quite clearly in the sensitive region immediately after they were formed, but because of the motion of the vapor they diffused rapidly.

Figure 3 is a top view photograph showing two fairly sharp tracks and many diffuse tracks formed along the path of the alphas emitted from a thorium source on the end of a toothpick fastened to a coil of wire which lies on the aluminum plate. The light source was cross illumination by a 200 watt slide projector and the camera was a Kodak 35 loaded with Super XX Eastman Kodak film. The camera was equipped with a 1+ portrait lens and was used with 1/200 th of a second shutter speed and an f/3.5 aperture.

Figure 3

Top view photograph showing tracks of alpha particles

from a thorium source in a diffusion cloud chamber
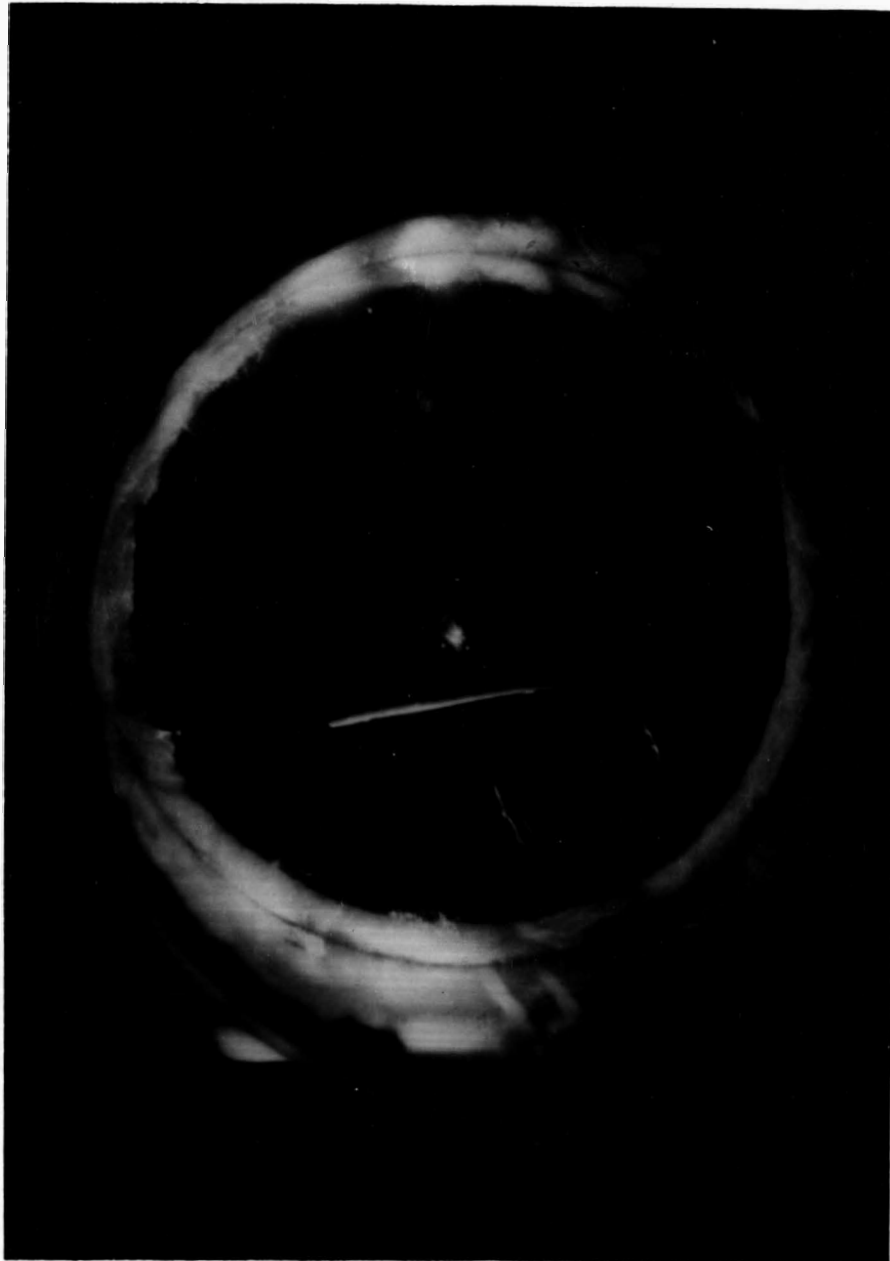
MECHANICS OF OPERATION

