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A Study of Local Electrostatic Filtration and Main Pre-Filtration on Airborne and Surface Dust Levels in Air-Conditioned Office Premises

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Abstract The impact of electrostatic precipitation as a useful form of particulate filtration in the breathing zone is investigated in an intervention study in an air-conditioned commercial office in central London. Surface dust deposition and airborne dust levels are measured in the open plan zones of two floors – a control floor and a floor where the intervention is effected. The intervention consists of a sequence of weekly scenarios where the main pre-filters of the air-handling unit are switched between new and old filters, and where the electrostatic filters, located as uniformly as practicable on the open plan areas, are switched on or off. This 2×2 set of interventions is repeated over 4 cycles. It was found that the breathing zone filtration (BZF) by electrostatic precipitators reduces airborne dust significantly and appears to be more efficient in reducing smaller sized particles. No significant effect of BZF filters in reducing surface dust deposition was detected.

Key words Deposition; Dust; Breathing zone filtration; Particle size distribution; Suspended particles (TSP).

Practical Implications
Breathing zone filtration (BZF) units were found to reduce airborne dust significantly. The effect was seen over and above the effect of the main air conditioning pre-filters in the building. The method of using the BZF units might help solve particle deposition problems in exceptionally dusty surroundings.

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Introduction

There is increasing evidence that indoor particulate matter is a significant contributor to sick building syndrome (SBS). In a cross-sectional epidemiological study of a problem high-rise building Armstrong et al. (1989) found that SBS symptoms were significantly associated with total suspended particulate levels, while Hodgson et al. (1992) concluded from a similar study that respirable suspended particulates was the strongest predictor of SBS symptoms. Kjaergaard and Brandt (1993) reported a very strong correlation between dust sedimentation rates at workplace desks and eye symptoms. In double-blind studies on the impact of surface dust cleaning regimes on SBS symptoms, Raw (1993) concluded that indoor surface pollution by particulate dust is a major risk factor for SBS symptoms. Kemp et al. (1998) found that improved cleaning regimes, improved certain SBS symptoms in a blinded crossover study. In a recent paper, Pan et al. (1999) showed the relevance of dust to SBS symptoms.

Among methods suggested for the alleviation of indoor particulate contamination, breathing zone filtration has been proposed as an effective form of source control by localized air filtration in each worker's breathing zone. Using such a system comprising a three-layer filter (polymer pre-filter, activated carbon polymer filter, and a HEPA filter) integrated into the office furniture, Hedge et al. (1991) reported a substantial reduction in dust exposure of desk-bound office workers. The system however suffers an energy penalty in that a large pressure drop occurs across the composite filter. Electrostatic precipitation has been developed as an energy efficient alternative.

This paper reports findings from the first phase of a larger study aimed at examining the impact of electrostatic precipitation units (located within the occupied

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Table 1 Schedule of the scenarios used in the study. No data was taken for week 11, and airborne dust measurements using the Grimm monitor started with week 5

Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Scenario	D	B	A	C	A	B	D	C	C	D	–	B	A	B	A	C	D

Notes: Scenario A=Old pre-filter, BZF Off; Scenario B=Old pre-filter, BZF On; Scenario C=New pre-filter, BZF Off; Scenario D=New pre-filter, BZF On

Table 2 Differences in surface dust levels measured during the intervention study, the second floor is the control floor

Floor	Generic Location	Filtration Status	Mean Diff.[a]	DF	t-value	p-value
3rd Floor	Workstation	BZF (Off,On)	0.039	16	0.118	0.9076
		Pre-filter (Old,New)	−0.462	16	−1.490	0.1557
	Thoroughfare	BZF (Off,On)	0.062	16	0.130	0.8984
		Pre-filter (Old,New)	−0.499	16	−1.082	0.2952
2nd Floor	Workstation	Pre-filter (Old,New)	−0.190	16	−0.395	0.6980
	Thoroughfare	Pre-filter (Old,New)	−0.255	16	−0.297	0.7703
3rd and 2nd Floor	W/S & Thoroughfare	BZF (Off,On)	0.063	16	0.099	0.922

[a] denotes the difference in mean values (% of light scattered) between the BZF off and on states or between the pre-filter old and new states

space) on airborne and desk-top settled dust and SBS reporting. Results on surface and airborne dust reduction effectiveness by electrostatic precipitation are discussed while the SBS study will be reported separately.

