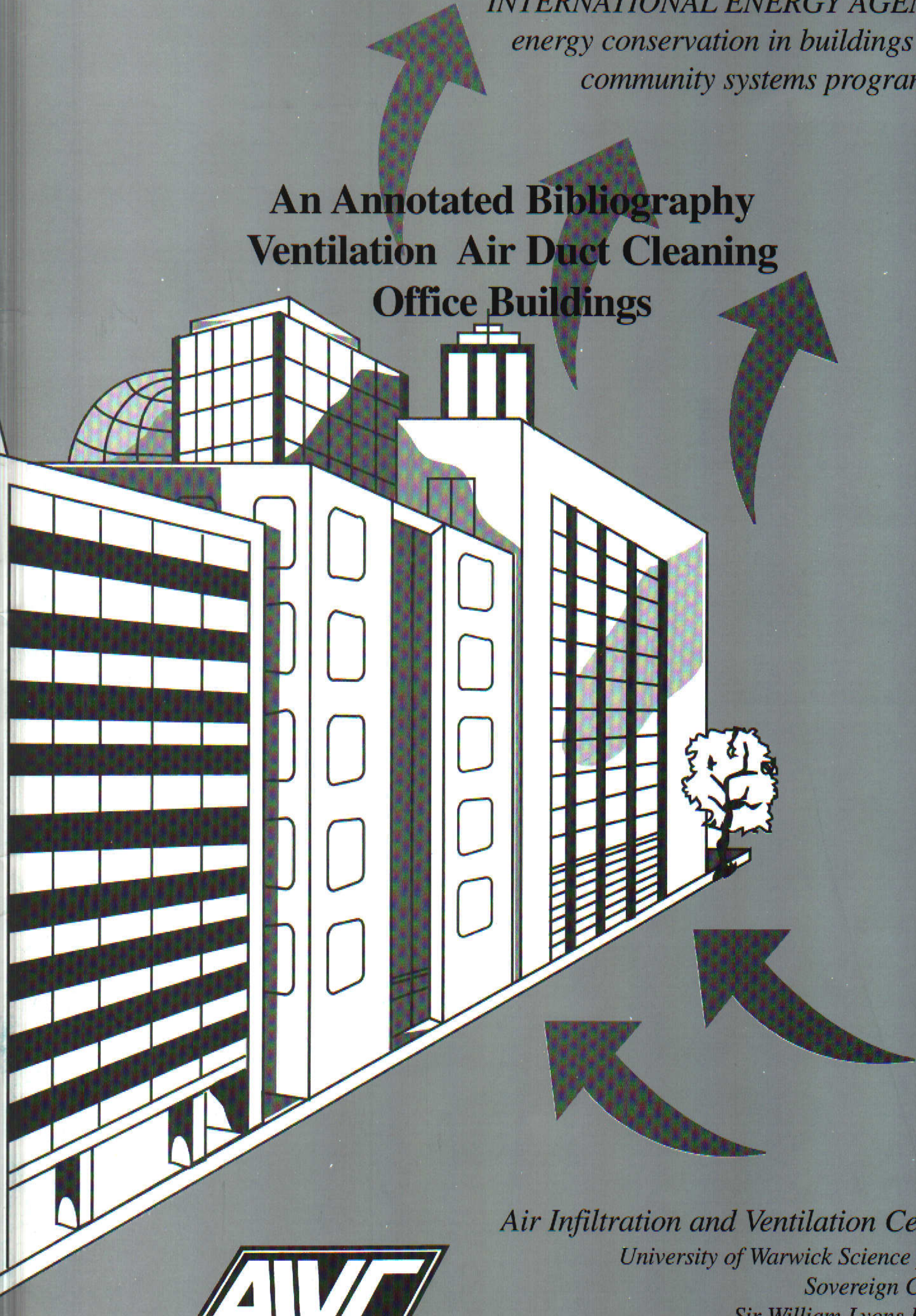
INTERNATIONAL ENERGY AGENCY
energy conservation in buildings and community systems programme

An Annotated Bibliography Ventilation Air Duct Cleaning Office Buildings



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Ventilation Air Duct Cleaning
An Annotated Bibliography

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September 2000

This report is part of the work of the IEA Energy Conservation in Buildings & Community Systems Programme.

Publication prepared by

Annex V Air Infiltration and Ventilation Centre

Document AIC-BIBLIOG-10-2000

ISBN 1 902177 14 7

Annex V Participating Countries:

Belgium, Denmark, Germany, Greece, Finland, France, Netherlands, New Zealand, Norway, Sweden, United Kingdom and the United States of America.

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Preface

International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an International Energy Programme. A basic aim of the IEA is to foster co-operation among the twenty-four IEA Participating Countries to increase energy security through energy conservation, development of alternative energy sources and energy research development and demonstration (RD&D).

Energy Conservation in Buildings and Community Systems

The IEA sponsors research and development in a number of areas related to energy. In one of these areas, energy conservation in buildings, the IEA is sponsoring various exercises to predict more accurately the energy use of buildings, including comparison of existing computer programs, building monitoring, comparison of calculation methods, as well as air quality and studies of occupancy.

The Executive Committee

Overall control of the programme is maintained by an Executive Committee, which not only monitors existing projects but identifies new areas where collaborative effort may be beneficial.

To date the following have been initiated by the Executive Committee (completed projects are identified by *):

I	Load Energy Determination of Buildings*
II	Ekistics and Advanced Community Energy Systems*
III	Energy Conservation in Residential Buildings*
IV	Glasgow Commercial Building Monitoring*
V	Air Infiltration and Ventilation Centre
VI	Energy Systems and Design of Communities*
VII	Local Government Energy Planning*
VIII	Inhabitant Behaviour with Regard to Ventilation*
IX	Minimum Ventilation Rates*
X	Building HVAC Systems Simulation*
XI	Energy Auditing*
XII	Windows and Fenestration*
XIII	Energy Management in Hospitals*
XIV	Condensation*
XV	Energy Efficiency in Schools*
XVI	BEMS - 1: Energy Management Procedures*
XVII	BEMS - 2: Evaluation and Emulation Techniques*
XVIII	Demand Controlled Ventilating Systems*

XIX	Low Slope Roof Systems*
XX	Air Flow Patterns within Buildings*
XXI	Thermal Modelling*
XXII	Energy Efficient Communities*
XXIII	Multizone Air Flow Modelling (COMIS)*
XXIV	Heat Air and Moisture Transfer in Envelopes*
XXV	Real Time HEVAC Simulation*
XXVI	Energy Efficient Ventilation of Large Enclosures*
XXVII	Evaluation and Demonstration of Domestic Ventilation Systems
XXVIII	Low Energy Cooling Systems
XXIX	Daylight in Buildings
XXX	Bringing Simulation to Application
XXXI	Energy Related Environmental Impact of Buildings
XXXII	Integral Building Envelope Performance Assessment
XXXIII	Advanced Local Energy Planning
XXXIV	Computer-Aided Evaluation of HVAC System Performance
XXXV	Control Strategies for Hybrid Ventilation in New and Retrofitted Office Buildings (HYBVENT)
XXXVI	Retrofitting in Educational Buildings - Energy Concept Adviser for Technical Retrofit Measures.
XXXVII	Low Exergy Systems for Heating and Cooling of Buildings.

Annex V Air Infiltration and Ventilation Centre
The Air Infiltration and Ventilation Centre was established by the Executive Committee following unanimous agreement that more needed to be understood about the impact of air change on energy use and indoor air quality. The purpose of the Centre is to promote an understanding of the complex behaviour of air flow in buildings and to advance the effective application of associated energy saving measures in both the design of new buildings and the improvement of the existing building stock.

The Participants in this task are Belgium, Denmark, Finland, France, Germany, Greece, Netherlands, New Zealand, Norway, Sweden, United Kingdom and the United States of America.

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Other Bibliographies in this series:

(1) Ventilation and Infiltration Characteristics of Lift Shafts and Stairwells;
(2) Garage Ventilation;
(3) Natural Ventilation;
(4) Air Intake Positioning to Avoid Contamination of Ventilation Air;
(5) Heat Pumps for Ventilation Exhaust Air Heat Recovery;
(6) Ventilation in Schools;
(7) Ventilation and Acoustics
(8) Passive Cooling Technology for Office Buildings;
(9) Impact of Urban Air Pollution on the Indoor Environment.

Scope

This bibliography is aimed at researchers, designers and engineers who are seeking an overview of current developments in duct cleanliness and design. References quoted in this document are taken from the AIVC's bibliographic database, AIRBASE and, subject to copyright restrictions are available to organisations in AIVC participating countries, through the Centre's library service.

1.0 Introduction

The quality of the indoor air depends not only upon the quality of the outdoor air, but also upon the cleanliness of the equipment and ductwork it passes through before reaching the occupied space. Stradford (#12660, 1998) outlines several system or maintenance reasons responsible for HVAC systems becoming dirty. For example, poor outdoor (supply) air quality (including a wide range of contaminant types and sizes); no filters present or ill fitted, poorly maintained filters; general neglect of air handling units and consequent leaks around worn seals. Other contributing factors include duct leakage and deteriorated fiberglass insulation, which finds its way into the system as a source of pollution. Such poor design and/or maintenance can lead to the accumulation of dusts, microbes, fungi and other waste products within the air distribution system of a building. As air is forced through these systems, dusts, odours, bacteria and viruses can be picked up and carried around the system along with the ventilation air. This is not only a supply end problem, along the whole ventilation process dust and pollution can be entrained within the ventilation air, and transported through the system to the exhaust. Re-entrainment is also possible. Summerville (#12658, 1998) also outlines a number of system and maintenance issues that contribute to the build up of debris in a HVAC system. For example, much depends upon the type of system, air velocity within the system, efficiency of the system filtration, the humidity within the system, the hours of operation, housekeeping practices, preventative maintenance programs, and the activities occurring within the building.

Luoma et al (#7896, 1993) undertook a comprehensive literature review focusing on the hygienic aspects of cleaning supply air ducts in ventilation systems. They found that the majority of the literature focused on cleaning exhaust ducts. Guidelines have been given by some organisations, but the authors felt that the scientific basis for these guidelines needed more research. The authors identified five steps to effective cleaning of ventilation ducts:

1. Initial test to determine the level of contamination;
2. Source removal;
3. Enscapsulation of remaining material;
4. Disinfection to prevent mould growth etc.;
5. Final testing.

Luoma concluded that duct cleaning provides a valuable means of preventing health effects and discomfort in buildings. Building managers felt that guidelines on the amount and content of acceptable debris would be helpful. However, such information is scarce, due to the complexity of forecasting re-suspension and microbial life cycles. The first standard issued by the Nordic Ventilation Group recommended that surface density of dust should not exceed $0.1 g/m^2$. However, the dust surface densities measured from 13 Danish and 8 Finnish buildings showed higher levels, with ranges from $0.7\text{-}3.5 g/m^2$. Many of the aspects raised in the review by Luoma have been studied further and are outlined in more detail below. The following subsequently focuses on the cleanliness of ventilation ductwork and examines the extent of this problem, typical contaminants, system design issues, and methods of cleaning and control.

2.0 Sources and Types of Contamination

Ductwork and ventilation system component contamination begins as soon as the equipment arrives on site during construction, despite existing guidance aimed at minimising such contamination (Smith and Wiech (#8753, 1994)). Once installed and in operation however, the process of dirt and dust entering the ductwork continues through a variety of factors, including poorly fitted or wrongly specified filters and poor overall maintenance, resulting in dust build up and fungi growth etc. Such build-ups can, over time, affect the quality of the ventilation air. Building owners and employers have a responsibility to the occupants of buildings to ensure such contamination is minimised. Legislation helps to keep a balance but often fails, because of the use of terms such as regular, clean, properly and contamination, which can be interpreted in a variety of ways. A further complication is the lack of information about the influence of surface roughness on dust absorption and suitability of the cleaning methods and results of cleaning. The authors conclude that regular maintenance is essential in preventing duct contamination build-up. With filters being used at the time of this study (1994) contamination is reported to deposit at a rate of 0.5 to 12 $g/m^2/yr$. Most contamination settles on the bottom, and other internal horizontal surfaces of ducts. Surface deposits with a density of 5 to 10 g/m^2 are visible and best described as a thick surface coating. There is little evidence to show density levels are affected by volume flow rate of ventilation supply systems, although other studies do agree that inorganic dust represents the majority of ductwork contamination. The remaining materials are macromolecular organic components, micro fungi and bacteria. Evidence has suggested that some fungi, does represent a health risk. Conditions have to be such that fungi can grow, and, under normal operating conditions, ventilation systems should not suffer from such contamination. Furthermore, conventional particulate filters can become a source of odour and viable particulates sufficient to contaminate the supply air. The level of water contamination was found to be an important factor, and therefore the authors suggest that filters should be kept as dry as possible to limit the potential for mould and fungi growth. Finally Smith and Wiech stress the importance of good system maintenance, which the ventilation industry cannot ignore.

The effect of duct cleaning on ventilation system hygiene and on the indoor air quality of six Finnish office buildings was studied by Luoma et al (#12962, 1999). None of the buildings studied had any reported problems, all had typically balanced supply and extract systems made of sheet metal and duct cleaning was carried out in line with the current Finnish regulations. These regulations recommend that cleaning be undertaken once every ten years. In recent years such cleaning procedures have also included ventilation supply as well as extract ducts, as the connection between ventilation system maintenance and indoor air quality has become more important. The most common cleaning technique used in Finland is mechanical loosening of the dust with rotating brushes. Particles are then removed by suction equipment from ductwork to filtration units. Luoma aimed to examine in more detail the effect of mechanical duct cleaning on ventilation system hygiene and IAQ in these buildings. During the study indoor temperatures were 23±2.1°C and relative humidities were 29±16%RH. Windows were kept closed during measurement periods and none of the systems had been cleaned before. In every building between 2 to 5 rooms were selected for IAQ measurements. Field measurements and a questionnaire was undertaken before the ducts were cleaned, and again a month after cleaning.

Data in particle mass concentration of fungal spores and bacteria, total volatile organic compounds (TVOC) and CO_2 concentrations were collected in both the supply air of selected rooms and in the vicinity of the supply air terminal device. Duct cleaning was undertaken by four companies all employing similar techniques. In all cases the ducts were initially pressurised, then rotating brushes loosened and dispersed the dirt. The dirt was then removed to a collection point by an air pressure device. Fans, heat exchangers, and terminal devices were then vacuum cleaned and washed with water and detergent where possible. The system was then readjusted. The study found that mass concentrations of particles, TVOC, fungi and CO_2 in indoor air were low or normal before and after cleaning. The authors conclude therefore that although duct cleaning could not significantly improve the air quality, it did not in fact reduce it. Again complaints about the IAQ were reported to be normal to low before and after cleaning. However, surface concentrations of dust did decrease from 6.5 to 2.1 g/m^2 and as low as 0.2-0.5 g/m^2 surface dust concentrations were obtained with careful mechanical cleaning of duct surfaces. Luoma concluded that duct cleaning did not have a measurable effect on the indoor air quality and that visual inspection and quantitative analysis of dirt in the ductwork are the most important factors with which the effects of duct cleaning can be evaluated.

In a similar Finnish study, Holopainen et al (#12963, 1999) also studied the effect of air duct cleaning on the indoor air quality of three buildings in Helsinki. In two buildings, ducts were cleaned using different cleaning methods (brushing, cleaning with pressurised air and manual cleaning) and the third building was left untouched as a control system. The air handling system in the two test buildings had been in operation for 26 and 30 years respectively, without any cleaning. The air quality in the buildings was evaluated by a trained sensory panel and tested by the occupants by repeating self-administered questionnaires before and after cleaning. An optical method was used to determine the amount of dust in the duct system. The air quality in each building was evaluated by the sensory panel and building occupants. The results of the study indicate an improvement of air quality due to cleaning of the air handling systems. This was more noticeable in one of the buildings with a higher number of respondents to the questionnaire. The result contradicts the findings of the sensory panel, which perceived the air quality less well after cleaning. Holopainen suggests that the time intervals between cleaning and measurement may be an influential factor. The panel evaluated the air quality 2 weeks after cleaning, and the questionnaire was issued 7-8 weeks after the cleaning. The cleaning may have changed the interior surface of the ducts so that it emitted more odourous substances immediately after cleaning than before, but the strength of the new source declined rapidly. Another explanation proposed by Holopainen, is that the cleaning work was carried out during normal working hours, therefore the occupants would have seen the work being undertaken and this could have influenced their response. The study also showed that new filters reduce the air quality level, and that the perceived quality of supply air actually improved in both uncleaned and cleaned duct systems with the introduction of new filters. The sensory panel also noticed a deterioration in the quality of the supply air when cleaning had been conducted by the hand-wiping process.

2.1 Dust contamination in ductwork

Pollution levels are affected, not only by the frequency and quality of the cleaning, but also by the choice of building materials, activities inside and outside of the building, the choice and presence of any dirt inhibiting measures and the volume of ventilation air flow (Dahl (#12667, 1999)). There are many sources of dirt within a building for example, sedentary occupants give off about 500,000 particles per minute, due to natural skin exfoliation. Textile fibres are released from clothing and further pollution is produced by work activities. Ventilation can remove significant amounts of dust (at 1 air change per hour approximately 50% of particles greater than 3-4 μm are removed, whilst at 10 air changes per hour, the same proportion of particles (50%) of size 10 μm will be removed). All of which can potentially contaminate the exhaust ducts through which they travel. Dirty ducts represent a fire hazard, by aiding the spread of fire, often faster than it is possible to shut down the fire preventing valves. Re-entrainment is another risk and consequence of poorly designed ventilation systems, this subject has been examined by Limb (1995 "Intake Positioning to Avoid Contamination of Ventilation Air"). Dahl also cites the Danish Town Hall Study as an example of the first large scale research project to confirm the effect of cleaning. This project is also examined by Anon (#2957, 1988), Skov and Valbjorn (#3262, 1987),(#4425, 1990), Franck and Skov (#4413, 1990), Gyntelberg et al (#8255, 1994) and Brohus and Hyldgaard (#11028, 1997).

