FURTHER STUDIES ON ELECTROSTATIC SEPARATION

by

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I. Introduction

At the last air cleaning seminar we presented a preliminary report of our studies on electrostatically charged aerosol filters. At that time we outlined some basic concepts of electrostatics such as methods for producing static electricity, mechanisms of charge reduction and measurement of charge. In addition, we reviewed existing information on the nature and behavior of the resin-wool filter. In this paper we shall attempt to bring you up to date on the results of our continuing research on the electrostatic effects in fiber filters.

II. Experimental Studies on the Effect of Aerosol Charge on Filter Efficiency

A. Apparatus and Procedure

The electrical mechanism of removal in a dry fibrous filter is related to the electrostatic force between the aerosol and the collecting surface. This force may be either a Coulomb or a polarization force[1]. The Coulomb force exerted on an aerosol particle possessing a charge Q_p in an electric field of intensity E surrounding a charged fiber is as follows;**

$$F_c = Q_p E$$

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** The units used are in the "unrationalized" cgs or Gaussian system. That is, F is in dynes, E in statvolts/cm, Q in statcoulombs, and r in centimeters.

The field E at a distance r from the axis of a long slender fiber charged uniformly with Qf units of charge per centimeter of length is as follows;

$$E = \frac{2Q_f}{kr}$$

Since the relative dielectric constant k for air is nearly 1, the Coulomb force experienced by the aerosol particle in air is;

$$F_c = \frac{2Q_pQ_f}{r}$$

Thus, the removal force is a function of the product of the charge on the individual particle and the charge on the fiber.

If F_c is negative, the particles tend to move from the aerosol stream onto the collecting surface, the net effect being an increase in filtering efficiency. Conversely, a positive value would indicate a lowering of efficiency.

In the case where one of the components is charged and the other is a dielectric, the force between the two may be a polarization force^2. An uncharged particle whose dielectric constant differs from that of the surrounding medium experiences a net force when placed in a non-uniform electric field.

Consider an uncharged particle in the non-uniform field E surrounding a long slender charged fiber in air. The inductive force on a particle of volume V and of dielectric constant k is as follows;

$$F_p = \frac{(k-1)VE}{4\pi} \quad \frac{\partial E}{\partial r}$$

where r is the radial distance from the fiber.

Thus, the collecting force on a dielectric particle is related to the absolute value of the electric field surrounding the charged fiber, as well as the field gradient. The motion of the particle will be in direction of the greatest field strength, that is, towards the fiber, regardless of the polarity of the fiber. Since $E = \frac{2Qf}{r}$, $F_p = \frac{(k-1)d^3Qf^2}{6r^3}$ where d is the particle diameter.

An evaluation, therefore, of the role of electrostatics in filtration must concern itself with two components - particle charge and fiber charge.

In this study we have divided our investigations into two phases. The first phase is concerned with the effects of particle charge on the filtration efficiency of an initially uncharged fiber filter. The remainder of this paper deals principally with this aspect and will include a description of the test procedure, apparatus and results.

The second phase is concerned with the effect of charged fibers on the efficiency of filtration of uncharged aerosol particles. Some exploratory work on this aspect has been initiated, and brief mention will be made of tests in progress.

a) Aerosol generator

Figure 1 shows the general layout of the entire test assembly. A 15 inch diameter steel drum open at the top houses a constant speed motor driving a horizontal 4 inch diameter brass disc.* From an overhead constant head tank, a solution of 0.1 percent methylene blue in 95 percent ethyl alcohol is fed through a hypodermic needle onto the center of the disc. The resulting thin liquid film is centrifuged off the edge to form a fine liquid spray consisting of droplets of two distinct sizes; the main droplets and the satellites, of approximately 1/3 the size of the main ones. The diameter of the main droplets is a function of the rotational speed, radius of the disc and physical characteristics of the liquid. An induced downward flow of air

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* The aerosol was generated by a spinning disc sprayer adapted from the unit developed by Walton & Prewett[3].

through the drum intercepts the satellites and conveys them into the inlet of the 5 1/4 inch test duct. Contact with dry room air results in the evaporation of ethanol from these droplets and solid spheres of methylene blue are formed. Particle size distribution, determined by means of a Cascade Impactor having a molecular filter (MF or Millipore Filter)* as the fifth stage, showed the aerosol to have a mass median diameter of 2.0 μ and a geometric standard deviation of 1.3. Loadings could be varied from about 0.1 to 1.7 mgs. per cubic meter with good reproducibility.

