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WATER-MIST SEPARATION IN CABIN AIR-CONDITIONING SYSTEMS

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SIEGFRIED HASINGER

EQUIPMENT LABORATORY

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WATER-MIST SEPARATION IN CABIN AIR-CONDITIONING SYSTEMS

SIEGFRIED HASINGER

EQUIPMENT LABORATORY

NOVEMBER 1953

RDO No. 664-803

**WRIGHT AIR DEVELOPMENT CENTER
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO**

FOREWORD

This report covers a test made by the Equipment Laboratory, Directorate of Laboratories, WADC, Wright-Patterson Air Force Base, Ohio, under RDO No. 664-803, Aircraft Air Conditioning, to determine the most feasible means of separating water mist from the air supply used to air condition aircraft cockpits and cabins. Tests were directed by Mr. Siegfried Hasinger, Project Engineer, and the report was prepared by Mr. Hasinger, with the assistance of Mr. E. G. Koepnick. The RCA Service Company, Inc., Camden, New Jersey, provided editorial and layout assistance in the preparation of this report.

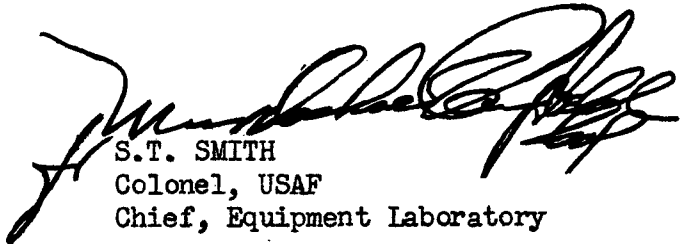
ABSTRACT

Tests were conducted by personnel of the Equipment Laboratory, Wright-Patterson Air Force Base, Ohio, between May 1951 and June 1952 to determine the most practical method of removing water mist from aircraft cabins. Three separation systems were tested: (1) cyclone separation, (2) filter separation, and (3) electrical precipitation. Cyclones proved to be impractical because of their size and pressure drop. Filters were found to require very little space but tended to be very sensitive to droplet size; in addition, they clogged rapidly with ice under freezing conditions. Experiments with electrical precipitation showed that this system eliminated many of the drawbacks of the other two systems; however, it was inferior to the filter in regard to size and complexity.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:



S.T. SMITH
Colonel, USAF
Chief, Equipment Laboratory

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WATER-MIST SEPARATION IN CABIN AIR-CONDITIONING SYSTEMS

SECTION I

INTRODUCTION

In air-conditioned aircraft cabins, under humid atmospheric conditions, the air discharged from the cooling turbine invariably contains water in the form of a fine mist which moistens the areas adjacent to the cabin air outlets. If the cabin temperature is below the dew point of the surrounding atmosphere, the cabin will eventually fill with mist, thus affecting visibility. This phenomena occurs quite frequently in tropical regions, especially at low altitudes near sea level.

There are several methods available to eliminate excess moisture. One way is to remove the water vapor from the air before it enters the cooling turbine by the use of an absorbent material or dehydrating agent such as silica gel. A second method is to cool the incoming air below its dew point, thereby converting the excess water vapor into liquid water which can then be drained off. These two methods would permit ice-free expansion in the turbine under sub-freezing temperatures. Previous investigations proved that the first method is quite bulky. The second method requires complex installations if a good efficiency is to be maintained.

Water mist can also be removed by cyclone, filter, or electric precipitation which agglomerate microscopic water droplets resulting in large drops which settle in the airstream. Primarily, this report is concerned with these systems with special emphasis placed on electric precipitation.

It is noted that sonic treatment of water vapor also causes agglomeration. 1, 2/* This method, however, is impractical and inefficient being limited to special applications.

SECTION II

CHARACTERISTICS OF WATER MIST

Mist Droplet Size

When humid air is cooled below its dew point, the water vapor in the air condenses into fine droplets. This is apparent with the expansion of moist air in the cooling turbine. The discharged air at the turbine outlet has the appearance of bluish smoke and is relatively

* Refer to page 22 for bibliographical references.

transparent. At some distance from the outlet the air becomes less transparent. This change in transparency is due to a change in the droplet size of the entrained water.

The average diameter of the droplets can be determined from certain well-known scattering and polarization effects on a beam of light. 3, 4, 5/ This effect was observed in the air discharged from a cooling turbine with a rating of 22 pounds per minute. Airplane conditions were simulated by heating the air upstream of the turbine and injecting water in the heated air for evaporation. The saturated air was then further heated to the desired turbine inlet temperature. The turbine was protected from entrained water by a sufficiently low flow velocity in the spray chamber. This allowed settling of water that did not evaporate. At the turbine outlet, a Plexiglas duct eight feet in length was attached. A dump valve behind the turbine outlet permitted a change in velocity in the duct. This arrangement was similar to that shown in Figure 1. Observations were recorded as shown in Table I.

TABLE I

Optical Phenomenon and Droplet Size for
Air Discharged from a Cooling Turbine

Distance from Turbine Outlet	Optical Phenomenon	Average Particle Size
1/2 ft.	Almost complete polarization of scattered light in perpendicular direction. Equal scattering intensity in and against the direction of the light beam.	0.4 micron
1 ft.	Less complete polarization and not as equal scattering intensity.	0.5 micron
2 ft.	Partial polarization and a marked difference in scattering intensity.	0.7 micron
4 ft.	Some polarization present and a great difference in scattering intensity.	1.0 micron
8 ft.	Practically no polarization and almost no scattering in direction against light beam.	1 to 2 microns

