THE DEVELOPMENT AND APPLICATION OF AN ELECTROSTATIC AIR CLEANING TECHNOLOGY

by

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ABSTRACT

There is a growing concern about the effects of indoor air particulate pollution, in relation to human health. The removal of indoor air pollution at its source is extremely difficult. Fine particles are continuously generated in outdoor air mainly by combustion processes. Coarse particles are constantly generated by activities indoors. There is a need for simple technology that can reduce these types of pollutants, which can work in conjunction with standard heating, ventilation and air conditioning (HVAC) systems.

A novel air cleaner was designed to harness the principles of electrostatic air cleaning, through the production of electrons. The electrostatic air cleaner (EAC system) needed to be tested to ascertain whether existing theories on the properties of electrostatics would apply. To investigate and develop the EAC system a series of experiments were conducted. The determination of the small air ion generating capacities using different voltages, the determination of the efficiency of carbon fibre thread as an electron emitter and an assessment of the concentration of hydrogen peroxide produced - through the use of new methodology and design of an enlarged interactive gas phase reactor (EIGPR) for use in a FT-IR spectrometer. To increase the understanding of the behaviour of particulate matter and other pollutants indoors, two investigations were conducted. Two nurseries in the city centre of Plymouth (UK) were monitored to assess variations in particles and 116 council owned properties in Torbay were assessed to ascertain the levels of particulates, humidity, temperature, house dust mites, damp and mould in private dwellings. To test the efficacy of the EAC system in a real life situation, the system was installed in a city centre office (Plymouth, UK) as part of a controlled trial.

The results from the nurseries and council houses confirm the problems people face with indoor air pollution. The studies showed that the EAC system needed to be able to cope with large variations in particle numbers and to be able to work in varying environmental conditions. The results from the investigation into the efficacy of the EAC system showed that with a 6.5 kV negative voltage generator, a reduction in fine and coarse particles would occur. Using carbon fibre threads as an emitter confirmed that they are the most suitable type of electron emitter. The results showed that the fibres do not deteriorate as quickly as needle type emitters and that dirt accumulation on the fibres only has a minor effect on the efficiency of the emitter. An analysis of electron chemical reactions using the EIGPR revealed that the EAC system could produce 0.44 ppb of hydrogen peroxide. Hydrogen peroxide has anti microbial properties, which would add to the improvement of air quality when the system is installed. The study of the city centre office showed that the EAC system could reduce fine particles by an extra 21 % in a room that already had an efficient air processor installed. The results from the development and application of the EAC system have led to a new design for an electrostatic air cleaner, termed a 'Full Electrostatic Air Cleaning system'. This system consists of a negative voltage generator and carbon fibre thread (the emitter) contained on a standard size ceiling tile. To aid the collection of particles, oxygen free radicals etc., the Full EAC system will be accompanied by a collector plate. This system will provide a weak electrostatic field within which indoor air will be cleaned of particulate matter.

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GLOSSARY

Abbreviations

ac h^{-1}	Air exchange rate per hour
AIVC	Air Infiltration and Ventilation Centre
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CIBSE	Chartered Institute of Building Service Engineers
COMEAP	Committee on the Medical Effects of Air Pollution
DC	Direct Current supply converted from an AC supply via a transformer
DETR	Department of the Environment, Transport and the Regions
DfEE	Department for Employment and Education
DoH	Department of Health
DRIFT	Diffuse Reflectance Infra Red Fourier Transform
EAC	Electrostatic Air Cleaning
EIGPR	Enlarged Interactive Gas Phase Reactor
EHT	Extra High Tension negative voltage generator
EPAQS	Expert Panel on Air Quality Standards
ETS	Environmental Tobacco Smoke
FT-IR	Fourier Transfer-Infra Red
HEPA	High Efficiency Particulate Air filters
HVAC	Heating, Ventilation and Air Conditioning
IEH	Institute of Environment and Health
IAQ	Indoor Air Quality
IR	Infra Red
Kbr	Potassium Bromide

GLOSSARY

Abbreviations continued

kV	Kilo Volts (1000 V)
m_e	The mass of an electron 9.1×10^{-31} kg
M	Moles per litre
MVOC	Volatile Organic Compounds from Microbes
MRC	Medical Research Council
PAH	Poly aromatic hydrocarbons
PM_{10}	Particulate Matter with an aerodynamic diameter that will pass through a size selective inlet with a 50 % efficiency cut off at 10 µm
PM_3	Particulate Matter with an aerodynamic diameter from 0.3 to 3.0 µm*
PM_7	Particulate Matter with an aerodynamic diameter from 3.0 to 7.µm*
ppb	parts per billion
ppm	parts per million
THHP	Torbay Healthy Housing Project.
RH	Relative Humidity
SEM	Scanning Electron Microscope
SBS	Sick Building Syndrome
SWAUDGP	South West Association of University Departments of General Practice
VDU	Visual Display Unit
VOC	Volatile Organic Compounds

* - These ranges were chosen based on the practical upper and lower limits of a MetOne particle counter used for all measurements (counted as number of particles/ litre of air).

GLOSSARY

Chemical formula	Name
C-H	Carbon-Hydrogen
CO	Carbon monoxide
CO_2	Carbon dioxide
H_2O_2	Hydrogen peroxide
O_3	Ozone
NO_2	Nitrous oxide

Terminology	Explanation
Aerodynamic diameter	The diameter of a unit density sphere (density = 1 $\mu g/ cm^3$), which has the same settling velocity as the particle in question
Bioload	Covers all airborne living organisms
Coarse particles	Defined as having an aerodynamic diameter of > 2.5 μm
Electron chemistry	The term is used in the broader sense to cover chemical reactions promoted either by the direct addition of free electrons and/ or chemical reactions promoted by air ions generated in-situ
Fine particles	Defined as having an aerodynamic diameter of < 2.5 μm
House Dust Mite Allergen	Defined as Der p1 - a group 1 faecal allergen (cysteine protease) from the species *Dermatophagoides pteronyssinus*
Relative Humidity	Absolute Humidity divided by the Absolute Humidity at saturation of air at the same temperature

RESEARCH ACTIVITIES

Conferences/Seminars participated

March 1998	Development in Air Quality, University of Exeter
June 1998	National Ventilation Conference, Garston

Presentations/Lectures given

February 1998	The South West Association of University Departments of General Practice, 6-7 February 1998, Dartington, Devon (UK). Non-attendance rates among children in Swedish day care centres before, during and after cleaning the indoor air using an electrostatic air cleaning technology - a controlled trial.
March 1998	Department of Primary Health Care & General Practice, Presentation of Research Project, Plymouth Post Graduate Medical School, Plymouth (UK). A double blind controlled study of electrostatic air cleaning and respiratory symptoms in child health care centres.
September 1998	19th AIVC conference on Ventilation Technologies in Urban areas, 28 - 30 September 1998, Oslo, (Norway). Non-attendance rates among children in Swedish day care centres before, during and after cleaning the indoor air using an electrostatic air cleaning technology - A controlled trial.

RESEARCH ACTIVITIES

Presentations/Lectures given (continued)

January 1999	SWAUDGP (National Conference) Electrostatic Air Cleaning in a modern urban office
March 1999	Inequalities in Health, 7th Annual Public Health Forum, Brighton The Torbay Healthy Housing Project
March 2000	Presentation given at the Health Improvement Beacon Service Meeting (Thursday 9), at Windsor House Plymouth The Torbay Healthy Housing Project
September 2000	21st AIVC, Innovations in Ventilation Technology, 26 - 29 September 2000, The Hague (Netherlands). Quantifying ventilation needs in Local Authority Housing - A case study.
December 2000	Chartered Institute of Building Service Engineers seminar, Ventilation and Indoor Air Quality in Schools, 12 December 2000. Is CO_2 really an adequate marker for good indoor air quality? - What about particulates?

RESEARCH ACTIVITIES

Miscellaneous

January 1998 onwards	Development of a database on articles/ information to support the research (as of December 2000 there are 666 references). This database will be offered for use by UOP students and eventually for release on the Internet.
March 1998	Invited and accepted to join the Scientific Board of the journal "The Science of the Total Environment" to review articles. Included the revision of report published by the Medical Research council - IEH assessment on indoor air quality in the home (2): Carbon monoxide.
	Assessment of different generators to install in the novel technology, particle reductions capacity and suitability of carbon fibre threads as an emitter.
Summer 1998	Designed, built and commissioned an enlarged interactive gas phase reactor to fit a Bruker IFS66, FT-IR spectrometer. Conducted experiment using the gas cell to calibrate a carbon monoxide monitor
September 1998	Supported and advised two project students: Gary Richard's MChem (Hons) project and Victoria Stanley's BSc third year project
October 1998	Submitted an abstract for a presentation at the CIBSE 1998 National Conference

January to November 1998	Application of Electrostatic Air Cleaning technology in the Cornwall and Devon Careers Office, Plymouth
	Analysis of particulate load in the University of Plymouth nursery, Roundabout Day care centre, Coxside, and the Nationwide Building society, Derry's Cross (all in Plymouth, UK).
January 1999	Began three year investigation into the indoor air quality in 116 council houses in Torbay (UK)
March 1999	Submitted and had accepted paper - Using a laser beam type particle counter, a small air-ion counter and a Fourier Transform Infra Red spectrometer to evaluate and suggest ways to enhance the indoor air quality in an urban office, at the Indoor Air 99 conference, Edinburgh, Scotland (unable to attend).
January – December 2000	Conceptual design of the final model of the EAC system
July 1999 - December 2000	Investigation of the production of hydrogen peroxide by the EAC system
	Completion of text for MPhil
December 2000	Active role in government debate about using carbon dioxide as an indoor air quality monitor in schools

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AUTHOR'S DECLARATION

At no time during the registration for the degree of Master of Philosophy has the author been registered for any other University award.

The author financed this study personally with aid from Neoventa AB and A C & T Ltd in the form of equipment loans and technical knowledge.

Relevant scientific seminars and conferences were regularly attended at which work was presented. The list of presentations given and papers prepared or accepted for publication are outlined in the previous sections titled 'List of papers' and 'Research Activities'.

Signed George Richards

Date 06 June 2001

SECTION 1. BACKGROUND

1.1. Indoor Air Quality

1.1.1. History of Indoor Air Quality Standards

It has been suggested that the architects and builders of the ancient Egyptian pyramids understood that there was a requirement for a constant supply of fresh air within the pyramids and therefore developed sophisticated mechanisms to increase air movement. Each pyramid has an air ventilation system powered by thermal forces, with no moving parts, which are still effective today, 4 - 5000 years after construction was completed. Through the ages, all buildings have been built with internal air moving systems to remove smoke from domestic fires, cooking and body odours (The National Trust, 2000). Dr. Pettenkofer from the University of Munich observed in 1858 that buildings needed to be ventilated and suggested using carbon dioxide concentrations to measure the 'cleanliness' of indoor air (Pettenkofer, 1858). It was generally accepted that ventilation was needed indoors to replace stale air with fresh outdoor air.

The major industrialisation and urbanisation that occurred during the last two centuries has created new problems for building designers trying to provide adequate ventilation. As more and more people were drawn into large urban areas to work in factories, this created a new situation whereby using outdoor air was no longer safe as a way of removing stale air from buildings. Concurrently private dwellings were made tighter to stop the ingress of 'industrial' smoke mixed with smoke from domestic space heating and cooking facilities. The requirement to ventilate for better personal well being took second place to keeping out visible airborne pollution.

Following the substantial rise in the cost of crude oil during the 1970's, major attempts were made to reduce the cost of space heating. Managers of commercial properties altered their heating, ventilation and air conditioning (HVAC) systems so that up to 80% of indoor air was re-circulated. In addition to this, buildings were designed to be 'tighter' to prevent heat loss and were fitted with double glazed windows and thermal insulation. Domestic buildings were treated in the same way, so that both the home and work environment produced similar environmental conditions. This has prevented natural ventilation, preventing the exchange of air and trapping airborne pollutants in the indoor environment.

Hines et al., (1993), indicated that in the USA, concentrations of nearly all volatile organic compounds (VOC), inorganic gaseous compounds, heavy metals, particulates and micro-organisms were higher in indoor environments than outdoors. Concentrations of indoor pollutants are often 2 – 5 times higher indoors when compared to outdoor levels (Etkin, 1995). The quality of indoor air is reduced due to a further addition of pollutants from indoor sources. These pollutants include environmental tobacco smoke (ETS), cooking and VOC emitting materials (Junker et al., 2000).

The first standards to be established in the world, concerning the regulation of forced air ventilation were initiated at the end of the 1930's by The American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE, 2000). The USA was at the time building substantial numbers of high-rise buildings. Due to the nature of the building design, there was a need to address the problems of stale air and odours. The initial recommendations made for ventilation rates were designed to reduce odour to a level acceptable to the occupants (Hines et al., 1993). Many of the world's Governments have only just begun to legislate minimum standards for indoor ventilation (Liddament, 1996; Daniels, 2000) and overall legislation for indoor air quality (IAQ) is patchy and weak. In the UK, the governing body for air quality standards is the Expert Panel on Air Quality Standards (EPAQS). The recommendations they give do not cover private dwellings. Until 2000, this was the case in America as well, however, ASHRAE has now recommended standard 62.2P for private dwellings, with regards to ventilation (ASHRAE, 2000). Although ASHRAE gives standards for ventilation to help improve IAQ, they point out the fact that the preferred method of reducing the concentration of indoor contaminants is through controlling the source of the pollutant (ASHRAE, 2000)

1.1.2. Indoor Air Quality and Health

Major changes in the air quality in work and home environments are now being linked to substantial increases in respiratory problems and other diseases. There is a relationship between poor IAQ and the increase seen in breathing related illnesses (Schwartz et al., 1996; EPAQS, 2000). There have been numerous papers that link airborne particulates with increased illnesses. The number of particles < 10 μm can be a strong indicator for a variety of health effects (Dockery et al., 1989; Pope and Dockery, 1992; Schwartz, 1994).

Epidemiological studies have made connections between airborne particulate matter, morbidity and mortality (COMEAP, 1995). Although, this link has not been proven to be causal (QUARG, 1993) it has still been put forward as one of the main causes of an increase in respiratory problems. Particulate pollution indoors has also often been linked with an increase of various symptoms known collectively as sick building syndrome (SBS) (Etkin, 1995). Etkin (1995) also outlines some of the physiological effects of indoor air contaminants as listed below:

- Chemical or mechanical irritation of tissues, including nerve endings at the site of deposition
- Impairment of respiratory mechanics
- Aggravation of existing respiratory or cardiovascular disease
- Reduction in particle clearance and other host defence mechanisms
- Impact on host immune system
- Morphologic changes in lung tissue
- Carcinogenesis

Particulates like many other indoor contaminants are also found to be at higher concentrations indoors than outdoors. The indoor environment also provides the largest amount of personal exposure to particulates. In the absence of indoor sources, indoor concentrations of particles tend to follow those outdoors with a slight time lag (EPAQS, 2000). These relationships obviously vary with location, number of occupants, type of activities conducted and the type of building and ventilation. The exposure to particulates in the home environment has been found in many cases to be greater than exposure in the work environment (Pellizzari et al., 1993).

There is a growing interest about how to measure and record airborne particles, especially as there are an increasing number of epidemiological studies that implicate non-biological airborne particulate matter as a trigger for breathing related illnesses (COMEAP, 1995; Namdeo et al., 1999). The UK Government operates a series of outdoor air pollution monitoring stations (Urban Network) across the country, which measure PM_{10} as a mass measurement ($\mu g/m^3$). Within the Urban Network, there are currently only four monitoring stations (EPAQS, 2000) that monitor PM_{10} and $PM_{2.5}$.

1.1.3. The Migration of Pollutants in Indoor Environments

Although the creation of some indoor pollutants may be limited to specific areas such as cooking emissions originating from the kitchen, these pollutants migrate throughout a building. Pollutants can be dispersed throughout a building on air and thermal currents. ETS is a major pollutant of private dwellings and can be found throughout a house even if smoking is confined to one area. Personal observations have shown that residual ETS can be found in a child's bedroom at least 12 hours after the tobacco has been smoked in a separate room. Modelling of contaminant exposure can demonstrate how pollutants such as carbon dioxide (CO_2), carbon monoxide (CO) and nitrogen dioxide (NO_2) can be found throughout a private dwelling (Huang et al., 2000).

Whilst preventing the release of pollutants at source is by far the most efficient way to reduce unwanted pollutants, it is not always possible. The next best method is to capture pollutants shortly after their release into the indoor environment. In a study by Junker et al., (2000), the spread of ETS in a large building via the HVAC system, was demonstrated. Clearly, pollutants not captured at source will spread over very long distances in a building serviced by HVAC systems since such systems have limited particulate reducing capabilities. Huang et al., (2000), have modelled the migration of air pollutants in localities that do not use HVAC equipment but rely on small local extractor vents in bathrooms and kitchens for ventilation. The migration of pollutants in such localities is driven by thermal stratification and the stack effect, i.e. natural movement of air upward through a narrowed area.

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1.2. Present Air Cleaning Technology

1.2.1 Filtration Systems

Generally, HVAC systems have some form of filter material installed. Filters are normally placed within the fresh air intake to prevent any major air borne contaminants and rain entering the system from outdoors, which may damage internal fans. Exhaust air outlets, returning air to the central processor from a room, often have filters installed to protect the fan from indoor airborne contaminants. The filters positioned on both sides of the fan protect a build up of contaminants on the fan, preventing the imbalance and disintegration of the blades. The filters surrounding the central processor of a HVAC are thus not primarily installed to clean the re-circulated indoor air (Kukadia et al., 1997). It is essential to provide air movement through a locality (ASHRAE, 2000). Pressure differences are required within a building to move air, created by either using a fan or making use of thermal differentials.

In general HVAC systems in the UK use F5 class filters that when new will filter out > 60 % of all particles larger than 5 μm. These F5 filters are not initially designed to handle any aromatic compounds and/ or gaseous products. As these filters become full of accumulated dirt, the power consumption required to force air through the filters rises to within 75% of the central air processors maximum output capacity. Overload and power cut offs can occur without warning. All air ducts have to be kept clean and be able to prevent the ingress of foreign material into the air ducts.

Filters trap particles through several different mechanisms. The main mechanism is direct interception, where particles become trapped because the diameter of the particle is greater than that of the filter pore size. Inertial interception occurs when particles hit the fibres of the filter material, rebound and change direction. Although the particles are not initially trapped, they eventually become trapped. The mechanism of diffusion affects very fine particles < 0.3 µm. These fine particles are buffeted by air molecules through Brownian motion and end up in the filter material (Air Safety Ltd., 1999). The different particle size fractions and their physical characteristics are described in section 1.3. It is important to note that as soon as a filter breaks down either because of poor fitment or damage/ production difficulties, fine particles will pass through and re-enter the filtered air space.

Although the option of decreasing the pore size of filter material will improve particulate removal, filters can be further enhanced through the introduction of electrostatic forces into the filter. Electret type filters work on the principal of containing fibres with either a positive or negative potential, with interspersed filter elements acting as electrical insulators. Therefore, all positively or negatively charged particles passing the filter will in theory be attracted by electrostatic forces created in the filter. Electret type filters are often designed to be reusable and washable.

There are a number of difficulties associated with most filter based air cleaning technologies. Filters start to loose their ability to collect particles etc., as soon as they are first used. In addition, traditional filters require high-energy inputs to drive large air volumes through the ducting and filters and to create enough pressure to move air through the filter. Based on these difficulties and the problems associated with HVAC systems in general, the idea of using HVAC systems in combination with an additional separate filter system would not reflect a step forward in improving IAQ. Therefore, any new technology must bypass these known drawbacks by using filter media in a different way or by designing completely new types of filters not requiring the main airflow from the central processor to pass through the filters. It should be reiterated that HVAC systems were originally not intended to remove particles but to supply air to a building at suitable temperatures.

Choosing a filter or particle removal system to cope with the wide differences in sizes and toxicity from the list of airborne particulate matter gives an indication of how difficult the problem is. A Landlord is today forced to choose a class of filters that will give a reasonable pressure drop across the filter during its calculated lifetime, knowing full well that many particles will slip right through the HVAC system. Certain modifications can be inserted into HVAC systems to reduce odorous gases without causing large expensive pressure drops in the ventilating system.

1.2.2. Indoor Air Cleaning Equipment Available for Domestic use

There are a number of air cleaners available to the Public that work on the principle of using a filtration system and or through the ionisation of air. Some of these units do work, as they can capture coarse and fine particulate matter and do oxidise some gaseous compounds.

Units produced by Philips (Holland), Amcor (Israel) and Honeywell (US) all work on the following principals:

STEP ONE - indoor air is sucked into the unit with a fan passing a filter.

STEP TWO - the pre-filtered air passes through the fan to an electrostatically charged filter where the fine particle fraction is removed.

STEP THREE - as the air leaves the unit it passes a charged electron emitter, from which electrons are released into the air.

In order for these units to remain viable, they have to be compact and relatively quiet, therefore, the amount of air that can be processed through the units is limited to ~100 m^3 h^{-1}. These units often deliver large numbers of negatively charged small air ions at random into a locality (Amcor, 1995). Apart from the internal collection of dirt, there is no way of controlling where charged dirt particles accumulate within a room. Further, there is the unknown risk that humans might breath in charged particles and/ or oxygen free radicals.

1.2.3. Electrostatic Air Cleaners for use in Conjunction with Existing Air Moving Equipment

There are some companies such as Trion Ltd., which produce systems similar to that described in 1.2.2 for use in work environments. These rely on electret filters and can remove particles with an efficiency of 99% at > 0.01 μm. These systems are extremely good at removing particulates however they still face the same problems with filter degradation and high-energy inputs, as outlined in Table 1.

Due to these limitations new technology needed to be designed that could clean air without filters but still encompass the reliable components of existing systems. The mechanism of electrostatic air cleaning has been used in a number of studies and has been found to be very effective in removing particulate matter (Pethig, 1984; ASHRAE, 2000).

Description	Particle range reduced (μm)	Power demand (W)	Limitations
Standard HVAC operating with simple filters, very common	> 5	800 – 1000	Does not reduce the fine particles that penetrate into the deep lung. Number of filter changes depends on degree of in/ outdoor air pollution.
HVAC operating with High Efficiency Particle Arresting (HEPA) filtration	> 0.1	> 3000	High running costs, - requires energy to overcome pressure drops across the filter; - replacement filters. Would be expected to reduce the number of fine particles in the supply air. Does not reduce particles generated in the room.
Enhanced HVAC with electrostatic filtration, (not very common)	> 0.01	~ 150	'Comfort parameters' dictate air speeds to be < 0.2 m sec^{-1} and that dB(A) levels > 55 should be avoided. These parameters limit the air and fan speeds that can be used. See further above.

TABLE 1 SUMMARY OF THE LIMITATIONS AND POWER DEMANDS OF PRESENT AIR MOVING EQUIPMENT

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1.3. Understanding Particles

1.3.1. General

Long-term studies of particle number variations can give an indication of the effectiveness of any installed air moving equipment in a building and how the addition of new air cleaning systems may improve IAQ. In order for any new air cleaning technology to be effective, it would be required to remove/ reduce from indoor air, the most commonly occurring particles present either in private homes and/ or in office type work situations. It is very difficult to give 'typical' values for the number of fine particles (< 2.5 μm) that an air cleaner needs to be able to cope with since the number of fine particles outdoors vary considerably. Typical numbers of coarse particles that an air cleaner must cope with are dictated by indoor activities.

Particles are usually measured as particulate matter (PM), usually followed by a subscript, which defines the maximum size of the particulate matter in that range. PM_{10} and $PM_{2.5}$ are the most commonly used definitions. The sizes are usually defined by measuring equipment such that particles, for example < 2.5 μm pass through a size selective inlet with a 50% efficiency cut of at 2.5 μm aerodynamic diameter. Aerodynamic diameter can be defined as the diameter of a unit density sphere (density = 1 μg/ cm^3), which has the same settling velocity as the particle in question (EPAQS, 2000).

The list of particles in Table 2 (Owen et al., 1992; Dolovich, 1997), with their respective size variations, is not comprehensive but covers many particles clearly recognisable in everyday situations. The size ranges tend to vary depending on which reference document is used. The variations stem from the differing measuring techniques and sites used for monitoring.

Airborne particle source	Approximate aerodynamic diameter (μm)
Asbestos	0.7 – 100
Auto emissions	0.05 – 100
Bacteria	0.5 – 10
Clay	0.1 – 40
Coal dust	1 – 90
Combustion particles	0.05 – 1
Disintegrated house dust mite faeces	0.8 - 1.8
Droplet nuclei that could contain live bacteria	0.2 – 5
Epithelial Cells (Humans)	0.1 – 9
Man made mineral fibres (glass wool, Fiberglas etc.)	0.1 – 1000
Mould spores	3 – 12
Pollen	8 – 100
Sea salt (marine aerosols)	0.03 – 0.5
Smouldering or flaming cooking oil	0.05 – 1
Spores (sometimes called spore dust)	3 – 40
Talc	0.6 – 50
Textile fibres	> 8
Tobacco smoke,	0.05 – 1
Viruses (Brosseau et al., 1994)	0.02 – 0.30

TABLE 2 DIFFERENT AIRBORNE PARTICLES DEFINED BY AERODYNAMIC DIAMETER

Particles indoors can be allergenic and release gaseous by-products. Further fungal allergens, mycotoxins, endotoxins (components from Gram negative bacteria) and volatile organic compounds from microbes (MVOC) often exist indoors (Flannigan, 1994).

1.3.2. Definition of Particle Sizes and Precipitation Speeds

Particles are usually given physical size boundaries based on their physical characteristics. These boundaries do vary slightly depending upon the source of the literature as shown in Table 3.

Particle size group	COMEAP (1995)	EPAQS (2000)
Nucleation mode	< 0.2 μm	< 0.1 μm
Accumulation mode	0.2 – 2 μm	0.1 - 1 μm
Coarse	> 2 μm	> 2 μm

TABLE 3 CLASSIFICATIONS OF PARTICLE SIZES BY PHYSICAL CHARACTERISTICS

Another way that particle sizes can be defined is by their ability to deposit in human lungs. Particles < 10 μm in diameter are often referred to as respirable suspended particulates (RSP) (Etkin, 1995), however, some literature defines the breakpoint for respirable particles at 2.5 μm and anything above this is termed as inhalable (COMEAP, 1995).

As particulate concentration is of major importance to health, particles are usually defined using the latter definition, so < 2.5 μm relates to the fine particle fraction and > 2.5 μm relates to coarse particles. This is the definition used in this thesis. The fine particle fraction can be further split into fine and ultra fine particles. Ultra fine particles are usually defined as < 0.2 μm, these are particles within the nucleation mode and are known to penetrate deep into human lungs.

Particles precipitate in a room without electrostatic fields and/ or air movement at rates, which are dependent on the aerodynamic diameter of the particle. Gravitational forces bring about this settling effect. The differences between different particle sizes are shown in Table 4.

Approximate particle aerodynamic diameter (μm)	**Precipitates under gravitational forces**	**How far (metres)**	**Time taken (seconds)**
100 i.e. pollen grain	Yes	1	2
10 i.e. HDM faeces	Yes	1	180
1 i.e. bacterium	Yes	1	14500
0.1 i.e. soot particle	Yes	1	6 – days

TABLE 4 DIFFERENT SETTLING RATES OF PARTICLES UNDER GRAVITATIONAL FORCES

1.3.3. Ultra Fine Particles (< 0.2 μm)

Particles in this size range (nucleation mode) are formed through condensation of hot vapours or are particles freshly formed within the atmosphere by gas to particle conversion (COMEAP, 1995). They have a transient existence and quickly coagulate into larger particles. Their greatest numbers occur around the 30 nm size range (COMEAP, 1995) and because there are very large numbers of ultra fine particles, as a whole they have a large combined surface area. If these particles adsorb or absorb gaseous compounds such as polyaromatic hydrocarbons (PAH) produced by combustion engines they can act as a highly toxic substance if/ when they reach the deeper human lung. Their numbers vary greatly, dependant on where samples are taken. One study has established that particles < 0.1 μm in diameter make up 80 % of the particle number in ambient air but only make up 1% of the total mass. On average 10 - 20 % of the mass of PM_{10} is made up of particles < 0.5 μm (Clarke et al., 1999). Numerous studies have identified that vehicle exhausts contribute fine and ultra fine particles in the ambient air (Namdeo et al., 1999).

The monitoring of ultra fine particle numbers requires very expensive and sophisticated equipment. This has resulted in a lack of knowledge about the number and behaviour of these particles. Ultra fine particles can penetrate deep into human lungs (Bates et al., 1966) as shown by the cross section of the human respiratory system in Fig. 1. Once in the lungs, around 16 - 22 % of ultra fine particles are retained in the alveolar region (COMEAP, 1995).

The movement of ultra fine particles is not influenced by Newtonian forces but by electrostatic and Brownian forces (COMEAP, 1995). The mass of an ultra fine particle is very small and the resultant mean kinetic energy of the particles is very low, limiting the movement of the particles. Ultra fine particles can remain suspended for a very long time and the slow air movement supplied by HVAC systems do not influence ultra fine particles (Deleanu, 1983). However, when ultra fine particles are exposed to an electrostatic field they are influenced by the directional flow of the field due to their physical properties i.e. low mass and small size. They are easy to capture on charged surfaces since standard physical properties such as gravity, strong air movement and damp does not influence them away from the charged surface.

The properties of ultra fine particles suggest that any electrostatic type air cleaner would be very efficient at removing them from indoor air. Therefore, it could be assumed that an electrostatic system would also remove combustion-related emissions and other toxic materials associated with the ultra fine particle fraction.

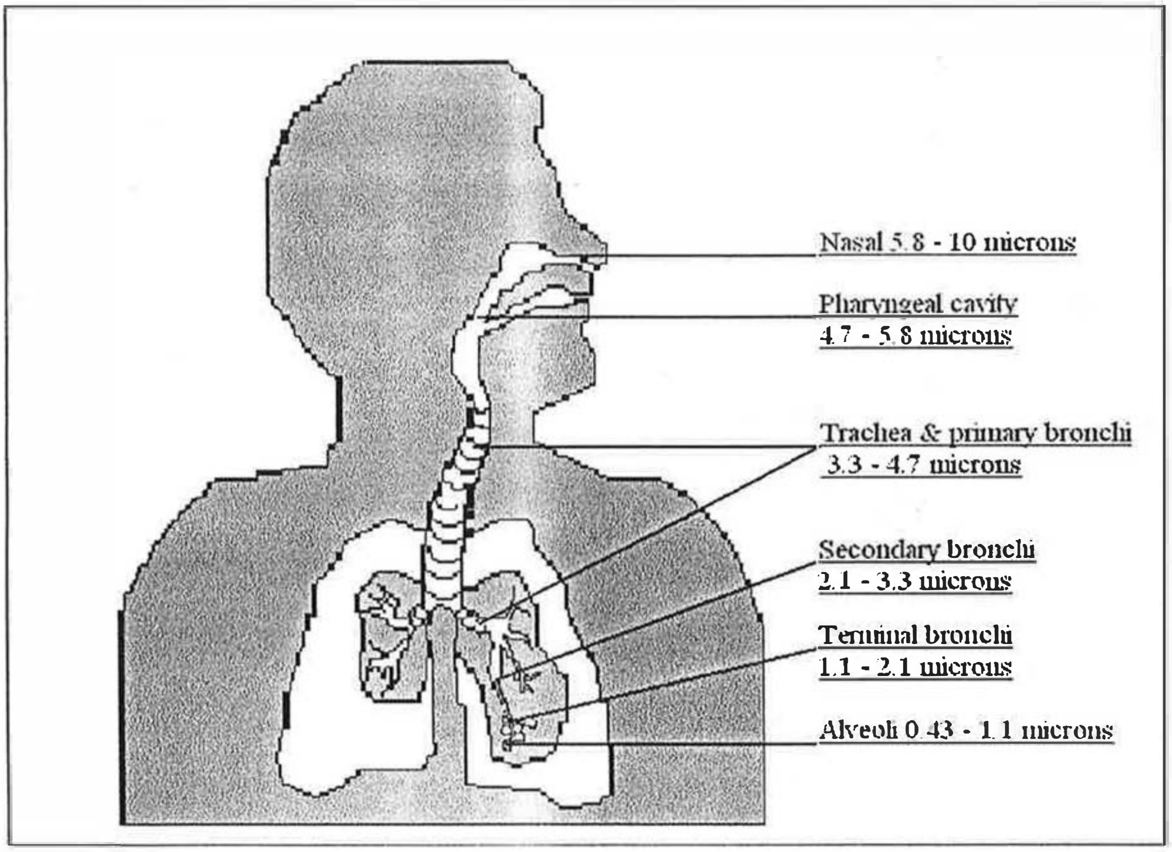

FIG. 1 DIAGRAM OF THE DIFFERENT STAGES OF PARTICLE DEPOSITION IN THE HUMAN RESPIRATORY TRACT

1.3.4. Fine Particles (< 2.5 μm)

Particles in this size range have grown from the nucleation mode by coagulation or condensation of vapours and in time will coalesce into larger particles. It might be correct to consider these particles as consisting of a number of ultra fine particles. The greatest numbers of fine particles occur around the 0.5 μm size range (COMEAP, 1995). These particles have a long lifetime and are not greatly influenced by gravitational forces. It has been suggested that fine particles descend under gravitational forces according to Stokes' law, which suggests that frictional forces exerted on a sphere are equivalent to gravitational forces. When such equilibrium is reached, the particles reach their terminal settling velocity (Wehner, 1962; Dolovich, 1997). In broad terms, Stokes Law can be expressed as a rate of sedimentation proportional to the square of the particle radius and strictly only applies to spherical particles.

Fine particle numbers vary greatly depending on where samples are taken. Numerous studies have identified that vehicle exhausts contribute large numbers of fine particles in the ambient air (Namdeo et al., 1999). Since fine particles remain airborne for long periods of time their absolute numbers lose direct correlation with traffic intensities.

The movement of fine particles is influenced by Newtonian forces and influenced by electrostatic forces. Fine particles are easy to contain on electrostatically charged surfaces. The mass of fine particles outdoors compared to the mass of all particles < 10 μm has been counted for either rural or urban areas to be ~ 60 % (COMEAP, 1995).

1.3.5. Coarse Particles (2.5 – 10 μm)

In the outdoor environment, coarse particles are formed through abrasion, often connected with traffic, airborne soil dust, industrial fallout products etc. Indoors they are generated by human activities. There is a broad agreement that coarse particles should be defined as < 10 μm and > 2.5 or 3.0 μm depending on which brand of particle counter is used. There is a far greater understanding of coarse particles compared to other particle fractions because their size makes them easier to measure. The mass of coarse particles compared to the mass of all particles < 10 μm has been estimated to be ~ 40 %, for either rural or urban areas (COMEAP, 1995). Coarse particles remain suspended for a short time because of their size and weight and settle quickly through gravitational forces. Most HVAC systems have filters designed to capture particles > 5μm and therefore only capture some of the coarse particle fraction. The movement of coarse particles is wholly dictated by Newtonian and atmospheric forces and is influenced to a lesser degree by electrostatic forces, due to their relatively large mass.

Coarse particles are trapped much higher up in the human respiratory system than smaller particles (Fig. 1). Therefore, they have different health implications to fine particles. Many allergenic particles such as pollen and mould spores are within the coarse particle range.

1.3.6. Electrically Charged Particles

Electrically charged particles can enter human lungs. Depending on the size of the charged particles they may enter into the deep lung, finally attaching themselves to soft tissue where they loose their charge (Scheuch et al., 1990). It is very difficult to track electrostatically charged particles in human lungs and the models that have been built of human lungs are not able to record charged aerosols.

When counting and tracking fine and ultra fine particles there is every chance that dust clouds of small particles will have charged particles symmetrically distributed throughout the cloud. This charging effect is often visible close to input vents from the HVAC systems. The fine particles acquire a positive charge when passing through the metal ducting and are attracted to the surroundings with lower electrostatic potential.

1.3.7. Measuring and Counting Particles

PM_{10} is measured world wide as a mass in $\mu g\ m^{-3}$. Mass measurements are normally conducted using a vacuum pump type instrument which draws air over a filter with a certain porosity, at a given temperature and relative humidity. The filter has to cope with a pressure drop which can carry 50 % of it's maximum load. Such instruments are easy to handle and cheap to purchase. There are several different types, gravimetrically oriented, cascade type etc.

There are a number of drawbacks when using mass measurements to determine air quality:

- The coarse particles in a sample can completely skew the results hiding the mass relationships indicated previously.
- Mass measurement results are based on dry weight (normalised weight) thereby avoiding all moisture adhered to particles that can have influences on breathing related problems.
- Since mass measurements 'hide' the sizeable existence of fine particles historical records for PM_{10} can be very misleading when trying to study the influence of particulate matter in indoor air in relation to breathing related illnesses.
- To be able to collect measurable quantities of particulate matter the monitors need to be run for at least 72 hours. Measurements are therefore an accumulative reading over time.
- The measurements represent average residual particulate loading
- The extended time to collect the particles and the subsequent heating process will eliminate any substances either attached to inert particles or vapour-based substances. All particles adsorb moisture somewhat depending on the surrounding RH and/ or physical/ chemical nature of the particle (Bates et al., 1966).

Much of present day scientific literature is still discussing PM_{10} measurements. Measuring particles in numbers per volume of air, where different sizes of particles are referred to as PM_{xx}, gives a more detailed understanding of airborne particulate loads. Measuring instruments which count particles by number have existed since the mid 1970's. Such equipment has not been widely used to classify IAQ up to now with reference to breathing related health conditions.

Fine and coarse particles can be counted by optical particle counters, which use a laser beam (MetOne, 1994). Whilst particle counters are easy to handle and not very expensive they are not frequently used, since historically, particles have been measured as a mass by simple particle impactors. Based on the limited availability of particle counters which can measure at the defined points between coarse, fine and ultra fine particles, many studies have used the figures > 0.1, 0.3 or 0.5 μm as a lower limit for fine particles and < 2.5 or 3.0 μm as the upper limit for fine particles. The differences are dictated by brand of equipment. Depending on which breakpoint is used to register the number of fine particles, substantially different values will be recorded for the number of ambient fine particles.

The principal operating component of particle number counters is a light scattering instrument. A light source is optically focused into a measured current of air. Particles will scatter the light and the scattered light impulses are counted to give the number of particles detected per volume of air. The actual differentiation of particle sizes can be done by varying the wavelength for the incident light (Haslop, 1989). All such instruments consider particles having an aerodynamic size. Some light scattering instruments will convert numbers of particles detected, into a mass measurement by comparing with a standardised substance (such as road dust from Arizona, USA) that has been pre-weighed and where individual particles have been counted.

Limitations exist when measuring larger particles because constant velocity entrance funnels to the air suction pump in the instrument have to be built to cope with coarse and fine particles. This requirement limits the maximum size of particles that can be counted. Accurate readings for all sizes of particles depend on clean optics, clean airflow paths and no interference from electrostatic forces in any way charging either the unit and/ or the intake nozzle. A principal drawing of a light scattering particle counter is shown in Fig. 2 (Hund, 1990).

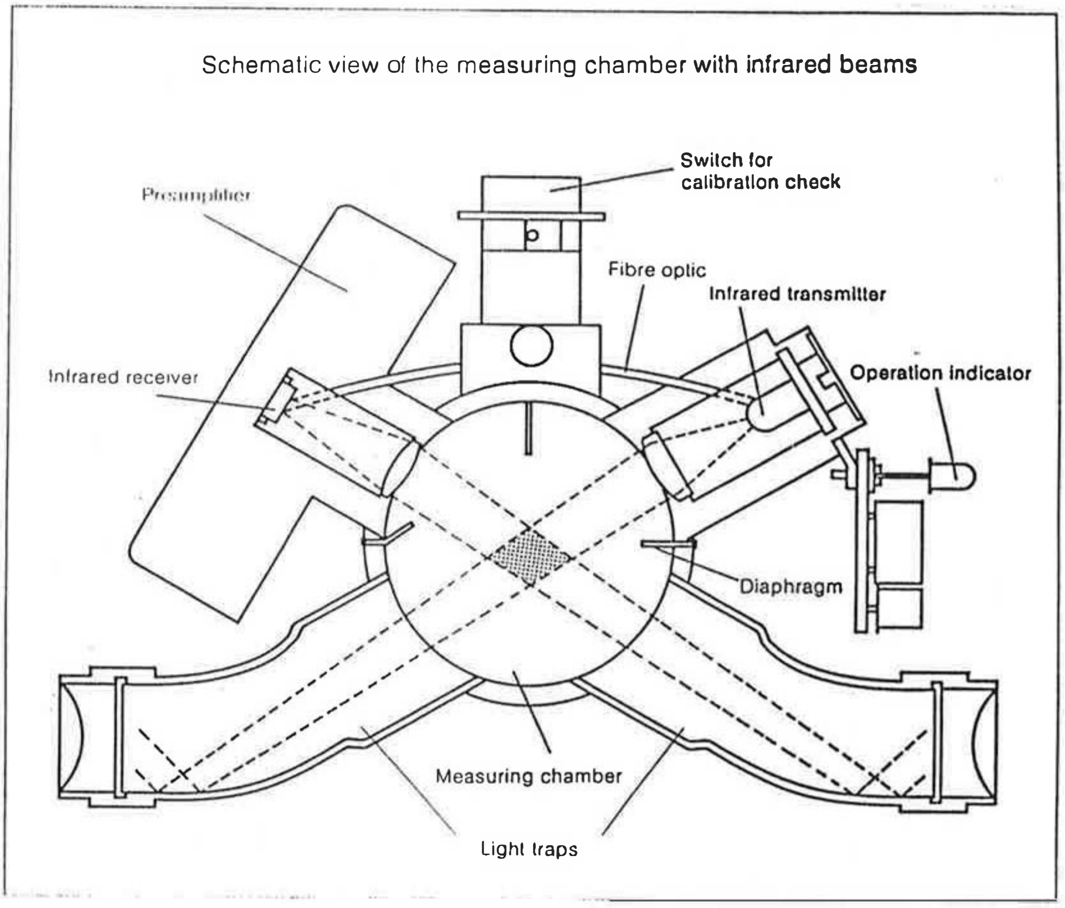

FIG. 2 PRINCIPAL DRAWING OF A LIGHT SCATTERING PARTICLE COUNTER

Whilst discrete counting can give snapshots for particle concentrations, continuous monitoring can give excellent insight into the variation of coarse particle generation and how ambient fine particulate loads impact the indoor environment.

