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ELECTROSTATIC PRECIPITATOR FOR MEASURING PARTICLE-SIZE DISTRIBUTION IN AEROSOLS

B. G. Saunders

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HEALTH PHYSICS DIVISION

ELECTROSTATIC PRECIPITATOR FOR MEASURING PARTICLE-SIZE DISTRIBUTION IN AEROSOLS

Report by: Bernard G. Saunders
Work by: R. L. Quinn

PROTECTIVE EQUIPMENT EVALUATION PROGRAM

(In Cooperation with the Army Chemical Corps)

E. G. Struxness, Group Leader

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INTRODUCTION

This report summarizes the work accomplished[1] in developing an electrostatic precipitator for the determination of particle-size distribution in smokes.

Devices of this sort have been constructed by other laboratories.[2] Their operation depends on the deposition of particles by electrostatic means along a plate at distances which correspond to the particle-size. Such devices have required that the deposited particles be counted under a microscope in order to determine the particle-size distribution. The object of this project was to develop an instrument that would operate semi-automatically by indicating the particle distribution electrically. The scheme was to collect the charge-bearing particles on a series of collector plates. Particles of each size-range would fall on a particular collector plate and impart charges at a measurable rate. Thus a comparison of the beam currents would give the size vs. number distribution.

STATUS

A precipitator (Fig. 1) designed to meet the proposed objective has been partially built and tested. Laminar flow of the smoke in the system is obtain-

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1. This work was performed under Contract W-7405-eng-26 during the period F.Y. 1951, F.Y. 1952. See Quarterly Progress Report ORNL-1352.
2. Rohmann, H., Zeits. f. Physik 17, 253 (1923).
   Lipscomb, William N., T. R. Rubin and J. H. Sturdivant, J. App. Phys. 18, 72 (1947). (Reported more fully in Final Report on OSRD Contract OEMsr-103, May 27, 1944.)
   Wilkening, M. H., Rev. Sci. Inst. 23, 13 (1952).
   Kraemer, H. F. and W. E. Ranz, Tech. Report No. 7, Engineering Experiment Station, Univ. of Illinois, September 30, 1952.
   Gillespie, T. and G. O. Langstroth, Can. J. of Chem. 30, 1056 (1952).

able. Under a condition of laminar flow the smoke stream can be seen to bend in an arc and diverge into a spectrum as anticipated. It was hoped that the performance of the precipitator could be determined by measuring the diameters of the collected particles as a function of their position. Samples were collected on plates for various operating conditions. Electron photomicrographs were made of the particles. At this reporting date none has been obtained which is sharp enough to permit measurement. Before further progress can be made this problem of obtaining satisfactory photomicrographs must be investigated.

THEORY

The electrostatic precipitator, when designed for the determination of particle-size distribution in smoke, is in essence an aerosol spectrometer.

A stream of aerosol containing charged particles is directed along an axis at right angles to both the gravitational field and an electrostatic field. Since each particle will move away from the axis with a velocity that depends on its mass and charge, there will be a dispersion of all the particles in the stream along a direction parallel to the axis.

In Fig. 2, the aerosol flows streamlined through a duct of rectangular cross section in the direction z. The cross section has its center at $x = 0$, $y = 0$ and is 2a wide and 2b high. Two plates, A and B, are at a difference of potential V. This electrostatic field exerts a force on each charged particle in a y-direction proportional to the charge of the particle. The gravitational field exerts a force in the same direction proportional to the mass of the particle. If the charged plate on the bottom is a collector plate, then each particle will be collected along the plate at a distance z from the entrance which is a function of the charge and mass of that particle.

The distance z can be calculated by knowing the function $\frac{dz}{dy}$. The function $\frac{dz}{dy}$ can be written $\frac{dz}{dt} \cdot \frac{dt}{dy}$, which in turn is equal to v_z/v_y. Thus

$$\frac{dz}{dy} = v_z/v_y \,, \tag{1}$$

where v_z is the component of velocity in the z-direction equal to the velocity of the aerosol stream, and v_y is the component of velocity in the y-direction due to the electrostatic and gravitational forces.

According to Stokes' law, corrected by Cunningham, a particle having radius r moves in a gas with a velocity $\vec{v}$ that is proportional to the forces acting on it. That is,

$$v = \frac{\left(1 + \frac{A\lambda}{r}\right)}{6\pi\eta r} \Sigma \vec{F}$$

where A = Cunningham's constant, λ = mean free path of the gas molecules, $\Sigma \vec{F}$ = the sum of the vector forces required to give a particle constant velocity $\vec{v}$ in the presence of a viscous drag, and η = coefficient of viscosity. The vector forces acting on a particle in the y-direction are the gravitational force mg, and the electrostatic force neE, where ne represents the total ionic charge on a particle.

Hence,

$$v_y = \frac{1 + \frac{A\lambda}{r}}{6\pi\eta r} (mg + neE). \tag{2}$$

When $mg \gg neE$, v_y is proportional to r^2 and small particles settle more slowly than large, as is the usual experience; but if $mg \ll neE$ (the case for particles in the micron and submicron range) then v_y is proportional to 1/r and small particles move more swiftly than larger ones of the same charge.

The velocity of the aerosol stream or particle in the duct in a direction parallel to the z axis varies with distance from the axis. Along the axis the velocity $v_z = v_o$; along the collecting plate $v_z = 0$.

The general equations[3] for laminar flow of a gas in a duct are:

$$\frac{\partial p}{\partial x} = 0; \quad \frac{\partial p}{\partial y} = 0; \quad \frac{\partial p}{\partial z} = \eta \left(\frac{\partial^2 v_z}{\partial x^2} + \frac{\partial^2 v_z}{\partial y^2} \right),$$

where p is the pressure of the gas and η is its viscosity.

The last equation may be reduced to

$$\frac{\partial^2 \Psi}{\partial x^2} + \frac{\partial^2 \Psi}{\partial y^2} = 0$$

by choosing the parameters τ and Ψ such that

$$\tau = -\frac{1}{2\eta} \frac{\partial p}{\partial z} \quad \text{and} \quad v_z = \Psi + \tau (b^2 - y^2) .$$

In the case of a duct that has a rectangular cross section, the boundary conditions are as follows:

along the four walls,

$$v_z = \Psi + \tau (b^2 - y^2) = 0;$$

at the sides,

$$-b \leq y \leq +b \quad \text{or} \quad \Psi = -\tau (b^2 - y^2);$$

at the top and bottom,

$$y = \pm b \quad \text{or} \quad \Psi = 0.$$

Solution of the differential equation gives

$$\Psi = -\frac{32 \tau b^2}{\pi^3} \left\{ \frac{\cosh(\pi x/2b)}{\cosh(\pi a/2b)} \cos \frac{\pi y}{2b} - \frac{1}{3^3} \frac{\cosh(3\pi x/2b)}{\cosh(3\pi a/2b)} \cos \frac{3\pi y}{2b} + \ldots \right\}$$

3. Cornish, R. J., Proc. Roy. Soc. A120, 691 (1928).

and,

$$v_z = \tau(b^2 - y^2) - \frac{32\,\tau\, b^2}{\pi^3}\left\{ \frac{\cosh(\pi x/2b)}{\cosh(\pi a/2b)} \cos\frac{\pi y}{2b} - \frac{1}{3^3}\,\frac{\cosh(3\pi x/2b)}{\cosh(3\pi a/2b)} \cos\frac{3\pi y}{2b} + \cdots \right\}$$

