UCRL- 84878
PREPRINT

CONF-800953--2

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MASTER

Fine Particle Society Fall Meeting
September 16-18, 1980
University of Maryland
College Park, Maryland

January 27, 1981

Lawrence
Livermore
Laboratory

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ELECTROSTATIC AIR FILTERS GENERATED BY ELECTRIC FIELDS*

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ABSTRACT

This paper presents theoretical and experimental findings on fibrous filters converted to electrostatic operation by a nonionizing electric field. Compared to a conventional fibrous filter, the electrostatic filter has a higher efficiency and a longer, useful life. The increased efficiency is attributed to a time independent attraction between polarized fibers and charged, polarized particles and a time dependent attraction between charged fibers and charged, polarized particles. The charge on the fibers results from a dynamic process of charge accumulation due to the particle deposits and a charge dissipation due to the fiber conductivity.

The extension in filter life with an applied electric field is due to changes in the particle deposition around individual fibers on a microscopic scale and changes in the particle deposition through the filter bed on a macroscopic scale. These changes result in a lower pressure drop across the filter than would occur without an electric field. On the microscopic scale, the effect of the applied electric field is to delay the formation of particle dendrites on the fibers. The air resistance of a fiber with a uniform particle surface coverage is significantly less than that of a fiber covered with particle dendrites. On a macroscopic scale, the increase in filter efficiency due to the electric field causes the particle deposit to form closer to the filter surface than occurs for the nonelectrified filter. Since the fiber volume fraction at the filter surface is less than it is within the filter bed, the particle deposits near the surface will produce a lower pressure drop than the same deposits within the filter bed.

*This work was performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48.

1. INTRODUCTION

New improvements in the performance of air filter media have historically occurred by using smaller diameter fibers in the filter media. Unfortunately, the resulting higher efficiency also produced a higher pressure drop. To compensate for the increased pressure drop, the area of the filter had to be increased by pleating the media. An attractive alternative to this historical cycle is the addition of electrostatic forces to the filter media. By converting a mechanical fibrous filter to electrostatic operation, one can dramatically increase the filter efficiency without increasing the pressure drop. Although there are many ways of generating an electrofibrous filter, all of the methods are based on either charging or polarizing the filter fibers. These methods can be further classified according to whether the filter media is permanently electrified or requires a continuous electrification. A more extensive review of electrified air filters can be found in references[1-3].

Hansen[1] developed the first permanently charged filter in 1930 by mixing powdered resin with wool fibers. The resin particles that coated the fibers were highly charged in the mixing process; thereby, in effect, producing charged fibers. Although a number of new permanently charged or polarized filters have been developed over the years, they have all suffered from the dissipation of charge or polarization due to particle loading and environmental factors. Despite the limited life of the fiber charge or polarization there is a great interest in these filters because they do not require auxiliary charging or polarizing equipment and can be treated as ordinary filter media. An intensive effort is underway by different research groups to extend the life of the fiber charge or polarization.

Continuously electrifying a filter medium eliminates the problem with the dissipation of fiber charge or polarization. However, this benefit is gained at the expense of significantly increasing the complexity of these fibers. The continuously charged filter requires a corona charging device upstream of the filter to charge aerosols. These aerosols can either be the original aerosols to be removed or aerosols added specifically to charge the filter. In either case, the filter becomes charged once the highly charged aerosols are captured by the filter. In contrast, the continuously polarized filter requires high voltage electrodes to generate an electric field across the filter media. The primary disadvantage of these continuously electrified filters is the expense and inconvenience of the additional hardware. Moreover, the high voltage and corona discharge may create hazards in certain applications.

The Lawrence Livermore National Laboratory (LLNL) has been investigating electrified air filters to develop an improved air filter system for the U. S. nuclear industry. High efficiency particulate air (HEPA) filters are presently used in the nuclear industry to remove radioactive aerosols. They are extremely effective and practical devices and will continue to be so despite the large number of new control devices presently available. However, HEPA filters generate a significant volume of radioactive waste and are costly to purchase and operate. In an effort to reduce the HEPA's operational cost and the volume of radioactive waste, the Department of Energy (DOE) has contracted LLNL to develop an improved filtration system that will extend the service life of HEPA filters. Since improving the performance of HEPA filters did not appear very promising, we concentrated on techniques that would reduce

the particle loading on the HEPA filter. However, because of the stringent safety and operational constraints, only techniques using prefilters appeared to have a greater potential for success than other methods using scrubbers or electrostatic precipitators. Electrifying the prefilter made this selection even more attractive.

Of the various electrified filters, we selected the one based on continuously polarizing a fibrous filter using a superimposed electric field. The filters using a corona discharge to continuously charge the fibrous media were not applicable because of the potential fire hazard. We also rejected the permanently charged or polarized filters because the charge or polarization could be irreversibly destroyed in field applications. However, we should emphasize that once the charge or polarization can be stabilized, these permanently electrified filters would make a better candidate than the continuously electrified filters.

The basic components of the electrified filter discussed in this report are illustrated in Figure 1. A fibrous filter medium is sandwiched between two perforated electrodes separated by a spacer. By applying high voltage to one electrode and grounding the other, an electric field is generated across the filter medium that polarizes the filter fibers. The fibrous filter media was selected because it has a significantly lower pressure drop than other media like the cloth media used in filter bags.

Figure 1. Components of electrified filter consisting of perforated electrodes, filter medium, electrode spacer and the filter holder.

2. EXPERIMENTAL APPARATUS

The experimental apparatus used in our study is shown in Figure 2. The major components of this system consist of an aerosol generator, a filter test duct, the electrostatic filter housing, diagnostic equipment for measuring filter efficiency and pressure drop, and variable speed blowers. The test apparatus is used for both accelerated clogging tests and efficiency tests. By rotating a large switching valve, aerosols can be passed directly into the filter test duct for accelerated clogging tests or to a by-pass hose and exhausted. Efficiency tests are made in the by-pass mode where a very low concentration of aerosol is obtained by pumping a small sample of the by-passed aerosol to the filter test duct. In this mode, a secondary air inlet valve is opened to maintain a constant air flow through the filter. Both inlet air sources are filtered with HEPA filters. The variable speed blower is adjusted to maintain a constant air flow through the filter as indicated by the output from the mass flowmeter. These adjustments are most frequently made during the accelerated clogging tests where the increase in filter resistance reduces the air flow.

Sodium chloride aerosols are used for the filter tests in this report. They are generated using one to four Wright nebulizers containing a 1% by weight solution of sodium chloride in water. To minimize the increase in the salt concentration due to evaporation, the solution is recirculated through a large reservoir. All obstructions to the aerosol transport are minimized by using valves with large openings and peristaltic pumps. The resulting system can produce a stable aerosol concentration and size distribution for up to eight or more hours. Measurements of the aerosol size distribution with an inertial impactor (Frontier Enterprises, Inc., Albuquerque, NM) indicated the aerosols have a log-normal distribution with an aerodynamic mass median diameter (AMMD) of $1.0 \mu\text{m}$ and a geometric standard deviation (σ_g) of 2.0.

Figure 2. Schematic of laboratory test apparatus.

The aerosols enter the filter test duct, which is an aluminum tube, 2 m long and 20.3 cm diameter. Another section of tubing, 1 m long, is positioned downstream of the filter housing to provide a uniform flow through the electrostatic filter. Measurements of the air velocity and salt concentration were taken across the duct and indicated a uniform distribution. Isokinetic sample probes and pressure taps were placed before and after the filter holder for efficiency and pressure drop measurements. A switching valve allowed aerosol measurements to be made before and after the electrostatic filter with the same instruments.

