THE DESIGN AND OPERATION OF A WILSON CLOUD CHAMBER

by

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1. Introduction

Statement of Problem

In this paper, the author is endeavoring to describe his efforts in the design, construction, and operation of a Wilson Cloud Chamber. The discussion and the cloud chamber itself are a first step in a broader program for the designing and building of adequate cloud chamber facilities for a future cosmic ray laboratory at the University of Arizona.

This project was divided into two phases: the first, the design and construction of a cloud chamber to be used for demonstration and/or research in cosmic radiation; the second, to operate the cloud chamber and to determine a procedure by which another person might operate it with a minimum amount of time loss in unnecessary steps.

Preliminary investigation revealed that most cloud chambers are built for either or both of two purposes, demonstration and/or research. The descriptions found in the literature were modified and the most desirable features were grouped together and adapted so that the required single chamber could be constructed. A few of the many possible combinations were drawn up and the best design
with respect to ease of operation and cost was chosen. The materials were then purchased and sent to Mr. Hartwein, the University machinist, together with detailed drawings, for the machining of the parts.

It was desired by the author that the procedure for the operation of the cloud chamber to its greatest effectiveness be determined. Some discussion of operating conditions is given in a book by J. G. Wilson (1). Though this book was of great help, it was by no means the solution to the effective operation required. Since the procedure had to be empirically determined, it should be pointed out that the conclusions reached do not necessarily give optimum operating conditions. There is always the possibility that some other set of conditions not investigated would bring better results. The procedure decided upon was specific in explanation and could be followed by another when using the chamber for the first time. This procedure will be discussed later in more detail.

Development of the Cloud Chamber

The cloud chamber was originally designed for the study of rain droplet formation on dust particles in an effort to provide an explanation for the common phenomenon, rain. At the present time, however, the cloud chamber has a greater value as it can be used in the study of cosmic ray phenomena, fission, artificial disintegration, alpha and beta particles, neutrons, gamma radiation and new
"elementary" particles.

Before continuing, it is necessary that the reader be made familiar with a few of the basic terms used in this discussion. Cloud chambers in general will be referred to as "cloud chambers" while the particular one designed, constructed and operated by the author will be referred to as "the Chamber". The "sensitive chamber", a feature common to all cloud chambers and to the Chamber, is a sealed compartment, filled with a non-condensable gas and a condensable vapor, in which the observable phenomena take place. The "control chamber", not common to all cloud chambers but present in the Chamber, is an air-tight compartment, in most cases adjacent to (in others, adjoining) the sensitive chamber. The pressure changes in this compartment stimulate a reaction in the sensitive chamber allowing the student to observe the various nuclear phenomena. Other terms, not used throughout the entire discussion, will be defined as necessary.

The first cloud chamber was probably built some seventy-five years ago. Around 1880 Aitken (2) started his investigations concerning the condensation of water vapor into drops. Attempting to produce the same conditions necessary for cloud formation, he found that when dust-free air was used, the drops would not be formed. According to his theory, it was necessary to have dust present in the air before water could condense into the form of droplets.
To reach his conclusion, he produced a supersaturated condition in a sealed chamber by causing a saturated vapor to undergo an expansion.

In 1897 C. T. R. Wilson (3) showed by a similar apparatus that droplets would form on agents other than dust particles. He made the speculation that charged particles might serve as nuclei for condensation. Two years later Wilson (4) found that X-rays and radioactive materials also produced, in some manner (now known as ionization), nuclei for condensation.

It was not until 1912 that Wilson (5) first used a cloud chamber to study the properties of various kinds of radiation. The 1912 model shown in Figure 1 consisted of a sensitive chamber, a control chamber, a water-sealed piston separating these two chambers, a clearing field (not shown), and a vacuum chamber which was connected to the control chamber by a valve. There was also another valve which connected the control chamber to the atmosphere. The actual working process of this model can be briefly explained as the creation of a supersaturated condition in the sensitive chamber by causing a saturated vapor to undergo an expansion. This was done by the opening of the valve connecting the control chamber to the atmosphere, allowing the air to enter the control chamber and thus compressing the gas in the sensitive chamber as the piston moved up. This valve was then closed and the other
valve, connecting the control and vacuum chambers, was opened, allowing the air to escape from the control chamber to the vacuum chamber. Thus the gas in the sensitive chamber expanded by pushing the piston down. By making a large number of expansions, Wilson was able to remove the dust from the sensitive chamber, and cause the supersaturated vapor to condense upon the ions present in this chamber. These ions, for the most part, were a result of the interaction of high energy charged particles with the non-condensable gas present in the chamber. Wilson found that a high energy charged particle (alpha particle) would leave in its path hundreds of ions on which the supersaturated vapor would condense to form drops. These drops formed a very thin trail which described the path of the charged particle through the chamber. The clearing field, made of two conducting rings in the sensitive chamber and connected to a battery by a switch, was turned on during the pause between expansions. This electric field removed almost all of the ions, so that in the next expansion there would not be a large number of stray ions. The stray ions remaining would act as condensing nuclei and would be visible as well as the desired tracks. If the number of stray ions were too great, the tracks would not be distinguishable. By the repetition of this experimental procedure, Wilson was able to see and to study the various properties of different kinds of radiation.
Figure 1.

Figure 2.
One of the earliest modifications of Wilson's cloud chamber was made by Shimizu (6) in 1921. In his cloud chamber, Shimizu eliminated the vacuum system, the control chamber, and the valves, as shown in Figure 2. He replaced them with a new mechanism for expansion which was a reciprocating piston driven by a slowly turning wheel. This created a sinusoidal movement of the piston rather than the 'jerky' movement produced in Wilson's cloud chamber. Because of this sinusoidal movement, good results were not obtained due to the fact that the ions forming the trails of high energy charged particles would diffuse before the expansion was complete.

To correct for the shortcomings of the Shimizu cloud chamber, P. M. S. Blackett (7) in 1927, made a few changes as shown in Figure 3. He introduced a stop to prevent the sinusoidal action of the piston. This small stop device was a metal block, which when inserted under lever arm prevented the arm from following the complete cycle allowed by the wheel. Instead, the lever arm was restricted to a half cycle. Also introduced in the Blackett chamber was the rubber seal used to separate the sensitive chamber from the atmosphere. This eliminated the friction which had been present in the Shimizu cloud chamber where it had been necessary to seal the sensitive chamber with a tightly fitting piston. In the Blackett chamber there were many breakdowns, though the cloud chamber averaged
Figure 3.

