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MULTIPLE HEPA FILTER TEST METHODS

January - December, 1976

by

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ABSTRACT

NOTICE
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The testing of tandem high-efficiency particulate air (HEPA) filter systems is of prime importance for the measurement of accurate overall system protection factors. A procedure, based on the use of an intra-cavity laser particle spectrometer, has been developed for measuring protection factors in the 10^6 range. A laboratory scale model of a filter system was constructed and initially tested to determine individual HEPA filter characteristics with regard to size and state (liquid or solid) of several test aerosols. Based on these laboratory measurements, in-situ testing has been successfully conducted on a number of single and tandem filter installations within the Los Alamos Scientific Laboratory as well as on extraordinary large single systems at Rocky Flats.

For the purpose of recovery and for simplified solid waste disposal, or prefiltering purposes, two versions of an inhomogeneous electric field air cleaner have been devised and are undergoing testing. Initial experience with one of the systems, which relies on an electrostatic spraying phenomenon, indicates performance efficiency of greater than 99.9% for flow velocities commonly used in air cleaning systems.

Among the effluents associated with nuclear fuel reprocessing is ^{129}I . An intra-cavity laser detection system is under development which shows promise of being able to detect mixing ratios of one part in 10^7 , I_2 in air.

I. TEST METHODS FOR TANDEM HEPA FILTER INSTALLATION

A. Introduction

Test methods for high-efficiency particulate air (HEPA) filter installations currently consist of testing individual stages of a multi-stage installation. The method currently used in this country consists of introducing a challenge aerosol of dioctyl phthalate (DOP) upstream of an individual stage and using a forward light-scattering photometer to make measurements upstream and downstream from the filter bank, of the light scattering produced by the introduced aerosol. The ratio of the upstream-to-downstream scattering signal intensities is then defined as the protection factor (PF) of the stage.

Light-scattering photometers currently in use have an effective dynamic range limited, primarily by sensitivity and signal-to-noise ratio, to 10^4 , hence limiting the measurable PF to this range. The PF, measured in this fashion, is simply a ratio of light-scattering signals which are not uniquely related to either the concentration or size distribution of the population of scatterers. Since the filtration process changes the size distribution, PFs determined in the above manner are quantitative only for the introduction of monodisperse aerosols and only then if size changes due to coagulation or other processes do not occur.

Because of the limitation of the present method of measurement, high-efficiency systems such as multi-stage installations can, at best, be evaluated only on a single-stage basis, and multi-ply media filters cannot be measured at all. Indeed, in some present and projected multi-stage installations, a stage-by-stage measurement may quite often be impractical and may also result in the assignment of an incorrect system PF.

A method of accurate testing to PFs of up to 10^6 would obviate the above difficulties and in addition decrease operational downtime and worker exposure during testing. The design, construction, and maintenance of new facilities may also become simpler and less expensive. The following results are intended to show the feasibility of one such method.

B. Laboratory Test Apparatus

The laboratory test apparatus and procedure have been previously reported.^{1,2} In brief, an instrumented wind tunnel was constructed with a 0.7-m³/min (25-cfm) nominal flow rate for the testing of two 20.3-cm by 20.3 cm by 10.2-cm (8-in. by 8-in. by 4-in.) HEPA filters in tandem such that the flow volume per unit filter surface area was comparable to a large scale industrial system. Precleaned room air is mixed with the challenge aerosol (generated by a Collison generator) to provide a concentration of up to 10^9 particles/liter. A smaller instrumented wind tunnel is used to sample and draw off approximately 0.5% of the challenge aerosol, this dilution being measured with a forward scattering photometer.

The principal detector is a Particle Measuring System ASAS 300* intra-cavity laser particle spectrometer and counter, which, in the optical configuration used for laboratory testing, can measure a minimum particle diameter of .06 μ m. Measured particles are sorted into a total of 60 channels or size bins with the smallest resolution steps at the low end of the spectrum, which covers .06 μ m to 2.9 μ m. Four selectable ranges of 15 channels each are used to span this range. During a filter test, the spectrometer samples the diluted challenge aerosol for a specified time. The count obtained is multiplied by the dilution ratio, as determined by the photometer, to

*Particle Measuring Systems, Inc., 1955 South 57th Court, Boulder, Colorado.

provide an upstream count rate. The downstream count rate is determined directly by the spectrometer. The quotient of these two rates defines the PF. All sampling is performed isokinetically.

C. Challenge Aerosol Characteristics

Laboratory test aerosols were produced by a six-stem Collison generator. Both solid and liquid aerosols were produced and characterized. The solid aerosol was produced from a 5% solution of NaCl in water. Its characteristic spectrum, when dry, is not lognormal. A very good empirical description is provided by

$$\frac{\ln N(D)}{\ln N(D_0)} = \exp [-K(D-D_0)], \quad \text{where} \quad (1)$$

$N(D_0)$ is the count of the smallest particle of diameter D_0 , and $N(D)$ is the count of particles at some other diameter D . A curve fitting procedure yields the constant K . An aerosol generated from a solution of 5% DOP in ethyl alcohol yields a distribution, shown in Fig. 1, quite similar to that of NaCl in water, and described by the same functional dependence.