Material and Methods

Building Description

The subject building is a six-storey deep plan, mechanically cooled and ventilated office building in central London surrounded by busy roads, and hence, potentially, a polluted site. Fresh air is drawn in via an air-handling unit located at the topmost (6th) floor. It is treated sequentially by a set of pre- and main-filters before being distributed through a ceiling duct system, and finally supplied to the office premises via induction units located at the perimeter of the building and in island units in the open plan spaces.

Two floors of the deep building were selected for the study: one (Floor 2) to serve as a control and the other (Floor 3) for assessing the impact of the breathing zone filtration (BZF) units. A total of 15 BZF units, which operate on the principle of electrostatic precipitation, were located as uniformly as practicable on the open plan areas of each floor studied.

Intervention Design

Two different interventions were scheduled: alternating between a set of new and old (used) pre-filters in the main building air-handling unit, and switching on and off the operation of the electrostatic filtration panels within the BZF units. The BZF units consist of two low-speed fans of diameter 0.4 m each with a double spiral electrostatic element, 0.07 m deep. Unwound, the electrostatic filter is 80 m in length. "The filter efficiency is >99% at the operational air flows. The Equivalent Clean Air flow rate was measured at approximately 400 m^3/h over the particle size range from 0.3 to 1 μm in diameter. The ozone generation of the unit was not measurable (< 10 ppb)" (Törnblom 1995). The BZF unit fans were left continuously running in order to keep the occupants 'blind' to the interventions. Therefore in the remaining text where the term "BZF units off" is used it refers to only the electrostatic element of the units being off – the fans are always on and air is always drawn through the units. The interventions were structured to give 4 scenarios, and 3 such sets were executed sequentially. However, the order of the scenarios within each set is randomly assigned. Once a scenario is established, the conditions are maintained for a week before the next scenario is implemented. The schedule of scenarios is given in Table 1.

For each scenario, the airborne dust and surface dust deposition levels were measured by techniques described below. The subjective response of the occupants in terms of SBS intensity was procured with a weekly questionnaire. The results of this work have been presented by Wyon et al. (2000).

Particulate Sampling and Measurement

Two categories of sampling locations were selected for particulate sampling based on office configuration, dust generation and deposition characteristics: workstations and thoroughfare areas. For each category, sampling locations were determined weekly on a random basis to provide unbiased samples. On the study floor (Floor 3), a total of 9 workstation and 5 thoroughfare locations were determined; while 3 workstation and 1 thoroughfare locations were selected for the control floor (Floor 2). Workstation samples were taken from occupant's desks while thoroughfare samples were taken from surfaces beside routes through the open plan offices.

Surface dust deposition was measured by means of a standardised technique (Schneider et al., 1996) which involved removing a sample of deposited dust with a forensic (fingerprint) tape, and measuring the light scattered from a laser beam passing through the tape before and after exposure with a commercially available instrument, the DustDetector, from BM Environmental Engineering (Dust Detector, 1996). The unit of measurement is the percentage of area covered by dust. These samples of deposited dust were measured at the end of each scenario so that the full impact of the scenario was monitored. It was assumed that the cleaning schedules did not differ during each scenario, however, it was not possible to ascertain the exact cleaning schedule.

