THE COALESCENCE OF LARGE AND SMALL WATER DROPS:

ITS EFFECT ON RAINFALL INTENSITY

by

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Coalescence of raindrops and cloud droplets has been studied in collaboration with W. Hitschfeld, by allowing drops of 3 mm diameter to fall through a three-metre column of cloud. The observed drop growth is expressed in terms of a collection efficiency, the fraction of the cloud water in the path of the drop, which is actually picked up. Collection efficiencies, using three clouds of different droplet-size distributions, are found to be in good agreement with aerodynamic collision efficiencies, calculated from a theory by Langmuir#. His assumption that collision always leads to coalescence is thus confirmed.

The effect on coalescence of charge on the drops, comparable to that observed on raindrops in nature, is found to be small.

In this thesis, the production of cloud, the experimental procedure, and the analysis of the results are described in detail. The increase in intensity of the radar signal from rain falling through cloud is evaluated.

#I. Langmuir, J. Met., 5, 175-192, 1948.

PREFACE

The writer has collaborated throughout the research reported in this thesis with Mr. Walter Hitschfeld.

Mr. Hitschfeld contributed largely to the theoretical aspects of the problem, extending Langmuir's theory to make it applicable to this particular experiment. The writer was responsible for analysing the results of the experiment in terms of the theory, so developed.

Both of us feel that our individual contributions to the development of the apparatus and of experimental procedure were comparable. The apparatus was built by us, with the exception of the Liquid Water Content Meter (LWCM) and the special dropper, which were made from our designs in the workshop of the Macdonald Physics Laboratory.

In writing the theses, the various items of the research were divided as nearly as possible according to the interest of each member in the particular item. This division was necessarily rather arbitrary, since each of us made some contribution to every part of the experiment. Where one thesis describes a phase of the work in detail, the other presents a brief review. The first three sections of Chapter 1 were written jointly with Mr. Hitschfeld. Other references to his thesis are noted specifically in the text by (Thesis H).

It is a pleasure for the writer to express his sincere appreciation of the imaginative and always helpful guidance of Dr. J. S. Marshall, who supervised the research.

The fellowship of several others who have worked on related problems under Dr. Marshall has been both enjoyable and fruitful. This group has included among others, Miss E. C. Rigby, Dr. W. McK. Palmer, and Mr. M. Bloom.

The writer is grateful to Dr. A.N. Shaw, Chairman of the Department of Physics, for his personal interest in the work; to Dr. Anna McPherson for her kindness in providing a microscope, and for her helpful suggestions with the microphotography; and to Dr. H.G.I. Watson, who lent some electrical equipment.

The writer would like to thank Mr. George Tweeddale for his careful construction of the LWCM and the dropper; and also the Physics Laboratory of Loyola College, which kindly lent a precision potentiometer.

Finally, the writer is indebted to the Defence Research Board for the provision of a grant, with which this research was largely financed; and to the Department of Veterans Affairs, from which the writer received financial assistance.

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CHAPTER 1

COALESCENCE: A FACTOR IN THE GROWTH OF RAINDROPS

1.01 Historical Introduction

The study of the atmosphere has received some attention for a long time, and some processes taking place aloft are quite well understood. Thus, for over eighty years, the formation of clouds has correctly been ascribed to the approximately adiabatic cooling of rising air masses. But the exact conditions under which clouds, which may have existed unchanged for many days, can suddenly shed their water and disappear have not yet been defined completely.

A great advance in the general understanding of this and related phenomena came when Schmauss (1919, 1920) suggested that clouds should be looked upon as colloidal suspensions (aerosols) which remain in colloidal equilibrium until, for some reason, coagulation (i.e. precipitation) sets in. This phraseology proved important because it focussed attention on microphysical processes, and it suggested that a knowledge of the (macroscopic) thermodynamic and aerodynamic conditions alone might not suffice to explain all atmospheric phenomena. Among the fruits of this newer point of view may be mentioned Findeisen's (1938, 1939) theory of condensation and sublimation nuclei which has recently found several interesting practical applications.

Bergeron (1933), also using the terms of the theory of colloids, summarized the factors which might be expected to affect the stability of clouds. He considered the following conditions to be conducive to precipitation:

(1) The cloud elements are uncharged, or carry charges of both signs.
(2) The cloud droplets differ in size.
(3) Temperature differences exist between neighbouring cloud elements.
(4) Turbulence or relative motion due to gravitational sedimentation occurs.
(5) All three phases of water (solid, liquid and vapour) exist together.

Factors (1) and (4) might lead to collision and fusion of the droplets; (2), (3) and (5), on the other hand, create vapour pressure gradients, causing a diffusion transport of water from the smaller to the larger, from the warmer to the colder, or from the liquid to the solid particles, respectively.

On analyzing these factors, Bergeron came to the conclusion that possibly all might be operative, but that only the fifth could generally be relied on to initiate the rapid growth of some particles at the expense of others, and to lead to particles of the observed sizes in sufficiently short time intervals. Findeisen (1938, 1939a) has greatly extended Bergeron's analysis, and affirmed that substantial precipitation could only be the result of processes involving the solid state - namely diffusion transport from water to ice particles, and aggregation among snow crystals.

Findeisen (1938) and Houghton (1938) also considered the further growth of particles falling through layers of cloud by accretion with cloud elements. They assumed that coalescence always occurred on collision, but they suspected that aerodynamic factors might inhibit collision of particles appreciably different in size. Findeisen (1939a) went so far as to maintain that coalescence among liquid elements could not be an important factor in the formation of precipitation.

There is, however, some meteorological evidence, partly from the tropics, that rain storms can develop from clouds at temperatures wholly above freezing, or that, even where the Bergeron-Findeisen theory accounts for the initiation of the precipitation, rapid development of rain below the freezing level plays an important part. (Simpson, 1941; Langmuir, 1948). This, contrary to the Bergeron-Findeisen view, would seem to emphasize the importance of coalescence, not only as a subsidiary process but as a possible primary effect. The observations of Köhler (1925) that the concentration of chloride in the cloud is roughly equal to that in rain water, would seem to lend further weight to this supposition.

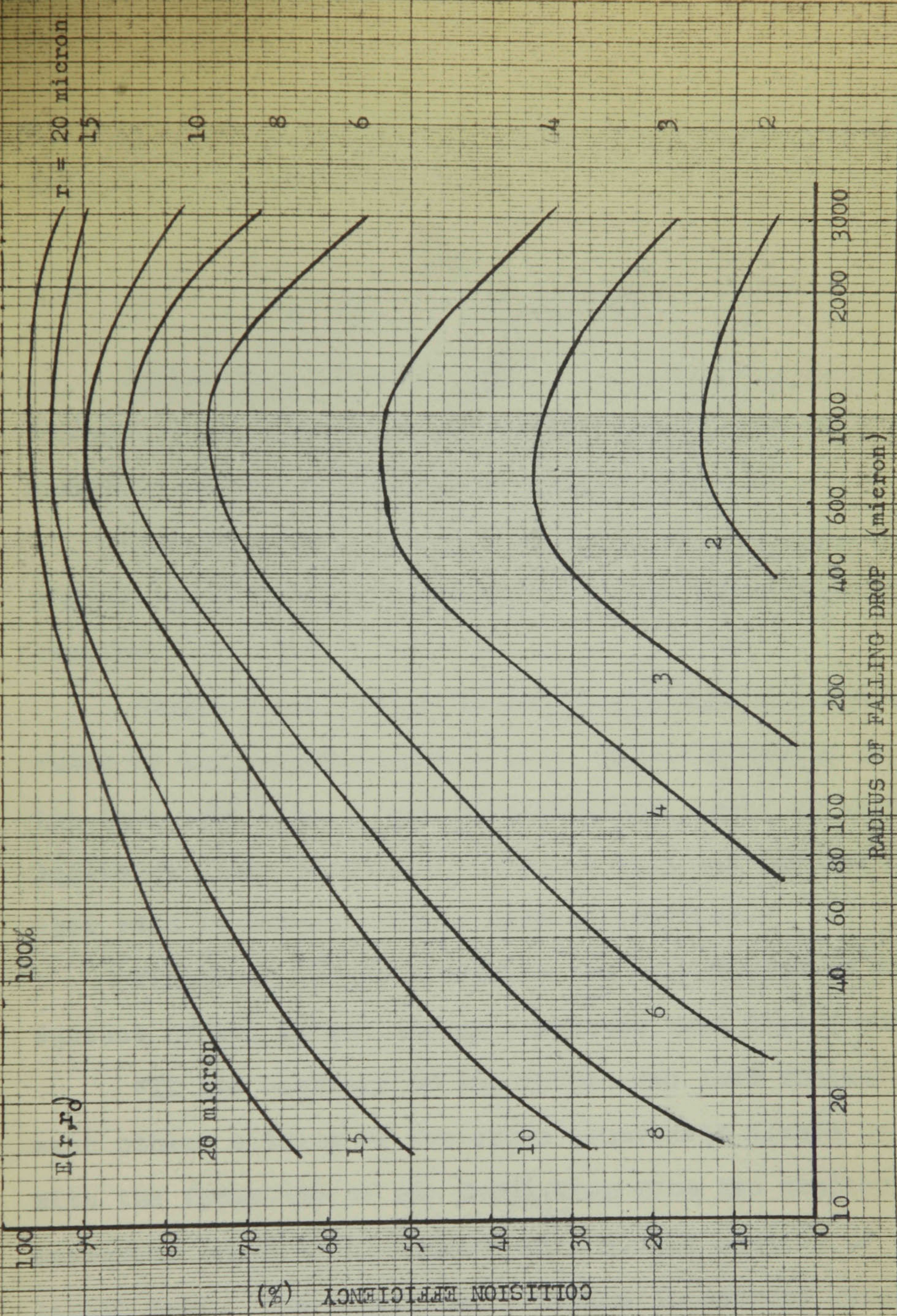
A renewed examination of the process of coalescence therefore appeared to be desirable. There are essentially two factors which have been thought to render accretion difficult. (1) The smaller droplets may be carried around the larger and more swiftly falling particles without coming into contact with them. This aerodynamic difficulty is discussed below in Section 1.02. (2) If particles do come into actual contact, it is still not certain that they will merge.

This point, and some arguments for and against such a merger ate discussed in Section 1.03.

1.02 Langmuir's Theory of Collision Efficiency

The aerodynamics of collision was the object of a thorough enquiry by Langmuir (1948). Drawing on the earlier investigation of a related problem (Langmuir and Blodgett, 1946), he examined the trajectories of the smaller droplets in the vicinity of a larger drop. From the shape of these trajectories he was able to calculate the collision efficiency, E, which may be defined as the ratio of the mass of cloud water with which the falling particle collides to that originally contained in the volume swept out by it. This efficiency is, in general, less than unity; it turns out to be a complicated function of the parameters of the relative motion. If the particles are considered to be moving at their terminal velocities, the results of Langmuir's analysis may be represented as a family of curves, showing E as a function of the drop radius r_o for various values of the droplet radius r. Graph 1.01, prepared from Table 4, (Langmuir, 1948) is such a plot.

Since Langmuir assumed that every collision leads to coalescence, he called E the collection efficiency. In the present work, we have distinguished the collision (contact) efficiency, E, from the collection (coalescence) efficiency,



COLLISION EFFICIENCY, E, as a function of r_o, the radius of the falling drop, and r, the radius of the cloud droplets, according to Langmuir's theory.

(From Table 4, Langmuir, 1948)

Graph 1.01

E', since the determination of the relationship between them was one of our objectives.

1.03 The Coalescence of Drop Surfaces in Contact

Meteorological text books, in discussing probable factors which play a part in the formation of precipitation generally make some reference to coalescence.

For instance, Humphreys (1920) in his text on the physics of the atmosphere, makes the following inconclusive remarks:

"Water drops do not unite on collision but rebound as shown by the scattering of a jet. This difficulty is met by the fact that when slightly electrified, drops do unite on collision (Lord Rayleigh), together with the further fact that rain is always more or less electrified."

Findeisen (1939) discusses the coagulation by mutual contact of two drops, and is convinced that this occurs.

"If the surfaces of two drops come into contact with each other, a union of the drops apparently always occurs. With the formation of one large drop from two smaller, surface energy is freed which appears as a slight heating of the liquid drop. The associated increase in entropy renders the union of contacting drops probable, and in fact it can be deduced from the results of experiments that the impact of clear drops always results in their coagulation."

However, the following experiments have been reported recently which lead to the opposite conclusion.

(1) Derjaguin and Prokhorov (1946) performed an experiment in which two large drops (of liquids other than water) at the ends of two capillary tubes were brought into contact. The drops remained without merging for long periods, if the surrounding atmosphere was not saturated with their vapour.

They observed a small hollow pocket between the two drops, the existence of which they attributed to air and vapour diffusion currents. The development of such a pocket prevented intimate contact between the two surfaces, thus rendering coalescence impossible. When the ambient vapour pressure reached equilibrium value, these pockets did not develop and the drops merged.

(2) Dady (1947) observed fog droplets of from 4 to 15 microns radius with a microscope, which had a field of view 0.4 mm in diameter, and 10 microns deep. He made calculations that predicted one collision between droplets in his field of view every 40 seconds. In a total of ten hours of observation, collisions were observed but no trajectories were seen to merge, from which he concluded that coalescence between droplets of this size must only be an exceptional phenomenon.

(3) Swinbank (1947) produced droplets (none greater than 2 microns radius) with an atomizer. The droplets were introduced

into a draught-proof chamber, where they were observed with a microscope. No coalescence occurred, either on "head-on" collisions, or on oblique ones; neither did the presence of an electric field produce coalescence, although the droplets were charged.

He also allowed a large drop to fall through the smaller droplets and observed (1) that the droplets were scattered in the path of the larger drop. From this, he concluded that coalescence was also unlikely for drop-droplet collisions.

The weakness of experiments of the type performed by Dady and Swinbank, lies in the difficulty of viewing these phenomena in the limited field of view of a microscope, particularly where rapidly moving particles are involved. It is interesting to note, however, that Langmuir's theory predicts a low aerodynamic collision efficiency for the droplet sizes investigated by these workers.

It should be mentioned that phenomena, similar to those observed in the above three experiments were first noticed by Lord Rayleigh (1879).

(1) He found that the drops formed when a jet of water breaks up, scatter through a considerable angle. He thought that this scattering was due to the fact that the drops bounded apart after colliding with one another.

(2) When fine jets of water from two electrically insulated

vessels were directed against each other, they rebounded.

In both experiments coalescence occurred when an electrified body was brought into the neighbourhood of the jets.

As far as the writers know, a satisfactory explanation of Rayleigh's observations, particularly of the sensitivity to charge, has not yet been given. It is possible, however, that the explanations of Derjaguin and Prokhorov, if applicable to water, might provide a starting point to the solution of this problem.

1.04 The Need for an Accretion Experiment

The contradictory results of these experiments and the appearance of Langmuir's aerodynamic theory (with his assumption that collision meant coalescence), resulted in a distinct need for verifying experimentally that accretion of cloud droplets by raindrops does take place.

Experiments of the type described in Section 1.03 were concerned with the microscopic study of coalescence, while none has apparently been performed which would investigate the macroscopic aspects of the problem.

Accordingly, it was decided to perform an experiment, with two objects:

(1) To determine if a raindrop moving relative to cloud droplets does grow by collection of the droplets;

and (2) if so, to compare the efficiencies of <u>collection</u> observed, with Langmuir's theoretical <u>collision</u> efficiencies, and thus determine whether contact always leads to coalescence.

Two approaches to this study were attempted. The first, which was eventually abondoned, is described in Chapter 2. The second is described in Chapters 3 to 8. In Chapter 9, the effect of coalescence on the intensity of the radar echoes from rain is discussed.

CHAPTER 2

THE SUSPENSION OF A WATER DROP IN A VERTICAL CURRENT OF AIR

2.01 Introduction

The investigation of the coalescence of large and small water drops can be approached in two ways. One is to hold the large drop stationary in an air stream containing cloud droplets; the other, to allow drops to fall through a cloud of much slower-falling droplets.

With the first of these methods, drop growth due to coalescence might be observed quantitatively by successive photographs, and possibly by knowing accurately the velocity of the air stream necessary to support the drop. With the other, weighing the drops before and after their transit through the cloud should reveal any increase in mass due to coalescence of the drop with the droplets, provided this increase is sufficiently large. In conjunction with either of these methods a tracer technique might be used. For example, the cloud droplets could be dyed with a material which would be such as to leave the surface tension and viscosity of the water unchanged. Subsequent analysis of the large drop for dye content should determine the amount of water picked up by it.

The suspension of a water drop in an air stream seemed an attractive experiment in itself and it was decided to begin the coalescence study with this project. However, successful suspension was not obtained with the apparatus developed for the purpose, and difficulties were foreseen with the problem of introducing cloud into an air system which would suspend the drop. So the suspension approach to the study of coalescence was abandoned in favour of the alternative falling-drop method.

The tracer technique was not developed since weighing the collected drops after their fall through a cloud was found to be an adequate means of detecting coalescence.

2.02 The Vertical Wind Tunnel

Early discussions on a suitable design for a vertical wind tunnel indicated that a velocity profile with a "trough" in the centre, might hold the drop suspended along the axis of the tunnel. The sides of the working section if tapered to open upwards (downstream) would provide a uniform drop in velocity up the tunnel, thus enhancing the stability of the drop in the vertical. (An upward displacement of the drop would result in its being in a region of lower velocity; a downward displacement would result in its being in a region of higher velocity. Thus, restoring forces of gravity and drag, respectively, would result in a condition of stable equilibrium for the drop in the vertical.) It was hoped that the velocity trough would provide the stability in the horizontal plane. In order that the input conditions (e.g. temperature and humidity of the air, the presence of cloud particles), could be controlled, it was thought more convenient to use a sucking rather than a blowing system. The source of power was a conventional cylinder type vacuum cleaner with a 450 watt (input) motor. To introduce the drops into the air stream, simple dropper mechanisms were placed centrally above the working section at such a distance as not to disturb conditions there.

Two wind tunnels were built, the second incorporating improvements gained from experience with the first. (Fig. 2.01 and Fig. 2.02). The second tunnel was designed to have the maximum cross-section through which the available motor could supply air at the terminal velocity of the largest drops used. At the bottom was a contraction section to reduce turbulence at the intake. In this section, from 3 to 5 equally spaced copper screens could be placed. These were of such a diameter as to leave at least 1 cm of free space all around them through which air could pass unimpeded. These screens, as well as providing a smoothing effect on the stream, would form a central impedance leading to the desired velocity trough. (This design follows that of the much larger vertical wind tunnel at the N.R.C. Montreal Road Laboratory, Ottawa.)

The main tunnel, in the lower quarter of which the drop would reside, was octagonal in cross-section and made of Lucite. Such a cross-section was desirable to approximate a circular one, without the problems of round tubes, should

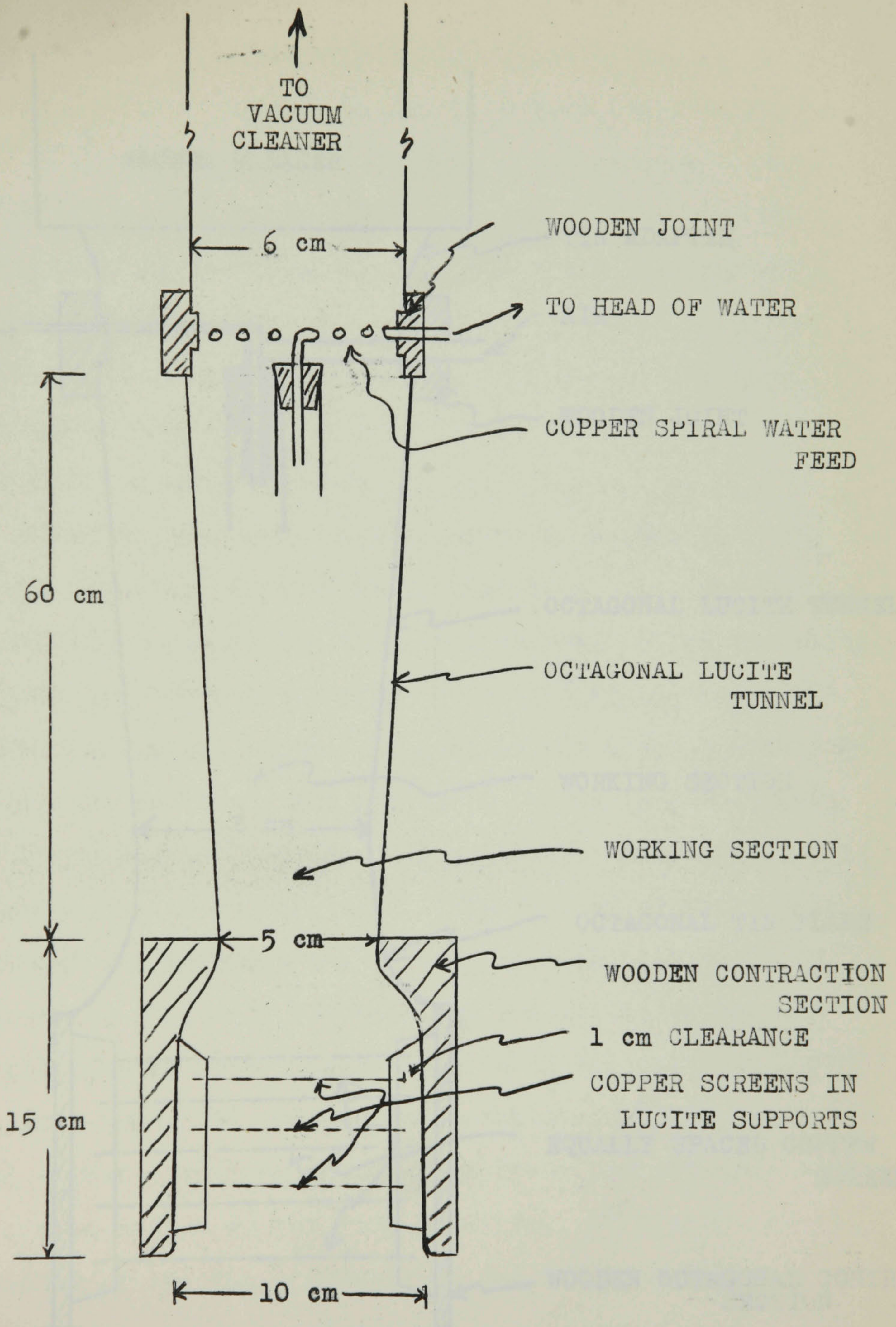


FIGURE 2.01 - The First Wind Tunnel

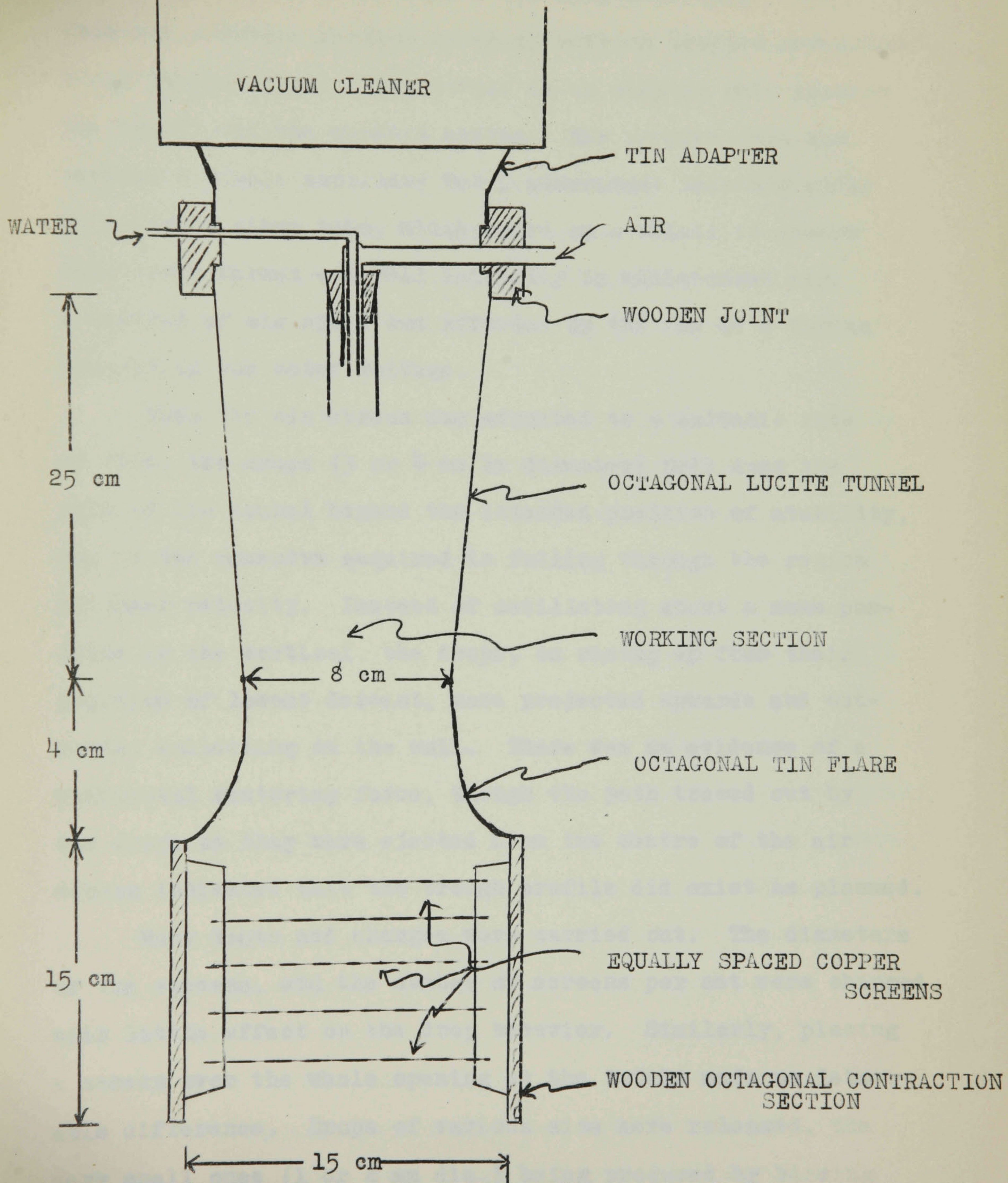


FIGURE 2.02 - The Second Wind Tunnel

photography be used to observe the suspended drop. Above this was a wooden section in which various dropper mechanisms could be placed and which served as an adapter unit between the tunnel and the suction system. The dropper used was usually a simple capillary tube, surrounded concentrically by a larger glass tube, which acted as a shield to assure that drops formed and fell initially in undisturbed air. A control of air speed was afforded by the use of a Variac regulating the motor voltage.

