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Controlling Airborne Contaminants in the Workplace

by The B.O.H.S.
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CONTROLLING AIRBORNE CONTAMINANTS IN THE WORKPLACE

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Figure 4.2	Taken from Dust Control, Part 1, Flatware Towing Process. British Ceramic Research Association.
Figure 4.3	Taken from Dust Extraction Systems in the Ceramics Industry. Health and Safety Executive.
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* See Acknowledgements

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INTRODUCTION

1.1 The Guide

This Guide is written as an aid to hygienists and others responsible for, or interested in, the control of exposure to air contaminants in the workplace. It concentrates on the control of toxic substances and does not, in the main text, deal with control of flammable or explosive hazards.

In 1822 a Frenchman named Patissier published a book entitled "Treatise on the Disease of Artisans, According to Ramazzini" (PATISSIER, 1822). His work probably represents the first time that the preventative principles of occupational hygiene were codified and written down. In the book the author mentions that, "as protection against noxious gases, workers should wear over mouth and nose a sponge soaked in certain liquids, depending on the vapours against which they are to protect the worker", but goes on to say, "that all such respirators are a nuisance for the worker and should not be used regularly", (TELEKY, 1948). Patissier concludes: "We therefore have to look for simple and cheap devices which do not bother the working man and are independent of his volition" (PATISSIER, 1822). He was referring to exhaust ventilation and following on in the spirit of his words we have concentrated on control of the source of contaminant as it is our view that exposure can be controlled by process control and/or engineering methods under most circumstances in industry, excluding some maintenance activities, work in enclosed spaces and emergencies. This approach is preferable to personal protection, in this case Respiratory Protective Equipment (RPE), because it is more reliable, effective and administratively simpler. The Guide does not deal with the selection and use of RPE but several useful references are identified in the Bibliography (Chapter 12).

The Guide sets out the basic outlines of good design and administrative principles, identifies common misconceptions and errors in design and points the reader to other more detailed texts and references. Although ventilation design is covered in some detail, the early chapters emphasize how important it is to study carefully processes and how exposure occurs, before ventilation systems are designed and installed. The reader is therefore encouraged to read the early chapters before proceeding to the material on ventilation.

To supplement the guide the Working Party also intends to publish a series of case studies in the control of air contaminants. For those readers interested in submitting material for publication, the rationale, a standard protocol and an example of a case study are included in Appendix 1.

1.2 Control Methods and Risk

The size of the risk that people exposed to hazardous materials run is determined firstly by the toxic properties of the material and secondly by the degree of exposure to which people are subjected and this, in turn, is determined by the effectiveness of the methods used to control exposure. If the methods applied are difficult to use or unreliable then excessive exposure may occur and the health and well being of those relying on the control methods may suffer. If the methods applied are efficient but not cost effective then, although adequate control is realised, it may be done so at undue cost.

Personal over-exposure to air contaminants can be judged by comparing hygiene measurements against Occupational Exposure Limits (OEL). In the UK these are called Control and Recommended Limits (HSE, 1986). Control limits are defined as the upper limits of exposure allowed and are judged as "reasonably practicable" for all processes and industries using a particular substance. Recommended Limits are also set but on a slightly different basis. Exposure at or below the limit is not necessarily risk free and some people's health may be affected; there is thus a requirement stated explicitly in the Health and Safety at Work Act (GREAT BRITAIN,1974) and the proposed Control of Substances Hazardous to Health Regulations (HSC, 1984) to reduce exposure to hazardous substances "so far as is reasonably practicable". It follows, from the definition of Control Limits, that, for many processes the normal range of exposures to a particular substance may lie below the Limit. In these cases the actual exposures which occur are not determined simply by compliance with the OEL but by the effectiveness of the process design, work methods and engineering controls in reducing exposure. The same can be said in the case of substances which have no OEL's. In these instances only general guidance on good occupational hygiene practice will be applied. Thus whether a substance has or has not got a specific OEL the fact remains that in a very real sense it is the effectiveness and efficiency of the measures applied to control air contaminants in the workplace that directly determine the exposure of work people and therefore the risk that those exposed people run.

Simply adhering to the OEL should not be the final measure of success, and cannot be so if no limit exists. If "so far as is reasonably practicable" is to have real meaning then it is important that the best (ie. most efficient and cost effective) methods are applied to reduce exposure to air contaminants. We hope that this Guide helps those responsible for air contaminant control to improve the definition of "reasonable practicability" for their industries and processes.

We would like your comments, criticisms and praise (if you have any) which we will take account of in any further editions of the Guide.

Finally, we would like to make a very important point, not in our own words but in those of a pioneer in the field. He made his remarks referring to exhaust ventilation but they apply equally to any method of air contaminant control.

> "The ultimate criterion of hood performance is not the provision of a "strong" suction, but the handling of an air volume which reduces the concentration of the contaminant in question ... Hoods are of no value in the prevention of occupational disease unless they eliminate the hazard", (DALLAVALLE, 1952).

The need to link exhaust ventilation design to hygiene measurements of exposure is unfortunately still missed nowadays. It is a link we emphasise in this Guide.

1.3 References

GREAT BRITAIN (1974), Health and Safety at Work Act etc. HMSO.

HEALTH AND SAFETY COMMISSION, (1984), Control of Substances Hazardous to Health. Draft Regulations and Draft Approved Code of Practice, HMSO.

HEALTH AND SAFETY EXECUTIVE, (1986), Occupational Exposure Limits. Guidance Note EH40/85, HMSO (issued annually).

PATISSIER, P. (1822), Traite des maladies des artisans d'apres Ramazzini. Paris.

TELEKY, L. (1948), History of factory and mine hygiene. Columbia University Press, New York.

DALLAVALLE, J.M. (1952), Exhaust hoods. 2nd Edition. Industrial Press Inc, New York.

2

MANAGEMENT OF AIR CONTAMINANT CONTROL

While there are many reasons why it may be necessary to consider the control of the emission of an air contaminant, the primary one is to prevent or minimise any hazard to workers or other people in the vicinity. The contaminant may be a nuisance either to oneself or to neighbours; there may be legal requirements where the dust or fume is flammable or explosive, toxic or obnoxious. It may be a cause of complaint or apprehension by people in the working area or in the vicinity where the material escapes from the building or is discharged through a stack or vent. And finally, the material emitted as a contaminant may itself be valuable and in a form that can be re-used or returned to some stage of the process.

2.1 Legal Requirements

All employers have a duty under the Health and Safety at Work Act 1974 (HASAWA) (HMSO, 1974) to protect their workers and to ensure, so far as is reasonably practicable, the safety and absence of risk to health of all their employees in connection with the use, handling, storage and transport of articles and substances and also the provision and maintenance of plant and systems of work that are, so far as is reasonably practicable, safe and without risk to health. In addition the Factories Act (HMSO, 1961) will apply to certain premises. This Act requires that the standard of control is that of "where practicable".

Where a hazard is identified then effective steps must be taken to eliminate or control the hazard. In the case where a control method, such as an exhaust system, is installed then steps must be taken to ensure that this functions effectively and is properly maintained so that it continues to operate effectively.

In addition employers now have duties to persons not in their employment and they are also required to use the best practicable means to prevent the emission to the atmosphere of noxious and offensive substances and to render harmless and inoffensive such substances as may be emitted.

Apart from the employer's duty there is now a specific duty imposed on any person who designs, manufactures, imports, erects or installs any article or substance to ensure that it is safe and without a risk to health when properly used, (HASAWA Section 6).

In the UK the Acts and most Regulations are written in general terms and do not set out specific standards of contamination that must not be exceeded. It is clearly necessary, however, to have some measure or yardstick to evaluate the conditions in the working area. It is needed to assist in making decisions about whether methods of control need to be applied or improved or whether a process should be changed or stopped. When it comes to actually setting a standard or Occupational Exposure Limit (OEL) it is found in practice that there are many problems.

2.2 HSE Precautionary Policy on the Safe Use of Toxic or Other Substances

To help in resolving some of these difficulties and to assist industry to meet its obligations, the HSE has now formulated a precautionary policy on the safe use of all toxic chemicals and other substances and particularly those that do not appear to have any definable threshold below which conditions may be considered to be safe, such as certain carcinogenic substances.

The policy is:

(a) That exposure should be kept as low as is reasonably practicable by the application of occupational hygiene principles and techniques appropriate to the route of entry into the body (inhalation, ingestion or absorption through the skin).

(b) That in any case exposure should be kept within the published standards, eg Control and Recommended Limits agreed by the HSC, by the application of engineering controls, or other suitable control techniques.

(c) Where necessary suitable respiratory and other protective equipment should be provided and used. The provision and use of personal protective equipment should normally be regarded as providing a back-up for other techniques which aim to control the risk at source, rather than as a first line of defence. In certain circumstances, however, personal protection may be the only reasonably practicable measure.

A point mentioned in Chapter 1 and which is important to keep in mind is that, in the case of toxic substances, exposure below the OEL may not be risk free and that legal duties are not necessarily discharged merely by meeting published limits.

The HASAW Act places a continuing statutory and enforceable duty on employers to ensure the health, safety and welfare at work of all his employees, so far as is reasonably practicable. There is thus a duty to reduce exposures even when they are below the OELs.

In most circumstances the effective control of a dust, gas or vapour particularly where there may be a health hazard, should not be thought of as an optional extra or as something to be added at a later date but as an integral part of the process, the costs of which should be considered in the same way and at the same time as all the other plant and process costs.

The initial appraisal of any new plant or process or a review of any existing plant, should, as a matter of course, include detailed consideration of all known risks to health and the likely costs of effective control measures. It should be borne in mind that any control system that has to be added after the plant has started to operate is likely to be less effective and more costly than if it were designed and installed as an integral part of the original scheme. Where the initial appraisal reveals that there may be a problem then, before embarking on a conventional ventilation system, the fundamental questions outlined in Chapters 3, 4 and 5 should be addressed.

The most effective method of control is not to make the contaminant at all and, while this may be considered the counsel of perfection, it is worth the most serious consideration. If it can be done, then the whole problem is eliminated at the outset. If the production of contaminant is minimised the final expenditure on control equipment may be dramatically reduced.

Where it is found that the problem cannot be eliminated, then consideration must be given to mechanical and organisational methods of controlling the hazard.

The type of management organisation which will be appropriate and practicable to deal with the control of toxic substances will vary with the size of the organisation. This point is dealt with in Chapter 4, in particular in Section 4.5.

2.3 Main Methods of Control

The hierarchy of approaches to control is as follows:

(a) NON-VENTILATION METHODS OF CONTROL (Chapter 5).

(b) TOTAL ENCLOSURE of the process (Chapter 7).

(c) PARTIAL ENCLOSURE OR BOOTH (Chapter 7).

(d) CAPTOR HOOD (Chapter 8).

(e) DILUTION OR DISPLACEMENT VENTILATION (with "spot" ventilation and/or air jets). (Chapter 9).

(f) PERSONAL PROTECTIVE EQUIPMENT (PPE) (not covered in this Guide)

The particular method to be used will depend on the extent and seriousness of the hazard, the ease with which it can be applied to a process and its cost effectiveness. The various methods, excluding personal protective equipment, are considered in some detail in Chapters 5.0-11.0.

2.4 References

HMSO (1974), Health and Safety at Work etc Act 1974.

HMSO (1961), The Factories Act 1961.

HMSO (1977), Articles and Substances for Use at Work, Health and Safety Executive, Guidance Note GS8.

HMSO (1977), Toxic Substances: A precautionary policy, Health and Safety Executive, Guidance Note EH18.

3

EXAMINING PROCESSES AND UNDERSTANDING EXPOSURE

3.1 Introduction

In order to anticipate problems with the control of air contaminants in the workplace in a cost-effective way it is essential to have a good understanding of how contaminants are generated, move in the atmosphere and cause exposure to workers. This chapter describes the properties of contaminants and how hygienists or other investigators should examine processes and make decisions on what methods of control may be needed.

3.2 Types of Air Contaminant

Contaminants can be present in the air as particles comprised of liquids or solids (commonly known as aerosols), as gases in the form of true gases or vapours, or in a combination of both particles and gaseous matter, (see Table 3.1).

The form in which an air contaminant is present will effect its potential toxicity; thus for instance, lead fume is more easily absorbed than coarse lead dust and represents a greater inhalation hazard (assuming equivalent air concentrations). During generation, the forms of the different contaminants are mainly determined by the physical and chemical properties of the parent materials from which they are derived. However, the particular form which a contaminant takes may be influenced by the process through which it is generated, for instance, oil mist generated during metal cutting tends to be of larger particle size than oil fume generated by the condensation of oil vapour after heat is applied, as during the curing of rubber. Before examining common methods by which air contaminants are generated in greater detail, it is useful to review the basic physical properties which govern the behaviour of aerosols, gases and vapours.

3.3 Properties of Air Contaminants

Assumptions concerning the behaviour of particles of hygienic importance and vapour or gas clouds can lead to false conceptions of how air contaminants move in the air.

It is often assumed that the densities of the materials from which particles are generated need to be taken into account when positioning the hood of an exhaust ventilation system, thus particles generated from dense materials (eg lead) are seen, incorrectly, to be "heavy" and therefore to sediment out of the air rapidly. Similarly, the weight of the molecules of a vapour is often thought to produce clouds of "heavy vapour" which sink en masse towards the floor (where the exhaust hood is frequently positioned!) The behaviour of air contaminants is reviewed in this section.

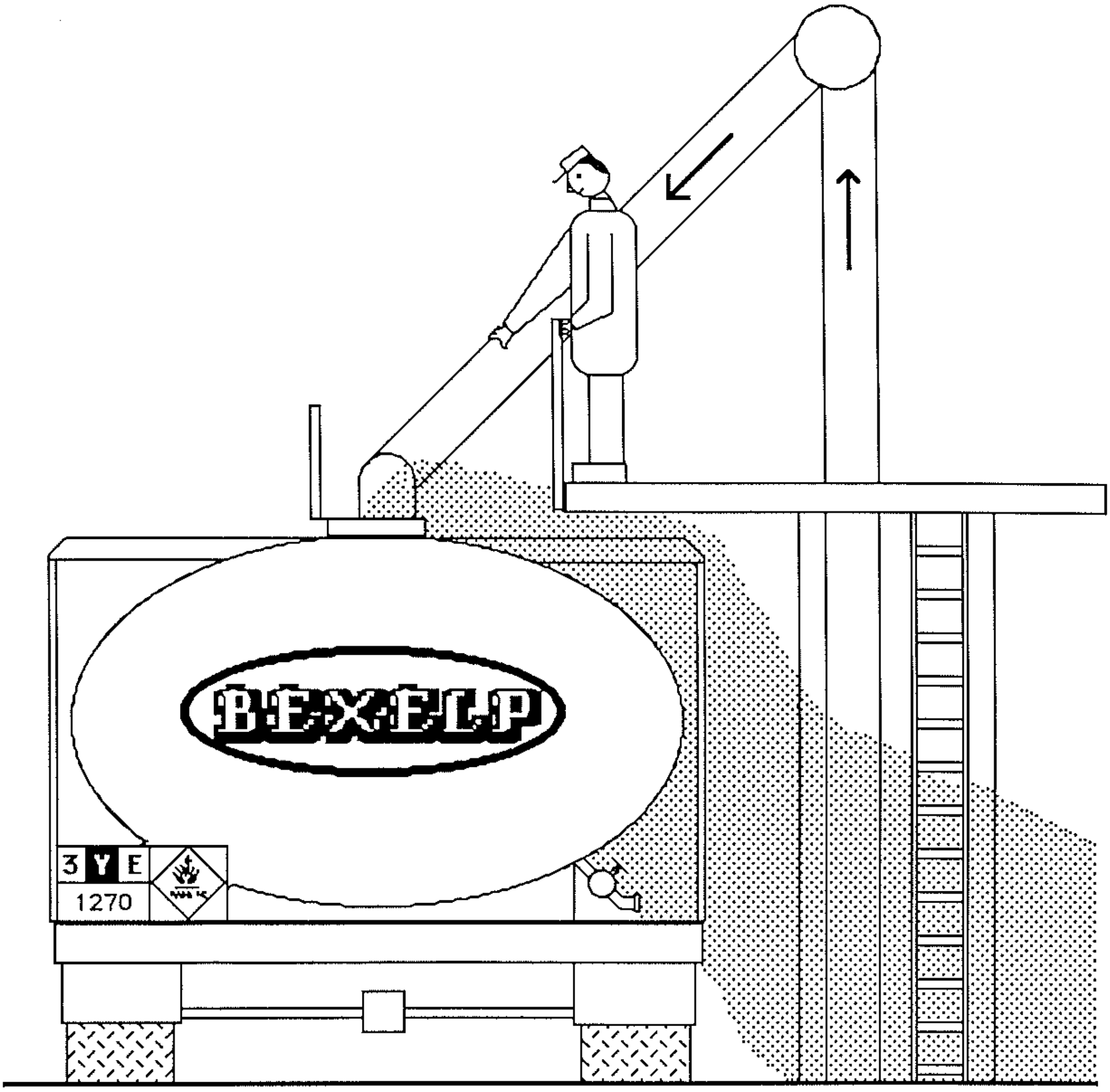

Figure 3.1
Petrol tanker loading - low rate of filling and low wind speed.
Heavier than air vapour/air mixture flows down the side of the tanker and can exceed the Lower Explosive Limit (LEL) (~ 1.3% by volume) up to about 5 metres away.
It is important therefore to pressurise any ground level control room.

Table 3.1
Characteristics of Airborne Contaminants in the Workplace

Name	Description	Examples	Size
GAS	Formless fluids that occupy a space or enclosure and can only be changed to a liquid or a solid state by the continued effect of increased pressure and/or decreased temperature (ie gases do not usually exist as liquids or solids at normal room temperatures and pressures).	Carbon monoxide, chlorine	Molecular
VAPOUR	Gaseous forms of substances that also exist in the solid or liquid state at normal temperatures and pressures. They can be condensed to these states only by either increasing the pressure and/or decreasing the temperature.	Mercury, ethyl alcohol, water	Molecular
DUST	Solid particles of wide size range and shape generated by mechanical processes such as abrasion and crushing, or released by handling or other disturbances.	Coal dust from coal cutting. Silica dust from sand blasting. Asbestos fibres from stripping asbestos insulation.	Wide ranging. Sizes of importance in occupational hygiene. 0.01-150µm.
MIST	An airborne suspension of liquid droplets generated by dispersal of a liquid by, for instance, splashing, bubble formation, nebulising or by condensation from the vapour or gaseous state (or phase) to the liquid state.	Oil mist from coolants used in metal cutting. Acid mists from electro-plating. Pesticide mists from spraying operations.	Wide ranging. Sizes of importance in occupational hygiene 0.01-150µm (Particles change in size once formed to greater or lesser degree depending upon liquid compositions).
FUME	Sub-micrometre particles often generated by condensation of materials from the gaseous state usually after volatilization from molten or liquid state. Fume particles may be solid or liquid or both depending upon the properties of the parent material. The formation of fumes is often accompanied by chemical reactions, for instance oxidation in the case of metal fumes.	Lead oxide fume, iron oxide fume. Rubber fumes. Phthalic anhydride fume.	0.001-1.0µm Agglomeration of particles may occur to produce larger aggregates.

3.3.1 Aerosols*

It is possible to calculate with a fair degree of accuracy the sedimentation rates of small particles in air (the final velocities which particles reach under the influence of gravity). Table 3.2 lists some "settling velocities" for spherical particles in the size range 0.01 micrometres - 100 micrometres,** from which it can be seen that there is a range of velocities and that the larger the particle the higher the terminal velocity. It is evident that sub-micrometre particles, once they become airborne, will take many hours to sediment out of still air. Also, if the general air movement present in most work places is taken into account (up to 0.25 - 0.3 ms^{-1}), it is plain that a large proportion of the particles below 100 micrometres will remain airborne for several seconds, minutes and perhaps hours depending upon the actual particle size.

Turning to the calculated "stopping distances" listed in Table 3.2, it is also evident that even if the particles in the 0.01-100 micrometre size range are propelled into the air with some force (initial velocity = 10.0 ms^{-1}) they will not travel far of their own accord before coming to rest. The conclusions from these calculations are that small particles remain suspended in air for long periods once formed and have little power of movement independent of the air in which they are suspended. Controlling exposure to fine particles is thus a matter of controlling the movement of the air in which the particles are suspended.

Table 3.2

Settling velocities and stopping distances for small spherical particles (based on Hinds, 1982)

Particle(1) diameter (µm)	Settling velocity ($m\ s^{-1}$)	Stopping distance(2) (m)
0.01	7.0×10^{-8}	6.8×10^{-8}
0.1	8.8×10^{-7}	8.8×10^{-7}
1.0	3.5×10^{-5}	3.6×10^{-5}
10.0	3.1×10^{-3}	2.3×10^{-3}
100.0	0.25	0.127

* An aerosol is a suspension of solid or liquid particles in a gas.

** The spherical particles are assumed to have a density of 10^3 kg m^{-3}, approximately the density of water and often called "Unit Density". Thus denser spheres, with equivalent falling speeds (ie equivalent aerodynamic diameters), will be physically smaller. Spheres made of lead, aluminium and soft wood, which all fall at the same rate as a 10 mm diameter drop of water, have physical diameters of 3.0 mm, 6.1 mm and 12.9 mm respectively.

(1) Particle density = 10^3 kg m^{-3} (ie unit density spheres)
(2) Initial particle velocity = 10.0 m s^{-1}

To damage the respiratory tract or be absorbed by the lungs particles have to be inhaled and gain entry to the respiratory system. There is a upper size limit above which particles are unlikely to penetrate into the lungs and be deposited. The particle size range of interest to the hygienist, when assessing the potential for absorption or damage to the lungs, is restricted to sizes ranging from sub-micrometre to 25 micrometres (approximately) (ie thoracic and respirable particulate mass). Particles larger than this can be inhaled but they deposit in the nose, mouth and extra-thoracic air spaces and do not penetrate to the lungs. Where absorption of chemicals via the lungs is the main concern of the hygienist, it is the fine particulate which is important. (Generally taken to be less than about 7 µm diameter for unit density spheres). (For more detail see ACGIH Annals, 1984).

It is the aerodynamic behaviour of particles which determine how they move in the air and where they deposit in the respiratory tract and not their chemical composition or the density of the material from which they were formed. Some of the important general properties of fine particles can be summarised as follows:

(i) Fine particles move with the air in which they are suspended. They follow air movement.

(ii) Fine particles sediment out of air slowly and therefore remain airborne for long periods of time.

(iii) Where absorption of a chemical into the body or storage of insoluble particles in the lungs is of concern then fine particles represent the main hazard. (Though larger particulate may cause harm if deposited in the nose, mouth and pharynx; see VINCENT and MARK (1981)).

(iv) Fine particles are not visible under normal diffuse lighting conditions and their generation and release may easily pass undetected and unsuspected.

3.3.2 Temperature and Air Movement

The density differences between volumes of air at different temperatures can be large and are important in occupational hygiene. Small changes in temperature make a large percentage difference in density and can cause volumes of contaminated air to flow up or down, away from a hot or cold source of contaminant. For instance an air volume 60°C above an ambient temperature of 20°C will be 20% lighter than the surrounding air and will rise away from the source. Such causes of air movement need to be allowed for when designing exhaust ventilation and can sometimes be used to advantage.

3.3.3 Vapour and Gas Clouds

The ratio of vapour to air molecules in a saturated vapour/air (V/A) mixture, such as exists in the space above a liquid in a sealed container, depends upon the volatility of the liquid. The higher the volatility, the greater the ratio of vapour to air molecules. The percentage of vapour molecules can be calculated by using the equation:

$$\frac{P_V}{P\ (\text{atmos})} \times \frac{100}{1} = C\ \%$$

P_V = liquid vapour pressure

P (atmos) = atmospheric pressure

Table 3.3
Density of vapour/air mixtures

Substance	Vapour pressure at 20°C in mm Hg	Ratio of molecular weight of the compound to that of air	Specific gravity of the saturated vapour air mixture at 20°C	Relative density of 5000 ppm vapour air mixture (air = 1.0)
Acetone	185	2.0	1.24	1.005
Benzene	75	2.7	1.16	1.0085
n-butyl alcohol	6.3	2.6	1.01	1.008
Carbon disulphide	300	2.6	1.6	1.008
Chloroform	160	4.1	1.65	1.016
Ethyl ether	439	2.6	1.9	1.008
Ethyl alcohol	43	1.6	1.03	1.003
2 methyloxyethanol	6	2.6	1.01	1.008
n-hexane	150	3.0	1.4	1.01
Styrene	5.5	3.5	1.02	1.012
Toluene	22	3.2	1.06	1.011
1,1,1 trichlorethane	100	4.6	1.47	1.017
Trichloroethylene	58	4.5	1.28	1.018
Xylene	10	3.7	1.04	1.014

Thus, for instance, the saturated vapour concentration of hexane at room temperature is:

$$\frac{150}{760} \times \frac{100}{1} = \sim 20\%$$

The weight of this saturated V/A mixture is determined by calculating the average molecular weight of the cloud and comparing this value with the reference value for air using the formula:

$$\text{Molecular Weight (MW) of Vapour/Air Mixutre} = \frac{C\% \times (\text{MW of the compound}) + (100\text{-}C\%) \times (29)^{*}}{100}$$

* 29 = average molecular weight of air.