For field use, thermal DOP generators are frequently used. The aerosol produced by a Cloud Maker* thermal DOP generator was introduced into a large chamber where forced mixing was accomplished with electric fans. No attempt was made to obtain an analytical expression for the size spectrum; however, the data are plotted in Fig. 2.

D. HEPA Filter Protection Factors - Laboratory Tests

1. Single-ply HEPA Characteristics. Many of the characteristics of tandem systems, as well as the consequences of testing, can be inferred from studies undertaken on individual single-ply HEPA filters. One area of interest is the variation of efficiency with size and composition of the challenge aerosol. Figure 3 displays the PF as a function of particle size for two filters, one tested with DOP and the other with NaCl. In these examples, maximum penetration occurs at about $0.20 \mu\text{m}$. Penetration falls off very rapidly for smaller as well as larger size particles, showing the respective influence of diffusion and direct impaction in the particle collection process. Figure 3 also shows that the quality control PFs (using $0.3\text{-}\mu\text{m}$ monodisperse DOP) are lower than those measured with the laser single particle spectrometer.

In a previous report,¹ the exponential decay of penetration was illustrated for HEPA filters challenged by NaCl aerosol. A similar experiment was performed using DOP as the challenge. An example of the downstream particle count rate is shown in Fig. 4. The penetration initially drops and then starts to increase. After a one-half hour period of flushing with clean air (dashed line), the challenge aerosol is then reintroduced, at which time the penetration returns to the

*Testing Machines, Inc., Amityville, New York.

Fig. 1.
Size distribution of 5% DOP in ethyl alcohol.

Fig. 2.
Size distribution of thermally generated DOP.

Fig. 3.
Protection factor as a function of particle size.

Fig. 4.
Size dependence of DOP penetration as a function of time.

neighborhood of its initial value. A somewhat similar situation is illustrated in Fig. 5. Examination of the filter media under high magnification before (Fig. 6) and after (Fig. 7) exposure to DOP indicated no obvious change in structure. The physical/chemical mechanism responsible for this temporal variation have not been investigated; however, in terms of nondestructive testing, that is, low loading and low pressure drop, DOP aerosol has superior characteristics over the solid NaCl.

2. Multi-ply Media HEPA Filter Tests. Twelve 20.3-cm by 20.3-cm (8-in. by 8-in.) cross-section two- and three-ply media HEPA filters were supplied by a HEPA filter manufacturer for testing. Quality control measurements had not been performed. Measurements were made with the laser particle spectrometer in all cases and with a forward scattering photometer when practicable. Collison-generated DOP was used as the test aerosol in all cases. Also tested were two Gore-Tex media filters. Table I summarizes these measurements.

What is immediately evident from these data is the lack of quality control; that is, the PFs range over several orders of magnitude and in some cases are no better than that provided by a good single-ply HEPA filter. One would expect the two-ply filters to have PFs in the 10^6 range and the three-ply filters to have PFs in the 10^8 to 10^9 range. The results for the Gore-Tex filters indicate that at best, they may be good as prefilters.

The comparison between spectrometer and photometer readings is reasonably good up to PFs of 10^6 , as measured by the spectrometer. Beyond that, the photometer readings become very suspect. This agrees well with the estimates of photometer noise limited readings.

3. Tandem HEPA Filter Tests. A series of measurements was performed on two-stage HEPA filter configurations using both 5% NaCl in water and 5% DOP in alcohol to generate the challenge aerosols. Background counts downstream of each filter section were made with the aerosol spectrometer. External leaks were sealed until the count rate was <1 per 10-min interval. This was done with a 0.7-M³/min (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 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 six sets of filters tested with NaCl. P is the PF, the subscripts refer to the position of the filter being tested (1, 2, or 2 + 1), and whether this is a DOP quality control determined (s) or measured (m) value. The values of P_{2m} are the ratio of P_{21m}/P_{1m} , where P_{1m} is the zero-time first filter PF, and P_{21m} is the overall factor for a 10-min period during which the penetration of the first filter (P_{1m}) is constantly decreasing. The product of P_{1s} and P_{2s} yields P_{21s} . During the 11-min period of testing with NaCl, the pressure drop across the 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. Table II indicates that overall PFs as high as 2.5×10^8 can be measured during a 10-min integration period.

Testing of similar configurations with DOP provided more information because the tests could be run for a longer period of time due to the different loading characteristics produced by DOP. Table III provides histories of the PF as a function of time. Unlike the systems tested with NaCl, where the loading on the first filter continually increased the PF to a value greater than would be expected from the quality control data, the DOP tested systems usually display a PF an order of

Fig. 5.

Size dependence of DOP penetration as a function of time.

Fig. 6.

Photomicrograph of HEPA filter media prior to exposure to DOP. (1000X).

Fig. 7.

Photomicrograph of HEPA filter media after exposure to DOP. (100X).

