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CONDENSATION NUCLEI
IN AEROSOLS

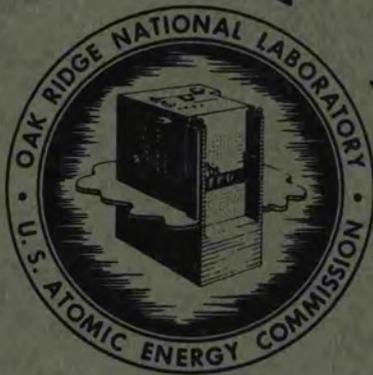
Bernard G. Saunders

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CLOUD CHAMBER FOR COUNTING CONDENSATION

NUCLEI IN AEROSOLS*

Bernard G. Saunders

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CLOUD CHAMBER FOR COUNTING CONDENSATION

NUCLEI IN AEROSOLS

ABSTRACT

In a cloud chamber which measures the concentration of nuclei in an aerosol, water vapor is supersaturated to condense on the aerosol particles in a small sample, and the resulting water droplets are photographed in an ultramicroscope. The number of droplets can then be counted in a microprint reader and the relative or absolute concentration of the aerosol determined. Two types of expansion cloud chambers may be used, the volume-defined and the pressure-defined. The system is completely automatic and operates continuously on a one-minute cycle, with as many as 4000 exposures being made without attention. During one cycle a sample of the aerosol is drawn into the apparatus, a frame of 16 mm motion picture film is advanced, the cloud chamber expands, and the resulting droplets are photographed by the illumination of a synchronized flashtube.

The slits which define the ultramicroscope light beam are interchangeable so that aerosol concentrations from 200 particles/cm³ to 2×10^6 particles/cm³ can be measured.

INTRODUCTION

The property of moisture to condense on nuclei of all kinds was first used by John Aitken in 1888¹ to count particles of dust and smoke in the air. An automatic device for the continuous counting of aerosols

was later developed by H. L. Green.² His apparatus employed an Aitken cloud chamber that was capable of repeating its cycle every two seconds. Droplets were condensed on the particles to be counted by the adiabatic expansion and consequent cooling of moist air. Part of the expansion chamber also served as the cell of an ultramicroscope. Collimated light traversed the cell, illuminating a narrow beam of droplets which were then photographed at 2.4 x magnification. Thus a count of the droplets within a measured area of the photographic film established the number of particles per unit volume of air.

Figure 1 shows the continuous-action cloud chamber built in this laboratory.* The cloud chamber is completely automatic and can take as many as 4000 pictures without the attention of an operator. The expansions are produced and photographed at one-minute intervals. The apparatus features interchangeable expansion cloud chambers employing the so-called "volume-defined" and "pressure-defined" methods of adiabatic expansion.

GENERAL OPERATION

Figure 2 shows in greater detail the volume-defined and pressure-defined chambers, the ultramicroscope cell used in conjunction with the chambers, the lamphouse and the camera. Droplets are condensed in the cell by adiabatic expansion and then illuminated and photographed by an ultramicroscope arrangement. A plan diagram of the optical system is shown in Figure 3. The slit is illuminated with light emitted by the flashtube, and a microscope objective focusses its image at the center of the ultramicroscope cell. Droplets suspended in the cell are thus

* Working drawings available upon request.

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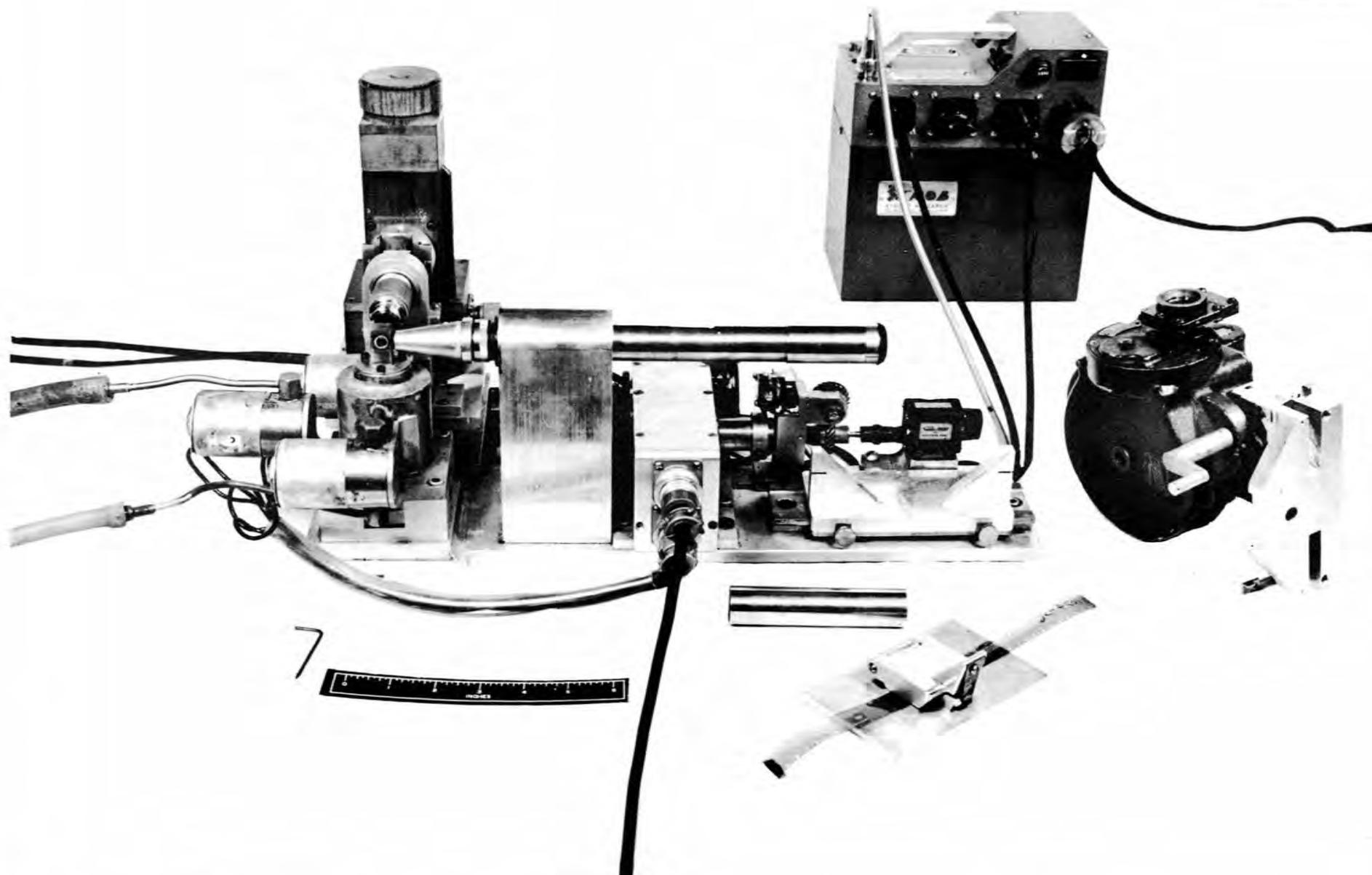