The filter housing is a polyethylene block that supports two electrodes separated by 1 cm. A wire screen with 90% open area was selected for the upstream electrode to minimize the masking of the filter, while the downstream electrode was a perforated aluminum plate with 40% open area. The pressure drop across the two electrodes was 5 Pa at 66 cm/s. Sandwiching a glass fiber filter between the two electrodes completed the filter housing assembly. Unless stated otherwise, all of our test results in this report were obtained using AF-18 filters (Johns Manville, Denver, CO), which have a number median fiber diameter of 3.5 μm . The air velocity through the filter was 66 cm/s unless stated otherwise. The electrostatic filter is produced by applying high voltage to the downstream electrode and grounding the upstream electrode. It is important to emphasize the electrostatic filter, discussed in this report, does not require a corona discharge for its operation.

Three different instruments were used to measure filter efficiency. A flame photometer (Frontier Enterprises, Inc., Albuquerque, NM) provided a continuous output that was proportional to the aerosol mass concentration. This instrument was used for both transient and steady state measurements. The laser optical counter (Particle Measurement Systems, Boulder, CO) and the electrical mobility analyzer (Thermal Systems, Inc., Minneapolis, MN) were used for the efficiency measurements as a function of particle size under steady state conditions. A peristaltic pump was required to bring the aerosol sample to the flame photometer. The other two instruments used a vacuum source. The temperature and relative humidity of the air stream were also measured. In general these measurements followed laboratory conditions with the temperature at 20°C and the relative humidity varying between 30 and 60%.

3. ELECTRIC FIELD INCREASES THE FILTER EFFICIENCY

3.1 Experimental Findings

Since the first investigations of electrified filters, it was recognized that these filters have a significantly higher efficiency than similar filters without any electrification. However, a comprehensive description of the higher efficiency was not available until recently[2-4]. Figures 3-5 illustrate the basic characteristics of the electrified filter generated with an applied electric field.

Figure 3 shows the filter efficiency plotted as a function of electric field for two layers of 6.4 mm thick, AF-18 medium. The same filter was tested at flow velocities of 0.65 m/s, 0.32 m/s and 0.16 m/s. With no electric field, the filter efficiency increases as the flow velocity increases, while the opposite occurs at higher electric field strengths. With no electric field, the filter efficiency is determined by mechanical capture mechanisms. Since the flame photometer used to obtain the data measures a quantity proportional to the particle mass, the efficiency measurement is primarily a measurement of the inertial capture mechanism. Thus, at higher

Figure 3. Filter efficiency as a function of electric field for two layers of AF-18 medium tested at different flow velocities.

velocities, the particle inertia will increase, thereby increasing the efficiency. However, when the electric field is applied, the primary factor controlling the efficiency increase is the residence time of the particles within the filter medium. The longer the particles remain within the filter medium, the greater time the electrical forces have to attract these particles to the fibers.

Figure 4 shows the efficiency as a function of particle diameter for the same filter with no electric field and with an applied electric field of 1 MV/m. The efficiency curve with no electric field shows the typical minimum for particles from 0.1 to 0.3 μm in diameter. The efficiency rapidly increased for both larger and smaller particles. We should note that all filters, including HEPA filters, have similar efficiency curves, although the efficiencies may be higher and the minimum may be shifted to a different particle size. When an electric field of 1 MV/m is applied, the efficiency increases dramatically over the entire range of particle sizes. As seen in Figure 4, the added electrical forces have almost eliminated the deep minimum in filter efficiency. This increase in filter efficiency occurs with no increase in pressure drop.

The efficiency measurements shown in Figure 3 and 4 were obtained under steady state conditions. Recent experiments[3,4] conducted under transient conditions have shown that the characteristics of the electrification process are much more complex than previously thought. Figure 5 shows the results of two experiments superimposed on the same graph in which the transient aerosol penetration was measured as the electric field was turned on and off. The noise in the original traces was averaged out to yield the smooth lines. As seen in Figure 5, the filter designated as "slightly conducting" shows an instantaneous decrease and increase in the penetration when the electric field

Figure 4. Filter efficiency as a function of particle size with and without an electric field.

Figure 5. Transient filter penetration with a "nonconducting" and a "slightly conducting" filter.

is turned on and off respectively. In contrast, the filter designated as "non-conducting" shows a pronounced delay in the penetration when the electric field is turned on and off. Note the delay is much greater when the electric field is removed than when it is applied. The major difference between the two filters was their conductivity; the "non-conducting" and "slightly conducting" filters had gross resistivities of 10^{10} ohm/cm and 10^8 ohm/cm respectively. A dye added to the "slightly conducting" filter, for identification purposes, was responsible for the increased conductivity.

3.2 Theoretical Models

We have developed a theoretical model for the filter efficiency that is consistent with the experimental observations seen in Figure 3-5. The trends seen in Figures 3 and 4 can be qualitatively explained based on Zebel's

theory[4,5] of electrostatic attraction between polarized fibers and charged and polarized particles. According to the single fiber model of filtration[6], the fraction, P, of aerosols penetrating the filter is given by

$$P = e^{-\left(\frac{2\alpha X}{(1-\alpha)\pi R}\right) \eta} \quad (1)$$

where η is the single fiber efficiency. The filter efficiency, η_f , is related to the penetration, P, by

$$\eta_f = 1 - P \quad (2)$$

A complete list of the symbols and definitions is given at the end of this paper.

Although it is widely recognized that η is a very complex function of mechanical and electrical parameters, qualitative trends can be obtained by approximating η as the sum of the efficiencies for the mechanical and individual electrical mechanisms

$$\eta = \eta_M + \sum_i \eta_i \quad (3)$$

According to Equations 1 and 2, an increase in the single fiber efficiency, η , will produce an increase in the filter efficiency, η_f . Zebe[4,5], has derived the following two equations of single fiber efficiency that represent the force between polarized particles and polarized fibers,

η_p , and the force between charged particles and polarized fibers, η_q :

$$\eta_p = \left(\frac{\epsilon_p - 1}{\epsilon_p + 2}\right) \left(\frac{\epsilon_f - 1}{\epsilon_f + 1}\right) \left(\frac{r^2 E^2 C}{6\pi\mu R V}\right) \quad (4)$$

$$\eta_q = \frac{\eta_e E C}{6\pi\mu v r} \left(\frac{1 + \frac{\epsilon_f - 1}{\epsilon_f + 1}}{1 + \frac{\eta_e E C}{6\pi\mu v r}} \right) \quad (5)$$

The single fiber efficiency for the mechanical mechanism, η_M , is a complex function and gives rise to the parabola shaped curve in Figure 4 with no applied electric field. However, since the filter efficiency shown in Figures 3 and 5 represent the mass efficiency, one can approximate the mechanical efficiency with the inertial term. Billings and Gussman[7] have shown that the inertial term can be approximated by

$$\eta_I \approx \frac{k_I V r^2}{R} \quad (6)$$

where k_I is a proportionality constant.

The combined single fiber efficiency obtained by adding Equations 4-6 is sufficient to explain the experimental trends seen in Figure 3. The two parameters varied in Figure 3 are the electric field strength, E, and the flow velocity, V. According to Equations 4-6, the filter efficiency increases with increasing V at E = 0, increases with increasing E at constant V, and decreases with increasing V at constant E. These theoretical trends are seen in the experimental data in Figure 3.

The experimental results shown in Figure 4 cover a range of particle sizes from 0.01 to 3.0 μm diameter. For very small particles the mechanical collection efficiency is dominated by diffusion of particles to the fibers and can be approximated[7] by

$$\eta_D \approx \frac{k_2}{(VRR)^{2/3}} \quad (7)$$

where k_2 is a proportionality constant.

Equation 7 predicts that, for small particles, the single fiber efficiency decreases as the particle size, r , increases. For very large particles, the mechanical collection efficiency is dominated by inertial impaction of particles to the fibers and is approximated by Equation 6. This equation predicts that the collection efficiency increases with particle size. The single fiber efficiency for all mechanical capture mechanisms first decreases, and then increases as the particle diameter is increased from 0.01 to 3.0 μm . This theoretical trend is verified in the experimental results seen in Figure 4 for filters with no applied field. When an electric field is applied, the filter fibers become polarized and increase the collection efficiency according to Equation 4 for polarized particles and Equation 5 for charged particles. Equation 4 is dominant for the larger particle sizes while Equation 5 is dominant for the smaller particle sizes. Therefore, when a strong electric field, E , is applied, the collection efficiency increases significantly over the entire particle size range. This theoretical prediction is observed in Figure 3.