By setting $v_z = v_o$ for $x = y = 0$ in the foregoing equation, the parameter τ may be written as a function of v_o. The general equation for v_z will then have the following form, where τ will now be implicit in v_o :

$$v_z = v_o \left[\frac{1 - \frac{y^2}{b^2} - \frac{32}{\pi^3}\left\{ \frac{\cosh(\pi x/2b)}{\cosh(\pi a/2b)} \cos\frac{\pi y}{2b} - \frac{1}{3^3}\,\frac{\cosh(3\pi x/2b)}{\cosh(3\pi a/2b)} \cos\frac{3\pi y}{2b} \right\}}{1 - \frac{32}{\pi^3}\left\{ \frac{1}{\cosh(\pi a/2b)} - \frac{1}{3^3\cosh(3\pi a/2b)} \right\}} \right].$$

Hence, from Eqs. 1 and 2, where mg $\ll$ Ene,

$$\frac{dz}{dy} = \frac{6\pi\,\eta\, r v_o}{\mathrm{Ene}(1 + \frac{A\lambda}{r})} \left[\frac{1 - \frac{y^2}{b^2} - \frac{32}{\pi^3}\left\{ \frac{\cosh(\pi x/2b)}{\cosh(\pi a/2b)} \cos\frac{\pi y}{2b} - \frac{1}{3^3}\,\frac{\cosh(3\pi x/2b)}{\cosh(3\pi a/2b)} \cos\frac{3\pi y}{2b} \right\}}{1 - \frac{32}{\pi^3}\left\{ \frac{1}{\cosh(\pi a/2b)} - \frac{1}{3^3\cosh(3\pi a/2b)} \right\}} \right]. \quad (3)$$

Thus, when a particle enters the duct at y_h at a height h above the bottom plate, it will travel a horizontal distance z_h before striking the plate. Lipscomb has integrated Eq. 3 to give the following:

$$z_h = \frac{6\pi\,\eta\, r v_o}{\mathrm{Ene}(1 + \frac{\lambda A}{r})}\,\frac{h^2}{b}\left(1 - \frac{h}{3b}\right) M, \quad (4)$$

where M has been written for the factor

$$M = 1 + \frac{32}{\pi^3\cosh(\pi a/2b)}\left[1 + \frac{32}{\pi^3\cosh \pi a/2b}\right]\left[1 - \frac{2d^2(1 - \cos(\pi h/2b))\cosh(\pi x/2b)}{\pi h^2(1 - h/3b)}\right]$$

As a first approximation, M may be taken equal to unity. Indeed, when the aerosol enters coaxially, that is, h = b, Eq. 4 reduces to

$$z = \frac{4\pi \eta b v_o}{Ene} \frac{r}{1 + \frac{\lambda A}{r}} . \qquad (5)$$

This equation states that a particle of given radius and charge will strike the collector plate at a distance z from the entrance. A second particle with idential charge but larger radius will therefore strike the collector plate at a distance $z + \Delta z$. A third particle, having the same radius of the second particle but a larger charge, will strike at a distance less than $z + \Delta z$, possibly z. Thus, particles of different radii might strike and be collected at the same point. Only when the particles are charged equally or they are charged as a function of their radii will they be deposited at distances commensurate with their sizes.

In the devices already cited, aerosol particles were charged by passing them through a flux of molecular ions. To produce the molecular ions, a wire was strung along the axis of a cylinder and maintained at a positive potential high enough to create a corona discharge about the wire. The corona generated a copious supply of negatively-charged molecules which migrated to the cylindrical anode. During this migration, if the molecules contacted aerosol particles which were flowing through the cylinder, they imparted ionic charges to the particles. A predicted by theory[4,5] and confirmed by experiment[5,6,7], the number of charges imparted to the particles varied with their radii.

A relationship used by Lipscomb and co-workers is the following:

$$n = E \left(1 + 2 \frac{K - 1}{K + 2}\right) \frac{r^2}{e} \frac{\pi i t}{E + \pi i t} + 0.07 \frac{irt}{Eue} , \qquad (6)$$

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4. Ladenburg, R., Ann der Phys. (5) 4, 863 (1930).
5. Arendt, P. and H. Kallman, Zeits. f. Phys. 35, 421 (1926).
6. Deutsch, W., Zeits. f. Tech. Phys. 7, 623 (1926).
7. Schweitzer, H., Ann der Phys. (5) 4, 33 (1930).

where n = number of charges collected by a particle of radius r and dielectric constant K, E = electrostatic field strength, u = mobility of the air ions, i = ion current per unit area, and t = time that the particle is in this field. This expression is the sum of two terms representing two types of charging: field charging and diffusion charging.

The first term of Eq. 6 results from the interception of ions by a particle, which is proportional to the area of the particle, πr^2. It is derived by integrating the differential equation for dn/dt, the rate of ion charging. The differential dn/dt is proportional to the field intensity at the surface of the particles, or

$$E\left(1 + 2\,\frac{K - 1}{K + 2}\right) - \frac{ne}{r^2} \quad ,$$

where $E\left(1 + 2\,\frac{K - 1}{K + 2}\right)$ represents the external field present at the surface of the particle due to polarization in the particle, and $-ne/r^2$ represents the repulsive field at the surface of the particle due to the charges it has acquired. Image fields are assumed to be negligible.

The second process, that of diffusion charging, is due to the Brownian motion of the charged molecules which causes them to surrender their charges upon collision with the particles. The rate at which the charges are accumulated depends on the image field and the field of repulsion due to the acquired charges. Lipscomb points out that the expressions for the two processes of field charging and diffusion charging are not strictly additive as shown in Eq. 6, since the two processes depend differently on the exponential power of the particle radius; that is, field charging is important for particles above one micron in radius, and diffusion charging is important for particles that are smaller.

RESULTS

The foregoing theory was considered in the design and construction of the electrostatic precipitator shown in Fig. 1. The work was divided into two parts: (1) the problem of obtaining the required conditions of laminar flow through the precipitator, and (2) the problem of charging the smoke particles and collecting them at the desired position on the collecting plate.

1. Laminar Flow

In trying to obtain suitable conditions of flow through the precipitator the unit was first constructed without collector plates or ionizer. About this time it was discovered that an electrostatic precipitator of similar design and purpose had already been constructed by Lipscomb and co-workers at the California Institute of Technology. From their report came the idea of installing the capillary glass tubes in the smoke stream and the 5 millimeter glass tubes in the air stream. These tubes improved the laminar flow at low rates considerably.

An attempt was made to make the smoke flow down the length of the precipitator as a thin ribbon. Due to unsatisfactory flow conditions, however, the ribbon of smoke had to be abandoned in favor of a thread of smoke. The result was laminar flow for flow rates of from 5 to 30 cm per second. Optimum flow conditions appeared to hold at 12 to 15 cm per second. At this flow rate a fine thread of smoke could be seen along the entire length of the collecting chamber. Thus the problem of obtaining the necessary conditions of laminar flow appeared to be solved.