Fig. 1. Photograph of Aerosol Cloud. The camera has been removed so that the droplets can be viewed through the microscope eyepiece. The flash-tube power supply and 16 mm film carriage are also shown.

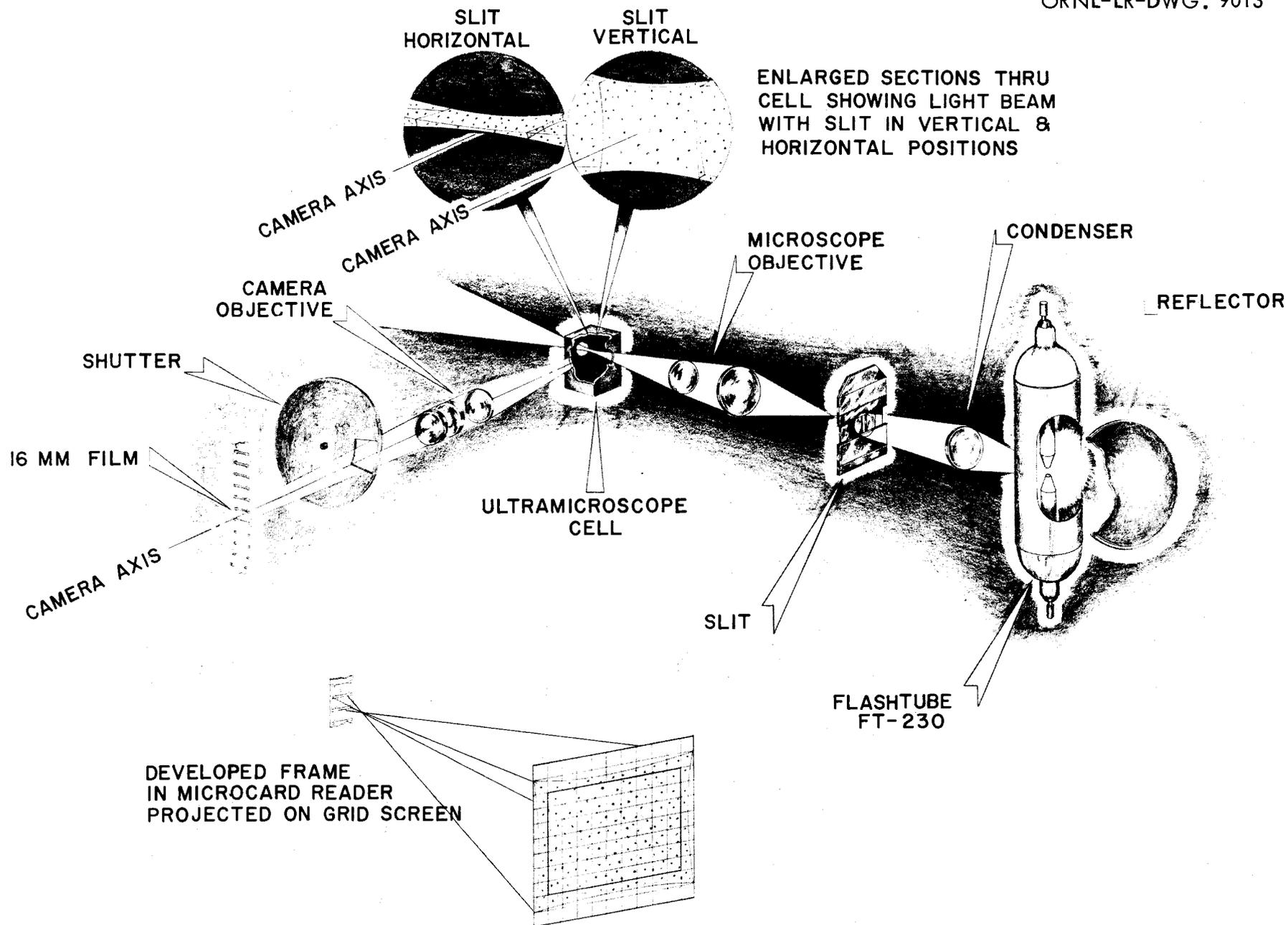


Fig. 3. Optical System Used for Photographing Droplets Condensed on Aerosol Nuclei.

illuminated along the path of the light beam. Each droplet scatters the incident light in all directions and may be seen from any angle. The camera axis in this apparatus is set at right angles to the axis of illumination. Light scattered along the camera axis is focussed by the camera objective upon a single frame of 16 mm motion picture film during the open period of the camera shutter. After the shutter closes, the chamber and cell are evacuated to remove the droplets and a fresh sample of aerosol is drawn in. The film advances to the next frame, an expansion is made, the shutter opens and the flashtube fires.