Zebel's theoretical model of electrofibrous filters generated by electric fields had been successful in predicting the filter behavior seen in Figures 3 and 4. However, the experimental measurements in Figure 5 show the presence of transients that are not predicted by his theory. According to Equations 4 and 5, the filter efficiency should change instantly with changes in applied field. However, based on transient penetration measurements, such as shown in Figure 5, we have concluded that an additional capture mechanism must be added to the theory[2-3]. The basis for this additional mechanism is illustrated in Figure 6. The larger and smaller circles represent the cross sections of the fibers and the charged particles respectively. The solid lines are the electrical lines of force, while the dashed lines are the particle trajectories. Although Figure 6 only shows the attraction for charged particles, the electrical capture mechanisms are equally valid for polarized particles. The particles can be polarized by either the fiber charge or by the external electric field.

When an external electric field is first applied to the filter, the only capture mechanism is due to the forces between a polarized fiber and a polarized or charged particle. The electric field instantly polarizes the fiber, which then attracts both charged and polarized particles. Zebel had derived Equations 4 and 5 based on this capture mechanism. However, the charged particles that deposit on the fiber then gradually build up a fiber charge, and, therefore, introduces the second mechanism. This mechanism is based on the force between charged fibers and charged or polarized particles.

Figure 6. Electrical capture mechanisms responsible for the increased filter efficiency.

The fiber with Q charge per unit length can subsequently capture charged or neutral particles. The charged particles are attracted by Coulombic forces, while the neutral particles are attracted by induction forces. For charged particles having a charge, ne , the single fiber efficiency is, [7].

$$\eta_{qp} = \frac{neQC}{3\mu Rv} \quad (8)$$

The corresponding single fiber efficiency for neutral particles is, [7]

$$\eta_{qp} = \frac{2}{3} \left(\frac{\epsilon_p - 1}{\epsilon_p + 2} \right) \left(\frac{Q^2 r^2 C}{R^3 \mu v} \right) \quad (9)$$

We should note that the induction force on the neutral particles in Equation 9 is produced by the fiber charge Q .

The neutral particle can also be polarized by the external electric field, in which case, the single fiber efficiency is proportional to QE instead of Q^2 . A similar cross term occurs when the fiber has a charge and is also polarized by the external electric field. In this case, a neutral particle can be polarized either by the fiber charge or by the electric field. Equation 4 represents the case in which the particle is polarized by the external field. If the particle is polarized by the fiber charge, then the single fiber efficiency term describing the attraction between polarized

particles and polarized fibers is proportional to QE . Therefore, once the fiber becomes charged in the presence of an external electric field, two additional single fiber efficiency terms involving QE are added to the combined fiber collection efficiency. If we replace the fixed variables in all of the single fiber efficiencies with constants, the resulting equation describing the differential decrease in the number of particles, dN , across a filter element of differential thickness, dx , is given by

$$-\frac{dN}{dx} = \frac{2\alpha N}{\pi R(1-\alpha)} = \eta_M + C_1 n_e E + C_2 E^2 + C_3 n_e Q + C_4 Q^2 + C_5 QE \quad (10)$$

The fiber charge Q is given by

$$\frac{dQ}{dt} = -\frac{\gamma Q}{\epsilon} - neV \frac{dN}{dx} \quad (11)$$

This equation is the sum of a dissipation term, $-\gamma Q/\epsilon$, and an accumulation term $-neV dN/dx$. Equations 10 and 11 represent a pair of coupled differential equations.

The solution of Equations 10 and 11 yields the filter penetration for transient conditions. Although this solution could also be used for steady state conditions, it is much easier to first simplify the equations. Under steady state conditions, the fiber charge would have a constant value which is determined by setting Equation 11 to zero and solving for Q . This steady state value would then be substituted in Equation 10 and the resulting equation integrated over the filter thickness using numerical techniques.

Although extensive numerical calculations are required to compute the transient and steady state penetrations, the experimental trends in Figure 5 can be qualitatively explained using Equation 11. Figure 5 shows that increased conductivity removes the large transients in filter penetration that occur for nonconducting filters when the electric field is applied and removed.

The explanation for the conductivity effect is based on Equation 11. For a nonconducting filter (small γ), a significant charge can build up on the fiber before the charge dissipation term ($-\gamma Q/\epsilon$) reaches equilibrium with the charge accumulation term ($-neV dN/dx$). However, the charge dissipation term for the conducting fiber (large γ) is so large that equilibrium between charge dissipation and accumulation is established with a negligible charge on the fibers.

Since the conducting fiber cannot develop a charge, the penetration will instantly increase to the initial penetration when the electric field is turned off. In contrast, the nonconducting filter has a significant fiber charge which bleeds off very slowly when the electric field is turned off. As a rough approximation, the accumulation term in Equation 11 can be ignored and the resulting equation integrated to yield

$$Q = Q_{ss} e^{-\frac{\gamma t}{\epsilon}} \quad (12)$$

where Q_{ss} is the steady state charge before the electric field is removed. In a more rigorous analysis, the accumulation term in Equation 11 does not reduce to zero because it is a function of the fiber charge, as shown in Equation 10. This results in a longer time for the charge to bleed off. Although the polarized fiber mechanism disappears immediately when the electric field is removed, the charged fiber mechanism persists until all of the charge bleeds off.

Figure 7 summarizes the contribution of the two theoretical mechanisms to the transient filter penetrations seen in experiments. This figure clearly shows the experimental transients are due to the charged fiber mechanism. All of the different mechanisms previously discussed that involve charged fibers and charged or polarized particles have been grouped together as charged fiber mechanisms. In a similar fashion, all of the previously discussed mechanisms involving polarized fibers have also been grouped together. Although Figure 7 shows a symmetrical transient for both fiber charging and discharging, asymmetrical transients are predicted when the charged fiber and polarized fiber mechanisms are considered together, as discussed previously. This figure also shows the large contribution of both of the mechanisms to the total decrease in filter penetration. Understanding the nature of the charged fiber mechanism is very important in practical applications because of its large contribution to the filter efficiency.

Figure 7. Contributions of polarized fiber and charged fiber mechanisms to the transient filter penetration.

4. ELECTRIC FIELD INCREASES THE FILTER SERVICE LIFE

4.1 Experimental Findings

It is widely known that, for solid particles, when a filter is placed in service the efficiency and air resistance increases as the filter becomes clogged with particles[8]. The increase in air resistance is of great practical importance since it determines the service life of a filter. Once the resistance of a filter has increased to the point where a pump or blower

can not pull the desired air flow, the filter must be either cleaned or replaced. Despite this common experience, filter clogging has remained one of the least understood aspects of filtration. This lack of understanding has created a dilemma for both users and designers of filtration systems, since most filters do not operate under clean conditions, but rather at various levels of filter clogging. Filter clogging has been especially difficult to understand because the formation and growth of particle deposits is a highly nonlinear process that depends on previously deposited particles in addition to all of the parameters describing filtration in a clean filter.

There are a number of experimental findings that illustrate the nature of filter clogging both with and without an applied electric field. We believe that all of the trends found for filter clogging without an electric field also apply to filter clogging with an electric field. Although we have not yet verified this experimentally, this belief is supported by the theoretical models described later in this report. The most common characteristic of filter clogging is the increase in filter efficiency and pressure drop with increased particle loading. Figure 8 illustrates this behavior with an AF-18 glass fiber filter being clogged with sodium chloride aerosols. Another well-known characteristic of filter clogging is the increase in filter service life with a decrease in the face velocity. Figure 9 shows the efficiency pressure drop across two different AF-18 filters as a function of the particle mass trapped on the filter. The two sets of curves represent filters that were operated at different face velocities, the circles at 66 cm/s and the squares at 12 cm/s. Although the service life of the filter operating at 12 cm/s can not be determined from Figure 9, it is significantly greater than the same filter operating at 66 cm/s.