A Stairmand disc and diffuser screen are provided in the duct to insure uniform cross-sectional distribution of the aerosol.

b) Aerosol charging device

The aerosol is charged by means of an ionizer section containing a series of electrodes consisting of fine wires and coplanar brass cylinders. A direct current power supply furnishes controlled voltages up to 12,000 volts and ion currents up to 150 microamperes. A unipolar corona discharge is established between the wire and cylinder electrodes. Particles entering the electric field between the wire and cylinder are charged as a result of bombardment of ions having the same polarity as the wire. The emerging aerosol, therefore, possesses a charge having predominantly the same polarity as the discharge electrode. Aerosol charge could be varied from test to test by varying the ionizing voltage and current.

c) Sampling

Sampling probes placed on either side of the test filter permit determination of filtration efficiency. The filter medium in the sampler is a MF (Hydrosol Assay Type) having an efficiency of approximately 100 percent. The sampling rate was 5 liters per minute.

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* Lovell Chemical Company, Watertown 72, Massachusetts

Mass concentration of methylene blue aerosol collected by the samplers is determined by dissolving the molecular filter in acetone, adding ethanol to dissolve the methylene blue and analyzing the solution colorimetrically on a Klett colorimeter.

d) Aerosol charge measurement

The filter medium used in these tests was 50 μ diameter glass fibers packed to a density of one pound per cubic foot. The filter was 5 1/4 inches in diameter and 1 inch thick. Aerosol charge measurements were made with a Faraday cage consisting of an 8 inch long brass collar around a Lucite filter holder as shown in Figure 2. A Rawson electrostatic voltmeter of low capacitance and high leakage resistance is connected to the Faraday cylinder. The capacitance of the entire electrical system including the meter is determined by a capacitance meter*. Electrical shielding of the measurement unit eliminates the effects of stray electric fields and capacitance. Critical parts of the test assembly are carefully grounded through conductors using soldered connections.

The product of the capacitance of a body and its potential equals its charge. Therefore, the collection of aerosol particles on the test filter is reflected by a steady change in voltage reading. Thus $dQ/_{dt} = C\ dV/_{dt}$**, that is, the product of the cylinder voltage change and the capacitance of the system is a measure of the net charge of collected aerosol per unit of time. Appropriate corrections are made for the charge carried by air ions, atmospheric dust and alcohol vapor.

Knowing the aerosol concentration upstream of the filter, as determined by the upstream sampler, it is possible to calculate the weight of methylene blue collected on the filter after correcting for measured filter efficiency.

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* General Radio 1612AL R-F Capacitance Meter 0 to 100 μμf.

** Where Q is in Statcoulombs, C in Statfarads and V in Statvolts.

From these data the ratio of charge to mass in terms of statcoulombs per gram can be calculated. Since the median particle size is known, a reasonably accurate approximation of the average electron charge units per particle can be obtained.

B. Test Results

Two series of runs were made, one with positively charged particles and the other with negatively charged particles. The superficial filtering velocity was 33 feet per minute with a filter resistance of 0.024 inches w.g. Aerosol loading ranged from 0.10 to 0.65 mgs/cubic meter for negative aerosol tests, and 0.19 to 1.7 mgs/cubic meter for positive aerosol tests. Although the filter used for the negative aerosol was a different one from that used with the positive aerosol, the medium, packing density, filtration velocity and resistance were quite similar.

It will be noted that the filter efficiency at zero charge was different for the two filters. This is of little significance since these tests were concerned only with the relative effect of aerosol charge on penetration.