1.3.8. Where Should Particles be Counted?

All particle counters take in air via a nozzle. This is designed to induce a constant velocity air intake with a defined rotational speed for the incoming air to cause as little disturbances as possible in the flow path of the air when scanned by the laser beam. Therefore, some care should be taken to avoid strong air movements in and around the air intake of the counter, when sampling in or outdoor air.

When counting particles an average value should be obtained covering the whole of a room. When counting particles in rooms with a HVAC system in operation, parts of a room may be poorly 'covered' by the forced air ventilation but frequently used, therefore counting particles elsewhere will not give a true picture of how people perceive IAQ. Taking readings at different heights in a locality especially over time gives a good understanding on the rate of precipitation for different size particles.

$PM_{2.5}$ is omnipresent outdoors and therefore measurements can be taken anywhere around a building to establish ambient levels. However, their numbers vary over a 24 h period and are very much dependent of traffic patterns (Liddament, 1998). Particles > 2.5 μm measured outdoors require some care to avoid false readings from local wind disturbance. Measurement of $PM_{2.5}$ indoors must take into account forced air ventilation movements, electrostatic forces in the room, type of air cleaning equipment in the HVAC system and height above the floor. Measured values will be around 25% less than outdoors for a standard HVAC system using grade F5 filters. If higher values are recorded, then the HVAC equipment is faulty and suspicions should be raised about leakage of additional particles from roof spaces and/ or insulation material surrounding air ducting.

In private houses or naturally ventilated localities (in both cases with no smokers present), the ratio between in/ outdoor values for fine particles gives an indication of the rate of ventilation. If the ratio is ~1:1 the ventilation is very good. If the ratio is < 1:1 this would indicate that the number of outdoor omnipresent particles are not penetrating indoors indicating a lack of ventilation i.e. a very tightly sealed house. Tobacco smoking in indoor environments is excluded from this statement since tobacco smoke totally outnumbers the fine particle numbers found indoors compared to outdoors (Abt et al., 2000).

1.3.9. Using Numbers of Particles to Determine Ventilation Rates

There is no direct translation of numbers of particles versus air exchange rates, however indirect estimates can be made. Particles < 2.5μm penetrate indoors as soon as ventilation is established and therefore the relationship between the numbers of fine particles in and out of doors in non-smoking environments is a good simple measure of rate of ventilation.

ASHRAE (2000) recommended that the total particle load indoors should not exceed 50 μg/ m^3 to prevent the exacerbation of respiratory problems. The UK government makes the same recommendation for outdoor air. COMEAP (1995) and EPAQS (2000), have established that 63 % of the mass of particles < 10 μm outdoors is < 2.5 μm in size. Abt et al., (2000), suggests that ~70% of ambient $PM_{2.5}$ penetrates indoors suggesting that the mass of $PM_{2.5}$ indoors would be 22.05 μg/ m^3 based on the ASHRAE 50 μg/ m^3 recommendation. In order to satisfy ASHRAE 62.2P recommendations, ventilation would have to be able to remove all coarse particulate matter in excess of 27.95 μg/ m^3 generated indoors. Without knowing the source, composition or weight of individual particles, the actual number of particles constituting these mass measurements is difficult to establish.

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1.4. Basic Theory of Using Electrostatic Forces to Clean Indoor Air

1.4.1 Introduction to Small Air Ions

Michael Faraday (1795-1867) chose the name 'ions' because according to Greek Mythology, ions were a group of people that were able to wander/ move without hindrance. Faraday had found that small air ions behaved in a similar way to this. Kotaka (1978), referred to research at the end of the eighteenth century by Coulomb and Matteucci that established that ordinary air would conduct electricity. A century later Elster and Geitel demonstrated that the ability of air to conduct electricity resides in positively and negatively charged particles of molecular size or slightly larger, termed 'air ions'. Phillips et al. (1964), states that C T R Wilson in 1889 demonstrated that it was charged air molecules that permitted air to conduct electricity. Simple small air ion indicators demonstrate the conductivity of air through air ions. Such indicators have a metal plate, which collects charged air ions. This plate is coupled to a capacitor and a flashing diode connected to a further small metal plate. When a person (acting as an earth pole) holds the small metal plate, an electrical circuit is formed from the person to the source of the ions, using air as a conductor. Flashes of the diode indicate that energy is conducted across the air gap between the ion indicator and an ion generator, with the help of ions.

Air ions are generated through a number of mechanisms such as radioactivity, radon gas, UV radiation and cosmic radiation. In this thesis, air ions were produced through corona discharge. Kotaka (1978) mentions that Tammet was the first person to develop corona type ion generators. Corona discharge is an exothermic (heat releasing) process yielding a superoxide radical anion (Massey, 1976). The release of electrons creates an open electric circuit into the airspace between the corona point and surrounding surfaces. This sets up an electrostatic field (a negative field). When electrons released from the corona discharge have energy in excess of 360 kJ mol^{-1}, oxygen radicals can be produced by the following reaction with oxygen (O_2) (Pethig, 1984):

$$O_2 + \text{electron} \gg O + O^-$$

A charge transfer process then forms air ions:

$$O_2 + O^- \gg O_2^{-\cdot} + O$$

Air ions are also formed from other atmospheric molecules such as nitrogen and carbon dioxide. Small air ions consist of one primary ion and 4 - 12 uncharged molecules of water vapour or other trace gas (Martinac, 1993; Phillips, 1964). These molecule clusters have a diameter of 0.001 - 0.003 μm.

The mobility within an electrostatic field of these ion clusters is 1.5 - 3.0 cm s^{-1}, with a field strength of $E = 1$ V cm^{-1}, hence ion mobility is expressed as 1.5 - 3.0 cm^2 s^{-1} V^{-1} (Backman, 1979; Fritzell, 1979). At the corona point, an electric field strength of in excess of 10^8 V m^{-1} is quite typical, which is in excess of the normal breakdown voltage of air ($\sim 3 \times 10^6$ V m^{-1}).

The field strength (E) at the tip of a new steel pin type electrode can be shown to be:

$$E \sim 2\ V/a\ \log_e(4x/a)$$

V = electrode voltage

a = radius of the top of the corona tip

x = distance to the nearest earth plane (Pethig, 1984).

Taking an example of an ion generator at 6.5 kV, with a corona tip of 7.5 μm and an earthed plane 1 metre from the emitter the field strength would be:

$$E = 2 \text{ x } 6500\ V/\ (7.5 \text{ x } 10^{-6}\ m) \text{ x } \log_e(4 \text{ x } 1\ m/\ (7.5 \text{ x } 10^{-6}\ m))$$

$$E = 2.2 \text{ x } 10^{10}\ V\ m^{-1}$$

Negatively charged small air ions are accelerated away from the emitter of electrons and are directed in the direction of the field. As soon as small air ions are generated in indoor air, they start to decay either through Brownian motion (buffeted by surrounding air molecules) or (if in an electrostatic field) are transported through a 'sea' of positively charged particles. Since Brownian motion is less significant in influencing the distance a small air ion travels when compared to the influence of electrostatic forces, the former is thought not to greatly influence the reduction of particles in air. The movement of electrons is enhanced with increased humidity, as moisture increases the conductivity of air (Spengler Electronic AG, 1996).

Clean outdoor air has ~ 2000 small ion pairs cm^{-3} and there is a close balance between positively and negatively charged ions. In one cm^3 of clean ambient air there are ~ 2.6 x 10^{19} neutral gas molecules where roughly 5.46 x 10^{18} are neutral oxygen molecules. There are approximately 1000 negatively charged small air ions in a cm^3 of air and therefore the ratio of neutral to negatively charged gas molecules is 5.46 x 10^{15}:1.

1.4.2. The Decay of Small Air Ions and the Reduction of Particles

Charged small air ions decay through the following processes:

1) Collision with a positively charged ion, forming a neutral molecule.

2) Collision with a non charged particle. The ion then loses it's electrostatic charge converting the neutral particle to a negatively charged particle. This charged particle can then continue the exchange of charges with other particles until a 'cluster' of particles forms a large enough mass to fall out of the air due to gravitational forces.

3) Negatively charged ions are attracted to positively charged surfaces where they lose their charge.

4) When collisions occur with particles (2), the numbers of particles in the air are reduced.

The main feature of small air ions used by electrostatic type air cleaners is the process described in 3. The processes numbered 1, 2 & 4 contribute insignificantly to the cleaning of indoor air.

1.4.3. The Measurement of Small Air Ions

An atmospheric air ion analyser can count the number of small air ions produced by an emitter. The air ion analyser used throughout this thesis uses principles established by Ebert in 1906. Such equipment has a fan to draw in a given air volume per second between two collector plates, (one positively and one negatively charged). There is a given electrostatic field between the plates and incoming charged ions will be captured by either plate, depending on their charge polarity (provided their mobility is fast enough). Between the collector plate and an earthed connection, an ammeter is installed. The current measured by the ammeter is proportional to the number of ions per volume of air drawn past the plates (n). This can be expressed as:

$$n = I\, V^{-1} q^{-1}$$

I = current measured in Ampere

q = charge of the ion [which is considered to be e = 1.602×10^{-19} C (Coulomb) for small air ions (Martinac, 1993; Kotaka, 1978)].

Measuring the current drawn by an electron emitter can give some indication of how many electrons are released/ generated at the emitter points. For example, a voltage of -13 kV, connected to a carbon fibre emitter and a measured current of 0.08 mA (1 Amp = 1 coulomb s^{-1}, therefore 0.00008 Amps divided by the charge of 1 electron (1.6×10^{-19})) is equivalent to the production of approximately 500×10^{12} electrons s^{-1}.

1.4.4. How can small air ions be used to Clean Indoor Air?

Primarily an electrostatic air cleaner cleans indoor air by reducing the number of particles < 10 μm in diameter through the decay processes described in 1.4.2. Some small air ions have properties that can reduce the viability of biologically active particles in the wider air masses surrounding a corona point. It was established in 1930 by Tchijewsky that ions could kill bacteria (Kotaka, 1978). Phillips et al., (1964) also established that air ions caused accelerated decay of biological aerosols. Phillips et al., were able to differentiate between decay rates attributed to physical decay and biological decay. When electrons are produced by corona discharge, they commonly form oxygen free radicals. These radicals are short lived and are thought to react with water vapour to form other reactive oxygen species. Reactive oxygen species are related to the biological effects of negative ions (Byczkowski & Gessner, 1988). In particular, one species, hydrogen peroxide, is known to have anti-microbial properties (Hyslop et al., 1995). The production of hydrogen peroxide from a corona discharge has been investigated previously, but only at an air-water interface (Challenger et al., 1996; Goldstein et al., 1992).

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1.5. Description of the New Electrostatic Air Cleaner

This section describes how the physical and chemical mechanisms of electrostatic air cleaning discussed in 1.4. can be initiated using certain equipment. The concept of using electrostatic forces is not new. For example, virtually all large industrial chimneys are fitted with electrostatic particle arresters, powered by very high voltage (2-300 000 V) generators. The company Trion Ltd (Trion, 1993) have for years specialised in producing air cleaners that make use of extra high voltage equipment to precipitate and collect fine particulate matter in air cleaners used in the US fleet of atomic powered submarines (personal correspondence, 2000). Such vessels are designed to stay submerged for very long periods and therefore must have excellent air re-circulating/ cleaning facilities.

Primarily the EAC system was intended to reduce particles < 10 μm, in an air volume, using a corona discharge point, which would:

1) Produce chemical compounds that can reduce the viability of biologically active particles.

2) Set up an electrostatic field to capture, direct and deposit particulates to a positively charged surface.

The main components of the new electrostatic air cleaner (referred to as the EAC system) are described below. In combination these components form an electrostatic air cleaner that was assumed able to produce the effects described in 1.4

An extra high tension negative voltage generator (EHT). The EAC system works on the principle of generating negative air ions via an electron emitter. These negative ions are capable of reducing the numbers of fine and coarse particles in indoor air by various mechanisms. The EAC system described in this thesis relies on an extra high tension (EHT) generator to produce a high voltage electrical charge at the emitter. The generator was based on a wiring diagram originally designed by Cockcroft and Walton (Hartley Jones, 1995). Fig. 3 shows a circuit diagram of the generator, which can reach a negative voltage of –13 kV. Whilst the unit functioned normally at most voltages, at -13 kV outputs became less easy to control. In addition, a voltage this high was deemed unsafe for use in close proximity to people. The diagram gives calculations for the number of electrons the unit would produce and the equivalent output current levels that were recorded when checked using a Pico-ammeter. To ensure that the current readings really represented the maximum currents possible preliminary readings were taken between an electron conductor, in this case the carbon fibre wire to earth. Fig. 3 also shows that two voltages could be used from the wiring diagram, -7700 V and -12 938 V. The reason for this set up was to ensure that:

A) The voltage drop from the main voltage (-12 938V) was not able to leak across the backing board/ plate onto any fixed surface where the ion emitter was positioned thereby causing substantial charging on the surrounding surfaces.

B) Soiling was reduced at the –7700 V voltage drop to earth. The ring of Aluminium tape surrounding the main ion generating carbon fibres is a very poor electron generator, therefore reducing soiling.

A carbon fibre thread emitter. This type of emitter has been suggested by Pethig (1984) and is the preferred emitter material for a number of manufacturers. Carbon fibres are thought to maintain efficiency longer than needle type emitters. The full benefit of using carbon fibre emitters is discussed in 2.2.

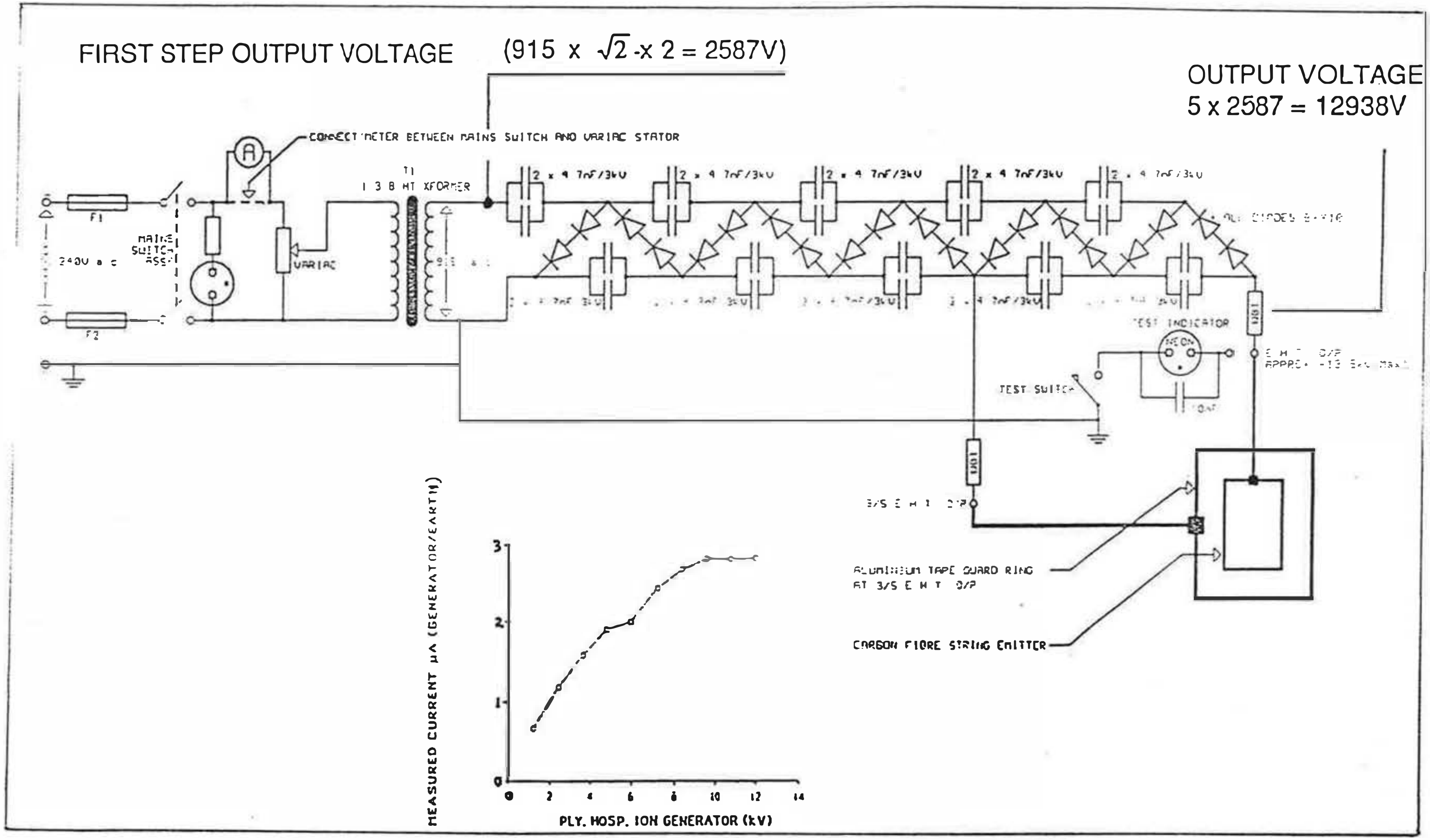

FIG. 3. CIRCUIT DIAGRAM OF THE EAC SYSTEM. NOT TO SCALE.

Electron Mirror: The electrostatic field set up by the EAC system would create a directional flow of ions, which removes particles in the processes discussed in 1.4. Particles with a mass and/ or an electrical charge are influenced within an electrostatic field. In order to enhance the efficiency of the new electrostatic air cleaner, an electron mirror (metal plate) was developed that would enhance and direct the spread of electrons/ small air ions away from the corona points.

The basic EAC system, consisting of a generator and an emitter, can be arranged in a number of ways to maximise electrostatic forces. Fig. 4 shows how the electrostatic air cleaner can be set up. The Figure indicates a forced air input with the electron emitters arranged around the forced air input. The generated electrons are thought to generate oxygen free radicals, convert existing water vapour into hydrogen peroxide and set up an electrostatic field between the emitters and the walls in the locality. The outcome measures of setting up a system such as this in a room are a slight change in the potential of the walls and floor, allowing particles to be collected on the wall and/ or allow positively charged particles to settle. Fig. 5 shows another similar arrangement. In this instance, one of the emitters is replaced with a positive pole. There are substantial practical and theoretical differences with this arrangement. Airborne particles entering the air gap 'covered' by a directional electrostatic field will be directed to one or other pole from which they can be removed. The air is cleaned from particles in a controlled way. All oxygen free radicals generated at the negative pole are under electrostatic 'control' in the field and therefore there is no risk that humans might breath in charged particles/ radicals. There are no commercially available indoor air cleaners using the concept.

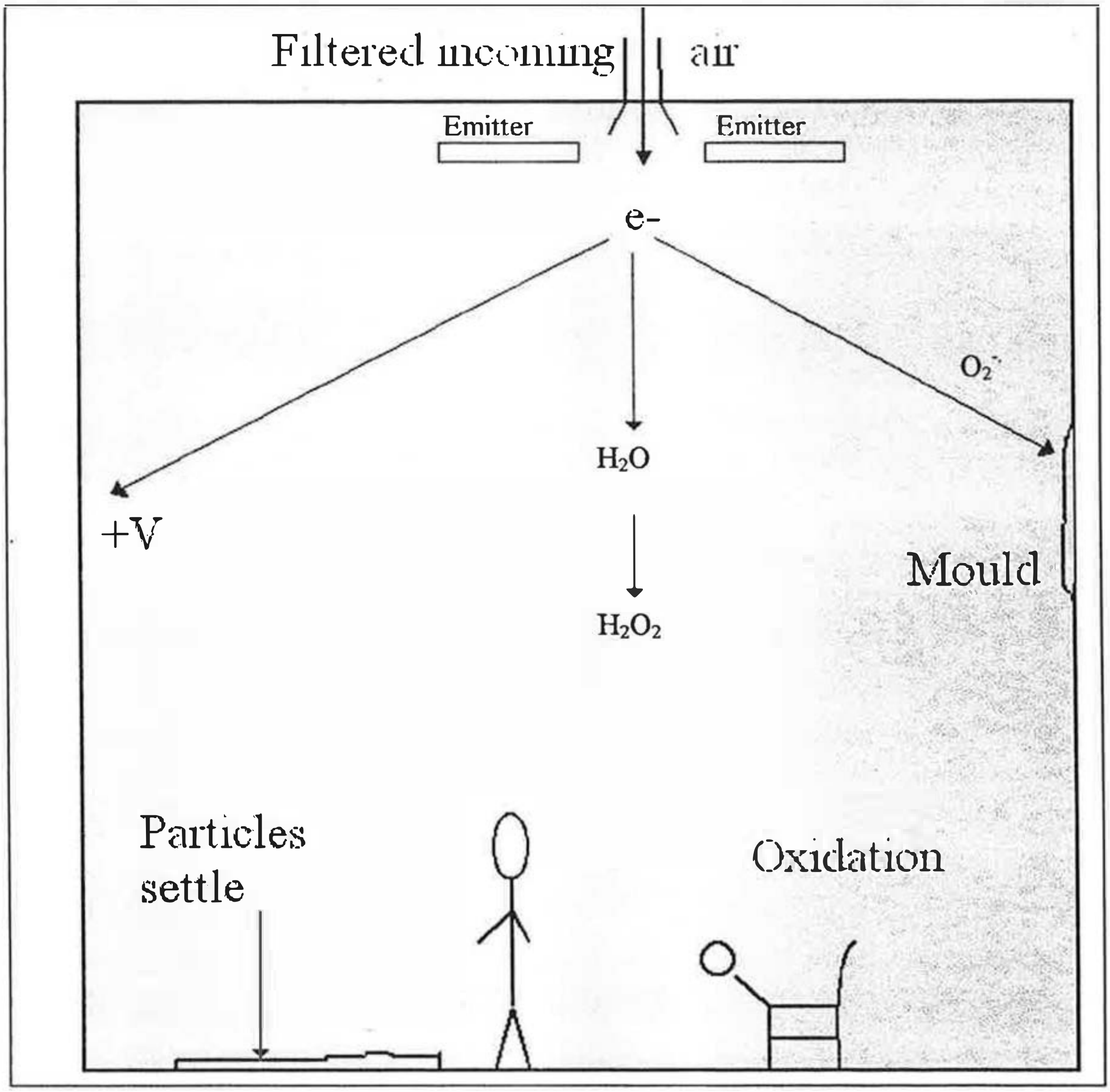

FIG. 4 DIAGRAM OF THE ARRANGEMENT AND ASSOCIATED MECHANISMS OF THE EAC SYSTEM (NOT TO SCALE)

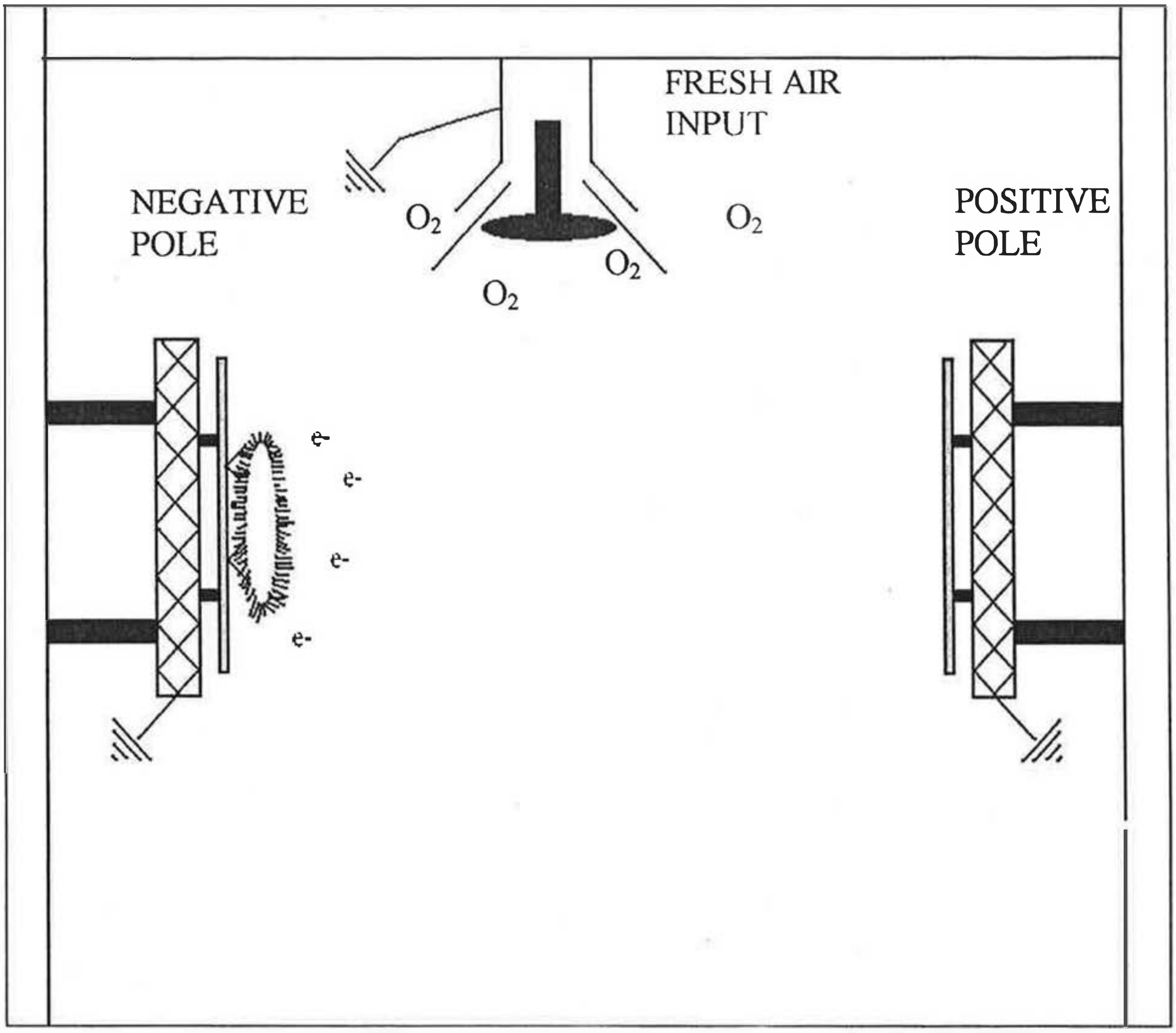

FIG. 5 DIAGRAM OF THE ARRANGEMENT AND ASSOCIATED MECHANISMS OF THE EAC SYSTEM (NOT TO SCALE)

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1.6. Aims of Study

The aim of this study was to develop and test an electrostatic air cleaning system (EAC system) based on the safe production of negative air ions and apply the EAC system in real life situations. In order to develop the EAC system a series of experiments were performed to:

- Determine the electron generating capacity and efficiency of the EAC system.
- Test the efficacy of individual components of the EAC system.
- Assess the actual requirements for IAQ. Tests were conducted in pre-school nurseries and in local authority housing to determine average concentrations of fine and coarse particles in the localities.
- Assess the application of the EAC system in a real life situation. Experimental EAC systems were installed in a city centre office where IAQ was assessed through monitoring particulate numbers and conducting subjective questionnaires to assess the occupants perception of air quality.

The combined results from these experiments were used to suggest a new design and new patent for a 'Full EAC system'. The EAC system used in this thesis was based on a design outlined in a British patent (GB 2304576). Although the patent mentions some technological applications, there was a need for further development and understanding of the air cleaning mechanisms involved. In addition, there was a need to test the efficacy of the EAC system as envisaged as a whole and to test its component parts.

SECTION 2. DEVELOPMENT OF THE ELECTROSTATIC AIR CLEANING SYSTEM

2.1. An Investigation of the Negative Ion Generating Capacity and Particle Removal Efficiency of the New Electrostatic Air Cleaning system

2.1.1. Experiment to Determine the Negative Ion Generating Capacity of Different Generators

To investigate the negative ion generating capacity of some of the commercially available generators, four generators, with different operating voltages, were tested. From these experiments (1) an appropriate generator and voltage operating range, were chosen and (2) tests could then be conducted to assess the particle reducing capacity of the chosen generator and carbon fibre based electron emitter, 1.5 metres in length.

2.1.1.1. Method

Four extra high tension negative voltage generators with different voltages were set up as part of the EAC system as described in 1.5. To assess the production of negatively and positively charged small air ions produced by each generator, an atmospheric air ion analyser (Type 134A. Medion, Oxted, England), was set at a distance of 13 cm from the emitter. The atmospheric air ion analyser selectively measures small air ions in the mobility range 1-2 $cm^2\ s^{-1}\ volt^{-1}$. Air was continuously drawn through the ion analyser at the rate of 5.0 litre s^{-1}. Each generator (and the emitter) was tested for 3 one-hour periods. The tests were conducted at room temperature (19 ^oC) and with a relative humidity of between 47 - 50 %. Before the experiments commenced background concentrations of negative and positive small air ions were measured. There was no forced air ventilation in the test room and there were no people present during the tests.

For aesthetic reasons it was envisaged that the EAC system would have a varnished wood surround. To investigate the effect of this decorative frame on ion production, the experiments described above were conducted on systems with and without varnished frames. To test if there was a significant difference between the two frames a two-tailed Student's t-Test was conducted. A consistent P value < 0.01 would indicate a significant difference.

2.1.1.2. Results

The results from systems with non-varnished and varnished frames are given in Table 5 & 6 respectively.

Description of negative voltage generators	**Temp (°C)**	**Frame earthed**	**Positive ions (no. cm^{-3})**	**Negative ions (no. cm^{-3})**	**Background conc. positive ions (no. cm^{-3})**	**Background conc. negative ions (no. cm^{-3})**
6.5 kV (US built)	18.5	yes	100	400	200	600
6.5 kV (US built)	18.5	no	100	16 - 21 000	"	"
6.5 kV (Amcor)	19	yes	100	400	1500	1600
6.5 kV (Amcor)	19	no	0	29 000	"	"
8.5 kV (Amcor)	18	yes	200	800	1900	1200
8.5 kV (Amcor)	18	no	0	28 000	"	"
12 kV (built in Derriford Hospital)	18.5	yes	0	11 000	100	300
12 kV (built in Derriford Hospital)	18.5	no	0	17 000	300	200

TABLE 5 NEGATIVE ION GENERATING CAPACITY OF DIFFERENT GENERATORS SET IN NON-VARNISHED FRAMES

Description of negative voltage generators	Temp (°C)	Frame earthed	Positive ions (no. cm^{-3})	Negative ions (no. cm^{-3})	Background conc. positive ions (no. cm^{-3})	Background conc. negative ions (no. cm^{-3})
6.5 kV (US built)	19	yes	80	600	200	600
6.5 kV (US built)	19.5	no	200	20 000	"	"
6.5 kV (Amcor)	18.5	yes	0	550		
6.5 kV (Amcor)	20	no	0	26 000	"	"
8.5 kV (Amcor)	16.5	yes	0	600	800	1000
8.5 kV (Amcor)	18	no	0	23 000	"	"
12 kV (built in Derriford Hospital)	17.5	yes	0	2600	200	0
12 kV (built in Derriford Hospital)	17.5	no	0	17 000	"	"

TABLE 6 NEGATIVE ION GENERATING CAPACITY OF DIFFERENT GENERATORS SET IN VARNISHED FRAMES

The results show that despite the large variation in operating voltage, the negative ion production only ranged from 16 000 to 29 000 (6.5 - 8.5 kV), for non-earthed frames. The exception to this was the 12 kV generator, which had the lowest negative ion generating capacity of all generators tested for non-earthed frames. There was no significant difference between the varnished and non-varnished frames (Student's t-Test, P = 0.08). The variation between the two types of frames can be explained by environmental conditions, which changed very slightly between the experiments. The greatest change occurred when the earth connection was removed from each system. This resulted in the majority of negative ions being released into the atmosphere.

The results indicated that a generator of either 6.5 or 8.5 kV capacity would produce enough negative ions to produce oxygen free radicals. Challenger et al., (1996) found that at an ion concentration of 10 000 ions cm^{-3}, 24 ppb of hydrogen peroxide would be produced at an air/ water interface. Although the system could produce > 20 000 ions cm^{-3}, at 6.5 kV, the system needed to be tested for its ability to reduce particulate levels at that voltage. The following section describes the particulate reducing capacity of the generator and system.

2.1.2. Experiment to Determine the Particulate Reducing Capacity of a 6.5 kV Extra High Tension Negative Voltage Generator

2.1.2.1. Description

A series of experiments were conducted to assess the reduction of fine and coarse particles in a closed room where the EAC system was installed. The apparatus used for this experiment consisted of a unit with a 6.5 kV negative voltage generator, connected to a carbon fibre thread. The frame of the system was not earthed and was unvarnished. The system was placed in the closed room (total volume 50 m^3) and left to run for over 7 hours. Approximately 30 minutes prior to the first measurements, a large number of particles were released into the room, to ensure an even distribution of particles throughout the room. Coarse particles were generated by blowing fine clay powder (ground to within a size range of 1 - 5μm) into the room with a vacuum cleaner, coupled in reverse. In a second set of experiments, a fine particulate load was created in the same room using a lighted cigarette to release fine particles with a size range of 0.01 - 5 μm. Prior to each experiment and the introduction of the high particulate loads, a count was taken of background particle concentrations in the room. The average concentrations were 26 500 fine particles $litre^{-1}$ of air and 280 coarse particles $litre^{-1}$ of air. A control experiment was performed where the EAC system was not installed but the conditions used were identical. There was no air movement within the room apart from the thermal movement of air. Each experiment was conducted in triplicate. At each time interval, three measurements were taken and a mean value was taken from the sum. Thus, the values entered into Tables 7 & 8 are mean values of the three experiments (within which each measurement was repeated three times to ensure accuracy).

Particles were measured using a MetOne Hand held Particle Counter (Model 227, MetOne, Oregon, USA). The counter was set to count in the following ranges:

0.3 - 3.0 μm (fine particles)

3.0 - 7.0 μm (coarse particles)

Although these are not the conventional ranges used to define fine and coarse particles, the ranges were limited by the settings of the particle counter. The particle counter was installed in the room and left to run continuously during the experiments. A test for significant differences between the room with and without the EAC system in operation was conducted using a Student's t-Test. A P–value < 0.05 would indicate a significant difference.

2.1.2.2. Results and Discussion

Experiment 1: The reduction of coarse particles. Table 7 and Figures 6 and 7 give the results for coarse particles in a room with and without the EAC system installed. The massive input of coarse particles into the room is reflected in the initial particle counts of > 70 000 particles litre^{-1} of air. In both cases, the particles settled quickly. However with the addition of small negatively charged air ions (16 –21 000 ions cm^{-3} measured 13 cm in front of the emitter unit (see Table 5) the particles settled out very much faster than in the same room without the air cleaning system in operation. With the air cleaning system in operation, all the coarse particles had settled out after 2.3 hours, whereas without the air cleaning system in operation the particles never completely settled out. A comparison of the results shows that after ~ 1 hour the difference in airborne particle numbers between the room with the added negative ions and the room without the ions was 1:4. There was a consistent significant difference between the results from the experiments with/ without the addition of small air ions after 1.1 hours from the start of the experiments ($P < 0.01$).

Hours	System installed (mean no. litre^{-1} of air)	No system (mean no. litre^{-1} of air)	P value (99 % confidence)
0.1	77200	73800	0.603
0.3	24500	38900	0.002
0.5	14500	24500	0.020
1.1	5100	21000	0.002
1.3	4100	13100	0.001
1.5	2100	10700	0.000
2.1	800	7300	0.000
2.3	200	4800	0.001
2.5	0	4650	0.000
3.1	0	3800	0.000
3.3	0	2800	0.000
3.5	0	3000	0.000
4.1	0	2850	0.000
4.3	0	2100	0.000
4.5	0	2000	0.000
5.1	0	1900	0.008
5.3	0	2000	0.001
5.5	0	2100	0.009
6.1	0	2250	0.000
6.3	0	2340	0.001
7.1	0	3000	0.000

TABLE 7 COMPARISON OF COARSE PARTICLE REDUCTION IN A ROOM WITH THE EAC SYSTEM INSTALLED AND A ROOM WITHOUT THE SYSTEM INSTALLED

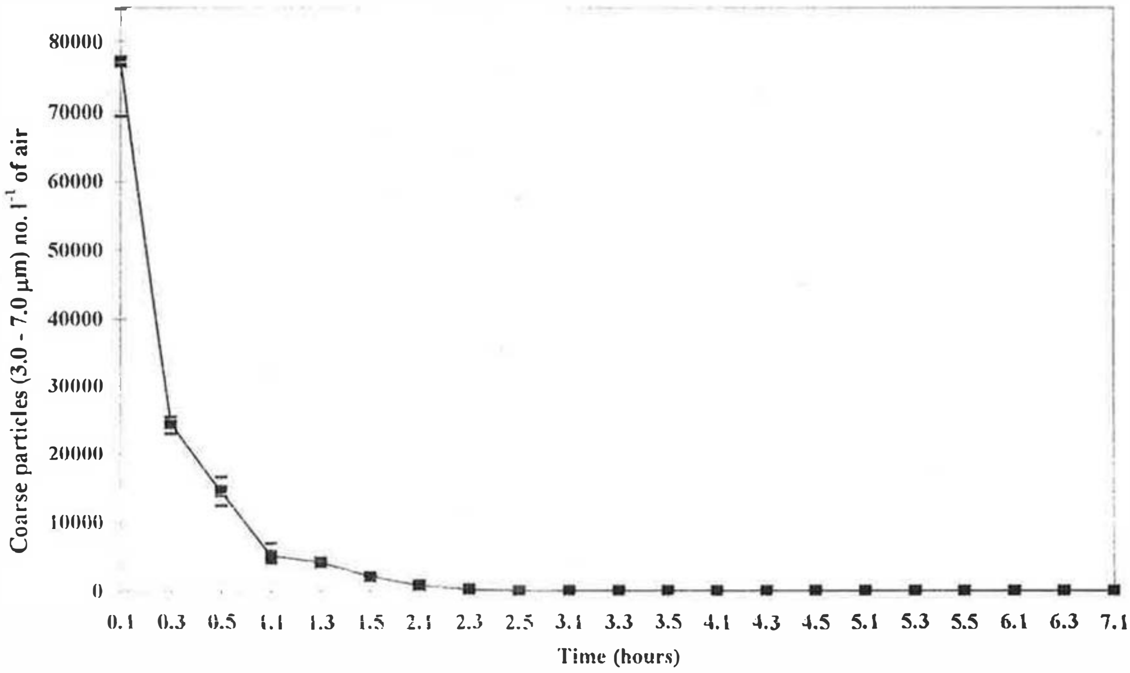

FIG. 6. A HIGH - LOW CHART OF THE CHANGE IN THE MEAN NO. OF COARSE PARTICLES EXPOSED TO NEGATIVE ION GENERATION

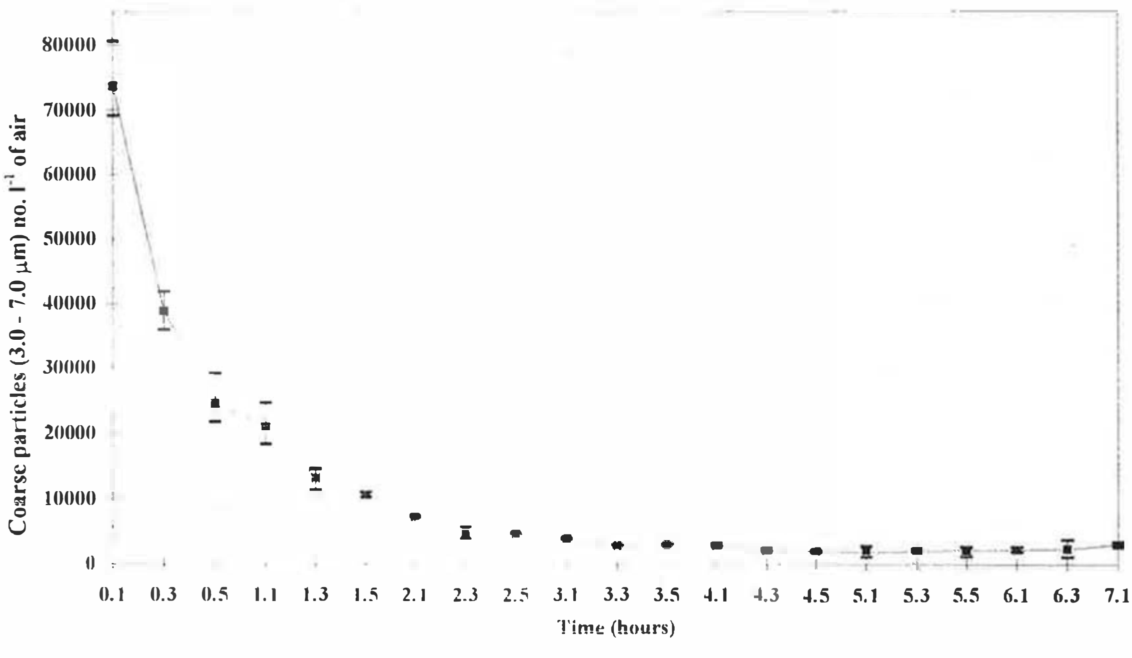

FIG. 7. A HIGH - LOW CHART OF THE CHANGE IN MEAN NO. OF COARSE PARTICLES NOT EXPOSED TO NEGATIVE ION GENERATION

Experiment 2: The reduction of fine particles. Table 8 and Figures 8 & 9 give the results for fine particles in a room with and without the EAC system installed. The graph and the table again show that particle numbers do settle out of the air. However because fine particles are not greatly influenced by gravitational forces (COMEAP, 1995), particles < 2 μm in size remain airborne. In the room with the EAC system, there is a major reduction in fine particles after just over an hour. There was a consistent significant difference between the results ($P < 0.01$) after the equipment had been running for 1.5 hours. The fine particles were influenced by the release of negative ions and were reduced in numbers by the mechanisms described in 1.4.