Figure 8. Filter efficiency and pressure drop during filter clogging.

Figure 9. Filter Efficiency and pressure drop across AF-18 filters during filter clogging at different face velocities.

Filter clogging can be expected to depend on all of the aerosol properties and most of the variables that determine the efficiency and pressure drop of clean filters. The only variable that is not expected to have an effect on filter clogging is the filter thickness. Although thicker filters have higher efficiencies and pressure drops, filter clogging should produce the same effect independent of the filter thickness. This follows because particle deposits generally decrease exponentially through the filter media, and clogging properties are determined by the particle deposit.

The relationship between particle size and filter clogging can be viewed either in terms of the effect different particle sizes have on filter clogging or in terms of the efficiency of clogged filters as a function of particle size. Figure 10 shows the increased pressure drop across a HEPA filter as it becomes clogged with different size particles[9]. The particle sizes in Figure 10 represent average values of three different heterodisperse aerosols used in the experiments. Based on these experimental results, Adley and Wisehart[9] concluded that small particles accelerate filter clogging compared to large particles.

The other relationship between particle size and filter clogging is shown in Figure 11 where the filter efficiency is plotted as a function of particle size at increasing stages of clogging. The parameter values adjacent to each of the efficiency curves represent the mass of sodium chloride trapped on the filter. The curve with zero particle mass represents the efficiency curve of a clean filter. Examination of the curves in Figure 11 shows that at increasing levels of clogging, the efficiency increases for all particle sizes and the point of minimum filter efficiency has shifted to smaller particle sizes. In contrast to the data in Figure 10, all of the curves in Figure 11 were generated with the same filter as it became clogged with sodium chloride aerosols having an average diameter of $1.0 \mu\text{m}$. The corresponding curves for the increase in pressure drop and average efficiency during filter clogging were previously given in Figure 8. Note that each of the efficiency points in Figure 8 represents an average of the efficiency curves in Figure 11.

Figure 10. Pressure drop across HEPA filters during filter clogging for three different particle sizes.

Figure 11. Filter efficiency as a function of particle size at increasing stages of clogging.

The preceding experimental findings pertain to clogging in fibrous filters with no applied electric field. Although the magnitude of the effects will differ for filter clogging in the presence of an electric field, the trends are expected to be the same. However, the most important effect of the electric field on filter clogging is the increased service life. In 1974, Ariman[10] was the first to report that a filter converted to electrostatic operation has a significantly lower pressure drop than a comparable mechanical filter having the same particle mass loading. He attributed this behavior to a more open, less restrictive particle deposit. Ariman had electrified the filter by using an upstream corona to precharge the aerosols. Since then numerous studies[11] have shown that electrifying the filter by either precharging aerosols or applying an electric field dramatically lowers the filter pressure drop. We can illustrate this behavior with experimental results obtained in our Laboratory. Figure 12 shows the pressure drop as a

Figure 12. Comparison of theoretical and experimental pressure drops for filters operating with and without an electric field during filter clogging.

function of the particle mass collected on the filter for two similar filters, one operated with no electric field and the other with a 10 kV/cm field. Clearly, the applied electric field produces a significant extension in the filter life. The filter medium and operating conditions were the same as reported earlier.

The extent to which an electric field increases the service life of a filter depends on many variables, the most obvious one being the electric field itself. In general, one can say that the higher the electric field the greater the filter life extension, although the process may be highly nonlinear depending on other parameters. One parameter that has been shown to significantly affect the decrease in pressure drop is the fiber packing fraction. Lamb et al[12] have shown that filters having a low packing density show a greater decrease in pressure drop than filters with a high packing density. They suggest that the more open structure of filters with a lower packing density can accommodate significantly higher particle loadings than the more restricted structure of filters having high packing densities.

Lamb et al[12] have also shown that the packing density within most filters vary greatly, the outer surface having a much lower density than the interior portion. This variation in packing density is very beneficial to having a superimposed electric field. In the absence of an electric field, the particles penetrate to a region within the filter where the packing density is higher therefore forming a heavy particle deposit within the filter volume. However, with an electric field the particles are captured by fibers on the front face of the filter, where more particle deposits can be accommodated because the fiber packing density is very low. Lamb et al[12] supported this hypothesis with photographs of particle deposits in filters with and without an electric field.

4.2 Morphology of Particle Deposits During Filter Clogging

The morphology of the particle deposits in clogged filters is the most important factor controlling the increase in filter efficiency and pressure drop. Knowing how the deposits initially form and change at increasing particle loadings and under different conditions is important for understanding the experimental observations of clogged filters that were discussed in the previous section. Payatakes[13] has characterized filter clogging as a sequential process in which the morphology of particle deposits goes through the following four major stages:

1. Particles deposit directly on the filter fibers. The deposit morphology is characterized by isolated particles randomly covering the fiber surface.
2. Particles deposit preferentially on previously deposited particles as well as directly on the fiber surface. The deposit morphology is characterized by extensive surface coverage of particle dendrites.
3. Particles deposit almost exclusively on particle dendrites. The deposit morphology is characterized by the particle dendrites intermeshing with their neighbors forming a coat of particles with nonuniform thickness around each fiber.
4. Particles deposit exclusively on the intermeshing particle dendrites. The deposit morphology is characterized by particle deposits bridging the gap between neighboring fibers.

Stages 1-3 were observed in laboratory experiments with monodisperse polystyrene and methylene blue spheres deposited on individual fibers[14,16]. Payatakes[13] recognized that there is an extensive overlap between the various stages, not only on individual fibers, but also through the depth of a fibrous filter. In many cases, fibers deep within the filter are at stage 1 while the fibers close to the front surface are at stage 4.

We took a series of electron micrographs of the particle deposits at increasing levels of filter clogging to determine the morphology of the deposits with heterodisperse aerosols and real filters. Previous studies were conducted with monodisperse spheres deposited on a single fiber. Although these more basic experiments are easier to interpret, we wanted to establish the morphology of the deposits under real conditions. We felt that the non-ideal structure of real filters may either alter the deposit morphology or introduce additional variables to the deposit morphology observed in single fiber studies. The purpose of these electron micrographs was to qualitatively describe the morphology of particle deposits for use in constructing realistic models of filter clogging.

Figure 13A-F show a series of electron micrographs of sodium chloride deposits at increasing levels of filter clogging. These electron micrographs were taken on the front surface of AF-4 filters which have a median fiber diameter of $0.73 \mu\text{m}$ and $\sigma = 2.0$. The average charge on the particles was determined to be 13 electron units. Figure 13A represents the first stage of filter clogging in which captured particles form a random covering over the fiber surface. At increasing particle loading, the deposit then covers the fiber surface more or less uniformly as shown in Figure 13B. Once the fiber surface is sufficiently covered, the incoming particles are captured on the

A

B

C

D

E

F

Figure 13. Electron micrographs of particle deposits showing different stages of filter clogging on AF-4 filters.

previous deposits to form particle dendrites as illustrated in Figures 13C and D. As more particles deposit on the filter, the particle dendrites on each fiber intermesh and finally bridge the gap between neighboring fibers. These trends are seen in Figures 13E and F. In general, the morphology of the particle deposits at various stages of filter clogging shown in Figure 13A-F agree with previous studies on single fibers[14-16]. Although the final stage of clogging, the bridging of particle dendrites between neighboring fibers, could not be observed in the single fiber studies, it was an obvious extrapolation of the clogging process.