Figure 4.
two hundred seventy expansions per hour.

Nineteen thirty-three was a year of great changes for the cloud chamber. First, C. T. R. Wilson (8) changed from a piston diaphragm operation to just a diaphragm. He used compressed air in the control chamber (Figure 4) to expand the diaphragm. The quality of the tracks, or trail of droplets, produced was better than those obtained by either Shimizu or Blackett as the fineness of the detail appearing in the photographs of the sensitive chamber was much improved.

Not brought out in Wilson's article was the fact that his chamber could be operated in any orientation without changing the design. This cloud chamber had been preceded by the original Wilson chamber which could be operated only in a horizontal orientation because of the water which sealed the piston, and the Shimizu and Blackett chambers which could be operated in either a horizontal or vertical orientation. Using Wilson's newest chamber, with the changes mentioned above, any orientation necessary for specific problems studied could be used.

Dahl, Hafstad, and Tuve (9) constructed a cloud chamber which was designed to allow easy adjustment for a loss of gas in the sensitive chamber. A loss of gas in the sensitive chamber (Figure 5) could be compensated by increasing the distance between the piston and the soft iron disk. This was done by changing the position of the lock
nuts (not shown) which held the piston and the disk to the rod. The pseudo-sensitive chamber contained the same gas vapor and under the same conditions as the sensitive chamber. However the inside of this chamber was completely hidden from view. An electro-magnet was used to move the piston, which produced the expansion of the gas in the sensitive chamber.

The big improvement was introduced by P. M. S. Blackett and G. F. S. Occialini (10) and more fully described a year later in another article by P. M. S. Blackett (11). In their experiment two Geiger counters, one above the chamber and one beneath, were connected to a coincidence circuit. A pulse from this circuit operated the expansion mechanism by opening a large valve with an electro-magnet. It is interesting to note that even though expansion should have occurred when both counters were tripped by a single ionizing particle, twenty-four out of the first hundred pictures showed no tracks. The twenty-four cases of blank pictures can, in part, be accounted for by the passage of two different particles through the counters, neither one of the particles having passed through the chamber. It is also likely that the circuit or the counters were misbehaving.

Moot-Smith (12) in 1934 designed a 'high-pressure' cloud chamber which operated at pressures of about fifteen atmospheres. The sensitive chamber (Figure 6) was sep-
arated from the control chamber by a thin diaphragm. Air from the control chamber was allowed to escape into a closed chamber (not shown). The closed chamber was designed in such a manner that only a small fraction of the air from the control chamber would enter the closed chamber. This prevented the diaphragm from being subjected to a large pressure difference, which would have ruptured it. The main reason for building this high pressure cloud chamber was that the gas in the sensitive chamber would have a much higher density. This meant that a single particle traveling a path one foot long in this cloud chamber would create as many ion pairs as a similar particle passing through an ordinary cloud chamber some ten feet deep. Large scale phenomena were shrunk into a much smaller volume, which made for easier study of the tracks. The main disadvantages were the long time necessary to reset the chamber for another expansion, and the bulkiness.

An important characteristic of any cloud chamber is the sensitive time. This can be defined as the length of time, during a single expansion, in which the chamber will record in the form of tracks, the paths of incident particles. A longer sensitive time, means that more tracks can be seen in a single expansion. In 1935 Bearden (13) designed a cloud chamber in which he tried to lengthen the sensitive time. This was accomplished with a bellows-type chamber connected to a dash pot. By adjusting the
valve on the dash pot piston (Figure 7), the rate of expansion could be changed. This meant that optimum conditions could be reached before the piston completed its stroke, and maintained while the piston was still in motion. More tracks were recorded for each expansion, though the quality was poorer than that obtained in Wilson's 1933 cloud chamber.

From 1935 to the present, many attempts have been made to increase the sensitive time to the order of magnitude of a few hours. The first successful continuously sensitive or diffusion-type cloud chamber was that designed by Langsdorf (14) in 1939. As one can see from Figure 8 the chamber was quite simple in construction and had no moving parts. To produce the required supersaturation, a vertical temperature gradient of about twenty degrees centigrade per centimeter was maintained. The main difficulty was the presence of convection currents, produced by the high temperature gradient, which distorted the tracks.

C. T. R. Wilson and J. G. Wilson (15) worked together in 1935 to introduce a falling cloud chamber and a radial expansion cloud chamber. The radial expansion cloud chamber (Figure 9) was composed of three compartments or chambers. They were the sensitive chamber, the control chamber, and a pseudo-sensitive chamber, located between the sensitive and control chambers. This pseudo-sensitive chamber was separated from the sensitive chamber by a porous
Figure 7.

Figure 8.
cylinder, which prevented the uneven radial expansion present in the pseudo-sensitive chamber from being present in the sensitive chamber. Though the pseudo-sensitive chamber contained the same mixture of gas and vapor as were used in the sensitive chamber, the uneven radial expansion produced too much distortion of the tracks. When a track forms inside the sensitive chamber, the main distorting force is that of gravity. By allowing the entire cloud chamber to fall when a particle tripped the counters, distortion due to gravity was removed to a large extent. Very little use has been made of these two principles. The falling cloud chamber involved too many engineering problems for the advantages achieved. The radial expansion cloud chamber gave rise to too much distortion of the tracks near the edges of the porous cylinder. However, the upper half of the cloud chamber shown in Figure 9 looks like a flat disk, and is applicable to situations where it is necessary to place the sensitive chamber in a very narrow space. The placing of a cloud chamber between the poles of a magnet is such a situation. Charged particles traveling perpendicular to the direction of the magnetic field are caused to move in arcs of circles. Knowledge of the magnetic field intensity and the radius of curvature of the arc is sufficient for the determination of the momentum of the particle.