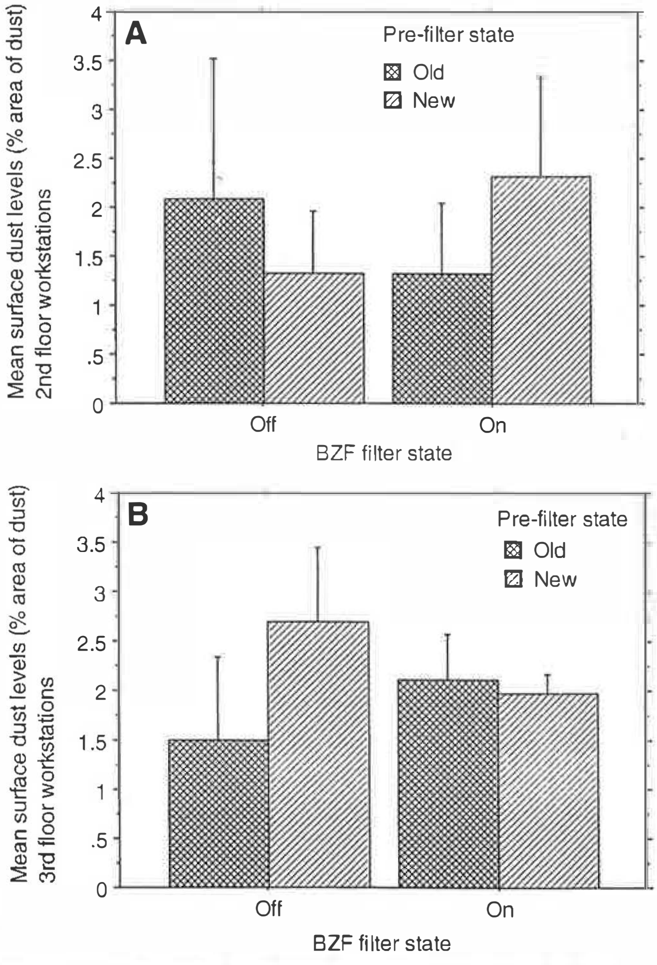

Fig. 1 A, B) Deposited surface dust on workstation desktops on both floors over the entire period, split by whether the BZF units were on or off, and whether the main supply pre-filters were new or old. (Units: % area covered by dust) (Bars show one standard deviation)

Airborne dust was measured at one-minute intervals throughout each scenario with a single Grimm "Workcheck 5" occupational health dust monitor which measures particle numbers in several size ranges based on a light scattering technique (Grimm, 1995). The monitor was placed on top of a filing cabinet at a height of 1.1 m towards one corner of the open plan area. The layout of the office space and the location of the Grimm instrument is shown in Appendix 2.

The particulate measurements utilised in this study are Total Suspended Particulates (TSP), PM10 and PM2 and have been expressed in units of $\mu g/m^3$. (The three size fractions are an inbuilt feature of the Grimm instrument and can't be changed in retrospect, also particle counts can not be retrieved in retrospect). A patented process is used by the Grimm to convert numbers of particles to a mass measurement; this process is based on a calibration with particles consisting of a high proportion of hydrocarbons. See Appendix 1 for more details.

Because of this difference in measurement technique there may be differences in readings when compared with background measurements from the National Automatic Urban Monitoring Network (AUN). The measurement method for the AUN network is based on the use of Tapered Element Oscillating Microbalances, (TEOMs). Elevated background levels of PM10 particles measured using TEOMs have been linked with an elevated risk of mortality (Dockery et al., 1993).

There are limitations associated with using the Grimm particle counter, the main ones are listed below;

- the very finest particles, those with diameters of less than 0.5 microns, are not measured.
- the Grimm instrument measures particles based on light scattering so may be affected by some types of particles having a higher reflectivity than others.
- the mass of particles in offices is likely to be different from that used in the mass correction process used by the Grimm instrument.

However, the same instrument with the same correction factor was used for each size fraction, so the ratio between experiments is assumed to be independent of the instrument. Unfortunately the filters were not weighed after the experiment to provide an accurate correction factor.

Table 3 Differences in airborne dust levels measured during the intervention study

			Mean Difference[a]	DF	t-value	P-value
BZF	TSP	Total	4.301	1690	7.200	<0.0001
		Occupied[b]	9.863	490	9.518	<0.0001
		Unoccupied	20021	1198	5.098	<0.0001
	PM10	Total	3.765	1690	10.004	<0.0001
		Occupied	8.151	490	11.601	<0.0001
		Unoccupied	1.967	1198	7.108	<0.0001
	PM2	Total[c]	0.805	1549	15.768	<0.0001
		Occupied	0.882	449	7.597	<0.0001
		Unoccupied	0.774	1098	14.385	<0.0001
Pre-filter	TSP	Total	1.230	1690	2.031	0.0424
		Occupied	2.704	490	2.412	0.0163
		Unoccupied	0.626	1198	1.564	0.1180
	PM10	Total	−0.150	1690	−0.388	0.6978
		Occupied	−1.139	490	−1.439	0.1509
		Unoccupied	0.255	1198	0.902	0.3670
	PM2	Total	0.232	1549	4.250	<0.0001
		Occupied	0.361	449	2.957	0.0033
		Unoccupied	0.180	1098	3.077	0.0021

[a] denotes the difference in mean values between the BZF off and on states or between the pre-filter old and new states
[b] occupied hours are between 0900 and 1900 hours, Mondays to Fridays
[c] Data for PM2 was not recorded during the first week, and hence the corresponding number of hours are less than that for TSP and PM10

Results

In addition to the indoor surface and airborne dust measurements, the outdoor background levels of PM10 and PM2.5 measured at the Bloomsbury monitoring site in central London [9] are presented. Firstly results are presented from the surface dust measurements, comparing readings taken when the Breathing Zone Filtration units were on or off, and when the pre-filters were new or old.