An important finding in our electron microscopy study was the extent to which the particle deposit morphology would vary within a given filter. Previous researchers[14-16] had recognized that there was a considerable overlap between different stages of filter clogging. The random nature of the particle trajectories was the primary reason for the overlapping stages of filter clogging. However, this overlap would generally occur between two sequential stages of filter clogging. For example, if a filter had an extensive covering of particle dendrites (stage 2), there would be a number of dendrites that would intermesh with neighboring dendrites (stage 3). At this level of filter clogging, it would be extremely unlikely to find a section of the fiber in stage 1.

In contrast to the single fiber studies, our studies on real filters show an extensive range of particle deposit morphologies coexisting within the same filter. Figures 13B and C are electron micrographs of different regions on the same filter. The deposits in Figure 13B are in stage 1 of filter clogging while the deposits in Figure 13C are in stage 2. Figures 14A, B and C show particle deposits at increasing magnification of another region within the same filter. These electron micrographs indicate that the particle deposits are in stages 3 and 4 of filter clogging. At the outer edges of Figures 14A the particle deposits have bridged extensively between neighboring fibers to the point where individual fibers are hardly visible. However, in the central region of Figure 14A, the particle deposits form a more or less uniform coating over individual fibers. Increasing the magnification within this region shows a very densely packed deposit that differs considerably from the more open structure seen in Figure 13E. We believe that the advanced stage of filter clogging in Figures 14A-C is due to the increased flow resulting from a less restrictive region of the filter. Davies[8] has described such preferential clogging in terms of plugging up holes in low quality filters.

The formation of a uniform coating around individual fibers or the bridging between neighboring fibers is determined by the presence or absence of a nearby fiber. Figure 15 illustrates the case where there is extensive bridging between neighboring fibers instead of a uniform coating around individual fibers. In contrast, the deposits in Figure 13E formed a more or less uniform coating around each fiber before bridging the gap between the two fibers. A final illustration of the variation in deposit morphology within a given filter is shown in Figures 16A-C. Although most of the deposits are in stages 2 or 3 of filter clogging, regions of the filter can be found with the particle deposits in stages 1 and 4. The filter media and experimental conditions used in generating Figures 15 and 16 were the same as used in Figures 13 and 14.

One of the primary reasons for our interest in the morphology of particle deposits is to understand the mechanism responsible for the lower pressure drop increase that occurs during filter clogging when an electric field is applied across the filter. To investigate this phenomenon we took a series of

14 A

14 B

14 C

Figure 14. Electron micrographs of particle deposits at increasing magnifications for a clogged AF-4 filter.

Figure 15.

Electron micrograph of a clogged AF-4 filter illustrating the bridging of particles across neighboring fibers.

16 A

16 B

16 C

Figure 16. Electron micrographs of particle deposits at increasing magnifications for a clogged AF-4 filter.

electron micrographs of filters that had been clogged either with or without a superimposed electric field. These electron micrographs are shown in Figures 17A-F. Figures 17A-C represent increasing magnifications of the particle deposits on the surface of an AF-18 filter with no electric field applied during filter clogging. The comparable case with an applied electric field is shown in Figures 17D-F. In these tests we used AF-18 filters, which have a median fiber diameter of $3.5 \mu\text{m}$ and $\sigma_g = 1.7$. We used these filters in this microscopy study because most of our previous experiments with a superimposed electric field were also conducted with these filters.

A comparison of the particle deposits in Figure 17A-C with those in Figures 17D-F show that the primary effect of the electric field is to increase the particle deposition on the front surface of the filter. Figures 17A-C show that, with no electric field, a heavy deposit of particles is formed below the top layer of fibers. The fibers on the surface have only a very light particle deposit that is characterized by filters in Stages 1 and 2 of filter clogging. In contrast, Figures 17D-F show that with an electric field, the major particle deposits occur on the surface fibers of the filter. Since the packing density of the fibers is considerably smaller on the surface than within the filter interior, particle deposits on the surface fibers will be less restrictive than those formed within the filter interior. This less

A

B

C

D

E

F

Figure 17. Electron micrographs of particle deposits at increasing magnifications for clogged AF-18 filters operated (A-C) with no electric field and (D-F) with an electric field.

restrictive deposit on the filter surface is partially responsible for the decreased pressure drop that occurs in filter clogging with an applied electric field. These observations have been previously reported by Lamb et al[12].

The understanding of filter clogging and the effects of an applied electric field requires an understanding of the filter efficiency. It is obvious that particle deposits can not form on fibers without first being collected on the fibers. Equation 1 can therefore be used to explain the major location of the particle deposits. The surface fibers in Figures 17A-C have a very light particle deposit because the fiber packing fraction, α , is very small and the fiber radius, R , is large. Moreover, for mechanical capture mechanisms, the single fiber efficiency, η , is inversely proportional to the fiber radius (see Equations 6 and 7). Therefore, according to Equation 1 the surface fibers will have a low particle collection because of the small α and large R values.

Figure 18 shows an electron micrograph of a surface fiber taken under similar conditions to those in Figures 17A-C. Although the filter itself was completely plugged, the surface fiber showed only a very light deposit. Also note that nearly all of the particle deposits in Figure 18 have a dendrite structure. This figure shows that the fiber has a very poor collection efficiency and particle collection occurs primarily on the particle dendrites. In contrast to Figures 17A-C and 18, the particle deposits seen in Figures 13-16 for the AF-4 filters are primarily on the surface fibers. Although the fiber packing fraction on the surface was also small, the small fiber radius of the AF-4 filters results in a high collection efficiency.

With an applied electric field the single fiber efficiency increases dramatically (see Equations 3, 4, 5, 8 and 9). This consequently increases the particle deposits on the surface fibers as seen in Figures 17D-F. The increased fiber efficiency for large diameter fibers with an applied electric field appears to produce similar particle deposits as the more efficient small diameter fibers. A comparison of Figures 14A-C with Figures 17D-F shows the similarity between the two deposits. The increased collection efficiency for the larger fibers in AF-18 filters having an applied electric field is also seen in Figures 19A and B. These figures are electron micrographs of particle deposits on the surface of AF-18 filters in which an electric field was applied. Figures 19A and B show a uniform and dense covering of particles over the fiber surface. This deposit is in sharp contrast to the very light particle deposits seen in Figure 18 for filter clogging in the absence of an electric field. Also note that most of the particles in Figures 19A and B are attached directly to the fiber whereas the particles in Figure 18 are attached to particle dendrites. This implies that in the presence of an electric field, the collection efficiency of the fiber is much greater than that of the particle dendrites. The opposite trend occurs without an electric field, where the collection efficiency of the fiber is very low and nearly all of the particles are captured on particle dendrites.

In our studies, the morphology of the particle deposit formed in the presence of an electric field appear to form a more uniform and densely packed deposit than the case without an electric field. This observation applies only for the early stages of filter clogging. This can be seen by comparing Figures 19A and B with Figures 13B and C. However, at the higher stages of filter clogging there appears to be little difference in the deposit morphologies with or without an electric field. This observation can be made

comparing the deposits in Figures 17D-F, which had a superimposed electric field, to the deposits in Figures 14A-C, which had no electric field. These findings are in sharp contrast with the results obtained by other investigators[17,18] for particle deposits on single fibers. They found that a superimposed electric field produces extremely long and linear particle dendrites. In the absence of an electric field the dendrites were short and highly branched. We have never seen this effect in our investigations.

Figure 18. Electron micrograph of a fiber on a clogged AF-18 filter operated with no electric field.

Figure 19. Electron micrographs of fibers on a clogged AF-18 filter operated with an electric field.