As described in the previous section, to achieve a
sufficient supersaturation ratio the warm alcohol vapor is
allowed to evaporate near the top surface of the chamber at
a temperature (T_o) slightly less than room temperature. The
saturation vapor pressure at this temperature is (P_o). As
the vapor diffuses down toward the refrigerated floor the
partial pressure (P_o) is greater than the saturation vapor
pressures at these lower temperatures and eventually the
vapor reaches such a level where the supersaturation ratio
is great enough to produce tracks. Assume (T_s) is the
temperature at the top of the sensitive region and (P_s) is
the saturation vapor pressure at (T_s). Then the super-
saturation ratio (S) at the top of the sensitive region is:
$S = P_o/P_s$.

Below the temperature (T_s) the supersaturation ratio
will probably increase. The exact value of (S) will depend
upon the amount of condensation that takes place because
this condensation controls the value of the vapor pressure
that actually exists in the sensitive region and below.

There will be a temperature gradient (G) established
between the top and bottom surface defined by $G = dT/ds$
where (s) is the vertical distance measured in the chamber
in centimeters. The gradient then is simply the change of
temperature per change in distance. If temperature is

plotted against distance for any cloud chamber, the curve could be thought of as a function $T = f(s)$ and dT/ds would be the slope of the curve at any point.

OPERATIONAL CONDITIONS

To study the temperature distribution within the chamber when tracks were observable, a copper-constantan thermocouple was used. The couple was a conventional two junction thermocouple made of #30 cotton covered wire. The calibration of the couple was checked after construction and the electromotive force agreed within the limits of experimental error with the values published for such a couple. The junction that was placed in the chamber was encased in glass tubing to help keep it vertical and give it rigidity. A chromel-alumel thermocouple of #18 wire was also used to determine if the thermal capacity of the couple had an appreciable effect on the temperature distribution. The readings of both couples were found to agree within the limits of error.

The electromotive force was measured with a Leeds Northrup potentiometer indicator which is calibrated to 1/2 of a millivolt and can be read to the nearest 1/4 of a millivolt which is equivilant to about 1/2°C for the thermocouples used.

Figure 4 is a graphical representation of temperature measurements at different distances vertically downward on the center axis of the chamber. These temperatures are representative of a number of trials and were taken after the conditions of the chamber had reached equilibrium and