TABLE I
MULTI-PLY AND GORE-TEX FILTER TEST RESULTS

Filter No.	Type	Spectrometer PF	Photometer PF
2A	07.6 cm (3 in.) 2-ply	6.4×10^4	
2B	07.6 cm (3 in.) 2-ply	3.7×10^3	6.4×10^3
2C	07.6 cm (3 in.) 2-ply	1.2×10^6	
2D	07.6 cm (3 in.) 2-ply	3.6×10^5	4.0×10^5
2E	07.6 cm (3 in.) 2-ply	4.8×10^2	2.6×10^2
3A	07.6 cm (3 in.) 3-ply	3.6×10^7	5.0×10^5
3B	07.6 cm (3 in.) 3-ply	1.7×10^5	3.3×10^5
3C	07.6 cm (3 in.) 3-ply	9.4×10^5	4.0×10^6
3D	07.6 cm (3 in.) 3-ply	8.5×10^4	6.2×10^4
3E	07.6 cm (3 in.) 3-ply	1.1×10^4	2.0×10^4
A452697	17.8 cm (7 in.) 2-ply	2.5×10^7	6.1×10^5
A452695	17.8 cm (7 in.) 3-ply	1.1×10^6	1.3×10^5
A482877	17.8 cm (7 in.) Gore-Tex		1.4×10^1
A482829	17.8 cm (7 in.) Gore-Tex		9.0×10^0

TABLE II
TANDEM PROTECTION FACTORS (NaCl)

Quality Control (0.3-μm DOP)	Measured (NaCl)
I	
$P_{1s} 7.2 \times 10^3$	$P_{1m} 1.1 \times 10^5$
$P_{2s} 1.3 \times 10^4$	$P_{2m} 1.5 \times 10^3$
$P_{21s} 9.4 \times 10^7$	$P_{21m} 1.6 \times 10^8$
II	
$P_{1s} 1.3 \times 10^4$	$P_{1m} 1.7 \times 10^4$
$P_{2s} 1.0 \times 10^4$	$P_{2m} 8.2 \times 10^2$
$P_{21} 1.3 \times 10^8$	$P_{21m} 1.4 \times 10^7$
III	
$P_{1s} 1.0 \times 10^4$	$P_{1m} 3.2 \times 10^4$
$P_{2s} 4.2 \times 10^8$	$P_{2m} 6.6 \times 10^8$
$P_{21s} 4.2 \times 10^7$	$P_{21m} 2.1 \times 10^8$
IV	
$P_{1s} 1.3 \times 10^4$	$P_{1m} 2.8 \times 10^5$
$P_{2s} 4.2 \times 10^8$	$P_{2m} 1.5 \times 10^2$
$P_{21s} 5.5 \times 10^7$	$P_{21m} 4.1 \times 10^7$
V	
$P_{1s} 8.3 \times 10^3$	$P_{1m} 4.7 \times 10^4$
$P_{2s} 4.2 \times 10^3$	$P_{2m} 5.1 \times 10^3$
$P_{21s} 3.5 \times 10^7$	$P_{21m} 2.4 \times 10^8$
VI	
$P_{1s} 1.3 \times 10^4$	$P_{21} > 1.3 \times 10^5$
$P_{2s} 4.2 \times 10^3$	$P_{2m} > 1.8 \times 10^3$
$P_{21} 5.5 \times 10^7$	$P_{21m} > 2.4 \times 10^8$

TABLE III

TANDEM PROTECTION FACTORS (DOP)

Quality Control	Measured (DOP)			
	Period #1	Period #2	Period #3	Period #4
	1 - 12 min	13 - 36 min	37 - 62 min	63 - 96 min
$P_{1s} 2.50 \times 10^4$	$P_{1m} 8.21 \times 10^3$	1.27×10^4	1.01×10^4	2.84×10^3
$P_{2s} 2.50 \times 10^4$	$P_{2m} 2.24 \times 10^3$	3.73×10^3	9.71×10^4	1.10×10^4
$P_{21s} 6.25 \times 10^8$	$P_{21m} 1.84 \times 10^7$	4.74×10^7	9.81×10^7	3.12×10^7
	1 - 11 min	12 - 17 min	18 - 23 min	24 - 27 min
$P_{1s} 2.50 \times 10^4$	$P_{1m} 5.80 \times 10^3$	6.80×10^3	5.05×10^3	4.24×10^3
$P_{2s} 2.50 \times 10^4$	$P_{2m} 4.35 \times 10^3$	7.42×10^3	5.56×10^3	4.76×10^3
$P_{21s} 6.25 \times 10^8$	$P_{21m} 2.53 \times 10^7$	5.05×10^7	2.81×10^7	2.02×10^7
	0 - 1 min	2 - 11 min	12 - 23 min	24 - 60 min
$P_{1s} 2.50 \times 10^4$	$P_{1m} 2.87 \times 10^3$	2.87×10^3	2.87×10^3	2.87×10^3
$P_{2s} 2.50 \times 10^4$	$P_{2m} 7.58 \times 10^3$	3.52×10^4	7.58×10^3	8.44×10^3
$P_{21s} 6.25 \times 10^8$	$P_{21m} 2.18 \times 10^7$	1.01×10^8	2.18×10^7	2.42×10^7
	4 - 9 min	10 - 40 min	41 - 45 min	46 - 50 min
$P_{1s} 5.00 \times 10^4$	$P_{1m} 2.44 \times 10^4$	6.29×10^4	3.14×10^3	5.22×10^3
$P_{2s} 5.00 \times 10^4$	$P_{2m} 2.07 \times 10^4$	4.82×10^4	1.79×10^4	2.42×10^4
$P_{21s} 2.50 \times 10^9$	$P_{21m} 5.05 \times 10^8$	3.03×10^9	5.62×10^7	1.26×10^8
	0 - 5 min	6 - 10 min	11 - 15 min	16 - 20 min
$P_{1s} 1.67 \times 10^4$	$P_{1m} 3.22 \times 10^3$	7.86×10^3	5.09×10^3	5.59×10^3
$P_{2s} 5.00 \times 10^4$	$P_{2m} 1.57 \times 10^4$	6.42×10^3	2.48×10^4	9.03×10^4
$P_{21s} 8.33 \times 10^8$	$P_{21m} 5.05 \times 10^7$	5.05×10^7	1.26×10^8	5.05×10^8

