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Deposition of Aerosols on a Charged Polystyrene Surface

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A study was made of the decrease in the concentration of coal and fluorescent pigment aerosols in a polystyrene chamber. Losses to the walls of the plastic chamber were as high as 85% for coal (75% for fluorescent pigment) in a 20-minute period. Wall loss rates decreased with increasing humidity. These losses were shown to be due to the electrostatic attraction between the charged aerosol and the natural charge on the plastic surface. Difference in the wall loss rate constant, β_e, was attributed to the variation of mobility distribution between the coal and fluorescent pigment aerosols. Areas of positive and negative charges on the plastic surface were mapped. Preliminary investigation of the electrostatic charge on coal particles has indicated that the median charge is about 40 to 200 elementary electronic charges.

Introduction

AS PART OF ITS RESPONSIBILITY under the Coal Mine Health and Safety Act of 1969, the U.S. Bureau of Mines is devoting considerable resources to the control of respirable dust in underground coal mines. This paper will report the results of one project in this area, a research program designed to investigate the possibility of utilizing the intrinsic electrical charge on coal particles to assist in dust suppression.

Traditionally, the relative ease of electrostatic charge buildup and retention of materials on surfaces has been highly undesirable, and elaborate precautions are taken to eliminate any static charges accumulating on insulating surfaces. This problem is especially acute in plastics, where very high resistivities lead to surface charge buildup, resulting in large accumulations of dust. It is clear, however, that, for dust cleaning of the air, this historically "bad" property of plastics may be a useful mechanism for dust collection.

The idea of electrostatic attraction of dust to a surface is not a new concept. Since the late 1800's, electrostatic precipitators have been in use, and they are currently employed successfully in many industries. They have, as yet, been found of no use in coal mines because of very high voltage requirements and the resulting safety problems. The significant difference between conventional electrostatic precipitators and the use of natural electrostatic charge on a plastic surface is the ability of the plastic to maintain this charge with no externally applied power. This may lead to possible underground coal mine usage of plastics in areas where a conventional electrostatic precipitator could not be used.

Experimental work in the area of spontaneous electrostatic deposition of aerosol is sparse. Dimmick and Akers[1] observed that at low humidity a 4-foot plastic chamber attracted cotton balls from a distance of 1 foot. Mercer[2] encountered 50% wall loss of aerosol in chambers of high dielectric constant. Lieberman and Rosinski[3] conducted a series of preliminary experiments to investigate the behavior of an aerosol cloud in a plastic chamber. It has been shown by Woodland and Ziegler[4] that both positive and negative

Reference to specific brands is made for identification only and does not imply endorsement by the Bureau of Mines.

charges could exist in random distribution throughout a plastic surface and that these charged surface areas could support potentials of the order of 10,000 volts. Lieberman and Rosinski hypothesized that the abnormally large variation in wall loss rate constants observed was the result of electrostatic forces between the high surface potentials and the electrical charge of the aerosol particles.

These few experiments prompted the Dust Control Group to expand the preliminary wall loss studies of Lieberman and Rosinski. Previous communications[5,6] have discussed the results of tests conducted in a low-humidity atmosphere. The purpose of this article is to discuss new results of wall loss behavior under various humidities ranging from less than 10 to 98%.

Apparatus and Procedure

Aerosol generation, apparatus, sampling procedures, and limitations of the system have been described in detail elsewhere.[5,6] However, a few words about the system are perhaps in order at this time.

Experiments were performed in an 86-cm-diameter polystyrene chamber. Aerosols were generated by spray atomization or dispersed in a dry powder by a Wright dust feeder.[7] Initial particle concentrations in the chamber were about 300 particles/cm^3. A typical size distribution determined by light scattering is given in Table I. Concentration changes were monitored by a light-scattering counter every 24 seconds. The volume sampling rate was 300 cm^3/min.