When a sufficient number of exposures has been made, the camera is removed to the darkroom and the strip of exposed film is developed. A frame of the film may then be placed in a special carrier attached to a microprint reader (Fig. 4). The droplets appearing in a given area of a grid on the screen are counted. Because the volume of aerosol represented by the grid area is known, the number of droplets per unit volume of aerosol taken into the cloud chamber is readily ascertained.

THE LAMPHOUSE

Each particle is photographed with light scattered at right angles, which requires intense incident light. The source of light in this instrument (Fig. 2) is an FT-230 flashtube^{*} and is operated from a Strob III Power Pack[†] rated at 2 KV and 200 watt seconds. The discharge in the flashtube

* General Electric Co., Nela Park, Cleveland, Ohio.

† Strob Research, Milwaukee, Wisconsin.

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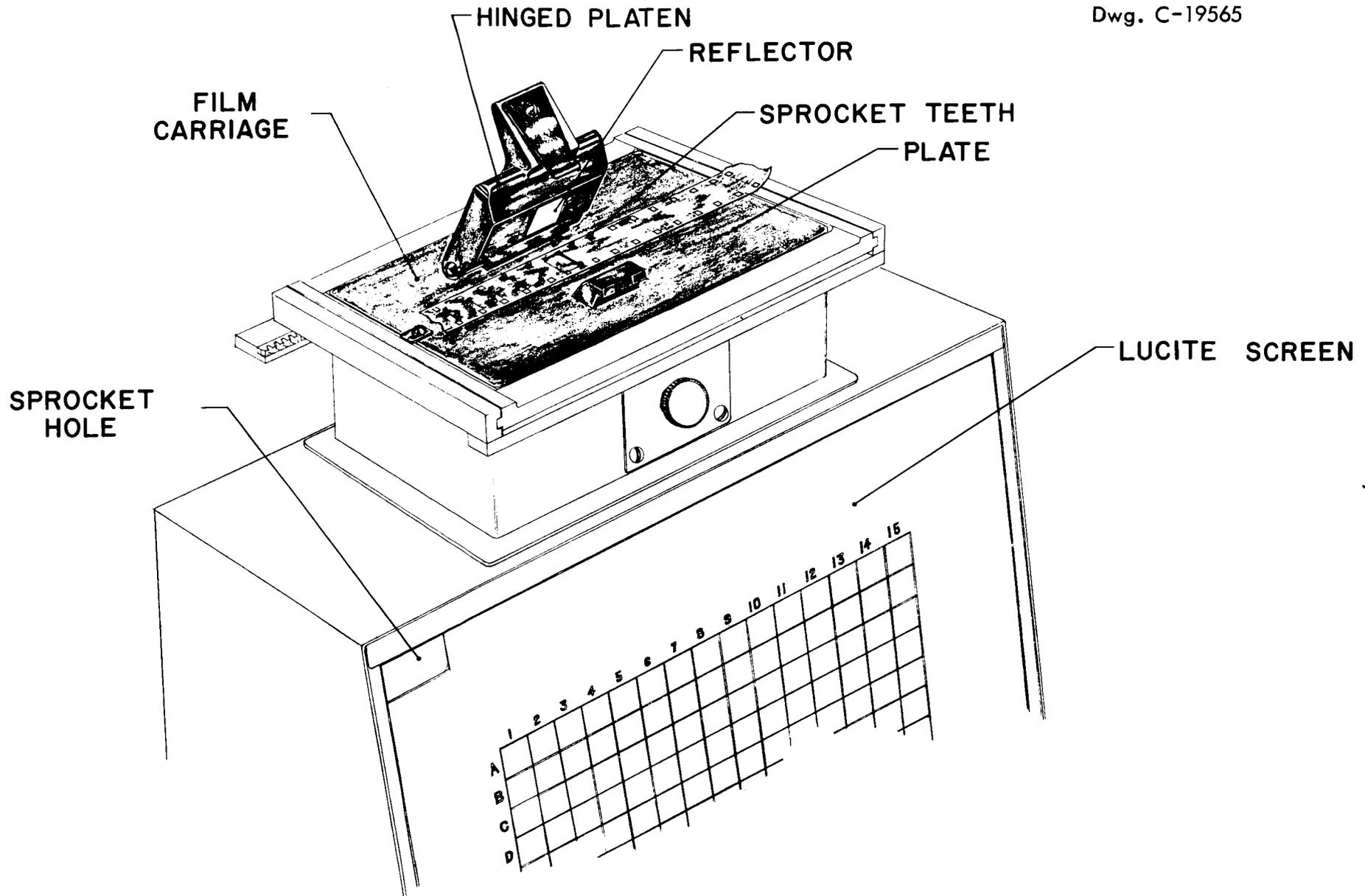


Fig. 4. View of Reader, 16 mm Film Carriage and Screen. Droplets in the ultramicroscope beam have been photographed on 16 mm film. When the platen is in the closed position a magnified image of the photograph will appear on the projection screen. The droplets in a given patch of squares can be counted.

takes place between two pointed electrodes 1 cm in diameter and separated by a gap of 3 mm, resulting in a concentrated arc of several thousand lumen seconds. This type of illumination was chosen in preference to a continuous source of illumination. Continuous sources such as the high-pressure Hg vapor lamp and the zirconium arc require exposures of the order of 1/50 sec, causing the images of the moving droplets to streak on the film; whereas the discharge in the FT-230 flashtube takes place in less than a millisecond, resulting in sharp images of the moving droplets (Fig. 5).

A condenser and mirror designed for use with a T-12 projection bulb in an 8 mm motion picture projector* makes it possible to concentrate a considerable fraction of the light on the slit. The lamp is synchronized to flash when the rotating shutter of the camera is open. This is accomplished by adjustment of a timing cam (Fig. 2). In the open position of the shutter, the snap-action switch is closed, completing the circuit of the tripping switch on the high-voltage power supply.

