

AIR CLEANING STUDIES AT HARVARD UNIVERSITY (1956-57)

Leslie Silverman
Harvard School of Public Health

The scope and functions of the Harvard Air Cleaning Laboratory are in the field of consultation, research, and development. The Harvard Air Cleaning Laboratory was established as the result of an AEC request of ten years ago. Our work can be described under five main objectives.

1. We are concerned with the development of test methods for the evaluation of equipment. In this respect I have appended to this paper a statement of policy in regard to these evaluations.

2. We are interested in the collection and correlation of information. This seminar (for the first time open to access permit holders) is in that regard. We desire to bring together all the available information that bears upon this problem.

3. There are many unsolved problems that continually develop in nuclear energy applications. We are often requested to provide evaluation of equipment for AEC application on an unbiased basis. This is done for sites or contractors desiring an opinion of their approach.

4. Our major responsibility is research on new procedures and modifications of existing ones to solve AEC problems.

5. We provide a certain amount of training and education for AEC personnel by assignment to our laboratory; by conference sessions with different groups; and by seminars such as this one.

It is rather interesting to point out what has happened in the 10 years we have been involved in the air and gas cleaning investigations for the Commission. I can remember the first session I attended on stack gas cleaning several years ago with AEC people. The wonderful performances of wet collectors were outlined to us along with some phenomenal results which later proved somewhat below par. One major advantage pointed out for wet collectors was the fact that once the aerosol was trapped in water in the air cleaner, you merely pumped it to the liquid waste disposal group and forgot about it. The circle has now been completed because the waste disposal boys now are going to make aerosols out of their liquid wastes. This again introduces new aerosol problems.

In AEC philosophy, as we interpret it for air and gas cleaning problems, the importance of containment has been well impressed upon us. We desire to place active materials in a situation from which they cannot disseminate and expose the site personnel or the public. Hence when considering the question of gas cleaning we believe the process should be modified so that gas or air volumes are maintained as low as possible. You will recall that some of the gas volumes mentioned at this seminar are in milliliters or liters per minute. Even in these small volumes considerable activity may be involved, hence the cleaning problems created by such small quantities can be serious.

Our efforts, as Professor Dennis has indicated, are now directed toward more information on economics. I believe Dr. Lieberman put his finger on what we are trying to do, essentially to get the cost of air and gas cleaning within reason for commercial as well as AEC applications. A number of engineers sometimes think in physicist's or academician's terms in regard to costs. In many cases this has been necessary because of health physics requirements.

In our development activities we have been interested in finding inexpensive methods of cleaning. One study we have continued for some time is in regard to electrostatic charging. We reported at previous seminars on charging fibrous filter beds, doing this either by mechanically rubbing or carding synthetic resin cloths or fibers in static beds and determining their performance and life. From this we have progressed to another basic approach, which Mr. Anderson will cover in detail, on the development of a "triboelectrified" fluidized bed for aerosol filtration.

Another problem with which we are concerned is the filtration or removal of fumes resulting from burning of liquid metals. At the moment unless it contains radioactive contami-

nants it is largely a nuisance problem. In the handling of the contaminated liquid metals it will become more serious. Mr. Kristal will report on this subject.

A problem that has plagued industry in general, as well as AEC, is the cleaning of particulates from high-temperature gases. Precipitator installations will perform well for certain aerosols in terms of public health or nuisance requirements. Their cost in large size installations can be expensive. A parallel project we are doing for the American Iron and Steel Institute is on high-temperature furnace gas cleaning. Some of this information will be of value for AEC and other activities. We have been working on an inexpensive slag wool filter which Professor Billings will cover in detail.

We have been asked by the AEC to develop an inexpensive air cleaner for the Bureau of Mines 30-lb/hr incinerator (BOMAEC-30). The Bureau was given a contract several years ago to develop an inexpensive incinerator for disposing of institutional radioactive wastes. It has turned out to be more expensive than anticipated. The problem of cleaning is also not as simple as planned. Plugging and bag cleaning difficulties are caused by tars formed during combustion. Complete combustion with a minimum production of a tar aerosol is desirable but absence of tar seems unlikely. The incinerator is a cylindrical tangentially overfired unit. For air cleaning it is provided with a spray type heat exchanger, followed by a cyclonic unit with glass cloth filter bags. An additional chamber is provided so that a combustible AEC filter may be inserted if necessary. This filter can be incinerated after its resistance becomes too high for adequate flow.

We have also considered the application of slag wool for an incinerator filter. Results are too preliminary to discuss in detail, but it appears to be useful as a prefilter or possibly the final filter. Because of its depth we are not concerned with plugging of tars as occurs on the glass cloth bag surface.

The slag wool development which Professor Billings will talk about has a corollary application for the removal of acid gases. This was discovered during field tests. We found in our field studies on open hearth furnaces that significant sulphur dioxide was removed by the wet slag wool. The wool used is made from basic blast furnace slag. It has considerable available alkali which serves a useful purpose in removing acids. Mr. Kurker will present detailed results of these studies.

The most recent application of slag wool investigated for AEC uses is to treat its surface with silver to determine its effectiveness for iodine removal. Iodine (I^{131}) removal is a considerable problem which is of frequent occurrence in chemical processing. At present silver nitrate coated Berl saddle reducers maintained by heaters at a temperature of about 150°C are used. For some operations they have applied caustic scrubbers which give efficiencies from 85 to 95 per cent. The silver nitrate reactors will remove 99 per cent or more I^{131} . There is need to further reduce effluents with less expensive devices and additional work on this problem is indicated.

We have made some preliminary studies that look promising. Slag wool has been coated by chemical silver mirroring using the Rochelle salts process. When operating this bed at 50 to 100 ft/min, the velocity used for removal of iron oxide fume, we obtained 96 to 97.5 per cent removal on a 2-in., 5-lb/cu ft layer with a resistance of approximately 1 in. water. Only milligrams of iodine must be removed in practice because of its high specific activity. We believe other techniques can be used to place reactive silver compounds on the fiber. Some site monitoring people at Savannah River have found it possible to dip CC-6 paper in silver nitrate solution. This will do a fairly good job in field monitoring for iodine. Silver or silver nitrate coating of slag wool looks promising as an inexpensive way to reduce effluents from present reducers or scrubbing equipment. It is being investigated further at the present time.

Tables 1 and 2 present data on the applications of slag wool to other aerosols. These data were obtained on Mineralite slag wool filters of 3 lb/cu ft density at velocities of 150 to 500 ft/min in the thickness stated. Resistance in inches of water gauge ranged from 1 to 3 in. on the average but values as high as 7 in. were obtained. Data in Table 1 were obtained with re-suspended Cottrell ash ($0.5\ \mu$ by count). The average efficiencies shown indicate that with rather high velocities for slag filters (our approach to getting economical size filtering units

nants it is largely a nuisance problem. In the handling of the contaminated liquid metals it will become more serious. Mr. Kristal will report on this subject.

A problem that has plagued industry in general, as well as AEC, is the cleaning of particulates from high-temperature gases. Precipitator installations will perform well for certain aerosols in terms of public health or nuisance requirements. Their cost in large size installations can be expensive. A parallel project we are doing for the American Iron and Steel Institute is on high-temperature furnace gas cleaning. Some of this information will be of value for AEC and other activities. We have been working on an inexpensive slag wool filter which Professor Billings will cover in detail.

We have been asked by the AEC to develop an inexpensive air cleaner for the Bureau of Mines 30-lb/hr incinerator (BOMAEC-30). The Bureau was given a contract several years ago to develop an inexpensive incinerator for disposing of institutional radioactive wastes. It has turned out to be more expensive than anticipated. The problem of cleaning is also not as simple as planned. Plugging and bag cleaning difficulties are caused by tars formed during combustion. Complete combustion with a minimum production of a tar aerosol is desirable but absence of tar seems unlikely. The incinerator is a cylindrical tangentially overfired unit. For air cleaning it is provided with a spray type heat exchanger, followed by a cyclonic unit with glass cloth filter bags. An additional chamber is provided so that a combustible AEC filter may be inserted if necessary. This filter can be incinerated after its resistance becomes too high for adequate flow.

We have also considered the application of slag wool for an incinerator filter. Results are too preliminary to discuss in detail, but it appears to be useful as a prefilter or possibly the final filter. Because of its depth we are not concerned with plugging of tars as occurs on the glass cloth bag surface.

The slag wool development which Professor Billings will talk about has a corollary application for the removal of acid gases. This was discovered during field tests. We found in our field studies on open hearth furnaces that significant sulphur dioxide was removed by the wet slag wool. The wool used is made from basic blast furnace slag. It has considerable available alkali which serves a useful purpose in removing acids. Mr. Kurker will present detailed results of these studies.

The most recent application of slag wool investigated for AEC uses is to treat its surface with silver to determine its effectiveness for iodine removal. Iodine (I^{131}) removal is a considerable problem which is of frequent occurrence in chemical processing. At present silver nitrate coated Berl saddle reducers maintained by heaters at a temperature of about 150°C are used. For some operations they have applied caustic scrubbers which give efficiencies from 85 to 95 per cent. The silver nitrate reactors will remove 99 per cent or more I^{131} . There is need to further reduce effluents with less expensive devices and additional work on this problem is indicated.

We have made some preliminary studies that look promising. Slag wool has been coated by chemical silver mirroring using the Rochelle salts process. When operating this bed at 50 to 100 ft/min, the velocity used for removal of iron oxide fume, we obtained 96 to 97.5 per cent removal on a 2-in., 5-lb/cu ft layer with a resistance of approximately 1 in. water. Only milligrams of iodine must be removed in practice because of its high specific activity. We believe other techniques can be used to place reactive silver compounds on the fiber. Some site monitoring people at Savannah River have found it possible to dip CC-6 paper in silver nitrate solution. This will do a fairly good job in field monitoring for iodine. Silver or silver nitrate coating of slag wool looks promising as an inexpensive way to reduce effluents from present reducers or scrubbing equipment. It is being investigated further at the present time.

Tables 1 and 2 present data on the applications of slag wool to other aerosols. These data were obtained on Mineralite slag wool filters of 3 lb/cu ft density at velocities of 150 to 500 ft/min in the thickness stated. Resistance in inches of water gauge ranged from 1 to 3 in. on the average but values as high as 7 in. were obtained. Data in Table 1 were obtained with re-suspended Cottrell ash ($0.5\ \mu$ by count). The average efficiencies shown indicate that with rather high velocities for slag filters (our approach to getting economical size filtering units

**Table 1—EFFICIENCY OF MINERALITE SLAG WOOL FILTERS
ON RESUSPENDED NBS FLY ASH**

Filter thickness in.*	Filtering velocity, ft/min	Average fly ash conc., g/cu ft	Average resistance, in. wg			Average operating time, mins.	Average efficiency, %	B, %†	B/Δ p
			Initial	Final	Δp				
1	150	0.068	1.00	1.94	0.94	139	83	52	55
1 (5)	150	0.066	1.48	2.35	0.87	97	84	26	30
1 (10)	150	0.062	3.80	6.30	2.50	128	92	18	7
2 (2.5)	150	0.064	0.91	1.34	0.43	118	87	31	72
2 (5)	150	0.066	2.74	5.00	2.26	181	96	28	12
1	170	0.100	1.13	2.13	1.00	68	88	52	52
1	210	0.068	1.22	1.58	0.36	56	69	29	81
1	235	0.094	1.89	3.09	1.20	52	81	51	42
1	275	0.095	2.50	3.30	0.80	28	68	26	32
1	300	0.200	2.36	4.17	1.81	30	76	87	48
1	330	0.078	3.12	3.67	0.55	18	60	16	29
1	500	0.160	4.12	7.36	3.24	19	59	50	15

*Three pound per cubic foot packing density except as indicated, other densities shown in parentheses.

†Fly ash collected per initial filter weight, by weighing (expressed as per cent).

**Table 2—RESULTS OF FLY ASH (CREATED BY DIRECT COAL BURNING) FILTER TESTS
MINERALITE SLAG WOOL**

Filter characteristics		Face vel., fpm	Temp., °F	Length of run, min.	Upstream concentration, g/ft ³		Volatiles, %	In-ital Δ p, "H ₂ O	In-crease Δ p, "H ₂ O	Total eff.,* %	Fly ash eff.,* %	Total A,† %	A/Δ p rise
					Total	Fly ash							
1	3	147	550	36	0.026	0.012	54	1.2	1.4	97.0	93.5	4.3	3.1
		135	460	39	0.019	0.0061	68	1.0	0.6	96.9	93.9	2.6	4.3
1	5	129	435	43	0.017	0.0063	65	2.3	0.7	98.9	99.0	1.8	2.6
		129	405	45	0.027	0.0091		2.6	3.0	99.8	99.0	2.9	1.0
1	10	134	475	30	0.040	0.011	75	2.7	1.1	98.8	95.0	1.8	1.6
		127	415	35	0.033	0.011		4.5	1.5	99.3	98.0	1.5	1.0
2	3	122	405	20	0.022	0.0075		1.4	0.4	98.0	94.0	0.95	2.3
2	5	134	410	32	0.029	0.010	65	1.9	0.4	98.0	94.0	1.2	3.0
		127	365	40	0.026	0.0058	78	2.1	0.6	99.4	96.2	1.4	2.3

*Gravimetric.

†Fly ash collected as total from upstream concentration, efficiency and time of run.

and possibly obtaining more filter life), we can obtain values as high as 96, but at extremely high velocities only 60 per cent removal is found. The B factor seen in Table 1 is a measure of the amount of material removed per unit weight of fiber expressed in per cent, in other words these filters remove a high percentage of their own weight. These are quite high on resuspended dust. On fume only 5 per cent removal is obtained, however, washing and reuse is possible for some particulates. In rating performance we divide the weight gain by the unit pressure drop as shown in column 10. The fly ash was generated by an NBS type solid aerosol generator. We know that this does not produce perfect dispersal.

Figure 1 indicates stain efficiencies of a given layer with continued testing time. The measurement of stain was done by the National Bureau of Standards technique. High stain efficiencies can be obtained as indicated. This performance would be comparable to fine fiber bonded fiber-glass values, but at higher velocities and corresponding resistance.

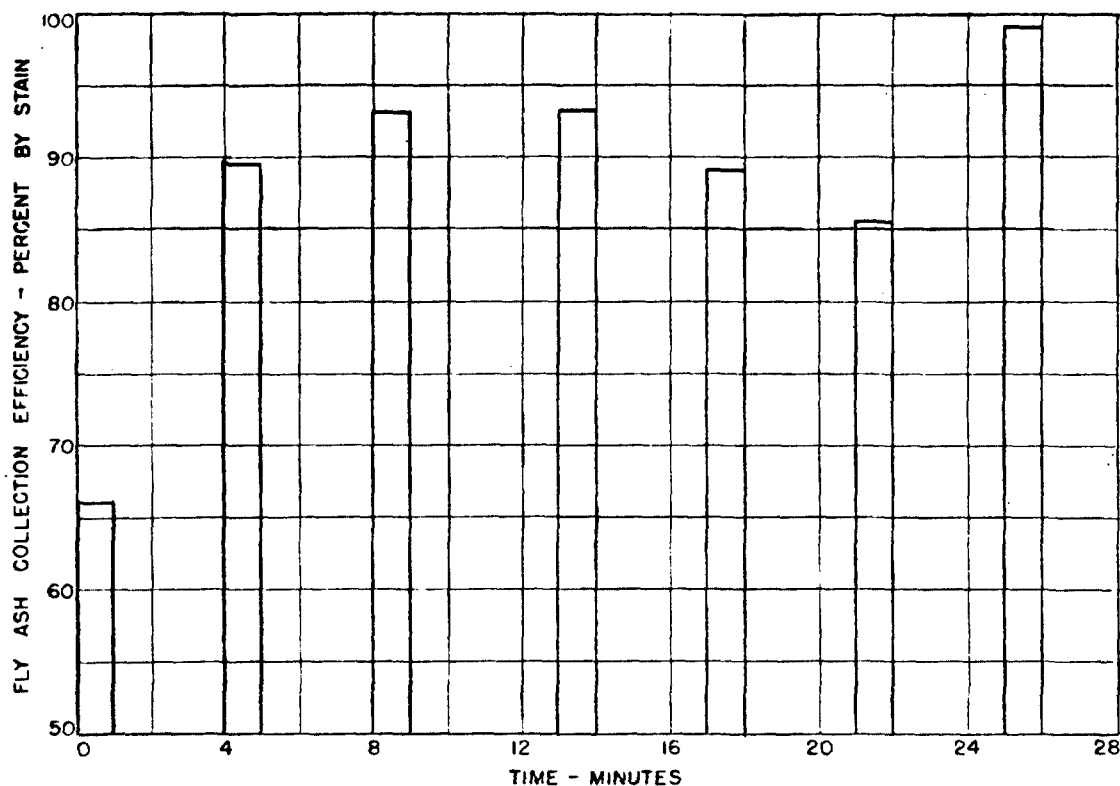


Fig. 1—Stain efficiency of slag wool filters for fly ash as a function of time.

Efficiency data are highly dependent on aerosol generation. Table 2 shows the results on slag wool beds tested against an aerosol created by burning powdered coal. It was not possible to burn the pulverized coal completely even with oxygen. Table 2 shows the per cent of combustibles remaining in the aerosol. These data were at fairly high loadings and temperatures. Slag wool will filter at 1100°F. Table 2 efficiencies are higher than those in Table 1 for resuspended fly ash. The recovery values, however, are below 5 per cent. Instead of a 50 per cent weight removal factor at these velocities we obtained only 10 per cent of this value. Apparently the aerosol generated by burning pulverized coal produces some freshly formed slag fume from the silicates present. This and fine carbon are the particulates which cause the filter to plug rapidly. The method of aerosol generation is obviously a prime factor in air cleaner evaluation. In our equipment evaluation work we employ a number of aerosols of different size ranges and characteristics, such as specific gravity and shape, to get performance data applicable to a wide range of conditions.

STATEMENT OF POLICY

The Evaluation of Commercial Air Cleaning Equipment by the Air Cleaning Laboratory of Harvard University Under Contract with the U. S. Atomic Energy Commission

The purpose of this memorandum is to delineate the status and policies of the Harvard University Air Cleaning Laboratory in relation to the evaluation of commercial dust collection apparatus.

1. Air and gas cleaning investigations conducted by this laboratory are performed under contract at the request of the U. S. Atomic Energy Commission. Our contractual obligations require that all requests for testing of commercial dust collectors originate with the Commission.

2. The purposes of such requests are: (1) to determine whether or not a new collector design or a novel modification of an existing collector appears to offer distinct advantages over and above those of other commercially available equipment; (2) to evaluate air cleaning equipment currently installed at AEC sites either through field or laboratory testing; (3) to evaluate representative models of commercial air cleaning apparatus to obtain performance data for basic designs, such as wet or dry inertial units, scrubbers, fabric filters, and electrostatic precipitators.

3. Since it is impossible for this laboratory to test every new air or gas cleaner that is conceived or developed, the joint policy of the AEC and the Air Cleaning Laboratory has been to avoid as much duplication as possible. If, based upon past experience and investigations, a new product appears to offer no specific advantages over competitive products, we do not consider a test program justifiable unless the manufacturer can substantiate his claims with performance data. Should the manufacturer's performance data show unusual merit according to accepted testing procedures we would recommend that the AEC consider evaluation tests. The manufacturer should be able to supply information on typical applications; collection efficiency for particles of varying size, physical properties and loadings; total pressure loss; water and power consumption; thermal and pressure limitations; space requirements; and gas handling capacity.

The priority assignment of such proposed tests, if undertaken, will depend upon whether or not there is an urgent need for this type of apparatus, since the activities of the Air Cleaning Laboratory are not limited by any means to evaluation and testing of commercial control equipment.

4. Rejection of a request to undertake evaluation tests on a dust collector does not necessarily imply that it is considered as unacceptable for AEC use.

5. There is no official policy that the AEC or its contractors must restrict their purchases to equipment recommended by the Air Cleaning Laboratory. A primary function of this laboratory is to act in advisory capacity to the Commission on air cleaning problems. Therefore, we are obliged to present the merits and disadvantages of any equipment under consideration.

6. There is no such thing as an "Air Cleaning Laboratory Approval." In view of the fact that time and cost limitations prevent a comprehensive survey of all commercial dust collecting equipment, we definitely wish to avoid associating the name of Harvard University or its Air Cleaning Laboratory with any commercial product regardless of source. It is our policy to recommend a group of competitive or equivalent products whenever possible.

7. Persons or manufacturers having an air cleaner of new or improved design potentially applicable to AEC operations and who can provide performance data as indicated in item 3, may contact the U. S. Atomic Energy Commission, Division of Reactor Development, Washington, D. C.

FURTHER INVESTIGATIONS OF THE CONTINUOUS SLAG WOOL FILTER

C. E. Billings, C. Kurker, Jr., E. C. Hickey, L. H. Levenbaum, and L. Silverman
Harvard School of Public Health

Results of the first pilot plant study on a continuous slag wool filter for open hearth fume have been reported.^{1,2} The following is a report on the continuation of that study with a redesigned filter unit.