TABLE I
Typical Size Distribution of Aerosols Used in Wall Loss Studies

Size Range (μm)	Percent in Range	
	Coal	Fluorescent Pigment
0.3–0.4	11	9
0.4–0.5	11	12
0.5–0.6	12	11
0.6–0.8	12	12
0.8–1.0	11	10
1.0–1.2	10	11
1.2–1.5	9	10
1.5–2.0	8	9
2.0–3.0	6	6
3.0–4.0	4	4
4.0–5.0	3	3
5.0–10	3	3

To obtain the desired relative humidity (R.H.) in the aerosol chamber, filtered air was bubbled through heated water before entering the chamber. All experiments were conducted at room temperature. The relative humidity was monitored throughout the experiment by a dew point hygrometer. The variation in humidity over the life of each experiment was less than 4%. This was not unexpected, because air volume removal from the chamber for measurement of aerosol concentration was less than 10%. The air removed was replaced with filtered room air at whatever humidity was present at the time of the experiment. The variation of humidity over all humidity ranges was less than 2% for a 2-hour period when no aerosol was withdrawn.

One of the major problems with humidities above 50% was the significant amount of condensation droplet (200 particles/cm^3 at 90% R.H.) formation in the aerosol chamber. The chamber atmosphere was therefore equilibrated for 30 to 40 minutes both to stabilize the relative humidity and to eliminate the water droplets by evaporation, sedimentation, and wall loss. Aerosol was admitted into the chamber when the water droplet concentration was below 20 particles/cm^3.

Interpretation of Data

Loss of aerosol from the chamber described above can, in principle, result from several effects. These are diffusion, coagulation, gravitation, and electrostatics. The equations describing expected concentration changes are listed in Table II. Calculated concentration decrease for the first of these experiments is shown to be insignificant. Thus, any concentration decrease greater than 10% within 20 minutes can be attrib-

TABLE II
Possible Wall Loss Mechanisms

Mechanism[a]	Equation[b]	Calculated Concentration Decrease in 20 Minutes
Diffusion	(1) $n=n_o \frac{6}{\pi} \sum_{l=1}^{\infty} \frac{1}{l^2} e^{-D\pi l^2 t/R^2}$	$< 1\%$
Coagulation	(2) $\frac{n_o-n}{n\,n_o} = +kt$	$< 1\%$
Gravitation	(3) $n=n_o \exp(-Bmgt/R)$	$<10\%$
Electrostatic	(4) $\frac{n}{n_o} = -\beta_e t$	$>10\%$

[a]Derivation of equations 1 through 3 can be found in N. A. Fuchs, *Mechanics of Aerosols,* Pergamon Press, New York (1964).

[b]where n = concentration at time t
n_o = initial concentration (t=O)
D = diffusion coefficient
A = area of sphere
t = time
d = wall layer thickness
v = volume of sphere
k = coagulation constant
B = particle mobility
R = sphere radius
g = gravitational constant
m = particle mass
βe = electrostatic wall loss rate constant

uted to an electrostatic interaction of charged aerosol particles and the charged sphere.

It has been shown[5,6] that the results obtained can be interpreted by using the equation of Longstroth and Gillespie[8] in which the rate of concentration loss in the chamber is

$$dn/dt = -\beta_e n \qquad (1)$$

where n = aerosol concentration.
t = time.
β_e = mean electrostatic wall loss rate constant.

This average wall loss rate constant can be expressed as

$$\beta_e \text{ proportional to } q_p/r_p \qquad (2)$$

where q_p = average particle charge.
r_p = average particle radius.

When comparing different aerosols of similar size distribution, any variation in β_e between aerosols will be due to charge differences only. For example, the aerosol of higher average charge will have a higher β_e and would show greater decrease of β_e with time (see references 5 and 6 for detailed explanation). Thus, from plots of β_e versus time for different aerosol systems having similar particle size distributions, qualitative information of relative charge distributions can be derived.