Hours	System installed (mean no./ litre of air)	No system (mean no./ litre of air)	P value (99 % confidence)
0.1	385100	387100	0.989
0.3	321400	352100	0.665
0.5	236100	335100	0.459
1.1	162400	296500	0.060
1.3	130100	274500	0.041
1.5	89100	246100	0.000
2.1	74100	221000	0.001
2.3	54000	192100	0.002
2.5	45600	167400	0.002
3.1	37500	151200	0.003
3.3	30000	146500	0.009
3.5	26100	131500	0.007
4.1	22100	111200	0.002
4.3	19600	100900	0.002
4.5	17500	96400	0.000
5.1	16800	78500	0.000
5.3	15600	69500	0.000
5.5	15300	66000	0.000
6.1	14680	59800	0.003
6.3	14100	56000	0.002
7.1	13500	54600	0.011

TABLE 8 COMPARISON OF FINE PARTICLE REDUCTION IN A ROOM WITH THE EAC SYSTEM INSTALLED AND A ROOM WITHOUT THE SYSTEM INSTALLED

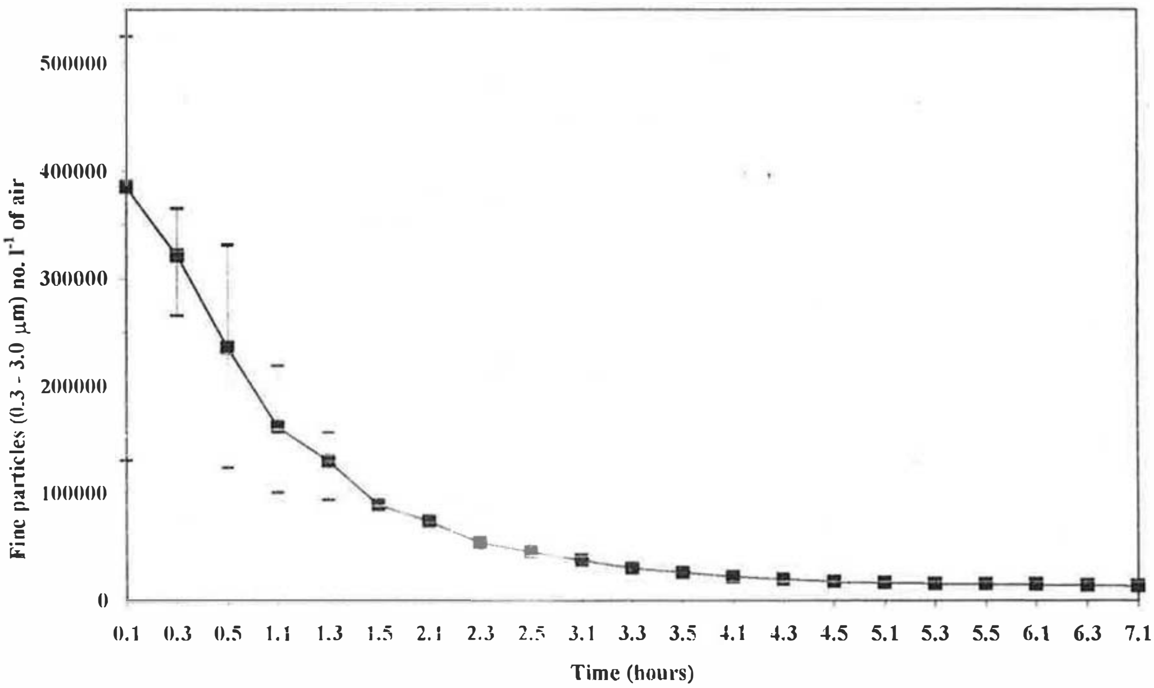

FIG. 8. A HIGH - LOW CHART OF THE CHANGE IN MEAN NO. OF FINE PARTICLES EXPOSED TO NEGATIVE ION GENERATION

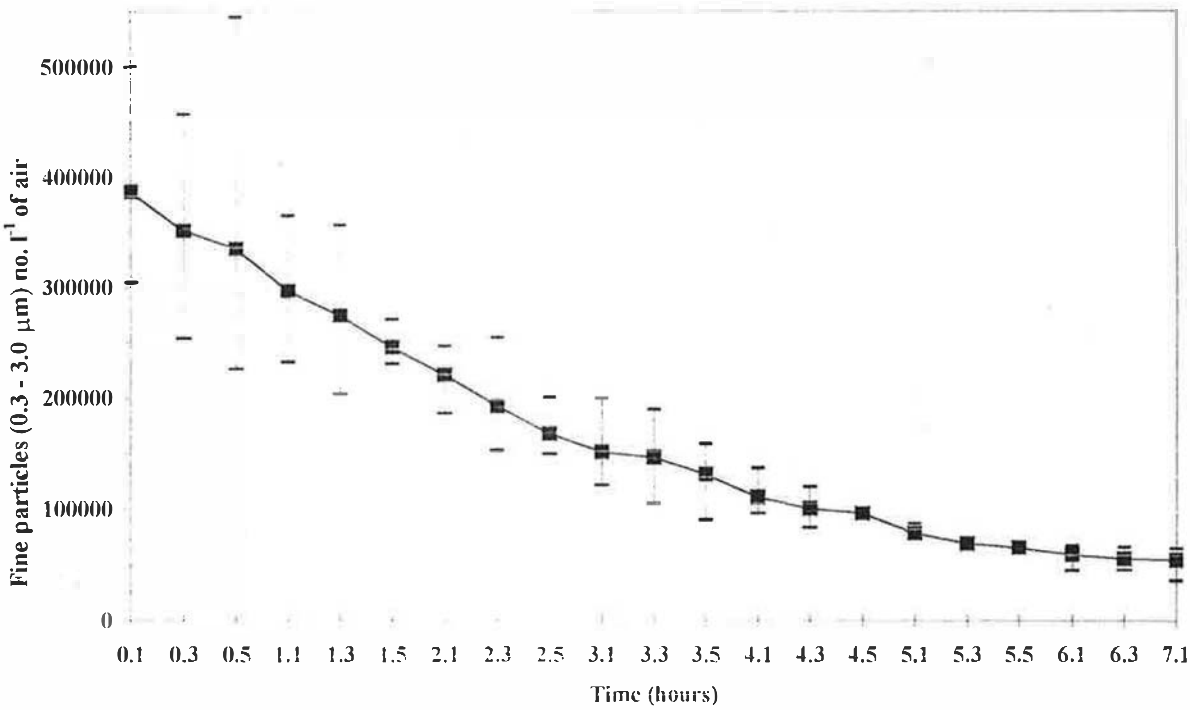

FIG. 9. A HIGH - LOW CHART OF THE CHANGE IN MEAN NO. OF FINE PARTICLES NOT EXPOSED TO NEGATIVE ION GENERATION

These experiments have shown that by using an extra high tension negative voltage generator with an output of > 6 kV that the following is possible:

- A system can be developed with a negative ion generating capacity in excess of 20 000 negative charged small air ions cm^{-3} of air.
- That there are enough negative ions generated by the EAC system to reduce both fine and coarse particles in a room

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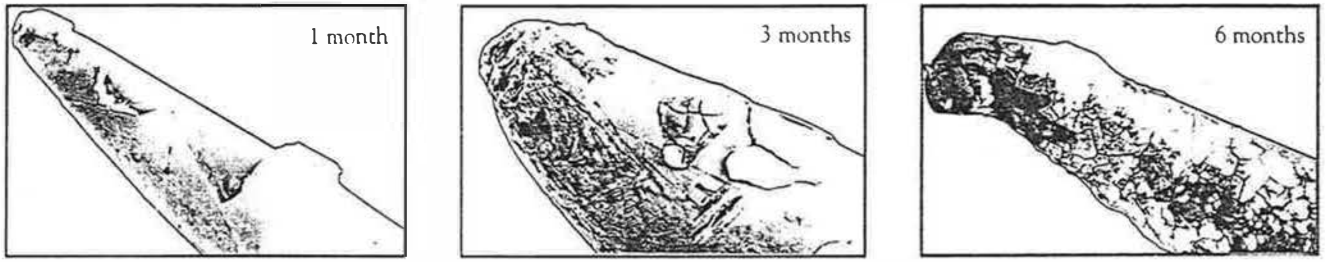
2.2. Determination of the Efficacy of Woven Carbon Fibre Thread as an Emitter of Electrons for the Electrostatic Air Cleaning System

2.2.1. Background

The generation of electrons and hence negative air ions requires a suitable emitter to release electrons. Many commercially available ion generators use steel or carbide-tipped metal needles to produce a corona discharge of electrons. These emitters are prone to producing ozone (O_3) (Pethig, 1984). It is postulated that O_3 is produced into the surrounding air through the occurrence of cold sparking at the interface between the original metal of the needle and corroded surfaces. Erosion on the needle tip is due to the sputtering of the metal (Liu et al., 1985). The rate of erosion of an emitter point is dependent upon the materials used to construct the emitter, the polarity and wave form of operating voltages and other factors such as current limitation (Blitshteyn & Shelton, 1985). The needle becomes increasingly corroded with age, as illustrated in Fig. 10. It can be seen that even after one month the very point of the needle has started to break up. The electrical discharges which occur as a result of the ageing of these conventional emitters is of sufficiently high energy to produce O_3 in atmospheres containing significant levels of oxygen. O_3 can have some beneficial air cleaning effects. It has anti-microbial properties and can mask odours by chemically oxidising malodorous compounds. However, it is known to cause adverse health effects in humans and should not be released ad hoc into human environments (Boeniger, 1995).



APPROXIMATE DIAMETER OF NEEDLE TIP = 0.1 mm

FIG. 10 THREE DIAGRAMS SHOWING THE DETERIORATION OF NEEDLE TYPE EMITTERS OVER TIME (FROM BIONIC PRODUCTS PTY LTD, 1993). MAGNIFICATION X100

The deterioration of the needles as described will reduce the efficacy of electron generation (Pethig, 1984), thereby affecting the efficiency of an air cleaner. Dirt accumulation, corrosion and blunting of the emitter tip can all prevent corona discharge (Pethig, 1984).

To avoid using metal needle point type emitters, certain manufacturers of air cleaners use woven carbon fibre thread to emit electrons. Pethig, (1984) recommends the use of carbon fibres as electron emitters because they are less likely to lose efficiency due to dirt accumulation or through the tip becoming blunted through corrosion. Carbon fibres do not corrode but are found to deteriorate in time through breakage along their crystalline structure. However, the carbon crystal structure is tetrahedral and carbon fibres are highly symmetrical at the molecular level. Therefore, breakage tends to produce new points of electron emission from which electrons are 'cleanly' emitted without any cold sparking. Whilst it is not possible to count exactly how many carbon fibre points are available for a thread it is accepted that several thousand fibres exist per 100 mm of thread, each with two possible electron emitter points. Thus, even if thousands of the emitter points are clogged by dirt on the thread, there will still be numerous points from which electrons can be produced. Since no other efficient electron emitters are available, carbon fibre threads will be used for the EAC system.

The EAC system will be used in dirt laden indoor air, where fine particles such as those from combustion emissions and tobacco smoke, could combine to form a coating on the carbon fibres. Hence, it was necessary to investigate how such a coating might affect the electron generating capacity of the thread. An investigation was designed to study the effect of dirt agglomeration on the carbon fibre thread in terms of electron production over time. If the fibres became encrusted to the extent that a large number of tips became covered then the production of ions could be reduced and the air cleaner would not be suitable for environments with high fine particulate pollution. However, if the fibres became encrusted with dirt but broke off leaving a clean break-surface, electron production would continue or if there were many more possible electron emitter points not clogged by dirt the thread would function normally. These attributes would be visible under an electron microscope. Previous measurements and visual inspections of used carbon fibres threads, revealed that the overall diameter of the threads reduced with increased usage, indicating that fibre breakage did occur and thus the fibres 'wore out' with use. Understanding the characteristics of carbon fibres was clearly an important requirement in order to determine the frequency of carbon fibre replacement required to maintain efficient air cleaning. The EAC system needed to be capable of operating for long periods without service to be viable.

Due to the fact that carbon fibres do not corrode in the same way as metal tipped emitters do, it is thought that little or no O_3 would be generated from the fibres. As a precautionary measure, the maximum output voltage of the generator was maintained below 7.5 kV. For most emitters this would keep the O_3 production below 1 ppb (Pethig, 1984). If small amounts of O_3 such as these were produced by the EAC system, it would be removed by heterogeneous reactions with indoor surfaces, where the O_3 deposits at significant rates (Reiss et al., 1995).

2.2.2. Description of the Carbon Fibre Thread Emitters suggested for use with the EAC system

The carbon fibres used for the EAC system in the experiments described in this thesis were manufactured by Eurocarbon, Holland. The thread was made from three yarns twisted together under a light tension. Each yarn was made from approximately 3000 pure carbon fibres, for every 100 mm length of thread. Each individual fibre is approximately 6 mm long with a diameter of 10-12 μm. The carbon fibres are interwoven with a carrier yarn made from 12000 man made fibres/ 100 mm that entrap the slippery carbon fibres and carry any longitudinal forces exerted on the thread. The thread is very lightly coated in paraffin to assist in the manufacturing process. The thread is delivered without any further coatings unless requested. The fibres are brittle and as such, individual fibres break off and become airborne. These fibres can be inhaled and can result in respiratory irritation (personal communication, Eurocarbon, 1998). Therefore, the manufacturer offers to coat the finished thread to trap loose fibres. This coating literally covers all the individual fibres in a thread, reducing its electron generating capacity if it is not removed before put into operation.

2.2.3. Procedures

Specimens of used carbon fibre thread were obtained from a fan assisted EAC type system that had been operating in the city centre of London (UK) for three weeks. The system produced approximately 15 000 negatively charged small air ions cm^{-3} of air. To assess the production of negatively charged small air ions produced by the EAC system, an atmospheric air ion analyser (Type 134A. Medion, Oxted, England), was set at a distance of 2 m from the emitter. Further samples of carbon fibre were taken after two months. The two month old thread would have had approximately 200 000 m^3 of air drawn through/ past it. When a specimen of thread was removed after two months of continuous use, the small air ion production of the system had fallen to 95% (~ 14 000 ions cm^{-3}) of its original capacity. The used thread was compared with virgin thread from the manufacturer.

The threads were viewed under a scanning electron microscope (SEM). The SEM works on the principle of scanning a focused beam of electrons across the surface of a specimen. When the beam of electrons is focused on the specimen, a range of emissions from the surface region occurs. These emissions include:

Back scattered electrons

Secondary electrons

Auger electrons

Characteristic x-rays

All of these emissions can be used to obtain an image of the specimen on a VDU screen. Secondary electrons are emitted from just below the surface of the specimen and are collected by a detector close to the specimen. Each electron captured by the detector causes a flash of light in a scintillation device. This passes down a light guide to a photo multiplier, which in turn converts it to an electrical signal. The final electrical signal is proportional to the number of secondary electrons emitted from the specimen, and is used to modulate the brightness of a display spot on a VDU screen (Bond, University of Plymouth, unpublished).

The specimens were coated with gold to a thickness of approximately one nanometre. The gold coating was used to enhance the reflective capacity of the specimens. The specimens were prepared as follows:

Specimen 1 virgin thread: A short length of thread was cut length wise and pasted onto a specimen holder. This enabled the thread to be viewed at 90° to its axial direction. This gave a clear picture of the formation of the thread and some indication of the interlocking of the three yarns.

Specimen 2 virgin thread: A short length of thread was cut and pasted onto a specimen holder with the ends facing upwards, exposing the cut surfaces of the fibres.

Specimen 3 & 4 thread used for 3 weeks and two months respectively: A short length of thread from each sample was cut length wise and pasted onto a specimen holder.

2.2.4. Results

Specimen 1: In the image produced from specimen 1 (Fig. 11), it is apparent that the carbon fibres had extremely smooth surfaces. The presence of a small number of particles on the fibres is thought to be a result of residual dirt from the manufacturing process.

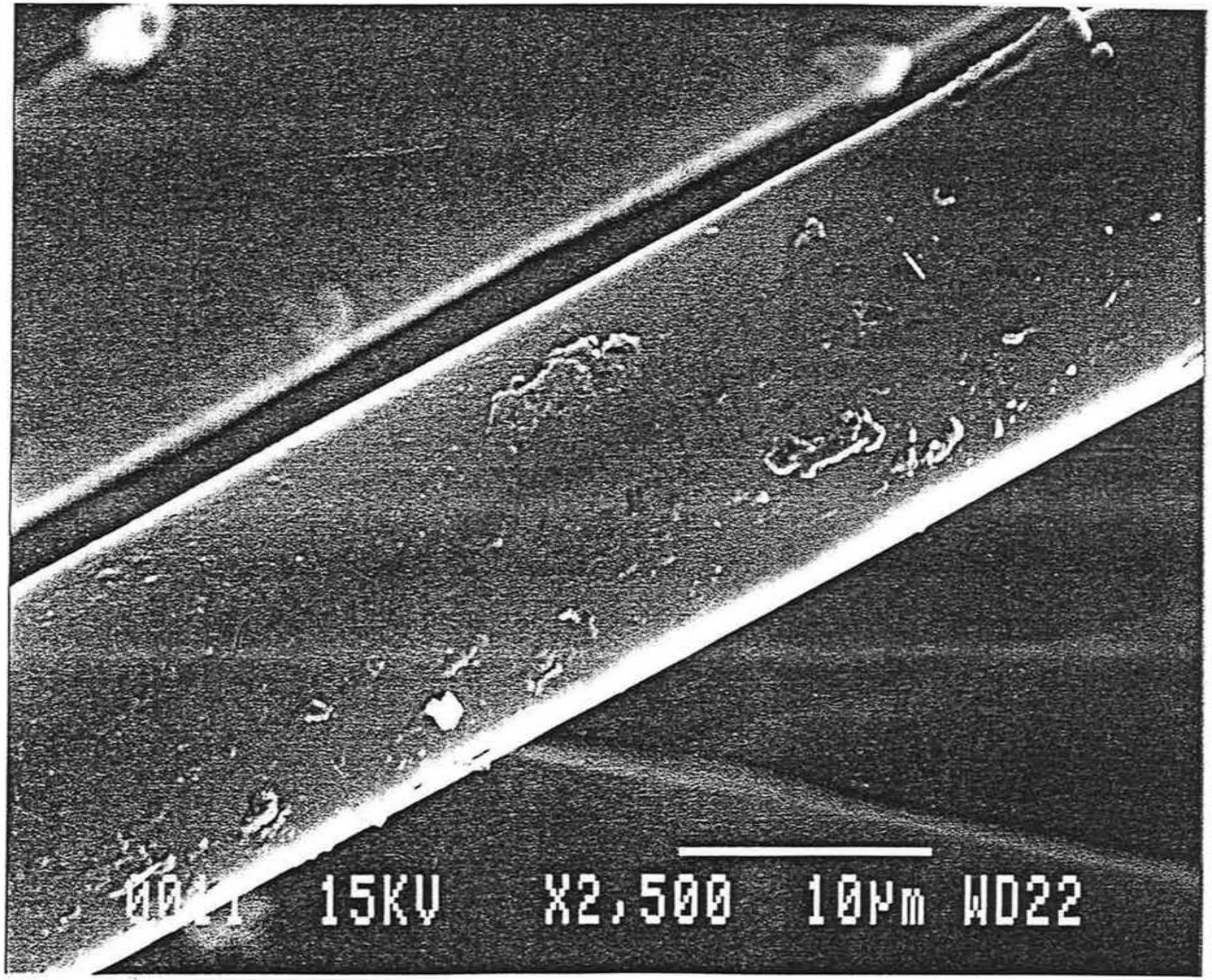


FIG. 11 SPECIMEN 1: VIRGIN CARBON FIBRE THREAD (X 2500)

Specimen 2: This specimen showed the 'snapped' points of the fibres (Fig. 12), which did not appear to have clean break points i.e. there were no fibres with ends at 90° to the length of the fibre. This confirms the idea that carbon fibres fracture along their crystalline structure since the break point appears at different angles to the length of the fibre and each breakpoint surface is similar in structure.

Specimen 3: This specimen shows how the fibres have accumulated particulate matter after 3 weeks (Fig. 13). Random patches of foreign material can be seen seemingly adhered to the cylindrical surface of the fibres. The fibres were not completely covered in dirt and the EAC system had been functioning at full capacity when the samples were taken.

Specimen 4: This specimen, taken after 2 months of use in an EAC system, showed the build up of particles on the fibres (Fig. 14). The foreign material covered the outlines of the individual fibres in the threads. By increasing the magnification of the microscope, it was possible to establish that under the outer 'layer' of dirty fibres, clean fibres were still available. These remaining fibres would account for the fact that the carbon fibre thread was still effectively producing small air ions even when the thread seemed to be dirty.

Fig. 15 gives a clear picture of the extent of 'clogging' on one of the fibres. The particles adhered to the fibre in Fig. 15 range from 8 μm in diameter to less than 0.1 μm. The smooth surface of the fibre has virtually disappeared under what is thought to be an accumulation of ultra fine particles, which have formed a lumpy 'coating' on the lateral walls of the fibre. The coating could also be an actual reaction to the electrical current in the fibre where the current could be affecting the paraffin coating of the fibre causing it to partially volatilise, leaving behind a higher molecular weight 'waxy' deposit.

FIG. 12 SPECIMEN 2: VIRGIN CARBON FIBRE THREAD - END VIEW (X 100)

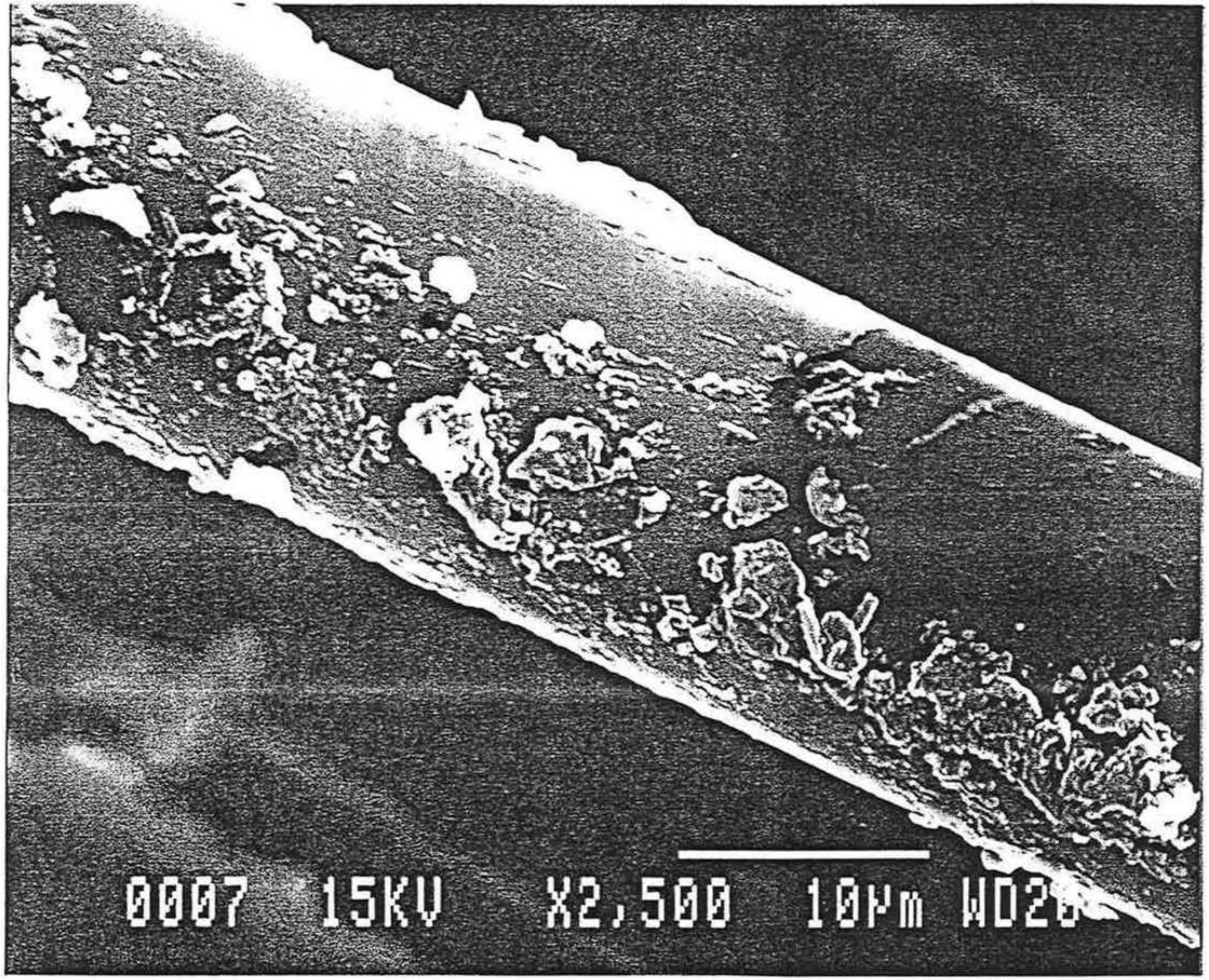


FIG. 13 SPECIMEN 3: CARBON FIBRE THREAD IN USE TO THREE WEEKS (X 2500)

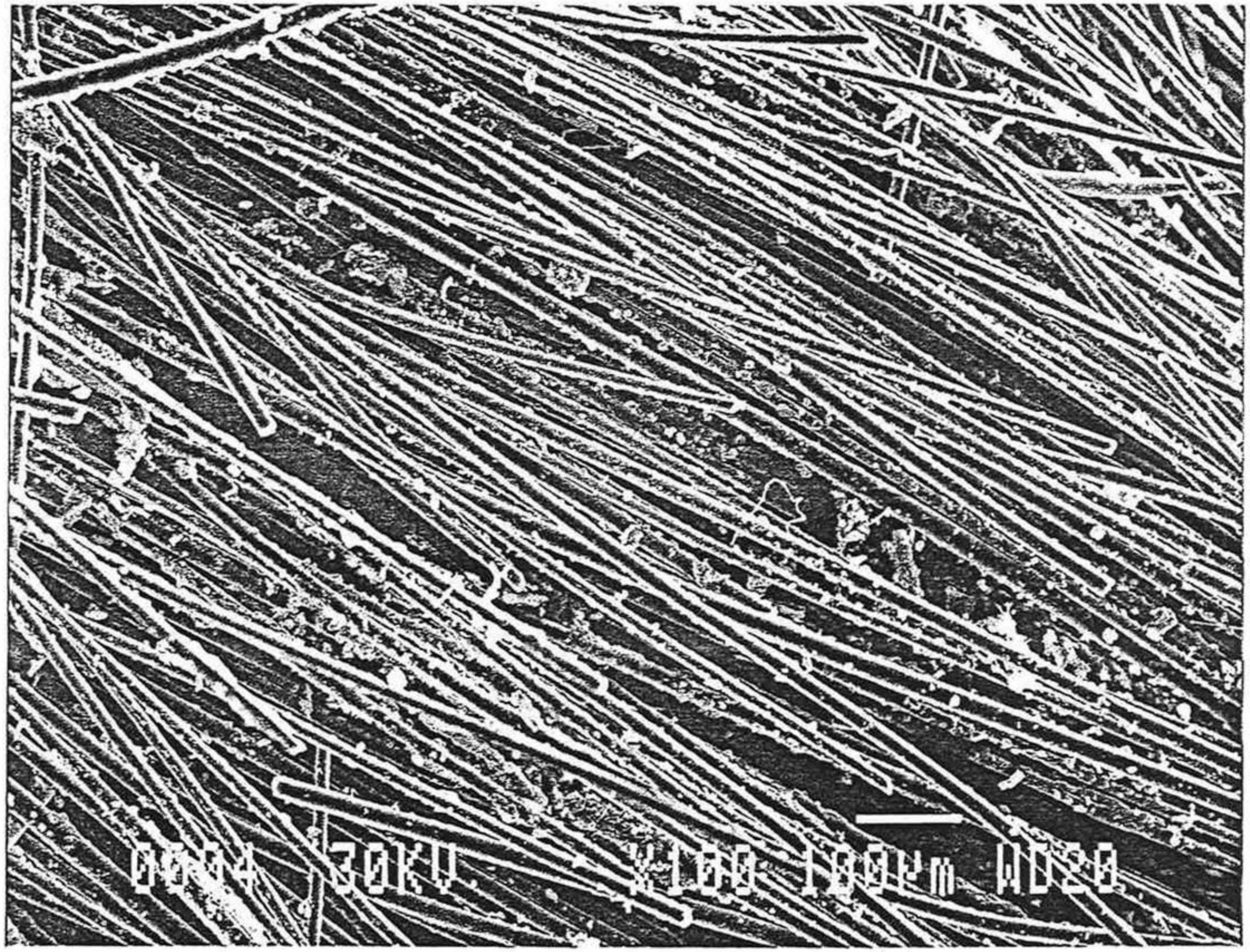


FIG. 14 SPECIMEN 4: CARBON FIBRE THREAD IN USE FOR TWO MONTHS (X 100)

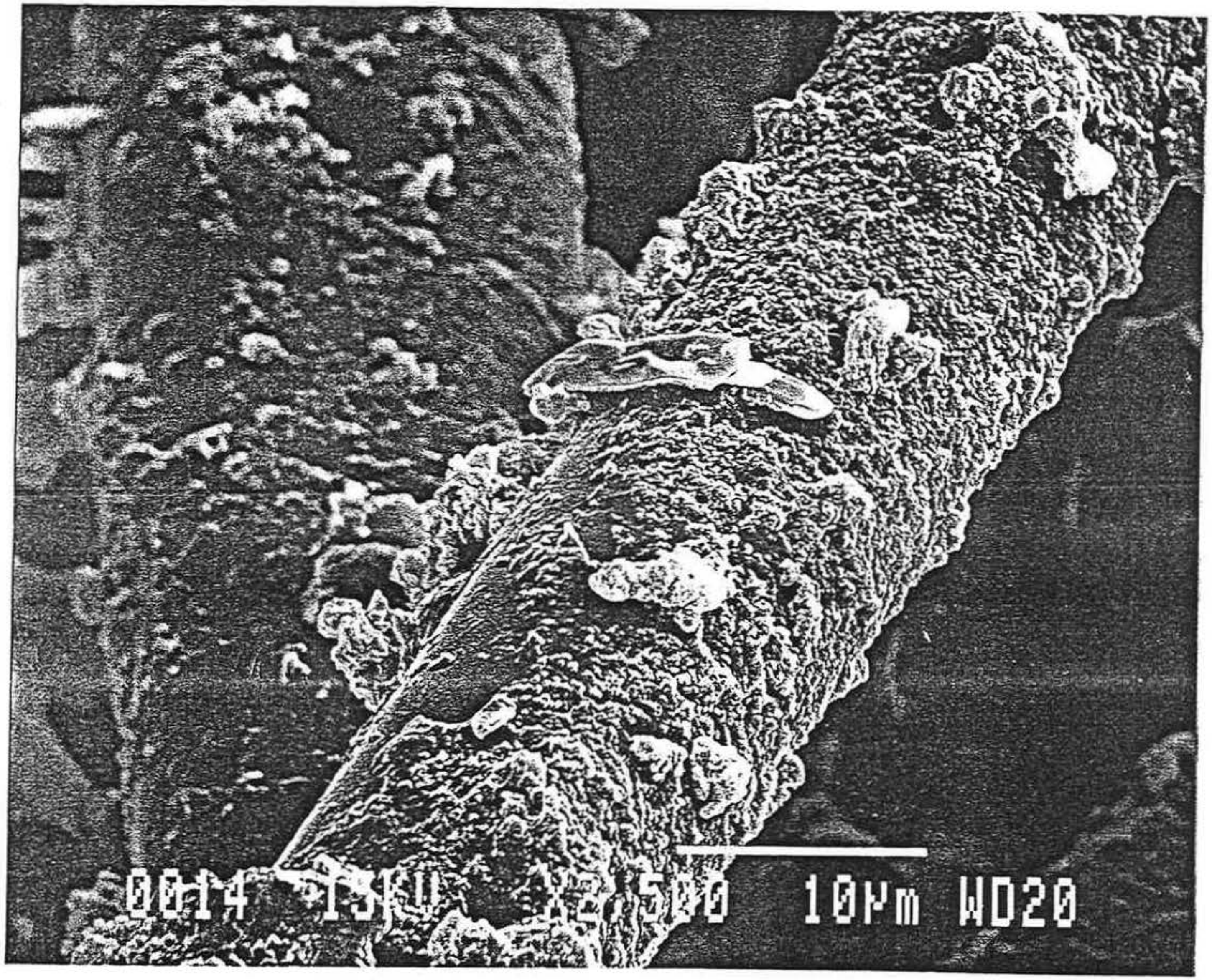


FIG. 15 SPECIMEN 4: CARBON FIBRE THREAD IN USE FOR TWO MONTHS (X 2500)

It may be possible to determine the source of the foreign material adhering to the fibre by using the microscope to determine the elements present. Alternatively, FT-IR spectroscopy might be used to determine the origin of organic components. The fact that each fibre would have been carrying a large negative electrical charge would cause the fibre to act as a negative pole, attracting positively charged material passing through the thread. There is substantial proof that dirt accumulation occurs. Early generations of EAC type equipment needed to be vacuum cleaned every two months to avoid reduced electron generating capacity, due to accumulation of light surface dust. This problem will need to be addressed in the commercial development of the EAC system.

Carbon fibre thread will be used as the emitter material for the EAC system based on the following conclusions:

- It has a reasonably long lifetime. Due to the structure of the carbon fibres, breaks always occur such that there are always fresh points to emit electrons, minimising electron production impairment.
- The fibres are slow to clog up. Despite the fact that the fibres showed an accumulation of dirt after 2 months the efficacy of the air cleaning system was only reduced by 5 %.
- Carbon fibres are inexpensive.

Further investigation into the efficiency of the carbon fibre threads will continue. Eurocarbon, Holland and A C & T Ltd.. UK, have offered to part fund further research into the crystalline structure of the fibres to ascertain if the electron output of each individual fibre can be increased based on a smaller breakage surface. There is also concern that assembly line workers are being exposed to 'loose' carbon fibres during production. One possible solution to this is to coat the individual fibres with wax that can be volatised by low heat after assembly. This would represent an additional stage in the manufacturing process and requires further investigation.

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2.3. Assessment of Airborne Particulate Pollution in Children's Nurseries

2.3.1. Background

The environment in which children work and play can have a major impact on their current health and future well being. One of the longest periods of exposure to infectious illnesses and high particulate loads occurs when children are at school or in a nursery. This is especially so for children aged 1 - 6 in nursery care, where the presence of more than six other children in a nursery can double a child's level of absenteeism through exposure to airborne pathogens (Dahl et al., 1991) or through bodily contact with pathogens. Children of this age are known to be particularly vulnerable to heavy metals as they absorb contaminants quicker than adults because of their different physiology and activities (Tong & Lam, 1998). The American Environmental Protection Agency states that pre-adolescent children are at risk from health impacts resulting from particulate matter exposure (Etkin, 1995). Particulate pollution has been linked to respiratory illnesses and other complaints in a number of studies conducted in nurseries (Dockery et al., 1989; Christensson & Krantz, 1992).

A three-year study of four Swedish nurseries was initiated to assess the effect of particle pollution on absenteeism in nurseries (*Paper no. 1*). Currently in Swedish schools and nurseries, the concentration of CO_2 indoors is used as a marker for IAQ (Swedish Government recommended maximum of 1000 ppm). In the four nurseries studied, these standards had been successfully met using a forced air ventilation system. The climate in Sweden requires children to spend the majority of their time indoors and their well being is therefore largely dependent on the quality of indoor air and could therefore, have a major influence on their well being.

To investigate whether the EAC system could be developed to improve IAQ in UK nurseries, a study was initiated in two Plymouth City centre nurseries (as described briefly *in Paper no. 2 & 3*). Both nurseries were located close to large roundabouts/ traffic junctions where 15 - 20 lanes of traffic meet and approximately 40 000 vehicles day^{-1} pass through (City of Plymouth Transport services, personal communication, 2000). Nursery no. 1 was located between high buildings, which created a 'canyon' effect, whereas nursery no. 2 was in an open position away from other buildings. Neither of these localities had forced air ventilation or filtration of incoming air and the ventilation regime was completely reliant on opening windows. The carbon dioxide concentrations at both sites were measured and found to be below 1000 ppm for the majority of the opening hours.

For reference, the results from a typical Swedish centre are used herein to be able to draw comparisons with the Plymouth nurseries. The results taken from the Swedish day care centre were measured during a period when no interventions were made to the air cleaning system. All three nurseries were situated near the coast and were expected to have the same ambient levels of marine aerosols, which can constitute a major portion of coarse particulate load outdoors in coastal areas (Chan et al., 2000).

Table 9 details the demographics for each nursery. The internal standards for cleanliness, staffing levels, available toys and types of activities were comparable for the Plymouth nurseries and the Swedish centre.

Nursery	Plymouth no. 1	Plymouth no. 2	Swedish centre
No. of children present at monitoring times	23	18 -20	30
Age of children	3 – 4	3 – 4	1 - 6
Type of ventilation	Open window	Open window	Controlled forced air
Total area m^2	64	93.5	42
Total volume m^3	192	355	147
Area per child (m^2/ child)	2.8	4.9	1.4
Volume per child (m^3/ child)	8.35	18.7	4.9

TABLE 9 COMPARISONS OF THE DEMOGRAPHICS OF EACH NURSERY

The level of particulate pollution was monitored by measuring the concentration of particles (number/ litre of air) in all three nurseries and by analysing the composition of the particles in one Plymouth nursery. The main reason for analysing particle composition was to confirm that the source of fine particles in the nursery was from outdoor combustion processes. A large variety of organic compounds may be found absorbed onto the surface of particles, including many hazardous contaminants from traffic pollution such as polycyclic aromatic hydrocarbons (PAH). Diesel and petrol vehicles are a significant source of ambient PAH in urban areas. Fluorenes, naphthalenes and phenanthrenes are commonly produced by the incomplete combustion and carbonisation of fuel (Williams, 1986). There is a strong link between PAH exposure and the concentration of fine particles, as PAH are normally distributed in the fine particle fraction (Monarca et al., 1997). Particles from other sources are chemically quite different. For example, human derived particulates are rich in discarded skin cells. As they are protein based, these are readily distinguishable.

2.3.2. Methods

Approximately 100 discrete readings of PM_3 and PM_7 (no./ litre of air) were taken at both Plymouth nurseries and 15 continuous 5-day measurements were taken with a MetOne particle counter at nursery no. 1. The MetOne counter sampled the air every 15 minutes (for 30 seconds) in a continuous sampling mode. Discrete samples were taken manually, also for 30-second periods. The MetOne also recorded relative humidity (RH %) and temperature (°C). The method of measurement in the Swedish nursery was identical.

Particle samples were taken from the playroom carpet in nursery no. 1, using a diaphragm vacuum pump attached to a length of Teflon tubing. Measurements were taken over one minute periods. The samples were placed in a dessicator for 24 hours to reduce interference from moisture. The samples were then analysed on a Bruker IFS 66 FT-IR spectrometer in a Graseby Specac Diffuse Reflectance Infrared Fourier Transform (DRIFT) accessory. The spectrometer was set for the following conditions. Resolution 4.0 - absorbance; zero filling 2; sample scans 32; wave numbers 400 - 4000 cm^{-1}. The spectrometer was fitted with a CO_2 scrubbed dry air purge. The sample cup of the DRIFT accessory was filled with freshly ground spectroscopic grade potassium bromide (KBr) in order to aid in sample alignment and to provide a useful background spectrum (KBr does not absorb in the IR). Each filter paper containing the particulate sample was placed on top of the cup and the FT-IR spectrum measured individually in order to determine absorbed organic compounds. A background reading was taken using a blank filter paper and this was subtracted from each sample spectrum. All DRIFT IR spectra are automatically corrected for absorbance using the standard methodology of the Kubelka Munk function, which uses corrected reflectance spectra to allow a search against absorbance spectra. The subtraction of the background spectrum of the filter paper was necessary because the filter paper contained IR active species such as cellulose. It is understood that in drying the samples before analysis, highly volatile compounds may have been lost.

Gas samples were collected from both of the Plymouth nurseries in 100 ml gas tight syringes, which were then sealed and later analysed in a gas tight 10 cm path length standard gas cell with KBr windows, on a Bruker IFSS 66 FT-IR spectrometer under the following conditions. Resolution 4.0 - absorbance; zero filling 2; sample scans 16; wave numbers 400 - 4000 cm^{-1}. The spectrometer was fitted with a CO_2 scrubbed dry air purge. Background spectra were measured with the FT-IR sample compartment sealed and containing no gas cells. Samples of outdoor air were also taken in the vicinity of the nurseries. These samples were also analysed on the FT-IR and then subtracted from the indoor spectra to give an indication as to whether the observed chemicals had an indoor or outdoor source.

2.3.3. Results

Table 10 & 11 show the results of the two Plymouth studies in comparison to one of the Swedish day care centres. A two-tailed Student's *t*-test was performed to compare differences for indoor and outdoor particulate concentrations for the two Plymouth sites. There was no significant difference in PM_3 concentrations between indoors and outdoors. However there was a significant difference between PM_7 concentrations indoors and outdoors ($P < 0.05$). Fig. 16 indicates that coarse particle numbers are lower in the nurseries with a larger volume of air available per child.

Nursery	Plymouth no. 1		Plymouth no. 2		Swedish centre (No EAC installed)	
Location	Outdoors	Indoors	Outdoors	Indoors	●utdoors	Indoors
Median	101	336	156	221	*	428
Range	40 – 205	135 – 446	31 – 218	129 - 333	*	340 – 649

*Due to the fact that this site had filtration installed for coarse particles, outdoor particles had no bearing on the indoor measurements.