There are several possible explanations for this discrepancy. Oak and Saville[17] stated that the formation of the long dendrites was very sensitive to the fiber orientation. If the fibers were not perpendicular to the electric field, the dendrites would be shorter and more disorganized as occurs for dendrite formation in the absence of an electric field. Considering the random orientation of the fibers in our filter, this is a likely explanation for the discrepancy in the two studies. Another possible explanation is the coulombic forces in our filter tests which were not present in the single fiber studies[17,18]. We have previously described how a fiber charge can be developed through a charge transfer from deposited particles. Nielson and Hill[19] had performed theoretical calculations of particle deposit morphologies that resulted from a coulombic attraction between charged fibers and charged particles. Their results showed that the coulombic forces produced a more dense and uniform particle deposit over the fibers than would occur with only mechanical forces. Our experimental findings are in good agreement with his predictions. A third difference between our study and the single fiber experiments is the shape and size distribution of the aerosols. The aerosols in the single fiber experiments were monodisperse spheres while the sodium chloride aerosols in our study were heterodisperse and had cubic and irregular shapes. One would expect the monodisperse spheres to form long, straight particle chains much easier than the heterodisperse and irregular shaped aerosols in our study. Thus, it appears that the fiber orientation effects, the additional coulombic forces, and the irregular shape and heterodisperse size of the sodium chloride aerosols can account for the absence of long chain dendrites in our experiments.

An important aspect of the particle deposit morphology that we were unable to examine in our study was the deposit on the downstream side of the filter fibers. Particles can not deposit on the downstream side of the fibers with only mechanical forces. However, with electrical forces there can be a significant deposit. These findings have been substantiated in theoretical[5,19,20] and experimental[18,21] studies. Understanding the particle deposition on the downstream side of the fibers is important because of the dramatic increase in the available filtering area and the increased service life that results from particle loading on both sides of the fiber surface.

Based on these discussions on the morphology of particle deposits with and without an electrical field, we can propose another explanation for the decreased pressure drop at the same particle mass loading that is observed for filters operating with an electric field. The previous explanation was based on the electric field shifting the particle deposits from the interior, more dense region of the filter to the surface, more open region. In addition to this macroscopic change in the deposit location within the filter, we have shown that there is a microscopic change in the deposit around individual fibers. We have shown that in the early stages of filter clogging, the electric field tends to form a more uniform and dense deposit over the fiber surface than occurs without an electric field. However, at the later stages of filter clogging, the morphology of the deposits do not appear to differ significantly with or without an electric field. The electric field, therefore, has the net effect of extending the duration of the early stages of filter clogging. Having the particles deposit on the downstream side of the fibers is a significant factor in prolonging the initial stages of filter clogging.

4.3 Theoretical Models

In recent years there have been several new approaches to developing theoretical models that predict filter clogging and its effect on filter efficiency and pressure drop. These theoretical models can be classified as either phenomenological theories or kinetic theories. The phenomenological approach describes filter clogging by a set of equations in which new parameters are used to describe the increased efficiency and drag due to the particle deposits. Although these parameters can be obtained in laboratory experiments, they do not provide an understanding of the mechanisms responsible for the increased efficiency and drag. In contrast, the kinetic theories begin with the fundamental mechanisms that are responsible for particle capture and air resistance. The increased filter efficiency and drag are then determined from the geometry of the deposited particles.

The most fundamental of kinetic theories is the simulation model developed by Tien et al[22,23]. This model combines trajectory calculations of individual particles with a random distribution of approaching particles upstream of the fiber, thereby imparting a stochastic nature to filter clogging. The geometry of the particle deposits is a direct result of the simulation method and requires no assumptions. Although the simulation model is the most accurate representation of filter clogging, it does not yield analytical equations which can be used for further analysis such as optimization studies. By introducing certain assumptions about the nature of the particle deposits, Payatakes[13,24] has developed a kinetic theory of filter clogging that yields analytic equations for the filter efficiency and pressure drop. His model retains all of the essential features of the particle trajectory calculations used in the simulation model. However, because of the approximations in the particle deposit geometry, additional features like the shadow effect[22] have to be added to the model. An important aspect of Payatakes' theory is the experimentally obtained parameters used in the phenomenological theories can be calculated from his theory[25].

Until the development of the kinetic theories described above, the phenomenological theories were the only means for theoretically describing filter clogging. Unfortunately, the parameters used in the phenomenological theories must be experimentally determined for each set of conditions, thereby severely restricting the method. A potentially more serious handicap of these theories is the variety of different forms of the basic differential equations[26]. The filter parameter values used to describe filter clogging will consequently vary with the different equations. We can illustrate this problem with the following equation for describing the relative decrease in particle concentration, N , across a filter element of thickness, X ,

$$-\frac{dN}{Ndx} = \lambda F(\alpha_p, \beta) \quad (13)$$

$$-\frac{dN}{Ndx} = \lambda + G(\alpha_p, \beta) \quad (14)$$

where λ is the filter coefficient for a clean filter. F and G are functions of the particle volume fraction, α_p , and the parameter, β , representing the increased particle capture. Since the functions F and G can be selected to fit the experimental data, either equation can be used to determine the increased efficiency during filter clogging. Other equations can also be

found to show an increased particle capture with increased filter clogging. These illustrations show that the fundamental problem with the previous phenomenological theories is the empirical nature of the differential equations. Moreover, the additional filtration parameters were incorporated into the equations with little regard to the mechanisms responsible for the increased efficiency and resistance.

Bergman et al[2,3] have recently developed a new approach to the phenomenological theories that eliminates the empirical nature of these theories. The formulation of this theory can be viewed as an extension of the single fiber theory applied to filter clogging. According to the single fiber theory[6]

$$\frac{-dN}{N} = \left(\frac{v}{VA} \right) da_f \quad (15)$$

where v is the average air velocity within the filter, V is the face velocity, A is the filter area and a_f is the total effective cross section area of the fibers. The variable a_f equals the product of the single fiber efficiency, η_f , and the total geometric cross section area of the fibers ag_f . It is important to note that the detailed mechanisms for particle capture by the fibers are all lumped in the parameter η_f . Equation 15 can also be integrated to yield Equation 1 after substituting for the fiber areas.

The extension of the single fiber theory was developed as follows. For a clean filter, incoming particles are only captured by the filter fibers. However for clogged filters, incoming particles can be captured either by the filter fibers or by previously captured particles. If the geometry of the previously deposited particles does not have a separate identity from the original fibers, then Equation 15 is still adequate to describe particle capture. Such a case would be represented by a close packed deposit on the fiber surface. The primary effect of this deposit would be to increase the fiber size. However, if the geometry of the previously deposited particles has a separate identity from the original fibers, then a new term must be added to Equation 15.

In analogy to the single fiber theory, this new term would be the effective cross section area of the particle deposits and the phenomenological equation would be

$$\frac{-dN}{N} = \frac{v}{VA} (\eta_f da_{GF} + \eta_p da_{GP}) \quad (16)$$

η_p is the efficiency factor for the particle deposits which have a geometric cross section area of ag_p . The detailed mechanism for particle capture by the particle deposits are included within the parameter η_p . Equation 16 also represents the generalized case where particles from closely packed deposits on the fibers as well as separate structures like dendrites. In analogy with the single fiber model, all of the interference effects between neighboring fibers and particle deposits are included within the efficiency factors. The corresponding phenomenological equation for the pressure drop during filter clogging is

$$d(\Delta P) = \mu V (C_{fd} a_{GF} + C_{pd} a_{GP}) \quad (17)$$

where C_f and C_p are the resistance coefficients for the fibers and particle deposits respectively. Using these generalized phenomenological equations, Bergman et al[2,3] have developed equations for the filter efficiency and pressure drop during filter clogging.

Once the general phenomenological equations for filter clogging are available, the problem of deriving theoretical equations is reduced to the problem of selecting appropriate functions for the geometric cross section areas of the fibers and particle deposits. The cross section area of a clean filter is $2RL$ where L is the projected length of the fibers within the filter element. Substituting this into Equations 16 and 17 and simplifying yields the fundamental equations for filter efficiency and pressure drop. Although the general practice has been to leave the efficiency coefficients for particle capture, η , in the final equation, this was not the case for the pressure drop equation. Most investigators have substituted either a theoretical or empirical function for the resistance coefficient.