Results and Discussion

Charge Islands

Various studies[9-11] of electrical charging characteristics of dusts indicate that, while charge mechanisms are extremely complicated, in general there is a symmetric charge distribution—that is, equal numbers of positive and negative particles. Even in those situations in which there is no symmetry, there are nonetheless substantial numbers of particles of both polarities.[12] Preliminary results (see Table IV) of coal aerosol charging studies tend to confirm the above conclusions.

Wall loss results of coal and fluorescent pigment aerosols[3,5,6] indicate that at low humidities approximately 70 to 80% of the aerosol is lost to the walls after 20 minutes. This is shown in Table III. This implies that

TABLE III
Percent of Aerosol Lost to Chamber Walls to Relative Humidities below 30%

Time (minutes)	Concentration Decrease% Coal[a]	Fluorescent Pigment	Fluorescent Pigment[b]
0	0	0	0
3	46	30	37
6	66	48	58
9	74	59	72
12	80	66	
15	83	73	
18	87	76	

[a]Taken from reference 6.

[b]Taken from reference 3. Results shown were derived by replotting data for the aerosol to 2.8 μm. This was done to make the fluorescent pigment data comparable to those of reference 6.

the chamber walls are charged both positively and negatively (charge islands). We have demonstrated that this is true.

Following a technique used by Woodland and Ziegler,[4] two aerosols, each of which fluoresced a different color under ultraviolet illumination, were successively passed through a Whitby ion generator[13] into the chamber. One aerosol was charged negatively, the other positively. On entering the chamber, the negative aerosol was attracted to the positive charged areas of the chamber wall, and the positive fluorescent aerosol was attracted to the negative charge islands. We have noted that the size and shape of these charge islands do not remain identical if the chamber is cleaned. New patterns arise and no two patterns have been identical. Additionally, in all patterns there are always islands of both positive and negative charge, as well as areas of no charge at all. Brief studies of potentials developed on these charge islands indicated a wide range of potentials varying from 0 volt (neutral areas) to over 10 kV within charge islands. These islands typically range from 1 mm to 10 cm in diameter with extreme irregularity in shape.

Aerosol Generation and Wall Loss Behavior at Humidities below 30%

The electrostatic wall loss rate constant, β_e, undoubtedly will vary with the method of generating the aerosol. This is shown in Figure 1. Comparison of initial β_e values indicates that the loss constant for coal dust dispersed dry is 60% higher than that of spray-dispersed coal dust. If the size distributions of the aerosols are equivalent, then this difference in initial β_e must be due to the average charge on the particles. Note that, as the highest mobility (charge/mass) particles

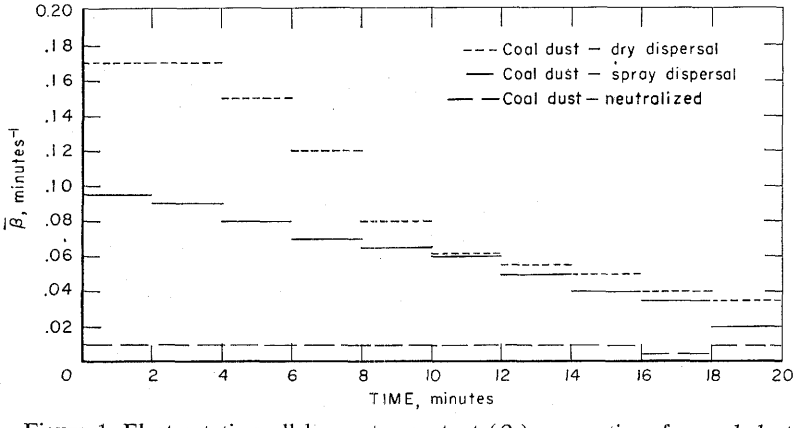

Figure 1. Electrostatic wall loss rate constant (β_e) versus time for coal dust. The dust was generated by two separate methods to produce different electrostatic charges on the resulting aerosol cloud. The β_e valves of a Boltzmann-neutralized coal dust cloud are shown for comparison to the other charged clouds.

are lost to the walls owing to electrostatic interaction, the β_e values of both dry- and spray-dispersed aerosol converge. After 10 to 12 minutes they are virtually equal, suggesting that the mobility distributions within both clouds are now equivalent.