When the air stream was adjusted to a suitable rate of flow, the drops (3 or 4 mm in diameter) fell down the axis of the tunnel beyond the intended position of stability, due to the momentum acquired in falling through the region of lower velocity. Instead of oscillating about a mean position in the vertical, the drops, on rising up from their position of lowest descent, were projected upwards and outwards, collecting on the wall. There was no evidence of a horizontal restoring force, though the path traced out by the drops as they were ejected from the centre of the air stream indicated that the trough profile did exist as planned.

Many tests and changes were carried out. The diameters of the screens, and the number of screens per set were changed with little effect on the drop behavior. Similarly, placing a screen over the whole opening at the intake made no detectable difference. Drops of various size were released, the very small ones (1 or 2 mm dia.) being produced by blowing air concentrically around the dropping capillary, thus forcing off drops before they were fully formed. The behavior of the small drops was no better than that of the easy-to-make larger ones.

The most nearly stable arrangement was arrived at by introducing the drops with a dropper drawn out to a fine point, which was inserted through a small hole in the tunnel at the level of the working section. Here drops might slide about momentarily in the horizontal plane and then quite erratically they would be thrown up and out of the central stream onto the wall of the tunnel. The trajectories of the drops as they were ejected from the central stream were randomly distributed and it was quite impossible to predict which side of the tunnel they would hit. Manual tilting of the whole apparatus, in an attempt to anticipate the motion of the drop and hence arrive at suspension, was tried. This was not at all successful due to the speed with which the drop slid about, and the impossibility of predicting the direction of its next move. Except for this latter experiment, great care was taken to ensure that the whole instrument was truly vertical, since it was thought that this condition might be critical. On no occasion was the time between release of the drop and its arrival at the wall of the tube greater than five seconds.

To make certain that the desired velocity profile did actually exist, traverses across the tunnel were taken at various levels with a simple Pitot tube, a glass tube drawn out and bent at the end, so that the open end pointed upstream.

With the aid of a sloping manometer attached to this tube, "$p + 0.5 \rho v^2$" was measured, ("static + dynamic" pressure), giving an indication of relative velocities across the flow.

Later, using a Serre's Disc at the end of a drawn out tube, the tube being perpendicular to the stream, "p" could be measured and hence absolute values of the velocity determined. Two of these traverses are shown in Fig. 2.03 indicating a distinct trough when the screens were in place, and the usual flat profile associated with turbulent flow when they were removed.

As an attempt to explain the sudden departure of the drop to the side, after its momentary hesitation in the central stream, calculations were made to see if the Magnus Effect could be operative. This is the familiar effect which causes a spinning ball to trace out a curved path. Near the edge of the velocity trough the drop would find itself in a velocity gradient, which could cause it to spin in such a direction as to bring into play a horizontal force which would propel the drop suddenly to the wall. However, treating the drop as a rigid sphere, for this force to exist, a 2 mm diameter drop must be making at least 40,000 r.p.m. (Goldstein, 1938). This seems ridiculously large, so it was concluded that this phenomenon was not the cause of the departure of the drop.

Throughout the experiment, many discussions were held, and experts consulted. One particularly reasonable argument

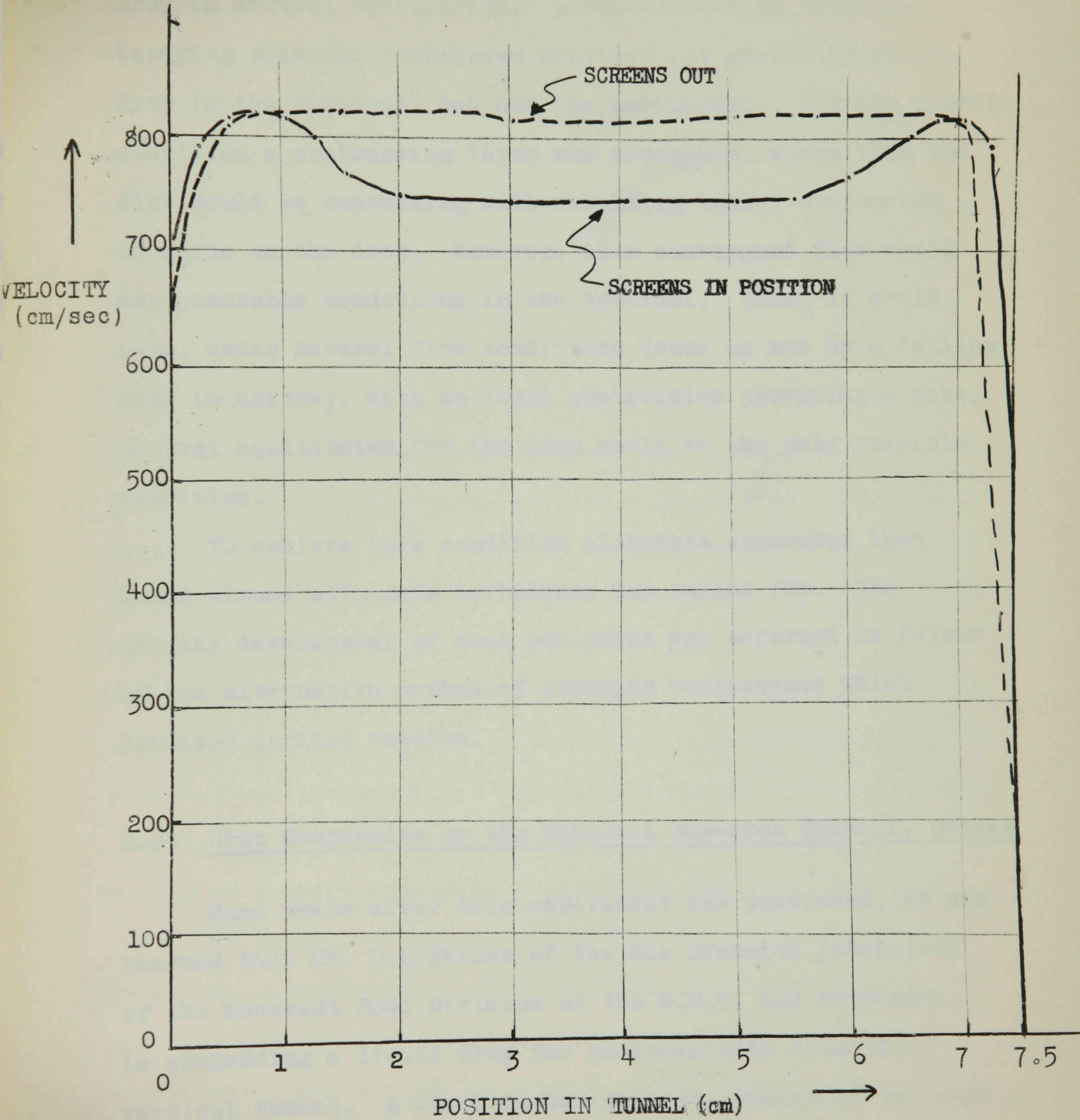


FIGURE 2.03 - Typical Traverse at the Working Section

held that the best that could be hoped for was to have the drop in neutral equilibrium. A tunnel such as this one, tapering outwards downstream provided for stability of the drop in the vertical, but not the horizontal. For the latter condition a contracting taper was necessary, since then the flow would be converging with resulting inward components of force on the drop; however, this convergent flow would mean unstable conditions in the vertical. Thus, it would seem, under natural flow conditions (such as met by a falling drop in nature), with no local obstruction providing a wake, neutral equilibrium for the drop would be the only possible condition.

To achieve this condition elaborate apparatus that would almost eliminate turbulence was called for. The lengthy development of such equipment was deferred in favour of the alternative method of studying coalescence which promised earlier results.

2.03 Drop Suspension at the National Research Council, Ottawa

Some weeks after this experiment was postponed, it was learned that Mr. D.K.Stiles of the Gas Dynamics Laboratory of the Montreal Road Division of the N.R.C. had succeeded in suspending a liquid drop for an indefinite time in a vertical tunnel. A visit to Mr. Stiles' laboratory was made by us, and the stability of the drop observed. His apparatus was remarkably similar to that described above. It was a suction system with a working section of similar dimensions to Tunnel #2, but of square cross-section. The intake section was, however, of different design. It consisted of a horizontal solid baffle (70 cm square) into the centre of which the working section (7 cm square) was connected by a very smooth flared opening. Around the outside of this large baffle (extending down about 60 cm) was a copper screen roughly hemispherical, which acted as a smoothing device for the intake.

The trough profile was formed with one screen, occupying the whole cross-section of the tunnel just above the flared opening. It was an ordinary copper screen, with extra wires inter-woven on it with a pattern so that the greatest density of wires was at the centre, thus the greatest impedance there. With this screen alone, suspension was not possible, though the trajectories of the falling drops indicated that a trough profile did exist. However, with the introduction of a second screen about 10 cm above the first, uniform except for a small obstruction at its centre (sometimes a knot of wire, sometimes a blob of solder) successful suspension was possible.

The drops left the dropper about 40 cm above the final position of suspension. (This dropper could be manoeuvred manually and its position was not very critical.) Several drops would fall and be thrown out of the stream, until one drop would suddenly plummet straight down the axis of the tunnel and come to rest about 5 cm above the small obstruction on the second screen. Stability in the horizontal plane was remarkable. The drop vibrated to and fro as if under very considerable restoring forces. It wandered about a mean position in the vertical, the amplitude of swing being about 4 cm.

As a result of inspecting this method, the following criticisms of our apparatus could be offered:

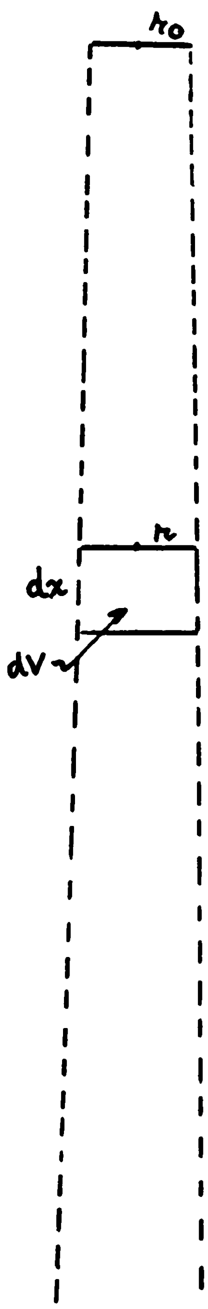
1) The intake section was of the wrong design. What is apparently needed to reduce turbulence to a minimum, is a baffle, extending far out in all directions from the opening. The intake section used by us did not satisfy this requirement at all and consequently must have introduced much unnecessary turbulence. Further, extensive shielding of the intake with copper and possibly also cheesecloth screens, is necessary. The opening of a nearby door, or a noise close by the intake shielding screens, could ruin the suspension of the drop in the Ottawa apparatus.

2) It appears that a small local obstacle of some sort is necessary for securing the desired stability of the drop. The appearance of the drop while suspended over the obstacle was strikingly like the "locked in" stability of the familiar ping-pong ball-on-a-jet-of-air experiment. Thus, it would appear that the successful suspension is due to the drop residing in the wake of the obstacle. It is not known to what extent this type of flow around the drop (as opposed to natural flow) would affect the studies for which the suspension was desired.

CHAPTER 3

THE FALL OF A DROP THROUGH A COLUMN OF CLOUD

3.01 The Principle of the Method



An alternative to the drop suspension method of studying coalescence is to allow the drop (or better, a number of drops) to fall through a cloud. A handicap in performing such an experiment in the laboratory is the limited distance of fall, (hence extent of cloud) possible. If the increase in mass of the drops through coalescence is to be detected by weighing, it is necessary to investigate whether increases susceptible to measurement with a standard balance could be expected.

Consider a drop of radius r falling through a cloud of liquid water content w.* Assume that there is an efficiency of collection, E' , the drop collecting a fraction E' of the droplets met in its descent through the cloud.# As the drop grows, it will sweep out a conical volume. When the drop has fallen a distance dx , the volume swept out

$$dV = \pi r^2 dx$$

Assuming a fraction E' of the total mass of water in the volume dV is picked up, the increase in

---

Langmuir's theory was developed in terms of an aerodynamic collision efficiency, E. He assumed that every collision resulted in coalescence. We are interested in measuring the collection efficiency, E' , comparing it with the theoretical collision efficiency and thus determining to what extent Langmuir's assumption was valid.

* Defined as the mass of liquid water per unit volume of cloud.

mass of the drop

$$dm = E'w\, dV$$

i.e.
$$dm = E'w\,\pi r^2 dx$$

Indoors, only a small distance of fall, h , is possible and the radius of the drop may be considered constant at its initial value, r_o. Then the increase in mass will be given by

$$\Delta m = E'\,\pi\, r_o^2\, w\, h$$

If n drops of radius r_o fall through the cloud, the above relation becomes

$$\Delta m = E'\,\pi\, r_o^2\, w\, h\, n$$

Assuming the following values:

$r_o = 0.15$ cm,
$w = 10$ gm. $m^{-3} = 10^{-5}$ gm. cm^{-3}, #
$h = 300$ cm,
$E' = 100\%$
and $n = 1$
then $\Delta m = 0.212 \times 10^{-3}$ gm.

Thus, one drop of 1.5 mm radius (having a mass of 14.2 mgm), in falling through 3 metres of cloud of liquid water content 10 $gm.m^{-3}$ has its mass increased by 0.212 mgm, provided that the collection efficiency is 100%. If 500 such

Natural cloudshave liquid water contents of from 0.1 to 5 $gm.m^{-3}$. The higher value, 10 $gm.m^{-3}$, used here, is readily obtainable with laboratory cloud, and is necessary to offset the small depth of cloud available indoors.

drops were to fall through the cloud the total increment in mass would be 106 mgm, a quantity readily measureable on a precision balance. Even if the collection efficiency should be as low as 10%, the resulting increment of 10.6 mgm should still be measureable.

3.02 The Experimental Arrangement

Approximately 500 drops of known size were released from a special dropper and fell through a 3-metre length of cloud of known properties. They were caught at the bottom in a receiving cup. The increase in mass due to the drops coalescing with cloud droplets was measured by weighing the dropper and the cup, before and after the transit of the drops through the cloud. The number of drops was determined with a special counter.

Another possible method of measuring the increase in mass would be to weigh the cup before and after the transit of a number of drops through the cloud, and to weigh the dropper before and after; from the two differences the increase in mass could be found. No device to count the drops would be necessary with this method, but this advantage would be offset by the extra weighings required. In addition, the loss of the partially-formed drop which was usually on the tip of the dropper after its use would be serious if the dropper was weighed alone. Keeping the dropper and receiver always together when not in use eliminated this hazard.

The apparatus consisted of: (1) a cloud generator, (two different types were used) which supplied cloud continuously to a long tube, or column; (2) a device to release the drops at the top of the column; (3) a container to catch them below; (4) a drop counter; (5) a precision balance and (6) an instrument (called the LWCM) to measure the liquid water content of the cloud.

The whole apparatus is shown in Plates 3.01 and 3.02 on the next two pages. The various features of the apparatus are described in the subsequent sections of this chapter. Cloud generation is discussed in Chapter 4.

A special problem arose in connection with this experiment, since the falling drop travelled through the cloud at velocities below terminal. Langmuir's determinations of the aerodynamic <u>collision</u> efficiency, E , were made in terms of terminal velocities only, and if a comparison of observed <u>collection</u> efficiency, E' , and collision efficiency was to be made, his work had to be adapted to the special case of a drop falling at velocities less than terminal.

The equation of motion of a drop falling from rest was set up and solved for the particular conditions of this experiment. (Thesis H). The collision efficiencies to be expected in the experiment, for a 1.5 mm radius drop falling from rest through a cloud are shown in Graph 7.02, page 89 , as a function of cloud droplet radius.

x

Box of Cloud Generator II x

Constant
Level
Water Tank

x

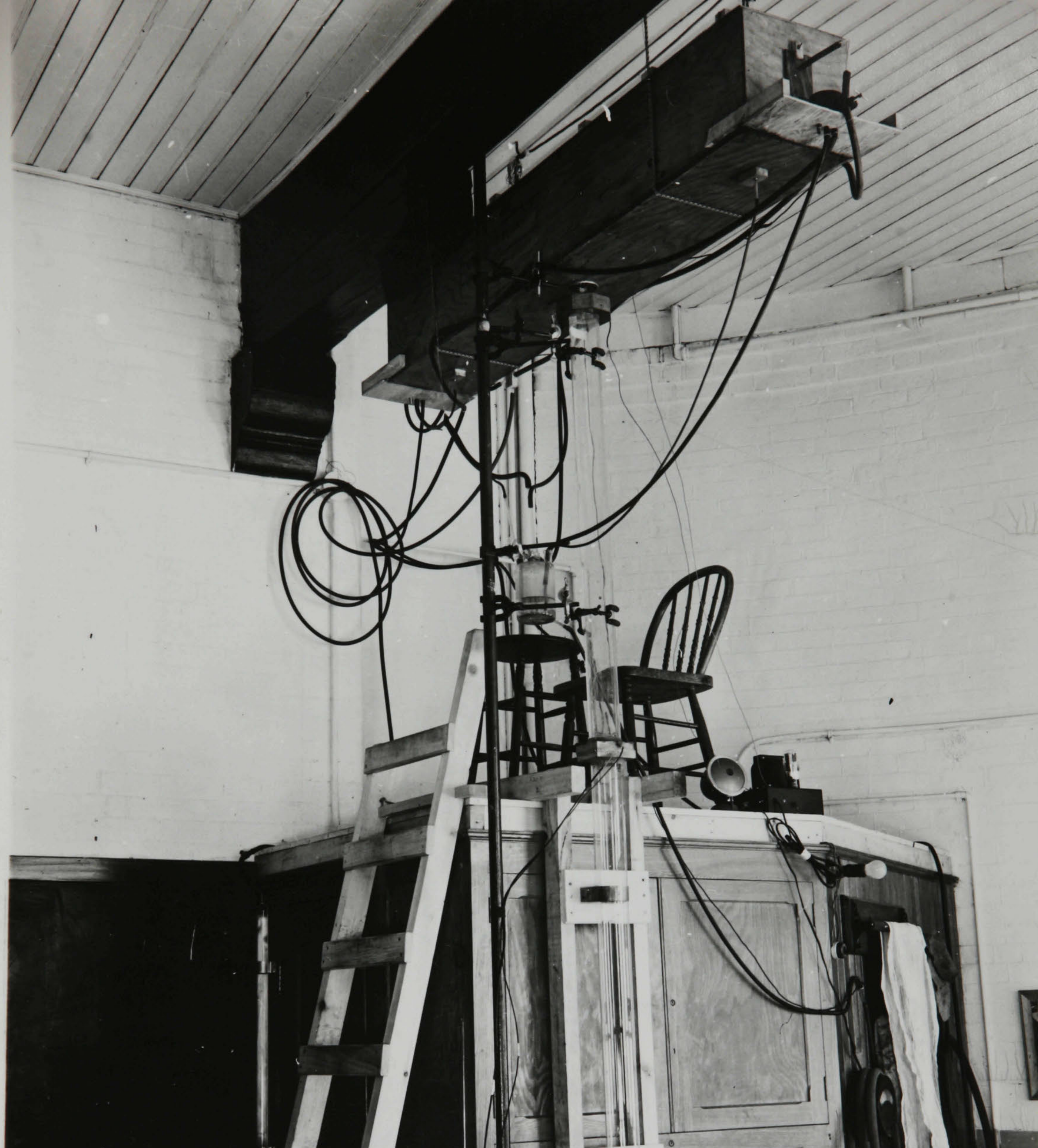
Cloud
Column

Cloud Temperature
Thermocouple Junction x

Platform x

x

Plate 3.01 - Upper Half of Apparatus



x Air Filter

x Flow manometer

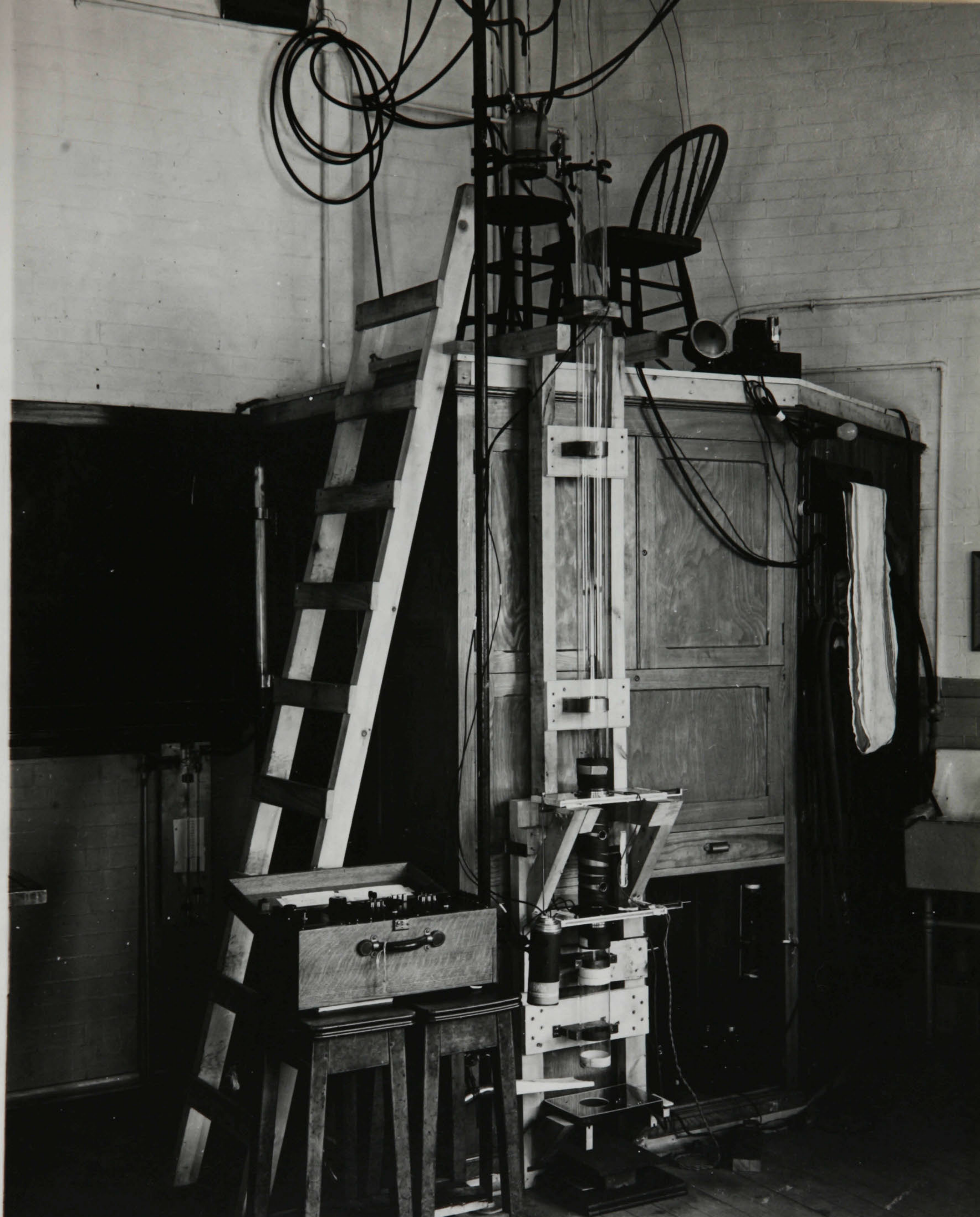
x Liquid Water
Content Meter

precision
Potentiometer x

x
Reference Junction Bath

Cloud-deflecting x
air current

Plate 3.02 - Lower Half of Apparatus



3.03 The Cloud Column

The chamber through which the drops fell was constructed of sections of glass tubing of inner diameter 8.0 cm, making a column about 3.5 m high. The column was fixed rigidly to the side of a tall cupboard, on top of which was a platform. From this platform the top of the cloud column was readily accessible. In the lower third of the column, a removable section was provided, in place of which the instrument to measure the liquid water content of the cloud could be put.

The cloud was introduced continuously at the top of the column and fell to the bottom. A few centimetres below the open bottom end of the column, the cloud was deflected by a moderate cross current, blown by a cylinder-type vacuum cleaner.

3.04 The Release and Capture of the Drops

Drops were introduced at the top of the column and caught in a cup situated just below the deflected cloud at the bottom. The dropper and receiving cup were weighed together before and after the transit of approximately 500 drops through the cloud column.

The increase in mass of the collected drops was thus a small difference between two large weighed quantities. Hence, it was necessary for the dropper and the catching device which were weighed together, to be as light as possible, (much less than 200 gm). In addition, they had to form a compact unit when together in order to fit conveniently on the scale pan of a balance. Accordingly a dropper was made, of aluminum, to the orifice of which hypodermic needles could be press fitted. (Fig.3.01, page 31). The dropper was equipped with a central plunger which controlled within narrow limits the rate of formation of drops about a mean value of 2 per second. The effective head of water, differences in which might affect the drop size, was rendered constant by a vertical tube connecting with the outside.

Hypodermic needles were carefully cut off and honed perpendicular to their axes, to ensure the smooth and spin-free detachment of the drops from the tip of the needle. It was found that needles of widely different bores produced drops only a little smaller or greater than 1.5 mm radius, but the rates of drop formation were different, small bore needles giving only about 1 drop per second. So a needle was chosen from which drops fell at the rate of about 2 per second. This needle was used throughout the experiment and gave drops of 1.59 mm radius. Their size was determined by measuring the mass of the dropper before and after the ejection of 50 drops. This was done on several different occasions and the mass of 50 drops was found to be constant to within 0.5%.