It is hard to say who was the first to make use of a deflecting magnetic field in the sensitive chamber. The
The earliest mentioned experimenter was Kapitza (16) who published a paper in 1926 describing a cloud chamber inside a large magnet. The main difficulty was that the cloud chamber and the camera had to be placed between the poles of the magnet, which reduced the magnetic field considerably. This difficulty has been remedied by the use of mirrors, or by placing the camera in a hollowed-out portion of one of the magnetic poles.

The Cloud Chamber Today

Many of the designs described in the previous section are still being used and improved upon today. For example, the continuously sensitive cloud chamber received a great deal of attention during the period from 1950 to 1952. Weddle and Nielsen (17) worked with an upward diffusion chamber. It was constructed in a similar manner to that shown in Figure 8, except that the bottom of the chamber was heated and the top cooled. Miller, Fowler, and Shutt (18) used a diffusion cloud chamber with a pressure of fifteen atmospheres. As a gas they used hydrogen, which is not usually used in high pressure or medium high pressure cloud chambers, because of its low density. Choyke and Nielsen (19) describe a low-pressure continuously sensitive cloud chamber, similar to that designed by Langsdorf, for the study of low energy events.

The rapidly reciprocating cloud chambers shown in Figures 2 and 3 were revived by Gaerttner and Yester (20)
for work with a pulsed accelerator. Fireman and McHaney (21) and Hodson, Loria, and Ryder (22) went a step further than Blackett and Occhialini (10) and built their counters inside the cloud chambers. These counters were not sealed off from the sensitive chambers. Therefore, when a picture was taken of the tracks it would show the discharge of the counter that tripped the expansion.

A number of articles have appeared describing cloud chambers containing an ionization chamber. Cohen (23) and Bridge, Hazen, Rossi, and Williams (24) used the ionization chamber to collect the negative ions. In their cloud chamber an electric pulse was amplified, recorded, and then used to trip the expansion of the cloud chamber. Droplets were formed on the remaining positive ions which produced fair quality tracks.

In spite of the large cost and construction difficulties, high pressure cloud chambers are still being built. Johnson and Shutt (25) describe a chamber operating under three hundred atmospheres of pressure, as compared to the fifteen atmosphere 'high pressure' cloud chamber of Moot-Smith. As was pointed out previously, high pressure cloud chambers record large scale phenomena in a small sensitive chamber. There are other methods used today to record large scale phenomena without building a huge sensitive chamber of say one hundred cubic feet. One method is to place a number of thin sheets of absorbers in the sensi-
tive chamber. This is not so effective as a high pressure chamber because it is impossible to observe events taking place in the absorbers. Another method is to use two or more cloud chambers separated by much thicker sheets of absorbers, usually from two to twelve inches thick. The main advantage to either of the two arrangements is the convenience of inserting these sheets, and the very low cost of adapting one or more cloud chambers for this application.

Attempts are being made continually to reduce the background fog and track distortions. These two defects determine the upper limits of accuracy of all observations made with a cloud chamber. Progress today is slow, as background fog and track distortion have been subjects for investigation for more than forty years. Another limitation to the accuracy obtainable with a cloud chamber is in the measurement of curvature of the tracks from photographs. Only rarely does the path of an incident particle lie in a plane parallel to the film in the camera. Bromly and Bradfield (29) recorded information with two cameras and then reproduced the track with two projectors, giving a three-dimensional effect.

Of the sources used for this discussion perhaps the best article on cloud chambers was that written by Das Gupta and Ghosh (26) about eight years ago. A good description of cloud chambers with particular emphasis on
application to cosmic ray research is in a book by Montgomery (27). H. Staub (28) covers a large number of detecting instruments in both theory and application. His theoretical discussion of droplet formation, though brief, is well done.
II. Theory of Drop Formation

The cloud chamber is an extremely useful tool in nuclear physics because of the great amount of information it can give about a single event. Its most important application is in cosmic ray physics. As fast moving, charged particles pass through a gas and vapor mixture, the gas molecules are ionized along the path of the particle. If the right conditions exist within the chamber, these gas ions can be made to act as nuclei for condensing vapor. The result will be visible water drops formed in the path of the incident particle. For the operation of a cloud chamber it is important to know under what conditions the vapor will condense on the ions.

In 1870 Lord Kelvin (see Das Gupta and Ghosh (26) worked out a fundamental relationship which is used to explain the growth of water drops.

1) \[ \ln \frac{P}{P^*} = \frac{2TM}{Rd\theta dr} \]

Where \( P \) and \( P^* \) are respectively the vapor pressures of a sphere of radius \( r \), and of a plane sheet; \( T \) is the surface tension, \( d \) is the density, and \( M \) is the molecular weight of the liquid; \( R \) is the universal gas constant; and \( \theta \) is the temperature (Kelvin). A close examination of the right hand side of equation (1) shows that \( P \) cannot be equal to \( P^* \) since the quantity on the right cannot be zero.
That is, of course, neglecting trivial cases where the drop has an infinite radius, or zero surface tension.

Suppose that a condition of supersaturation can be created above a plane surface of a liquid. It is possible to define the term, degree of supersaturation \( S \), by the relationship

\[
2) \quad S = \frac{P_S}{P^*}
\]

where \( P_S \) is the vapor pressure of the supersaturated vapor, and would, of course, be greater than \( P^* \). Now if the supersaturated vapor were in equilibrium with a droplet of radius \( r \), the following would hold, since \( P_S = P \)

\[
3) \quad S = \frac{2TM}{R\delta dr}
\]

Solving for the radius in terms of the degree of supersaturation we have

\[
4) \quad r = \frac{R\delta d}{2TM} \left[ \ln S \right]^{-1}
\]

A drop with a radius larger than the equilibrium value will grow in size indefinitely. A drop with smaller radius will evaporate. This is a case of unstable equilibrium. In Figure 10, values of \( S \) are plotted against \( r \). Drops to the left of the curve evaporate, while drops to the right will grow larger. Since dust particles have radii from \( 10^{-4} \) to \( 10^{-6} \) cm., they will serve as nuclei for low values of \( S \) (1.001 to 1.12 respectively). A water
molecule has a radius of $1.5 \times 10^{-8}$ cm. It would require a supersaturation greater than 235 for the molecule to act as a nucleus. Diatomic molecules have radii up to about $3 \times 10^{-8}$ cm, and would require a supersaturation of about 50 to act as a nucleus of condensation. Aggregates of molecules and large polyatomic molecules resulting from contamination usually have radii greater than $5 \times 10^{-8}$ cm. These present a problem in the operation of a cloud chamber and will be discussed in greater detail later.

