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ABSTRACT

A laboratory apparatus has been constructed for testing two HEPA filters in a series configuration. The apparatus consists of an instrumented wind tunnel in which the HEPA filters are mounted, and an auxiliary wind tunnel for obtaining diluted samples of the challenge aerosol upstream of the first filter.

Measurements performed with a single particle aerosol spectrometer demonstrate the capability for measuring overall protection factors of greater than 2.5×10^8 . The decay of penetration as a function of time in individual HEPA filters indicates no preferential size discrimination in the range of $0.1 \mu\text{m}$ to $1.0 \mu\text{m}$; nor is there a preferential size discrimination of penetration in this same range.

A theoretical feasibility study has been performed on the use of an inhomogeneous electric field/induced aerosol electric dipole interaction for potential use as an air cleaning mechanism. Numerical evaluation of a coaxial cylinder geometry indicates that the method is feasible for collection of particles down to $0.1 \mu\text{m}$ under typical airflow velocity conditions. Small modifications in the geometry may be incorporated to create an instrument capable of measuring particle size. Geometries other than coaxial cylinders are also under investigation.

I. SUMMARY

An optical aerosol spectrometer was used to measure the protection factor of two HEPA filters in tandem configuration. Adequate sensitivity exists to measure protection factors of 2.5×10^8 during 10-min periods of testing without substantially increasing the pressure drop across the filter system. Increases in spectrometer sensitivity and challenge aerosol concentration, and use of a less physically dense aerosol show promise of increasing the sensitivity of the method to measure protection factors of 10^9 .

Similar measurements on individual filter stages challenged by solid aerosol particles display a penetration which decreases exponentially with time and appears to be independent of particle size in the range 0.1 to $1.0 \mu\text{m}$. The penetration half-lives of the 7 filters measured varied from 1.6 to 13.5 min.

Calculations were performed on the feasibility of collecting uncharged particles down to $0.1 \mu\text{m}$ in an inhomogeneous electric field via an induced electric dipole interaction. The calculations reveal that efficient collection will occur for flow velocities equivalent to those in use in electrostatic precipitation and HEPA filter systems and with lower power requirements than the former and less flow impedance than the latter. A further advantage over HEPA filters is reduction in solid waste. A simple design modification in conjunction with a single particle detector (optical or piezoelectric) appears capable of transforming the device into a size spectrometer. Geometries other than cylindrical, e.g., quadrupole, are also under study.

II. TEST METHODS FOR TANDEM HEPA FILTER INSTALLATION

A. Introduction

HEPA filters used for air cleaning purposes by ERDA contractors are frequently arranged in a tandem configuration of two or more filter banks. In some facilities two banks of filters are mounted back-to-back on a common frame. New design criteria¹ preclude this configuration since present in-place test methods can only define protection factors of 10^4 . If more sensitive test methods were developed, performance of existing tandem filter banks could be validated, and simpler and less expensive designs used in future installations. Existing in-place test methods only permit measurements of the efficiency of individual stages rather than the entire system. In existing facilities a large decrease in operational downtime and worker exposure could be realized by such a test method. The design of new facilities should also become simpler and less expensive. Since it is far more desirable to measure entire system performance, i.e., protection factors of order 10^9 , a laboratory scale experiment has been initiated to determine the feasibility of such a measurement.

B. Background and Test Apparatus

The design criteria for the laboratory scale experiment were predicated on the method to be used for measurement of downstream aerosol concentration. Considering the protection factor desire, an initial challenge of 10^9 particles/liter would be attenuated, after passage through 2 HEPA filters, to as little as one particle/liter. Greater challenge concentrations (of approximately $0.3 \mu\text{m CMD}$) would load the first filter so excessively that the testing procedure would be destructive. A conventional forward light-scattering photometer² is incapable of measuring the low concentrations anticipated downstream of two HEPA filters. Filter sampling, even with a tracer aerosol such as uranine, would require impractically long sampling periods to obtain a detectable concentration. The required sensitivity dictated a device capable of counting and measuring single particles.