TABLE 10 COMPARISONS OF PM_7 CONCENTRATIONS BETWEEN THE TWO PLYMOUTH SITES AND THE SWEDISH CENTRE DURING THE DAYTIME (NO. OF PARTICLES/ LITRE OF AIR)

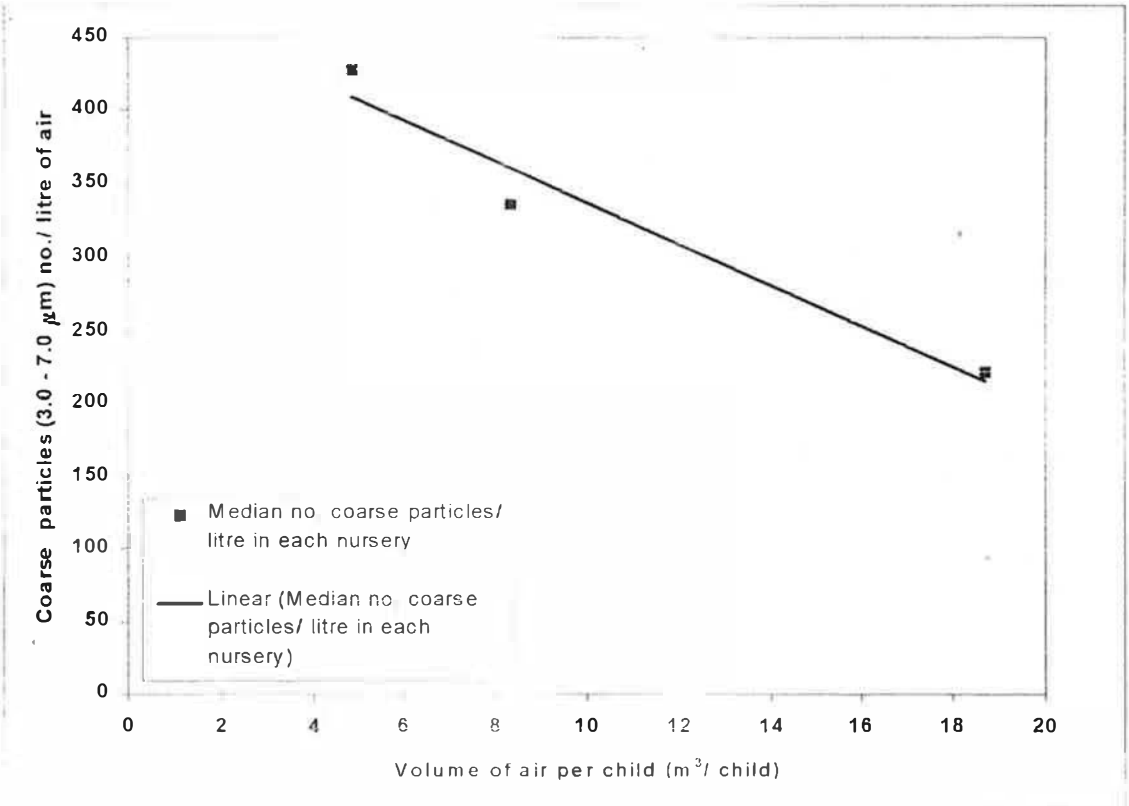

FIG. 16 COMPARISON OF THE NUMBER OF COARSE PARTICLES PER LITRE OF AIR WITH THE VOLUMETRIC MEASUREMENT PER CHILD IN EACH NURSERY

Nursery	Plymouth no. 1		Plymouth no. 2		Swedish centre (Without installation of EAC, unpublished data)	
Location	Outdoors	Indoors	Outdoors	Indoors	Outdoors	Indoors
Median	64270	69697	57944	61413	59960	38068
Range	18086 - 256630	23977 – 259019	25044 - 132862	27318 - 127796	21893 - 265537	19774 – 186441

TABLE 11 COMPARISONS OF PM_3 CONCENTRATIONS BETWEEN THE TWO PLYMOUTH SITES AND THE SWEDISH CENTRE DURING THE DAYTIME (NO. OF PARTICLES/ LITRE OF AIR)

Fig. 17 shows the typical diurnal pattern of particulate concentrations in nursery no. 1. This may be compared to a similar recording taken in one of the Swedish nurseries (Fig. 18).

The DRIFT analysis of the particulate samples from nursery no. 1 revealed the presence of PAH.

The FT-IR analysis of gas samples revealed gases associated with traffic emissions. The following absorbances in wave numbers (cm^{-1}) and their assignments were typical (Dr D J Harwood, University of Plymouth, personal communication); see Fig. 19 for an example of a spectrum.

650 - 970 region of aromatic C-H skeletal vibration. Aromatics from traffic emissions, perfumes etc.

~1260 shows Aliphatic C-H bend typical of a skin cell related spectra and absent from outdoor (traffic emissions) spectra.

2339 & 2360 CO_2 peaks

2800 - 3000 region of C-H stretch aliphatics.

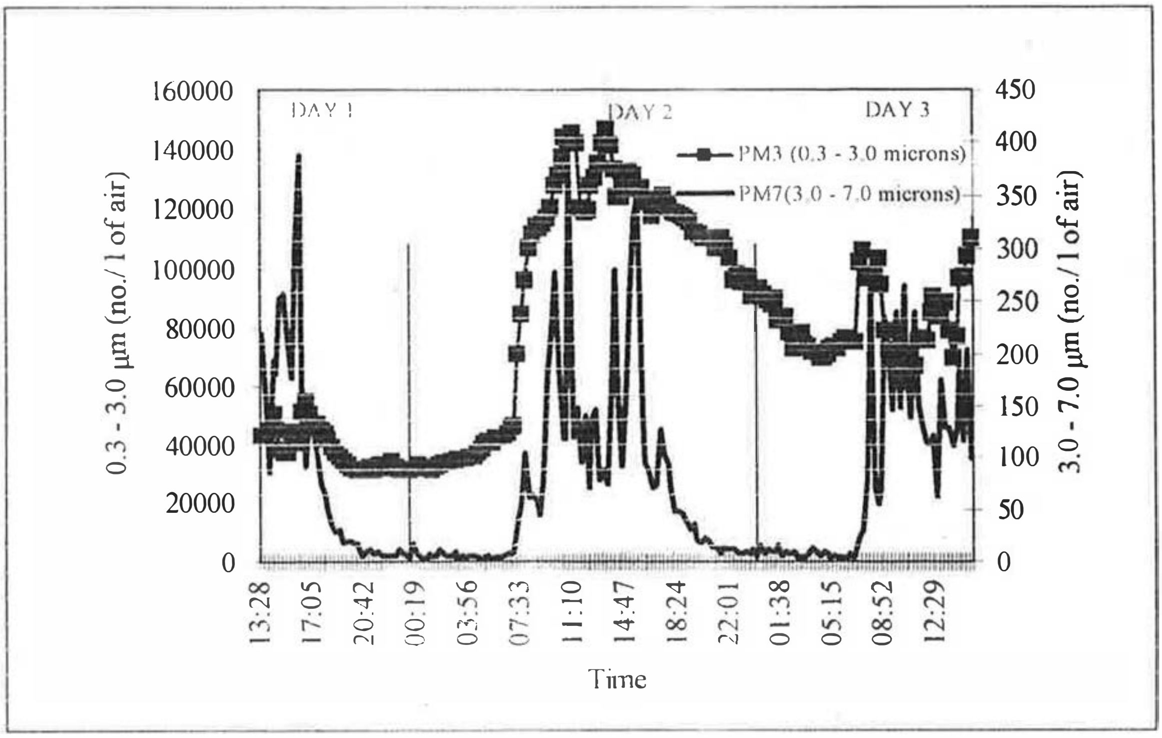

FIG. 17 PARTICLE COUNTS OVER 48 HOURS IN NURSERY NO. 1

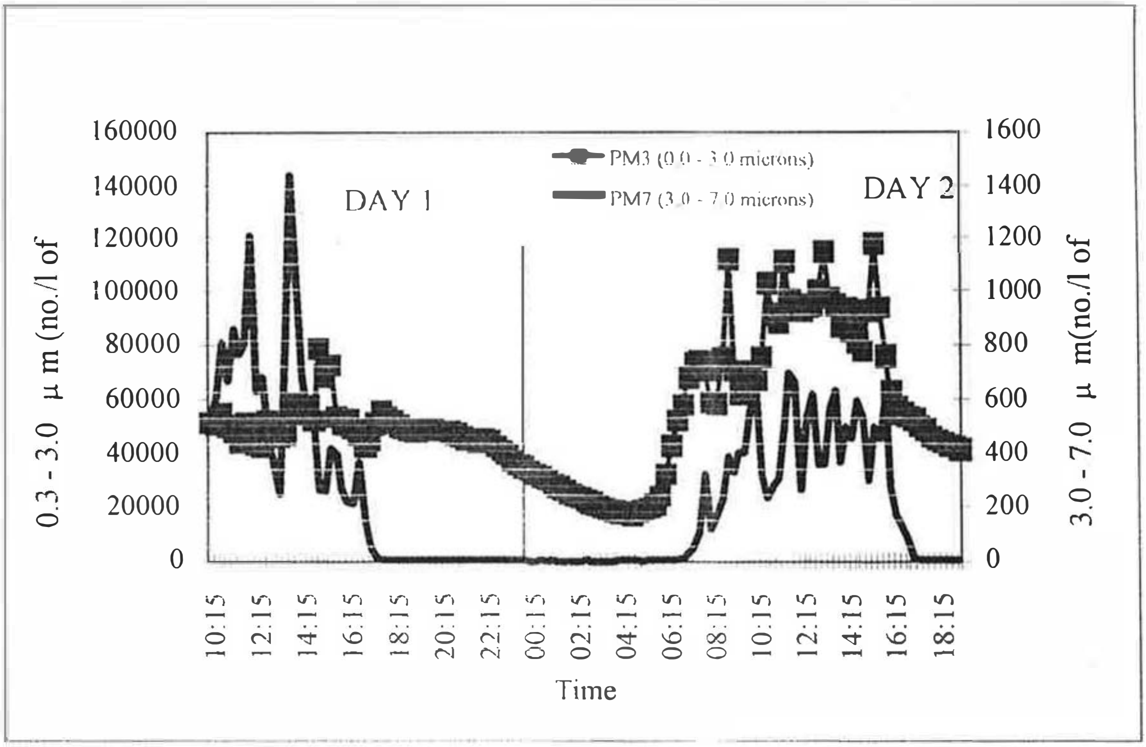

FIG. 18 PARTICLE COUNTS OVER 24 HOURS IN THE SWEDISH DAY CARE CENTRE

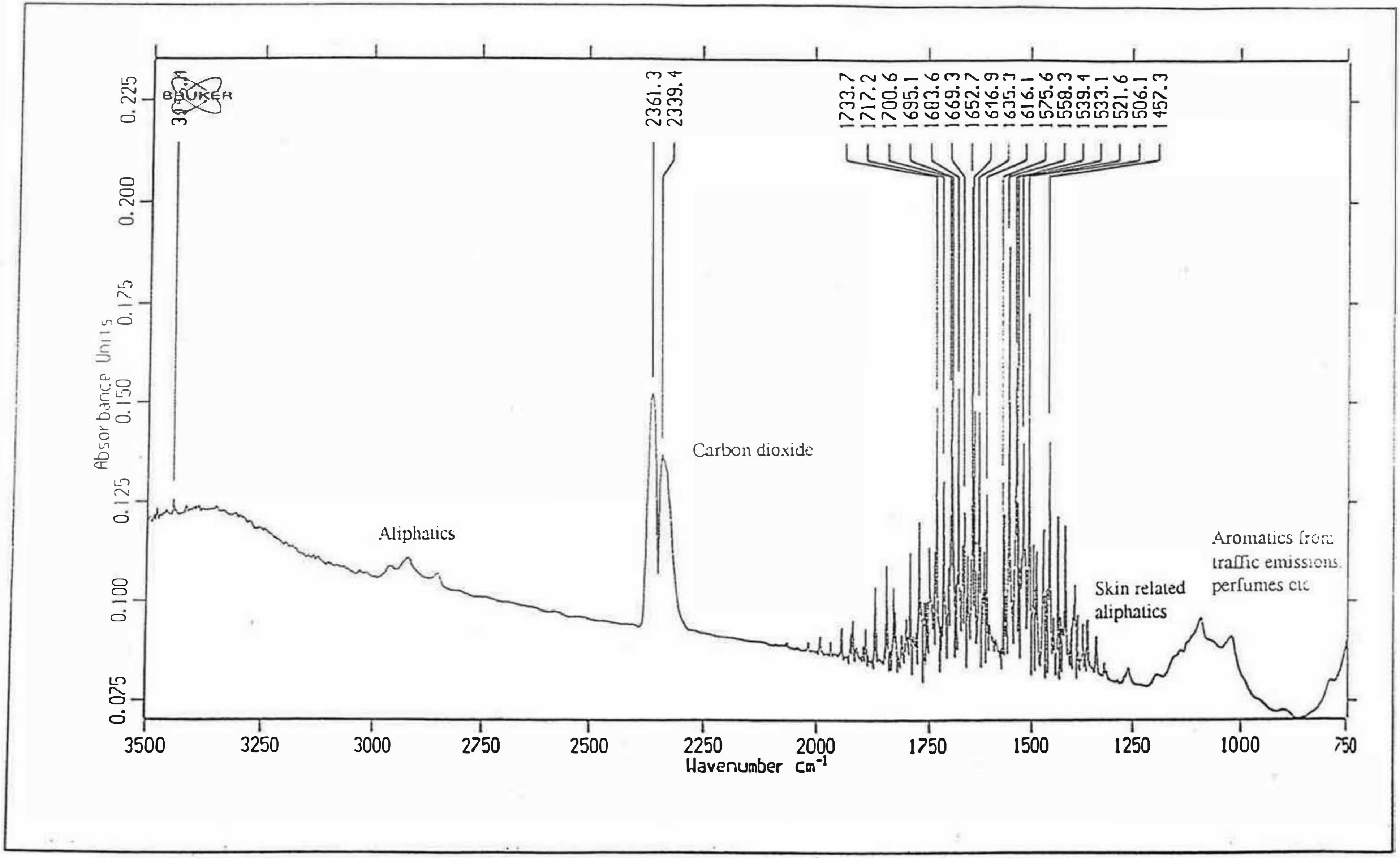

FIG. 19 TYPICAL SPECTRUM OF GAS ABSORBANCES FOUND IN NURSERY 2

2.3.4. Discussion

The data in Table 9 demonstrate that the Swedish centre had a larger number of children within a smaller space when compared to the Plymouth nurseries. Hence, the Swedish centre had more children to create particles and less air volume with which to dilute the particles. The fact that the Swedish centre had a smaller air volume to child ratio is shown by the large number of coarse particles per litre of air within the centres (Fig. 16).

The fact that coarse particles are generated indoors by the activities of the children is reflected in the results, as there is a significant difference between outdoor and indoor concentrations of PM_7 for both of the Plymouth nurseries ($P < 0.05$). Coarse particles are normally considered to be created indoors (Christensson & Krantz, 1992). In the Swedish centre the forced air ventilation had difficulty in coping with the continuous generation of large numbers of coarse particles as shown by the high median value (428) and the high maximum value (649) in Table 10. This can be explained in part by the fact that there were a large number of children in the centre. However, another Swedish study found that even in a room with only 5 - 6 children the forced air ventilation could barely maintain an average of 126 particles/ litre of air (Christensson & Juringe, 1995).

A Student's *t*-test comparing indoor and outdoor PM_3 reflected the fact that there was no significant difference between indoor and outdoor concentrations of fine particles in the Plymouth nurseries. This means either that both centres have their windows open frequently or that their respective building structures are far from airtight, allowing substantial ingress of fine particles from outdoors. The PM_3 values from Sweden demonstrate the difference made by the basic forced air ventilation installed, as there was an average reduction of 25% from outdoors to indoors. It must be noted however that this reduction was not significant ($P > 0.05$) and that the installed forced air ventilation had difficulties in dealing with large fluctuations in fine particles. Any reduction in fine particles would have been as a consequence of particles adhering to internal ductwork, since the installed ventilation system was not designed to remove fine particles drawn in from outdoors and only filtered out particles > 5 μm in diameter.

The data collected from the Plymouth nurseries indicates that the sites are facing similar problems to the Swedish centre in connection with the removal of coarse particles. It would seem that the forced air moving system in Sweden is inadequate with regard to the removal of coarse particles. The implication being that the forced air ventilation system in Sweden, which operated at 7 litres/ second/ child had no greater effect than the open window ventilating regime at the Plymouth nurseries. Although the particle concentrations in Sweden were different, a comparison of continuous measurements shows that there were strong similarities in diurnal fluctuations with the Plymouth nurseries (Fig. 17 & 18). The differences in the median values for fine particles indoors between the Swedish centre and the Plymouth nurseries confirmed that the air handling system in Sweden did reduce fine particles as described whereas the Plymouth nurseries offer no protection against ingress of fine particulate matter. The open window systems in the Plymouth nurseries do not offer any protection against toxic particles entering the building. Contaminants are known to enter through windows from traffic emissions (Tong & Lam, 1998). It is interesting to note that the absolute numbers of fine particles surrounding the three nurseries are very similar despite the fact that the Plymouth nurseries were located in Plymouth city centre, whereas the Swedish centre was located in a residential area of a small country town.

Fig. 17 & 18 show that both classes of particles are greatly reduced during the night. PM_7 had time to completely settle under gravitational forces and PM_3 was substantially reduced. The measurements shown in Fig. 17 trace the number of coarse particles with time and clearly reflect the activities in nursery no. 1. For example, at 6.00 - 7.00 am the cleaner arrives, around 8.30 am the children arrive and equipment for play activities is set up - these activities and other movements throughout the day increase the coarse particulate load in the atmosphere. From 4.30 - 5.30 p.m. the children go home, after which time the particles begin to settle out. An understanding of the movement of particles could be used to decide when and how to ventilate a locality, especially one wholly dependent on natural ventilation.

The fluctuations in PM_3 concentration in the Plymouth nurseries occurred because there was no filtration of fine particles entering the localities. The change in PM_3 concentration shown in Fig. 17 would therefore reflect the variations over a 24-hour period caused by outdoor activities, wind movement and changing traffic intensity. This strong relationship between fine particles indoors and the change in fine particle concentrations outdoors has been previously shown (COMEAP, 1995). The characteristics of fine particle concentrations are shown in Fig. 18, where the diurnal variations are clearly shown. There is a decline in numbers during the night indicating the importance of the effect of traffic volume on fine particle numbers in the nurseries.

Thus, it is feasible to improve the poor IAQ in the two Plymouth nurseries monitored either through the installation of:

1) Simple EAC equipment assisted by slow moving ceiling mounted fans, OR

2) Commercially available air cleaners supplemented by EAC equipment to reduce the fine particulate matter. This option has been demonstrated in a study of a city centre office (*Paper no. 7 & 8*).

These studies show that the EAC system needs to be able to cope with a wide range of particle concentrations. The EAC system needs to consistently be able to cope with high concentrations of fine particles entering the locality and coarse particles constantly generated inside. The position of the dirt collector plates is important in order to avoid unsightly accumulation and frequent redecoration (see *Paper no. 1*).

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2.4. Torbay Healthy Housing Project - Defining the Requirement for Good Indoor Air Quality (IAQ) in Private Dwellings

2.4.1. Introduction

A study was initiated to investigate the IAQ in 116 local government owned houses in Torbay (UK). A 'randomised to waiting list' controlled study was devised in collaboration with the South and West Devon Health Authority (recording medically reported, as well as self reported, illnesses in the population) and a team of environmental scientists (looking for possible relationships between medical conditions and indoor air pollutants). This was seen as a unique opportunity to collect suitable data in order to aid in the development of EAC technology, suitable for home use. The environmental assessment included the recording of 34 parameters in three locations for 116 houses (see Table 12). A mean value was taken for each location from triplicate measurements for relative humidity, temperature, particle numbers, wall & wall surface dampness and small air ions. Singular samples were taken of house dust mite allergen, mould and gas.

Main parameters	Units	Outdoors	Living room	Selected Bedroom
Relative Humidity	%	✓	✓	✓
Temperature	^{0}C	✓	✓	✓
PM_7 & PM_3	no. l^{-1} of air	✓	✓	✓
Wall/ wall surface dampness	WME %			✓
CO, CO_2, VOC, NO_x	ppm/ppb	✓	✓	
House Dust Mite allergen Der p 1	μg & μg g^{-1} dust			✓
Small -/+ charged air ions	no. cm^{-3} of air	✓	✓	
Mould counts	no. $slide^{-1}$			✓
Wind speed and direction	m sec^{-1}	✓		

TABLE 12 PARAMETERS AND RELEVANT UNITS MEASURED IN EACH HOUSE

The enclosed papers presented at the South West Association of University Departments of General Practice conference March 2000 (*Paper no. 4*) and the 21st AIVC conference September 2000 (*Paper no. 5*) describe the study. The material presented in *Paper no. 4* gave a basic description of the overall study design. Some preliminary results from the first year of the study were presented, including the average values for the parameters measured (shown in Table 13 & 14). The results indicated that the concentrations of fine and coarse particles were higher indoors than outdoors. The results showed that mould and house dust mites (*Dermatophagoides pteronyssinus*) were present in the majority of samples taken.

The study is explained further in *Paper no. 5*, which details the methodology, equipment and reasons for choosing the parameters measured. Basic summary statistics were presented. Comparisons were made between the outdoor and indoor concentrations for each parameter. The analysis of fine particles shows that in Torbay, in households with smokers there was a major difference in fine particle numbers when compared to non-smoking households. Coarse particle numbers were mainly affected by the number of people living in the house. Coarse particle numbers were on average greater in the living room than in the selected bedroom.

2.4.2. Further Statistical Development of the Torbay Results

A more detailed statistical analysis of the results from year one was conducted to assess relationships between the environmental parameters. The characterisation of the parameters has been investigated using distribution analysis. Table 13 & 14 present basic statistical summaries for the main environmental parameters measured in the houses.

TABLE 13 BASIC SUMMARY STATISTICS FOR THE TORBAY STUDY

Parameter	Number	Average*	Range	Standard deviation	Distribution	Correlations with:
PM_3 Outdoors (no./l of air)	116	88988.2	7769 - 495565	109404	non-normal (positive skew) 1.869[a] 0.002[b]	
PM_3 in Living room (LR) (no./l of air)	116	238543.8	16475 - 450612	135584.5	normal 1.237[a] 0.094[b]	PM_3 outdoors = 0.341[c], 0.000[d] PM_3 in the SB = 0.896[c], 0.000[d] No. smokers/ house = 0.473[c], 0.000[d]
PM_3 in Selected bedroom (SB) (no./l of air)	115	218402.7	11121 - 449590	124767.5	normal 1.251[a] 0.087[b]	PM_3 outdoors = 0.382[c], 0.000[d] PM_3 in the LR = 0.896[c], 0.000[d] No. smokers/ house = 0.436[c], 0.000[d] Wall surface dampness = 0.297[c], 0.029[d]
PM_7 Outdoors (no./l of air)	116	73	9 - 810	97.32	non-normal (positive skew) 2.411[a] 0.000[b]	
PM_7 in LR (no./l of air)	116	299	86 - 1097	204.84	non-normal (positive skew) 1.694[a] 0.006[b]	PM_7 in the SB = 0.896[c], 0.000[d] No. people/ house = 0.302[c], 0.001[d]
PM_7 in SB (no./l of air)	115	186	59 - 1133	170.29	non-normal (positive skew) 1.880[a] 0.002[b]	PM_7 in the LR = 0.896c, 0.000d
Temperature °C Outdoors	116	10	3 - 15.5	2.49	non-normal (positive skew)** 1.634[a] 0.01[b]	
Temperature °C in LR	116	18	12 - 24	1.98	normal 1.320[a] 0.061[b]	Temp. outdoors = 0.236[c], 0.011[d] Temp. in the SB = 0.619[c], 0.000[d] RH LR= -0.203[c], 0.029[d]
Temperature °C in SB	116	16	11.5 - 21	1.94	non-normal (positive skew) 1.508[a] 0.021[b]	Temp. in the LR = 0.619[c], 0.000[d] RH SB = -0.307[c], 0.001[d]

[a] one sample Kolmogorov-Smirnov test statistic [b & d] P values (0.01 significance level) [c] Pearson correlation coefficient

*Average expressed as mean in groups with normal distribution and median in groups with a non-normal distribution

**Although statistic results in a non-normal distribution the histogram revealed a normal distribution

TABLE 14 BASIC SUMMARY STATISTICS FOR THE TORBAY STUDY

Parameter	Number	*Average	Range	Standard deviation	Distribution	Correlations with:
Relative humidity % Outdoors	116	62.22	32 - 86.5	11.63	normal 1.125^a 0.159^b	
Relative humidity % in LR	116	51.27	34 - 78	9.16	normal 1.589^a 0.879^b	Temp. in the LR = -0.205^c, 0.029^d RH SB = 0.727^c, 0.000^d Temp. outdoors = 0.414^c, 0.000^d PM_7 outdoors = 0.295^c, 0.001^d PM_3 outdoors = 0.195^c, 0.035^d HDM 1 = 0.218^c, 0.028^d
Relative humidity % in SB	116	56.01	37 - 78	8.93	normal 0.993^a 0.278^b	Temp.SB = -0.307^c, 0.001^d RH LR = 0.5297^c, 0.000^d Temp. outdoors = 0.462^c, 0.000^d RH outdoors = 0.727^c, 0.000^d Wall surface dampness = 0.340^c, 0.011^d HDM 1 = 0.234^c, 0.019^d
1 House dust mite allergen Der p1 μg/g of dust	101	2.72	0.06 - 8	1.63	normal 0.994^a 0.276^b	RH LR = 0.218^c, 0.028^d RH SB = 0.234^c, 0.019^d Temp. outdoors = 0.226^c, 0.023^d HDM 2 = 0.811^c, 0.000^d
2 House dust mite allergen Total Der p1 μg	101	0.1703	0 - 0.72	0.158	non-normal (positive skew) 1.695^a 0.006^b	No. of all pets/ house = 0.249^c, 0.013^d No. big pets/ house = 0.245^c, 0.013^d HDM 2 = 0.811^c, 0.000^d
Mould count in SB (no./ slide)	116	12.39	0 - > 50	14.33	non-normal (positive skew) 2.811^a 0.000^b	PM_7 outdoors = 0.304^c, 0.001^d Wall surface dampness = 0.361^c, 0.007^d

^{a} one sample Kolmogorov-Smirnov test statistic $^{b\,\&\,d}$ P values (0.01 significance level) ^{c} Pearson correlation coefficient
*Average expressed as mean in groups with normal distribution and median in groups with a non-normal distribution
**Although statistic results in a non-normal distribution the histogram revealed a normal distribution

The various parameters studied were subjected to statistical analysis in order to investigate interrelationships between them, following a test for normal distribution. Correlation and regression analysis was conducted to assess any relationships between individual parameters.

Tobacco smoke is known to have a major influence on fine particle concentrations in indoor air. Hence, the data for PM_3 was split into separate groups to demonstrate how average values change with or without smokers (Table 15). To test the strength of the correlations shown in Table 13 & 14, a backward regression analysis was performed (Table 16). The backward method of selection of the independent variable enters all of the independents in a given block in a single step and then removes them one by one based on specific removal criteria. Once again, the strong influence of smoking on fine particle concentration was demonstrated. Other interesting links are shown between wall surface dampness, coarse particles outdoors and mould; house dust mite allergen and humidity and there was an inverse relationship between temperature and humidity.

	Smokers (n = 84)	**Non-Smokers (n = 32)**	**Significant difference (Students t-test)**
Living room	277 624 (± 121 452)	134 818 (±121 124)	$P < 0.05$
Selected Bedroom	252 799 (± 109 832)	127 392 (± 117 200)	$P < 0.05$

TABLE 15 COMPARISONS OF THE AVERAGE FINE PARTICLE CONCENTRATIONS IN HOUSES WITH OR WITHOUT SMOKERS

Dependent variable (Refer to Table 13 & 14 for the numbers of samples recorded for each dependent	R^2	Constant	Predictors	Coefficient	Standard error	P =
PM_3 Living room	0.807	17603.35	PM_3 Selected bedroom	0.934	0.051	0.000
			No. smokers/ house	14787.126	6954.535	0.036
PM_3 Selected bedroom	0.805	18765.9	PM_3 Living room	0.789	0.041	0.000
PM_7 Living room	0.172	143.21	PM_7 Selected bedroom	0.349	0.104	0.001
			No. people/ house	30.177	9.846	0.003
PM_7 Selected bedroom	0.102	140.489	PM_7 Living room	0.265	0.074	0.001
RH Living room	0.651	16.441	RH Selected bedroom	0.518	0.078	0.000
			RH Outdoors	0.18	0.053	0.001
			Temp. Living room	-0.686	0.285	0.018
			Temp Outdoors	0.508	0.249	0.044
			PM_7 Outdoors	0.023	0.005	0.000
RH Selected bedroom	0.741	29.517	RH Outdoors	0.159	0.051	0.002
			RH Living room	0.574	0.071	0.000
			Temp. Outdoors	0.864	0.229	0.000
			Temp. Selected bedroom	-1.323	0.257	0.000
Temp. Living room	0.497	10.064	RH Living room	-0.0571	0.016	0.001
			Temp. Outdoors	0.218	0.06	0.000
			Temp. Selected bedroom	0.571	0.07	0.000
			PM_3 Outdoors	0.026	0.04	0.038
Temp. Selected bedroom	0.428	8.525	RH Selected bedroom	-0.047	0.016	0.003
			Temp. Living room	0.571	0.07	0.000
Mould Selected bedroom	0.202	4.96	PM_7 Outdoors	0.03	0.015	0.037
			Wall surface dampness	0.677	0.258	0.011
House Dust Mites (HDM1) $\mu g\ g^{-1}$	0.656	0.324	HDM2	8.37	0.584	0.000
House Dust Mites (HDM2)Total μg	0.678	-0.055	No. of Pets/ house	0.0107	0.005	0.026
			HDM 1	0.076	0.006	0.000

TABLE 16 RESULTS FROM BACKWARD REGRESSION ANALYSIS PERFORMED ON THE TORBAY DATA

2.4.3. How do these Results Relate to the EAC system?

Based on the first year of investigation of the 116 households in Torbay, it is quite clear that an installed EAC system must be able to operate within the following environmental conditions.

- Temperature range of 11 - 24 °C
- Relative humidity range of 34 - 78 %

Personal observations made during the study would suggest that people would spare little time to maintain an air cleaning system. Therefore, the system must be able to:

- Collect and safely 'store' coarse particles for a minimum of 180 days*
- Collect and safely 'store' fine particles for a minimum of 180 days*

* This time is just an estimate of how long before a system would need to be cleaned or need replacement parts before the equipment becomes aesthetically displeasing through soiling.

The first year's database was robust enough to identify differences between individual houses and to assess links between certain parameters. In theory, if the primary requirements listed above can be accommodated by the EAC system then predictions could be made as to an expected air cleaning effect for the houses. Previous work has shown that in a school environment, fine and coarse particulate matter can be dramatically reduced (see *Paper no. 1*). Although schools are very different environments from homes and have substantially larger volumes and more people, the EAC system should still be able to substantially reduce particle concentrations in the houses.

The following predictions were made for the air cleaning effect that could be expected if the EAC system was installed in the living room of one of the Torbay houses, based on the results from this section and the experiments conducted in the Swedish day care centres (*Papers 1-3*).

- A 60 - 80 % reduction in the average number of continuously generated fine particles in the living room
- A 40 - 50 % reduction in the average number of continuously generated coarse particles in the living room
- A continuous reduction of fine particles in the bedrooms. This is due to the strong correlation between PM_3 in the living room and bedroom

These predictions will be tested after the completion of the current three-year study in Torbay. The systems cannot be installed before then, as they would interfere with possible improvements brought about by the renovations to the properties during years 2 and 3 of the study, since an evaluation of the housing improvements is a substantial component of the research project with the Health Authority.

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2.5. The Design and Development of an In Line Multi functional Gas Cell for a FT-IR Spectrometer

2.5.1. Background

The physical mechanism of particle reduction in an electrostatic field is outlined in 1.4 and 1.5 and is clearly understood. The chemical reactions that may take place in an atmosphere within an electrostatic field are not completely understood. There is very little reported research in the scientific literature about the possible chemical reactions initiated by the ionisation of indoor air and there is no information on this subject available to the public when purchasing indoor air cleaners. Pethig (1984) described some of the chemical reactions that are thought to take place when electrons, having sufficient energy, are released into the atmosphere. A number of studies have associated ion generation with the production of superoxide, which reacts with atmospheric components to produce chemicals such as hydrogen peroxide (Goldstein et al., 1992; Challenger et al., 1996). Prior to Goldstein's studies, Kerr et al., 1982 had carried out 'smog chamber' experiments to determine the chemical compounds produced in typical London air/smoke/fog mixtures. This was performed in a closed gas cell subjected to irradiation with ultra violet light. Kerr postulated that hydrogen peroxide was formed but did not indicate the concentrations produced.

It is not easy to study electron chemistry in a normal atmosphere in real time. It was clearly important to discover the range of electrostatic field strengths that would be available for the EAC system and to ascertain that the field strength chosen would be safe for general use. To aid in the development of the EAC system, any chemical reactions that might occur in an electrostatic field needed to be studied, especially the nature and concentrations of ions being produced. A method was required for a real time, on-line study of indoor atmospheric chemistry in conjunction with suitable instrumentation to determine any chemical reaction mechanisms created by the EAC system.

A previous experiment assessing the amount of hydrogen peroxide (H_2O_2) produced in an air-water interface by an EAC system had successfully quantified H_2O_2 production at 24 – 54 ppb, using chemiluminescence (Challenger et al., 1996). However, this method did not allow real time measurements of all the components involved such as changes in the concentrations of other chemicals in the atmosphere e.g. carbon dioxide. Reliable instrumentation and methodologies were needed that could detect environmental concentrations of different gases in different atmospheres. One of the most effective and accurate instruments for gas analysis is a Fourier Transform Infra Red Spectrometer (FT-IR), which can detect any chemical species giving rise to an infra red absorption spectrum. The spectrometer used for these experiments was a Bruker IFS 66 FT-IR spectrometer, which works on a non-dispersive principle. Within the FT-IR, the infra red (IR) beam is split into two pathways in a Michelson Interferometer containing a Kevlar beam splitter. One part of the incident beam undergoes reflection followed by refraction, the other refraction followed by reflection. This creates a path length difference in the two parts of the incident beam, which may be recombined to give a specific wavelength of IR light, dependent upon the position of a computer controlled moving mirror. This recombined beam is directed through the sample compartment of the FT-IR and onto the IR detector (Fig. 20). The absorbance of a particular wavelength of IR light is characteristic of a vibration mode of a molecule placed in the IR beam. The entire mid IR range can be scanned (typically 400 to 4000 wavenumber cm^{-1}) and an infra red spectrum created which is characterised by the molecular bonding in the sample. The IR spectrum of a chemical compound is unique and essentially is a "fingerprint" of the chemical's molecular structure (Cross & Jones, 1969).

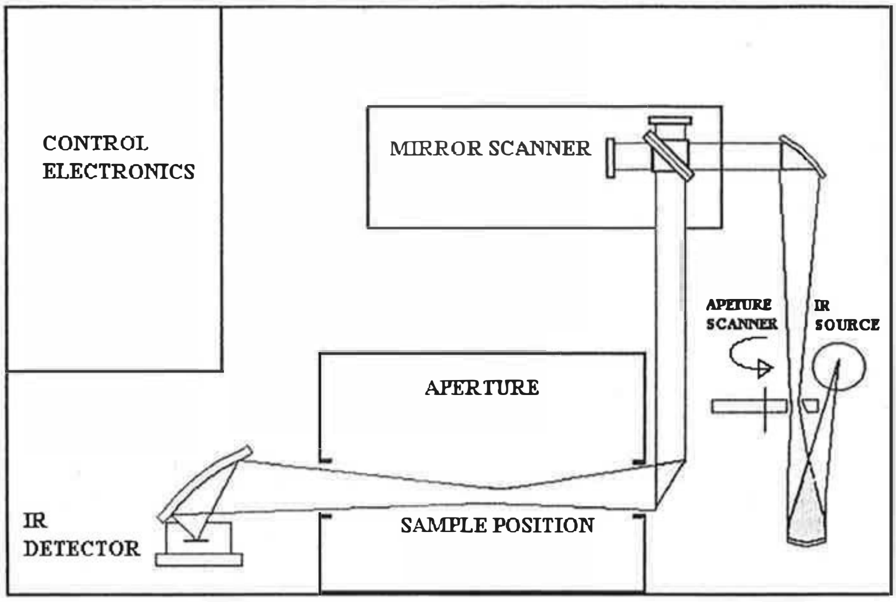

FIG. 20 SCHEMATIC DIAGRAM OF THE INFRA RED BEAM AND INTERNAL COMPONENTS OF A FT-IR SPECTROMETER. (NOT TO SCALE)

The Bruker FT-IR already has some accessories that allow in line (in compartment) analysis of gas phase chemical reactions. These accessories can have path lengths of up to 10 metres, created by the use of multiple reflections. These types of gas cells are capable of detection and analysis of very low levels of compounds down to ppb (parts per billion). However, these gas cells do not allow the exposure of the sample to electron bombardment, whilst the sample is within the cell. This is because the ports are designed purely with the idea of input and output of gaseous samples in mind. A more versatile gas cell was required that had a number of ports to allow the insertion of carbon fibres (attached to an EHT generator) as well as a flow through of gases. The facility to operate at varying humidity and the ability to operate concurrently with other instrumentation was also required.

To overcome these difficulties a multi-functional gas cell was designed and built for the Bruker IFS 66 FT-IR spectrometer which would allow in line, real time experiments using the extra high voltage generation of electrons. The gas cell referred to as an Enlarged Interactive Gas Phase Reactor (EIGPR) was built to allow it to fit in the sample compartment of the FT-IR. This allowed the IR beam to pass through the EIGPR unhindered (Fig. 21). A description of the dimensions of the EIGPR is given in Table 17.

Characteristic	Specification	
Height	Total height 260 mm	Internal 188 mm
Width	Total width 250 mm	Internal 238 mm
Depth	Total depth 210 mm	Internal 198 mm
Volume	8859.3 cm	
Path length	238 mm	
Windows	50 mm diameter (KBr)	
Ports	2 x 6 mm diameter sealable ports in the lid; 2 x 12 mm diameter stop cocks; facilities to add further ports when required	
Materials	Non-reactive walls bonded together with glue that does react with a sample within the cell.	

TABLE 17 SPECIFICATIONS FOR THE EIGPR

The specifications and numbered components listed 1 – 13 below follow those presented in a pending UK Patent application (Patent application number 0031669.5). Fig. 22 shows the detailed specification of the EIGPR.

1 FT-IR spectrometer
2 Inlet port
3 Outlet port
4 Fixing port
5 Light transmissive windows
6 Main vessel
7 Carbon fibre port
8 Lid
9 Blanking plates
10 FT-IR aperture
11 Carbon fibre thread
12 EAC system
13 Ports for light transmissive windows

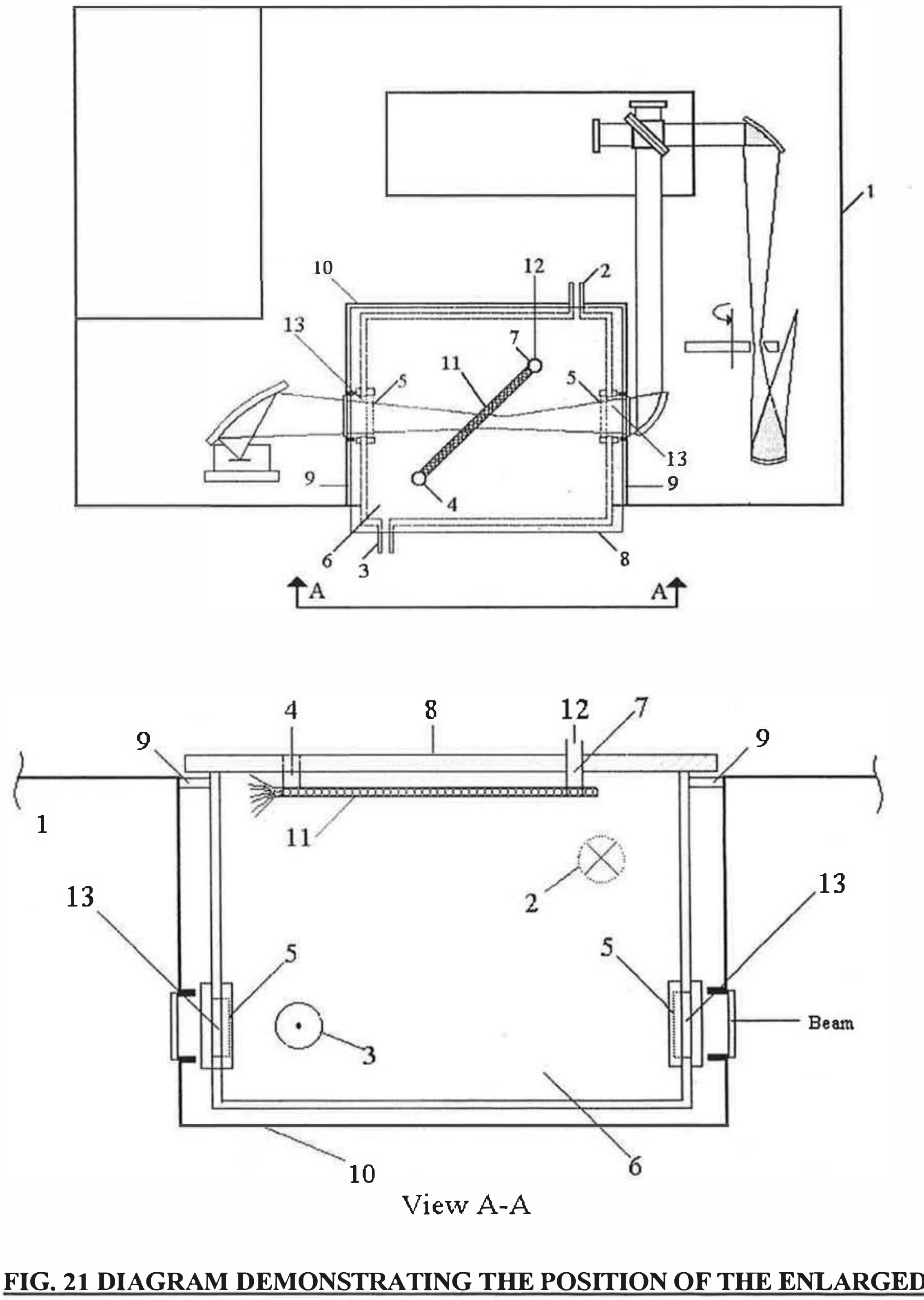

FIG. 21 DIAGRAM DEMONSTRATING THE POSITION OF THE ENLARGED INTERACTIVE GAS PHASE REACTOR IN RELATION TO A SPECTROMETER (NOT TO SCALE)

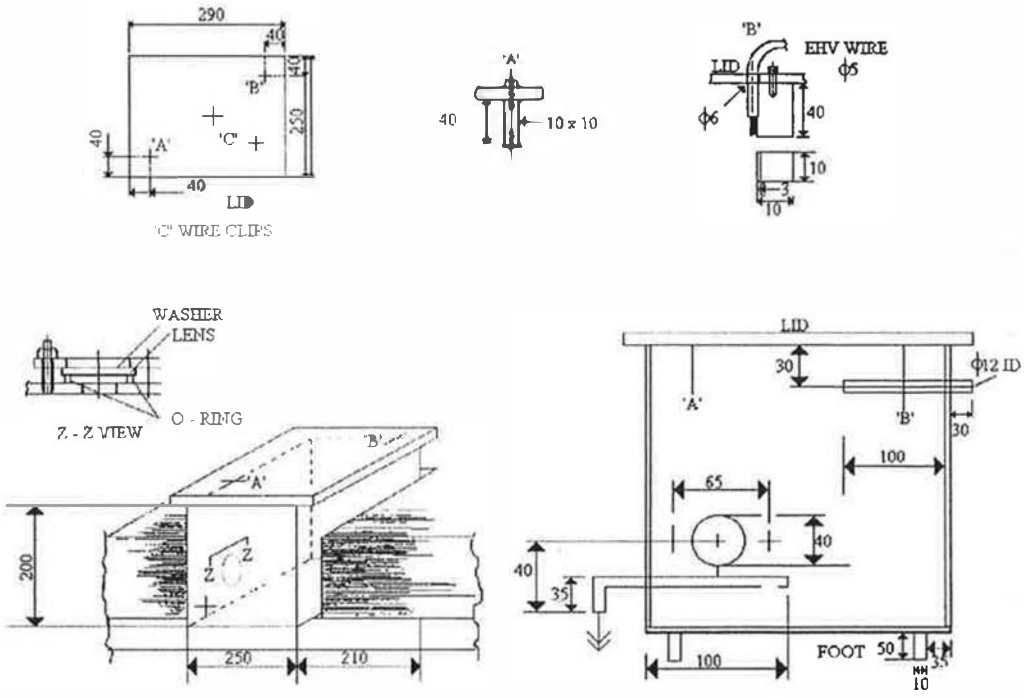

FIG. 22 DETAILED SPECIFICATION OF THE EIGPR. ALL MEASUREMENTS IN mm. (NOT TO SCALE)

The ports of the EIGPR were designed to allow a continuous flow through of air or other gaseous sample, as required. Two additional ports allowed the insertion of a carbon fibre thread connected to an EHT generator and or the insertion of probes for additional monitoring equipment such as air ion analysers or relative humidity and temperature monitors. In order to use the EHT generator with the EIGPR it was necessary to earth the reactor to a high quality earth via substantial resistors to limit any current flow to a minimum. This prevented uncontrollable electric/ electrostatic disturbances of the equipment. The EIGPR was used to study electron induced chemical reactions in different gas mixtures at various voltages. The following section describes the assessment of ion production and H_2O_2 production at different voltages and different relative humidity levels.