The Danish Town Hall Study took place during 1984 and 1985, and included 28 local administration buildings in Copenhagen. Results indicated that the risk of developing Sick Building Syndrome was shown to increase with rising dust levels. The risk was especially high if the dust contained large amounts of macromolecular material, such as organic material in the form of food remains, skin, hair etc. Dahl (#12667, 1999) discusses "Dust and the Sick Building Syndrome" a follow-up to The Danish Town Hall Study. Results indicated a dominance of gram negative bacteria leading to headaches, tiredness etc, and inorganic dust particles leading to the general irritation of mucus membranes. Dahl notes that in new buildings dust from concrete and mineral wool fibres can accidentally find themselves drawn into the ventilation channels and be blown out when the ventilation system is started, causing irritation and SBS symptoms amongst occupants. Other forms of contamination cited include, soot, fat and grease, and waste remaining from construction and system installation. Rust and other products of corrosion, including fibres from duct liners or sound attenuators, as well as animals and insects both living and putrefied. These can nurture fungal and bacterial micro-oganisms that further pollute the indoor environment. Regular inspection of HVAC systems is therefore essential, to enable cleaning and disinfection as necessary.

Thirteen HVAC plants in schools and offices were investigated by Valbjorn et al (#8429, 1990), six were equipped with recirculation and seven were full fresh air systems. None of the buildings had humidification or cooling coils. Dust samples were taken from the horizontal duct sections and from filters to determine the amount of dust per duct area, concentration of fungi, bacteria and potential antigenic material (macromolecular organic dust, MOD). Odours and VOC's were also analysed. Results showed that the average dust deposited in the supply air ducts was 6.8 g/m^2. Valbjorn found that the occurrence of dust was low in the ducts of the ventilation systems tested, and of no or minor importance to the air flow rate. The investigated dust did not differ microbiologically from floor dust from offices as to macromolecular organic components and micro fungi. However, there were less bacteria than in floor dust and off gassing and odour emission of the dust was insignificant. The study did not indicate the potential absorption of the dusts if the system was switched off, nor did it indicate how the risk factor would change if humidification or cooling were present.

Methods to evaluate the composition and accumulation of dusts in ventilation ducts have been developed and reported by Laatikainen et al (#5627, 1991). Samples of settled dust were collected in one apartment, one school and four office buildings in Kuopio, Finland. None of the systems had ever been cleaned, and they aged between 5 and 11 years. The total mass of dust was determined gravimetrically, the counts of fungal spores and bacteria were determined by culture methods and the pollen was counted by microscopy. The total protein concentration of the dust was determined by the Coomassie Brilliant Blue method. *(See Spector (#12647, 1978)* Results indicate that the average surface densities of all samples, was 18.2 g/m^2. The accumulation rate of the dust ranged from 0.51 to 12.8 g/m^2 per year (April, May and June) and in September from 0.26 to 1.73 g/m^2 per year, with the overall average being 2.3 g/m^2 per year. This represents a three fold increase when compared against the Danish Town Hall study, possibly due to one of the studied ventilation systems being more dirty compared to the others. The average inorganic residue of the dust was 80%, while no correlations could be found regarding protein concentrations. The average protein concentration was 195 mg/m^2 and the average proportion of the protein was 0.7% of total dust. The average count of total pollen of the dust was 9.0%. It was therefore determined that the majority of the protein found in the studied dust samples originated from pollen. The results indicate that the pollen protein is the major component of the total protein, with protein contributions of spores, bacteria and other sources being negligible. Fibres and heavy metals were not analysed.

The level of dust in air ducts was compared by Holopainen et al (#12961, 1999). Using a vacuum test, a tape method test and an optical method. Holopainen and his colleagues found that most samples were more contaminated than the NADCA 1992 standard (0.1g/m^2), and the correlation between the vacuum test and tape method was best when the level of accumulated dust was between 2-8 g/m^2 on the examined surface measured with the vacuum test. Highest loads of accumulated dust were found on the bottom surfaces of the air ducts on places were air speed was low, such as terminal units. The results indicated that the vacuum test is the most important method to determine the amount of dust in the air duct. However, the high resolution weighting required, makes it impractical for field applications. The tape method is useful for field applications especially for new installations where dust layers are thin. The optical method indicted that the composition of dust has a significant influence on the reading. The highest dust accumulation on the duct surface was 8.4 g/m^2 measured with the vacuum test, the optical device gave only 12% reduction of light for the same sampling point, which challenges the reliability of the optical test method. Holopainen concludes that the study demonstrated how poorly the results from the tested methods correlate, and that only the results with the same method are comparable. The results may be biased due to different sampling points, even though the location of the sampling was the same, the exact sampled areas were different.

The amounts, quality and factors affecting dust deposition in supply air ducts of eight non industrial mechanically ventilated buildings was studied by Pasanen et al (#5997, 1992). Four systems also had recirculation, with between 39 to 68% of total air flow being re-used. The temperature of the recirculated air was 10°C below ambient air temperature levels. The age of the ventilation systems varied between 4 to 31 years old and one of the systems was cleaned prior to sampling. Results showed that the average surface density was 10.6 g/m^2 (range 1.2 to 58.3 g/m^2). The yearly accumulation rate of dust was determined to be 3.5 g/m^2/year (1.2-8.3 g/m^2/year), and the proportion of inorganic material in the duct was found to be 82%. These results indicate that the accumulated dust levels in the ventilation systems originate from outdoors, which may further indicate air leakage between the filter cassette and assembly frame. Soil debris during building construction was also found in the ducts of some buildings. The average proportion of total pollen was 71 mg/g of which about 90% originated from surrounding coniferous trees. Since all systems were fitted with filters of class EU5 or better, and should have been able to separate out particles as large as pollen grains, Pasanen suggests that in the systems studied there had been filter frame leakage or that ventilation had been in operation at times without filters. Further, Pasanen found that the average count of viable fungal spores in the dust of air ducts was moderately low (990 fungal colony forming units/gram), which agrees well with other studies. The fungal genera found in the dust was similar to outdoor air genera in Finland, indicating that fungal growth has not occurred inside the system. In conclusion, Pasanen noted that the amount of settled dust in the supply air ducts was low and therefore had little overall effect on the air flow rates within these ducts. The dust in these ducts was found to compare well with ambient dust composition, indicating filter frame leakage or the system had been in operation without a filter at all. Therefore, in properly maintained HVAC systems the settled dust in the supply air ducts should have little or no impact on the indoor air quality of the building. However, if surfaces are moistened due to condensation etc, then there exists an opportunity for fungal growth. Although in general, the coarser the filter the more debris is accumulated in the main air ducts and vice versa.

The surface density of dust settled in ventilation ducts of 23 single Finnish family houses located in or close to the city of Kuopio in Central Finland was studied by Kalliokoski et al (#9587, 1995). The ducts and other parts of the ventilation systems were then cleaned, ventilation was balanced and small faults observed were repaired. All of the owners had engaged a professional cleaning company to clean the system. They used a rotating brush to clean the ducts, and compressed air and vacuum to clean the fans. The filters were changed, the heat recovery units washed and other parts of the air handling unit (AHU) cleaned. Dust was collected on a filter installed in the depressurising unit and determined gravimetrically. In each building, dust from the supply and exhaust ducts was taken on separate filters, and the surface density and annual accumulation rate of dust deposited on the surface calculated. Air flow rates were measured prior to and after cleaning. The mean surface area of dust was 1.6 g/m^2 in the supply air of houses with central air heating and 0.5g/m^2 in central air heating. More dust was found in exhaust ducts (mean surface density 2.2g/m^2) in the air heating houses and 1.0 g/m^2 in other houses. Examination of the dusts found that the proportion of organic matter and concentrations of viable fungal spores were higher in the exhaust ducts than in the supply air ducts. The fungal spore concentrations were higher in dust collected from the ducts of air heating houses than from those with central heating. No major sources of fungal floral dust were observed between supply and exhaust ducts or type of ventilation system. Before cleaning and maintenance, air exchange rates were below the Finnish standard of 0.5 1/h in most houses, especially those with central air heating. Contamination of the ventilation system was the main problem in six houses, although other common faults included improper location of supply air intake (i.e. attic) kitchen range exhaust connected to the exhaust duct of general ventilation, wrong rotation direction or other electrical problem of the fan and filter frame leaks. The authors conclude that, despite typical filters in single family houses being of coarse (EU3 or 4) grade, dust accumulation rates were lower than observed in other similar studies. The proportion of organic matter and concentrations of fungal spores were also higher in the ducts of the studied residences than in those of offices. Possibly due to the high summer concentrations at the time of the study. After cleaning and readjusting the ventilation, the air exchange rate increased in 70% of the houses and 65% of them reached the Finnish required ventilation rate of 0.5 1/h. The authors note that proper maintenance is essential to ensure that correct air exchange rates are maintained.

Pasanen et al (#10838, 1997) focused on the content of the settled dust samples taken from the single-family Finnish house study outlined by Kalliokoski, to determine the total fungal spore concentrations (both culturable and total) in the dust. As the ducts were being cleaned dust samples were collected on a filter installed in the depressurising unit and determined gravimetrically. Dust samples were stored in closed packages at room temperature before the analysis. The mean annual accumulation rate of dust was 0.1g/m^2 in the supply ducts and 0.2 g/m^2 in the exhaust ducts. The proportion of organic matter in the dust varied from 2% to 74%, being higher in the air heating systems compared to other systems and being higher in the exhaust ducts than supply ducts. The authors found that fungal spore concentrations were higher in air heating systems compared to those in the other ventilation systems. However the air heating systems were cleaned and dust collected in early autumn, when spore concentrations of outdoor air usually varies between 10-10^3 colony forming units/m^3 (cfm) while the other systems were cleaned later in the autumn and winter when spore concentrations normally decrease to 1-10^2cfm^3 . The fungal flora in dust may also be seasonally affected, however the main fungal genera was the same for both types of system. It was also noticed in this study that there were no differences in total spore concentrations between the supply and extract ducts. The results of this study show that conditions in air ducts such as variations in temperature and humidity do not favour viability of fungal spores. The results also support the theory that the survival time of microorganisms in air filters is only a few days. A higher proportion of culturable fungal spores in dust in the exhaust ducts are possible due to more stable moisture conditions for survival of spores and the effect of indoor fungal sources. In conclusion, the study showed that in spite of a lower dust accumulation rate, fungal contamination in air ducts is heavier in the single-family houses studied than in some offices. Also the presence of non culturable spores in accumulated dust and supply air may also be significant because of their possible allergenic properties.

In a similar study dust and fungal samples were collected from the duct work of a Canadian office complex ventilation system, before and after cleaning (Collett et al (#12964, 1999)). The complex comprised three interconnected buildings served by five independent HVAC systems. Surface sampling for total dust and viable fungi was undertaken at 21 locations within the five HVAC systems before and after cleaning. Sheet metal surfaces in both the air handling units and air distribution ductwork were tested. The surface fungal testing was performed using commercially available contact slides containing Rose Bengal agar medium. Respirable suspended particles were taken within the occupied space of the office complex before and after HVAC system cleaning, which consisted of non-destructive mechanical and manual scrubbing and abrasion. Loose materials were removed from the internal surfaces of the systems using mechanical disruption and vacuuming. Negative pressure was maintained within the ductwork at all times during cleaning to prevent the propagation of aerosolised debris into occupied areas. A visual inspection of the HVAC system, before cleaning showed that components such as fans, coils and turning vanes etc, had a considerable accumulation of dust and debris. Examining the data after cleaning, the system met the specifications set out by the building owners, which included no visible contaminates present in the HVAC system, the aggregate mass of interior surface dust should not exceed 0.05mg/m^2 and surface fungal levels should be less than 100 cfu/m^3. However, the two methods of sampling viable fungi used in this study yielded conflicting data. The authors suggest that the high flow rate required for vacuum collection reduced the viability of fungal propagules according to their individual sensitivities. Despite the variance in gravimetric and contact slide datasets, a number of trends could be seen. Reductions in fungal levels after cleaning were directly related to the initial dust loading at the particular areas sampled. Also, those areas that showed higher relative pre-cleaning dust levels tended to harbour lower milligram-mass concentrations of viable fungi than HVAC areas with lower pre-cleaning dust levels. It is likely that, over time, various factors such as surface desiccation and mechanical sieving will cause stratification of viable fungal propagules towards the lower extent of a dust mat within an air duct. Therefore, under these circumstances it could be expected that the recovery efficiency of viable fungal propagules would diminish at increasing dust loads.

An experimental monitoring campaign on selected air conditioning systems in Milan (a hospital ward, a surgical suite, the data processing centre of a bank, and a first class hotel) is reported by Sacchi (#9570, 1995). The study examined the specific presence of particles in suspension inside the air handling unit and found that compared to the outside air, there could be as many as twice the amount of particles per unit of volume, in these units, despite containing filters. Sacchi suggests that the shape and confined nature of these units results in a build up of suspended particles. The authors also found that centralised air filtration at the air handling unit must be integrated with local filtration on air terminal devices, according to a well differentiated selection logic for the filters. They also studied the number of colonies of moulds and yeast present in a sample as well as the bacterial charge of the same sample. The lowest bacterial charge was found immediately downstream of the humidification device. The supply air in the lecture room of the hospital ward had low bacterial charge, however it was found to be powerless to control the bacterial contamination of the room itself, immediately downstream of the supply duct, the bacterial charge was so high it was impossible to count the colonies. The authors further suggest that the system supplying the room is being serviced, and as a consequence the room is not always under positive pressure, this could allow a build up of bacteria within the room. In conclusion the geometric irregularities in the air handling units generate vortices of dust particles, which reduce the filtration efficiency during operation transitions. The same occurs in the air supply ducts, which are designed to be integrated with spaces and deflectors in order to prevent the build-up of stationary vortices, which retain the particles in suspension. Importantly, whenever such vortices are present, the air samples taken to evaluate air cleanliness yield meaningless results.

The presence of allergens, such as dust and moulds in heat recovery ventilation HVR systems and associated ductwork is investigated by Watters (#12377, 1999). In most houses in the province of Nova Scotia, Canada, little or no attention is paid to the maintenance or overall condition of ventilation ductwork and cores. Ten single family homes built within the last decade, where included, four R2000 houses, and six conventionally built houses. Four houses were tested in 1996 and the remainder in early 1997. Samples from the ductwork and HRV cores in the conventional installed HRV systems of these houses were tested for dust and mould. The ductwork and cores were then vacuum cleaned using standard techniques and equipment (truck mounted and portable power vacuum). The systems were then re-tested. A video camera was used to visually inspect the ductwork before and after cleaning. Two houses were re-tested a further three times over the fifteen month test period. It was noted that both the truck mounted system and the portable power vacuum system were originally designed to be used in forced air heating and air conditioning systems. However over the past several years they have also been used to clean smaller duct systems. A number of adaptations have occurred, but the overall operation has remained the same, in that compressed air is sent through the ductwork while the duct system was put under a negative pressure. No brushes were used due to the small size, inaccessibility and type of ductwork commonly found in HRV's. None of the companies had viewed the ducts either before or after cleaning and therefore did not have any idea how successful their cleaning operation had been. Video results showed cleaning to be hit and miss. Cleaning was also affected by size of duct and location of ductwork. Companies typically took between 3 to 5 hours to clean the system, which cost about $150.00 Canadian dollars. Results from the study showed that mould counts were high in the ductwork and cores with higher counts in the fresh air supply to the HRV. No correlation could be found between the levels of the surface counts in the system and air samples taken in the house. Watters found that homeowners are generally not well informed on what the purpose of the HRV and how to control or maintain and optimise its performance. In conventional houses there were no filters on exhaust grilles in kitchens and bathrooms, whilst in the R2000 houses all except one had filters in the bathroom. Several recommendations were made by the author, including duct work using solid, not flexible, duct work from the exterior fresh air hood to the HRV, to allow easier cleaning. In conclusion Watters found that current duct cleaning methods are not adequate for cleaning duct work in central ventilation systems and that further testing of airborne mould levels in houses with central ventilation systems is needed to determine whether such systems contribute to the poorer and improved occupant health.

The growth factor requirements for fungi and bacteria, in deposited dust, inside ducts of air conditioning systems, was studied by Sugawara (#12852, 1997). The presence of seven metallic elements in dust were estimated by atomic absorption spectrophotometer. Three different organic matters (amino acid, carbohydrate and lipid), found to be the major components of dust, were quantified. The fungi and bacteria that had previously been detected in the dust were inoculated on six different test media based on mineral or organic matters to compare their growth rate. Results indicated that dust samples contain Na and Fe, which had found their way into the indoor environment. Sugawara suggests more research is required to determine the potential impact on human health such contamination could have. Results also indicated that fungi proliferate more significantly than bacteria in duct environments. Even with little nutrient, spores formed and survived. Should conditions in the duct change, fungal contamination could be more prolific. If the humidity inside ducts is shown to be high, due to the condensation of the supply air in summer and humidified air in winter, the air conditioning systems may serve as reservoirs of microbial proliferation. Previous research by the author suggests that 66% relative humidity will slow fungal growth and 55% RH will stop its growth. Cleaning the ventilation duct system is therefore recommended to control such fungal growth and subsequent spread into the indoor environment.

The minimum transport velocities required to prevent settling and plugging of ductwork, for different kinds of dusts, for local exhaust ventilation (LEV's) systems was examined by Pocovi et al (#11149, 1997). For horizontal ducts, saltation, settling and pick up velocities were measured and empirical exponential relationships derived. Such LEV's are used in many industrial processes to capture contaminated air. These systems are important not only from a health hazard point of view but also to increase the recovery of valuable products in the whole process. Pocovi outlines the derived formulae and equations in the paper. Results of the study found that a minimum transport velocity is required to prevent settling and plugging of ductwork, while excessively high velocities waste energy and may cause rapid abrasion of ductwork. The design velocity (used to operate the system) has to be higher than the minimum transport velocity, which has to be high enough to protect the system against different situations such as sticky or wet materials, electrostatic effects etc.