So that the drops might be formed and released in undisturbed air, and to prevent cloud from reaching the dropper, a cylindrical glass shield some 30 cm long and 3 cm diameter surrounded the needle when the dropper was

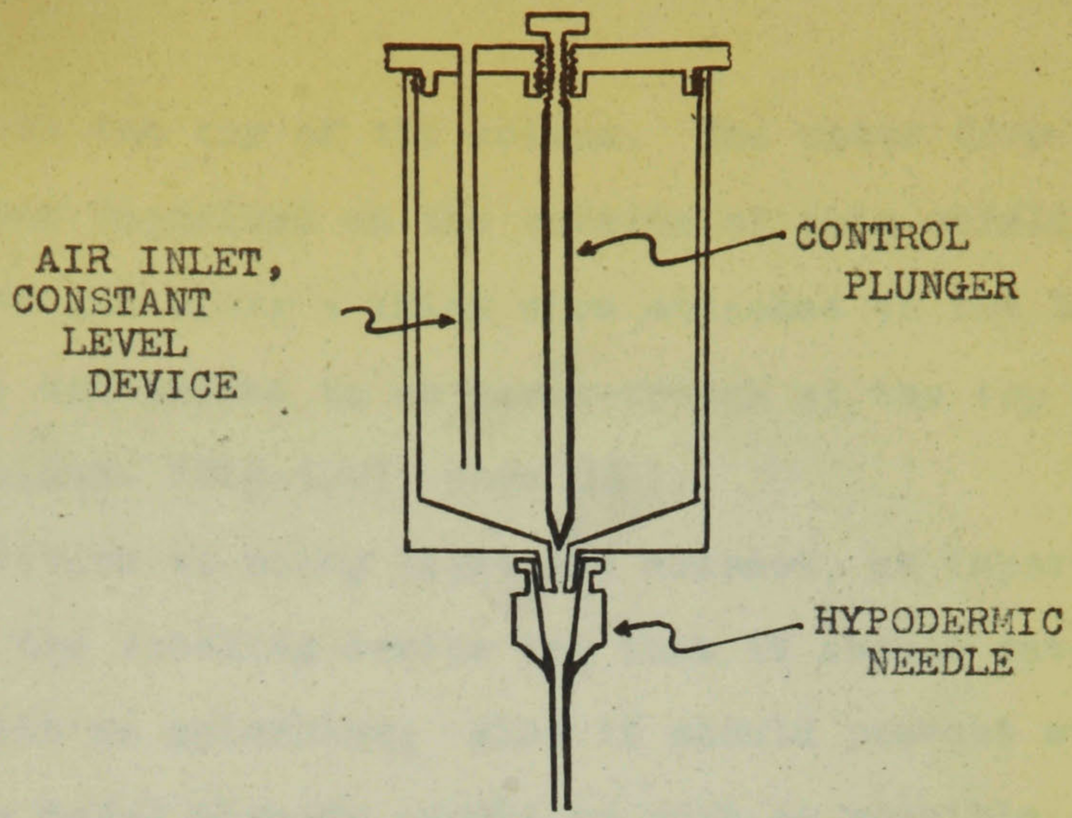


Fig 3.01 - Cross-section of Dropper and Needle
(Actual Size)

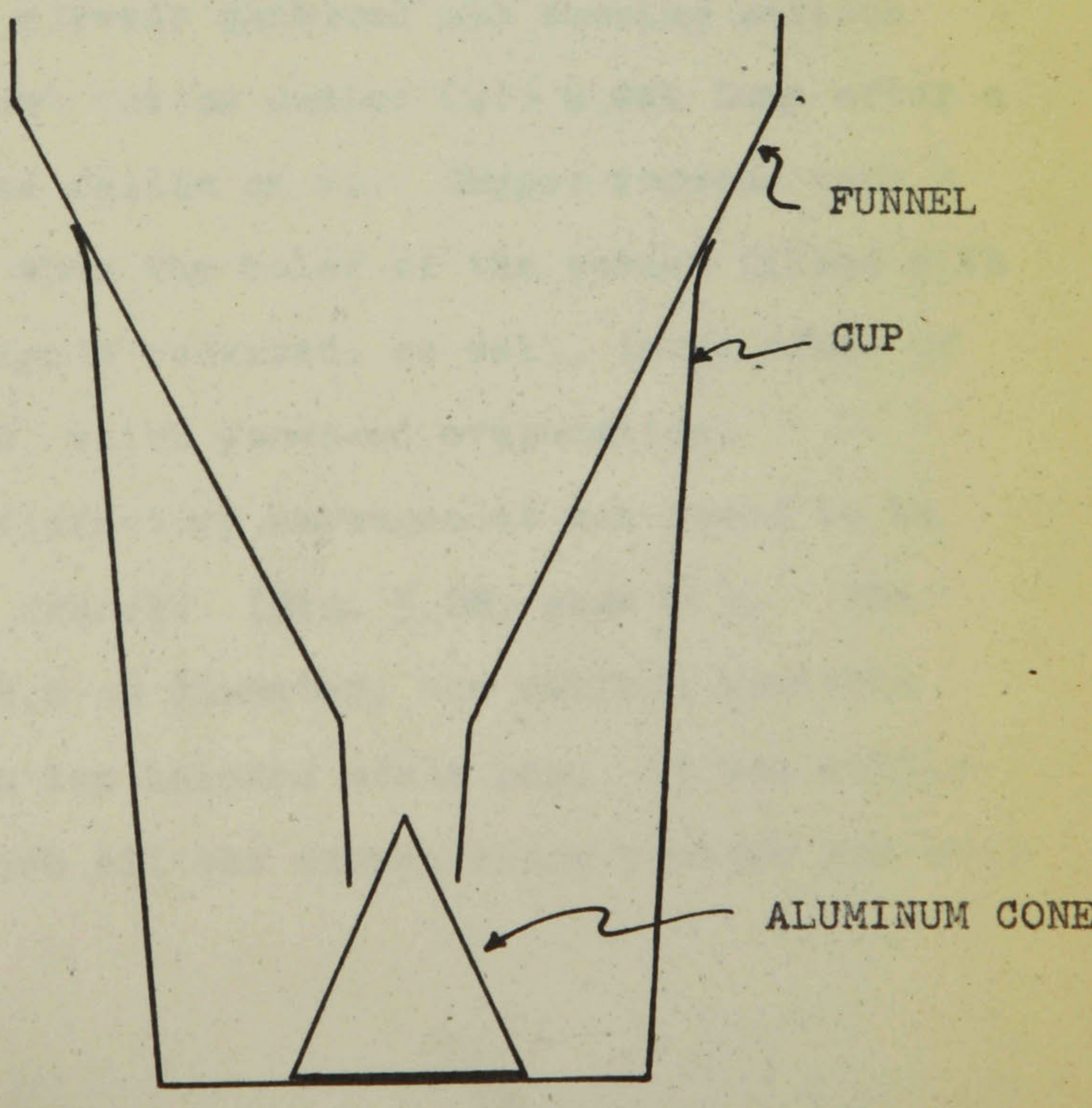


Fig. 3.02 - Cross-section of Cup, Funnel and Cone
(Actual Size)

in position at the top of the column. The water from cloud droplets which deposited on the outside of this shielding tube ran down and along a thick wire attached to the bottom of the tube, and thence to an eaves-trough at the top of the cloud column. (Fig.3.03, page 33).

In addition to being light and compact, an important property of the catching device was that it should catch the drops with no splashing; also it should prevent evaporation of the water already caught as much as possible. Considerable time was spent in trials with various shock absorbers placed in a cup. Glass wool proved unsatisfactory, 100 drops or so being sufficient to clear a hole in the wool, into which subsequent drops could fall unimpeded, hitting the water already gathered and causing serious splashes. Absorbent cotton matted into a wet lump after a number of drops had fallen on it. Copper screens were a little better but when the holes of the screen filled with water, splashing again occurred; as well, large areas of water were exposed, which enhanced evaporation.

The most satisfactory arrangement was found to be a plastic cup and funnel. (Fig. 3.02, page 31). The funnel mouth was 8.0 cm diameter, the maximum possible which would fit on the balance scale pan. It was sufficiently wide to catch all the drops, whose scatter was over

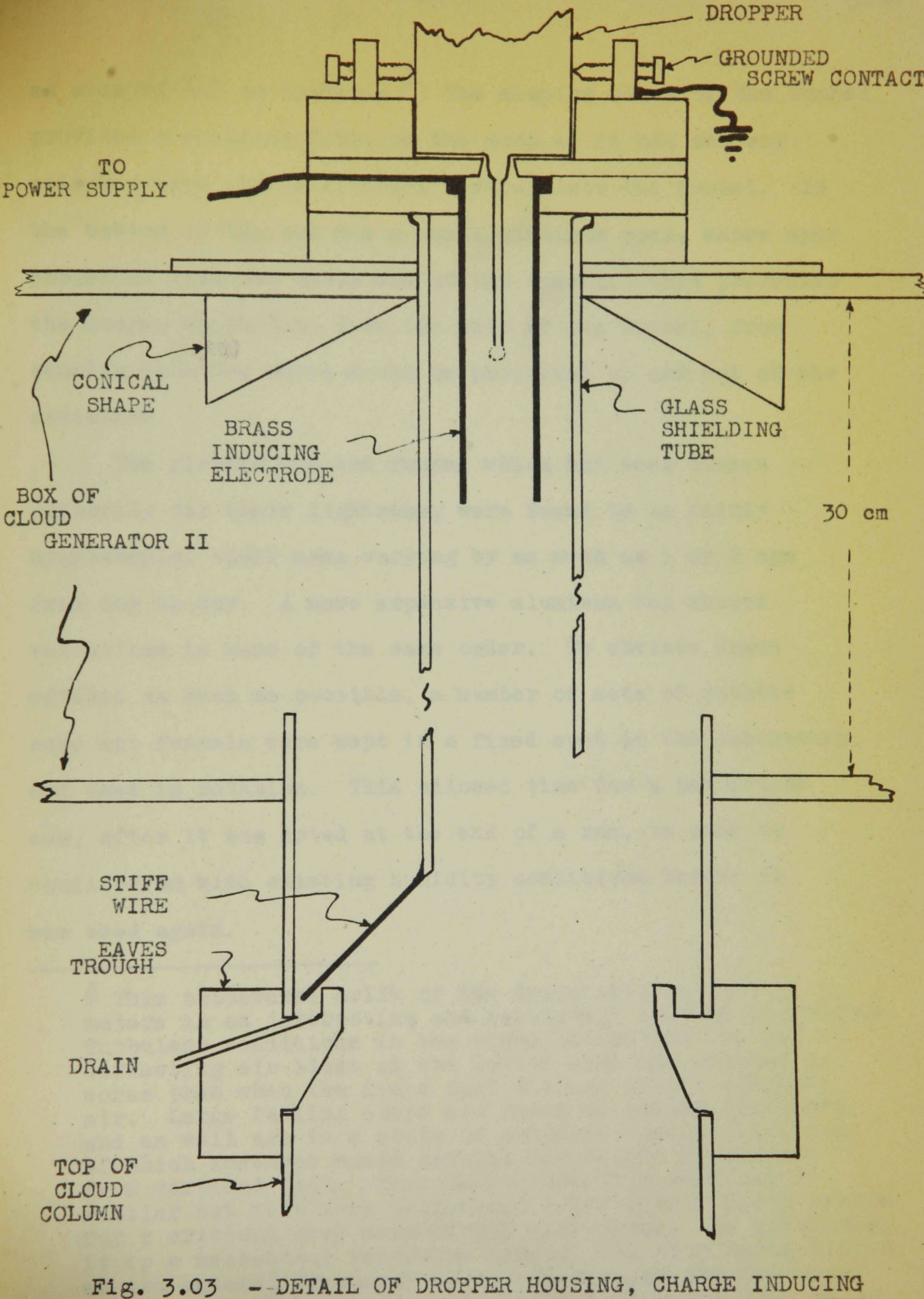


Fig. 3.03 - DETAIL OF DROPPER HOUSING, CHARGE INDUCING ELECTRODE, AND SHIELDING TUBE AS USED WITH CLOUD GENERATOR II

an area of 4-5 cm diameter.# The sloping sides of the funnel provided a shearing force on the drop as it hit and any splashes were always directed further into the funnel. In the bottom of the cup was a small aluminum cone, whose apex projected into the small end of the funnel. This prevented the drops, which fell down the axis of the funnel, from causing splashes which would be projected up and out of the container.

The plastic cup and funnel which had been chosen primarily for their lightness, were found to be fairly hygroscopic, their mass varying by as much as 1 or 2 mgm from day to day. A more expensive aluminum cup showed variations in mass of the same order. To obviate these effects as much as possible, a number of sets of plastic cups and funnels were kept in a fixed spot in the laboratory, and used in rotation. This allowed time for a particular cup, after it was dried at the end of a run, to come to equilibrium with existing humidity conditions before it was used again.

This transverse drift of the drops after a fall of 3 meters is an interesting and relatively unknown phenomenon. Turbulent conditions in the cloud column and the cloud-deflecting air blast at the bottom make the scatter no worse than when the drops fall through nearly stagnant air. Large falling drops are known to become flattened and as well are in a state of constant oscillation, both of which features could account for slight departures from vertical fall. Ross Gunn (1949, (1)) analyses a similar but much more pronounced drift effect which occurs for a critical drop mass of 500 micrograms. He attributes it to a mechanical resonance effect, the drop being driven at its natural frequency of oscillation, by the frequency of eddy detachments adjacent to the drop. Our drop being well out of the size range where this effect is active, the observed drift occurring in this experiment must be attributed to the non-spherical shape of our 3 mm diameter drop.

In order to weigh the dropper and receiver together, a lid in the form of an annular ring was made, of Lucite. This fitted tightly in the top of the funnel. The aluminum dropper fitted in the centre hole and was suspended on the ring so that its top was flush with the top of the cup. In this way the whole assembly was stable as it rested on the scale pan. The joints between the separate items of this assembly were all tight enough to keep evaporation losses to less than 1 mgm during transport of the cup to and from the balance. The whole assembly is shown on the balance in Plate 3.03, and taken apart in Plate 3.04, on the following pages.

3.05 Counting the Drops

The large number of drops and their fairly rapid rate of formation made necessary some sort of counting device. This device, of course, could not disturb the drops, the dropper or the catching cup. Photo-electric methods were not thought feasible due to the drift of the drops, and the presence of varying amounts of stray water on the inside walls of the glass column.

A counter, which proved to be well suited to the requirements of the experiment, was built. Its essential feature was a standard gramophone crystal "pick-up" complete with needle, which was mounted so that a small hole in the edge of the funnel could be placed just touching the needle.

Plate 3.03 - Dropper and Cup in Position on the Scale Pan of the Balance


GRAM-ATIC BALANCE
137.8

x Plastic Cup

Plastic Funnel x

Aluminum Cone

x
Aluminum dropper
and Hypodermic
Needle

x

x
Top of
Dropper

x
Annular Lid

Plate 3.04 - The Cup Assembly, Dismantled.

The impulse caused by a drop striking the funnel and activating the crystal was fed to a two-stage amplifier which in turn drove a mechanical counter via a relay, and a loudspeaker. The loudspeaker volume, and the bias of the gas tube which operated the relay could be independently controlled. The loudspeaker proved to be a useful conjunct to the counter, supplying the necessary evidence when the occasional drop struck the cup but did not trigger the counter.

Acoustic feedback occurred with the apparatus at first, which was successfully eliminated by the insertion of a low value coupling condenser in the audio output stage of the amplifier. This suppressed the low frequencies which had apparently been causing the feedback.

The gramophone crystal was mounted on the underside of a sheet of Lucite, beside a hole of 8.0 cm diameter in the sheet concentric with the cloud column. (Plate 3.05, page 39). The Lucite protected the crystal from wetting by the cloud which was deflected just over it, and, being transparent, made the fitting of the funnel to the needle easy. It was found necessary to mount the catching cup and the Lucite sheet holding the crystal on sponge rubber pads to prevent outside disturbances from triggering the counter.

3.06 Weighing the Drops

Preliminary tests indicated that the conventional type laboratory balance was hardly suitable in view of the many x Cloud Column

x
Amplifier and
Power Supply

x
Cloud-deflecting
Air Current

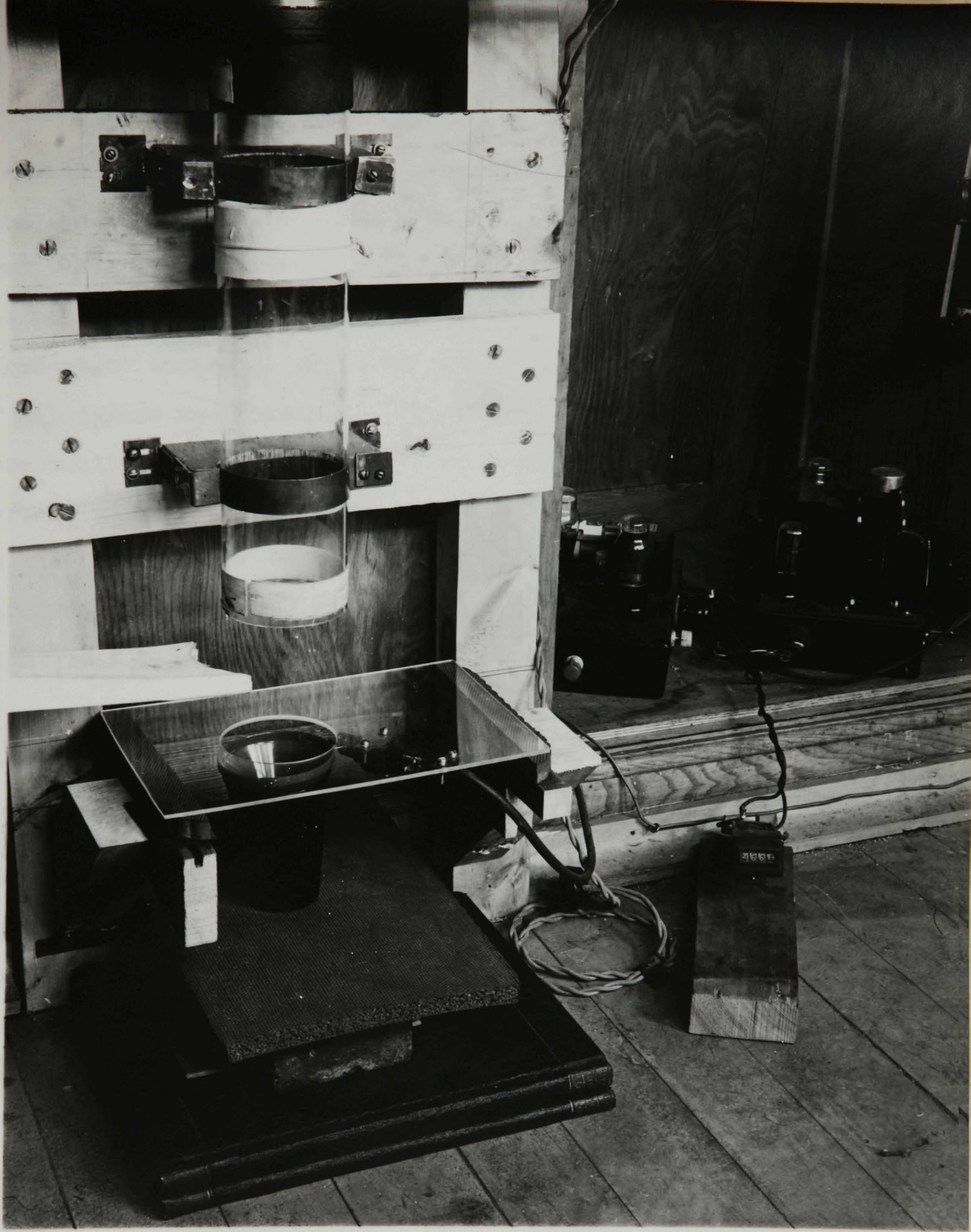
x Lucite sheet

x Crystal "pick-up"
and gramophone needle

x Cup and Funnel

x
Counter

Plate 3.05 - Detail of Bottom of Cloud Column



weighings which had to be performed. Speed and ease of weighing were essential in dealing with the small masses involved. These conditions were well satisfied when the laboratory acquired a constant-load directing-reading "Gram-atic" balance. Rapid and accurate weighing to tenths of milligrams was possible. The decigram and heavier weights were built-in and controlled by external knobs. The last three figures of a result were read on a projected scale on the front of the balance. A convenient feature was the zero adjust system, which affected only the path of the light beam projecting this scale.

3.07 Charging the Drops

To investigate the effect on the coalescence of rain-drops and cloud droplets, due to charge on the raindrop, a mechanism was incorporated in the apparatus to give the drops an electrical charge of known sign and magnitude as they left the dropper. The method was based on one used by Ross Gunn (1949 (2)). Concentric with and just inside the cylindrical glass shield surrounding the dropper needle was a brass cylinder of 1.5 cm outer diameter and 6.0 cm long. The dropper was insulated from this brass cylinder by a Lucite plate, and it could be grounded by a screw clamp which made contact with its outside wall. (Fig. 3.03, page 33).

The potential of the brass cylinder could be made positive or negative with respect to the grounded aluminum dropper with a power supply connected through a reversing switch. Ross Gunn (vide supra) found the following relation to hold for this arrangement:

$$Q = k\, r_0 (V + \varphi)$$

where V is the potential difference between the inducing electrode and the dropper, in esu,

r_0 is the radius of the drop, in cm,

φ is the contact potential, in esu,

Q is the charge on each drop, in esu,

k is a constant of proportionality.

He found the contact potential between the brass cylinder and the water to be of the order of 0.25 volts and in such a direction as to put a small negative charge on the drop if no inducing voltage was applied. Since our inducing potential was 360 volts, this correction is entirely negligible. With calibrating apparatus at his disposal, he determined k to be 1.03. If we assume $k = 1$, a good first approximation to the charge induced will be given by

$$Q = r_0 V \quad \text{with units as above.}$$

For our drop of $r_0 = 1.59 \times 10^{-1}$ cm, and with $V = 360$ volts, the charge carried away by the drop would be ± 0.191 esu, or ± 11.3 esu/gm # of water dropped.

Of the order of the maximum charge observed on raindrops in thunderstorms. (Ross Gunn, 1947).

A rough test to determine the effectiveness of this charging mechanism was made. An aluminum cup was connected to a laboratory type gold-leaf electroscope and 100 drops allowed to fall in the cup. Equal deflections of the leaf were observed for potentials of each sign on the inducing electrode, the charge on the drops being of opposite sign to that of the inducing electrode.

CHAPTER 4

THE PRODUCTION OF CLOUDS

4.01 Introduction

For the purposes of this experiment a continuous supply of a cloud composed of uniform and controllable droplet sizes would be ideal. It should have a rather high liquid water content - from 5 to 20 $gm.m^{-3}$. A homogeneous cloud would be desirable in order to determine the collection efficiency, E' for a given cloud droplet size. As well, experimentation with such a cloud is made easier since correlation among its properties - droplet size, number of droplets per unit volume, and liquid water content - is then relatively simple.

Unfortunately, the production of such a homogeneous water cloud is of a more complex nature than was at first realized. Inhomogeneous water clouds may be produced in a number of ways, and a review of these is presented in the next section. Considerable time was spent in experimenting with some of them, with a view to the eventual production of a homogeneous cloud. These experiments are discussed in subsequent sections of this chapter. The two cloud generators actually used in the experiment are described in Sections 4.03 and 4.07 respectively.

4.02 A Review of Methods of Cloud Production

Much work has been done on the production of aerosols (suspensions of solid or liquid particles in a gas) and clouds in the past ten years, due to the interest in screening smokes and the deposition of toxic liquids. The methods of generating a cloud fall into two categories, those produced by (1) Condensation Processes, and (2) Mechanical Dispersion Processes.

1) Condensation Processes. In this classification are those clouds which are formed by the condensation of vapour upon suitable nuclei, such as smoke and salt particles, positive and negative ions etc. An adiabatic expansion of warm saturated air is the process by which natural clouds are formed and is the method so fully developed in connection with Wilson cloud chambers. It enables excellent control of the droplet sizes through the control of the degree of expansion (and hence supersaturation) and the number and kind of condensation nuclei.

With expansion methods, the cloud is produced in a region whose walls must be at the temperature of the original saturated air. If the cloud is to be used at the lower temperature after expansion, it must be removed immediately from the production chamber to prevent evaporation of the droplets. The difficulty of doing this, coupled with the essentially discontinuous nature of the expansion process makes this method rather unsuitable for the research under discussion. However, methods of producing cloud for our purposes by adiabatic expansions, are discussed in Section 4.06.

As opposed to the volume cooling of a mass of air by an adiabatic expansion, cooling by mixing with a mass of colder air may produce a cloud. This is generally an inefficient process, part of the vapour being required always to saturate the colder air as it warms up. However, it has the advantage of possible continuous operation.

Sinclair and LaMer (1949) achieved considerable success in generating homogeneous aerosols of liquids <u>other than water</u> with a condensation method. A stream of dry and well-filtered air was saturated with the vapour of a liquid and mixed with another well-filtered air stream carrying condensation nuclei. These latter were produced by a high voltage spark, or by heating a coil which had been dipped in a salt solution. The mixture of nuclei and vapour laden air passed into a "reheater", whose temperature was about 300°C. This reheater thoroughly mixed and uniformly heated the nuclei and vapour. The mixture was then allowed to rise slowly out of a chimney 2 cm in diameter and 50 cm long, in which the vapour condensed uniformly on the condensation nuclei, a cloud of very uniform particle size being produced. To prevent coagulation destroying the uniformity of particle size, ten to one hundred-fold dilution with dry filtered air was necessary at this stage.

The particle size could be increased by increasing the initial temperature of the saturated air, by increasing its volume relative to the air containing the nuclei, or by decreasing the rate of production of the nuclei. The radius of the largest particle generated was 10 microns, and the liquid water contents of the clouds were one to ten grams per cubic metre.

Experiments with a method similar to this were undertaken by us and are described in Section 4.04.

2) Mechanical Dispersion Processes. These processes include atomization, centrifuging and explosive disruption of the liquid directly into the gas.

Explosive disruption can be dismissed at once as being unsuitable for this experiment.

An ingenious centrifuging method has been developed by Walton and Prewitt (1949) and improved by May (1949). In it, water is fed onto a small spinning disc, which is air driven. Droplets, which are centrifuged off the edge of the disc are found to be very uniform in size, their size being a simple function of the disc velocity and diameter. The rotor and stator of the apparatus are small precision pieces and the satisfactory behavior of the machine depends on its being mounted on rubber, with extremely flexible supply connections to it.

The droplets fall in an annular ring about the spinning disc, the radius of the projected ring, in inches, being equal to one-tenth of the droplet diameter, in microns. That is to say, droplets of 20 microns diameter or greater would reside in annular rings or radius 2 inches or greater. Droplets of this order of size, which are of interest to us, would thus have to be led away from the apparatus and fed into the cloud column. The maximum rate of water feed is 1 cm^3 per minute which could provide a liquid water content of the order desired for our experiment.