In a cloud chamber ions resulting from collisions of high energy charged particles with gas molecules act as nuclei for condensation. A relationship similar to equation (1) is given by H. H. Staub (28):

$$\ln S = \frac{M}{R \theta d r} \left(2T - \frac{e^2}{6\pi \varepsilon r^3} - \frac{K - 1}{K}\right)$$

where $e$ is the charge on the ion, and $K$ is the dielectric constant of the liquid. An exact solution of (5) for $r$ would be quite difficult. As was done in Figure 10 for equation (4), Figure 11 shows the relation between the supersaturation and the radius for a singly charged droplet. The points A, B, and C represent drops whose position on the graph indicate their size ($r$) and the degree of supersaturation ($S$) that surrounds them. The arrows indicate the tendency of the drops either to grow or to evaporate. Under the curve all drops will tend to evaporate, while above the curve they will tend to condense. However, a drop (A) under the curve will not evaporate to
zero radius, but to the point of intersection with the curve at a point near a'. A point (B) outside the curve but below and to the left of the maximum point (M) will grow until it also intersects the curve at some point near b'. The portion of the curve to the left of (M) represents a state of stable equilibrium. All charged drops (C) to the right of the curve from (M) to r equals infinity, or above the point (M) will tend to grow indefinitely. The remaining portion of the curve to the left of (M) represents unstable equilibrium.

The arrows that represent growth tendencies indicate constant value of S, which in actual operation is not the case. The dotted lines indicate more nearly the actual paths that drops represented by points (C) would take. These drops would grow until they reached the curve at c' and c". As the supersaturation continues to fall, the state of the drop initially at c' will slide along the curve to c" where equilibrium between the supersaturated vapor and plane surface ($P_S = P^*$) is achieved. The drop at c" will evaporate along some curve going from c" to c"'. The point c"' corresponds to a supersaturation of one. The slope of the dotted lines depends upon the number of growing drops present, as they compete for the excess vapor present. In general larger numbers of growing drops will give steeper slopes.

In a Wilson cloud chamber the supersaturation is
produced by an adiabatic expansion of a gas and vapor mixture. We wish to control this expansion so as to produce a particular degree of supersaturation. Let us consider a vapor whose mass is \( m_0 \), and is originally at a pressure \( P_0 \), in a volume \( V_0 \), and at a temperature \( \theta_0 \).

6) \[ P_0 V_0 = m_0 R \theta_0 \]

Suppose that this vapor undergoes an adiabatic expansion. Immediately following the expansion we have

7) \[ P_1 V_1 = m_0 R \theta_1 \]

If the vapor is saturated before expansion, then it will be supersaturated after expansion, since the mass is the same and the temperature lower. The vapor will condense until equilibrium is reached. At which time

8) \[ P_2 V_1 = m_2 R \theta_2 \]

This condensation will change the temperature only slightly, so that to a good approximation \( \theta_1 \approx \theta_2 \). Therefore

9) \[ P_2 V_1 = m_2 R \theta_1 \]

Solving for \( m_0/m_2 \)

10) \[ \frac{m_0}{m_2} = \frac{P_0 V_0 \theta_1}{P_2 V_1 \theta_0} \]

For an adiabatic process

11) \[ \theta_0 V_o^{-1} = \theta_1 V_1^{-1} \]

12) \[ \frac{m_0}{m_2} = \frac{P_0 V_0}{P_2 V_1} \]

The ratio \( V_1/V_0 \) is called the expansion ratio \( E \). It can be easily measured from the geometry of the cloud chamber. The ratio \( m_0/m_2 \) is the mass of the vapor present divided
by the mass of the vapor present at equilibrium, the
temperature being held constant. This is the usual defini­
tion of degree of saturation (or supersaturation). Re­
writing equation (12)

\[ S = \frac{P_0}{P_2} \left( \frac{1}{E} \right)^{\gamma} \]

The value of \( \gamma \) is not that of the vapor, but of the vapor
and gas mixture. It can be calculated by the following
equation given by Das Gupta and Ghosh (26)

\[ \gamma = 1 + \frac{\sum P_1}{\sum \frac{P_1}{\eta - 1}} \]

where \( P_1 \) is the partial vapor pressure due to the gas or
vapor 1.

Figure 11 indicates that a supersaturation of four
will allow condensation on charged particles of all sizes.
In practice, however, the supersaturation is made greater
than this minimum value. H. H. Staub (28) indicates for
water vapor the best tracks are produced at supersaturation
of 5.7, for ethyl alcohol 2.5, and for an optimum mixture
of water and ethyl alcohol (40% to 60% by volume) 1.9.
III. Design of the Chamber

As was previously mentioned, the Chamber was the first step in a program to build cloud chamber facilities for a cosmic ray laboratory at the University of Arizona. Though the continuously sensitive cloud chamber is the simplest to construct and put into operation, and the easiest to demonstrate, it does not give good enough tracks to be used for research. Because of this last characteristic it was decided that the first project would not be a continuous type chamber. The type of cloud chamber meeting all the requirements best was the Wilson cloud chamber shown in Figure (12). By changing certain features of this chamber it was possible to meet the requirements even better. After a number of designs were drawn, the one shown in Figure (13) was selected.

Sensitive Chamber

Figure (13) shows the sensitive chamber defined by: a pyrex cylinder, three eighths of an inch thick, eight inches high, with a twelve inch outside diameter; a window of mirror quality plate glass, half an inch thick and cut in a circle twelve inches in diameter; and a quarter inch brass plate, fifteen inches square, with about eighty quarter inch holes evenly spaced over a circular area eleven and a half inches in diameter and centered at the
Figure 12

From Das Gupta and Ghosh
Control Rod
Threaded Sleeve
Piston Support
Fast Valve
Back Brass Plate
Perforated Brass Plate
Hex Brass Rods
Diaphragms
Sensitive Chamber
Pyrex Cylinder
Front Brass Plate
Glass Window
Window Brackets

Figure 13
center of the plate. Between the window and the cylinder was a half inch brass plate, fifteen inches on a side, with a ten-inch diameter hole cut out of the center. The brass plates were separated from the cylinder and the window by gaskets cut from a sheet of Ameripol D-2 1/4 (neoprene), one sixteenth of an inch thick. The two brass plates were held together by twelve half-inch diameter hex brass rods. Twelve L shaped brackets pressed the glass window against the front brass plate.