In a similar study, Wallin (#8254, 1994) outlines the development of a generic numerical model for particle deposition on internal pipe or duct surfaces of air transport systems. Developed to more fully understand the fouling process in duct systems and to facilitate predictions of the deposition rate, the model uses validated physical models and empirical relations for the particle processes, deposition processes and airflow resistance. It also accounts for the combined effects of Brownian movement and turbulent deposition, and sedimentation in straight duct sections and impaction in bends. The research omits influences by thermophoresis, and charge effects, since isothermal conditions are assumed in the first case and particles are supposed to have reached electrostatic equilibrium. The simulation program assumes fully developed turbulent flow at the entrance section of each individual flow resistance, and equivalent particle size for polydisperse aerosols with deposition mechanisms included. Wallin states that the performance of the iterative solution method regarding the non-linear equation set, has been obtained, since high accuracy is maintained concerning start value predictions as well as each element of the residual vector. So far, no problems have occurred regarding stability and convergence. Wallin concludes that the simulation technique is a powerful tool, however it is important that the model synthesis is validated in order to control the effects of both modelling and numerical imperfections. From the tests, Wallin notes that simulation airflow rates change as indicated by in-situ measurements in exhaust systems and the deposition rates increase rapidly in ducts as the internal roughness accumulates. During the same time period, the magnitude of alterations in the pressure drop is of minor importance. With the use of high classification filters for dry deposition it is possible to protect air supply systems efficiently, provided there is no air leakage in the duct system, air handling units, or between filter and filter holder. Finally, results have indicated that periodic maintenance is essential within duct systems exposed to heavy particle contamination although measures can be taken to reduce the deposition velocity and consequently the need for servicing the systems. Comprehensive details regarding the computer model and simulation tests run are outlined within the document.

A numerical simulation of turbulent flow in ventilation ducts has also been undertaken by Jovicic (#12235, 1999). The author uses a numerical method to solve the Reynolds-Averaged Navier Stokes (RANS) equations with turbulence models for complex geometry and high Reynolds number flows. This model is used to perform a highly resolved computation of the turbulent flow in a strongly curved part of a ventilation duct. The author outlines the numerical method used and modelled experiments using CFD techniques. The results show that most global features of the flow field are correctly resolved but differences between measured and simulated results still remain. A key feature in obtaining the correct primary flow is the prediction of secondary motion with reasonable fidelity. The breakdown of the secondary motion into a complex multi-cellular pattern at about 90° of the bend, leads to distortion of the stream wise velocity profile near the inner wall. Differences between measured and computed values at that location are possibly due to failures of the isotropic two-equation turbulence model. The author notes that in order to predict secondary flow more precisely it is necessary to use more grid points near the walls. Also using non-linear constitutive relations for Reynolds stress tensor components, instead of Boussinesq's relation, may also lead to improved results.

Particle deposition from turbulent flow in ventilation duct work, is also modelled by Sippola et al (#12231, 1999). Sippola compares three published turbulent deposition models with experimental data, to determine the fraction of particles which penetrate a single duct run of a ventilation systems for a typical five storey commercial office building. For simulation, the duct wall is assumed to be a perfect sink for particles and all roughness is assumed to be three dimensional sand grain type roughness. Turbulence is assumed to be fully developed, and particles considered are spherical with a density of 1.0 g/cm^3 and a diameter range from 0.1 to 10μm. Comparisons undertaken between the three test models predict that the penetration of particles is essentially independent of particle size for particles less than 2μm in diameter. For particles over 2μm, penetration due to gravitational settling is reduced. Overall these results indicate that deposition may significantly modify the particle concentrations in air flowing through ventilation ducts. Overall comparisons of deposition models show poor agreement with each other and experimental data, especially when rough surfaces are considered. A possible explanation is that the models are only able to accommodate sand grain type roughness, therefore a valid comparison between model and experiment is not possible.

Using a theoretical model, Fransson (#10059, 1996) undertakes comparisons with measured data and investigates particle deposition in ventilation air supply ducts. Fransson found that the model compared well with measured values of pollutant concentrations upstream of the filter. However, measured results show a greater proportion of the dirt on the duct wall compared with the results from the model. A possible explanation could be the precipitation of zinc from the galvanised ducting. Downstream of the filter the theoretical calculations indicated that there should be a considerable difference in the quantities of dust before and after the filter. Measurements did not compare well, indicating failings in filter performance, according to the author. The investigation has not indicated a direct link between the quantities of pollutants on the bottom of the duct and in the air. Particles have not migrated from the duct surface to the supply air in the systems investigated, although there were minor contributions in respect of gaseous emissions in certain cases. Overall the study found that the main particle deposition occurs in the intake duct and the air filter. Quality control of air filters is consequently the most important achievement to reduce a potential risk of air pollution in the supply air.

Riffat et al (#10343, 1997) too investigate the deposition rate of aerosol particles in a ventilation system. Using galvanised steel square duct system and single zone chamber the downstream end was connected to an axial fan by means of a diffuser. Static velocity pressure and particle tappings were positioned along the duct. Oil smoke was injected into the duct inlet with the fan off. Once a uniform concentration had been achieved, the dust monitors were switched on at the same time as the fan, to a set speed. The oil smoke concentrations were measured using infra red particle monitors, a series of four air flow rates were used for a straight duct, a reducer, a single 90° bend, a double 90° bend, and dampers, the plate was angled at 0°, 30°, 45°, and 60° to the flow. Particle and tracer gas concentrations were monitored using a concentration-decay method, which is time-dependent and therefore transient. This transient flow was then compared to steady state CFD simulation. For all comparisons the experimental and CFD results follow the same trend, however the deposition ratio of experimental results was shown to be larger. The authors suggest that the experimental measuring equipment only allows accuracy to within 5%, and an assumption made for the CFD simulation was that particles are trapped onto the boundary surface when contact between then is made, not allowing any re-suspension of particles. In conclusion, the study found that for all, fittings less deposition was noticed as the air flow rate increased. By inspection the particles followed the general shape of the flow, but did get caught up in the turbulent boundary layer resulting in deposition. The highest rate of deposition occurred in the damper and the least in the reducer.

2.2 Oil residue contamination in ductwork

The oils traditionally used to provide corrosion protection to HVAC components made of galvanised steel, form a sticky layer on the surface. In the manufacturing process of sharp bends and bows in this steel, lubricants are also used. Once constructed, part of this lubricant often remains as a thin layer on the inside surface of the product. Such oils and lubricant, act to increase dust accumulation and serve as a potential growth media for microbes. Evaporation of hydrocarbons from oil residue reduces the perceived quality of the air passing through dirty ventilation systems. More recently air duct manufacturers have used mainly sheet metal which is corrosion protected by chromium acid treatment or organic inactivation process of the zinc surface.

The hygienic properties of processing oils, used in the manufacture of galvanised metal air ducts, (one vegetable and one mineral based), is examined by Pasanen et al (#12968, 1993, #8772, 1995). The authors studied the evaporation of the oil from the galvanised metal surface, with a trained panel evaluating the odour emission of oil residues. Laboratory tests were also undertaken to investigate the oils in order to determine whether they had the potential to act as nutrients for fungi with *Penicillium brevi-compactum*. Pasanen then examined the evaporation of oil residues and the water binding capacity of the residues for increasing relative humidities (RH) at the range of 70-100%. They found that after 10 months the residue of mineral oil was 60% and vegetable oil was 79% of the original amount. Further the residues of both processing oils promoted the accumulation of dust within the ducts and provided a sufficient amount of nutrients for fungal growth. The oil residues were also capable of binding water at high relative humidities, which may cause release of fungal spores under humid conditions because lack of water seems to be the only factor restricting fungal growth in ducts. The residues of both oils had high odour emissions and it can be assumed, therefore, that oil residues contribute significantly to odours emitted in a recently built ventilation system. Odour emissions from residue of vegetable oil based processing oil increased during storage at room temperature. To attain a higher indoor air quality, more evaporative, odourless or washable processing oils should be developed.

In a more recent study, Pasanen et al (#12312, 1999) aims to develop a consistent method to determine oil concentrations on HVAC component surfaces. Three different sampling methods were tested, two swiping methods and a filter contact method. Two kinds of commercially available galvanised sheet metal were chosen as test surfaces, one protected with chromium acid and the other treated with oil mist (approx. 200-500mg/m^2). Results showed that the average amounts of protective oil on the surfaces ranged from 0.5-0.9g/m^2. The filter contact method gave the best results compared to both the swiping methods. It was also shown that the distribution of the oil on the various surfaces of metal shipped from the steel mill was not even. Such uneven distribution somewhat limits the estimation of repeatability, which was hoped for in this study. The filter contact method was found to be the most effective method with oil levels ranging from 530 to 960 mg/m^2. Oil levels on the surface of sheet metal treated with chromium acid were very low. They were measured by glass wool and cotton wool swiping and ranged from the detection limit of 1mg/m^2 to 5mg/m^2. Most samples were below the detection limit. The filter contact method showed 2mg/m^2 to 29mg/m^2, with 70% of the samples below the detection limit of 2mg/m^2. Again variation was found in the unequal distribution of minor oil residues on the sheet metal from the mill, which affected the results. Pasanen concludes that galvanised steel metal coated with protection oil, contained 500-1000 mg/m^2 of oil. While the oil concentrations were low on the sheet metal surface treated with chromium acid instead of oil. A wide range of oil concentrations were seen on the same sheet and also in the manufactured components. The variation should be taken into account in sampling design. The filter contact method showed the best recovery and repeatability and the method was good compared to the glass wool and cotton swiping methods.

2.3 Fungal growth contamination in ductwork

Fungi form a large group of organisms that feed on dead organic material. They reproduce both sexually and asexually and produce an abundance of spores which are easily carried on air currents that circulate throughout the building. Although found dispersed around a building they colonise on damp surfaces where moisture and nutrition are present. Once established, they can be hard to eradicate. From studies, the most prevalent in allergic respiratory disease identified in this paper are *Cladosporium, Alternaria, Penicillium*, and *Aspergillus*. These fungi along with high dust levels and low relative humidity are the most commonly encountered problems in buildings with sick building syndrome. Increased levels of airborne dust and low relative humidities play an important role in elevating allergic reactions in the indoor environment. One of the most common allergenic sources in buildings is dust, its composition dependant upon the surrounding and types of activities commonly undertaken within the building. House dust contains many allergenic substances (animal dander, dead insect and spider parts, house mite and cockroach faeces and remains of bacteria, fungi, moulds and their spores, and dried animal excretions), while office dust is less likely to contain such items as animal dander, but may contain other materials associated with office activities, such as paper dust. The control of relative humidity (RH) is vital in the control of fungi and allergens. Low RH decreases the multiplication of fungi and moulds, but can cause occupant discomfort, as well as a build up static electricity that can shock occupants and damage computer equipment. Whilst with high RH, condensation can occur, providing moisture, which allows bacteria, fungi, moulds and mites to spread. The optimum humidity for fungal and mould growth is above 70%. An essential HVAC maintenance and cleaning regime is vital in preventing the growth and spread of these bacteria (Anon #6451, 1992).

The effect of diurnal swings in temperature inside ventilation ducts is examined by Pasanen et al (#6877, 1993). Such variations can cause water condensation which can lead to possible fungal growth. In this study germination time and sporulation of fungus, *Penicillium verrucosum*, were studied on dusty, galvanised steel sheet under different moisture conditions at room temperature. The effects were amplified in an experimental situation and in the field air temperatures and the dew point temperature of air in the duct were monitored continuously for a week. The results of the fungal growth experiments indicate that fungal spores are able to germinate and sporulate on the dusty steel surface of the ventilation system when the surface becomes moist for just a few hours. Measurements showed that water condensing conditions occur in real life in ducts situated in cold spaces, when air humidity is high and when ventilation is turned off for nights and weekends. Although the experiments, conducted in central Finland, did not result in significant emissions of spores, Pasanen concludes that in warmer and more humid climates there is a real risk of fungal growth and significant release of spores in ventilation ducts located in unheated spaces. This risk can be eliminated by placing all ventilation ductwork in warm spaces, or by maintaining continuous forced airflow through them, or by increasing the thickness of insulation around ducts in cold spaces.

Foarde et al (#12959, 1999) investigated the impact of relative humidity, air velocity and amplification on fungal emissions, by undertaking a series of dynamic chamber studies using mini ducts. The experiments were conducted in a room size dynamic microbial test chamber (2.44m x 2.44m x 2.44m), constructed of stainless steel walls and floor and an acrylic drop-in-ceiling. Temperatures (18-32°C) and RH (55 to 95%) control are provided via an air handling unit (AHU) with an air circulation rate of 1.4 to 4.8 m^3/min. The chamber contained eight mini ducts with the blower forcing the air through a High Efficiency Particle (HEPA) filter and then through the mini ducts. Two types of fibreglass duct liners and one fibreglass duct board were studied. *Penicillium chrysogenum* and *Aspergillus versicolor* were selected as test organisms, because their occurrence on this form for media is well documented. The materials were then artificially soiled (using sieved 250 µm duct dust), and then inoculated in an aerosol, deposition chamber. After a short autoclave cycle the material pieces were tested in the mini ducts, with a temperature of 23.5°C, relative humidity of 94% and air velocity of 2.5 m/s being maintained. At the start of the emission rate determination the chamber RH was reduced to 64%. The experiment was repeated sequentially for six 1 hour samples. At the completion of each sixth hour RH was returned to 94%. After the 8 week experiment, results were analysed and conclusions drawn. When comparing the surface and emission data, the authors noted that for *A versicolor* under the test conditions a surface load directly influenced the emission rate, i.e. as the surface concentration of organisms increased the emission rate increased until a stable population was reached, then emissions remained constant. The authors also found that as the relative humidity decreased, the emission rates increased. In examinations of the different air flow rates, it was seen that, as the air flow rates increased, so did the emission rates. In conclusion Foarde notes that for the limited data set, they have determined that emission rates are inversely proportional to RH, but directly related to air flow and surface loading.

An empty government building in South Florida is the focus of a study by Price et al (#10825, 1995). The building was vacated in 1992 because of extensive microbiological contamination, resulting from water leaks, condensation and consistently elevated relative humidity levels (>70%). Fungal contamination of the building components and interior furnishings (including carpets, textiles, gypsum wall board and vinyl wall coverings) was also extensive. Price took samples and examined the buildings ventilation ductwork for signs of fungi growth, then examined duct liners and duct board as to their ability to absorb and grow fungi under a variety of relative humidity conditions. Results indicated that all samples of fiberglass insulation from the building were positive for fungi upon direct microscopic examination, enrichment culture and after incubation in the moisture chamber. None of these samples appeared to be colonised by the unaided eye. The common species found in the fiberglass was *Aspergillus versicolor* with *Cladosporium spp.* and *Stachybotrys atra* were also found. Sections of the duct liner facing material that had been cleaned and coated with paint containing phosphated quaternary amine complex were free of fungal colonisation, enrichment culture of the fiberglass liner matrix demonstrated that fungi were still present in the liner. Price concludes that their studies have demonstrated that fiberglass duct board and duct liner from a building with heavy fungal contamination showed hygroscopic and were colonised by fungi. Although they did not find any differences in the water uptake between new and used materials, other researchers have noted that dust laden ducts and fiberglass show greater tendencies to absorb moisture. They have shown that in as little as 48 hours, used and unused HVAC fiberglass insulation can pick up significant amounts of moisture. In situ these amounts of moisture can provide favourable growth and reproductive conditions for a variety of fungi. In the building under study the mouldy gypsum board and all ceiling tiles, carpets and porous materials have been removed. Decreases in densities of airborne fungal conidia were noted and attributed to the use of high efficiency filters and the cleaning of some surfaces with chlorine dioxide. Price further notes that future disinfection practices will only be effective if moisture control and good maintenance procedures are employed, this is especially true in humid environments where the control of excessive moisture levels is important.

Buttner et al (#12956, 1999) conducted an experiment to study the dispersal of spores from fungal colonies present on contaminated galvanised metal, rigid fibrous duct board and fibreglass duct liner. The sample materials were then inserted into duct sections of a test air handling system. The experimental room ($4m^2x2.2m$) was used to represent a residential environment. The materials to be tested were cut into sections 0.19mx0.61m and coated with an autoclaved blend of finely sifted vacuum dust and vermiculite to provide a base for fungal growth. Duplicate pieces of each material were inoculated with spores and incubated in individual humidity chambers at 24°C for 13 days. The contaminated duct was then installed downstream of the blower in a straight section of duct. Before any measurements were undertaken, background levels of airborne culturable *P. chrysogenum* and of *P. chrysogenum* sized particles were measured. After the contaminated section had been inserted into the duct, the HVAC system was activated for 5 minutes (duct velocity 2.8 m/s) and then air samples were taken. The HVAC system was turned off for approximately2-3 hours until measurements of spore sized particles reached a steady state condition. The HVAC was then turned on again for a further 5 minutes and a second round of samples taken. This was then repeated once more. Buttner concludes that no significant difference was found in contamination level of the three duct materials before installation in the room HVAC system. However, after the system had been in operation for 5 minutes, the highest concentrations of airborne fungi were measured during the first cycle of measurements, regardless of the type of material or measurement method. The metal duct released the greatest number of airborne fungi followed by the fibreglass duct liner and finally the rigid fibrous duct board released the least amount of fungi. However the authors did not consider these differences to be statistically significant.

The effectiveness of passive stack ventilation systems (PSV), and their application in Swedish schools is examined by Blomsterberg (#11579, 1998). An important issue for these types of systems is their dependency upon the weather. Users are not only responsible for opening windows, vents etc, to achieve improvements in the indoor air quality, but they must also agree that such a change is required. However, insufficient ventilation and high moisture levels are possible risks associated with these systems. Blomsterberg identifies a variety of potential problems with these systems, including a reduction in air quality brought about its route through underground concrete ducts. In summer, warm moist air could be cooled and condensed in the duct, possibly leading to microbial growth, again potentially reducing air quality. The study aims to determine ventilation, pressure conditions, CO_2 levels and risk of moisture damage for PSV ventilated schools with underground supply ducts. Three schools of similar design and ventilation systems were chosen to undertake this project. In one school the outdoor air enters through the roof ridge through a vertical shaft, while for the other two schools air enters through underground concrete pipes. Such pipes were believed to cool the supply air during summer and preheat during winter. It was found that from measuring points located in roofs, moisture levels were higher due to moisture diffusion and convection. In some places associated microbial growth is also evident. The values in the underground ducts during late spring and early summer show that levels of over 80% relative humidity (RH) do occur at times. Therefore the risk of microbial growth on materials within the building is a factor for consideration. Blomsterberg concludes that the supply air flow through the underground duct can, without a supply fan, be low and even reverse in warm weather. There is a risk of microbial growth in the underground supply duct during spring and summer. Two important factors are the choice of material and cleaning, of which little information is available.