This apparatus on the whole seemed well suited to our needs, but since cloud generation was only one of the subsidiary projects to the main experiment, it was felt that the time necessary to construct the machine could not be afforded.

Pressure, or hydraulic nozzles will produce a cloud. These are the kind of nozzles used in domestic oil burners, in which liquid is ejected under pressure from various shaped orifices. The clouds contain large droplets, but have a very large range of droplet sizes. The most common type of these nozzles is made with a whirl chamber, which gives a spinning motion to the liquid as it leaves the orifice. The resulting thin sheet of liquid breaks up into a hollow spray.

Gas atomizing nozzles constitute the other well known way of atomizing liquids. A liquid is fed, generally under pressure into a high velocity air stream where it is shattered into droplets of many sizes. Of this type is the common

atomizer in which air, escaping from a small horizontal jet passes over the openings of a vertical tube in which the liquid resides. The reduction in pressure above the vertical tube due to the high speed air stream results in liquid being forced up the tube and consequently shattered. The resulting cloud has a large range of droplet sizes, though not so great as with hydraulic nozzles.

A method of successive filtering of the output of atomizing nozzles, has come to our attention since the conclusion of the experiment.# In it, particles of the cloud are accelerated to a constant velocity by passing the cloud at a known rate through jets of pre-determined cross-sectional area. The differences in momenta of the various-sized droplets result in their separation. This is brought about by arranging to have all droplets of radius r or greater, impact on a target directly in front of the jet, while the others having less momentum execute a 90° turn with the air. Successive passage through systems of jets of pre-determined cross-section apparently will produce a cloud having 90% of its liquid mass in droplets, whose radii lie within a range of 1 or 2 microns. It is not known how great a liquid water content can be tolerated in this process, but possibly with a number of jet systems, a suitably high value of this variable could be reached.

It is well known that in devices where water is broken

#This method, described by Puck, in a U.S.Government report, is to be published in the Journal of Physical and Colloid Chemistry.

by large shearing forces, the droplets which are produced carry an electric charge. (Chapman, 1934, for instance). This is considered to be a major disadvantage of this method of cloud production for our particular experiment, its effect upon coalescence being unknown.

Clouds generated by two of the mechanisms outlined above were eventually used; both clouds were heterogeneous. (1) A cloud was produced by the mixing of steam and relatively cool room air, and (2) a cloud was produced by simple atomizers. The first method resulted in a cloud of mostly small droplets for which Langmuir's theoretical collision efficiencies would be low. Consequently, attempts were made to produce larger droplets by this method, which proved fruitless. (Section 4.04). A resort to atomizers was made as being the most expedient method of generating continuously a cloud of large enough droplets.

4.03 Cloud Generator I

The first cloud was produced by mixing steam with room air, and cooling the mixture to room temperature. (This will be referred to in future as Cloud I). Water was boiled in a 2-litre flask at a gauge pressure of 2 cm of mercury. The steam escaped from an orifice of 2 mm diameter, into a glass tube of 1.6 cm diameter. The reduction of pressure in the vicinity of this jet of escaping steam brought air at room temperature into the system through an opening in the glass tube at this point. (Fig. 4.01, next page). Here, air and steam mixed and supersaturation occurred with some of the excess vapour condensing on nuclei present in the air. The mixture of droplets and saturated air passed up through two water-cooled condensers, each 1 metre long, and emerged at the top where it was very nearly at room temperature. Vapour which condensed on the cold inner walls of the condenser ran back and was collected at the bottom. The emergent cloud was introduced into the top of the cloud column with rubber tubing which was connected to a small opening beside the hole in which the dropper resided.

The cloud fell down the column and a current of air blown horizontally was sufficient to deflect it from the cup below. The generation of cloud at a constant rate ensured that the cloud properties within the column would remain steady. A film of condensate which formed on the inner walls of the column indicated that the air carrying the cloud particles was saturated.

A sample of the cloud droplets was collected on a specially coated slide (Section 5.03) and examined under a microscope. They were found to be mostly very small (less than 5 microns in radius), with the occasional droplet of radius greater than 10 microns. The cloud was thus not homogeneous. Measurements of w with an evaporation method (described in thesis H) showed it to be of the order of 20 $gm.m^{-3}$.

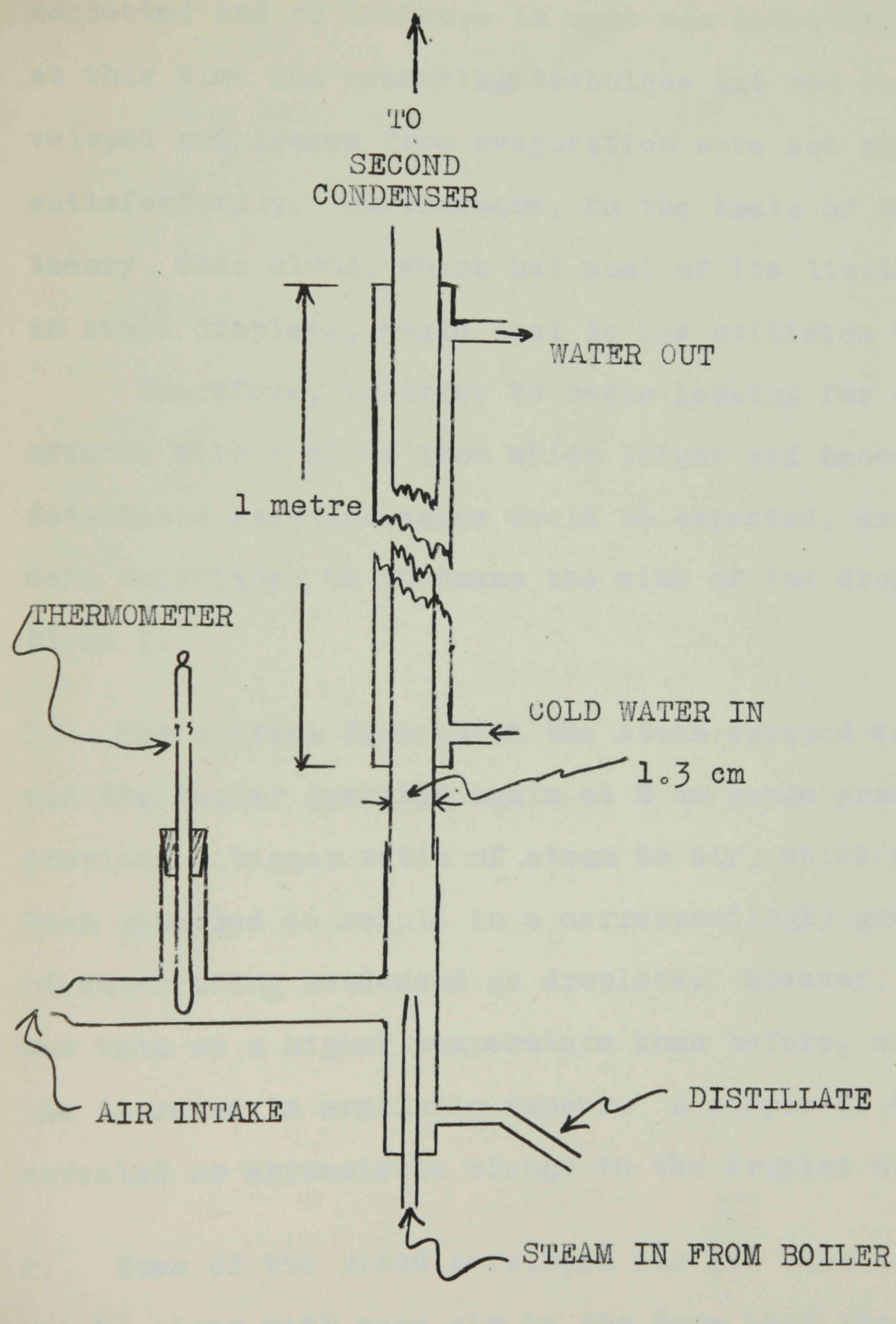


FIGURE 4.01 - Cloud Generator I

4.04 Attempts to Produce Larger Droplets in Cloud I

Trial dropping runs with this condensation cloud were conducted and no increase in mass was detectable. However, at this time the measuring technique had not been fully developed and losses from evaporation were not compensated for satisfactorily. Furthermore, on the basis of Langmuir's theory, this cloud, which had most of its liquid water content in small droplets, would lead to low collision efficiencies.

Therefore, in order to begin looking for coalescence effects with a cloud from which larger and hence more readily detectable mass increases would be expected, experiments were undertaken to increase the size of the droplets in Cloud I.

1. The orifice from which the steam escaped was made larger, and the boiler operated again at 2 cm gauge pressure. This provided a bigger ratio of steam to air, which might have been expected to result in a correspondingly greater amount of water being condensed as droplets. However, the mixture was then at a higher temperature than before, which offset the increase in available vapour. A sample of the droplets revealed no appreciable change in the droplet sizes.

2. Some of the cloud developed was fed back into the air intake along with room air in the hope that the vapour would condense on the droplets rather than on the condensation nuclei. The saturation vapour pressure at a given temperature

over a tiny droplet, (or hygroscopic nucleus) is less than that over a large droplet. Therefore, saturation conditions for the small droplet are supersaturation conditions for the larger. Hence, one could expect growth of the larger droplets rather than the formation of new ones. Again, no change was noticed in the size distribution picture. The failure of this feedback method points out a weakness of the apparatus. The region in which the mixing took place was so small that the steam and air mixture passed up into the condenser in a fraction of a second, where the vapour available for droplet growth became lost on the walls as condensate. Thus the droplets were exposed to supersaturation conditions only momentarily.

About this time, the process of Sinclair and LaMer (loc. cit.) was published, and the adaption of their method to the production of water clouds was attempted.

Air from the laboratory pressure system was passed through a glass wool filter and into a bottle of water (at nearly 100°C), in which it bubbled from a tube punctured with fine holes. Air from a pump was similarly filtered and fed past a heated coil, which had been dipped in a salt solution. This provided a source of condensation nuclei. The nuclei-laden air passed into the top of the bottle of hot water and there mixed with the saturated air. The mixture passed out of this bottle and through a condenser with steam circulating around it. This served as the mixer and reheater of Sinclair and LaMer's apparatus. Beyond this, the mixture flowed down through a water-cooled tube of 2 cm diameter, in which it was gradually cooled. The resulting cloud was composed of small droplets of the order of those obtained with the previous apparatus, and it was not homogeneous.

It was soon realized that this method was not adaptable to water-cloud generation. It depends on the surface cooling of the reheated saturated air-nuclei mixture. This can never lead to a cloud of any considerable water content, since the greater part of the vapour will always condense on the walls rather than on the nuclei.

An interesting feature of this experiment was that on closing off the air supplying the nuclei, the cloud still formed. An additional filter of several sheets of Whatman # 42 filter paper (for the finest precipitates) was placed in series with the glass wool filter in the saturated air supply. Even then, a cloud of small droplets started to form about half way down the cooling condenser. Since it is not likely that 5-fold supersaturation, which is necessary to produce condensation in the absence of nuclei, existed with cold walls in the vicinity, we must conclude that the filters used were not sufficiently sensitive.

At this time, it was decided to leave Cloud I as it was first produced, and use it as a cloud from which a low collection efficiency might be expected, and to try other methods of producing a cloud of larger droplets.

In the following section, analysis of the system of Cloud Generator I is given before describing the other methods. (Sections 4.06 and 4.07).

4.05 An Analysis of Cloud Production by Mixing two Masses of Air.

In this section we shall analyse the mixing process that took place in Cloud Generator I, offer some criticisms of it, and suggest a more suitable apparatus to produce cloud by mixing two masses of air.

In Cloud Generator I, room air at 20°C was mixed with vapour at 100°C and the mixture surface cooled in the condensers to 20°C, at which temperature it was fed to the cloud column. The variables which were measured at the time were the following:

- Rate of flow of final cloud: 500 $cm^3.sec^{-1}$ OR 1 m^3.2000 sec^{-1}
- Rate of efflux of vapour from boiler: 220 $mgm.sec^{-1}$ OR 440 gm.2000 sec^{-1}
- Liquid water content of final cloud: 20 $gm.m^{-3}$
- Relative humidity of input air: 25%

(These have been referred to unit volume of 1 m^3, or unit time of 2000 sec for convenience in the following consideration.)

From these values, the magnitudes of the other variables entering into the mixing process have been calculated. The following diagram shows the relative masses of the constituents involved, referred to 1 m^3 or 2000 sec:-

1) PRIOR TO MIXING		and	2) AFTER MIXING AND SURFACE COOLING	
Dry air at 20°C:	1178 gm		Dry air at 20°C :	1178 gm
Vapour at 20°C : (25% of 17.3 gm)	4.3 gm	2.9% →	Vapour at 20°C :	17.3 gm
Vapour at 100°C:	440 gm	4.6% →	Liquid droplets :	20 gm
		92.5% →	Surface condensate:	407 gm

DIAGRAM I

Note: 1) Measured values underlined.
2) The decrease in volume of the dry air of 1.6%, as it is brought to saturation during the process, has been neglected.

It is seen that out of 440 gm of vapour, 2.9% went to saturate the air, only 4.6 % appeared as droplets and 92.5% was lost on the surface of the cooling tubes.

One may well ask:

1) Why was the liquid water content of the final cloud so very small, only 20 $gm.m^{-3}$? With the aid of a saturation vapour pressure/temperature curve, one can find the equilibrium temperature of two masses of air after mixing. (Brunt, 1941). For the masses in Diagram I, the equilibrium temperature is found to be approximately 64°C, from which one calculates that the supersaturation occurring should have given a w of over 200 $gm.m^{-3}$ at this stage.

The following are probably reasons why the w obtained was only 10% of this:

a) The region in which the mixing took place was too narrow, (Fig. 4.01, page 51) and it is most probable that the mixture had already passed up into the cooling tubes before it had come to thermal equilibrium. Droplet growth which would begin at the initial mixing of air and vapour, would be arrested prematurely, due to the mixture passing too quickly into a region bounded by water-cooled walls. Therefore, vapour which might have condensed on droplets, condensed instead on the cold walls.

b) Some of the droplets, which were formed at the initial mixing, probably hit the walls as they passed up the 2 metre-long cooling tubes, and hence did not appear in the final cloud. The flow was fairly turbulent in these tubes, particularly at the join of the two condensers. This would lead to droplets colliding with the wall and running back as distillate. Thus, some fraction of the 92.5% of vapour, shown in Diagram I as having been lost as condensate, was probably lost by collision.

2) Why were predominantly small droplets produced by this generator?

This could be due to the following:

a) The mixing time was so short, as mentioned above, that droplet growth was arrested by condensation of the available vapour on the walls.

b) The droplets, most likely to be lost by collision with the walls are the large ones, since their greater momentum makes them more vulnerable if the air stream changes direction suddenly.

c) The presence of too many condensation nuclei in the air would lead to the production of many small droplets, rather than fewer large ones. Let us assume that the room air contained 150,000 nuclei per cm^3. (This is rather a high value, but often found in the air over large cities. (Gibbs, 1924)). If a droplet of 3 microns radius (10^{-10} gm mass) was formed on each nucleus, and no droplets were lost on the way to the cloud column, the cloud would have a w of 15 $gm.m^{-3}$.

About one half of the observed 20 $gm.m^{-3}$ was present in droplets of less than 3 microns radius. (Graph 7.03, Section 7.02). Therefore, more than 100,000 droplets per cm^3 must have been required for half the liquid water content alone. In addition, we have seen that it is probable that more droplets were produced than appeared in the final cloud. It would seem, therefore, that the presence of too many nuclei could have been responsible for the smallness of the droplets. Certainly there were too many nuclei to produce a 20 $gm.m^{-3}$ cloud, homogeneous in droplets of 5 microns radius, (5×10^{-10} gm mass), which would require only 40,000 droplets (nuclei) per cm^3.

From the experience gained with this system, and in the light of the above considerations, it would seem that the following features should be incorporated in an apparatus, with which a cloud of large droplets would be produced by mixing two masses of air.

1) Surface cooling should be eliminated. This would mean that the equilibrium temperature of the mixture should be room temperature. To accomplish this, colder air, and a larger air/ vapour mass ratio would be necessary.

2) The mixing region should be large enough for equilibrium to be reached and droplet growth completed, before the mixture touches a wall colder than itself.

3) The supply of nuclei in the air should be controllable.

Diagram II below, similar to Diagram I, shows the masses and temperatures of air and vapour which, upon mixing, would produce a cloud of 20 $gm.m^{-3}$ at the same rate of flow (500 $cm^3.sec^{-1}$) as in Cloud Generator I.

1) PRIOR TO MIXING		2) AFTER MIXING
Dry air at -21°C: 1178 gm		Dry air at 20°C: 1178 gm
Vapour at -21°C: 0.7 gm	45% →	Vapour at 20°C: 17.3 gm
Vapour at 100 °C: 36.6 gm	55% →	Liquid at 20°C: 20 gm

DIAGRAM II

Note: 1) Density of air at -21°C is 1400 $gm.m^{-3}$. Therefore Slightly less than 1 m^3 of air would be supplied for each m^3 of cloud.

2) Calculations of the initial temperature necessary to bring the final temperature to 20°C have been made assuming an average Latent Heat of 560 cal. gm^{-1}

during the mixing, and c_p (vapour) $\doteq$ 0.46, and c_p (dry air) $\doteq$ 0.22.

3) Only one tenth of the mass of vapour at 100°C used in Cloud Generator I would be required in this projected apparatus.

In practice, the apparatus in which the mixing would take place, must provide for intimate blending of the steam and cold air in a large space, bounded by walls at 20°C. (Fig. 4.02 on the following page suggests how this apparatus might look).

The successful operation would depend largely on the efficient mixing of the two fluid streams, and different nozzles would have to be tried. It is felt that homogeneous droplet production would be difficult with any mixing process, since the process is turbulent by nature, and random vapour pressure gradients would most likely exist. The cold air would have to be taken from a cooling unit in well-insulated pipes and the rates of flow of air and vapour adjusted to give the desired cloud.

4.06 Cloud Production by Adiabatic Cooling of Saturated Air.

An appraisal of cloud manufacture by means of adiabatic expansions was undertaken. If air is freed from large hygroscopic nuclei, (by preliminary expansions or by filtering) condensation will not take place until an expansion ratio

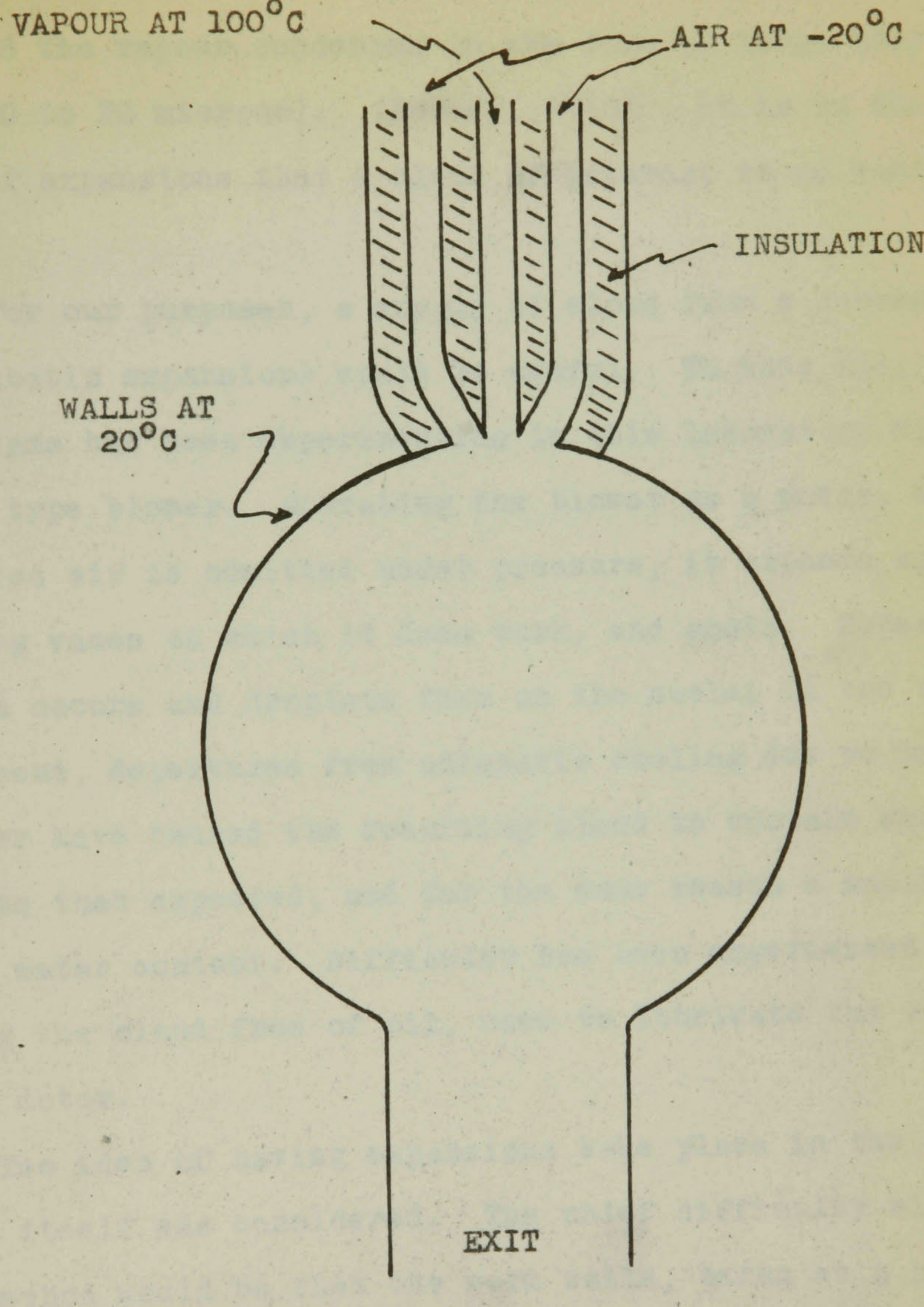


Fig. 4.02 - Projected Apparatus to Produce Cloud by Mixing Two Masses of Air

of 1.25 is reached. At this stage, condensation occurs on negative ions in the air. For expansion ratios between 1.25 and 1.38 the vapour condenses in the form of large droplets (r = 200 to 20 microns). (Dorsey, 1940). It is in this range of expansions that a cloud of interest to us would appear.

For our purposes, a supply of cloud from a succession of adiabatic expansions would be useful. To this end, Mr. G.N. Adams has been experimenting in this laboratory with a vane type blower. Operating the blower as a motor, warm saturated air is admitted under pressure, it expands against receding vanes on which it does work, and cools. Supersaturation occurs and droplets form on the nuclei in the air. At present, departures from adiabatic cooling due to heat transfer have caused the resulting cloud to contain smaller droplets than expected, and for the same reason a smaller liquid water content. Difficulty has been experienced in keeping the cloud free of oil, used to lubricate the vanes of the motor.

The idea of having expansions take place in the cloud column itself was considered. The chief difficulty with this method would be that the warm walls, being at a higher temperature than the cloud after the expansion, would tend to evaporate the droplets almost immediately after they were formed.

One way of getting around this difficulty would be to produce a cloud in a separate chamber and remove it immediately to the cloud column. A cloud generator consisting of two small expansion chambers with circular metal bellows for walls was considered. The two chambers would operate alternately at the top of the column, and immediately after each expansion, the bottom of the chamber would be opened, the bellows collapsed and the cloud ejected.

It was thought impractical to spend time building a device such as this, since there were mechanical methods, promising earlier production of a cloud of large droplets.

4.07 Cloud Generator II

A simple atomizer consisting of two tubes, one for air and one for water, set at right angles to each other was found on first trial to result in a cloud of larger droplets.

A sample of the droplets was collected on a greased slide and examined with a microscope. It appeared that the largest mass of water was in droplets of radii greater than 10 microns.#

It was found later that this slide-sampling technique discriminated against small droplets, and hence did not give complete information about the droplet-size distribution. Using another method (Section 5.03) showed this atomizer cloud, though possessing a fair number of large droplets, to have still a large percentage of its total liquid mass in droplets less than 5 microns in radius.

This method of cloud generation was considered the most expedient to proceed with in view of the many difficulties encountered with the others. It produced a continuous supply of cloud, little equipment was required to run and maintain it, and it gave promise of having a suitable liquid water content.

Accordingly, a large box, 6 feet long and 1 foot in cross-section was constructed of plywood on a frame of 1" x 2" lumber. (Plate 3.01, page 27). This box housed two atomizers, one at each end and was sufficiently large to allow room for mixing of the two clouds at the centre.

An atomizer consisted of two stainless steel tubes, or needles, mounted at right angles on a metal plate. (Fig. 4.03, next page). The tubes fitted in slots on the side of the metal plate and were forced into these slots by a smaller plate screwed down to the other. The two steel tubes, once adjusted, were then kept rigidly fixed in position. The horizontal tube of each atomizer was connected into the laboratory air pressure system in series with an uncalibrated flow manometer and a glass wool filter. By means of the manometer, the flow was kept constant from day to day, its initial reading having been determined by trial. The vertical tube of each atomizer was connected by a short rubber tube to a constant level water tank, one for each atomizer, situated at each end and outside the box. These were supplied with tap water.