The measurements of indoor airborne dust levels made using the Grimm monitor are next presented. Outdoor levels of particulate are then considered together with their effect on indoor levels.

Surface Dust Measurements

Since surface dust samples were taken from random locations on the second and third floors, the randomisation of the locations mean that spatial analysis of the measurements is not possible. The analysis is therefore based on averages taken from all locations on each floor for each week and thus compares how each floor's surface dust differs from week to week and from scenario to scenario.

When the means of all readings are compared for periods which have the same filter states, BZF units are on or off, and main supply pre-filters old or new, the differences seen are not statistically significant. The results are presented in Table 2. In the table, the P-value is a measure of how likely the result seen could have arisen by chance. A P-value of <0.05 is generally taken as being statistically significant. The t-value is a measure of how important a particular variable is in determining the result seen and the degrees of freedom variable (DF), in this case, is equal to the number of measurements used in the calculation.

The difference in dust deposition between the states for floor 2 (control floor) and floor 3 workstations, measured in terms of percentage of area covered by dust, are shown in Figure 1A and B. In Figure 1A it can be seen that there is no systematic difference in surface dust levels seen when the BZF units are on or off which could might be used to normalise any differences that might be seen in the deposited dust levels on the third floor. By comparing levels of surface dust seen on the control floor, the effect of the supply filters without the BZF filters can be examined; again no significant effect is seen. In Figure 1B there is a large difference in levels seen for the scenarios with BZF off and new or old supply pre-filters but it is not significant. In fact none of the differences seen in surface dust levels are significant.

Airborne Particulate Measurements

Measured data from the Grimm has been averaged to give weekly figures to allow comparison with the surface dust measurements. The differences in airborne dust levels between weeks with different filter states are shown in Table 3. In all cases the levels of airborne dust are significantly lower with the BZF units on (P<0.0001), and these are shown as shaded cells. The levels of TSP and PM10 do not vary significantly whether the supply pre-filters are old or new. How-