2.5.2. Analysis of Electron Induced Chemical Reactions Caused by the Production of Negative Ions

In section 1.4, the generation of electrons in ordinary air (RH ~ 50 %) resulting in the generation of superoxide was discussed. Superoxide rapidly forms chemicals such as hydrogen peroxide when it reacts with water in the atmosphere. Hydrogen peroxide formed in ordinary air by this reaction has been shown to have bactericidal effects. The amount of H_2O_2 produced through the release of electrons near an air/ water interface, using an EHT generator has been investigated previously by Challenger et al. (1996). However, the methodology used for the experiments had to be modified in order to study the production of H_2O_2 in a normal atmosphere (i.e. with a typical relative humidity). A detailed study was conducted to quantify the production of H_2O_2 in indoor air for varying levels of relative humidity, as described in *Paper no. 6.*

The study described in *Paper no.* 6 demonstrated how the EIGPR functioned as a fully interactive accessory to a FT-IR spectrometer. The EIGPR allowed concurrent measurements of ion production, H_2O_2 production, changes in other gases present and the measurement of relative humidity and temperature. The EIGPR could also have allowed these measurements to be made for different atmospheric conditions. The air inside the cell was manipulated to simulate different atmospheric humidity levels in real time.

The study showed that 0.44 ppb of H_2O_2 was produced when the relative humidity was at 47%. In an atmosphere with very high RH ~ 96 % this was increased to 945 ppb. The EIGPR made it possible to link voltage to ion production and ion production to H_2O_2 production.

Although H_2O_2 is produced in human cells as a primary defence mechanism, there are concerns about possible adverse health effects in humans brought about by exposure to H_2O_2. Humans have an anti-oxidant defence system. The products of the reduction of superoxide in human cells are O_2 and H_2O_2. A separate anti-oxidant will then change H_2O_2 to O_2 or H_2O. The detoxification process of oxygen free radicals is described in more detail in *Paper no. 6*. It is interesting to note that H_2O_2 is produced in humans at the levels shown in Table 18. These concentrations are substantially higher than the concentration produced by the EHT generator, therefore the levels produced by the system are thought not to be detrimental to human health. This is further confirmed by the fact that the system produces concentrations below the HSE's recommended occupational exposure limit of 1 ppm (HSE, personal communication, 2000).

Body fluid	Approximate concentration
Male urine (Hyslop et al., 1995) Female urine (Hyslop et al., 1995)	106 μM 88 μM
Eye humors (Hyslop et al., 1995)	59 μM (aqueous), 29 μM (vitreous)
Saliva (Sznajder et al., 1989)	18 μM
Exhaled breath (Sznajder et al., 1989)	Undetectable

TABLE 18 EXAMPLES OF HYDROGEN PEROXIDE CONCENTRATIONS PRODUCED BY THE HUMAN BODY

The counter argument to the idea that the concentrations are too low to produce adverse health effects would be that they are also too low to have any effect on microbes exposed to the H_2O_2 produced during negative ion generation. Goldstein et al., (1992) states that $O_2^{\cdot-}$ (superoxide) is produced naturally by gas ionisation in the atmosphere at concentrations of one $O_2^{\cdot-}$ ion for every $10^{15} - 10^{16}$ non-ionised molecule. Despite this, low concentrations of $O_2^{-\cdot}$ and its associated products still have biological activity. This would suggest that the low concentrations produced by the EAC system could have a significant bactericidal activity, reducing the numbers of microbes present in an atmosphere. Further, because of the highly oxidising properties of superoxide, there might be a possibility of viricidal activity as well. The assessment of the electron chemistry that occurs whilst the EAC system (EAC system) is in use, is now more clearly understood.

The experiments using the EIGPR have allowed the determination of:

- The amount of H_2O_2 produced in normal, dry and wet air by the EAC system at different voltages.
- The number of negative air ions produced in normal, dry and wet air by the EAC system at different voltages.
- The kinetics of ion production in relation to H_2O_2 concentrations produced by the negative ionisation of indoor air, are now better understood.

The experiment also demonstrated that the EAC system has the capability of producing sufficient concentrations of ions to reduce the particulate load in the EIGPR and still produce superoxide.

2.5.3. Suggestions for Further Experiments with the EIGPR

- Investigation of other gas phase reactions linked with the mass release of electrons.
- Investigation of the chemistry of atmospheric gases at various temperatures with various concentrations of negatively charged small air ions.

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SECTION 3. THE APPLICATION OF THE EAC SYSTEM

3. The Application of the EAC system in a Modern Urban Office

3.1. Background

Concerns were raised by Plymouth city council (UK), about one of their own administrative centres. The eight people employed there had made several complaints about the air quality of the office and had linked it to their own state of health. The managers of the office were interested in installing air cleaning equipment that could improve IAQ and therefore allowed a study to be conducted as described in *Paper no. 7 & 8.*

3.2. How can the study of the City Centre Office aid the Development of the EAC system?

Previous experiments based on testing the basic concepts of the EAC system have been directed at the development of the system to assess its capacity to generate negative ions, reduce airborne particles or to assess the production of anti-microbial chemicals. Emphasis has also been placed on understanding the requirement for good IAQ in private dwellings and children's nurseries. Following the development research, a study was needed that actually applied the EAC system to a real situation.

During an initial assessment of the city office as described in *Paper no. 8,* it was decided that the EAC system would have the greatest impact on the reduction of fine particle numbers in the office. Preliminary measurements showed very low concentrations of coarse particulates and no presence of visible moulds. Therefore, mould levels were not tested for in the experiment.

3.3. Results and Discussion

The study of the Plymouth office confirmed the air cleaning capacity of the EAC system, showing that even in a room where 20% of fine particles and 67% of coarse particles had already been removed from the incoming/ recycled air, there was still a further reduction with the introduction of the EAC system. When an EAC system was installed in the office, the fine particles were reduced by a further 21 % and coarse particles by a further 3 %.

An important result of the study is that the mechanism of particle removal in such a room is more greatly understood. The fact that the air cleaning capacity of the system did not increase with an increase in negative ion production (see details in *Paper no. 6*), suggests that it was the forces within the electrostatic field that removed the particles. The particles would have been directed towards the negative emitter or towards positive surfaces depending on their charge. This information is important as decisions can be made to keep the number of negative ions to a minimum. This will avoid concerns about health risks associated with breathing negatively charged fine and ultra fine particles but still produce an air cleaning effect.

The study emphasised the fact that the system needs a specific positively charged collection surface near to the emitter (directing the electrostatic field) to stop erratic movement of negative ions within the room and to prevent soiling of other positively charged surfaces in the room, such as filing cabinets and desks. It was difficult to assess the extent of soiling because of the regular cleaning of the office and the relatively short period of the trials.

The reductions in the number of fine particles shown in this study were not as dramatic as those shown in *Paper no. 1*, however there were a number of technical differences between the studies. The experiment conducted in the Swedish day care centre relied on a version of the EAC system that had very simple emitters suspended either side of an air supply duct, forcing air through an electrostatic field. All the internal surfaces of the Swedish site acted as earthed collection surfaces. In the Plymouth office, free standing air moving systems were used in addition to the air movement provided by the existing outdoor air supply. If the equipment in the office had been arranged in a similar fashion to that in the day care centre, larger reductions in particles may have been shown.

Although there were only a small number of employees (n = 8), the MM-Questionnaire (developed by Andersson et al., 1993) indicated that the employees perceived an improvement in the IAQ, only after the selective removal of fine particles in the office. There were also reductions in complaints about dry air, dust and dirt, consistent with the fine particulate reduction in the office. The link between fine particles and respiratory problems was further confirmed by the fact that complaints about respiratory irritation decreased after the installation of the system (see Table 19). Despite the fact that the existing air moving system had substantially reduced the number of coarse particles these complaints had persisted, suggesting a stronger link between the complaints and fine particles than with coarse particles. It is difficult to make firm conclusions about the change in perception of IAQ because of the small number of people studied.

Symptoms (yes, often) %	Stage 1 No EAC system	Stage 2 With EAC system
Av. No. of fine particles litre^{-1} of air	**77 000**	**42 500**
Av. No. of coarse particles litre^{-1} of air	**34**	**29**
Fatigue	15	15
Feeling heavy headed	48	35
Headache	50	25
Nausea/ dizziness	0	0
Difficulties concentrating	2	2
Itching, burning or irritation of the eyes	0	0
Irritated, stuffy or runny nose	15	0
Hoarse, dry throat	15	0
Cough	0	0
Dry flushed facial skin	0	0
Scaling/ itching scalp or ears	0	0
Hands dry, itching red skin	0	0
Other	0	0

TABLE 19 RESULTS FROM THE QUESTIONNAIRE CONDUCTED IN A CITY CENTRE OFFICE ASSESSING COMMON SYMPTOMS

The results from the symptom part of the questionnaire also showed that the employees did not report dry skin, scaly scalp or other skin irritations after the installation of the EAC system. Symptoms such as irritation of the eyes, mucous membranes and skin are linked to exposure to hydrogen peroxide (Proctor et al., 1988). This would suggest that any hydrogen peroxide produced by the system did not adversely affect the employees. This is only an indication and would need a full medical study to confirm that there are no adverse health effects. It can be assumed that the technology would be able to provide reductions for fine particles (21%) in similar offices, since future applications of the EAC system will use similar components to those used in this study.

The beneficial effects that have been confirmed by this study are:

- A reduction in both fine and coarse particles. The reduction in the fine particle fraction was clearly of significance, since the locality already had low indoor values for the coarse particle fraction.
- An improvement in IAQ as perceived by regular users of the room.

3.4. Recommendations for the Further Development of the EAC system

From this study and research discussed in previous sections it is suggested that:

- The system is installed with an associated earthed collector plate, where the collector plate should have a replaceable/ cleanable surface from which dirt could be removed. The plate needs to be easily maintained because it will become dirty, especially when the equipment is in use in inner city areas. A plate will set up a directional electrostatic field and will prevent random soiling of positively charged surfaces and prevent negative ions erratically entering the airspace of a room.
- The negative ion production needs to be regulated to suit individual environments.

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SECTION 4. FURTHER WORK

4. Suggestions For Further Work

It is not known if the Full EAC system will cause any electromagnetic disturbances generated by the established electrostatic field. These disturbances could affect computers, mobile phones or the health of people working near the system. Tests would have to be carried out by an approved laboratory such as British Standards Institution, Product Testing, for the Full EAC system to meet appropriate British Standards. In addition, there are currently no recommendations for the release of negative ions into a human environment (HSE, 2000, personal communication). However, as currently envisaged the Full EAC system is not thought to pose a health threat, as the production of hydrogen peroxide is under the HSE limit of 1 ppm and the release of negative ions is within a restricted area.

The collector plates might not be aesthetically acceptable as envisaged. A source of disposable paper, able to transmit an electrical signal, has been identified that will cover the collector plates enabling the paper to assume a positive charge. This will facilitate the simple replacement or regular exchange of collection surface. However, no experiments have been carried out in a live environment using the suggested paper to collect airborne particulates. Preliminary tests of this paper have been conducted but no quantitative results are available yet. The psychological effect of having a constant visible reminder of the amount of dirt being removed from an indoor environment also requires investigation. There will be positive and negative effects expected with the installation of a collector plate.

Capacity testing has not been carried out on the 'Full EAC system' (see Appendix 1), since no working model exists. Tests will be conducted with ion counters, and particle counters to establish the reduction of fine and coarse particles. Field strength meters will be able to establish the reach of any electrostatic field. Once measurements are taken, adjustments can be made to the units or more units could be added to obtain the desired improvement of IAQ. Nothing is known about how particles not accepting any electrostatic charge will fare in the system.

Full-scale experiments need to be conducted to find an optimum distance between the emitter and collector plate to collect the optimum number of particles and the largest reduction in activity of live micro-organisms.

From a human health point of view, it is necessary to investigate if raised levels of oxygen free radicals actually can reach the most sensitive parts of human lungs, possibly causing permanent damage. This could be investigated using pathological studies of exposed pigs for example, since porcine lungs are very similar in construction to their human counterparts. Existing models of human lungs designed to track how and where particles of different sizes are deposited, do not take into account particles carrying an electrostatic charge. Such models would therefore not be applicable in studying the transportation and deposition of particles from existing room air cleaners in the human lung. Possibly radioisotope labelling could be used to investigate whether there is a problem. Intuitively, fine negatively charged particles should become trapped in the moist upper respiratory tract as wet surfaces are positively charged. Fine positively charged particles might travel further into the deep lung.

Due to the fact that it is preferable not to generate ozone indoors, additional effort should be made to prevent the Full EAC system from producing ozone. An investigation could be carried out to determine whether different emitter materials would need to be used in different environmental conditions. For example in extremely cold environments, such as refrigerated rooms would the system still work with the materials outlined in Appendix 1.

Although this thesis has investigated the production of reactive oxygen species in indoor air through the generation of electrons. there needs to be further similar investigations of different gaseous reactions in electron-enriched air. These experiments can be conducted within the enlarged interactive gas phase reactor (EIGPR) purpose built for the research in this thesis. As well as looking at chemical reactions, the effect of the chemical species produced on the viability of micro-organisms should be investigated. Using equipment to produce electrons that in their turn produce oxygen free radicals offers a potentially good method of reducing the viability of live micro-organisms. Initially tests can be carried out in the EIGPR cell to determine the effect on the microbes without having to speciate them.

The investigation of chemical reactions in an electron-enriched atmosphere should also take into consideration any possible oxidation of volatile organic compounds (VOC). This would also include microbial VOC (MVOC). It is important to understand these reactions to be able to determine any deleterious or beneficial changes in the atmosphere brought about by installing the system.

APPENDIX 1

THE FULL EAC SYSTEM - PROPOSED UK PATENT APPLICATION FOR A WORKING MODEL

A1.1. Foreword

Dr. D J Harwood from the Department of Environmental Sciences at the University of Plymouth, England has assured the writer and single owner of the information in Appendix 1 that the initial circulation of this document is restricted and therefore will not violate the confidentiality required by the UK Patent Office. The UK Patent Office has previewed the concepts for 'the Full Electrostatic Air Cleaning (EAC) System' and has given a very favourable evaluation, indicating that at the time of their evaluation (June 2000) no hindrance existed for a full UK patent to be granted.

A1.2. Desirability of the Electrostatic Air Cleaner as a 'Full EAC System'

There is a documented need to provide clean indoor air in the personal micro-environment. It is generally accepted in the scientific community that, since we spend 80 - 90% of our time indoors, the indoor environment represents a major source of exposure to many airborne pollutants (Donaldson & Donaldson, 1993). Further, epidemiological studies have verified that particles can cause respiratory problems (COMEAP, 1995; Schwartz et al., 1996).

In urban areas, especially in large conurbations, the quality of available outdoor air can be compromised by pollution, making it very expensive to clean incoming air. In order to reduce energy costs, approximately 90% of air processed by HVAC equipment is re-circulated, largely polluted indoor air. People and their activities within a room generate particles (skin cells, dust etc.) and spread biologically active materials (allergic substances, infectious materials etc.) throughout the re-circulated air. Modern HVAC systems, which clean the re-circulated air at a central point, cannot react quickly, or forcefully enough to remove the fresh, continuously generated particles and pollutants within a building. Whilst it is always advisable to minimise air contamination at the source, it is obvious that without reducing the number of people in a building the generation of pollutants will not be reduced. The latest business trend to concentrate company operations in call centres, where desk bound staff are tightly packed into office type buildings is counter productive in terms of attempts to enhance IAQ using standard type HVAC systems. By the year 2002 there will be more than 500 000 people employed in such centres (Datamonitor, 1998). The number of possible air exchange rates per hour (ac h^{-1}) has to be limited in a locality to approximately 2 - 3 complete changes of air per hour, before causing problems with draft and noise from air movement. The International Standard ISO 7730 suggests a maximum velocity of air movement in an occupied zone of between 0.15 and 0.25 m s^{-1}, where the variations are seasonally related to time of year. People working in buildings with standard HVAC systems, are often subjected to poor air quality, despite the fact that HVAC systems are in continuous operation. Many studies have confirmed that it is difficult to ensure complete coverage and sufficient exchange of air in a room, no matter how the inlets and outlets for the HVAC forced air supply/ extraction are arranged (Riffat et al., 1997). In private dwellings, such considerations seldom arise and therefore the degree of indoor air contamination varies widely between rooms.

The subject of fine particulate reduction in indoor air is at the forefront of scientific research and great emphasis is placed on finding solutions to particulate pollution (COMEAP, 1995; IEH, 2000). For example, in 1999 the DETR released a Newsletter stipulating the need for more research into the effects of particulates on Human health (DETR, 1999). The Expert Panel on Air Quality Standards (EPAQS) has recently issued a Draft Document, stating their views on airborne particles (What is the appropriate measurement on which to base a standard? EPAQS, 2000). The document is clearly concerned about the health effects of fine particles and wishes to give good advice on how to quantify or characterise the fine particle fraction in indoor air.

A1.3. Description of the Theory behind the Full EAC system

A1.3.1. Background

Based on the results of the study of a Plymouth city centre office, there was evidence that the air cleaner could be developed further using all the investigations in this thesis, to provide a 'Full EAC system'. The ability to develop a comprehensive air cleaning system with the ability to reduce particles, especially those < 2.5 μm, is especially interesting since no other similar systems are available.

A1.3.2. Description of the Air Cleaning Mechanisms of the Full EAC System

A negative electrostatic field can be created between an electron emitter (which generates negatively charged oxygen molecules) and a positively charged surface. In the air space covered by the field, some ordinary atmospheric gases will be oxidised through gas phase reactions with charged oxygen molecules. It has been determined that oxidation does occur via a mechanism involving the addition of electrons (electron chemistry) in a controlled experiment using an enlarged interactive gas phase reactor (EIGPR). Further, the reactive oxygen species generated are known to slow down the growth of micro-organisms. Within the electrostatic field, both coarse and fine particles are removed through several mechanisms. Since most particles carry an electrical charge, they are attracted to either the negative or the positive pole depending on their charge. This physically removes particles from the air. When establishing an electrostatic field with a potential difference of ~ 7000 V between the two poles, positively charged particles are joined by electrons or negatively charged small air ions. This can result in particles acquiring a negative charge. Numerous experiments have established that the vast majority of positive particles within an electrostatic field attain a negative charge and are then collected on a positively charged collector plate (Pethig, 1984). It has been established that fine particles have important health implications for humans, but they have previously been difficult to remove from indoor air using standard filter technology. The collection of coarse particles near to their source is desirable to prevent the particles from ever reaching a HVAC system. Humans typically breath at a rate of 10 000 - 20 000 litres of air day^{-1}, depending on activity levels and therefore constantly inhale particles. Coarse particles > 2.5 μm are either exhaled quickly or become trapped in the upper respiratory tract. Fine particles < 2.5 μm enter the deep lung. Depending on their chemical composition and any surface adsorbed chemicals they may have toxic effects.

Within a generated negative electrostatic field the following actions occur:

- The creation of a directional flow of coarse and fine particles towards an earthed collector surface.
- The disruption of the metabolism of biologically active particles i.e. microbes.
- Chemical changes in gaseous compounds in the air.
- Particles consisting of live micro-organisms suspended in the air such as pollen, spores and bacteria (bioload) have a mass (Rylander, 1995) and will be affected by the directional forces in the electrostatic field.
- The positive polarity of walls and room furniture might be reduced, thereby reducing opposing forces between these objects and positively charged particles. Positively charged particles would be less likely to become airborne and therefore settle faster.

A1.3.3. Description of the Actual Components of the Full EAC System

The Full EAC system is based on adapting and complimenting the EAC system, with an installed collector plate to act as an earthed surface. The Full EAC system has been designed to operate safely within an office type environment. The hardware can be built onto a standard ceiling tile, which would normally form part of a false or suspended inner ceiling. This set up allows the hardware to be hidden and to be installed away from office staff. In Fig. 23, a basic sketch of the preliminary design of the prototype system is given.

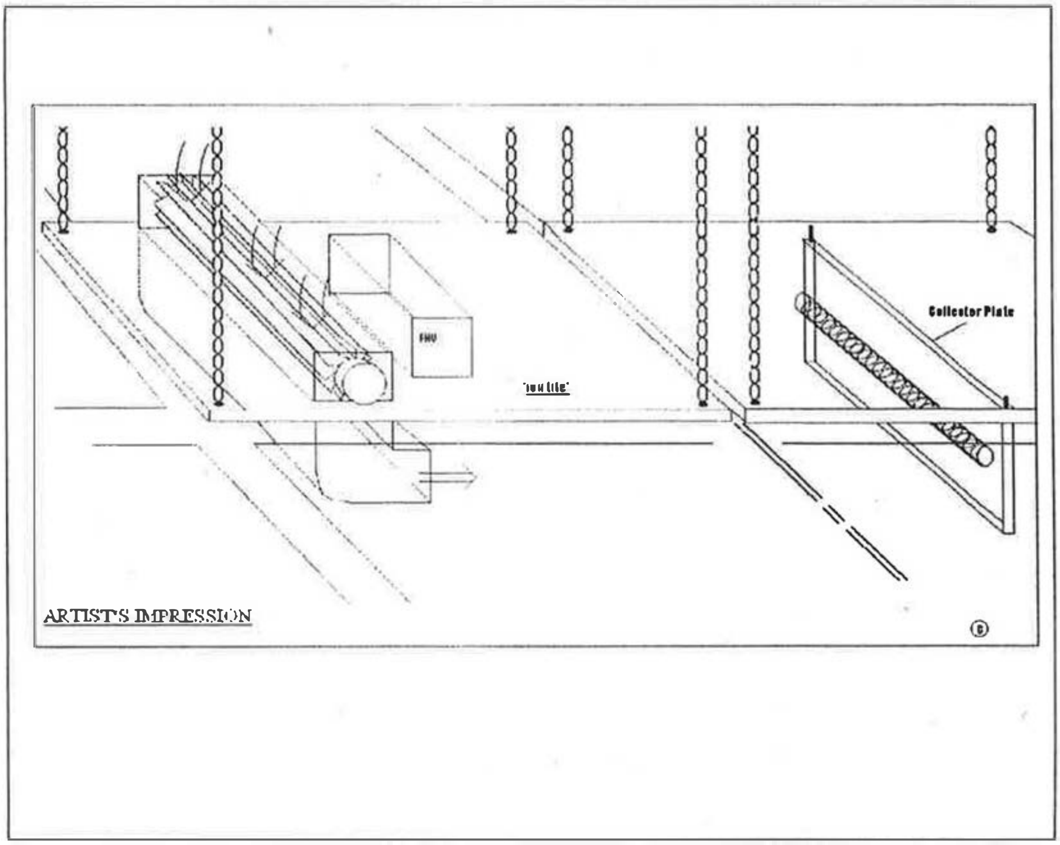

FIG. 23 SIMPLE DIAGRAM OF THE FULL EAC SYSTEM

The Full EAC system with its associated collector plate would ensure the following:

1) The collection of the majority of particles removed from the air onto the collector plate. This would reduce concerns in respect to the soiling of positively charged surfaces such as walls and cupboards.
2) Oxygen free radicals will not be erratically released into the micro-environment of the workers. The collector plate will set up a defined electrostatic field, which controls the direction of electrons and small air ions, keeping them away from occupants. This would also reduce concerns about possible adverse effects brought about by being exposed to a weak electrostatic field.

3) The spatial control of the generated electrostatic field will allow a large volume of air to be cleaned within a room, whilst people are present, without the need for the air to be drawn to a central processor before it is cleaned.

The emitter and collector plate need to be placed at an appropriate distance apart to be able to clean a substantial volume of air, whilst still maintaining a field between the opposite poles. Reducing the distance between the negative and positive poles increases the number of ions produced (Pethig, 1984). Fig. 24 shows that electron generation diminishes as the earthed collector is moved away from the emitter.

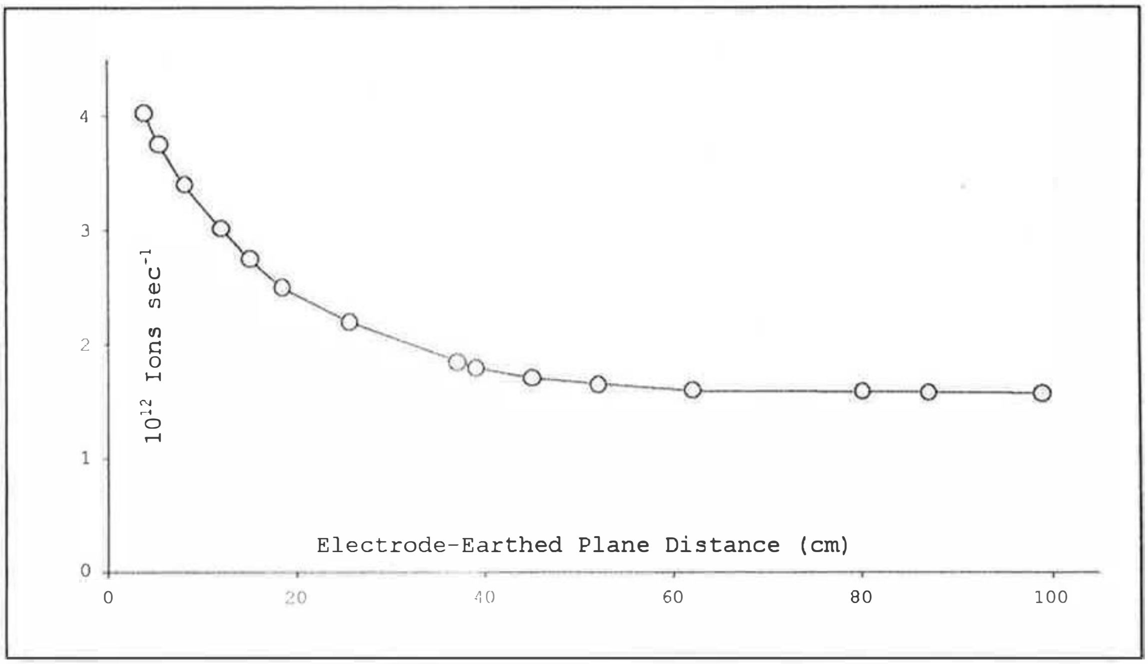

FIG. 24 THE GENERATION OF IONS AS A FUNCTION OF THE DISTANCE FROM AN EARTHED PLANE (FROM PETHIG, 1984)

The hardware of the Full EAC system consists of the components listed below:

The ceiling tile (the base): A standard sized ceiling 'tile' is used, which is made out of light weight material, that can be laid into a false ceiling tile grid without further fixing.

The air moving equipment: Mounted on the topside of the ceiling tile, out of sight, is a slow rotating, wide, cross flow type fan. The fan moves heated, dirt-laden air originating from the locality from above the false ceiling, back into the locality, directed through the emitter at the collector plate. This would therefore, create a 'virtual volume' within the locality, through which dirt-laden air passes and loses its particulate load. Power consumption would be around 60 W. The fan could also take air directly from the locality treating it in the same way.

The air cleaning equipment: Mounted adjacent to the cross flow fan on the upside of the ceiling tile, is an extra high negative voltage (EHT) generator (generating 6000 - 7500 V). This is connected to an emitter consisting of a length of carbon fibre thread, positioned in the outgoing air stream of the fan. On the underside (room side) of the Full EAC system, specially charged diffuser bars direct the air into the 'virtual space'.

The Collector plate: There are two viable options at present for the collector plate:

a) A sheet of metal that is permanently earthed and surrounded by insulating material. This sheet is covered with electrically conducting paper. Particulates collect on the paper, which can be easily renewed.

b) An earthed vertical steel pole that collects particulate matter, which is then wiped clean.

Whilst the components described here are not new, the arrangement and application of the components is unique. The new approach allows the cleaning of the indoor air within a room whilst people are present, carefully controlling both residual dirt collection and deposition of generated residual oxygen free radicals. No filter material is used.

Preliminary calculations indicate that the Full EAC system will be able to:

- Process 100 - 150m^3 of air h^{-1}, which is equivalent to one air exchange $hour^{-1}$ for a room 30 m^2.
- Produce in access of 10^{12} electrons $second^{-1}$ (Pethig, 1984), into an air stream directed to a particulate collection plate.
- Produce field strengths of ≅ -15 kV one metre from the electron emitter, creating an electrostatic field covering a volume of at least 1 m^3.

A1.4. How does the Full EAC System differ from Conventional Systems?

The concept of the Full EAC system is a significant step forward in the indoor air cleaning industry. Although other companies have produced electrostatic air cleaning systems they are normally mounted in a central air-processing unit, far removed from each locality. Small, stand-alone units are not permanent solutions for the urban environment and therefore will not be discussed herein. Extensive patent and literature searches have not revealed any research into producing a filter-less indoor air cleaning system, which will set up an electrostatic field within a room to capture airborne particles.

The limitations of existing systems are described below:

- Standard HVAC systems use filters, (classification F 5, British Standard 6540 part 1), that filter particles > 5μm (source Camfil Ltd., Lancashire, England, July 2000, a large British manufacturer of filters for HVAC systems). There are substantial limitations when using these systems, since they can only re-circulate air at a limited rate before draft and noise problems set in. Filters with a higher specification (having a smaller pore size) require very high-pressure drops across the filter, which in turn will require a higher energy input to drive fans. This substantially increases costs. The fan drive motors have to be designed to drive air through both new unclogged filters and virtually full filters. The Full EAC system does not require filters and therefore needs less power to re-circulate air.

- Advanced HVAC systems remove particles with a size of > 0.01 μm using HEPA filters in the re-circulated air, whilst the air is in the actual air processor - the Full EAC system will remove similar sized particles in the locality where people are working, whilst they are working.
- Conventional air handling equipment takes up to 20 % of internal building volume. The suggested equipment requires no additional space.
- The inability of conventional filter based systems to remove/ reduce the viability of micro-organisms in the room, is addressed. The Full EAC system will not create risks from a build up of bacteria in filters. In recent years, several people in the UK have died from Legionella bacteria 'cultured' in poorly maintained air coolers in standard HVAC equipment.
- There are advanced plans/ designs to build naturally ventilated buildings (Kolokotroni, 2000). There are no known means of cleaning the incoming outdoor air used to cool such a building. Since the full EAC system works independently of standard/ enhanced HVAC systems, it is suitable for use in naturally ventilated buildings, without a HVAC system installed.

A1.5. Conclusion

The Full EAC system and associated application engineering is a way forward in addressing the problem of poor indoor air quality, especially for urban localities. The process of urbanisation is a continuing social phenomenon and hence the demand for clean indoor air will increase as our understanding of possible damages to our health can be traced to poor indoor air quality. Illnesses associated with SBS, might well be mainly a function of poor indoor air quality. People are a substantial source of air borne pollution. If people are brought together, air borne pollutants follow and there are likely to be ensuing health problems. Given such circumstances any technology that goes some way to removing air borne pollutants indoors would seem an advancement in indoor air technology and well worth further investigation.

The Full EAC system represents a realistic design for a commercially viable air cleaner. The particular design chosen, which encompasses a collector plate takes into account the hardware tested during the development stage of this thesis. The investigations undertaken herein have given a greater understanding of the mechanisms by which electrostatic air cleaning produces cleaner air.

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APPENDIX 2

LIST OF PAPERS

Part of the research for this MPhil was based on the following enclosed papers in chronological order as listed below:

1 Rosén K G, Richardson G, Would removing indoor air particulates in children's environments reduce rates of absenteeism - A hypothesis. The Science of the Total Environment 1999; 234: 87-93.

2 Rosén KG, Richardson G, Harwood D. Non-attendance rates among children in Swedish day care centres before, during and after cleaning the indoor air using an electrostatic air cleaning technology - a controlled trial. In proceedings of: The South West Association of University Departments of General Practice, 6-7 February 1998, Dartington, Devon (UK).

3 Richardson G, Rosén K G. Non-attendance rates among children in Swedish day care centres before, during and after cleaning the indoor air using an electrostatic air cleaning technology - A controlled trial. In proceedings of: The 19th AIVC conference on Ventilation Technologies in Urban areas, 28 - 30 September 1998, Oslo, (Norway).

4 Richardson G, Harwood DJ. Environmental assessment of a council estate with 116 houses, in the West country, winter 99. In proceedings of: The South West Association of University Departments of General Practice annual seminar, 3 - 4 March 2000, Exeter, Devon (UK).

5 Richardson G, Eick SA, Harwood DJ. Quantifying ventilation needs in Local Authority Housing - A case study. In proceedings of: The 21st AIVC, Innovations in Ventilation Technology, 26 - 29 September 2000, The Hague (Netherlands).

6 Richardson G, Eick SA, Harwood DJ, Rosén KG, Dobbs F. Indoor air quality, Part 2: Negative air ionisation and the generation of hydrogen peroxide. The Science of the Total Environment (Submitted 2000).

7 Richardson G, Harwood D J, Crossman S A, Linking absenteeism to levels of air borne particulate matter and traffic related gases in an inner city office - A controlled trial using new Electrostatic Air Cleaning technology (EAC). In proceedings of: The South West Association of University Departments of General Practice annual seminar, 22 - 23 January 1999, Ewloe, Flintshire, Wales (UK).

8 Richardson G, Harwood DJ, Eick SA, Dobbs F, Rosén KG. Reduction of fine airborne particulates (PM_3) in a small city centre office, by altering electrostatic forces. The Science of the Total Environment 2001; 269: 145 – 155.

PAPER NUMBER 1

Rosén KG, Richardson G. Would removing indoor air particulates in children's environments reduce rates of absenteeism – A hypothesis. The Science of the Total Environment 1999; 234: 87 – 93.

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The Science of the Total Environment 234 (1999) 87–93

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Would removing indoor air particulates in children's environments reduce rate of absenteeism — A hypothesis

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Abstract

To conduct a controlled trial to test the ability of a newly developed electrostatic air cleaning technology (EAC) to improve Indoor Air Quality (IAQ) as defined by levels of airborne particles and to investigate the potential to reduce non-attendance rates due to illness among children in two Swedish day care centres. The EAC technology was shown to significantly reduce the indoor particulate load for very fine particles caused by outdoor air pollution by 78% and to reduce the number of fine particles produced indoors by 45%. To test the hypothesis, non-attendance was followed in two centres during 3 years. The EAC technology was in operation during year 2. Non-attendance rates among children in the larger day-care centre decreased by 55%, equalling those levels noted in family-based day care. It is speculated that the air cleaning effect may be due to alterations in electrostatic forces operating within the room enabling fine particulate matter to more easily become and stay airborne. The EAC technology is cost-efficient and might be a way forward to improve IAQ. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Indoor air quality; Air pollution; Day care centres; Absenteeism; Children

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1. Introduction

Indoor air quality (IAQ) is a complex function of outdoor air quality, indoor activities past and present, design of ventilation systems, number of air changes per minute, building design/size and emissions from the building materials. Up to now, volatile organic compounds (VOCs) have been associated with the adverse effects noticed in the indoor environment. However, at a recent Nordic Scientific Consensus meeting, Andersson et al. (1996) reviewed 120 publications and established that present data are inconclusive.

Recently, fine particulate matter generated by the combustion process and the diesel engine in particular, has come to the fore as a potential cause of respiratory symptoms among those children and adults suffering from chronic respiratory disorders (Schwartz, 1994) but also as an adjuvant for the development of allergy (Devalia et al., 1994).

In a questionnaire-based study covering 39 Swedish schools, Norbäck and Smedje (1996) reported on a positive relationship between respirable dust and airway infections in adults as well as between viable airborne bacteria and moulds and asthma in children.

Ståhlberg (1980) and Dahl et al. (1991) noted the negative consequences from the indoor environment in the two- to threefold increase in upper respiratory tract infections (URTI) and the use of antibiotics among children attending daycare centres where most of their time is spent indoors. URTI among children causes a socioeconomic inconvenience and aggravates asthma (Sporik et al., 1992).

Thus the issue of IAQ is of great importance as more time is spent indoors and data is accumulating to show the consequences of poor IAQ.

Although epidemiological studies are important to identify a potential problem, interventional studies are equally relevant to study the mechanisms behind the problem and to explore potential remedies.

In Sweden increased forced air ventilation rates have been tried over many years as a method to improve indoor air quality, in public and private buildings. In 1994, Sweden set a new standard for IAQ, based on a maximum carbon dioxide concentration of 1000 ppm in an attempt to further control the IAQ issue (NSBOSH, 1993). Surprisingly few data are available to prove how effective the approach has been (Norbäck and Smedje, 1996).

It appears as if the concentration of respirable particles is a significant factor influencing the quality of the indoor environment. Increased forced air ventilation does not necessarily reduce the number of particulates as efficiently as carbon dioxide and VOCs are removed.

Electrostatic mechanisms provide an alternative means to control the movement of fine airborne particles (Jackson, 1975). One way of generating electrostatic fields in a room, is to produce free electrons in the air. Some of these electrons will combine with oxygen and a negatively charged small air ion is produced. There is empirical evidence that such charged air can reduce the growth of microorganisms (Krüger and Reed, 1976). This observation has been further strengthened by the observation that small amounts of hydrogen peroxide are produced with increasing levels of negative air ions (Challenger et al., 1996). Hydrogen peroxide may act to reduce the growth of microorganisms (Hyslop et al., 1995).

Thus, the delivery of free electrons into the indoor air has the potential to enhance the air quality by reducing the number of airborne particles through electrostatic 'filtering' mechanisms and via the hydrogen peroxide mechanism reduce the growth of microorganisms.

2. Hypothesis

Does the production of free electrons into the indoor air have the ability to reduce the number of airborne particles of a defined size in children's day care centres?

Would the potential improvement in IAQ from such a system, reduce the non-attendance rate due to sickness among the children in these day care centres?

To evaluate these hypotheses, electron producing devices [Electrostatic Air Cleaning (EAC) system, Neoventor Medicinsk Innovation AB, Kungälv, Sweden] were installed in two Swedish day care centres. The non-attendance rates among the children were recorded over a 3 year period. The concentration of fine (> 3 μm, < 7 μm) and very fine (> 0.3 μm, < 3 μm) airborne particulate matter was recorded.

3. Methodology

Although the EAC system is not regarded as a medical device, its use in children's day care centres was approved by the Ethics committee, Faculty of Medicine, University of Gothenburg, Sweden. Parents were given written and direct information at meetings.

Two day care centres, A and B, were chosen in collaboration with the municipality of Uddevalla, located on the west coast of Sweden, to be equipped with EAC-systems. Centre A was an older building with a large group of children whereas centre B was located in a modern building with half as many children using the premises on a daily basis. The two buildings had controlled forced air ventilation that fulfilled the standards required of 7 l/s per child (NSBOSH, 1993). No other changes were undertaken in the centres during the 3-year trial. Table 1 provides further details.

The local Social Services office registers and

Table 1
Basic data and annual non-attendance rates

Day care centre	A	B
EAC	Yes	Yes
Built, year	1975	1991
Number of children attending	63	30
Range of age of children, years	1–6	1–6
Non-attendance due to sickness, annual rates (%)		
Year 1	8.31	9.20
Year 2, EAC year	3.75**	6.09
Year 3	7.94*	5.92

*$P < 0.05$, paired t-test.
**$P < 0.01$, paired t-test.

collates figures for non-attendance among pre-school children indicating reasons for the absence. The non-attendance rates due to illness used for this research were taken from this database.

Comparisons of non-attendance rates were made over a 3-year period with year 2 being the year of 'EAC'-treatment in centres A and B.

4. The EAC-system

The EAC-system delivers a high voltage (7 kV negative polarity), DC current (< 0.5 mA) to a frayed multi carbon fibre thread (the emitter) positioned close to each ceiling-mounted forced air inlet without the generation of ozone. The number of small air ions produced was regularly measured using an atmospheric ion analyser (Medion type 134A). EAC-systems were only installed in rooms used by the children in the day care centres. Throughout the time of the study negative air ion levels of 20 000–40 000/cm^3, at a height of 1 m above the floor were recorded. A standard DC electrical field recorder (ELTEX Q475C) recorded a negatively charged electrostatic field of −30 kVm, at a distance of 30 cm from the emitters. The field strength 1 m from the emitter was −15 kVm which is equivalent to the field strength of a TV set (positive electrostatic field). The walls of the rooms in centre A became slightly negatively charged (1.5–2.0 kVm) compared with a zero or slightly positive charge previously recorded. No alteration of wall charge was noted in centre B.

The EAC systems were in operation throughout the second year from the first week in April of year 2 until the first week in April of year 3. They were then turned off with the equipment left in place throughout the third year.

5. Measurements of airborne particles

A MET-ONE model 227B (Met-One, Oregon, USA) laser beam particle counter was used to record the number of particles per litre of ambient air.