The shape of the Curves in Figures 3 and 4 indicate that the filter efficiency gradually increases with aerosol charge from an initial value at zero charge to a maximum value, remaining constant with increasing aerosol charge. The results are similar in the case of the positive and negative aerosols.

The maximum increase in percent removal due to charge in either case is the same, namely $\left(\frac{72.5-64.5}{64.5}\right)100 = 12.4\%$ for the negative aerosol, and $\left(\frac{85-75.5}{74.5}\right)100 = 12.7\%$ for the positive aerosol. Also noteworthy is the fact that, with either polarity, the maximum efficiency is reached at an aerosol charge of about 2×10^5 statcoulombs per gram.

Test results can be explained as follows: The initial or "zero charge" penetration through the filter is determined by its inherent mechanical filtration efficiency. As filtration time increases, the deposition of charged particles on the filter gradually causes it to become charged. As this filter charge increases, the electric field at the filter surface becomes more intense. Thus, approaching charged particles experience an increasing Coulomb repulsion until the electric field is sufficiently high to retard or repel oncoming particles.

For the purpose of this discussion let us assume that the filter surface represents a uniformly charged infinite plane. This, admittedly is an over-simplification of the field conditions, but nevertheless it is a limiting case[4]. Then; $E = \frac{2\pi\sigma}{k}$ where E = Electric field intensity

σ = electric charge density at filter surface

k = dielectric constant = 1 for air.

Since the repulsive force F_e on an approaching particle with a charge of Q_p is as follows: $F_e = EQ_p$, then $F_e = \frac{2\pi\sigma Q_p}{k}$ but $\sigma = \frac{\Delta Q \cdot t}{A}$ where ΔQ is the filter charge increment per unit of time. Therefore $F_e = \frac{2\pi\Delta Q \cdot t \cdot Q_p}{Ak}$

This electrical replusion causes the particles to decelerate. However, as the particles slow down the viscous drag force of the airstream on the particle increases as follows:

$$F_d = 3\pi\eta d\Delta V$$

F_d = drag force

η = viscosity of air

d = particle diameter

ΔV = velocity of particle relative to the airstream.

Since $F_e = F_d = 3\pi\eta d\,\Delta V$, $\Delta V(\text{fpm}) = (2.6 \times 10^5)\Delta Q \cdot t \cdot Q_p$

Values of ΔV during filtration of positive aerosols of relatively low and high charge respectively were calculated and plotted in Figure 5. It will be noted that the repelling effect of the filter, as it gradually becomes charged by virtue of deposited charged particles, is of significant magnitude. This reduction of particle velocity reduces filter penetration since it increases the effectiveness of such removal factors as gravitational, diffusional and electrostatic forces normally operating in mechanical filtration. The repelling effect in the case of the more highly charged aerosol is much more marked.

From a comparison of the slopes of the two curves it may be inferred that at aerosol charge values slightly higher than 2.2 x 10^5 Statcoulombs per gram the repulsion effect of the filter reaches a maximum. It follows therefore, that beyond this point filter efficiency assumes a constant maximum value. This is in general agreement with experimental results shown in Figure 8 which indicate that percent removal of aerosol reaches a maximum at an aerosol charge of about 2 x 10^5 Statcoulombs per gram.

The above explanation is based on the assumption that the filter represents a uniformly charged infinite plane. The actual shape and intensity of the electric field at the surface of the test filter is more complex than this. The actual charge density at the filter face is lower than assumed, and therefore the electrostatic effects are less marked. Nevertheless, these figures serve to demonstrate the general character of these effects and how they vary with aerosol charge.

The failure of the filter to attain a removal value closer to 100 percent may be attributed to the fact that the test aerosol was not completely homogeneous in size and not uniformly charged, consequently, there existed particles possessing a charge below the critical value.

III. Effect of Fiber Charge on Filter Penetration

As mentioned previously, the electrostatic mechanism in filtration involves two components - the particle charge and the fiber charge. The former was discussed above, however, the fiber charge effects may be of equal or greater importance.