magnitude less than inferred from the quality control data. The variation with time is not monotonic. The percentage error associated with the counts determining P_{21m} in both tables is typically $\approx 25\%$.

Under conditions in which long integration times are required to obtain a statistically significant count downstream of a tandem system, DOP appears to be a better challenging agent than NaCl in that it produces less of a penetration change and a smaller pressure drop during the duration of the test, and also provides more conservative test data. Using DOP the initial pressure drop of about 19 mm (.75 in.) H_2O across the first filter would rise to a maximum of 31 mm (1.23 in.) but then decrease to 25 mm (1.00 in.) after a short period of clean air flushing. This was not true with filters challenged by NaCl. The excessive upstream concentrations required give rise to a concern, which will be investigated, over agglomeration processes that may occur for either aerosol between the upstream measurement point and the first filter face.

E. In-Situ Testing of HEPA Filters

1. Single Filter Installations. In Sec. C, the characteristics of an aerosol produced by a Cloud Maker thermal DOP generator were presented. Because of the convenience of portability and use, these devices were used to provide the upstream challenge aerosol for in-place testing. In order to provide sufficient aerosol, as many as three such generators were employed to provide up to a total of 15 gm/min of generated aerosol.

In order to provide a greater sampling volume, the laser particle spectrometer was optically modified so that the flow rate in the sample cavity was increased by a factor of eight. This modification resulted in a loss of size detection below $.12\ \mu\text{m}$. As previously described, a diluter section was employed in order to enable measurement of the high concentration challenge aerosol. A forward scattering photometer was used to measure the dilution ratio; that is, the ratio of the number of particles drawn into the diluter to those in the challenged ambient upstream air. The upstream challenge count per unit time is then given by the product of the spectrometer count and the reciprocal of the dilution ratio. The downstream count rate was measured directly with the spectrometer alone.

Prior to each measurement, the background downstream count rate was measured so that it could be subtracted from the measurement made during the test. This background count invariably appears to originate from leaks in the ductwork between the filter plenum and the fan. The vacuum produced by the fan draws ambient aerosols into the duct through the leak. For single-stage systems, this background leakage is a small fraction of the downstream measurement. However, for highly efficient two-stage systems, the background may, in some cases, completely mask the penetrating DOP aerosol. Upstream of the filters, the background is completely negligible compared to the challenge aerosol.

One single-stage $566\text{-m}^3/\text{min}$ (20 000 cfm) system tested using the single particle laser spectrometer and Cloud Maker thermal DOP generator yielded a PF of $5 \text{ by } 10^3 \pm 16\%$ for a 30-s integration time. A forward light-scattering photometer usually used for this test was unable to provide a reading out of the background noise. Extrapolation to determine the requirements for a similar two-stage system results in three aerosol generators, 20-min integration time, and an accuracy of $\pm 40\%$. A $5662\text{-M}^3/\text{min}$ (200 000 cfm) single-stage system would require only that the integration time be extended to 5 min to provide the same accuracy as for the $566\text{-M}^3/\text{min}$ (20 000 cfm) stage system.

A single bank system operating at $4530\text{-M}^3/\text{min}$ (160 000 cfm) at Rocky Flats was chosen as representative of ultralarge systems. In addition, this system had never before been successfully tested, and information on its performance was desired. The installation consists of a very large filter plenum chamber with several intake ducts and four large exhaust ducts. The outputs of two thermal DOP generators were directed into two intake ducts on opposite sides of the plenum. A third DOP generator output was directed to the upstream side of the plenum. Four equally spaced isokinetic sampling stations were stationed on the downstream side of the filter plenum. Upstream sampling was accomplished by means of the photometer and dilution apparatus described under Sec. I-B. Downstream sampling was performed on each of the four downstream ducts. This sampling procedure was performed both isokinetically and an-isokinetically, with only a few per cent difference in the results. The stepwise procedure consisted of making downstream background measurements of one minute each, turning on the generators, and after allowing for generator output stabilization, taking 1-min downstream readings on each of the four ducts. The sampling probes and spectrometer were then moved to the upstream sampling ports where four upstream measurements were made. The whole procedure, once the sampling stations were in place and the generators loaded, could be performed well within the 30-min limit of generator time. The efficiencies for the four sections are: $(99.87 \pm .02)\%$, $(99.97 \pm .02)\%$, $(99.97 \pm .01)\%$, $(99.93 \pm .02)\%$. The possible errors were computed from two sets of background

measurements. The efficiency for the system as a whole was computed by individually summing the upstream, downstream, and background measurements rather than averaging the four duct measurements. The figure arrived at in this way is $(99.95 \pm .01) \%$.