The base of the lamphouse contains the ignition transformer[/] and capacitor for the trigger circuit (see Fig. 6). The trigger electrode is a split brass sleeve that fits the glass envelope of the flashtube. The base also provides a grounded socket for the flashtube. The socket set screw can be reached with a wrench inserted through a hole in the side of the base. A transmitting tube insulated plate cap is clamped to the high voltage electrode of the tube. The cap is connected to the rest of the trigger circuit through the high-voltage duct.

* Eastman Kodak Co., Rochester, New York.

[/] Type T-22R44, Thordarson Electric Mfg. Div., Chicago, Illinois.

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Fig. 5. Enlargement of a 16 mm Frame Showing
Water Droplets Photographed in the Ultramicroscope
Beam.

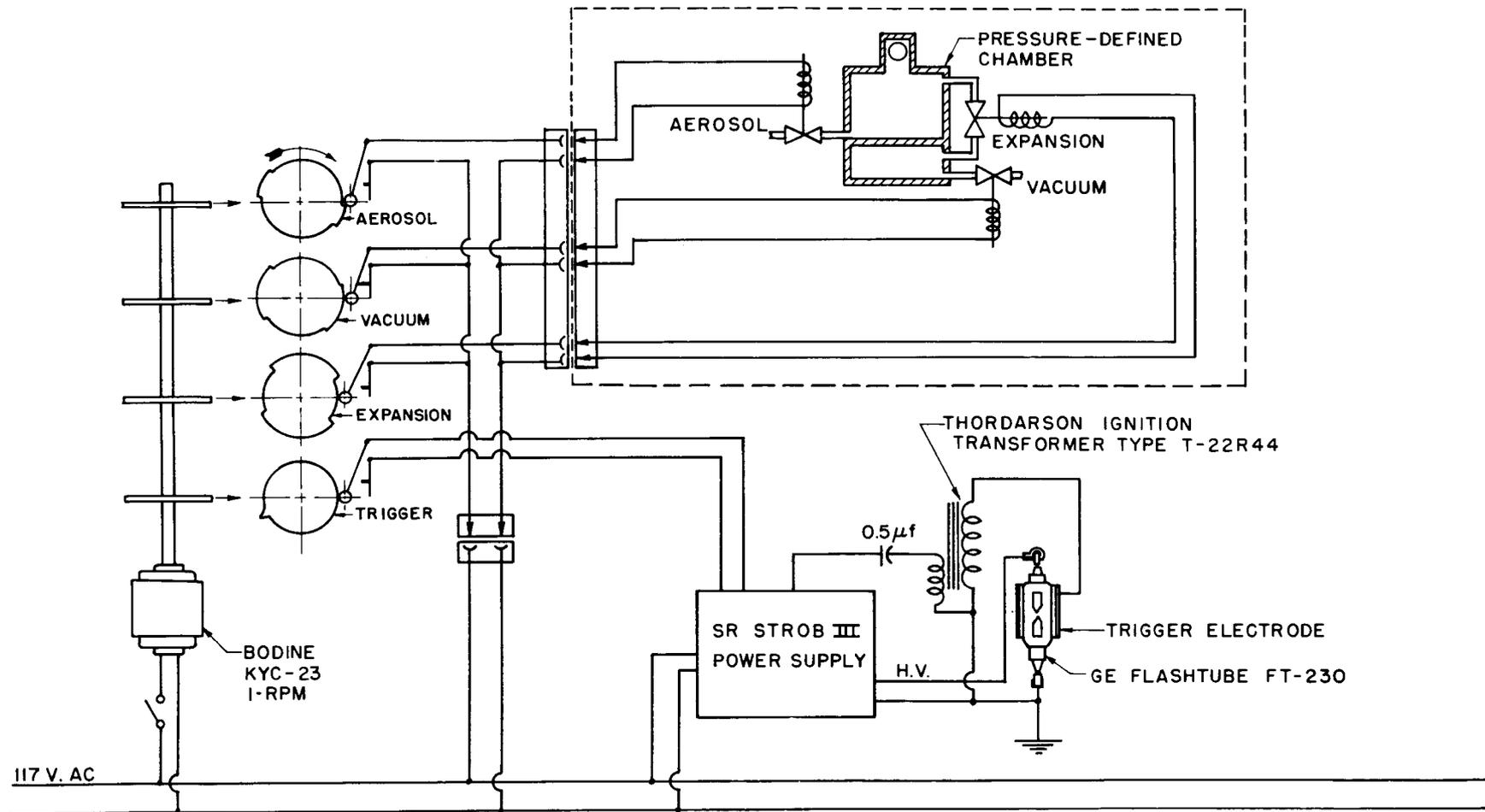


Fig. 6. Diagram of Electrical Circuit.

The lamphouse is made of Micarta. The top section is ventilated and may be removed to allow access to the flashtube.

THE SLIT

The slit defines the cross-sectional area of the light beam passing through the cell. The slit was made non-adjustable to prevent an accidental change in the cross-sectional area of the beam, once the instrument had been calibrated. To produce beams of varying widths, the slit and its frame may be removed from the holder and replaced by another. In its normal operating position, the long axis of the slit is perpendicular to the baseboard of the apparatus. Provision is made to rotate the slit frame and beam 90° about the optical axis.

The slit assembly consists of a frame, jaw plates, holder, cup and sleeve. The slit jaws are made of tool steel and beveled 45° by a surface grinder. The slit or jaw opening was examined optically to check its parallelness. Three sets of frames and slits were made, the slits being $1/4$ " long and 0.010", 0.020", and 0.200" wide. The cup to which the frame is attached rotates about the sleeve. A screw in the sleeve runs in a slot of the cup and limits the rotation to 90° . A slot in the sleeve permits the sleeve, cup and slit as a unit to move away from or toward the flashtube, thereby making it possible to focus the arc onto the slit. The optimum separation of the slit from the flashtube was found by loading the holder with projection paper and photographing the electrodes by their own illumination. Such a picture is shown in Fig. 7.