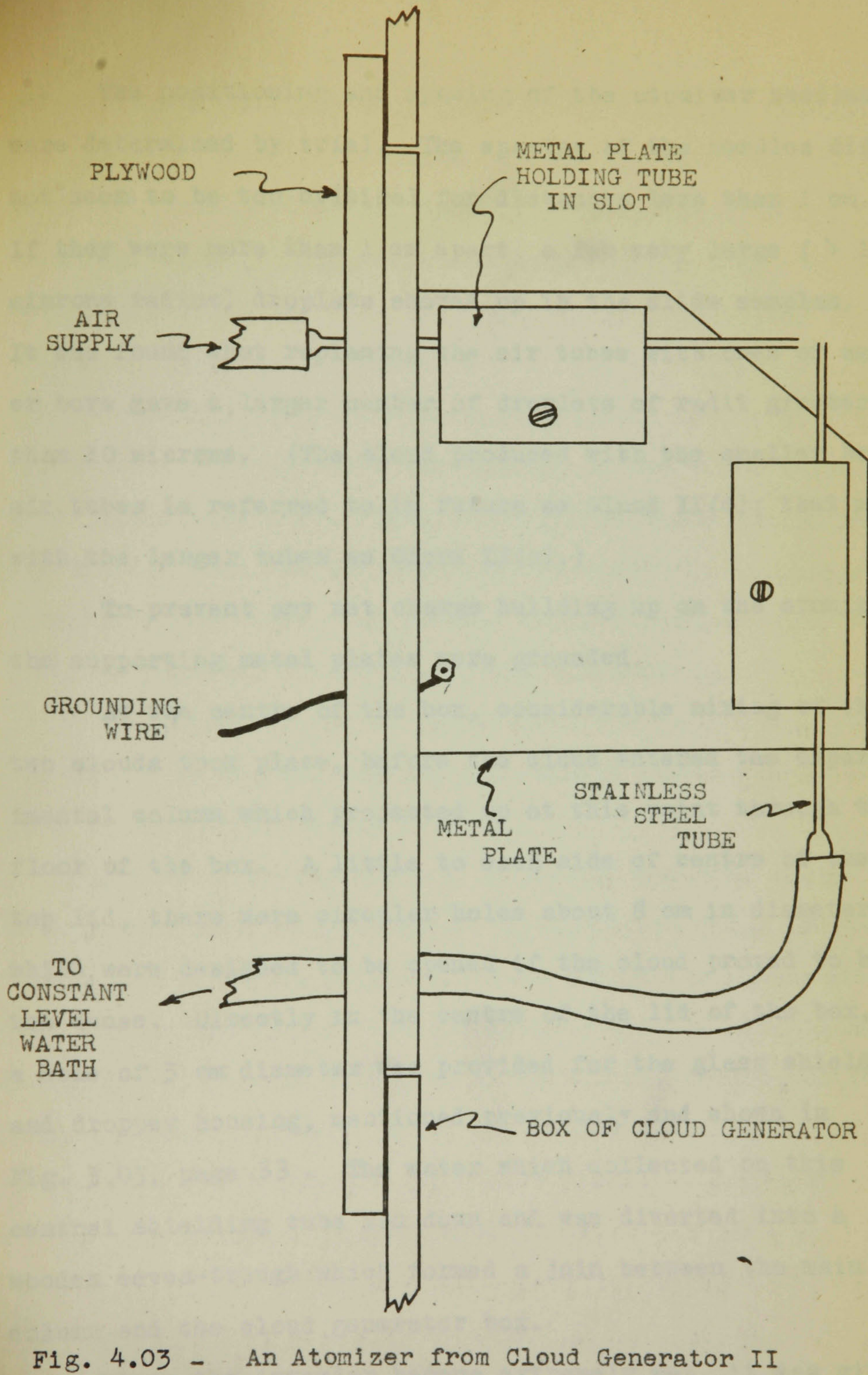


Fig. 4.03 - An Atomizer from Cloud Generator II

The positioning and spacing of the atomizer needles were determined by trial. The spacing of the needles did not seem to be too critical for distances less than 1 cm. If they were more than 1 cm apart, a few very large (> 100 microns radius) droplets showed up in the slide samples. It was found that replacing the air tubes with ones of smaller bore gave a larger number of droplets of radii greater than 10 microns. (The cloud produced with the smaller bore air tubes is referred to in future as Cloud II(d); that made with the larger tubes as Cloud II(c).)

To prevent any net charge building up on the atomizers, the supporting metal plates were grounded.

At the centre of the box, considerable mixing of the two clouds took place, before the cloud entered the experimental column which projected up at this point through the floor of the box. A little to each side of centre of the top lid, there were circular holes about 8 cm in diameter, which were designed to be opened if the cloud proved to be too dense. Directly in the centre of the lid of the box, a hole of 3 cm diameter was provided for the glass shield and dropper housing, mentioned previously and shown in Fig. 3.03, page 33. The water which collected on this central shielding tube ran down and was diverted into a wooden eaves-trough which formed a join between the main column and the cloud generator box.

Since the interior became extremely wet, it was given several coats of shellac, and all the joints were sealed with plastic cement. Suitable precautions were taken to drain off excess water and to divert stray water, which, dripping inside, might cause splashes to fall down the cloud column and into the cup. Three openings in the floor of the box drained the excess water from there, and it was found necessary to mount a conical shape on the under side of the lid, central above the opening of the cloud column. (Fig. 3.03, page 33). Stray water drops which accumulated there could then run down the sloping sides and drip harmlessly off the outer edge of this eave, the outer edge having been of a greater diameter than the cloud column.

The whole box was suspended from the ceiling of the laboratory on chains, leaving just enough room above it to insert the dropper in its housing.

The appearance of such a laboratory-produced cloud is perhaps worthy of note here. As the cloud fell down the column it was almost invisible, even though its water content was 10 to 20 times that of natural clouds. The illumination of the cloud with a thin light beam enabled one to study it visually and pick out any turbulent regions, but it was found from experience, that a visual estimate of its properties could be very misleading.

CHAPTER 5

MEASUREMENT OF CLOUD PROPERTIES

5.01 Introduction

From the relation

$$\Delta m = E' \pi r_o^2 w h n$$

it is evident that to measure accurately the collection efficiency E', of n drops of radius r_o falling a distance h through a cloud, we must know the liquid water content w of the cloud accurately. Presuming that r_o, h and n can be measured to any desired degree of accuracy, the accuracy of the observed value of E' will depend directly on the accuracy of measurement of w, and of Δm. In addition, the distribution of the cloud droplets with size must be accurately known in order to evaluate Langmuir's theoretical collision efficiency, E, for the cloud and hence to compare this collision efficiency with the observed collection efficiency, E'.

Methods by which these two properties, liquid water content and droplet-size distribution of a natural cloud can be determined, are critically reviewed in a paper by Houghton and Radford (1937). With a laboratory cloud, adaptations of general methods must be made to suit the particular experiment. The various methods applied with our two clouds are described in detail elsewhere (Thesis H.) The methods finally adopted to determine each of the properties for this experiment is reviewed briefly here.

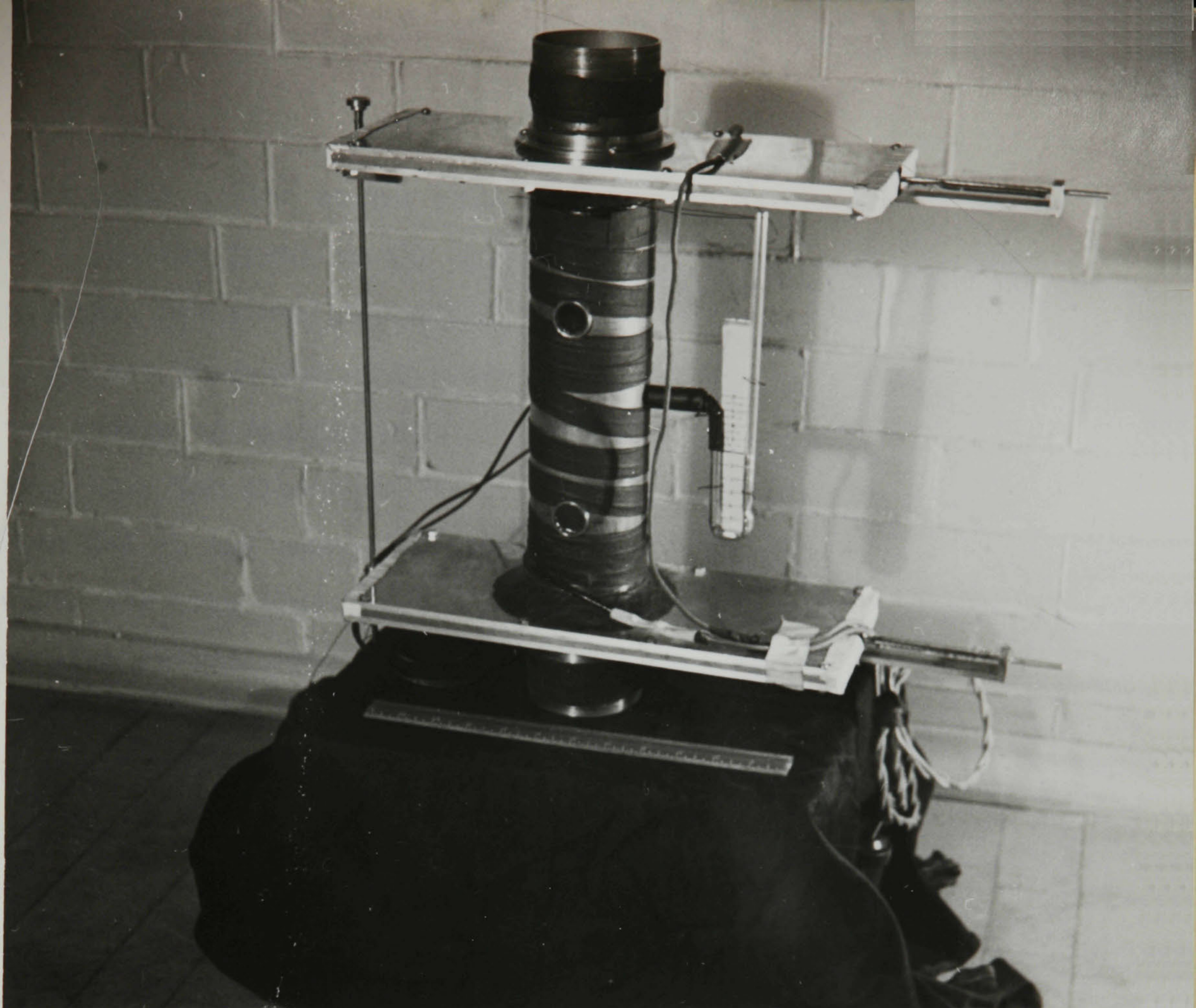
5.02 The Liquid Water Content, w.

This was determined with an instrument which measured the dew point of a sample of the cloud, when the droplets in the sample were evaporated into it. The difference between the vapour density at the dew point of the sample and the saturation vapour density at the initial temperature of the cloud gave the mass of water, which was originally in the form of liquid droplets.

The instrument has been named a Liquid Water Content Meter and will be referred to as the LWCM. A photograph of the LWCM removed from its position in the lower part of the column, is shown in Plate 5.01 on the following page, and it can be seen in position in Plate 3.02, page 28.

The LWCM consisted basically of a brass cylinder of the same diameter as the cloud column and about 30 cm long. It was equipped with two spring-loaded aluminum shutters which, when released simultaneously, slid across the column and closed off a 30 cm-long sample of cloud. This sample was then immediately sealed in by screwing up threaded brass sections of the same diameter as the cylinder, which forced the shutters against rubber seals. The captured sample of cloud was then heated electrically with a heating element, which was wound around the cylinder; as well, a hot air blast was directed at both shutters. Heat was supplied until the liquid droplets inside evaporated. The pressure of the heated mixture could be read on a mercury manometer connected

Plate 5.01 - The Liquid Water Content Meter



to a small outlet on the side of the cylindrical chamber.

On the front of the instrument were two small Lucite windows, one above the other. Through the bottom one, a light was projected onto a shiny copper disc, situated in the centre of the far side of the cylinder, and insulated from it. The disc was viewed through the top window. Embedded in the centre of the thin disc was a constantan wire, the disc thus forming one junction of a copper-constantan thermocouple. The other junction resided in a 'Thermos' bottle of cold water nearby. After heating the sample, cold air was blown on the back of the copper and one observer watched through the top window for the formation of dew. The dew point was determined with a potentiometer, operated by another observer. The initial temperature of the cloud was measured previously by an alternative thermocouple junction projecting into the cloud above the LWCM.

The saturation vapour density at the two temperatures was found from tables (Handbook of Chemistry and Physics, 1945). The difference between these vapour densities was the liquid water content of the cloud.

The whole measurement occupied two observers about twenty minutes. The method was found to be quite satisfactory, once the troubles, experienced with such initial models, were eliminated.

Checks on the reliability of the instrument were made on three occasions, by introducing a known mass of water.

Having determined the relative humidity of the air, and the volume of the interior of the instrument, the w to be expected from this mass of water was calculated. An average difference of 0.25 $gm.m^{-3}$ was found between the calculated and the observed liquid water content, the observed liquid water content having been lower.

5.03 The Distribution of the Cloud Droplets with Size

To determine the size distribution of the cloud droplets it was found necessary to use two lengthy procedures. The first was found to be unreliable for droplets less than about 10 microns in radius, so it was necessary to use a second method to obtain information about the mass of water present in droplets smaller than these.

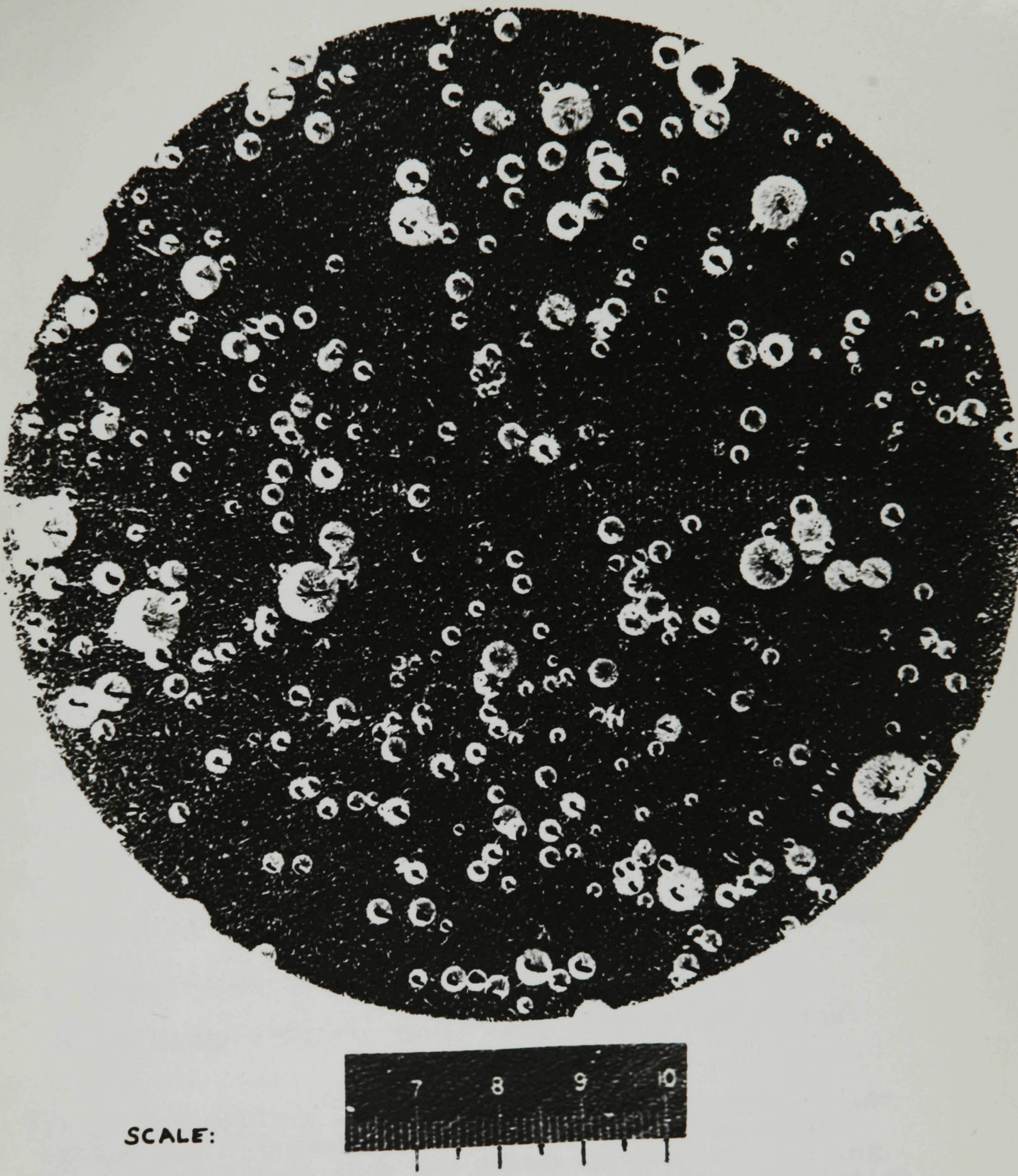
The first, which is a well-known method, (Houghton and Radford, 1938), was to allow droplets to collect on a specially coated glass slide. The slide was carefully cleaned and coated with vaseline, or a mixture of vaseline and mineral oil. It was then inserted into the bottom of the cloud column on a large cork of the same diameter as the column. At the same time, the top shutter of the LWCM, two feet higher up the column, was closed. The lower section of the cloud column then acted as a sedimentation chamber and the droplets settled onto the greased slide.

The slide was then examined with a microscope, fitted with a calibrated eyepiece scale. The distribution could be taken visually, or better from photographic records. These photographs were made by projecting light from a strong source through the microscope system. (A small displacement of the whole lens system with respect to the slide enabled a real image of the droplets to be formed outside the lens system, beyond the eyepiece). A totally reflecting prism placed on the eyepiece made the beam horizontal, and a mirror directed this horizontal beam down, so that a convenient enlarged image of the slide could be viewed beside the microscope, and photographic papers exposed there. Usually, ten such photographs were necessary to evaluate this part of the distribution. A typical photograph is shown in Plate 5.02 on the following page.

It was noticed that after a considerable time had been allowed for the droplets to settle on the slide, a number of small ones were still in the sedimentation chamber, and showed no signs of settling out. It was decided to wait two minutes, then close the second shutter of the LWCM and determine the liquid water content of these remaining droplets. The w of these was found to be a surprisingly large percentage of the total w of the cloud. This meant that for some reason, the smaller droplets, (found later to be 5 microns radius or less) did not settle out. No explanation has been found for this phenomenon,

Plate 5.02 - A Typical Photograph of Cloud Droplets Collected on a Greased Slide

(Note: This is a photostat copy. The mark on each droplet is the tick placed on it, at the time the distribution was analysed.)


7 8 9 10
SCALE:
1 UNIT = 17 μ
0 170 340 μ

unless it could be that droplets of this size never settle on a surface, but rebound after contact.#

Thus, in order to supplement the information from the slides which appeared to be unreliable for small droplets, it was necessary to use another method to evaluate their contribution to the w of the cloud. This method consisted in taking a series of readings with the LWCM, allowing successively greater times between the closing of the top and bottom shutters. Thus the contribution to w of successively smaller droplets was measured. These values of w were plotted against the time interval. Then, by interpreting the size of the droplets which would still remain in the LWCM after a given time (Thesis H), the mass of liquid associated with a given droplet size interval was found. For time intervals between the closing of the top and the bottom shutters of greater than $1\frac{1}{2}$ minutes, no change was observed in the w values. The subsequent analysis indicated that this was due to droplets of about 5 microns radius or less, remaining suspended in the sedimentation chamber.

Since large droplets would fall quickly out of the

#It is interesting to note that cloud droplet-size distributions obtained by various workers using slide techniques always show the number of droplets falling off below about 3 microns radius. The one distribution which has come to our attention (Findeisen, 1939) which showed a steady increase in the number of droplets below 5 microns, was obtained with a diffraction technique, in which settling of the droplets onto a surface played no part. This brings up the interesting conjecture that the much-used slide technique has given, all along, an untrue representation of the number of tiny droplets in a cloud or fog.

LWCM, this latter procedure was not reliable for large droplets. The slide sampling technique was not reliable for the smaller droplets. Therefore it was necessary to combine the two sets of information to obtain the complete distribution of droplets with size; (considered in detail in Thesis H). These are shown for each cloud used in the experiment in Graph 7.03, page 90 .

CHAPTER 6

THE EXPERIMENTAL PROCEDURE

6.01 Taking Measurements

Two participants were required in performing the experimental runs. We shall assume in this description that Cloud Generator II was in use; with the other, the box of C.G.II was lifted out of the way and an adapter placed directly on top of the column to house the dropper.

At the beginning of a day, the air supply was adjusted to its fixed value as read on the flow manometer, and the cloud-deflecting blower at the bottom of the column started up. Two fans kept the air in the laboratory circulating and abolished large temperature gradients. A period of half an hour was left to allow the cloud generating system to become steady. A droplet-size distribution, if taken previously, was presumed to hold for the same adjustment of the air flow, the same atomizer needle positions and the same temperature conditions in the room.

Two determinations of w were then made, two having been taken in order to be certain of the value of this quantity. Agreement to within 5% was usually found.

To obtain each value of Δm, two experimental runs were made, which have been named the Measuring Run, and the Test Run.

At the beginning of the Measuring Run, the dropper was filled with distilled water (one filling giving more than 1000 drops), then fitted with the cup assembly and weighed. One observer on the platform inserted the dropper in position at the top of the column while the other set the cup and funnel against the needle of the gramophone crystal below.

Five hundred drops were then released, at the rate of about two a second. This number of drops was considered high enough for a detectable mass difference, and to release them took only four minutes.

During the run, the observer at the bottom watched the funnel and surrounding Lucite sheet, which were illuminated, in order to detect any splashes which might occur as the drops hit the funnel. (On two or three occasions, splashes were observed to be projected from the funnel surface, and fall on the Lucite sheet, and the run was cancelled.) The observer at the top made the occasional adjustment to the control plunger of the dropper during the run, to keep the rate of formation of drops at about 2 per second. Each drop, as it hit the funnel, triggered the counter and the impact was heard clearly in the loudspeaker. If an occasional drop failed to activate the counter, that it did hit could be easily verified from the amplified effect of the impact. If, for any reason, a drop failed to hit the funnel at all (this rarely happened), it could be detected by the interruption in the uniform rate of the pulses from the loudspeaker.

After this Measuring Run, the cup, funnel and dropper were immediately reassembled and weighed. The increase in mass thus obtained was that due to coalescence of the larger drop with the cloud droplets, less any mass of water which evaporated from the drop remnants on the funnel, or from the water in the cup during the run. (Or, this increase in mass might not be the true one, due to the occasional cloud droplet reaching the funnel. The effect of this latter would be very small in comparison to the evaporation losses observed).

To cancel these errors, a Test Run was made. Immediately after the second weighing, the cup and wet funnel were replaced in position under the column and left there for the same length of time as taken for the Measuring Run. The third weighing after this procedure, gave a figure, which, subtracted from that obtained by the second weighing, showed a loss. This loss was then added to the original increase to give the net Δm .

It is interesting to note how well justified the Test Run was. The Measuring and Test Runs gave two values, a and b, which, added together, gave the net gain, Δm . The next pair of runs would sometimes give a much lower a reading but a higher b reading which would bring the net gain to a value much the same as the first.

This phenomenon is not completely understood though it seems logical to look for an explanation in the evaporation of the drop remnants in the funnel. The cup could be so placed that at the end of a run, most of the drops had fallen closely around the axis of the funnel giving a compact pattern of drop remnants. In this case, the increase observed in the Measuring Run would be large and the loss in the Test Run, small. In another case when the remnants were spread out over the surface of the funnel, the magnitudes of the readings were reversed, but the total closely the same.

An experimental day generally included runs with the drops uncharged, and charged positively or negatively. Since a scatter was observed in successive runs for the same electrical condition of the falling drop, three or four runs were usually taken to establish a mean Δm , with which an observed collection efficiency would be calculated. The probable error of the arithmetic mean of Δm , for a number of such runs was found to be of the order of $\pm 3\%$ (occasionally more, but most often less).

Every few runs, the relative humidity of the room air was calculated from the wet and dry bulb readings of a sling psychrometer, in order to be certain that there were no large changes. Actually, the Test Run made the experiment independent of the relative humidity but it was thought wise to keep track of any variations which would affect evaporation during the Test Run.

The period of observation was concluded in most cases with two final determinations of the liquid water content. Usually, the values of the liquid water content at the beginning of the experiment agreed, to within 5%, with those at the end. Occasional variations greater than this were observed which are difficult to explain, since the quantities involved in the cloud manufacture were kept rigidly constant.

6.02 Remarks on the Experimental Procedure

The final technique, described above, evolved rather slowly. Among the troubles which were gradually eliminated during many preliminary trials, were the following:

1) The LWCM gave inconsistent readings at first. The rubber seals against which the shutters closed were not satisfactory and leaks developed there. With rubber of greater resilience, this difficulty was overcome successfully, though the readings were still not as consistent as expected. Stronger springs were installed on the shutters to ensure that there was no erratic error in the sampling. Finally, the cloud deflection system was changed from an exhausting, to a blowing system with a marked improvement in the consistency of the readings found with the LWCM. It appeared that the original exhaust system had created a low pressure region at the bottom of the column and the resulting pressure gradient caused room air to flow into the column through the open slits in the shutter housing of the LWCM. This air, mixing with the cloud, probably modified erratically the liquid water content. After the change to the blowing system, the cloud was found to be flowing smoothly through the LWCM, whereas it had been

rather turbulent before. In order to be certain that these open slits did not influence the cloud, they were sealed up at this time.

2) After a number of complete and apparently successful runs had been taken, the bottom section of the cloud column was redesigned. It had incorporated a bulky eaves-trough, originally intended to catch stray water which developed around the opening to the exhaust stream. With the change to blowing, this eaves-trough became unnecessary. The cup, which had been partially obscured by the eaves-trough could now be clearly observed during the runs. It was then noticed that the occasional drop falling centrally through the funnel could cause a splash to be projected right out of the cup. This led to the small aluminum cone being placed in the base of the cup, and in turn to a decided increase in the observed Δm.

3) Many observed collection efficiencies were then accumulated, which in general gave values lower than the collision efficiencies calculated from Langmuir's theory. These theoretical collision efficiencies had been worked out on the basis of the droplet-size distributions observed with the coated slide technique, and it had been assumed that any droplets which did not settle on the slide were not only small (less than 2 or 3 microns in radius) but represented a negligible portion of the total water content of the cloud. The subsequent

investigation and discovery that this was not the case, led to new and lower values of the theoretical collision efficiency. However, by this time, changes had been made in the atomizer tube positions and it was found impossible to reproduce the original cloud, and hence find the complete droplet-size distribution for it.

CHAPTER 7

RESULTS

7.01 Graph 7.01

The results are presented in two forms in Graphs 7.01 and 7.04 on the following pages.

Graph 7.01 shows Δm, the measured increase in mass, plotted against w, the measured liquid water content, for the three clouds used in this experiment.