The attraction of airborne dust and lint to synthetic fibers and fabrics during textile processing operations suggests the use of these media in aerosol filters. The new synthetic fibers are known to develop and retain high static charges and this aerosol collection ability is related to electrostatic forces.

Before initiating tests to determine the significance of fiber charge on filter performance it was necessary to devise techniques for both producing electrostatically charged fibers and for measuring such charges. The method developed for charge measurement involved the Faraday effect (Figure 6). The Faraday cylinder described previously is connected to a Rawson electrostatic voltmeter in parallel with a calibrated air capacitor as a range extender.

It was observed that by briefly rubbing a sample of certain plastic fibers and dropping it into the Faraday cylinder a substantial deflection on the voltmeter could be obtained. The product of this voltage and the total capacitance of the system is equal to the net charge on the fibers in units of statcoulombs per gram.

Figure 7 shows the results of two tests made with 70 μ Saran fibers. In Test #1 the fibers were hand rubbed, whereas in the second test the charge was generated by rolling the fiber mass in a glass cylinder.

It will be noted that charge decreases exponentially with weight. Plotted on log-log paper, the average slope of these curves is -0.38. Analysis of these data disclosed that these results are in close agreement with the theoretical relationship between mass and the ratio of charge to mass for a sphere having a uniform charge density on its surface. A comparable plot of this relationship would yield a line with a slope of -0.33.

These results represent experimental verification of the fact that in charging fibers in this manner, essentially the net charge is distributed on the outer surface of the fiber wad, since tribo-electrification can occur only at the contact surface between the wad and the hand or glass cylinder.

This method of charging therefore was not considered satisfactory as it did not distribute the charge throughout the filter mass. Another technique was devised in which the fibers were electrostatically charged by means of a set of wool hand carders. It was observed that after several strokes of the hand carders Saran fibers became highly charged. The mechanism involved in this method is likewise tribo-electrification. In 2 series of tests, known weights of Saran fibers were hand carded and dropped into the Faraday cage. From the voltage reading and capacitance the fiber charge was calculated. The results are shown in Figure 8. Each point represents an average of 5 measurements.

The significant conclusions to be derived from these results are as follows:

1. The plot of Q/M vs Q is based on 2 series of measurements made on different days. Since the points fall very close to the line it is evident that the procedure is quite reproducible.

2. The values of charge obtained by this method are about 18 times higher than the previous method involving rolling in a glass cylinder, thus demonstrating the greater effectiveness of this technique for charging the fibers.

3. The calculated value of maximum surface charge density on the fibers is 0.8 statcoulombs per cubic meter which compares quite favorably with reported values of about 0.6 encountered in industrial practice, and

2.0 for charging belts of Van de Graaff electrostatic generators[5].

In one series of tests the samples were carded with 40 strokes while in the other 20 strokes were used. It was subsequently determined that these high values of fiber charge could be reached after only 3 or 4 strokes of the hand carders. Thus it was concluded that these results represented the limiting charge densities attainable by this technique.

Since this method of charging the fibers is relatively simple, reproducible, and capable of generating satisfactorily high charge levels it was adopted as standard procedure for this phase of our studies.

IV Conclusion

It is planned to construct fiber filters charged in this manner to determine the relationship between charge intensity and aerosol removal efficiency. Also of interest will be the life of such a charge and its variation, if any during operation. From such investigations it is hoped to obtain a better understanding of the electrostatic effects in aerosol filtration.

References

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4. Gilbert, N. E., "Electricity and Magnetism", MacMillam Company, New York, 1941.