A saturated hexane/air mixture, at room temperature, has a density of ~ 40% more than that of air.

Similar calculations have been done for a variety of organic liquids commonly used in industry (Table 3.3). The table also lists the ratio of the molecular weight of the compound compared to that of air. Some texts quote this figure in the belief that it indicates the actual weight of a saturated V/A mixture, which is incorrect and may mislead. Table 3.3 also illustrates that at relatively high concentrations the difference in density between a V/A mixture and air is small and once a saturated V/A cloud is diluted the initial density difference becomes insignificant.

As saturated V/A mixtures are heavier than air, though not as heavy as the molecular weight ratios would indicate, they will flow downwards under the influence of gravity. What happens next is determined by how rapidly the V/A mixture is diluted and on the vapour's chemical and toxicological properties.

In the main body of a workroom the air is in continuous random, small scale motion and this general turbulence is superimposed on more systematic patterns of air movement generated by machinery, temperature differences and external weather conditions. In such circumstances as the saturated V/A mixture flows, it is rapidly diluted at its boundaries and may be dissipated before having flowed any distance. The vapour emitted by the source is soon spread through the workroom. However, there are circumstances where dilution and dissipation are inhibited, for instance:

(i) Where vapour/air mixtures can flow along channels which minimise mixing with air.

(ii) Where vapour/air mixtures can flow along the relatively still air or "boundary layer" adjacent to many solid surfaces, eg table tops and floors.

(iii) Where there is very little infiltration of clean air into a space and little general air turbulence, eg enclosed spaces such as storage tanks or sumps. Under these circumstances vapour/air mixtures may collect and remain for long periods.

(iv) Where a large volume of liquid is heated and/or spilled and massive quantities of vapour are released suddenly. The cloud produced is large and not diluted quickly. Under these circumstances it may travel considerable distances through a structure before meeting a source of ignition.

(v) Where a relatively large volume of vapour is released continuously, eg during tanker loading (Figure 3.1).

If the vapour is flammable and the concentration of vapour in the flowing saturated V/A mixture is greater than the Lower Explosive Limit (LEL), a flammable hazard may exist. The vapour may also have toxic effects and usually, if this is the case, these can occur at concentrations well below those required to cause a flammable hazard, eg for hexane the LEL is ~ 10,000 ppm whereas the Recommended Limit (HSE, 1986) (to control the toxic hazard) is 100 ppm, two orders of magnitude lower. Where a liquid substance has flammable and toxic properties, applying control measures simply to deal with the flammable hazard may well not control the potential toxic hazard, as the following example illustrates: Figure 3.2 illustrates a common misconception of how heavier-than-air saturated V/A mixtures behave. Figure 3.3 illustrates what happens in practice.

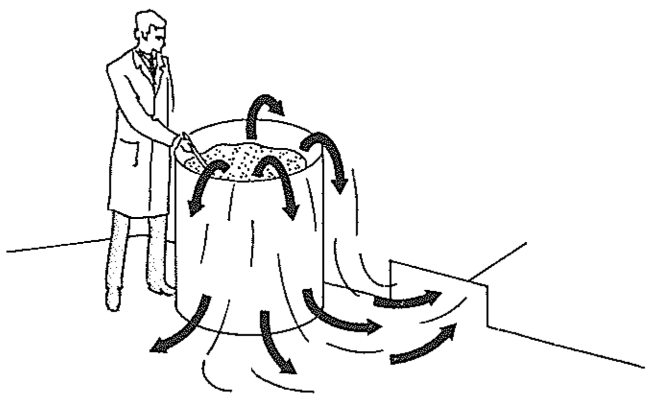

Figure 3.2
FICTION - liquid in the container evaporates and vapour/air mixture flows onto the floor where it is extracted by the floor level exhaust slot.

Figure 3.3
FACT - liquid in the container evaporates and some of the vapour/air mixture flows onto the floor and is partially extracted by the floor level exhaust slot. The major portion of the vapour/air mixture mixes with the room air.

A saturated vapour/air mixture will exist just above the liquid surface. Some mixing with room air will occur at the top of the open vessel but the vapour/air mixture will still be slightly heavier than air. Some will spill over the side of the container and flow in a sheet down to the floor, (this moving layer is sometimes just visible due to the slight difference in the refractive index between the vapour/air mixture and the surrounding air).

It may run along the floor for some short distance mixing with the room air as it goes. If the vapour/air mixture on the floor comes across a source of ignition a flammable hazard may exist. If ignition occurs, the flame front may flash back to the container. To control this potential flammable hazard low level ventilation may be applied to scavenge the vapour/air mixture from the floor near the container. Flame-proof equipment will be required in the workroom to remove potential sources of ignition. The most reliable method of removing the flammable hazard would be to prevent the escape of the flammable vapour/air mixture.

The open vessel of volatile liquid also poses another hazard if the liquid substance it contains is toxic. The first two sets of controls, the low level ventilation and the flame-proofing, will not control the over-exposure of operators working near the open vessel. Vapour will diffuse out of the vessel into the workroom air from the liquid surface. Also, as the vapour/air mixture runs down the side of the vessel, it mixes with the room air. This mixing continues as the moving layer crosses the floor and eventually a point is reached where there is hardly any difference between density of mixture and that of the room air and the flow stops. By means of both processes large quantities of vapour diffuse into the air and may, if exposure is not controlled, pose a toxic hazard. Only containment in a sealed system will reliably eliminate both the flammable and the toxic hazard. Unfortunately it is all too common for people to control the potential flammable hazard posed by the flow of thin layers of vapour/air mixtures and believe that by doing so they have controlled any potential health hazard. The approach when dealing with flammable and toxic hazards is different though there is some overlap. Also in dealing with flammable hazards one is concerned with controlling occasional and unlikely chains of events often involving equipment, whereas in controlling exposure to a chronic toxic hazard the concern is with long term low-level exposure of personnel. Controlling for the one hazard may not control the other. (The same logic applies to lighter-than-air gases which pose both a potential flammable and toxic hazard).

3.4 Summary

Fine particles which can be inhaled and deposited in the lungs, once formed remain airborne for long periods and move with the air in which they are suspended. Vapour/air mixtures, at the concentrations normally found in the workplace, away from the point of generation, have densities virtually identical to that of air unless vapour dilution is inhibited. In both cases contaminants disperse only because of the motion of the air in which they are located.

Thus the problem of controlling exposure to potentially toxic materials, be they fine particles or vapours, is reduced to one of containing the air in which they are mixed, or controlling its direction of flow.

3.5 Material Information

To assess the likelihood of overexposure to toxic substances the hygienist or other investigator needs to make a careful appraisal of the work processes. To make such an appraisal requires information on the substances used and the processes and methods involved in materials handling. In the case of substances used in manufacture, the investigator requires information on the physical and toxic properties of the materials. At the start of such an evaluation a "materials inventory" is normally drawn up so that materials which are likely to pose a problem can be identified.

Under Section 6 of the Health and Safety at Work Act manufacturers and suppliers are obliged to provide such information on their goods. The reliability and usefulness of the material data sheets however, often leaves much to be desired (see for instance FRANKEL 1982), and the investigator may need to be persistent and resourceful in his/her enquiries. Individual materials tend to stand out of materials inventories because they are relatively highly toxic or they are used either in quantity or at high temperatures and pressures. In the latter cases, the potential for over exposure may be great and this excessive exposure may pose a health hazard or nuisance even though the material itself is not considered highly toxic.

3.6 Generation of Air Contaminants

Potentially hazardous contaminants may become airborne by means of a variety of physical mechanisms, some of which are listed in Table 3.4. Some common processes which emit dust are illustrated in Figures 3.4-3.5. The level of potential exposure is usually related to the rate at which a contaminant is released into the workplace air which in turn is related to the chemical and physical nature of the contaminant and the process by which it is generated and the rate at which it is removed.

Table 3.4

Some circumstances where air contaminants may be generated

1 Where air passes through material.
2 Where evaporation of volatile liquids occurs.
3 Where material falls freely through the air and comes to a sudden halt (in a container, hopper or heap).
4 Where powdered material is vibrated.
5 Where solid material is abraded, agitated or tumbled.
6 Where material is transferred, dispersed or sampled.
7 Where heat is applied or generated.
8 Where liquid is agitated and splashed and/or bubbles are formed.

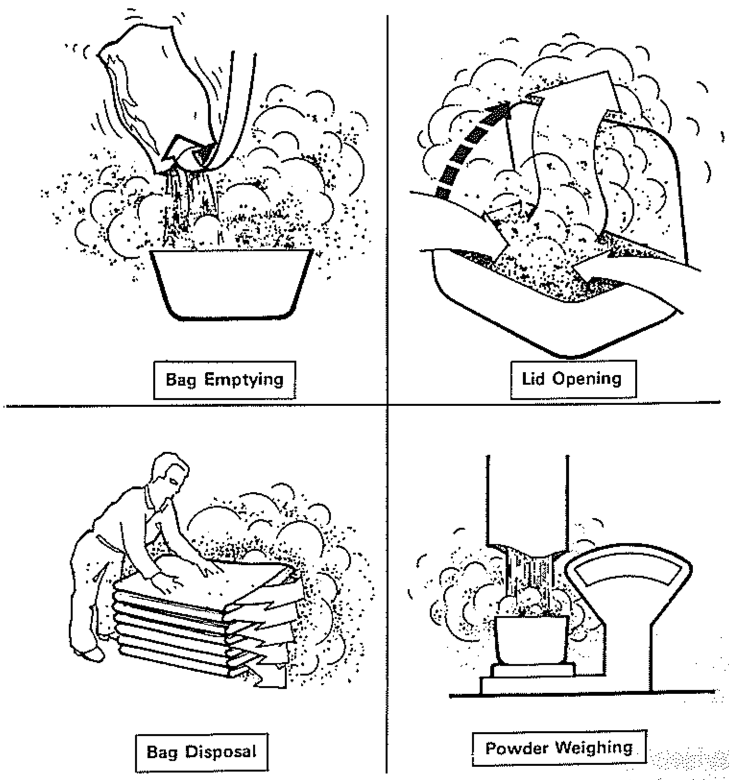

Figure 3.4
Dust liberation in powder handling and weighing (redrawn from Hammond, 1980).

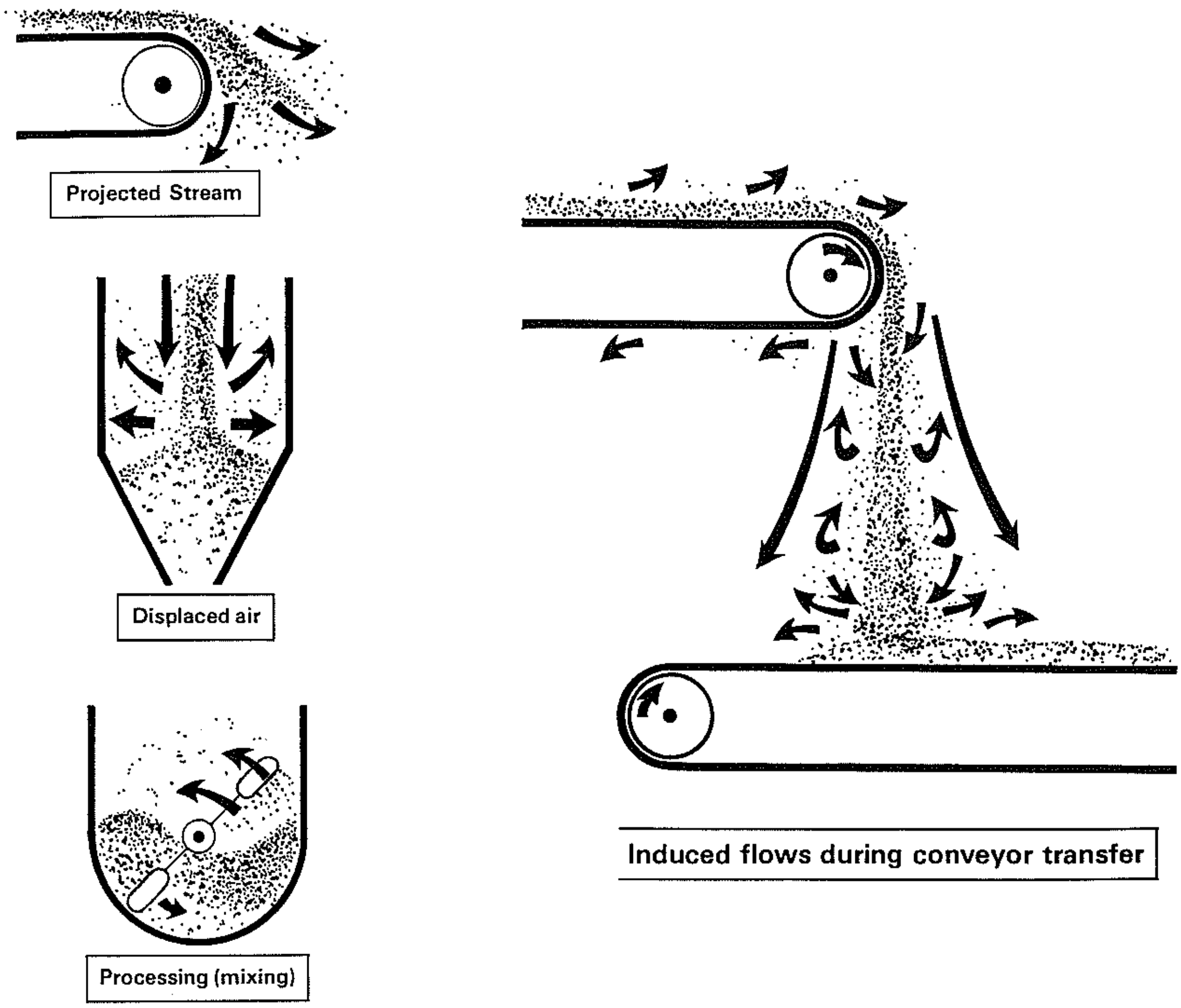

Figure 3.5
Examples of dust liberating processes.

3.6.1 Vapour Pressure

The rate at which vapour is given off from a liquid surface is linearly related to its vapour pressure (VP). Thus for liquids of equivalent toxicity and process utility it is better, from an occupational hygiene viewpoint, to choose the material with the lowest VP. Other measures of volatility include boiling point and drying time. The former is often available but cannot be easily used to predict the vapour pressure of the liquid at different temperatures. The latter is a useful supplement to VP and is used as a yardstick by comparing the drying time of an organic solvent with a highly volatile reference liquid, usually ethyl ether (ACGIH, 1984).

Data may also be available on the rate of use of the liquid material from which order of magnitude estimates of exposure can be calculated, eg Hemeon offers "a rough scale of typical use rates" for organic solvents for various paint processes which is reproduced in Table 3.5.

Table 3.5

Organic solvent application rates for various operations (crude estimates taken from Hemeon 1963)

Operation	Cubic Centimetres/Minute/Worker
Manual application by small brush	1.0 - 1.5
Manual application by large brush	10.0
Gross, manual application (unusual)	35.0 - 70
Mechanical coating operations	16.0 - 95.0
Spray painting	12.0 - 25.0

Vapour pressure rises and falls with increase and decrease in temperature and yet VP data are normally given as single point values, eg 20^{o}C. The Clapeyron equation is often used for extrapolation to other temperatures but the more accurate equation is that derived by Antoine.

$$\ln P_o = A - \frac{B}{T + C}$$

Po = Partial pressure
T = Absolute temperature ^{o}K
A}
B} = Antoine coefficients
C}

Various references exist with tabulations of Antoine coefficients. Poppendorf (1984) recently reviewed the subject and identifies the most useful texts for the hygienist (BOUBLIK et al (1973), REID et al (1977) and DREISBACK (1955, 1958 and 1961). He also proposes a simple combination of occupational exposure limit (OEL) and vapour pressure to allow a comparison of the likely hazard two materials may pose. The potential magnitude of hazard is calculated as a ratio and is called the Vapour Hazard Index (VHI).

$$\text{VHI} = \log \frac{\text{Saturated vapour concentration of compound VP (ppm)}}{\text{Occupational Exposure Level of compound (ppm)}}$$

The VHI certainly allows an initial comparison of likely hazard but should never be used as the sole basis of assessment as process and work practice factors may intervene to raise or lower personal exposure. Also it does use the single figure OELs as an index of toxicity which authorities such as the American Conference of Governmental Industrial Hygienists (ACGIH) specifically warn against. Nevertheless, initial comparisons of materials with similar toxic actions are possible by this method.

3.6.2 Dustiness

For powdered solid material from which fine dust clouds may be generated by various mechanisms, there is no reliable way, as yet, of predicting the likely rate of dust release. Research into mechanisms and methods of prediction is being conducted at Warren Spring (see Chapter 12) and the BOHS Technology Committee recently published a summary and comparison of the various methods of measuring "dustiness" which should help standardisation of tests and comparability of results in the future (HAMMOND et al, 1984).

3.7 Work Processes and Exposure

Armed with a knowledge of the materials which could potentially pose problems and an appreciation of which materials become airborne in quantity, the hygienist needs to consider the production process and address the following questions: Is over-exposure likely to occur? If so, where and to which groups of workers?

To answer these questions the sources of emission in a process need to be identified and characterised and an understanding gained of how workers interact with the process. It may be possible to build up quickly a qualitative feel for whether the process is likely to pose a problem. Thus, a highly volatile liquid with well documented toxic effects, used continuously in an open process, where people have to work in close proximity to the source, is very likely to result in over-exposure. Conversely, in the case of involatile low toxicity liquid, used intermittently in an enclosed process where people do not work close to the source, over-exposure is extremely unlikely. Usually the decision as to the likelihood of over exposure is less clear cut. A check list of questions and information that should be ideally available is presented in Table 3.6.

Table 3.6

Characterising sources of emission (based on Burton 1982)

1 Locate all potential sources of emission.

2 Identify which sources of emission contribute to exposure.

3 Determine the relative contribution of each source identified.

4 Note the characteristics of each contributor to exposure noted: chemical composition, temperature, rate of emission, direction of emission, initial emission velocity, whether continuous or intermittent including timing of emissions.

5 Note the characteristics of the ambient air: air temperature, movement (direction and velocity and variability), mixing potential, inlet and outlet flow conditions, room air changes per hour.

6 Observe worker interaction with emission source.

7 Observe work methods and investigate the basis of work method design.

The quantitative relationship between process emissions and exposure is an under-researched area and almost certainly the hygienist will be forced to make crude estimates in many instances. It is only by making such estimates and coupling them with qualitative and quantitative assessments, together with careful observations of the work process, that the investigator will understand how exposure is occurring, which are the primary sources of exposure and which are secondary and therefore where control can best be applied. In making an assessment it is important to call upon the experience of, and involve those closely involved with the work process. Such people include, the workers and their representatives, the supervisory staff, the production and works manager and the health and safety personnel if such people are employed. It is the first group which have the most subtle feel for what actually happens on a day to day basis and all groups will certainly have opinions on what they consider to be the materials and processes most likely to cause problems. Ultimately though, it is the hygienist who must take all the information, culled, calculated and supplied by others, and put together a coherent picture of the process, work method, sources of emission and how these are likely to relate to exposure.

It is worth spending considerable time on this evaluation stage. Unfortunately this is precisely the stage which is often either missed entirely or given only a cursory glance. It cannot be over-stressed how important it is to gain a deep understanding of how and where contaminants are emitted and how people's exposure relates to the sources of emission. Without this understanding exposure cannot be controlled effectively.

Two common examples involving simple work processes which cause exposure are illustrated in Figures 3.6 and 3.7. Although the unrecognised sources of exposure illustrated may appear too obvious to miss, it is amazing how often this occurs. Anticipating or identifying areas where excessive exposure to harmful substances may occur is a subtle skill which requires good process knowledge and a deep appreciation of the fundamental principles of occupational hygiene (also see Section 4.2.1). If the points outlined in this sub-section are followed such simple design errors as those illustrated in Figures 3.6 and 3.7 should not occur.

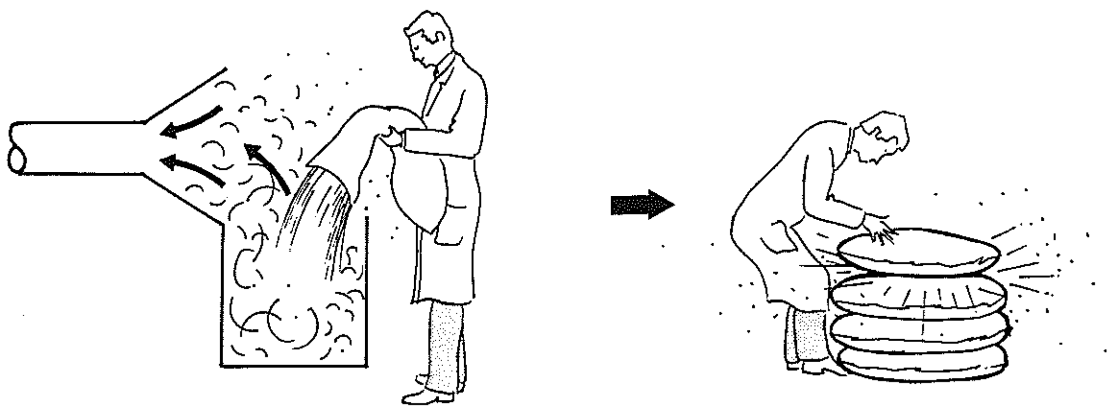

Figure 3.6
Sack emptying controlled, sack disposal uncontrolled.

Examining Processes

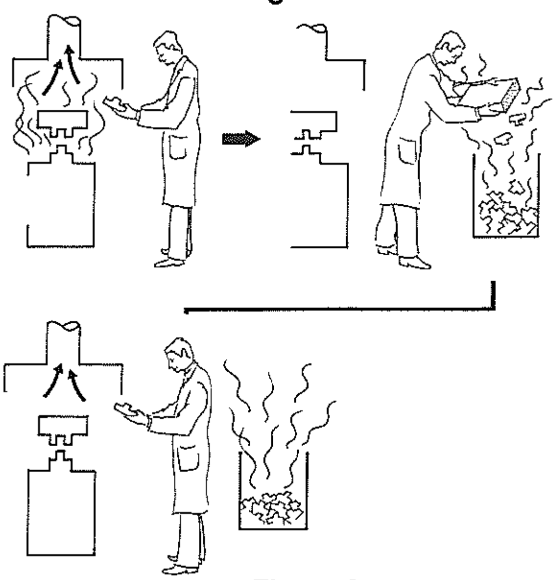

Figure 3.7
Fumes at press controlled, fumes from hot components in bin uncontrolled.

3.8 Non-Inhalation Risk

The emphasis in this Guide is on the control of airborne contaminants. This is deliberate because, for the large majority of cases where exposure to toxic substances occurs, the material gains entry to the body via the lungs. In the case of particulate material the site of damage is often the lung tissue itself. Occupational hygienists have traditionally stressed the importance of air contaminants and inhalation as the main route of entry, perhaps, on occasions, over- stressing the point and neglecting the other two potential routes of entry, namely ingestion and percutaneous absorption.

The ingestion risk can be significant in the case of soluble particulates which contaminate the skin, clothing and workplace. If adequate washing and eating facilites are not present and used and if housekeeping is poor then transfer of toxic particulates from the hands to food and drink may occur and in some cases it is found to be the main cause of excessive absorption. Processes which involve production or use of lead compounds are long standing examples of where the hygienist must be alert to the possibility of ingestion as a significant route of entry.