2. Tandem Filter Installations. The methodology for testing tandem HEPA filter installations is precisely the same as that employed for single filter systems and described in the preceding section.

Two 700-M³/min (25 000 cfm) tandem HEPA filter installations were measured with the laser particle spectrometer system. Background measurements were made immediately before introduction of DOP aerosol and were used to correct the downstream test readings. One system on floor 2, wing 2, provided an overall PF of 3.6 by 10⁶. However, immediately after the test, the background increased by an order of magnitude. Whether or not this was coincidental with a large upstream release or a reaction of the DOP with chemical residue on the filters is not known. A second system had to be tested in individual stages because of excessive background counts. The combined measurements yielded a PF of 2.0 by 10⁶. A 453-M³/min (16 000 cfm) system located at another site provided a PF of 6.1 by 10⁶. This system has a moisture trap between the first and second stages which may interfere with the measurement. An attempt will be made in the near future to circumvent the moisture trap.

In-situ testing was temporarily discontinued in November 1976 because of problems which developed in the laser spectrometer plasma tube and also due to sample chamber leakage. The instrument is now undergoing repair and will be available in early 1977.

The single most difficult problem encountered in in-situ tandem HEPA filter testing is excessive background which appears to be caused by ambient air leaking into the negative pressure region of the ducting between the plenum and fan. Because of this, it seems reasonable to start considering the use of a specific aerosol, having the desirable properties of DOP, and yet labeled in such a fashion that, with appropriate instrumentation, only this aerosol will be detected. In this fashion, the problem of background should be obviated.

II. INHOMOGENEOUS ELECTRIC FIELD AIR CLEANER

A. Introduction

In many cases, particularly for recovery and/or simplified solid waste disposal or prefiltering purposes, it is desirable to have an air cleaning system in which the particulate material collected may be concentrated. This may be accomplished by flowing the aerosol laden air through a matrix of coaxial cylinders with a high electric field across each coaxial pair. The electric field will induce a dipole moment on the aerosol particles which will then be subject to a force in the direction of the central cylinder due to the field gradient produced by the coaxial configuration. Calculations based on such a system indicate the possibility of 100% collection for 1.0- μ m particles in slow laminar flow, providing the particles stick to the collector surface. Power requirements are not expected to be high since the only work to be done is that required to overcome viscous drag forces acting to resist the particle motion, permitting operation of this air cleaner during emergency conditions with use of a capacitor bank. The interaction of the carrier gas (air) with the electric field is considered negligible.

A variation of this procedure, which appears to be highly effective, relies on what appears to be electrostatic spraying of a conducting fluid, for example, water, coated on the inner electrode, into the inter-electrode region. This spray apparently acts as an ion sheath which interacts with the particulates, which are in turn collected in a fashion similar to that of a conventional electrostatic precipitator.

B. Theoretical Description

A complete theoretical description of the nonliquid conducting medium has already appeared in a previous report² as well as in the Proceedings of the 14th ERDA Air Cleaning Conference.³ Briefly, the induced dipole force on a particle in an inhomogeneous electric field is given by

$$\vec{F} = (\vec{P} \cdot \nabla) \vec{E}, \text{ where} \quad (2)$$

$\vec{F}$ = force
 ∇ = gradient operator.
 $\vec{P}$ = induced dipole moment, proportional to $\vec{E}$
 $\vec{E}$ = electric field strength.

The viscous force F_d , encountered by the aerosol particle is given by

$$\vec{F}_d = \frac{6\pi\eta R}{1+A\lambda/R} \vec{v}, \text{ where} \quad (3)$$

$\vec{v}$ = velocity
 η = viscosity
 R = particle radius
 λ = molecular mean free path
 A = constant

Combining these equations and utilizing the electric field expression for a coaxial cylinder configuration leads to a differential equation which can be solved to yield

$$r^4 = b^4 - \alpha t, \text{ where} \quad (4)$$

r = radial distance from the center of the cylindrical configuration
 b = radius of the outer cylinder
 t = time
 α = constant

The axial flow through such a configuration can be obtained from first principles to yield

$$v(r) = \gamma[a^2 - r^2 + (b^2 - a^2) \frac{\ln r/a}{\ln b/a}], \text{ where} \quad (5)$$

$v(r)$ = flow velocity at radius r

$\gamma = \text{constant}$

$a = \text{radius of inner cylinder .}$

Combining Eqs. 4 and 5 and performing a further integration and subsequent algebraic manipulation results in a trajectory equation of the form

$$z - z_0 = \frac{\gamma}{\alpha} [a^2 b^4 - b^6 \frac{1}{\ln b/a} - \frac{2}{3} b^6 + \frac{b^6}{\ln b/a} (1/b - 1/4)] , \quad (6)$$

for particles which enter the system at the end of the outer cylinder at z_0 and are collected downstream, a distance $z - z_0$, on the inner cylinder.