Figure 4

Variation of temperature with vertical distance for a diffusion type cloud chamber
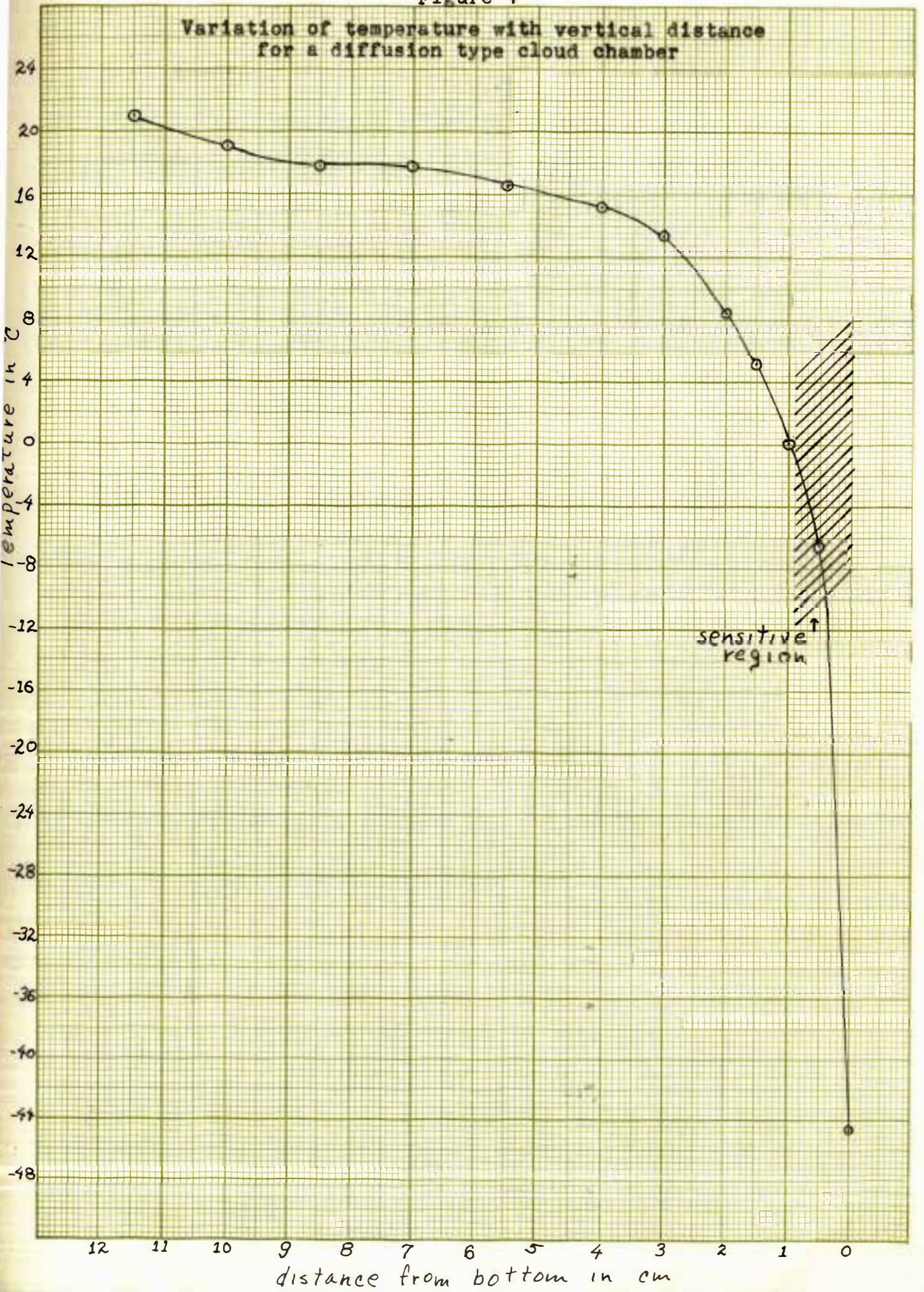
tracks were observable. The shaded section on the graph shows the sensitive region of the chamber. That is, that layer in the chamber where tracks are being formed.

The temperature of the top surface is, of course, dependent upon the temperature of the room. A change in room temperature tends to change the character of the temperature-distance curve at the top very slightly and leave the bottom of the curve unchanged.

Figure 5 shows data representative of a number of trials for both the transient and equilibrium states. The transient state exists during the period when the bottom plate is still cooling and clear tracks have already started to form. The equilibrium state is the normal operating state of the chamber and exists after the temperature gradient in the chamber has settled down. It has been reported that the tracks are better during the transient state. In the present chamber, however, no significant difference was noted.