Garrison et al (#12680, 1991) studied thirteen homes in the US before and after they had been cleaned by professional duct cleaning companies to determine the presence of fungal colony forming units (cfu's). Four different homes with single HVAC systems were used as controls for the studies. Two sample sets were taken from each HVAC system before cleaning. Six HVAC systems in Phase I and 5 in Phase II received cleaning. The cleaning process includes treatment with disinfectant, duct sealing and introduction of electrostatic filters. After cleaning, the systems were allowed to operate under, what the occupant considered to be normal conditions, with no special tests or operation conditions suggested or imposed. The systems were then re-sampled after 48 hours and then weekly after cleaning. The cleanliness of HVAC systems were analysed by exposing sterile 2% malt extract media plates at a 90° angle to the airflow at the air supply and air return vents. The baseline of fungal colony forming units was found to be similar in the control houses to the study houses. Eight weeks after cleaning, the study houses demonstrated an overall reduction in fungal colony forming units of 91.6% for Phase I houses, and 84.4% for houses in Phase II. With respect to air supply vents only, the study houses demonstrated a 95% reduction in cfu's for Phase I and 98% reduction for Phase II. No significant change was observed in the control houses over the test period. Garrison suggests that duct cleaning appeared to reduce the number of fungal colonies entering and leaving the HVAC system, suggesting that the HVAC contained a significant percentage of total fungal load in these homes. Individual effects of specific HVAC cleaning methods could not be determined from this study. However, the combination of cleaning practices used in this study did lead to the reported reduction in fungal colony forming units in these residential HVAC systems.

In a similar study, Kumagai et al (#12853, 1997) measure levels of TVOC and numbers of fungi inside HVAC systems in seven buildings in central Tokyo, Japan. Two duct systems of one building were cleaned and the remainder were left as they were found. TVOC's were measured with a photo-acoustic spectroscopy gas monitor. The deposited dust of the air duct system, was collected by a vacuum cleaner, and then 100g of the dust was dissolved into 100ml of sodium chloride solution. This was then cultured on Potato Dextrose Agar plates, incubated at 25°C for 48 hours and resulting colonies of fungi were counted to obtain the number of fungal colony forming units per gram. The average TVOC concentration was 600 $\mu g/m^3$ and the range was 300 to 950 $\mu g/m^3$. The outdoor TVOC concentration was subtracted leaving a mean TVOC of 188 $\mu g/m^3$ from the HVAC system itself. This ranged from 13 to 529 $\mu g/m^3$. The population of fungi was found to be approximately 1000 colony forming units/g with no significant difference between samples. The effects of duct cleaning on the TVOC concentrations shows that after cleaning the concentrations were 0.26 to 0.42 times lower compared to before cleaning. The effect of stopping and re-starting the fans was evident in an increase in air borne dust levels. Levels of TVOC increased when the fan was switched off and remained higher during cleaning. After cleaning TVOC levels did not rise even when the fan restarted. Kumagai concludes that their study identifies a link between the TVOC concentration and the population of fungi in dust (fungal colony forming units/gram). They state that cleaning is effective in controlling the fungi contamination of duct and the TVOC generated from the dust surface.

2.4 Chemical emissions in ductwork

Different levels of dust contamination, under different temperature, relative humidity and air velocity conditions, were studied by Torkki and Seppanen (#10088, 1996). Three duct configurations were tested, two new ducts, one cleaned with normally used solvents (RM55) and the second had not been cleaned after leaving the production line. Finally, a 20 year old dirty supply air duct from an office building. The duct sections were brought into the laboratory and installed into a test unit. Decipol levels were assessed by a trained panel on the air before and after the test duct. Volatile Organic Compounds (VOC's) were also determined before and after the duct section. The test was conducted under positive pressurise, to restrict the ingress of outside pollutants. The sensory assessments were conducted with an established airflow of 0.9l/s for such tests. Results showed that new uncleaned, and old dirty ductwork generate odours, while new cleaned ducts produced clean supply air. Torkki and Seppanen undertook regression analyses on every chemical compound found from the chemical samples and for TVOC. Several dependencies were found for several chemical compounds. The paper does not outline these, but does tabulate the most specific 50. The surface from new uncleaned and cleaned ducts, show that the surfaces absorb the chemicals more than they desorb them, while the old dirty duct absorbs as much as it desorbs. TVOC emissions reacted almost in the same way in the different ducts as the single compounds did. They further conclude that, the type of duct surface (cleaned, oiled or dirty) had a greater impact on the odour emissions, than temperature and relative humidities. The authors were very surprised by the high odours emitted from the new uncleaned and old dirty ducts, these representing the majority of ducts commonly existing in buildings. Pasanen et al (#8772, 1995) have shown that the oil used in the manufacture of ducts promotes dust accumulation in newly assembled air ducts. Thus the paper shows that cleaning had a significant effect on reducing the odour emissions of the ductwork. The dust layer represents a good storage material for odour and therefore cleaning should be undertaken as often as needed, but on a regular basis.

Both chemical and sensory measurements where used by Bjorkroth et al (#11032, 1997) to determine the effect of duct cleanliness and environmental conditions on the supply air. This study extends research outlined above (Torkki and Seppanen (#10088, 1996). Using the same duct configurations, new, uncleaned containing lubricant oil and an old dusty section of duct. Bjorkroth found that the tests showed the cleanliness of air handling unit and ducts do have an influence on air quality. Long ducts greatly determine the final quality of the supply air. Thus the cleanliness of new ducts should always be ensured. New, uncleaned ducts might be as bad, a pollution source as old and dusty ones due to the oil residue on the duct surfaces. Ducts also show strong adsorption and desorption effects. The most important environmental parameter affecting emissions in terms of olfs per surface, are cleanliness of the duct and air velocity. Emissions increase along with air velocity. Therefore flow rates through the duct had almost no effect on supply air quality and supply air quality cannot be improved by increasing flow rates.

The reactive compounds formed in the supply air during entry into the building, using simulated ventilation equipment is studied experimentally by Andersson et al (#10085, 1996).Conducted in more extreme conditions than in a real life situation (higher than ambient), and extending a previous study by Sundell et al (#6867, 1993), in which it was suggested that volatile organic compounds could react with inorganic gases in the outdoor, air such as ozone or nitrogen oxides. This process resulted in the conversion of VOC's into reactive products such as aldehydes and acids, which where not determined by the method used for sampling and analysis of VOC's. This current study aims to determine whether the reactions between ozone and VOC's of various kinds are fast enough to occur in the supply air duct and also to determine the reaction products. Styrene was used as a VOC in the study. The experimental setup is described in the paper. Experiments were conducted at high styrene and ozone level (145 $\mu g/m^3$ of styrene and 600 $\mu g/m^3$ (300ppb) of ozone); and a low level (87 $\mu g/m^3$ of styrene and 120$\mu g/m^3$ (60ppb) of ozone). Experiments showed that at low levels 50% of the original ozone disappeared, while at high levels 89% disappeared. The reaction products found were benzaldehyde and formaldehyde. As well as occurring in the supply air the absorbent itself reacts with ozone forming benzaldehyde and acetophenone. Styrene is absorbed, and when ozone containing air passes, a reaction on the absorbent may occur. To show a reaction occurs in the duct, styrene was first generated and sampling was carried out on both adsorbents. Then only ozone was generated and sampling was continued on the same adsorbents tubes. Styrene reacted and produced benzaldehyde. This is interpreted by Andersson, who suggested that the reaction took place on the adsorbent, but to a lower extent than in tests in the polytetrafluoroethylene (PTFE) tube. Therefore, in conclusion, the results show the possibility of the reaction of VOC's with ozone in the supply air duct, forming potentially irritating compounds.

A major problematic hospital complex is reported by Anon (#11684, 1998), where for more than six years staff complaints were registered. Symptom reports began in 1987 when kitchen workers in the Canadian hospital complex began complaining of folliculitis, wheezing, eye irritation, sore throat and headaches. Within two years 80% of the 160 workers were suffering from these symptoms. Investigations pointed to sodium hydroxide used in the dish washing machine. The machine exhausted to a courtyard, near to the outdoor air intake. Corrections were made and improvements in symptoms were noted. However, some workers still complained, some of the complaints received were from workers on the other side of the complex. However, these were thought to be unconnected. In 1989 the number of complaints from workers increased further. Occupants in areas other than kitchen experienced a greater prevalence of bronchial hyper reactivity. They reported nausea, diarrhoea, weight loss, hair loss, recurrent infections and myalgia. The outbreak peaked in 1993 when 700 people were affected from a total workforce of 1250. Because all three buildings in the complex were affected, each with different ventilation systems, investigators focused on common elements in all three buildings. The cafeteria was suggested as a focal point, since all workers visited the building at some point. The HVAC system in the building with the cafeteria was investigated. It was determined that the system had not been probably commissioned, resulting in poor balancing. Also there was insufficient re-entrainment of exhaust and an underground passageway had insufficient ventilation. Poor maintenance and cleaning was also thought to have a part to play. Workers removed dirt and debris from the ducts within the building. For reasons of energy conservation, workers had closed the O/A dampers, leaving the building with no O/A supply. However, the one common thing about all three buildings on the complex was they shared a steam heating system and a steam boiler was used in a common humidification system. The maintenance staff used anti-corrosives in the boiler water, which was then reused eventually for humidification. Instead of adding anti-corrosives in a steady feed, workers would add them in batches, often 5-10 times above recommended levels. Because of condensation in the ductwork, mould and fungal contamination could have been the cause of the problem. The investigators recommended an upgrade of the ventilation systems and correct balancing. They also replaced the humidification system installing one that uses a separate water supply without anti-corrosives. These actions resulted in no new reports of symptoms.

2.5 Other forms of contamination in ductwork

The potential risks from grease and odours emitted from commercial kitchen exhaust systems, is discussed by Stoneman (#12664, 1999). In traditional systems, hot greasy air is collected under a canopy and passes through grease traps before entering the plenum and ductwork leading to the extraction fan and discharge louvres. In many catering kitchens grease and fat deposits are allowed to build up and are then periodically removed by mechanical cleaning and washing. Cleaning takes place every 3, 6 or 12 months. Initially entrained droplets of grease are removed first, achieved by using grease traps. These may or may not be effective and consist of either mesh pads or baffles that force air to change direction twice, causing the grease droplet to hit the baffles and run down into a collection well. Higher levels of removal are achieved by cartridge filters, which change air direction four times, but at the expense of pressure drop. In larger systems waterwash systems can be used to reduce grease levels, but these are built into the system and are not usually added later to existing kitchens. Another approach is to have a gas fired heated catalyst mesh pad in the duct above the grill to encourage the combustion of entrained grease. Such systems may still not be sufficient to avoid duct cleaning. Stoneman discusses a new device that treats the contaminated air by using ultraviolet-C enhanced oxidation technology. Special UV light tubes are installed behind the grease traps in a kitchen canopy or in the ducting in a reactor box. Hot dirty air containing vaporised cooling oil, water vapour and entrained fat passes over the light tubes where ozone is generated, and, under the intense light, fatty deposits and odours are broken down into smaller molecules and destroyed. Any ozone entering the duct reacts to gradually destroy the grease previously deposited. This leads to a grease free down-stream duct. Stoneman notes that the power consumption for a typical unit treating 6 canopies would consume less than 1kW, and such systems are kept grease free and do not need to be cleaned. This represents a significant cost saving, which can be used to offset the initial investment.

Newton (#12670, 1999) also discusses the build up of pollutants in kitchen exhaust systems, and outlines the need for such ducts to be clean in order to ensure adequate fire safety measures are maintained. Newton suggests that the recent trend of food preparation in a factory process, has led to large buildings, with high values for machinery and plant. The high hygiene considerations now required have further led to the extensive use of combustible insulting panels which would result in a total loss of plant and equipment if there were ever a fire. Even small fires can cause hygiene problems, smoke and fire damage could result in the eventual loss of valuable contracts. In most such buildings a fire suppression system is installed as an integral part of the ventilation exhaust system. A vital factor in preventing the spread of fire is the cleanliness of ventilation ductwork downstream of the fire suppression system. Newton notes that despite the original quality of materials and installation, few ducts are designed to resist actual fires within them. Gaps open up in the standard sheet duct, allowing direct flame impingement on surrounding materials. Often these materials are combustible, resulting in rapid fire spread. To control such exposure, regular cleaning of ductwork is essential, the frequency depends upon the time required to minimise deposits. The author briefly outlines a cleaning regime agreed by a London hotel. This includes the daily examination and cleaning of cooker hoods and primary filters, weekly examination of accessible ductwork areas by kitchen porters, and the full scale cleaning of the entire duct system, by professionals on a 6 monthly basis. In high risk installations such as commercial kitchens, fire preventing devices should be fitted as standard. Such systems include, fixed fire extinguishing systems, dry powder or CO_2. Traditionally the use of dampers and baffles have been used to prevent the spread of fire, operating by a temperature sensitive fusible link. However, these are likely to form grease traps in commercial kitchen environments, reducing their overall performance. Therefore, where these devices have been designed into the system, it is essential that cleaning and inspection be thorough and regular.

A literature review, relating to the emissions of glass fibres from fibrous glass duct board systems and sheet metal ducts internally lined with fibrous glass duct liners, is outlined by Woods and Goodwin (#12973, 1997). They found that the thermal and acoustical properties of these materials are well documented, however, the effects of moisture and contaminants on these materials are considered as system constraints and the properties associated with them are not so well identified in the literature. Although moisture is seen as affecting the thermal and acoustical properties of these materials, contamination is seen more of a health problem. As a consequence, product literature and handbooks provide some quantitative guidance on moisture control, but none regarding contaminant control. The review also found that fibres used in the manufacture of these products were associated mainly with glass wool, which is characterised with an average fibre diameter in the range 1 to 10 μm and a variability of the diameters of 50%, fibre lengths were usually greater than 250 μm and most had a high composition of sodium and boric oxides (i.e., Na_2O and B_2O_3) and the presence of binders. Such characteristics are useful in comparisons with other insulation materials such as rock and slag wools. For the majority of studies examined (9/10), a comparison of concentrations of man-made mineral fibres (MMMF) and man-made vitreous fibres (MMVF) in the outdoor air with HVAC duct work containing glass fibre material and in occupied spaces, indicates that the ranges of MMVF and MMMF measured within HVAC ductwork closely matches the ranges measured in the outdoor air (10^{-1} to 10^4 fibres/m^3). Of all studies providing original measurements of glass fibre concentrations related to the presence of fibrous glass duct board or duct lining, none reported on emission rates, either as direct measurements or as calculated values. It is reported that during construction and installation, concentrations of fibrous glass duct board may be high, but do rapidly fall. The quality of the ductwork construction is also an influencing factor in the initial and long-term emission rates of glass fibres. In conclusion, the authors draw three findings from their review. Firstly, the use of fibrous glass duct lining and duct board system can provide the intended thermal and acoustical benefits while maintaining occupant exposure of glass fibres to near background or outdoor air concentrations. Secondly, the thermal and acoustical properties of these installations may fail, if adequate care is not undertaken to ensure they are properly installed and maintained. And finally more field and laboratory studies are required.

3.0 Protocols and Maintenance

3.1 When to clean?

Duct cleaning has often been seen as a universal remedy for indoor air quality problems in buildings, however, Bolsaitus (#12659, 1993) suggests that cost benefit analysis should be used as a method of achieving a balance between the cost of cleaning operations and its relative benefit. On the cost side, duct cleaning can be considered a particular maintenance strategy, used in combination with filtration, humidity regulation, contamination source control and other HVAC operations strategies. Any real or perceived benefits must be based on risk assessments. Such an analysis is difficult, due to the large and varied nature of the indoor air quality problem. The technical literature relating to problems that affect air system cleaning (heating, ventilating and air conditioning (HVAC) and air duct systems), range from medical research on the health effects of bacteria and allergens in indoor environments to resistance of materials to aggressive environments, to the design, operation and maintenance of air handling systems for optimal performance. The complexity of systems combines with the use of an increasingly complex array of products in buildings and an increased awareness that chronic exposure to even trace concentrations of chemical contaminants, may result in delayed toxic effects. Regular maintenance, including duct cleaning, can reduce several, but not all of the potential indoor air quality problem areas. From analyses aimed at quantifying the frequency of incidence of particular causes of indoor air quality problems, duct cleaning or treatment, would address the immediate indoor air quality problem of sick building syndrome in less that 10% of cases. While in another 10 to 20% of cases, an indoor contamination problem may be compounded by excessive dust through adsorption and desorption of volatile organic compounds. These statistics only relate to buildings identified as sick, although, data regarding building maintenance programs and climatological variables are unavailable. Indoor air quality benefits, derived from air duct cleaning are not well quantified, since information needed to undertake risk assessments is insufficient. Some statistical compilations on the causes of SBS indicate that duct cleaning may be effective for remediating SBS in only a limited number of cases. Its effectiveness as a part of HVAC system maintenance schedules needs further research.

Summerville (#12658, 1998) states that duct cleaning is a misleading term, implying that just the ducting network of the HVAC system is cleaned. To be effective, the whole system, including the ductwork, fans, coils and other components should be cleaned. A clean system does not pollute the incoming ventilation air. In addition it runs more efficiently, reduces energy costs and lasts longer. Summerville notes, that when considering HVAC system cleaning, three areas should be examined. Firstly, the overall efficiency of the ventilation system should be considered, this has a direct correlation to the quality of the air within the building. Dirty systems restrict airflow, which can have a serious impact on the indoor air quality of the building. Secondly the use of low efficiency filters allows dust, chemical residues, grease and other foreign matter through the system and into the building. Finally, a good maintenance program for mechanical components is essential in preventing indoor air quality (IAQ) problems. In most cases HVAC cleaning alone will not solve IAQ problems. However, it can reduce the threat of indoor air pollution when conducted in conjunction with a program of regular building maintenance and IAQ evaluations. The most frequent contaminant found in HVAC system is common nuisance dust. Although the presence of a light film of dust is typical within many HVAC systems, it may not necessitate cleaning. The presence of excessive dust accumulations within a HVAC system can lead to the emission of biological contamination. As humidity levels within the system rise throughout the day, the chances of the growth in microbial contamination increase. The effective control of fungal contamination within HVAC systems is a matter of minimising the available nutrient sources (dust, dirt etc), and regulating the moisture levels within the system. Musty smells emitted from supply vents may be the first signs of microbial growth. As these sites of contamination dry out, the smells could disappear, and then reappear as humidity levels begin to rise again. Depending upon the use and age of the building, hazardous material may or may not be present, for example, asbestos. Specifications for the cleaning project should take account of these materials if they are known to be present. Some species of microbes may fall into this category, and should be identified. However, Summerville notes that it is generally only appropriate to sample and identify species of fungi when there are diagnosed illnesses within the building, which can be related to SBS. The location and concentration of dusts, microbial growth sites and other debris determine the need for system cleaning and decontamination. Summerville identifies the sources of contamination with a HVAC system in the table below:

Sources of HVAC system contamination	
The ducting network	
Porous insulation within the ducting network	Water damaged or contaminated material of this nature should be removed and replaced. The use of sealants to cover interior ductwork surfaces is not recommended as a long term barrier to prevent microbial growth. They might also affect the fire rating of the ductwork.
Filters	Ineffective sealing may lead to the by-pass of unfiltered air, into the system.
Cooling coils and condensate trays	Could become contaminated with organic dust. When coils produce moisture microbial growth becomes possible. Careful cleaning of any parts of coils and drip pans can reduce microbial pollutants. Once cleaned, these components should be thoroughly rinsed and dried to prevent exposure of building occupants to the cleaning chemicals.
Fans and fan housings	The organic dust load may cause mould or fungal growth on the metal surfaces, especially when high humidity is experienced.