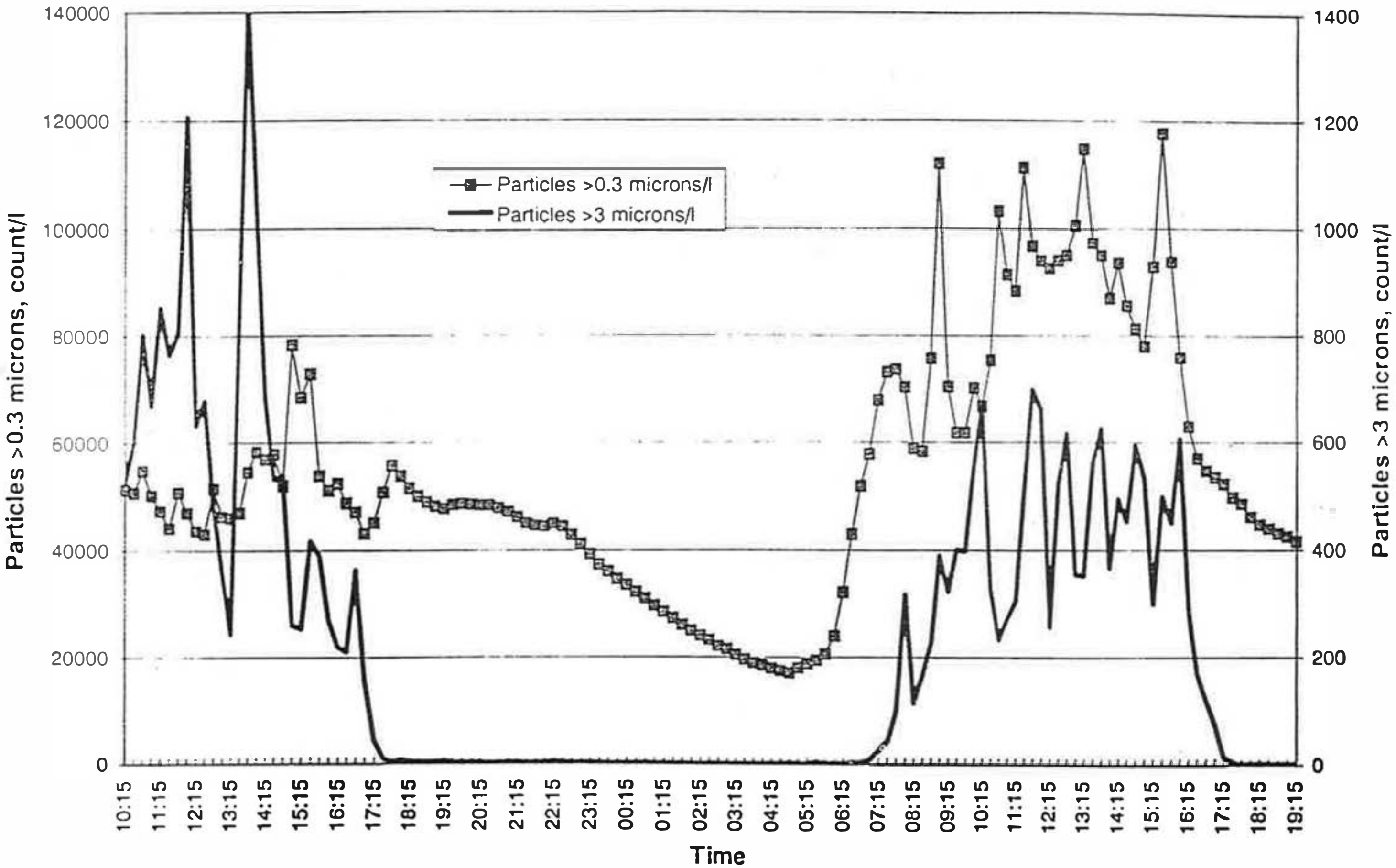

Fig. 1. A representative recording of the number per litre of air borne particles of two sizes, > 0.3 μm and > 3.0 μm, during a 33-h period in a day care centre room. Note how the very fine particles stay air borne throughout the night and markedly increase as the ventilation system is turned on at 06.00 h. The larger size particles increased as the staff and children made use of the room in the morning and fluctuated throughout the day depending on the activity level.

The particle counter was set to measure:

(i) Very fine particles defined as > 0.3 and < 3.0 μm and
(ii) Fine particles, > 3.0 and < 7.0 μm in size

Comparisons were made intermittently between indoor and outdoor particle counts at varying weather conditions. Indoor particle counts were recorded for 24-h periods in centre A only. Measurements were taken during a 30-s period every 5 min. Particle counts were made in one playroom at a height of 1.2 m and at a distance of 3 m away from the forced air inlet.

Fig. 1 gives an example of a 24-h recording of how the number of particles varies depending on the level of activity in the room. This was most pronounced for particles > 3 μm. The number of these particles dropped to zero during the night, increasing again as staff entered the room in the morning. The number of very fine particles also increased in the morning when the ventilation system was switched on, prior to the arrival of the staff.

Thus, the particles measured represented:

(i) Very fine particles, > 0.3 and < 3.0 μm, entering the room from the outside air through the ventilation ducts. The relationship between in- and outdoor concentrations was used to quantify IAQ.
(ii) Fine particles of size > 3.0 and < 7.0 μm generated from activities within the room. The average reading recorded during office hours, 08.00–15.00 h was used to quantify IAQ.

The carbon fibre threads were vacuum-cleaned every third month to ensure their function.

Statistical analysis for absenteeism was performed using two-tailed, paired Student's *t*-test and for particulates, unpaired Student's *t*-test.

6. Results

The outdoor air was always found to have a higher concentration of very fine particles than the indoor air. On average, a 25% reduction of very fine particles was noted under normal conditions as the air passed through the existing ventilation system and settled within the room. This difference was markedly enhanced when the EAC-system was in operation showing, on average a 78% reduction of very fine particles ($n = 17$, $P < 0.001$).

The average daily count of fine particles was recorded on 10 occasions, four without and six with EAC. A significant reduction was noted with the EAC-system as the daily averages decreased from 428 (median, range: 340–649) particles/litre of air to 232 (range: 166–287), $P < 0.01$.

Table 1 gives a comparison of absenteeism during the 3-year period. Centre A had a significant reduction in absenteeism from 8.31 to 3.75% returning to 7.94% during the third year.

Table 1 also give the non-attendance rates for the smaller and more modern day-care centre B. This centre showed a decrease by 33% comparing years 1 and 2. This difference did not reach statistical significance. There were no epidemics noted among the children.

An observation was made regarding a difference in wall dirt deposition as in centre B the walls required repainting, something not required in centre A.

7. Discussion

The aim of the study was to conduct a trial to test the ability of a newly developed electrostatic air cleaning device to improve IAQ as defined by levels of airborne particles and to investigate the potential to reduce non-attendance rates among children in day care centres. Non-attendance rates among children in Swedish day care centres are known to increase almost threefold compared with family-based day care. Primarily due to viral URTI which is related to the number of children (Dahl et al., 1991) and possibly the load of biologically active airborne particles.

Repeated measurements were undertaken in order to demonstrate effects on the number of airborne particulate matter. The non-attendance rate due to illness was provided from the records on absenteeism kept by the Social Services administration. This independent data collection together with the unlikeness that the children per se would alter their behaviour due to some equipment being mounted in the ceiling should reduce the methodological error. Leaving the equipment mounted after it was turned off further reduced this risk. Furthermore, by including data obtained on a yearly basis short-term trends due to seasonal variation in URTI can be excluded and the non-attendance rates noted during years 1 and 3 are in keeping with previously published data (Dahl et al., 1991).

It appears logical to assume that the very fine particles generated outdoors, and reduced by 78%, became trapped as the air entered the room and passed close to the EAC system, the site where the negative electrostatic field was the strongest and the dirt deposition the most marked. The larger size particles generated by the activity within the room became less airborne (45% reduction) either by not leaving their source (humans or horizontal surfaces) so easily due to the alteration of the electrostatic field within the room and/or being captured by the strong electrostatic field operating close to the EAC emitters. It took approximately 2 weeks for the walls in centre A to obtain a slight negative electrostatic charge as compared with the overall positive charge noted initially. Not until this was achieved did the reduction in particles reach its maximum in reducing airborne particulate matter, indicating that a negative electrostatic field effect is important.

IAQ and its impact on the indoor environment is not only a function of the concentration of airborne particles. Equally relevant is the potential biological activity of these particles (Seaton et al., 1995). This bioload concept includes fine respirable particles generated by microorganisms. Our own experimental work on enhanced negative air ionisation has demonstrated the generation of hydrogen peroxide in the range of 0.7–1 μM at 20–50 000 negative air ions/ml of air (Challenger et al., 1996). Hyslop et al. (1995) recently reported on hydrogen peroxide as a potent antibiotic. They showed a bacteriostatic effect at 25 μM without any signs of affecting the growth of human fibroblasts. To what extent a hydrogen peroxide concentration of 1 μM operating over time would affect the growth of microorganisms remains to be tested. However, our own observational data have indicated a marked decrease in airborne moulds in rooms after 2–5 months of EAC treatment.

To our knowledge no previous attempt has been made to study interventional procedures and their capacity to improve indoor air quality, relating the effects to the non-attendance rate among children. In the current study a substantial reduction of indoor air particles was shown to be possible by altering the electrostatic fields within the rooms. The impact of this on non-attendance rates among children in the larger day-care centre was most striking with a 55% decrease and non-attendance rates equalling those noted in family-based day care (Dahl et al., 1991). The lack of a significant reduction in nursery B may be due to a smaller number of children, 30 vs. 63, and thereby the effect of independent factors, such as a change in age distribution, would increase.

Obviously, the possibility also exists of other mechanisms affecting the outcome, such as different building materials, wooden boards vs. plaster of paris boards, age of the buildings and their previous history. Assuming the reason behind a reduction in infection rates is dependent on the ability of particulate matter to leave a surface, centre A showed evidence of a change in indoor structural surface electrical charge, not seen in centre B. Perhaps such an effect also did apply to the surface of children making an alteration in the predominant positive charge more likely and thereby reducing the repellent electrical forces that would otherwise keep the human-generated particles airborne.

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PAPER NUMBER 2

Rosén KG, Richardson G, Harwood D. Non-attendance rates among children in Swedish day care centres before, during and after cleaning the indoor air using an electrostatic air cleaning technology – A controlled trial. In proceedings of: The South West Association of University Departments of General Practice, 6 –7 February 1998, Dartington, Devon, UK.

South West Association of University Departments of General Practice

6 and 7 February 1998

Dartington Hall
Dartington
Devon

Title	**Non attendance rates among children in Swedish day care centres before,during and after cleaning the indoor air using an electrostatic air cleaning technology - a controlled trial**
Authors	**Karl G Rosén, George Richardson, David Harwood**
Institution	**Department of Environmental Science, University of Plymouth**

Introduction And Aims: To conduct a controlled trial to test the ability of a newly developed electrostatic air cleaning technology (EAC) to improve Indoor Air Quality (IAQ) as defined by levels of air borne particles and to investigate the potential to reduce non-attendance rates due to illness among children in two Swedish day care centres.

Methods: The EAC technology was shown to significantly reduce the indoor particulate load for very fine particles (>0.3µm) caused by outdoor air pollution, by 78% and to reduce the number of particles (>3.0µm) produced indoors by 45%.
Non-attendance was followed for two "treated" centres and two control centres during three years.

Results: The EAC technology was in operation during year two. Non-attendance rates among children in the larger day care centre decreased by 55%, equalling those noted in family based day care.

Subsequently (autumn 1997; Dept. for Environmental Science, Plymouth University) experiments have been carried out on the oxidation of common indoor gases, with some excellent results. Thus the EAC - technology might be used to oxidise traffic and people related gaseous by-products. Further research is required to quantify and to optimise this feature of the EAC technology.

Conclusions: The EAC technology is cost efficient and might be a way forward to improve IAQ.

PAPER NUMBER 3

Richardson G, Rosén KG. Non-attendance rates among children in Swedish day care centres before, during and after cleaning the indoor air using an electrostatic air cleaning technology – A controlled trial. In proceedings of: The 19th AIVC conference on Ventilation Technologies in Urban areas, 28 – 30 September 1998, Oslo, Norway.

VENTILATION TECHNOLOGIES IN URBAN AREAS

19TH ANNUAL AIVC CONFERENCE
OSLO, NORWAY, 28-30 SEPTEMBER 1998

NON ATTENDANCE RATES AMONG CHILDREN IN SWEDISH DAY-CARE CENTRES BEFORE, DURING AND AFTER CLEANING THE INDOOR AIR USING AN ELECTROSTATIC AIR CLEANING TECHNOLOGY – A CONTROLLED TRIAL

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NON ATTENDANCE RATES AMONG CHILDREN IN SWEDISH DAY CARE CENTRES BEFORE, DURING AND AFTER CLEANING THE INDOOR AIR USING AN ELECTROSTATIC AIR CLEANING TECHNOLOGY - A CONTROLLED TRIAL.

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ABSTRACT

To conduct a controlled trial to test the ability of a newly developed electrostatic air cleaning technology (EAC) to improve Indoor Air Quality (IAQ) as defined by levels of air borne particles and to investigate the potential to reduce non-attendance rates due to illness among children in two Swedish day care centres. The EAC technology was shown to significantly reduce the indoor particulate load for very fine particles (>0.3μm) caused by outdoor air pollution by 78% and to reduce the number of particles (>3.0μm) produced indoors by 45%.

Non-attendance was followed for two "treated" centres and two control centres during three years. The EAC technology was in operation during year two. Non-attendance rates among children in the larger day-care centre decreased by 55%, equalling those noted in family based day care.

The EAC technology is cost efficient and might be a way forward to improve IAQ.

INTRODUCTION:

Indoor air quality (IAQ) is a complex function of outdoor air quality, indoor activities past and present, design of ventilation systems, number of air changes per min., building design/size and emissions from the building materials.

Recently, fine particulate matter generated by the combustion process and the diesel engine in particular, has come to the fore as a potential cause of respiratory symptoms among those children and adults suffering from chronic respiratory disorders[1,2] but also as an adjuvant for the development of allergy[3].

In a questionnaire based study covering 39 Swedish schools, Norbäck and Smedje reported on a positive relationship between respirable dust generated indoors and airway infections in adults as well as between viable airborne bacteria and moulds and asthma in children[4].

Upper respiratory tract infections (URTI) are two to three times more common, as is the use of antibiotics, among children attending day-care centres where most of their time is spent indoors[5,6].

In Sweden increased forced air ventilation rates have been tried over many years as a method to improve indoor air quality, in public and private buildings. In 1994, Sweden set a new standard for IAQ, based on a maximum carbon dioxide concentration of 1000 PPM in an attempt to further control the IAQ issue[7]. Surprisingly few data are available to prove how effective the approach has been[4].

Electrostatic mechanisms provide an alternative means to control the movement of fine air borne particles[8]. One way of generating electrostatic fields in a room, is to produce free electrons in the air. Some of these electrons will combine with oxygen and a negatively charged small air ion is produced. There is empirical evidence that such charged air can reduce the growth of micro-organisms[9]. This observation has been further strengthened by the observation that small amounts of hydrogen peroxide are produced with increasing levels of negative air ions[10].
Thus, the delivery of free electrons into the indoor air has the potential to enhance the air quality by reducing the number of airborne particles through electrostatic 'filtering' mechanisms and via the hydrogen peroxide mechanism reduce the growth of micro-organisms[11].

HYPOTHESIS:

Does the production of free electrons into the indoor air have the ability to reduce the number of air borne particles of a defined size in a busy children's day care centre?
Would the potential improvement in IAQ from such a system, reduce the non-attendance rate due to sickness among the children in day care centres?

To evaluate these hypotheses, an electron producing device (Electrostatic Air Cleaning, EAC - system) was constructed and installed in two Swedish day care centres. The non attendance rates among the children were recorded over a three year period. The concentration of fine (> 3μm) and very fine (> 0,3μm) air borne particulate matter was recorded. The number of absent children was compared with day-care centres of similar size and design without the EAC technology.

METHODOLOGY:

Although the EAC system is not regarded as a medical device, it's use in children's day care centres was approved by the Ethics committee, Faculty of Medicine, University of Gothenburg, Sweden. Parents were given written and direct information at meetings.

Two day care centres, A and B, were equipped with EAC-systems. Centre A was built 1975 with a large group of children (63) whereas centre B was located in a modern building, built 1991, with half as many children using the premises on a daily basis. Control centres A_{ref} and B_{ref} were chosen on the basis of size, locality and age. The control centres were both located within less then 1.5 km of the corresponding EAC equipped units and covered the same residential area of the town. All buildings had controlled forced air ventilation that fulfilled the standards required. No other changes were undertaken in the four day-care centres during the 3 year trial.

The local Social Services office register and collate figures for non-attendance among pre-school children indicating reasons for the absence. The non-attendance rates due to illness used for this research were taken from this database.
Comparisons of non-attendance rates were made over a three year period with year two being the year of 'EAC'-treatment in centres A and B. centre B_{ref} did not start to operate until august 1993, therefore the period included in the three year analysis of centres B and B_{ref} has been restricted to 8 months (1 Aug. 1993 - 13 March 1994)

THE EAC-SYSTEM:
The EAC- system delivers a high voltage (7 kV negative polarity), DC current (< 0,5 mA) to a carbon fibre thread (the emittor) positioned close to each ceiling mounted forced air inlet. The number of small air ions produced was regularly measured using an atmospheric ion analyser (Medion type 134A). EAC - systems were only installed in rooms used by the children in the day care centres. Throughout the time of the study negative air ion levels of 20.000-40.000 per cm^3, at a height of 1m above the floor were recorded. A negatively charged electrostatic field of -30 kVm was recorded by a standard DC electrical field recorder (Eltex Q475C), at a distance of 30 cm from the emitters. The field strength one meter from the emittor was -15 kVm which is equivalent to the field strength of a TV set (positive electrostatic field). The walls of the rooms became slightly negatively charged (1.5 - 2.0 kVm) compared with a zero or slightly positive charge in a standard room.
The EAC systems were in operation throughout the second year from the first week in April 1994 to the first week in April 1995. They were then turned off with the equipment left in place throughout the third year.

MEASUREMENTS OF AIR BORNE PARTICLES:
A MET-ONE model 2110 (Met-One, Oregon, USA) laser beam particle counter was used to record the number of particles per litre of ambient air.
The particle counter was set to measure, particles > 0,3 and >3,0 µm in size. Comparisons were made intermittently between indoor and outdoor particle counts. Indoor particles counts were recorded over 24-hour periods. Measurements were taken during a 30 second period every 5 minutes. Particle counts were made in one playroom at a height of 1.2 m and at a distance of three meters away from the forced air inlet.

Figure 1

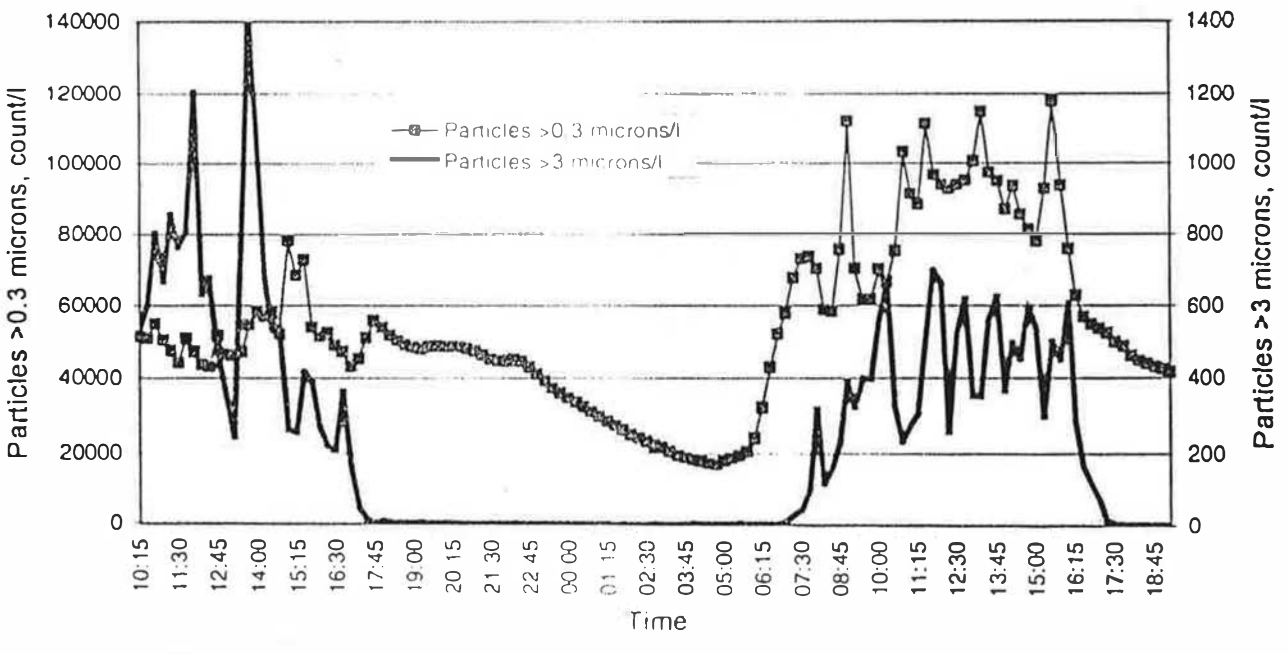


Figure 1 gives an example of a 24-hour recording of how the number of particles varies in a play room, depending on the level of activity in the room. This was most pronounced for particles >3 μm. The number of these particles dropped to zero during the night, increasing again as staff entered the room in the morning. The number of very fine airborne particles also increased in the morning when the ventilation system was switched on, prior to the arrival of the staff.

Thus, the particles measured represented:

a) Very fine particles, those > 0.3μm, entering the room from the outside air through the ventilation ducts. The relationship between in- and outdoor concentrations was used to quantify IAQ.

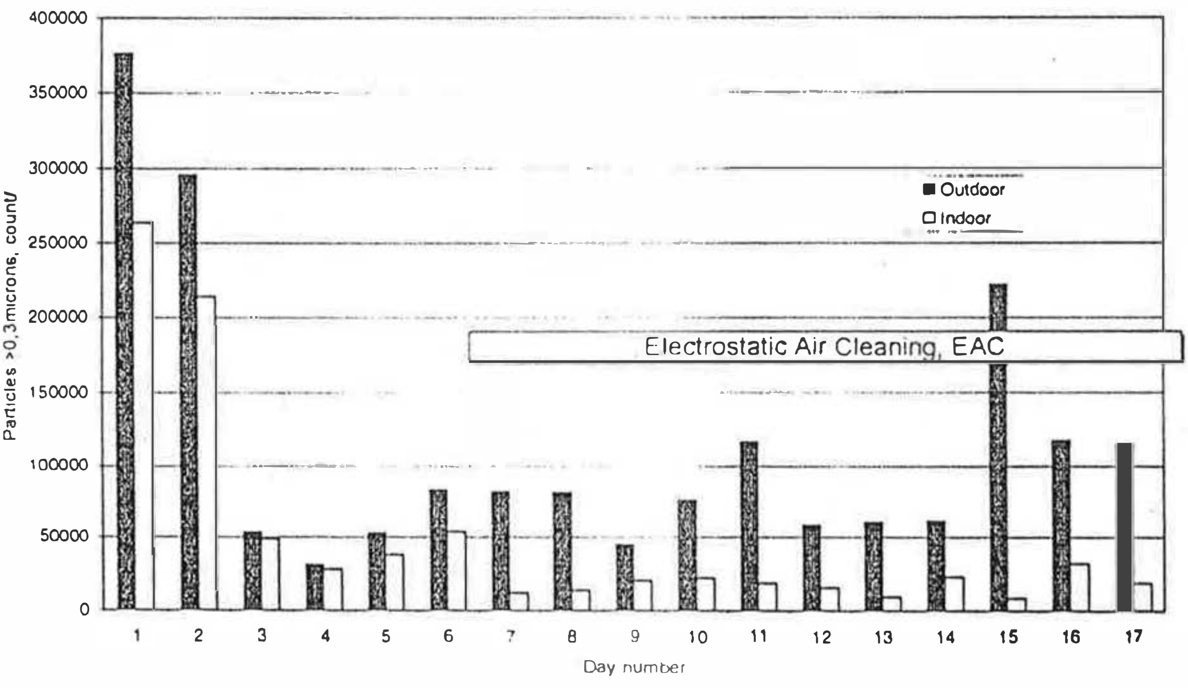
b) Particles of a size >3.0μm generated from activities within the room. The average reading recorded during office hours, 08:00 - 15:00 was used to quantify IAQ.

The carbon fibre threads were vacuum-cleaned every third month to ensure their function.. Statistical analysis of the data was performed using two - tailed, paired students T-test.

RESULTS:

The outdoor air was always found to have a higher concentration of particles > 0.3 μm, than the indoor air. This is illustrated in Figure 2 showing parallel in- and outdoor measurements with and without the EAC-system in use. On average, a 25 % reduction of particles > 0.3μm was noted

Figure 2



under normal conditions as the air passed through the existing ventilation system and settled within the room. This difference was markedly enhanced when the EAC-system was in operation showing, on average a 78 % reduction of particles > 0.3 μm ($p < 0.001$).

The average daily count of particles >3.0 μm was recorded on ten occasions, four without and six with EAC. A significant reduction was noted with the EAC-system as the daily averages decreased from 428 (median, range: 340 - 649) particles per litre of air to 232 (range: 166 - 287), p <0.01.

Figure 3

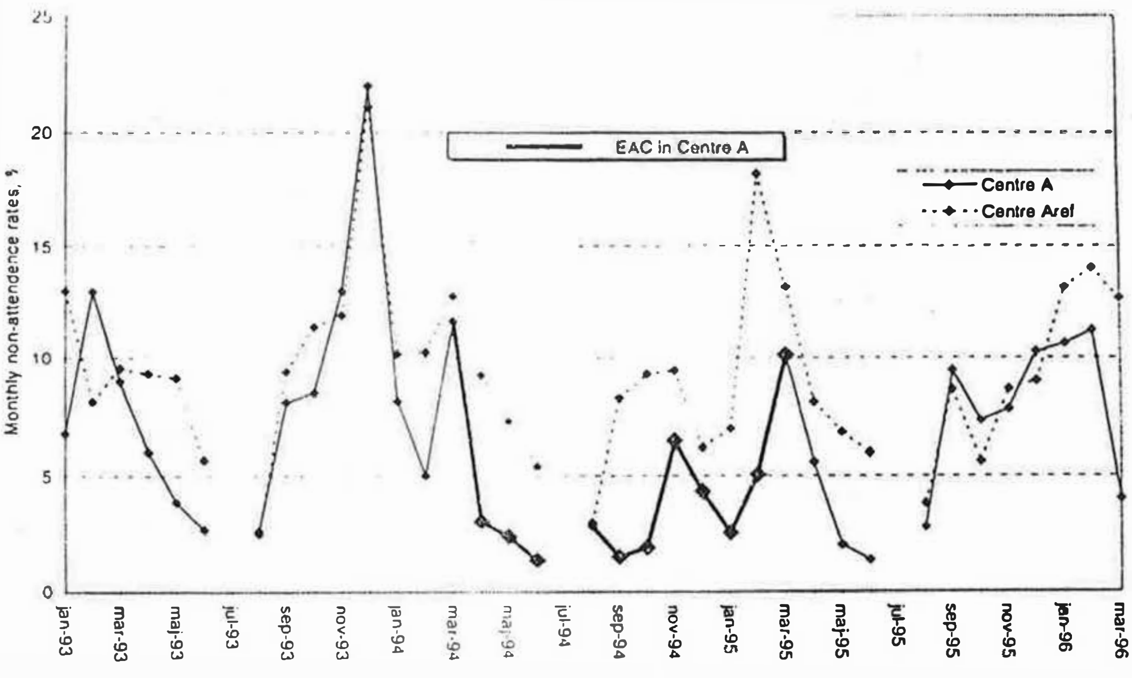


Figure 3 shows the monthly figures for non-attendance rates due to sickness comparing the tw larger day care centres A and A_{ref}. The two centres followed a similar pattern during year 1 and whereas during year 2 when the EAC-system was in operation centre A consistently showe lower non attendance figures than centre A_{ref}. (The graphs are disjointed because of summe vacations.)

Table I

Non-attendance due to sickness, annual rates (%)

	Centre A		Centre A_{ref}	Centre B		Centre B_{ref}
1993-94	8.31	**	10.31	9.20	*	5.46
	**					
1994-95, EAC year	3.75	***	8.75	6.09		6.76
	*					
1995-96	7.94	*	8.76	5.92	**	9.21

* = p<0.05, ** = p<0.01, *** = p<0.001, paired T-test

Table I gives a comparison of absenteeism during the three year period in the four centres. Centre A had a significant reduction in absenteeism from 8.31% to 3.75% returning to 7.94% during the third year. It appeared as if centre A was significantly healthier than centre A_{ref} with 19 and 9% less sick children year 1 and 3, respectively. This difference became highly significant with 57% less sick children in centre A during the EAC year.
Table I also gives the non-attendance rates for the smaller and more modern day-care centres B and B_{ref}. centre B showed a decrease by 33% as compared with an increase in non-attendance by 23% in centre B_{ref} comparing year 1 and 2. These differences did not reach statistical significance. Note the increase in non-attendance in the newly built centre B_{ref} which became significant during the third year ($p<0.05$).

When the EAC system was turned off the staff in centre B complained of the stuffiness of the indoor air and had the ventilation system checked. The system was operating according to specifications. The only side effect noted during the EAC year was an accumulation of dirt around the emitters. This was markedly reduced by placing a metal sheet between the emitting thread and the ceiling. More dirt was noted when cleaning the floors on a daily basis. The parents also noted that the children's socks became more dirty during the EAC year.

DISCUSSION:

The aim of the study was to conduct a controlled trial to test the ability of a newly developed electrostatic air cleaning device to improve IAQ as defined by levels of air borne particles and to investigate the potential to reduce non-attendance rates among children in day care centres. These are known for an almost three-fold increase in non-attendance, primarily due to viral URTI which is related to the number of children[6] and possibly the load of biologically active air borne particles.

In the larger centre repeated measurement were undertaken in order to demonstrate effects on the number of air borne particulate matter. The non attendance rate due to illness was provided from the records on absenteeism kept by the Social Services administration. This independent data collection together with the unlikeness that the children *per se* would alter their behaviour due to some equipment being mounted in the ceiling, should reduce the methodological error. This risk was further reduced by leaving the equipment mounted after it was turned off. Furthermore by including data obtained on a yearly basis short term trends due to seasonal variation in URTI can be excluded.

It was obvious that the EAC - system altered the pattern of dirt deposition with more dirt deposited on the floor and around the emitters. It appears logical to assume that the very fine particles generated outdoors, and reduced by 78%, got trapped as the air entered the room and passed close to the EAC system, the site where the negative electrostatic field was the strongest. The larger size particles generated by the activity within the room became less airborne (45% reduction) either by not leaving their source (humans or horizontal surfaces) so easily due to the alteration of the electrostatic field within the room and/or being captured by the strong electrostatic field operating close to the EAC emitters. It took approximately two weeks for the walls to obtain a slight negative electrostatic charge as compared with the overall positive charge noted initially. Not until this was achieved did the reduction in particles become maximal, indicating that the negative electrostatic field effect is important.

IAQ and its impact on the indoor environment is not only a function of the concentration of air borne particles. Equally relevant is the potential biological activity of these particles[13]. This bioload concept includes fine respirable particles generated by micro-organisms. Our own experimental work on enhanced negative air ionisation has demonstrated the generation of hydrogen peroxide in the range of 0.7 to 1 μM at 20-50 000 negative air ions per ml of air[10]. Hyslop and collaborators recently reported on hydrogen peroxide as a potent antibiotic[11]. They showed a bacteriostatic effect at 25μM without any signs of affecting the growth of human fibroblasts. To what extent a hydrogen peroxide concentration of 1μM operating over time would affect the growth of micro-organisms remains to be tested. However, own observational data has indicated a marked decrease in air borne moulds in rooms after two to five months of EAC treatment.

To our knowledge no previous attempt has been made to study interventional procedures and their capacity to improve indoor quality, relating the effects on the non attendance rate among children. Hawkins, in a previous controlled trial on negative air ionisation showed positive effects on subjective parameters such as headaches etc[12]. Such observational studies need to be substantiated by more detailed research into possible mechanisms. In the current study a substantial reduction of indoor air particles was achieved by altering of the electrostatic fields within the rooms. The impact of this on non-attendance rates among children in the larger day-care centre was most striking with a 55% decrease and non-attendance rates equalling those noted in family based day care[6].

Un-expectantly, centre B_{ref} which was established in a new building in August 1993, showed a significant increase in the non-attendance rate from 5.46 to 9.21% ($p < 0.05$) during the three year period. Perhaps the biological history of a building and its accumulated bioload should also be considered when assessing the state of a building from a health perspective.
Whatever the complexity of factors affecting the indoor environment, it appears as if electrons released into the room thereby generating a weak negative electrostatic field and an increased level of negative air ionisation could significantly enhance IAQ with a potential to reduce URT among children attending large day care centres.

Acknowledgements.
The authors are indebted to Erland Holmdal, Bia Håkanson-Michalski, Lena Johansson and the municipality of Uddevalla, Sweden for financial support and help with data collection, to Rickard Bergström, Ph.D. Department of Environmental and Occupational Medicine, University of Göteborg for guidance on IAQ issues and to John Curnow, Department of Biomedical Engineering and Medical Physics for help with the electrical science. Financial support was also provided from a Regional Enterprise Grant no ERG (PL) 151, The Government Office For The South West, UK

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PAPER NUMBER 4

Richardson G, Harwood DJ. Environmental assessment of a council estate with 116 houses, in the West country, winter 99. In proceedings of: The South West Association of University Departments of General Practice annual seminar, 3 –4 March 2000, Exeter, Devon, UK.

SOUTH WEST ASSOCIATION

OF

UNIVERSITY DEPARTMENTS

OF

GENERAL PRACTICE

3 & 4 MARCH 2000

UNIVERSITY OF EXETER
INSTITUTE OF GENERAL PRACTICE

THISTLE HOTEL
QUEEN STREET
EXETER

Title	Environmental assessment of a council estate with 116 houses, in the West Country, winter 99.
Author(s)	Richardson G, Harwood D J.
Time	Saturday 0930 - Chatsworth Room

Introduction and Aims: Tenants were supported by a community development project to carry out an environmental study to investigate if housing conditions were responsible for 60% of the households having at least one person registered with asthma. The houses had different combinations of ventilation, heating, insulation and indoor hygiene.

Methods: 34 parameters were recorded for each house during January - March 1999. The study will be repeated for two more years each spring. During 1999 and 2000 all houses are to be fully modernised.

The parameters included:

-weather conditions and location
-number of fine particles (PM_3) and coarse particles (PM_7) in/ outdoors
-relative humidity and temperature in/ outdoors
-ventilation rate/ CO_2 in living room
-dampness, mould growth and airborne mould counts (Bioload)
-positive/ negative small air ion count in/ outdoors
-number of occupants and pets
-total energy costs
-smoking
-gas analysis
-dust mite counts

Major results: The quality of indoor air was much worse than outdoors, especially for PM_3, PM_7 and CO_2. High concentrations were also found for Bioload and dust mites.

Conclusions: Strong links exist between environmental conditions indoors and mites, moulds, etc. Since all the houses were of the same construction, differences in indoor air quality come from how the Tenants manage their houses. When the study is complete it will allow an environmental assessment of houses before and after modernisation. This three year study will be linked to a parallel study of the Tenant's health. The results from the two studies will be analysed for any statistical link between indoor air quality and health.

PAPER NUMBER 5

Richardson G, Eick SA, Harwood DJ. Quantifying ventilation needs in Local Authority housing – A case study. In proceedings of: The 21sr AIVC conference, Innovations in Ventilation Technology, 26 – 29 September 2000, The Hague, Netherlands.

INTERNATIONAL ENERGY AGENCY
Energy Conservation in Buildings and Community Systems
Air Infiltration and Ventilation Centre

Innovations in Ventilation Technology

The 21st AIVC Annual Conference
held at The Hague, Netherlands
26-29 September 2000

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Keynote Address by Prof. Ir. J.J.M. Cauberg

Quantifying ventilation needs in Local Authority Housing - A case study

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On behalf of the Torbay Healthy Housing Group.

Keywords: PM_{10} & $PM_{2.5}$; Indoor Air Quality (IAQ); Local Authority houses.

Synopsis

A Tool Kit was developed to assess indoor air quality. The Tool Kit was designed to be robust, reliable, universal and to provide data that could be linked with other studies assessing health, social factors and building conditions for any given locality. A case study using the Tool Kit to assess 116 Local Authority houses is described.

Introduction

Overview

A community survey was carried out in 1997, by the Tenants of a Local Authority owned housing estate, after the Tenants had voiced concerns about the state of their housing conditions and whether these conditions were affecting their health. An initial survey of 96 households revealed that 64% of the households suffered damp conditions and that there was at least one occupant with a respiratory illness in 60% of the houses. The population participating in the survey, had a normal social and age distribution representative of any housing estate population in the UK.

Following the community survey a decision was made by the Local Authority to fully investigate any links between physical conditions in the houses and the Tenants' health. Although the houses were of the same size, age and construction they had different combinations of ventilation, insulation and personal household management. Therefore, the investigation needed to be multi-disciplinary, taking into consideration the existing building conditions, socio-economic factors, health factors and the indoor air quality (IAQ) in each individual house. The survey also led to a commitment from the Local Authority to renovate the properties to meet the latest UK Government recommended standards for housing. The commitment to upgrade the housing stock over a two year period opened up a unique opportunity to conduct a comprehensive study.

A 'randomised to waiting list' controlled trial was initiated (with the estate stratified into streets, with one house equalling one unit and a population of 509 people), based on five parallel studies, over two years:

1. An environmental assessment of the IAQ, outdoor air quality and rates ventilation for individual houses concentrating on major parameters linked to ill health. This study would register any changes in IAQ, ventilation rates and how the Tenants managed their properties, before and after the renovations.
2. Personal health checks conducted through face to face private interviews between Tenants and a community nurse.

3. A prevalence study of illnesses (mainly respiratory), including the recording of the number of people and pets per household, the number of smokers per household and the type of cooking and heating systems installed.
4. The recording of personal social details.
5. Details of the physical attributes of the property as assessed by SAP ratings (DETR, 1998 a).

All the parameters recorded in each study were carefully chosen to look for confounding factors associated with certain illnesses.

Theory behind a 'Tool Kit' for measuring IAQ and ventilation

In order to fulfil the requirement for an environmental assessment of the air quality and ventilation rates in the houses (parallel study no 1), a method of monitoring had to be designed which was reliable and robust. The method required a 'Tool Kit' to monitor the chosen parameters. The design of the Tool Kit had to be universally functional and easy to handle. There was no prior agreement with the Local Authority before the investigation began, as to which parameters would be recorded, indeed there are no UK Government guidelines as to which IAQ parameters are the most important in relation to human health (COMEAP, 1997). Therefore the parameters measured were based on extensive studies of scientific literature and chosen to be representative of IAQ, ventilation rates and factors generally related to poor health. The parameters chosen and their measurement had to be readily understandable by all the other groups involved in the parallel studies and compatible with the methodology used in these studies.

To allow for analysis of the results collected by the Tool Kit, together with the results from the parallel-studies, the measurements needed to be quantitative rather than qualitative. Although the data collected by the Tool Kit could not be the basis of a judgement about 'good or bad' IAQ and ventilation rates, the quality of the indoor environment could be assessed in conjunction with results from other parallel studies in a holistic analysis.

The Tool Kit was designed originally to take a 'snap shot' of the air quality in the Local Authority houses. It reflected how the Tenants managed ventilation, heating, the reduction of aerosolised contaminants, relative humidity and any other indoor air pollutants. The Tool Kit had to be easy to operate in a limited time period, as 116 houses were to be assessed, which logistically did not allow for extensive studies of each house. When the 'snap shots' of the air quality are compared before and after the renovation programme for the houses, an assessment can be made as to whether the IAQ and or ventilation regimes/ rates have changed. The 'snap shot' will also show whether the Tenants have changed their management of indoor air/ ventilation. Assessing changes in the Tenant's health throughout the renovation programme might allow links to be made between changes in physical parameters and health.

This paper describes the science and methodology behind the Tool Kit and describes a case study undertaken in the Local Authority housing.

Methodology

Background

The composition of indoor air in general is characterised by a number of factors:

- Outdoor air borne pollutants - 60 -70% of fine (< 2.5 µm) and coarse (> 2.5 µm) particles penetrate into buildings (Dockery et al. 1981, Thatcher et al. 1995). The sources of these particles can be defined as bio-aerosols (bioload), mineral, combustion, home/ personal care and radioactive aerosols (Owen and Ensor, 1992).

- Outdoor weather conditions - The weather, location and orientation of the dwelling are important factors affecting IAQ and ventilation rates.
- Human and larger animals' (pets) physical activities - These activities create fresh particles through abrasion and 'old' particles are re-suspended (Ekberg, 1994). These activities are normally associated with coarse particles, together with exhaled water molecules (which also lead to increases in relative humidity).
- Tobacco smoking and food preparation - Smoke and the emissions from cooking, create a very large number of fine particles, along with gaseous compounds such as nitrous oxides and particles with adsorbed poly aromatic hydrocarbons (Abt et al, 2000).
- Specific contaminants - Some sources and activities release specific contaminants such as formaldehyde or lead. However these are relatively unusual and were therefore not included in the Tool Kit. An exception was made for the measurement of the house dust mite (HDM) allergen, Der p 1 as it is implicated as a factor in respiratory disorders (ENDS, 1996).

Previous work (Rosén and Richardson, 1999) demonstrated the variation of fine and coarse particle numbers over time, in localities where intense changes in activity levels occur and how this might be linked to breathing related illnesses or problems. Strong links have been found between outdoor levels of particulates and human health problems (COMEAP, 1997; DETR, 1998b), therefore by implication, indoor air should also be assessed for similar links. Consequently this work focuses on the design of a Tool Kit capable of assessing IAQ and rates of ventilation in a given locality, during one visit lasting 1 hour, with particular emphasis on particulate concentrations. An array of scientific instruments were used to measure the various parameters.

Description of the universal Tool Kit

A Tool Kit was required, to sample and record data for further research on the quality of indoor air and ventilation rates, meeting the following criteria:

- The ability to record robust data without any prior preparations in a locality. All measurements were made in triplicate.
- The equipment had to be easy to set up and run in the limited time available. For example, measurement of coarse particles was carried out within 15 minutes of arrival in each location to equalise any settling effects after any initial disturbance.[1]
- The Tool Kit had to be portable by one person and completely functional without causing disruption in the locality. All test methods had to be non-destructive and intrinsically safe, especially since some units of the Tool Kit had to be left running unsupervised for up to one hour.
- The data had to be collected and recorded in a manner that was easily computerised. The resultant data spread sheets had to be compatible with statistical packages such as Microsoft Excel and SPSS 9.0 for Windows.
- Data collection had to be unobtrusive, therefore every attempt was made to use low noise equipment powered by batteries and no structural changes were required.