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Fig. 7. Image of Flash-Tube Electrodes at Position of Slit. This photograph was made by placing a piece of photographic paper at the position of the slit and flashing the tube.

MICROSCOPE OBJECTIVE

The purpose of the microscope objective is to produce a narrow beam at the center of the cell a fraction of a millimeter in width. Since the beam converges at the center of the cell, the working distance of the objective must be greater than 13 mm, the half-width of the cell. The objective chosen for this apparatus was a Spencer 5x achromatic objective with an N.A. of 0.14 and a working distance of 25 mm. It is screwed into the end of a tube (Fig. 2) which can turn in its mount. In this way it is possible to adjust the focus so that the slit image will fall inside the cell.

Dowel pins on the pedestal relocate the mount if it should be removed.

THE ULTRAMICROSCOPE CELL

The ultramicroscope cell through which the beam of light passes is sealed to the expansion chamber by means of an "O" ring and three Allen screws. The inside of the cell is painted optically black. The three windows are fragments of microscope cover glass.

The windows were cemented to the cell in the following manner. The cell was placed on a hot plate until red wax could be "tinned" around each hole. The windows were warmed on the plate and stuck over the window holes. The cell was then placed back on the plate until the windows sealed fast without air bubbles.

When the cloud chamber apparatus was first put into use, the windows occasionally would fog on the inside. This was later corrected by gently flowing air, preheated to 40° C, over the outside of the cell during a run.

EXPANSION CHAMBERS

Most dust and smoke particles are so small that they do not scatter enough light to be photographed. Fortunately, water vapor can be made to condense on the particles in the form of droplets if the particles are surrounded by an atmosphere supersaturated with water vapor. Thus, even particles as small as 10^{-7} cm can be detected.

If air, saturated with water vapor, is reduced in temperature, supersaturation will result. One method of doing this is to expand the mixture of air and vapor adiabatically. Adiabatic expansion may be achieved either by allowing the mixture to pass into another compartment at lower pressure, known³ as the "pressure-defined" method, or by increasing the volume of the compartment that contains the mixture, known as the "volume-defined" method.

For both cases, the change of temperature that takes place in the gaseous mixture is a measure of the supersaturation. In order for water vapor to condense on all nuclei that are 10^{-7} cm in radius or larger,⁴ the humidity in the chamber must rise to 300% of its original value. This requires a temperature drop of about 30° C below room temperature. In the pressure-defined operation, the change of temperature from an initial temperature θ_i to a final temperature θ_f is expressed by the relation⁵

$$\frac{V_f}{V_i} = \left(\frac{\theta_i}{\theta_f} \right)^{\gamma/(\gamma - 1)} \quad (\gamma = \text{ratio of specific heats}),$$

when the mixture of air and water vapor expands from an initial volume

V_i at atmospheric pressure into another compartment of volume $V_f - V_i$ (V_f equals the combined volume of the chamber compartment) at zero pressure.

In the volume-defined operation, where the volume occupied by the mixture changes from V_i to V_f ,

$$\frac{V_f}{V_i} = \left(\frac{\theta_i}{\theta_f} \right)^{1/(\gamma - 1)}$$

In order to obtain a temperature drop of 30° C, the ratio V_f/V_i for the pressure-defined chamber turns out to be 1.44 and for the volume-defined chamber 1.3, which must be considered in the design of the chamber. The cloud chamber apparatus described here is so constructed that the two chambers can be used interchangeably. The completed instrument, of course, requires only one chamber. The pressure-defined chamber was found to be the more trouble-free of the two types that were tested. Both are shown in Fig. 8.

Pieces of wet blotting paper were used in the chambers for saturating the aerosol. An eye-dropper of water was sufficient to wet the blotter and provide enough moisture for 60 to 70 expansions. Longer runs were obtained by passing the aerosol through a vessel of heated water in order to presaturate the aerosol.