Skin absorption can be significant where workers come into sustained skin contact with organic, lipid soluble liquids. The rate of percutaneous absorption varies with the particular compound. Thus for instance styrene is absorbed at a rate an order of magnitude higher than benzene. However in both cases continuous immersion of the hands in the liquid would be required for the rate of skin absorption to be significant compared with inhalation at the permitted occupational exposure level (AITIO et al, 1984). With some materials, such as dimethyl formamide or phenol, skin absorption can be a very significant route of entry, and these examples raise a general point. For relatively involatile liquids which can pass through the skin easily, inhalation, in all but very unusual circumstances (eg where liquid is sprayed into the air) will not be a significant route of entry and the possibility of percutaneous absorption then becomes the area on which to focus. In some circumstances liquid which rapidly penetrates the skin can act as a vehicle for dissolved materials, eg various organo-phosphorous pesticides. Where ingestion or percutaneous absorbtion is significant or a suspected primary route of entry then biological monitoring methods will be needed to supplement or replace air monitoring.

The hygienist will, quite correctly, concentrate on the control of over-exposure to air contaminants but with certain materials and processes should be alert to the other two routes of entry.

3.9 Qualitative Assessment of Processes - Revealing Air Movements and Air Contaminants

3.9.1 Smoke Tracers

In order to restrict or control the movement of air contaminants it is useful, if not essential, to be able to see how the contaminated volume of air moves. Gases and vapours do not absorb visible light and fine respirable particles are also not visible under normal lighting conditions. The simplest method of making air movement visible is to release a cloud of smoke into the air volume of interest. Smoke generators in the form of small tubes or pellets, canisters or large theatrical smoke machines exist. Tubes are commercially available or can be manufactured in a laboratory, and usually contain either concentrated sulphuric acid or titanium tetrachloride absorbed into inert granules. When air is driven through the tube by means of an aspirator a white cloud of acid smoke is produced. A continuous stream of smoke can be produced by coupling a tube to a small positive pressure pump operated at a flow rate of around 30cc/minute (eg a battery operated low flow sampling pump or a mains operated fish tank pump). Alternatively if a large volume of smoke is required, for instance, to investigate the movement of a plume of contaminant above a hot source or the integrity of a local exhaust ventilation system, then smoke pellets, canisters or machines will be required (see Appendix 2). The smoke from such sources can be irritant and care should be taken in their use. Also smoke will trigger smoke alarms and arrangements should be made when large volumes of smoke may be released to take account of this possibility.

The main use of smoke tracers is to make visible the dispersion of contaminants away from the source (the use of tracers for assessing the effectiveness of local exhaust ventilation is dealt with in Chapter 11). Examples of the use of smoke tracers for this purpose are given below:

(i) If general air turbulence is increased by the process, the effect on the rate at which the contaminant is dispersed away from the source can be judged qualitatively.

(ii) If unidirectional air flow(s) are generated by the process, smoke tracers can be used to reveal their presence and give some indication of the extent and direction of contaminated air movement. This is particularly important when it comes to designing exhaust ventilation for rotating machinery such as grinding wheels and circular saws.

(iii) If the source of contaminant is hot, the "rate of rise" of the contaminated plume can be assessed semi-quantitatively by timing the movement of the smoke clouds.

Note that in both (ii) and (iii) a video recording of the movement of the smoke greatly improves the utility of the method. By playing back the film in slow motion, the investigator can time and note the behaviour of the smoke tracer far more accurately and conveniently than at the time of the actual test.

3.9.2 The Dust or Tyndall Lamp

As only particles larger than 25 micrometres (approximately) can be seen individually by the naked eye, a special technique must be used to study clouds of fine particles. The most convenient to use is the "dust lamp" employing the Tyndall effect which can reveal the presence of fine particles normally invisible under diffuse lighting conditions.

William Tyndall in the late 19th Century discovered that if a parallel beam of light was projected onto a cloud of small particles, the most intensively scattered light was in the forward direction within a narrow angle to the direction of the beam. He used this forward scattering or "Tyndall" effect to investigate the "filtering power" of the lungs for small particles. The Tyndall effect is easily seen by a person standing close to, and looking up the track of a sun beam that penetrates a darkened room. A fine particulate cloud is seen as a hazy smoke.

The dust lamp has been used by engineers and hygienists in designing exhaust ventilation hoods in the UK since the early 1950s (see for instance OTTIGNON and LAWRIE 1951, BLOOR and PALMER 1957, HIGGINS and BRIGHT 1971 and HSE 1975). Details of commercially available devices and notes on the use of the associated camera are given in the Appendix to this chapter.

The principle of operation is as follows (see Figures 3.8, 3.9 and 3.10): a bright parallel beam of light is shone through the area where the investigator suspects a dust cloud to be present. The observer shields his or her eyes from the main beam of the light by means of a piece of card held in position with a floor stand, or by using the worker's body or a convenient piece of machinery as a shield. The dust cloud should be observed looking up the beam towards the source of illumination and against a darker background, for instance a portable curtain or large piece of black card, if possible. Sunlight and other sources of bright light present need to be suppressed and the aim should be to observe at some 5-15^{o} off the centreline of the beam to pick up the most intense scattering. Dense clouds of some size and concentration are made visible with the dust lamp under normal lighting conditions but to see small clouds, for instance leaks, or trace the extended movement of a cloud as much as possible, the background ambient lighting needs to be suppressed. Simply turning off the lights, blocking out light from immediately adjacent windows and using a black curtain as a dark background are often sufficient to get good observations, though extreme measures such as turning off all the lights, blocking all the windows or perhaps returning on the night shift may be called for on occasions to get maximum sensitivity. As with the use of smoke tracers mentioned earlier, use of a video camera greatly enhances the value of this technique.

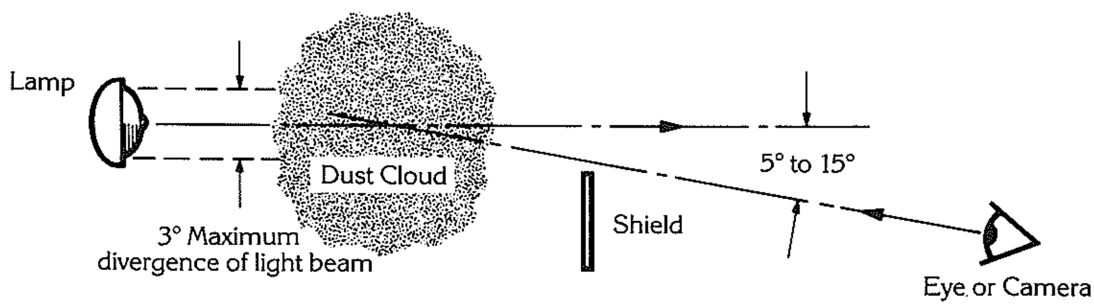

Figure 3.8
How to position a Tyndall lamp to observe respirable dust.

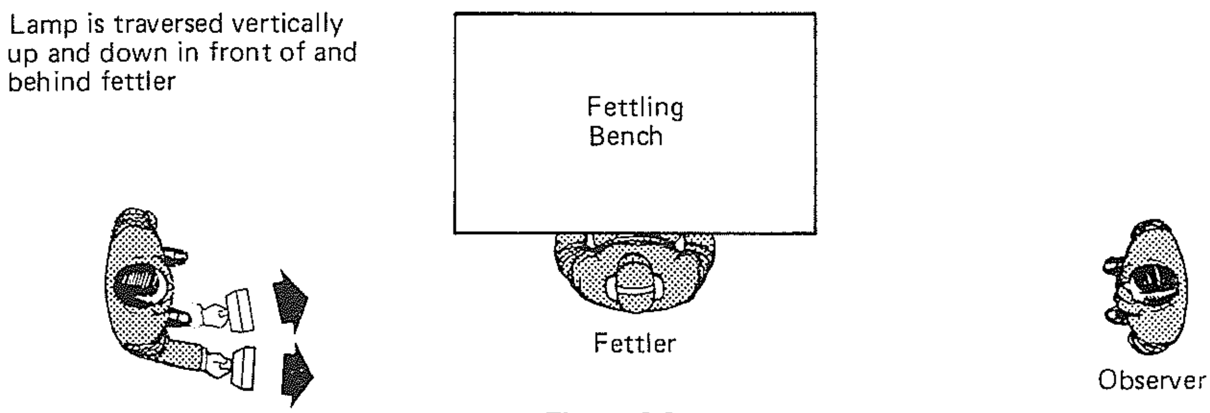

Figure 3.9
Diagram of dust lamp in use.

Examining Processes

Using the dust lamp the early investigators (MINISTRY OF LABOUR AND NATIONAL SERVICE, 1956) were surprised by their observations; thus in the case of pedestal grinders:

> "... photography of the dust cloud resulting from grinding, showed that the conventional local exhaust system is by no means as efficient as was supposed". P 10.

and similarly for portable grinding wheels the dust lamp:

> "... indicated the dust of small size range did not follow the line of sparks but flowed over the wheel top and appeared as a vortex between the wheel and the operator's face. The work indicated that dust control systems which had been arrange to collect large particles such as sparks, failed to collect dust of the dangerous size range". P 10.

Figure 3.10
Double ended pedestal grinder with ineffective exhaust ventilation.
Note: workers body is used to screen the observe from the direct dust lamp beam and a firebrick was ground instead of a metal component to increase the density of the dust cloud and thereby the forward scattering of light.
The movement of the uncontrolled dust cloud could thus be followed more easily.

Unfortunately the lessons learnt by these investigators do not appear to have penetrated the conrciousness of many designers and exhaust ventilation hoods are still designed and positioned on the basis of unwarranted assumptions as to the movement of the fine particles in contaminated air. We would urge any investigator attempting to locate sources of fine dust or to track the movement of fine particle clouds to borrow, make or buy a dust lamp.

3.9.3 Gas/Vapour Clouds

3.9.3.1 Infra-Red Photography

The dust lamp is easy to use, cheap and an extremely powerful tool in experienced hands; an equivalent technique for viewing gases and vapours is needed.

The vast majority of gases and vapours of concern to the hygienist have dipole moments in their molecular structure which cause them to have strong absorption peaks in the infra-red (IR) region. This property can be exploited to make gas and vapour clouds visible.

The technique involves the use of a heated flat screen, some 15^{o} C above ambient temperature, and an IR camera fitted with a filter, which cuts out most of the IR radiation outside a relatively narrow waveband centred on the absorption peak for the gas of interest (see ALLANDER and LJUNGQVIST 1979, and CARLSSON et al 1982). The screen is positioned one side of the source and the IR camera the other. If gas is emitted a certain amount of IR is absorbed and a dark cloud appears on the camera monitor, see Figures 3.11-3.14. The technique can be calibrated to give semi-quantitative results.

As currently reported the technique is not sensitive to very low concentrations of gas or vapour but there are plans to increase sensitivity by using monochromatic IR radiation produced by a laser. Developments have so far been based in the research laboratory and the method is liable to remain a research technique until the price of the basic equipment (the camera and the filters) falls or simpler methods of producing IR pictures are developed. The basic method is simple and appears to have great promise.

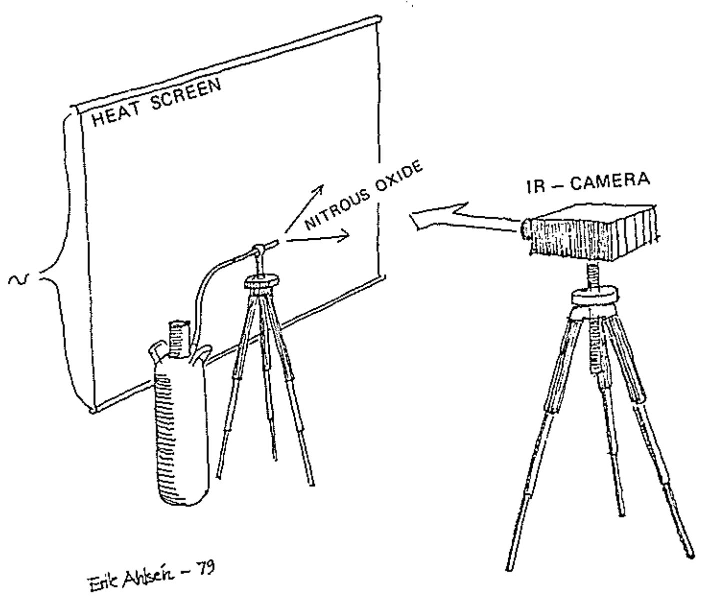

Figure 3.11
General arrangement of infra-red test apparatus.

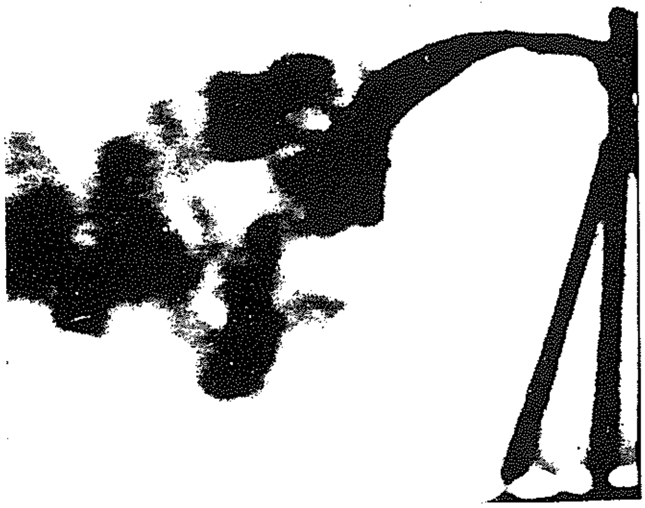

Figure 3.12
IR photograph of nitrous oxide release from gas bottle shown in Figure 3.11
(IR camera fitted with a narrow band filter centred on 4.5 μm).
(Figures 3.11 and 3.12 taken from ALLANDER and LJUNGVIST, 1979).

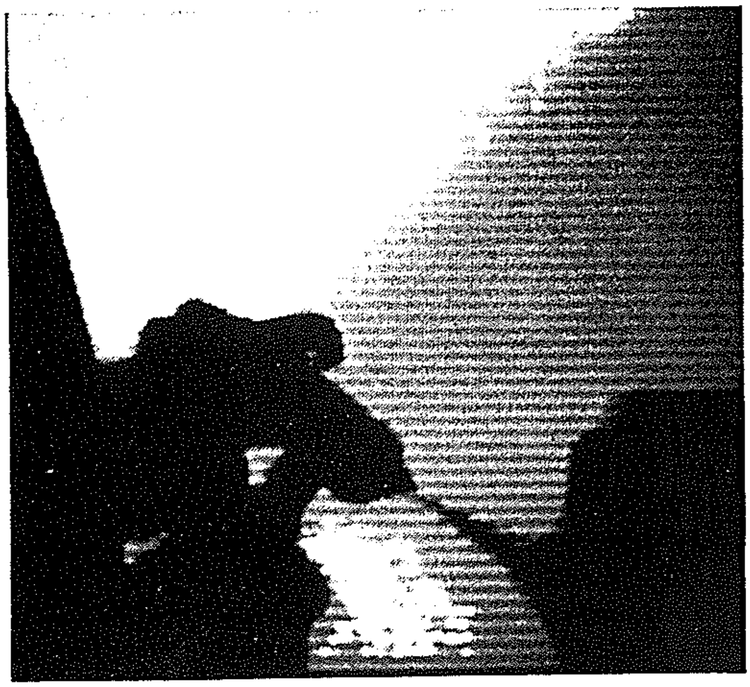

Figure 3.13
IR photograph of solvent evaporation from a paint spray jet.

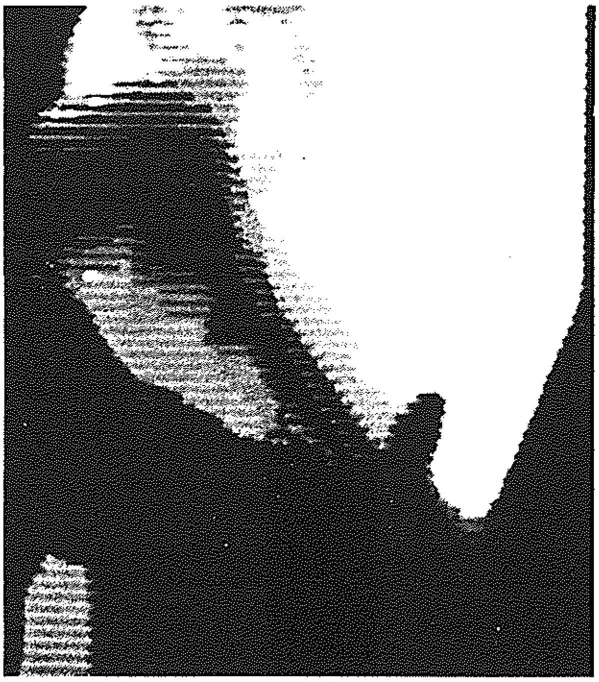

Figure 3.14
IR photograph of a worker brushing a spray gun with paint thinner. Although operation is done under exhaust ventilation vapour is clearly seen rising towards the worker's breathing zone.
(Figures 3.13 and 3.14 taken from CARLSSON et al, 1982).

3.9.3.2 Schlieren Photography

Another qualitative method is Schlieren photography which is based on the visualisation of small differences in density due for example to temperature or concentration gradients. These density differences cause changes in the refractive index of the gas which can be made visible by the deviation of a light beam (CLARK and MULLAN (1978), CLARK (1983)). The method is strictly a research technique. It involves the use of expensive mirrors and is time consuming and delicate to set up. While useful as a research tool, it does not lend itself to regular, routine use in the field by the hygienst or other investigator.

3.10 Quantitative Assessment

It may be possible, if the rate of emission of a material is known, to calculate the potential range of exposures which a process is capable of generating. Such calculations are really only possible for processes involving liquids at present (see for instance JONES ET AL 1984) Also the interaction between the source(s) and the air movement in the personal and general environment in the workplace make prediction of likely personal exposure difficult and haphazard. The only accurate method of gaining a quantitative understanding of personal exposure, and how processes in the workplace relate to this exposure, is to do air sampling.

3.10.1 Air Sampling

The details of air sampling will not be covered in this Guide. The reader should refer to the standard texts on the subject (eg HSE's MDHS Series and NIOSH's equivalent, ACGIH 1983, CULLIS and FIRTH 1981 and GILL and ASHTON 1982).

Examining Processes

Static sampling at different distances from sources of emission give some idea of potential exposure close to the source and the distribution of contaminant concentrations in the workplace. Personal sampling, properly planned, will supply information on the likely range of exposures of different groups of people. If the work methods and work routine are well understood and characterised, it may be possible to relate personal exposures to the static sampling results. This is often surprisingly difficult in practice, unless individual exposure is solely due to the background ambient levels where people do not work close to the source of contaminant. Where this is not the case "Static samplers may grossly misrepresent the exposure of individual workers who are likely to be exposed to airborne contamination of their own making", (SHERWOOD, 1966). With both types of sampling, particularly the personal, it is important to recognise how variable the results will be and how carefully measurements, before and after controls are implemented, will need to be planned to get meaningful results (see HSE 1984, and IOH 1982, 1984).

3.10.2 Continuous Monitoring

Continuous and semi-continuous monitors exist for measurement of gases, vapours and aerosols. Some are highly selective for particular contaminants and others are less so. In all cases these instruments can be powerful survey tools in experienced hands. Because of their bulk they are not easily used for personal sampling over long periods; however the processes which cause exposure during parts of the work cycle can often be investigated. Such monitors may be used in the following ways:

1 For ranking sources of emission in a qualitative or semi-quantitative fashion.

2 For identifying small leaks, which may be very significant in terms of personal exposure.

3 For studying the changing distribution of contaminant in the workplace.

4 For studying the exposure of the individual at various times in the work cycle and gaining an intimate understanding of the relationship between the process and personal exposure.

5 For demonstration to the worker the effects of his or her work practice and to management, the need for improved control or better maintenance.

The efficiency of continuous monitors is greatly enhanced if the changing signal can be recorded on a chart recorder or a data logger for subsequent analysis.

Well planned personal and static sampling coupled with continuous monitoring will enable the hygienist or other investigator to gain a good appreciation of how personal exposure occurs, and rank the various sources of emission and specific work operations in terms of their contribution to exposure. Such measurements follow naturally from the initial assessment of materials and processes covered in Sections 3.3 - 3.7.

Having identified problem materials and processes, investigated their pattern of contaminant release and assessed their contribution to personal exposure, the hygienist or other investigator has the foundations on which to build a rational approach to controlling personal exposure.

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3.12 APPENDIX: RECORDING DUST LAMP OBSERVATIONS

A single lens reflex camera with integral metering is the optimum choice. The best angle to collect the maximum scattered light is readily found by trial and error.

Fast, narrow angle lenses are preferable to the standard, fairly wide angle optics normally supplied as standard with most single reflex cameras. For 35mm format focal lengths of the order 85-105mm have been found by the writer to be the most useful. The fastest lens available should be used - generally not slower than f/2.5.

Black and white films are probably easier to use than colour film stock. The faster emulsions for the latter tend to be balanced for daylight and correction filters may be needed with artificial light sources. Filters introduce significant light losses, often halving film speeds. There is also the problem that at low light levels colour balance and contrast are impaired.

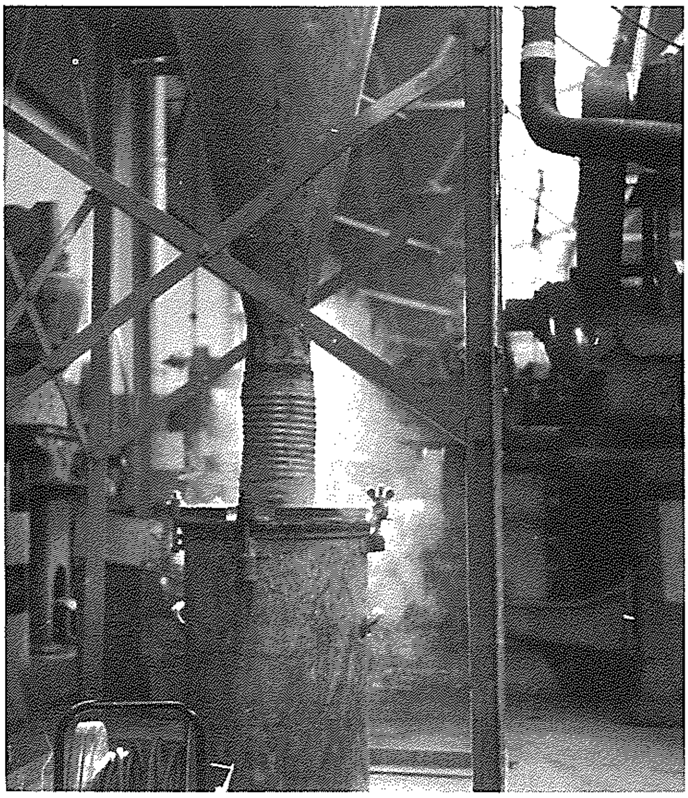


Figure 3.15
Asbestos dust leaking from a cyclone pre-filter
(film = Ilford FP4, 125 ASA. Camera = twin lens-reflex, tripod mounted.
Aperture f/4.5 and exposure ~ 1/30 second).
Photograph courtesy of G.L. Lee.

Conventional black and white film stock based on silver emulsions can be force developed to give high emulsion speeds, enabling photography under very low light conditions. Thus, Ilford HP4/5 film stock, standard rating 400 ASA, can be rated at 800, 1600 or even 3200 ASA. Unfortunately force development also increases the grain size of silver halide emulsions and at 3200 ASA, the grain size is such that degradation of the particulate cloud image is almost certain to occur. Silver halide emulsions are not really useful at speeds above 800 ASA, and even at this speed some grain has to be tolerated.

Modern black and white emulsions based on dyes totally eliminate the grain problems. They can be rated at high speeds if required. Ilford XP1 film has been found particularly useful, producing good quality, grainless negatives of excellent contrast. A minor disadvantage is the need to process at a temperature above ambient.

Observations can be recorded on cine-film and again, single lens reflex cameras are preferable. Recordings on video-tape are also possible, but one of the more modern video cameras capable of working under low light conditions is needed.

A useful addition to the hygienist's armoury when using the dust lamp is a small flashgun. This can be used to fill in the foreground of the photograph so that the detail of the people and the process can be seen and not simply indistinct dark silhoettes.