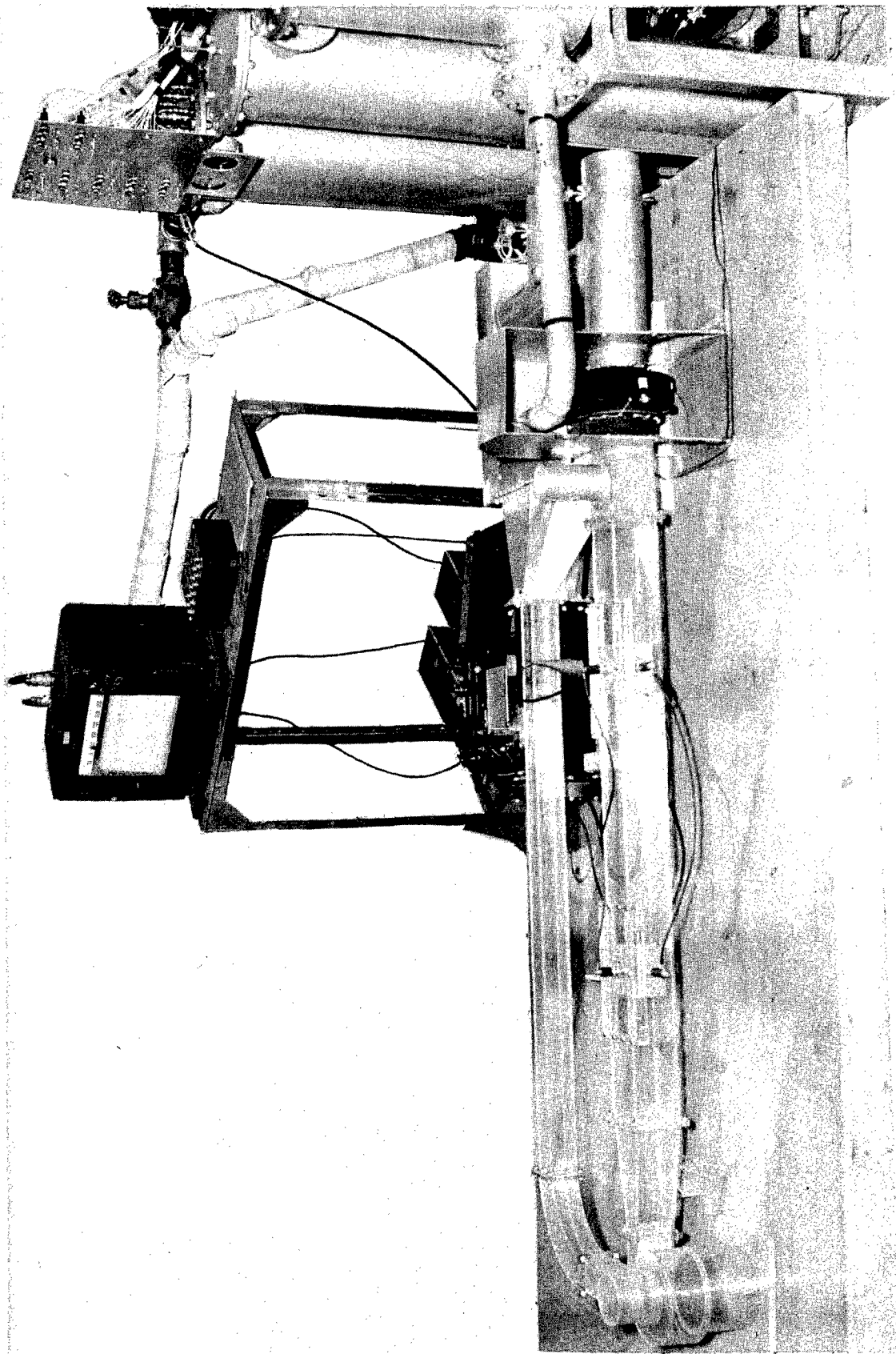


Fig. 1 Test Setup for Observation of Droplet Size in Air Discharged from a Cooling Turbine

The mean velocity of the air was approximately 50 feet per second. The temperature in the duct rose about 10°F along the entire length. This can be attributed to the heat transferred from the outside, i.e., no heat of condensation appears while the droplet size changes. Thus, the condensation process must be assumed to be practically completed at the turbine outlet. Increase in the size of the droplet is brought about by agglomeration of finer droplets. Theoretically, the growth within certain limits is proportional to the square root of the time. 3/ The present test results conform very well to this theory. The increasing opaqueness of the mist is explained by the extinction law, i.e., transparency is strongly reduced as the particle size increases despite a decrease in the number of particles.

The size of the droplets in the mist suggests the use of cyclone, filter, or electric precipitation as possible means of separating water mist from the air.

SECTION III

CYCLONE OR CENTRIFUGAL SEPARATION

Theoretical Considerations

The design of a cyclone, assuming certain simplifying conditions, can be based on the following well-known relation:

$$\frac{d}{n} = v_s \cdot v \cdot \frac{2}{g} \pi \quad (1)$$

d = deflection, i.e., radial distance of travel of a particle in the cyclone

n = number of turns of the particle in its spiral movement through the cyclone

v_s = settling velocity of the particle in still air plotted in Figure 2.

v = peripheral velocity of the particle in the cyclone.

g = gravitational constant

This relation indicates that the cyclone diameter does not influence the deflection of the particle. The relation is plotted in Figure 3 using data from Figure 2. It can be seen, for instance, that the peripheral velocity of a 1-micron particle at 100 ft/sec experiences only .025 in. deflection during one turn. This means that for the complete separation of 1-micron particles within one turn, the air stream in the cyclone must not be thicker than .025 in. This shows

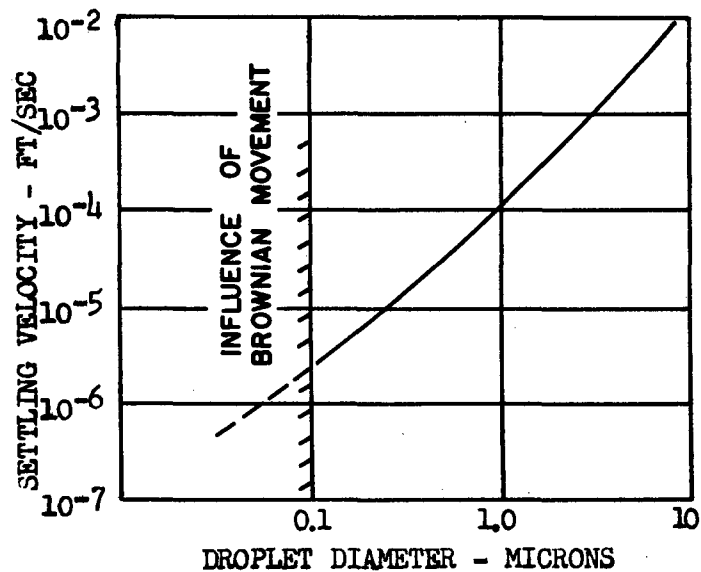


Fig. 2 Settling Velocity vs Droplet Size for Water Droplets Settling in Still Air.

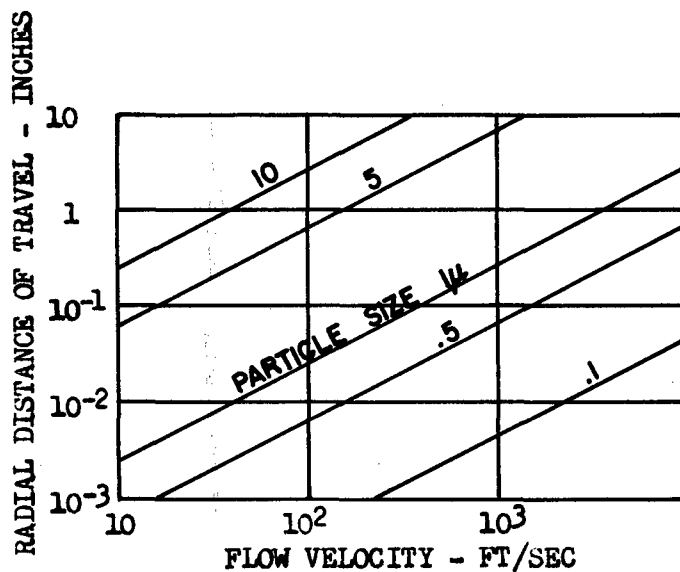


Fig. 3 Radial Distance of Travel (Separation Distance) vs Flow Velocity for the Separation of Water Droplets in a Cyclone.

how important it is to apply rather small cyclones in order to eliminate the dead-center space. To handle sufficient air flow a number of small units must be operated in parallel.