After the system has been cleaned and restored to use, a preventative program of maintenance (PPM) should prevent any recurrence of problems. Such programs should include: identifying and correcting the cause of the contamination; controlling the contaminated area, to prevent the spread of contaminants; source removal of fungi, contaminated dust, debris and other materials within the ventilation system and treating microbial affected areas with anti-microbial agents as necessary; and finally making regular visual inspections of the complete system.

How Clean is Clean? This is the question posed by Mulhern and Mateson (#12654). On the one hand, source removal is considered to be sufficient, while on the other hand it is considered to be only half the job. The standard approach in the United States, according to Mulhern and Mateson, involves the attachment of a high volume vacuum to the duct system for approximately 30 to 45 minutes. The vacuum is then removed, the registers are cleaned and the old filter replaced. The job for many contractors, according to the authors, is then considered complete. Some contractors attempt to dislodge dust by using brushes and abrading the interior surfaces of the ducts (as far as they can reach). Whilst others utilise "power brush" equipment (as far as they can reach) to dislodge even more dust particles. From a source removal approach these procedures are correct and achieve a certain level of cleanliness. However, how clean is clean? If a household has an allergy to mould/mildew source removal will not resolve this problem, even though the duct system might be the only or largest storage source of the allergen. Carpets, rugs and upholstery could be the generator, or alternatively so could the coils and humidifiers. Glass fibre particles from old, insulated ducts with broken, torn or decomposed composite or liners represent another form of contaminant where source removal would be ineffective. Every time the blower starts the glass fibre will be generated and blown out of the system into the occupied space. Therefore duct cleaning is not just about source removal. Mulhern and Mateson outline five steps to achieve effective duct cleaning:

1. Initial testing to determine the presence or absence of contaminants and to identify them;
2. Source removal;
3. Encapsulation of materials not removed during the source removal process;
4. Disinfection (when necessary); and finally
5. Testing to document success of the job.

Although adopting this approach will lead to a more thorough and complete job, it will undoubtedly also be more expensive.

3.2 How often to clean (Maintenance programmes and standards)

3.2.1 Maintenance programmes

Regular maintenance ensures that the system is kept clean and any blockages or build-ups of dirt etc in the system are minimised. Nathanson (#10837,1997) found that in 21% of indoor air contamination cases, microbial contamination was the main contributing factor. Although inspection can often reveal mould on contaminated surfaces, a microbial source cannot always be detected visually or by its odour. Nathanson describes a microbial sampling protocol in which airborne and surface samples are taken and analysed by a mycologist who will be able to qualify and quantify the microbial species and interpret the results. The protocol gives guidance for interpretation of results, even though "safe" limits have not yet been scientifically determined. The author outlines the main visual inspection reservoirs, which should be considered as possible sources of contamination and places to look for potential microbial growth. With regards to remedial action, the main areas to examine are the outside air, air filters, the HVAC system and the occupied space. The on-site investigation begins outside, with the air intake and continues through the HVAC system to the workplace. Important considerations include the avoidance of pollutant entrainment into the air intake from cooling towers and evaporative coolers located close to upwind of the intake, and the restriction of rain entering the air intake. The location of sanitary and kitchen vents and exhaust from the building or adjacent to the building can also contaminate air intakes. Any stagnant water, leaves and soil should be removed from the roof near any air intakes. Bird droppings should be removed, as they can contain infectious fungi. Finally air intakes should be covered with a screen. With regards to the filtration system, ensure the filters are well seated with no gaps. Filters should be dry, have a sufficient dust spot efficiency rating and be replaced at regular and specified intervals. HVAC system components should have easy access for maintenance and cleaning. Any surfaces lined with acoustic insulation should be intact, maintained and cleaned at least once a year. The central supply duct should also be similarly maintained. Any water sources should be examined at regular intervals and general water quality should be monitored. Hard surfaces, contaminated with microbial slime should be disinfected when the building is unoccupied. Moisture incursion due to leaks, spills and blocked or dirty condensate pans and humidifier reservoirs should be minimised and if dirty should be cleaned. While prevention is the best defence, reduction of the nutrients that support microbial growth, proper filtration, housekeeping and quick corrective action in the event of a water spill is the best way to avoid microbial problems. Fungal spores can be released into the air months after a wet area has dried. Investigation into the occupied spaces centre around good housekeeping, minimising dust, spills and wetted carpets etc. Personal humidifiers should not be used, and relative humidity conditions should not exceed 60% (according to ASHRAE 55-1992). In conclusion, Nathanson states that preventative maintenance is probably the single most important factor for controlling microbial contamination in buildings. HVAC system components and office areas should be kept clean, free of dust, particulates and stagnant water. If IAQ complaints continue after simple remedial measures have been undertaken, airborne and surface microbial levels should be monitored as part of an assessment progress. These should clarify any sources of pollution, after which professional advice should be sought.

Post cleaning procedures are examined by Gray (#12360, 1999). A post cleaning inspection of a number of important areas such as, small ducts, ensuring all doors and access areas are closed and secure to prevent poor system performance and fire risks is carried out. Another important action is to ensure all hoses and flexible connections have been re-established after cleaning. Fire dampers should be checked for dirt and after duct cleaning has been undertaken are inspected to ensure they are in working order. Such dampers should be tested and regularly maintained. During cleaning, airflow regulating dampers may have been moved from their present position. These should be re-set after cleaning. Depending upon damper design this may be an easy operation or more complicated. In any case it should be undertaken properly and with care. Following cleaning, the air flows may have altered and therefore should be checked by a commissioning specialist at hand over. Once the system has been cleaned, the most sensible option is to regularly check the main high risk locations, such as air intakes, pre heat coils, filters, cooling coils, drain pans and pipework etc and at the same time try to prevent the entry of dirt into the system. Further Gray concludes, that medium and high velocity duct systems, can often prove to be self-cleaning, because the velocities involved are at dust transportation velocity above 10m/s.

The importance of regular maintenance of all mechanical equipment is emphasised by Neal (#6496, 1992). Such equipment may appear to operate satisfactorily, over time the build-up of dusts and dirt may result in higher operating costs and shorter lifetimes. Amongst the many issues discussed in this article on the efficiency of air conditioners in the real world, Neal outlines the problems associated with ductwork. A major factor in reducing the life of the central air conditioner is inadequate volume of return air back to the indoor coil. Too little air across the indoor coil can potentially lower the coil temperature so low, that ice forms. This puts a central air conditioner into destruction mode. Shutting the dampers on supply registers or closing unused rooms is not a good strategy with central air. Studies have revealed a host of problems including supply grilles that supply no air; ducts detached from the boots of grilles; only the crawl space of attics being supplied with conditioned air; supply ducts with holes large enough to stick a human head through and flex ducts in a crawl space that have been chewed through by a dog. Moves to tighten ducts, will lead to a host of other problems, such as poorly sized duct systems unable to provide the amount of air required for the equipment to work at its rated efficiency. A further issue discussed by the author is the designed ductwork air flow across the indoor coil. Unless the ductwork design and blower speed provide this volume of air, there is no way that the device can provide the rated capacity and energy efficiency. Causes of low duct airflow are sited as being dirty filters, dirty coil or closed registers, but the most frequent is inadequate return duct sizing. Another problem is associated with the use of flex duct. Installers invariably do not take into account adequately, the frictional losses for corrugated air surface, estimated at approximately three times as large as for smooth wall duct.

Pallari and Louma (#7039, 1993) exemplify the issues raised in the above papers, in an investigation of several demonstration buildings constructed in the 1980's, to see if the new systems, designed to achieve better energy efficiency and indoor air quality, actually worked. Some of the buildings had experienced problems during the commissioning and installation phases. In this follow-up study, maintenance staff were asked about the malfunctioning of the devices and the need for reparation. The regular maintenance included changing filters every third to sixth month, vacuum cleaning of the heat recovery units every twelfth month (only in single family homes) and cleaning ducts and air terminal devices when necessary. Exhaust air flows and pressure conditions were also measured during the visits to the buildings. The authors' conclude that normal maintenance work is insufficient to ensure the building and system remains in design condition in the long term. In one building where the HVAC system was maintained by the service staff, the gaskets of the engine doors were worn out and partly totally missing. The exhaust filter was not fastened properly, allowing a large proportion of the exhaust air flow to pass to the heat exchanger without filtering. The result had been a fall in measured air flow rate of 39% between 1980 and the supply air flow had correspondingly fallen 13%. In another building where the system was maintained by service staff, the fans and filters where dirty. The poor quality of work done by these service staff could be related to the fact that not enough time had been reserved to maintenance work.

Price (#12662, 1999) highlights the current practices undertaken by the industry to sell duct cleaning. Two approaches are commonly used, the first is scare tactics and the second relies on the threat of litigation to coerce the client into having the ducts cleaned. Price notes however, that in reality most selling of such services is indirect, and should encompass more than just cleaning operations. A complete indoor air quality management program should be the aim. These programs should include a detailed inspection and evaluation of the building systems, and practical cost-effective recommendations to improve the air quality within the buildings, which may or may not include, duct cleaning. HVAC system inspection should be a key element to any inspection. The outdoor air intake should be the starting point to any system inspection, apart from the obvious ambient air quality, other factors include siting, general location and quality of surrounding areas and quality of the inlet itself and system components etc. Following this initial check, the investigation should continue inside the system, with the filtration system, and other system components such as humidifiers, insulation, fans and blowers as well as signs of poorly maintained fittings, seals, joints and access holes. The ductwork can then be examined, with observations at several points along the ductwork. Of special importance are main ducts, branch ducts, low pressure and high pressure ducts, volume boxes, dampers and coils. The efficiency of the building ventilation system should be examined, to ensure that adequate air is reaching occupants and that there are no areas of stagnant air, not serviced by the moving ventilation air. Return air systems should be examined for the occurrence of dirt and obstructions or loose material such as insulation. Such inspections and associated reports provide the building owner with documented data on the condition of the air distribution system, supported by photographic evidence. Such inspections are also designed to lead to further work, for example if contamination is suspected then a cleaning operation would be required. This type of report could be the first step in establishing a comprehensive IAQ management program for the building.

Any system or building inspection should be undertaken by competent and capable people, appropriately trained to undertake such surveys and advise on their findings. Loader (#12665, 1999) examines the subject of training within the ventilation hygiene industry, which is very important because getting it wrong can be very visible, costly and dangerous. Proper and adequate training is essential, technicians and hygiene professionals come from the ductwork, engineering and building services trades or from the cleaning industry. Although cleaning ventilation ducts is a major element of the profession, it is not the sole element. Other elements include general health and safety issues, and skills in working in confined spaces and rope access. Much training is internal and on the job, with some modular and external courses also being utilised. For example, equipment suppliers can offer guidance for use of their cleaning equipment, and a number of suppliers offer seminars on general industry information plus specific information regarding their products. In conclusion, Loader emphasises the importance of training and its' necessary provision for the continuation of high service levels expected within the industry.

3.2.2 Standards and guidance

Finland's first attempts to produce hygienic guidelines for ductwork is briefly outlined by Leskinen (#4954, 1991). This work led the way to further, more far reaching guidelines such as those discussed by Sateri (#11561, 1998) and Pasanen (#12362, 1999). This more recent research outlines the proposed Finnish classification of cleanliness of ventilation systems. These guidelines are divided into two sections, the first deals with maintaining the cleanliness of ventilation system components, and the second outlines guidelines for the design and construction of new clean systems. The classification is based on the quality of the outside air as well as the cleanliness of ventilation system components, and is primarily concerned with the cleanliness of ventilation systems in new or refurbished buildings. As has already been discussed, the supply air quality is directly dependant upon the quality of outdoor air, air handling (filtering, humidifying etc) and the cleanliness of the ventilation system. Therefore good site planning, ventilation system design and efficient filtering will help play an important part in the quality of the indoor supply air.

Sateri (#11561, 1998) suggests that any good classification system should have good and easily measurable criteria and therefore cannot be based on emissions from building materials, because the chemical indicators (for example, TVOC's) do not display significant differences between good and bad quality of supply air. The proposed classification system is basically a tool, which outlines target and design values for ventilation systems and its components. Clients can formulate their wishes about cleaner systems and manufacturers can use the system to grade their products. While contractors get information about new cleaner installation procedures. The overall target is to ensure good quality supply air. The following contaminants are discussed within the classification. Substances harmful to health; microbes (mould and bacteria); man made mineral fibres; odours and dirt; dust and particles. Ventilation components are classified by the use of third party laboratory measurements and quality control agreements leading to official acceptance. The manufacturer declares the cleanliness properties at its own expense. This system should ensure components do not have to be checked on site, cleanliness labels and the conditioning of packaging should be sufficient. The section containing the guidelines, provides cleanliness criteria that can be measured in the commissioning of the ventilation system. Components either fulfil the cleanliness category or not. They should ensure the component will not contribute to the hazardous substances in the supply air, will not emit odours or gaseous pollutants, and shall not contain any visible dust of the inner surfaces. Finally they shall not contribute to the growth of harmful substances within the system. In the paper Sateri discusses these criteria specifically related to ducts, fittings, dampers and air terminal devices in more detail within the paper. With regards to the second section, the guidelines, the author sets out the two categories for the design and construction of clean ventilation systems. In the first category the system has to fulfil 5 requirements, including the stipulation that the supply air has a filter of class F7/EU7. The second category has 4 requirements including a supply air side filter of at least F4/EU4. Finally the guidelines also give requirements for various details in design and construction of the system. For example, guidance of the installation of components and instructions on the use and maintenance of the system.

The European and world wide standards in place relating to ventilation hygiene are briefly outlined by Trebilco (#12361, 1999). Many relate to the quality of outdoor air such as the UK National Air Quality Standards (EPAQS) and the WHO guidelines for Europe. Such standards cover many pollutants and should be referred to directly for information. Standards more specific include the NADCA (National Air Duct Cleaners Association) 1992 - 01 standard (Mechanical Cleaning of non-Porous Air Conveyancing System Components), which provides performance requirements and evaluation criteria for the mechanical cleaning of non-porous ductwork, fans coils and other non porous components of commercial and residential air conveyance systems (#8077, 1992). This standard also includes the protocol for carrying out the NADCA Dust Vacuum Sampling technique, which is now a widely accepted method across the world. In the UK an Approved Code of Practice states that mechanical ventilation systems (including air conditioning systems), should be regularly and properly cleaned, tested and maintained to ensure that they are kept clean and free from anything which may contaminate the air. The Ventilation Hygiene Group within the Heating and Ventilation Contractors Association, produced a good practice for the Cleanliness of Ventilation Systems (TR17) (published in May 1998). For the first time in Europe this standard brings together the various aspects of design and cleaning methodologies and includes a unique testing method for ascertaining when system cleaning is required. The code of practice examines system hygiene in terms of:

1. Design and access to the internal surfaces of the ventilation systems;
2. System components consideration;
3. System testing (inspection/monitoring);
4. Cleaning methods;
5. Kitchen extract systems;
6. Hazardous contamination;
7. Verification of cleanliness; and
8. Health and Safety.

The document also contains several appendices, containing information about legislation, testing methods and microbiological contamination.

The German guidelines, VDI 6022, "Hygienic standards for ventilation and air conditioning systems" are outlined by Funk (#12957, 1999). These guidelines cover the design and operation of HVAC systems in offices, assembly rooms and factories and also cover standards for hygiene training. Funk outlines the basic requirements of what is meant by hygienic, in that they create a physiologically satisfactory room climate and hygienic indoor air. Intakes should be above surrounding surfaces to minimise the amount of impurities that can be drawn in, general emissions and short-circuiting. Other requirements include, the specification that interior acoustic or thermal lining should be made from abrasion proof material, harmless to health and accessible for cleaning. Air filters should be designed so they can be installed, and if necessary replaced, in a manor that minimises or does not lead to the introduction of airborne germs in inorganic or organic dusts. On a more specific note the requirements state that if the system contains a humidifier, the total bacterial count (TS-Blut-Agar) in the humidifier water shall not exceed 1000 KBE/ml^2 (at an incubation of 20°C±1°C and 36°C±1°C). With regards to legionella, the total bacterial count shall not exceed 1/ml. The requirement also gives guidelines to what a regular hygiene inspection should include. For example, guidelines regarding walk around inspections, inspections of hygiene conditions including specific dab tests of filters, humidifiers and heat exchangers and details of the written report to the operator on the results.

Such inspections shall be carried out every two years in systems equipped with air humidification, and every three years in systems without humidification. Finally the requirements outline the qualification and training requirements of inspection personnel, reiterating the final comments of several similar papers, emphasising that inspection and maintenance of HVAC systems should only be carried out by personnel appropriately trained to do so.

The US National Air Duct Cleaners Association issues a wide range of standards and guidance relating to the state of ventilation ducting and associated pollution. More information about the NADCA and its publications can be found on their web site (www.nadca.com). They also issue guidelines relating to the General Specification for Cleaning of Commercial HVAC systems, Understanding Microbial Contamination in HVAC systems and Requirements for the installation of service openings in HVAC systems (NADCA-05-1997).