In the manufacture of steel by the open hearth process, a shallow bath of molten metal is reduced in carbon content by directing an oil or gas flame across the exposed upper surface. A roof above the bath directs the heat down onto the metal. Vaporization and agitation of the molten bath cause fine particles of iron oxide to be dispersed in the gas, along with the particles of other materials present in the reaction, such as lime, ore, and silicates. Mean size of these particles is less than 0.1μ by counts so that many are carried through the heat exchanger and on out the stack. Temperature of the gas is about 1400°F after leaving the heat exchanger and it may be carrying an average particulate loading of 0.4 grain/cu ft. For a 250-ton furnace this represents about a ton of fume per day.

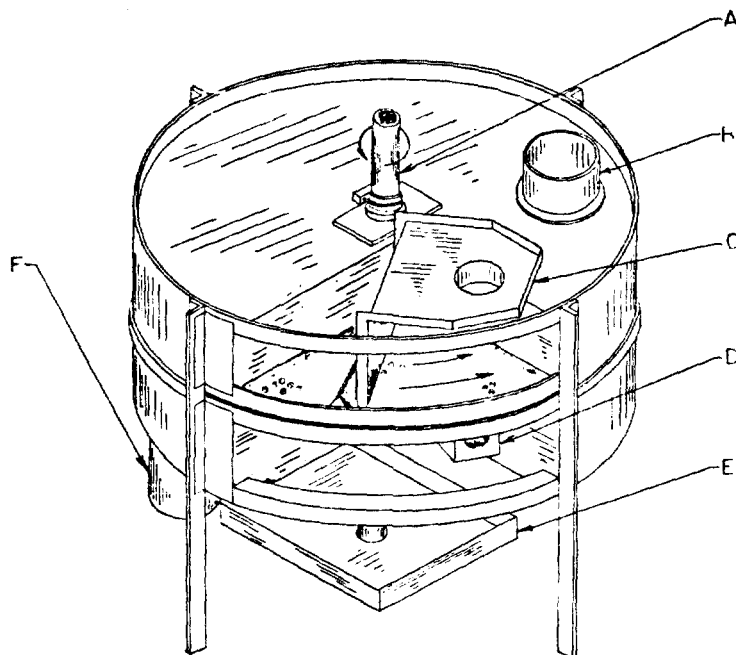


Fig. 1— Continuous slag wool filter for high-temperature fume— Pilot Plant II.

The American Iron and Steel Institute through its Subcommittee on Air Pollution Abatement is sponsoring research on high-temperature gas cleaning at Harvard University. One phase of this research has been directed toward the use of slag wool as a filter fiber. Wool is made by spinning or blowing molten slag from the blast furnace, and its present primary use is for thermal insulation.

Laboratory studies have shown that a 1-in. thick layer of slag wool, at a packing density of 5 lb/cu ft, will remove over 90 per cent of a fine iron oxide fume from a 1000°F gas stream at 100 fpm filtering velocity. Resistance to flow is about 2 in. of water initially and increases as the fume is collected. Each pound of fiber will take up about 5 per cent of its own weight while causing the resistance to rise an additional 2 in.

In the first pilot tests on an open hearth furnace, a continuous web of slag wool was formed from the fiber and was carried by a conveyor into a gas plenum to filter the fume. An average

collection efficiency of about 60 per cent was obtained in this unit. Lowered efficiency was attributed to mechanical factors such as the difficulty of sealing the moving bed of fibers to a stationary surface and to thin areas in the bed produced during formation.

With the experience gained from this first study, a second pilot plant unit has been constructed and tested under identical conditions. Since space requirements are at a premium in an existing steel mill the new pilot plant incorporates a circular disc to carry the filter bed in and out of the gas stream, instead of the former conveyor belt. A disc yields maximum usable area and operations take place over the whole surface, as opposed to a chain conveyor where a certain proportion cannot be used.

This unit is shown in Fig. 1. A 4-ft diameter disc of $\frac{3}{16}$ -in. perforated steel is driven by a central shaft (A), through a gas plenum covering three quarters of the disc. As in the original unit, a suspension of slurry of the slag wool fibers in water is used to form the filter bed. The slurry is introduced at tray (C), where it flows over the left edge and down onto the disc in the open quadrant. The majority of the water runs through the perforations in the disc into sump (E), leaving the fiber behind on the surface as a wet lap. As the disc slowly rotates, the fiber bed passes over a dewatering suction box (D) where the interstitial water is removed. The bed then advances into the hot gas plenum where it dries and acts as a fiber filter. This unit filters 750 cfm of gas at temperatures over 900°F. After three-fourths of a revolution the used web emerges and is removed to a fiber washing stage for recovery and reuse. Gas from the furnace enters and leaves the filter at (B) and (F) respectively.

Figure 2 shows a schematic representation of the complete unit including the main slurry tank at the bottom, and overhead surge tank, and fiber slurry and hot gas flow lines.

Figure 3 is a picture of the unit set up for tests in a steel plant. The overhead tank is shown on the right. Slurry flows down to the filter from the constant level tank through the line running from the lower right corner up into the center of the picture. Hot gas enters through the large line on the left, and leaves through the Venturi shown below this line, passing to the fan and stack in the background. The mechanism in the center is used to drive the disc. Used fiber enters the washing tank at the top of Fig. 4 and is carried by overflowing water onto a vibrating separation screen directly beneath the water box shown in the center. Dirty water is filtered (again by slag wool) in the liquid filter at the lower section. Clean fiber and clean water are returned to the main tank from this area.

Another phase of the high-temperature gas cleaning program has been directed toward methods of inducing particulate agglomeration in open hearth fume. If the fume particle size can be increased to an appreciable degree then filter performance should be better, efficiency will be higher, and the rate of build-up of filter resistance will be lower, thus requiring less fiber per unit of time. A rotary screw agglomerator has been developed which consists of several flights or turns of a standard conveyor screw housed in a cylindrical chamber, as shown in Fig. 5. Gas is caused to flow in a tight spiral path and particulate material is subjected to turbulent, centrifugal, and thermal forces which should cause agglomeration and wall deposition. The screw is rotated slowly to keep the walls of the cylinder clean. Figure 6 shows the agglomerator installed during the recent field studies for use with the pilot filter unit.

A number of filter tests have been made both with and without the agglomerator in series. Without the agglomerator, the average collection efficiency was not substantially different from that obtained in the first pilot unit (i.e., about 60 per cent) with values ranging from 10 per cent to 90 per cent as was previously found. The lowered efficiency is believed to be due to the same two factors, peripheral leakage of the open hearth fume by the filter bed, and nonuniform bed formation. To obtain a better edge seal, the circular disc rides in a peripheral track formed by two rolled angle iron rings above and below the disc. As the filter bed is formed, fibers are deliberately overlapped onto the upper surface of the top angle. This then provides a drag seal so that when the bed rotates the fibers should take whatever form is required to keep gas from leaking past the filter.

Since the efficiency with this method of sealing was not significantly higher than with the previous unit, it was suggested that perhaps a moving seal of such simple construction would be insufficient. Therefore, a series of tests were made with stationary filter beds to attempt to

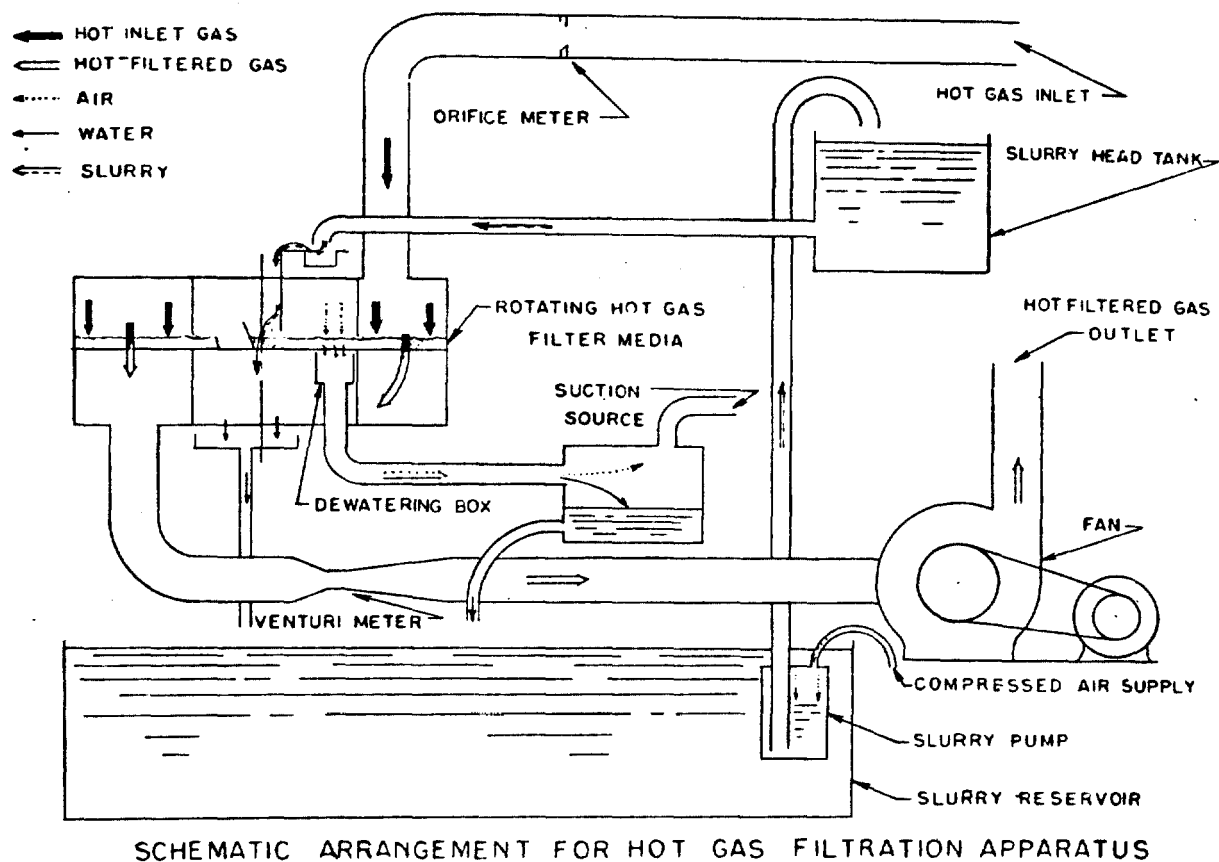


Fig. 2—Schematic arrangement for hot gas filtration apparatus.

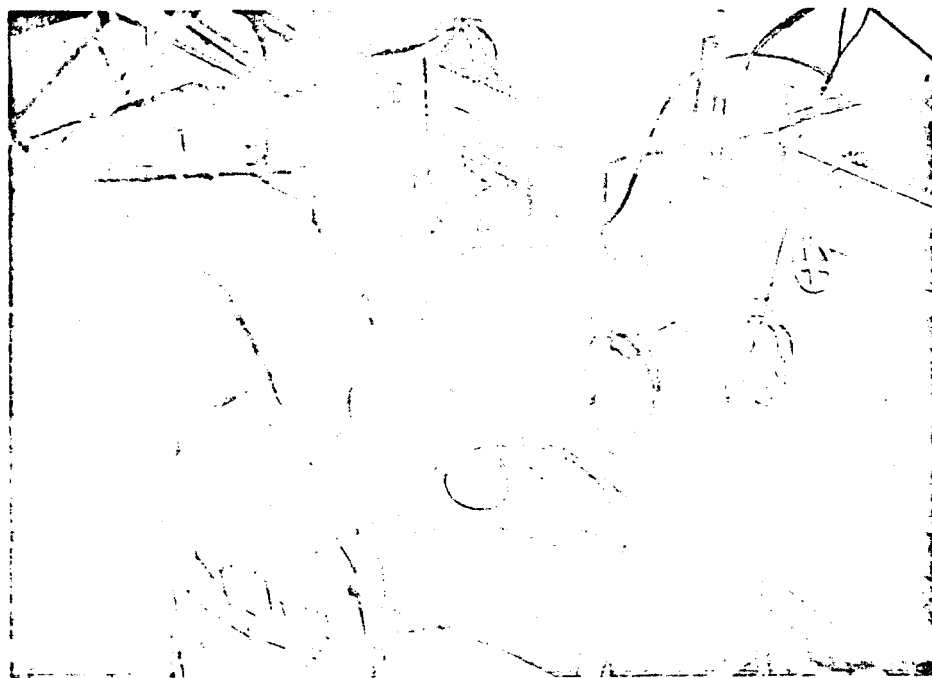


Fig. 3—Field installation of continuous slag wool filter—Pilot Plant II.

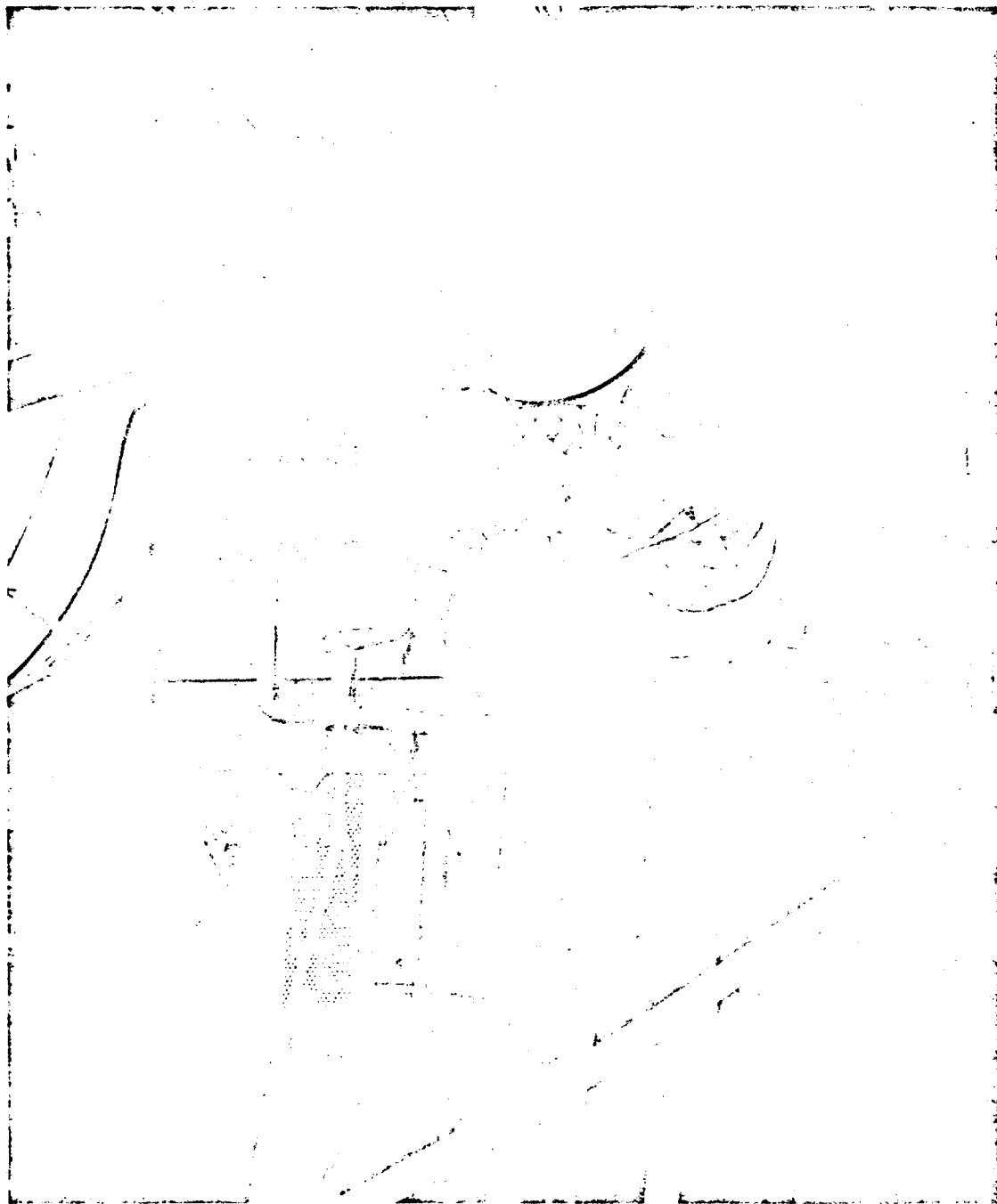


Fig. 4—Used fiber reclaiming system for continuous slag wool filter—Pilot Plant II.

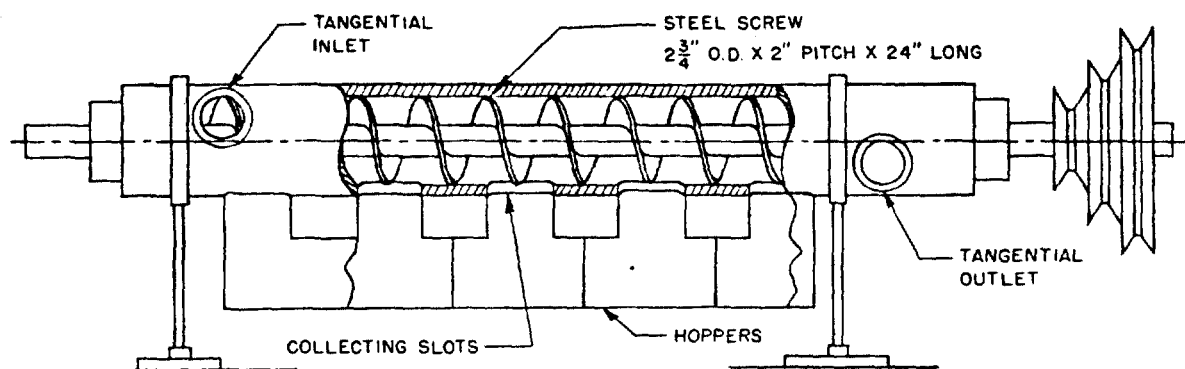


Fig. 5—Rotary screw agglomerator and inertial collector.

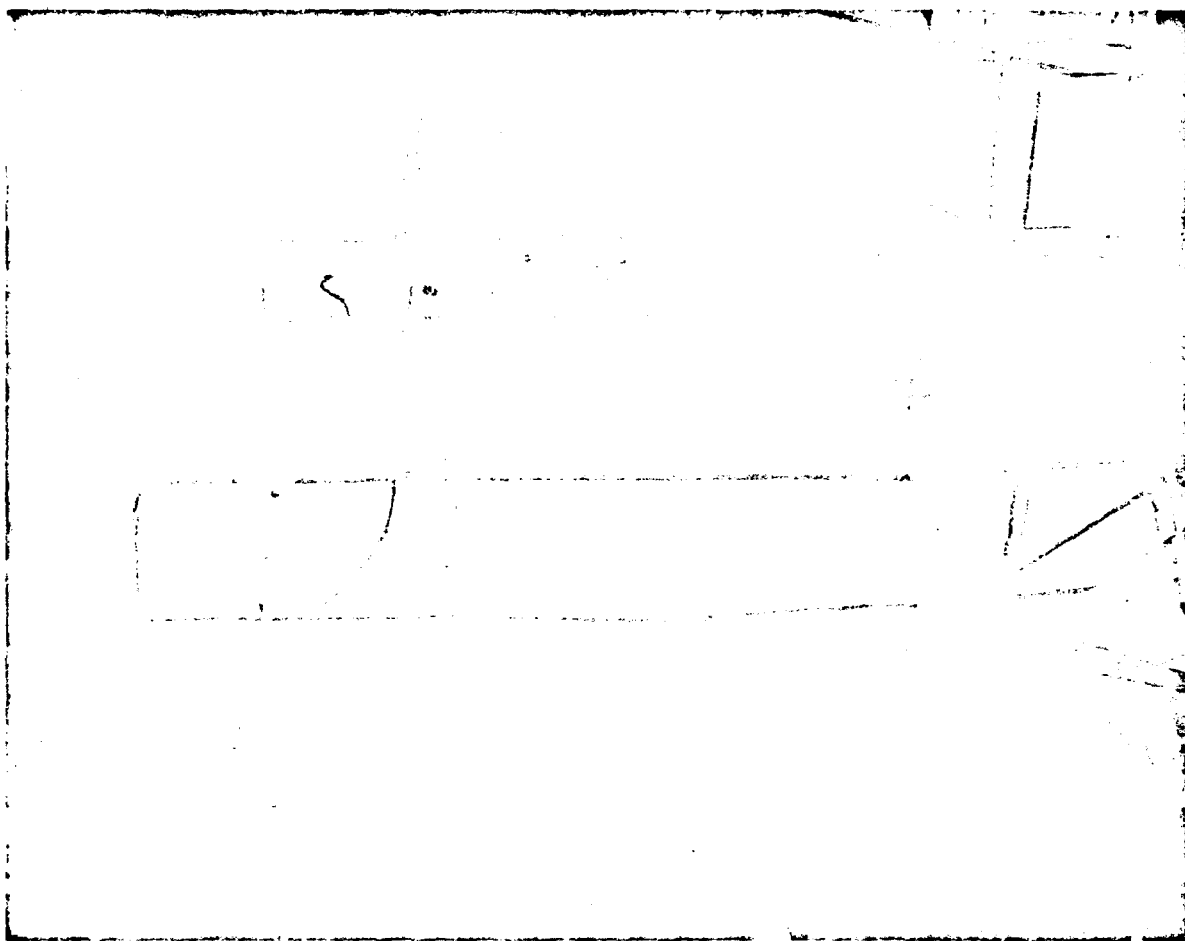


Fig. 6—Twelve-inch rotary screw agglomerator installed for field tests—Pilot Plant II.

eliminate the effect of peripheral leakage by the moving seal. A clean bed was run into the unit before the gas was admitted from the flue, and held stationary while the resistance to gas flow was allowed to increase. The average efficiency of these runs was 75 per cent, ranging from 40 per cent to 90 per cent, with half being about 90 per cent or better.