The overlying grid is the observed collection efficiency E', calculated from

$$\Delta m = E' \pi r_o^2 \, w \, h \, n$$ where $n =$ the number of drops per run. This can be written as

$$E' = k \frac{\Delta m}{w} \qquad \text{where the constant } k = \frac{1}{\pi r_o^2 \, h \, n}$$

In this experiment, $n = 500$, $r_o = 1.59 \times 10^{-1}$ cm, and $h = 317$ cm for Cloud I and 330 cm for Cloud II.#

Thus,

$k = 7.94 \times 10^{-5}\ cm^{-3}$ for Cloud I, and

$k = 7.64 \times 10^{-5}\ cm^{-3}$ for Cloud II.

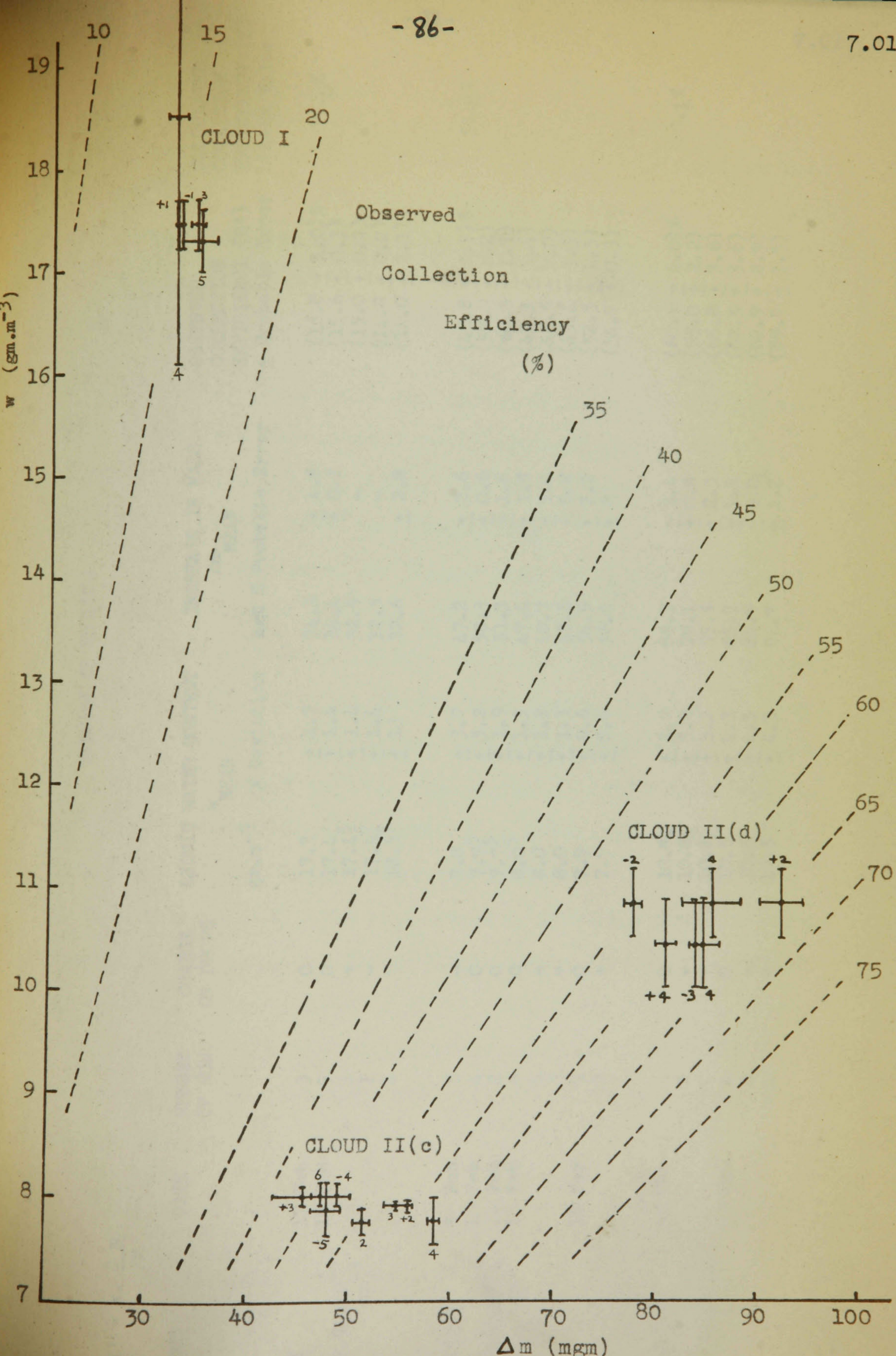
Expressing Δm in gm, and w in $gm.cm^{-3}$, E' is a dimensionless quantity.

The distance of fall through Cloud I (the condensation cloud) was slightly less than through Cloud II (atomizer cloud) because of the different arrangement at the top of the cloud column with each.

Three families of points appear on the graph, one for each cloud used. (Cloud II(d) was made with air tubes of smaller bore in the atomizers than those used to make Cloud II(c).) The small number beside each experimental point indicates the number of runs which determined Δm. A "+" or a "-" indicates the sign of the charge on the falling drop. The probable error of the arithmetic mean of the measured values of Δm, and the deviation from the arithmetic mean of the measured values of w, associated with a given point are shown by horizontal and vertical lines through the point.#

The particular use of this graph is to show the range of w and of Δm and hence of E', covered with the three clouds. A typical point is the one in Cloud II(c) with "-5" under it. This means that 5 runs were taken with the falling drop negatively charged to determine that point. The arithmetic mean of the five values of Δm was 47.2 mgm, the mean measured w for the cloud having been 7.8_5 $gm.m^{-3}$. The spreads in these determinations are shown by horizontal and vertical lines, respectively, through the points. The collection efficiency is seen to be approximately 47%.

When two w values were determined at the beginning of a set of runs, and two at the end, the mean value of each pair was found. Call these mean 1 and mean 2. The w for the day was taken as the mean of mean 1 and mean 2. This was thought to be the best method of treatment of these measurements in order to arrive at the most likely value of w for the day. The deviation shown in Graph 7.01 is the deviation of mean 1 and mean 2 from this over-all mean value.


CLOUD I
Observed
Collection
Efficiency
(%)
10
15
20
35
40
45
50
55
60
65
70
75
CLOUD II(d)
CLOUD II(c)
w (gm.m^{-3})
Δm (mgm)
7
8
9
10
11
12
13
14
15
16
17
18
19
30
40
50
60
70
80
90
100

Graph 7.01

SUMMARY OF RESULTS

$$E' = k.\ \frac{\Delta m}{w}$$

CLOUD	DATE	NUMBER OF RUNS	CHARGE ON DROPS	LIQUID WATER CONTENT w_{MEAN} gm.m^{-3}	% Deviation	INCREASE IN MASS Δm_{MEAN} mgm	% Probable Error	OBSERVED COLLECTION EFFICIENCY (E') ± Probable Error	CALCULATED COLLISION EFFICIENCY (E) Likely Value
I	17 Feb	3	0	17.3	± 1.7	34.8	± 4.8	(16.0 ± 1.0)%	15.0%
	18 Feb	3	0	17.4_5	± 1.4	34.4	± 0.2	(15.6 ± 0.3)	
$k=7.94\times10^{-5}$ cm^{-3}		1	+	17.4_5	± 1.4	32.9	-	(15.0 ± 0.2)	
		1	-	17.4_5	± 1.4	32.5	-	(14.8 ± 0.2)	
		4	0	18.5^5	± 13	32.6	± 2.8	(14.0 ± 2.1)	
II(c)	8 Feb	5	-	7.8_5	± 3.7	47.2	± 2.6	(45.8 ± 2.9)%	51.8%
	10 Feb	4	0	7.7_5	± 3.2	58.3	± 0.6	(57.4 ± 2.2)	
$k=7.64\times10^{-5}$ cm^{-3}	14 Feb	2	0	7.7_5	± 1.9	51.3	± 1.6	(50.6 ± 1.3)	
	15 Feb	6	0	8.0^5	± 1.3	47.4	± 1.8	(45.3 ± 1.4)	
		4	-	8.0	± 1.3	48.7	± 3.0	(46.5 ± 2.0)	
		3	+	8.0	± 1.3	45.5	± 6.8	(43.4 ± 3.5)	
	16 Feb	3	0	7.9	± 0.6	54.9	± 2.2	(52.5 ± 1.5)	
		2	+	7.9	± 0.6	56.6	± 0	(54.7 ± 0.3)	
II(d)	22 Feb	4	0	10.8_5	± 3.2	86.5	± 3.4	(60.9 ± 4.0)%	60.1%
		2	-	10.8_5	± 3.2	78.1	± 0.8	(55.0 ± 2.2)	
$k=7.64\times10^{-5}$ cm^{-3}		2	+	10.8_5	± 3.2	93.5	± 2.3	(65.8 ± 3.6)	
	25 Feb	4	0	10.5^5	± 4.3	85.7	± 1.5	(62.5 ± 3.6)	
		3	-	10.5	± 4.3	84.9	± 0.0_4	(62.9 ± 2.9)	
		4	+	10.5	± 4.3	81.7	± 1.2	(59.7 ± 3.3)	

The complete data from which these points are plotted are given in the Appendix. A summary of the data is presented on the page following Graph 7.01.

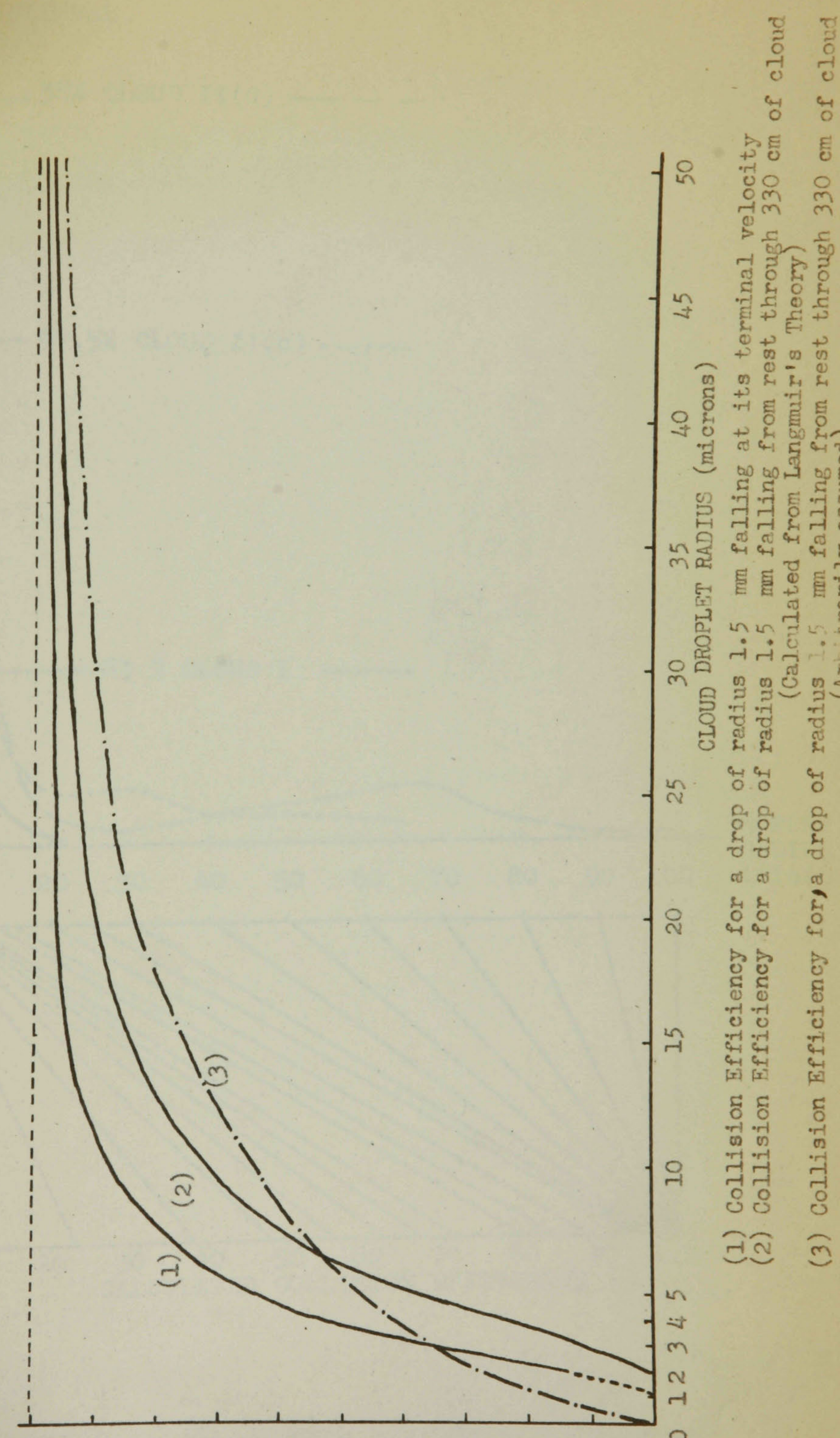
7.02 <u>Graphs 7.02 and 7.03</u>

In order to compare the observed collection efficiencies with Langmuir's theoretical collision efficiencies for our particular clouds and falling drop size, Graphs 7.02 and 7.03 on the following pages have been drawn.

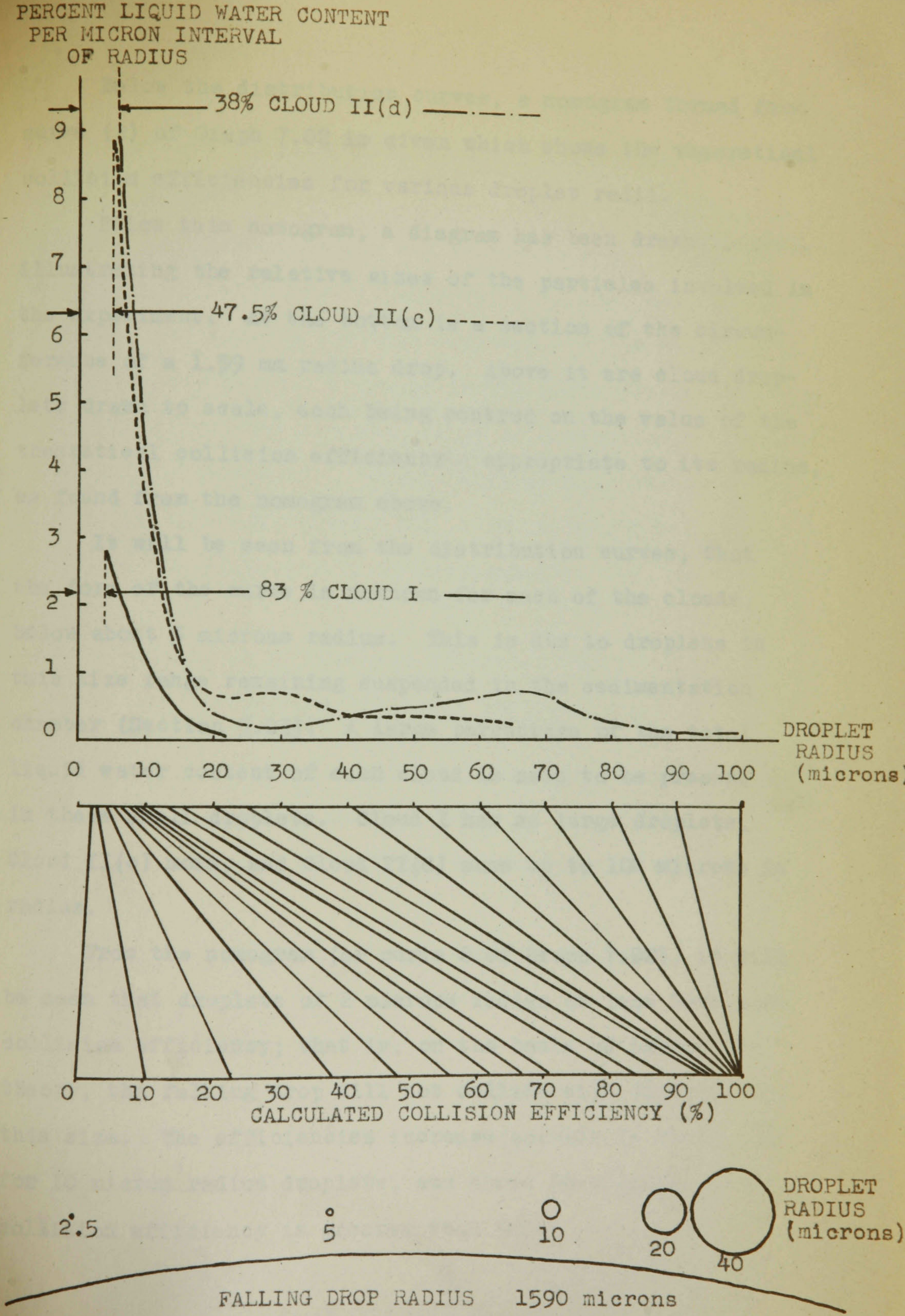
Graph 7.02 shows the theoretical collision efficiency of a 1.5 mm radius drop as a function of cloud droplet radius, (E(r)). Two curves are shown, curve (1) is for the drop falling at terminal velocity (taken from Langmuir's curves, Graph 1.01) and curve (2) is for the particular case of non-terminal fall which obtained in this experiment.# (This modification to Langmuir's theory is discussed in detail in Thesis H). Curve (3) is discussed in Section 7.05.

In Graph 7.03, the droplet-size distributions are shown for the three clouds. The ordinate scale is the percentage of the total liquid water content present in droplets whose radii lie in a one micron interval; call this ordinate w'(r). These curves were obtained from the experimental distribution curves (Thesis H.).

#The modifications to Langmuir's theory were calculated in terms of a 1.5 mm radius drop. The drop used in this experiment had a radius of 1.59 mm. The error resulting from this, has been neglected and is probably less than 1%.


COLLISION EFFICIENCY (%)
0
10
20
30
40
50
60
70
80
90
100
CLOUD DROPLET RADIUS (microns)
0
1
2
3
4
5
10
15
20
25
30
35
40
45
50
(1)
(2)
(3)
(1) Collision Efficiency for a drop of radius 1.5 mm falling at its terminal velocity
(2) Collision Efficiency for a drop of radius 1.5 mm falling from rest through 330 cm of cloud
(Calculated from Langmuir's Theory)
(3) Collision Efficiency for, a drop of radius 1.5 mm falling from rest through 330 cm of cloud
(Arbitrarily assumed)

Graph 7.02


PERCENT LIQUID WATER CONTENT
PER MICRON INTERVAL
OF RADIUS
38% CLOUD II(d)
47.5% CLOUD II(c)
83 % CLOUD I
DROPLET
RADIUS
(microns)
CALCULATED COLLISION EFFICIENCY (%)
DROPLET
RADIUS
(microns)
2.5
5
10
20
40
FALLING DROP RADIUS 1590 microns

Graph 7.03

Below the distribution curves, a nomogram formed from curve (2) of Graph 7.02 is given which shows the theoretical collision efficiencies for various droplet radii.

Below this nomogram, a diagram has been drawn illustrating the relative sizes of the particles involved in the experiment. At the bottom is a section of the circumference of a 1.59 mm radius drop. Above it are cloud droplets drawn to scale, each being centred on the value of the theoretical collision efficiency appropriate to its radius, as found from the nomogram above.

It will be seen from the distribution curves, that the form of the curve is unknown for each of the clouds, below about 5 microns radius. This is due to droplets in this size range remaining suspended in the sedimentation chamber (Section 5.03). A large percentage of the total liquid water content of each cloud is seen to be present in these small droplets. Cloud I has no large droplets, Cloud II(c) more, and Cloud II(d) some up to 100 microns in radius.

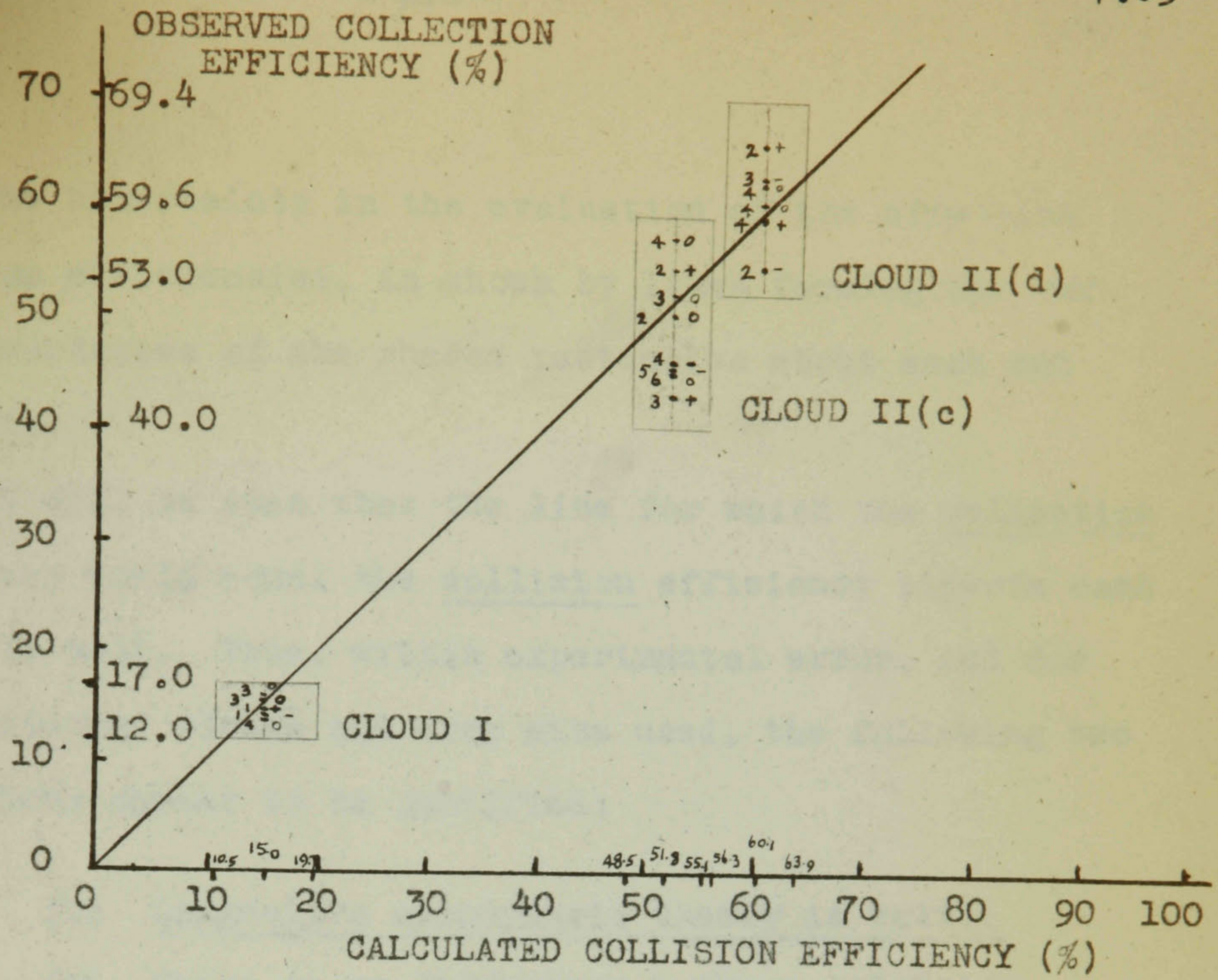
From the nomogram (or curve 2 of Graph 7.02), it will be seen that droplets of 2 microns radius or less have zero collision efficiency; that is, on the basis of Langmuir's theory, the falling drop will not collide with droplets of this size. The efficiencies increase quickly to about 70% for 10 micron radius droplets, and above 50 microns, the collision efficiency is greater than 98%.

The effective collision efficiency for each of the three clouds has been determined by summing the products E(r).w'(r) and dividing by 100%, E(r) having been taken from curve (2). An uncertainty in the value of this effective collision efficiency arises due to the lack of knowledge of the form of each distribution curve in the small droplet region. By choosing possible extremes for the shape of the curves in this region, a spread in the value of the effective collision efficiency for each cloud is determined. (Treated in detail in Thesis H). Within this spread, the most likely value of E has been chosen, and is $15._0\%$, $51._8\%$ and $60._1\%$ for Clouds I, II(c) and II(d) respectively.

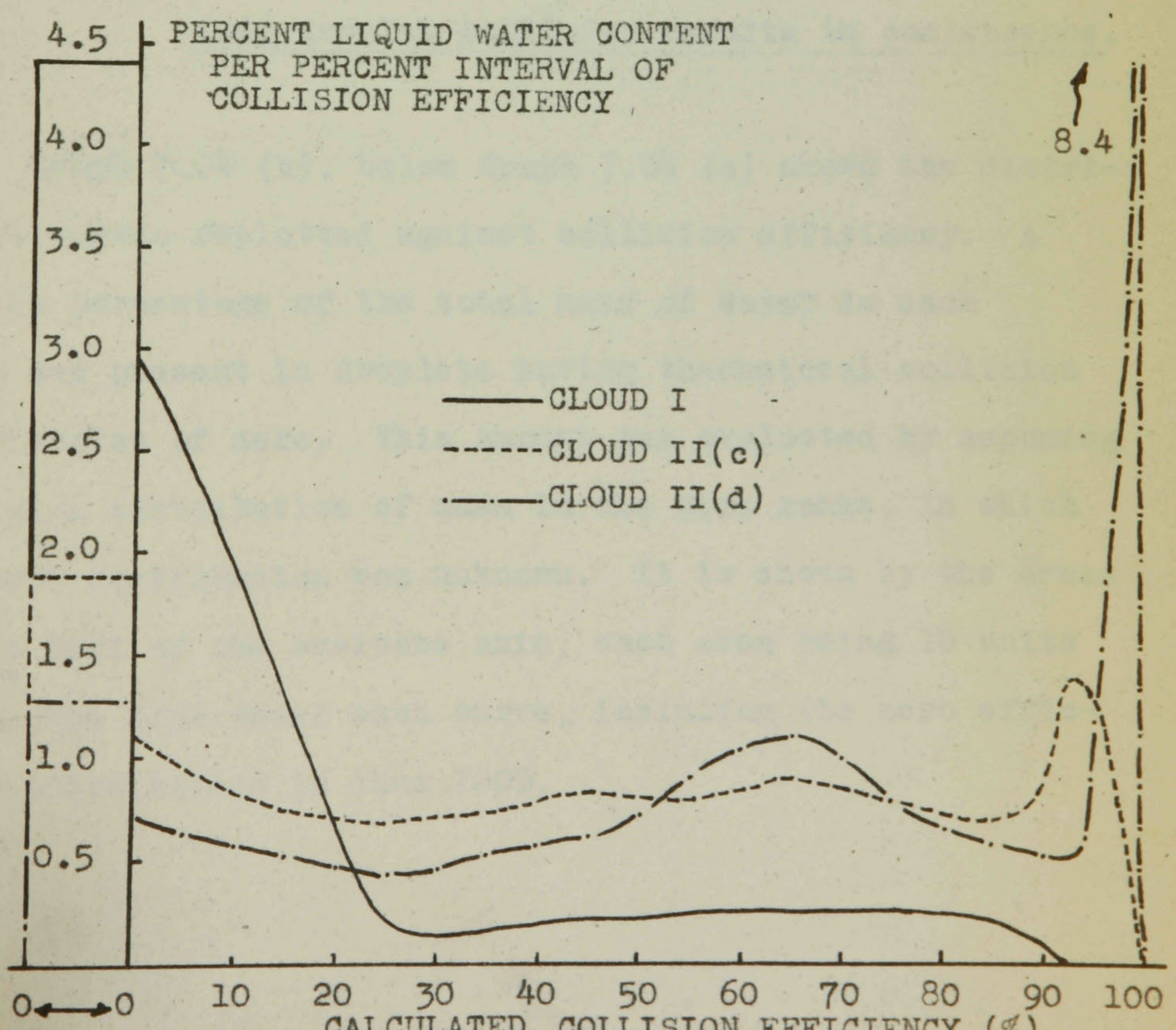
7.03 A Comparison of Observed Collection Efficiencies and Theoretical Collision Efficiencies

In Graph 7.04(a) the observed collection efficiencies for each of the clouds (determined from $E' = k\frac{\Delta m}{w}$) have been plotted against the effective collision efficiency of each cloud.