A sensitive, laser operated, optical single particle counter and spectrometer was chosen as the detector. This device relies on the scattering of laser light at 633 nm within the optical cavity of a He-Ne laser. The He-Ne laser, being a low gain

device, has an intra-cavity radiation field some 500 times as great as the rated output power. It is the scattering³ of this intense field by a particle, which is detected and measured. The detector signals are sorted and stored in a 16-channel multi-channel analyzer. By use of a range selection switch, a size spectrum in $0.1 \mu\text{m}$ increments; from $0.1 \mu\text{m}$ to $5.0 \mu\text{m}$ may be measured in concentrations as high as $10^7/\text{liter}$ with less than 1% coincidence error.

A laboratory wind tunnel was constructed for testing two $20.3 \text{ cm} \times 20.3 \text{ cm} \times 10.2 \text{ cm}$ (8" x 8" x 4") HEPA filters in tandem (Fig. 1). This system is simply a scaled-down version of a typical HEPA industrial system, the flow volume per unit filter surface area being the same in both cases. In this manner, the feasibility of the measurement could be verified without the necessity of first building a high volume challenge aerosol generator. Clean air was provided by filtration of room air through a $30.5 \text{ cm} \times 30.5 \text{ cm} \times 15.3 \text{ cm}$ (12" x 12" x 6") filter. The design airflow was 25 cfm and appropriate orifice plates for flow measurements, isokinetic probes for sampling, and pressure gauges at each filter station were incorporated into the system. In order to enable measurements of the challenge concentration upstream of the first filter, a diluter stage consisting of a second wind tunnel was also constructed so that 0.2% of the challenge aerosol could be sampled by the diluter and measured by the optical single particle counter. The dilution ratio is variable and is confirmed by either filter sampling or photometer sampling of the challenge and diluted aerosol. A six stem (24 jet) Collision type aerosol generator (Fig. 2) was constructed to provide the challenge aerosol.

C. Challenge Aerosol Characterization

Initial testing was performed using a 5% NaCl + 0.1% uranine solution. The 0.1% uranine was sufficient to provide fluorometer readings of filter samples that were taken to obtain dilution ratios of samples obtained upstream of the first HEPA filter, and determine protection factors of HEPA #1 if desired. The mode of the size distribution, as measured with the spectrometer, was $0.2 \mu\text{m}$. A plot of the cumulative distribution function on log-normal probability paper (Fig. 3) produced a straight line fit for the aerosol size spectrum from $0.1 \mu\text{m}$ to 0.9

μm and then curved over in the region $0.9 \mu\text{m}$ to $1.5 \mu\text{m}$, indicating an excess number (as compared to the log-normal distribution) of particles in the larger size range. This departure may perhaps be explained by collision and subsequent agglomeration of particles due to electrostatic charge and high concentration of $10^6/\text{cm}^3$. The log-normal part of the distribution yielded a value of count median diameter of $0.26 \mu\text{m}$ and geometric standard deviation of 2.42. The mode as computed from CMD and σ_g is $0.12 \mu\text{m}$ as compared to the observed value of $0.20 \mu\text{m}$. The difference in the values is consistent with the accuracy of the measurements and the deviation of the distribution from log-normal. A similar measurement (Fig. 3) made downstream from the first filter essentially duplicates the challenge aerosol result, indicating no size discrimination by the filter.

Filter sampling of the generator output yielded a loading factor of 3.10 grams/hr of dry aerosol on the first HEPA filter, as determined by the uranine tracer. This loading produced a 15% increase in pressure drop across the filter during an 11-min test run. The spectrometer total count reading at the diluter, corrected for the dilution factor, was 7.5×10^5 particles/ cm^3 above $0.1 \mu\text{m}$ (lower limit of spectrometer) in size. This is very close to the generator design figure of 10^6 particles/ cm^3 , particularly since that portion of the spectrum below 0.1μ has not been included. These count figures yield an arithmetic mass mean particle diameter of $0.44 \mu\text{m}$.