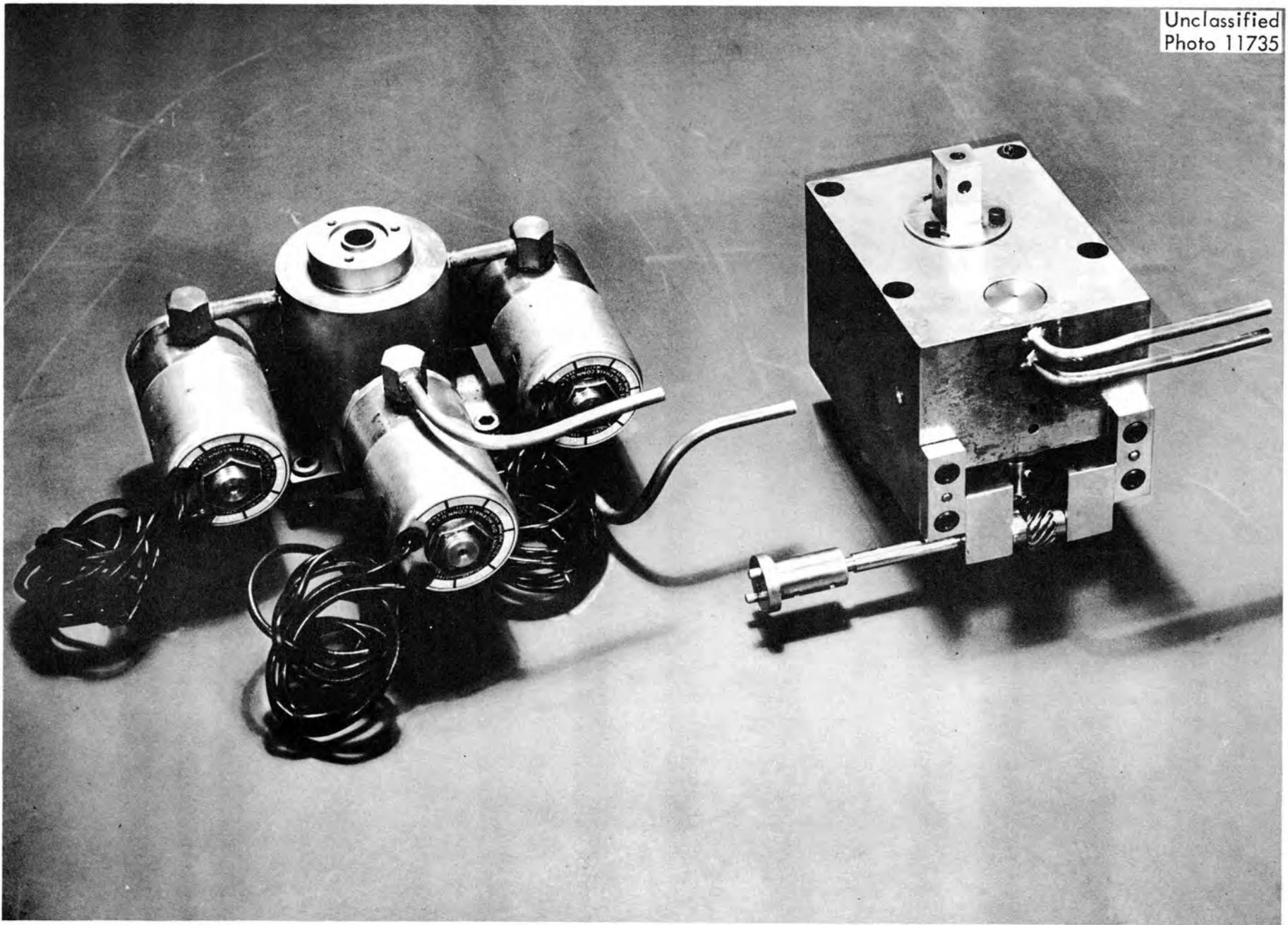


Fig. 8. Photograph of the Pressure-Defined Chamber (left) and Volume-Defined Chamber (right).

Pressure-Defined Chamber

The pressure-defined chamber is shown in Fig. 2. A vacuum pump is connected by rubber hose to one line and an aerosol generator is connected to the other. The upper compartment and cell are filled with a mixture of aerosol and water vapor at atmospheric pressure. The mixture expands into the evacuated lower compartment through the expansion valve, producing supersaturation in the upper compartment and the cell. The complete cycle of operation is as follows: with all three valves open, both compartments are continuously flushed with aerosol as it passes from generator to pump. The expansion valve then closes and the aerosol pressure comes to equilibrium with the pressure in the generator. At the same time moist blotters in the upper compartment and lower part of the cell saturate the air with water vapor, and the lower compartment is evacuated. The aerosol and vacuum valves close. The expansion valve opens, permitting the water-saturated aerosol to expand from the upper to the lower compartment and producing a state of supersaturation in the upper compartment and ultramicroscope cell. Water droplets form on the nuclei and are photographed. The aerosol and vacuum valves open and the cycle repeats.

The three valves are solenoid valves* that operate on 115 volts A.C. They are connected to snap-action switches through 6-wire cable. The cams which open and close the snap-action switches are on a common shaft geared to a 1 r.p.m. motor† through a slip clutch. A slip

* Type V5, Skinner Electric Valve Div., New Britain, Connecticut.

† Type KYC-23, Bodine Electric Co., Chicago, Illinois.

clutch is used should the film bind in the camera. It is situated next to the motor so that if the motor slips, synchronization will be preserved between the cams and the camera.

The inside diameter of the chamber is 1.875". The two compartments were formed by drilling a solid block of brass from both ends and leaving a partition. A cap is sealed to the bottom compartment by an "O"-ring. The effective volume of the compartment, and hence the expansion ratio, can be increased or decreased by changing the dimensions of the disk that is fastened to it.

Volume-Defined Chamber

When the volume-defined chamber is used, the cams that actuate the solenoid valves are no longer used and the cable to the solenoids is disconnected.

Green expanded his chamber by sliding a piston in a cylinder. The expansion ratio was a function of the stroke and was controlled by the lift of a rocker arm. Since this arrangement is sometimes subject to leaking around the piston, and the stroke may change after calibration, a fixed-stroke, unleakable chamber was built. Figures 2 and 8 show the volume-defined chamber. A steel sylphon bellows sealed at its lower end is used for changing the volume. It is actuated by a spring which works against the pressure of the aerosol.

The chamber block is bored to accept a tapered plug which acts as a quadruple stopcock. The plug of the stopcock rotates continuously by means of a gear and coupling in a counter-clockwise direction as viewed from above. Details of the expansion chamber and the four sections of

of the plug are shown in Fig. 9. The vacuum pump is connected to the inside of the expansion bellows and ultramicroscope cell, or compartment I, through vacuum valve I, and to the outside of the bellows, or compartment O, through vacuum valve O. The aerosol generator is connected to compartment I through the aerosol valve. The air vent is open to the room and is connected to compartment O through the air valve. Cycle: all valves except the vacuum valve O are open, and the aerosol from the generator circulates inside compartment I. Also, compartment O surrounding the bellows is at atmospheric pressure and is in equilibrium with the aerosol pressure. Under these conditions, the bellows is compressed by the spring. Next, the vacuum valve I closes and the aerosol in compartment I becomes saturated with water vapor from the damp blotter. The aerosol and air valves close. The vacuum valve O then opens, and compartment O is quickly evacuated. The pressure of the vapor and gas in compartment I expands the bellows against the pressure of the spring. The temperature falls and droplets condense on the aerosol particles. The droplets are photographed and vacuum valve O closes. The other three valves open to equalize the pressure and flush the chamber, the spring compresses, and the cycle repeats.