5. National Bureau of Standards Circular C438, "Static Electricity", Washington, D. C., 1942.

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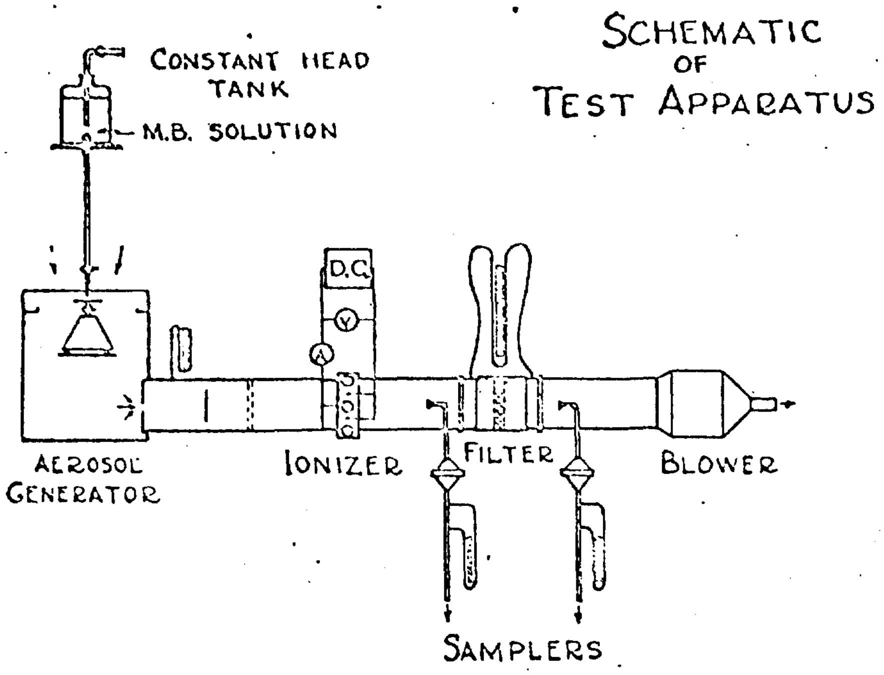