The most important aspect in developing the phenomenological equations of filter clogging is the proper selection of the cross section area of the particle deposits and the fibers. The scanning electron micrographs of the particle deposits in Figures 13-19 show that the deposits have a very complex geometry that varies considerably over the filter fibers and during the clogging process. An accurate mathematical description of these deposits appears to be hopeless. Because of the complexity of the deposits, we have constructed idealized deposit geometries that are mathematically simple to describe and yet retain the essential features of the deposits.

Figure 20 shows a schematic of the idealized particle deposits that we used in deriving theoretical equations for the filter efficiency and pressure drop. We have shown three different geometries of the particle deposits, each of which has a different function for the cross section area. Each of these geometries yields a different set of equations for the pressure drop and efficiency during filter clogging. The dendrite model is characterized by a series of particle chains, i.e. dendrites, extending from the fiber surface. Photographs of the particle dendrites in previous single fiber studies[14-18] look very much like the dendrite model. The closest approximations to this model in our experiments are seen in Figures 13D, 15 and 16B and C where the particle deposits are in an advanced stage of clogging.

The increasing fiber model represents a geometry where the particles are more or less closely packed around the fiber and have the effect of increasing the fiber radius. We would expect that the initial particle deposits on a clean fiber, with or without an electric field, could be approximated by this model. The particle deposits shown in Figures 13A and B and 19A and B can be represented by the increasing fiber model. In these cases the particles cover the fiber surface prior to dendrite growth. In certain cases, the increasing fiber model can also be used to represent particle deposits in a heavily loaded filter as shown in Figures 14A and B and 17E and F.

The increasing fiber model and the dendrite model of filter clogging represent limiting cases of a more realistic model shown in Figure 20 as the combined model. An example of this type of deposit can be seen in Figure 13C where the particle deposits form a rough coating over the fiber in addition to particle dendrites. All three models in Figure 20 show the particle deposit on the front side of the fiber, as would be expected for mechanical collection.

Figure 20. Schematic of the particle deposits used in the three filter clogging models.

However, if particles are collected by electrical forces the deposits can also form on the back side of the fibers. Our phenomenological theory can readily accommodate deposits around the entire fiber.

The combined model can be viewed as a combination of dendrite and increasing fiber models, the proportion of the two models changing with different stages of filter clogging. In the beginning (stage 1) the particle deposits on a clean fiber can be characterized in terms of the increasing fiber model. However, once a sufficient number of particles have deposited, particle dendrites begin to form (stage 2) and the deposit begins to resemble the dendrite model. At increasing levels of clogging the neighboring dendrites intermesh (stage 3) and the deposit once again resembles the increasing fiber model. These models finally break down at the final stage of filter

clogging where particle deposits bridge the gap between neighboring fibers and form an internal cake (stage 4). However when the filter finally reaches this stage it is generally thrown away or cleaned. A mathematical description of this stage of clogging is therefore not as important as the earlier stages.

One of the most important properties of the deposit geometry is the resistance to air flow. For a given amount of deposit, the dendrite model has the highest air resistance while the increasing fiber model has the least. Understanding the factors that control the deposit geometry is important for understanding how the filter resistance changes during filter clogging.

The idealized models of particle deposits in Figure 20 are then used to derive equations for the filter efficiency and pressure drop. The key step in this process is to determine the cross section area of the deposits. For the dendrite model, the area was determined by treating the particle chains as fibers having a given fiber diameter and a length. The diameter of the particle chains must be greater or equal to the particle diameter. Although the concept of treating particle dendrites as short fiber segments is initially strange, we can not think of a better geometric equivalent to the particle chain. However since the fiber segments (i.e. dendrites) are attached to the primary filter fiber, there will be a significant hydrodynamic interference between fibers and dendrites. This hydrodynamic interference can be theoretically treated in the same fashion as the interference between neighboring fibers in a tightly packed fibrous filter. Disregarding this

interference effect, the accuracy of approximating particle dendrites as fibers will improve the larger the dendrites. Thus, we would expect the dendrite model to approximate filter clogging at the higher stages of clogging.

We can demonstrate that particle dendrites can be treated as newly formed fibers. Figure 21 shows three graphs of filter efficiency plotted as a function of particle diameter. The two solid curves were taken from Figure 11, one representing a clean AF-18 filter (median fiber diameter is $3.5 \mu\text{m}$) and the other representing the same filter after being clogged with 5.7 g of sodium chloride aerosols. The number median diameter of the aerosols was $0.28 \mu\text{m}$. Figure 21 also shows a dashed curve representing the efficiency of a clean AF-4 filter which has a median fiber diameter of $0.73 \mu\text{m}$. Note that this filter has nearly the same efficiency as the filter with a large fiber size but clogged with small diameter particles. The particle deposits have effectively transformed the large diameter fibers into small diameter fibers. It would be very difficult to distinguish the clean filter with the small diameter fibers from the clogged filter with the large diameter fibers. This point is further illustrated in Figure 8, which shows the average filter efficiency and pressure drop during filter clogging for the same two filters. The efficiency and pressure drop of the filter with the large diameter fibers increases with filter clogging until a point is reached where it can not be distinguished from the clean filter with the small diameter fibers. Based on the observations in Figures 8 and 21 it became very appealing to think of particle dendrites in terms of newly formed fibers.

Once the dendrites are treated as newly formed fibers, the geometric area of the deposit can be calculated in the same fashion as the original fibers. The geometric area of the clean fibers, a_{gf} , and particle fibers, a_{gp} , are

Figure 21. Comparison of the filter efficiencies as a function of particle size for a clean AF-4 filter with a clean and clogged AF-18 filter.

then substituted into Equations 16 and 27. After simplifying the results we have the following equations for the penetration, P , and the pressure drop, ΔP , during filter clogging.

$$P = P_0 \exp - \left(\frac{\pi V t r^2 N_0 \eta_p}{2} \right) \quad (18)$$

$$\Delta P = \Delta P_0 \left(1 + \frac{R \alpha_p}{r \alpha_F} \right) \left(1 + \frac{R^2 \alpha_p}{r^2 \alpha_F} \right)^{1/2} \quad (19)$$

Details of the derivation were given in a previous publications[3]. The penetration, P_0 , and pressure drop, ΔP_0 , for the clean filter are given by Equations 1 and 20 respectively.

$$\Delta P_0 = 16 \mu V x \alpha_F^{3/2} / R^2 \quad (20)$$

Equation 20 is a simplified version of Davies'[27] empirical equation for the pressure drop.

Theoretical equations of the penetration and pressure drop can also be derived for the increasing fiber model. Since the particle deposits in this case do not have an identity separate from the original fiber, the area, a_{gp} , is zero. The clogging effects due to particle deposits are incorporated in the area of the fiber, a_{gf} , by allowing the fiber diameter to increase as the deposits increase. Substituting this increasing area function, a_{gf} , and $a_{gp} = 0$ into Equations 16 and 17 yields.

$$P = P_0 \exp - \left[\frac{16 r^3 V t N_0 \eta_2}{(1 - \alpha_F) \pi R_0} \right] \quad (21)$$

$$\Delta P = \Delta P_0 \left(1 + \frac{12 \alpha_p}{\pi \alpha_F} \right)^{1/2} \quad (22)$$

where the penetration, P_0 , and pressure drop, ΔP_0 , for the clean filter are given by Equations 1 and 20 respectively. The details of this derivation were also given previously[3]. We have not yet derived the corresponding equations for the combined model. Note that the effect of the electric field is not explicitly incorporated in these theoretical equations. Since the derivations of these equations were based on the geometry of the particle deposits, they can be used to explain filter clogging with and without an electric field.

We have tested our theoretical models with laboratory experiments and find good qualitative agreement. These comparisons were made primarily with the dendrite model using Equations 18 and 19. We found that the dendrite model is a better representation of the deposit morphology than the increasing fiber model for the major portion of filter clogging. However during stage 1 of filter clogging, the increasing fiber model appears to be more accurate.

Figure 22. Pressure drop data from Figure 9 replotted to normalize the pressure drop increase for different face velocities.