D. Single HEPA Filter Protection Factor

Three individual HEPA filters were measured by taking filter samples upstream and downstream from the filter and analyzing for uranine. Because of the low downstream concentrations, sampling periods of 30 min or more were required. In Table I below, the specified protection factors are those computed from the penetration figures provided with the filter, based on $0.3 \mu\text{m}$ DOP quality control tests at Hanford.

The purpose of these tests was to compare the quality control testing performed using a DOP challenge and a forward light-scattering photometer with the testing performed using solid NaCl aerosol. Forward light-scattering photometers are advertised to measure total mass. The uranine tracer also does this, so the measurements should be comparable except for the difference in challenge aerosol and

TABLE I
PROTECTION FACTOR BY TYPE OF PENETRATION

DOP PENETRATION ($0.3 \mu\text{m}$ DOP)	NaCl PENETRATION Polydisperse/NaCl + uranine
<u>Specified</u>	<u>Measured</u>
7.14×10^3	1.76×10^5
6.25×10^3	1.23×10^5
7.14×10^3	3.65×10^4

loading due to the long time required to obtain filter samples.

In all cases, the measured protection factor is considerably higher. One reason for this will become apparent from the following experiment, using real time continuous counting, which makes manifest the decrease in penetration with time.

A filter with DOP quality control protection factor of 8.3×10^3 was monitored for 11 sequential 2-min periods, for a total of 22 min, using the aerosol spectrometer. The penetration of this filter decayed exponentially with a half-life of 4.5 min. This same penetration decay was consistent for all size ranges, i.e., penetration was not size dependent for particles between 0.1 and $1.0 \mu\text{m}$ (Fig. 4). Extrapolation to zero time sampling yielded a count protection factor of 9.8×10^4 , an order of magnitude greater than determined by DOP quality control testing.

A similar experiment was conducted with a second filter with a DOP quality control determined protection factor of 7.1×10^3 . The penetration for this filter remained constant for 8 min and then assumed an exponential decay with half-life of 1.9 min as shown in Fig. 5. Spectral decomposition of the decay rates indicated some variation as a function of size, but probably within the figure of merit associated with the data. The initial constant penetration was probably due to a leak which finally was plugged by the challenge aerosol. Even so, the measured protection factor was 1.1×10^5 , more than an order of magnitude greater than the DOP figure.

While performing these and subsequent tests, substantial leaks were discovered in the cases of several of the test filters. A coating of RTV cement was sufficient to stop the leaks.

E. Multiple HEPA Filter Protection Factors

The procedure used for testing two cascaded HEPA filters is as follows. Background counts downstream of each filter section were made with the aerosol spectrometer and external leaks sealed until the count rate was less than 1 per 10-min interval. This was done with a 25 cfm airflow with no aerosol generation. With the generator turned on, a 1-min sample was taken downstream of the first filter. A subsequent 10-min sample was then taken downstream of the second filter. Samples were then obtained downstream of the first filter for 10 more 1-min sample periods so that an interpolated (back to time zero) penetration decay curve could be obtained. A 1-min sample was taken at the diluter stage and the dilution factor was determined by photometer and/or filter samples obtained between the diluter and the main wind tunnel.

Table II summarizes the results of the 6 sets of filters measured.

P is the protection factor, the subscripts refer to the position of the filter (1, 2 or 2 + 1), and whether this is a DOP quality control determined (s) or measured (m) value. The values of P_{21m} are