The spread of each of the observed efficiencies (due to the combined spreads of the measured values of Δm and w) is shown by vertical lines extending through each point. These overlap and the over-all spread of the points is included within the horizontal boundaries of the shaded rectangles. The number of runs determining Δm, and the charge on the falling drop are shown beside each observed point.



Graph 7.04(a)



Graph 7.04(b)

The uncertainty in the evaluation of the effective collision efficiencies, is shown by lines forming the vertical boundaries of the shaded rectangles about each set of points.

It will be seen that the line for which the collection efficiency would equal the collision efficiency bisects each rectangle well. Thus, within experimental error, and for the particular clouds and drop size used, the following two conclusions appear to be justified:

(1) Langmuir's aerodynamic theory is valid.

(2) There is no difference between collision and collection efficiency; that is, every drop-droplet collision results in coalescence.

Graph 7.04 (b), below Graph 7.04 (a) shows the distribution curves replotted against collision efficiency. A certain percentage of the total mass of water in each cloud was present in droplets having theoretical collision efficiencies of zero. This amount was evaluated by assuming a uniform distribution of mass in the size range, in which the true distribution was unknown. It is shown by the areas to the left of the ordinate axis, each area being 10 units wide. The area under each curve, including the zero efficiency contribution is thus 100%.

Graph 7.04 (b), shows for instance, that low collision efficiencies are to be expected from Cloud I, since 44% (4.4 x 10) of the total liquid water content was present in droplets of zero efficiency (less than 2 microns radius).

It is seen that higher efficiencies would be expected from Cloud II(d), since only 13% of the total w had zero efficiency, and 8.4% of the total w was in droplets of 99% efficiency.

7.04 An Appraisal of the Experiment as a Check of Langmuir's Theory

The question arises as to how well this experiment verifies Langmuir's theory. It is apparent that any number of curves of collision efficiency as a function of droplet radius (Graph 7.02) could give the same effective collision efficiency for one of our three heterogeneous clouds. However, could a curve other than Langmuir's (as modified for this experiment) be chosen which would give, for <u>all three clouds</u>, the same effective collision efficiencies as were actually calculated?

In order to test the sensitivity of the effective collision efficiencies to changes in the form of these efficiency/droplet radius curves, curve (3) of Graph 7.02 was arbitrarily chosen. It gives an efficiency to the small droplets, which, with curve (2) had none, and reduces the efficiency of droplets, 7 microns in radius and larger. Since Cloud I had the largest percentage (44%) of its liquid water content in droplets of zero efficiency, this new curve should produce the largest change in the value of the effective collision efficiency with Cloud I; smaller changes would be expected in Clouds II (c) and II (d) which had smaller "zero efficiency water contents", and more large droplets, the latter being less affected by the assumed curve.

The effective collision efficiencies using this assumed curve have been calculated from the distribution curves of Graph 7.03. This was done as before, using curve (3) of Graph 7.02, this time, as E(r). Only the lowest value of the effective collision efficiency for each cloud was evaluated. This is the one obtained by distributing the mass of water equally among the droplet sizes which are unknown, (i.e. assuming the distribution curve to be horizontal in the unknown region).

The following table compares the lowest values of this calculated collision efficiency, assuming curve (3) of Graph 7.02, with the lowest values actually used in the experiment, which were calculated from curve (2).

	E Low		% Deviation of E (3) from E(2)
	Curve (2)	Curve (3)	
Cloud I	10.5	29.7	183 %
Cloud II(c)	48.5	58.8	21.2 %
Cloud II(d)	56.3	65.0	15.5 %

Thus, a modest change in the form of the efficiency/droplet radius curves produces changes in the effective collision efficiencies of our three clouds, all of which would have been easily detectable in the experiment.

A curve, which in turn would modify curve (3) in the important region of small droplet radii, could be obtained by bringing curve (3) down more steeply from 50% efficiency at 6 microns radius to zero efficiency at 1 micron radius. This would result in deviations from the lowest values used for Clouds I, II(c) and II(d) of 87%, 11% and 8.5% respectively. Thus, closer agreement for Cloud II(d) but a deviation so large as to be readily detected with Cloud I, if not the other two.

This trial with hypothetical curves suggests that the departure from the Langmuir curve would have to be quite small if it were not to change the effective efficiency of at least one of the three clouds enough to be detected experimentally.

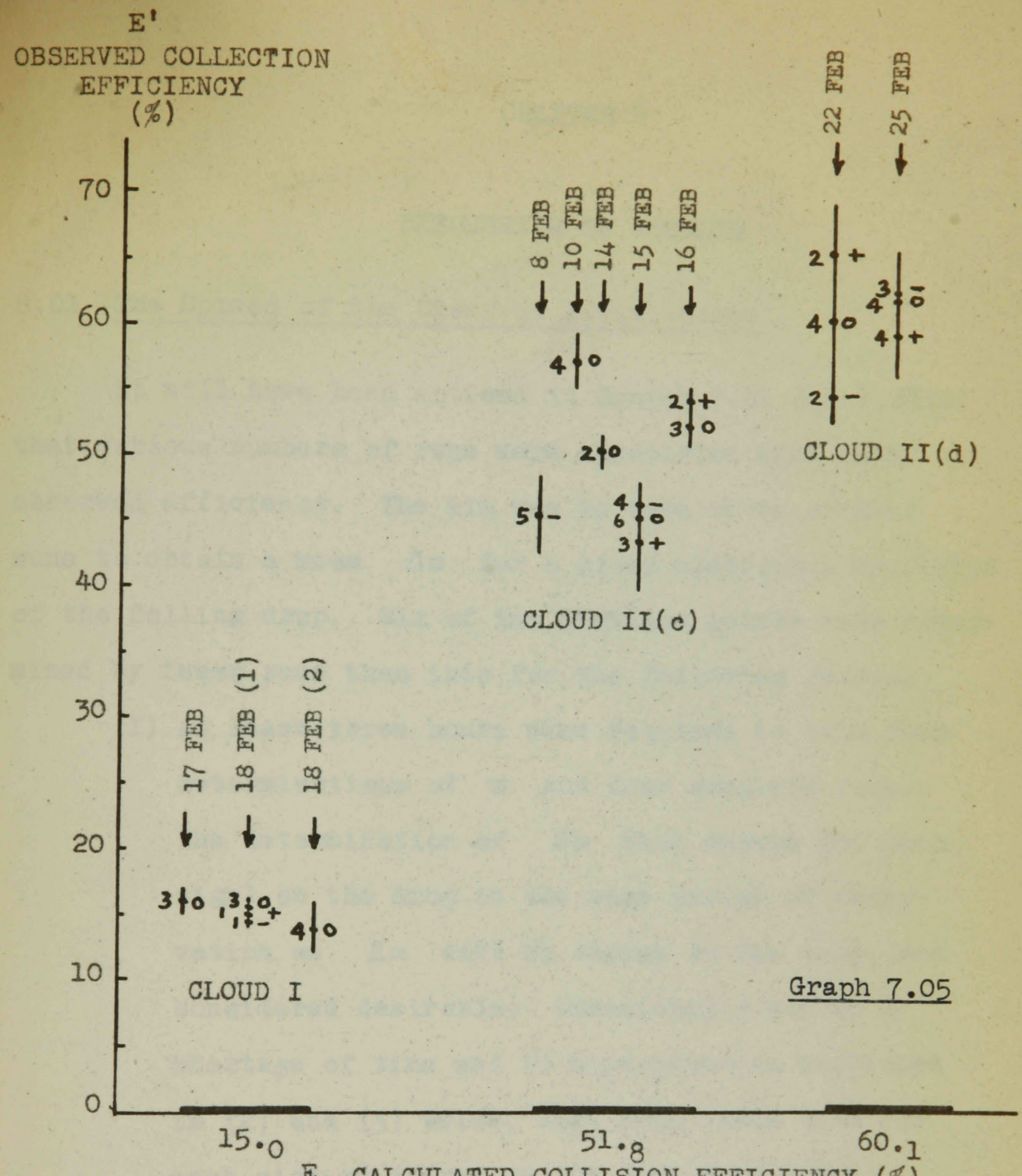
7.05 Graphs 7.05 and 7.06

In Graph 7.05, the observed efficiencies of Graph 7.04(a) have been plotted against a distorted collision efficiency scale. The scale has been enlarged in the region of the three values of collision efficiency chosen for each cloud, so that the points observed on different days can be seen separately. The errors in each observed efficiency, the number of runs determining each point, and the sign of the charge on the falling drop are indicated in the same way as on the other graphs.

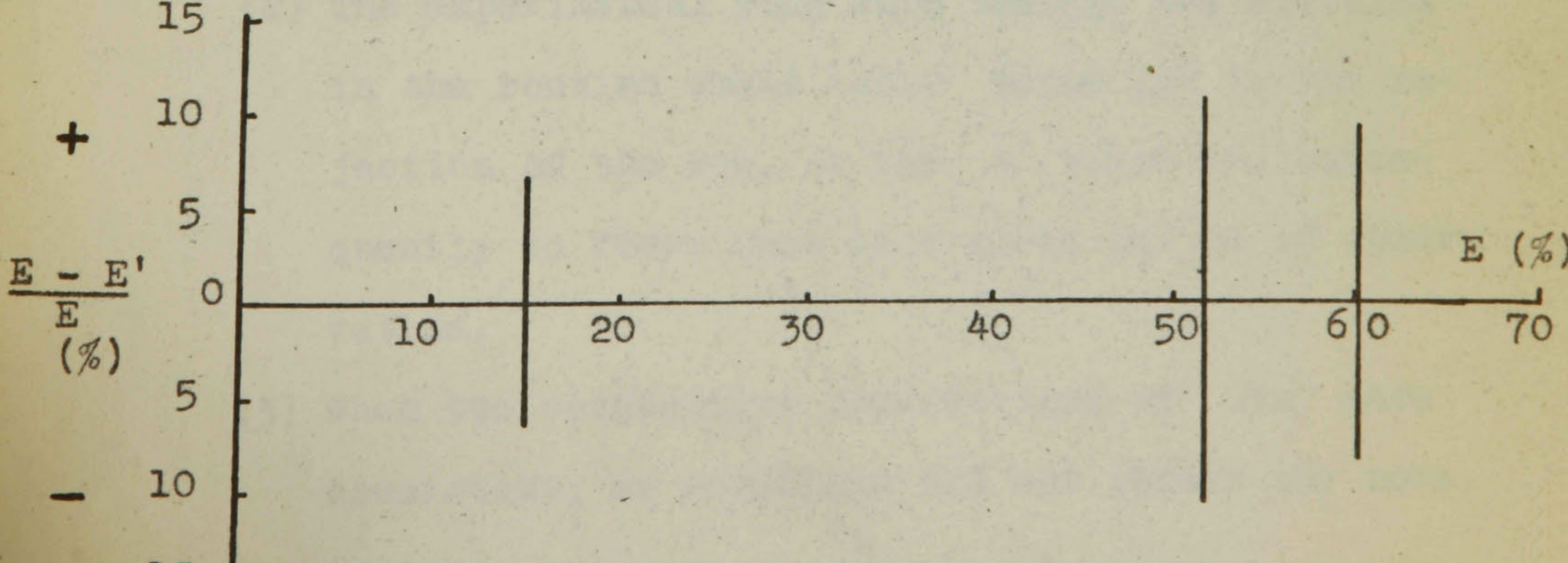
From this graph, the relatively unimportant effect of charge on the collection efficiency can be seen. In connection with any cloud, values of E' for positively or negatively charged drops lie randomly on both sides of the E' values for uncharged drops.

Graph 7.06 shows the maximum percentage deviation of the observed collection efficiency, E', from the most likely value of the calculated collision efficiency E to be about ±10%.

These graphs will be discussed further in the next chapter.



Graph 7.05



Graph 7.06

CHAPTER 8

DISCUSSION OF RESULTS

8.01 The Spread of the Observed Efficiencies

It will have been noticed in Graphs 7.01 and 7.04(a) that various numbers of runs were associated with each observed efficiency. The aim was to take three or four runs to obtain a mean Δm for a given electrical condition of the falling drop. Six of the nineteen points were determined by fewer runs than this for the following reasons:

(1) At least three hours were required to take four determinations of w and four complete runs. The determination of Δm with charge (of each sign) on the drop in the same period of observation as Δm with no charge on the drop, was considered desirable. Occasionally due to a shortage of time and to circumstances mentioned in (2) and (3) below, less than three runs for each sign of charge on the drop were taken.

(2) The experimental runs were taxing, and mistakes in the routine would occur, which led to the rejection of the run, or the w value and consequently to fewer runs in a given period of observation.

(3) When two consecutive observations of Δm were consistent, we sometimes did not obtain any more.

It was with the "charged" runs, in particular, that this procedure was followed, since preliminary runs had indicated the small effect on Δm, of charge on the falling drop. The fact that two runs were consistent is not meant to imply however, that the observed efficiencies in these cases are more reliable than those in which the mean of four Δm values was obtained.

It is difficult to say how significant the weighting of the observed E's according to the number of runs determining them would be, and this has not been done.

From Graph 7.06, the maximum percentage deviation of the observed collection efficiency from the most likely value of the calculated collision efficiency is seen to be of the order of $\pm$ 10%. For any one point, the percentage deviation is, in general, less.

In order to determine whether this deviation is due to particularly large deviations in one of the two quantities, w or Δm which determine E', the following table has been drawn up. In it, the spread of the <u>mean values</u> of Δm and of w observed with each cloud has been expressed as a percentage of the lower value. (The spread of the Δm values due to charge on the falling drop was small compared to their over-all scatter, so the presence of charge has been ignored in compiling this table.)

	w_{mean}		$\frac{w_h - w_L}{w_L}$	Δm_{mean}		$\frac{\Delta m_h - \Delta m_L}{\Delta m_L}$
	Low	High		Low	High	
Cloud I	17.3	18.5	7%	32.5	34.8	7%
Cloud II (c)	7.7_5	8.0	3%	45.5	58.3	28%
Cloud II (d)	10.5	10.8_5	3%	78.1	93.5	20%

It is seen that most of the blame for the deviation of E' must be laid on Δm, which varied by as much as 28% with a given cloud. The spread between the lowest and highest w values actually measured with a given cloud was greater than shown here (about 15%) but since the mean value of several w's was used to determine E', the spread between the mean values has been considered here.

Some possible causes of the variations shown above are discussed in the next two sections.

8.02 Possible Causes of Variation of "w"

While the spread of the mean values of w for a given cloud was only 3%, the spread between the lowest and highest values measured was larger,- of the order of 15%.

In this section, an attempt is made to distinguish between actual changes in liquid water content of the cloud supplied to the column, and possible variations arising from the measuring technique, in order to explain the observed spread. No definite conclusions can be drawn, however, and it must be admitted that variations in w of the order of 15% cannot be explained satisfactorily.

(a) Actual Variation

In the case of the atomizer clouds (II(c) and II (d)), it is difficult to find reasons for actual variations of the liquid water content. The air supply was kept at a constant value, and the atomizer needles were fixed firmly in position. Thus, the rate of cloud production should have been steady.

The cloud temperature varied slightly, both on a given day (maximum variation: 0.6 centigrade degrees) and from day to day (maximum variation 1.6 centigrade degrees). These temperature variations could have meant appreciable changes in the vapour content of the saturated droplet-bearing air. However, no correlation has been found between the direction of temperature variation, and the observed variation in w.

The w of the condensation cloud (Cloud I) was found to be quite sensitive to changes in boiler pressure. Since this was appreciated, care was taken to watch that the pressure stayed at the chosen value. The position of the nozzle, from which the vapour escaped, was also critical, and in refilling the boiler, this might be changed with a resulting modification of w. This is thought to be the reason for the larger variation, (7%), which appeared in the table of Section 8.01.

(b) Variations in Measurement

The following are sources of error in the measurement of w , all of which are believed to be small.

1. In the calibration of the LWCM, an average error of 0.25 $gm.m^{-3}$ or about 3% of a typical w value was found. This error was such that the measured w values would be low. Erratic errors within this systematic error might have caused variations of the order of 1% in the measured liquid water content.
2. Any errors in "first-sighting" the dew on the shiny copper disc, and errors in following the temperature changes on the potentiometer were estimated to be about 1%. (Thesis H).
3. The hygroscopic nature of the Lucite windows and the rubber seals inside the LWCM may be a more important factor. The largest possible variation in the moisture content of the hygroscopic elements inside the LWCM has been estimated to be about 1 mgm. This could cause a maximum error of 6% in the measured w, since with a cloud of 10 $gm.m^{-3}$, there would be only 15.8 mgm of cloud water in the sample captured by the instrument. This error might conceivably vary from one w determination to another, but a 1% variation of w from this cause would probably be large.

4. Wetting of the interior of the LWCM by cloud droplets, in the time after the instrument was dried and inserted in the column, and before the actual determination was made, is found to produce a negligible effect on w. For, if we consider that 100 droplets of 50 microns radius did collect somewhere inside (none were ever observed), a typical w value would be changed by less than ½%.
5. Leaks at the flanges joining the shutter housings to the body of the LWCM were a source of trouble at one time, but these were successfully sealed with apiezon wax; leaks, smaller than could easily be detected, could be shown to contribute negligibly to the variations in w observed.
6. Inconsistency in isolating samples of the cloud with the instrument might have caused variations in the measured w values. However, the rigid release mechanism ensured that the shutters were released simultaneously, and consistently so. The closing speed of the shutters was determined approximately by visual comparison with a camera shutter, on two occasions, and no variation could be detected.

8.03 Possible Causes of Variations of "Δm"

(a) Actual Variation

An actual variation of the mass accreted by the 500 drops could have been caused by (1) an appreciable variation of the cloud droplet distribution in the column and (2) a change in the falling drop size, from one dropping run to the next.

There is no apparent reason why (1) should have occurred, since cloud was continuously produced and continually flowed through the column. It might have been that the droplet distribution was not uniform over the cross-section of the column, but with 500 drops falling over slightly different paths and each suffering over 100,000 collisions, any variations due to this cause should have averaged out during a run.

Groups of 50 drops were weighed on several different occasions and their masses agreed to within 0.5%, so (2) is entirely negligible.

(b) Variations in Measurement

Since it seems unlikely that Δm actually varied for a given cloud and falling drop size, we must look for the variations in the measured Δm.

1. A source of unknown error is the breaking of the drop as it hits the funnel. Presumably the drop shatters into little droplets which are deflected at angles, grouped around the angle of reflection determined by the angle of incidence of the drops

with respect to the sloping side of the funnel. This side was at such an angle that most of the splashes should be deflected further into the funnel. There is the possibility however, that droplets could be produced by the impact which might rebound at such an angle as to be projected out of the funnel. If these droplets were large, they should have been visible to the observer who watched the illuminated surface of the Lucite sheet (Plate 3.05, page 39) during the run. Indeed, several times during the experiment, runs were cancelled due to a splash having been seen to land on the Lucite plate. However, there could conceivably have been an erratic loss of water due to droplets which escaped observation, having been projected from the funnel. On the radical assumption that one fragment of 100 microns radius was lost with each drop which hit the funnel, 2 mgm would be lost in every 500 drop runs or roughly 4% of a typical Δm.

2. The loss of water due to large splashes rebounding from the collected water in the cup was eliminated by the cone placed with its apex sticking up into the funnel. However, any such splash effects as those in (1) above might be altered in an erratic manner depending on how many drops in a given run fell axially into the funnel and consequently hit

the cone. It is felt that these drops were much less likely to produce any splashes which could escape, The fraction of the 500 drops which fell axially varied from run to run and depended on the placing of the cup and the position of the dropper above.

Both (1) and (2) would always lead to a value of Δm, lower than the true one.

3. Evaporation of the accumulated drops in the cup, and of the drop remnants on the funnel is certainly a possible cause of variations in Δm. The Test Run was designed to compensate for these evaporation losses and one is impressed with how well it did do this. Examining a number of runs, (Appendix-page v, February 15, for example) the variations of Δm in successive Measuring Runs are seen to have been often very large, but the opposite trend in the Test Runs brought the final Δm values to remarkable agreement.

Nevertheless, it is probable that there was still some irregularity in the compensation which led to too large or too small a value for Δm. In the Test Run, the cup and funnel were exposed under the column for the same length of time as taken for the Measuring Run. The rate of evaporation seemed to depend on the area of water exposed, that is on the pattern of drop remnants in the funnel.

As has been mentioned in Section 6.01, this was quite different from run to run. On the occasions when evaporation was large (remnants dispersed all over funnel surface) in both runs, the final Δm was usually a little lower than that of a preceding run, in which evaporation had been small. (See, for instance, Appendix, Cloud II(c), 15 February, Runs 7 and 6). It would seem that evaporation may have been under-compensated for in these cases.

However, it may be that the Test Run over-compensated, and thus led to too high values for Δm. This is a possibility since during the Measuring Run, the water was accumulating all the time and in the Test Run, the whole amount of collected water was exposed. (Offsetting this somewhat is the fact that 50 drops probably were sufficient to establish a "splash pattern" on the funnel surface).

The true picture must be some combination of the effects outlined here, and it is not possible to say which might have contributed the most to variations in the measured Δm.

However, to sum up:- There are certainly sources of error in the measurement of Δm. The magnitudes of the errors are unknown, but their direction is such as to lead generally to a smaller value of Δm than the actual one, but could give a larger.

8.04 The Effect of Charge on the Observed Efficiencies

(a) Charge on the Falling Drop

All the possibilities involved in determining the effect of charge on coalescence were not investigated in this experiment. The one specific thing which was done was to induce a positive charge, or a negative charge on the drops which was carried away as they left the tip of the hypodermic needle. The cloud droplets were most probably charged as well, charges on the droplets in the condensation cloud having been of a much smaller order than those on the atomizer cloud droplets. No measurements of these charges were made.

The charge on the large drops was comparable with that observed on raindrops in nature. Ross Gunn (1947) found an average charge of 0.04 esu on drops in thunderstorms.# The charge on each of our 3 mm diameter drops was 0.19 esu. Assuming a typical raindrop diameter of 1.5 to 2 mm, the average charge observed by Ross Gunn was between 9.5 and 23.5 esu/gm of rain water. (Other observations of charge on rain at the ground give smaller values. (Gschwend -see Simpson 1942), (Simpson, 1909).

The charge on the drops in this experiment having been $\pm$ 11.3 esu per gram of water dropped, an effect on the collection efficiency comparable with that to be expected in nature, should have been observed.

#The charged drops were examined on actual flights through thunderstorms, the magnitude of the charge having been measured by the electrical impulse produced on an oscillograph by a drop passing through an inducing ring situated outside the aircraft. The drop sizes were not measured.

To summarize the effects on the efficiencies due to this charge, the following table has been drawn up. In it the magnitudes and the directions of the deviations in the observed collection efficiencies when charge was on the drop from those obtained when no charge was on it, are given, for the three clouds.

The sum of the uncertainties in the two efficiencies is shown with the deviation.

CLOUD	DAY	$E'_o - E'_+$	$E'_o - E'_-$
I	18 Feb.	(+0.6 ± 0.5)%	(+0.8 ± 0.5)%
II(c)	15 Feb.	(+1.9 ± 4.9)%	(-1.2 ± 3.4)%
	16 Feb.	(-2.2 ± 1.8)%	
II(d)	22 Feb.	(-4.9 ± 7.6)%	(+5.9 ± 6.2)%
	25 Feb.	(+2.8 ± 6.9)%	(-0.4 ± 6.5)%

It is seen that the effect due to charge on the falling drop is small compared with the limits of accuracy of the experiment.

It is worth noting, however, that any effect due to a charge of this magnitude (±11.3 esu per gm) on the raindrop is small enough to be of little meteorological significance.

(b) Charge on the Cloud Droplets

In Cloud I, any charges on the droplets would be those of the original condensation nuclei and hence of very small magnitude.

In Cloud II, where water was shattered to make the cloud, it is probable that much greater charges existed on the droplets. However, in Graph 7.04(a) the observed efficiencies with Cloud I were in as good agreement with the theoretical collision efficiencies, as were those with Cloud II. Thus any effect of what were probably much greater charges on the droplets of Cloud II did not show up.

Since Cloud I and Cloud II were of quite different efficiencies, however, the effect of cloud droplet charges on coalescence must be considered still uncertain.

8.05 Falling Drop Size

In the experiment, only one falling drop size was used for two reasons:

(1) It is difficult to produce drops of much less than 3 mm diameter, by the straightforward method of allowing them to form naturally at an orifice. Smaller hypodermic needles than the one used were tried, but gave only slightly smaller drops (2.8 mm diameter); their rate of detachment was much slower and would have doubled the time for a 500-drop run.

Other ways of producing smaller drops of uniform size in fairly rapid succession are not suitable for this experiment. Two of these are: (1) An air blast concentric with the dropper axis, which forcibly detaches the drops before they are fully formed, and (2) the breaking up of a fine stream of water with mechanical vibrations of a suitable frequency.