C. Experimental Results

1. Small Scale. Figure 8 schematically displays the very low velocity laboratory scale coaxial inhomogeneous electric field apparatus initially designed to confirm the theoretical development. Monodisperse PSL aerosol dispersed by a Lövelace generator is sent through a ^{85}Kr aerosol charge neutralizer. A charged particle precollector composed of two parallel plates 0.30 m by 0.06 m with 0.015 m spacing was constructed to filter out charged particles not neutralized by the ^{85}Kr neutralizer. A coating of silicon oil was used on these plates to enhance their retentivity. After leaving the precollector, the aerosol is introduced into a second, smaller precollector (.19 by .13 by .015 m) housed in a box which has as one of its sides a HEPA filter to allow pressure within the box to remain at the ambient value. The aerosol within the box is drawn in through the outer annular region of the inhomogeneous field collector. This outer annulus serves to define the initial conditions so that a monodisperse aerosol will be localized on the .63-m-long collector rod. Detection of particles was with a single particle laser spectrometer.

The design airflow turned out to be too low to introduce a significant amount of aerosol into the system, so the average flow velocity was increased to 0.05 m/s. This, coupled with the fact that the spectrometer was limited to an upper size of $2.9 \mu\text{m}$ restricted particle measurement size to standard $2.01 \mu\text{m}$ PSL particles. Although very little loss in transmission was anticipated, 100% collection was obtained at 8 kV, as shown in Fig. 9. In order to determine if a large population of charged particles still existed, the precollectors were deactivated. This resulted in a 25% increase in total population entering the collector, but resulted in an almost identical penetration curve as illustrated in Fig. 9.

If a Boltzman distribution for the charge is assumed, 10% of the particles have zero charge, and 9% have one charge of +1 and -1. Singly charged particles should still be capable of getting through the collector. The result of an approximate calculation of the collection efficiency, presupposing this distribution, is shown by the solid line in Fig. 9.

A calculation was also performed assuming that the particles drawn into the drift tube immediately migrated to a position midway between the tube and collector. These results also indicated that the uncharged particles would not be collected. The possibility of corona charging from the collector was discarded by using a radio to detect corona discharge. The current flow was also monitored with a microammeter. To summarize, it appears that the system is collecting neutral particles far more effectively than predicted by theory.

Various coatings were applied to the collector to enhance the sticking of particles. Substances used were silicone oil, silicone grease, apiezon grease, glycol, and water. All but the latter two had no effect on the transmission curve. Water and glycol produced zero penetration at 6 to 7 kV not only for 2- μ m particles but all the way down the spectrum to 0.1- μ m particles (penetration <1%) as shown in Fig. 10. The collection was accompanied by corona, apparently induced by the liquid. Visual examination of the apparatus disclosed aerosol on the interior of the drift tube. In the case of glycol, some glycol was also found in the drift tube. The mechanism appears to be that of electrostatic spraying of the medium coating the collector electrode. The droplets thus formed would be expected to be highly charged and thus attracted to the drift tube. During their traverse, they interact with the aerosol particles so that the system of particle and droplet are deposited on the surface of the drift tube.

A typical transmission plot for a mixture of 2.0-, 1.0-, and .53- μ m particles, collector-coated with glycol, is shown in Fig. 10.

2. Large Scale. A larger version of the modified inhomogeneous electric field device was constructed and tested. The system is cylindrical, with a 7.6-cm diam and 127.0-cm length. The outer coaxial electrode was wound with cotton thread which could be soaked with water or ethylene glycol to provide electric field spraying. Flow rates were varied from 1 to 12 cfm. This system was installed on the laboratory HEPA filter test wind tunnel.

At 4 cfm, using glycol more than 99.9% of 1.1- μ m particles were collected with a voltage of 7.0 kV and current of 7.5 μ A (power consumption of .05 W). For particles less than .4 μ m, the collection efficiency dropped to 99.6% at 9 kV and 12 μ A. Using water as the coating, 99.8% of 1.1- μ m particles were collected at 10 kV and 18 μ A. For particles less than .4 μ m, 99.8% were collected at 10 kV and 12 μ A. Water appears to collect small particles most efficiently; glycol, the larger particles. A negatively charged wet central electrode is more efficient than one that is positively charged. Figures 11 and 12 display typical transmission curves for water- and glycol-covered electrodes, respectively.

Increased flow rates cut the collection efficiency down by several per cent, but this can probably be rectified by increasing the length of the collector section and/or increasing the current and voltage.

The curves of particle transmission plotted against current are quite similar to those obtained for conventional precipitators, but the voltage and current values are orders of magnitude smaller. In addition, the liquid deposited along with the particulates prevents a charged dielectric buildup, which would decrease the voltage difference from forming.

In comparing this system with HEPA filters, note that the typical 28.3-M³/min (1000-cfm) has an approach velocity of 76.2 M/min and the 7.6-cm diam electrostatic section, operated at .11 M³/min, has an approach velocity of 24.4 M/min. Changing length, current, and voltage would enable this value to go to 76.2 M/min. Experiments have yet to be conducted with larger diameter units or with square cross-section units.