Tests with Cyclones

A small-diameter cyclone was tested consisting of a simple tube, five-eighths of an inch in diameter and five inches long. One end had a tangential inlet; the other end was open for the discharge of air. This cyclone is shown in Figure 4. After the air passed through the

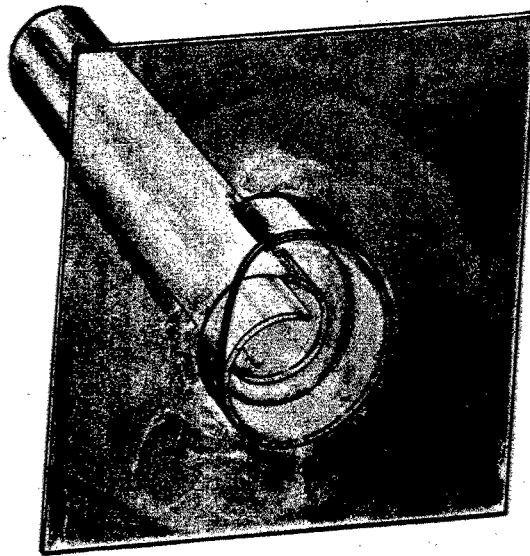


Fig. 4 Centrifugal Type Water Separator (Cyclone)

cyclone, it was reheated and any remaining entrained water was evaporated. From the dew point of the reheated air with and without the cyclone, the amount of the separated water in connection with air flow measurement could be determined. An ordinary wet and dry-bulb mercury thermometer was used for determining the dew point. The separated water was collected and checked against the amount found by the dew-point method. The amounts agreed within five per cent. For shorter tests only the dew points were measured.

Results

The cyclone showed 70% efficiency, handled about 1.2 lb/min air

flow and caused a pressure drop of 41 inches of water. The droplet size was in the range of 1 to 2 microns. From the pattern of the precipitated water on the tube walls it could be seen that the air stream made about 3-1/2 turns before leaving the cyclone. The inlet velocity, calculated from the flow rate and the inlet cross section, was 200 ft/sec. Since the air stream was directed downward with an inclination of about 40° against the tube axis, the effective component was about 150 ft/sec. With this velocity, and a particle size of 1.5 microns, Figure 3 yields a separation distance of 0.08 in. per turn, or for 3-1/2 turns and 70% efficiency a distance of .4 in. The air stream thickness, calculated from the continuity law and disregarding losses in the cyclone, was 0.2 in. Losses tend to increase the air stream thickness. Thus, the agreement can be considered satisfactory at least for purposes of an order of magnitude consideration.

Pressure drop across any moisture removal device, installed downstream of the cooling turbine, results in a reduction in the available turbine expansion ratio, hence a reduction in the temperature drop across the turbine and an increase in the turbine outlet temperature. Thus, for two different devices that separate water mist (entrained moisture) with equal efficiency, the device with the lower pressure drop will be able to remove a larger quantity of water mist, on a #water per #air basis, and produce a lower dew point in the aircraft cabin.

Cyclone separators are feasible if a number of small units are applied. They require a rather high pressure drop for a good separation efficiency.

SECTION IV

FILTER SEPARATION

Types of Filters

The characteristics of the filters investigated are presented in Table II.

TABLE II

Filter Characteristics				
Fiber Material	Fiber Diameter	Filter Area	Filter Weight	Filter Thickness
Fiber Glass Wool	0.001 in.	3.14 sq in	0.075 oz.	7/32 inches
Fiber Glass Cloth	0.0003 in.	3.14 sq in	0.043 oz.	1/32 inches
Copper Wire	0.01 in.	3.14 sq in	1.7 oz.	1-3/4 inches
Nylon	0.005 in.	3.14 sq in	0.19 oz.	9/32 inches

Efficiency of filters (see Figure 5) increases with pressure drop. This indicates that the separation of the droplets in the filter is accomplished in a manner similar to that of the cyclone. In the course of numerous deflections within the filter, the droplets are thrown to the fibers of the filter. Each pore in the filter may be considered as a minute cyclone unit. As with the cyclone, the filter is essentially sensitive to droplet size. In these tests the droplet size was from one to two microns.

Fiber Arrangement

The pores in the filter must not be too small because the capillary attraction of the water in the pores reduces the air flow rate at low pressures. The average pore size in the glass wool filter was found to be 6×10^{-3} inches. The capillary attraction with this size diameter amounts to seven inches of water column. The fiber diameter should not be made too small, as the drag coefficient of the fibers increases with decreasing fiber diameter due to the decreasing Reynolds Number. The optimum diameter should be such that the product of the surface area and the drag coefficient is at a minimum. In order to obtain maximum performance from the filter fibers within a certain filter area, the fibers should lay in a position perpendicular to the general direction of the air flow. This position offers the best opportunity to deflect the air, which is necessary for separation. Otherwise, the fibers should be arranged in a random manner, since they will then present a maximum surface area to the passing air. It also assures an even spacing of fibers throughout the filter. The filter pad should be compressed to maintain sufficiently close spacing and the fibers must be flexible enough to withstand the compression without breaking.

To prepare a filter possessing the above properties, the following technique was applied to the nylon fiber filter:

a. The nylon fibers were cut in one-fourth to one-half inch long pieces. Nylon was chosen mainly because it is very flexible.

b. The cut fibers were passed through a screen, broken up into single fibers, and were allowed to settle on the filter. This method takes advantage of the fact that particles settling in air or liquid tend to direct their longitudinal axes in a horizontal position. The fibers in the completed filter take this position. Care was taken to insure an even fiber distribution across the entire filter area.

c. The loose filter pad was then firmly compressed by hand between 1/8-inch mesh screens.

Figure 6 shows the filter-type separator used in the experiments.