Figure 1. Schematic of Test Apparatus

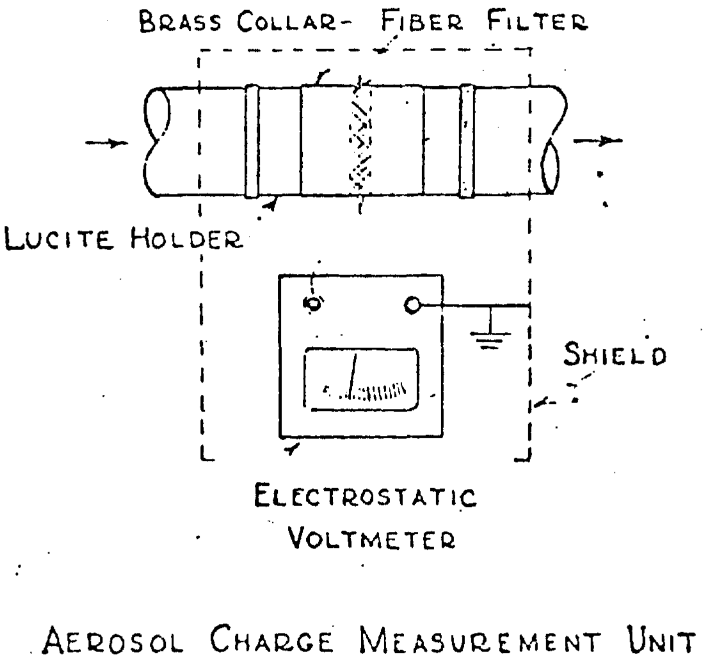


Figure 2. Aerosol Charge Measurement Unit

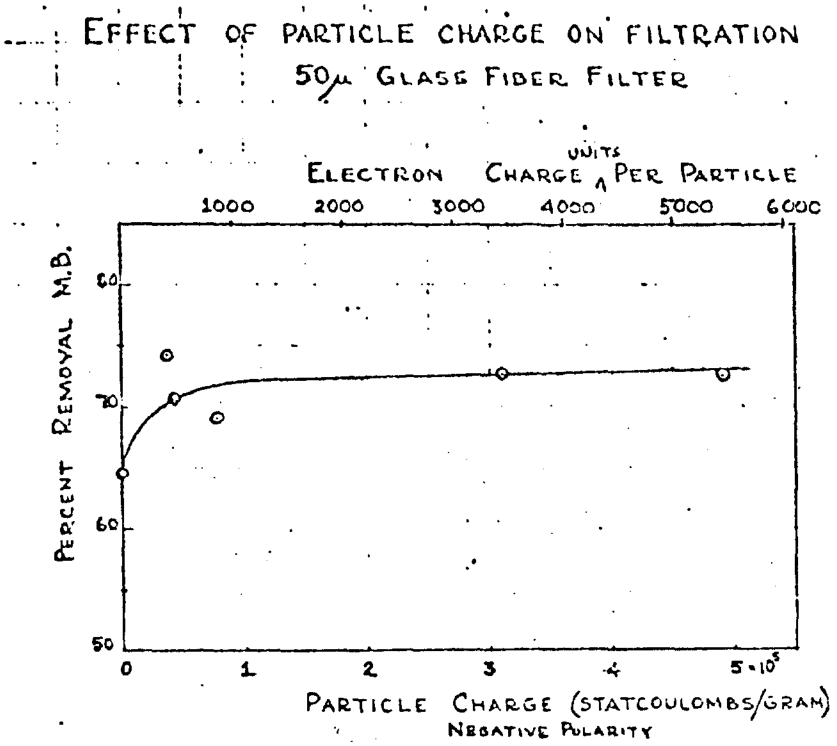
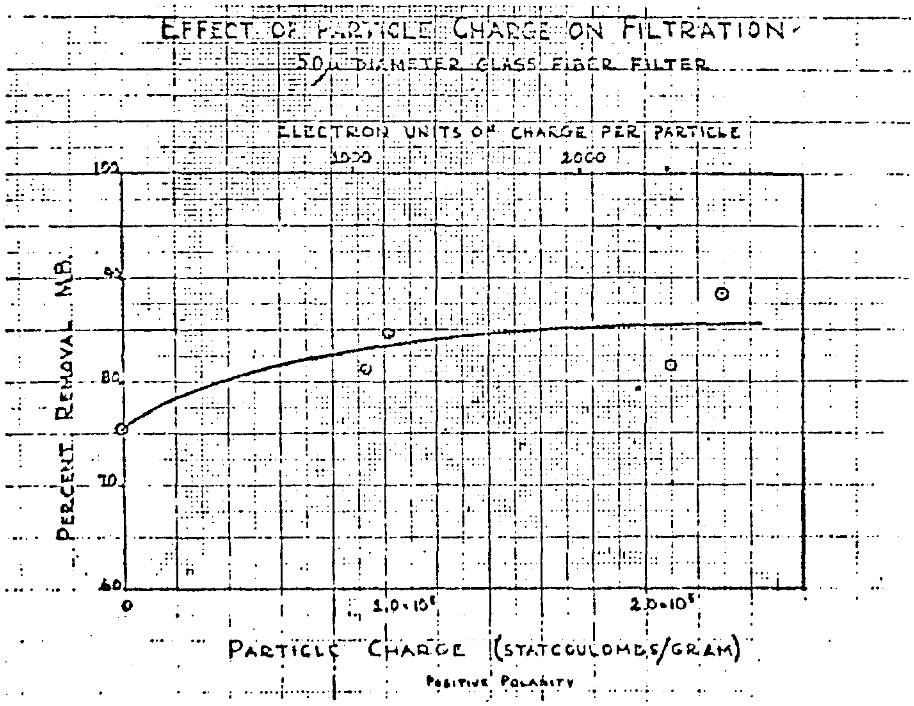


