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ENHANCING AIR PURIFICATION

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ABSTRACT

Although filters and charcoal beds in ducts effectively remove many room contaminants that are carried to them via the ducts, a large proportion of the contaminants that are found in room air do not reach them. The reason, as shown in an earlier paper, is that the motion of contaminants less than one micron in size is determined more by the normal electrical forces in any room than by the air currents. Thus, a large proportion of the contaminant load in a room tends to plateout on people and objects. This results in adverse effects on health and comfort. What is needed is a means to enhance the natural process of aerosol coagulation to increase particle size so air currents can more readily entrain and return the particulates to the filters via the ducts.

Research that shows a means of enhancing aerosol coagulation, the use of in-duct complex electrical fields, and its application is described in this report. First, the relevant physics is summarized. Then the results of two experiments testing and verifying this means to enhance coagulation are detailed. Then an experiment using groups of people exposed to tobacco smoke, a ubiquitous environmental contaminant, is reported. Research using other common building contaminants, i.e., formaldehyde and sulphur dioxide, is also reported. Statistical analyses of these data show that removal of gaseous contaminants can also be enhanced by these means. The substantial implications for health and comfort are then discussed.

INTRODUCTION

Although filters and charcoal beds in ducts effectively remove many room contaminants that are carried to them via the ducts, a large proportion of the contaminants that are typically found in room air do not reach them. The reason, as shown in an earlier paper, is that the motion of contaminants less than one micron in size is determined more by the normal electrical forces in a room than by air currents, a well-established fact of physics (Frey 1986a). Thus, a large proportion of the contaminant load in a room tends to plateout on people and objects. This results in adverse effects on health and comfort.

What is needed is a means to enhance the natural process of aerosol coagulation so as to more rapidly increase particle size. Then air currents will be the dominant force and can return the particulates to the filters via the ducts.

In this article, some of the basic physics that determine whether contaminants are returned to a filter via the ducts is summarized. A means of accelerating coagulation of particulates via in-duct complex electric fields is suggested. Then the procedures and results of two experiments testing the suggestion are presented. The findings from these experiments are then extended with a description of experimentation with humans exposed to tobacco smoke. Then a set of complementary experiments with two gaseous contaminants, which absorb and adsorb onto particles, are described. The statistical analyses of the latter experiments show that operation of the in-duct complex electrical fields significantly reduces the room concentration of these gaseous contaminants. The implications for health and comfort are then discussed.

ATMOSPHERIC PHYSICS

Aerosols vary in size, concentration, and settling time. Their salient characteristics are summarized in Tables 1 and 2. More than 98% of particles in room air are one micron or less in size and, as noted in the tables, essentially do not settle out of the air by gravity. The electrical forces are important in controlling these because they are virtually always charged. Aerosols acquire charge by three basic mechanisms: diffusion charging, field charging, and static electrification. The details of these mechanisms can be found in Frey (1986a).

TABLE 1

Characteristics of aerosols

Particle size in microns	Percentage of particles by count	by weight
10–30	< 1	28
5–10	< 1	52
3–5	< 1	11
1–3	1	5
0.5–1	6	2
<0.5	92	1

TABLE 2

Particle setting time in still air

Particle size in microns	Time required to settle 8 feet
100	8 seconds
10	13 minutes
1	19 hours
0.1	79 days
0.01	∞

Given the charged particle generated by a mechanism noted above, consider the effect of the ever-present electrical fields on it. The electric field that exists in the space about a charged object causes a charged particle that is in this space to experience a force, the electrostatic force. Specifically, the force on a particle with n elementary units of charge (e) in an electric field (E) is $F_E = neE$. The field strength at any point in the space is equal to the potential gradient at that point.

Given the charged particle and the electrical field in the space, we can consider more specifically what happens when aerosol particles collide with one another, as they constantly do. They adhere to each other and thus grow to form larger particles with a consequent decrease in number of particles. When the motion of the particles is due to Brownian motion, the growth process is called thermal coagulation. It is a spontaneous and always present phenomenon. When the motion is due to gravity or electrical forces or from aerodynamic effects, the process is called kinematic coagulation. Coagu-

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lation is the most important phenomenon in the interactions in aerosols.

Electrical forces between particles increase coagulation by enhancing the substantial thermal coagulation mechanism. With low intensity and fairly homogeneous electrical fields, collisions of aerosol particles of opposite signs are increased but collisions between particles of the same sign are reduced. The net effect is little change in coagulation for aerosols with Boltzman equilibrium charge distribution. But there can be a significant increase in coagulation of aerosols with a strong bipolar charge distribution or in strong nonhomogeneous fields.

Aerosol particles will attach firmly to any surface they contact, not just to each other. The adhesive forces on micron size particles exceed other forces by orders of magnitude. They are a prime factor in contamination.

The importance of these adhesive forces, which are primarily electrical, in contamination can be seen by considering how high they are compared to removal forces. Adhesive forces are proportional to d, and removal forces are proportional to d^2 for air currents and d^3 for vibration and centrifugal stress. Consequently, the smaller the particle size, the less likely it will be displaced from a surface.

In sum, the electrical characteristics of particles, the normal electrical fields in spaces, and the electrical characteristics of objects and surfaces in the space are some of the primary determinants of contamination.

Given this basic physics, contamination control could be enhanced if coagulation could be accelerated. Thus, larger particles are less influenced by the normal electrical forces in a space and more by the air currents. Thus, they can be more readily carried to the filters via the ducts. Such acceleration should occur if particulates in a duct encounter a complex non-homogeneous electrical field with suitable characteristics.

The objective of the first experiment was to determine if the concentration of respirable particulates in room air, i.e., tobacco smoke, would be influenced by passing the air through a complex high-frequency, high-voltage electric field located in the supply duct.