TABLE II
PROTECTION FACTOR

Filter Number	Quality Control (0.3 μ m DOP)	Measured (NaCl + Uranine)
I		
184 948	$P_{1s} 7.2 \times 10^3$	$P_{1m} 1.1 \times 10^5$
184 961	$P_{2s} 1.3 \times 10^4$	$P_{2m} 1.5 \times 10^3$
	$P_{21s} 9.4 \times 10^7$	$P_{21m} 1.6 \times 10^8$
II		
184 961	$P_{1s} 1.3 \times 10^4$	$P_{1m} 1.7 \times 10^4$
184 951	$P_{2s} 1.0 \times 10^4$	$P_{2m} 8.2 \times 10^2$
	$P_{21s} 1.3 \times 10^8$	$P_{21m} 1.4 \times 10^7$
III		
184 949	$P_{1s} 1.0 \times 10^4$	$P_{1m} 3.2 \times 10^4$
184 947	$P_{2s} 4.2 \times 10^3$	$P_{2m} 6.6 \times 10^3$
	$P_{21s} 4.2 \times 10^7$	$P_{21m} 2.1 \times 10^8$
IV		
184 953	$P_{1s} 1.3 \times 10^4$	$P_{1m} 2.8 \times 10^5$
184 947	$P_{2s} 4.2 \times 10^3$	$P_{2m} 1.5 \times 10^2$
	$P_{21s} 5.5 \times 10^7$	$P_{21m} 4.1 \times 10^7$
V		
184 984	$P_{1s} 8.3 \times 10^3$	$P_{1m} 4.7 \times 10^4$
184 947	$P_{2s} 4.2 \times 10^3$	$P_{2m} 5.1 \times 10^3$
	$P_{21s} 3.5 \times 10^7$	$P_{21m} 2.4 \times 10^8$
VI		
184 952	$P_{1s} 1.3 \times 10^4$	$P_{1m} > 1.3 \times 10^5$
184 947	$P_{2s} 4.2 \times 10^3$	$P_{2m} > 1.8 \times 10^3$
	$P_{21s} 5.5 \times 10^7$	$P_{21m} > 2.4 \times 10^8$

actual measured operational values integrated over a 10-min interval and have not been corrected for the penetration decay of the first filter. Such a correction would decrease P_{1m} and would be applied to P_{21m} hence decreasing it. The values of P_{2m} are derived from the ratio of P_{21m}/P_{1m} . To re-iterate, P_{1m} is the zero-time first filter protection factor, and P_{21m} is the overall factor for a 10-min period during which the penetration of the first filter is constantly decreasing. The product of P_{1s} and P_{2s} yields P_{21s} . During an 11-min period of testing, the pressure drop across the first filter increases by about 15%. This loading makes it mandatory that, at least with a NaCl challenge aerosol, the testing period be kept as short as possible. It may be that a DOP challenge aerosol will not present this problem. This hypothesis will be checked.

These preliminary measurements indicate that overall protection factors as high as 2.5×10^8 can be measured during a 10-min integration period. A physically less dense aerosol coupled with a spectrometer sensitive to 0.05 μ m particles may extend the measurements to 1×10^9 .

There is little consistency between the DOP quality control determined protection factors and those measured using the optical particle counter. This is to be expected on the grounds that the forward light-scattering photometer, at best, is good only to somewhat over 3 orders of magnitude, being signal/noise ratio-limited at the high sensitivity end and probably photomultiplier tube-saturated in the low sensitivity region. Further discrepancy is to be expected because of the difference in size distribution and optical properties between DOP and NaCl aerosols. The 3 to 4 order of magnitude measurement capability of the forward light-scattering photometer is adequate for single stage measurements if size discrimination effects due to the filter are not incurred. If size discrimination does occur, then because of the scattering dependence on particle size,⁴ the photometer measures the ratio of light scattered from the populations rather than the ratios of particle counts or of mass. In any case, it does not measure or count individual particles and therefore does not provide an absolute measurement.

An unexplainable discrepancy appears for filter #184 947, where the derived P_{2m} values in data III, V, and VI are reasonably consistent, but not for data IV.

The extrapolated first filter decay curves provide widely scattered penetration decay rates with a range of half-lives of 1.6 min to 13.5 min, with an average of about 4 min.