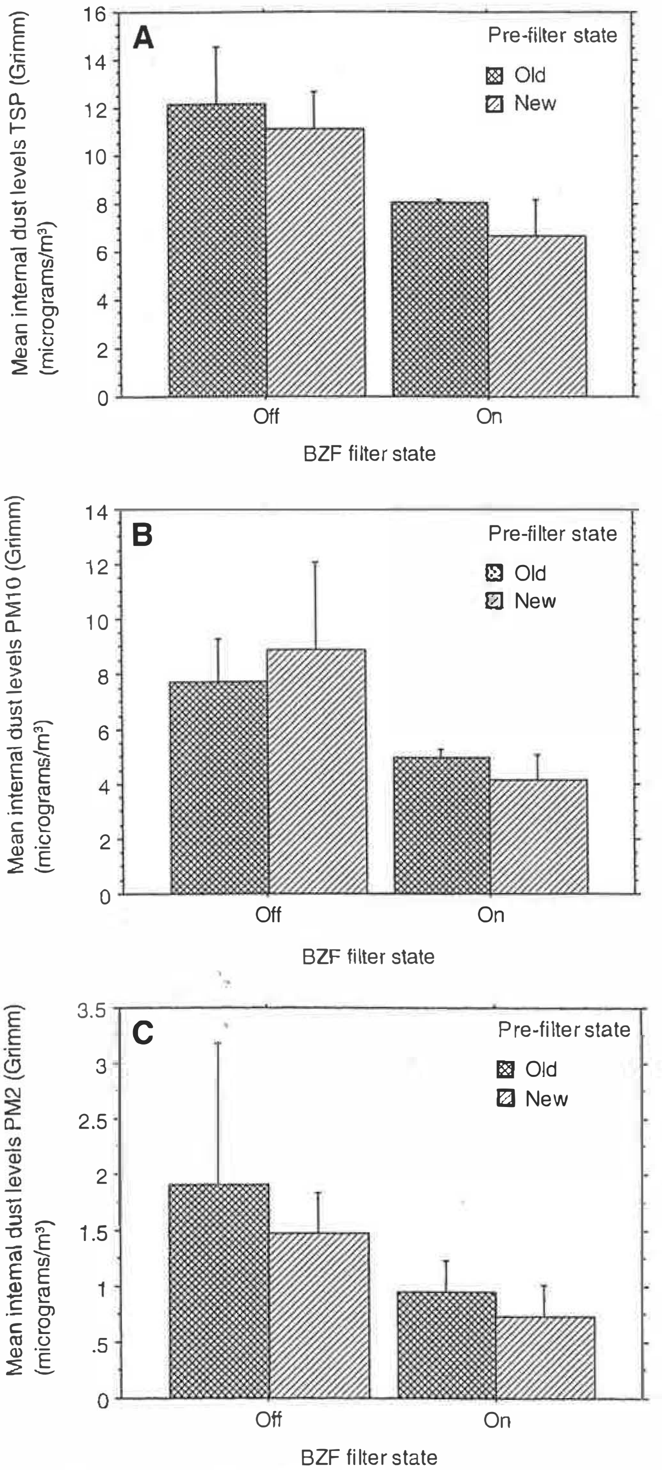

Fig. 2 Comparison of outdoor PM2.5 and PM10 readings for periods with the BZF unit on and off (left) and for periods with new or old main supply pre-filters (right). (Bars show one standard deviation)

ever, there is a significant reduction in the PM2 levels when the pre-filters are new, the reason for this is not clear.

In Figure 2A–C, the effects on each of the size fractions of airborne dust of each scenario are shown. In

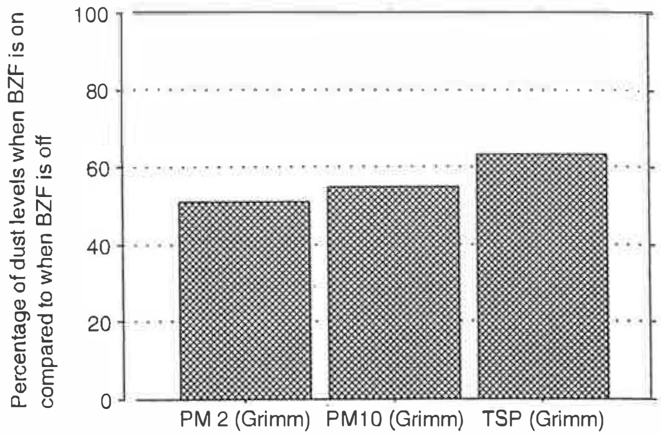

Fig. 3 Reduction in airborne dust levels for three size fractions with the BZF units on or off

each case the levels with the BZF unit on are lower than with it off. The supply pre-filter seems to affect the levels of TSP and of PM2 but not the PM10 levels. From these graphs the effects of the BZF filter are clearly seen as being greater than any effects of the supply pre-filter.

The ratios of on:off dust levels for the BZF unit are plotted for each size fraction in Figure 3 and expressed as a percentage. In Figure 3, it can be seen that for the BZF unit the smaller the size fraction, the larger the difference between on and off mean values of airborne dust. The dust levels with the BZF unit on are 50% of the level with it off for the PM2 fraction. The suggestion is therefore that the BZF units are more effective at removing the smaller particles than the larger particles. There is no such relationship seen with the supply pre-filter.

Outdoor Particulate Levels

Outdoor levels of particulates were measured at the nearby Bloomsbury monitoring site in central London. This is classed as an urban background site and as such is comparable to the levels expected outside the study building at the roof top level, which is where the main air intakes for the building are situated.