EXPERIMENT 1

Tobacco smoke consists of respirable-size particulates and gases that are well characterized and can be generated in a simple, reliable manner. Mainstream smoke is that which is inhaled by a smoker; consequently, many of the pollutants are filtered out in the smoker's lungs, i.e., 70% of the particulate manner. Sidestream smoke is the unfiltered smoke emitted from an idling cigarette, cigar, or pipe. It has been found that 75% of sidestream particles remained suspended in a test chamber after 2.5 hours. Their median size is 0.7 microns with no particles greater than two microns. Thus, we used sidestream smoke to test the possibility that specific electric fields in a duct would influence the concentration of particulates in a room.

Experimental Setup and Method

The testing was carried out in a room 2.7 × 4.3 × 2.4 m (9 × 14 × 8 ft) with a floor of vinyl tile and walls and ceiling paneled as shown in Figure 1. The paneling was coated with polyurethane varnish and the joints were sealed with duct tape. The room had its own air-handling system. Air entered the room through supply diffusers at one side, passed across the room, and exited into a duct through return grilles at an air change rate of 21 per hour. In the duct, the air passed sequentially through a 55% ASHRAE-rated filter, three electric field screens, the blower, and then re-entered the room through the supply diffusers. The air in the room was purged to the outside between test runs and replaced by building air. The electric field screens installed in the duct perpendicular to the airflow were 60 × 60 cm (2 × 2 ft), except the center one (screen B), which was 5 cm (2 in) larger. They were spaced 7.6 cm (3 in) apart. The screens consisted of 0.6 cm (.25 in) mesh hardware cloth. Electric field generators supplied a 700 V pp 177 kHz signal that was applied to screen B and also a 25 kV DC signal that was applied to screens A and C. The current was less than 3 ma. No ozone is produced by this system. The data supporting this conclusion are detailed in Appendix A. The mean temperature in the room was 22°C (72°F) and the mean relative humidity was 70% during the testing.

Particle concentration was measured by mass and light scattering. Mass measurement was accomplished with the use of a respirable aerosol mass monitor. The mass monitor collects essentially all respirable particles (0.01 to 10 microns) on a quartz crystal sensor which detects mass concentrations as low as 0.01 mg/m^3 and as high as 50 mg/m^3 on a real-time basis. It was set to continuously take 24-second samples. The teflon tube air intake was located in the center of the room and was held in place by a vertical wooden rod.

The laser light-scattering measurement system consisted of a helium-neon laser, a phototransistor detector, a potentiometric amplifier with a DC offset module and strip recorder, and a digital voltmeter. The laser beam passed diagonally across the room, 107 cm (3.5 ft) above the floor, and impinged upon the phototransistor detector.

The procedure was to purge the room to baseline particulate concentration, generate smoke to increase the particulates to a standard level, stop the smoke production, and then measure the decrease in concentration over the following 30 minutes. An ordered, counterbalanced sequence of 16 test runs was used, as is shown in Table 3. The experiment was replicated twice with comparable results.

TABLE 3

Test sequence used. The x indicates the test condition used in each particular run

Run No.	Filter in	Filter out	Field on	Field off
1	x			x
2	x		x	
3		x	x	
4		x		x
5		x	x	
6		x		x
7	x			x
8	x		x	
9		x		x
10		x	x	
11	x		x	
12	x			x
13	x		x	
14				x
15		x		x
16		x	x	

Specifically, the air-handling system was turned on and the air in the test room purged to the outside until the level of airborne particles in the test room reached a standardized baseline condition. Tobacco smoke was then generated inside the test room at the location noted in Figure 1 with a device that "smoked" cigars, providing sidestream smoke. The

TABLE 4

Overall analysis of variance of mass monitor data. The comparison of electric field on vs. off is denoted by A. B denotes the change in aerosol concentration over time.

Source	SS	df	MS	F ratio	Significance
Between					
A	259	3	86	35.94	< .001
SWG	28	12	2.4		
Within					
B	2953	2	1296	1693.89	< .001
AB	63	6	10	13.82	< .001
B X SWG	18	24	.8		

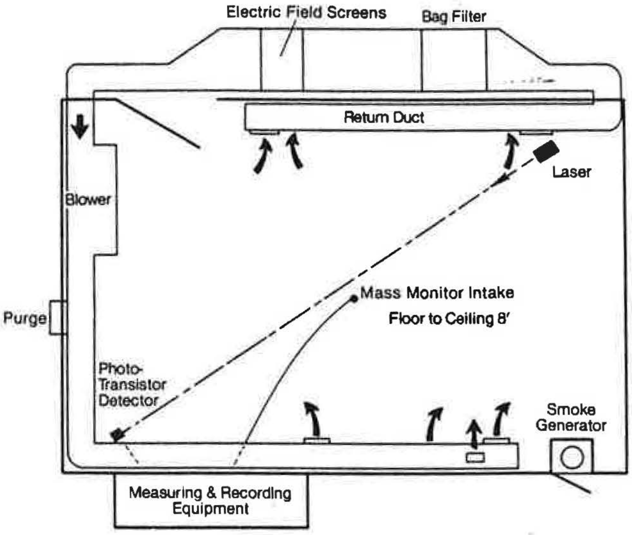

Figure 1 *Test facility showing air-handling system and measurement setup*

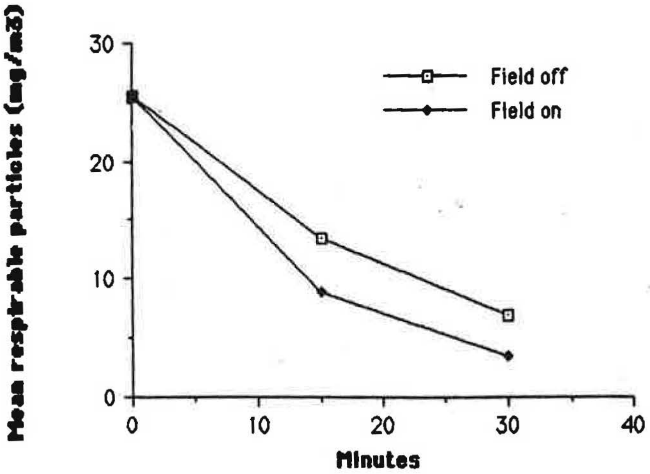

Figure 2 *Plot of mean tobacco smoke particle concentration as measured by mass*

TABLE 5

Analysis of variance comparing particle mass with electric field on vs. off with a 55% filter in the system. Note that at the start of the runs there were no significant differences between groups in particle mass as per design.