2. Charging

The problem of charging the smoke particles and collecting them at the desired positions on the collecting plate was next studied. For purposes

of experimentation, one long collecting plate was used instead of a series of small ones. The small ones were to be added later if it appeared that the precipitator would work.

Since a uniform ion current of only 10^{-8} amp per cm^2 is required to charge smoke particles sufficiently for proper precipitation an alpha particle source of Po^{210} was used instead of a corona discharge. Such a charging mechanism is believed to be more stable and reproducible than one that uses a corona discharge, thus giving a steadier ion current. To make certain that only ions of one polarity would attach themselves to the smoke particles, the alpha source of Po^{210} was located at a distance of approximately 2.5 in. from the smoke stream. This was well beyond the range of the alpha particles.

In operation, alpha particles ionize the air molecules on one side of the smoke stream. The ionized molecules are then pulled through the smoke stream by an electric field impressed across the charging device. The smoke particles must penetrate one inch through this negative ion stream before passing into the deflecting region of the spectrometer. Smoke particles that move at the rate of 14 cm/sec are in the field of negative ions for a period of approximately $\frac{2.54}{14} = 0.182$ sec.

A current density of 10^{-8} amperes per cm^2 represents the collection of $10^{-8}/1.6 \times 10^{-19} = 6.24 \times 10^{10}$ ions per second per cm^2, since one ion possesses 1.6×10^{-19} coulomb of charge. It requires approximately 35 electron volts to ionize a molecule of air, or a total energy of $35 \times 6.25 \times 10^{10} = 2.2 \times 10^6$ Mev (million electron volts) to produce an ion current of 10^{-8} amperes. Since each alpha particle from Po^{210} has an energy of 5.3 Mev, this total energy is equivalent to $2.2 \times 10^6/5.3 = 4.1 \times 10^5$ alpha particles per second, or $4.1 \times 10^5/3.7 \times 10^7 = 1.1 \times 10^{-2}$ millicurie of Po^{210}. Actually, an alpha

source of 2.5 mc spread over one square inch was used. Since half of the activity was absorbed by the mounting plate, this gave a theoretical current of 1.66×10^{-7} amp/cm^2 instead of 10^{-8} amp/cm^2 when all of the ions were collected while being produced. Figure 3 shows a graph of the currents measured under different collecting voltages.

Assuming that Eq. 6 is valid in the case of particle-charging between two parallel plates, a sample calculation shows at what distances, z, smoke particles will be deposited in the precipitator shown in Fig. 1.

The following operating conditions are typical:

$$i = 1 \times 10^{-7} \text{ amp/cm}^2 = 300 \text{ statamps/cm}^2,$$

$$E = 26.5 \text{ kv} = 9.28 \text{ statvolts/cm},$$

$$v_o = 14 \text{ cm/sec},$$

$$t = 0.182 \text{ sec},$$

$$u = 1.7 \text{ cm/sec/v/cm} = 510 \text{ cm/sec/statv/cm},$$

$$K = 2.5,$$

$$e = 4.8 \times 10^{-10} \text{ e.s.u.}$$

Substituting these values into Eq. 6, one obtains

$$n = 3.1 \times 10^{10} r^2 + 1.3 \times 10^6 r \quad (r \text{ in cm});$$

$$n = 310 r^2 + 130 r \quad (r \text{ in } \mu).$$

Also employing Eq. 5,

$$z = \frac{4\pi \eta b v_o}{Ene} \frac{r}{1 + \frac{\lambda A}{r}},$$

where

$$\eta = 1.8 \times 10^{-4} \text{ poise}$$

$$b = 3.18 \text{ cm}$$

$$\lambda = 10^{-5} \text{ cm}$$

$A = 0.874$

$v_o = 14$ cm/sec

$$z = \frac{2.10 \times 10^8 \, r}{\left(1 + \frac{0.874 \times 10^{-5}}{r}\right) E} \frac{r}{n} \qquad (r \text{ in cm})$$

$$z = \frac{21{,}000}{\left(1 + \frac{0.874}{r}\right) E} \frac{r}{n} \qquad (r \text{ in } \mu) .$$

If the voltage across the collecting plates is 4 kv, or E = 2 statvolts/cm, the following table may be constructed:

Particle Size $r(\mu)$	No. of Charges/Particle $n = 310\ r^2 + 130\ r$	Distance to Point of Precipitation z(cm)
0.005	0.007 + 0.65 = 0.66	2.84
0.01	0.03 + 1.3 = 1.33	10.8
0.02	0.124 + 2.6 = 2.72	13.0
0.05	0.775 + 6.5 = 7.28	27.3
0.10	3.1 + 13 = 16.1	35.0
0.20	12.4 + 26 = 38.4	38.5
0.50	77.5 + 65 = 142.5	31.2
1.00	310 + 130 = 440	21.9
2.00	1240 + 260 = 1500	13.4
5.00	7750 + 650 = 8400	6.14

Since a smoke particle cannot pick up a fraction of a charge, all values of n are rounded off to whole numbers in the calculation of z.

It may be seen from Table 1 that along the middle section of the collector plates particles of two size ranges are collected at any given distance z. Operating the precipitator under the conditions already cited, and using rosin smoke, the measurement of particle numbers by beam currents is limited to sizes below 0.2 μ, provided no sizes greater than 0.2 μ are present.

In order to study particle charging and collection, laminar flow was first obtained before a run was made. Rosin smoke, the same source of particles used by Lipscomb and his group, was always used.

Then, when voltage was applied to the ionizer and the collecting plates, the smoke stream could be seen to bend toward the collecting plate and to spread out until it became invisible. An attempt was made to collect samples at different distances along the collecting plate and to determine their size distribution with an electron microscope. Poor photographs of the particles, however, were obtained. (See Figs. 4 - 10.) The particles appeard indistinct and fuzzy around the edges; not at all like the pictures shown in Lipscomb's Final Report. The reason for the difference is not understood.

An attempt was made to measure the ion current resulting from the deposition of charged smoke particles onto the collector plate. Currents were of the order of 10^{-13} amp and were measured with an electrometer having a high impedance. The results were far from satisfactory due to leakage resistance and stray capacitance.

CONCLUSION

An electrostatic precipitator has been constructed that sorts smoke particles according to size. Attempts to calibrate it for size distribution

have so far been unsuccessful.

Two methods of calibration were tried. In the first method, particles of rosin smoke were collected and examined for size under an electron microscope. The micrographs were not sharp, making it impossible to assign radii to the particles photographed. It was seen that further study of this problem would be necessary before suitable electron micrographs could be obtained.

The second method of calibration depended on the measurement of ionic currents of the particle beam at various points along the collecting electrode where it impinged. By passing smokes of known homogeneous size range through the precipitator, it was hoped that relative beam currents could be obtained.

A preliminary investigation was made to see how accurately beam currents could be measured. Rosin smoke was used for the test. It was concluded that a more precise technique of measurement would have to be developed before this method of calibration could become fruitful, and indeed before the objective of this project -- the determination of particle sizes from the measurement of ion currents -- could be achieved.

Once these difficulties are surmounted and the precipitator is calibrated, it should become a most useful tool in aerosol research.