III. IODINE DETECTION

A. Introduction

Work has been in progress since October to develop an optical method for the measurement of iodine in air samples. The object is to have a continuous or near real time display of the iodine concentration. There is a need for such a technique for testing absorbent beds which remove iodine from the out gas of reactor and nuclear fuel reprocessing operations.

INHOMOGENEOUS ELECTRIC FIELD AIR CLEANER

Fig. 8.
Inhomogeneous field apparatus.

Fig. 9.
Aerosol transmission as a function of applied voltage.

Fig. 10.
Aerosol transmission as a function of applied voltage.

Fig. 11.

Aerosol transmission as a function of current.

Fig. 12.

Aerosol transmission as a function of current.

The instrumentation under development will monitor the iodine by the absorption, by I_2 , of helium-neon laser radiation at 632-nm wavelength. It is expected that the final instrument will be portable, rugged, inexpensive, and provide continuous readout capability.

B. Theoretical Analysis

The determination of the quantity of a particular gas in a sample of air by the absorption of light is straightforward. In point of fact, it is not so commonly used because several conditions must be satisfied before the procedure is practical.

If special techniques, such as the use of lasers, are not utilized, these conditions include the requirement that the absorption be several per cent for each meter of optical path, and that none of the other gases which might be present in the sample have significant absorptions at the same wavelengths as the gas of interest. The requirement that the absorption be several per cent per meter eliminates the majority of gases except those absorbing in the infrared. The requirement that no other gases absorb in the same wavelength region is often not satisfied in the infrared. Thus, the direct use of optical absorption is not usually a viable technique for monitoring the quantity of a gas present in the air.

The use of a laser as the light source for the absorption can sometimes make practical an optical absorption measurement that would normally not be possible. The avoidance of the restrictions mentioned above are due in one case to the very narrow wavelength span of a laser beam, which is almost monochromatic. The probability that any gas will have an absorption in a given wavelength interval is proportional to the width of the interval. Hence, the narrower the width of the source, the smaller the chance that the absorption by a secondary gas will also occur at this wavelength. The difficulty lies in obtaining a laser emission at the same wavelength as the absorption of the gas to be monitored and preventing it from drifting to other wavelengths, but that is not a problem in the present case.

The greatest advantage of the laser is the ability to use absorptions which are only a fraction of a per cent per meter of pathlength. This advantage is realized by introducing the gas into the cavity of a low gain laser.

The laser develops its output intensity by virtue of the amplification in the beam intensity as it traverses the cavity. The gain of the He-Ne laser is not great, so high reflectivity mirrors are placed at the ends of the cavity. In the present case, over 99.5% of the radiation reaching the mirrors is reflected back into the cavity. Less than 0.5% is permitted to leave the cavity, the remainder being caused to undergo multiple traversals of the amplifying region. Therefore, if the gas sample is introduced into the laser cavity, that is, the region within the high reflectivity mirrors, but not in the same region as the amplifying medium (plasma), the effective absorption experienced by the laser radiation is increased by a factor of almost two orders of magnitude.

The net effect of this increased path is even more spectacular than the two orders of magnitude would indicate. In the case of normal absorption, the intensity of the light beam decreases exponentially, so that the ratio of the intensity when there is no absorption, I_0 , and the intensity I after a path of length X in a medium with an absorption coefficient K is

$$I/I_0 = \exp (-KX). \quad (7)$$

Thus, an infinite path is required for the beam intensity, I , to become zero. On the other hand, within the laser cavity, the beam intensity is amplified by a factor G_0 with each traversal of the cavity. If within the laser cavity a gas sample cell of length X and a loss K per unit length is introduced, then to a first approximation, the net gain decreases from G_0 to G per traversal, where

$$G = G_0 - kX. \quad (8)$$

It is not useful for a measuring system, but for illustrative purposes, if X is made large enough for kX to equal G_0 . Then, the net gain, G , is zero, and the laser output is zero. This illustrates that absorption within the laser cavity has an enhanced effect over the increased pathlength outside the cavity, because no finite path would reduce the laser beam to zero intensity if the path were outside the cavity.

There are losses in the cavity other than the absorption by the sample gas. When these losses are allowed for, the relative output power, I/I_0 , from the laser as a function of the single traversal absorption loss can be determined.⁴ The result is shown in Fig. 13, where it can be seen that a 0.4% single traversal loss in the cavity results in a 50% decrease in the laser output.

C. Experimental

The approach used in the experimental work has been to first test several aspects which were felt to be potential problem areas. During the testing of these aspects, other problems which were not anticipated would be expected to appear, and these could be corrected before the final experimental arrangement was constructed. The final experimental setup is now being constructed, and this approach seems to have resulted in an efficient development schedule.

The experimental arrangement which has been used up to this time is shown in Fig. 14. The laser is mounted at the left. The gas sample is introduced by placing a cell in the central region.

Fig. 13.
Relative power vs fractional loss.

Fig. 14.
Laser iodine detector.

In the final unit the gas will be caused to flow through the cell. An absorption cell can be introduced into the laser beam after it leaves the cavity by placing it in the far right hand end of the experimental setup. This permits comparisons of the absorption inside and outside the cavity to be made. In particular, the value of the absorption coefficient obtained from the literature⁶ has been checked in this way. The work carried out using absorption cells within the cavity has verified the preliminary estimates of the variation of output power with iodine content.