Source	SS	df	MS	F ratio	Significance
Start					
Between	13	1	13	3.88	ns
Within	20	6	3.4		
15 minutes					
Between	43	1	43	51.11	< .001
Within	5	6	.8		
30 minutes					
Between	24	1	24	273.10	< .001
Within	.5	6	.1		

TABLE 6

Analysis of variance of the laser light scattering data with the filter in. The comparison of electric field on vs. off is denoted by A. B denotes the change in aerosol concentration over time.

Source	SS	df	MS	F ratio	Significance
Between					
A	417	1	417	17.37	< .01
SWG	144	6	24		
Within					
B	15603	5	3120	2592.68	< .001
AB	8	5	1.7	1.45	ns
B X SWG	36	30	1.2		

smoke was blown toward the center of the room with a 45 cfm muffin fan. Sufficient cigars (approximately 2) were smoked with the device to bring the smoke density in the test room to a standard level (i.e., 25 mg/m^3). At this point, the smoke generator was turned off and a 30-minute run was started. The smoke density was measured with the mass monitor at the start of a run, at 15 minutes into the run, and at the end of the 30-minute run. Light-scattering measurements were made every 5 minutes during a run. At the end of each run, the room was purged to baseline level and the next test in the series was then begun.

Results

The mean respirable mass measured during the runs in the different conditions is shown in Figure 2. The significance of the differences between the means was tested with an overall analysis of variance and is summarized in Table 4. The differences between air treatment conditions (A) were significant at the .001 level. The general reduction with time in the measured particulates (B) was also significant, as would be expected, since no new smoke was added to the room during a run.

Since there were statistically significant differences in treatment effects (A), more detailed analyses of the data were appropriate. A one-way analysis of variance comparing the test conditions at the start of the runs showed no significant differences among treatment groups. Thus, as intended, the tests for the different treatment conditions all started with the same particulate mass in the room. The treatment conditions at the 15-minute and 30-minute points were signifi-

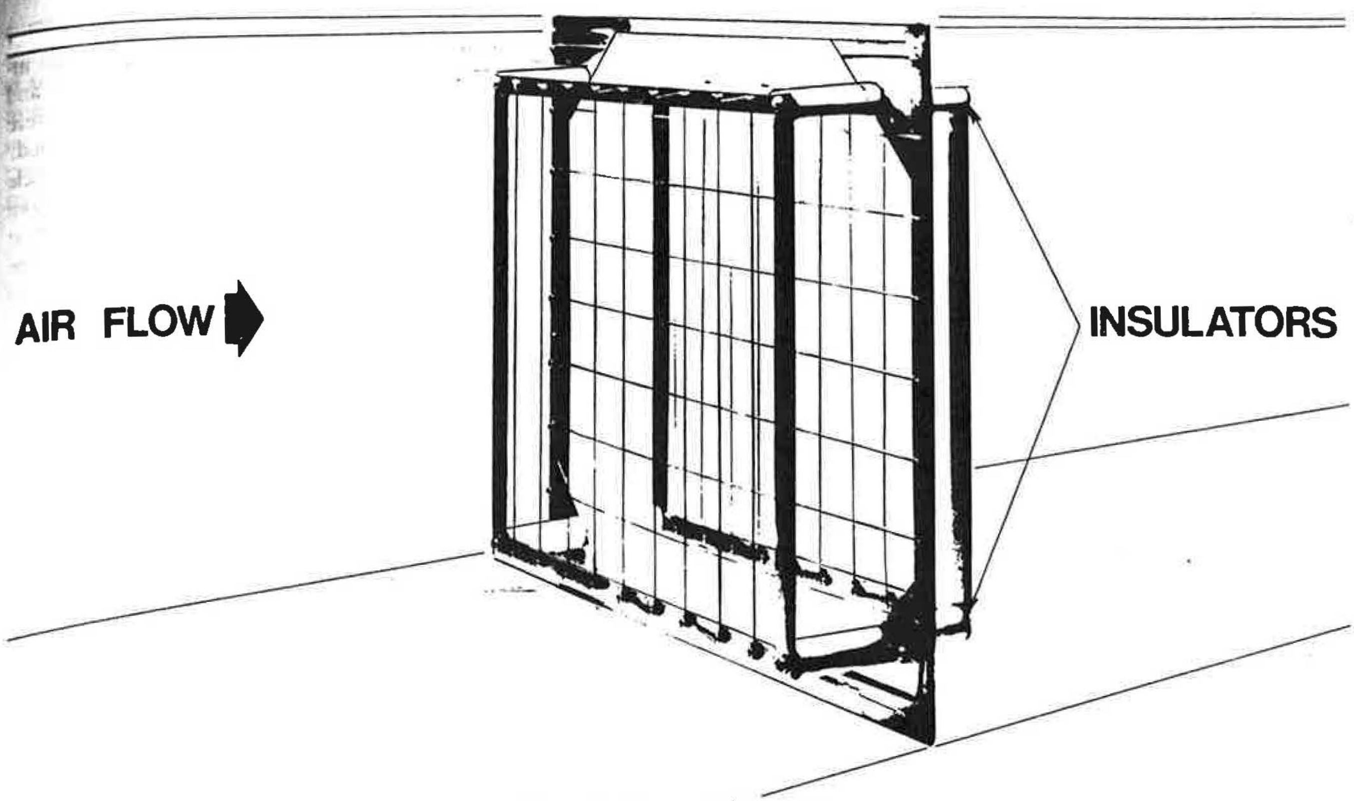

Figure 3 Electric field screens

cantly different at the .001 level, as shown in Table 5. Specifically, at the 15-minute point, the measured respirable mass with the electric field off was 13.6 mg/m³; with the electric field on it was 8.9 mg/m³. At the 30-minute point, the measured respirable mass with the electric field off was 6.8 mg/m³; with the electric field on it was 3.3 mg/m³. The laser light-scattering test yielded similar results, as shown in Table 6.