Figure 1 also includes, for comparison, the results of similar wall loss tests made on coal aerosol neutralized with a ^{85}Kr source (Thermo Systems, Inc., Minneapolis, Minnesota) before entering the sphere. Residence time in the neutralizer was 11 seconds; comparison with the data of Fry[14] indicated that this was sufficient time to assure neutralization to near a Boltzmann charge equilibrium, the charging level due to thermal equilibrium in an atmosphere of both positive and negative ions.

The wall loss test results for this neutralized aerosol, of known charge distribution, are presented to serve as a reference for comparison with the behavior of aerosols generated by different techniques. It is apparent from Figure 1 that the electrostatic wall loss rate constant for both methods of generation of coal dust is much higher than for the case of a neutralized aerosol which has a Boltzmann charge distribution. This is true even after 20 minutes has elapsed. Thus, the aerosol cloud in both cases has a higher charge distribution than an equilibrated aerosol, even after 80% of the highest mobility particles have been lost to the walls.

To support these conclusions the electrostatic charge on coal particles was measured. The technique was identical to that described by Whitby and Liu.[15] A Whitby aerosol analyzer[16] was used as a mobility analyzer with the outlet connected to the Royco optical particle counter. At each voltage in the analyzer, those particles having a mobility below a certain critical value will just escape the analyzer and thus be counted by the Royco. By varying the voltage on the analyzer and taking Royco counts, the distribution of particle mobilities, and therefore of particle charge, can be derived.

The preliminary experimental data are summarized in Table IV. The charges are given in elementary electron units and represent the mean charge, disregarding sign when dispersed from a Wright dust feeder.

We have, as yet, not measured the electrical charging behavior of coal dust dispersed from the nebulizer. Spray electrification is, however, independent of material dispersed, and depends only on droplet size, ion concentration, and liquid used for suspension.[2] Thus Table IV includes the maximum charge possible for spray dispersal as indicated by Mercer.[2] Also given are the charges expected on polystyrene spheres atomized from an alcohol suspension. These

TABLE IV
Charging Characteristics of Aerosol Particles

Diameter (μm)	Average Charge, Boltzmann Equilibrium	Maximum Charge, Spray Electrification[a]	Average Charge, Latex Spheres[b]	Charge Characteristics, Coal Dust—Dry Dispersal				
				Median	84%[c]	Percent Positive	Percent Negative	Percent Neutral
0.5	1.6	8	5	40	110	55	40	5
1.0	2.4	21	6	86	240	50	46	4
1.5	2.6	40	8					
2.0	4.1	75	10	200	550	49	49	2

[a]Results based on data from reference 2.

[b]Results based on data from reference 17 (see text for details).

[c]This number means, for example, that 84% of the 0.5-μm particles carried less than 110 elementary charges.

values were derived by plotting Fry's[14] experimental data below 5 μm and fitting to the exponential equation:

$$q = Ae^{kDp} \tag{3}$$

where

q = particle charge.
A, k = constants.
Dp = particle diameter.

The average charge under Boltzmann equilibrium is given in Table IV. This charge is obtained from the distribution function given by Keefe *et al.*[17]

$$f(n) = \frac{\exp\ [-(ne)^2/DpKT]}{\Sigma\exp\ [-(ne)^2/DpKT]} \tag{4}$$

where $f(n)$ is the fraction of particles carrying (ne) charges, D_p is the particle diameter, K is the Boltzmann constant, and T is the absolute temperature.