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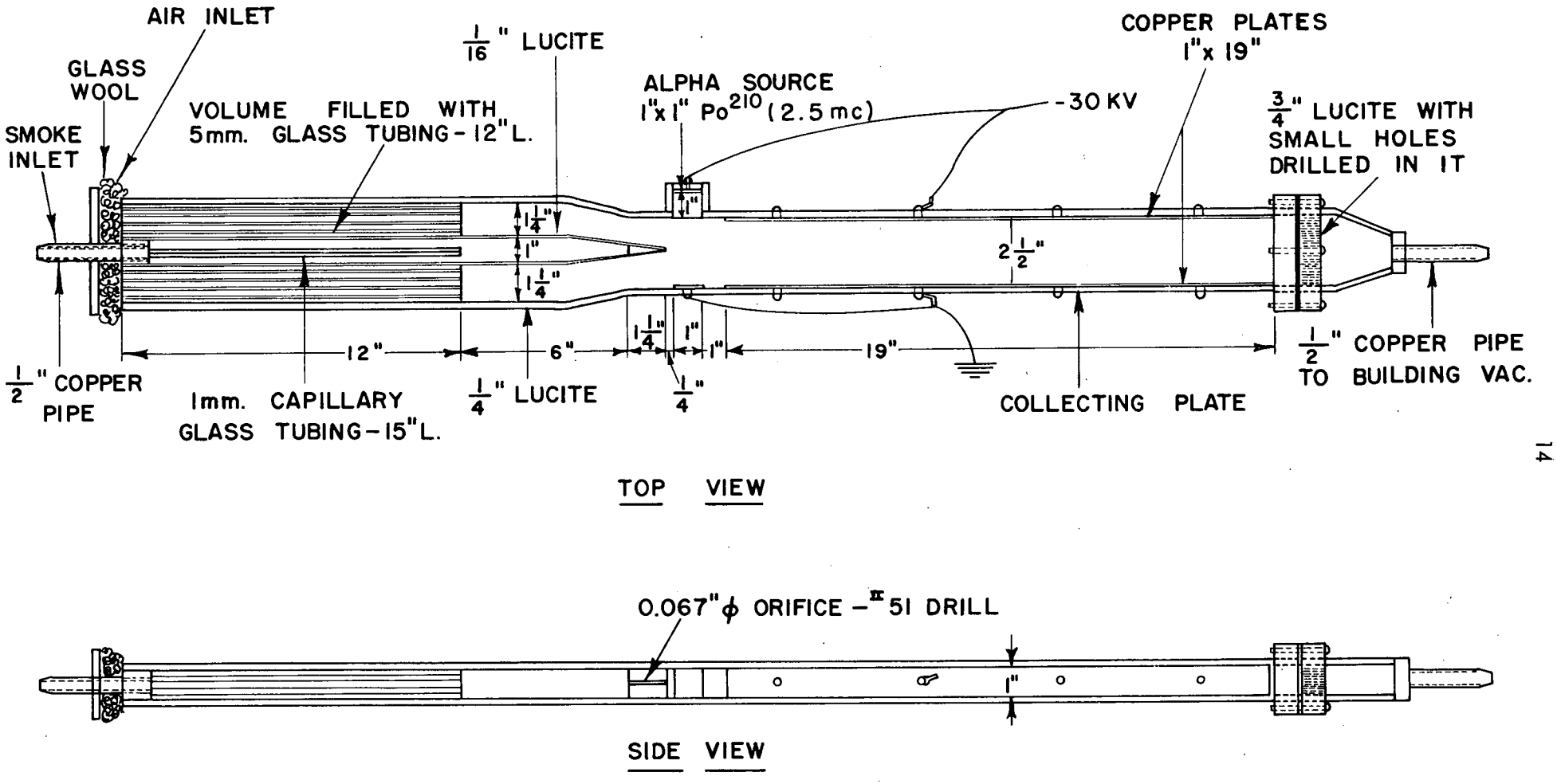

FIGURE 1 ELECTROSTATIC PRECIPITATOR

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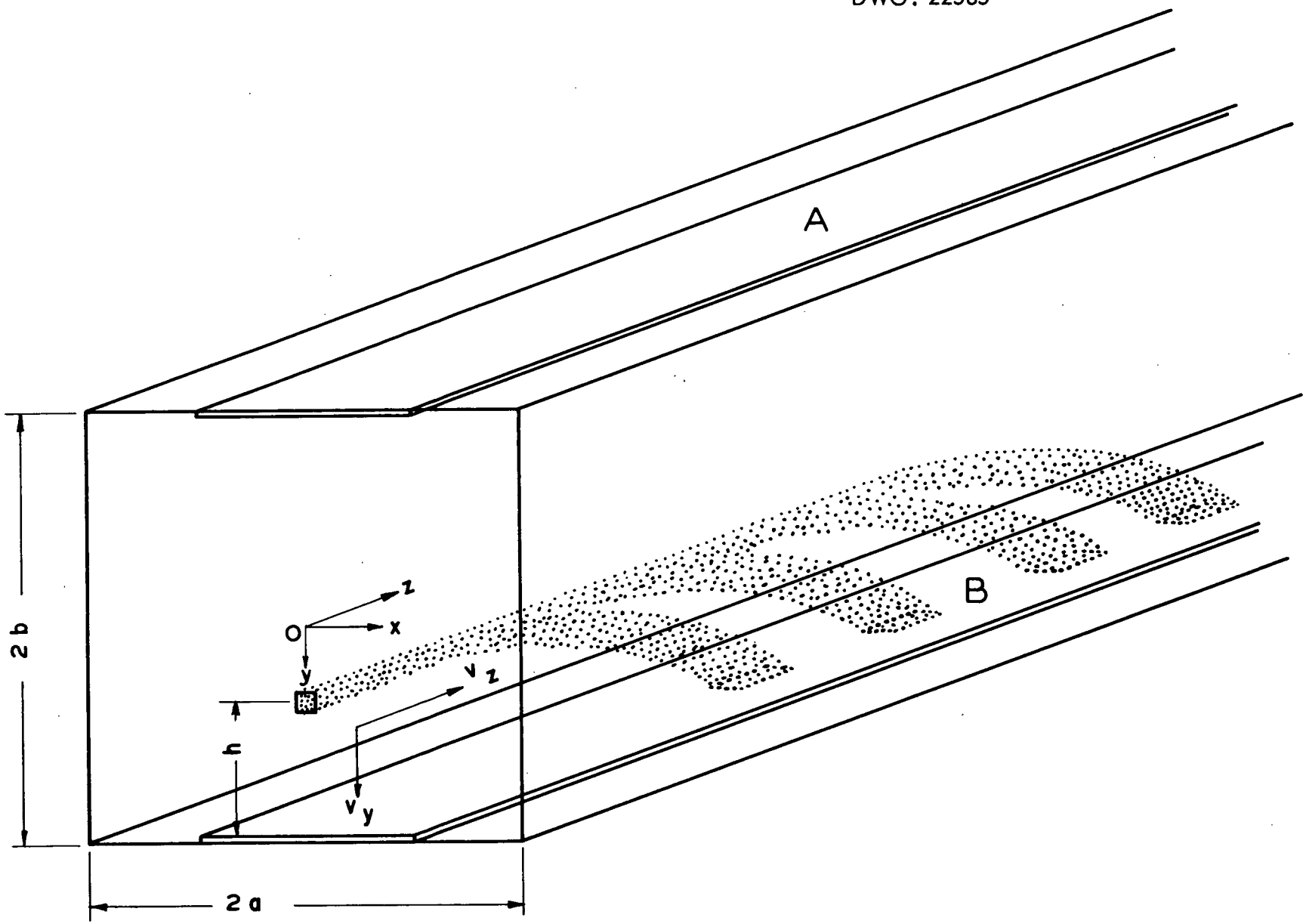