To investigate the effects of the agglomerator in the inlet line to the filter, tests were made with (1) the filter operating normally, i.e., rotating slowly, and (2) stationary filter beds. The average efficiency of the normally operating filter based on the inlet loading to the filter, not including whatever was removed in the screw agglomerator, was about 60 per cent also, the same as for operation without the agglomerator. When the unit-combination was operated with a stationary bed, however, the average efficiency of the filter rose to 87 per cent, or very near values found in laboratory tests. Two-thirds of the efficiency measurements were greater than about 90 per cent, ranging from 60 to 98 per cent.

Since the filter was stationary, a criterion of 10 in. water was used as opposed to the 4 in. water criterion used for continuous filter operation. Average resistance of the stationary beds was 6 in. water for the filter only; and 6.3 in. water for the combination agglomerator plus filter. The ranges were 1.1 to 10.8 in. water, filter only, and 1.3 to 11.0 in. water, filter and agglomerator.

To further establish the effect of the agglomerator, the average increase in resistance per unit of time for stationary beds can be compared. If the change in resistance is divided by the time interval during the change, an average value of 0.216 in. water is obtained for the filter alone, and 0.163 in. water/min for the combination of agglomerator and filter, indicating a definite advantage for the combination. The resistance across the agglomerator was about 1.5 in. water. If the clean filter resistance is assumed to be 2 in. water and 2 in. water increment is allowed, as previously assumed, then the stationary filter alone will operate 9.3 min without exceeding 4 in. water. The similar comparison for the combined agglomerator and filter is 12.3 min, or about 30 per cent longer. This implies that the agglomerator will extend fiber usage by about 30 per cent, or that 30 per cent less fiber is required.

Fume loading to the unit ranged from practically none to more than 0.3 grain/cu ft, as found in the first study, depending on furnace operation.

Other investigations were made on the removal of sulphur dioxide by the fiber bed. It has been found that a damp bed of basic slag fiber will collect acid gases with a reasonable efficiency. A study was made for the efficiency of SO_2 removal, analysis being made by three separate methods, primarily to check their reliability: I_2 -KI, nephelometrically as BaSO_4 , and with the specific fuchsin-formaldehyde technique. Average sulphur dioxide removal efficiency was 50 per cent, combining the data for all tests.

More extensive analyses of the field results have been presented elsewhere^{3,4} and are available upon request. These tests have indicated the feasibility of use of slag wool on a pilot plant basis for continuous filtration of high-temperature fume. Based on these tests a larger unit is contemplated for 5000 cfm of furnace gas.

Additional investigations into the mechanisms of agglomeration of submicron fumes and their practical applications are presently being conducted in the laboratory.

REFERENCES

1. L. Silverman, W. D. Small, and C. E. Billings, High Temperature Filtration Studies with Mineral Wool, Fourth AEC Cleaning Conference, TID-7513(Pt.1), June 1956.
2. C. E. Billings, W. D. Small, and L. Silverman, Pilot Plant Studies of a Continuous Slag Wool Filter for Open Hearth Fume, Air Pollution Control Assoc. 5: 159, November 1955.
3. C. E. Billings, L. H. Levenbaum, C. Kurker, Jr., E. C. Hickey, and L. Silverman, Open Hearth Stack Gas Cleaning Studies, Semi-Annual Report (SA-7) for Nov. 1, 1956 to Apr. 30, 1957, Harvard University, September 1957.
4. C. E. Billings, C. Kurker, Jr., E. C. Hickey, and L. Silverman, Further Investigations of the Continuous Slag Wool Filter, Air Pollution Control Assoc. (In Press), 1957.

SLAG WOOL FOR ACID GAS AND MIST REMOVAL

Charles Kurker, Jr., Charles E. Billings, and Leslie Silverman
Harvard School of Public Health

1 INTRODUCTION

Economical methods for air pollution control from steel production operations are under investigation at Harvard University through the support of the American Iron and Steel Institute. The atomic energy industry is not usually concerned with the visibility loss aspect of air pollution because of much lower toxicity levels. However, some of the developments of this project may be useful. Studies¹ have indicated that a 1-in. thick pad of slag wool, at 5 lb/cu ft packing density, will collect 80 to 95 per cent of submicron iron oxide fume from gas streams up to 1200°F at a filtering velocity of 100 fpm. By continuously forming fiber filters from a water slurry, it is possible to reclaim the slag wool as much as eight times. Under these conditions, each pound of fiber will recover $\frac{1}{2}$ lb of fume, while filter resistance is maintained continuously at 4 in. water. Collected fume is removed from fibers by reslurrying. After separation of the liquid it is reused by filtering through wet slag wool layers.

During field studies of a continuous slag wool filter pilot plant on open hearth fume, a certain amount of fiber attrition was observed which could be attributed to acid attack by sulfur dioxide in the flue gas. Preliminary tests indicated that slag wool was removing sulfur compounds. Subsequent laboratory studies showed that these fibers remove substantial amounts of SO₂ gas and H₂SO₄ mist. Laboratory filters exposed to acid mist deteriorate similarly to those used in the field.

Many commercially available slag fibers contain in excess of 25 per cent CaO, from limestone used as a flux. Acid gas and mist removal efficiency have been investigated as to their application to off-gases and other air pollutants.

Simultaneous removal of acid gas and particulate materials is a unique feature of the slag wool filter which was not originally anticipated. It is useful for applications requiring simultaneous collection of aerosol particles and acid gases. One additional feature is that it can be used at high temperatures, up to 1200°F. Slag fiber cost is low, ranging from \$20 to \$40 per ton.

2 FIBER CHARACTERISTICS

Three kinds of mineral fibers were evaluated. Mineralite wool is made from basic blast furnace slag which is spun into fibers about 4 μ in diameter. Baldwin-Hill loose insulation wool is spun from a mixture of copper and iron slags and also has a mean fiber size of 4 μ .

Kaowool (Babcock and Wilcox Co.) is made by melting kaolin clay ($\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$) in an electric furnace and spinning 4 μ fibers. Kaowool A is designated as lubricated and Kaowool B as unlubricated. We have not tested these fibers for upper temperature limit, but it is presumably close to 2000°F.

The alkalinity of each of these four fibers was determined by immersion in known amounts of acid and titrating with a standard base. Results are given in Table 1. It can be seen that alkalinity is slightly dependent upon the normality of the acid. Based on several runs, approximately 1 g of Mineralite fiber will react with, and neutralize, 8.5 meq (0.31 g) of HCl and 6.0 meq (0.29 g) of H₂SO₄.

Our basic slag wool fibers thus will neutralize about $\frac{1}{3}$ g of acid per 1 g of wool. Mineralite fibers are slightly more alkaline, but Kaowool fibers are effectively neutral.

These wools were tested dynamically as filters and absorbers for acid gases and mists. Six-inch diameter pads were placed in the equipment shown previously (Fig. 1, reference 1, p 276) and their performance measured at various filtering velocities, dry and wet, and at room

Table 1—FIBER CHARACTERISTICS OF MINERAL WOOLS USED FOR
ACID GAS AND MIST STUDIES

Wool	Approx. diameter, μ	Acid	Normality	Alkalinity, meq/g	Remarks
Mineralite	4	HCL	0.1	3.6	Basic
Mineralite	4	HCL	0.3	9.9	blast
Mineralite	4	HCL	1.0	12.2	furnace
Mineralite	4	H ₂ SO ₄	0.1	3.2	slag.
Mineralite	4	H ₂ SO ₄	0.3	9.4	white
Mineralite	4	H ₂ SO ₄	0.7	14.3	
Baldwin-Hill	4	HCL	0.1	2.8	Nonferrous
Baldwin-Hill	4	HCL	0.3	6.0	copper and
Baldwin-Hill	4	HCL	1.0	6.0	iron slag
Baldwin-Hill	4	H ₂ SO ₄	0.1	2.6	
Baldwin-Hill	4	H ₂ SO ₄	0.3	7.0	
Baldwin-Hill	4	H ₂ SO ₄	0.7	8.5	
Kaowool A	4	HCL	0.1	0.2	Kaolin
Kaowool A	4	HCL	0.7	0.3	wool
Kaowool B	4	H ₂ SO ₄	0.1	0.1	
Kaowool B	4	H ₂ SO ₄	0.7	0.3	

and elevated temperatures. All filters were formed from a 1 per cent water slurry of the fibers and dried prior to tests, except as noted.

3 ACID MIST STUDIES

3.1 Sulfuric Acid (H₂SO₄)

To investigate the cause of the slag wool fiber attrition observed during field studies, preliminary tests were made on Mineralite and Baldwin-Hill filters with sulfuric acid mist generated by dropping 50 per cent acid on a heated plate, approximate particle size 0.8 μ mass median diameter.² Samples were collected upstream and downstream of the test filters on Millipore filters and analyzed by titration with NaOH.

Results of these studies are presented in Table 2. Average collection efficiency was 52 per cent for B-H filters and 69 per cent for Mineralite filters. This exposure produced a condition identical to that observed on slag wool that had been used to filter open hearth stack gases during pilot plant field studies. The upstream face of the filters showed deterioration of the fibers and additional embrittlement was observed throughout the depth. It was concluded from these results that acid attack (H₂SO₄) was the principal cause of fiber attrition in field tests.

Further acid mist removal studies were made to investigate usable filter life on Mineralite fiber. Mist was generated with a compressed air aspirator. Large droplets were removed by impingement on a baffle placed in front of the nozzle, and also by elutriation as the mist rose upward to leave the container, approximate particle size 4.5 μ mass median diameter (reference 2, p. 19). Samples were collected upstream and downstream of the test filter on Millipore paper and analyzed by conductivity.

Results of these tests are shown in Table 2, lines 6 and 7, and the efficiency is recorded as a function of time. Over a one-hour period there was no serious loss in efficiency due to acid attack of the fibers. The filters when removed were observed to be in good condition and attacked slightly at the upstream face. Qualitative observation indicated that only a small part

Table 2—SLAG WOOL FILTER* EFFICIENCY FOR SULFURIC ACID MIST

Wool	Average inlet conc., [†] mg/m ³	Filtering velocity, [‡] fpm	Resistance, in. H ₂ O		Efficiency during period, %			Average efficiency, %
			Initial	Final	0-20 min	20-40 min	40-60 min	
Mineralite	50	500						65
Mineralite	100	2000						73
Baldwin-Hill	200	320						32
Baldwin-Hill	100	550						56
Baldwin-Hill	50	970						68
Mineralite	50	120	0.35	0.42	63	69	70	69
Mineralite	100	65	0.50	0.56	73	71	70	71

*All filters 2 in. thick and 4 lb/cu ft packing density.

[†]100 mg/m³ = 25 ppm H₂SO₄.

[‡]At 70°F.

of the fiber had reacted. Average filter efficiency during these tests, 70 per cent, was about the same as in the first group.

Since the fiber alkalinity indicated that Mineralite fibers could neutralize about 0.4 g of sulfuric acid per gram of wool, a calculation of the total amount of material collected by the filter is indicative of the relative amount of total possible acid recovery during these tests. In the last test, line 7, the initial filter weight was about 50 g. It was exposed to 20 cu ft of air per minute, at 100 fpm.

Total acid removed by the filter is then: $65 \text{ mg/m}^3 \times 20/35 \text{ m}^3/\text{min} \times 60 \text{ min} \times 0.71 = 1580 \text{ mg}$.

Fifty grams of fiber should be expected to neutralize a maximum of $0.4 \times 50 = 20 \text{ g}$ of H₂SO₄. The amount recovered of the possible total is then $1.58/20 \times 10 = 7.9$ per cent, which agrees with the observation of the filter itself. On this basis maximum filter life would be about 10 to 15 hr at this concentration.

The assumption that all fiber alkalinity is available for reaction may not be strictly correct because mist collection occurs primarily at the fiber surface. A sulfate layer on the surface would interfere with further reaction and effectively reduce the total amount of material collected.

Higher concentrations will presumably reduce life in direct proportion to concentration. Higher efficiency can be obtained with a deeper filter bed, in accordance with the logarithmic penetration law. Resistance would be expected to increase in direct proportion to bed length.

3.2 Sulfur Trioxide (SO₃)

Tests with sulfuric acid mist discussed above were made with relatively large particles. If the acid is formed from oxidation of sulfur at high temperature, then the gaseous sulfur trioxide will absorb moisture from the air and form very small particles. An attempt was made to use catalytic conversion of SO₂ to SO₃ with vanadium pentoxide in a device similar to that of Gillespie³ to generate small particles. Because of technical difficulties encountered and catalyst poisoning, this method was not used.

Sulfur trioxide generation was accomplished in preliminary equipment by oxidizing SO₂ gas with ozone. A stream of commercial oxygen (3 liters/min) was passed through a small laboratory electrostatic precipitator (15 kv, a-c) (reference 4, p. 158) where approximately 10 per cent was found to be converted to ozone. The oxygen-ozone stream was then combined with SO₂ gas (0.05 liters/min) and passed into a 40 liter carboy whose walls were moistened by blotters. From the total gas flow and carboy volume a residence time of 13 min was allowed for conversion of SO₂ to SO₃. A white mist emerged from the carboy outlet, indicating that the generation method was successful. To obtain the SO₃ free of residual SO₂, stoichiometric volumes

were used, but variations in ozone production led to some doubt as to the complete oxidation of SO_2 . A further acid gas absorbent would probably have been required. The efficiency of conversion was not determined. This method was therefore abandoned in favor of the one described below.

Tests of Mineralite fiber on SO_3 were made by gently heating fuming sulfuric acid and passing the vapor-mist combination through a large electrostatic precipitator to remove H_2SO_4 droplets. The gaseous SO_3 escaped and passed into the test unit, picking up moisture rapidly from dilution room air to form small droplets. From the work of Gillespie (reference 3, p. 16) it has been shown that this occurs very rapidly (approximately 0.01 sec.) and that particles so produced are on the order of 0.5μ mass median diameter.

Test results are given in Table 3. Average collection efficiency of 2-in. thick filters was 31 per cent, and no significant change in efficiency was observed during a continuous running period of 100 min. Efficiencies are lower than those for H_2SO_4 mist because of the smaller

Table 3—SLAG WOOL FILTER* EFFICIENCY FOR SULFUR TRIOXIDE MIST

Average inlet conc., [†] mg/m ³	Resistance, [‡] in. H ₂ O		Efficiency during period, %				Average efficiency, %
	Initial	Final	0–25 min	25–50 min	50–75 min	75–100 min	
98	0.64	0.69	22	40	41		34
56	0.70	0.78	33	36	31	30	32
37	0.40	0.68	19	32	23	30	26

*All filters 2 in. thick and 4 lb/cu ft packing density, Mineralite fiber.

[†]100 mg/m³ = 31 ppm, SO_3 .

[‡]At 100 fpm filtering velocity, 70°F.

particle size. The total filter life can be estimated from calculations; for example, at an average inlet concentration of 50 mg/m³, the filter was tested for 100 min at an average efficiency of 31 per cent, so amount of fiber used would be:

$$50 \text{ mg/m}^3 \times 20/35 \text{ m}^3/\text{min} \times 100 \text{ min} \times 0.31 = 880 \text{ mg}$$

$$0.88/20 \times 100 = 4.4\%$$

Expected filter life at an average concentration of 50 mg/m³ would be about 2.7 hr, or approximately twice as long as found during H_2SO_4 tests, where the concentration was 90 mg/m³ or about twice as high. The same limitation of sulfate formation on fiber surfaces discussed above is possible here, so the estimate given above may be too high.

3.3 Nitric Acid (HNO_3)

Mineralite slag wool filters were tested on nitric acid mist generated by dispersing concentrated HNO_3 (80 per cent) with a compressed air aspirator² as was done for sulfuric acid mist. Samples were collected before and after the test filter on Millipore filters followed by sintered glass absorbers. Colorimetric analysis was made with the brucine reagent described by Snell.⁵

Dry slag wool filters were tested at filtering velocities of 50, 100, and 150 fpm at room temperature. Two runs were also made at room temperature and 100 fpm velocity with filters that contained moisture remaining after partial drying. Two tests were made at a gas temperature of 500°F. Data for these tests are indicated in Table 4. Increased filtering velocity makes a slight but significant increase in filter efficiency at constant inlet loading as seen by comparing the average efficiency at 50 fpm (74 per cent) with that at 150 fpm (84 per cent). A threefold increase in filter loading at constant velocity, lines 2 and 3, makes an appreciable

improvement in efficiency, from 75 to 87 per cent. The outlet concentration has increased only slightly in this case from 35 mg/m³ to 40 mg/m³, indicating that the generation of the higher concentration did not produce a significantly greater quantity of large particles.

Table 4—SLAG WOOL FILTER^a EFFICIENCY FOR NITRIC ACID MIST

Filtering velocity, fpm	Average inlet conc., ^b mg/m ³	Resistance, ^c in. H ₂ O		A, ^d %	Efficiency during period, %					Average efficiency, %	No. of tests
		Initial	Final		0-20 min	20-40 min	40-60 min	60-80 min	>80 min		
50	123	0.30	0.43	5	70	81	77	79	66 ^e	74	2
100	139	0.49	0.72	9	80	72	76	71	70 ^f	75	3
100	309	0.53	0.81	22	82	94	72	54		87	1
150	141	0.98	1.25	13	90	91	80	56		84	2
100 ^g	234	0.95	0.57	9	41	42	54	68		49	1
100 ^g	314	0.83	0.41	17		80	63	51	50 ^h	60	1
100 ^k		1.28	1.28		42	45	79	68		58	2

^aAll filters 2 in. thick and 4 lb/cu ft packing density, Mineralite fiber.

^b100 mg/m³ = 39 ppm HNO₃.

^cAt indicated filtering velocity, 70°F, except line 9 at 500°F.

^dFilter rating factor based on first 80 min of test, pounds of material collected per 100 lb of slag wool, calculated from inlet mist loading (L), flow rate (Q), time exposed (T), filter efficiency (E), and initial weight of filter (W): $A = LQTE/W$, expressed as per cent.

^eAt 110 min.

^fAt 170 min.

^gFilter contained residual moisture from formation process at start of test.

^hAt 150 min.

^kAt 500°F.

Filters tested with residual moisture, lines 5 and 6, showed a slightly lower average efficiency than dry ones at the same filtering velocity. Wet filters were observed to sag slightly away from the upper surface of the filter holder. This could have caused peripheral leakage around the filter, causing lower efficiency, average about 55 per cent. The resistance of these filters fell during testing, columns 3 and 4, as interstitial moisture dried out.

Two tests at high temperature indicated a slightly lowered collection efficiency. This is either due to evaporation of mist droplets to a smaller size, to the gas phase, or to the effects of high temperature on impaction efficiency (presumably the mist particle size is in the range of impaction rather than diffusion). The theoretical consideration of filtration mechanisms at elevated temperatures have been presented recently.⁶

The calculated filter rating factor indicated in Table 4 (A, %; column 5) represents the amount of nitric acid mist the filter recovers per hundred pounds of slag wool. All filters tested, at room temperature, reacted with the acid to form a white powdery product, presumably calcium or potassium nitrate, on the upstream face for about the first half inch. Most measurements were for 1½ hr with some extended nearly 3 hr. During this period no significant loss of efficiency occurred to indicate a "break-point" or total utilization of the filter capacity to collect acid mist. Filter rating factors ranged from 5 to 15 per cent on an inlet concentration of approximately 125 mg/m³ of mist, and it is presumed that filters could operate ten times as long without substantial decrease in efficiency or a total run time of probably about 20 hours. With a threefold increase in inlet loading, lines 2 and 3, the filter rating factor increased by about the same amount, from about 8 to about 22.

Average dry filter efficiency at 100 fpm, room temperature, is about 80 per cent. Higher inlet concentration and filtering velocity apparently produce improved collection efficiency.

4 ACID GAS STUDIES

4.1 Sulfur Dioxide (SO₂)

As discussed under sulfuric acid mist, tests were initiated in the laboratory to determine the cause of slag wool fiber attrition observed during field tests of the first pilot plant filter unit. A comparable series of tests was also made with SO₂ gas since this is the major product from sulfur-bearing fuel. Commercial cylinder gas was metered into the test unit and samples were collected in sintered glass absorbers containing hydrogen peroxide. Analysis was made by measuring the electrical conductivity of the solution. Results of these tests, presented in Table 5, indicate 0 per cent removal for all dry filter beds and for wet Kaowool fibers. In all

Table 5—SLAG WOOL FILTER* EFFICIENCY FOR SULFUR DIOXIDE GAS

Wool	Filtering velocity, [†] fpm	Average inlet conc., ppm	Average efficiency, %	Remarks
Mineralite	100		0	Dry
Baldwin-Hill	100		0	Dry
Kaowool A	100		0	Dry
Kaowool B	100		0	Dry
Mineralite	300	50	24	Wet
Mineralite	300	100	29	Wet
Mineralite	300	200	12	Wet
Baldwin-Hill	300	50	20	Wet
Baldwin-Hill	300	100	27	Wet
Baldwin-Hill	300	200	31	Wet
Kaowool A			0	Wet
Kaowool B			0	Wet

*All filters 2 in. thick and 4 lb/cu ft packing density.