Figure 4A and B show the levels of outdoor particulate concentration split by the state of the internal filters. These figures are included to show the outdoor levels during the times that each scenario was being tested. From these it can be seen that when the BZF units were on the outdoor particulate levels happened to be higher than when they were off. The outdoor levelswere also higher when the pre-filters were new. The assumption that outdoor particulate levels (PM10) affect indoor levels of particulates (PM10 Grimm) is examined and the results are presented in Figure 4C and D. These show that there is no consistent relation-

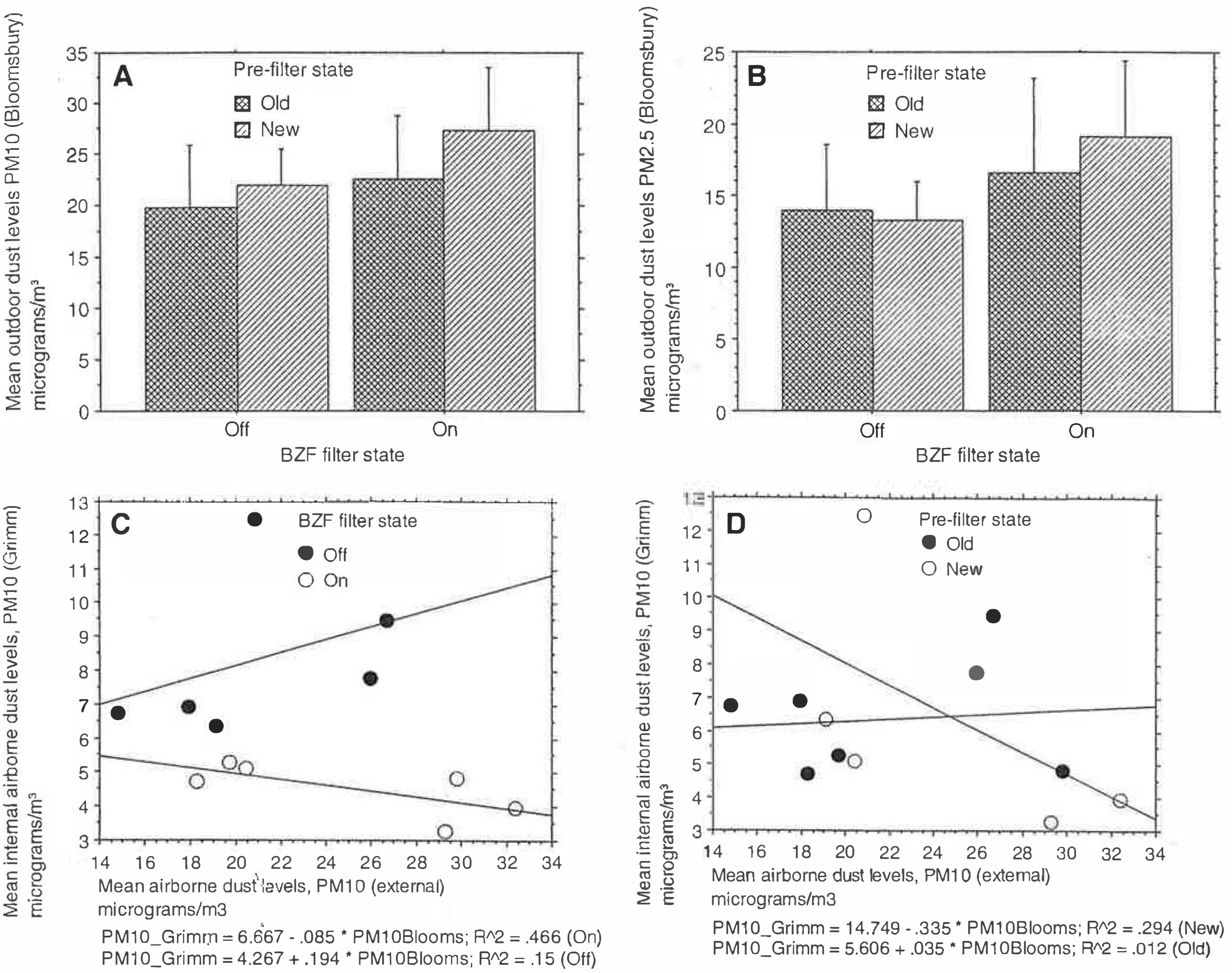

Fig. 4 A) Levels of outdoor PM10 measurements during each scenario. (Bars show one standard deviation). B) Levels of outdoor PM2.5 measurements during each scenario. (Bars show one standard deviation). C) Comparison between indoor and outdoor PM10 levels showing measurements taken when the BZF units were on or off. D) Comparison between indoor and outdoor PM10 levels showing measurements taken when the supply pre-filters were old or new

ship between indoor and outdoor particulate levels. In Figure 4C, it can clearly be seen that when the Breathing Zone Filtration units are on, the levels of indoor airborne dust are always lower than when the units are off. Figure 4D shows how there is no consistent relationship that is due to the state of the supply pre-filters.