From examination of figure 4 one can see that the sensitive region is a small fraction of the total distance. In an effort to expand this distance, the temperature of the top surface was changed to 0°C and figure 6 is representative of the trials taken under these conditions. To hold the top surface at 0°C the lid of the chamber was replaced by a flat metal container filled with ice cubes and water. To give a comparison with normal operation the points of the curve
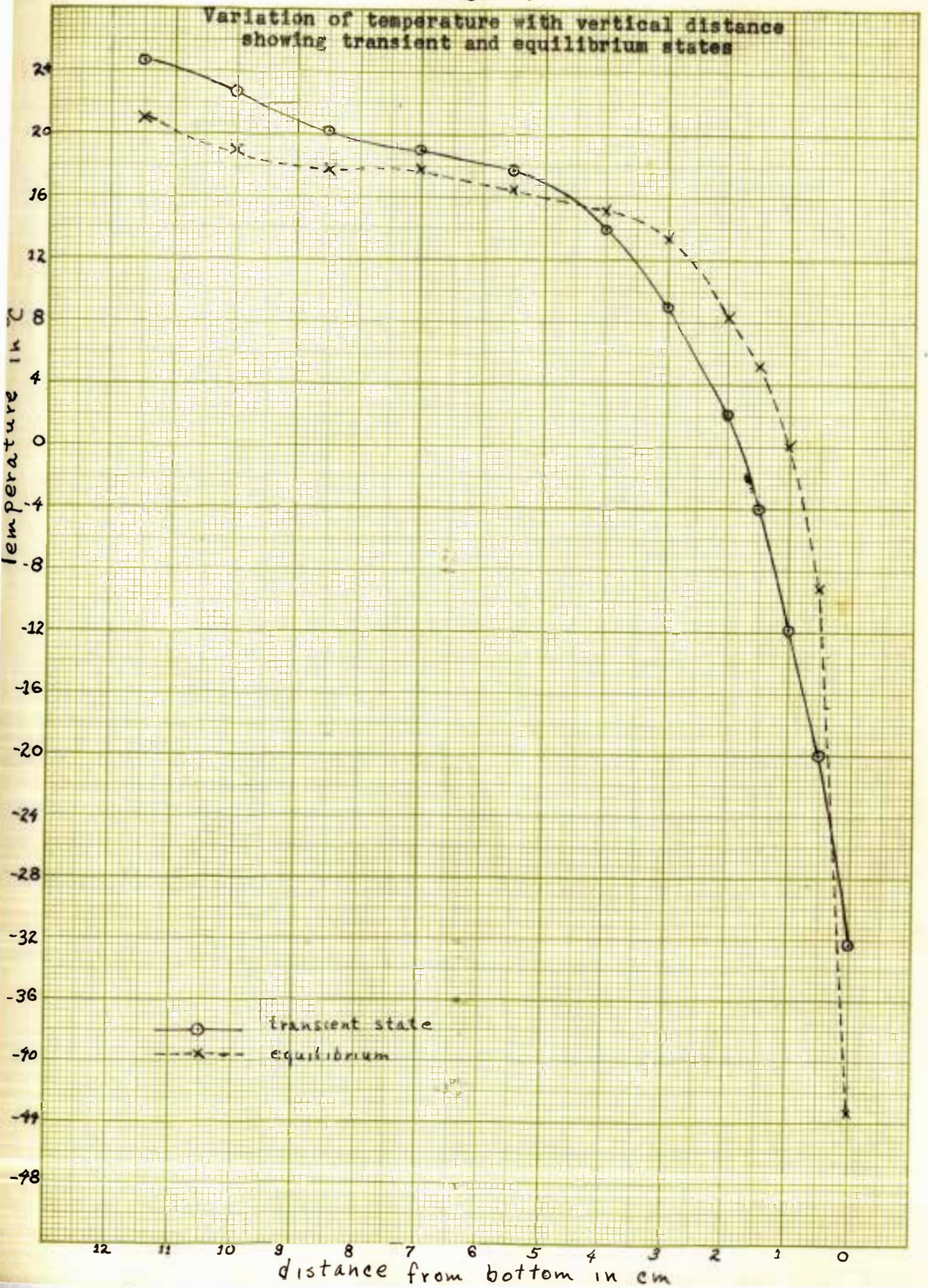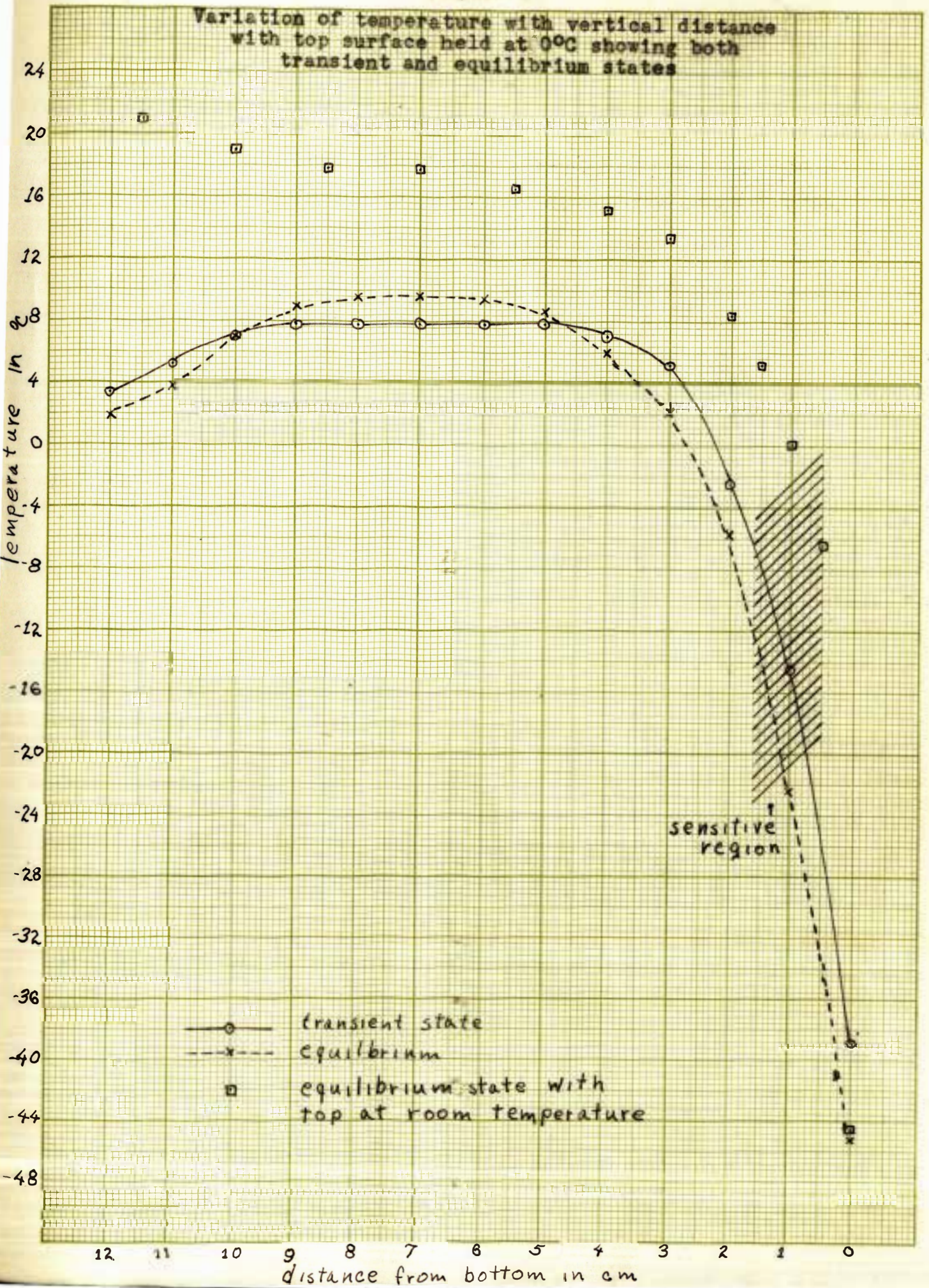
Figure 5