It was decided that since the pyrex cylinder would be the most difficult part to obtain, it should be ordered first. An extra deep cylinder was chosen with the idea that it could be cut down if necessary. The front window was first ordered in pyrex, but because of the poor quality of the window received, it was returned and a mirror quality plate glass window purchased.

Since it was unknown at the time of design, just how much stress would be placed on the window, half-inch glass was used to prevent breaking. Also it was believed that the pyrex cylinder would not be able to withstand so great a force as would the glass window. Therefore a half-inch front brass plate was placed between the two pieces of glass so that the force on one of them would be independent of that on the other. Other advantages obtained were: the operator could make changes inside the sensitive chamber by removing only the front glass window, and brass plate.
could be used to support horizontally placed sheets of various materials inside the sensitive chamber.

On the back edge of the pyrex cylinder was placed a quarter-inch brass plate through which was drilled a large number of holes. By spacing the holes uniformly it was hoped that any uneven or turbulent expansion produced between the plate and the diaphragm could be eliminated in part by the perforated brass plate. The turbulence could be further reduced by plugging up the appropriate holes with small corks.

Neoprene was chosen for a gasket material because it resists grease and alcohol much better than does gum rubber. It was originally planned that one thirty-second of an inch stock would be used for the diaphragm. However, we were unable to obtain this thinner stock in quantities less than twenty-five square yards, so an identical Hycar sheet was purchased.

As a device to help prevent the breaking of the glass parts Allen-head bolts were used. This type of bolt was used throughout the chamber, even where no glass parts were involved. The Allen-head bolt requires a special type of tool which is available only with a short handle. This made it difficult for the operator to apply a very large torque to the bolts.

The clearing field electrodes were made of two strips of aluminum foil cemented to the glass cylinder. They did
not encircle the cylinder because it was felt that a short circuit could result if condensed vapor on the bottom of the cylinder were to form a connection between them. A 6,000 volt radio-frequency supply (see Figure 14) was used to provide the electric field. By assuming the semi-circular electrodes were parallel plates, the field strength was calculated. The calculated value of three hundred volts per centimeter was larger than the actual value. H. H. Staub (28) mentioned that the values of the field strength for cloud chamber clearing fields ranged from ten volts per centimeter to three hundred volts per centimeter. It was possible to apply the six thousand volts to the electrodes only after an extra gasket was placed on each end of the pyrex cylinder for insulation from the brass plates. The low current feature of this power supply was desirable as it was safe to work around the chamber with the supply on. Another method of constructing a clearing field has been reported by Klaiber and Baldwin (30) who coated the front glass with a highly transparent conducting material.

**Control Chamber**

The control chamber consists of a quarter-inch brass cylinder with an inside diameter of twelve inches, a brass piston, the diaphragm, and the quarter-inch back brass plate. As shown in Figure 13, the brass cylinder and the perforated brass plate are pressed together tightly to hold
Figure 14

Perforated Brass Plate

Figure 15
the diaphragm in place. At the time of design it was not known just how much pressure would be necessary to prevent the diaphragm from pulling away from the plate and cylinder, so a thick seamless brass cylinder was purchased. The back brass plate was held against the brass cylinder by twelve hex rods and bolts. Gaskets were used between all brass components connected to the control chamber in order to prevent leaks. The two sets of hex brass rods were fastened to the perforated brass plate by means of studs. All bolts, studs, rods, and nuts used in the cloud chamber were one quarter inch in diameter and had twenty-eight threads to the inch (called S.A.E. or National Fine threads).

Expansion Ratio Control

The diaphragm was limited in its motion by the perforated brass plate and the piston. The position of the piston is adjusted from the outside by the threaded control rod. Originally it was intended that the diaphragm be attached to the piston with a cement. This idea was discarded when it was found that none of the available glues or cements would hold. The first method actually tried was to allow the diaphragm to move back and forth between the perforated plate and the piston, the latter acting as a stop.

Figure 15 shows the diaphragm in three different positions. Though the information used for this figure
was obtained under static conditions, it was believed that the position of the piston during an expansion would follow the indicated pattern. This was further substantiated by the observation of turbulence in the sensitive chamber. To correct for the uneven expansion of the diaphragm, which produced a greater expansion at the center than at the edges, a number of holes (eight) in the perforated brass plate were plugged with corks. When some of the center holes were stopped with these corks a definite reduction in the turbulence was observed.

When the Hycar sheet finally did arrive another arrangement (shown in Figure 16) was tried. This arrangement called for two diaphragms with the piston in between. As can be seen in the figure, the two diaphragms remained close to the piston even during a fast expansion. The only way that the front diaphragm could bulge would be for air to become trapped between the diaphragms.

The motion of the piston was limited by the perforated brass plate and the control rod. Two control rods, the longer one for smaller expansion ratios and the shorter for larger expansion ratios were constructed so that a large range of expansion ratios could be used, varying from 1.00 to 1.35. Though this wide range could have been achieved with a single rod, two rods proved to be the most economical.

In the chapter on droplet formation, it was assumed
that the expansion of the gas in the sensitive chamber would be adiabatic. This would require an instantaneous expansion, or an infinite force on the diaphragm. A slow expansion has the effect of reducing the degree of supersaturation, as it allows more time for heat to go from the walls of the sensitive chamber to the gas inside. To reduce the time necessary for the expansion to take place, the mass of the piston was made as small as possible. This was done by hollowing out the piston support. When the piston was against the perforated brass plate there was a small quantity of air trapped between the piston support and the control rod. To prevent this air from acting as a cushion and slowing down the expansion, two small holes were bored in the supporting rod as shown in Figure 16.