[†]At 70°F.

cases the fibers appeared to be unaltered. Wet Mineralite filters removed an average of 26 per cent SO₂ which reacted with the fibers and caused bleaching and size reduction. Upon drying, the filter was white, brittle, and powdery. This condition was similar to that observed in field tests. Comparable tests with Baldwin-Hill wool gave an efficiency of 22 per cent.

Sulfur dioxide samples have since been taken during continuous field operation of a second pilot plant unit.⁷ Filters were formed continuously by the slurry process, so that there was residual moisture present. Samples were analyzed by three different methods to evaluate the most useful one, with results as reported in Table 6. The method indicated as I₂-KI is the one worked out by Pearce and Schrenk,⁸ the fuchsin method is that of Stang, Zatek, and Robson,⁹ and the BaSO₄ method is the turbidimetric estimate of the precipitate.

Average inlet sulfur dioxide concentration by each method is 66 ppm I₂-KI, 62 ppm fuchsin, and 98 ppm BaSO₄, indicating that the I₂-KI and fuchsin methods give similar results. Average positive collection efficiency by each of the three methods is 39 per cent I₂-KI, 72 per cent fuchsin, and 13 per cent BaSO₄. For all positive tests average collection is 49 per cent.

After the first four preliminary tests with I₂-KI, the testing was done serially as indicated by numbers in the last column of Table 6. Simultaneous upstream and downstream samples were taken for each of the three methods in succession. In test 1, the I₂-KI method was used first, line 5, then the sample for fuchsin analysis was obtained, line 9, and finally the BaSO₄ sample was taken, line 13. This procedure was repeated in tests 2, 3, and 4. Comparing concentration and efficiency results on the basis of test number does not give a strong correlation between methods of analysis. A comparison of average inlet concentrations indicates that the specific fuchsin method yields the lowest value while the nonspecific I₂-KI and BaSO₄ methods give results that are somewhat higher.

Table 6—SULFUR DIOXIDE REMOVAL BY CONTINUOUS SLAG WOOL FILTER
OPERATING ON OPEN HEARTH FUME

Filtering velocity, fpm	Average resistance, in. H ₂ O	SO ₂ concentration, ppm		Efficiency, %	Temperature, °F	Analytical method for SO ₂	Test No.*
		Inlet	Outlet				
88	7.2	38	56		750	I ₂ -KI	1
77	7.1	56	13	73	800	I ₂ -KI	2
88	6.3	36	25	30	820	I ₂ -KI	3
110	4.8	24	14	42	830	I ₂ -KI	4
110	3.2	43	65		850	I ₂ -KI	1
101	3.9	74	102		850	I ₂ -KI	2
89	5.9	189	125	34	900	I ₂ -KI	3
109	3.3	68	58	16	840	I ₂ -KI	4
102	3.9	45	19	59	860	Fuchsin	1
101	4.0	94	38	61	880	Fuchsin	2
79	6.8	70	8	89	900	Fuchsin	3
97	3.2	43	10	78	775	Fuchsin	4
92	4.1	55	59		740	BaSO ₄	1
100	4.6	176	235		920	BaSO ₄	2
108	4.1	90	78	13	870	BaSO ₄	3
98	4.2	72	77		830	BaSO ₄	4

*First four I₂-KI tests were preliminary.

Based on these tests, the slag wool filter removes about 50 per cent of SO₂ from an average of 75 ppm in open hearth furnace gas, while performing its primary function as a particulate filter. Filters in the above tests were approximately 1 in. thick and 4 lb/cu ft packing density, so that improved performance on the gas could be obtained by a thicker filter.

4.2 Nitrogen Dioxide (NO₂)

The efficiency of Mineralite slag wool filters was determined on nitrogen dioxide gas by metering commercial cylinder gas into the test unit. Samples were collected upstream and downstream of the test filter in sintered glass absorbers with sulfanilic acid and α -naphthylamine solution.⁵ The resulting color was measured on a colorimeter. Test results are given in Table 7. Average efficiency of dry filters was 10 per cent and of wet filters 28 per cent. There was no marked decrease in collection efficiency during 80 min continuous testing.

Table 7—SLAG WOOL FILTER* EFFICIENCY FOR NITROGEN DIOXIDE GAS

Filtering velocity, [†] fpm	Average inlet conc., ppm	Resistance, in. H ₂ O		Efficiency during period, %			Average efficiency, %	Remarks
		Initial	Final	0-15 min	15-45 min	45-80 min		
100	30	0.45	0.48	11	12	8	10	Dry
100	35	1.28	0.94	27	22	35	28	Wet

*All filters 2 in. thick and 4 lb/cu ft packing density, Mineralite fiber.

[†]At 70°F.

Table 8—MINERAL WOOL FILTER EFFICIENCY FOR HYDROFLUORIC ACID GAS

Wool*	Filter vel., fpm	Inlet conc., ppm	Resistance, [†] in. H ₂ O		A, [‡] %	Efficiency during period, %						Min. eff., %	Max. time, min	No. of tests
			Initial	Final		0-10 min	10-25 min	25-40 min	40-55 min	55-70 min	70-85 min			
M	80 ₄	390	0.8	1.4	13	80	78	65	65	40	23	0	120	2
M	160 ₄	310	2.3	4.8	15	59	72	63	47	31	21	0	110	2
M [§]	80 ₅	580	3.7	1.2	16		80	80	83	94	90	62	180	2
M [§]	160 ₅	440	8.9	4.6	35	93	96	97	97	95	67	46	90	2
M [¶]	160 ₃	350	2.4	3.5	6	32	48	50	40	33		0	170	2
B-H	80 ₄	490	1.2	2.1	9	65	69	60	45	31	29	12	135	4
B-H	160 ₄	250	2.1	4.5	14	75	96	94	73	49		6	100	2
B-H [§]	80 ₅	420	5.2	2.0	12		73	66	60	53	38	11	160	2
B-H [¶]	160 ₄	480	6.8	7.2	10	45	15					4	55	2
K-A	80 ₄	260	4.2	0.2	4	48	67	33				9	80	2
K-A	160 ₃	300	5.9	0.3	21	76	81	48				25	55	2
K-B	80 ₃	480	2.5	0.8	7	48	33					6	30	2
K-B	160 ₄	430	3.7	0.6	18	68	41					24	30	2

*All filters 2 in. thick, packing density varied from 3 to 5 lb/cu ft, as indicated by subscript. Wool tested: Mineralite (M), Baldwin-Hill (B-H), and Kaowool A (K-A) and B (K-B).

[†]At indicated filtering velocity, 70°F, except lines 5 and 9 at 500°F.

[‡]Filter rating factor based on first 60 min of test (prorated for shorter tests), pounds of acid recovered per 100 lb of fiber.

[§]Contained residual moisture from formation process at start of test.

[¶]At 500°F.

4.3 Hydrogen Fluoride (HF)

Hydrofluoric acid gas and mist removal was then investigated. Anhydrous HF was supplied from a cylinder and metered through a polyethylene tubing flowmeter. Samples were collected upstream and downstream of the filter in sintered glass absorbers.

The fluoride ion was determined by its bleaching action on ferric thiocyanate.⁵

Mineralite, Baldwin-Hill, and Kaowool filters were tested dry at room temperature at filtering velocities of 80 and 160 fpm as shown in Table 8. Mineralite and B-H filters were also tested dry at 460°F and wet at room temperature.

The pressure loss for dry Mineralite and B-H filters increased with HF exposure time as a result of the HF plasticizing reaction with the fibers. A powdery product was formed which increased the surface area for reaction, and also filled voids, causing an improved efficiency, up to saturation. The reaction is assumed to take place in two steps. First, the alkalinity of the fibers is neutralized by the acid, and second, the HF reacts with the silicates in the fibers. Mineralite and B-H filters were bleached to a white and grayish-white color after reaction, but no holes were visible. Reaction occurred throughout the depth of the filter.

Kaowool filter pressure losses decreased continuously from the start of HF exposure. On removal from the test unit these filters felt wet and contained many holes.

Wet Mineralite and B-H filters were tested and their resistance decreased steadily due to drying.

Several tests were made at elevated temperatures with Mineralite and B-H filters. The filters showed very little visible reaction. Apparently water acts as an absorbent in the reaction between the fibers and the HF, and at 460°F, no water is present. At room temperature HF picks up a considerable amount of water and the reaction with filters is quite rapid.

Table 8 also shows the variation of removal efficiency with time. Mineralite and B-H fibers have longer life and higher removal efficiency than Kaowool. Filtering velocity, exposure time, and acid concentration are governing factors in the life of a filter. In every case a definite "break-point" was observed when filter efficiency dropped sharply to indicate that the fiber had been consumed for practical purposes.

In most cases the "A" factor was higher for Mineralite. Efficiency for the wet Mineralite filters was higher than 90 per cent.

5 SUMMARY AND CONCLUSIONS

Investigations of acid collection by Mineral wool filters have indicated that 2-in. thick filters at 4 lb/cu ft packing density remove from 30 to 80 per cent of acid mist and up to 72 per cent of acid gases. Slag wool fibers have an alkaline residual due to the use of limestone as a flux which may run as high as 50 per cent of fiber weight (average 35 per cent). For most mineral acid tests (excepting HF) the total filter life depends upon the acid concentrations. Continuous fiber replacement can be achieved with equipment discussed in another section, so that acid gas and mist removal can be obtained automatically over extended periods. Table 9 summarizes the results of the tests.

Acid gas collection is generally improved (excepting HF) by the presence of moisture on slag wool filters. Absorption occurs in the acid-moisture-alkali reaction by leaching the flux from the fibers. Hydrogen fluoride collection is due to alkali neutralization and also to direct reaction of the acid with silicates in the fiber.

Additional filter studies on this phase of the project are being conducted on phosphoric and hydrochloric acids, silicon tetrafluoride and ammonium bifluoride. Parallel investigations are being conducted on the use of slag wool for fly ash, iodine, and incinerator effluent gases and particulates.

The use of slag wool for the combined simultaneous removal of acid gases, mists, and solid particulates presents a unique method with application for many problems.

Table 9—SUMMARY OF TEST RESULTS

Wool*	Acid mist	Acid gas	Approx. av. eff., %	Approx. loading	Approx. life, hr
Mineralite	H ₂ SO ₄		70	90 mg/m ³	12
Mineralite	SO ₃		31	50 mg/m ³	24
Mineralite	HNO ₃		80	125 mg/m ³	20
Mineralite		SO ₂	49	75 ppm	
Mineralite		NO ₂	20	30 ppm	
Mineralite		HF	72	400 ppm	1
Baldwin-Hill	H ₂ SO ₄		52	90 mg/m ³	12
Baldwin-Hill		SO ₂	22	300 ppm	
Baldwin-Hill		HF	60	500 ppm	1
Kaowool A		SO ₂	0	300 ppm	
Kaowool A		HF	60	300 ppm	1/2
Kaowool B		SO ₂	0	300 ppm	
Kaowool B		HF	40	500 ppm	1/2

*Average velocity 100 fpm, filter thickness 2 in., packing density 4 lb/cu ft.

LITERATURE CITED

1. L. Silverman, W. D. Small, and C. E. Billings, High Temperature Filtration Studies with Mineral Wool, Fourth AEC Air Cleaning Conference Held at Argonne National Laboratory, November 1955, TID-7513(Pt. 1), TISE, Oak Ridge, Tenn., June 1956.
2. E. M. Berly, M. W. First, and L. Silverman, Removal of Soluble Gases and Particulates from Air Streams (with Special Reference to Fluorides) USAEC, NYO-1585, Harvard University, April 1952.
3. G. R. Gillespie, Particle Size Distribution in Hygroscopic Aerosols, Univ. Ill. Eng. Expt. Sta., Tech. Rept. No. 9, USAEC, SO-1010, May 1953.
4. P. Drinker and T. Hatch, "Industrial Dust," 2nd Ed., McGraw-Hill Book Co., Inc., New York, 1954.
5. F. D. Snell and C. T. Snell, "Colorimetric Methods of Analysis," Vol. 1, D. Van Nostrand Co., New York, 1936.
6. L. Silverman, W. D. Small, I. L. Beauchamp, and C. E. Billings, Open Hearth Stack Gas Cleaning Studies, Semi-Annual Report (SA-2) for May 1, 1954 to October 31, 1954. Harvard University, December 1955.
7. C. E. Billings, C. Kurker, Jr., E. C. Hickey, and L. Silverman, Further Investigations of the Continuous Slag Wool Filter, Presented before the 50th Ann. Meeting, Air Pollution Control Association, St. Louis, Mo., June 1955, and to be published JAPCA, 1958.
8. S. J. Pearce and H. H. Schrenk, Determination of Sulfur Dioxide in Air by Means of the Midget Impinger, U. S. Bureau of Mines, Report of Investigation 4282, May 1948.
9. A. M. Stang, J. E. Zatek, and C. D. Robson, A Colorimetric Method for the Determination of Sulfur Dioxide in Air. AIHA Quart., 12: 5, March 1951.

AGGLOMERATION OF PARTICULATE MATERIALS

Edward C. Hickey, C. E. Billings, and Leslie Silverman
Harvard School of Public Health

1 INTRODUCTION

The factors affecting submicron particulate agglomeration are being studied as part of research in methods of cleaning high-temperature gas streams sponsored by the American Iron and Steel Institute at Harvard University. The primary objective is to induce particulate agglomeration in dynamic gas streams so that particle size may be increased and simple and economical gas equipment can be used. Although methods are being developed principally for the controlling of air pollution from steel production operations, they also may have application in other high-temperature problems, particularly those associated with nuclear energy processes such as incineration of radioactive wastes or use of nuclear fuels as heat sources for power production.

During the making of steel in the open hearth process, large quantities of iron oxide fume particles about 0.03μ count median diameter are generated from vaporization of the metal at high temperature. Since the gas from the furnace may be carrying an average loading of 0.4 grain/cu ft, this represents a serious problem from the standpoint of obscuring visibility even when discharged from high stacks. Due to the fine particle size and high dust loadings, any agglomeration which occurs among the particles by natural or induced methods can be an important consideration in the development or application of cleaning equipment. Increased agglomeration will improve the collection efficiency of devices such as the slag wool filter presently under development and permit each pound of fiber to recover more fume before a limiting resistance is reached.

2 AGGLOMERATION MECHANISMS

Iron oxide is a metallurgical fume which is produced in high concentrations and flocculates vigorously. Natural Brownian diffusion causes significant agglomeration when particle number concentrations exceed 10^6 per cubic centimeter (2.8×10^{10} particles/cu ft).¹ For a count median particle size of 0.03μ and a weight concentration of 0.4 grain/cu ft as found in field studies, particle numbers are on the order of 10^{18} per cubic foot which indicates that agglomeration will occur naturally.

Unaided diffusional agglomeration will proceed according to the following equation for homogeneous aerosol particles:

$$-\frac{dn}{dt} = Hn^2 \quad (1)$$

and if this is integrated using n_0 as the initial concentration, then:

$$\frac{1}{n} - \frac{1}{n_0} = Ht \quad (2)$$

where n is the number concentration at any time, t , and H is the coagulation constant which for ferric-oxide has been shown to be 6.7×10^{-10} cc/sec.² One can determine the rapidity with which agglomeration occurs in this fume by solving equation (2) for the time required to reduce the initial concentration above 10^{15} per cubic foot, or approximately 0.35×10^{11} per cubic centimeter to one-tenth of this value¹ as follows:

$$\frac{1}{0.35 \times 10^{10}} - \frac{1}{0.35 \times 10^{11}} = 6.7 \times 10^{-10}t$$

from which the time is on the order of 0.4 sec. Calculations of this type³ have indicated that the time required for passage of fume through the furnace heat exchanger (waste heat boilers) is sufficient to cause significant agglomeration. Electron photomicrographs of fume from before and after the waste heat boiler have shown an increase in count median particle diameter from 0.047 μ entering the boiler to 0.057 μ leaving.

In addition to diffusional processes, agglomeration will be promoted by any other forces which can be applied to particles to cause them to move, such as turbulence in the gas or thermal, electrostatic, magnetic, and sonic effects. Due to the high temperature of flue gases (1000°F), the thermal effects are probably of major significance. Laboratory studies on agglomeration are concerned with induced turbulent and thermal mechanisms.

3 MEASUREMENT OF PARTICULATE AGGLOMERATION

An instrument for the direct measurement of agglomeration of iron oxide fume less than 0.2 μ is required so that characteristics of agglomerators may be determined. Previous investigations of the phenomena have been successfully conducted by using the small particles as nuclei for condensation of water in a supersaturated atmosphere. This increases their size making them visible under proper lighting. A commercially available model (General Electric) has been tried for this purpose, but was found to have too low a particle concentration range. A laboratory instrument has been constructed and tested using this principle. The particle cloud is introduced into a chamber, after saturation, and a slight vacuum is applied, causing moisture to condense on the particles. The actual or relative number concentration of particles is determined by the amount of light transmitted through the cloud to a photocell. Tests were conducted with various aerosols, such as ammonium chloride and iron oxide fume produced by thermal decomposition of iron carbonyl. The light response of the cell is linear to a certain number concentration but beyond this point it increases too rapidly to enable an estimation of large particle numbers to be made reliably. It is now proposed to modify this counting chamber by the addition of a small Polaroid Land Camera which permits a photograph of a known volume of cloud to be made, from which direct counts can be taken. Agglomeration measured in this manner should be indicated by decreases in particle number at different points in the screw agglomerator. The development, construction, testing, and modifications of this instrument are presented in a recent report.⁴

To produce turbulent, centrifugal, and thermal forces in a dynamic aerosol stream, a device has been developed which consists of a standard conveyor screw mounted on a steel pipe shaft and enclosed in a sheet metal casing with tangential inlet and outlet ports. This unit provides an extended gas path in a relatively small space which gives increased contact time. Centrifugal and turbulent forces have an opportunity to act in the rapidly spiralling gas, and if the walls of the container are cooler than the gas a significant thermal force is present.⁵ Particles moving under these conditions have an increased chance of colliding with others in the gas. If deposition occurs on the walls of the container, slow rotation of the screw will remove this material to a collecting hopper at the bottom.

4 AGGLOMERATOR TESTS

A 3-in. laboratory screw agglomerator was constructed and tested using an iron oxide fume generated from combustion of iron carbonyl. The screw was rotated to keep the walls free from deposits and to push the material through slots into hoppers beneath as shown in Fig. 5, p 118. Although it was not constructed as a collecting device, tests indicated that it acted as a low efficiency inertial separator when operated nonisothermally (uninsulated). When a small settling chamber was located downstream of the agglomerator, collection efficiencies ranged from 25 to 83 per cent with an average value of 47 per cent. Inlet temperature was 500°F, outlet temperature 300°F, inlet velocity of about 3700 fpm, and loadings ranged from 0.12 to 0.18 grain/cu ft. Similar tests conducted under isothermal conditions (entire agglomerator insulated) showed negligible collection efficiency. It is concluded that a large tempera-

ture difference is necessary to produce collection and that thermal deposition is the major factor.

Pilot plant field studies on a 12-in. rotary screw agglomerator on open hearth fume showed collection efficiencies in the order of 15 per cent with inlet temperature 1000°F, outlet temperature 500°F, inlet velocity 3000 fpm, and loading on the order of 0.15 grain/cu ft. In addition to efficiency studies on the 12-in. agglomerator, samples were collected upstream and downstream on electron microscope targets with a special 15 kv a-c electrostatic precipitator, to determine the extent of particle build-up. Electron photomicrographs showed a 30 per cent increase in particle size in passage through the unit. It is interesting to note that the particle size increase of iron oxide fume was found to be approximately 30 per cent in both passage through the waste heat boiler and the 12-in. agglomerator.

In both laboratory and field studies it has been observed that a high-temperature drop occurs between the inlet and outlet. Gas temperature decreases on the order of 40 per cent. It is believed that the turbulent flow at the boundary layer film inside the agglomerator considerably increases the transfer of heat to the ambient air.

After completing determination of gas flow characteristics on three geometrically similar rotary screw agglomerators, the agglomerating, collecting, and heat transfer characteristics of a 6-in. diameter unit was investigated in the laboratory. Heat transfer properties were measured at 1000°F and 700°F inlet temperatures and inlet gas velocities of 3000 to 5000 fpm. Gas temperature drops from 1000°F to 700°F or from 700°F to 500°F in going from the inlet to the outlet of the screw, a distance of about 4 ft. In addition to these studies with tangential gas inlet and outlet, studies are also being conducted at present with axial inlet and outlet, to determine the effects of the axial location.

Over-all coefficient of heat transfer for the uninsulated screw casing ranged from 2 to 3½ times greater than values reported in the literature, and also those calculated from theory, for gas to air cooling tubes. When a water spray was introduced on the outside of the casing, heat transfer increased to above twice the gas to air values. The large increase in heat transfer in the rotary screw is probably due to the turbulent spiralling flow causing a reduction in boundary layer film thickness. In effect, the rotary screw agglomerator is a self-cleaning heat exchanger with a potential heat transfer more than twice that of equivalent tubular type exchangers.