F. Future Work

A newer model spectrometer with increased sensitivity (to 0.05 μ m) will be procured. A less dense aerosol, such as pure uranine or DOP will be employed in order to decrease the ratio of aerodynamic to geometric size, thereby possibly increasing the penetration. A 5% uranine solution will make it possible to acquire short period HEPA #1 penetrations for direct comparison to the spectrometer readings. Additional data on the spectral features of penetration decay will also be acquired. This latter data is required in order to determine if there is a preferential size that penetrates HEPA #1 and therefore has a higher probability of penetrating the system.

Extrapolation of the measurement to large (1000 to 10 000 cfm) systems will initially be performed using a thermal DOP generator.⁵ The basic problem that will be encountered is producing the 10^9 particle/liter challenge concentration for such systems. This will require generation capabilities of 40 to 400 times that of the prototype laboratory system. It may also be necessary to build another diluter for upstream measurements.

III. INHOMOGENEOUS ELECTRIC FIELD AIR CLEANER

For applications requiring the filtration of air contaminated with radioactive particles of enriched uranium, plutonium or other transuranium elements, it appears desirable to collect the material in a fashion more amenable to recovery than is now practical when material is collected on HEPA filters. Most U and Pu facilities presently use filtration systems which, while they perform well, make the recovery of valuable materials difficult. It may also be desirable to substantially reduce the loading to which HEPA filters are subjected, hence reducing the frequency of filter tests and changes. This would alleviate the filter disposal problem which presents a considerable volume for solid waste disposal. HEPA filters are also subject to mechanical failure such as blowout due to explosion, fire, or other sources of over-pressure. These limitations would appear to make a search for an alternate recovery/disposal method attractive.

One method that may obviate these problems consists of a large matrix of highly charged coaxial conducting cylinders which utilize an induced dipole interaction to collect the particles on the inner cylinders. The design would be such as to allow for periodic withdrawal and cleaning or replacement of the inner cylinders, either process readily lending itself to recovery of the collected material. The exhaust flow would finally pass a conventional HEPA filter installation which would act as a back-up system and would also be used for collection of small quantities of particles (mostly very small) that were not collected by the electrostatic system. Under the assumption that laminar flow conditions are required, typical plenum dimensions would be five times greater than a HEPA filter installation. However, if it is found experimentally that laminar flow is not required, the plenum dimensions could be significantly reduced.

B. Theoretical Analysis

The following mathematically describes a feasibility study, indicating how this collector may function.

We consider a flow of particulates in air, with the particulates assumed to be electrically neutral, or else to have had most of the charged particles removed by conventional electrostatic methods. The principle to be invoked for the transport of the uncharged particles to a collection surface is that of an induced dipole interaction between the particle and an applied inhomogeneous electric field.

The induced dipole moment of a spherical particle in a locally uniform field approximation is given by

$$\vec{p} = 4 \pi R^3 \epsilon_0 \frac{k-1}{k+2} \vec{E} \quad (1)$$

where $\vec{p}$ = induced dipole moment
 $\vec{E}$ = electric field strength
 R = particle radius
 ϵ_0 = permittivity of vacuum
 k = dielectric constant

A typical value of k is 10. For conductors, $(k-1)/(k+2)$ approaches unity.

The field at a radial distance r produced by a potential, V , applied between two coaxial cylinders is given by

$$\vec{E} = -\frac{\hat{r}}{r} \frac{V}{\ln b/a} \quad (2)$$

where b = radius of outer cylinder
 a = radius of inner cylinder
 r = unit radius vector.

The force on the particle is given by

$$\vec{F} = (\vec{p} \cdot \nabla) \vec{E} = -4\pi R^3 \epsilon_0 \frac{k-1}{k+2} \frac{V^2}{\ln^2 b/a} \frac{\hat{r}}{r^3} = -\frac{\alpha \hat{r}}{r^3} \quad (3)$$

As an example, for $b = 6.0$ mm, $a = 1.0$ mm, and a voltage of 10 kV (calculated to be below breakdown), a $0.1 \mu\text{m}$ particle in the weakest region of the field, i.e., at the outer wall, will experience a force that is 200 times stronger than the gravitational force.