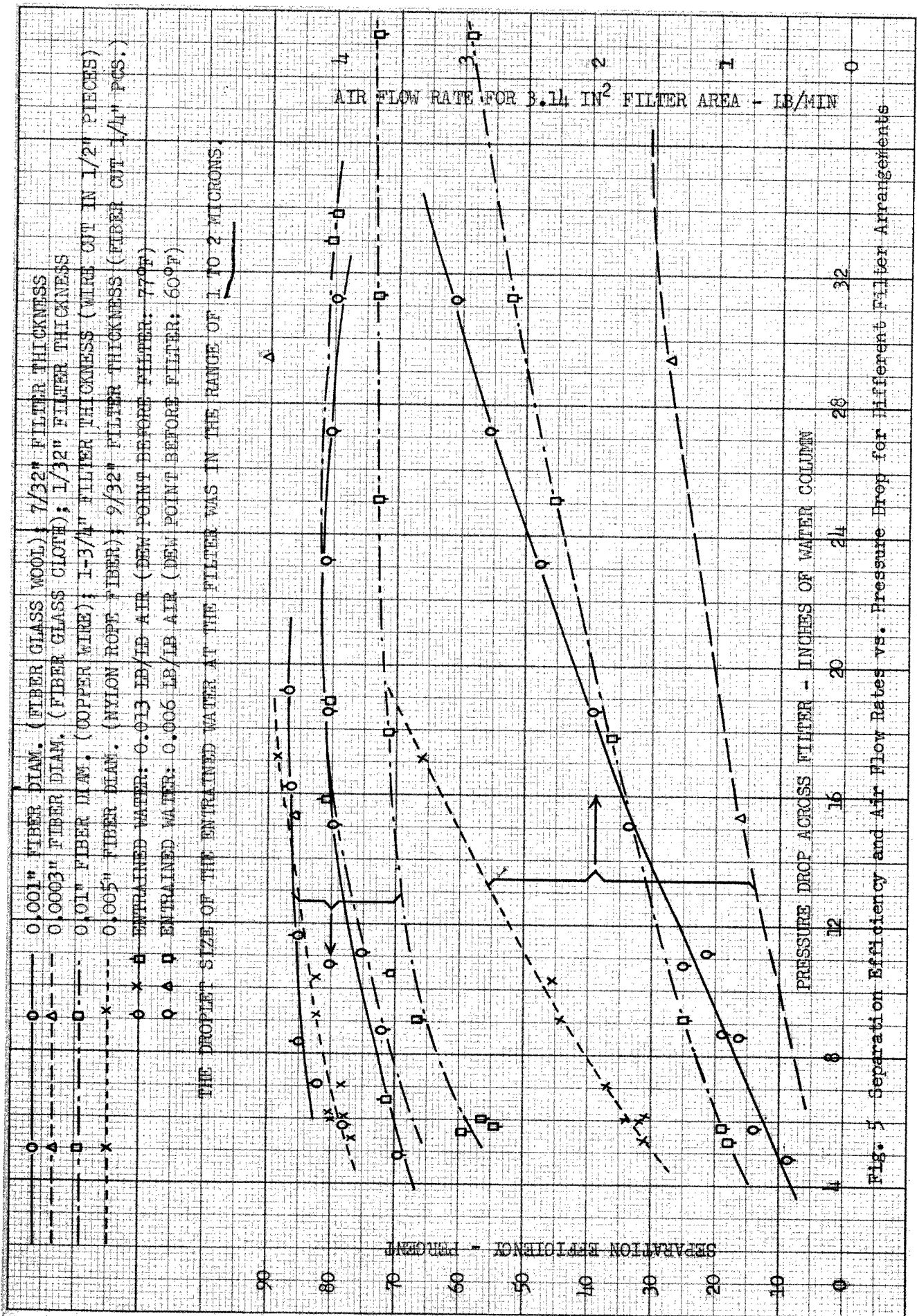


Fig. 5 Separation Efficiency and Air Flow Rates vs. Pressure Drop for Different Filter Arrangements

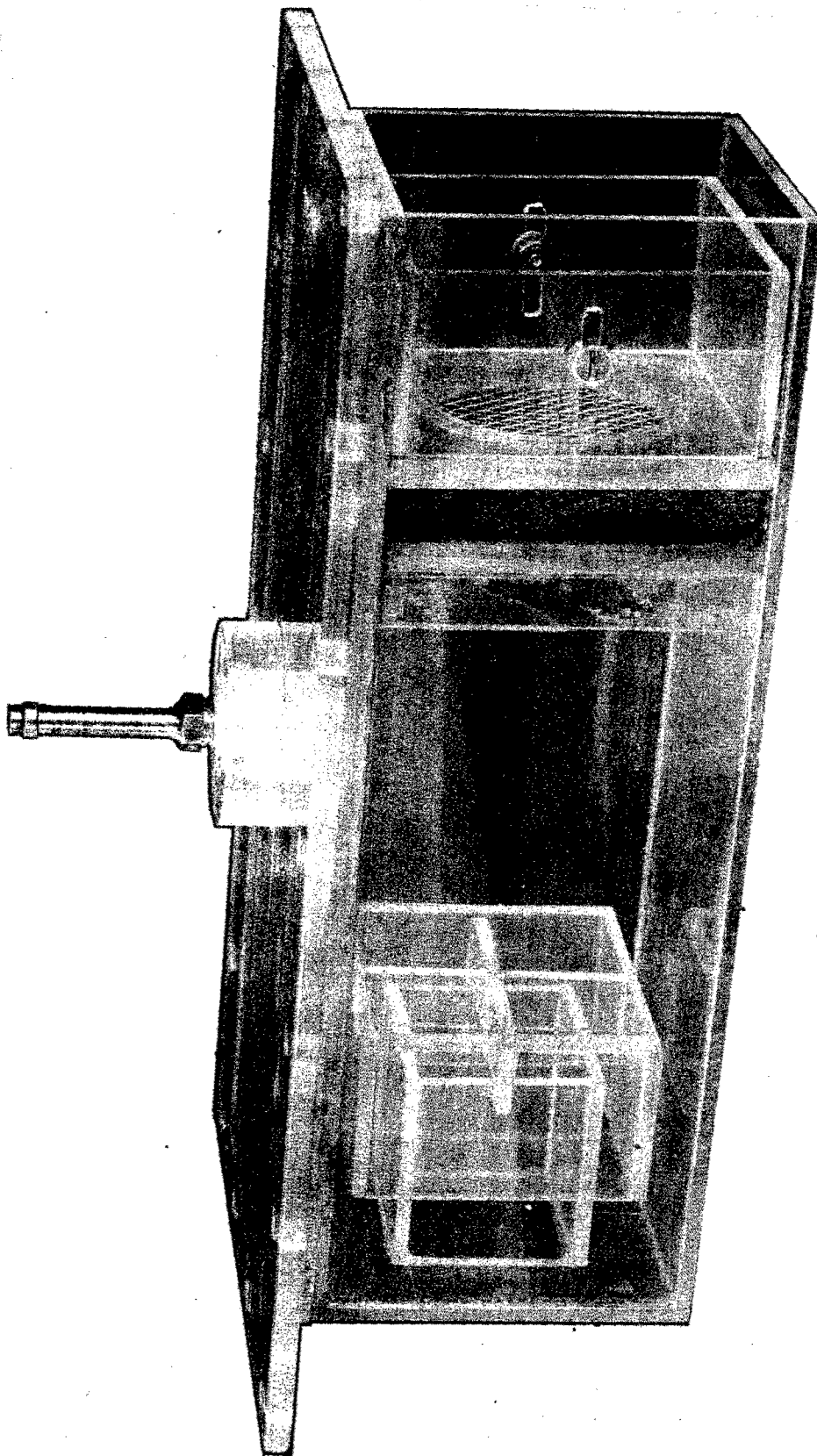


Fig. 6 Filter Type Water Separator

Test Results

The test results as shown in Figure 5 seem to justify the above described filter arrangement, but it should be noted that filters are sensitive to droplet size. The same filter has no separation effect at four inches water pressure drop if placed one foot from the turbine outlet. An important factor to be taken into consideration with filters is that they become clogged readily under freezing temperatures. They have, however, the advantage of being simple and of small size.

SECTION V

ELECTRIC PRECIPITATION

General Principle of Electric Precipitation

Electric precipitation is a common method for separating particles below 10 microns and is practically the only method for industrial separation below 0.1 micron. ^{6/} It is applicable for dry particles as well as for liquid particles, including sulfuric acid. The basic principle is essentially the following: (1) air containing the particles is passed through a negative corona discharge produced on a thin wire or any sharply edged electrode, (2) the particles become charged by gas ions produced in the corona discharge by the collision of gas molecules and electrons, and (3) in the electrostatic field between the electrodes, the negatively charged particles are deflected to the oppositely charged electrode and are deposited there if enough time is allowed for the particles to reach it.

Theoretical Considerations

For an order of magnitude calculation the expected precipitator size may be derived from the well known relation for the separation efficiency:

$$\eta = 1 - e^{\left(\frac{-2 F w L}{R v}\right)} \quad (2)$$

where

F = Electric field intensity, volts per unit length

w = Specific separation velocity (velocity per unit field intensity)

L = Length of collecting electrode in flow direction

v = Air flow velocity

R = Radius of collecting electrode

In the encountered range of particle sizes .25 to 1.5 microns the specific separation velocity assumes practically a constant value. 6/

Taking the significant ratio

$$\frac{\text{collecting area}}{\text{air flow}} = \frac{2 R \pi L}{R^2 \pi \delta v} = \frac{2 L}{\delta R v} = \alpha \quad (3)$$

and combining this with Equation 2, we obtain

$$\eta = 1 - e^{-F \alpha \delta} \quad (4)$$

δ = density of air

→ Plots of Equation (4) are given by Figure 9 for field intensities of 12,000 and 30,000 volts/in for an air density of .0765 #/cu ft and a separating velocity of .2 in/sec. The region of present day operation for dust precipitation is indicated as well as the recommended operating region for water separation. The smaller specific collecting area obtained in the present tests may be explained by the fact that while dust is redispersed at higher flow velocities, water will stick to the collecting electrode and will leave it only in the form of big drops. For separation efficiencies of around 70%, quite reasonable areas of the collecting electrode result.