REFERENCES

1. "Handbook on Aerosols," Supt. Doc., U. S. Gov't. Printing Office, Washington, D. C., Chapters 4 and 5, 1950.
2. W. Cawood and R. Whytlaw-Gray, The Influence of Pressure on the Coagulation of Ferric Oxide Smokes, Trans. Faraday Soc., p. 1059, Gurney and Jackson, London, 1936.
3. L. Silverman, W. D. Small, I. L. Beauchamp, and C. E. Billings, Open Hearth Stack Gas Cleaning Studies, Semi-Annual Report (SA-2) for May 1, 1954 to October 31, 1954, Harvard University, 1955.
4. E. C. Hickey, M. Wharton-Ali, L. Silverman, and C. E. Billings, Open Hearth Stack Gas Cleaning Studies, Semi-Annual Report (SA-6) for May 1, 1956 to October 31, 1956, Harvard University, 1957.
5. R. L. Saxton and W. E. Ranz, Thermal Force on an Aerosol Particle in Temperature Gradient, Technical Report Number 6, SO-1007, Engineering Experiment Station, University of Illinois, 1951.

PROGRESS REPORT ON FILTRATION OF A FRESHLY GENERATED NaK FUME

Edward Kristal, Richard Dennis, and Leslie Silverman
Harvard School of Public Health

1 INTRODUCTION

The Harvard University Air Cleaning Laboratory was requested to evaluate the performance of various commercial filters with a mixed sodium-potassium (NaK) oxide aerosol. The desired operating characteristics, as specified originally, were as follows:

1. The filter should be noncombustible.
2. The space requirements for the cleaning system should approximate those of standard Absolute type (AEC) filters, that is, a 24-in. square filter handles 500 and 1000 cfm for 6 and 12 in. of filter depth, respectively. Additional depth is available for prefiltering if required.
3. The total fume holding capacity for a 1000-cfm filter should be approximately $\frac{1}{2}$ lb (3500 grains) without excessive pressure loss across the filter. This is equivalent to 3.5 grains/cu ft of filtering capacity.
4. The pressure loss across the filtration device at rated gas flow should be as low as possible although resistances as high as 15 in. water are permissible.
5. The filter should be at least 90 per cent efficient by weight.
6. Filter units should be corrosion resistant during the period of expected service, i.e., until maximum holding capacity is reached ($\frac{1}{2}$ lb).

It was proposed, originally, that Absolute type filters be investigated in view of their high efficiency for submicron material. Furthermore, tentative building design and space allocation for gas cleaning equipment made dry filtration a desirable, and economic, choice, although it was recognized that other devices, i.e., a Venturi scrubber or low voltage electrostatic precipitator, might produce satisfactory cleaning.

The following report presents results of tests conducted in this laboratory with several types of dry filtration equipment on commercially available and experimental filters. Aerosol generation apparatus, analytical procedures, and test duct systems are described briefly.

For any one filter design the efficiency, pressure loss, and fume holding capacity are indicated with respect to air flow rate. The feasibility of employing any one of the dry filters evaluated in the laboratory is based upon the original design criteria, i.e., efficiency, holding capacity, pressure loss, and resistance to corrosion and combustion.

2 TEST PROCEDURES

2.1 Test Apparatus

Preliminary tests to evaluate analytical methods were conducted with 500 cfm cellulose-asbestos AEC type filters mounted in a special 24-in. square ductwork system. Rapid plugging of these filters with a pure sodium oxide fume, produced by burning metallic sodium, indicated that they were unsuitable for this application. A filter fire which occurred during this test series indicated that combustion hazards should be reduced by scaling down test apparatus.

The final test system, Fig. 1, consisted of two, 8-in. square ducts made up in 4-ft sections with provision to mount test filters between them. A high speed centrifugal exhaustor of 50-cfm capacity with 10 in. water pressure loss across the filter was connected to the test duct.

The inlet to the test system consisted of a 2-in. diameter, 5-in. length of pipe connected to a 3-in. diameter, 8-in. length of pipe which in turn was attached to the 8-in. square duct. A Stairmand disc in the 3-in. diameter pipe provided high velocity mixing of the metal fume and air. Further mixing was obtained in the 8-in. square duct with the use of an additional Stairmand plate. An air flow calibration vs entry loss to the smaller pipe provided the necessary flow metering. Pressure taps were located immediately before and after the filter to measure resistance.

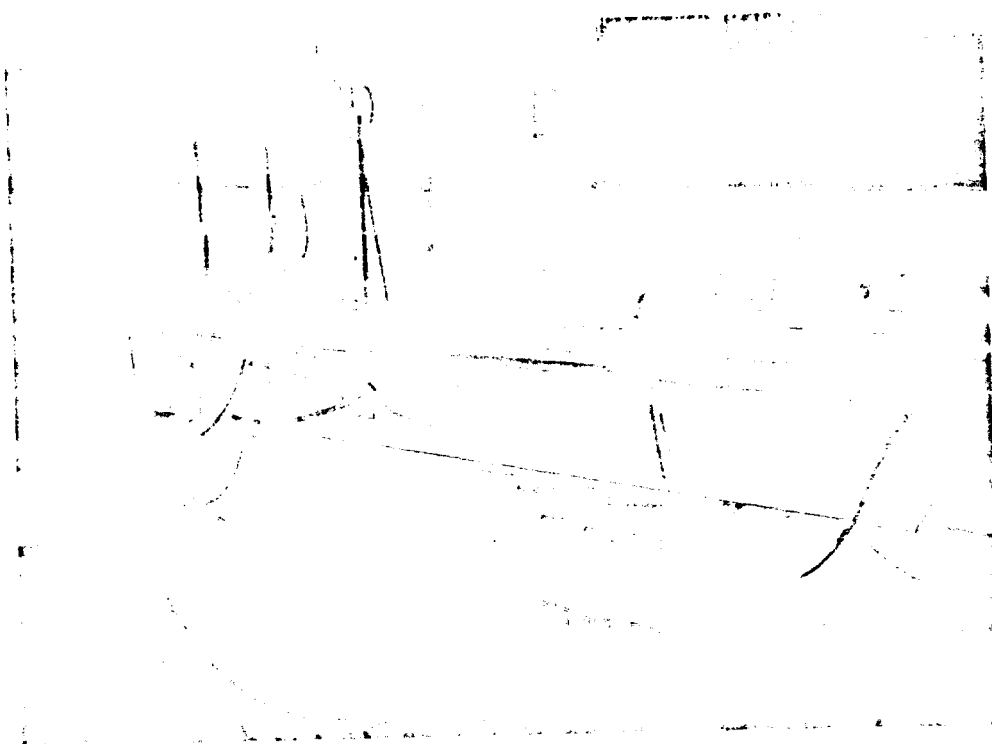


Fig. 1—Filter test assembly.

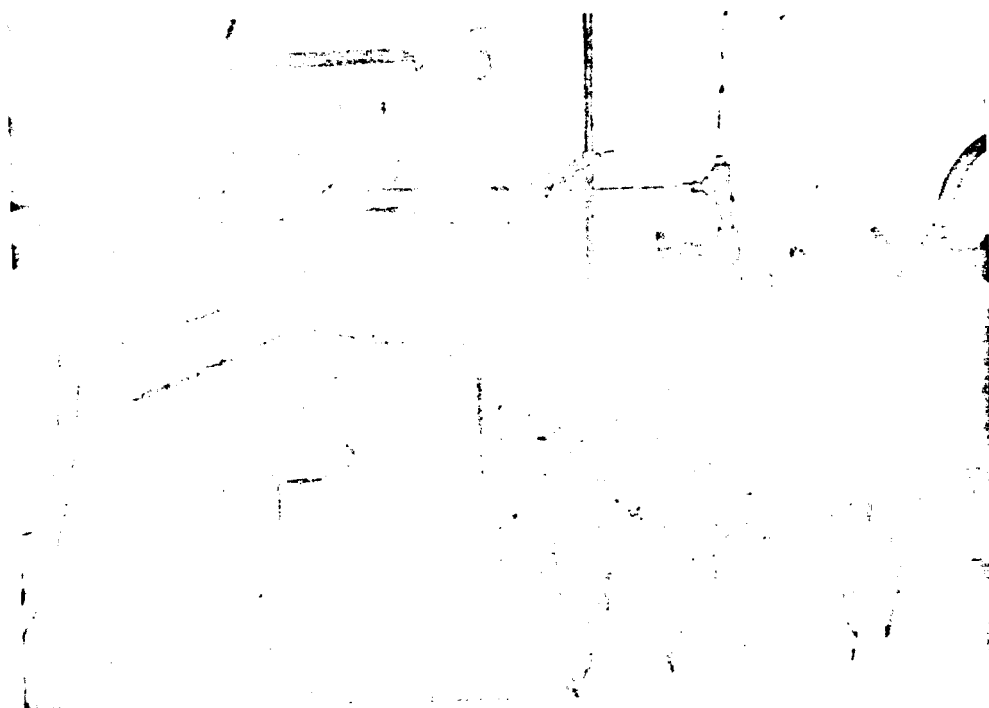


Fig. 2—Generation equipment for NaK aerosol.

2.2 Fume Generation Equipment

A mixed sodium and potassium oxide fume was generated, Fig. 2, by burning the liquid metal at the tip of a $\frac{1}{4}$ -in. diameter brass feed tube placed near the inlet to the test filter system. A continuous and very slow flow of liquid metal was ejected from the metal reservoir by application of pressure from a nitrogen cylinder. Inlet fume concentrations within the test gas stream ranged from 0.2 to 2.0 grains/1000 cu ft of air. Loadings as high as 10 grains/1000 cu ft could be generated continuously. Loadings estimated at 50 grains/1000 cu ft were obtainable for brief periods.

2.3 Sampling and Analytical Methods

Aerosol samples upstream and downstream of the test filter were collected with HA Millipore filter papers which were located in holders placed in and facing the gas stream.

After sampling, Millipore filters were washed individually several times with water that had been distilled and demineralized. The washings were made up to known volumes and subsequently analyzed for sodium content with a Beckman Flame Spectrophotometer. The spectrophotometer permitted very rapid determination of sodium for concentrations as low as 0.1 mg/liter of solution. The intense sodium background in the sample made it difficult to determine the amount of potassium present by this technique.

Metal fume concentrations approaching commercial pleated filters and the total quantity of fume deposited on them were determined by continuous aerosol sampling. However, when test filter media could be removed and washed in a leaching tank, the total filter loading was determined directly by analyzing an aliquot of the washings.

The final composition of the reaction product collected on the filter is probably a mixture of sodium and potassium hydroxides plus an undetermined amount of water. Because of this factor, air concentrations (grains/1000 cu ft) and filter holding capacities (pounds) are expressed in terms of metallic sodium.

The liquid metal used to generate the fume contained 56 per cent sodium and 44 per cent potassium. Assuming complete conversion to hydroxides following oxidation there would be 3 g of mixed hydroxides for every gram of sodium.

Based on a criteria of $\frac{1}{2}$ lb of mixed hydroxides for a 24- by 24- by 12-in. filter, the equivalent loading for a 50-cfm test filter should be about 3 g of metallic sodium.

3 TEST RESULTS

3.1 Absolute Filters

Fume Holding Capacity vs Pressure Loss. Initial tests were conducted with 50 cfm capacity, all glass, 8- by 8- by $5\frac{7}{8}$ -in. filters. Collection efficiency of these filters decreased from an original value of 99.9 per cent to approximately 99.5 per cent after intermittent exposures to fume loadings over a period of several days.

By continuously loading a clean filter with 0.4 to 0.6 g of sodium, the pressure loss was increased from 0.8 to 5 in. water. A conservative linear extrapolation of these data indicates that 3 g of sodium would raise the pressure loss to approximately 30 in. water. Since pressure loss is a function of filter loading raised to some power greater than one, actual pressure losses would probably exceed this value. Upon standing approximately four days following loading, the pressure loss returned to its initial value. The filter was loaded again and upon further standing was found to return to approximately its initial pressure loss although as much as 1.2 g of sodium were deposited on it. This phenomenon was attributed to the deliquescent properties of the fume which, through hydroxide formation, cause chemical destruction of the glass fiber. Since the filtration system must be able to handle a liquid metal spill in a short time, the reduction of pressure loss upon standing is of limited practical use.

Additional tests were conducted with a cellulose-asbestos filter. Loading-pressure loss characteristics were essentially the same as those for all-glass filters but initial collection efficiency was slightly lower (99.4 per cent).

Agglomeration Studies. The possibility that natural agglomeration mechanisms might be enhanced by increasing fume retention time within a ventilation system was investigated in the laboratory. Two 55-gal drums, with baffles, placed between the fume generator and the test filter increased fume holding time from 2.6 to 9.6 sec. No improvements were noted in filtration characteristics, based upon tests on a Cambridge Absolute filter.

3.2 High Efficiency Roughing Filter

The Cambridge Aerosolve 95 filter was rated at 50 cfm with a clean pressure loss of 0.32 to 0.38 in. water and an average discoloration efficiency of 90 to 95 per cent against atmospheric dust. The clean pressure loss was found to be 0.36 in. water at rated flow. Initial weight collection efficiency was 55 per cent for the NaK fume which was far below minimum collection requirements. When the pressure loss increased to 4 in. water, corresponding to a filter loading of 0.4 g of sodium, the efficiency of the Aerosolve 95 increased to 94 per cent.

The Cambridge Aerosolve 85 filter was less than 10 per cent efficient which precluded its practical application for NaK removal.

3.3 Combination High Efficiency Roughing and Absolute Filter

An attempt to increase the fume retention of a filtration system while maintaining high efficiency was made by placing an Aerosolve 95 filter upstream of the Absolute filter. The prefilter was intended to prevent the rapid plugging of the Absolute filter. The initial resistance of the combination was 2 in. water. After loading the system with 0.6 g of sodium, the pressure loss rose to 6.7 in. water. Extrapolation indicated that a loss in excess of 30 in. water would result with fume retention of 3 g of sodium.

The failure of this system to provide high fume holding capacity at moderate resistance is attributed to the small (relative to the Absolute filter) filtration area of the prefilter. This resulted in rapid plugging of the prefilter despite its initial low efficiency. Since the commercial filters tested did not meet design criteria, several experimental filters were fabricated and tested in the laboratory.

3.4 Slag Wool Filter

Basic slag wool appeared to offer some advantages as a dry filter media because of its low cost, fire-resistant properties, and availability in small fiber sizes, 4 μ . Slag wool filters were prepared by (1) slurring the bulk medium in a washing tank with compressed air agitation to disperse fibers and remove shot and (2) by subsequent dewatering and drying of the cleaned slurry to form the filter bed.

Table 1—PRESSURE LOSS, FUME RETAINED, AND COLLECTION EFFICIENCY OF SLAG WOOL FILTERS (4 μ FIBER DIAMETER)

Packing density, lb/ft ³	Filter weight, lb	Filter depth, in.	Pressure loss		Fume retained as Na, g	Collection efficiency, %
			Initial, in. water	Final, in. water		
11.4	0.141	0.52	2.1	11.9	0.0964	84.6
11.0	0.137	0.53	1.4	10.6	0.0793	71.8
6.6	0.245	1.57	7.7	±29	0.44	97.8
6.2	0.229	1.57	6.9	9.9	0.23	95.3

Table 1 gives pressure loss, fume retention, and collection efficiency for the slag wool filters tested. Examination of the filter bed showed that most of the fume had caked on the upstream surface which caused high resistance and reduced fume holding capacity. The efficiency of these filters at the higher packing densities was satisfactory but eventual reaction between the alkali and fiber would destroy the medium.

3.5 Curled Glass Fiber Filter

The performance of filter beds composed of 30 μ curled glass fibers are tabulated in Table 2. The initial efficiency of the densest filter tested (packing density of 6.4 lb/cu ft) was only 68.1 per cent. The holding capacity which extrapolated to 3 g of sodium for an approximate pressure drop of 30 in. water was also well below cleaning requirements. Alkali-glass reaction would be similar to the slag wool.

Table 2—PRESSURE LOSS, FUME RETAINED, AND COLLECTION EFFICIENCY OF GLASS FIBER FILTERS (30 μ FIBER DIAMETER)

Packing density, lb/ft ³	Filter depth, in.	Pressure loss		Fume retained as Na, g	Collection efficiency, %
		Initial, in. water	Final, in. water		
1.5	2.5	0.24	0.33	0.093	17.6
3.3	2.5	0.94	4.72	0.578	46.5
6.4	2.5	0.98	2.03	0.322	68.1
6.4 one	2.5		4.07	0.565	84.1
6.4 filter	2.5		5.46	0.688	91.4
6.4 used	2.5		7.96	0.830	95.1

3.6 Curled Saran Fiber Filter

Another filter tested was a 30 denier curled saran fiber bed, Table 3. The initial efficiency was lower than desired and the extrapolated pressure loss, for 3 g of sodium retained, was considerably in excess of 30 in. water.

Table 3—PRESSURE LOSS, FUME RETAINED, AND COLLECTION EFFICIENCY OF CURLED SARAN FIBER FILTERS (30 μ FIBER DIAMETER)

Packing density, lb/ft ³	Filter depth, in.	Pressure loss		Cumulative fume retained as Na, g	Collection efficiency, %
		Initial, in. water	Final, in. water		
7.0	5	2.13	2.72	0.097	75.0
7.0	5	2.72	3.93	0.212	81.2
7.0	5	3.93	7.07	0.444	93.3

3.7 Bulk Dynel Fiber Filter

Several tests were made with beds composed of bulk, 3 denier, Dynel fibers which has a mean diameter of 29.5 μ according to microscopic size measurements. The spread in data, Table 4, was attributed to the difficulty of hand-packing uniformly a loose fiber of variable bulk density.

This fiber appeared to approach the desired filtration criteria except for the difficulty of reproducibility in packing. To minimize the packing problem it was decided to obtain a more uniform nonwoven, bonded, Dynel fabric, cut into pads.

3.8 Nonwoven Bonded Dynel Fiber Filter

Efficiency and Loading Study. A nonwoven Dynel medium* consisted of loosely felted fibers bonded by spraying with various adhesives to form a $\frac{3}{8}$ -in. thick pad. The adhesive may

*Fabricated by J. P. Stevens Co., New York, N. Y.

Table 4—PRESSURE LOSS, FUME RETAINED, AND COLLECTION
EFFICIENCY OF BULK DYNEL FIBER FILTERS (29.5 μ FIBER DIAMETER)

Packing density, lb/ft ³	Filter depth, in.	Pressure loss		Fume retained as Na, g	Collection efficiency, %
		Initial, in. water	Final, in. water		
4.0	4	4.6	7.86	3.6	69.2
4.0	4	4.4			75.2
4.8	4	8.6	9.2		74.4
4.8	4	7.4	12.8	2.5	88.1
4.8	4	10.9	12.2	2.6	88.8

be applied throughout its depth or to one or both surfaces. Preliminary studies with a coarse, 45 μ average diameter, nonwoven Dynel filter bed indicated very low efficiencies.

Final tests, Table 5, were conducted with units composed of mixed 3 and 6 denier fibers (average diameter by microscopic examination 29.5 μ) which were surface-sprayed on both sides. The weight of the fabric was given as 8.0 oz/sq ft by the manufacturer.

Table 5—INITIAL PRESSURE LOSS AND COLLECTION EFFICIENCY VS NUMBER OF
LAYERS OF NONWOVEN, BONDED, DYNEL FIBER FILTERS (AVERAGE
DIAMETER 29.5 μ , WEIGHT PER LAYER 0.0202 LB)

Packing density, lb/ft ³	Filter depth, in.	Pressure loss initial, in. water	Number of layers	Collection efficiency, %
2.79	4 $\frac{5}{8}$	2.75	15	36.1
3.72	5 $\frac{5}{8}$	4.18	20	48.5
6.51	4 $\frac{5}{8}$	8.35	35	69.5
6.45	6	10.90	45	81.4

Table 6—COMPARISON OF CALCULATED AND EXPERIMENTAL COLLECTION VS NUMBER
OF LAYERS OF A NONWOVEN, BONDED, DYNEL FIBER (AVERAGE DIAMETER 29.5 μ)

Packing density, lb/ft ³	Filter depth, in.	Pressure loss initial, in. water	Number of layers	Experimental collection efficiency, %	Calculated* collection, %
			5		15.0
2.79	4 $\frac{5}{8}$	2.75	15	36.1	39.6
3.72	4 $\frac{5}{8}$	4.18	20	48.5	47.8
6.51	4 $\frac{5}{8}$	8.35	35	69.5	68.0
6.45	6	10.90	45	81.4	76.9

*Calculations based on the assumption that 5 layers of the bonded fiber will remove 15% of the fume, and that the log penetrations law is applicable.

Tests with a filter composed of 45 layers of bonded Dynel fiber indicated a fume retention of 7.5 g of sodium accompanied by a 6-in. rise in pressure loss (10.9 to 16.8 in. water). Final pressure loss for a 3-g holding was calculated to be 14 in. water.

The relationship between collection efficiency and number of pads or layers was closely approximated by the log penetration law as shown in Table 6. It is estimated that 70 layers of 29.5 μ fibers will be required to obtain a collection efficiency of 90 per cent.

No significant change in collection efficiency was observed over the face velocity range of 90 to 200 fpm.

Resistance Study. There are two direct methods to reduce the pressure loss of the 45 layer filter discussed in the preceding section; reduce the packing density by increasing the depth of bed or decrease the filter face velocity. It was necessary to determine the effect of these variables on pressure loss. Experimental data indicated that pressure loss could be expressed by the following relationship:

$$\frac{\Delta p}{L} = K (\rho')^{1.3} V^{1.25} \quad (1)$$

where: Δp refers to pressure loss, ρ' to packing density, V to face velocity, and L to bed depth (consistent units).