FIG. 2

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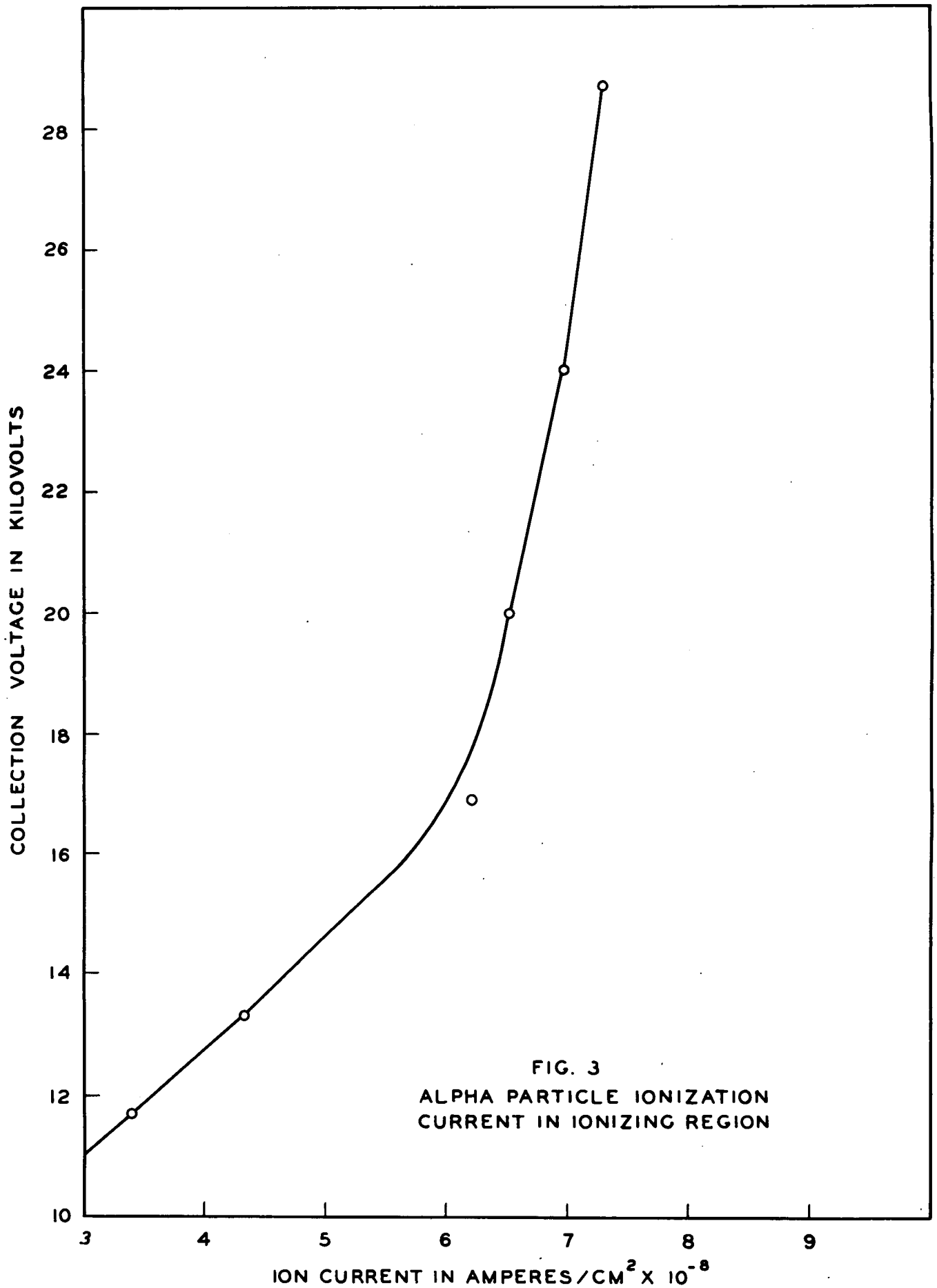

FIG. 3
ALPHA PARTICLE IONIZATION
CURRENT IN IONIZING REGION

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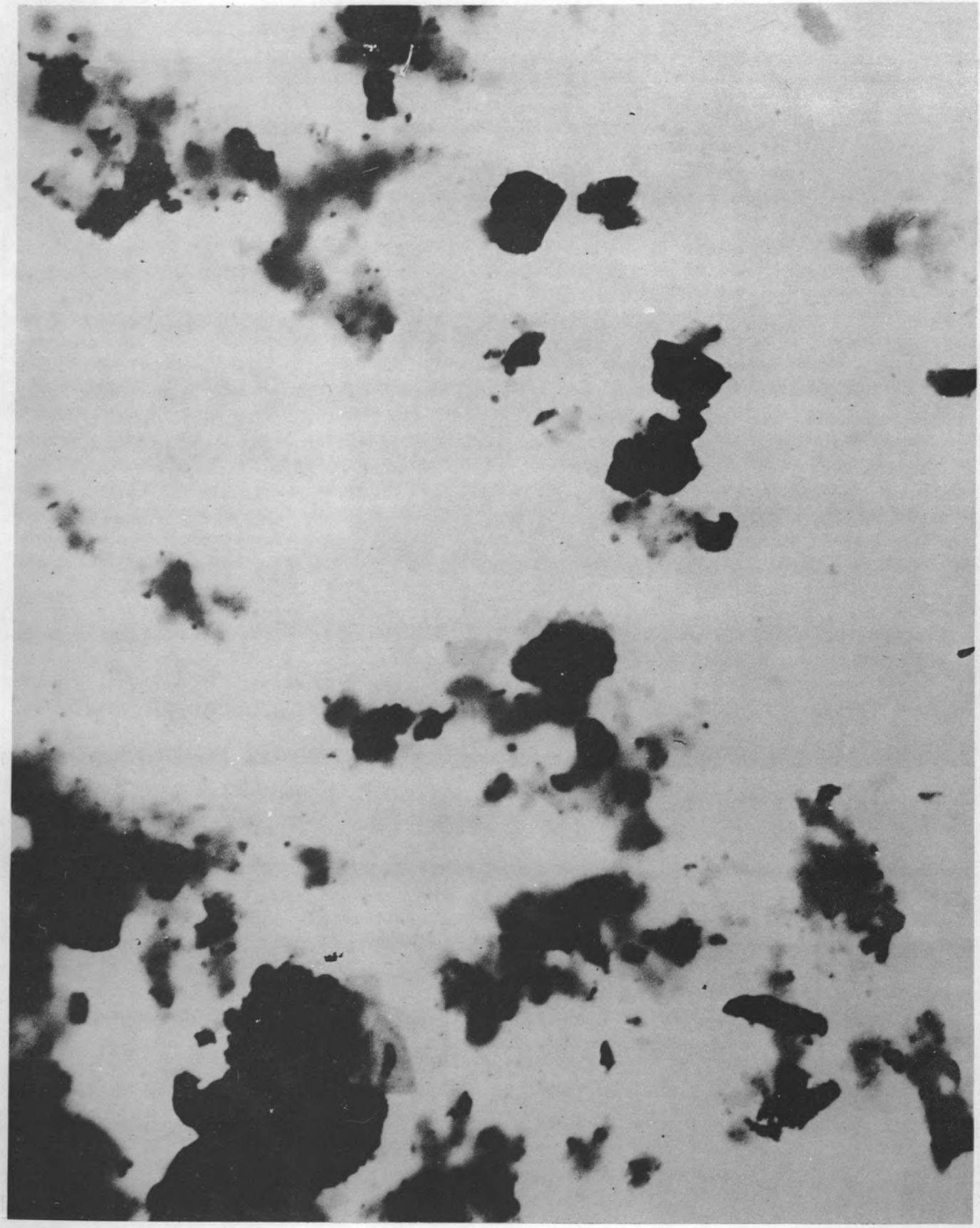