Fast Valve

The actual design of this valve was one of the most difficult jobs. In order to obtain fast expansions it is necessary to get the air out of the control chamber as quickly as possible. This meant a valve with a long stroke and large surface area. The area of the valve was limited by the force that the compressed air inside the control chamber exerted on it and by the space remaining on the back plate of the Chamber.

A magnet was obtained from an old loud speaker. By the size of the wire it was estimated that a pulse of fifteen amps for about five seconds would cause a rise in
temperature of about one or two degrees. Since it was not known what pressure would be used in the control chamber to force the piston against the perforated brass plate, the dimensions of the valve were estimated from the valve shown in Figure 12. The estimate turned out to be the maximum size that could be conveniently made with this particular loud speaker magnet. About the only changes made in the magnet were the drilling of a few holes for the valve stem and threaded rods, and the cutting away of the housing so that the valve could come in contact with the core of the magnet.

By moving the nuts that hold the magnet housing in place, the magnet can be held at any distance away from the valve seat, which determines the stroke of the valve. The area of the valve cannot be changed so easily, since it depends upon the size of the opening in the valve seat. About the only way to change the effective area of the valve would be to make another valve seat with the proper size of the opening.

The valve spring holds the valve to the valve seat by pushing on the spring seat, which is firmly attached to the valve stem. Greater force can be applied to the valve by compressing the valve with the adjustment bar. A round piece of neoprene was cemented to the valve to insure a good seal.

Descriptions of other valves can be found in articles
by Fu-Hsing Chu and G. E. Valley (31), J. L. Zar (32),
R. P. Shutt and W. L. Whittemore (33), and B. Meyer and
W. Stodick (34).

Illumination

Proper illumination of the sensitive chamber is very
important, especially if the tracks, composed of very fine
droplets of water, are to be photographed. In most cloud
chambers the light strikes the droplets perpendicular to
the direction of observation (either by eye or camera).
Recently two authors, R. R. Rau (35) and E. W. Cowan (36),
have constructed cloud chambers illuminated from the rear,
so that the light is directed almost into the camera.

This method of illumination does not really concern
us as the Chamber was designed so that rear illumination
could not be used. In either case, it is desirable that
very little light be reflected by the back wall of the
sensitive chamber while the droplets must be illuminated
to the maximum extent. The first step was to darken the
bright brass parts inside the sensitive chamber with a
dull black paint. A piece of black felt or black cotton,
when placed over the front side of the perforated brass
plate, would lessen the reflection as well as tend to remove
turbulence from the sensitive chamber. As the difference
between using the black cloth and the black paint inside
the sensitive chamber was not detectable, the easiest method,
which was the paint, was used.
The background was cut down still further by not allowing the light to shine directly upon the perforated brass plate. This was accomplished by using a parallel beam of light from a fluorescent tube, placed at the focus of a cylindrical mirror shaped in a parabola. The light that entered the sensitive chamber without first being reflected by the mirror was removed from the beam by painting the portion of the fluorescent tube that faced the sensitive chamber black. While painting the tube darkened the background, it also produced a region of slightly lower intensity in the center of the sensitive chamber as shown in Figure 18. By moving the source about an inch away from the focus toward the Chamber, the beam of light was made to converge slightly (see Figure 19). This last arrangement gave a fair illumination throughout the sensitive chamber, with very little background.

Other Controls

In addition to the fast expansion valve were two other valves. One connected the control chamber to the compressor and the other, the control chamber to the atmosphere. Schematically the valves are arranged exactly the same way as were the valves in Wilson's radial expansion cloud chamber (see Figure 9). The valve connecting the control chamber with the atmosphere is called the slow expansion valve.

Sources of Materials

All brass used in the Chamber was purchased from the
Source at Focus

Sensitive Chamber

Source 1" away From Focus

Figure 18

Figure 19
American Copper and Brass Company. From the American Packing and Gasket Company were purchased the pyrex cylinder, the pyrex window (returned because of poor quality), and the Hycar sheet. Thunderbird Sales Corporation provided us with the D-24 Ameripol (neoprene) sheet. A number of companies were consulted for various types of relays. Answers were received from Tung-Sol, Western Electric, Leach Relay Company, and Advance Electric and Relay Company. Tung-Sol had the best line of time delay relays and Advance Electric had the most complete selection.
IV. Operation

The instruction given in this chapter should be followed for the first few times that the operator uses the Chamber. Short cuts can be taken, but not before the operator has followed the procedure indicated at least once.

Assembly

The sensitive chamber must be cleansed of all dirt and foreign matter, because these materials tend to get into the sensitive gas and act as condensation nuclei. The brass plates were cleaned with Dutch Cleanser, which acted as a fine abrasive. Afterwards the plates were rinsed with tap water. Carbon tetrachloride was used to clean the gaskets and diaphragm. It was noted that the cloth used with the carbon tetrachloride was blackened, which indicated that the carbon tetrachloride reacted with the neoprene. The blackening was so slight that no other cleaners were tried. Finally the cylinder and the window were cleaned with carbon tetrachloride to remove the grease. Next came a washing with Dreft and a rinsing with plenty of water. This wash and rinse process was repeated three to five times. Following the final rinse the glass was rinsed in distilled water. All parts were allowed to dry before they were assembled.

The twelve long hex rods and the twelve short hex rods
were attached to the perforated brass plate. Next the dia-
phragm, brass cylinder, gasket, and back plate were joined
together. The valve and expansion control usually were
left attached to the back plate, otherwise they now should
be attached.

The diaphragm material was not stretched to the full
extent the first time it was used. Instead the piston
was held two, four, and then six centimeters from the
perforated plate by a pressure difference between the control
and sensitive chambers. This pressure difference was usually
provided by reducing the pressure in the control chamber
below atmospheric. It would have been possible to have
assembled the Chamber and raised the pressure in the sensi-
tive chamber above atmospheric. The three positions indi-
cated above were held for eight hours each, which helped to
fatigue the diaphragm. Failure to fatigue the diaphragm
may cause it to rupture when first stretched.