In contrast to many optical absorption experiments, the limiting sensitivity of the final apparatus will not be determined by the sensitivity of the detector, or by the power of the laser, but by the temporal stability of the output. In tests of the stability of the laser, a 2% rms variation of the output power with roughly a 1-min period was observed. Monitoring the power supply indicated the power supply was not the source of the variation, and the time constant was too short for the variation to be attributed to the mechanical mounting system. It was therefore concluded to be due to the plasma tube.

On the basis of this information a 10-s sample cycle has been selected. The air to be tested will be observed for 5 s, then a sample of standard air will be observed for 5 s. Only the difference in the output power between the two samples will be required. The difference will be averaged over a 60-s period. This sampling technique will essentially eliminate the effects of laser instability.

The effect of thermal expansion varying the laser cavity length, and thereby causing small shifts in the output wavelength was examined by the use of a piezoelectric mirror mount at one end of the cavity. The cavity length could then be varied more than the wavelength of the output

by application of a voltage to the piezoelectric crystal. With shorter cavities this effect can be quite important,⁶ but with the present 60-cm cavity length and the iodine lines broadened by the ambient atmosphere pressure, no significant effect was observable. This was one of the effects which had been anticipated as a significant problem. The fact that it is not a problem has simplified the project.

The work completed up to this time indicates that the instrument will have a precision of 3 by 10^{12} molecules/cm³ (approximately a mixing ratio of 10^{-7}), which is the originally estimated potential.

IV. FUTURE WORK

A. Filter Testing

Several more tandem HEPA filter installations will be tested and the downstream background problem will be evaluated. Specifications will be drawn up for a complete field test system for tandem HEPA filter installations. Equipment will be purchased and constructed to meet those specifications and additional field measurements will be made. The writing of a standardized procedure manual will complete this phase of the program.

Because of the problems associated with large background signals due to ambient aerosol being drawn into the downstream ductwork because of leaks in the ductwork, a program designed to label and recognize a specific challenge aerosol will be initiated. It is anticipated that an optical technique, such as the absorption and subsequent fluorescence of the test aerosol, will be initially studied along with the French uranine system.

B. Inhomogeneous Electric Field Air Cleaner and Applications

A two-meter precollector and three-meter drift tube have been constructed for further investigation of both neutral particle collection and the electrostatic spraying phenomenon. Larger diameter configurations of the wet modification cleaner will be tested. Other liquid media will also be tested. Design considerations for construction of a pilot scale collector, and the mechanism for recovering collected material will be initiated.

Applications of the collector for HEPA prefiltering and for use in hostile environments such as vitrification off gas filtering will be investigated.

C. Iodine Detection

The work up to this time has used the isotope ¹²⁷I. This has been used for the convenience of not dealing with a radioactive substance. The absorption lines of the different isotopes are at slightly different wavelengths. The laser transition of ²⁰Ne coincides with an absorption line of ¹²⁷I₂, whereas the laser transition of ²²Ne coincides with an absorption line of ¹²⁹I₂. The lines are almost coincidental, but there is the potential to distinguish between the two isotopes. This potential will be explored in future work.

Another problem which has received little attention to date, but which is of significance to the final instrument, is the measurement of samples which have a large I₂ mixing ratio. For mixing ratios which are sufficiently large, the laser will not lase, but it is desirable to have a single instrument which will cover the entire range of I₂ mixing ratios which might be encountered. Some alternate approaches to this problem have been considered. These will be evaluated and tested after the final experimental setup has been completed.

In actual test situations, the iodine will not all be in the form of I_2 , but the total iodine content is to be determined. The procedure to avoid this problem is to pyrolyze the molecules containing iodine and thereby release the iodine, which will quickly take the form of I_2 . This is a straightforward process, but it has yet to be implemented into the system. After implementation it will permit measurements of iodine in the airstream in the form of I_2 or the total iodine content. Thus, the fraction in each of the two states can also be measured. Work on this problem will be completed by the end of FY 1977.

V. PUBLICATIONS AND PRESENTATIONS (1976)

A. Publications

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2. B. G. Schuster and D. J. Osetek, "The Use of a Single Particle Intra-Cavity Laser Particle Spectrometer for Measurements of HEPA Filters and Filter Systems," Proc. 14th ERDA Air Cleaning Conf., 1976.
3. B. G. Schuster, "Inhomogeneous Electric Field Air Cleaner," Proc. 14th ERDA Air Cleaning Conf., 1976.
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2. B. G. Schuster and D. J. Osetek, "The Use of a Single Particle Intra-Cavity Laser Particle Spectrometer for Measurements of HEPA Filters and Filter Systems," 14th ERDA Air Cleaning Conf., August 1976.
3. B. G. Schuster, "Inhomogeneous Electric Field Air Cleaner," 14th ERDA Air Cleaning Conf., August 1976.
4. T. G. Kyle, "Use of Interferograms for Temperature Soundings of the Atmosphere," Garmisch, Germany (August 19-27, 1976).

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3. B. G. Schuster, "Inhomogeneous Electric Field Air Cleaner," Proc. 14th ERDA Air Cleaning Conf., August 2-4, 1976, Sun Valley, Idaho.
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