Table 3.7

Commercially available dust lamps**

Supplier*	Description	Price Approx
Laniro	Ionbeam Quartzcolour MOD 3150 2kW 2kW 240 or 110V	£200 (including barn doors and safety glass)
	Ionbeam Quartzcolour MOD 3124 800W 240V also takes 800W 110V	£100 (including barn doors and safety glass)
	(Bulb prices approx £30 - 2 kW £16 - 800W, 1kW)	
Hedler*	Jetlux 100, 1kW, 220V	£80
Wotan*	AL100 Studio 100W 12V rechargeable 10 minutes duration	£100 (includes charger)
Custom made dust lamp		
A&G Marketing Co Bridlehouse Clavering Road Brent Pelham Buntingford HERTS	Dust lamp 110W 12V Rechargeable 20 minutes duration	£600 (includes stand)

Photographic stands may be used to position the mains operated lamps (approx cost £30).

* These imported lamps should be available from most professional photographic suppliers.

** Taken from Annexe 5 of the HSE Report of the Asbestos Working Group 1982/3. Chairman: S. Grant.

4

DESIGNING TO CONTROL EXPOSURE

4.1 Process Modification and Exhaust Ventilation

The last chapter went into some detail and emphasised the importance of studying the process to be controlled and how primary and secondary sources cause exposure. This information can be used in the application of non-ventilation methods of control to reduce the residual problem to be dealt with by local exhaust ventilation to manageable and cost-effective proportions. These techniques are the subject of the next chapter and the point we wish to emphasise here is that the process to be controlled and past work methods employed should never be treated as immutable by the exhaust ventilation designer. The size, cost and effectiveness of the local exhaust ventilation (LEV) applied to a process will be influenced by how well the LEV designer has understood the process and how well the LEV is integrated with it. Where there are many sources of emission and exposure, some of large size, in many instances it will be essential to apply non-ventilation methods of control to the process and work methods, to bring the problem down to a size where LEV can be realistically applied.

When introducing changes to the work method or process it is vital, if the efforts of the designer are to be successful, that he or she works closely with the workpeople and production or works engineer. The efficiency of the work method and the quality of the product should not be adversely affected by the changes introduced and should, if anything, be improved. In practice, because of the intensity of observation and depth of thought applied to the problem of understanding the process and reducing exposure, it is often possible to devise more ergonomically sound work methods and increase the efficiency of the process. By approaching the problem in this way the hygienist or other investigator gains the support of the management and workforce alike.

4.1.1 The Integrated Approach - An Example

Excellent examples of the integration of process, work method and LEV which gained widespread acceptance in the pottery industry can be found in the research work of the British Ceramics Research Association (BCRA). For instance in the process known as "flatware towing", china plates were rotated on a circular horizontal stand, shaped with a metal tool and finally abraded with a piece of "tow" or cloth. Workers were exposed from two primary sources; the projected stream of large particles with fine particles in their wake and fine dust generated and dispersed from the rotating airstream at the periphery of the plate when the abrasive cloth was applied. Secondary sources included dust collected on work overalls, tools and tool rack, and abrasive cloth pieces. The work was normally done in an LEV hood but it was known to be inefficient and workers were exposed to fine dust clouds which posed a significant silicotic risk. See Figures 4.1 and 4.2 for details of the process and problems encountered.

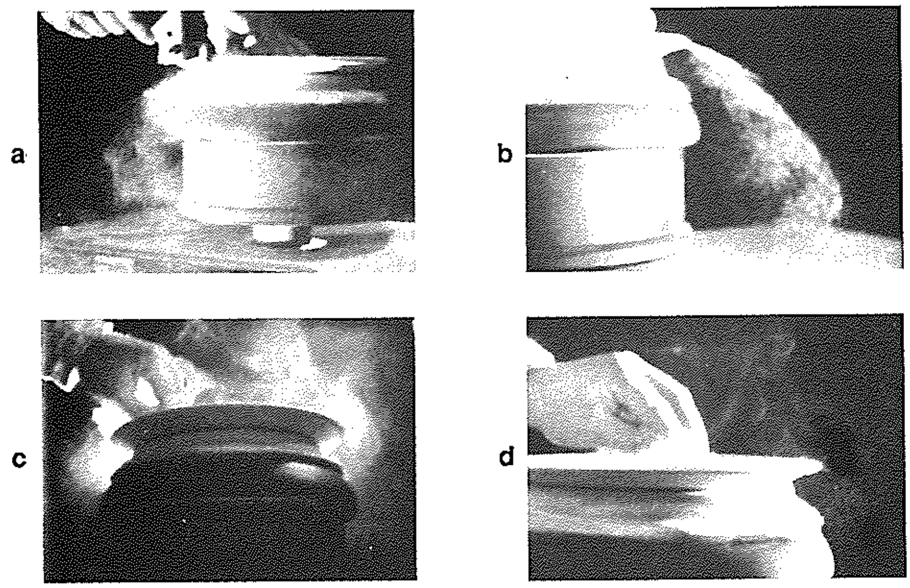


Figure 4.1. (a-d) Some dust creating processes in Flatware Towing. (a) metal tool applied to the edge of the ware projects a dust stream towards the worker. (b) abrasive paper applied to edge of ware, (c & d) abrassion of surface of ware with "tow cloth" applying firm and light pressure.

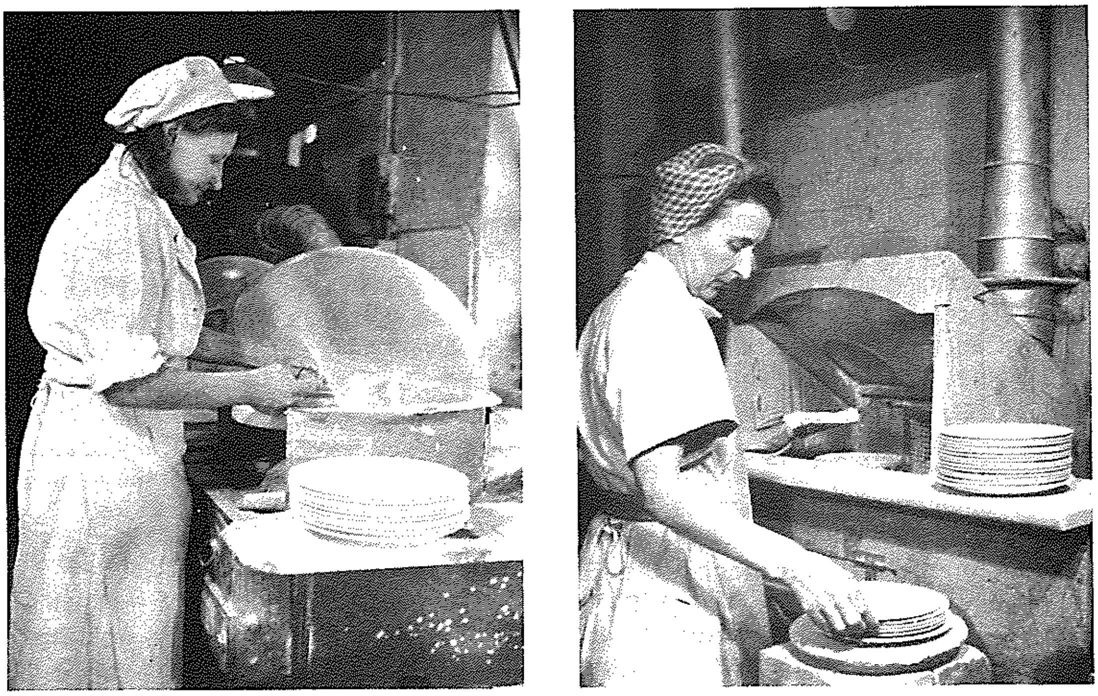


Figure 4.2. Two old hood designs (problems included: no physical separation of the workers breathing zones from the process; flatware and tools stored outside the hood; no air jet in hood to blow off residual dust. In the case of hood (a) the projected dust stream struck the workers midriff heavily contaminating her clothing and the perspex dome rapidly became scratched and difficult to see through).

Designing

After careful study and research BLOOR and PALMER (1957) developed a new hood which had the following features:

(i) the projected dust stream was contained within the hood by raising the front edge of the enclosure and moving the turntable back so that the stream fell below the front edge.
(ii) the workers' breathing zone was physically separated from the process by means of a glass screen.
(iii) a fixed, pressure regulated air jet was positioned inside the hood to blow residual dust off the plates. Previously operators had to use their own breath.
(iv) open sides allow some airflow over shelving where dusty plates were stored.
(v) a perforated tool rack was positioned <u>inside</u> the hood which reduced the transfer of dust into the workplace. (The turntable spindle was offset slightly to allow for the rack).

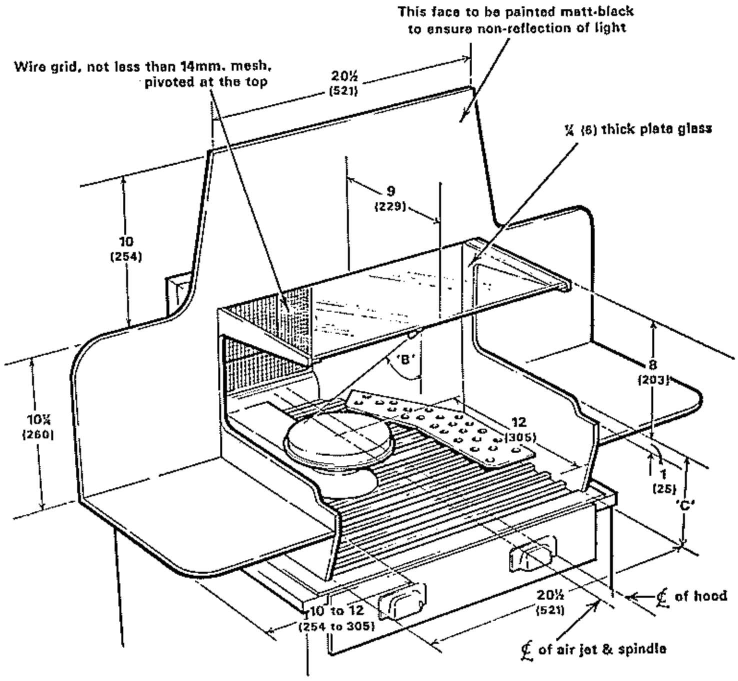
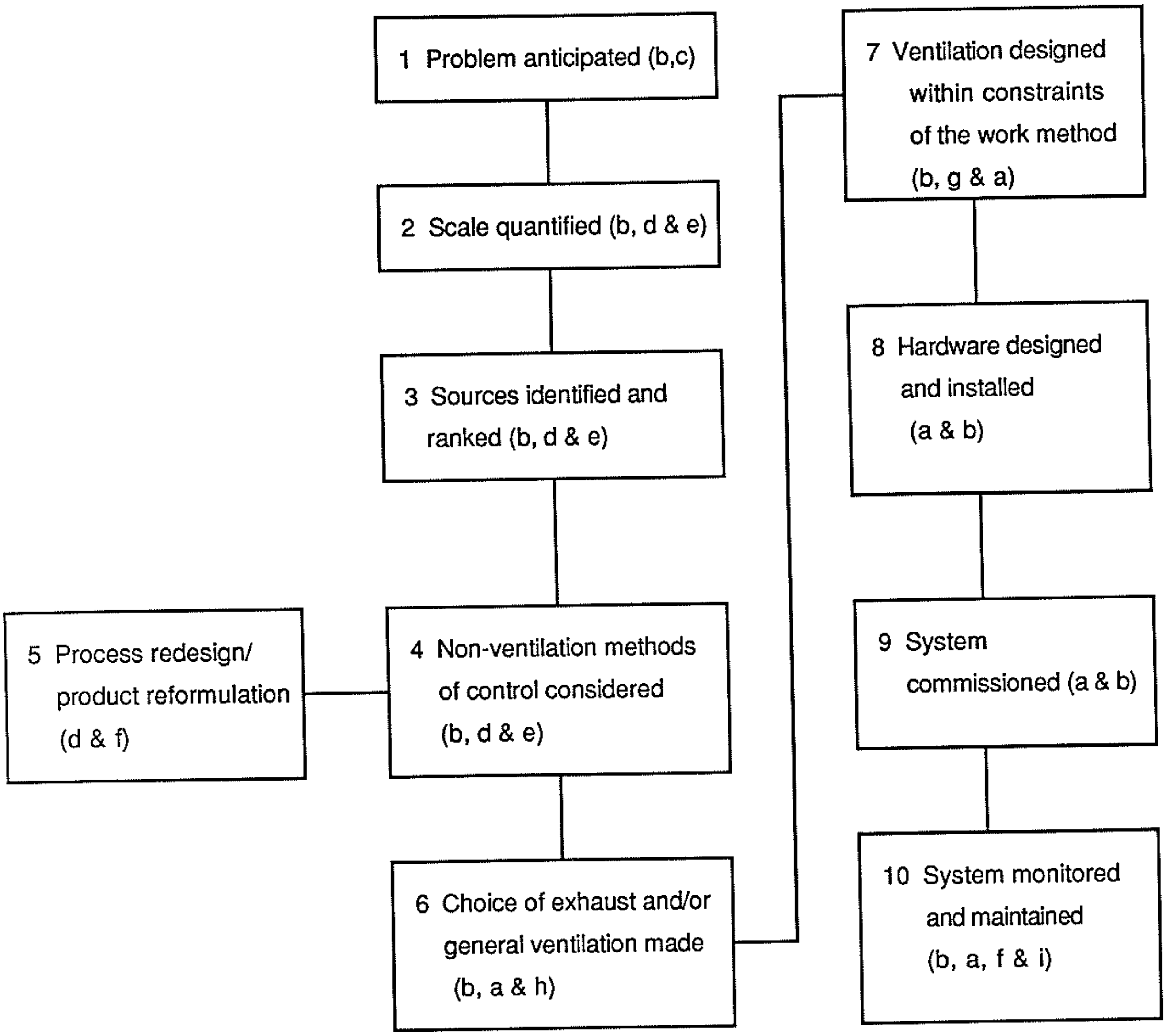


Figure 4.3. Final design of flatware towing hood. (A linear air velocity, measured 50mm above the centre of the ware, of ~ 1.5 s^{-1} was recommended, which represents a volumetric flowrate of ~ 0.28m^3s^{-1} for this design of hood).

In a separate exercise BLOOR and DINSDALE (1962) have demonstrated that dust laden cotton overalls were a significant source of personal dust exposure and identified Terylene as having the lowest dust release characteristics of the materials tested.

It is evident from the above example that controlling dust exposure from "flatware towing" involved far more than simply positioning an LEV hood somewhere in the vicinity of the most obvious source of dust.

Other examples of the importance of the careful, integrated approach to LEV design and the application of process modification are given in MINISTRY OF LABOUR and NATIONAL SERVICE (1956), GRAY and HEWITT (1982) (see Chapter 5.0 for summary) and CAPLAN et al (1984). An example of a current problem which has developed recently in the UK is the use of baths of methylene chloride to strip wooden furniture of paint. A methylene chloride/methanol mixture is often used and if effective LEV slot extraction is applied solvent loss by evaporation can be excessive and expensive. Simply changing to a methylene chloride/toluene mixture (which is not miscible with water) allows the use of a water layer in the dipping baths which dramatically reduces vapour release and allows the application of LEV to control residual vapour escape. In this case the process had to be changed in order to make the application of LEV viable at all.



SKILLS REQUIRED = ()

a Ventilation Engineering
b Occupational Hygiene
c Occupational Medicine
d Production Engineering
e Chemical Engineering
f Training
g Ergonomics
h Accountancy
i Organisation & Management

Figure 4.4

Designing an airborne contaminant control system - with disciplines/skills required at each stage

4.2 The Design Process

The person(s) responsible for controlling exposure can easily jump to inaccurate judgements as to where and how to apply controls if the evaluation stage described in Chapter 3.0 is omitted. However, this stage is but one step in the design process. If all the choices and decisions that may need to be made in the design of contaminant control methods are made explicit, the decision-tree can look daunting, (SHERWOOD and ALESBURY, 1983).

With emphasis on ventilation and after simplification the stages and questions which may need to be addressed when controlling exposure to air contaminants are summarised in Table 4.1. The list is not exhaustive, but even a cursory reading brings home the point that the person(s) responsible for the design, installation and continued effective operation of a control system requires a wide range of knowledge and skills. Figure 4.4 though a simplification attempts to identify disciplinary knowledge required at each stage and the areas of knowledge with which a designer should be familiar are elaborated in Table 4.2.

The importance of integrating LEV design with process and work method modification has been emphasised. By examining the range of knowledge and skills required across the whole design process, two obvious points stand out. Firstly, it is evident that in the design process there are several stages to consider before exhaust ventilation is considered. Secondly, the skills involved are not simply engineering based although these are vitally important.

Table 4.1

Steps in the contaminant control design process

1 With an understanding of the contaminants' potential health effects decide upon what level of exposure or emission is tolerable.

2 Identify all sources of contaminant emission and rank in order of magnitude.

3 Study the process and people's work methods.

4 Perform occupational hygiene measurements and re-rank sources and tasks in terms of contribution to personal exposure.

5 Control by Non-Ventilation: consider how the number and/or emission rates of sources can be reduced. Start with the sources which are most significant for personal exposure.

6 Control by Exhaust Ventilation: consider the type(s), shape and size of hood most applicable. (Optimum position and shape may require a re-design of the work method. Do not treat present methods as immutable).

7 Decide on appropriate capture velocities and distances or face velocities (when dealing with receptor hoods).

8 Calculate the required volumetric flowrate.

9 If at all possible install a prototype and solicit opinion of users - alter design.

10 Design ductwork to transport the extracted air in the most energy efficient way (ie to minimise friction losses).

11 Plan how replacement air will enter the workshop, what air cleaning may be required and how exhaust will be discharged from the building.

12 Choose an appropriate duty fan, allowing for inevitable wear and drop in efficiency.

Designing

13 Plan commissioning, record keeping, inspection and maintenance - (not just how, but who and how often).

14 Is the objective set in step 1 met? - If not why not? Solution may require repetition of steps 2-12.

Additional Questions

(i) Is the system designed for ease of maintenance?

(ii) Will the hardware material specified take the duty imposed?

(iii) Will the process change and is the change foreseeable?

(iv) What qualitative or quantitative tests will be required to confirm the effectiveness of the system?

(v) Have the views of the system users been sought on what design alterations may be required?

(vi) What additional problems may have been created? (eg noise, dust explosion risk, water pollution risk etc).

4.2.1 Occupational Hygiene and Design

It is evident from the approach outlined in this chapter and Chapter 3 that to control health hazards due to exposure to airborne substances in the workplace requires a particular frame of mind, a specialist fund of knowledge and a sensitive way of looking at processes and exposure. To control exposure effectively may require a mix of all knowledge and skills identified in Table 4.2.

The designer must have a sufficient understanding of the toxicology and potential health effects of the materials used in a process to make a preliminary assessment of the potential for harm. He or she must know enough about the form air contaminants take and how they are generated to identify points in the production process where contaminants may be released. The person must then be able to assess qualitatively and/or quantitatively the principal sources of exposure and make cost-effective recommendations, in the form of a range of technically feasible options, to control over-exposure. It goes, almost without saying, that to undertake these several tasks requires intelligence, training, commitment and experience. The profession which aims to integrate the disparate mix of subjects and skills listed in Table 4.2, to enable a person to recognise, evaluate and control potential health hazards, is known as occupational hygiene. It follows that the well-trained professional occupational hygienist has a central role to play in the control of airborne contaminants. Such a person is in an excellent position to co-ordinate the activities of the various people involved in the design, installation and maintenance of LEV. For large schemes and in large organisations particularly the successful approach will necessarily be based on teamwork and the hygienist co-ordinator should possess all the skills and knowledge listed in Table 4.2, though not necessarily all to the same degree.

Table 4.2

Knowledge and skills required to control exposure to airborne contaminants

1 Knowledge of processes and work methods.

2 Ability to understand how people are exposed especially in the environment close to the process.

3 Appreciation of the magnitude of the risk to health that exposure might pose and ability to measure exposure.

4 Knowledge of the behaviour of particles and gases in air.

5 Knowledge of the aerodynamics of LEV hoods and general ventilation.

6 Theoretical and practical knowledge of LEV system design.

7 Understanding of the principles of ergonomics.

8 Ability to design for ease of maintenance with enough understanding of machinery reliability to plan an effective maintenance programme.

9 Appreciation of the management organisation necessary to test and maintain the control system.

4.3 Present Day Practice

Having considered the various steps in the design process and the skills which may need to be brought to bear it is instructive to consider what actually happens in industry. Some of the all too common errors in LEV design are identified in Chapter 11.0.

Those hygienists and others responsible for assessing the effectiveness of LEV will have come across these and many more examples. Though there are notable exceptions (usually in the larger organisations), the majority of LEV systems installed in the UK are badly designed, inefficient and not cost-effective; worse still, non-ventilation solutions are rarely given committed consideration. Once the ventilation path is chosen the problem tends to be treated as an "engineering problem" pure and simple with a strong emphasis on duct work, fans and air cleaners. Somehow the subtleties of air contaminant control get lost in the process.

There is a general lack of appreciation of the complexities of the design problems illustrated earlier. This is reinforced or perhaps partially caused by the division of the design of control solutions into autonomous departmental/professional compartments. So, for instance, the hygienist may indicate by measurements that there is a problem and the engineer is left to "solve it".

The common errors in design familiar to many readers, some of which are listed in Chapter 11.0, are not new. Careful examination of Factory Inspectorate (FI) Committee reports and the observations of important figures in the development of LEV theory and practice suggest that exhaust ventilation systems have been inadequately designed, installed and maintained and have failed to work efficiently for similar reasons since the turn of the century (Table 4.3). While understanding of airflow into hoods and through ductwork has developed since the turn of the century, if J.S. Haldane (who chaired the first FI Committee) and Stephen Grant (who chaired the latest) could compare notes on the general state of LEV design they would find much in common to discuss. If progress is to be made it is essential that those responsible for the solutions to air contaminant problems appreciate the importance of an integrated, multidisciplinary approach to design and the part that occupational hygiene has to play in this process.

Table 4.3

Chronology of observations on exhaust ventilation by notable authorities and committees

"With regard to all exhaust openings for extraction of dust etc it must be clearly borne in mind that in whatever direction the opening may point, the air feed is all round: hence the radius within which a perceptible draught is produced towards the opening is extremely limited". **Haldane et al, 1907**

Designing

"As the object of hoods is to concentrate the draught on the fumes or dust to be removed from the work, position in regard to origin of the fumes or dust requires first consideration. Generally hoods applied err in having too wide an opening, or they are placed too far away from the source of danger". **Legge & Goadby, 1912**

"Ventilation engineers have, generally, displayed little enterprise in making experiments for the removal of dust and most exhaust systems are on stereotyped lines". **Macklin & Middleton, 1923**

"In spite of many valuable contributions made in recent years on the subject, relatively few designs apply the scientific principles involved ... Hoods are still constructed and installed without any certainty that they will perform as expected". **Dallavalle, 1952**

"It sometimes seems that engineers experience such sheer satisfaction in their ability to handle the design of duct work on a neatly quantitative basis, that they are led to slight the initial problem of selecting suitable exhaust or ventilation rates as though they were a minor detail to be covered as quickly as possible ... whereas the part they slight is the essential of industrial ventilation". **Hemeon, 1963**

"Problems of this sort (inadequate exhaust ventilation) frequently arise due to lack of knowledge of the simple basic principles of airflow into an exhaust hood, the failure to assess the need for control properly when a production plant is designed and also from a failure to maintain the exhaust plant after it has been installed". **Health and Safety Executive, 1976**

"The proliferation of examples of bad practice is evidence in itself that there is widespread scope for improvement. The conclusion is inescapable that the solutions to problems are known but application of the solutions is not consistent". **Health and Safety Commission, 1983**

4.4 Design Methods, Specification and Involving the Users

Airborne contamination control, including LEV, is an under-researched area of science and technology and has been so for many years (PINEY, 1986). The need for something better has been evident to people working in the field for decades. LAWRIE in 1961, noted that there was "a need for some research worker to interest himself in the fundamental principles covering these special cases (the design of individual unique LEV systems) so that design engineers would no longer be forced to empiricism - determining each answer by trial and error". More recently, FIRST (1983) made a similar point in an evocative manner; "just as one no longer designs bridges and aeroplanes by trial-and-error methods, so should we abandon our empirical approach to the design of controls for occupational health exposures ---- the profession (industrial hygiene) is still living off Dallavalle's 1930 doctoral thesis and Silverman's 1942 doctoral thesis for its entire body of local exhaust ventilation theory". Although there has been progress see, for instance, the work of Fletcher and other work cited in Chapters 7 and 8, the last quote is substantially correct. "Design" is still a semi-empirical art form which allows no accurate prediction of exposure reduction. The importance of a variety of factors which can and do effect the performance of LEV was investigated by means of simplified theoretical models by ROACH (1981). He demonstrated that "capture velocities" and "face velocities" (see Chapters 7 and 8) by themselves are not the only-significant factors which lead to a reduction in exposure. Other factors such as:

(i) the position of the source
(ii) the rate of release of the source
(iii) the size of the hood
(iv) the position of the replacement air inlets
(v) turbulence in the hood and the resulting turbulent diffusivity

can all have important effects on ventilation performance. Roach emphasises that no LEV system is 100% effective and it would be a step forward from specifying face velocities if design criteria were stated in terms of the percentage containment required. Even so there still remains the problem of relating containment efficiencies to likely personal exposures. This can be done in simple circumstances in the field of noise control where it is possible to relate equipment noise emission levels to likely workplace noise levels. It may be possible to attain this level of predictability in the area of air contaminant control and there is a sore need for systematic, fundamental research in this field. In the meantime the designer needs to be acquainted with the principles of good LEV design and layout and aware that simply meeting a specification of so many metres per second air velocity at the entrance to an LEV hood may not sufficiently reduce the exposure of people relying on the system for protection. Other factors such as those listed above will have to be allowed for. It may be useful to measure the capture or containment efficiency of the system (see Chapter 11.0); and it should be borne in mind by the designer, customer and contractor that the ultimate test of success is the measurement of personal exposure reduction. At present few ventilation contractors or designers are prepared or able to work to contract specifications in terms of personal exposure results. However, the more client companies, particularly the large ones, move in this direction the greater will be the stimulus to contractors to produce good, well researched LEV designs.