By means of the relations indicated in Eq. 1, it was estimated that a filter bed composed of 70 layers of bonded Dynel, packed to a 24-in. depth,† would be 90 per cent efficient in the collection of freshly generated NaK fume. The initial (clean) and final pressure loss for the bed should be 12.7 and 15 in. water, respectively, at a face velocity of 180 fpm. This is equivalent to an air flow of 700 cfm through a filter face area of 4 sq ft.

Procedure for Reclaiming Filters. When it is desired to clean the filter, the following procedure has been found satisfactory:

1. Gently submerge the filter in the horizontal position in water.
2. Slowly remove the filter and allow it to drain and dry.
3. If immediate use is necessary, replace the filters in air cleaning system and maintain a reduced air flow through them so that the pressure across the filter does not exceed 8 in. water until dry.

4 CONCLUSIONS

Commercial and experimental filters were tested for the filtration of a mixed sodium and potassium oxide fume. One experimental model approached the requirements of efficiency, fume retention, maximum pressure loss, corrosion, and fire resistance. This filter was composed of a nonwoven Dynel fabric having an average fiber diameter of 29.5 μ . Performance characteristics for a 24- by 24- by 24-in. filter, based upon extrapolation of test data are as follows:

1. Air flow, 700 cfm (180 fpm)
2. Initial resistance, 13.0 in. water
3. Final resistance, 15 in. water
4. Efficiency, 90 per cent
5. Fume holding capacity, 0.5 lb mixed sodium and potassium hydroxides

Improved performance can be anticipated if finer fibers are incorporated into nonwoven media for fabrication of filter units. A graded density filter should give optimum results.

The estimated cost of this reusable medium for this filter is \$25. With proper washing techniques, the plugged medium can be restored.

†This depth does not interfere with previous construction since space was provided for prefilters.

DEVELOPMENT OF A "TRIBOELECTRIFIED" FLUIDIZED BED FOR AEROSOL FILTRATION

David M. Anderson and Leslie Silverman
Harvard School of Public Health

1 INTRODUCTION

Electrostatic effects in aerosol filtration have been known to exist for some time. It has only been recently, however, that any fundamental research has been undertaken to delineate the magnitude of the electrostatic forces.¹⁻³ The use of mechanically induced electrostatic charges on fibrous media and on fabrics has been investigated.^{2,3} It has been shown that the filtering efficiency of such media, due to interception, inertial impaction, gravity, and diffusion, can be increased significantly, in some cases more than doubled because of the added electrostatic forces.

The most vexing problem encountered in the use of fibrous and fabric media has been the difficulty of continually replacing the charge which is constantly "leaking" off the surfaces of the fibers to ground. Some success has been found in continually charging the surface of fabric media but the studies have shown³ that for optimum utilization of electrostatic forces a longer path of aerosol travel is necessary than can be attained with fabrics. It is also important that the surface charge producing the electrostatic forces be distributed uniformly throughout the media and not merely on the surface layers. Several methods have been considered for continually charging a deep fibrous bed but the necessity for obtaining intimate contact between the fiber surfaces and the charging surfaces created problems which were not readily solved.

"Triboelectrification" requires an intimate contact between two dissimilar materials.⁴ Such an intimate contact is much easier to obtain with spheres than with cylinders because of their geometries. This concept involves using a packed bed of spheres of a chargeable material continually charged by some means. Since beds of spherical materials are easily fluidized they provide the contact necessary for triboelectrification, i.e., the random motion and "turnover" of the fluidized spheres. The dissimilar charging material can be the walls of the container, provided enough mixing of the bed is attained. If such is not the case then the charging material itself can be fluidized in a mixed bed.

Thus, it appears that a study of the electrostatic properties of fluidized beds as they effect aerosol filtration may be fruitful in the eventual development of a practical, high efficiency, continually charged electrostatic filter.

2 THEORY

2.1 Triboelectrification

An extensive search of the literature on this subject has been made, the results of which are reported elsewhere.³ In summary it can be stated that the several theories explaining the "contact" charging mechanisms are not consistent and that a complete and rigorous theory awaits further developments in the field of solid state physics. Most investigators have shown, however, that the charge generated on two dissimilar materials is independent of the relative motion, contact time, and pressure between the two and depends only on the intimate contact and subsequent separation of the two.

The most important property of a material, next to its inherent "chargeability," is its ability to "hold" a charge. This is related to its surface resistivity when dry and its water adsorption characteristics. In general, plastics possess high surface resistivities and low moisture adsorption properties and therefore "hold" a charge for considerable periods of time. Whether plastics in general possess any special intrinsic property which permits them to acquire high charges (in preference to nonplastic materials) is not known but experiments show that high surface charge densities are acquired and can be maintained provided the humidity is not too high.²

2.2 Fluidization

The term "fluidization" is used to designate the gas-solid contacting process in which a bed of finely divided solid particles is lifted and agitated by a rising stream of process gas. At the lower end of the velocity range, the amount of lifting is slight, the bed behaving like a boiling liquid, hence the term "boiling bed."

As the velocity is increased, a point is reached where the pressure drop becomes equal to the sum of the weight of the bed per unit cross-sectional area plus the friction of the bed against the walls. At this point, for free-flowing materials, the bed expands and assumes a more open arrangement so that the gas can flow without the pressure drop exceeding the unit bed weight. Another increment of velocity results in over-all circulation of the bed, often with transient upward-flowing gas streams in channels that contain relatively few particles, and downflow of clumps of particles. This is called "aggregative" fluidization. It is this aggregative vibration and circulation which it is hoped will produce the necessary triboelectrification of the bed.

2.3 Electrostatics and Electrostatic Attraction

Charge measurement. The basic principle of static charge measurement makes use of the "Faraday cage" and is based upon a fundamental theorem of electrostatics which states that "the space completely enclosed within the outer bounding surface of a conductor, or within any surface, every point of which lies in conducting material, contains a zero total net electric charge."⁵ If a net free charge $+q$ be located within a closed cavity of a conductor, a charge totaling exactly $-q$ must appear as surface charge on that part of the conductor boundary which forms the cavity, i.e., the inner surface of the cavity. Such surface charge is said to be "induced" by the presence of the free charge $+q$. This charge $-q$ distributes itself over the cavity boundary such that the surface becomes equipotential; this is a function of the surface geometry or capacitance, C , defined as Q/V which has the units of length (in the unrationalized cgs electrostatic system, C has the units cm or statfarads). Thus by measuring V and C the enclosed charge $+q$ is determined.

Electrostatic collection forces. The data obtained to date do not justify extensive theoretical treatment. The basic electrostatic collection forces, however, have been delineated previously.¹⁻³ Basically we shall consider three forces: coulombic attraction, image attraction, and "dielectrophoresis." The latter two are often called "inductive" forces.

3 MACROSCOPIC CHARGING TESTS

3.1 Manual Tests

Of primary importance in this study is the ability of the bed particles to acquire and hold a charge. Synthetic plastic materials have shown the best possibilities and preliminary measurements were made with them. Materials available in spheres in the fluidization size range were: (1) Dylene Polystyrene unlubricated beads (Koppers Company, Pittsburgh, Pa.), (2) Styrene-Divinylbenzene microspheres (Dow Chemical Company, Midland, Mich.), and (3) Urea-formaldehyde "Micro-balloons" (Colton Chemical Company, Cleveland, Ohio).

The apparatus for measuring the surface charge on the experimental spheres (Fig. 1) has been developed by Rossano² and is based on the "Faraday ice pail" principle. A charged object when placed in the cage will induce a charge of equal sign and magnitude on the metal sleeve surrounding the Lucite tube (11 in. long, $5\frac{1}{4}$ in. diameter) and on the metal wires and plates of the leads, capacitor, and voltmeter. Provided the material is placed within the central portion of the cage (central 1 in. long) most of the field lines from the charged object will terminate on this brass sleeve. The electrostatic problem involved has been solved by Masters.⁶

The easiest and most efficient method for obtaining a static charge on spheres by the contact mechanism is by shaking small amounts of material in containers of large contacting surface. The preliminary charges determined below were obtained in this manner although in a fluidized bed the contacting efficiency will not be as high. The material was shaken with a rotary action for one minute and then carefully poured into a glass beaker housed in the Faraday cage and the induced voltage measured.

In Table 1 the results of this limited evaluation are shown. Tests were made at a temperature and humidity below the limit for which charge leakage from surfaces of high resistivity becomes important.³

From the quantitative data and qualitative observations of Table 1, several observations can be made. Using the same particulate material (Dylene-Polystyrene) and varying the container in which contact charging occurs (tests 2 and 3) the conducting material (steel) produces an effective net charge of several orders of magnitude greater than the dielectric (glass) for the same weight of material. The term effective combines the charge produced and the force necessary for separation of charge. It is this energy for separation which results in the net charge left on each surface. Presumably the greater the force necessary for separating a particle from the wall, the greater the charge apparent on separation although this effect may be somewhat obscured by Van der Waal's forces. The ideal material for contacting is that which will readily give up a particle and retain an appreciable charge. In these experiments the force for dislodging the particles was attained by rapping the side of the container vigorously with a wooden stick and was measured only qualitatively.

On the basis of the observed facts that only the portion at or near the walls has significant charge (tests 1, 2, 3) and that smaller increments of the same material show a higher average charge per particle (tests 3 and 4) it is obvious that a large ratio of charging to charged area is necessary. These observations agree with those of Rossano.² A comparison of tests 4 and 5 show that Dylene Polystyrene appears better for contact charging than Styrene-Divinylbenzene. Both of these materials are essentially polystyrene with the latter having an 8 per cent divinylbenzene molecular cross linkage. This change in molecular structure is apparently sufficient to change the surface work function from above that of steel to below that of steel.⁷ The latter material may charge as highly as the former but the surface forces holding these particles are greater so that the effective charge per unit mass is less for the same weight of material.

The final material tested, urea-formaldehyde, shows no net charge developed since the surface forces in this case are so great none of it can be dislodged from the walls, even with violent agitation. The first two materials have about the same size and density and are directly comparable. This material exists as fine hollow spheres ($16\ \mu$, mean diameter vs $200\ \mu$ mean diameter) and has an effective specific gravity of 0.3 vs 1.05 for the other two materials. Thus the mass per particle is very much smaller and the image forces (from initial contact-separation) evidently cause "welding."

The maximum charge density magnitude developed (test 4) is very encouraging and shows that, although crude, the contact-charging method used is very efficient. Rossano² using Saran fibers and taking great care to charge in small increments using steel teeth drawn through a fibrous bundle was able to develop a maximum surface charge density of $0.72\ \text{statcoulombs/cm}^2$ or about 9 per cent of the theoretical limit before gaseous discharge.⁸ Test 4 shows a maximum charge of $2.36\ \text{statcoulombs/cm}^2$ or nearly 30 per cent of maximum. Considering that in very efficient static generators, e.g., Van der Graaf machines, the highest charge developed is only 25 per cent of theoretical maximum, these results are indeed encouraging.



Fig. 1—Apparatus for measuring surface charge.

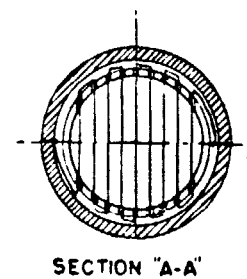
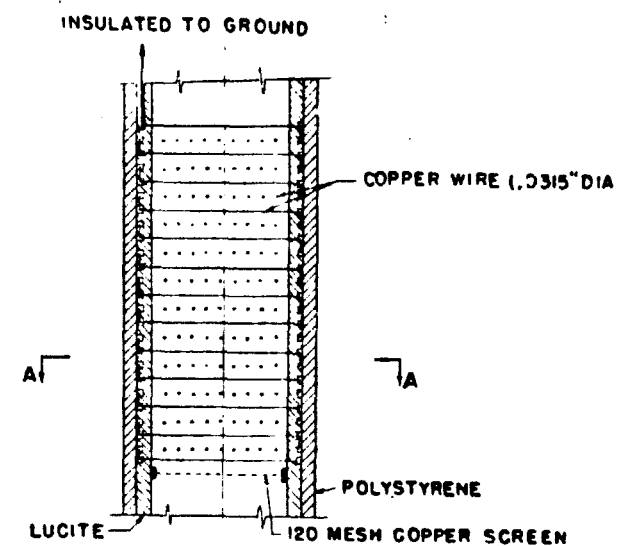


Fig. 2—Wire matrix system for "in-situ" bed charging.

Table 1—MECHANICALLY PRODUCED STATIC CHARGE ON VARIOUS FLUIDIZED BED MEDIA*

Test No.	Material	Container	Sample weight, g	Q/M, statcoul/g	Q/part. statcoul	Average surface charge density, statcoul/cm ²	Percent of theoretical maximum, %	Remarks
1	Dylene-Polystyrene	Polyethylene bottle	30	-0.73	-0.33×10^{-5}	0.0026	0.03	Most charge appears from fraction of particles which will dislodge from wall—some remains.
2	Dylene-Polystyrene	Pyrex glass flask	10	-6.05	-2.72×10^{-5}	0.022	0.34	All charge from wall—bound particles, most of which will not dislodge.
3	Dylene-Polystyrene	Steel can†	10	-130.0	-59.0×10^{-5}	0.47	5.80	Most charge from wall—bound particles, most of which dislodges.
4	Dylene-Polystyrene	Steel can†	1.0	-656.0	-295.0×10^{-5}	2.36	29.5	All particles adhere to wall and may be dislodged completely.
5	Styrene-Divinylbenzene	Steel can‡	1.0	+379.0	$+170.0 \times 10^{-5}$	1.36	17.0	All particles adhere to wall but fair percentage will not dislodge.
6	Urea-Formaldehyde	Steel can‡	1.0	0	0	0	0	No charge observed except on wall-bound particles which will not dislodge at all.

*t = 78.5°F, w = 75 grains water per pound of dry air.

†Particles possess such a high charge that on removal of beaker from Faraday cage the electrostatic repulsive force (due to like-charged particles) causes them to jump right out of beaker, a distance of 6 in. to 8 in. vertically. While in cage the particle fields are compelled to terminate on the metal.

‡Same as above but particles do not jump as high.

3.2 Fluidized Bed Tests

The beds tested were housed in a polystyrene tube, 1 ft by $1\frac{3}{4}$ -in. O. D. by $1\frac{1}{2}$ -in. I. D., and supported on 120 mesh copper screen (polystyrene having the highest surface resistivity of available transparent plastics—necessary for bed observation).

For initial tests heterogeneous charging was accomplished by the introduction of 14 by 18 mesh copper flyscreen (wire diam., 0.011 in.) circles at various points within the fluidized media. These screens could be grounded by an insulated wire running out the top of the test section. The plane of these screens was perpendicular to air flow. In later tests these screens were replaced by a copper wire grid arrangement as shown in Fig. 2. Copper wire (0.0315-in. diam.) was threaded through opposite holes $\frac{1}{8}$ in. apart in alternately perpendicular layers $\frac{1}{8}$ in. apart in the central 3-in. length of a 1 ft by 1.50-in. O. D. by 1.24-in. I. D. lucite tube. The mesh was thus composed of a single strand of wire in the form of 25 layers of 9 parallel wires each ($\frac{1}{8}$ in. apart), the wire direction in each succeeding layer perpendicular to the preceding one. (For a section of one layer see Fig. 2.) The total length of wire in each layer was 9.44 in. for a total wire length of 19.7 ft. The volume occupied by the wire was such as to make the 3-in. central tube of the lucite cylinder have a porosity of 0.952. The entire lucite tube assembly fitted neatly into the polystyrene tube of previous tests. The mesh system could be grounded by an insulated wire running between the two tubes in a notched channel. The retaining screen was a 120 mesh screen butt-fitted $\frac{1}{8}$ in. below the first wire layer.

Charge measurement was accomplished by the use of the Rawson voltmeter, air capacitors, and a Faraday cylinder arrangement in the form of 5 in. or 10 in. lengths of aluminum foil or aluminum-coated Mylar film wrapped around the outside of the polystyrene tube. A copper wire surrounded this cylinder and provided access to the voltmeter system. The outside Faraday cylinders were between 98 and 99.5 per cent efficient for measuring charge enclosed within their central 2 in. lengths, the maximum bed expansion.⁶

When it was found that ambient air possessed high charges at certain times (due to charged atmospheric dust and ions) a prefilter was added upstream of the test section. This consisted of a 6-in. diameter circle of MSA 1106B glass filter paper mounted in an appropriate cone assembly. The comparatively large cross-sectional area reduced pressure loss. This media is reported to be >99 per cent efficient on atmospheric dust⁹ over the velocity range in which it was used. Nevertheless tests were made to determine the charge in the filtered air. These results are reported with the appropriate data.

Koppers Dylene was the first material tested since it was available in the largest quantities. A preliminary investigation showed that the 40 to 50 mesh fraction was the largest size which would flow through 14 by 18 mesh screening without clogging. This fraction was therefore used since the highest ratio of contacted to contacting areas was obtained.

Table 2 presents the results of tests using ambient unfiltered air as the fluidizing medium.

The first test shows that a comparatively low charging rate (0.025 esu/g/min) is accomplished by contacts between the wall and beads and that within 90 min an asymptotic level of charge is reached. This is due to the building up at the wall of a heavy coating of particles "bound" by image forces. In test 2, where contacts between the beads and a copper screen were added, a comparable effect (to test 1) occurred. Since the screen was not grounded the *net* charge increase must also have been due to wall contacting. In test 3, however, *non*-asymptotic *net* charging occurred under the same conditions. It was concluded that the added charge must have come from charged particles in the fluidizing air stream. Tests 4 through 9 were repeat tests with the charging screen grounded. In tests 4, 5, and 6 *non*-asymptotic charging occurred indicating possible *net* charging from the screen which is now possible, or, perhaps, added charge from the air (dust and ions). Run 4 shows a comparatively large charging rate which lasts at least 8 hr. This would be very encouraging if it were possible to attribute the charging action to the screen alone. Runs 7, 8, and 9, however, show that this is probably not the case since charging becomes asymptotic, stops, or discharging can occur, all at the same conditions as before. In tests 10 through 14 various changes in charging surfaces and conditions were made primarily in an attempt to reduce the poor quality of fluidization caused by the single copper screen. Two screens (test 10) produced even poorer conditions but

**Table 2—NET CHARGE BUILD-UP ON POLYSTYRENE BEADS BY FLUIDIZATION
WITH UNFILTERED AIR***

Run No.	Bed No.	Charging source	Fluid. vel., fpm	Fluid. qual.	Bed expans., %	Maximum generated† charge, esu/g	Time, min	Average build-up rate, esu/g min
1	1	Wall only	86	Smooth	100	-2.24	90	-0.025
2	2	1 screen‡ at 1 in., (U)	86	Poor¶	Variable	-0.60	60	-0.010
3	3	1 screen‡ at 1 in., (U)	86	Poor	Variable	None	60	-0.022
4	2	1 screen§ at 1 in., (G)	86	Poor	Variable	None	500	-0.263
5	3	1 screen§ at 1 in., (G)	86	Poor	Variable	None	60	-0.022
6	9	1 screen§ at 1 in., (G)	86	Poor	Variable	None	30	-0.094
7	1	1 screen§ at 1 in., (G)	86	Poor	Variable	-0.22	6	-0.037
8	7	1 screen§ at 1 in., (G)	86	Poor	Variable	loses chg.	120	+0.008
9	9	1 screen§ at 1 in., (G)	86	Poor	Variable	0.00	60	0.00
10	10	2 screens at 0.5 in. & 1.0 in., (G)	86	Very poor**	Variable			
11	11	18 parallel wires, .07 in. apart, 1 in., (G)	66	Smooth	100	-0.71	5	-0.147
12	12	1 screen at 1¼ in., (U)	100	Poor	Variable	None	15	-0.270
13	12	1 screen at 1¼ in., (G)	100	Poor	Variable	-1.20	10	-0.120
14	14	1 screen at 1¼ in., (U) plus tobacco smoke	115	Poor	Variable	None	10	-0.563

*40-50 mesh; Dylene 3, Koppers Co.; one-inch deep (settled) beds; 18.3 g; fluidization air at 76-83°F and 45-75 grains water per pound dry air.

†Corrected for meter leakage.

‡18 by 14 mesh copper screen, 0.011 in. diam.; U, ungrounded.

¶Segregated above screen.

§G, grounded.

**Segregated above second screen.

parallel wires (test 11) interfered very little with smooth fluidization. This is presumably due to the absence of "holdup" which is accelerated at wire-crossing points. The charging stops, however, after 5 min, indicating a coating of the wires (observable) which prevents further net charging. Increasing the fluidization velocity and, therefore, particle momentum, seems to produce less wire coating (tests 12, 13, and 14) as evidenced by higher charge build-up rates but this again is obscured by possible charge addition from the air. Tobacco smoke, for example, when introduced in run 14 produces a charge build-up rate (non-asymptotic) of a very high level. The obvious method for clarifying the possibility of aerosol capture charging was by the use of prefiltered air for fluidization.

A 6-in. diameter filter circle of MSA 1106B media was placed upstream as a prefilter. Tests were made with highly charged tobacco smoke which showed no passage of collectable charged particles.