Figure 3. Effect of Particle Charge on Filtration - Test Results



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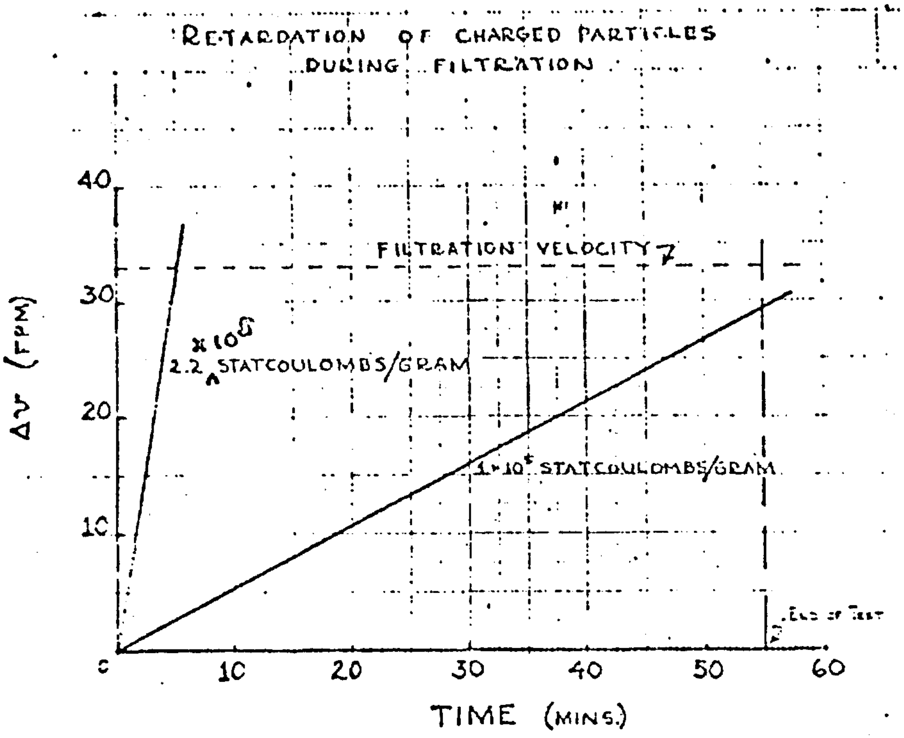