THE CAMERA

The camera is a Bell and Howell model 70, 16 mm motion picture camera. A lock was removed from the camera spring and a gear box, Fig. 2, was attached so the camera could be turned by an external shaft. Also, a pin was inserted to hold down the starting button, and a removable hand-crank was made to fit the external shaft. A saddle was made for the camera which locks into place on the mount by means of a latch. A slip-tube connects

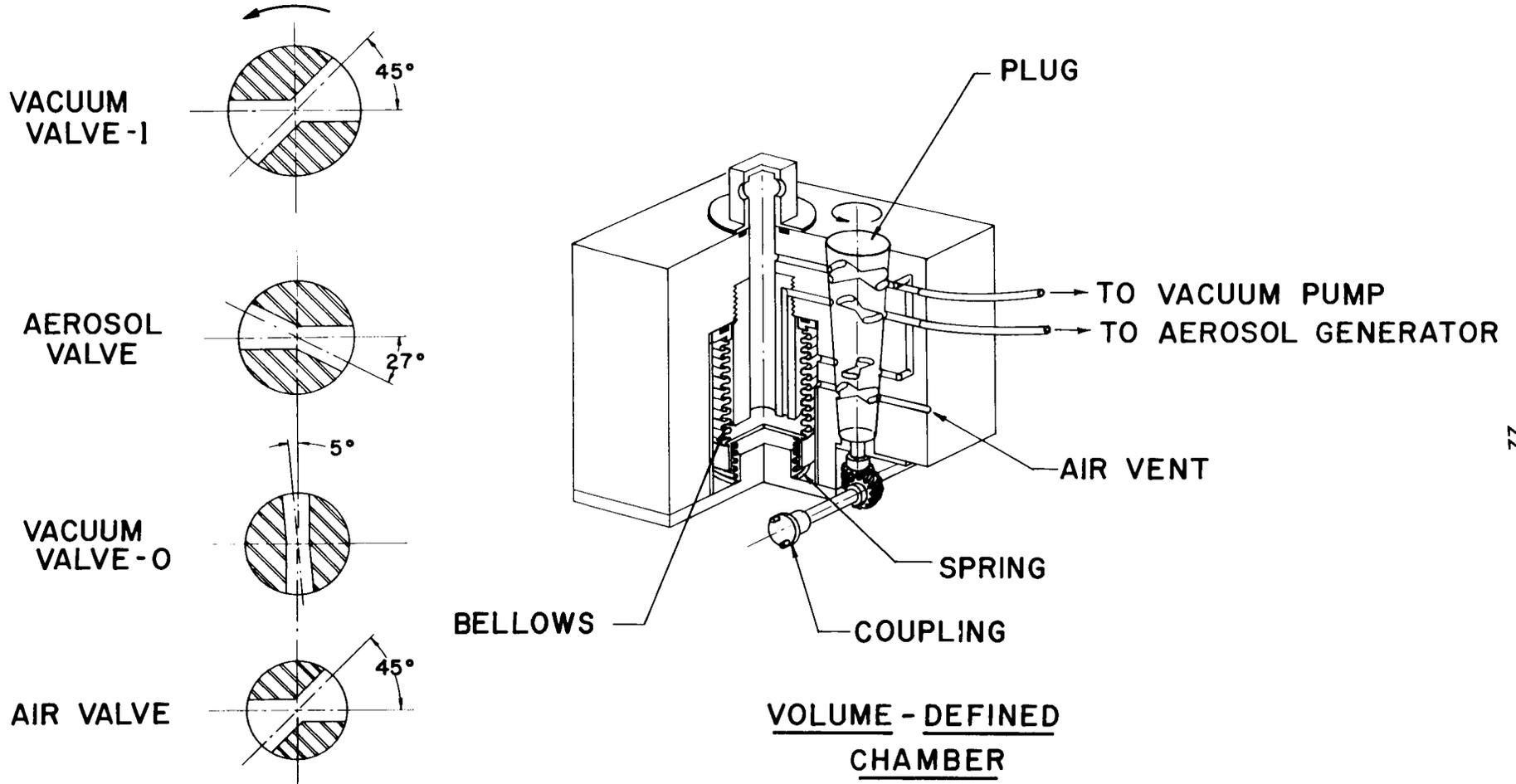


Fig. 9. Schematic Drawing of Volume-Defined Chamber Showing How Expansion is Achieved With a Spring-Loaded Bellows. The four sections of the stopcock plug are layed out to show their relative orientation.

the camera with the support block. This design allows the camera to be removed to the darkroom for loading or unloading and replaced on the mount without varying its distance from the camera lens by more than 0.001". Also, there is a tube containing a 10x microscope eyepiece at one end which can be substituted for the slip-tube and camera. The eyepiece and camera objective serve as a microscope so that the droplets can be directly observed. The mount was machined to slide on a way, a feature that was useful for getting a desired image-to-object ratio.

An external shutter is used as a precaution against fogging the film when the camera is separated from the apparatus. The shutter is a simple metal slide that can be withdrawn at the beginning of a series. The cycle of operation was timed to fire the FT-230 tube once each minute, the maximum firing rate recommended by the manufacturer. This sets the open time of the shutter to 45 seconds, thus making fogging from stray light possible. To reduce the open time of the shutter to a minimum, yet allow for backlash of the camera gears, a new rotary shutter was made with an opening slightly larger than the camera aperture. A conical tube snaps over the camera objective in order to exclude room light from the camera. There is a gap of 1/16" between the snout of the tube and the cell window to allow free passage of the warm air which is sometimes used to prevent window fogging. A revolution counter* is connected to the main drive shaft to keep track of the exposures.

* Model No. F112135, Veeder-Root, Inc., Hartford, Connecticut.