Discussion

Statistical analyses of these data indicate that passing room air through specific in-duct electric fields substantially reduces the respirable aerosol mass in a room. The mass measurement instrument indicates the electric fields reduce the aerosol mass in the room by approximately half.

EXPERIMENT 2

Since the in-duct fields were effective in reducing room contamination, experiment 2 was designed to determine if an acceleration of coagulation takes place when the in-duct fields are in operation.

Experimental Setup and Method

The testing was carried out in a room 4 m by 11 m by 2.5 m high (13 × 36 × 8 ft). Air entered the room through a pair of slot supply diffusers near the ceiling centerline, passed down through the room, and exited into a duct through a pair of slot return grilles at the bottom of the walls that were parallel to the diffuser slots. In the duct, the air passed sequentially through a smoking device, a 55% ASHRAE-rated filter, a blower, three electric field screens, and then re-entered the room through the supply diffusers. The room air change rate was 10 per hour with 50% recirculation. The air supply was filtered through activated alumina to remove moisture. The temperature ranged about 70°F with a low relative humidity. Comparable results have been obtained with the full range of humidities typically encountered in buildings. The air in the room was purged to the outside between test runs and said runs were separated by at least two days.

The three electric field screens shown in Figure 3 (A, B, and C with A upstream) were installed in the duct. Screens A and C were 53 × 45 cm and screen B was 55 × 51 cm. Screens A and C consisted of vertical bands of 0.33 cm braided wire 4.5 cm apart on centers. The bands on screen B were horizontal and 5.5 cm apart. The screens were spaced 7.6 cm apart. Electric field generators supplied a 700 V pp, 177 kHz signal that was applied to screen B and also a 25 kV DC signal that was applied to screens A and C. The current was less than 3 ma.

The smoke was generated by burning cigarettes in a smoking device in the duct. For a 75-minute period in each run, a mean rate of 1044 mg/min of airborne burned cigarette products was produced. This mean was calculated from the pre-burn weight of the cigarettes burned less the ash and butts remaining from each run. No run deviated more than 7% from this mean.

Two particle-measuring instruments were used concurrently in the experiment. One was a particle monitor, which measured particle concentration and size by light scattering. Particles of 0.5 micron diameter and larger can be detected in concentrations up to 10 million particles/ft³. Particle size range threshold is selectable and includes 0.5 micron and larger, 1.0 micron and larger, and 2.0 microns and larger. The instrument has a sampling flow rate of 0.01 cfm.

The other instrument used was an aerosol particle analyzer, which measures particle concentration and size by mass. It is a 10-stage cascade impactor with quartz crystal microbalance mass monitors in each stage. Two unsealed crystals, one for particle collection and one for temperature sensing, are used in each stage. By use of a crystal pair with the same temperature characteristics, the reference crystal nulls out any temperature effect on the sensing crystal. The nominal aerodynamic diameters (50% cutoff) for particles of a mass density of 2 g/cm^3 are in microns: 0.05, 0.1, 0.2, 0.4, 0.8, 1.6, 3.2, 6.4, 12.5, and 25. The instrument was set for continuous, automatic sampling of the air, with sampling periods of 180 seconds. This instrument provided a printout of the frequency and mass for each stage at the end of each 180-second sampling period throughout each test run. The two instruments were located on horizontal surfaces 45 cm high on opposite sides of the room, 90 cm from the wall.

During each 90-minute test run, there was no smoke introduced into the air for the first 15 minutes. During the next 20 minutes, the smoking of the cigarettes began and the smoke distribution in the room was allowed to stabilize. During the remaining 55 minutes, the smoking was held at an essentially constant rate. Thus, the primary data for the analyses were the last 55 minutes of each experimental run.

A counterbalanced experimental design was used with the electric fields off for days 1 and 4 and on for days 2 and 3.

Results and Discussion

In accordance with a standard experimental design intended to null out any possible trend effects, the days 1 and 4 data (field off) gathered after smoke levels stabilized were combined and the days 2 and 3 data (field on) were combined.

The mean counts of the on vs. off data for each particle size and larger (0.5 micron, 1 micron, 2 microns) are shown in Figure 4. The statistical analysis of these data shows that the mean particle count of size 0.5 micron and larger for the field off condition was 30,013 and for the field on it was 24,882. This difference is statistically significant at the .01 level (t = 3.63). The mean particle count of size 1 micron and larger for the field off condition was 5638 and for the field on it was 2653. This difference is significant at the .01 level (t = 3.53). The mean particle count of size 2 microns and larger for the field off condition was 2466 and for the field on it was 1217. This difference is significant at the .01 level (t = 2.99).

Statistical tests of the cascade impactor data obtained before smoking began (during the first 15 minutes) showed that there were no significant differences between runs in the