Finally it is important to remember that design is not simply a matter of getting the hardware right. People use exhaust ventilation systems and when the effectiveness of the system is dependent on the correct positioning by the worker of the hood close to the process or the process close to or inside the hood it is essential that the people who have to use the system are involved in its design. It is essential for two reasons; firstly because it motivates and involves people and draws upon their, often considerable, tacit knowledge and secondly because it is important that the LEV is integrated with the work method and the only sure way of ensuring this is to try out a prototype design and ask for feedback. It may be that by careful adjustment the old work method need hardly be changed but often a revised work method will have to be developed. The work people, supervisers and others will feel more commited to the new work method if they have had a say in its design. It is almost inevitable, if this approach is not taken, and the exhaust ventilation or other control method does interfere with the work process that it will not be acceptable to the workforce or the supervisors and will not be used properly, if it is used at all.

4.5 The Designer or Design Team

Having described the design process and the range of skills that the designer or design team should properly possess there remains the problem of who within or without the organisation should be responsible for air contaminant control. The answer varies and depends upon the size of the organisation.

The manager in industry is often unsure of who to turn to for advice and possibly is unaware that other people may have dealt with similar problems. Faced with this dilemma, a local ventilation contractor is often consulted; these are usually small organisations who have developed an expertise in the manufacture and installation of sheet metalwork systems and other hardware associated with ventilation systems. Alternatively, the work is delegated to an engineer or contracted out to an engineering consultant. Few of these contractors or consultants are likely to have available the knowledge and skills required to control airborne contaminants as outlined in Table 4.2, and unless they can demonstrate that they have these capabilities they should not be consulted at this stage of the project.

In large or medium sized organisations a project team or working group should be identified who can react as necessary and appropriate to deal with specific projects. The degree of involvement of the team members and the time devoted to any particular project will depend on circumstances and the scale of the problem; however, in general, this team approach has been found to be the best way to assemble the disciplines identified in Figure 4.4.

Designing

We feel that the hygienist is best suited to act as the focal point of the working group. Other members should be selected to encompass as many as possible of the skills identified in Table 4.2 and disciplines in Figure 4.4, and where appropriate, the group should have the authority to co-opt other members. To be fully effective, the working group should be convened by and report to, or be chaired by, a senior manager who has the executive authority to act on recommendations produced by the group.

The cost of setting up such a working group clearly has to be taken into account; however, if convened only when necessary to react to specific projects and to plan and report on action, we feel that this is a very cost-effective way of resolving airborne contaminant problems involving far less expenditure than that which is currently wasted on ineffective LEV systems. Furthermore, the production of a design brief and specification enables the supply and installation to be put out to competitive tender, and eliminating the design process from this costing has, in our experience, not only led to more effective control but also considerable cost savings.

Large organisations may employ an occupational hygienist who specialises in control. Many large companies do not and, even in those that do, the hygienist is often not brought in at an early enough stage in the design of a new process and is left with the problem of making adjustments to designs which are fundamentally misconceived. Large organisations, in our view, should employ professional hygienists and should involve them early on in the design of new processes. For companies that decide that a senior engineer or engineering manager should be responsible for air contaminant control it is vital that this person has had an appropriate grounding in the principles of occupational hygiene and control and can direct, with the project team hygiene technicians who have also been appropriately trained (see Appendix 4 for the addresses of training organisations and examining bodies).

A few medium sized organisations that deal with a large range of potentially hazardous processes employ hygienists but most do not. Small organisations are not in a position to employ full-time hygienists. Such organisations still require the skills of a professional hygienist versed in air contaminant control but their problem is to recognise when to call upon this person's services and obtain these services on demand. One solution is to retain the services of a consultant occupational hygienist. A list is available from the Institute of Occupational Hygiene (see Appendix 4). Another solution is for a senior individual to be trained and aware of the need for carefully planned air contaminant control. This manager could, in medium sized organisations, call upon the skills and commitment of the safety committee and safety representatives to suggest when a consultant may be needed.

4.6 The Contractor

If the design principles of the control system and details of its eventual operations and maintenance are overseen by the 'Contaminant Control Project Team' or consulting hygienist then the criteria for selection of a contractor are confined to their expertise in converting a design brief to a manufactured and installed solution. Manufacture and installation of hardware are covered by industry associations or British Standards, and the tender document should be carefully drawn up to refer to appropriate standards, regulations and health and safety requirements for contractors working on site.

When selecting contractors, a useful starting point is to refer to the relevant trade association, such as the Heating and Ventilating Contractors Association, and to select firms from their membership who list "Industrial Ventilation" as one of their specialities. When dealing with new companies, it is always worthwhile taking up references and either phoning or preferably visiting other companies for whom they have performed work to obtain an impartial view of their capabilities.

Many small and medium sized companies do not currently employ the services of an occupational hygienist or organise a design team. Such companies rely completely upon the contractor to design the air contaminant control system.

4.7 User Motivation and Training

For exhaust ventilation to be effective people need to know how to use it properly. Particularly if it is mobile it will need positioning correctly or it may need manual adjustment, eg opening a damper or closing the sash on a fumecupboard. Most importantly, people need to know why they should bother to do these things; they need to be motivated.

Motivation comes from understanding what the health risks from the contaminant are and therefore why it is important to use the control methods provided. It is also important that the user has confidence in the control methods applied and believes that they will protect his or her health. A good appreciation of the potential risk is especially important when the risk is chronic or latent in nature. In these cases there will be no short term warning that anything is amiss even if the long term risk due to current uncontrolled exposure is significant. Thus, for instance, asbestos and lead give no sensory warning of their presence and that excessive exposure, with potential long term consequences, is occurring. Work people need to be honestly told why they should use the controls provided and they need to be shown how to use the controls properly. To use the controls properly people need to know how the controls work and should not simply be given a series of instructions to learn by rote. Apart from retraining the people directly involved in the process and new entrants, supervisors and some managers will need training so that they can identify changes in the work method which reduce the effectiveness of the control methods. This point brings us back full circle to design. When a person is seen to use the control method incorrectly, eg working too far from a captor hood, there is a two part question which needs to be asked. Is that individual working that way because he or she does not know any better, OR, because there is no other way to do the job and the person is forced to work in a way which defeats the control method? If the control method is difficult to use or gets in the way, then it is the control method which needs redesigning, (Section 4.4). If the control method is well designed but still misused then the individual needs training in the use of the correct method and motivation to use it properly.

Apart from using the control methods correctly there are a set of daily checks, on exhaust ventilation particularly, which can be most usefully undertaken by individual workers or their representatives or by the supervisory staff. Section 11 outlines the type and frequency of checks and maintenance which should be done on any exhaust ventilation system. The sort of checks which workers or others could easily do every day would include: visual checks on the systems physical integrity, a check on the hood airflow rate via a static pressure gauge connected to the duct behind the hood, and a check on fabric filter condition, again by reference to the static pressure drop, in this case across the filter unit. Such regular inspection is an important part of any maintenance progamme and again it reinforces the users' awareness of how the exhaust system works and is supposed to be used.

4.8 Conclusion

Designing methods of air contaminant control including LEV is usually a complex and time consuming business. In order to produce effective, cost-efficient designs, it is time well spent (see Chapter 6). In the following, specific areas of air contaminant control have been separated into discrete chapters for convenience. The main message of this chapter, however, is to emphasise how important it is that the hygienist or other designer does not treat the solution to an air contaminant problem as a collection of watertight monodisciplinary or monoprofessional compartments, but deliberately plans the solution to a problem as an integrated whole.

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5

NON-VENTILATION METHODS OF CONTROL

5.1 Introduction

There is a hierarchy of control options which need to be considered when attempting to control exposure to air contaminants, Table 5.1. For instance it may be possible to reduce the rate of release of a contaminant by using a less volatile or dusty material, by altering the product formulation, or by altering the design of the production process. There are various practical reasons why non-ventilation solutions are overlooked, but perhaps the main one is that they often have too many implications up-stream in the production process and there is too much organisational inertia to overcome once a process or product has arrived on the shopfloor. At this point ventilation may appear to be a cheap option but as Chapter 6.0 indicates, this may be an illusion. In our experience non-ventilation methods of control are rarely given enough consideration.

Table 5.1

Hierarchy of control options (in order of preference)

1 Non-ventilation
   (a) Elimination or substitution of toxic substances
   (b) Substitution or alteration of the process
   (c) Segregation of high release from low release processes
2 Local Exhaust Ventilation
3 General or Dilution Ventilation
4 Respiratory Protection

In areas of manufacturing industry which cater for rapidly changing markets, product reformulation happens frequently. Where cost-competitiveness is more important the emphasis will be on cost reducing or quality enhancing process modifications. Elimination or substitution of materials or processes is not unusual in such industries. It should be possible, given the commitment, to include in the list of priorities considered at times of change, the need to eliminate or substitute a hazardous material or redesign an unacceptably high release process.

If the contaminant can be eliminated or its rate of release can be reduced, the need for ventilation can be minimised. With elimination, the process is inherently safer and with reduction, large capital and running cost savings are possible, though, even if a less toxic substitute is available, uncontrolled exposure should not be allowed to occur (HSE, 1984). From the point of view of both the people exposed to the contaminant and those considering the costs of control, it is wise to expend time and effort investigating non-ventilation methods of control.

5.2 Elimination or Substitution of Toxic Substances

The most effective method of controlling exposure to a toxic substance is to eliminate the substance from the process by changing to a less or non-toxic equivalent. Where a substance is highly toxic and not central to the production process, elimination and/or substitution may be a viable option. A change of materials may well have an effect on production methods and possibly on the final product. Such a change will involve considerable team effort and liaison between the research, development and marketing functions within the organisation and with the suppliers of raw materials. For such an approach to be successful in an industry which requires a co-ordinated effort on a national scale, this will probably require liaison between the appropriate HSC Industrial Advisory Committee (IAC) and the Industry's Trade Association.

Substitution can be successful. Examples include: the use of lead-free glazes in the ceramics industry to eliminate a serious problem by a change of material. Similarly, elimination or reduction of lead in paints has reduced health hazards in their manufacture, use and disposal. The substitution of alumina ground flint considerably reduced free crystalline silica exposure in the potteries (HSE, 1983). It should also be kept in mind that, when dealing with flammable materials, non-flammable equivalents may be available. Other examples of substitution which have been attempted or are possible are listed in Table 5.2.

Table 5.2

Examples of material substitution

1 Sandstone replaced by Carborundum grinding wheels

2 Mineral oils containing polycyclic aromatic hydrocarbons (PAHs) replaced by solvent refined oils with greatly reduced PAHs

3 Asbestos replaced by synthetic mineral fibre and other substitutes

4 Benzene-containing hydrocarbons replaced by benzene-free or low benzene substitutes, eg toluene

5 Sand used in abrasive cleaning replaced by chilled iron or steel shotblasting

6 Carbon tetrachloride replaced by less toxic and/or less volatile alternative chlorinated hydrocarbons, eg 111-trichlorethane.

If the toxic material cannot be eliminated from the process it may be possible to use a substitute which is less volatile or dusty but has equivalent chemical/physical properties. Thus highly volatile liquids may be replaced by less volatile, for instance water based, equivalents. In the rubber industry, a large number of potentially toxic powders are decanted and weighed at the beginning of the production process. In recent years an effort has been made by some suppliers to produce oil bound or pelletised forms which release less dust when handled (RAPRA, 1979). This may not eliminate, but it does reduce the magnitude of the problem. Exhaust ventilation may still be required, but the size and hence the cost of the system can be reduced. There is a large amount of data available concerning the vapour pressures of liquids from which the relative volatility of different liquids can be deduced. There are as yet no similar data readily available to judge the relative "dustiness" of different powders or materials. The BOHS Technology Committee Working Party on Dustiness Estimation is looking at ways of standardising test methods and the interested reader should consult their work (HAMMOND et al, 1985).

Non-Ventilation Methods

Consideration should also be given to how the raw material is received into the works and how the finished or part finished product is despatched. For instance, the use of tote bins, sealed containers or impermeable bags, rather than containers such as paper sacks which are liable to split and leak, can prevent spillage. Paper sacks are a particular problem as each time the open sack is moved a cloud of dust can be created.

A common source of exposure is the emptying of bags or sacks into process equipment. Whenever economically feasible, mechanical opening and emptying within containment should be practiced. Simply persuading the supplier to deliver the material in rigid containers can reduce spillage and eliminate a significant source of dust exposure. Also it may be possible for the material to be handled or delivered as a liquid or slurry rather than as a dry material which is likely to release airborne dust. Even a small amount of moisture in a material can sometimes make a substantial difference to the amount of dust produced. For example, foundry greensand with a moisture content of about 3%, less than the amount needed for normal working, is practically dust free when handled.

5.3 Substitution or Alteration of the Process

Having considered the possibilities for elimination or substitution of problematic materials it is important to study the production process in detail. It is often possible to anticipate processes at which, or circumstances where, a contaminant is likely to become airborne. One very simple but common way in which airborne dust is produced is by the use of hand scoops or shovels to transfer materials from a large drum or container to a small drum or feed hopper. It may be possible to eliminate this part of a process by arranging to feed the machine directly from a tote bin or by the use of small, flexible spiral feeders.

Other circumstances where contaminants are likely to be released and become airborne are identified in Chapter 3.0, Section 3.6.

It may be possible to eliminate or minimise these sources or causes of release, but it is also important to "stand back from the process" and consider operations further upstream which may contribute to a problem at a later stage in the process. For instance, such items of plant as dilute phase pneumatic conveyors, high speed mixers, screw conveyors and elevators may be producing fine material which may become airborne at a later stage in the process. If this possibility is recognised it may be possible to alter the operation and reduce the generation of fine particles.

The change required in the process may be very simple. In the case of volatile liquids simply applying careful attention to detailed housekeeping procedures and workplace design can reduce vapour exposure. Tight fitting lids, pumping rather than pouring, rapid clean up of spills coupled with smooth, impermeable floors and work surfaces are all common methods of reducing emissions and exposure. For instance, the main sources of emission and exposure in paint mixing rooms are spills, large numbers of loose fitting covers on containers and rapid evaporation of vapour as hydrocarbon solvent is poured from one container to another. Process control on each of these sources coupled with adequate general ventilation can dramatically reduce exposure. Figures 5.1 and 5.2 show two examples of floating plastic balls being used to reduce the exposed liquid surface area in process. In Figure 5.1 the liquid evaporation rate is reduced and in Figure 5.2 the formation of bubbles which would produce an acid mist is suppressed. Cleanliness and good housekeeping are a fundamental part of good occupational hygiene practice, and contribute very significantly to the control of substances hazardous to health. Health and safety legislation reinforces the need for an adequate standard of cleanliness, and occupiers of premises subject to the Factories Act 1961 have a statutory duty to maintain their premises in a clean state. Although for other premises the Health and Safety at Work etc Act 1974 does not contain any similar specific requirement, the need to ensure an adequate standard of good housekeeping is implicit in the general responsibilities given to all employers.

Non-Ventilation Methods

The handling and use of process materials should be organised so as to avoid spillages and leaks, and where these do occur, they should be cleared up promptly and safely. Dry brushing of powdered and other particulate materials produces large clouds of airborne dust and should never be used to clean up spillages or settled dust. Carefully organised wet brushing can work well, however the best method of cleaning up dusty materials is to use a vacuum system - either a fixed installation with a number of suction points to which flexible hoses and nozzles may be fitted, or a mobile vacuum cleaner. Where dusts hazardous to health are handled, mobile vacuum cleaners should meet the type H specification of BS 5415 (1976 and 1985).

Figure 5.1
Plastic balls reduce evaporation from liquid surface
(photograph courtesy of Capricorn Chemicals Ltd, Stratford, London).

Other examples of process changes which can reduce air contaminant emissions and exposures are listed in Table 5.3.

Table 5.3

Changes of process which reduce airborne contaminants

1 Dry processes to wet processes

The addition of a small amount of water to foundry sand to suppress dust is well known. The use of oil or resin bound powders is a more recent example of the application of the same principle (RAPRA, 1979).

2 High uncontrolled temperatures to low controlled temperatures

Large soldering irons are often heated in gas furnaces. The temperature of the iron is uncontrolled and lead fume from the solder can be "significant", as defined in the Approved Code of Practice (HSE, 1985). Thermostatically controlled "electrical" irons result in considerable energy cost savings and cause little or no lead fume release.

3 Powder handling

General

(a) minimise and enclose height of powder fall
(b) shield powder from draughts during fall and when moving on conveyor system
(c) enclose conveyors and maintain slight negative pressure within the enclosure

Specific

(d) purchase or prepare standard, weighed amounts under ventilation control
(e) automate weighing/metering and feed direct from silos or hoppers
(f) purchase in or decant into rigid containers. This does away with the use of sacks within the factory area.

4 Liquid handling

An open process is changed to a closed process
Open pouring is changed to closed pumping
Open topped containers are replaced with containers by self-closing, close fitting tops
Manual liquid transfer is changed to automatic/semi automatic metered transfer

5 Spraying

Substitutes include: electrostatic spraying, airless spraying, dipping, and brush painting for small items.

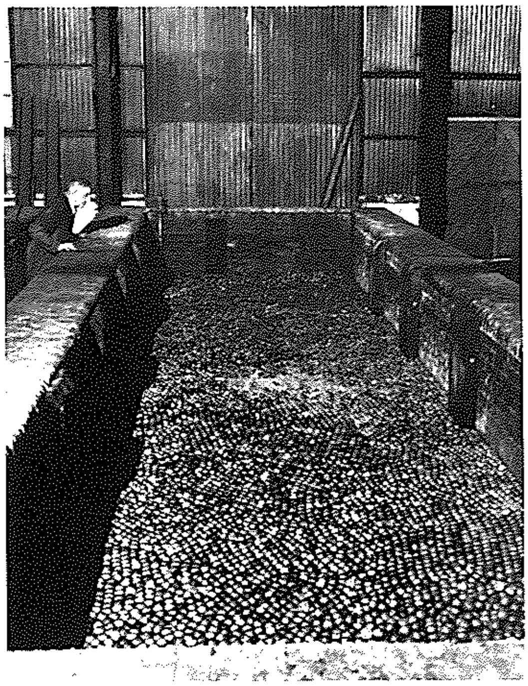

Figure 5.2
Plastic balls reduce mist formation in a metal treatment tank.

Non-Ventilation Methods

5.4 Changing Materials and Processes

Substitution of substances and processes have been covered separately. This separation in reality is artificial and, in many cases where non-ventilation methods of control are applied, a mix of the two approaches is used. Thus, if a substitute material or form of material is used, this usually affects processes downstream. For instance, if a pelletised or oil bound version of a powder is introduced, to reduce airborne dust exposure, prolonged, more vigorous or higher temperature mixing may be required to ensure as thorough a mix as occurred with the powder based material (RAPRA, 1979). These problems can often be anticipated in a qualitative way but the introduction of substitutes and their successful continued use will require persistence on the part of the hygienist and other staff. Another example, which illustrates the importance of combining and integrating process and material changes, is in the control of particulate emissions from welding processes. The possibilities for changes which would reduce fume production and in some cases improve weld quality have been reviewed by GRAY and HEWITT (1982).

5.5 Segregating High Release from Low Release Processes

It is often the case, especially in manufacturing industry, that processes at certain points in production are "dirtier" than others. For instance, powder may be unloaded and weighed or liquid may be decanted into a mixing vessel at the start of a production process. Heat may be applied at a later stage in production resulting in release of contaminant. Whatever the exact pattern of release may be, the physical separation (segregation) of dirty operations will at least ensure that the clean ones remain uncontaminated. This does not control the exposure of those involved in the "dirty" process, in fact segregation may reduce the natural air movement and increase exposure for those directly involved, but it does limit the movement of contaminant within the factory. Control by non-ventilation and ventilation methods can then be concentrated in the problem areas.

5.6 References

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6

THE COSTS OF VENTILATION

6.1 Energy and Cost Implications of Ventilation Systems

The energy required to provide ventilation can be divided into that required to overcome air friction in the hardware and that required to heat the replacement air, when air is discharged to the atmosphere. In most cases and at most times of the year the latter is far more costly.

The theoretical power required to overcome the frictional resistance of a ventilation system can be found by using the air power formula given in Section 10.4.2 and dividing that value by the efficiency of the fan. This gives the fan power which can be converted to cost figures by using the energy cost figures given in Table 6.1. As most fans are powered by electricity and normally run during peak electrical supply periods the costs per kilowatt hour for direct electricity should be used.

Table 6.1

Comparable energy costs (UK)

Energy Source	Estimated fuel cost per kWh (Jan 86) pence.	Approximate heating cost per kWh using the authors' estimation of conversion efficiencies (Jan '86) pence.
Electricity - direct	3.8	3.8
off peak	1.9	1.9
Oil - 35 sec	1.9	2.7
- 3500 sec	1.2	1.8
Gas - natural	1.3	2.0
propane	1.9	3.1
butane	1.8	3.0
Solid fuel - coal	0.18	1.7
- industrial coke	1.25	2.5

Example: A fan operating on a ventilation system is 70% efficient; it handles 2 m^3s^{-1} of air at a pressure of 1.5 kPa. What are its electrical running costs?

Air power = 2 x 1.5 3 kW
Fan power = 3/0.7 = 4.3 kW

Electrical cost per kWh from Table 6.1 is 3.80 p.

Thus for every hour the fan is run the power costs will be:

4.3 x 3.80 = 16.34 p

Assuming the fan is run for ten hours per day for 240 days per year the annual power cost will be:

240 x 10 x 16.34 = 39216 p or £392

Where extracted air is discarded to atmosphere the energy required to provide heated replacement air will depend upon the outside air temperature and the designed inside temperature. In Britain meteorological records are available for many sites from which average annual frequency of outside temperatures can be provided. Taken from the records of outside temperatures at Heathrow Airport averaged over the period 1949-1979 annual frequency of hourly values of dry bulb air temperature are given for a typical South of England site in Figure 6.1.