The North America Insulation Manufacturing Association (NAIMA) present a manual of recommended practices for the inspection, opening, cleaning, re-closing and return to service after cleaning of air ducts, incorporating fibrous glass thermal and acoustical insulation. Their primary objective is to ensure the structural and functional integrity of the duct system is maintained after it has been opened, cleaned and returned to service. Main considerations are to ensure the acoustical and air tightness characteristics are unaltered. The guidance note covers evaluation of the scope of the problem, pre cleaning inspection, opening ducts for cleaning, cleaning methods, sequencing of work, sanitising and sealing. Also covered are guidance on closing of duct systems after cleaning as well as final inspection procedures. The guidelines also contain a section structured as frequently asked questions, they examine how to decide if, and when insulated ducts need to be cleaned. Such questions include: What are the symptoms?; What's in the incoming air?; What's in the inside air?; and What kind of equipment is in use? Three cleaning methods are discussed: Contact vacuuming, air washing and power brushing. These have been explained in section 3.3.2, Cleaning methods. The main document however, concentrates on a review of detailed inspection procedures.

Carrie et al (#10613, 1999) outline various related national standards and building regulations, as part of a European project funded by the SAVEII (Specific Action on Vigorous Energy Efficiency) program, of the Commission of the European Communities - Directorate General for Energy (DG XVII), which considers all aspects of ventilation duct leakage. Countries covered include Australia, Austria, Denmark, France, Germany, Sweden, Switzerland, The Netherlands, United Kingdom, the United States as well as several general European standards, including the work of CEN 156 "Ventilation in Buildings". Part of which is formalised in the European Standard DD ENV 12097:1997 "Ventilation for buildings - Ductwork - Requirements for ductwork components to facilitate maintenance of ductwork systems". This guidance states that air distribution systems should be designed, manufactured and installed in such a way as to allow cleaning of all internal surfaces and components. Components include dampers, sensors, and air flow measuring devices etc, and should in turn be installed to allow cleaning to be undertaken. It also states that access openings should be unobstructed by suspended ceilings, electric wires, pipes or other ducts. The use of sharp bends and abrupt reductions should be avoided as well as the avoidance of sharp screws or other such objects that can cause injury to cleaning personnel. The standard also covers details regarding dimensions of service openings and their location, for system components as well as the ducts themselves. Three levels of cleanliness are considered, the basic level, covers cleanliness of the ductwork leaving the manufacturers' site, on arrival on site, and during installation. The intermediate level includes all the basic considerations plus additional conditions such as the installation working area should be clean and dry and protected for the elements and the open ends on completed duct work and overnight work in progress should be sealed. Finally the standard recommends some advanced levels of cleanliness. These are considered to extend the intermediate requirements, and include cleanliness issues during transportation, where all ductwork should be sealed either by blanking or capping duct ends, bagging small fittings, surface wrapping or shrink wrapping.

The background and details of the new European Directive covering biocides and disinfectants, and its impact of the ventilation industry is discussed by Clarke (#12666, 1999). The biocidal Products Directive aims to harmonise the European market for biocidal products as well as aiming to provide a high level of protection for humans and the environment. After 5 years of negotiations the final text was published in May 1998 reference (98/8), from then on member states have 24 months to implement the Directive, that is until 14 May 2000. The formal definition of biocidal products can be simplified to mean any product that is to control unwanted organisms, but that is not a food additive, a plant protection product (an agricultural pesticide) a medicine, a veterinary medicine or a cosmetic. The Directive covers 23 product types, divided into 4 groups. Disinfectants and general biocidal products; Preservatives (used in paints and for wood); Pest control (rodenticides and insecticides) and other biocidal products (preservations for food and feed stocks, antifouling products and embalming and taxidermist product). Common biocidal products are used in the ventilation industry as disinfectants in air conditioning systems to prevent legionnaires' disease, swimming pools etc, and to disinfect ventilation ducts. Preservations for liquid cooling and processing systems are used to prevent water and other liquids in cooling and processing systems from developing harmful organisms, such as microbes, algae and mussels. The overriding rule of the directive is that only those biocidal products outlined in the directive will be allowed to be put on the market and approval of active substances and biocidal products is a two-step process. Although the author explains the strategy behind the implementation of the Directive in the United Kingdom and its progress to date, the background to the Directive applied to all of Europe. The overall effect on the ventilation industry includes the registration of all biocidal products with the Health and Safely Executive, carrying an ID number. All products will have been fully tested in line with requirements of the Directive ensuring the safety of the user and to the environment. The risks associated with the product are also outlined on the label, as well as how they should be used, and how they should be disposed of.

A Guidance document outlining the process for conducting a ventilation hygiene contract, from managerial issues through to technical aspects of cleaning has been prepared by Loyd (#10976, 1997) (#10319, 1996). The guidance is applicable to the UK health and safety requirements of mechanical ventilation systems, including air conditioning. The guidance states that in the UK there are no standards covering the required level of cleanliness of ventilation ductwork, therefore inspections and maintenance are vital. Where cleaning may be required, a representative amount of the system should be inspected, with reports written to highlight the findings. This should then be followed by a detailed examination including air handling plant and both main and terminal units, as well as fresh air intakes, ductwork, filtration etc. Monitoring the indoor air quality may give an indication as to the level of cleanliness of the ventilation system, although the relationship between air quality and the level of cleanliness of the ventilation system may not be direct. Loyd states that at the time of writing, no UK standards exist on how to sample or measure such air quality. Although organisations accredited under the National Accreditation of Measurement and Sampling should be used to undertake such tests. The document also outlines the various cleaning methods, for example, manual vacuuming, hand washing, steam cleaning, chemical spray, mechanical brushing, air jetting, high volume air blast and hard scraping, and their appropriate method to use on each HVAC system component. These are outlined in more detail in section 3.3.2 of this report. Two tests can be used to determine how well a duct surface has been cleaned, measuring dirt per unit area of duct surface or measuring the amount of bacteria and fungi per unit area of duct surface where disinfectant has formed part of the cleaning process. Also included in the guidance note is information regarding the removal of cleaning odours, system balancing and re-balancing after cleaning.

A review of ventilation system hygiene by the same author (Loyd #10977, 1996) covers many of the same issues but in more detail. The author outlines the various forms of legislation regarding duct cleaning from Scandinavia, France, United Kingdom, United States of America and Japan. The nature and sources of contaminants are also discussed, with detailed discussion of micro-organisms and dirt contamination. Various methods are outlined to limit the level of contamination within buildings and ductwork. The key issues regarding limiting such contamination are discussed, for example, care should be taken to ensure ductwork remains clean during construction. According to the Building Services Research Information Association's (BSRIA) Commissioning Guide for Air Systems, several procedures to maintain cleanliness of ductwork during installation include: using the system fan to blow dirt through the system before the final connections are made and not commissioning extract systems before building work is complete. The internal surface roughness of ductwork can be important in deposition of particles within the duct and low efficiency and poor fitting filters can promote the build up of ducts in the system, especially at coils, fan chambers and dampers. At air intakes and exhausts, bird screens should be fitted and louvers with low rain penetration should be used. The review also covers the space requirements around ductwork to facilitate adequate cleaning and inspection, as well as the various types of hygiene access doors used and types of cleaning devices and equipment used for inspection and cleaning.

The United States' Environmental Protection Agency issue guidelines for residential consumers relating to ventilation ductwork entitled "Should you have the Air Ducts in your Home Cleaned?" The present paper briefly outlines the contents of the report section by section (Anon (#12663, 1999)), including What is duct cleaning?; Deciding whether or not to have your ducts cleaned; Suggestions for choosing a duct cleaning service provider?; What to expect of an Air duct cleaning provider; How to prevent duct contamination; and finally a consumer checklist. The paper comments on each section of the report, which is available on the internet at www.epa.gov/iaq/airduct.html. The report itself contains a consumer checklist, below, which aims to guide consumers through the decision making process.

	US EPA Consumer Checklist
	Learn as much as possible about air duct cleaning before you decide to have your ducts cleaned by reading this guidance and contacting the sources of information provided.
	Consider other possible sources of indoor air pollution first if you suspect an indoor air quality problem exists in your home.
	Have your air ducts cleaned if they are visibly contaminated with substantial mold growth, pests or vermin, or are clogged with substantial deposits of dust or debris.
	Ask the service provider to show you any mold or other biological contamination they say exists. Get laboratory confirmation of mold growth or decide to rely on your own judgement and common sense in evaluating apparent mold growth.
	Get estimates from at least three service providers.
	Check references.
	Ask the service provider whether he/she holds any relevant state licenses. As of 1996, the following states require air duct cleaners to hold special licenses: Arizona, Arkansas, California, Florida, Georgia, Michigan and Texas. Other states may also require licenses.
	Insist that the service provider give you knowledgeable and complete answers to your questions.
	Find out whether your ducts are made of sheet metal, flex duct, or constructed of fiber glass duct board or lined with fiber glass since the methods of cleaning vary depending on duct type. Remember, a combination of these elements may be present.
	Permit the application of biocides in your ducts only if necessary to control mold growth and only after assuring yourself that the product will be applied strictly according to label directions. As a precaution, you and your pets should leave the premises during application.
	Do not permit the use of sealants except under unusual circumstances where other alternatives are not feasible.
	Make sure the service provider follows the National Air Duct Cleaning Association's (NADCA) standards and, if the ducts are constructed of flex duct, duct board, or lined with fiber glass, the guidelines of the North American Insulation Manufacturers Association (NAIMA).
	Commit to a preventive maintenance program of yearly inspections of your heating and cooling system, regular filter changes, and steps to prevent moisture contamination.

3.3 How to Clean

The various techniques commonly used to clean ventilation systems and ductwork have been reviewed by several authors, and are outlined below. An initial inspection should be carried out prior to any cleaning taking place, a report outlining the level of contamination and methods used to clean the system should then be issued. Once cleaning has taken place, a post inspection, report or maintenance schedule can be established.

3.3.1 Inspection.

Ventilation system inspection is essential for a variety of reasons, following air quality complaints, system malfunction or performance reduction, risk assessment, legislation compliance, or as part of a maintenance programme (Yri (#12668, 1999)). Visual inspection in the form of a walkthrough, or by using remote control cameras represent the main inspection methods. Yri notes that while many air-handling units are accessible, air duct systems tend to be more inaccessible, therefore remote control cameras and borescopes are used. A number of different types and their uses are outlined by the author. The type of inspection as well as the equipment used also varies, from a quick spot check, taking a couple of hours to more detailed programmes taking several weeks or months. Whichever inspection method is adopted, if the inspection forms part of the ongoing monitoring process, it is important that the methodology and equipment adopted remain constant throughout. As long as no special problems exist, a sample of ductwork could be examined. The choice of inspection method and/or equipment depends upon several factors including, access, size and lengths of ductwork, size and type of access into duct, location in duct of specific item to be inspected, if known. The occurrence of obstacles/internal features, availability of electrical power and whether or not documentation of internal condition is required. Following inspection a report is issued to the client, outlining findings, conclusions and recommendations. Based on these findings, cleaning could then be undertaken. Other recommendations could also include amendments to maintenance schedules, repairs, and possibly air testing and monitoring.

Loyd (#12656, 1995) also examines the procedures and equipment for ventilation systems and ductwork inspections. With the implementation of the Workplace Regulations in the UK, ventilation systems are now required to be regularly and properly maintained to ensure they are kept clean and free from anything which may contaminate the air. Inspections of ventilation systems usually start by checking the outside air intake. A simple smoke test can determine whether outside air is entering the system. Loyd also outlines the most commonly used optical remote instruments, known as borescopes and the remote controlled inspection vehicles for filming the internal conditions. Ductwork inspection procedures also include examination of filters. If a filter is in good condition there should be less contamination downstream of the filter. Monitoring the pressure drop across filters may provide a guide to filter condition, but may not indicate the level of contamination emitted from a filter. Visual checks should therefore be made to ensure that gaskets are correctly fitted, clips are not broken or missing and the filters are held into their frames with no gaps through which air may pass. If fire dampers are fitted these too should be included in the inspection. Periodicity of inspection should depend primarily upon the level of contamination of the air passing through the duct. In most cases an annual inspection may be adequate, however in dust laden atmospheres fire dampers should be inspected more frequently. These may be laid down by local fire brigade requirements. The author outlines the recommended inspection procedures for fire dampers, in all, 18 points are discussed, covering all aspects to ensure the device functions correctly. Further items to check include volume control dampers, the hygiene of coils, fans and insulation; presence of water; and condition of condensate drain pipes and humidifier reservoirs. Persons undertaking such inspections should take a number of precautions to protect themselves, the building and the indoor environment. Initially the ventilation system will be shut down during inspection. Inspection itself many dislodge debris, which will, unless retrieved get blown out into the building. Occupants should be advised that such an inspection is underway, and if the system is believed to be particularly dirty, the building should be occupant free. Adequate protective clothing should be worn by the inspection team, including respirators, especially if microbiological contamination is involved. Other precautions include the disconnection of electrical equipment, and the protection of the office environment from damage, both by the inspection team and by material being extracted from the system. Loyd concludes by stating that besides the legal requirements, a regular inspection should be part of the buildings standard maintenance programme.

Inspection is also considered a prerequisite to cleaning, for Dahl (#12667, 1999),who suggests a visual inspection and collection of dirt samples. Dust measurements can be taken from dirt deposits with gel-tape-tests, and air particle counts, tests of micro-organisms are collected on contact plates and incubated and interpreted, air samples may also be used (i.e. RCS sampler). Dahl concludes by noting that in Norway industrial standards have been developed for regulation of the cleanliness of different surfaces, the table below summarises this standard.

Surface	Cleaning Classes					
	A:HIGH		B:NORMAL		C:LOW	
	Norm	Max	Norm	Max	Norm	Max
Furniture (Settled building cleanliness)	0.7%	1.0%	1.5%	2.0%	2.5%	4.0%
Walls, ceiling, floor	1.0%	1.5%	2.0%	3.0%	3.0%	5.0%
Carpet floor Dust Index*	2.0%	3.0%	3.0%	5.0%	5.0%	7.0%
Surfaces of the furniture High surfaces, Shelves	1.0%	1.5%	3.0%	4.5%	4.0%	6.0%
Cavity before closed	2.0%	3.0%	3.0%	5.0%	4.0%	6.0%
Inside surfaces in the ventilation ducts	3.0%	5.0%	5.0%	7.0%	7.0%	10.0%

*Measurements reported as dust-index according to the industrial standards.
The Dust cover percentage is measured shortly after cleaning has been completed. The measurements are taken using the BM Dust detector. The regulations on cleaning quality of internal surfaces in ventilation systems are based on measurements taken in the CLEAN Building Project.

3.3.2 Cleaning techniques

Once an inspection has been carried out and an agreed cleaning program commissioned, cleaning can be undertaken. Summerville (#12658, 1998) discusses the preparation of the site before cleaning, occupant safety and protection from contaminants, containment strategies and ensuring sufficient access to the system. Also covered are cleaning methodologies and equipment. He notes that source removal is recommended, employing the vacuum collection units, brushing, compressed air washing, hand or contact vacuuming (often HEPA) filtered, power washing, usually for components rather than ductwork, such as coils, fans, grills and diffusers etc). To be effective, source removal must loosen the dust and debris from within the HVAC system by agitation and then extract it away from the system. Once surface contaminants have been removed, a surface treatment is applied to remove the more stubborn contaminants and disinfect the elements of the system to prevent any re-growth. After the successful cleaning of the system, air balance within the system should be re-calibrated, checked and a maintenance program should be instigated.

Several authors identify and discuss the wide variety of duct cleaning methods commonly used. Amongst them Trebilco (#12669, 1999), categorises them into two groups, manual duct cleaning, is used where other methods would be inefficient or not possible, and includes hand wiping, scraping, brushing and vacuuming. Mechanical powered brush cleaning on the other hand, uses a rotating brush usually on a long rotating shaft to mechanically agitate the duct surface to loosen the deposit. This method is usually used in conjunction with mobile high volume filtered extraction unit. Compressed air cleaning systems either directly agitate the dirt in the duct or provides motive power for flailing tubes or balls. There are low (below 3 bar) and high volume (up to 9 bar) types. In low volume types the air is supplied to the cleaning head via a tube, there are three types of cleaning head; an air whip (has a number of flailing rubber or plastic tubes attached, which whip about in the duct and mechanically agitate the dust walls). A skipper ball is a plastic construction, with the air causing the ball the strike the duct surface and agitate the deposit). Finally an air lance or gun can be used, firing compressed air at the duct wall to blow any deposits off the surface of the duct. With high volume cleaning a larger compressed air source is used. The air is supplied via a semi rigid hose to a specially shaped nozzle head. The speed and volume of the air is used to directly clean the duct wall, helping lift the deposit off and transport it to a collection drum. Robotic cleaning methods consist of a tracked or wheeled buggy used to transport the cleaning tools into the duct. A control and power cable connect the device to the technician, and a video camera records and enables the extent of the build up to be determined. The machine contains an air compressed cleaner or scraper, with facilities to adjust position. Chemical washing is not used widely, but may be carried out after the main source removal cleaning has been undertaken to provide a final deep clean or sanitisation. The methods outlined above represent the main techniques employed for duct cleaning, however, other methods, such as high pressure (hot) water jetting, and solid carbon dioxide sand blasting can also be used. A proprietary system in which plastic balls are poured into one end of the duct connected to a large air handling unit, and bounce and rebound their way towards the extractor agitating the duct walls and removing dirt as they go is another system.

The North America Insulation Manufacturing Association (NAIMA), present a manual of cleaning fibrous glass insulated air duct systems. They highlight three of the most common duct cleaning methods. Contact vacuuming, involving the use of a portable hand operated vacuum cleaner being used in direct contact with the inside duct surfaces to dislodge and remove dirt and debris. This method requires more and larger access into the ductwork compared with other methods. Because the duct is not being subjected to negative pressure, dust and dirt can escape from the duct during cleaning. Other methods include, air washing and power brushing which do involve negative pressure. Air washing uses compressed air to loosen any accumulated dirt on the inside of ductwork, loosened debris being drawn into the cleaning device. Power brushing uses a pneumatic or electrically powered rotating brush to loosed debris, which is then drawn downstream and into the vacuum collector. During this process care is required not to damage soft materials such as acoustic insulation, duct liners of filter surfaces. For this reason only soft bristle brushes are used. Other methods such as steam cleaning are also used to clean uninsulated sheet metal ducts, however because such methods involve the generation of moisture they should not be undertaken on duct work which has integral insulation.