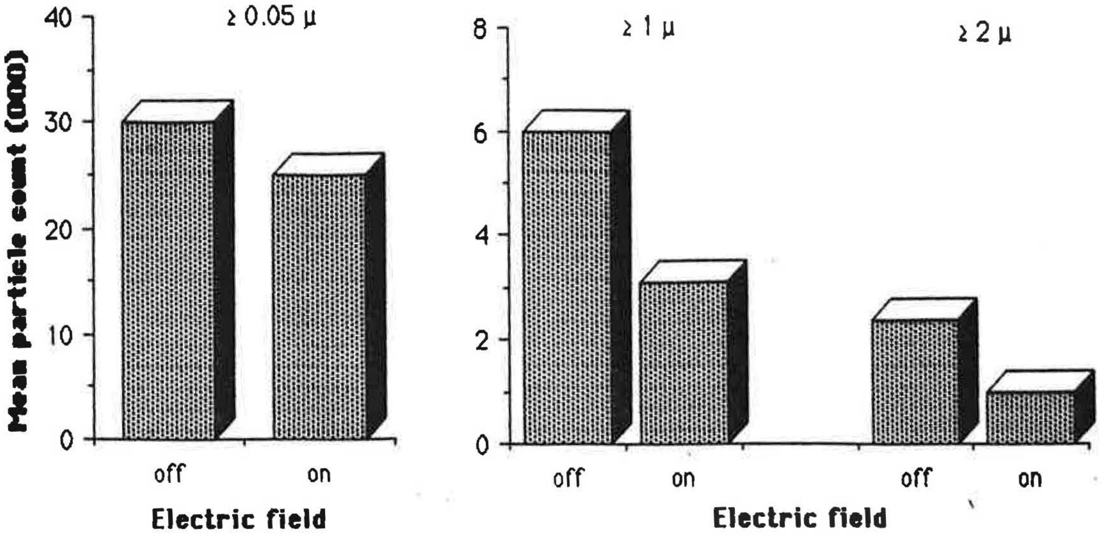

Figure 4 Comparison of mean particle counts with electric field off vs. on

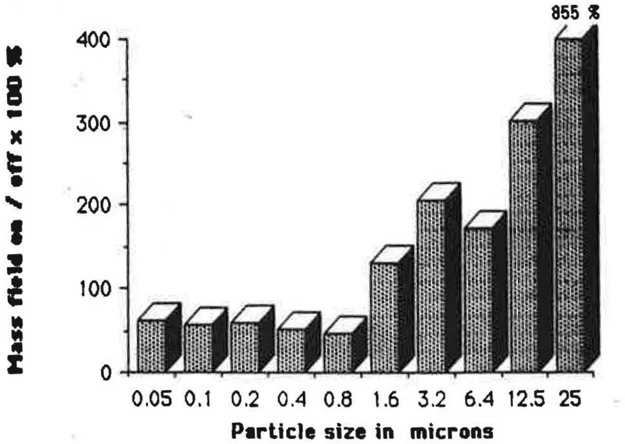

Figure 5 Percent decrement or increment in particle mass from baseline of 100% when the electric field was on. The baseline is the field off data. The difference in mass between on and off conditions at each particle size was statistically significant, except at the 1.6 micron size.

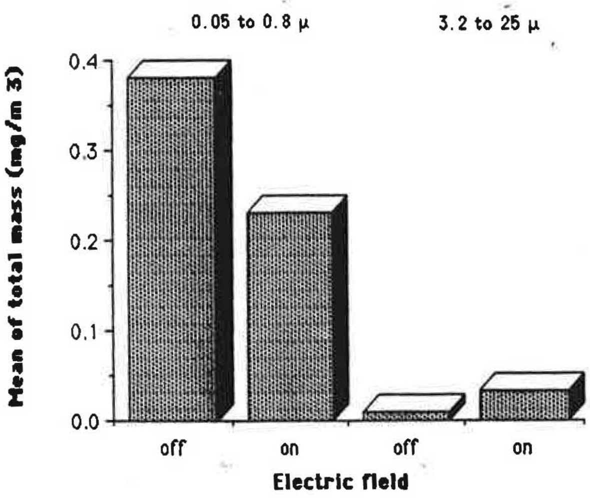

Figure 6 Comparison of mean masses with electric field off vs. on

number of particles at the various sizes. Thus, all testing started from the same pre-smoke baseline. The first objective in analyzing the cascade impactor data was to see if the results from the two instruments were consistent. Since one instrument operates by light scattering and the other operates by mass measurement, one would expect substantial, though not complete, correlation in the results.

The particle monitor measured all particulates in the air 0.5 microns and larger. A comparable set of data from the cascade impactor was obtained by summing the data from the first seven stages of the impactor, which includes all particulates 0.4 microns and larger. The mean mass for the electric field on condition, day 2 and 3 data, was significantly less than that for the off condition, day 1 and 4 data ($t = 3.03$, $p < .005$). Thus, both instruments indicated that the electric field in the duct was significantly decreasing the particulate concentration in the room.

The crystals for two of the ten stages, the 0.05 micron and the 0.1 micron, overloaded during the last 35 minutes of some of the runs. In the following statistical analyses in which data from those two stages are included, the analyses were done without the data obtained from those two crystals during the time they were overloaded. This minor loss of data had no influence on the conclusions drawn.

A statistical analysis using the data from all 10 stages was carried out. The results were comparable to what was found with the seven stages; there were differences and they were significant ($t = 5.02$, $p < .005$).

Statistical analyses were also done stage by stage. These showed that the operation of the in-duct electric field substantially reduced the mass of small particulates in the air and slightly increased the mass of large particulates. This relationship is shown in Figure 5 as percent decrease or increase in mass from the mass determined in the no-electric field condition. The difference between field on vs. off data at each stage was statistically significant except for the 1.6 micron stage data.

Since the 1.6 micron size seemed to be the transition point, it was used as a break point in further analyses. The mean mass for the small particles (0.05 to 0.8 microns) was calculated. For the electric field on condition, it was 0.232 mg/m^3; and for the off condition, it was 0.378 mg/m^3, as shown in Figure 6. Thus, the operation of the electric field reduced the mass of small particles in the room air to 61% of what it was in the field off condition.

The mean mass for the large particles (3.2 to 25. microns) was calculated. For the electric field on condition, it was 0.033 mg/m^3; for the off condition it was 0.009 mg/m^3. Thus, the operation of the electric field increased the mass of the large particles in the air to 367% of what it was in the off condition.

Note that the loss of small particle mass is not balanced by the gain in large particle mass. The gain of 367% in large particle mass in the field on condition accounts for only 6% of the mass lost in small particles. The other 94% of the decrement in small particle mass is going elsewhere. In view of the fact that there is a significant increase in large particles, these data could be interpreted to indicate that this 94% of small particle mass that is unaccounted for is being deposited in the filter. Earlier research shows that it is not plating out in the room (Frey 1986a).