CAMERA OBJECTIVE

The camera objective is a Bausch and Lomb Micro-Tessar lens having a relative aperture of $f:4.5$ and a focal length of 48 mm. Since the lens was to be used for low-power photomicrography, it was essential to use one having good definition and minimum curvature of field. This lens has a depth of field of 0.4 mm when used at this aperture and magnification. The beam produced by the 0.200" slit is slightly less than 0.4 mm, and so all the illuminated droplets will be sharp when photographed at full aperture.

The lens is screwed into a tube and clamped with a set screw. The tube is screwed into the support block, thus enabling one to focus the droplets of the light beam on the film in the camera aperture. Initial focussing was done with the aid of a piece of scratched slide glass in the camera aperture, a mirror and a 5x magnifier. The camera objective was focussed until the image of the droplets fell in the plane of the film emulsion. More precise focussing was then achieved by making a series of droplet photographs.

ADJUSTMENT

An auxiliary light source was found to be indispensable in aligning the optical system, checking the synchronization of the camera and cams, and observing the behavior of the droplets, that is, their lifetime and rate of fall. The lamp which proved to be the most satisfactory for this purpose was a Zirconarc photomicrographic lamp.* When the zirconium arc was used,

* Fisch-Schurman Corporation, New Rochelle, New York.

the reflector and reflector cup of the lamphouse were removed and the beam from the arc adjusted to fall between the electrodes of the FT-230 tube. As an aid to lining up the system, the ultramicroscope cell was removed and replaced by an inverted 5 ml beaker containing cigarette smoke. During actual operation the droplets were illuminated by continuous light and could be watched through the microscope eyepiece during their growth and evaporation which ordinarily lasted one or two seconds. In this way the timing cam could be advanced or delayed so that the FT-230 arc would flash an instant after the droplets were seen to form.

PROCESSING

On the basis of quickness to dry, speed and resolving power, DuPont 16 mm film, Type 930 - Rapid Reversal Pan, was selected for general use in the apparatus. Under ordinary operating conditions, the camera was loaded with a 100-foot spool. No take-up spool was required since only thirty or forty frames at most were exposed at a time. The hand-crank was used to advance the film a few frames after exposure so that the foot-or-so length of film could be snipped off in the darkroom. The film was then tray-developed as a lantern slide in Dektol (Type D-72) solution. Because of the fast drying time of the film, counting could be started one hour after the last exposure had been made.

READER

A film carriage was made to fit a Microcard* reader. No alteration

* Model 3, Northern Engraving and Mfg. Co., LaCrosse, Wisconsin.

of the reader was necessary. In use, the glass platen may be lifted out and the film carriage dropped into place.

Since this reader normally operates by reflected light from a Microcard, a reflecting surface was used for illuminating the processed 16 mm films. A piece of single-weight glossy printing paper was cemented to the hinged platen of the carriage. Sprocket teeth were made of drill rod and inserted into the aluminum plate. This precision positioning of the film is necessary when counting over the same area in various exposures. A sheet of Lucite was cut to fit over the projection screen, where it could be taped into place. The rear side of the Lucite was engraved with a gridwork of centimeter squares. The ordinate and abscissa were letter and numbered, respectively, so that reference could be made to a given area. Also an L-shaped mark was engraved in the corner of the screen. The film carriage could then be racked over by the reader controls until the image of the film sprocket hole registered with the L-shaped mark.

CALIBRATION

To measure relative concentrations of particles, it is necessary only to maintain each frame in registration with the grid while counting, and to count over the same patch of squares in each frame. This assures one that he is counting over the same volume of particle space in the beam.

To measure the absolute number of particles in a given volume of expanded aerosol, it is necessary to know the over-all optical magnification of the particle space as seen on the screen of the reader. This magnification was established by first photographing a scale graduated in intervals of 10 μ , when the scale occupied the particle space in the beam.

This procedure also was used for selecting a 16 mm film of maximum resolving power.

The cell was removed from the cloud chamber and a microscope stage micrometer was substituted in its place, care being taken to place the plane of the slide in the beam axis and perpendicular to the camera axis. All optical components were permanently locked into position. The micrometer slide was illuminated by a desk lamp, and the telescope was used to adjust the lamp position for maximum contrast. The ruling on the slide was photographed in the 16 mm camera. The developed film was then placed in the carrier of the reader in order to cast the image of the micrometer across the grid. One side of each grid square was found to represent 130 μ of particle space, giving an over-all linear magnification of 1/0.013, or 76.9. Thus with any of the three slits in the vertical position, one grid square would represent an area of luminous aerosol of $1.69 \times 10^{-4} \text{ cm}^2$, or a volume of $1.69 \times 10^{-4} \times (\text{width of beam}) \text{ cm}^3$. In order to measure the width of the beam as produced by a given slit, the beam was rotated 90° as shown in Fig. 3. To do this the cell was replaced, the slit was rotated 90° , and a photograph was taken using a concentrated aerosol which gave the beam well-defined boundaries. The width of the beam image for the 0.020" slit spanned 2.8 grid squares, and thus the beam itself was 364 μ wide. Hence one grid square represented $6.15 \times 10^{-6} \text{ cm}^3$ of aerosol in the beam. The volume for the 0.200" slit, accordingly, was ten times larger.

Droplets are counted by using a hand tally. The counting accuracy, of course, depends on the total number of droplets counted on all frames. Ordinarily, from 1 droplet to 2×10^3 droplets can be counted on a single frame.

Since the screen is 15 x 20 grid squares in area, these values represent a range in particle concentration of about 200 particles/cm³ to 2 x 10⁶ particles/cm³ in the expanded state, depending on the slit that is used. Multiplying by the known expansion ratio gives the absolute number of particles in the aerosol.

ACKNOWLEDGEMENTS

The author wishes to show his appreciation to Sam Pierce and J. M. Hume for their engineering design, E. W. Davis for his fabrication, and Paul Oliver for his illustrations.

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