Discussion

There were several limitations of this study, mainly due to the available budget. Of these the most significant was the lack of indoor air temperature and relative humidity monitoring. Other limitations were those associated with the BZF units themselves. No base case activity monitoring was carried out. In retrospect, both the control and the study floors should have been monitored for dust levels before and after the study period for one week each to ascertain a base level of activity.

Unfortunately it was not possible to measure air exchange rates with outside which would have been helpful in the analysis of the contribution of outdoor particulate concentration to the indoor level.

The Grimm dust monitor was placed in the most representative location possible, even so, it may be affected by conditions in its immediate vicinity, however the comparative nature of the study allows the comparison of week to week means and is assumed to be largely independent of sensor location.

Conclusions

It was found that indoor levels of both surface and airborne dust are were unrelated to outdoor particulate levels. This suggests that the supply pre-filters are effective at removing the majority of outdoor dust when either new or old ones are used. This is contrary to the findings of Wallace, who did find a relationship between indoor and outdoor particulate levels (Wallace, 1996). The differences between these two findings might be explained in part by different cleaning regimes, building leakage rates, indoor activity levels and air conditioning factors including pre-filters and duct differences.

The implication of this is that a major proportion of the indoor dust is generated by indoor office activities. The different levels of surface dust seen on the 2nd and 3rd floors could be considered as backing up this supposition. There is a also a possibility that some of the increase seen between 2nd and 3rd floors is due to the continuous running of the BZF fans.

The study has not shown that the BZF units are effective in reducing desktop dust deposition; however, it has shown that electrostatic precipitation at the breathing zone level using BZF filtration units is effective in reducing airborne dust. Measurements of indoor levels of 3 size fractions of airborne dust also show also that the BZF units appear to remove smaller size fractions more effectively than larger fractions. TSP, PM10 and PM2 dust levels are reduced to 63%, 54% and 51% respectively, when compared to the levels when the BZF electrostatic filtration is turned off (see Figure 3). This finding is different to that expected from electrostatic precipitators given in ASHRAE (1992), where the larger particles are more efficiently removed than the smaller ones. A possible reason for this might be the specific aerodynamics of the spiral deposition plates in the BZF units.

That the BZF units seem more efficient in removing smaller sized particles is potentially useful in mitigating SBS symptoms caused by particulate contamination. Smaller sized particles, particularly those nearer the sub-micron range have a deeper penetration in the human breathing system, notably to the alveolic region, where it is recognised that the greatest harm is done. It is also notable that this is achieved without the need to resort to HEPA filters, thus providing a potentially energy efficient method of removing smaller sized particles in the indoor environment. The relative performance of electrostatic precipitation and other forms of BZF filtration, including energy consumption, needs to be further explored.

Acknowledgements

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Appendix 1

Operation of the Grimm Dustcheck 5 (Grimm, 1995).

All units of the 1.100 series use light-scattering technology for single-particle counts, whereby a semiconductor-laser serves as the light-source. The scattered signal from the particle passing through the laser beam and is collected at approximately 90° by a mirror and transferred to a recipient-diode. The signal of the diode passes, after a corresponding reinforcement, a multi-channel size classifier. A pulse height analyzer then classifies the signal transmitted in each channel. These counts can be displayed and are also stored in the data storage card and may be transferred via the RS 232 for further analysis.

The ambient-air, to be analyzed, is drawn into the unit via an internal volume-controlled pump at a rate of 1.2 l/min. The sample passes through the sample cell, past the laser diode detector and is collected onto a 47-mm PTFE filter. The entire sample is collected on the PTFE filter, which can then be analyzed gravimetricly for verification of the reported aerosol's mass. Additionally, further chemical analysis can be performed on the deposited residue. The pump also generates the necessary clean sheath air, which is filtered and passes through the sheath air regulator back in to optical chamber. This is to ensure that no dust contamination comes in contact with the laser-optic assembly. This particle free airflow is also used for the reference-zero test during the auto-calibration.