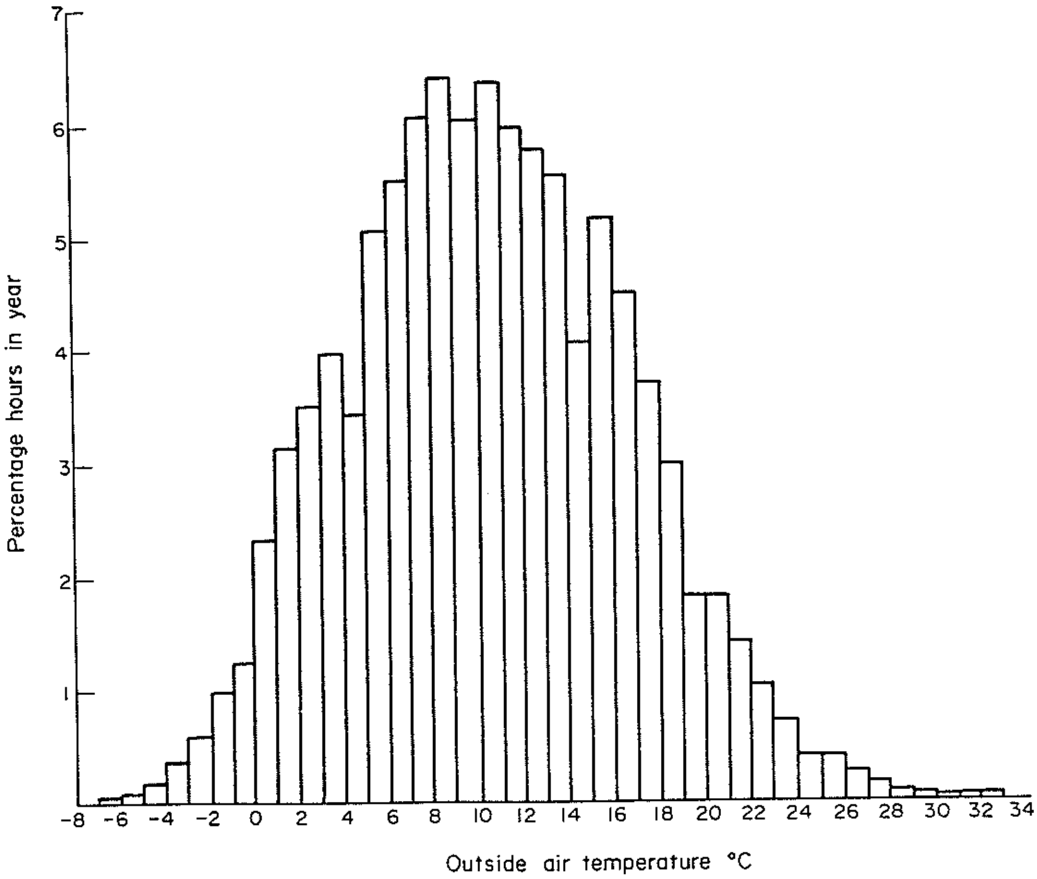

Figure 6.1
Annual frequency of occurrence of hourly values of air dry bulb temperature (°C) at London Airport (Heathrow) (1949-1976).

From Figure 6.1 it can be deduced that the percentage of time in an average year when air temperature is between 0°C and 1°C is 2.25% which represents 197 hours. From the diagram in Figure 6.2 the heating power required to raise 1 m^3s from a given outside air temperature to a given inside temperature can be obtained by reading on the left hand ordinate the power corresponding to the intersection of a vertical line representing outside air temperature and an inclined line representing inside air temperature.

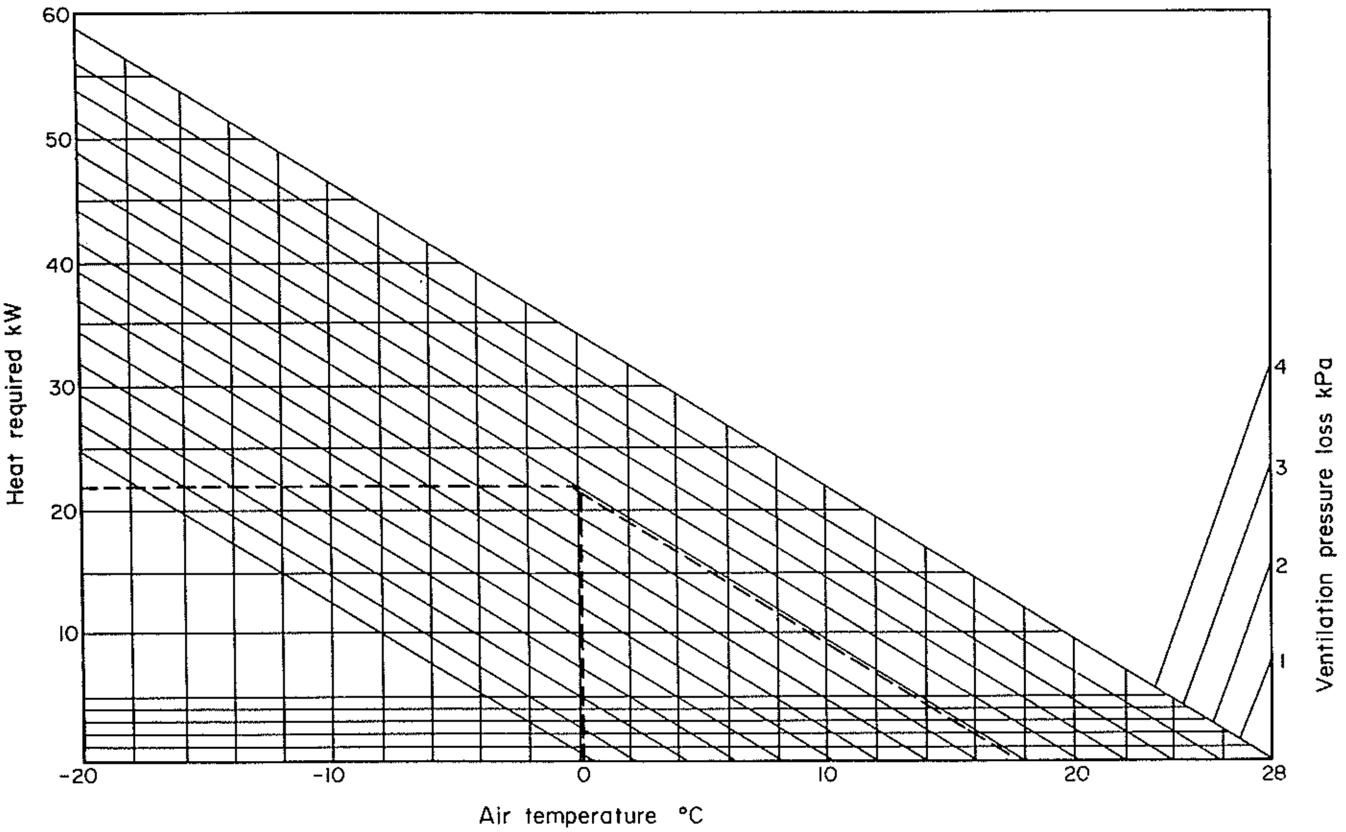

Figure 6.2
Chart for estimating energy requirements for heating and moving 1 m^3s^{-1}.

Example: the heat required to raise outside air at 0°C to inside at 18°C can be read as 22.5 kW as shown in the broken lines on the diagram. Thus in one year the energy required to raise the air from 0°C to 18°C is:

22.5 x 197 = 4432 kWh

This exercise can be repeated for each one degree increment of outside air temperature throughout a typical year using a range of outside temperatures from say -6°C to 18°C.

Using this method of calculation typical heating requirements for discarding 1 m^3s^{-1} of air are given below:

Intermittent running (10 hours per day, 240 days per year): 23500 kWh

Continuous running (24 hours per day, 365 days per year): 86000 kWh.

Costs

The costs of providing this heating load will depend upon the type of fuel used for the space heating of the building and the tariff that the owner has agreed with his fuel supplier. Some typical fuel costs are given in Table 6.1 from which an estimate can be obtained.

Examples: intermittent running, fuel: 35 s oil, £940 per annum
coal, £400 per annum

Continuous running, fuel: natural gas, £1720 per annum
coke £2150 per annum

6.2 Capital Costs of Exhaust Ventilation Systems*

6.2.1 Introduction

The capital expenditure involved in the provision of an adequate extraction system is dependent upon a number of variables.

This section describes the significant cost items which need to be included, and, where possible, relates them to the volume of air moved per unit time. In all cases SI units have been used, but it should be noted that the majority of equipment manufacturers still employ Imperial units (see Appendix on Units of Measurement).

Each of the main components of a system is discussed separately, likely cost boundaries are provided, and the limitations identified. Hence, for any specified air flow and filter requirement, the formulae and graphs may be used to build up a cost figure and a worked example is included in explanation. A number of systems are included as examples, together with their estimated costs.

The approach adopted was to acquire "real" data from manufacturers, fabricators, installers and suppliers. Considerable difficulty was encountered when attempting to obtain sufficient data to ensure reliable cost models. Therefore the cost information in this section should be regarded as indicative of only the order of cost likely to be encountered for this type of work. A comprehensive source of costs will be published by HSE in the near future.

The type of installations to which the costs in this section apply are either those to be provided for an existing building or those to be provided for a new building but by a separate extraction contractor. These small scale separate contracts differ significantly in price level and structure from those where the extraction system is part of a complete heating and ventilation installation for a new building, or those where specialist systems such as high velocity, low volume extraction have been specified.

It appears, therefore, that there is no established market for the small scale work covered by this type of installation and hence the normally accepted building price books are not directly applicable.

6.2.2 Fans and Air Cleaners

In industrial extract systems the requirement for an air mover is esential unless the air has sufficient buoyancy to rise through a vertical system unaided. That mover is normally a fan although compressed air or steam jets can be used in low resistance systems. Fans can either be installed alone or as an integral part of a filter unit.

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* The research on which this section is based was done by Keith Chapman and Neil Trowbridge from the Surveying Department of Portsmouth Polytechnic.

Costs

Some typical fan costs are given in Tables 6.2 and 6.3.

Table 6.2

Axial flow fans, single stage including motor and starter

Fan dia mm	300	500	750	1200
Fan duty m^3s^{-1}	0.5	2.0	2.3	5.5
Pressure (Pa)	150	500	150	250
Speed (rs^{-1})	47	48	16	12
Cost (£)	370	560	660	1275

Table 6.3

Centrifugal fans including motor, starter and V-belt drive

Fan duty m^3s^{-1}	2.5	5.0	10.0	15.0
Pressure (Pa)	700	725	800	850
Speed (rs^{-1})	28	18	12	10
Cost (£)	1000	1570	4200	6000

Air Cleaners

Information is given for the following types of dust collector all of which incorporate a fan.

Small fabric filter - Figure 6.3
Fabric filter - Figure 6.4
Low voltage electrostatic precipitator - Figure 6.5
Cyclone - Figure 6.6
Reverse jet fabric filter - Figures 6.7 and 6.8

It should be noted that costs increase as the filter efficiency required increases. However, it appears that there is a large variation in cost for devices of similar order of efficiency or type, but of different design.

It is also important to realise that the efficiency required determines to a large extent the type of equipment. Thus fabric filters only become competitive when high efficiencies are required.

6.2.3 Ducting

The fabrication and installation of most extract ventilation systems appear generally to be undertaken by small contractors, in many cases with working proprietors, who are often involved in general sheet metal work. The opportunity for the establishment of reliable market controlled price levels is therefore limited. The resulting erratic price structure causes significant difficulty in identifying dependable cost data.

The disparity between the firms involved in ductwork of this type and those concerned with substantial mechanical and electrical installations such as heating, ventilating, air conditioning, refrigeration, etc renders invalid the application of much widely available published data (eg Spon's and similar building industry price books).

Figures 6.9 and 6.10 provide the "best estimate" and can only give a general guideline to expected costs.

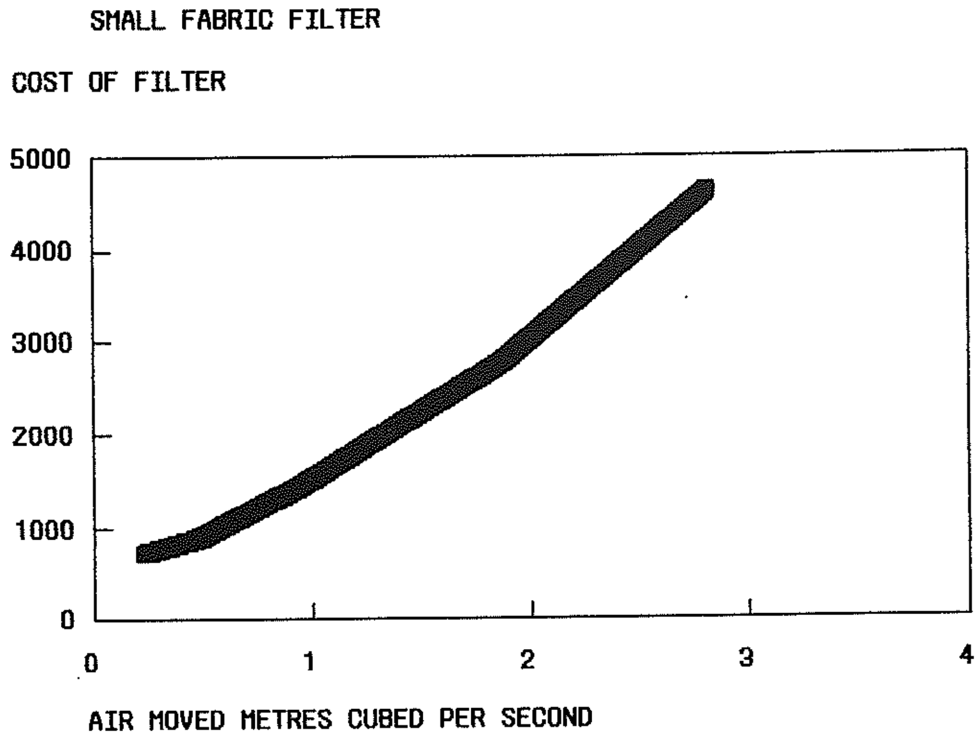


Figure 6.3
Small fabric filter.

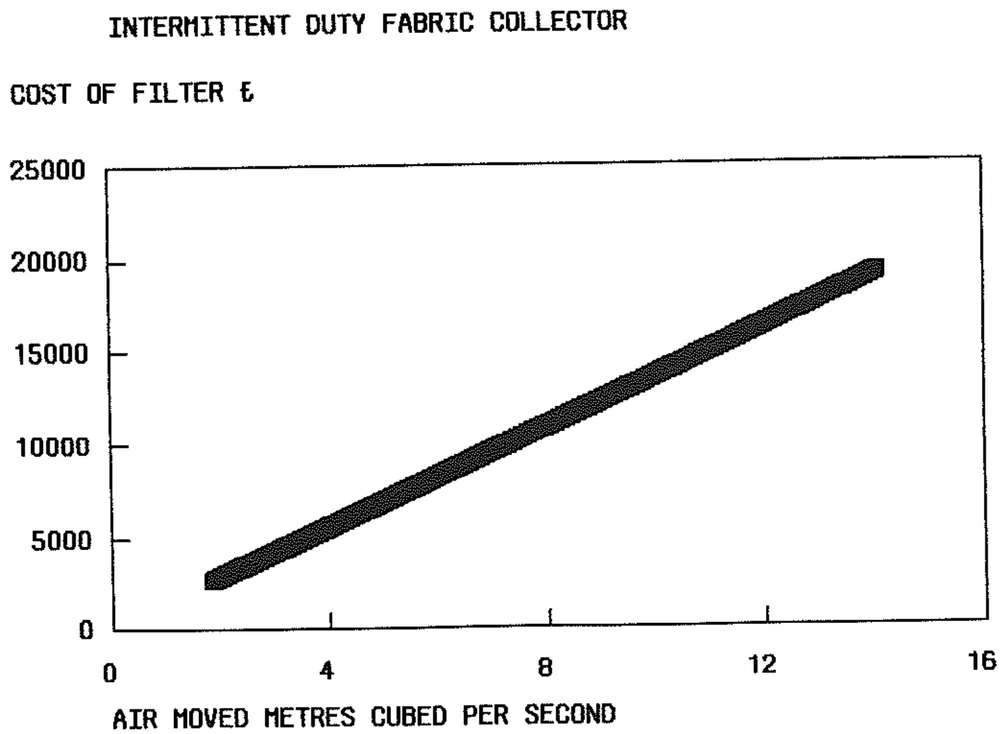


Figure 6.4
Intermittent duty fabric collector.

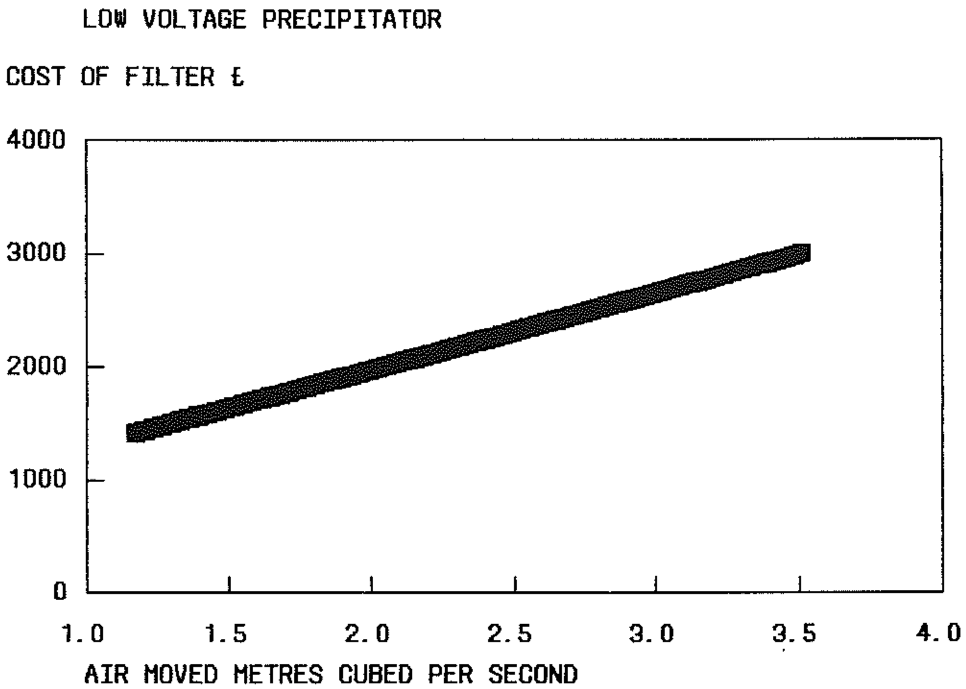


Figure 6.5
Low voltage precipitator.

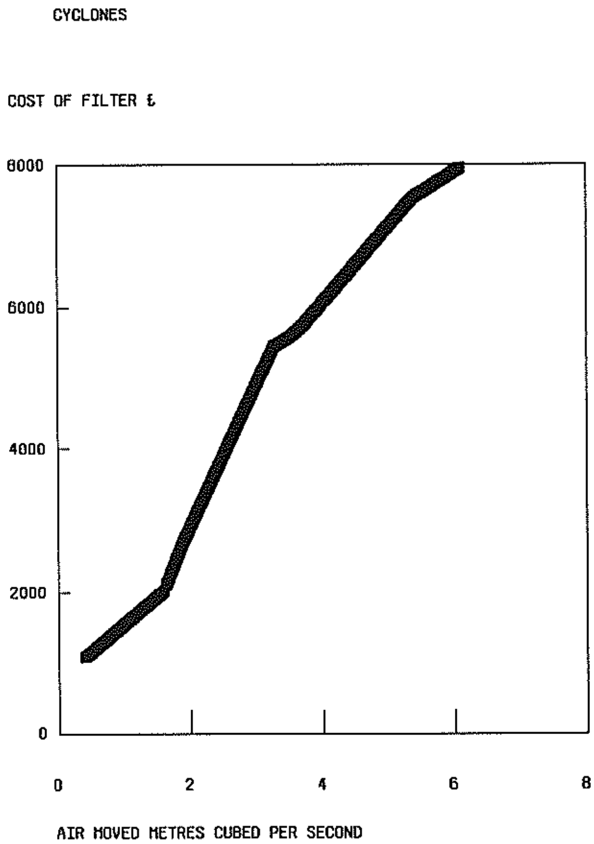


Figure 6.6
Cyclone.

Costs

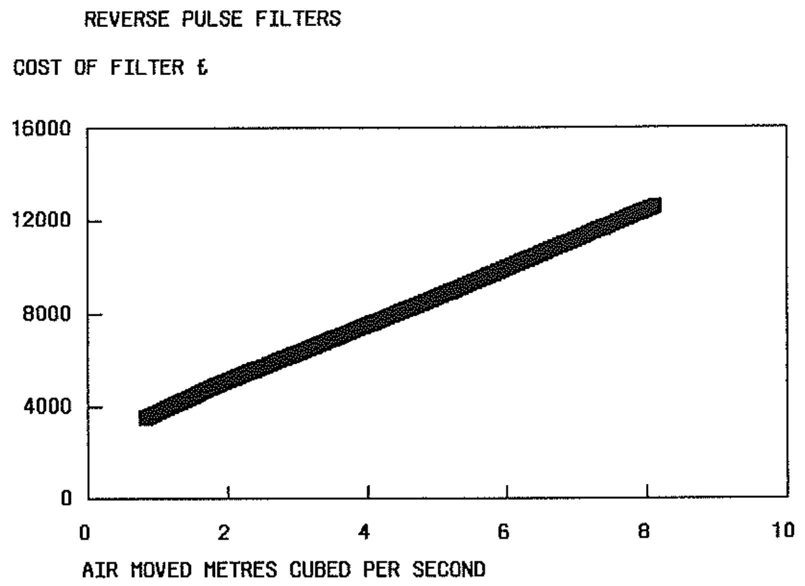
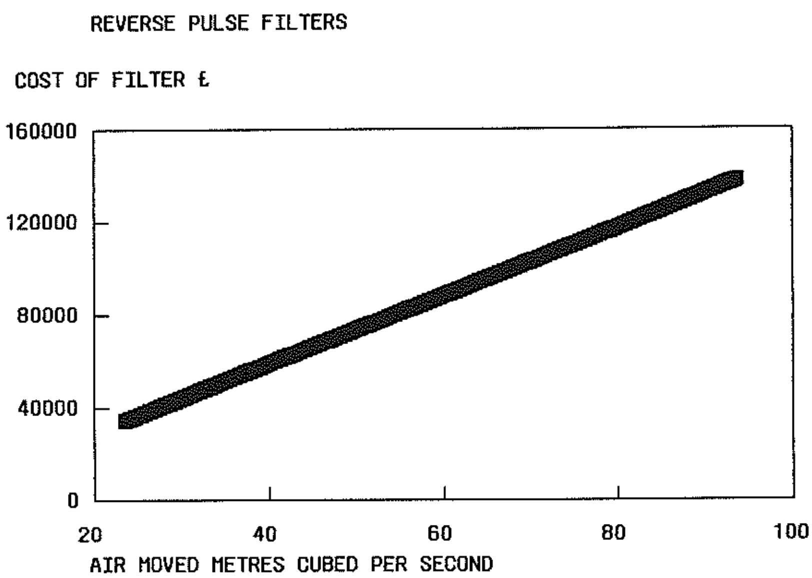


Figure 6.7
Reverse pulse filter.



THESE COSTS EXCLUDE FANS & THEIR ASSOCIATED PRICES

Figure 6.8
Reverse pulse filter.

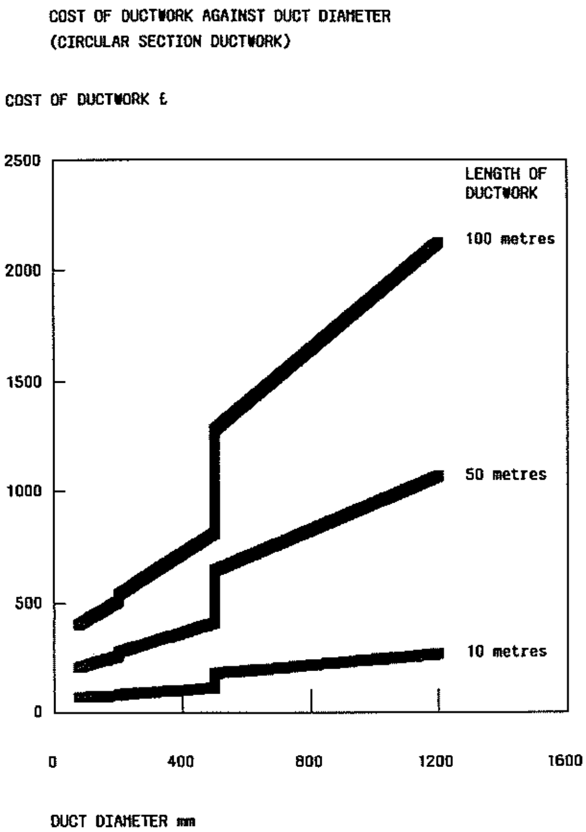


Figure 6.9
Cost of Ductwork (£)

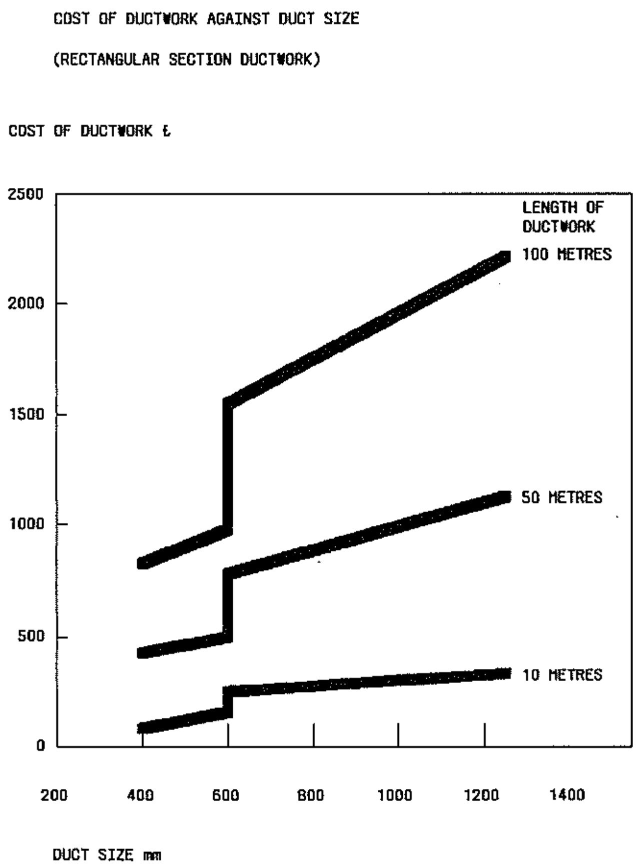


Figure 6.10
Cost of Ductwork (£)

6.2.4 Hoods, canopies and enclosures

In this case the primary cost determinant is not the volume of air shifted but the type of intake facility required, which in turn is primarily dependent upon the process to be ventilated and its location (ie floor mounted, roof intake, bench mounted etc).