After the stretching period, measurements were made of
the distance (d) between the perforated brass plate and the
front diaphragm, and the distance (c) between the knob on
the control rod and the threaded sleeve (Figure 13) as
functions of the pressure difference (p) between the control
chamber and the atmosphere in the following manner. The
long control rod was inserted in the threaded sleeve and
tightened down until it pressed the piston against the per-
forated plate. Since there was no pressure gauge connected
to the control chamber, both the compressor tank, which had a gauge, and the control chamber were evacuated together. The control rod was backed off one centimeter and the pressure in the control chamber reduced until the piston support met the control rod, determined by the measurement of the distance between the diaphragm and the perforated plate. This process was repeated until the piston reached the maximum point reached in the fatiguing process, and the values obtained were recorded for later use. Two new Hycar diaphragms, arranged as shown in Figure 16, were used for the following numbers. The distance (c) was exactly one centimeter longer than (d) and therefore omitted from the table.

<table>
<thead>
<tr>
<th>Distance in cm. from plate to diaphragm</th>
<th>0.0</th>
<th>1.0</th>
<th>2.0</th>
<th>3.0</th>
<th>4.0</th>
<th>5.0</th>
<th>6.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure in lb./in.²</td>
<td>0.0</td>
<td>0.1</td>
<td>0.3</td>
<td>0.7</td>
<td>1.0</td>
<td>1.3</td>
<td>2.0</td>
</tr>
</tbody>
</table>

The gaskets were given a very thin coating of vacuum grease along the portion which would be pressed by the cylinder and the brass plates. Then the gaskets, pyrex cylinder, and brass plates were placed in position, and the bolts tightened just enough to hold the cylinder firmly in place. At no time was a bolt tightened with a jerk, as this is an excellent way to strip threads, or more important, to break the glass. Before the glass plate was placed on the Chamber, 4.0 cc. of the condensed vapor were poured on the floor of the chamber. The desired amount of any liquid should be just enough so that five or six drops will remain on the bottom of the pyrex cylinder after the sensitive
chamber reaches saturation. More than this amount does not improve the operation of the chamber and can be undesirable if the liquid reacts with the grease used to seal the chamber. If a radioactive source was desired inside the sensitive chamber it was inserted at this time. The glass plate was separated from the front brass plate by a gasket, held in position with two blocks of wood, and tightened in the same manner as was the cylinder. Care should be taken to see that the plate does not touch any of the bolts as this was believed to have caused the breaking of a glass plate.

**Production of Tracks**

A vacuum pump was connected to the valve on the front plate and the air in the sensitive chamber removed. Care was taken so that too much of the vapor was not removed from the sensitive chamber, otherwise it would be impossible to obtain a saturated condition before an expansion. The first time the Chamber was filled, both the liquid and the gas were loaded through the side valve. This caused a mess on the front glass window as the liquid squirted in, which later left spots after the liquid evaporated. The control valve was adjusted so that the piston could move only four centimeters from the perforated brass plate. Gas was forced into the sensitive chamber until the pressure inside the sensitive chamber was just enough to displace the piston four centimeters from the perforated plate.

On page 27, the degree of supersaturation is given in
terms of the expansion ratio \( E \), the pressure \( P_0 \) of the gas before an expansion, the pressure \( P_2 \) of the gas after an expansion, and the ratio of the specific heats of the gas and vapor mixture \( \gamma \). If \( \gamma \) is not known it should be determined from equation (14). The expansion ratio was calculated from its definition on page 26. Since the gas was enclosed in approximately a right circular cylinder, the ratio of the volumes would be approximately equal to the ratio of the distances, before and after an expansion, from the diaphragm to the glass window. The valve connecting the compressor and the control chamber was opened until the pressure in the control chamber was the same as that in the compressor (about twelve pounds per square inch).

About thirty seconds were allowed for the gas to reach thermal equilibrium with the Chamber, the pressure was observed the instant before and the instant after a fast expansion. After the gauge pressures were changed to absolute pressures, the values of \( P_0 \), \( P_2 \), \( E \), and \( \gamma \) were substituted into equation 13. The calculated value of \( S \) was compared with the desired supersaturation and an estimation made of a better value for \( E \). The control rod was then set for the estimated expansion ratio and another expansion made. Again the degree of supersaturation was computed and another expansion ratio tried, until finally the desired degree of supersaturation was reached. As the Chamber leaked about a pound per square inch per week, it was
necessary to add about two extra pounds of pressure. The extra pressure was desirable as it gave the piston a greater acceleration, thus speeding up the expansion.

It is suggested by the author that the Chamber be allowed to stand for several hours after filling. Though the Chamber will have to stand about fifteen minutes for the gas to become saturated, the additional time allows a large amount of the dust to settle out of the sensitive gas. Whether or not the dust is allowed to settle, a number of slow expansions must be made. The fastest way to get rid of the dust is to maintain the correct supersaturation for long periods of time. A slow expansion acts in two ways to settle dust particles. First, the degree of supersaturation is lower than that produced by a fast expansion. As low supersaturations do not favor the growth of very small droplets, these small particles will not be able to compete with the large particles for the surplus vapor. Secondly, the conditions that favor the growth of the larger droplets can be maintained for longer periods of time, which gives these droplets more time to settle.

The first expansions produced very little change in the appearance of the droplets. As more and more slow expansions were made, it became increasingly difficult to obtain droplets. Finally, when the total number of droplets produced in the entire sensitive chamber was about one hundred, it was time to try a fast expansion. An alpha
source, placed in the sensitive chamber, was used to determine optimum conditions. Once these conditions were reached the alpha source was removed and the Chamber again placed in operation.

Results

A great deal of the operation time of the Chamber was spent in the study of turbulence and contamination. The turbulence was not really identified as such until a small cylinder, three inches in diameter and two inches high, was placed in the sensitive chamber with its axis parallel to the axis of the Chamber. It was noticed that the droplets formed inside the cylinder were all moving toward the perforated brass plate. Since a single thick diaphragm was used (see Figure 15), an attempt was made to remove the turbulence by inserting corks in some of the holes in the perforated plate. Nearly all signs of turbulence disappeared when a circle of eight corks were placed near the center of the plate. Soon after the Hycar sheet arrived, it was cut into two diaphragms and arranged in the Chamber as shown in Figure 16. With this arrangement no visible turbulence was detected in the sensitive chamber.