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1 Unlike coarse particles, fine particles have settling rates [illegible] 1 m/ h, therefore the number of fine particles are not affected over the short measuring period in the house (Thatcher, 1995).

Parameters recorded by the Tool Kit

The following table lists the main parameters recorded by the Tool Kit. In the majority of cases parallel measurements were taken outdoors, to allow an assessment of the level of infiltration of outdoor pollutants.

Main parameters	Units	Outdoors	Indoors
RH (Relative Humidity)	%	X	X
Temperature	°C	X	X
PM_3 (fine particles) & PM_7 (coarse particles)	No./ l air/ 30 sec.	X	X
Wall/ wall surface dampness	WME %		X
CO, CO_2, Volatile Organic Compounds, NO_x	ppm/ppb	X	X
House Dust Mites (HDM allergen Der p 1)	µg* & µg/ g dust		X
Small -/+ charged air ions	No.'s/ cm^3 of air	X	X
Mould counts	no.'s/ slide		X
Wind speed and direction	m/ sec	X	

* total µg per sample.

The total data set available from each visit comprised 34 parameters.

Details such as study number, time and date of data entry were used to locate data sets from each visit, allowing a seamless integration of data between the parallel studies, which also used the same data locators.

The equipment and methodology used by the Tool Kit

- PM_3 (fine particles 0.3 to 3.0 µm) and PM_7 (coarse particles 3.0 to 7.0 µm) were measured using a laser beam particle counter, equipped with a temperature (°C)/ relative humidity (RH %) probe, (Met One model 227B, Oregon, USA). Particles were counted per litre of air, continuously over a 30 second period, both in and out of doors (5 % coincidence error at 70,671 particles/ litre). The characteristics of the counter defined the particle size ranges used. All measurements were taken 1.5 m above floor level.
- Positively and negatively charged small atmospheric air ions, with a mobility range of 0.05 cm^2/ sec/ V (Medion specification sheet, 1975), were counted in and out of doors using an Atmospheric Ion Analyser, type 134A (calibration tolerance ± 5%) Medion, Oxted, England. All measurements were taken 1 m above floor level.
- Electrostatic fields were recorded with a static locator, model SCANFIELD, with a variable range of '+' or '-', 0 to 100 kV depending on the proximity to a source. All measurements were taken 0.5 m above floor level.
- Details of climatic conditions were noted including temperature, relative humidity, wind direction and wind speed. Government Meteorological Office reports were used to verify recorded details.

- Moisture (Damp) on wall surfaces and in the actual fabric of the walls was recorded by a PROTIMETER, made by Protimeter PLC, Marlow, UK. The Protimeter measures Wood Moisture Equivalent (the moisture that timber would adopt if kept in contact with the material measured, over time) with an accuracy of ± 1%.
- Carbon monoxide (CO) was measured with a CO detector (measuring in parts per million - ppm), made by Kane International, Welwyn Garden City, UK.
- Gas samples (for analysis of CO_2, NO_x and other gases) were collected in 100 ml syringes with a multi use sealing system, allowing subsequent analysis by Fourier Transform-Infra Red spectroscopy (FT-IR).
- Mould spores were collected on Hygicult slides with a 18 cm^2 growth/ collection area, made by Orion Corporation, Orion Diagnostica, Finland. The slides were exposed for one hour, then cultivated at room temperature in their plastic containers for 7-10 days. The Hygicult slides' growth medium was pre-moistened. A colour photograph was taken of each slide after cultivation.
- Dust samples were taken for later analysis off site to determine the levels of dust mite allergens present. The samples were trapped on a special filter material using a VorWerk VK 130, vacuum cleaner (without the EB 350 attachment) made by VORWERK, Germany. The filter material (VILENE), was made by Vileda, Germany. It is a breathable, saturation bonded mixture of 30% viscose, 30% polyester and 40% polyamide fibres. Basis weight 90 ± 10% g/ m^2. The dust samples were then sent for laboratory analysis of HDM allergen (Der p 1) content in the collected dust, according to the Elisa process (as described by Luczynska et al, 1989).

A case study of 116 Local Authority houses

General

A community worker with a good local knowledge, booked each house visit by correspondence and verbal confirmation with householders. The Researcher/ data collector was chosen from a different town with no connections with the Tenants or their surroundings. The researcher was instructed not to afford any help or comments during each visit even when Tenants expressly asked questions about the survey in general or results from measurements within their house (Tenant participation: Year 1 - 91%; Year 2 - 93%). Measurements were taken in the living room of each house and in a selected bedroom (SB), where at least one person regularly slept, who suffered from a respiratory illness. The houses had a similar internal layout, with a total volume of approximately 220m^3.

Site description

The housing estate was situated in a dedicated residential area, far from any major roads, with no through traffic or industry nearby. Virtually the only diesel driven vehicles on the estate were a regular bus service (once per hour), delivery vans and a few private cars. There were only 8 houses using coal fire as their only source of heating on the estate. The other houses used various combinations of gas and electric central heating.

Time scale

The study had to fit in with the house renovations, with time allowed for the Tenants to adjust to the renovations before an IAQ assessment took place. The Local Authority renovated the houses during suitable weather conditions (to avoid rain when re-roofing the houses). Hence, the timing for the execution of the study coincided with the coldest period of the year, from the end of

January to mid-March. During this period all children of school age were away from the houses for most of the day. The data could only be collected between 09:30 and 15:00 from the houses to minimise disruption for the Tenants.

The staggered plan of renovation allowed different data sets to be recorded as follows;
Year 1 – Comparisons were made between individual houses and the whole data set for any parameter.
(Between year 1 and 2, 50% of the houses were renovated to meet Government recommendations).

Year 2 - Measurements as for year 1, plus;
comparisons can be made between non-renovated and renovated houses, by comparing to Year 1 results and between the different houses within Year 2.
(Between year 2 and 3, the remaining houses will be renovated).

Year 3 - Measurements as for year 1, plus;
comparisons can be made between non-renovated and renovated houses by comparing to the Year 1 & 2 results respectively.

Eventually comparisons can be drawn between IAQ, social and personal conditions for Tenants and between the renovated houses and the non-renovated houses from previous years. The results can be divided into groups of houses with smokers and non-smokers. This distinction is important since tobacco smoke has such a major influence on the number of fine particles indoors and the deposition of tobacco related compounds (Abt et al, 2000).

Modifications made to the universal Tool Kit for the case study

- Dust samples were collected from a mattress in the SB. 1 m^2 of the mattress was vacuumed during a 1 minute period. The mattress was chosen as the sampling point as there is a significant exposure to HDM when in bed (Antonicelli et al, 1991; Htut, 1994).
- Since all the houses had a similar internal layout, measurements could be taken in the same place in every house, except for variations in the position of the SB. Measurements for damp were only carried out in the SB, wherever damp was visible or suspected.
- The Researcher made observations of any unusual circumstances experienced i.e. houses surrounded by excessive coal fire smoke. Sometimes, against recommendations, Tenants would vacuum clean the whole house just before the Researcher visited, thereby distorting measurements of air borne particles.

The assessment of ventilation rates in the houses whilst people were present (given limited time) was not possible using conventional measuring systems, such as releasing smoke or carbon dioxide. Ventilation rates can however be empirically determined by comparing in/ and out of door values for a number of parameters.

Results and Discussion

The quantitative results gained from the first year of the case study serve as a good example of the results that could be expected from the Tool Kit. As the data from the study were so extensive only a few results will be discussed in detail. Examples of how these results can be represented are given in figures 1 - 5. Figure 1 shows the average difference (n = 116) between outdoor and indoor levels of certain parameters. To test for significant statistical correlation's between certain parameters a Pearson correlation (2 tailed) test was conducted using SPSS 9.0 for Windows.

PM_3 - The results showed a strong correlation ($p < 0.01$) between the number of PM_3 and the number of smokers per household (see Figure 2). The ratio between PM_3 in the SB compared to the level of PM_3 outdoors was 1.4:1 for households with no smokers and 4.7:1 for households with smokers.

PM_7 - The results showed a strong correlation ($p < 0.01$) between the number of PM_7 and the number of people and large pets per household. The number of large pets was added as they also markedly affect PM_7. Figure 3 illustrates how the number of PM_7 increases with an increasing number of 'bodies' in the houses. The average ratio between PM_7 in the SB compared to the level of PM_7 outdoors was 2.5: 1 for all households. The average ratio between PM_7 in the living room compared to the level of PM_7 outdoors was 3.7:1.

RH & Temperature - The average RH for all houses was found to be lower indoors than outdoors, however when calculated as absolute humidity, the moisture content of the air was actually greater in the SB (13.1 g of water/Kg of air compared to 9.2 g/Kg outdoors).

CO_2 - Carbon dioxide levels were compared indoors and outdoors (Figure 4) for each house. Although in theory comparisons can be drawn between the number of people in the house, the CO_2 concentrations and the rate of ventilation, in practice this does not provide a reliable indication of ventilation. This is because the number of permanent residents were not representative of the number of people actually present when the samples were taken.

Damp - The wall surface dampness in the houses varied from completely dry walls to walls saturated with water and visible mould. In the selected bedrooms, 46% of the houses had a RH of 45-55%. The average number of mould colonies in the bedrooms was 9.4 per slide. The variation in the number of moulds per house is shown in Figure 5. Figure 5 also shows that there is no visible increase in the number of mould colonies when compared with increasing RH.

HDM - The average amount of HDM allergen Der p 1 in 1 g of dust taken from the mattresses in the bedrooms was 2.72 μg. This value is above the critical level of allergen for sensitisation of > 2μg/ g suggested by the International Workshop on dust mite allergens and asthma (International Workshop Report, 1989).

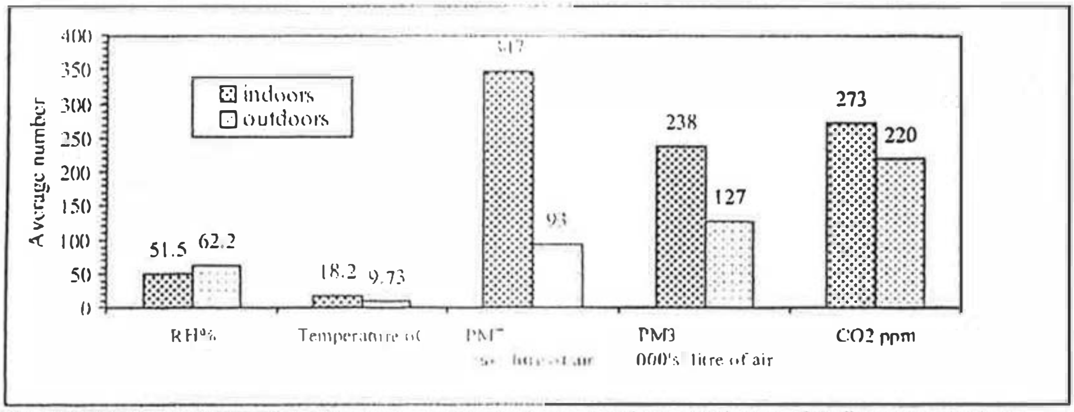

Figure 1: Comparison of the average value indoors against outdoors, for five parameters.

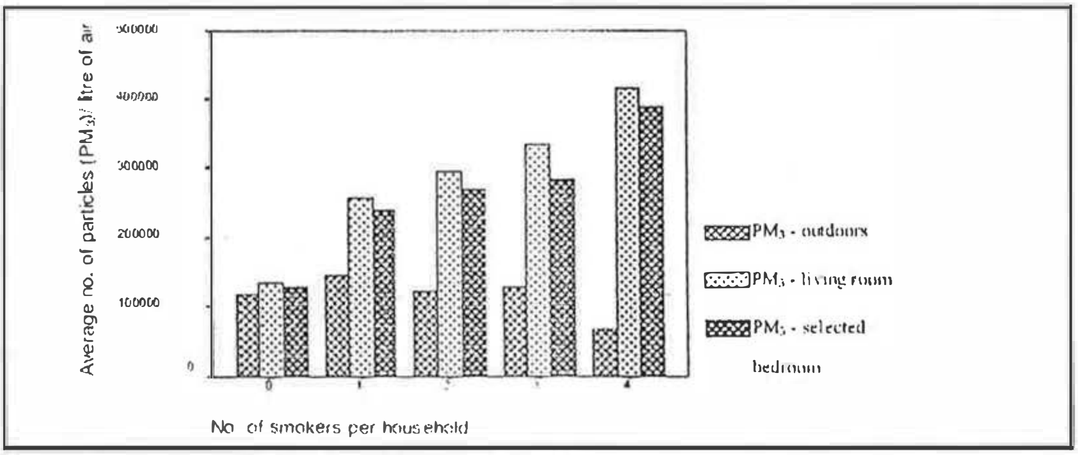

Figure 2: The effect of the number of smokers per household, on the number of PM_3.

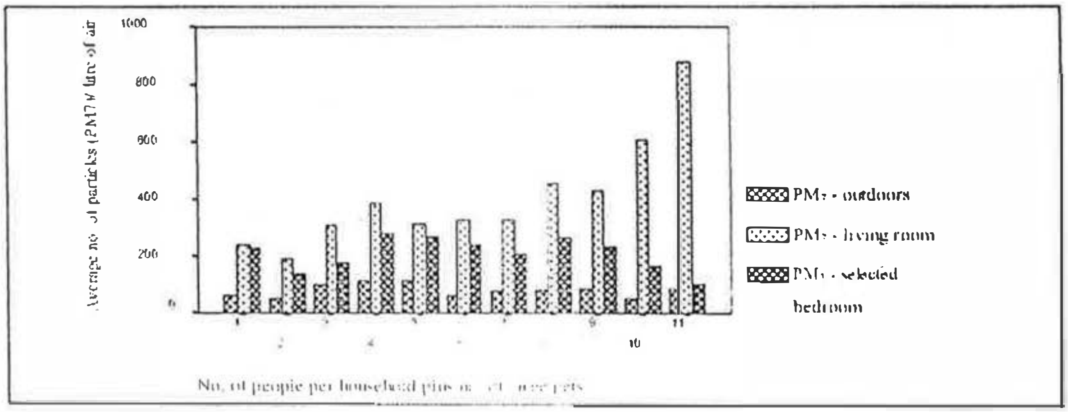

Figure 3: The effect of the number of people and large pets per household, on the number of PM_7

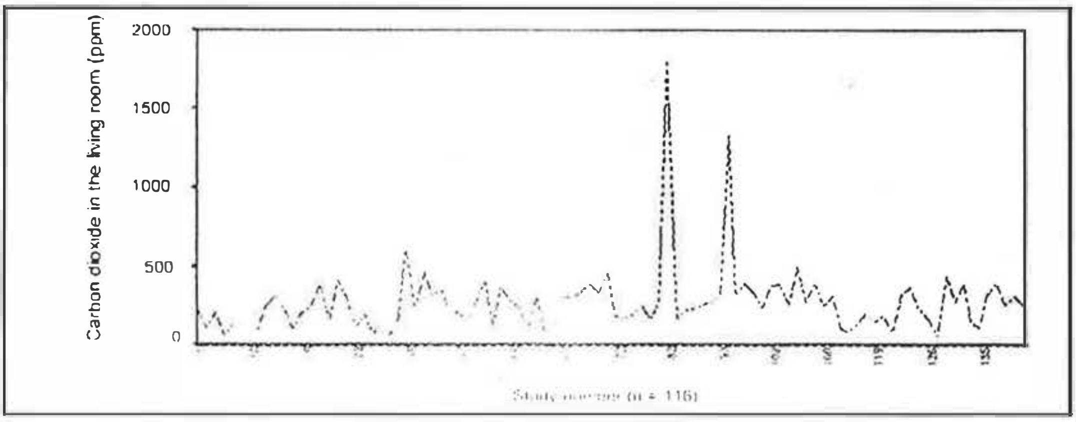

Figure 4: The level of carbon dioxide in the living rooms of individual houses.

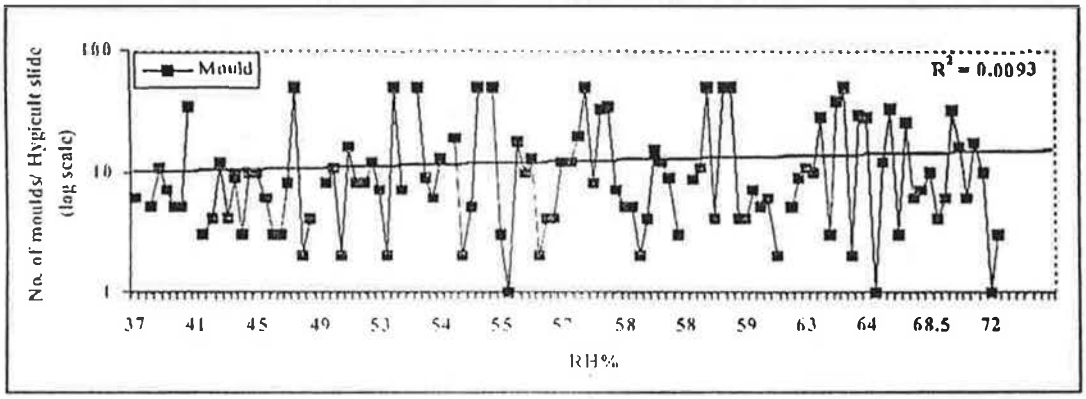

Figure 5: Comparison of the number of moulds per slide against Relative Humidity (RH%).

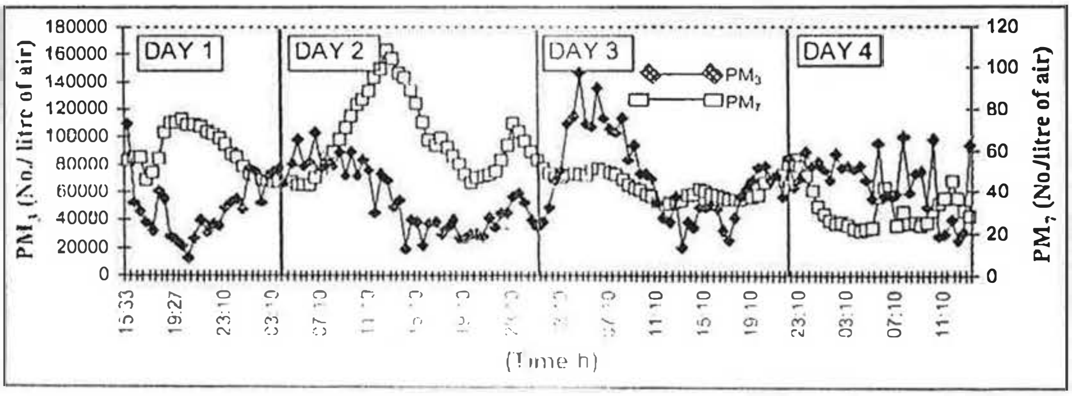

Figure 6: An example of how particulate numbers vary throughout the day in a city centre office.

Quantification of ventilation rates

Since PM_3 indoors can only be removed by movement of air through adequate ventilation, the total number of PM_3 indoors is a relevant parameter for gauging the degree of ventilation in a locality. By comparing the difference between the total number of PM_3 indoors to outdoor levels, past and present rates of ventilation can be assessed.

However, relative humidity is not easily comparable with outdoor values as there is generally a higher level outdoors. A comparison can be made of internal RH, for example between the SB and the living room. Internal air movement should equalise RH throughout the house, given time. For example, during the night exuded moisture in the bedrooms remains trapped if there is no internal air movement. Internal temperature is also difficult to compare with outdoor values. Whilst it is possible to appreciate that during cold weather people prefer not to ventilate because of increased heating costs, this makes it difficult to compare temperature in/ outdoors to gauge ventilation. If major differences were found in the temperature of different rooms, this would suggest low internal air movement.

Given the circumstances of the case study the use of CO_2 levels as a measurement of ventilation rates was extremely difficult.

The ideal proliferation and living conditions for HDM are not solely dependent on ventilation, but also temperature, RH and household management. The recorded conditions for the case study do not initially assist in determining ventilation rates.

Analysis of the Tool Kit methodology

The Tool Kit has been used over a period of 2 years under widely differing circumstances and in each case has provided robust information for all parameters recorded. The Tool Kit has shown that it is possible to use a standard approach when assessing IAQ irrespective of local environmental factors. However, the studies using the Tool Kit have revealed some difficulties that need to be addressed for any future major study:

- To remain impartial when dealing with the occupants/ owners of a locality. It is very difficult to remain courteous and yet not respond to direct questions from people within a locality being tested about any problems with their indoor environment. Advice was not given to the Tenants in the case study since it may have influenced future results.
- As the gas samples had to be analysed off site there are concerns that the chemical composition of the samples may change during transport.
- Mould samples were not speciated. Counting the number of colonies gave a good indication as to the quantity of mould circulating in the air but no assessment was made whether the moulds were particularly harmful to health
- The recording of electrostatic fields in the living room did not contribute any useful information, since few significant fields were encountered. In subsequent studies, measurements will be made of electrostatic fields 70 cm in front of ordinary television sets, since some TV sets give rise to substantial electrostatic fields.
- Given the time limit of one hour, it was not possible to measure particulates in $\mu g/m^3$, as the equipment required for this needed a longer sampling time.
- To be able to use CO_2 recordings as a measure for 'ventilation', the recordings will have to be set against the number of people present at the time of and just prior to measuring.

The Tool Kit gave a very comprehensive set of results, which were easy to manipulate, even though the interpretation was time consuming. The results from the case study show the types of statistical and graphical interpretations that can be made. The Tool Kit has so far proven to be reliable, operational in sensible time periods and is easily handled by one person. When used in conjunction with results from health studies etc., further statistical analysis will be applied to the data, including regression analysis to search for any links between the IAQ and the health of any occupants.

When the Tool Kit has been in use for some time and a substantial bank of data on IAQ/ and ventilation rates has been collated, it should be possible to develop guidelines on how to establish good quality indoor environmental conditions. How house owners will be able to measure parameters to meet recommendations, without reliance on outside expertise is difficult to understand at the moment, since a complete Tool Kit costs around £10,000. Furthermore if Local or Central Government were to introduce legislation on minimum standards, the enforcement of such legislation would be extremely difficult.

Whilst it is possible to manipulate the data sets presented herein in many different ways it is not possible to generate data continuously over a longer period of time. The enclosed Fig 6 exemplifies how human activities influence particles throughout an extended time period in an office locality used only during the day and equipped with a central air processing system. A substantially modified Tool Kit, with associated cost implications, would be required to monitor the changes in temperature, RH, $PM_{2.5}$ and PM_{10} over an extended time period.

Further analysis needs to be carried out to determine the minimum number of localities required to generate statistically reliable results, for an extremely large number of localities. It may be that a smaller study would be sufficient to represent the whole number. In the future an analysis will be conducted in order to reduce the parameter set i.e. where two or more variables have very high correlation's, there will only be a need to measure one of them.

Specifically for the case study, the combination of the results from the parallel studies and the assessment of IAQ, might clarify any effect of housing improvements on changes in respiratory health. If a locality still has unexplained problems despite the fact that a full study has been made using the Tool Kit, then the locality would have to be re-examined for other more unusual pollutants. The Tool Kit will possibly enable other interested parties to pinpoint which householders in the reviewed case study need help to get the best from their renovated houses in order to improve IAQ. Using a standardised tool kit would allow an insight into possible relationships between illnesses presented in doctors' surgeries and the domestic indoor environment.

Conclusions

Case study

The Tool Kit's full potential cannot be fully assessed since only two years of the case study has been completed and no comparisons have been drawn between the environmental assessment and the other parallel studies. Therefore no conclusions can be made as to whether the Tenants have poor IAQ, or if their housing conditions are influencing their health. Once the data is available for the renovated houses, it will be possible to assess the effect of housing improvements on respiratory illnesses.

Rates of ventilation

Although the Tool Kit cannot give direct ventilation rates expressed in m^3 / sec, it is possible to relate degrees of ventilation with the level of certain parameters.

General

The Tool Kit has so far met the criteria set, however, when more details are available from these studies an in depth analysis of the efficacy of the Tool Kit will be made.

Abbreviations

Term used	Definition
Der p 1	allergen from HDM
FT-IR	Fourier Transfer -Infra Red spectroscopy.
HDM	House Dust Mites. *Dermatophagoides pteronyssinus.*
IAQ	Indoor Air Quality
PM_x	particulate matter with an x aerodynamic diameter given in microns.
ppm/ ppb	parts per million/ parts per billion
RH	Relative Humidity %.
SB	selected bedroom where somebody regularly slept that had breathing problems
µm/ µg	micron or micro-meter/ micro-gram. 1µm/ µg is equivalent to 0.001mm/ 0.001 mg.
WME	Wood Moisture Equivalent %.

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PAPER NUMBER 6

Richardson G, Eick SA, Harwood DJ, Rosén KG, Dobbs F. Indoor air quality, Part 2: Negative air ionisation and the generation of hydrogen peroxide. The Science of the Total Environment (Submitted 2000)

Indoor air quality, Part 2: Negative air ionisation and the generation of hydrogen peroxide

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Abstract

The aim of this study was to continue the investigation of the production of low concentrations of hydrogen peroxide (H_2O_2), using a single polarity (DC) extra high tension (EHT) negative voltage generator. Part 1 of these studies showed the production of H_2O_2 at the air-water interface (Challenger et al, 1996). A specially designed enlarged interactive gas phase reactor (EIGPR) was used to assess the production of H_2O_2 in indoor air with varying humidity levels. Small negative air ions were produced using a carbon fibre thread electron emitter, charged with a single negative polarity, variable DC current (0 - 7.5 kV). Negative ion concentrations ranged from 0 - 21 000 ions/ cm^3. Hydrogen peroxide generation ranged from 0.46 µg/ l in ordinary air (RH 47%) to 936 µg/ l in wet air (RH 96%). This study demonstrates that it is possible to produce low concentrations of hydrogen peroxide in ordinary air subjected to negative air ionisation.

Keywords: Hydrogen Peroxide; Superoxide; Negative air ions; Indoor air; EIGPR; EHT; FT-IR spectroscopy.

1. Introduction

There is a need to improve indoor air quality (IAQ) by reducing airborne contaminants, such as fine particulate matter and micro-organisms known to affect humans. The ionisation of air by negatively charged small air ions provides a mechanism for the physical removal of particulate matter from ambient air by electrostatic forces (Rosén & Richardson, 1999; Richardson et al, 2000). This mechanism applies to inert particles such as tobacco smoke and to biological aerosols containing microbes (Estola, 1979). The survival rate of exposed micro-organisms could also be affected by a chemo-toxic mechanism caused by the release of negative ions, which results in bactericidal or bacteriostatic actions. A study by Phillips et al (1964), showed that exposure to negative air ions could increase the death rate of biological aerosols, containing *Serratia marcescens*. Many commercially available ionisers may produce hydrogen peroxide (H_2O_2) (Goldstein et al, 1992) and might also produce ozone (Pethig, 1984), especially through electrical discharges from ageing needle type emitter points. Both hydrogen peroxide and ozone are anti-microbial agents that might have been involved in the decay rate of aerosols in Phillips' (1964) study. The use of ozone in this respect should be limited because of the risk to human health (Boeniger, 1995). The production of ozone can be limited by keeping the voltage applied to an emitter to below 7.5 kV (Pethig, 1984).

Previous work (Part 1) with an extra high tension (EHT) negative voltage generator has established that when electrons are added to indoor air, superoxide ($O_2^{\bullet -}$) is produced. When superoxide reacts with water low concentrations of H_2O_2 are formed at the air/ water interface (Challenger et al, 1996). H_2O_2 is a natural component of air, with anti-microbial effects (Hyslop et al, 1995). Challenger et al (1996) demonstrated that H_2O_2 was generated when water was exposed to negatively ionised air. The concentration of H_2O_2 in a cuvette of water, was measured using chemiluminesence after exposure to negatively ionised air. Equations

(1,2 & 3) occur in the air water interface between electrons and water molecules, when the water is exposed to ionisation (Challenger, 1996):

$$e^{-} + H_2O \rightarrow e_{aq}^{-} \qquad (1)$$

$$O_2 + e_{aq}^{-} \rightarrow O_2^{-\cdot} \qquad (2)$$

$$2\,O_2^{-\cdot} + 2H^{+} \rightleftharpoons 2\,OH^{-} + [2\,O] \rightleftharpoons H_2O_2 + O_2 \qquad (3)$$

It was postulated that these reactions would also occur in indoor air, without a standing body of water. The object of the current study was to demonstrate the generation of H_2O_2 in indoor air, in relation to the production of negatively charged small air ions (superoxide), through the reaction of the electrons in indoor air.

An enlarged interactive gas phase reactor (EIGPR, patent pending) was designed to fit into the sample compartment of a Bruker IFS66 Fourier Transform Infra-Red spectrometer. This allowed the measurement of changes in H_2O_2 concentration in a sample of indoor air when exposed to electrons. A FT-IR spectrometer was used as it provided accurate measurements of H_2O_2 in parts per billion. The use of an instrument that measured in the gas phase rather than liquid samples allowed real time measurements to be taken of H_2O_2 production in the air. This provided a more realistic representation of the production in indoor environments.

The purpose of this study was to demonstrate the production of H_2O_2 in indoor air, with varying humidity levels and varying concentrations of negatively charged air ions.

2. Methods

2.1. Instrumentation and conditions

All measurements to record gas phase reactions were taken in a Bruker IFS66 Fourier Transfer Infra Red (FT-IR) spectrometer, under the following conditions. Resolution 4.0 - absorbance; zero filling 2; sample scans 16; wave numbers 400 - 4000 cm^{-1}. The spectrometer was fitted with a CO_2 scrubbed dry air purge. Background spectra were measured in the FT-IR sample compartment, which was sealed and empty.

A gas tight enlarged interactive gas phase reactor (EIGPR), built to exactly fit within the aperture of the FT-IR (still allowing the purge of the instrument to function) was used for all the experiments. The dimensions of the Plexiglas EIGPR were - length 23.8 cm x depth 19.8 cm x height 18.8 cm (volume = 8859 cm^3). The EIGPR was arranged to work in line with the spectrometer, allowing the infra red beam of the FT-IR to pass through 5 cm diameter potassium bromide (KBr) windows fitted to the EIGPR. The new reactor has a path length of 23.8 cm, as compared with a standard gas cell with a path length of 10 cm. The EIGPR was designed with various inlets/ outlets to allow the connection to an EHT generator and or allow continuous flow of various gases. A length (20 cm) of carbon fibre thread was suspended along the top of the inside of the EIGPR and attached to a single polarity (DC), EHT generator, based on a Cockcroft-Walton circuit diagram (Department of Medical Physics, Plymouth). The connector for the carbon fibre thread was electrically double insulated against the Plexiglas. The negative voltage applied to the carbon fibre could be varied up to a maximum output of -7.5 kV.

2.2. Procedures

2.2.1. H_2O_2 calibration

For the measurement of hydrogen peroxide, the FT-IR was used to scan at wave numbers 850 - 900 cm^{-1}, where peroxides can be measured as - O - O - stretching vibrations (Lambert et al, 1987). H_2O_2 has been measured approximately at 865 cm^{-1} (Webbook, 2000). Although there are a number of characteristic absorbencies of H_2O_2 in the mid-IR, preliminary work with H_2O_2 showed that the - O - O - stretching vibration was least affected by background noise.

To determine the concentration of H_2O_2 produced in the EIGPR a calibration curve was plotted. Standards were made using a 30 wt % H_2O_2 solution in water (BDH Laboratory supplies, Poole, UK), evaporated in a sterile 104 cm^3 gas cell, (both ports were sealed). The corresponding absorbance units of progressively lower concentrations of H_2O_2, starting with 16 μg of H_2O_2/ litre of air were recorded.

2.2.2. Reduction of particulate matter in the EIGPR

A particle counter was used in parallel with an atmospheric air ion analyser to check that the EHT electron generator had enough capacity to produce sufficient small air ions to reduce particle numbers, whilst still producing enough ions for the production of H_2O_2. Particulate matter concentrations were measured as fine particles 0.3 to 3.0 μm and coarse particles 3.0 to 7.0 μm (no./ l of air), using a laser beam particle counter with a temperature (°C)/ relative humidity (RH) probe, (Met One model 227B, Oregon, USA). Particle numbers were counted within the EIGPR at 0 and -7.5kV.

2.2.3. Production of small air ions

To assess the production of ions generated per kV, an atmospheric air ion analyser (Type 134A. Medion, Oxted, England) that selectively measures small air ions in the mobility range 1-2 cm^2 /sec /volt, was attached to an outlet of the EIGPR. Air was continuously drawn through the EIGPR by the ion analyser at a rate of 5.0 l/ s. The air ion analyser, the extra high voltage generator and the EIGPR were all connected via resistors to a common high grade earth. Measurements were taken at voltages ranging from 0 to -7.5 kV, in ordinary, dry and wet air.

2.2.4. Generation of H_2O_2 in ordinary air

The indoor air used for this experiment and for all other experiments was ambient air from a laboratory with forced air ventilation and filtration for coarse particles. To reduce the risk of fluctuations in the quality of the air, only two people were present during the experiments. A background spectrum was recorded and then the EIGPR was filled and sealed with indoor air at a temperature of 20 °C and ~ 40 % relative humidity. Measurements were taken with the EHT generator set at 0, -3, -6 & -7.5 kV respectively. This experimental condition is referred to as ordinary air.

2.2.5. Generation of H_2O_2 in 'dry' air

The EIGPR was filled with indoor air and 4 watch glasses, each containing 50g of calcium chloride ($CaCl_2$) crystals, then sealed. The $CaCl_2$ was left inside the EIGPR for 88 hours to remove as much moisture as possible from the air. Measurements were taken with the EHT set at 0, -3, -6 and -7.5 kV respectively. This experimental condition is referred to as dry air.

2.2.6. Generation of H_2O_2 in wet air (96% RH)

The EIGPR was filled with indoor air and sealed for 20 hours with a wet paper towel enclosed. The paper towel was drenched in de-ionised, distilled water (DDW) obtained from a Milli-Q system. This enabled complete saturation of the atmosphere within the EIGPR, characterised by running condensation on the inner surfaces of the cell. Measurements were taken with the EHT set at 0, -3, -6 and -7.5 kV. It was necessary to re-polish the KBr windows of the reactor frequently with this type of experiment. This experimental condition is referred to as wet air.

2.3. General

Statistical analysis was conducted using a Pearsons correlation to determine if there was a significant change in particle numbers at 0 and -7.5 kV. All measurements were taken in triplicate and a mean value was calculated from those measurements. A standard deviation was calculated for each experiment to determine the level of error. Before the FT-IR spectrum of each gas sample was measured, the sample compartment and spectrometer bench were thoroughly purged to prevent contamination from previous samples.

3. Results

3.1. H_2O_2 Calibration

Fig.1 shows the linear calibration curve (r = 0.98) for known concentrations of H_2O_2 and the absorbance units of these concentrations at wave number 865 cm^{-1}.

3.2. Reduction of particulate matter in the EIGPR

The ordinary air contained a mean of 161 300 fine particles/ litre of air and 382 coarse particles/ litre of air. After the introduction of electrons (at -7.5 kV), fine particles were reduced by 40% ($P < 0.05$) and coarse particles were reduced by 68% ($P < 0.05$). This confirmed that the EHT generator was operational inside the EIGPR.

3.3. Production of small air ions

The ion concentration in ordinary/ dry air and wet air showed a linear relationship (r = 0.95 and 0.86 respectively) with voltage (Fig.2). Ion concentration ranged from 0 - 21 000 ions/

cm^3 of air. The presence of increased relative humidity in wet air, reduced the number of measurable small air ions by 25 - 80 %. The greatest difference was at voltages below - 6 kV. The least difference was found at higher voltages where there was only an average 25% difference between ions produced in wet air and ordinary air. No production of ions was observed below –4 kV.

3.4. Production of H_2O_2

Table 1 gives the results for H_2O_2 production at the three different humidity levels, along with corresponding voltages and ion production. The H_2O_2 concentration in ordinary air without applied voltage, was found to be below the detection limit of the spectrometer. When voltage was applied, H_2O_2 production ranged between 0.46 μg/ l in ordinary air and 936 μg/ l, in wet air. The production in dry air was below the detection limit at all voltages. At voltages lower than -6 kV, no detectable additional H_2O_2 was produced in any of the experiments.

3.5. Experimental problems

The lenses of the EIGPR started to cloud over during the wet air experiments, due to the inner surfaces being affected by water. This could possibly be the formation of potassium compounds on the inner surface of the lenses.

4. Discussion

The present study focuses on the generation of H_2O_2, in relationship to a low range of ion production in indoor air by using electron discharge from a carbon fibre thread emitter attached to an EHT generator. Carbon fibre emitters do not give rise to discharges or cold sparking and therefore do not generate ozone. This is because carbon fibres do not corrode (Pethig, 1984) and when the fibres break off they always fracture along crystalline structures, forming an identical morphology to that originally present. This is a result of the high degree of symmetry in the structure of carbon fibres. Steel or carbide tipped emitters used in many conventional ionisers corrode over short time periods and cause cold sparking between the corroded and non-corroded metal. This can, and does, produce ozone.

The results showed that in indoor air the small air ion concentration did not exceed 21 000 ions/ cm^3 and that ions were produced irrespective of the relative humidity inside the EIGPR. The reduced number of negative ions in the wet air can be explained by ion recombination in a gas phase and by $O_2^{-\cdot}$ dismutation in the presence of water vapour (Goldstein et al, 1992). There was a significant difficulty in obtaining stable values for ion concentrations within the EIGPR. This problem had also occurred in Part 1. However, it only marginally effected estimates of the number of ions required to produce H_2O_2. The instability of ion concentration was mostly dependent on micro current leakage to earth, despite measures taken to electrically insulate the EIGPR. The observation that ions were not produced for voltages below –4 kV probably is related to the relative permitivity of air with respect to the generation of electrons. This observation is thought to be a function of the electron energy in relation to the carbon fibre/ air interface.

In ordinary air at -7.5 kV (21 000 ions/ cm^3) the EHT generator produced an average of 0.46 ppb. This can be compared to H_2O_2 concentrations produced in the human body. The humors of the human eye can contain around 2 ppm of aqueous H_2O_2 (Hyslop et al, 1995). In Part 1 Challenger et al (1998) gave values of 24 ppb at ion concentrations of 10 - 20 000 ions/ cm^3. The massive difference in values is due to the different conditions under which each part of the study was conducted. In Part 1, H_2O_2 was produced and measurements were taken from the water in the cuvettes, rather than from the air itself. Goldstein et al (1992) actually produced 1.7 ppm of H_2O_2 in experiments around an air/ water interface, although this was at considerably higher ion concentrations (10^6 ions/ cm^3). In the present study, the experiments were conducted with indoor air and gas phase measurements were taken by the FT-IR, giving a more realistic representation of H_2O_2 production in an indoor environment. This would suggest that the latest method used gives a more correct analysis of how much H_2O_2 is actually produced when exposing indoor air to electrons/ oxygen free radicals. Equations (4 & 5) represent what would occur when electrons are added to indoor air and react with atmospheric molecules:

$$O_2 + e^- \rightarrow O_2^{-\cdot}$$

$$O_2^{-\cdot} + 2H_2O \rightarrow 2\,H_2O_2 \qquad (4)$$

$$2\,O_2^{-\cdot} + 2H^+ \rightleftharpoons 2\,OH^- + [2\,O] \rightleftharpoons H_2O_2 + O_2 \qquad (5)$$

The production of H_2O_2 in dry atmospheres was below the detection limit of the FT-IR.

In a wet atmosphere, the same reactions as shown by equations 4 & 5 could be expected. There was a substantial increase in the production of H_2O_2 due to the increased availability of water and increased generation of superoxide in the wet atmosphere. The concentration of H_2O_2 in wet air (936 ppb) produced at -7.5 kV could be a concern, as it is close to the UK Health & Safety Executives (HSE) recommendation for an 8 hour time weighted average occupational exposure standard of 1 ppm. The HSE recommendation is given to limit the likelihood of irritation to eyes, mucous membranes and skin or bleaching of the hair (ACGIH, 2000). However, the wet air experiment does not represent a typical indoor environment and the results may only be applicable in cases where the EHT negative voltage generator is installed in environments with consistently very high relative humidity. In such conditions, virtually all of the H_2O_2 would probably dissolve in the widespread condensation and this should minimise contact with the human respiratory surfaces and eyes. Studies made on the amount of H_2O_2 in the exhaled breath and saliva of normal healthy humans, indicated undetectable levels and approximately 500 ppb, respectively (Sznajder et al, 1989). Further studies of exhaled breath by Sznajder on humans with respiratory problems have documented H_2O_2 concentrations of up to 80 ppb.

Reactive oxygen species such as superoxide and hydrogen peroxide are an integral part of the human environment and as a consequence, an anti-oxidant defence system has developed in humans. This defence system involves the dismutation of superoxide by superoxide dismutase (SOD), which has not developed to the same degree in micro-organisms (Fridovich, 1989; Halliwell & Gutteridge, 1989; Gardener & Fridovich, 1991). The dismutation of superoxide results in the production of O_2 and H_2O_2. Hydrogen peroxide is then detoxified by another antioxidant or catalase to H_2O and O_2 (Michelson et al, 1977; Byczkowski & Gessner, 1988; Fridovich et al, 1989). All reactive oxygen species are related to the biological effects of negative ions (Byczkowski & Gessner, 1988).

Evidence from Part 1 of this study showing the production of H_2O_2 has been reinforced by the present study, which has given a more realistic demonstration of H_2O_2 production in indoor air. This ability to produce H_2O_2 within standard safety limits is of interest for the reduction of microbes indoors.