Variation of temperature with vertical distance showing transient and equilibrium states

Figure 6

Variation of temperature with vertical distance with top surface held at 0°C showing both transient and equilibrium states

of figure 4 are repeated here.

Also, temperature readings were taken to show the
temperature as a function of the radius. The measurements
were taken: (1) down the center axis of the chamber, (2) down
a vertical axis 2.3 cm from the center, and (3) down a verti-
cal axis 4.8 cm from the center. Figure 7 contains infor-
mation representative of a number of trials showing this
variation of temperature with radius. The solid lines are
equi-temperature lines.

Figure 7

Equi-temperature lines showing variation of temperature with radial distance in a diffusion chamber
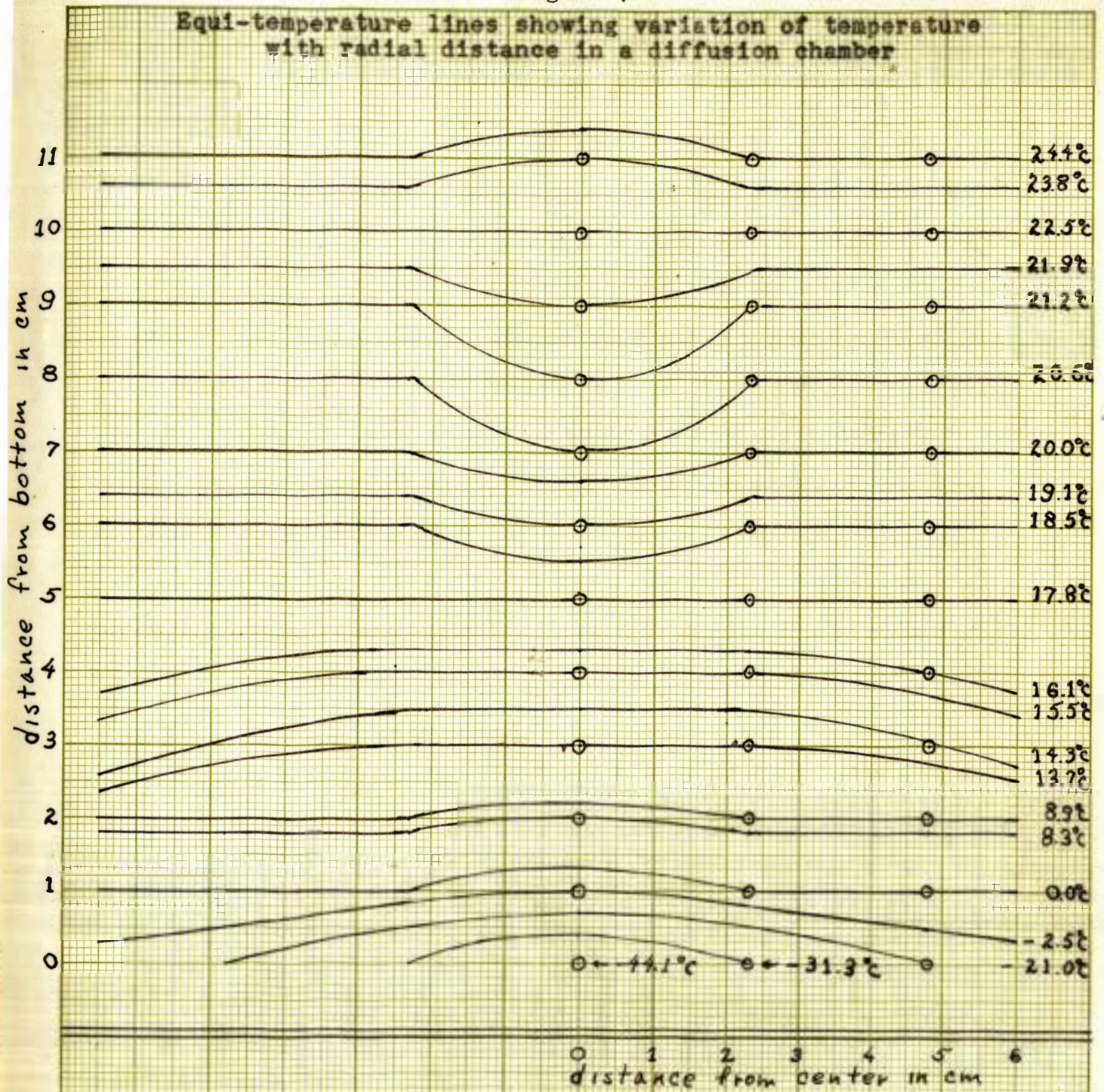
DISCUSSION OF RESULTS