A comparatively big collecting area can be arranged within a small space if the air is sent through a number of small channels, the walls of which serve as the collecting electrode. Each of the channels will have a discharge electrode in its center.

Design and Testing of a Precipitator

A precipitator with 24 square channels as shown in Figures 7 and 8 was built and tested. Significant performance data are entered in Figure 9. The test procedure was the same as with the cyclone and filter. The design data are shown in Table III.

The precipitator was made as long as possible, although its length was limited by the spacing of the electrodes. The channel walls were made up of 0.04-inch brass sheets, which were slotted half way, then placed together crosswise and soldered at the channel ends. In Figures 7 and 8 a center electrode is shown. Figure 10 is a schematic drawing of a single channel. Figure 11 gives the pressure-drop characteristic of the precipitator.

Center Electrode

At first, a plain 0.008-inch wire was used throughout the entire channel length. Intense sparking, caused by the big drops adhering to the ends of the channels, occurred at the channel outlets after the

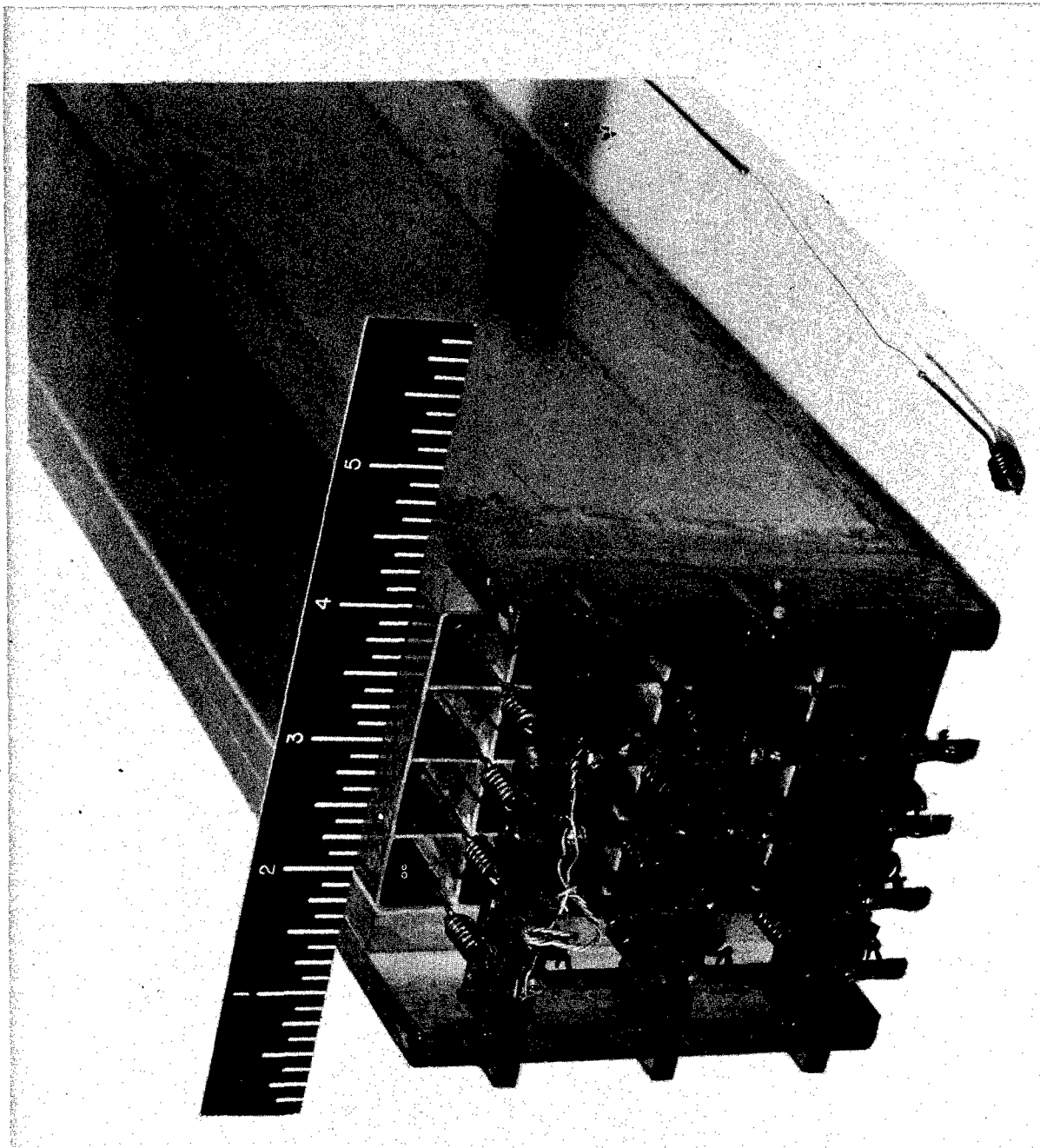


Fig. 7 Electric Precipitator Type Water Separator, Three-Quarter Front View

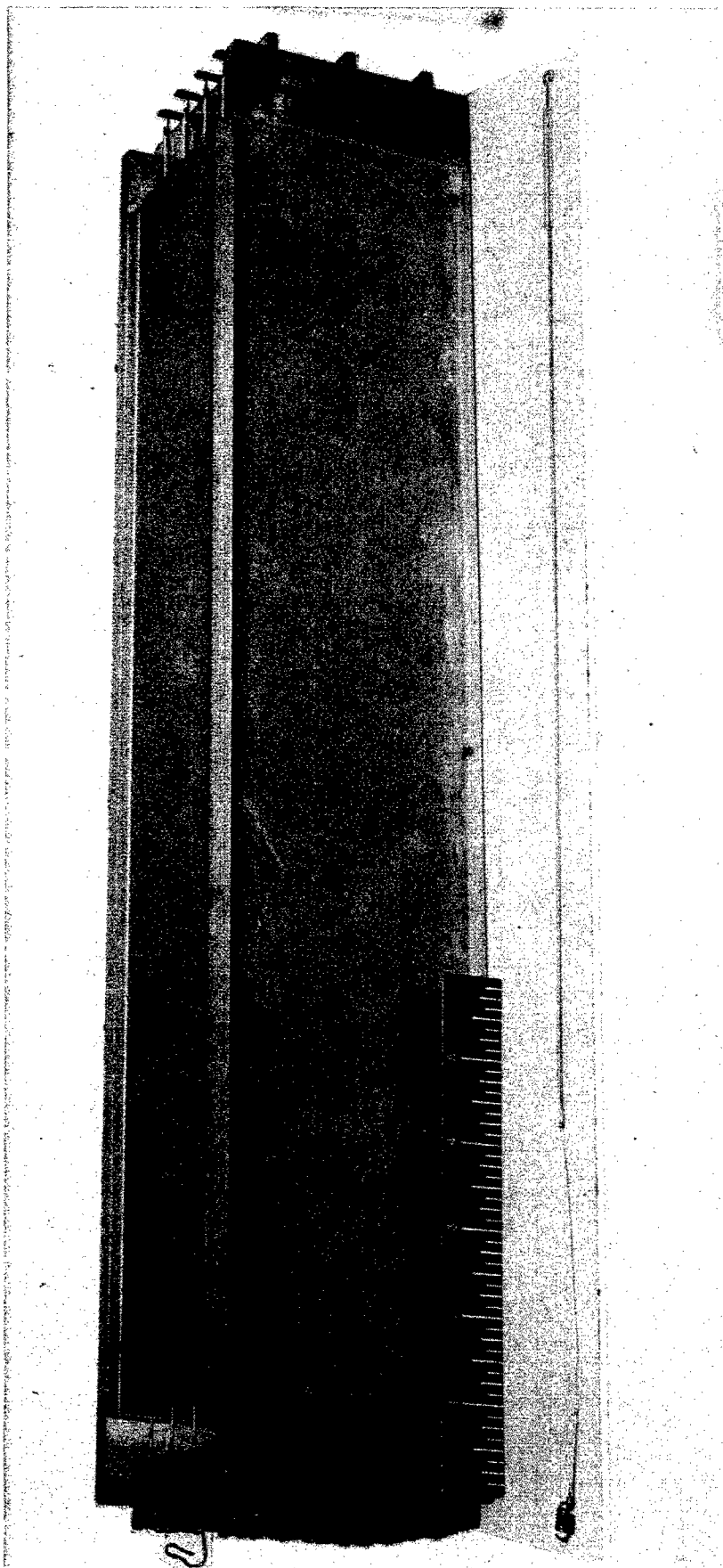
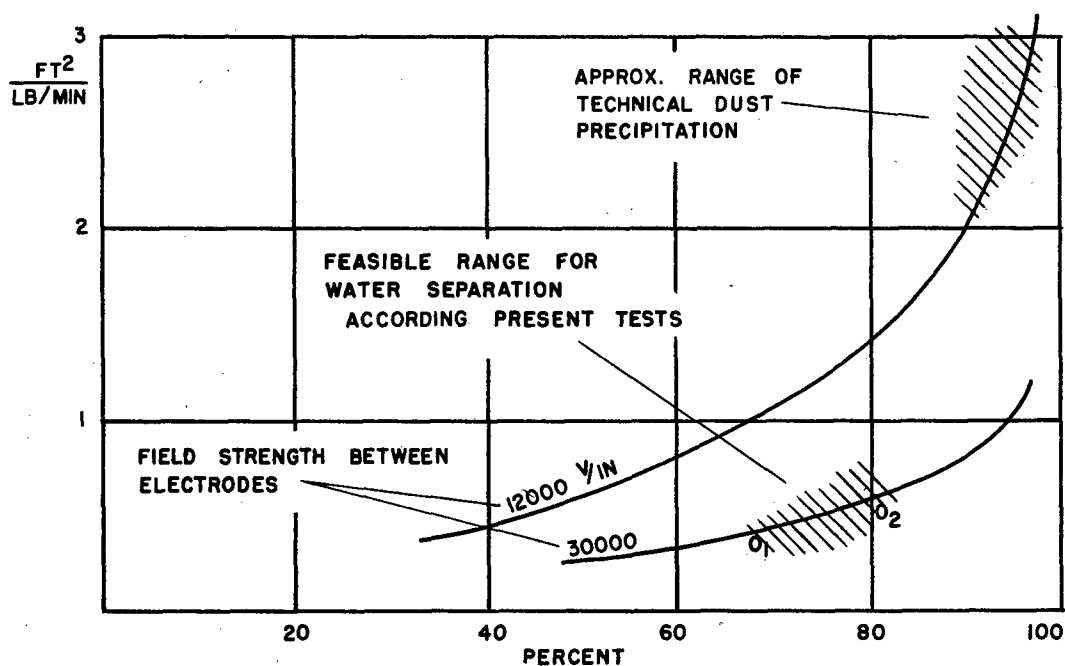


Fig. 8 Electric Precipitator - Side View

TABLE III

Design Data for the Precipitator

Channel Length	16 inches
Channel size	9/16 inch by 9/16 inch
Total flow cross section	6.7 square inches
Total collecting area i.e., total wall area touched by the air flow	5.6 square feet
Length of discharge wire	3 inches
Diameter of discharge wire	0.008 inch
Diameter of deflecting electrode	0.037 inch
Average spring tension on the center electrode	5 lbs



Test points: O₁. Air flow 13.5 lb/min. entrained water 0.008 lb/lb. air.

O₂. Air flow 11.5 lb/min. entrained water 0.0075 lb/lb air.

Precipitator: 16" channel length; 6.7 in² cross section.

Fig. 9 Area of Collecting Electrode Related to Air Flow vs. Separation Efficiency.

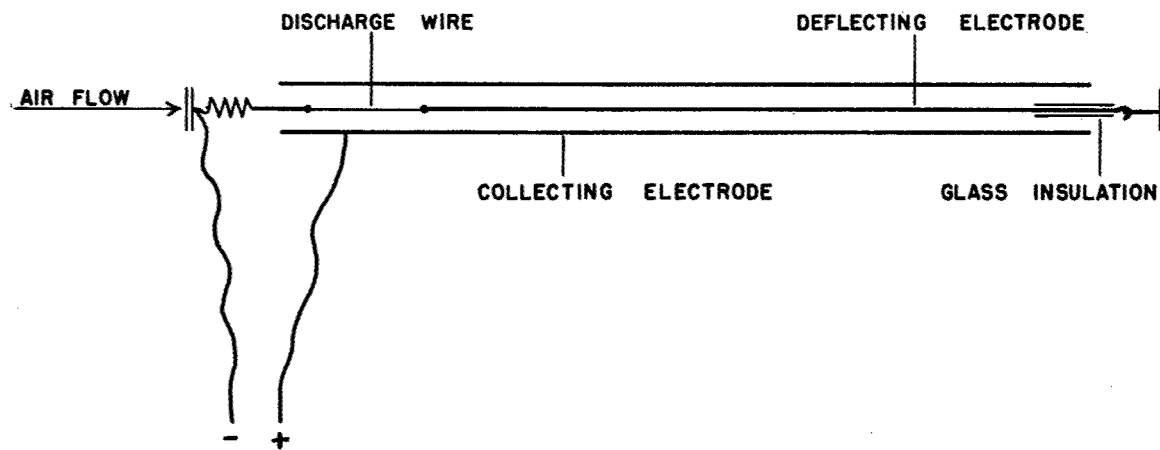


Fig. 10 Schematic Drawing of a Precipitator Channel.