The possibilities vary considerably, ranging from simple duct gratings, through a wide variety of hood forms to full scale booths which totally enclose the process and operators. Accordingly, costs can vary from an insignificant proportion to 50% or more of total system costs for specially designed hoods.

An indication of possible cost levels for two fairly common hood forms is provided below.

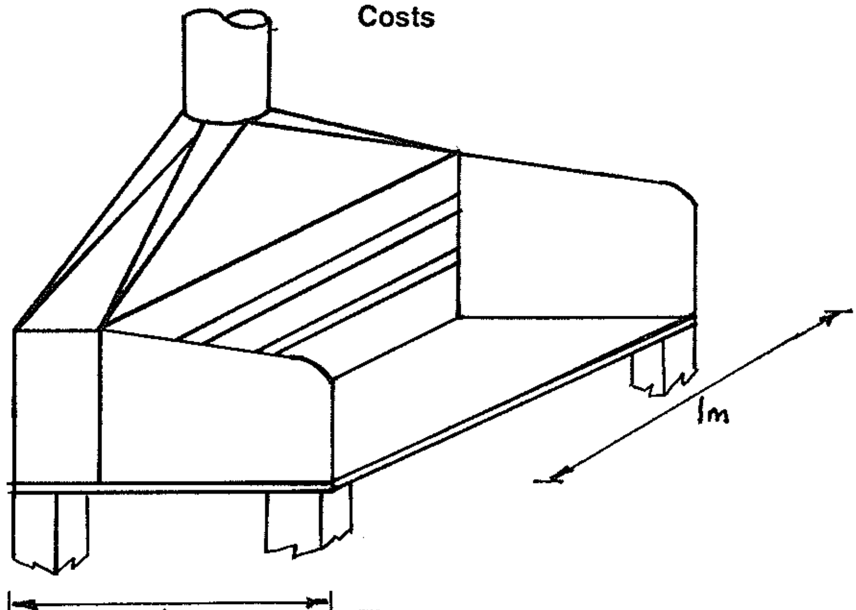


Figure 6.11
Approximate cost (excluding bench) work surface and ducting = £300.

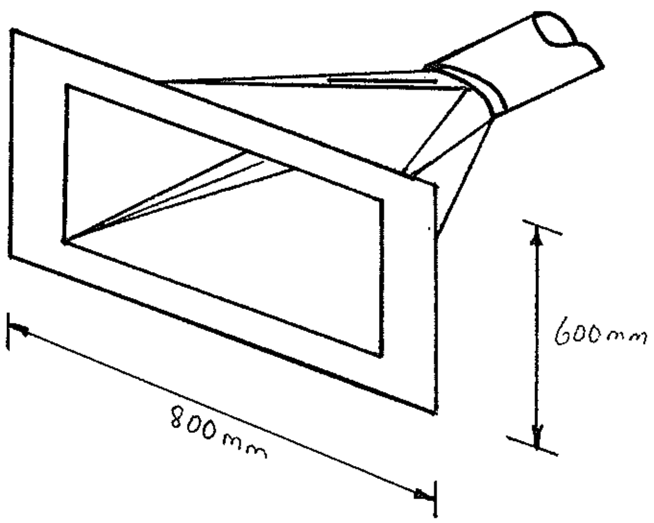


Figure 6.12
Approximate cost (excluding ducting) = £150.

6.2.5 Installation and design

The costs in the preceding sub-sections are exclusive of installation and design.

The most significant factors in respect of installation costs are the extent and complexity of the ductwork system together with the ease of access to ductwork locations. As a very general guide, where systems are straightforward the following allowances might be made:

Ductwork Cost £	Allowance £
< 1000	250
1000-2500	500
> 2500	20% of ductwork costs

In the case of simple installations, it is common for the design of the system to be undertaken by the fabrication and installation contractor, and the guide costs given above allow for this situation. However, for the more complex or critical systems it is necessary to employ design consultants. Here design costs can be a very considerable factor and, together with the relatively high level of consultant's fees, could result in design costs exceeding the cost of ductwork and hood fabrication and installation.

6.2.6 On-costs and price levels

The cost information given in the above sub-section excludes any provision for the contractor's profits, general overheads and site establishment costs. The prices charged by contractors to cover these costs vary considerably depending upon such matters as the extent of the work, whether it is part of more substantial mechanical engineering works, the operational complexity of the work, location of the works relative to the contractor's base, duration of the works and, perhaps above all, the competitiveness of the market for that type of work in the contractor's area of operation at the time.

The effect of these matters is likely to be an addition of anything between 5% and 40% - but as a very general guide it is suggested that where no particular difficulties are envisaged an allowance of 15% would be appropriate.

The cost information given in this section reflects price levels in mid 1985 for work in densely populated areas of the United Kingdom, outside London.

With regard to location in the United Kingdom, at the time of writing perhaps 20% would need to be added for Central London, and price levels for work of this kind in remote areas would be critically dependent upon the particular circumstances.

There are several indices published which provide a mechanism for updating costs in the field of mechanical services. Two are:

1 Mechanical Engineering Cost Index of the Building Cost Information Services (available to subscribers).

2 Spon's Mechanical Services Cost Indices in Spon's Mechanical and Electrical Services Price Book 1986, E & FN Spon, 11 New Fetter Lane, London, EC4P 4EE.

Example

6.2.7 A worked example

An extraction system is required for a woodworking shop having six extract hoods. The basic requirements are as follows: total volume flow rate 2.2 m^3/s through a single cyclone dust collector, with a total duct run of 80 m, and required transport velocity of 17.5 m/s.

Calculation

$$\text{Required duct cross sectional area} = \frac{2.2}{17.5} = 0.125\ m^2$$

this corresponds to a duct diameter of 400 mm.

Application of graphs

Reference should be made to Section 6.2.3 to find out the capital cost of the ductwork.

Costs

An 80 m length of 400 mm dia duct (Figure 6.9)	600
Six simple hoods at 150	900
Cyclone dust collector (Figure 6.6)	3000
Installation	1000
Total	5500
plus 15% on costs	825
Grand total	6325

6.2.8 The capital cost of some typical industrial extraction systems

1 Multiple hood extract system for rod welding at 10 work stations

Assume 5 bench units with flanged slot hoods, each extracting 0.5 m^3/s, and 5 floor units with the same extract rate, comprising 5 m flexible hoses dropping from duct run in roofspace to simple tapered hood ends.

Centrifugal fan (about 5 m^3/s) in roof space discharging to open air through drain-type stack. Total duct run 100 m.

£14,500

2 Multiple point extract for car service area

Assume an 8 point underfloor system, but cost ventilation system only. Flow at each point to be 0.05 m^3/s, centrifugal fan at floor level discharging direct to outside with 5 m high stack. Total duct run 50 m.

£3,000

3 Woodworking shop

Assume following equipment:

1 bandsaw	0.5 m^3/s
2 router/planers	0.25 each
1 disc sander	0.25
1 horizontal belt sander	0.5
1 circular saw	0.25

Total extract 2.0 m^3/s by centrifugal fan through chiptraps on machines and single cyclone before fan; discharge to open air through 3 m stack. Total duct run 80 m.

£5,500

4 Paint spraying section

Assume 1 large booth with face opening 10 m^2, airflow to be 5 m^3s^{-1}. Also 5 small booths, each with face opening of 2 m^3s^{-1}, airflow for each 1.5 m^3s^{-1}. 10 m ducting, with wet centrifugal collector discharging at height of 5 m. Include cost of system to supply warmed make-up air with same flowrate.

£9,900

6.3 Cost Saving Method

There is a variety of ways by which the overall costs of exhaust ventilation systems can be reduced. They are dealt with below under six separate headings but in reality the hygienist or other practitioner would attempt to apply a combination of methods.

6.3.1 Non-ventilation methods

Some of the options available have been covered in Chapter 5. If the size or number of sources of contaminant can be reduced then the size of exhaust ventilation plant required to control the residual emissions can also be reduced with concomittent capital and running cost savings. As was emphasised in Chapters 4 and 5 it is well worth spending time applying or experimenting with non-ventilation methods of control before considering the type and size of exhaust ventilation system required.

6.3.2 Design

A well designed exhaust ventilation system which adequately controls exposure using the minimum amount of air necessary will be smaller and have a lower volumetric flow rate than a badly designed system; it will probably be cheaper to buy and certainly will be cheaper to run. The basics of good design are covered in Chapters 4 and 10 and a few additional points are listed below in Table 6.4. Also, some of the design features which can be incorporated to minimise the volume flowrate and some of the problems which can occur when redesigning existing systems are reviewed by GILL (1980).

Table 6.4

Some good design features

(i) Hoods should be close to and surround sources as much as possible, (enclosure or receptor hoods are far more effective than captor hoods, Section 8.7).

(ii) Design should take account of, and use if possible, process induced airflow.

(iii) All ductwork runs should be designed to reduce friction losses to a minimum (ie avoid sharp bends and sudden contractions or expansions in section).

(iv) Ductwork material and thickness should be designed for anticipated duty.

(v) Air cleaner should be the appropriate type and size.

(vi) All components, hoods, ductwork and aircleaners should be designed for ease of inspection and maintenance.

6.3.3 Variable extract requirement

It is often the case, especially where a large number of identical processes are served by a multibranch system, that only a proportion of the processes are being run at any one time. Usually the exhaust ventilation system is sized to provide an adequate airflow rate for all the hoods in the system assuming they will all be required. A considerable running cost saving can be made if the system is designed to have a variable volumetric flow rate and to be responsive to the number of work stations requiring exhaust ventilation. The designer needs to determine the number of hoods required (average and maximum) and devise some method of sensing that a particular work station is in use and requires exhaust ventilation. One method is to link the hood duct damper to the process with a delayed over-run to deal with residual contaminant, (WORWOOD, 1986). Another method has been developed for a soldering operation (ASKER-BROWNE and ALESBURY, 1986). In this case the work was skilled and fastidious and required good lighting. A small spotlight was attached to a movable captor hood and the light switch was connected in turn to a pneumatic damper. When the light was switched on the damper opened.

Variable flowrate systems are smaller in size than conventional systems but are probably more expensive because of the additional cost of a variable speed fan, powered dampers and the associated controls and sensors. However, the running costs of such systems can be significantly lower.

6.3.4 Cyclical processes

Many processes particularly in manufacturing industry are cyclical and emit contaminants only at certain times in the operating cycle. If the times and periods over which contaminants are released in quantity are known then the extract system can be synchronised with these periods. As with the option discussed in Section 6.3.3 there will always need for some extraction applied to deal with residual escape of contaminant. Car tyre curing presses are a case in point and a flexible exhaust ventilation system for a group of tyre presses has been developed and described by WORWOOD (1986). Cold rubber tyres are heated under pressure in a closed mould for a given period after which time the cured tyre is removed. It is only during the period when the rubber is hot and exposed to the air that hot rubber fume is evolved. Worwood found in a group of 16 presses there were periods when none of them were open and that the maximum number open at any one time was ten. Applying the extraction only when it was needed and using a variable speed fan to cope with the variable demand Worwood found that with a group of 50 presses which had a designed extract requirement of 25 m^3s^{-1} the worst case mean volume flow rate was 10.5 m^3s^{-1}, less than 50% of the flow rate originally planned. This approach could be applied to many cyclical processes. However a note of warning should be sounded. To apply the approach effectively it is important to identify correctly the periods during which contaminants are released and not to reduce the extract rate until contaminant evolution has ceased. Also the system should be designed to fail to safety, ie if a sensor or timer fails the extract to a particular process should then run continuously and not simply stop. It may also be advisable to have a manual over-ride to allow continuous running to deal with contingencies.

6.3.5 Heat Recovery

It is sometimes possible to recover some of the heat in the exhaust air discharged from the building if there is a sufficient temperature difference between the outside and exhaust air and the exhaust volume makes the capital outlay economic. The subject has been reviewed by GILL (1980). He considered that none of the techniques could be considered until temperature differences of at least 20^oC were present. The options available include, the thermal wheel, heat pipes, parallel plate heat-exchangers and run-round coils. None are likely to be cost effective at present for the majority of systems because exhausted air usually contains low grade heat and the volumes involved are relatively small. Processes which create large volumes of hot air such as metal smelting and glass manufacture are obvious candidates. To decide on whether the technique is economic the Chartered Institute of Building Services (CIBS) recommend the "Accumulated Cost" method of comparison (CIBS, 1977). In this method the operating costs which include power, maintenance and replacements, interest charges and administrative and anciliary costs over the life of the plant (or at least the first 10 or so years) are added to the capital costs. These costs then need to be compared with the projected heating cost savings over the same period.

6.3.6 Recirculation

Figure 6.13 shows the basic components of a recirculation system.

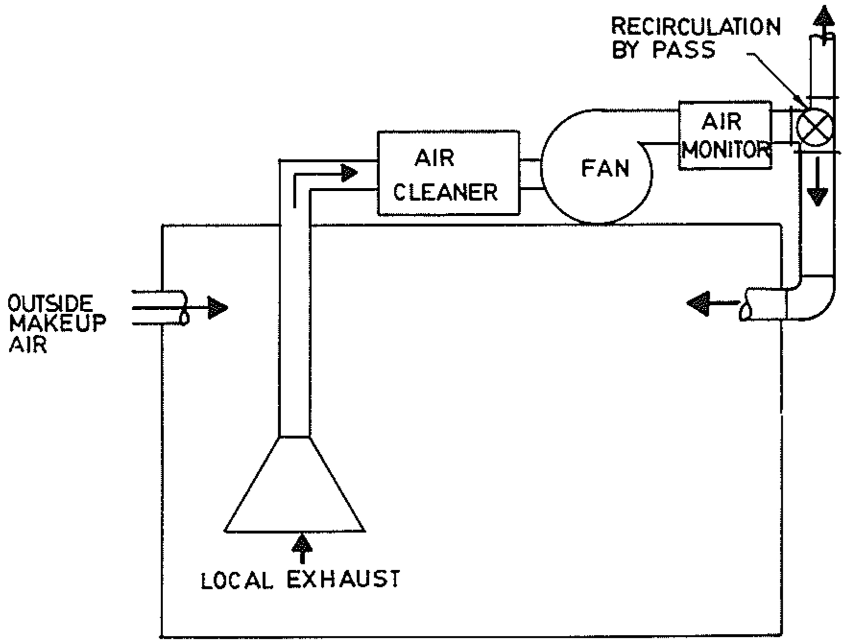


Figure 6.13
The basic components of a recirculation system (taken from GOODFELLOW, 1985).

Recirculation offers the promise of considerable running cost savings. Whether it is technically viable depends upon the type and quantity of the contaminants which need to be filtered from the exhaust air stream. And whether it is financially viable depends upon the additional capital cost balanced against the savings in heating or (in hot climates) cooling costs.

To use recirculation safely various questions need to be answered:

(i) Are the types and quantities of contaminant known?
(ii) Do suitable air cleaners exist?
(iii) Does reliable air monitoring equipment exist?
(iv) How likely is it that the system, particularly the monitoring equipment, will be inspected, tested and maintained?

In designing any exhaust ventilation system the hygienist needs a good knowledge of the process. This is particularly so when a recirculation system is being considered. If the contaminant is an aerosol there are a variety of air cleaners available. Cyclones are not efficient enough and wet collectors produce humid air and are costly. Fabric filters and electro-static precipitators can be suitable. They must be of very high efficiency. If the contaminant contains significant quantities of gas or vapour adsorbers (usually charcoal) are a possibility but they have limited capacity and with incinerators humidity is again a problem. Also, both options are expensive. Thus it is usually only technically and financially viable to recirculate air where the principle contaminant is an aerosol.

Costs

The most important component in the system is the air monitor. This can either detect the contaminant directly in the air stream from the air cleaner or, where the contaminant is an aerosol, a very high efficiency fabric filter can be used. In this case the pressure drop across the filter is measured. In both cases the air monitor is used to control the amount of air recirculated back into the workplace. Whatever method of monitoring is chosen it must be robust and reliable. If it fails it must do so safely, eg exhaust air is no longer recycled but the by-pass opens (Figure 6.13) and contaminated air is vented outside the building.

Once the designer has information on the type and quantity of contaminant, the efficiency of the proposed air cleaner and additional data on other sources of ventilation, he or she should construct a simple mathematical model of the workplace and roughly determine the exposure of the workforce. HUGHES and AMENDOLA (1982) put forward a simple model and NAYAK et al (1978) have developed a more complex model which takes into account other exhaust ventilation systems and the effects of general ventilation (both natural and powered).

Well designed, built and maintained recirculation systems exist. They save considerable air heating or cooling costs while maintaining worker exposure at what are regarded as acceptable levels. However the decision to install a system should not simply be driven by commercial criteria. The technical feasibility of the system should be evaluated first. Crucially important are whether air cleaners and air monitors of sufficient reliability exist. More important still is the answer to the question: Will the system be inspected, tested and maintained?

6.4 References

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WORWOOD, J.A., (1986), The application of methods of control and sizing for increased energy efficiency in local exhaust ventilation systems in the rubber industry. 5th International Environment and Safety Conference. September 1985. IES Ltd, Newgate, Sandpit Lane, St Albans, Herts, AL4 OBS.

7

ENCLOSURES AND OTHER RECEIVING HOODS

There are many types of enclosures used to control contaminants by various sections of industry, ranging from the use of completely gas-tight systems, working at high pressure or under a vacuum, to light-weight flexible covers used in conjunction with a small exhaust system to maintain an inward air-flow through any small apertures. The term may also be extended to embrace the many types of booth that are widely used.

7.1 Total Enclosures

This type of enclosure is completely air or gas tight and can therefore provide complete protection. While such enclosures are not commonly used for contaminant control in industry in general, they are widely used both in the chemical industry and where radioactive materials are handled. If the enclosure is relied upon as the only method of control, it must be strong enough to remain dust or gas tight under all conditions of working unless proper provision is made to vent or release any excess pressure safely. Venting is usually to another vessel or via a filter or scrubber to a vent stack. If there is any possibility of flammable or explosive concentrations developing then it is essential that effective methods of protection or suppression should be installed unless the containment is strong enough to resist the high pressures that may develop.

The concentration of hazardous material inside the enclosure may be very high and proper provision must be made to clean, purge and test the enclosure before there is any attempt to enter for any purpose.

Alternatively entry should only be made by persons wearing suitable and effective personal protective equipment under close supervision. This is of particular importance where process machinery is installed in the enclosure. Under these conditions plant may become heavily contaminated and the concentration of dangerous contaminants within the enclosure may be much greater than when plant is operated in the open workshop. Production or maintenance staff must not be allowed to enter to check operations or to make small adjustments without proper precautions having been observed.

7.2 Partial Enclosures

A partial enclosure has openings for the entry and egress of materials. Enclosures are widely used in conjunction with an exhaust system and can be a most effective means of control. An enclosure is also, in many instances, an economic system as it does not usually have to be as substantial as is required for total enclosure and the exhaust system can be of modest proportion if the openings in the enclosure are kept as small as practicable.

Enclosures

It has been demonstrated that the fitting of flexible rubberised covers to all the conveying, crushing and screening plant of a quarry, together with a modest amount of exhaust ventilation, enabled better control to be achieved than was practicable by exhaust ventilation using the captor principle alone and there are many instances where the fitting of a simple lid to a melting pot or heated vessel has transformed a difficult situation.

The amount of exhaust air that is needed for any particular enclosure will depend on the total area of all the openings into the enclosure and on the velocity of the entering air. With most enclosures it is also necessary to make an allowance for the leakage which normally occurs through covers, light-weight flanges and joints in the enclosure, thus for instance (HERIOT, 1980) recommends 10^{-3} m^3s^{-1} for each metre of flanged joint on a bucket conveyor.

The velocity of the air entering the openings must be such that it will overcome any tendency for the contaminated air inside to escape. This tendency is influenced by many conditions both inside and outside the enclosure. Moving machinery, the operation of controls and the handling of material may all create turbulence within the enclosure, whilst the generation of heat may produce convection currents, all of which may cause contaminants to be forced out of the enclosure. Outside the enclosure, air movements caused by draughts, the passage of transport and even by people walking past or working close to an opening, have been found to draw contaminated air out of an enclosure. To ensure effective control, the entering air must, therefore, overcome all these other air movements and maintain an inward flow under all conditions of working. For this reason it is difficult to define a single velocity that is suitable in all cases and it is therefore essential that careful investigation of the local conditions in the vicinity of any hood should be made.

In quiet conditions where there is little air movement an inward air velocity of 0.5 ms^{-1} may suffice but in more difficult circumstances 2 ms^{-1} or more may be needed. In many normal working conditions in factories a velocity of 1 ms^{-1} is often used.

When a suitable air velocity has been established and the area of the openings in the enclosure has been reduced to the practical minimum the volume of air to be extracted can be determined by multiplying the total area of the openings by the air velocity:

$$Q = AV$$

where
Q = Air volume m^3s^{-1}
A = Area of opening m^2
V = Air velocity ms^{-1}

While an enclosure must be large enough to accommodate all the contaminant producing processes, it should not be made any larger than is necessary for proper working; a close enclosure around the working parts is always likely to provide better control, and be cheaper, than a large enclosure.

7.2.1 Booths

Booths may be considered as a particular form of partial enclosure from which one wall or a part of a wall has been removed. The contaminant is either released within the booth (eg fumecupboards) or is propelled into it from a source close by (eg in paint spraying booths or canopy hoods over hot processes) (Figure 7.1). Although booths are widely used throughout industry as a means of control of many different sorts of pollution they are generally less effective than the use of an enclosure. While, with good design and careful operation, they can be made to give reasonable control of a contaminant, in practice it is found that problems can arise in operation.

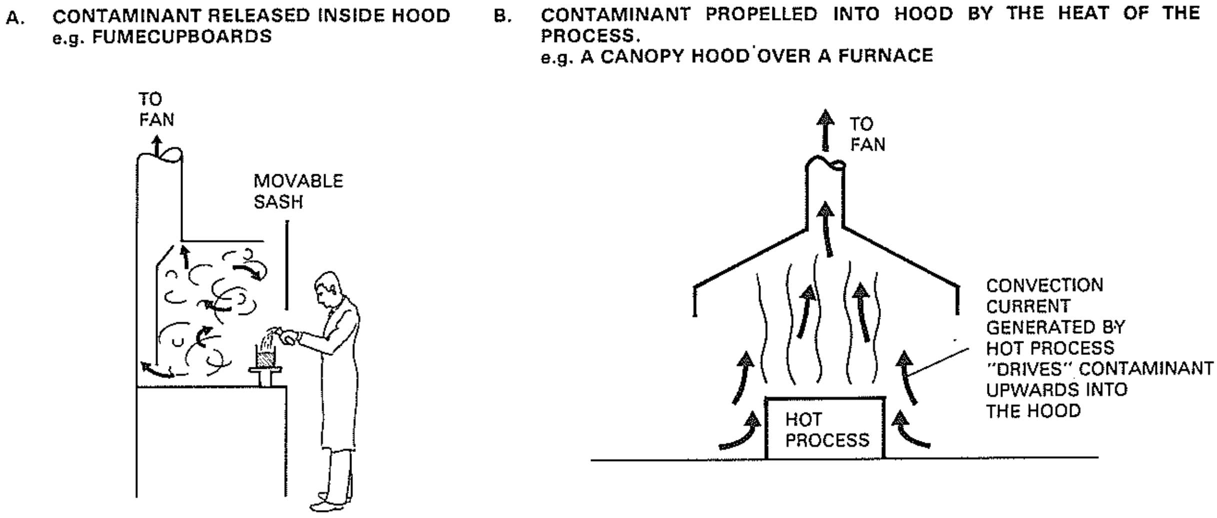

Figure 7.1
Examples of partial enclosures or receptor hoods.