1 μ

20,000 X

ROSIN SMOKE PARTICLES

FIG. 4

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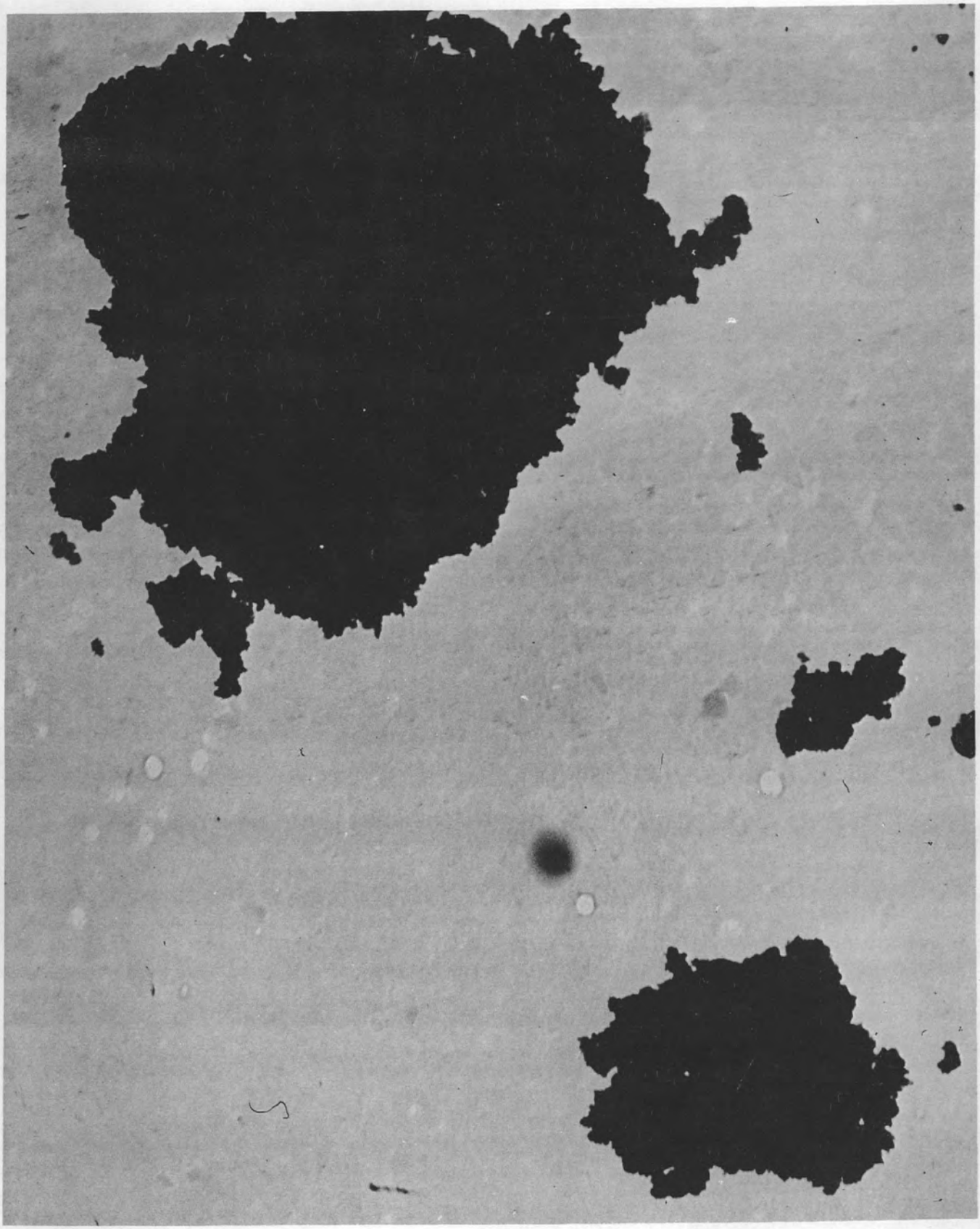

1μ

20,000 X

ROSIN SMOKE PARTICLES

FIG. 5

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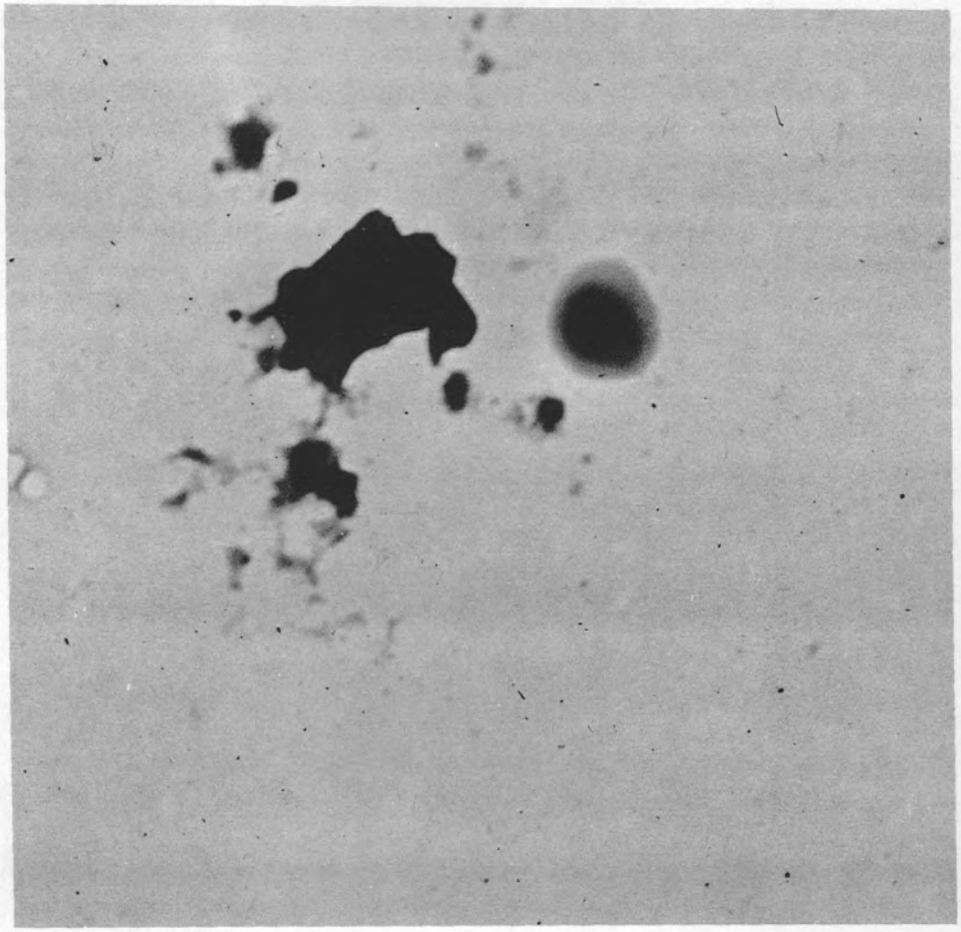