Table 3 summarizes the important tests with prefiltered air. The charges were computed correcting for meter leakage. In tests 1 through 4 asymptotic charge levels were reached, proving conclusively that once the walls and screen become coated further charging is impossible. In test 1 it should be noted that a comparatively high asymptotic level of charge, -47.5 esu/g, is reached when compared to the tests of Table 2 where aerosol capture charging was probably minimal, i.e., tests 1, 2, 7, 8, 9, 11, 13. This is attributed to the greater bed expansion although the bed was still segregated as in Table 2. This high expansion represents more kinetic energy per particle which causes a slower rate of build-up of the wall and screen coatings. Nevertheless these coatings are still formed. It will be noted that tests 1 and 2 were

run alternately grounded and ungrounded. By this technique a clearer picture of the actual charging process is obtained. The original data show that charging due to wall contacts *stops* much before that due to the interspersed screen or in other words, direct impingement of the fluidized beads on the wires helps inhibit the charge-destroying coating process. It will also be noted that when the fluidized material is changed to nylon spheres (test 2) the sign of the charge reverses. This is due to a "surface states" phenomenon.¹⁰ This material (nylon) is of a different size range, fluidized at a low velocity (to prevent "slugging") so the data of tests 1 and 2 are not directly comparable. In test 3 the nylon spheres eventually coat the tube walls (when this is the only charging surface) and charging stops, exactly in the same way as with polystyrene.

In test 4 the bed of test 3 was allowed to discharge for 26 days in an attempt to determine the effect of screen charging alone. It was necessary to use the same bed in both tests since any change of media introduces different distributions in charge densities due to different arrangements of particles and particle surface states. In this test, charge build-up proceeded very rapidly to an asymptotic level about one-half that of test 4. Since the bed was undisturbed except for the introduction of the charging screen it is assumed that the wall coating remains intact. Therefore, this additional charging can be attributed to screen charging alone. Obviously then the screen quickly becomes coated and no increase in net charge can then occur. For this test the observed bed expansion was lower than that in test 3 (practically zero) and thus very little motion for dislodging the wire coating existed. This probably accounts for the rapid attainment of equilibrium charge.

For tests 5 and 6, Table 3, the apparatus of Fig. 2 was used. In the initial charging runs with the wire grid system the Mylar film-Faraday cylinder method employed in previous tests was used to measure the charges generated. However, the "bound" charge effect due to the matrix interference was found to obscure all but a very small percentage of the charge from the surrounding cylinder. This then suggested the use of the matrix charging system itself as the charge-measuring system. Such was the system which was employed in test 6, Table 3, and used in all succeeding tests. The shielding error of this system is 6.0 per cent (as determined by comparison of total charge measured by grid system connected to voltmeter directly and that measured by an "outside" Faraday cylinder).

In test 5, the grid system was grounded during fluidization and charge was measured by pouring the bed into a separate Faraday cage. Thus it was not possible to determine whether or not charging was asymptotic. At 75 per cent expansion the matrix contacting process generated a charge of about -340 esu on 12.2 g of 40 to 50 mesh Dylene in 15 min of operation. This was the average net charge generated on that portion of the bed easily dislodged (gravity) from the bed matrix. A mono-particle layer remained on the matrix which could only be removed by violent agitation. Table 4 shows the charge distribution on the bed "as poured" from the cylinder. Generally speaking the mixing of charged spheres seems to be fair, with the portions closest to the matrix having the highest charge per particle, as is to be expected. This indicates significant migration of charged spheres through the bed, which is very encouraging.

In test 6 the matrix was not grounded but connected directly to the electrostatic voltmeter for charge measurement. Test 6 shows a continuous charge increase in the bed of the order of 13 esu/min (corrected for leakage) during operation at about 100 per cent expansion. This rate is 3 times higher than that due to highly charged atmospheric dust (test 4, Table 2) and is indicative of the feasibility of "in bed" charging. One important consideration is the time duration for which this charging will continue. A qualitative observation is the increasing force which must be applied in rapping the bed, obviously due to the greater attracting forces which occur as the particle charge increases with continued operation.

Table 5 shows the important charge measurements for the bed of test 6. It indicates that merely from the pouring action into the bed a charge is generated which is of the order of the asymptotic values of previous tests. This charge increases at the rate of about 1.0 esu/g/min during fluidization. This is based on an entire bed average. Item 4 shows that the mono-particle layer which is the most difficult to remove possesses charges as high as 30 per cent of maximum (8 esu/cm²). These particles were removed by a high speed air jet. Their charge

Table 3—NET CHARGE BUILD-UP ON POLYSTYRENE* AND NYLON†
BEADS BY FLUIDIZATION WITH PREFILTERED AIR

Run No.	Media	Bed wt., g	Settled bed depth, in.	Charging source	Fluid vel., fpm	Fluid qual.	Bed expans., %	Maximum generated‡ charge, esu/g	Time, min	Average build-up rate, esu/g/min
1	Dylene*	13.7	0.75	1 screen§ at 1½ in. U & G	115	Poor¶	300	-47.5	100	-0.475
2	Zytel§	22.6	1.0	1 screen at 1 in. U & G	30	Poor	20	+16.2	75	+0.215
3	Zytel†	22.6	1.0	Wall only	30	Smooth	20	+11.5	30	+0.383
4	Zytel**	22.6	1.0	1 screen at 1 in., U	30	Poor	20	+5.3	6	+0.884
5	Dylene	12.2	1.0	Matrix G††	72	Smooth with rapping	75	None	15	-1.83
6	Dylene	12.2	1.0	Matrix, U	105	Smooth with rapping	110	None	10	-2.13

Note: Prefiltration with 1106B media adequate as measured by introduction of charged tobacco smoke.

*40-50 mesh Dylene 3 (Koppers Co.); fluidization air at 74-82°F.

†50-100 mesh Zytel 31 (Du Pont); 43-70 grains water per pound dry air.

‡Corrected for meter leakage.

§18 by 14 mesh copper screen, 0.011 in. diam; grounded and ungrounded intermittently.

¶Segregated above charging screen.

**Bed of test #3, after discharging for 26 days.

††Matrix system: 0.032 in. D. copper wire threaded through 1.5 in. O.D. by 1.24 in. I.D. Lucite tube, ¼ in. on centers with succeeding layers perpendicular.

Table 4—CHARGE DISTRIBUTION IN BED #5 (TABLE 3) "AS POURED"

	(1) Bed weight, %	(2) Total charge, %	Ratio (2/1)
First	24.4	8.2	0.34
Next	18.4	15.8	0.86
Next	15.7	26.0	1.65
Next	9.8	25.0	2.56
Next	31.7	25.0	0.79
	100.0	100.0	

*Does not include a particle layer not dislodged easily (approx. 30% of bed weight).

is in the order of the highest charges produced mechanically (test 4, Table 1) and indicates charging is *very* efficient provided removal of the spheres is possible. It should also be pointed out that the matrix in this test was *not* grounded so that an infinite supply of conduction electrons does not seem to be necessary.

Table 5—NET CHARGE DEVELOPED IN BED #6 (TABLE 3)

	Total, esu	Weight, g	Charge per gram, esu/g
Original charge as poured into tube	-130.0	12.2	10.7
Indicated charge increase during 10 min fluid.	-134.0	12.2	11.0
Total charge (free pouring mat.) after 30 min fluid.	-224.0	6.9	32.5
Total charge on mono-particle layer	-136.0	0.336	403.0

4 FLUIDIZATION PROCESS

4.1 Unhindered Fluidization

Of primary concern in this research program is the determination of the behavior of the fluidized bed particles during the process of fluidization. The following tests were made to observe the quality of fluidization, to determine the appropriate quantitative correlation applying to the flow mechanisms, and to determine the charge generated on the bed due to triboelectrification, using *the vessel walls alone* as the contacting medium, and the distribution of this charge through the bed due to the fluidization process.

The fluidized media tests were the Koppers Dylene-Polystyrene beads (30 to 60 mesh). The equipment used in these tests is shown schematically in Fig. 3. Air flow passed upward through a calibrated rotameter (set of 5 used—from 0.1 to 30 liters/min), through a 4 in.-straightening section composed of soda straws, through the bed section and downstream straightening extension piece, and then to the pump. The bed section was a 1.4-in. diameter by 7.4-in. long pyrex glass tube. The bed section (1 in. long) was placed in the geometric center of the tube. The bed itself was supported on 120 mesh copper screening supported between two thin lucite rings which make a butt fit against the tube wall. The condition of the bed and its expansion was observed through the glass tube. Charges due to fluidization were measured in the equipment shown in Fig. 1.

Qualitatively the bed behaved like a boiling after fluidization began with "bubbles" rising $\frac{1}{8}$ in. to $\frac{1}{2}$ in. above the surface of the majority of material. These bubbles were formed by air pockets and indicated aggregative fluidization. This phenomenon occurred only mildly at low velocities (<30 to 40 fpm), most of the material experiencing a confined oscillating motion "particulate" fluidization. At high velocities (>40 fpm) the bubbles spread throughout the entire bed and aggregative fluidization predominated. The point where actual fluidization occurred was difficult to determine, the expansion taking place very slowly over a wide velocity range. The velocity point for first fluidization was therefore determined by the intercept of the observed expansion curve. A striking fact noted was that after continued fluidization the static charge generated was sufficient to hold the bed together and expansion then took place evenly with a minimum of bubbling.

Measurements were made of bed pressure loss, bed expansion, and superficial bed velocity using a 1 in. deep (settled) bed of Koppers beads. The pressure loss curves showed an increasing ΔP after fluidization indicating some "slugging." Fluidization occurred at a pressure loss of 0.62 in. water. Theoretically it should start when the bed weight equals pressure loss (0.60 in. water). The calculated¹¹ velocity of fluidization, 13.6 fpm, also agrees well with the observed value, 11.0 fpm (provided the appropriate mean diameter is used in calculations). When the friction factor-Reynolds number correlation is made it is found that the Carman-Kozeny *fixed bed* correlation is followed from $R_e = 0.1$ to $R_e = 50$, one smooth curve covering the entire range of fixed and fluidized conditions.

Table 6 shows the charge developed on the beads due to fluidization for various times at various velocities. For all these tests the charge was found to reside almost entirely on particles at or near the vessel (glass) walls. The average charge reported was for the entire weight of bed and therefore was lower than the maximum charge per particle which occurred

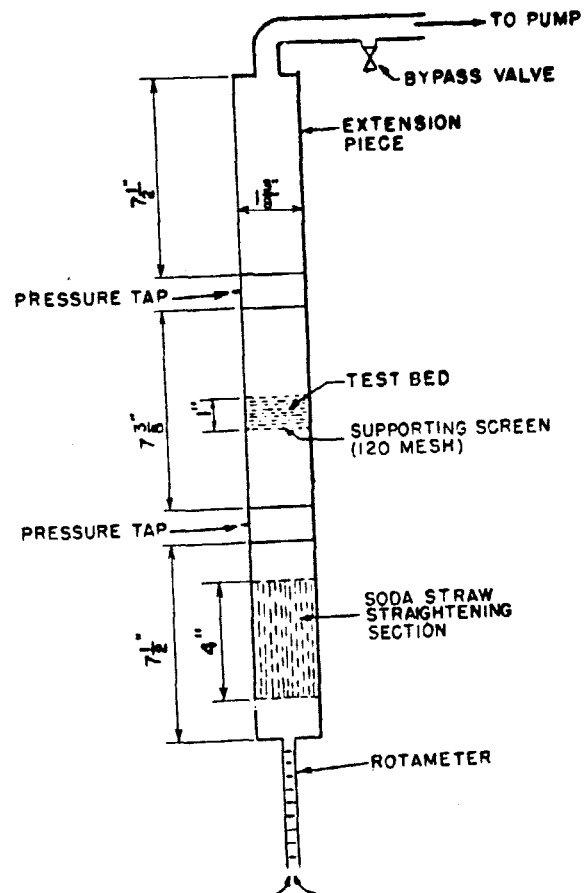


Fig. 3—Apparatus for preliminary fluidization studies.

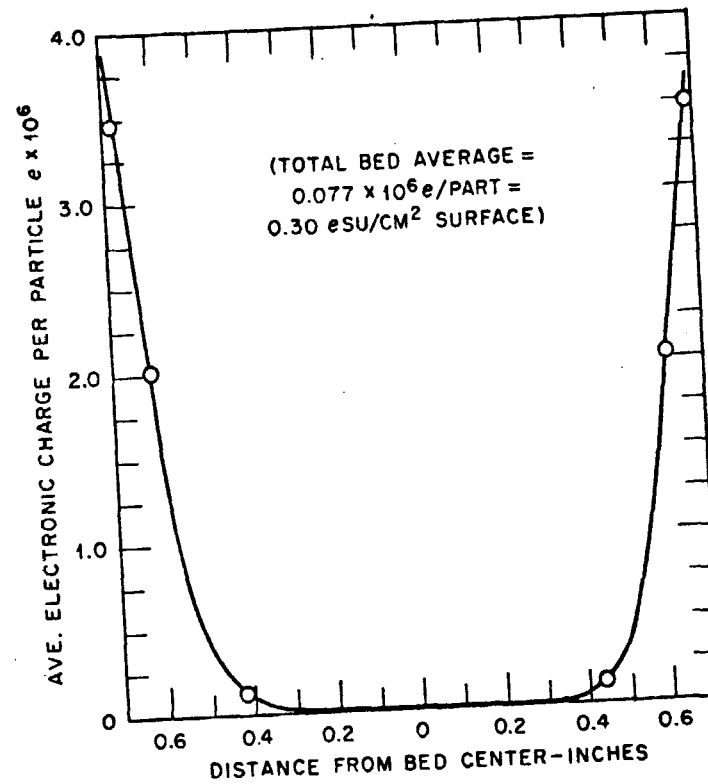


Fig. 4—Charge distribution on Koppers beads fluidized for two hours at 50 fpm.

Table 6—CHARGE DEVELOPED ON KOPPERS BEADS DURING FLUIDIZATION*

Test No.	Time of fluidization, min	Average velocity of fluidization, fpm	Bed expansion, %	Average particle surface charge density, statcoulombs/cm ²
1	5	13	0	0.021
2	15	24	12	0.054
3	25	28	16	0.049
4	120	50	40	0.298
5	Mechanical charging plus 10 min fluid.	22	10	0.086

*t = 77°F, w = 68 grains water per pound dry air.

near the walls. The results of Table 6 show a trend for increasing charge per particle by increasing the time and velocity of fluidization, or in other words, the total air kinetic energy.

Test 4 shows the average charge throughout the bed after prolonged fluidization. Figure 4 represents how this charge is actually distributed throughout the bed. As expected, the charge is very high near the walls and descends to a very low value part way into the bed so that the central area of 0.4-in. radius is effectively at zero charge. Near the walls the maximum charge is roughly 3.4×10^6 electron charges per particle or 1.30 statcoulombs/cm² which is comparable to the maximum charge attained mechanically with a high contacting surface to contacted surface ratio (see Table 1, test 4). Since all of the charging occurs at the walls then the decreasing charge density per particle is probably due to few particles of maximum charge (i.e., 3.4×10^6 e/part) having migrated towards the bed center. This comparatively poor charged distribution should be compared to that obtained with a matrix (Table 4). For the latter case a fairly uniform cross-sectional distribution results.

4.2 Hindered Fluidization

In the columns, Fluidization Quality, of Tables 2 and 3, it will be noted that with the presence of the charging screen the quality of fluidization is very poor, most of the bed, in all cases, segregating above the charging screen, in spite of the fact that the fluidized solids flow through the screen quite easily in single passes. This segregation is due to the coating of the wires with several layers of particles which eventually prevent passage of more solids through the mesh openings. This wire coating phenomenon proved to be the most important single observation and can be attributed directly to "image forces" attracting the charged spheres to the conducting wires. These forces are due to the "bound" charges appearing in the conductor.

The wire matrix system introduced interferences throughout the bed. With 40 to 50 mesh Dylene spheres packed in a 1-in. bed it was found that the wire matrix prevented fluidization until a velocity of 69 fpm (roughly 5 times the theoretical point). At this point there was a sudden expansion to 50 per cent and a fall in pressure drop from 3.0 in. water to 0.39 in. water. Before fluidization the bed had acted as a packed bed with the pressure drop increasing linearly with velocity. The expansion then proceeded smoothly to 100 per cent at 87 fpm above which point channeling started to become apparent as indicated by a falling pressure drop. An indication of the effect of wire coatings was seen by slowly reducing the air velocity back to zero. About 37 per cent of the bed volume remained adhered to the matrix above the settled bed. Gentle rapping dislodged all but about 10 per cent of the total bed volume. It was obvious that for the system under test some form of gentle rapping should be employed to help promote uniform expansion by inhibiting the coating process. (It may be possible, however, that an experimentally determined combination of fluidized material, particle size, matrix arrangement and wire size, and fluidization velocity will produce uniform bed operation without the added mechanical aspect of "rapping.")

The bed (40 to 50 mesh Dylene) was observed again while gently rapping, by hand, the outside of the tube with a wooden stick. The observed bed behavior (expansion) under these

conditions: the bed first expands at about 11 fpm (extrapolated) which is very close to the theoretical value for an unhindered bed (13.6 fpm). It then expands very smoothly through the matrix up to an expansion of about 100 per cent (90 fpm). At this point the bed pressure drop, which had remained constant at 0.43 in. water began to fall indicating channeling and also, therefore, significant matrix coating. Once channeling started it proceeded rapidly with the pressure drop falling rapidly at the same velocity indicating a self-accelerating process. Eventually the wires became so heavily coated that the bed lost its identity as such even with violent rapping.

In the tests of Tables 2 and 3 no attempt was made to correlate actual fluidization velocities, expansions, and resistance with the theoretical, since the presence of the charging screen interfered with smooth fluidization. For rough comparisons however, the polystyrene material should fluidize at 13.6 fpm with a loss of 0.63 in. H₂O/in. settled bed and Nylon spheres at 9.0 fpm with 0.77 in. H₂O/in. settled bed. Fluidization velocities are determined by the Lowenstein method¹² and pressure drops by the Lapple method.¹¹ Measured pressure drops were lower than theoretical, perhaps due to some channeling, while fluidization velocities were kept above the critical points in all cases.

5 PERFORMANCE TESTS (COLLECTION EFFICIENCY)

5.1 Preliminary (Atmospheric Dust)

The whole value of this over-all study hinges on the effectiveness of the electrostatic aerosol collection mechanisms which may, or may not, occur in a triboelectrified fluidized bed. It is therefore important to determine, at the outset, whether any increase in filtration performance can be attained in this manner, and if such performance is attained, whether it is done so at an energy requirement and with advantages compatible with existing methods of air cleaning. The following tests were made to determine qualitatively whether the effectiveness of the proposed filtration mechanism warranted a full investigation.

A simple and rapid means of evaluating filter performance is by using atmospheric dust as the test aerosol and determining efficiency by the stain density technique.^{13,14} The following tests were made in this manner on fixed and fluidized beds of Koppers Dylene-Polystyrene beads.

The equipment used consisted of the apparatus shown in Fig. 3, modified so that aerosol samples could be taken. All tests shown were made on the same day and aerosol characteristics were considered constant.

Table 7 shows the results of four tests made on similar beds: 14.9 g of Koppers Polystyrene, 1-in. bed. The charge shown is based on an average per unit weight of bed and therefore does not represent an equally distributed charge.

Table 7—PRELIMINARY STAIN DENSITY EFFICIENCIES OF TRIBOELECTRIFIED FLUIDIZED BEDS*

Test No.	Superficial bed velocity, fpm	Bed expansion, %	Average unit surface charge, statcoulombs/cm ²	N _{Re}	Stain efficiency, %
1	13.4	0	0.021†	5.0	64
2	13.4	0	0.049‡	5.0	89
3	13.4	0	0.086§	5.0	96-100
4	30.0	18	0.086§	18.0	97-98

*Koppers Polystyrene Beads, Mg = 200 μ, t = 70°F, w = 60 grains water per pound dry air.

†All charged particles at wall.

‡Most charged particles at wall—some distribution through bed.

§Most charged particles at wall—fair distribution through bed.

It is obvious that in a fixed bed even the limited charging attained can cause a very significant improvement in efficiency. For test 2 the charged filter cross section is probably less than one-half the total filter cross section (see Fig. 4) yet the increase in efficiency over an essentially uncharged bed (test 1) is very significant, i.e., nearly a 40 per cent increase in effectiveness. Albrecht¹⁵ has shown that the flow distribution through such a bed is very uniform, each channel essentially having the same velocity profile despite the tortuous path. Therefore with only half the aerosol being exposed to comparatively small electric fields, a significant over-all improvement is observable.

When the average particle field strength is increased and better distribution through the bed is attained, the efficiency becomes very high in comparison to an uncharged bed (test 3). The importance of good distribution of charged particles through the bed is apparent. Finally, when the particles are separated due to fluidizing and the fields become correspondingly less intense, the over-all removal remains about the same (test 4), i.e., the attracting fields are still strong enough for very efficient performance. Therefore it may be assumed that during continual charging operation sufficient electrostatic effects still occur. Thus it appears that a highly effective electrostatic filter which may be continually charged in a simple manner is feasible.

5.2 Comprehensive

Equipment and Methods. Since the preliminary tests indicated that the triboelectrified fluidized bed process showed promise, further development was indicated. In this work the control and measurement of aerosol and bed properties and variables were investigated under suitable conditions.^{16,17}

Figures 5 and 6 show the experimental equipment in front and rear views, respectively.