In sum, the statistical analysis of the data indicated that the operation of these specific electric fields in the duct significantly reduced the particle count in the room. The statistical analyses of the cascade impactor data support that conclusion and suggest enhanced coagulation is occurring. The shift in particle size can be interpreted as the operation of the electric field causing the small particles to coalesce into larger particles, which are more readily trapped in the filter (Frey 1985). Thus, there is a means, based on theory and data, for enhancing the effectiveness of filters. Consequently, there are significant implications for controlling contamination and improving human health and comfort. This latter was tested in an extension of this experiment which is described in experiment 3.

EXPERIMENT 3

Experiment Setup and Method

The setup was the same as in the prior experiment except that it was a one-pass system.

Subjects

Forty-eight smokers and forty-eight nonsmokers were asked to rate the degree of odor and also irritation due to cigarette smoke. They were seated in four rows, eight seats to a row. Nonsmokers sat in the first two rows and smokers occupied the two rows behind them. Sixteen smokers and sixteen nonsmokers were tested for each of three air change rates: 5, 7.5, and 10 per hour. Each set of 32 subjects was tested for 1.5 hours for one day with the in-duct electric fields off and again for 1.5 hours at the same time of day with the fields on. The order of the control test vs. the experimental test was counterbalanced across the three air change rate conditions. That is, 5 and 10 air change tests were run with field off on the first day and field on the second day and vice versa with the 7.5 changes tests. Subjects had no knowledge of the test conditions and were simply asked to rate the odor and irritation once every five minutes during each test. Age and sex composition of the groups varied, with the ages ranging from 18 to 59. Every effort was made to have all subjects retested on the second day of an experimental-control series. If all subjects were not able to return, the group was supplemented with additional volunteers so that the number of smokers and nonsmokers was constant. The data from the fill-in subjects were not used.

In the 10 air change test, 28 subjects (11 male, 17 female) were present for both the experimental and control tests. In the 7.5 air change test, 26 subjects (22 male, 4 female) were present for both tests. In the 5 air change test, 29 subjects (14 male, 15 female) were present for both tests. All statistical comparisons were made within the subsets of subjects present for both tests. An effort was made to minimize "demand" characteristics of the situation. Subjects were identified only by seat number, age, and sex, not by name.

A rating scale developed by Yaglou was adapted as the primary measure. It is not ideal, but there is a data base available to use as a reference. Subjects were asked to rate the perceived odor and irritation once every five minutes on a labeled scale of 0 to 5, as shown in Table 7.

A possible limitation of the Yaglou scale was that the labels may have constrained the use of the extreme end of the scale; all labels at 3 and above were termed "objectionable." This mode of labeling may have artificially limited the scale so that raters were reluctant to use these "extreme" ratings. In fact, the data suggest that this did occur to some degree; almost all ratings fell within the range of 0, 1, 2, and 3.

Smokers were instructed to smoke a minimum of three cigarettes over the 1.5-hour test period. Butt counts indicated that the number of cigarettes smoked was relatively constant

TABLE 7

Sensory scale for strength of cigarette smoke odor or for degree of irritation to eyes, nose, and throat (from Yaglou 1955)

Index No.	Description
0	Imperceptible odor or irritation
1	Threshold of odor or irritation perception. Not objectionable.
2	Moderate odor or irritation. Acceptable level.
3	Objectionable odor or irritation. Unpleasant. Regarded with disfavor.
4	Very objectionable. Strong odor or irritation but endurable.
5	Very strong, intolerable odor or irritation. Causes significant discomfort

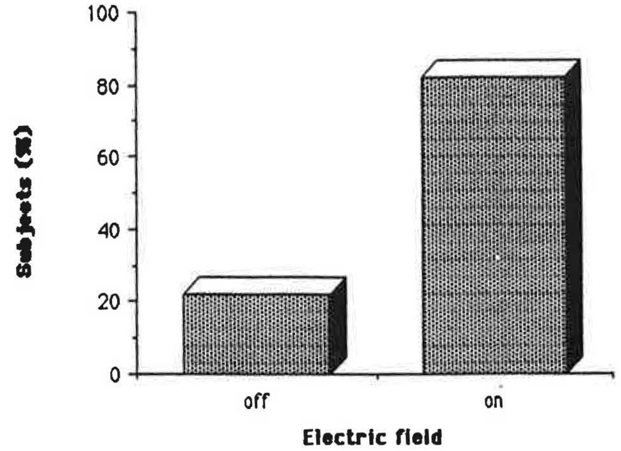

Figure 7 *Percentage of subjects who found the room acceptable (irritation measure) when the electric field was on compared to when the field was off. The air change rate was 5 per hour.*

TABLE 8

Average ratings of electric field effect by all subjects, smokers and non-smokers, for both irritation (top half of table) and odor (bottom half of table) at all air change rates

Irritation	air change rate/hr	acceptable	objectionable
field off (smokers)			
	5		*
	7.5		*
	10		*
field on (smokers)			
	5	*	
	7.5	*	
	10	*	
field off (non smokers)			
	5		*
	7.5		*
	10		*
field on (non smokers)			
	5	*	
	7.5	*	
	10	*	

Odor	air change rate/hr	acceptable	objectionable
field off (smokers)			
	5		*
	7.5	*	
	10	*	
field on (smokers)			
	5	*	
	7.5	*	
	10	*	
field off (non smokers)			
	5		*
	7.5		*
	10	*	
field on (non smokers)			
	5		*
	7.5	*	
	10	*	

from one air change test to the next (mean = 56, SEM = 1.52). The three-cigarette criterion was chosen because an earlier, unrelated, test showed that smokers in a similar situation smoked an average of 2.7 cigarettes per hour. Generally, all subjects lit a cigarette at the beginning of the test. Thereafter, 10-minute counts indicated that an average of about five cigarettes were being smoked at any given time. There was a slight increase in smoking in the last 10 minutes. This may have reflected the subjects' attempt to comply with the quota they had been assigned.