From figure 4 the temperature (T_o) at the blotter is 19°C. At this temperature the saturation vapor pressure (P_o) is 41.6 mm of Hg. Also, at the top of the sensitive layer the temperature (T_s) is -0.5°C. At this temperature the saturation vapor pressure (P_s) is 10.8 mm of Hg. This gives a value of S = 4.0 which is in good agreement with the value predicted as necessary for drop formation since the top of the sensitive layer could only be measured within about 2 mm.

The saturation vapor pressures used above were taken from the Handbook of Chemistry and Physics, thirty-first edition, page 1873.

From figure 6, (T_o) is 9°C and (T_s) is -12°C. Then (P_o) is 22.3 mm of Hg and (P_s) is 5.3 mm of Hg. This gives a value of S = 4.2 and is also in fair agreement.

For a rough approximation of the temperature gradient near the sensitive region one can take the change of temperature and distance across it, i.e. $G = \Delta T/\Delta s$. For figure 4 between 0 and 1 cm (G) is found to be 44.5°C/cm. From figure 6 between 0.5 and 1.5 cm (G) is found to be 19°C/cm.

If it was assumed that (P_o) was constant throughout the sensitive region, it would naturally follow that a smaller temperature gradient would broaden the sensitive layer, since it would start farther from the bottom.

However, it is seen in figure 6 that the effect of the smaller gradient is simply to raise the entire sensitive region and not affect its thickness.

If the radioactive source is removed from the chamber the region below the previous sensitive layer will show clear tracks of occasional cosmic rays which pass through it. In this case, since there is no condensation for appreciable periods of time, the assumption of a constant (P_o) in the sensitive region is more nearly correct.

Thus, for the purpose of cosmic ray study, the sensitive region is broadened by a reduction of temperature gradient but, when there is a great amount of condensation taking place, the amount of vapor available for condensation on ions formed in the lower part of the sensitive region is probably the main factor. In the latter case the super-saturation ratio could possibly fall below a value of 4.1 at the bottom of the chamber if the condensation were great enough in the sensitive region.

The curve for the transient state in figure 5 shows a temperature gradient of $24.4^{\circ}C/cm$ in the sensitive region. A broader sensitive layer is not observed however, but this is probably due to the fact that during this period the alcohol has not had a chance to evaporate enough to saturate the air in the upper part of the chamber. It is also feasible to assume that (P_o) is not constant during this

period since it is probably in a transient state of its own.

Figure 7 shows that there is a difference in temperature radially outward, but except very near the bottom of the chamber the difference is not great. At the top of the sensitive layer the temperature is evidently quite even since no change in thickness or height of the sensitive layer is noticeable..

CONCLUSIONS

Experience with this particular cloud chamber would seem to indicate that one of its most serious limitations for quantitative experimental work is the rapid motion of the vapor resulting in bad distortion of the tracks. This perhaps would not be serious if the tracks were photographed using a specially designed high speed pulsed light with high intensity. Also redesigning the cooling plate or shortening the overall length of the chamber might tend to help this problem. However, shortening the chamber would probably increase the temperature gradient in the sensitive region which would be undesirable if a wide sensitive region were needed in experimental work.

For the purpose of cosmic ray study a broader sensitive region may be accomplished by decreasing the temperature gradient. Another method of doing this other than just cooling the top would be to control the temperature at three points in the chamber. For instance, hold the top surface at room temperature, the bottom surface at $-45^{\circ}C$, and a surface in the middle at about $6^{\circ}C$. This would have the effect of giving a more uniform temperature gradient throughout the chamber and of decreasing the temperature gradient near the bottom of the chamber.

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