1 μ

20,000 X

ROSIN SMOKE PARTICLES

FIG. 6

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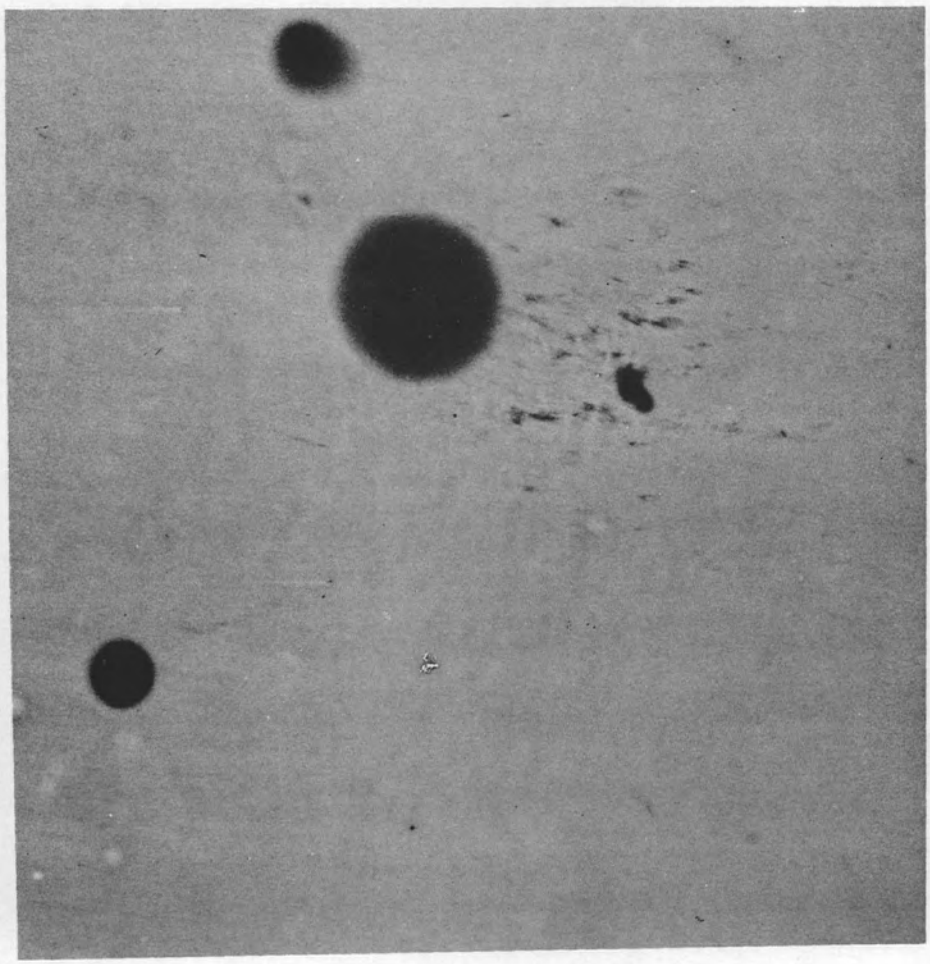

1 μ

20,000 X

ROSIN SMOKE PARTICLES

FIG. 7

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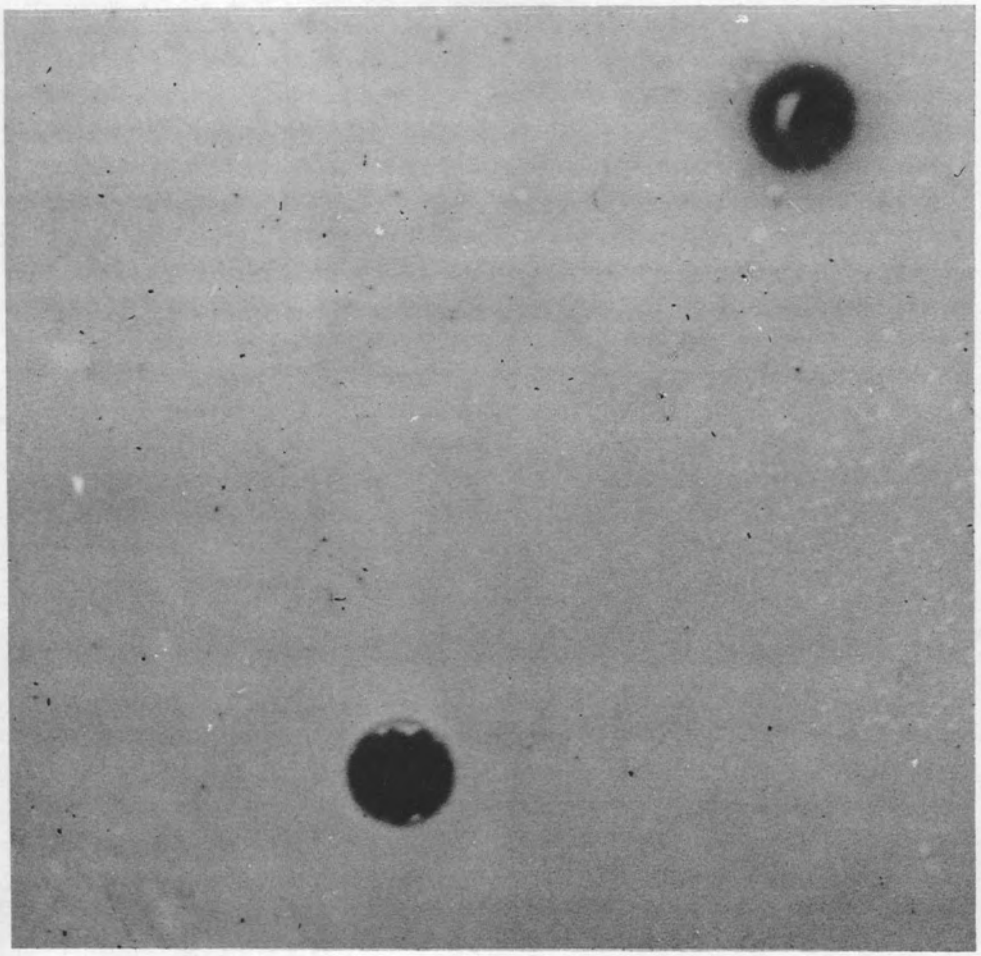