The experimental parameters that were tested against the dendrite model were the effects of face velocity, particle size and applied electric field. Figure 9 shows the significant decrease in pressure drop that occurs during filter clogging when the face velocity is reduced. According to Equations 19 and 20 the pressure drop increases in direct proportion to the face velocity at any level of filter clogging. Therefore replotting the data in Figure 9 as $(\Delta P - \Delta P_0)/V$ should normalize the increase in pressure drop with respect to the face velocity at any stage of filter clogging. Figure 22 shows good agreement with these theoretical predictions.

The effect of particle size on filter clogging, previously seen in Figure 10, showed that the smaller particle sizes accelerate the increase in pressure drop compared to the larger particle sizes. This data was generated using HEPA filters, which characteristically have a very small fiber radius, R , and a large fiber packing fraction, α_F . Under these conditions, the square root term in Equation 19 reduces to 1 because the factor $R^2 \alpha_F / r^2$ becomes vanishingly small. The increase in pressure drop is then inversely proportional to the particle size and plots of $(\Delta P - \Delta P_0)r$ versus particle mass will be independent of particle size. Replotting the data from Figure 10 in this fashion in Figure 23 confirms this theoretical prediction.

The final comparison of our theoretical clogging models with laboratory experiments is shown in Figure 12. This figure shows the significant effect of an applied electric field on lowering the pressure drop during filter clogging. We have also plotted the theoretical curves for the dendrite and increasing fiber models using Equations 19 and 22 respectively. The small difference in the initial pressure drop is due to slight variations in the two filters. Figure 12 shows that the filter having the applied electric field closely follows the pressure drop predicted by the increasing fiber model at low particle mass. However, at high mass loadings the electrostatic filter deviates sharply from the increasing fiber model and tends to follow the rate predicted for the dendrite model. The filter without an electric field also follows a similar trend, first approximating the increasing fiber model and then approximating the dendrite model as the filter begins clogging with particles. Comparing the two cases with and without an applied electric field shows the primary effect of the electric field is to delay the formation of

Figure 23. Pressure drop data from Figure 10 replotted to normalize the pressure drop increase for different particle sizes.

dendrites. Electron micrographs have shown that the electric field produces a more uniform particle coverage over the fiber surface prior to dendrite formation than occurs without an electric field (compare Figures 19A and B with Figures 13A and B). Having the particles deposit on the downstream side of the fiber due to electrostatic attraction, further increases the amount of deposit on the fiber before the rapid formation of dendrites.

Based on the successful comparisons between the three experimental findings and our theoretical clogging models, we can conclude that our clogging models provide a good qualitative prediction of observed results. However, using our theoretical models to analyze the effects of an electric field on filter clogging is only partially correct. The theoretical models describe the effects of filter clogging only in terms of individual fibers. They do not include the macroscopic shift in particle deposit toward the filter surface when an electric field is used. This shift in particle deposits produces a decrease in the pressure drop if the fiber packing density is much lower at the filter surface than in its interior.

5. SUMMARY

The Lawrence Livermore National Laboratory has a comprehensive program funded by the U. S. Department of Energy to investigate the use of electrofibrous filters in the nuclear industry. The objective of this program is to develop prototype filters that will be used as prefilters to reduce the load on HEPA filters. Although the program also includes prototype development and field evaluations, we have only presented the results from our theoretical modelling and small-scale laboratory experiments. These theoretical and laboratory studies will be used to optimize the design of our prototype filters.

The fibrous filters in this investigation were converted to electrostatic operation by applying a nonionizing electric field across the filter medium. Compared to a conventional fibrous filter, the electrostatic filter has a

higher efficiency and a longer, useful life. The increased efficiency is attributed to a time independent attraction between polarized fibers and charged, polarized particles. The charge on the fibers results from a dynamic process of charge accumulation due to the particle deposits and a charge dissipation due to the fiber conductivity.

Much of this paper was devoted to characterizing filter clogging and its effect on filter efficiency and pressure drop. Experiments were conducted that illustrated the effects of particle mass accumulation, particle size, face velocity and a superimposed electric field. One of the most important findings in our study showed that the particle deposits can be treated as newly formed fibers.

We also conducted an extensive microscopy study of the deposit morphologies during the various stages of filter clogging. Although these micrographs are in general agreement with previous studies on single fibers, they showed that the deposit morphologies can vary significantly within the filter. In the beginning stages of filter clogging the deposited particles form a random coating over the fiber surface. At high particle loadings, the deposits are characterized by particle dendrites extending from the fiber surface. Mathematical models of these limiting stages were developed by treating the initial surface covering as an increase in fiber diameter and the particle dendrites as newly formed fibers.

The extension in filter life with an applied electric field is due to changes in the particle deposition around individual fibers on a microscopic scale and changes in the particle deposition through the filter bed on a macroscopic scale. On the microscopic scale, the effect of the applied electric field is to delay the formation of particle dendrites on the fibers. The air resistance of a fiber with a uniform particle surface coverage is significantly less than that of a fiber covered with particle dendrites. On a macroscopic scale, the increase in filter efficiency due to the electric field causes the particle deposit to form closer to the filter surface than occurs for the nonelectrified filter. Since the fiber volume fraction at the filter surface is less than it is within the filter bed, the particle deposits near the surface will produce a lower pressure drop than the same deposits within the filter bed. These changes result in a lower pressure drop across the filter than would occur without an electric field.

SYMBOLS USED

A	= filter cross sectional area (m^2).
A_F	= effective fiber area (m^2).
a_p	= effective particle area (m^2).
a_{GF}	= geometric fiber area (m^2).
a_{GP}	= geometric particle deposit area (m^2).
α	= total or fiber volume fraction.
α_F	= fiber volume fraction.
α_p	= particle volume fraction.
β	= parameter representing increased particle capture during filter clogging.
C	= Cunningham correction factor.
C_1, C_2, C_3, C_4, C_5	= constants.
C_F	= resistance coefficient for fibers.

C_p	= resistance coefficient for particles.
γ	= fiber conductivity (S).
E	= effective electric field strength (V/m).
e	= elementary unit of electric charge (C).
ϵ_F	= dielectric constant of filter.
ϵ_p	= dielectric constant of particle.
ϵ	= permittivity of fiber (F/m).
F	= function describing increased particle capture during filter clogging.
G	= function describing increased particle capture during filter clogging.
k_1, k_2	= constants.
L	= total fiber length (m).
λ	= filter coefficient for a clean filter.
μ	= viscosity of air (Pa.s).
N	= particle number concentration (m^{-3}).
N_0	= initial particle number concentration (m^{-3}).
n	= number of elementary charge units.
η	= total single fiber efficiency.
η_M	= single fiber efficiency for mechanical capture mechanisms.
η_D	= single fiber efficiency for diffusion capture mechanisms.
η_i	= single fiber efficiency for electrical capture mechanisms.
η_I	= single fiber efficiency for inertial impaction capture mechanism.
η_p	= single fiber efficiency for the polarized-fiber, polarized-particle capture mechanism.
η_{pq}	= single fiber efficiency for the polarized-fiber, charged particle capture mechanism.
$\eta_{p'q}$	= single fiber efficiency for the charged-fiber, polarized-particle capture mechanism.
η_2	= sum of the single fiber efficiencies that are independent of the fiber radius.
η_p	= efficiency factor for particle capture by particle deposits.
η_F	= efficiency factor for particle capture by fibers.
η	= filter efficiency
P	= filter penetration
P_0	= initial filter penetration.
ΔP	= filter pressure drop (Pa).
ΔP_0	= initial filter pressure drop (Pa).
Q	= fiber charge (C).
Q_{ss}	= steady state fiber charge (C).
R	= fiber radius (m).
R_0	= initial fiber radius (m).
r	= particle radius (m).
t	= time (s).
V	= filter face velocity (m/s).
v	= air velocity inside filter (m/s).
x	= filter thickness (m).

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