At the beginning of each measurement, the instrument initiates a self-test, which last approximately 30 s. The actual dust-measurement begins when the LCD displays the first result. Subsequent results will be displayed every 6 seconds. The real-time dust-concentration measurement data are transferred each minute to the removable data storage-card, if used. The data is also available via the built-in RS-232 serial port. This data may be transmitted to an external computer or printer. This data is available in intervals of every 6 s (fast-mode) or every 60 s (normal mode). Other options for data retrieval times are available via the PC software.

Appendix 2

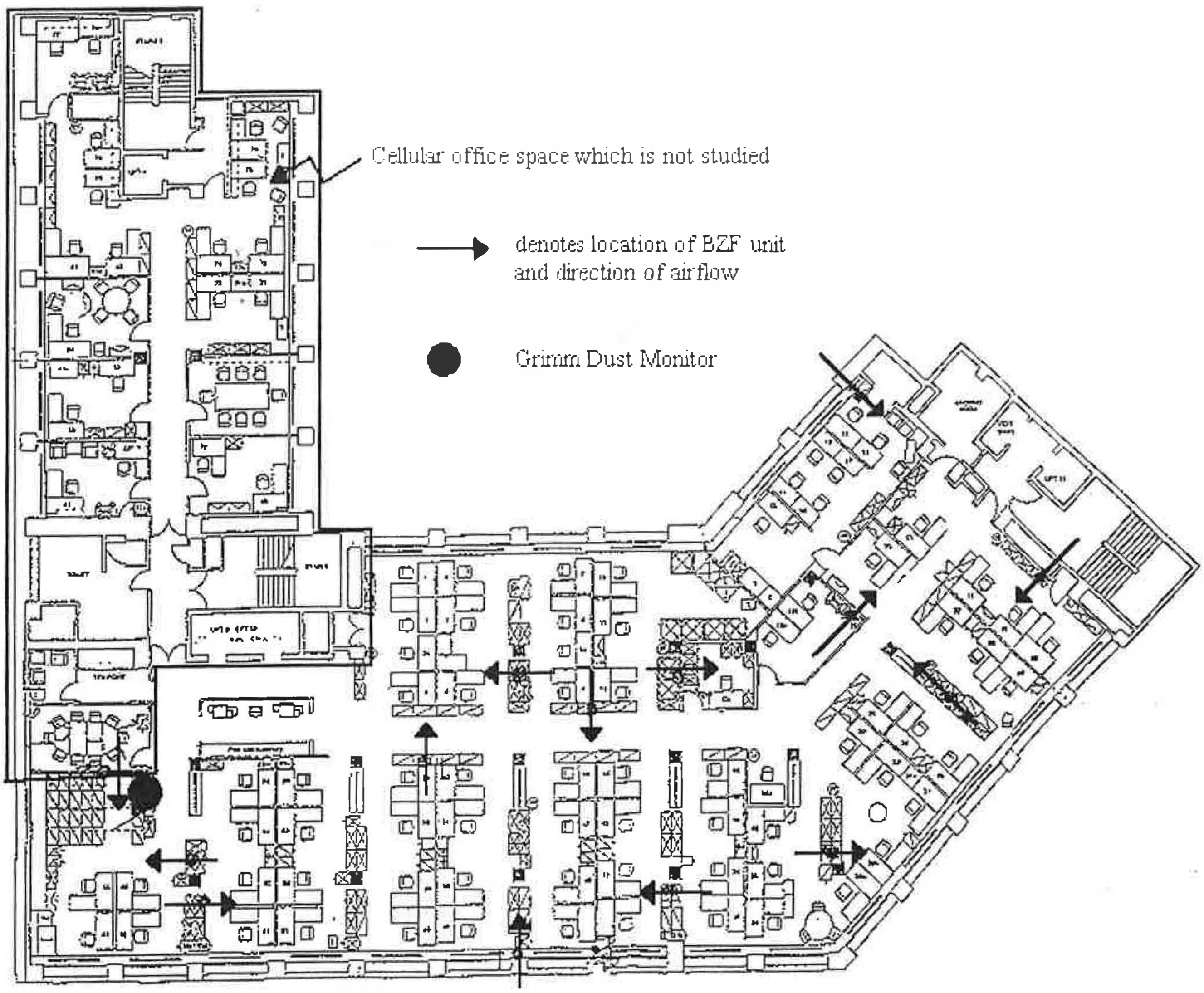

Fig. 1 Plan of Floor subjected to intervention indicating locations of the BZF units