The values given in Table IV are consistent with the results obtained in the wall loss experiments. At any one size, the dry-dispersed coal aerosol always has a higher charge than that dispersed by the spray system. Furthermore both dry and spray aerosols have a higher charge than neutralized dust. For example, at 1 μm the Boltzmann charge is 2.4 elementary charges, whereas for the spray system Fry's experimental data show about 6 or 7 unit charges (the maximum possible is 21 charges). The results of dry-dispersed coal show 86 unit charges, a factor of almost 40 higher than a Boltzmann aerosol and a factor of 4 over maximum possible for spray electrification. The dry-dispersed coal dust data in the table also indicate that the aerosol was approximately symmetric, and that at least 80% of the particles were charged. Thus, the loss of about 80% of the dust suggests the presence of positive and negative charge islands, as discussed previously. Gillespie[18] also attempted to show that the wall loss behavior depends on method of aerosol dispersal. He generated aerosols by different mechanisms and then measured electrostatic charging of the resultant aerosols. He then further demonstrated the direct influence of electric charge on the wall loss rate constant. His results lend further support to the above conclusions.

Humidity and Wall Loss Behavior

All the previous experiments on spontaneous electrostatic deposition have been performed at humidities below 30%. However, a preliminary study of humidities in the Pittsburgh coal seam has indicated 75 $\pm$ 10% R.H. to be typical in the mine, where some areas can have 90 to 100% R.H. (R. L. Stein and W. H. Ryback, private communication, U.S. Bureau of Mines, 1972). Thus, to determine the general usefulness of the spontaneous deposition technique, experiments under controlled humidities to 100% have been completed.

The electrostatic charge behavior on the walls of a chamber will be affected by a change in relative humidity within the chamber because of the thin water layer that forms on the chamber wall at high humidities. This behavior will vary, depending on the specific properties of the materials used to construct

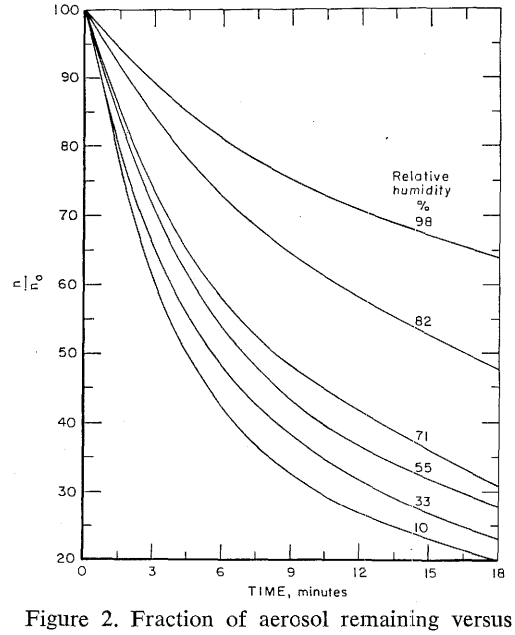

Figure 2. Fraction of aerosol remaining versus time for several relative humidities. Aerosol generated by a Wright dust feeder.

the aerosol chamber. Polystyrene, used as the material for the chamber in these experiments, maintains a high surface resistivity at high humidities.[4] Thus wall loss in a chamber constructed of this material should represent a "best" case; that is, aerosol loss in any other type of chamber of high dielectric will probably be less than that of a polystyrene chamber at the same high ($< 70\%$) relative humidity. Polystyrene was purposefully chosen for this reason.

The data, which are reproducible to $\pm 15\%$, are summarized in Figures 2 through 5. Figure 2 is a plot of the aerosol fraction remaining versus time for several humidities to 98%. The results are plotted in this manner to eliminate the differences in initial concentration. The results clearly indicate that the electrostatic interaction between aerosol and wall diminishes with increasing humidity. As was discussed in the procedure section, the chamber was stabilized for 30 to 40 minutes at any humidity before admitting aerosol. Droplets either evaporated or were captured by the chamber wall. A thin water layer on the chamber surface will, of course, lower the electrostatic charge potential of the wall. However, our experiments have not allowed us to distinguish between possible causes of this smaller wall–aerosol interaction. Whether the wall loses charge, the dust loses charge, or a combination of both occurs is difficult to assess from these experiments. Nonetheless, it is abvious that there is a definite increase in areosol stability at high humidities.