Loyd (#10976, 1997) highlights the wide variety of cleaning methods, outlined in the table overleaf:

Duct Cleaning Methods identified by Loyd (#10976)	
Manual vacuuming	Wet or dry suction cleaners with brushes to clean ductwork containing dry atmospheric deposits.
Hand washing/wiping	Simple wiping process used in conjunction with cleaning agents.
Hand wipe in clean room environment	For clean rooms manual vacuuming is followed by a thorough hand wipe with specifically designed materials. "Takrags", anti static dusters, lint free cloths and specialist cleaning solutions are typically used for this high grade clean.
Steam washing	Used where contamination is heavier. Selected cleaning agents break down the deposits of grease etc, reinforced by high pressure water and steam cleaning at temperatures up to 150°C and followed by thorough rinsing. The waste is either directed into collection barrels using sheeting methods or collected with wet suction cleaners. The material is then neutralized and washed down the drain. Care should be taken to prevent damage from possible leaks at duct joints.
Chemical sprays	Suitable for heat exchange coils and ductwork. Special cleaning agents break down stubborn deposits.
Mechanical brushing	Suitable for small sections of ductwork. Flexible brushes of different lengths, diameters and bristle grades are used depending upon the duct. It is vital that the brushing system used is capable of agitating all internal surfaces of the ductwork, whether circular, oval rectangular or square. This is normally accompanied by a sectional extraction technique.
Air jetting using high pressure and high volume flexible air jetting devices.	This is normally accompanied by a sectional extraction technique. Coils can be cleaned using compressed air.
High volume air blast	Involves using a limited amount of injection points, mainly plant room ducting. Air at high volume and pressure is fed into the duct system whilst the system is running. This increases the air velocity through the ducting. Most of the loose deposits are collected by filter media which are fixed over the outlet and inlet points. This technique has limited application and is not normally used in commercial buildings.
Sectional	Extraction involves cleaning the ductwork in sections. This maximises the extraction velocity. Mobile extraction units are used to create sufficient air flow whilst air jetting and rotary brushing remove the loosened deposits. The dirt laden air is then passed through a dust collector to remove any particles before being exhausted.
Sectional blocking	Requires sealing sections of ductwork as cleaning progresses to prevent cross contamination. High density foam blocks or tight fitting air bags of different sizes are used to seal off cleaned areas.
Sealing or encapsulation	Used where accessibility is poor or cleaning is required to an ultra deep level or where fibrous linings are present a sealing solution may be applied. The sealant will prevent movement of any remaining particles, although dirty surfaces may prevent proper adherence of the sealant. The acoustic properties of coated internal insulation, fire safety and potential for off gassing should be considered.
Hand scraping	Is more appropriate where surfaces have heavy sticky deposits such as in kitchen extracts may need to undergo an initial scraping with a stiff (1 to 4" wide) steel scraping tool to reduce to a fine film prior to either other finishing techniques.

Four cleaning methods are highlighted by Fugler (#7730, 1993), having been used by professional cleaning firms during a study to investigate the efficiency of residential duct cleaning.

1. Cleaning with an industrial vacuum and brushes. This method consists of the use of large brushes designed to fit snuggly against the inside of the ducts. Any debris or dust is pushed to the end of the ducts to cleanouts, where they are removed with a vacuum system. The vacuums are used to both push the debris and to draw in the debris depending on the access of the duct. Certain vacuum cleaners use high efficiency HEPA filters. In some cases, a biociode agent is sprayed over the system's components and in the ducts.
2. Cleaning with industrial vacuum and air spray. This is similar to that outlined above, except it uses an air compressor to increase the pressure in the ducts. The air compressor produces a jet of air in the ducts which pushes the dust toward the vacuum cleaner.
3. Vacuum truck. Employed by the largest companies. The companies' truck contains a high powered vacuum cleaner and air compressor. The vacuum cleaner is attached to the fan casing of the system. Return ducts are then sprayed with an air compressor. The dust is then sucked back through the system into the companies' truck.
4. Vacuum truck and metal ball. Similar to the vacuum truck method however a selection of metal balls attached to the end of the air compressor stir up the air being sucked into the truck.

Fugler further states that frequent advertisements by professional duct cleaning companies outline the benefits of duct cleaning, which include, improvements in ventilation flow rates, reduction in airborne dust, better comfort and lower energy costs. Despite the fact that in many cases duct cleaning is necessary, it is difficult to quantitatively assess the actual results of such processes. To backup this comment, Fugler outlines a study he conducted on thirty-three houses. All households had a forced air heating system which needed cleaning. A general questionnaire was completed outlining the overall dimensions of the house, number of occupants and lifestyle questions. Sixteen cleaning companies were used, employing the methods outlined above. After cleaning it was found that the fan pressure did not increase, tests on voltages of fans and system equipment before and after cleaning indicated that cleaning did not significantly reduce energy consumption and may have even increased it. Further, the supply flow rates increased by approximately 1 l/s (not statistically significant), whilst in half of the houses studied, supply air flow rates actually reduced. Cleaning the fan alone resulted in a 3 l/s (6 cfm) increase flow rate, but the author noted that this too, is not statistically significant. The return air flow rates increased by 3 l/s (6 cfm), but again this is not significant at the 95% confidence interval. Overall, in 44% of cases studied the return air flow rates were reduced following cleaning. Therefore cleaning the ducts did not have a significant influence on return air flow rates. The indirect effect of cleaning is the readjustment of system dampers and registers after cleaning, which the author states could have a more beneficial effect on dust removal than the cleaning itself.

The effects of using biotical detergents and disinfectants on mould and micro organisms commonly found in ventilation ductwork is discussed by Pasanen et al (#12653, 1993). Such substances differ in chemical nature, mode of operation, durability, effectiveness, toxicity, safety and cost. Pasanen notes that two groups are available; bound agents which bind themselves chemically to the surface of the duct working continuously when in direct contact with micro organisms, and unbound agents which disappear or decrease in effectiveness by evaporation of subsequent washing. Biocides used for these purposes include Hypochlorites, Hydrogen peroxide, Quaternary ammonium compounds, and alcohols (ethanol, propanol and isopropanal). Diluted ethanol (50% to 90%) is a more efficient biocide than concentrated ethanol (99%). Phenols and aldehydes are also used as biocides. Many biocides are potential irritants for eyes, skin and mucous membranes, and are not recommended for occupied spaces. However, less harmful biocides such as alcohols and diluted hydrogen peroxide are not effective enough because of the short-term effect. If the ventilation systems is heavily contaminated with micro-organisms the use of biocides is unavoidable for complete cleaning. However, proper use involves careful cleaning of air ducts before the antimicrobial treatment. The ventilation system should be shut off and occupants evacuated. Biocides may be effective for bacteria, but not sufficient for fungal spores. This paper outlines work to test the fungicidal effects of biocides and cleaning detergents used for air duct cleaning in Finland. Four fungal species common in indoor and outdoor environments were chosen; *Penicillium verrucosum* and *Aspergillus versicolor* (commonly found indoors) and *Cladosporium sphaerospermum* and *Aureobasidium pullulans* (DSM 62074) are commonly found outdoors. Samples of each were prepared on agar plates, once established biocides were introduced to test their effectiveness. Results indicated that the strongest recommended concentrations of each product gave the best or equal inhibition results when compared with the strongest tested concentration. This indicates that there is no reason to use products more concentrated than recommended. Alkalic products containing chlorine, quaternary ammonium salts and butyl glycol were the most effective inhibitors. Two of the strongest concentrations containing glycol were also effective for all fungal species tested, although fungal colonies were found inside the treated area at the dilution of 1/50. The effectiveness of the products appeared to decrease with time, after 10 days evaporation of the disinfectant below the effective dose of the products lead to a reduction in effectiveness.

An extension of a study outlined earlier (Holopainen #12961, #12963, 1999) compared three duct cleaning methods (#12958, 1999), rotating brushes, compressed air cleaning and wiping by hand. The results of this study showed that there is a significant reduction in the amount of the dust with all the tested methods. The bottom surface, where dust accumulation is highest was most effectively cleaned. The best results were shown in the building in which the rotating brushes were used. In comparisons of cleaning methods, brushing achieved 20-21% reduction in light transmission, while compressed air and hand wiping showed, 16% and 15% respectively. Before cleaning the amount of dust on the bottom surface of the duct was 3.2-9.8 g/m^2 and after air duct cleaning 0.98-1.30 g/m^2 by using the tape method. Based on the tape method the brushing was slightly better than compressed air cleaning. Visual inspection of cleaning showed that hand wiping achieved the best results. In conclusion Holopainen found that the best cleaning method was hand wiping. Brushing was identified as a suitable method to clean round air ducts, with this method, it is possible to loosen congealed dust from the duct surfaces. Holopainen emphasised the importance of selecting a suitable brush depending upon the type of dust, and that dust should be removed from the duct with air over 20 m/s.

An extensive literature survey (80 references) has been undertaken by Brosseau et al (#12634, #12635, 2000) to address the non-routine cleaning of ducts and other components of HVAC systems. Presented in two papers, the first (#12634) concentrates on the pollutants and effectiveness of the cleaning process, whilst the second (#12635) focuses on the overall resultant health effects and effectiveness of the cleaning companies. Brosseau notes that there appears to be an information gap between the presence if indoor air complaints and the decision to clean and decontaminate HVAC systems. There is no well established decision process, to link specific types of complaints to particular contaminants and their sources. If such a link does exists there appears to be no method to determine the appropriate cleaning or decontamination procedure for a particular contaminant of HVAC component. There is also no clear method of assessing the effectiveness of cleaning and methods of reducing contamination further. This study focuses on these issues with the type and nature of contaminant, duct cleaning methods, measured contaminant levels and the effects of duct and air handling cleaning all considered. What emerges from the survey is that the nature or the contaminant, their sources and resulting health problems represent a diverse mix. It is not therefore always possible to determine the specific cause of a building related illness, however the building HVAC system is believed to a contributing factor in many cases. Some studies have shown that building related illness are more prevalent in mechanical ventilated buildings than naturally ventilated ones. Other findings demonstrate that the occurrence of some building related illnesses are attributed to changes in HVAC system settings, such as reductions in air flow rates. A common form of pollution identified by many studies relates to biological agents, these not only contaminate HVAC systems, but also have the potential for growth within those systems. Thus numerous bacteria, some viruses and particularly fungi are targeted for control. This study suggests that nearly all cleaning of HVAC systems is "non-routine". There was in fact, little evidence of the use of routine cleaning protocols, with cleaning being initiated when the build up of dust of debris was either visible or being deposited on supply diffusers. The detection of microbial deposits, especially mould and odours also led to cleaning. However there was an agreement that cleaning, even non-routine cleaning, would be needed less, if more attention to paid to preventing contamination in the first instance. More attention to source control, better control of relative humidity and greater use of pre filters where some of the main issues raised. The authors finally note that with regards to HVAC cleaning, each building and situation must be evaluated on an individual basis to ensure that the control and cleaning methods used are appropriate for the building and level of contamination present.

In the second paper by Brosseau et al (#12635, 2000) she discusses the health implications of poor cleaning practices and examines a number of companies approach to duct and system cleaning. Surveys were conducted of representative duct cleaning companies to determine their recommended approach to duct and HVAC systems cleaning. Interviews were also conducted of trade associations, academia, government agencies and consulting firms to gain their assessment of the cleaning process. Cleaning HVAC systems can present a number of hazards for cleaning personnel, including the risks associated with working in confined spaces and the use of chemicals such as biocides and antimicrobial pesticides (inhalation and irritation). The use of specialist equipment also presents several problems, including the confined space itself providing a difficult working environment and the high noise levels, exacerbated by the confined space. Of equal importance are the contaminants being removed and the health problems associated with inhalation and contact. Care should also be taken when removing contaminated filters, insulation etc, as this could result in the release of aerollergens into the indoor air, possibly exposing not only the maintenance personnel, but also the building occupants. Therefore, it is vital that the correct protective equipment and clothing be worn for the correct application, and recommended local or national standards followed (e.g. OSHA). Responses were received from thirteen of the thirty one companies surveyed during this study. All had been undertaking air handling cleaning for more than two years; most had been doing them for between 5 to 10 years. The companies reported a variety of other services, the most common being duct vacuuming, cleaning of diffusers and coils and disinfection. Companies indicated that occupant complaints were the most common reason that clients requested duct cleaning (41% of all jobs) followed by recommendations by professionals (23% of all jobs). Seventy seven percent of companies indicated that they do not carry out a cleaning trial prior to determining the appropriate cleaning method for a system. Eighty five percent indicated that the air handling unit is almost always cleaned when the ductwork is cleaned. The most common material found was lined sheet metal in air handling units and unlined sheet metal in ducts. If a damaged duct liner was found, 92% of companies would either remove or encapsulate it. The most common contaminants of ducts were visible accumulated dust, followed by litter, visibly wet or water accumulation, and obvious mould growth. Companies reported finding contamination most often in return ductwork, turning vanes and dampers the inside surface of air handling, return chases and coils. When asked about the chemical treatments, most companies indicated the use of biocides and disinfectants, a large number of anti-microbial paints and less than 50% used deodorants, encapsulates/sealants and cleaning solutions without biocides. The effectiveness of cleaning was almost always determined before and after cleaning by visual inspection. There was a general feeling that antimicrobial chemical treatment was effective for less than one year, while vacuuming with HEPA, manual brushing and HEPA vacuuming and power brushing and vacuuming were all effective for more than one year. The survey of professionals favoured manual rather than power cleaning methods and all agreed that cleaning activities could add additional contamination problems.

4.0 System Conditions

4.1 Filtration

Filtration as part of an integrated air supply system consists of different stages, Charkowska (#8486, 1994) considers four such stages. The first is the pre-filter (normally of EU class 4), and mounted on the air conditioning unit air intake, protecting the system components from material that could restrict or impede their operation. The second stage, normally EU class 7, are recommended to be placed behind all main devices of the air handling unit, cleaning air of smaller dust particles, smokes, vapours and pollens. The third stage air filter, normally EU class 9, is placed in room air intake, and should remove respirable dust size particles. Finally placed on the room outlet is an exhaust air filter, again EU class 9. Applied to prevent moving the pollution to the room from the exhaust ducts during installation malfunction. A number of assumptions have been made or data collected and analysed before such filters are specified. For example, the concentration of dust in the outdoor air should be known or assumed. A simplified model of indoor emission has also to be assumed, this will consider both average size aerosols (exhaled by occupants and created by their activities) and fine aerosols, created during the condensation processes, such as through cooking etc. The influence of previously settled dust emissions should be considered (from areas inside the ventilation and air conditioning units, regarded as secondary sources of pollution). The relevant pressure losses over the system should be estimated, with new clean filters as well with filters nearing their renewal date. Charlowska undertook a number of tests in which he considered increasing amounts of pollution, whether pollution is emitted directly into rooms and also the periodicity of maintenance procedures. He concluded that, in most cases only one stage of filtration causes inadequate purification of outdoor air. The multi-stage filtration described above is a means of efficiently protecting the people and devices from the results of air pollution. Proper and adequate maintenance of air conditioning and ductwork is however essential, this improves cleanliness of air supplied to room, makes the filters service life longer and reduces installation running costs. Contamination of the air conditioning unit and ductwork have been found to reduce the efficiency of the air cleaning process, the influence of this contamination can be reduced when a multi-stage filtration system is used throughout a system. However, the more filters integrated within a system the greater the capital, installation and maintenance costs. Such costs should be carefully balanced against the positive impact such filtration can have on the overall indoor environment and occupants of the building.

Hagstrom et al (#11146, 1997) examine filters in an industrial environment. They have attempted to devise a methodology for the control of particulate contaminants and to define the basic criteria for design and optimal selection of supply and recirculation filters. The methodology considers outdoor air quality, desired indoor air quality, emissions from the processes and cleaning of ductwork and equipment. A prerequisite to filter selection is

information about typical particle concentrations and the size distribution in the air to be filtered. A number of assumptions have to therefore be made, regarding the quality of the outdoor air, any possible hazardous contaminants and the total concentrations are expected to be below occupational exposure levels. The study outlines a new design approach based on the definition of target levels for filter performance, based on three classes:
Class 1- T5/10 - The maximum allowable penetration of 5μm particles is 10%. This filter is assumed to effectively capture large particles, which may cause dust accumulation e.g. in ventilation ducts (settling dust).
Class 2 - T1/10 – The maximum allowable penetration for 1μm particles is 10% (minimum efficiency 90%). This filter is assumed to cause significant decrease in the concentration of those particles which effectively deposit in the human respiratory system.
Class 3 - T0,5/10 – The maximum allowable penetration for 0.5μm particles is 10%. This filter is assumed to be effective even for fine particles i.e. the particles which originate from combustion processes (traffic and energy production) and atmospheric gas to particle conversion.

This form of classification clearly describes filter performance in terms of maximum penetration at a certain particle size value. Hagstrom then considers industrial environments in terms of 5 categories. These are: covered process, working environments in industry, spaces with special cleanliness requirements, laboratories, kitchens, smoking rooms and offices, and other official spaces and residential areas. He states that the weak correlation between filter classification and performance has in the past led to non-fact based selections of filters. However, new test methods based on filter's fractional efficiency have made it possible to compare performances of filters and filter media in practice. The currently used filter classifications have too many classes to make a real distinction between different classes. To add to the confusion, several manufacturers' EU6 class filters show a wide variation in filter performance, when new methods are used. In tests, initial efficiencies of some EU6 class filters displayed poorer performances than that of EU5 class filters. Therefore Hagstrom used standard tests, and defined several glass fibre bag filters of different classes, against the recommended cleanliness classes. Target level T5/10 Filter class EU4 (EU5), Target level T1/10 Filter class EU7 and finally T0,5/10 filter class EU8.

Hagstrom also suggests that the most important technical figure in system optimisation is the maximum allowable final pressure drop of filter, which depends on the allowed air flow change during operation and fan performance. This should be calculated at the design phase and corrected after installation. The properties of filter material and construction should also be taken into account. The filter selection should always be started from the target level, a cost benefit analysis can then be carried out to determine the acceptable filtering methods applicable to the job. The assumptions made at the design stage and the lack of data available about the performance of filters in real situations makes their selection based on older methods more questionable. Therefore economical optimisation can be used in single cases effectively, especially during operation time, when more accurate information about local conditions are available. Hagstrom hoped to extend this work to publish guidelines for filter selection, optimisation and maintenance.