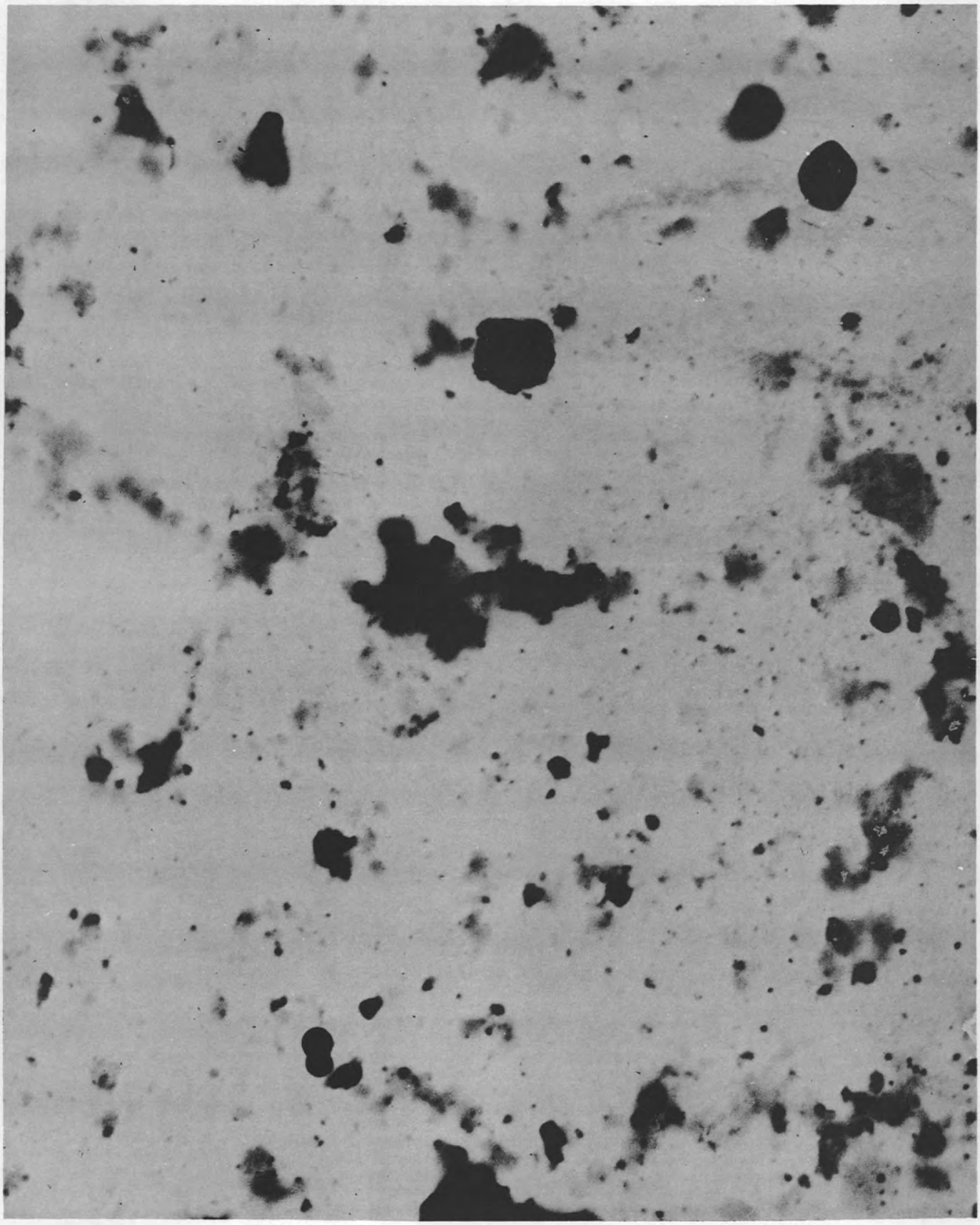
1 μ

20,000 X

ROSIN SMOKE PARTICLES

FIG. 8

UNCLASSIFIED
PHOTO 2719



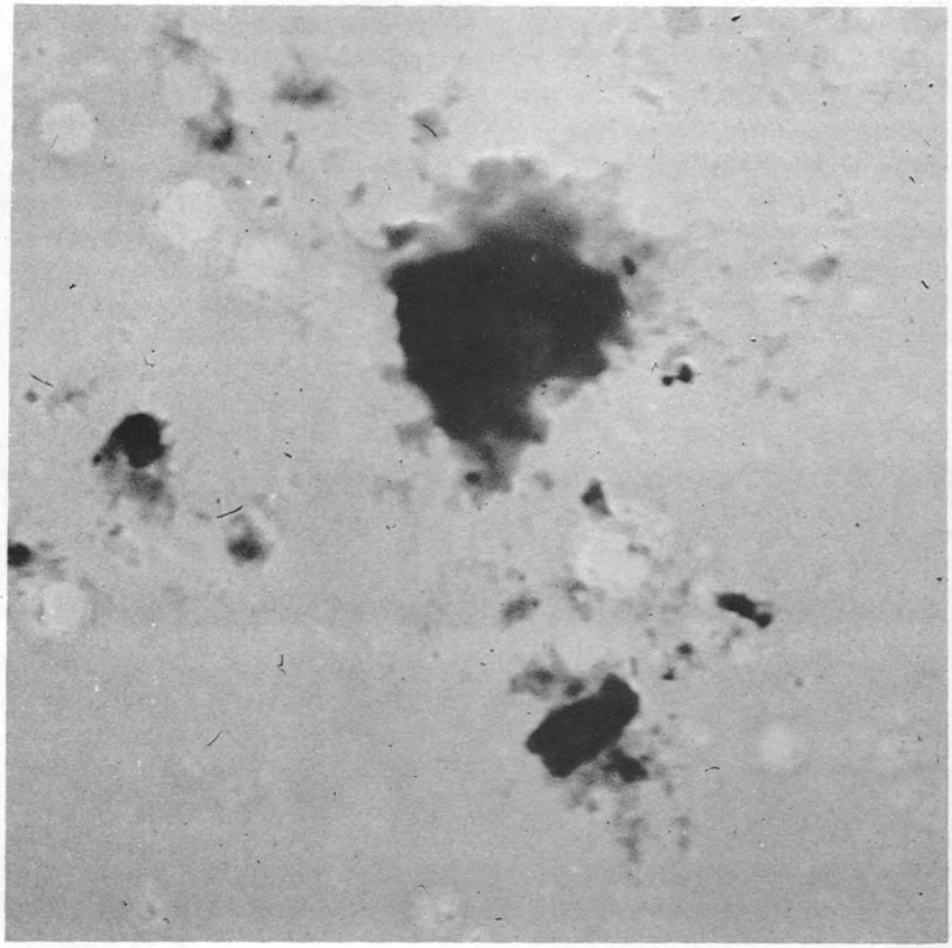
1μ

20,000 X

ROSIN SMOKE PARTICLES

FIG. 9

UNCLASSIFIED
PHOTO 2738



1 μ

20,000 X

ROSIN SMOKE PARTICLES

FIG. 10