Results

The data were analyzed for the last half hour of each test. This interval was chosen because pilot research indicated that measures of irritability and odor gradually increased during the first hour of exposure and then stabilized. Averages of the six 5-minute ratings made during that interval were calculated for each subject for the field on condition and the field off condition. All statistical comparisons were made within subjects for a given air change condition. Thus, subjects who did not appear for the retest were not included in the analysis. Since Yaglou ratings are on an ordinal scale, the permissive presentation allowed by the mathematical model underlying it is categorization. Categorizations of average ratings of electric field effect by all subjects (smokers and nonsmokers) for both odor and irritation at all air changes are shown in Table 8. These categorizations show consistency across all air change conditions. Average ratings during the field on condition are systematically more acceptable than during the field off condition. With the field off, many of the average ratings fall in the unacceptable range even when the air change rate was as high as 10. It is interesting to note that smokers and nonsmokers do not differ markedly in their ratings. These ratings also indicate that odor and irritation are more objectionable for the lower air change rate (5) than for the higher air change rates (7.5 and 10).

Statistical comparisons of field on vs. field off conditions were done for smokers and non-smokers combined for each air change condition. Parametric and non-parametric tests yielded similar results, so for consistency with the rest of the report the parametric test results are presented.

Since prior tests indicated that the in-duct field would reduce perceived irritability due to cigarette smoke, one-tailed matched-pair t-tests were used. Indications were that the irritability measures were somewhat more sensitive and reliable than the odor measures, perhaps because they reflected a more "global" measure. For this reason, final statistical tests were done on irritability measures only. It was found that the level of irritation was significantly less in the field on condition for the 5, 7.5, and 10 air change rates: $t = 3.64$, $p \leq .001$, $t = 1.54$, $p \leq .05$, $t = 3.18$, $p \leq .01$, respectively. How much so can be seen in Figure 7.

Discussion

It is clear that complex in-duct electrical fields, even in a one-pass system such as used here, significantly improve the perceived air quality in a room. In general, it made acceptable a cigarette smoke environment which would otherwise be unacceptable to people. This is consistent with earlier findings with odorants (Frey 1983, 1986b).

EXPERIMENTS 4 AND 5

Since gaseous contaminants absorb or adsorb on particulates to varying degrees, this line of experimentation was extended to determine the effects of in-duct fields on two gaseous contaminants that are significant to human health and comfort.

Experiment Setup and Method

The gases used were formaldehyde and sulphur dioxide. There were two series of experiments using these gases. In the first series, the initial gas concentrations were set at levels at which the effects on people are just noticeable. In the second series, the initial gas concentrations were set at levels that would be hazardous to people with short exposure. The testing was carried out in the room and with the air-handling system described in Experiment 1.

The upstream electrical field screen installed in the duct was 60 × 60 cm (24 × 24 in) and the downstream one was 50 × 50 cm (20 × 20 in). They were spaced 7.6 cm (3 in) apart. The screens consisted of a .33-cm-wide tinned copper braid. Electric field generators supplied a 25 kV DC signal that was applied to the upstream screen and a 700 V peak-to-peak 177 kHz signal that was applied to the downstream screen. The current was less than 3 ma.

A gas detector tube system was used as the measuring instrument. The detector tubes contain calorimetric reagents adsorbed on fine grain silica gel, activated alumina, or other adsorbing media. The reagents are sensitive to particular gases or vapors and react quantitatively to provide a length-of-stain indication. Each detector tube contains a precise amount of detecting reagent in a constant inner diameter glass tube that is hermetically sealed at both ends. When a measurement was to be taken, the tips were broken off a tube and it was placed in the center of the room and connected to the sampling pump via a hose. The chemical reagent in the detector tube reacted with the sample gas and a color stain developed, starting at the inlet of the detector tube. The gas concentration was measured as the location of the interface of the stained-to-unstained reagent when staining stopped. The calibration curve on most detector tubes is a straight line, and points on the scale are at equal intervals. The calibration scales are printed on the basis of individual production lots. Therefore, possible confounding factors such as the variation of inner tube diameters, precision of tube packing, and the quality and reactivity of each reagent are eliminated. Two evaluators independently read each tube in the first series. One evaluator had no knowledge of the test conditions, so the experiment was double-blind for him. Because of the reliability of the evaluators, as noted in the results, there was only one evaluator in the second series.

The procedure was that the air-handling system was turned on and the air in the test room purged to the outside for 30 minutes. This reduced the concentration of the gas of interest down to normal ambient, as verified by a detector tube measurement at the end of each purge. A gas, such as sulphur dioxide, was then injected into the test room. Sufficient gas was injected to bring the concentration up to approximately the predetermined standard concentration, noted below, that was used in the test. At this point, the gas was turned off and the 60-minute run was started. The gas concentration was measured with detector tubes 5 minutes after injection stopped, 30 minutes into the run, and at the end of the 60-minute run. At the end of each run, the room was purged to baseline concentration and the next run in the test was then begun. There were 12 runs for each gas in each of the two series, six with the fields on and six with them off. The runs were done in an ordered, counterbalanced sequence.

TABLE 9

The initial gas concentrations were set at the level of first noticeable effects in people. The in-duct complex electrical fields reduced, as compared to controls, the concentrations as shown. The significance levels were determined with use of the analysis of variance.

	end of 30 minutes		end of 60 minutes	
Gas	mean percent reduction	signif.	mean percent reduction	signif.
HCHO	26	.001	39	.01
SO_2		ns	22	.05

The mean concentration at the 5, 30, and 60 minute points for the above tests were formaldehyde 2.8, 2.5, 1.5 ppm and sulphur dioxide 25.3, 18.7, 14.3 ppm.

The initial gas concentrations in the test results noted below were set at the level hazardous to people when exposed for a short period.

HCHO	39	.001	49	.01
SO_2	13	.01	14	.001

The mean concentration at the 5, 30, and 60 minute points were formaldehyde 4.3, 2.0, 1.3 ppm and sulphur dioxide 49.8, 40.5, 32.9 ppm.

The sulphur dioxide was injected into the center of the room via a hose connected to a cylinder of gas located outside the room. The formaldehyde was injected into the room with an airbrush spraying a 10% formaldehyde solution.