The aerosol, gentian violet, was generated from an alcohol solution by a modified spinning disc method.¹⁸

At a point on the side of the generator drum the aerosol was drawn out by a controlled airstream. A significant vortical type flow was induced in the drum from the spinning disc. This was removed by passing the aerosol through a narrow throat Venturi section. Calculations show that at the minimum total volume contemplated for the unit, the Reynolds number at the Venturi throat > 2000 and thus turbulent mixing occurs.

The mixed stream was then passed through a 6-in. soda straw section to distribute the flow in the larger diameter glass tube, 1.5-in. I.D., which makes up the remainder of the test sections. At the end of the soda straw section the flow was split equally by 90° turns into two vertical sections. These constitute the upstream and downstream sampling tubes and consisted of rounded 90° turns leading to 18-in. vertical tubes. The joints of the system were made using cut bicycle tube sections which cause the glass tubes to butt firmly and also are essentially leakproof. Either section could house the fluidized bed for test.

The test system for this study was designed to preclude possible sampling errors. The entire air volume was sampled thus obviating aliquot percentage and isokinetic difficulties.¹⁹ This method was possible because of the small total air volumes used. All that was required for accurate sampling was that the flow be split *exactly* at the tee-section and that inertial separation, if it did occur, be the same for each branch of the system. Initial tests showed duplication of sample concentrations within ±5 per cent.

The aerosol samplers are shown in more detail in Fig. 7. They are constructed from nominal 1-in. brass unions, specially machined. Type 1 is used for total volumes of 0.5 to 20 liters/min. Type 2 is used for higher volumes up to 200 liters/min if necessary.

The sampling pumps were two Leiman Brothers cycloidal type. A prefilter (1106B) medium was placed upstream of the test section tee and downstream of the aerosol generating tank. It was connected to the aerosol line by two pinch clamps so that prefiltered air or aerosol could be directed to the sampling sections. (See sketch, Fig. 8.)

A special rapping device was constructed so that bed agitation could be duplicated from run to run. It consisted of a weighted steel arm with a 1-in. diameter lucite hammer head

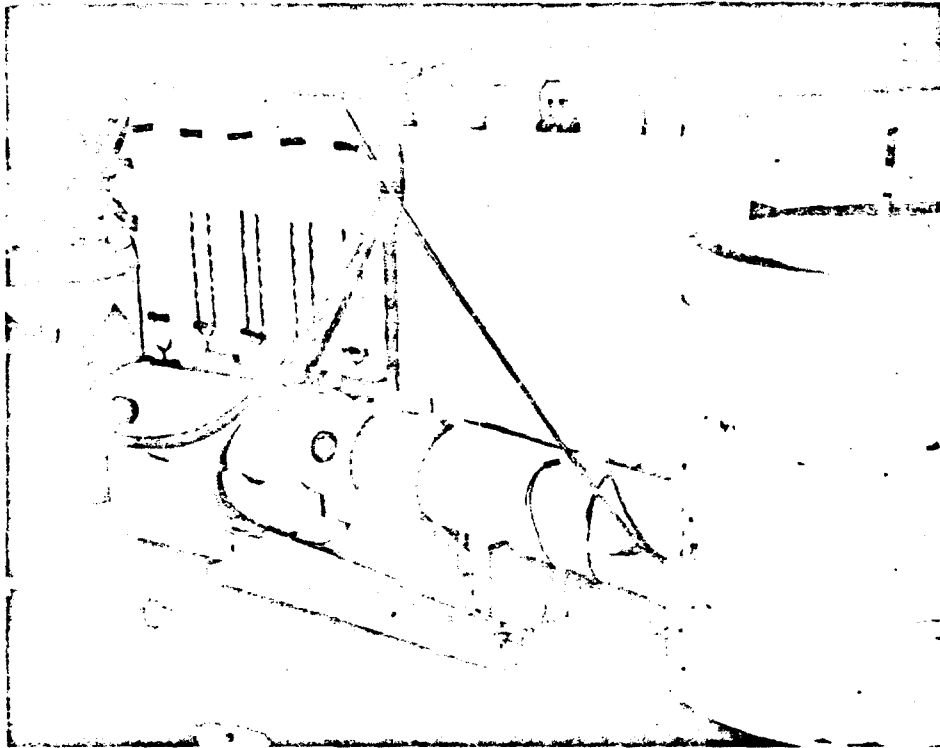


Fig. 5—Equipment for comprehensive tests, front view.

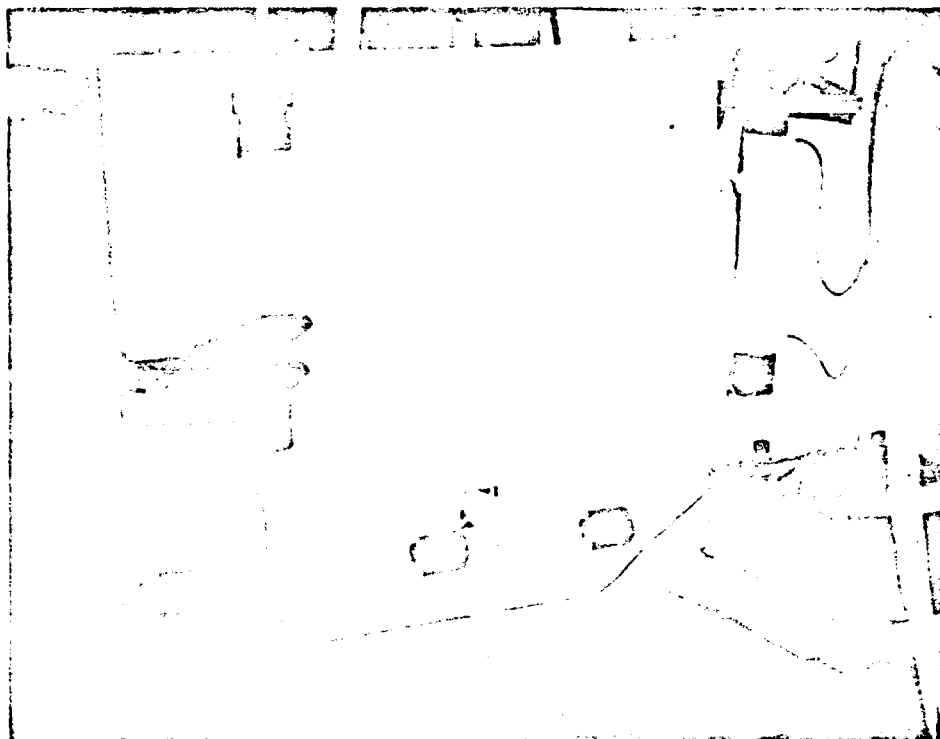


Fig. 6—Equipment for comprehensive tests, rear view.

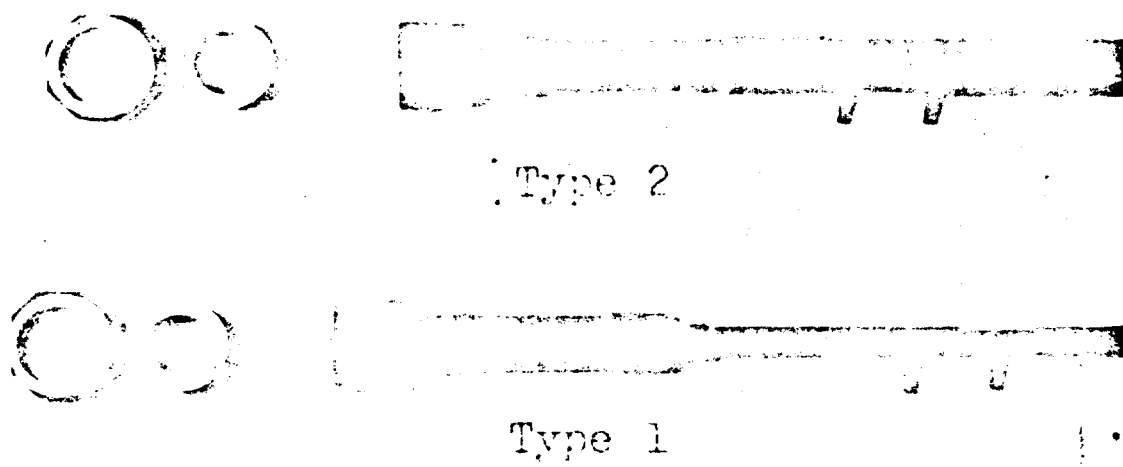


Fig. 7—Aerosol samplers.

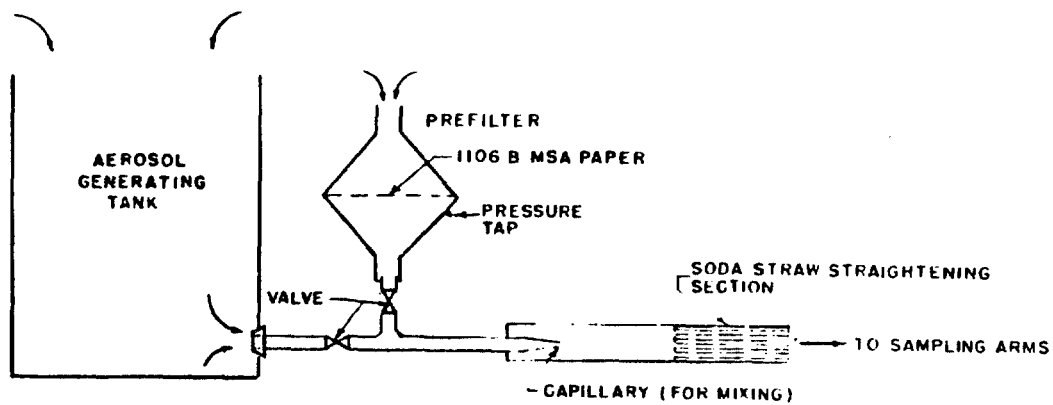


Fig. 8—Sketch of prefilter arrangement.

which was pivoted from the side of a special housing. A small EMC motor with a special gear reducer served to lift the hammer arm by means of an eccentric gear. The hammer fell back striking the side of test bed section with the lucite head. This action served to remove some particles from the matrix. In the following tests the hammer was geared to strike the tube 40 times/min. This device is subject to change.

The bed charge was measured by means of the matrix system itself. In some cases when the humidity is very high the only method of bed charge measurement is by pouring the bed into a separate Faraday cage at the end of the run. This is so because of extremely rapid charge leakage from the beads themselves and from the voltmeter-matrix-air capacitor measuring circuit.

The generating tank was opened to a 6-in. diameter duct system which withdraws several cubic feet per minute of dilution air and aerosol. This duct system served to measure net particle charge by the method developed by Rossano¹⁸ (see Fig. 17, p. III-28a). A high efficiency filter paper is mounted in the Faraday cylinder of this apparatus. Upstream and downstream samples are taken isokinetically to determine the paper efficiency. Charge is induced on the cylinder, which, when corrected for efficiency, yields average net particle charge. The comparatively large volumes handled through this system are necessary to obtain accurate Q_p measurements.

Since high efficiencies are involved low downstream concentrations are encountered. To obtain greatest accuracy an accurate and sensitive spectrophotometer, the Beckman DU, was employed. It is essential to use an aerosol material with a high molar absorptancy index for colorimetric analysis. Gentian violet possesses the greatest index of available dyes. The absorptancy-concentration curve for GV is linear, with the equation, $C = 4.06 A$ ($C = \gamma/\text{ml}$, $A = \text{absorbance}$).

In the following tests the weight fraction of GV was held constant at 1.54×10^{-4} (14 $\mu\text{g}/\text{ml}$) yielding an aerosol of $M_g = 0.49 \mu$ ($\sigma_g = 1.6$). This is equivalent to a mean volume diameter, $D_v = 0.67 \mu$. The specific gravity of the GV (Harleco, 96 per cent pure) was determined by a pycnometer technique using 50 centistokes Dow-Corning Silicone oil in which GV is insoluble, and found to be 1.16 g/ml. Thus numbers concentration of the generated aerosol could be computed:

$$N = 5.47 \times 10^6 \text{ particles}/\mu\text{g GV (using } D_v = 0.67 \mu)$$

Experimental tests. The efficiencies to be reported here were confined to one bed material, Koppers' Dylene "3", 40 to 50 mesh, and one operating velocity, 50 fpm, equivalent to a bed expansion of approximately 60 per cent. One-inch beds, 12.2 g of material were used throughout. Table 8 summarizes the pertinent data of these tests. Fresh bed material was used for each test.

The "uncharged" efficiency was determined at 10 fpm through the settled bed since it is impossible to have an uncharged operating fluidized bed. This zero charge level was obtained at the highest velocity before fluidization (13 fpm) and any contact charge generated in pouring the material was allowed to leak to ground for 4 time constants. It is to be expected that if no charge existed on the beads when fluidized, efficiency would fall, since targets become farther apart and velocities are increased. Thus, although not determined at the same velocity, the 10 fpm tests are considered zero charge levels for the 50 fpm tests.

1. *Charge levels.* Aerosol charge varied between 40 and 140 e/part, positive. It is believed that this is due to variations in σ_g of the aerosol both with regard to size and charge. Thus the mean size 0.49μ might probably be represented by a mean charge of +90 e/part., or a surface density of 38 per cent max. Again when further data are available the variation Q_p will be taken into account by the use of dimensionless variables including Q_p , Q_{bed} , bed size etc., as used by Kraemer.¹

Bed charge (net) varied widely from zero to 35 esu/g (2.6 per cent max.). Leakage of charge from the bed also varied widely with some dependence on humidity. The charge generation rate was, on the average, quite low in comparison to that produced by fluidization at 100 fpm, 1.0 esu/g/min vs about 0.10 esu/g/min at 50 fpm. This is to be expected because of the lower kinetic energy involved. In tests 11 and 12 charge was generated at 100 fpm before

Table 8--SUMMARY OF PERFORMANCE TESTS ON FLUIDIZED POLYSTYRENE BEADS*

Test No.	Absolute humidity, grains/lb.	Aerosol charge, elec./part.	Ave. total bed charge, esu/g	Aerosol conc. upstream, $\mu\text{g}/\text{m}^3$	Collection efficiency, %	Bed resistance, in. water
1	77	+ 46	0	29.4	71.5	0.65
2	77	+ 43	0	23.8	72.3	0.68
3	87	+ 71	< -1.2	16.6	94.6	0.59
4	68	+ 76	-1.6	15.6	97.1	0.51
5	68	+ 128	-2.8	18.1	96.2	0.47
6	68	+ 76	-3.6	12.5	96.4	0.49
7	68	+ 76	(-10.6)	13.0	90.6	0.55
8	83	+ 71	(- 0.8)	17.7	98.1	0.55
9	51	+ 131	(-16.1)	17.9	93.5	0.41
10	82	+ 77	(-35.4)	27.2	94.1	0.45
11	43	+ 146	-14.7	17.2	96.7	0.51
12	43	+ 146	-16.9	17.9	95.0	0.46

Note: Tests 1 and 2 unfluidized at 10 fpm; all tests for 30 min operation; bed charge developed by fluidization before test at 50 fpm except for tests 11 and 12 were pre-fluidization at 100 fpm; charge values in parenthesis for free flowing fraction of bed not total bed ave.

*Aerosol = Gentian Violet, Mg = 0.49 μ ; Bed = 12.2 gms, 40-50 mesh, Dylene 3, one-inch settled bed; Velocity = 50 fpm; Expansion = 60%.

filtration at 50 fpm to produce higher net charges and the generation rates here were more nearly those of the previous 100 fpm tests. The charge generation rate was, however, asymptotic indicating strong particle adhesion even at this velocity. It will be noted that the final average charge levels (total bed) are quite low (about 3.0 esu/g, ave.) when charging is accomplished only by fluidization at 50 fpm. Furthermore when this final charge is compared to initial bed charge (from pouring) in most cases particle charge leakage nearly obscures the generation rate. The data are not sufficient to attempt generation rate vs time constant correlations but this is the method to be followed in following tests.

The charge on the free flowing material in the bed is listed for several tests but is not too reliable since it is determined by pouring into a separate Faraday cage, an action which in itself produces charging. These values are useful as order of magnitude levels especially in runs where average total bed charge measurements are doubtful or missing.

Generally speaking charge generation is poor in comparison to levels possible, when operating at 50 fpm for this material. Nevertheless, efficiency tests were still made to determine the effectiveness of low charge levels on the bed material.

2. *Pressure loss.* Theoretical maximum ΔP for unhindered fluidization is 0.63 in. water. The values in Table 8 of tests 1 and 2 are close. However, during fluidization it will be noted that pressure loss is less varying between 0.41 and 0.59 in. water. The resistance is lower due to the matrix coating process which reduces the amount of freely fluidized material by as much as 30 per cent. It varies due to the process of adhesion but for most cases becomes constant once an equilibrium is reached between adhesion vs "sluffing off" due to rapping. An average operating ΔP for 50 fpm operation at equilibrium is 0.50 in. water.

3. *Aerosol concentration.* The upstream concentration of aerosol particles averages about 15 to 20 $\mu\text{g}/\text{m}^3$. These levels are in the order of "background" dust loadings in air. The concentration for this particle size is limited to these values because of the aerosol generation process and the minute GV concentration of the feed.

4. *Bed efficiency.* It appears that even at very low particle charge (bed particles) values, -1.0 esu/g, efficiency is quite high and, moreover, remains relatively constant despite increased surface charge. This indicates that coulombic attractive forces (negative bed particles, positive aerosol particles) are important. If they were not, and inductive forces predominated, there would necessarily be an increase in efficiency as bed particle charge increased. Another important effect is probably bipolar bed particle charging which is not reflected in net charge measurements at all.

Although these data are limited to one type bed and one operating velocity, it would not perhaps be remiss to compare this operating performance with competitive devices. Thus, for example, CC-6 paper will filter 0.7μ methylene blue at 99.98 per cent efficiency (count) at 0.25 in. water/fpm. Cottrell precipitators will filter 0.3μ DOP at 99.1 per cent (weight) at very low power requirements (roughly 0.001 in. water/fpm). This fluidized bed filters 0.5μ GV at 94.5 to 98.5 per cent efficiency (weight) at 0.01 in. water/fpm. Thus, it now seems probable that filtration will approach that of high efficiency devices at power requirements close to those of precipitators and only a fraction of that of AEC type papers. Moreover the power requirements become even less as filtration velocity increases (ΔP remains constant) and, if the high efficiency holds, the mechanism of collection now under study may be as effective as single stage precipitators at about the same operating power, without high capital cost.

Since humidity effect are of great interest in this work, the data of Table 8 are considered as a function of humidity alone. It is obvious that the high efficiency remains approximately constant up to absolute humidities as high as 90 grains per pound dry air. This is encouraging in view of previous work with fiber and fabric filters. Further data are necessary, however, before definite conclusions should be drawn.

6 FUTURE WORK

This study is being continued along the same lines. Contemplated variables are: bed material and particle size, fluidization velocity, (bed porosity and depth), and aerosol size. In addition, more efficient charging systems will be developed, if possible.

REFERENCES

1. H. F. Kraemer and H. F. Johnstone, *Ind. Eng. Chem.*, 47, 2426 (1955).
2. A. T. Rossano, Jr. and L. Silverman, *Heat and Vent.*, 51, 102 (1954).
3. L. Silverman, E. W. Conners, Jr. and D. M. Anderson, *Ind. Eng. Chem.*, 47, 952 (1955).
4. L. B. Loeb, *Science*, 102, 573 (1945).
5. E. R. Peck, "Electricity and Magnetism," McGraw-Hill Book Company, Inc., New York, 1953.
6. J. I. Masters, *Rev. Sci. Instr.*, 24, 586 (1953).
7. J. W. Peterson, *J. Appl. Phys.*, 25, 907 (1954).
8. National Bureau of Standards, "Static Electricity," *Circ. C438*, (1942).
9. W. J. Smith, and N. F. Suprenant, *Properties of Various Filtering Media for Atmospheric Dust Sampling*, presented to Amer. Soc. for Testing Mat., Philadelphia, July 1, 1953.
10. F. A. Vick, *Brit. J. Appl. Phys.*, Supplement No. 2, p. S1, 1953.
11. C. E. Lapple, "Fluid and Particle Mechanics," 1st ed., University of Delaware, Newark, Delaware, 1954.
12. J. Lowenstein, *Chem. Eng.*, p. 189, April, 1955.
13. P. Drinker and T. Hatch, "Industrial Dust," 2nd ed., McGraw-Hill Book Company, Inc., New York, 1954.
14. M. W. First, et al., *Air Cleaning Studies—Progress Report*, Feb. 1951-June 1952, USAEC, NYO-1581, Harvard University, April 21, 1952.
15. F. Albrecht, *Physik Z.*, 32, 48 (1931).

16. W. B. Kunkel, J. Appl. Phy., 21, 820 (1950).
17. D. Sinclair, Stability of Aerosols and Behavior of Aerosol Particles, Ch. 3 of "Handbook on Aerosols," USAEC, Washington, D. C., 1950.
18. A. T. Rossano, Jr., "Electrostatic Mechanisms in Fiber Filtration of Aerosols," Sc.D. Thesis, Harvard University, 1954.
19. H. H. Watson, Am. Ind. Hyg. Assoc. Quart., 15, 21 (1954).