Figure 5. Retardation of Charged Particles during Filtration

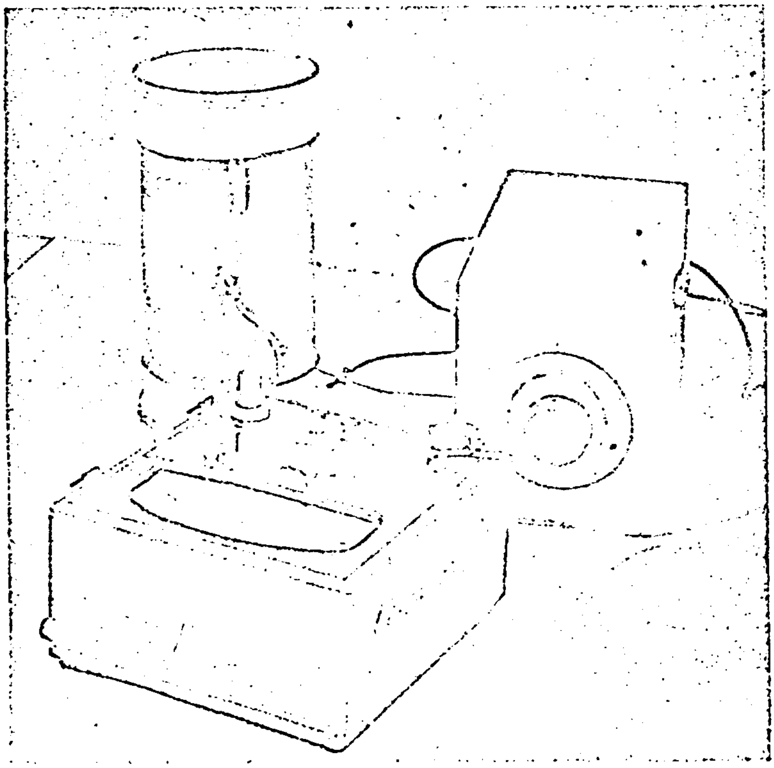

Figure 6. Apparatus for Measuring Fiber Charge

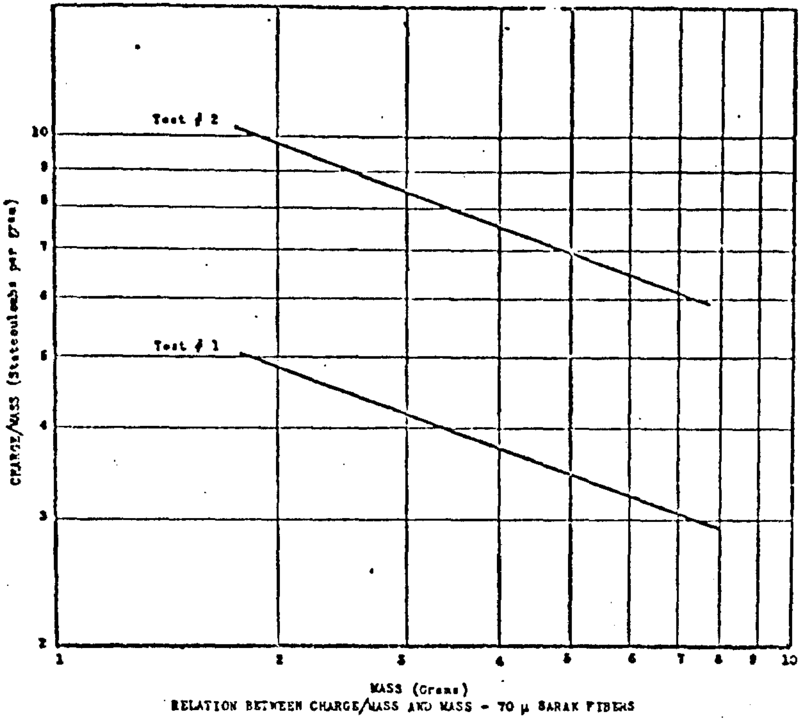

Figure 7. Relation Between Charge/Mass and Mass

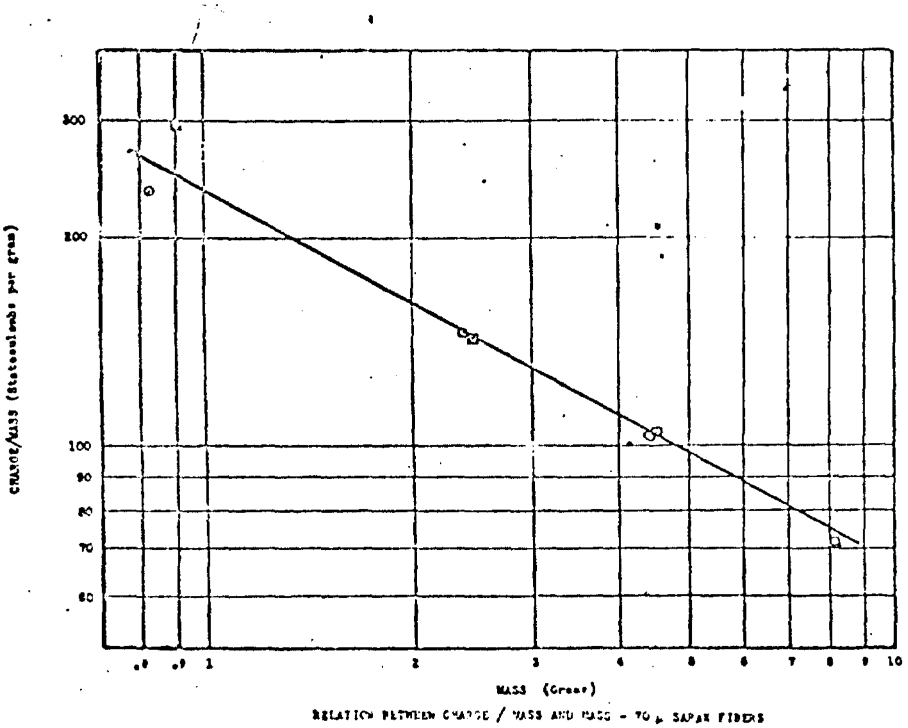

Figure 8. Relation Between Charge/Mass and Mass