Results

The first question addressed was the reliability of the readings of the detector tubes. Pearson product-moment correlations were computed between the data provided by evaluators 1 and 2. There was near perfect correlation in each set of their readings ($r > .95$). This indicates that they were reliably reading the detector tubes and were doing so without bias.

There was natural decay in gas concentrations over time without the electrical field on. Thus, for clarity of presentation, the data are presented as the percent reduction in the field on condition compared to the control (field off) condition. For testing the significance of the differences between conditions, an analysis of variance was done on the data. The results of the statistical analyses for each of the gases for the first series are shown in the upper part of Table 9. The results of the second series are shown in the lower part.

Discussion

These data on gases extend the finding that passing room air through in-duct complex electrical fields has a significant effect on the concentration of contaminants in a room. The extent and rate of the effect varies as a function of which gas is used, as has been shown in other experiments (Frey 1986c, 1988). The amount of adsorption on particulates or molecular composition are the factors most likely to be involved in this.

CONCLUSIONS

Although filters and charcoal beds effectively remove many room contaminants that are carried to them via the

TABLE 10

Photography Test Sequence

Film Frame Exposure (sec.)	Lens	Aperture
1	1/4	4
2	1/4	5.6
3	1/4	8
4	1/2	5.6
5	1/2	8
6	1/2	11
7	1	8
8	1	11
9	1	16
10	2	5.6
11	2	8
12	2	11
13	4	8
14	4	11
15	4	16
16	10	8
17	10	11
18	10	16
19	1/4	8
20	1/2	8
21	1	8
22	2	8
23	4	8
24	10	8

ducts, a large proportion of the contaminants that are typically found in room air do not reach them. As has been shown (Frey 1986), this is in large part because the motion of contaminants less than one micron in size is determined more by the normal electrical forces in a room rather than by air currents. Thus, a large proportion of the contaminants in a room tend to plateout on people and objects. This results in adverse effects on health and comfort. In this report, a means to enhance the natural process of coagulation so as to more rapidly increase particle size is shown. As a consequence, we have a means to make air currents the dominant force so particulates can be more readily carried to the filters via the ducts. Thus, we have a means to enhance the effectiveness of filters and charcoal beds and in so doing improve air purification. There are also implications for enhancing the control of bacteria which have yet to be tested.

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APPENDIX A

Two commonly used techniques were used to determine if the screens were creating ozone, i.e., time exposure photography and ozone meter measurements. Specifically:

1. If the screens produced ozone via corona, the corona could be detected by time exposure photography. A standardized series of 360 photographs of operating screens were taken.
2. If the screens produced ozone, this ozone could be measured adjacent to the screens when the system is in operation. Four hundred and eighty ozone measurements were made under standard operating conditions.

Details of the photographic procedure and the results are as follows. The camera was used by a professional photographer. Black and white ASA 400 film was used. A series of 360 photographs were taken of screen assemblies installed in a plenum. The screen assemblies were photographed from the downstream side as well as the upstream side using a wide variety of exposure times (from 1/4 to 10 seconds) and lens apertures from f 4 to f 16. A typical test sequence is shown in Table 10.

No corona was found in any of the 360 photographs that were taken and developed by the photographer. The results were consistent roll-to-roll regardless of the exposure time or lens aperture.

Details of the ozone meter procedure and results are as follows.

A monitor that can measure ozone levels down to 0.001 ppm was used. Ozone levels were measured three times a day over five days in seven locations, i.e., outside the building, inside the test room with only the fan running, inside the test room with the electric fields on, inside the plenum, both 15 cm (6 in) upstream and 15 cm (6 in) downstream, and one meter (39 in) downstream of the screens with the fields on and off. Table 11 is a sample of an actual log used in recording ozone levels.

An analysis of variance of the data showed that there were no significant differences in ozone measured when the fields were on vs. off, as is shown in Table 12. The ozone readings recorded were consistent with the Environmental

TABLE 11

Sample of actual logged results of ozone readings (ppm)

Test	outside bldg	inside lab	inside test room	inside plenum (6 in upstream)		inside plenum (6 in downstream)	
1	0.001	0.001	0.001	0.001	0.001	0.001	0.001
2	0.001	0.001	0.001	0.001	0.001	0.001	0.001
3	0.001	0.000	0.000	0.000	0.000	0.000	0.000
4	0.002	0.001	0.001	0.001	0.001	0.001	0.001
5	0.003	0.002	0.002	0.003	0.003	0.003	0.003
6	0.002	0.001	0.001	0.001	0.003	0.001	0.002
7	0.003	0.002	0.002	0.002	0.002	0.002	0.002
8	0.003	0.002	0.002	0.002	0.003	0.002	0.003
9	0.002	0.001	0.001	0.001	0.001	0.001	0.001
10	0.003	0.002	0.002	0.003	0.003	0.003	0.003

Protection Agency's outdoor ozone readings for the area at the times the measurements were made.

TABLE 12

Anova Summary Table

Source	SS	df	MS	F ratio	Signif
A	2.5	3	0.85	0.99	ns
B	0	1	0	0	ns
AB	0.2	3	0.07	0.08	ns
Within	62	72	0.86		

DISCUSSION

Carl Lawson, LRW Engineers Inc., Tampa, FL: Do you feel that the electric-charged field will help with absorption of HCHO, CO_2, and CO?

A.H. Frey, Randomline Inc., Huntingdon Valley, PA: The research with in-duct complex fields shows that they enhance the removal of these chemicals from room air. This research has been published. I will give you the references after the session. The references will also be published in the Proceedings.

Charles J. Weschler, Bell Communications Research, Red Bank, NJ: How do you explain the reported effect of the electrical field on gas phase molecules such as carbon dioxide or sulfur dioxide?

Frey: It is well established in the literature that gas phase molecules absorb and adsorb onto particles to varying extents. Thus, to the extent that the particles coagulate and are then caught in the filter, the absorbed and adsorbed gas phase molecules will also be retained in the filter. It is comparable to the gas molecules adsorbing on charcoal particles and these being caught in the filter.