Contamination was the hardest defect to correct. It can be removed from the glass and pyrex by a thorough cleaning. However, impurities in the brass, and probably in the grease also, cannot be removed entirely by ordinary methods. As a result, large molecules of contamination
became more and more dense as time went on. As these molecules compete with the ions for the surplus vapor, there was a slowly increasing amount of background droplets, until only alpha particles could be seen. Although some electrons were believed to have been observed, the number of cases were so small that no conclusive statement can be made.

The clearing field was increased from eight hundred volts between the electrodes to six thousand volts. As this almost ten-fold increase had very little effect on the background, it was assumed that the background was composed of neutral particles for the most part. This substantiated the belief that there existed a severe case of contamination.

The grease was removed from all parts of the sensitive chamber so that the effect of its presence could be studied. However, the sensitive chamber leaked so badly that it was not possible to remove the dust before the pressure dropped below the operating point. It was during the second attempt without the grease that the glass window was cracked. Although the cause was not known, it was believed that the glass was so close to a bolt that as the threads moved along the edge of the glass, vibrations were set up in the glass, which when coupled with the stress due to the brackets, broke the glass.

No conclusion could be reached as to the cause of the
diffuse character of the alpha tracks, although it was believed that they resulted from too slow an expansion. This, of course, would be hard to assert, though the problem must be solved or eliminated before the Chamber can be used for research.
Suggested Changes

There are a number of minor changes that could be made in the Chamber that would make it a better tool for research and demonstration. First would be the polishing of the brass and pyrex surfaces that are pressed together to form the seal. A better seal of the sensitive chamber could mean one or more of the following: the additional amount of gas placed in the sensitive chamber would stay longer, the seal would be as effective as before the polishing with less pressure on the glass parts, and/or the grease could be omitted altogether. The first two items are not too important for improving the operation of the Chamber. However, the removal of the grease from the sensitive chamber is important, as the grease is a potential source of contamination. A better method of polishing the brass parts would be to chrome plate them. This would not only provide a smooth surface for the seal but would remove a second source of contamination, the brass, from the sensitive chamber.

Another change would be in connection with the piston. The bracket that holds the piston to its support is also used to hold the back diaphragm in position. A small lip is provided on the bracket to distribute the force holding
the bracket and piston together to a small area of the diaphragm. It was noticed rather late in the experiment that the diaphragm was pulling loose from the piston. This can be corrected by reducing the surface area on this lip even more.

The following last suggestion applies only to demonstration. During the operation of the Chamber, it was noticed that the brass cylinder required less force to hold it in place than did the pyrex cylinder. It would be better if a pyrex cylinder were substituted for the brass cylinder as this would allow the students to see the control chamber in operation.

**Additions Necessary for Future Research**

If any quantitative work is to be done with the Chamber it will be necessary to have a permanent record of the events being studied. This requires a camera with a rather short focal length. If there is the possibility that the camera will later be adapted for automatic winding, it is suggested that consideration be given to the problem of constructing the entire camera. J. B. McQuitty and R. H. Frost (37) give a description and a diagram of such a camera. It would probably be less expensive in the long run to build the camera than to try to adapt a commercial camera for this purpose. If the camera could be properly shielded from external light, it would not even be necessary to have a shutter.
A magnetic deflection field is very important in cloud chamber work, as it enables the observer to determine the momentum and sign of an ionizing particle. However, such magnet must be large so that the field is uniform through the sensitive chamber, or perhaps symmetrical as described by A. M. Cormack (45). The cost of installation and operation of large electro-magnets is quite high. A possible solution for this problem is found in an article by Rl P. Shutt and W. L. Whittemore (38), which describes a method of calculating the size of a permanent magnet for a particular cloud chamber.

Controls

Most cloud chambers are controlled automatically by electronic circuits. Descriptions of such controls appear in articles by W. Y. Chang and J. R. Winckle (39), F. L. Allen (40), and A. L. Hodson et. al. (22). It is possible, however, to design a control network that would operate almost entirely by relays. The important operations necessary for a fully automatic cloud chamber are as follows:

1. A pulse from a coincidence circuit or a single G. M. tube trips the expansion valve and cuts off the clearing field.

2. After a delay from .01 to .5 seconds, which allows the expansion to take place, the camera and then the flash tubes are set off.

3. The film is changed, the clearing field is applied
to remove the ions and the gas is slowly compressed to prevent unnecessary heating in the sensitive chamber.

4. A slow expansion is used to remove condensing nuclei by the opening of a very small valve.

5. This is followed by a slow compression as in 3.

6. It may be necessary to repeat steps 4 and 5 a number of times as was done to remove dust particles.

7. A reset mechanism operates and the Chamber is ready to respond again to a pulse.

With the exception of the triggering circuit from the G. M. tube (or tubes) and the discharge circuit for the flash tubes, the circuit can be made of delay relays, latching relays, and ordinary relays. Relays have the advantage of being more dependable than electronic circuits, in that there are no tubes to burn out.

For camera work a much stronger light source must be built. About the only parts of the present illumination system that can be used are the two chrome mirrors. The most popular source is a discharge tube operated by a large capacitance (usually several hundred micro farads at two thousand volts). These tubes can be purchased from the Amglo Corporation or from General Electric Company at a cost of eighty dollars for a seventeen inch long tube. More elaborate systems than the one described here can be found in articles by E. J. Lofgren (41), C. Ballairo et al. (42), and L. H. Berryman et al. (43).
Suggested Problems

Contamination is always a problem in cloud chamber operation. A good description of various phases of contamination is found in an article by J. T. Mercie and J. L. Need (144). These workers discovered that their contamination came from the compressed gas tank used to fill the sensitive chamber. This is a possibility as the helium tank is an oil-filled type.

During the last week of operation of the Chamber the glass window was cracked. No conclusive results could be reached as to what caused the break. Further investigation, such as looking for strain with polarized light, should be made and the cause corrected, if possible, before the Chamber can be used for either demonstration or research.

Very little research can be done without a camera for recording the events. With a camera the specific ionization, that is, the number of ions per unit length of the track, can be measured. Results will be improved if a timing mechanism is used, so that the camera would take the picture after a fixed period of time had elapsed following the expansion.
Bibliography