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Table 1

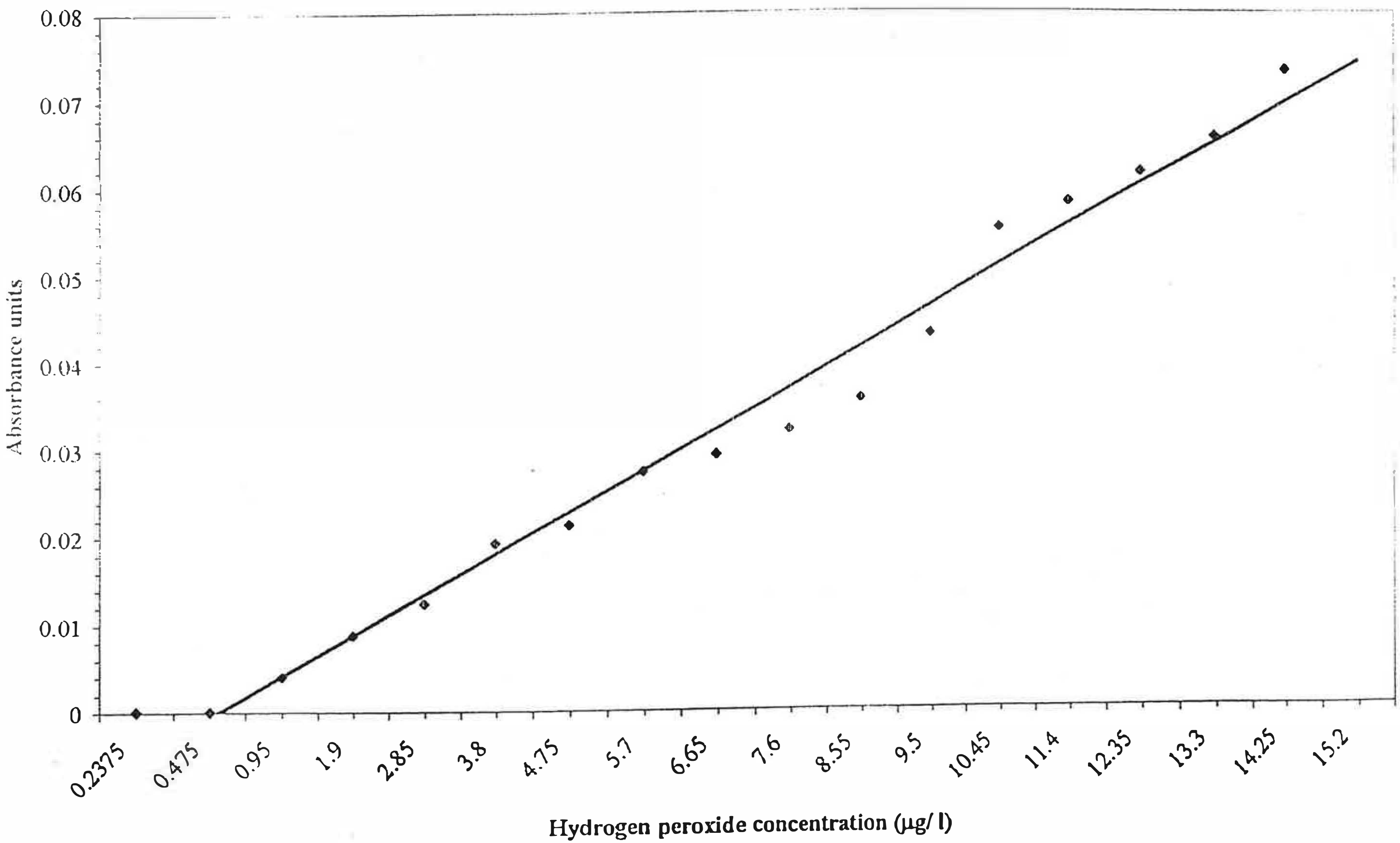
Hydrogen peroxide compared to voltage and ion production

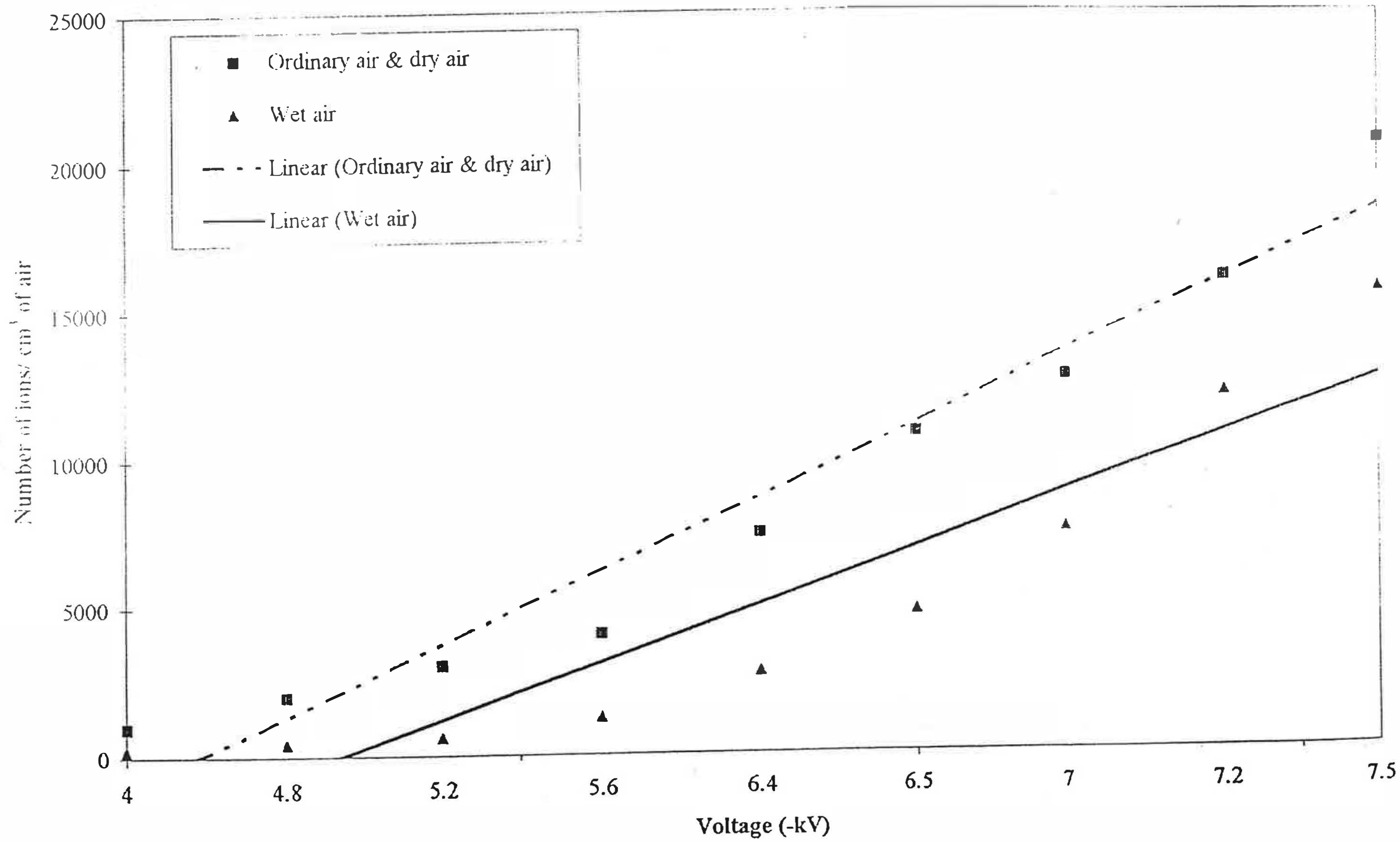
Conditions	Voltage (-kV)	Approx. ion concentration (ions/ cm^3 of air)	H_2O_2 (ppb or µg/ l)	Standard deviation (±)
Indoor air (47% RH)	6	5000	Trace	-
	7.5	21000	0.46	0.028
Dry air (6% RH)	6	5000	Below detection	-
	7.5	21000	Below detection	-
Wet air (96% RH)	6	1500	Trace	-
	7.5	15000	936	11

CAPTIONS

Fig.1 Hydrogen peroxide calibration chart using a IFS66 Bruker FT-IR spectrometer.

Fig.2 Calibration chart of number of ions against voltage in ordinary/ dry and wet air.


0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
Absorbance units
0.2375
0.475
0.95
1.9
2.85
3.8
4.75
5.7
6.65
7.6
8.55
9.5
10.45
11.4
12.35
13.3
14.25
15.2
Hydrogen peroxide concentration (µg/ l)



Ordinary air & dry air
Wet air
Linear (Ordinary air & dry air)
Linear (Wet air)
25000
20000
15000
10000
5000
0
4
4.8
5.2
5.6
6.4
6.5
7
7.2
7.5
Voltage (-kV)

PAPER NUMBER 7

Richardson G, Harwood DJ, Crossman SA. Linking absenteeism to levels of air borne particulate matter and traffic related gases in an inner city office – A controlled trial using new Electrostatic Air Cleaning technology (EAC). In proceedings of: The South West Association of University Departments of General Practice annual seminar, 22 - 23 January 1999, Ewloe, Flintshire, Wales, UK.

SOUTH WEST ASSOCIATION OF UNIVERSITY DEPARTMENTS OF GENERAL PRACTICE

JANUARY 22nd - 23rd 1999

St David's Park Hotel
Ewloe, Flintshire

WALES 1999

CONFERENCE HANDBOOK

Hosted by the Division of General Practice in Wales

Title, Room, Time Date	**Linking Absenteeism to Levels of Air Borne Particulate Matter and Traffic Related Gases in an Inner City Office - A Controlled Trial Using New Electrostatic Air Cleaning Technology (EAC) Beamaris Room, 11.00 am, Saturday 23rd January**
Authors	**G Richardson, D Harwood, S Crossman**
University	***Plymouth***

INTRODUCTION AND AIMS: To establish the degree to which a newly developed cost effective electrostatic air cleaning tec (EAC) can improve the indoor environment by;

- reducing numbers of air borne particles
- oxidising traffic and people related gaseous by-products in an urban office environment.
- reducing levels of absenteeism related to poor Indoor Air Quality (IAQ).

METHODS: Detailed evaluation of existing air moving systems was undertaken to establish base line data, recording the indoor particulate load for very fine particles (> 0,3μm) generated outdoors with associated traffic related gases and for particles (> 3,0μm) generated by human activities.

A Laser Beam type Particle counter, a Fourier Transform Infra Red Spectrometer and a Small Air Ion counter were used to record the results from the step by step integration of the EAC technology with existing state of the art air moving equipment.

RESULTS: A clear link was established between the introduction of the new technology and the substantial reduction of PM 3 and the reduction of other predominantly traffic originated measurables (NO_X and CO).

Absenteeism is reduced after the application of the new technology and in particular URTI's are reduced.

CONCLUSIONS: The study indicates that it is not possible to improve all aspects of poor indoor air using one technique alone. Poor IAQ is a multi-factorial problem requiring a more sophisticated approach.
The new technology substantially improves the quality of indoor air by reducing the number of air borne particles, thereby reducing absenteeism

Further experiments need to be carried out, in order to develop the new technology to be able to oxidise traffic and people related gaseous by-products.

PAPER NUMBER 8

Richardson G, Harwood DJ, Eick SA, Dobbs F, Rosén KG. Reduction of fine airborne particulates (PM_3) in a small city centre office, by altering electrostatic forces. The Science of the Total Environment 2001; 269: 145 – 155.

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Reduction of fine airborne particulates (PM_3) in a small city centre office, by altering electrostatic forces

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Abstract

A two stage intervention study was carried out to establish the degree to which a newly developed, electrostatic air cleaning (EAC) system can improve indoor air quality (IAQ) by reducing the number of airborne fine particles. The IAQ and how employees in a city centre office (49 m^2) perceived it, was monitored from May until November 1998. The number of fine particles, PM_3 (0.3–3.0 μm), number of coarse particles, PM_7 (3.0–7.0 μm); number of small positive and negative air ions; relative humidity and temperature were recorded in and out of doors. To assess the employees' perception of any changes in their work environment, a questionnaire was completed. Number of particles, relative humidity and temperature were also recorded in a nearby office, equipped with an identical air processor, where no interventions were made. The results from the first intervention (Stage 1), comparing number of airborne particles outdoors to indoors, gave a 19% reduction for PM_3 and a 67% reduction for PM_7 ($P < 0.001$). The reduction in PM_3 was inconsistent and not statistically significant ($P = 0.3$). The reduction in PM_7 from outdoors and the removal of PM_7 created indoors was achieved by optimizing the existing air moving equipment. The results from the second intervention (Stage 2 — with EAC units installed) comparing indoor to outdoor values, gave a further reduction in PM_3 of 21% ($P < 0.001$) and a further 3% reduction for PM_7 ($P > 0.05$). Therefore, at the end of Stage 2, the total reductions in particles from outdoors to indoors were 40% for PM_3 and 70% for PM_7 ($P < 0.001$). The Stage 2 results strongly suggest that electrostatic forces, created by the EAC unit(s) improved the removal of PM_3, with no further significant improvement in the reduction of PM_7. The questionnaire indicated an improvement in the IAQ, as perceived by the employees. The results suggest that the EAC system is effective in reducing PM_3 and thereby improving IAQ in an urban office.

Keywords: PM_3; PM_7; Indoor air quality; Electrostatic forces; MM Questionnaire; Small air ions

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1. Introduction

The current UK standard for ambient airborne particulate matter is 50 $\mu g/m^3$, measured as the 99th percentile of a daily maximum running 24-h mean. This standard applies to PM_{10} – particulate matter that will pass through a size selective inlet with a 50% efficiency cut-off at 10 μm (DETR, 1999). It is generally accepted that approximately 60% of the mass of ambient PM_{10} consists of fine particles < 2.5 μm ($PM_{2.5}$), as indicated in studies by Harrison et al. (1997) and Clarke et al. (1999). However, these mass proportions will vary with locality due to a wide variety of environmental factors and seasonal changes. There is currently no separate standard set for $PM_{2.5}$ in the UK.

The importance of fine particles from a health perspective is now recognized. A study conducted in six North American cities, by Schwartz et al. (1996) suggested that increased daily mortality is specifically associated with fine particle exposure. The fine particle fraction consists of a large number of ultra fine particles < 1 μm (COMEAP, 1995), that can penetrate into the alveoli of the human lung, whereas coarse particles mainly deposit in the bronchial region and, therefore, have different health and toxicological implications. (Wilson and Shuh, 1997). In comparison to coarse particles, fine particles contain proportionally higher concentrations of harmful acids, polycyclic aromatic hydrocarbons (PAH) and heavy metals (Arden Pope III et al., 1991; Brook et al., 1997; Clarke et al., 1999). Indoor airborne particulate matter consists of a mixture of bio-aerosols, such as microbes and pollen, minerals, combustion emissions and other chemical aerosols (Owen et al., 1992). The majority of fine particles in an outdoor urban environment are assumed to be generated by combustion processes (DETR, 1999) and approximately 75% of these outdoor fine particles could be expected to reach indoors (Rosén and Richardson, 1999). The amount of particles reaching the indoor environment is of significance because people spend up to 90% of their time indoors (Donaldson and Donaldson, 1993; Kirchner et al., 1997). Exposure to fine particles indoors can be linked to breathing-related illnesses (DETR, 1998) therefore, by reducing the numbers of fine particles, ill health due to poor indoor air quality (IAQ) should be reduced (Dockery et al., 1993; Holgate, 1997). The exposure to fine particles can be approximately 19×10^6 particles over 24 h for an adult, based on an average fine particle concentration of 100 000/l indoors, an average adult ventilation rate of 780 l/h (COMEAP, 1995) and a re-suspension rate of 99% $[100\,000 \times 780 \times 24 \times (1-0.99)]$.

This study continues to explore the use of an electrostatic air cleaning (EAC) system as suggested by Rosén and Richardson (1999), to reduce fine particulate matter indoors by altering electrostatic forces within a room. If it is assumed that airborne particles may become electrostatically charged, there is an opportunity to control the mobility of these particles and thereby clean the air.

This study includes a subjective assessment of the employees' perception of their working environment, through the use of the MM-Questionnaire.[1] The questionnaire was developed to assess perception of indoor environments and includes questions about IAQ parameters and symptoms usually related to poor IAQ (Andersson, 1998).

2. Hypotheses

(1) That there would be a further reduction of fine particles indoors compared with outdoors following the installation of an EAC system (irrespective of outdoor fluctuations), in addition to any reduction achieved by the existing air-cleaning equipment.

(2) That the reduction of fine particles indoors would improve IAQ as assessed by the standardized MM-Questionnaire.

[1] The MM is an abbreviation of the Swedish word Miljömedicin (environmental medicine).

3. Methods

3.1. Main site description

All measurements were taken over 7 months in an administrative office (Fig. 1) in the city centre of Plymouth, England, that had:

- A continuously operating forced fresh air ventilation system. The fresh air intake outdoors was located 5 m above ground. The fresh air supply had a manual speed control that was often set at zero prior to this study because the employees complained about draught and noise.
- No existing fine particle filtration for the incoming air.
- No mixing of the exhaust and incoming air.
- Three ceiling mounted, 1 m diameter slow moving fans and one multi-purpose air-processor, with a condensation removal facility. This was the only unit used to heat, cool and filter the indoor air (through continuous re-circulation).
- Seven employees and normal office working hours (the office was empty during weekends). There were no changes in employees during the study.
- No public access and no smoking allowed.
- Daily, early morning cleaning routines, to vacuum clean (without a micropore filter) the carpeted floor and wipe away surface dust.

The employees were not aware of how the installed EAC system operated or how it might influence their working environment. The cleaning routine and materials used were not varied before or during the study and did not cause any associated complaints.

3.2. Interventions to existing equipment in the main site and description of the EAC system

The interventions were applied in two stages:

Stage 1 (5 May–19 July): The existing air processing equipment was optimized to perform according to original specifications, e.g. adjusting the volume of incoming air to 0.128 m^3/s (= 2.0 air-exchanges/h) and re-directing the air inlet louvers to avoid draughts. The existing equipment

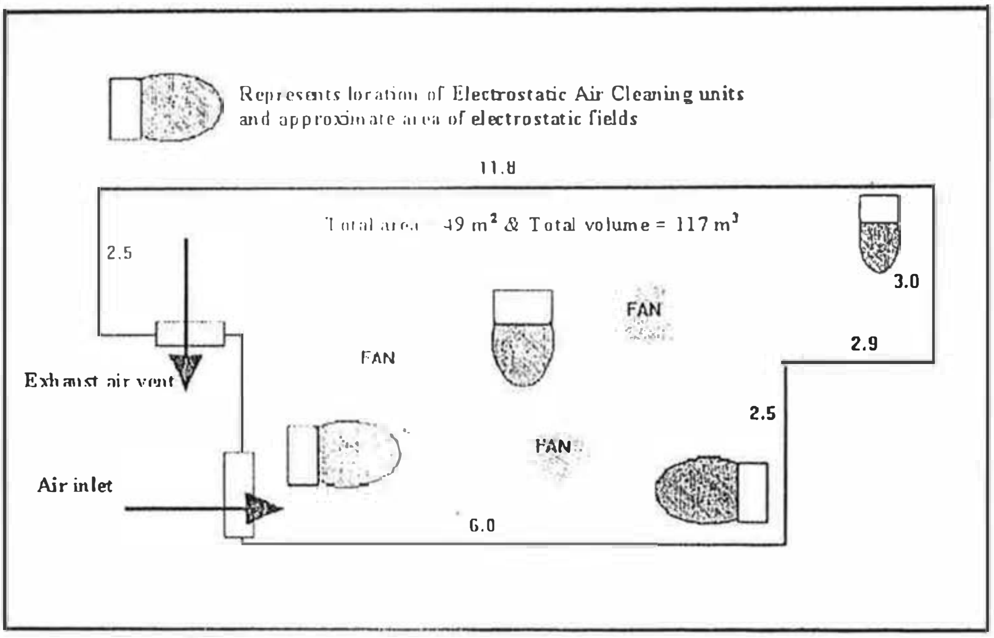

Fig. 1. Schematic [illegible] layout (main site). Measurements in meters.

was optimized first as it was not deemed useful to compare the EAC system with existing equipment that was not used to its full potential. Therefore no pre-Stage 1 data were recorded. The optimized equipment was in operation for 6 weeks before the employees were asked to complete the questionnaire. This allowed the employees time to adjust to the new conditions in the office.

Stage 2 (20 July–1 September): Installation of one EAC unit.

Description:

- One free standing, fan-assisted unit, delivering approximately 55 000 negatively charged small air ions/cm^3 of air (measured 3.5 m directly in front of the unit), with an airflow of 90 m^3/h.

Stage 2 (1 September–27 November): Installation of a further three EAC units.

Descriptions:

- One unit mounted directly in front of the fresh air inlet, delivering approximately 100 000 negatively charged small air ions/cm^3 of air (measured 2.5 m directly in front of the unit).
- One wall mounted unit delivering approximately 1500 negatively charged small air ions/cm^3 of air (measured 0.5 m directly in front of the unit).
- One free standing, fan-assisted unit, delivering approximately 15 000 negatively charged small air ions/cm^3 of air (measured 2.0 m directly in front of the unit), with an airflow of 50 m^3/h.

All EAC units (designed/modified by AC&T Ltd.) delivered a high voltage (7 kV negative polarity) DC current (< 0.5 mA) to a multi-strand carbon fibre thread (the emitter). This established electrostatic fields within the office between the emitter and positive surfaces (which act as particle collectors). The field strength measured 1 m from each emitter was −15 kV, which is similar to that of a typical television set. At the end of Stage 2, the total air volume forced through the artificially induced electrostatic fields was 600 m^3/h, as indicated in Fig. 1. The EAC units had no influence on temperature or humidity. The installation of the EAC units did not affect the day-to-day running or the design of the office and the study did not give rise to any complaints from the employees. All EAC units were in continuous operation for 24 h/day.

3.3. Sampling method — main site

- Particulate matter was measured as PM_3 (0.3 to 3.0 μm) and PM_7 (3.0 to 7.0 μm) using a laser beam particle counter with a temperature (°C)/relative humidity (RH%) probe (Met One model 227B, Oregon, USA). Particles were counted per litre of air, continuously over a 30-s period. The Met One particle counter has two channels, one which measures particles > 0.3 μm and a second which can read > 1.0, > 3.0 or > 5.0 μm up to a maximum limit of 7.0 μm. Hence, the characteristics of the counter defined the particle ranges used in this study, with 3.0 μm used as the upper limit for fine particles.
- During Stage 1 and the latter part of Stage 2, there were 55 discrete particle counts taken. Each count was the average of three readings. Also, during Stage 2, counts were taken for 11 consecutive 5-day periods (every 30 min).
- Statistical analysis of particle reduction was performed using a two-tailed, paired Student's *t*-test. This test was used to attain a *P* value. A value < 0.05 represented a statistically significant reduction in particle numbers.
- Positively and negatively charged small atmospheric air ions, with a mobility range of 0.05 cm^2/s per V, were counted using an atmospheric ion analyser, type 134A (Medion, Oxted, England).
- All measurements were taken 1.5 m above floor level and 1.5 m in front of the fresh air inlet.
- Days absent due to reported illness were monitored between July and December 1997 and between July and December 1998, by the office administration.

- Confidential MM-Questionnaire forms (MM040 EA) were completed by the seven employees at the end of the Stage 1 intervention and by the same employees after the completion of the Stage 2 intervention.

3.4. *Sampling method — outdoors*

Particles, relative humidity, temperature and small air ions, were measured using the same methodology as described in Section 3.3. There were 66 discrete measurements taken throughout the study.

3.5. *Control site*

A nearby office of similar size (seven employees), with an identical air processor to the main site, was chosen as a control site. No public access or smoking was allowed indoors. There were 27 discrete measurements taken throughout 4 months (June–September). Particles, relative humidity and temperature, were measured using the same methodology as described in Section 3.3.

A control site was established to record PM_3 in an office where no interventions were being made and to assess any natural fluctuations occurring in PM_3 levels indoors, emanating from outdoors. Small air ion measurements were not taken and a questionnaire was not carried out. Staff absenteeism was not recorded. The control site was used primarily as a source of comparison for fine particles, temperature and humidity measurements.

4. Results

4.1. *Main site*

4.1.1. *Stage 1*

The average particle counts from the Stage 1 intervention were as follows:

- PM_3 (fine particulate matter) indoors was 77 000 particles/l of air (±58 750 Standard deviation — S.D.). The value outdoors was 99 000 particles/l of air (±78 160 S.D.). The number of PM_3 indoors during Stage 1 was reduced from outdoor levels by 19%. The percentage reduction of PM_3 indoors from outdoors, varied from 0 to 40% (Fig. 2). These reductions were not significant ($P > 0.05$).
- PM_7 (coarse particulate matter) indoors was 34 particles/l of air (±13 S.D.). The value outdoors was 105 particles/l of air (±42 S.D.). The number of PM_7 indoors during Stage 1 was 67% less than outdoors. These reductions were significant ($P < 0.001$).

4.1.2. *Stage 2*

The average particle counts from the Stage 2 intervention (with EAC units installed) were as follows:

- PM_3 indoors during the first part of Stage 2 was 42 500 particles/l of air (±20 220 S.D.). The value outdoors was 71 700 particles/l of air (±34 170 S.D.). The number of PM_3 indoors during the first part of Stage 2 was 42% less than outdoors ($P < 0.001$). The percentage reduction of PM_3 varied from 30 to 58% (Fig. 2).
- PM_3 indoors during the second part of Stage 2 was 51 100 particles/l of air (±9000 S.D.). The value outdoors was 80 100 particles/l of air (±13 000 S.D.). The number of PM_3 indoors during the second part of Stage 2 was 37% less than outdoors ($P < 0.001$). The percentage reduction of PM_3 varied from 33 to 44% (Fig. 2). Throughout the whole of Stage 2, PM_3 indoors was 40% ($P < 0.001$) less than outdoors.
- PM_7 indoors for the whole of Stage 2 was 29 particles/l of air (±13 S.D.). The value outdoors was 99 particles/l of air (±42 S.D.). The number of PM_7 indoors during Stage 2 was 70% less than outdoors. These reductions were significant ($P < 0.001$).

When comparing the difference in PM_3 reductions between the first and second part of Stage 2, there was no significant difference ($P > 0.05$), despite the installation of 3 more EAC units. When comparing PM_7 reductions indoors

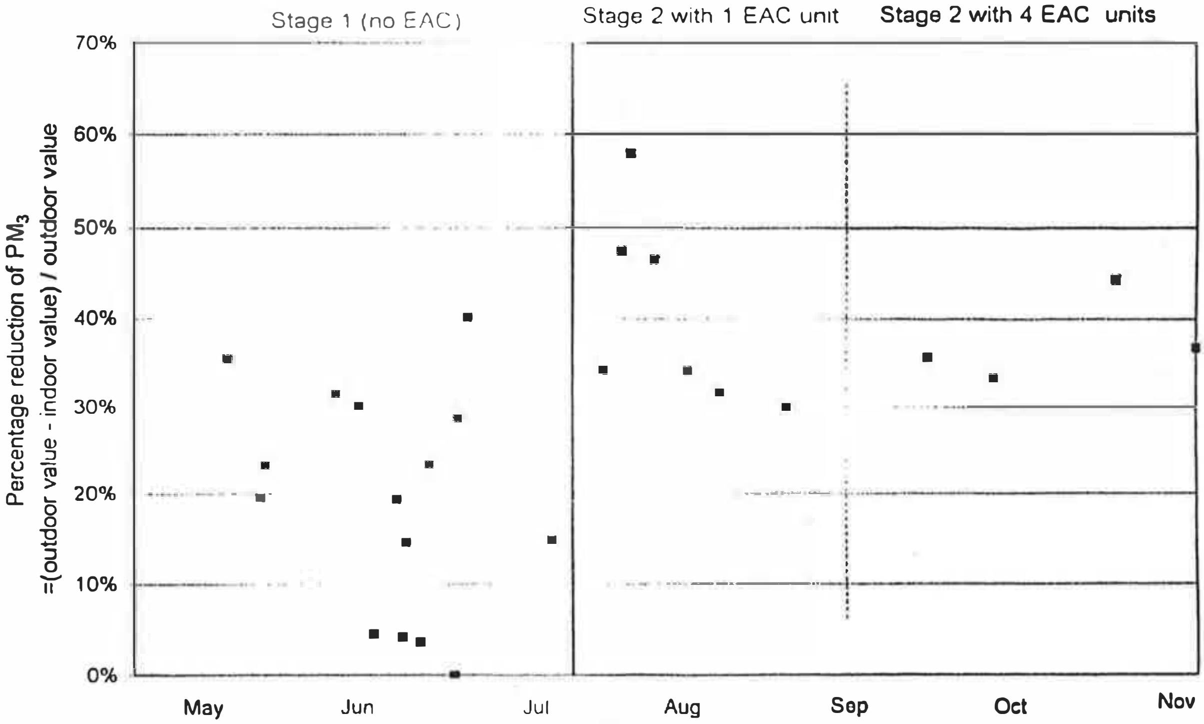

Fig. 2. Scatter chart showing the reductions in PM_3 indoors taken at discrete points throughout the intervention in the main site.

the 3% increase between Stage 1 and Stage 2 was found not to be significant ($P > 0.05$). Fig. 3 illustrates the typical variations in particulate numbers over a 5-day period during Stage 2. Fig. 3 also reveals the sudden increase in PM_7 on Monday 14 September, which was caused by a minor repair to shelving. This fluctuation had no influence on the outcome of this study.

4.1.3. Small air ions

The number of small air ions/cm^3 of air outdoors during the study ranged from 100 to 3600 positive and 0 to 800 negative small air ions. Throughout the trial period the air entering the office through the air inlet, contained approximately 800 positive and 0 negative small air ions/cm^3 of air. The small air ion counts in the office are given in Table 1. With one EAC unit installed there was no significant change in the number of negative air ions, however, with the introduction of three more units, the numbers increased dramatically.

4.1.4. Days absent

The data set (number of absences) was too small to analyse statistically. However, absence rates were very low and similar in the collection periods before and after the interventions.

4.1.5. The MM-Questionnaire

The outcome of the MM-Questionnaire indicated the poor quality of the office air before the second intervention and how the employees' perception of IAQ improved after the installation of the EAC units (Fig. 4). However, the small number of employees did not allow any statistical analysis. Noteworthy changes in perception were (numbers refer to Fig. 4 and the environmental factors listed in Table 2):

Table 1
Average number of positive and negative small air ions in the office (main site)[a]

	Positive (No. of ions/ cm^3 of air)	Negative (No. of ions/ cm^3 of air)
Stage 1	1100	100
Stage 2 (20 July–1 September)	1400	135
Stage 2 (1 September–27 November)	600	15 500

[a] *Note:* Calibration tolerance for the ion collector is ± 5%.

1: The substantial reduction in complaints about dust and dirt
6: The substantial reduction of complaints about stuffy bad air.
7: The reduction in complaints about dry air

There were also reduced complaints about the office temperature being either too high or low (see numbers 3 and 5). Complaints of noise were also substantially reduced (number 11).

4.1.6. Humidity (RH) and temperature

The average relative humidity (RH%) indoors throughout Stage 1 was 44% (range 38–60) and 46% (40–60) during Stage 2. For the whole 7-month period the average relative humidity was 51% outdoors (range 36–75). The average temperature (°C) indoors throughout Stage 1 was 21°C (range 17–25) and 23°C (range 17–25) during Stage 2. For the whole 7-month period the average temperature outdoors was 20°C (range 15–23).

4.2. Control site

The average particle counts for the control site throughout the 4 months of monitoring were as follows:

- PM_3 indoors was 75 100 particles/l of air (± 34 200 S.D.). The value outdoors was 99 000 particles/l of air (± 78 160 S.D.). The number of PM_3 indoors was 25% less than outdoors ($P < 0.05$).
- PM_7 indoors was 40 particles/l of air (± 11

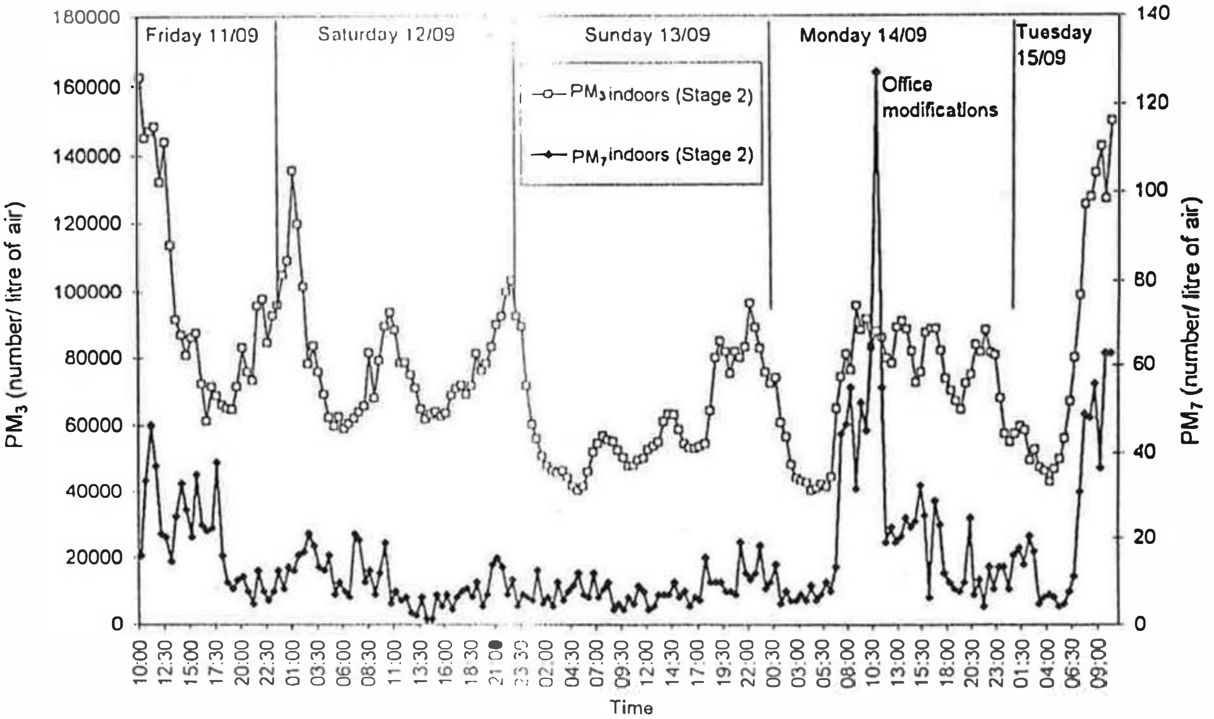

Fig. 3. A graph representing the typical variations of PM_3 and PM_7 indoors during Stage 2 (main site).

Table 2
Results from the MM-Questionnaire

Environmental factors (numbers refer to Fig. 4)	Stage 1	Stage 2	Reduction (%)
1 Dust and dirt	45	15	66
2 Draught	58	48	17
3 Room temperature too high	70	25	64
4 Varying room temperature	70	70	0
5 Room temperature too low	45	0	100
6 Stuffy bad air	70	14	80
7 Dry air	60	25	58
8 Unpleasant odour	0	0	0
9 Static electricity, often causing shocks	0	0	0
10 Passive smoking	0	0	0
11 Noise	45	15	66
12 Light that is dim or causes glare or other reflections	0	0	0

S.D.). The value outdoors was 99 particles/l of air (±42 S.D.). The number of PM_3 indoors was 60% less than outdoors ($P < 0.05$).

- The average relative humidity was 47% (39–54) and the average temperature was 22°C (21–23) indoors.

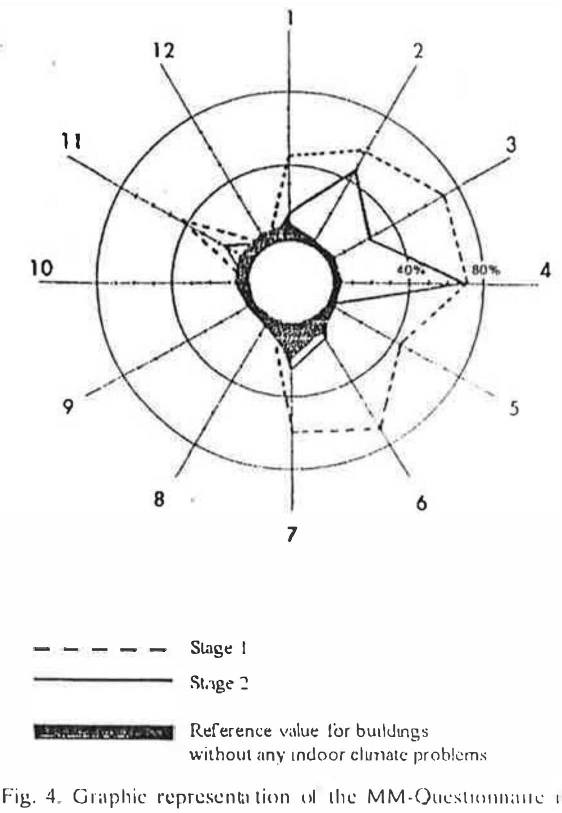

Fig. 4. Graphic representation of the MM-Questionnaire results, numbers refer to Table 2.

5. Discussion

This study was initiated to test the ability of the EAC system to reduce PM_3 in an urban office, irrespective of outdoor fluctuations and the possible addition of PM_3 generated indoors by human activities. The results achieved by the EAC system were compared with the results obtained using standard air processing equipment.

5.1. Stage 1

Indoor values of PM_3 are dependant on outdoor atmospheric conditions and air pollution from solid and fossil fuel combustion processes. During Stage 1, outdoor values of 24 000–280 000 particles/l for PM_3, exemplify the large variations in numbers that an indoor air cleaning system must be able to handle. The reduction of PM_3 during Stage 1 was 19% at the main site, as compared with a 25% reduction recorded for the control site. These reductions were similar to those found previously by Rosén and Richardson (1999). The reductions in PM_3 were attributed to a combination of particle loss through the ducting and the air processor. In Stage 1 the existing air handling equipment was very effective in maintaining a low level of PM_7 indoors, despite the continuous generation of PM_3 through human activity. The low level of PM_3 was maintained throughout the two stages and was not further significantly reduced by the introduction of the EAC units.

5.2. Stage 2

The results from Stage 2 provided evidence that there was a further reduction of PM_3 following the installation of the EAC system, in addition to the 19% given by the existing equipment. There were consistent statistically significant reductions for PM_3 (Fig. 2) throughout Stage 2, increasing the cleaning capacity from 19 to 40%. The EAC system was able to cope with outdoor variations of PM_3 and any additional PM_3 created in the office.

5.3. Small air ions

Small air ion counts measured indoors were not related to outdoor values since the input air had to pass through 15 m of earthed metal ducting and pass through two earthed steel fans. Hence the incoming fresh air had no negative ions and substantially reduced numbers of positively charged air ions compared to outdoor air.

The EAC system produces negatively charged small air ions, which are thought to have a role in the reduction of air borne particles (Martinac, 1993). Despite the fact that there was no increase in the number of negatively charged air ions during the first part of Stage 2 (Table 1), there was still a significant reduction in the number of PM_3 indoors (42%, $P < 0.001$). It is unlikely that natural forces such as sedimentation had any part in the removal of PM_3 from the ambient air in the office, as fine particles are not significantly influenced by gravity (COMEAP, 1995). The EAC system could have influenced the fine particles in the office through two different mechanisms. The first and most likely explanation for the reduction of PM_3 is the exposure of PM_3 to weak negative electrostatic fields. A possible second mechanism could have involved many positively charged fine particles adhering to small negatively charged air ions, forming particles of a larger aerodynamic diameter (Backman, 1979). It is less likely that this 'clustering' mechanism was the main cause of the reduction in PM_3, as the results indicate that there were no further reductions when the number of negatively charged air ions increased from 135 to 15 500/cm^3 of air (Table 1).

5.4. Control site

Monitored values at the control site verified that the existing air cleaning equipment performed consistently (25%) throughout and gave similar reductions to those measured at the main site during Stage 1 (19%). Therefore, during Stage 2, the identical air cleaning equipment in the main site could be assumed to have behaved in a similar manner.

5.5. The MM-Questionnaire

The MM-Questionnaire is a standardized method of assessing how human perceptions of their working environment correlate with physical properties of the indoor air. The results from the questionnaire indicated that the reduction of fine particles could indeed improve the employees' perception of IAQ. This link between the perception of air quality and levels of fine particles has been made previously. A study of 40 schools in Uppsala, Sweden found that IAQ is perceived as 'worse' at high levels of exposure to volatile organic compounds, moulds, bacteria and respirable dust (Smedje et al., 1997). In the main site, there were reductions in complaints about dust and dirt, a complaint that is strongly associated with levels of fine particles. There were also substantial reductions in complaints about dry air and stuffy bad air. All of these complaints have been linked to fine particles and an inadequate fresh air supply (Andersson, 1998). The questionnaire could not pinpoint which component was the most relevant to changes in perception about dust and dirt, stuffy bad air and dry air — the reduction of PM_3 alone or the reduction of PM_3 plus an increase in the number of negatively charged air ions.

Although the existing equipment maintained very low levels of PM_7, the employees still complained about their work environment and it was only when PM_3 was substantially reduced that complaints subsided. The questionnaire indicated that reducing PM_7 alone may not be enough to improve IAQ and reduce associated complaints.

There were also major changes in the perception of low/high temperature and noise, two parameters that were not influenced by the installation of the EAC system. Fang et al. (1998) have shown that increasing temperature and humidity can influence human perception of air quality when exposed to differing indoor pollutants. The concern with the present study was that changes in temperature might have influenced the employees' perception of IAQ. However, despite the fact that the average indoor temperature actually increased during Stage 2, they still perceived an improvement in their IAQ. Noise is very unlikely to have an influence on air quality and the change in the perception of noise was outside the scope of this investigation.

5.6. Humidity (RH) and temperature

The indoor humidity levels during the study period were typical of an office environment. The range of indoor temperatures confirms the employees' perceptions of varying temperatures. Whilst the UK Health and Safety Executive (HSE) do not give an upper limit for temperature, the averages of 21 and 23°C were comparable with a generally acceptable range of 19–21°C (HSE, 1999, personal communication). The corresponding data from the control site gave similar results to the main site, confirming the efficiency of the optimized original equipment. It is unlikely that these parameters had any influence on the reduction of PM_3 levels in the office. The results from the control site gave no indication that a rise in temperature during the summer months caused any change in PM_3 levels. PM_3 reductions from outdoors to indoors in the control site remained stable throughout the monitoring period and were not reduced or increased by minor changes in indoor temperature and humidity.

6. Conclusions

This study establishes that it is not possible to improve all aspects of poor indoor air quality (IAQ) using only one approach to tackle site dependent problems. For example, simply optimizing the existing air moving equipment in an office may not be sufficient to improve IAQ. The installation of an Electrostatic Air Cleaning (EAC) system reduced fine particulates (measured as PM_3) by altering electrostatic forces within the office (Hypothesis 1). This gave a reduction in PM_3 in addition to that achieved by the existing optimized equipment. The MM-Questionnaire indicated a relationship between the perception of IAQ and the recorded changes in physical environmental factors. The reduction of fine particulates in the office did change the perceived IAQ (Hypothesis 2). This intervention study has demonstrated the ability of the simple EAC system to reduce the number of fine airborne particulates and enhance the perception of IAQ.

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