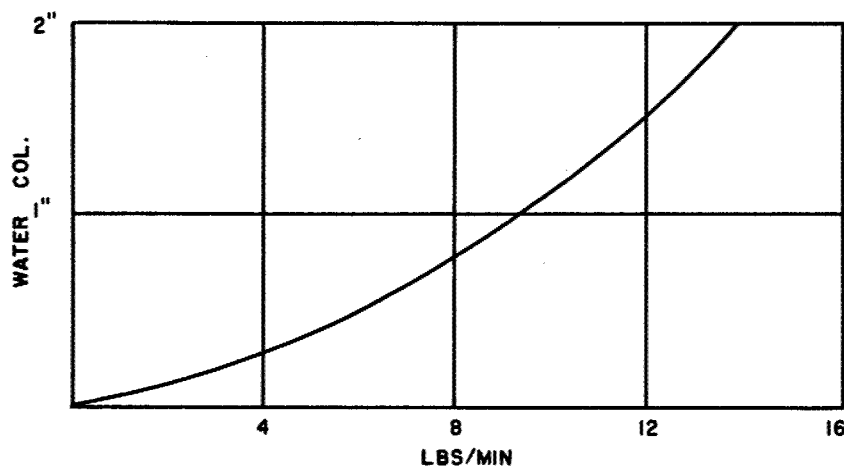


Fig. 11 Pressure Drop vs. Air Flow for Electric Precipitator with 16 in. Channel Length and 6.7 in² Total Flow Cross Section.

precipitator was in operation for a while. A glass tube slipped over the end of the center wire (see Figure 8 at right end of precipitator) eliminated the sparking and continuous operation was possible. With the thin wire extending through the entire channel length, the air discharged from the precipitator had an unpleasant odor stemming from the ozone and nitrogen oxide which were produced in the corona discharge.

A special test in a V-shaped channel showed that the corona discharge could be confined to a small portion of the center electrode at the channel inlet without essentially affecting the precipitation. For the precipitator, a thin wire fastened between two thicker ones as shown in Figures 7 and 8 was then used as center electrode. With this arrangement, the current input was reduced by about four times because of the reduced corona discharge and no annoying odor was present. A chemical analysis of the discharged air conducted by the Materials Laboratory, WADC, revealed an average content of .2 parts per million by volume of nitrogen oxide. The ozone content was about 2.2 parts per million by volume, at 11 lb/min air flow and about 75% separation efficiency. These gases or a mixture of both gases are perceptible by their odor at concentrations which are essentially lower than those at which they become harmful. 13, 14/

To obtain further proof if any annoying odor would be produced in a cabin, the test setup was connected to an F-84 cockpit. About 8 lb/min of air could be discharged into the cabin compartment. In the cabin, practically no perceptible odor could be detected with the separator on or off. It was, however, possible with the precipitator on to eliminate immediately the fog which was present in the cabin.

No exact alignment of the center electrode is necessary for effective operation of the precipitator. The corona discharge, which can be seen at higher currents as a faint bluish light around the thin wire, is hardly changed in its distribution if the wire is 10% off center. However, a proper alignment of the center electrode increases the breakdown voltage of the precipitator and a better maximum performance is obtained. Any pointed protrusion from the electrodes will lower the breakdown limit. The test precipitator was not of precision design. The center wires were adjusted to the center by visual means and the channel walls were somewhat wavy in places. The deviations in the average electrode clearances amounted to about 10%. Electrodes other than a thin wire may be used. For instance, a rod thick enough to be self-supporting and ground to a triangular cross section, showed an intense corona discharge.

Operating Position

All recorded tests were made with the precipitator in a vertical position. However, in a special test the plastic duct in which the precipitator was located (see Figure 12) was freely moved around during operation. No change in operation occurred, even after bringing the precipitator into a horizontal position for about 10 minutes.

Icing Conditions

At icing conditions, the separated ice particles cling to the channel walls. But before the channels themselves fill with ice, the

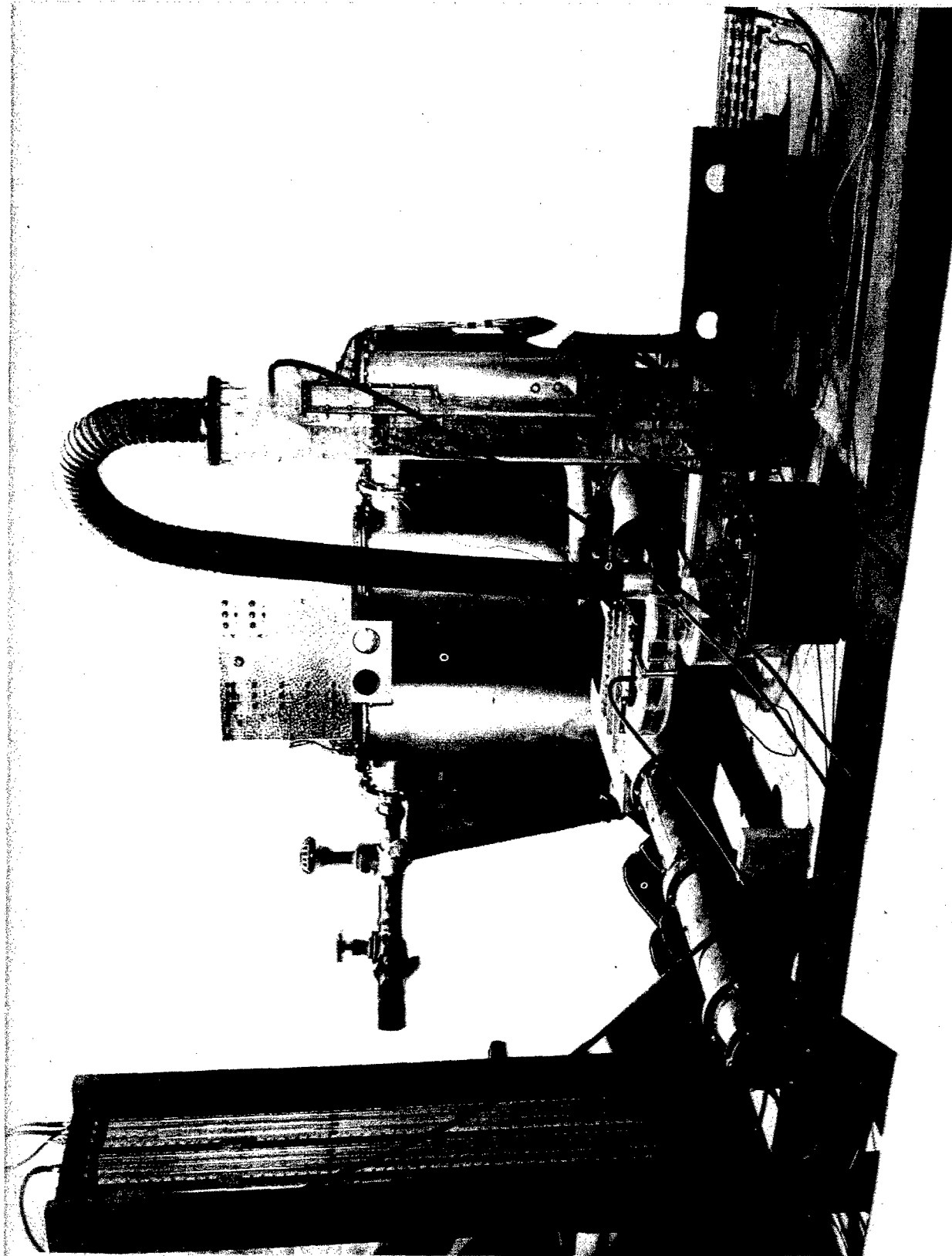


Fig. 12 Water Precipitator Test Setup

channel inlets are clogged by ice particles which accumulate even with the precipitator off. It remains to be investigated if, with wider channels, the accumulated ice will be broken off by the air stream. Ice between the electrodes causes electrical breakdown only when it starts melting. Properly heated channel walls might prevent ice accumulation in the channels without heating the air itself above freezing.