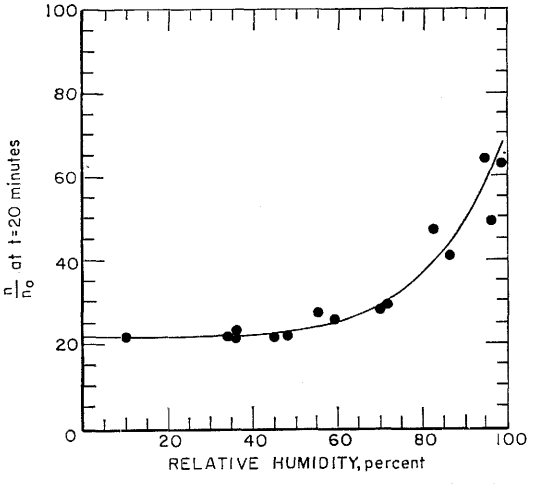

Figure 3. Percent coal dust remaining in the charmber after 20 minutes versus relative humidity. The coal dust was generated by a Wright dust feeder.

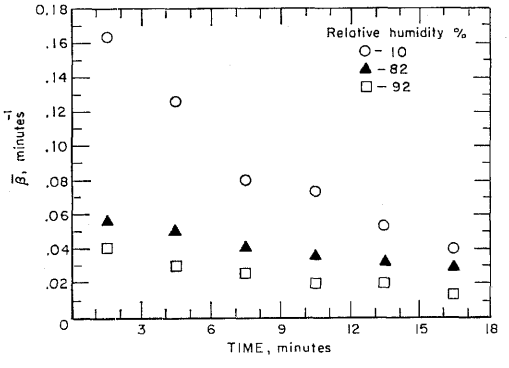

Figure 4. Electrostatic wall loss rate constant versus time for three representative humidities. The coal dust was generated by a Wright dust feeder.

The percent aerosol remaining in the chamber after 20 minutes is shown in Figure 3. There is a slow rise in aerosol remaining to about 50% R.H. at which point there is a rapid increase in aerosol remaining as the percentage of relative humidity is increased.

Figure 4 is the derived plot of β_e as a

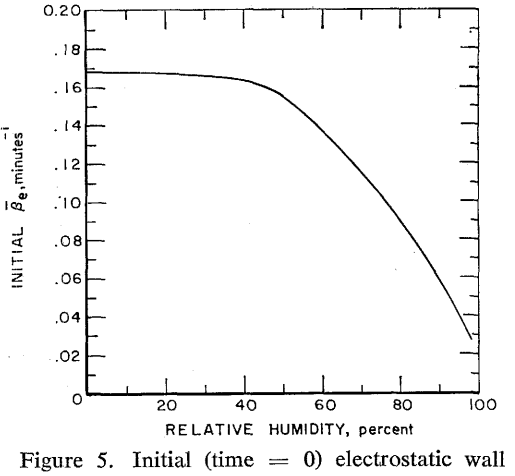

Figure 5. Initial (time = 0) electrostatic wall loss rate constant versus relative humidity for coal dust produced by a Wright dust feeder.