Test methods for air cleaners are evaluated by Hanley et al (#8288, 1994) and Ensor et al (#12661, 1995). Their aim was to develop a test apparatus and procedure to quantify the functional filtration efficiency of air cleaners over the 0.01 to 3μm diameter size range and to quantify efficiency of several induct air cleaners typical of those used in US residential and office ventilation systems. In their paper the authors review current test methods, and note that they only determine overall efficiencies for ambient aerosol or other test aerosols, and provide only limited data. Because particles in this range are respirable and can remain airborne for prolonged time periods, the measurement of air cleaner fractional efficiency is necessary to determine their applicability to indoor air quality issues. The authors also outline related work in this field and describe their test rig and instrumentation, together with details of how the tests were conducted. The tests involve two basic phases, the first is the fractional filtration efficiency test, and the other is loading the filter with a relatively coarse dust. This dust can significantly alter the efficiency of the filter. The tests began by setting the airflow rate to the desired level, then verifying that the aerosol measuring devices read at or near zero. The test proceeds with measuring the clean filter pressure drop and initial fractional filtration efficiency. The load dust was then injected into the upstream air until the air cleaner's pressure drop reached 125Pa. The fractional efficiency measurement was then repeated. A second dust loading was then performed to bring the air cleaner's pressure drop to 250 Pa. The fractional efficiency measurement was then repeated. It was found that the fractional filtration efficiency of air cleaners is often strongly dependant upon particle size, flow rate and duct loading. Naturally loaded and artifically loaded filters show similar efficiency curves. A minimum in filtration efficiency was often observed in the 0.1 and 0.5µm diameter size range. The typical US furnace filter had a clean fractional filtration efficiency of less than about 10% for particle diameters between 0.02 and 1µm. The efficiency improved with dust loading, but remained below 20% over the 0.03 to 0.3µm diameter range. The air cleaners generally showed increased filtration efficiency with dust loading. A notable exception was the charged fibre filter, which showed a decrease in efficiency after dust loading. The charged fibre filter appears to have had a significantly increased initial filtration efficiency due to the electrostatic charge on the fibres. Dust loading however, appears to have inhibited this electrostatic effect, and the filtration efficiency was seen to be much lower than for the clean condition. Finally the self charging panel filter had a relatively low filtration efficiency, similar to that for the furnace filter.

Ensor (#12661, 1995) briefly presents the model for such tests and guidance to the type of data required. Particle size collection efficiency is usually around 0.1 to 1.0 µm range, with overall efficiency being a function of filter design and air flow rate. Biological and viable material of this size can be removed by normal filtration. The removal of gasses is dependent upon the chemical and physical properties of specific compounds. The absorption of a gas is not a steady state process, with gases being absorbed and desorbed as changes in concentration cause shifts from equilibrium. Two laboratory tests, with media samples and full scale air cleaners, under two application conditions are described. Filtering the outdoor air and filtering indoor re-circulated air, with the relative humidities and temperature being carefully monitored, due to the sensitivities of activated charcoal used to make the filters. The efficiency of the air cleaning devices as well as simply the filters is also a consideration. Ensor found that a number of factors affect the application and selection of air cleaners, for example their location, the variability of air flow and pressures through the duct system, the relative infiltration and exfiltration of the building. He also found that contaminants within the building may consist of a complex mix, which will affect the efficiency as well as maintenance, ease of use and capital costs of air cleaners.

The deposition of small particles along the length of ductwork is examined by Lai (#11611, 1998), who undertook an experimental study to investigate the principle. The author suggests that this process may compliment or even eventually provide an effective alternative to ventilation system filtration, especially electrostatic precipitator. By increasing the roughness of the ventilation ductwork particle deposition can be increased. Small tracer particles of size 0.7-7.1 µm were used to study deposition enhancement with streamwise-periodic mounted on one of the principal walls, under turbulent flow. A new and highly sensitive technique was used to determine the spatial mass flux along the ribbed duct. It was found that on some surfaces particle deposition enhancement was as much as seven times higher than on smooth surfaces. Periodic averages of mass transfer coefficients for different particle sizes were evaluated. The friction factor was approximately three times the smooth duct value. The author outlines the experimental and theoretical method behind this work in more detail in the paper. This work was intended to investigate particle deposition along a roughened surface, and how to modify or improve the capture efficiency of current designs of some common devices such as electrostatic precipitator, and is not intended to apply to existing filters.

The moisture content of different commercial air filter media under controlled static conditions, is examined by Bock et al (#12855, 1997). Knowing the amount of water in a material can help prevent microbial growth, which depends upon the physical and chemical properties of the material, the nutrients which they provide but more importantly on the free water loosely held, by adsorptive and absorptive forces, in the capillary spaces and on the surface of materials. New commercially available air filters, with different depth filter media from five manufacturers were studied. Three bag filters, consisting of spun glass and organic synthetic (polymer) fibres, and two cassette type filters, composed of spun glass and cellulose fibres. The bag filters consist of filter media progressively laid one behind the other, while cassette filters consist of folder filter mats zigzagged within the cassette casing. Experimental field and laboratory tests were conducted and the filters were analysed. After 7 and 14 days the humid mass was weighed and desiccated over night. The samples were stored in an exsiccator with a drying agent for 24 hours, then the dry mass determined. From the ratio of dry mass to wet mass, the moisture content was determined. Laboratory results showed that the moisture content of the studied media differed considerably. The water binding capacity depended upon the used filter material, the textile structure of the filter media and the chemical treatment of the fibres. It was found that atmospheric dust loading increased the moisture content of the filter media. The polymer fibre material had a lower moisture content than the spun glass media after 2 weeks in a humidity chamber. The bulgy glass material also showed a higher ability of water binding capacity than the folded glass "zigzag paper material". Natural cellulose fibres generally show a higher ability to bind water than spun glass of polymer fibres. Bock therefore found that by comparing new and used filter media, subjected to 14 days trial, with new filter media they showed low moisture contents ranging from 1.5 to 20.7%. For used (soiled) media a higher moisture content is indicated (from 9.5 to 65% at 97% equilibrium relative humidity (ERH)). The deposited material (dust) in the used air filter is responsible for the main part of the moisture bound by the media at the given climatic conditions. As service life increased so did the moisture content. It was assumed by the authors that the majority of the water held was by adsorptive and/or absorptive forces in the capillary spaces and on the surfaces of the atmospheric dust. This means that only a part of the amount of water present in air filter materials is available for possibly undesirable growth of moulds and bacteria. However they state that experience has shown that excessive mould and bacteria growth inside air filters is rare.

Neumeister et al (#12856, 1997) studied different filtration material (synthetic fiberglass and cellulose) to determine the existence of any relationship between fungi and poor air quality. Experiments were conducted on a pre-filter of a large HVAC system. The normal pre-filter (fibreglass type EU7 filter) was replaced with the three standard filter types commonly available in Germany. These were EU6 cellulose, EU6 synthetic and EU7 fiberglass. Each material was placed in the pre-filter for one month, after which samples were analysed for fungal contamination. Four samples were punched out of each filter, two were analysed immediately for fungal contamination, the results of which were used as base levels for future tests. All cultures were incubated for 5 days at 20±2°C. The remaining two samples of each filter where placed in a climate chamber for three weeks. The psychometric parameters of temperature (22.5°C) and relative humidity (60%, 75%, 90%, 95% and 100%) were controlled as well as the air flow rates, controlled at normal (30 litres/min for 24hr/day), reduced (4 litres/min for 24hr/day) and intermittent (30 l/m but turned on 08.00 and off 18.00 between Monday and Friday). Samples were then analysed for fungal colonisation. After one month of normal off site operation the three filter materials showed different levels of fungal contamination. The highest colony forming units were extracted from the synthetic material (2770 cfu/m^2) with lower numbers extracted from the fiberglass (369 cfu/m^2) and lowest from cellulose material (101 cfu/m^2). Climatic chamber results showed that fungal counts were significantly reduced on all media types after three weeks. However there was a general trend in fungal colonisation at relative humidities with highest at 60% and 100% and a slight but evident reduction between 90% and 95%. Previous studies have indicted that micro organisims can be deposited on the surface of air filters. Indeed in this study only samples nurtured on agar plates, did in fact show fungi species, such as *Cladosporium spec, Botrytis cinerea* and *Penicillium,* which have been shown to be harmful to humans. However, experimental results have found that micro-organisms either do not grow on air filters or can only grow in restricted numbers. This indicates that fungal genera detected appear to be influenced differently by various parameters manipulated in experiments. The reduction in all fungi genera contamination after weeks in the climatic chamber may be because the air used in the climatic chamber was filtered, and did not contain the fresh or new spores required to re-colonise. This suggests that fungi cannot grow easily on filter material. Another explanation suggested by the author is that the filters used in the experiments were new, and consequently did not contain the build up of dirt and dust required for fungi to grow.

Similar results are reported by Schleibinger et al (#12854, 1997), who took one synthetic and two glass fibre filters, after a 4-month service life as a prefilter in a large HVAC system in Germany. The three filters were then placed in a laboratory HVAC system for a further three weeks under various climatic conditions, to monitor microbial growth and the occurrence of volatile organic compounds produced by micro-organisms (bacteria, yeast's and fungi). Although these micro-organisms decreased in cfu counts after three weeks, under most conditions volatile organic compounds produced by micro-organisms like formaldehyde, acetaldehyde and acetone were found in higher concentrations downstream of the filters.

4.2 Duct leakage

Leaky duct work can significantly affect the ventilation rates of a building, which then impact upon the energy used for heating or cooling. Since fan power demand is a function of the airflow rate passing through it, additional energy losses may occur due to inadequate sizing and leakage airflow compensation. Poor airtightness can also contribute to the entry of pollutants and lead to insufficient ventilation rates.

Carrie et al (#12857, 1999) discuss the conclusions of a European project funded by the SAVEII (Specific Action on Vigorous Energy Efficiency) program of the Commission of the European Communities - Directorate General for Energy (DG XVII). The report considers all aspects of ventilation duct leakage. The most important factors include duct airtightness, which should be minimised where possible to ensure cost and energy penalties are reduced. Other important reasons to minimise such air leakage include improving flow balancing of the system, to control leakage noise and to minimise the entry or exit of pollutants into/out of the duct work system. Thermal insulation and a vapour barrier acts to reduce conduction losses, especially important where conditioned air is being moved from the plant room to the occupied space.

Pressure drop is another important issue, being directly linked to the fan energy use. Of more importance here is the supply of clean air to the occupied space. Dusts and other contaminants build up on the surface of the ducts, fan blades and coils during system operation. Such contamination can lead to microbial growth of surfaces, especially in ducts with internal thermal insulation, and then into the occupied space. In smaller dimension ducts this can lead to a reduction in airflow rate. To minimise these effects the system should be inspected and periodically cleaned. The system components therefore should be accessible and able to withstand effective cleaning. A leaky duct under positive pressure will exfiltrate ventilation air intended to supply the occupied space. If the system fan is unable to compensate for this exfilration the building may be under ventilated. The report shows the effect on a steady state concentration of CO_2, in which under extreme cases the concentration of the pollutant is increased by about 30%. The report also notes that in the Nordic countries a greater awareness exists of the need to have clean ducts. Inspection hatches are frequently placed to facilitate cleaning. After regular inspection intervals (2 to 9 years) cleaning is undertaken as necessary. Hospitals or other specialist facilities are inspected and cleaned more regularly. Robot cleaning is not used very much due to the high capital cost, and they may be obstructed by joints, rivets etc. Carrie notes that in many other countries, cleaning access is in general poor and duct systems are rarely inspected or cleaned, with maintenance being often restricted to the minimum. Finally when being installed or being repaired, installations are rarely cleaned. Other interim reports from this project include Carrie et al (#10613, 1997); Liddament (#11707, 1998), Andersson (#11708, 1997);(#11709, 1998) and (#11710, 1997).

Residential ventilation duct leakage is examined by Gammage et al (#1649, 1984), who outlines a study in which 31 homes in east Tennessee where investigated to determine the levels of duct leakage evident in domestic heating and ventilation systems. The objectives were to evaluate quantitatively the impact of central ductwork systems and operating duct fans on air infiltration and air leakage parameters. For the 31 homes, the mean value of the rate of exchange between indoor and outdoor in closed up houses was 0.44 changes per hour with the central duct fan switched off. With the fan running this nearly doubled to 0.78 ach. The main driving force for this enhanced air leakage is air escaping from joints in the central ductwork at locations outside the main living area. Such zones include garages, crawlspaces, attics and ductwork next to heat pumps located outside. In return ducts under negative pressure, such as those located in garages, the increase in air leakage is due to ingress rather than egress. Gammage states that such ingress can lead to indoor air quality problems, which impact heavily on the occupants and living space.

In a similar study, Matthews et al (#2808, 1987) investigated 39 homes in the same US state. Findings indicate that forced air HVAC systems contribute to air quality problems by large scale mixing of conditioned air and introducing pollutant laden air via leaks within the duct system, from garages and crawlspaces. Tracer gas studies were conducted to further investigate these problems. Matthews concluded that proportionally large increases in air infiltration rates occur with forced air HVAC operation in normally tight houses. Such increases can be reduced by sealing of external HVAC units and ductwork systems. Benefits include energy conservation and reduced pollutant entrainment from polluting areas such as crawlspaces and garages.

5.0 Conclusions

Dust is the most common contaminant of mechanical ventilation and air conditioning equipment and associated ductwork. However dust is not the only contaminant, other contamination is caused by pollen, soot, rust, fat, grease as well as animals and insects (alive and dead) and waste remaining from construction. Dusts, pollens and soot can travel through the system and cause occupant irritation and indoor air pollution. Animals and insects, when alive can transmit smells and odours, and when dead also transit fungal and bacterial micro-organisms. Grease, fat and oils used in duct manufacture and as by-products from cooking etc. can trap dusts being carried by the ventilation air leading to build-ups of contamination on plant (coils, fans and dampers etc) as well as inside the ductwork itself. Such build up of particles can emit odours or, when wet or damp, micro bacterial and fungal organisms.

Over time, HVAC systems get dirty for a wide variety of reasons. These might include polluted outdoor air, poorly fitting or maintained filters and plant, a general lack of maintenance or infestation by animals or insects. Adequate and proper maintenance and cleaning is therefore essential throughout the lifetime of the system. Guidelines for cleaning are not very specific, common terms used include such expressions as regular, properly and contamination. These provide yet more confusion and variability in cleaning effectiveness.

When and how often to clean is another area of confusion, not only amongst the building owners and occupants but also amongst maintenance and professional cleaning companies. There are no clear guidelines as to when ducts are considered dirty or clean. Cost-benefit analyses, thorough examination of filters, the overall efficiency of the ventilation system and maintenance programs have all been suggested as methods of determining when to clean. All studies and investigations highlighted in this review agree that regular cleaning and maintenance is essential in the proper and correct running of HVAC systems as well as the health and comfort of occupants.

Despite there being great uncertainty as to whether to clean at all, once a decision has been made to proceed, a variety of standards exist to aid maintenance and contract staff in the cleaning process. These standards and general guidance notes outline the types of cleaning methods available and applicable to particular circumstances; the types of contaminants found in duct systems and how to clean and sanitise them; how to establish and undertake a cleaning regime as part of planned maintenance schedules and advice on post cleaning system adjustment and re-balancing.

Fundamental to any cleaning process is pre-inspection. This outlines all the work that needs to be done and provides a benchmark to the state of the system before cleaning was undertaken. Inspection should include all ventilation and air conditioning plant, filters, dampers, inlets, outlets and the duct system itself, as well as outside conditions and outside/indoor air quality measurements. Once a report has been issued, benchmarking the state of the system, a number of cleaning techniques can be employed. These include both manual and mechanical, wet and dry methods.

The most common duct cleaning techniques are: Contact vacuuming, involving the use of a portable hand operated vacuum cleaner, being used in direct contact with the inside duct surfaces to dislodge and remove dirt and debris subjected to negative pressure. This allows for the escape of dust and dirt from the duct, during cleaning. Air washing uses compressed air to lossen any accumulated dirt on the inside of ductwork. Any loosened debris is drawn into the cleaning device. Power brushing uses a pneumatic or electrically powered rotating brush to loosen debris. Such material is then drawn downstream and into the vacuum collector. Other methods highlighted include hand washing/wiping, hand scraping, steam washing, chemical spraying, air jetting, high volume air blasting, sectional extraction and sealing or encapsulation. An important part of any cleaning process is re-setting the system and system rebalance.

A number of key system conditions play a major role in ventilation system contamination and its prevention. The location of air inlets although fixed after construction, should be checked and maintained. Are inlets close to outlets? Are inlets free to allow the passage or air? Have inlets become blocked by close buildings, vegetation or fences? etc. Most importantly, has the supply air been contaminated? Inlets positioned in good locations during construction could now find new buildings, car parks, waste areas close by. All these could influence the quality of the supply air. Grilles should be fitted to restrict animal and insect ingress and prevent the build up of leaves and vegetation. Where air quality is not good, pre-filters are installed to remove obvious contamination. The main filtration equipment of the HVAC system thus provides added air cleaning. Filters should be of the required classification to restrict the most common pollutants at that site, for example EU5, EU7 or EU8. The classification chosen depends upon the filter performance in terms of maximum penetration at a certain particle size value. Some studies have indicated that the filters themselves can add to the contamination levels in ventilation ducts, however other studies have shown that micro-bacterial contamination is minimal. Suggesting that fungi cannot grow easily on filter material. Heavily dust laden filters can restrict air flow and lead to a reduction in the indoor air quality of poorly maintained buildings. Leaky ductwork can also significantly affect the ventilation rates of a building, which can affect the amount of energy used for heating or cooling. Since fan power demand is a function of the airflow rate passing through it, additional energy losses may occur due to inadequate sizing and leakage airflow compensation. Poor airtightness can also contribute to the entry of pollutants and insufficient ventilation rates.

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Canadian Mortgage and Housing Corporation (CMHC)
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Building Services Research Information Association (BSRIA)
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(www.dcs1.com/boards/duct/messages/139.html)

American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE)
(www.ashrae.org)

Chartered Institution of Building Services Engineers (CIBSE)
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AIVC Air Infiltration and Ventilation Centre

The Air Infiltration and Ventilation Centre provides technical support in air infiltration and ventilation research and application. The aim is to promote an understanding of the complex behaviour of air flow in buildings and to advance the effective application of associated energy saving measures in both the design of new buildings and the improvement of the existing building stock.