Operating Characteristics

An attempt was made to establish operating characteristics for the precipitator. The terminal voltage was plotted against the current through the precipitator for different air flow and humidity conditions. The effect of altitude could be determined only for zero air flow since no exhaust system for altitude tests was available. The curves, 1 through 8 in Figure 13, were derived from actual tests. The straight inclined lines represent the characteristic of the power supply. These were obtained by connecting all points of the test curves with equal primary voltage points. By changing the operating conditions, e.g., from zero entrained water to high water content, the point of operation moves along a line of constant primary voltage in the indicated example from lower to higher voltage and from higher to lower current.

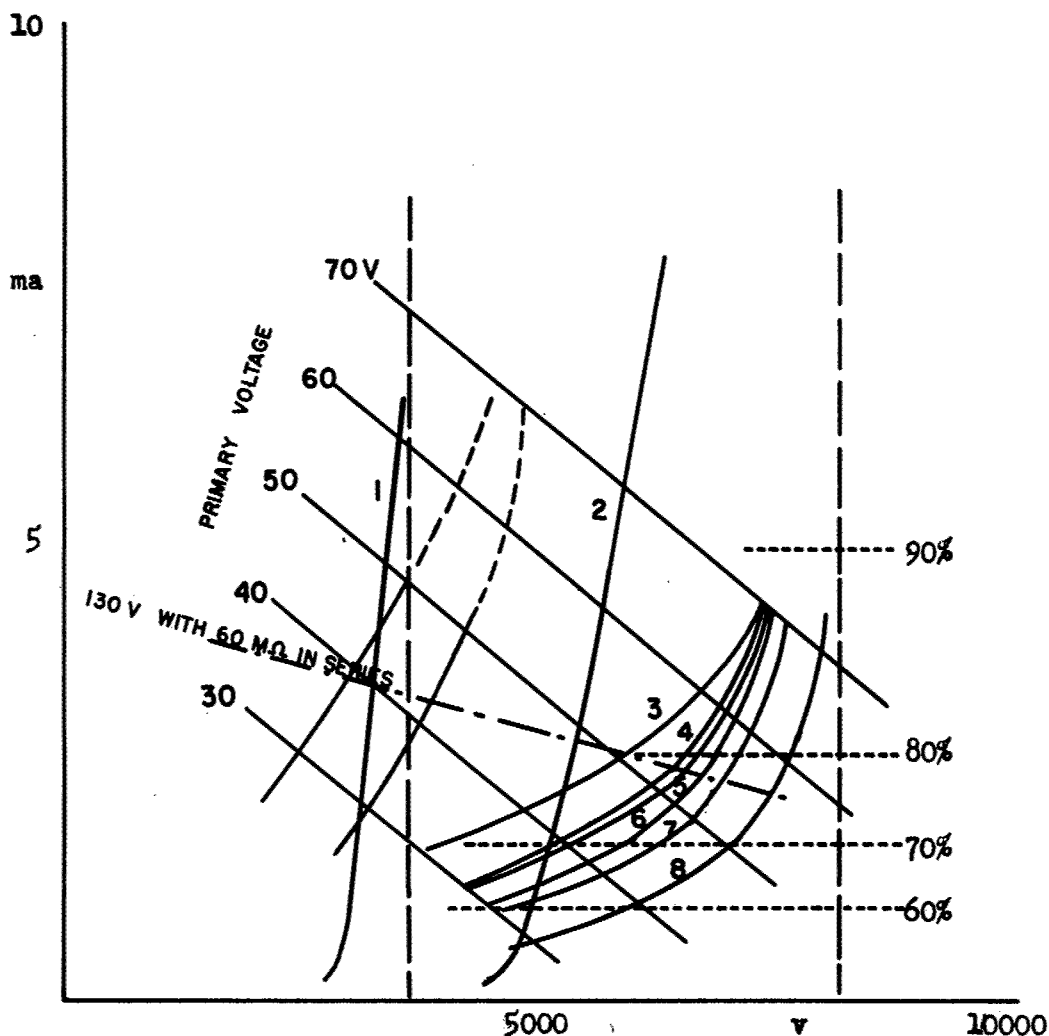
The efficiencies which are entered in Figure 13 are presented in a simplified form. The efficiency decreases with decreasing field strength and air density; thus, lower efficiency will result with increasing altitude. However, for practical applications, this efficiency decrease would be, in general, compensated for by a decreased entrained moisture content and a reduced air flow within the air conditioning system with increased aircraft altitude. The general behavior of an electric precipitator can be noted from Figure 13. With the power supply at a constant setting, almost all air flow and humidity conditions at sea level can be handled without breakdown if a flat enough power supply characteristic is applied. A very flat power supply characteristic is also needed under altitude conditions. These conditions may be compensated for by installation of current stabilizers. A curve for one such stabilizer is shown on Figure 13. In this test a 60 megohm resistance was placed in electrical series with the high voltage leads to the separator.

SECTION VI

CONCLUSIONS

The mist droplet size in the air discharged by the cabin air conditioning system changes from below the wave length of light at the turbine outlet to one to two microns at several feet from the turbine.

The filter and electric precipitator appear to be the only practical means for water mist separation. The cyclone system is effective only when a number of small units are used in parallel. The only advantage of the cyclone, that of handling icing conditions due to its large flow cross-section, is lost with a decrease in the unit size.



— — — — — breakdown voltage in 0 and 20,000 ft. pressure altitude.
 — — — — — probable positions of curves (3) to (8) for 20,000 ft.

- CURVE: (1) 0 lb/min dry air, 20,000 ft pressure altitude.
 (2) 0-12 lb/min dry air, 0 ft.
 (3) 11 lb/min. air, 0.005 lb/lb entrained water, 0 ft.
 (4) 8.5 lb/min. air, 0.007 lb/lb entrained water, 0 ft.
 (5) 13 lb/min. air, 0.0065 lb/lb entrained water, 0 ft.
 (6) 13 lb/min. air, 0.0055 lb/lb entrained water, 0 ft.
 (7) 9 lb/min. air, 0.0095 lb/lb entrained water, 0 ft.
 (8) 8 lb/min. air, 0.008 lb/lb entrained water, 0 ft.

Fig. 13 Operating Characteristic of the Electric Precipitator. The Straight Inclined Lines Represent the Characteristic of the Power Supply and the Numbered Curves that of the Precipitator.

The filter constitutes an arrangement of small cyclone units which are represented by the pores in the filter. A filter that is designed to operate by centrifugal action requires only four inches of water pressure drop (at one to two microns droplet size) for 75 per cent efficiency with an air flow rate of four-tenths pounds per square inch filter area. If the filter is placed closer to the turbine, efficiency decreases. A big disadvantage of the filter is that it clogs immediately under freezing conditions.

Electric precipitation is a feasible method for water mist separation. Although it requires more space than the filter, it eliminates a number of the drawbacks encountered with the filter. It can be placed close to the turbine since the separation is not affected by the droplet size. Under freezing conditions it takes several minutes for the passages to become clogged by ice particles, as opposed to almost instantaneous icing using the other systems. Icing in the electric precipitator can be overcome by the development of a heating system for the channel. The greatest advantage of electric precipitation is its low pressure drop. This is shown by the fact that at an air flow rate of two pounds per minute per square inch flow cross section and at a length of 16 inches of the precipitation electrode, an efficiency of 80 per cent with 1.5 inches of water pressure drop can be obtained. The electric precipitator is of special value in instances where the mist in the cabin is of short duration. It need not be bypassed for normal operation because of its low flow resistance. However, sub-freezing conditions should be avoided unless a precipitator heating system is devised.

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