TABLE V
Comparison of Wall Loss Constants for Various Relative Humidities

Humidity	$\beta \times 10^{3a}$ (min^{-1})	$\beta_e \times 10^3$ $t=2$ min (min^{-1})	$\beta_e \times 10^3$ $t=16$ min (min^{-1})	$\beta_e \times 10^3$ (min^{-1}) (Boltzmann-neutralized)
10	1.8	168	42	10
20	1.9	165	42	10
30	2.0	164	42	10
40	2.1	162	41	10
50	2.2	154	41	10
60	2.9	136	41	10
70	3.2	114	40	10
80	4.5	89	38	10
90	6.8	57	20	10

[a]Results based on data from R. L. Stein and W. H. Ryback, private communication, U.S. Bureau of Mines (1972).

function of relative humidity for three representative humidities. The initial β_e values are extremely sensitive to changes in humidity. However, after 20 to 30 minutes the aerosol-wall interaction will be nearly equivalent, despite any differences in humidity. Finally, in Figure 5, note that the initial β_e (which represents the maximum electrostatic interaction) is about 17×10^{-2} min^{-1} at less than 20% R.H. The β_e value decreases rapidly after 50% R.H.; by 80% R.H. β_e is nearly half its original value. By 95% R.H., β_e is one fourth as large and is rapidly approaching the Boltzmann-neutralized value of $\beta_e = 10 \times 10^{-3}$ $min.^{-1}$ Nonetheless, while wall loss is reduced, enough static charge remains on the wall to decrease initial concentration by 30% at 98% humidity.

The effect of relative humidity on wall loss behavior has been previously reported.[19] Table V compares the results previously reported with the wall loss results in this work. The β values of Gillespie and Langstroth increase with increasing humidity. These values of β are constant with time, while β_e values vary with time (Figure 4). The rise in β in the wooden (and hence nonstatic) chamber was explained by Gillespie and Langstroth in terms of H_2O vapor absorption on the NH_4Cl aerosol used in these experiments. The higher humidity increased vapor absorption and hence increased sedimentation. On the other hand, the present results show that β_e decreases with humidity as a result of the decreased electrostatic interaction. However, it is apparent from the data in Table V that, even after 16 minutes at 90% R.H., $\beta_e = 14 \times 10^{-3}$ min^{-1}, which is double that due to nonstatic wall loss; that is, electrostatics is still significant.

The results given above indicate that electrostatic deposition is strongly influenced by both the relative humidity of the air and the charge of the aerosol particles. To date there is no evidence of the charging levels of coal aerosol in the underground coal mine environments. A brief set of experiments was therefore performed to determine if coal dust is charged higher than a Boltzmann-equilibrated aerosol. Tests comparing the capture efficiency of a 30-cm-long Plexiglas tube with that of an identical copper tube were performed at a belt-line transfer point in an operating coal mine (R.H. 67%). The results, based on eight sets of tests, indicated that the Plexiglas tube captured 30% more dust by weight than the copper tube. These results suggest that coal dust is charged to higher than a Boltzmann level, although the test information is insufficient to give quantitative answers. These preliminary experiments are giving promising results for actual coal mine airborne dust capture and will be continued.

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New Association for Aerosol Research

A new scientific association for aerosol research was founded on October 18, 1972, in Frankfurt a.M., Germany. Purpose of the 'Gesellschaft für Aerosolforschung' (GAF) is to advance all fields of aerosol research in science and technology. With the growing importance of aerosols in various disciplines like biology, medicine, chemistry, physics, technology, meteorology, hygiene and many others, the new association will serve to bring scientists of all aspects of aerosol research together and to provide means of contact for all people in the scientific and technical community who have an interest in aerosol problems. GAF will make a particular effort to advance the interdisciplinary cooperation in aerosol research. The new association will operate on an international level. Presently, GAF has members in several countries, including Austria, France and the United States.

A board was elected at the founding session. The members agreed to give priority to an effort to continue and to extend an annual meeting on airborne matter which had been held in Frankfurt and Mainz in the past. Professor Dr. Böhlau, Frankfurt/Bad Soden, was elected chairman of the board and Professor Dr. Straubel will serve as secretary general. Inquiries may be directed to: Gesellschaft für Aerosolforschung, 6232 Bad Soden bei Frankfurt/Main, Rossertstrassee 11, Germany. (Telephone 06196-27051.)