The success of method (2) has been demonstrated by Mr. R.Magarvey, of this laboratory, who has used an acoustic drop generator of this sort in an experiment to determine the heat transfer from falling drops. Method (1) was used by us in the earlier wind tunnel experiments.

However, both of these methods are difficult to apply to this experiment, in which the dropper, filled with water, must be light and must be weighed before and after a run, and in which the loss of even a fraction of a drop cannot be tolerated.

2. A 3 mm diameter drop happened to be very convenient for this experiment, since it is for drops of approximately this size that Langmuir's theory predicts a maximum collision efficiency for each cloud droplet size. (Graph 1.01). Slightly larger or slightly smaller drops, which could be made by ordinary dropping methods, are still in the range for which maximum collision efficiency is predicted.

8.06 Possible Further Experiments

The following are possible modifications to the experiment, which have not been investigated.

(1) The atomizer clouds were made with tap water. The effect of a distilled water cloud on the efficiency would be interesting to observe, but would probably not lead to results very different from those already obtained. The condenser cloud droplets were effectively distilled water, and seemed to exhibit no effect on E' which would distinguish them from the less-pure atomized droplets.

(2) Similarly, making the drop of tap water is another possible variation of the experiment.

(3) The effect of an ambient temperature greatly different than 20°C was not investigated. At 0°C, the surface tension of water changes by only 4% of that at 20°C, but its viscosity increases by 79%. It would be of interest to determine if this appreciable viscosity change would influence the coalescence process.

CHAPTER 9

THE EFFECT OF COALESCENCE ON THE RADAR SIGNAL FROM CONTINUOUS RAIN

Continuous rain is characterized by its steady nature, and is free from the considerable updrafts and turbulence associated with rain showers. This type of rain often extends over wide areas, and is of uniform intensity. The radar signal returned from such rain shows a corresponding uniform intensity in the horizontal. Below the freezing level, the rain falls through varying thicknesses of relatively quiescent cloud, and in this region accretion should occur, with a consequent increase in the intensity of the radar signal from the rain. This increase should be readily detectable from the radar picture, since the process is not complicated by the large updrafts associated with showery rain.

The following development is concerned with finding the increase in intensity of the radar echo in terms of w, the liquid water content of the cloud, and E, the collection efficiency.

Suppose that just below the freezing level, the raindrop-size distribution (Marshall and Palmer, 1948) is given by

$$N_D = N_o \, \varepsilon^{-\Lambda D} \qquad (1)$$

Where D is the diameter,

$N_D \, \delta D$ is the number of drops of diameter between D and $D + \delta D$ in unit volume of space,

N_o is a constant,

and Λ is a function of R, the rate of rainfall.

The intensity of the radar signal from rain is proportional to a quantity z, where

$$z = \int_0^\infty N_D \, D^6 \, dD$$

$$= N_o \int_0^\infty \varepsilon^{-\Lambda D} \, D^6 \, dD \qquad (2)$$

If we now consider all the drops to fall a distance x, through a cloud of liquid water content w, then the increase in mass, Δm of one drop due to coalescence will be

$$\Delta m = E \frac{\pi D^2}{4} w \, \Delta x \qquad (3)$$

where E is the collection efficiency. As well,

$$\Delta m = \rho \frac{\pi D^2 \Delta D}{2} \qquad (4)$$

where ρ is the density of water.

Combining (3) and (4),

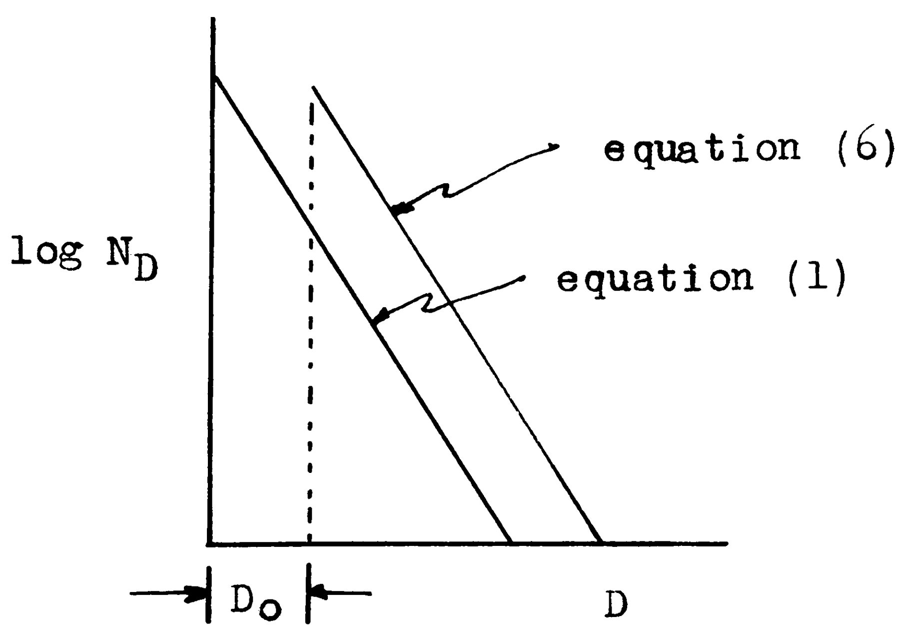
$$\Delta D = \frac{E \, w}{2 \rho} \Delta x \qquad (5)$$

If we assume an average E for all raindrops and a uniform w throughout the distance Δx, every drop diameter will increase by the same amount, D ($= D_o$). This will lead to a new drop-size distribution, given by

$$N_D = N_o \, \varepsilon^{-\Lambda(D - D_o)}$$

$$= N_o \, \varepsilon^{-\Lambda D} \, \varepsilon^{\Lambda D_o} \qquad (6)$$

That is, the distribution curve given by equation (1) will shift to the right an amount D_o.



After the rain has fallen a distance Δx through the cloud, the quantity z (equation (2)) now becomes

$$z_1 = N_o \, \varepsilon^{\Lambda D_o} \int_{D_o}^{\infty} \varepsilon^{-\Lambda D} \, D^6 \, dD \qquad (7)$$

To a good approximation,# we can replace the lower limit of the integral by 0.

In equation (5), if we put $E = 1$; $w = 1 \text{ gm.m}^{-3} = 10^{-6} \text{gm.cm}^{-3}$, $\rho = 1 \text{ gm.cm}^{-3}$ and $\Delta x = 1 \text{ km} = 10^5 \text{ cm}^3$, one finds $D_o = 0.5$ mm. The contribution to $N_D D^6$ of drops of diameter less than 1 mm is small, and less than 0.5 mm, entirely negligible.

Thus, equation (7) becomes

$$z_1 = N_o \varepsilon^{\Lambda D_o} \int_o^\infty \varepsilon^{-\Lambda D} D^6 \, dD$$

The ratio of this z_1 to the original z (equation (2)) is then

$$\frac{z_1}{z} = \varepsilon^{\Lambda D_o}$$

Or, in terms of the intensity I of the radar signal

$$\frac{I_1}{I} = \varepsilon^{\Lambda D_o} \qquad (8)$$

To express this intensity change in decibels, equation (8) becomes

$$\Delta L = 10 \log_{10} \left(\frac{I_1}{I} \right) = 10 \Lambda D_o \log_{10} \varepsilon$$

where ΔL is the change in intensity level.

Substituting from equation (5) for D_o

$$\Delta L = 5 \Lambda \log_{10} \varepsilon \quad \frac{E\,w}{\rho} \quad \Delta x \qquad (9)$$

Now, Marshall and Palmer, (loc.cit.) found the empirical relation,

$$\Lambda = 41 R^{-0.21} cm^{-1}$$

Where R is the rate of rainfall in $mm.hr^{-1}$.

In the following table, Λ is evaluated for various rates of rainfall, and in the last column equation (9) is shown, in decibels per kilometre of fall, if w is in grams per cubic metre. (ρ = 1 gm. cm^{-3} and $\log_{10} \varepsilon = 0.434$).

R $mm.hr^{-1}$	Λ cm^{-1}	$\frac{\Delta L}{\Delta x}$ $db.km^{-1}$
1	41	8.9 E w
3	32.3	7.0 E w
10	25.3	5.5 E w
30	20.1	4.4 E w

Thus, if the product E w is 1 $gm.m^{-3}$ and the rate of rainfall initially 1 mm. hr^{-1}, the intensity of the radar return should increase by 8.9 decibels per kilometre of fall of the rain relative to the cloud. Since $R \propto z^{\frac{1}{2}}$ approximately, the "decibel" increase in the rate of rainfall should be about half that of the above intensity. In either case, this increase is rather large.

The scarcity of published information about the w and droplet sizes of natural clouds prevents an accurate statement of the size of the product E w. However, Neiburger (1949) gives some measurements of w in stratus clouds over California, and shows some typical droplet-size distributions. Using one of these, and assuming an average E for all drop sizes, (for each cloud droplet radius), an effective E for this particular stratus cloud is 0.8. Taking an average w of 0.3 gm,m^{-3}, the produce E w becomes 0.24 and for R = 1 $mm.hr^{-1}$,

$$\frac{\Delta L}{\Delta x} = 2.1 \text{ db.km}^{-1}.$$

This is a more modest increase but still easily detectable.

A brief inspection of a few continuous rain pictures from an AN/TPS-10A radar, used for weather observations at Dawson College, St.John's, P.Q., reveals no detectable increase in radar return from rain below the freezing level. If future records confirm the increase to be very small, this might be attributed to clouds associated with continuous rain, (1) having a low w, and/or (2) having small effective E's, or (3) not extending very far below the freezing level. Or, it may be that in the case of continuous rain extending over a large area, the rain may very quickly "wash out" the large droplets from the cloud. If this is the case, one should expect to find the cloud in this region below the freezing level through which rain is falling, to be composed of tiny droplets only (less than 2 microns in radius).

APPENDIX

In the following pages, the complete experimental data are presented. The ten periods of observation are shown separately, three with Cloud I, five with Cloud II(c), and two with Cloud II(d).

The mean w and the mean Δm values for each period are shown below the data along with the collection efficiency, evaluated from $E' = k \frac{\Delta m_{MEAN}}{w_{MEAN}}$. With the mean w value for the period,,the percentage deviation of the measured values from it is given; with the mean Δm value, the percent probable error of the mean is given. Each value of E' is shown with its probable error, which is the sum of the percent errors in Δm_M and w_M, expressed in units of E'.

The nineteen E' values thus found are those shown in the graphs of Chapter 7; the summary of this data appears in Chapter 7, page 87.

CLOUD I

17 February

RUN	TIME (hrs)	CHARGE ON DROP	NUMBER OF DROPS	TIME FOR MEAS. RUN (m:s)	MEASURING RUN mass, before and after (gm)	GAIN (mgm)	TEST RUN mass, before and after (gm)	LOSS (mgm)	NET GAIN (mgm)	NET GAIN FOR 500 DROPS (mgm)
(1)	1625	0	503	4:20	137,6570 137.6690	12.0	137.6690 137.6411	27.9	39.9	39.7
(2)	1645	0	514	4:25	136.7740 136.7700	-4.0	136.7700 136.7319	38.1	34.1	33.2
(3)	1735	0	500	4:25	137.3940 137.4056	11.6	137.4056 137.3856	20.0	31.6	31.6

LIQUID WATER CONTENT
Before Only: 17.6 $gm.m^{-3}$
17.0

$w_M = 17.3\ gm.m^{-3} \pm 1.7\%$

ZERO CHARGE

$\Delta m_M = 34.8\ mgm \pm 4.8\%$

$E' = (16.0 \pm 1.0)\%$

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18 February

RUN	TIME (hrs)	CHARGE ON DROP	NUMBER OF DROPS	TIME FOR MEAS. RUN (m:s)	MEASURING RUN mass, before and after (gm)	GAIN (mgm)	TEST RUN mass, before and after (gm)	LOSS (mgm)	NET GAIN (mgm)	NET GAIN FOR 500 DROPS (mgm)
(1)	1145	0	500	4:10	146.4610 146.4890	28.0	146.4890 146.4830	6.0	34.0	34.0
(2)	1155	0	501	4:25	140.9355 140.9622	26.7	140.9622 140.4542	8.0	34.7	34.6
(3)	1220	-	503	4:10	139.4048 139.4289	24.1	139.4289 139.4203	8.6	32.7	32.5
(4)	1230	+	496	3:55	145.4949 145.5189	24.0	145.5189 145.5102	8.7	32.7	32.9
(5)	1245	0	500	4:15	135.6383 135.6602	21.9	135.6602 135.6475	12.8	34.7	34.7

LIQUID WATER CONTENT
Before: 17.2 $gm.m^{-3}$
After: 17.7

$w_M = 17.4_5 gm.m^{-3} \pm 1.4\%$

ZERO CHARGE

$\Delta m_M = 34.4\ mgm \pm 0.2\%$

$E' = (15.6 \pm 0.3)\%$

POSITIVE CHARGE

$\Delta m_M = 32.9\ mgm$

$E' = (15.0 \pm 0.2)\%$

NEGATIVE CHARGE

$\Delta m_M = 32.5\ mgm$

$E' = (14.8 \pm 0.2)\%$

CLOUD I

18 February

RUN	TIME (hrs)	CHARGE ON DROP	NUMBER OF DROPS	TIME FOR MEAS. RUN (m:s)	MEASURING RUN mass, before and after (gm)	GAIN (mgm)	TEST RUN mass, before and after (gm)	LOSS (mgm)	NET GAIN (mgm)	NET GAIN FOR 500 DROPS (mgm)
(1)	1610	0	501	4:25	143.5733 143.5949	21.6	143.5949 143.5830	11.9	33.5	33.4
(2)	1625	0	502	4:25	139.5106 139.5400	29.4	139.5400 139.5375	2.5	31.9	31.8
(3)	1640	0	506	4:15	145.7828 145.8151	32.3	145.8151 145.8177	-2.6	29.7	29.3
(4)	1655	0	509	4:25	137.2528 137.2801	27.3	137.2801 137.2708	9.3	36.6	36.0

LIQUID WATER CONTENT

Before: 16.0 $gm.m^{-3}$
21.5

After: 20.1
16.5

$w_M = 18.5 \pm 13\%$

ZERO CHARGE:

$\Delta m_n = 32.6$ mgm $\pm$ 2.8%

$E' = (14.0 \pm 2.1)\%$

CLOUD II(c)

8 February

RUN	TIME (hrs)	CHARGE ON DROP	NUMBER OF DROPS	TIME FOR MEAS. RUN (m:s)	MEASURING RUN mass, before and after (gm)	GAIN (mgm)	TEST RUN mass, before and after (gm)	LOSS (mgm)	NET GAIN (mgm)	NET GAIN FOR 500 DROPS (mgm)
(1)	1730	-	4:00	512	147.1059 147.1456	39.7	147.1456 147.1304	15.2	54.9	53.6
(2)	1745	-	4:15	512	138.2803 138.3113	31.0	138.3113 138.2946	16.7	47.7	46.6
(3)	1815	-	4:35	612	141.8461 141.8673	21.2	141.8673 141.8320	35.3	56.5	46.2
(4)	2015	-	4:05	514	145.1637 145.1918	28.1	145.1918 145.1710	20.8	48.9	47.6
(5)	2030	-	4:05	514	136.0490 136.0734	24.4	136.0734 136.0546	18.8	43.2	42.0

LIQUID WATER CONTENT
Before: 8.3 $gm.m^{-3}$
8.0
After: 7.6
7.5

$w_M = 7.8\ gm.m^{-3} \pm 3.7\%$

NEGATIVE CHARGE:

$\Delta m_M = 47.2$ mgm $\pm$ 2.6%

$E' = (45.8 \pm 2.9)\%$

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10 February

RUN	TIME (hrs)	CHARGE ON DROP	NUMBER OF DROPS	TIME FOR MEAS. RUN (m:s)	MEASURING RUN mass, before and after (gm)	GAIN (mgm)	TEST RUN mass, before and after (gm)	LOSS (mgm)	NET GAIN (mgm)	NET GAIN FOR 500 DROPS (mgm)
(1)	2140	0	4:10	516	145.8801 145.9290	48.9	145.9290 145.9162	12.8	61.7	59.8
(2)	2155	0	4:15	509	137.5747 137.6000	25.3	137.6000 137.5665	33.5	58.8	57.7
(3)	2200	0	4:10	511	145.6821 145.7213	39.2	145.7213 145.7015	19.8	59.0	57.6
(4)	2220	0	4:35	508	135.3810 135.4197	38.7	135.4197 135.3991	20.6	59.3	58.2

LIQUID WATER CONTENT
After Only: 8.0 $gm.m^{-3}$
7.5

$w_M = 7.7_5\ gm.m^{-3} \pm 3.2\%$

ZERO CHARGE:

$\Delta m_M = 58.3$ mgm $\pm$ 0.6%

$E' = (57.4 \pm 2.2)\%$

A.

CLOUD II(c)

15 February

RUN	TIME (hrs)	CHARGE ON DROP	NUMBER OF DROPS	TIME FOR MEAS. RUN (m:s)	MEASURING RUN mass, before and after (gm)	GAIN (mgm)	TEST RUN mass, before and after (gm)	LOSS (mgm)	NET GAIN (mgm)	NET GAIN FOR 500 DROPS (mgm)
(1)	1145	0	516	4:20	135.8652 135.8901	24.9	135.8901 135.8685	21.6	46.5	45.0
(2)	1210	0	503	3:55	137.6115 137.6346	23.1	137.6346 137.6100	24.6	47.7	47.3
(3)	1225	0	509	4:30	143.0185 143.0389	20.4	143.0389 143.0116	27.3	47.7	46.8
(4)	1240	0	511	4:20	135.5932 135.6158	22.6	135.6158 135.5922	23.6	46.2	45.2
(5)	1515	+	500	4:05	145.7614 145.7974	36.0	145.7974 145.7802	17.2	53.2	53.2
(6)	1525	+	504	4:25	136.7820 136.8091	27.1	136.8091 136.7816	17.5	44.6	44.2
(7)	1545	+	536	4:30	145.1874 145.1972	9.8	145.1972 145.1652	32.0	41.8	39.0
(8)	1630	0	511	4:20	145.6630 145.6945	31.5	145.6945 145.6780	16.5	48.0	47.0
(9)	1700	-	500	4:30	143.6923 143.7221	29.8	143.7221 143.7021	20.0	49.8	49.8
(10)	1715	-	504	4:15	136.3911 136.4260	24.9	136.4260 136.4074	18.6	43.5	43.1
(11)	1730	-	505	4:25	143.9925 144.0253	32.8	144.0253 144.0041	21.2	54.0	53.5
(12)	1750	-	508	4:25	136.6340 136.6615	33.5	136.6675 136.6520	15.5	49.0	48.2
(13)	1800	0	502	4:30	144.3583 144.3964	38.1	144.3964 144.3810	15.4	53.5	53.3

LIQUID WATER CONTENT

Before: 8.4 $gm.m^{-3}$
8.3

During: 7.6
8.0

After: 7.8

$w_M = 8.0\ gm.m^{-3} \pm 1.3\%$

ZERO CHARGE

$\Delta m_M = 47.4$ mgm $\pm$ 1.8%

$E' = (45.3 \pm 1.4)\%$

NEGATIVE CHARGE

$\Delta m_M = 48.7$ mgm $\pm$ 3.0%

$E' = (46.5 \pm 2.0)\%$

POSITIVE CHARGE

$\Delta m_M = 45.5$ mgm $\pm$6.8%

$E' = (43.4 \pm 3.5)\%$

CLOUD II(c)

16 February

RUN	TIME (hrs)	CHARGE ON DROP	NUMBER OF DROPS	TIME FOR MEAS. RUN (m:s)	MEASURING RUN mass, before and after (gm)	GAIN (mgm)	TEST RUN mass, before and after (gm)	LOSS (mgm)	NET GAIN (mgm)	NET GAIN FOR 500 DROPS (mgm)
(1)	1620	0	4:05	506	145.2898 145.3220	32.2	145.3220 145.3010	21.0	53.2	52.6
(2)	1635	0	4:10	503	138.2732 138.3110	37.8	138.3110 138.2900	21.0	58.8	58.5
(3)	1650	+	4:25	509	145.2382 145.2825	44.3	145.2825 145.2691	13.4	57.7	56.6
(4)	1705	+	4:30	511	133.7825 133.8212	38.7	133.8212 133.8020	19.2	57.9	56.6
(5)	1720	0	4:15	514	144.9880 145.0305	42.5	145.0305 145.0180	12.5	55.0	53.5

LIQUID WATER CONTENT
Before: 7.8 $gm.m^{-3}$
8.0
After: 7.8
7.9

$w_M = 7.9\ gm.m^{-3} \pm 0.6\%$

ZERO CHARGE

$\Delta m_M = 54.9$ mgm $\pm$ 2.2%

$E' = (52.5 \pm 1.5)\%$

POSITIVE CHARGE

$\Delta m_M = 56.6$ mgm $\pm$ 0.0%

$E' = (54.7 \pm 0.3)\%$

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14 February

RUN	TIME (hrs)	CHARGE ON DROP	NUMBER OF DROPS	TIME FOR MEAS. RUN (m:s)	MEASURING RUN mass, before and after (gm)	GAIN (mgm)	TEST RUN mass, before and after (gm)	LOSS (mgm)	NET GAIN (mgm)	NET GAIN FOR 500 DROPS (mgm)
(1)	1225	0	4:25	511	136.5893 136.6270	37.7	136.6270 136.6110	16.0	53.7	52.5
(2)	1235	0	4:25	506	143.6475 143.6806	33.1	143.6806 143.6630	17.6	50.7	50.1

LIQUID WATER CONTENT
After: 7.6 $gm.m^{-3}$
7.9

$w_M = 7.7_5\ gm.m^{-3} \pm 1.9\%$

ZERO CHARGE:

$\Delta m_M = 51.3$ mgm $\pm$ 1.6%

$E' = (50.6 \pm 1.3)\%$

CLOUD II(d)

22 February

RUN	TIME (hrs)	CHARGE ON DROPS	NUMBER OF DROPS	TIME FOR MEAS. RUN (m:s)	MEASURING RUN mass, before and after (gm)	GAIN (mgm)	TEST RUN mass, before and after (gm)	LOSS (mgm)	NET GAIN (mgm)	NET GAIN FOR 500 DROPS (mgm)
(1)	1555	0	507	4:05	146.7440 146.8186	74.6	146.8186 146.8065	12.1	86.7	85.5
(2)	1610	0	504	4:10	138.8900 138.9743	84.3	138.9743 138.9611	13.2	97.5	96.6
(3)	1620	0	500	4:15	144.4654 144.5350	69.6	144.5350 144.5242	10.8	80.4	80.4
(4)	1635	0	505	4:25	133.0709 133.1371	66.2	133.1371 133.1190	18.1	84.3	83.4
(5)	1645	-	502	4:15	146.9886 147.0521	63.5	147.0521 147.0364	15.7	79.2	79.0
(6)	1700	-	504	4:10	135.6426 135.7076	65.0	135.7076 135.6950	12.6	77.6	77.1
(7)	1715	+	502	4:25	144.4811 144.5504	69.3	144.5504 144.5290	21.4	90.7	90.3
(8)	1730	+	502	4:20	136.9700 136.0518	81.8	136.0518 136.0365	15.3	97.1	96.7

LIQUID WATER CONTENT

Before: 11.4 $gm.m^{-3}$
11.0

After: 10.4
10.6

$w_M = 10.8_5 gm.m^{-3} \pm 3.2\%$

ZERO CHARGE:

$\Delta m_M = 86.5$ mgm $\pm$ 3.4%

$E' = (60.9 \pm 4.0)\%$

NEGATIVE CHARGE:

$\Delta m_M = 78.1$ mgm $\pm$ 0.8%

$E' = (55.0 \pm 2.2)\%$

POSITIVE CHARGE:

$\Delta m_M = 93.5$ mgm $\pm$ 2.3%

$E' = (65.8 \pm 3.6)\%$

A.

CLOUD II(d)

25 February

RUN	TIME (hrs)	CHARGE ON DROP	NUMBER OF DROPS	TIME FOR MEAS. RUN (m:s)	MEASURING RUN mass, before and after (gm)	GAIN (mgm)	TEST RUN mass, before and after (gm)	LOSS (mgm)	NET GAIN (mgm)	NET GAIN FOR 500 DROPS (mgm)
(1)	1445	0	499	4:15	145.2502 145.3106	60.4	145.3106 145.2843	26.3	86.7	86.9
(2)	1500	0	505	4:20	136.5627 136.6268	64.1	136.6268 136.6110	15.8	79.9	79.2
(3)	1510	+	504	4:10	143.3763 143.4160	39.7	143.4160 143.3728	43.2	82.9	82.2
(4)	1530	+	508	4:30	137.2480 137.3200	72.0	137.3200 137.3052	14.8	86.8	85.4
(5)	1540	0	506	4:05	145.9708 146.0370	66.2	146.0370 146.0135	23.5	89.7	88.6
(6)	1555	-	501	4:35	136.1590 136.2148	55.8	136.2148 136.1862	28.6	84.4	84.2
(7)	1605	-	502	4:05	149.1753 149.2321	56.8	132.3610 132.3329	28.1	84.9	84.5
(8)	1620	0	502	4:15	137.9877 137.0536	65.9	137.0536 137.0310	22.6	88.5	88.1
(9)	1635	+	504	4:05	146.2694 146.3272	57.8	146.3272 146.3067	20.5	78.3	77.7
(10)	1645	+	504	4:20	134.5211 134.5761	55.0	134.5761 134.5491	27.0	82.0	81.5
(11)	1700	-	503	4:35	145.7281 145.7938	65.7	145.7938 145.7730	20.8	86.5	86.0

A.

LIQUID WATER CONTENT

Before: 10.2 $gm.m^{-3}$
10.0

After: 10.9
10.9

$w_M = 10.5\ gm.m^{-3} \pm 4.3\%$

ZERO CHARGE:

$\Delta m_M = 85.7$ mgm $\pm$ 1.5%

<u>E' = (62.5± 3.6)%</u>

NEGATIVE CHARGE:

$\Delta m_M = 84.9$ mgm $\pm$ 0.04%

<u>E' = (62.9 ± 2.9)%</u>

POSITIVE CHARGE:

$\Delta m_M = 81.7$mgm $\pm$ 1.2%

<u>E' = (59.7 ± 3.3)%</u>

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