Besides the electrical driving force on the particle, a viscous velocity-dependent force will exist. This is given, for small particles, by the product of the Stokes force and the slip correction factor, i.e.,

$$\vec{F}_d = \frac{6\pi \eta R}{1+A \lambda/R} \vec{v} = B\vec{v} \quad (4)$$

where η is the viscosity [which must be transformed to the mks units used in Eq. (3)], v is the velocity, λ the molecular mean free path, and A is a constant.

The equations of motion can now be written as

$$m \left[\ddot{r} - r \dot{\theta}^2 \right] + B\dot{r} + \frac{\alpha}{r^3} = 0 \quad (5)$$

$$m \left[2 \dot{r} \dot{\theta} + r \ddot{\theta} \right] + B r \dot{\theta} = 0 \quad (6)$$

where r is the radial distance from the center of the cylindrical system, θ is the polar angle and m is the particle mass. For initial conditions of $r = b$, $\theta = \theta_0$, $\dot{\theta} = \dot{\theta}_0$, the first integral of Eq. (6) becomes

$$\dot{\theta} = \frac{b^2}{r^2} \dot{\theta}_0 \exp \left[-\frac{B}{m} t \right] \quad (7)$$

Evaluation of m/B results in an e^{-1} damping of 2.65×10^{-4} s, which is infinitesimal compared to

other time constants of the system. For all practical purposes, the angular motion is instantaneously damped out, i.e., $\dot{\theta} = 0$. Equation (5) may now be rewritten as

$$m\ddot{r} + B\dot{r} + \frac{\alpha}{r^3} = 0 \quad (8)$$

Unfortunately, this is a non-linear equation not amenable to analytic solution. An approximate solution can be obtained by considering the equilibrium case, i.e., $\ddot{r} = 0$. In this case, $\dot{r}$ is obtained directly, and the time required for a $0.1 \mu\text{m}$ particle to move from b to a is given by

$$\tau = \int_b^a \frac{dr}{\dot{r}} = \int_b^a \frac{-Br^3}{\alpha} dr =$$

$$\frac{3\eta \ln^2 b/a}{8R^2 \epsilon_0 V^2} \left(\frac{k+2}{k-1} \right) \frac{b^4}{1+A \lambda/R} = 4 \text{ s} \quad (9)$$

Hence, for a laminar flow (no radial accelerations), a flow rate of 1 m/s through a 4-meter-long collector will result in complete collection of particles down to $0.1 \mu\text{m}$ diameter. Smaller particles flowing closer to the central electrode will also be collected. Different values of the parameters V , b , and a , will result in substantially different values of τ .

It may be possible to eliminate the pre-collector for charged particles by employing an alternating potential. This will not affect the direction of motion of the uncharged particles.

The central collecting electrode can be installed so that it can be wiped or otherwise cleaned. In practice, a large matrix of such collectors would be used, backed up by HEPA filters as an additional protective measure. Power requirements would be extremely small, and use of a capacitor as a supplemental energy source would permit operation for limited time periods following a power outage.

C. Work for Future

During FY 76 we propose to build an experimental single unit with electrostatic pre-collector. Efficiency measurements would be performed with the commercially available PMS single particle light-scattering photometer. This photometer makes use of the scattering in the intense radiation field of a He-Ne laser to provide single particle size measurements as small as $0.05\text{ }\mu\text{m}$. Various modifications of the experiment would be investigated including the effects of turbulent flow and alternating fields. Initial experiments will confirm the theoretical performance of this system, and indicate which design parameters are critical.

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Fig. 1. Laboratory wind tunnel, photometer, and single particle spectrometer.

Fig. 2. Collision aerosol generator.

Fig. 3. Cumulative aerosol distribution function.

Fig. 4. Size dependence of penetration decay.

Fig. 5. Size dependence of penetration decay.