The problems that occur are often due to turbulence generated either within or outside the booth and causing contaminated air to spill or leak out of the enclosure. For a booth to provide effective control the inward air-flow must be such that the contaminant produced is drawn away from an operator and not allowed to escape. Where the contaminant is produced at a high velocity, such as when paint or glazes are being sprayed, then the air velocity at the face of the booth must be high enough to overcome the movement produced by the spray and also to prevent particles or globules rebounding and escaping from the booth. These high face velocities can themselves cause problems by generating eddies in the corners of the booth and also around the operator, resulting in leakage.

With all booths it is important to obtain an even and stable air-flow over the whole open face of the booth. Various methods can be used to produce an even air-flow pattern such as by making the booth considerably deeper than it is wide and high, by making multiple extract connections to the booth, by the provision of long slotted outlet connections, or by the use of a plenum chamber at the rear of the booth with a perforated plate covering the whole of the rear of the booth. This latter method is the basis of the so-called "laminar-flow" booth that has been designed for certain operations. (HERIOT and WILKINSON, 1979).

When a booth is large enough for an operator to enter it is clearly important that he or she should never be between the work and the air exhaust apertures. If this occurs then the operator will be standing in the polluted air stream as it moves towards the exhaust duct (unless the booth is of the closed type with a vertical downflow ventilation system as described by CORNU et al, 1986). It is found in practice, however, that operators often inadvertantly do just this as they move around the job for ease of working or so as to do the work properly. A useful method of encouraging an operator to remain in the correct position is to provide a turn-table or jig that enables the work to be placed in the best working position without the need for the operator to move into an unsafe position. It is also important to provide adequate handling facilities to enable the work to be moved into and taken out of the booth easily and to provide good lighting for the operator to see his or her task. If either of these are neglected the work will inevitably be done outside the booth, and away from the influence of the air extraction system. Finally, problems can occur because of turbulence generated by the workers own body.

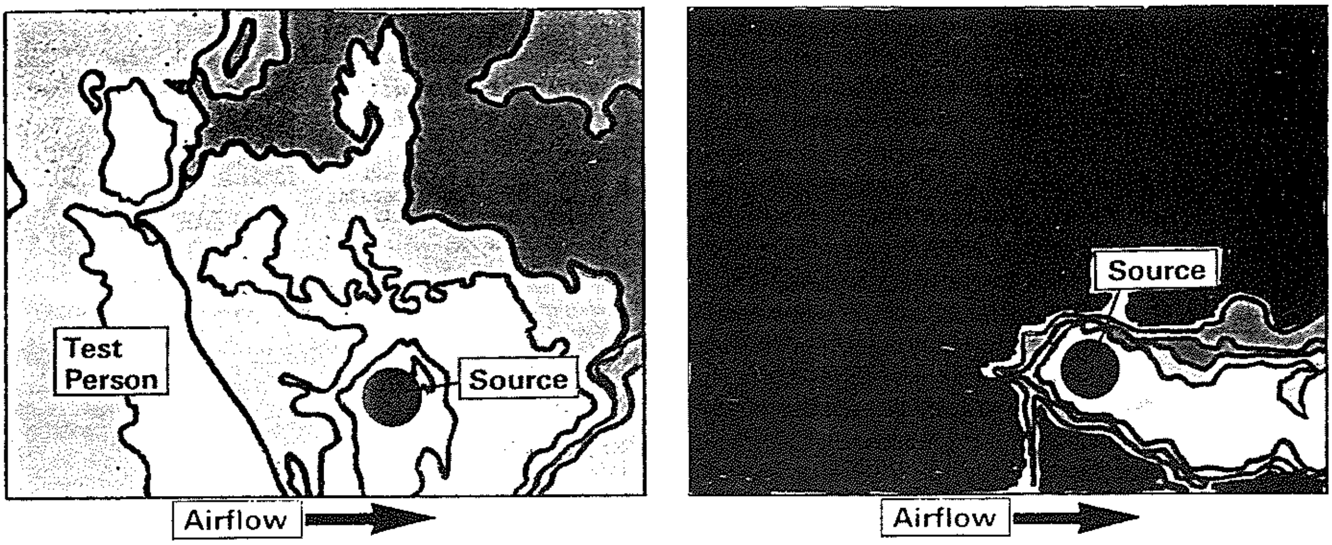

Figure 7.2
Infra red photography of the dispersal of gas from a small source in a unidirectional airflow shows the effect of a person standing upstream and close to the source.
(Based on Allander and Ljungqvist, 1979).

A turbulent wake exists in front of a person standing at a ventilation booth (rear outlet). If the person works close to the source, contaminant will be trapped in the wake which may extend to the breathing zone. Booth effectiveness is often reduced by this phenomenon. Solutions to this problem include: (1) a partial barrier between the worker's face and the source. (2) increasing the distance between the worker and the source. (3) in the case of large booths, a smooth airflow in the booth with the worker standing side-on to the air flow works well.

7.3 Laboratory Fume Cupboards

A fume cupboard is a special type of partial enclosure that has been developed for a particular purpose with many variations on the basic design for special uses. In general, a fume cupboard is an open fronted booth fitted with a vertically sliding window or sash. The sash is opened while equipment is being set up in the cupboard and then lowered to some extent when the apparatus is being operated and when contaminants may be produced. Air is usually extracted from the top or back of the cupboard and a baffle is fitted so that some of the air is drawn from the top and some from near the bottom of the cupboard. In some designs a by-pass is incorporated in an endeavour to maintain a reasonably balanced air-flow when the sash is open or closed. Side fairings and a curved sill may also be used to help in maintaining a stable air-flow through the open face.

A great deal of work has been carried out to improve the performance of these cupboards but problems can still arise.

The BOHS report and the draft British Standard should be studied in detail before designing, purchasing or installing these cupboards. (BOHS 1975, BSI 1982, see also HUGHES 1980, PINEY and CARROLL 1983 (for a brief overview) and COOK and HUGHES, 1986).

7.4 Hoods Over Hot Processes

These hoods are special instances of partial enclosures, often called canopy hoods, where the heat of the process causes air convection which propels the contaminant into the hood. They may range in scale from small hoods over very small heated baths to the very large fume collecting systems used over large electric-arc steel furnaces. For the successful design and operation of any system a knowledge of a number of independent variables is necessary. Among these are the rate of heat release of the source of the fume, the rate and method of the release of the fume, ie is it continuous or intermittent, the geometry of the hood or proposed capture system. The constraints imposed by the process, the fume hood section, the fume flow rate at the hood and the rate and nature of the cross draughts that may occur also affect the design and operation of these hoods.

The measurement or estimation of some of these variables may be difficult but they must be considered. A common cause of failure in such canopy systems has been the failure to determine or predict properly the volume of the fume to be controlled or the actual direction and shape of the plume so that the plume has either missed the hood or a large proportion of the fume has spilled out of the hood after it has once entered.

Hot fume released from a source will rise and entrain shop air until the mean temperature of the plume is close to that of the ambient air. The amount of diluted fume to be extracted by the hood may therefore be much greater than the original volume if there is a considerable distance between the source and the hood. If the plume temperature is low and the amount of cold shop air entrained is large it may not reach a hood or extraction system mounted at a high level in a roof space. It is apparent therefore that the hood should be as close as possible to the source of the fume, as the volume to be extracted will be less and there will be less chance of the fume being deflected or spilling out of the hood. The hood must also be emptied by the extraction system as quickly as the process fills it.

Where possible the enclosure of the source should be the first consideration rather than the use of a remote hood. This has been done, for example, over lead melting and refining furnaces, where the enclosure has been provided with doors or covers which give access for charging and skimming, and the stirrer has been fitted into the top of the cover.

The measurement of plume velocity and volume may not be easy but BAMFORD (1961) has described a number of methods used to determine the rate of rise of dust and fumes from hot castings and has also given the air velocities needed to deflect the rising plume. In addition to the normal gas or air-flow measuring techniques, BAMFORD (1961) and GOODFELLOW and BENDER (1980) have described the use of cine photography to determine the flow rate, volume and direction of a plume. This is a technique that is simple, expedient and cheap to use on existing installations while nowadays a video camera and recorder would be more convenient.

Formulae to predict the plume velocity and air-flow volume were produced by HEMEON (1963). More recently BENDER (1979) has set out the relevant basic equations (see Appendix 7.7). It is suggested that these basic equations should be used instead of earlier formulae when calculating plume velocities or volumes.

For large and complex fume control systems the use of modelling techniques is an important design process. For this to be completely satisfactory the model should be both dimensionally and dynamically similar. It has also been shown that it is possible to use water as the modelling fluid with a considerable saving in the size and complexity of the model (SKARET, 1986).

GOODFELLOW and BENDER (1980) have described the techniques while FLUX (1974) and MARCHAND (1974) have described the work done during the design of very large fume extraction systems in two large electric-arc steel melting shops.

7.5 Push-Pull or Jet Assisted Hoods

As a supply air-jet or blowing jet will move air for a much greater distance than an exhaust opening it can be a useful device to assist in the control of contaminants where these are released over a wide area such as an open tank or heated bath. The blowing jet is used to carry the contaminant to a point where it can be collected by the receiving exhaust hood.

Enclosures

While this has been done successfully in some cases there have been many instances where the scheme has failed or has made conditions worse by entraining contaminated air, overloading the receiving hood and spreading contaminant over a wide area of the workshop. Failure has often been due to a lack of detailed design considerations at the initial stages (see Appendix for basic jet equations).

Probably the most common cause of difficulty is where the "throw" of the blowing jet is excessive thus causing the entrained pollutant to be carried beyond the exhaust hood. If the jet is allowed to impinge on parts of the structure or on large articles being passed through the jet, then considerable turbulence can be caused which again causes the contaminant to be dispersed.

A free air jet expands at an included angle of about 24^{o} and entrains ambient air while the centreline velocity decreases with distance. From consideration of the conservation of momentum the mass flow through any plane perpendicular to the jet remains constant (Figure 7.3).

When a jet is aligned close to a plane surface such as the liquid in a tank the expansion will occur only above the free surface and therefore only half the angle of the cone should be used to determine the area of the jet . However, where the liquid level is well below the jet level then approaching full expansion may take place (Figure 7.4).

When a jet is used over a heated area such as a hot bath or vat then the stream will be deflected upwards. In this case it will be necessary to raise the position of the exhaust hood so that the stream is intercepted.

For a detailed treatment of the theory of air jets see BATURIN, V.V. (1972) and for the application of air jets and exhaust ventilation see HEMEON (1963) and CURD (1986).

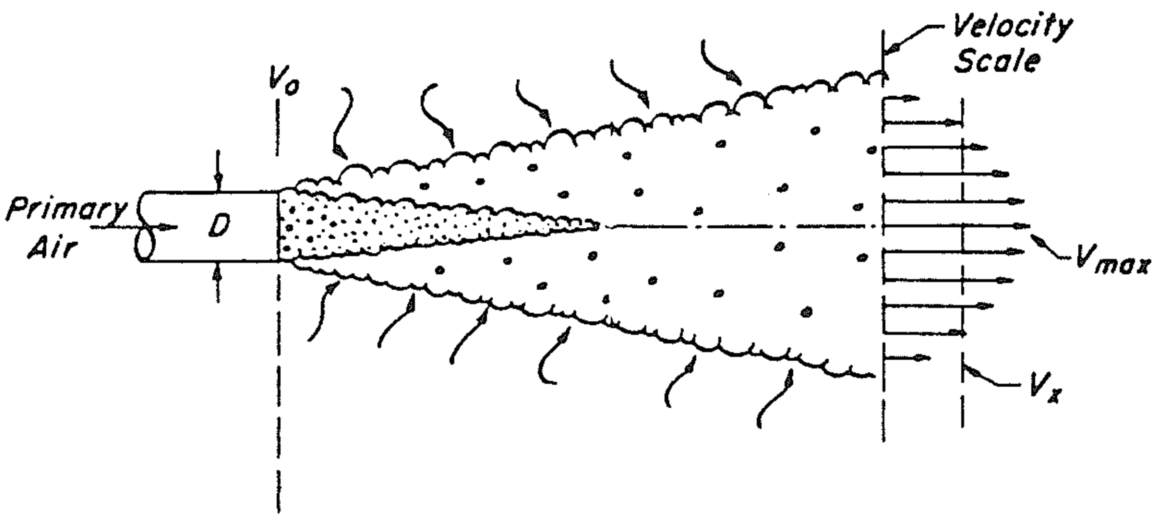

Figure 7.3

An air jet showing the primary air core and expanded jet comprising primary and entrained air. V_o = face velocity, V_x = average velocity and V_{max} = maximum velocity. (Taken from HEMEON, 1963).

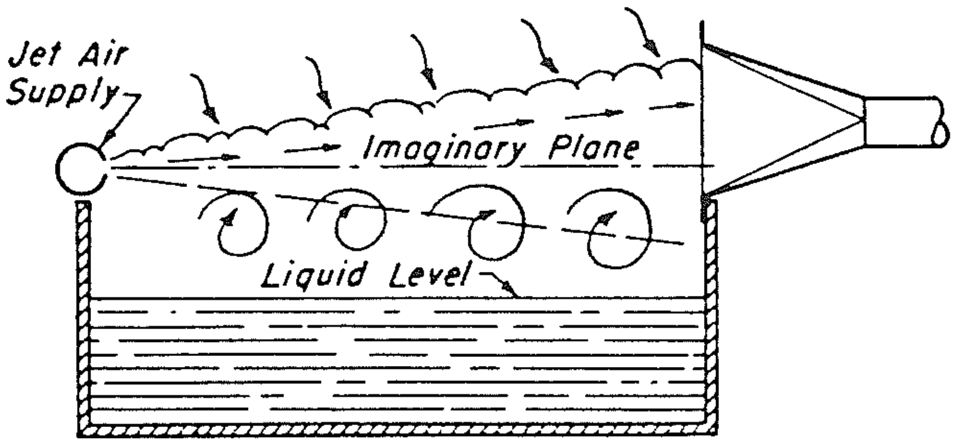

Figure 7.4
A push-pull system (taken from HEMEON, 1963).

A recent paper by HUEBENER, D.J. and HUGHES, R.T. (1985) has examined its application to a plating bath and has shown that better emission control and significant energy savings can be achieved by the correct application of a push-pull system (see Chapter 9, Section 9.10 for a discussion of the use of air jets in general ventilation).

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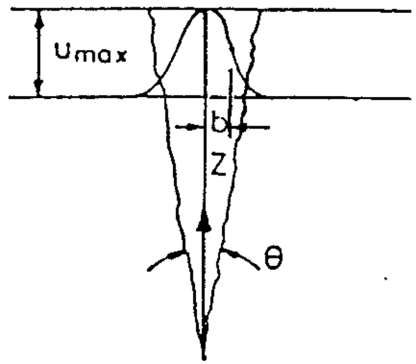
7.7 Appendix

Basic jet equations for line and point sources (taken from BENDER (1979)). See Sections 7.4 and 7.5.

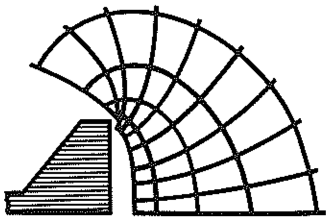
	Dim's.	Point Jet	Line Jet	Point Plume	Line Plume
Characterizing Source Quantity	V_s assumed uniform	"Massless" Momentum Flux $M = Q_s V_s [m^4/sec^2]$	"Massless" Momentum Flux $M = Q_s V_s [m^3/sec^2]$	Buoyancy Flux = const. $F = Q_s \Delta_s [m^4/sec^3]$	Buoyancy Flux = const. $F = Q_s \Delta_s [m^3/sec^3]$
Volume Flow Rate Q	$\frac{m^3}{sec}$	$\left(\frac{8M}{\pi}\right)^{1/2} \pi \alpha Z = u_{max} \pi b^2$	$4\left(\frac{\alpha M}{\sqrt{2}}\right)^{1/2} Z^{1/2} = u_{max}\sqrt{\pi}\, b$	$\frac{6\pi\alpha}{5}\left(\frac{18F\alpha}{5\pi}\right)^{1/3} Z^{5/3} = u_{max} \pi b^2$	$2\alpha\left(\frac{F}{\alpha}\right)^{1/3} Z = u_{max}\sqrt{\pi}\, b$
Mass Flux G	$\frac{g}{sec}$	$Q\rho_0$	$Q\rho_0$	$Q\rho_0$	$Q\rho_0$
"Massless" Momentum Flux M	$\frac{m^4}{sec^2}$	M = const.	M = const.	$\frac{\pi}{2}\left(\frac{18F\alpha}{5\pi}\right)^{2/3} Z^{4/3} = \frac{u_{max}^2 \pi b^2}{2}$	$\sqrt{2}\alpha\left(\frac{F}{\alpha}\right)^{2/3} Z = u_{max}^2 \sqrt{\pi/2}\, b$
Kin. Energy Flux (power) E	$\frac{gm^2}{sec^3}$	$\frac{\rho_0}{3\alpha}\left(\frac{2M^3}{\pi}\right)^{1/2} Z^{-1} = \rho_0 u_{max}^3 \frac{\pi b^2}{3}$	$\rho_0\left(\frac{M^3\sqrt{2}}{\alpha}\right)^{1/2} Z^{-1/2} = \rho_0 u_{max}^3 \sqrt{\pi/3}\,\frac{b}{2}$	$\rho_0 F Z = \rho_0 u_{max}^3 \frac{\pi b^2}{3}$	$\frac{\rho_0 F}{\sqrt{3}} Z = \rho_0 u_{max}^3 \sqrt{\pi/3}\,\frac{b}{2}$
Center Line Velocity U_{max}	$\frac{m}{sec}$	$\left(\frac{M}{2\pi}\right)^{1/2} \frac{1}{\alpha} Z^{-1}$	$\left(\frac{M}{\sqrt{2}\alpha}\right)^{1/2} Z^{-1/2}$	$\frac{5}{6\alpha}\left(\frac{18\alpha F}{5\pi}\right)^{1/3} Z^{-1/3}$	$\left(\frac{F}{\alpha}\right)^{1/3}$ = const.
θ (approx.)	Deg.	18.	24.	18.	28.

See footnotes



T	local plume temperature	°K, °R
T_0	temperature of ambient fluid	°K, °R
Δ	local plume buoyancy	m/sec², ft/sec²
ρ	local plume fluid density	g/m³, lb/ft³
ρ_1	hood exhaust fluid density	"
ρ_0	ambient fluid density	"

Assumptions:
1. **similar gaussian profiles:** $u = u_{max}\exp[-r^2/b^2]$
2. **small density difference**
3. **entrainment velocity:** $V(b) = \alpha u_{max}$
4. **equal spread of buoyancy and velocity profiles**



8

CAPTOR HOODS

Whereas with the receptor hood the process itself pushes the contaminant into the extract inlet or the contaminant is released in the inlet, the captor hood pulls the contaminant, which would otherwise not have been captured, into the hood. The airflow must therefore "reach out", overcome any tendency of the contaminated air to disperse and draw it into the hood.

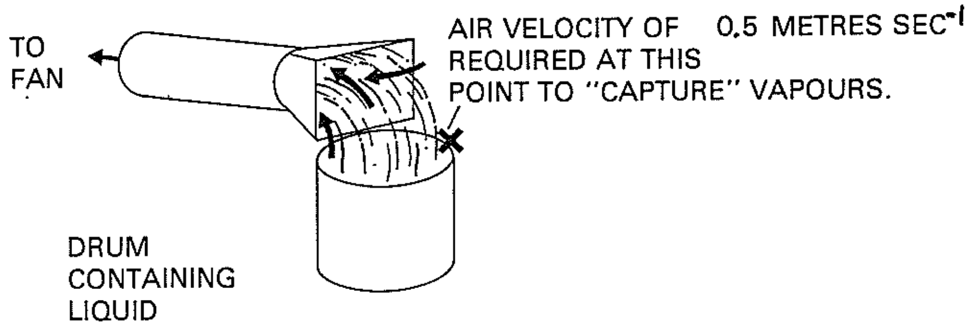
In designing an exhaust ventilation system it is important to observe the process before any ventilation is applied in order to identify the nature of the source (see Section 3.1.1). Small particles of respirable size (even those with high initial velocities), vapours and gases tend to move with an airflow; coarse particles, especially those generated with high velocity, will not readily be diverted from their natural path. Although it is the former group which presents the major health hazard, the production of coarse particles is usually accompanied by that of fine dust. Whilst a local exhaust ventilation system cannot in general be designed for the removal of large particles, it may be possible to site the hood so as to intercept the trajectories of such particles. By observing the process, the production of pollutant and its natural movement can be determined; it is this natural movement which must be overcome by the system (see Chapter 3.0 Examining Processes and Understanding Exposure).

8.1 Capture Velocity

The velocity induced near the source of the contaminant which is necessary to ensure the capture of the pollutant is usually termed the capture velocity. The concept of capture velocity is central to the design of this type of hood (see Figure 8.1 for a simple illustration of capture velocity).

Although there are objections which can be made to the velocity/capture concept, it is an approach which can produce good results and at the present time there appears to be no viable alternative. It should nevertheless be used with caution. Recent measurements (FLETCHER and JOHNSON, 1985) show that the hood capture efficiency of gases and sub-micron particles, released at low velocities, depends on the velocity induced at the point of release; this supports the capture velocity concept. However, measurements of capture efficiencies of releases directed away from hoods, at all but very low velocities, have shown that the concept is not valid in general. Where contaminants are emitted with significant velocity away from the hood, the face velocity and total mass flow of air induced by the hood in the region of generation become more important than simply the air velocity induced at the source, ie the "capture velocity".

A. QUIET EVAPORATION OF LIQUID



B. FILLING DRUM WITH LIQUID

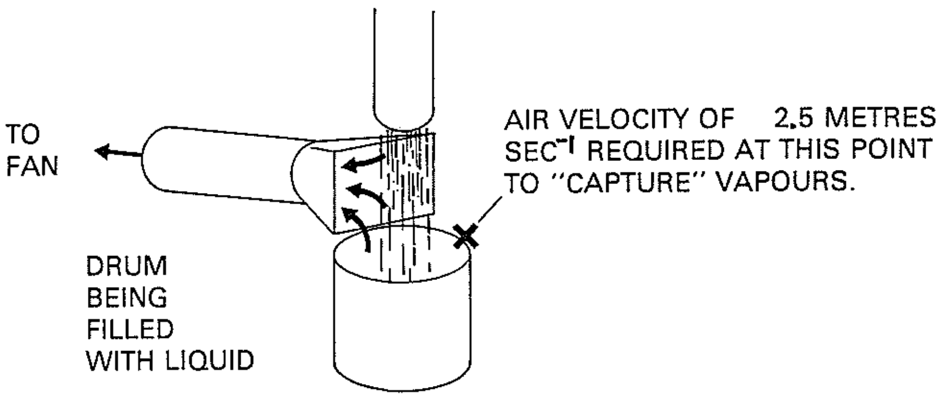


Figure 8.1
CAPTURE VELOCITY - A SIMPLIFIED ILLUSTRATION
The energy of the air movement in the region of the process determines the appropriate capture velocity for that process (see Section 8.1 for further discussion).

The capture velocity must overcome the movement of the contaminant which may be due to the movement of air from the process (eg thermal currents), to movement of the operator, to natural draughts or to the momentum with which the contaminant is released (eg during grinding). Tables of suggested capture velocities are available in the literature (eg ACGIH, 1984) but these should be treated with care. Capture velocities as low as 0.25 ms^{-1} are sometimes given, but air movements throughout the workplace will usually have higher velocities than this, and a value of 0.5 ms^{-1} should be regarded as a minimum. The table below gives a rough guide to the range of capture velocities.

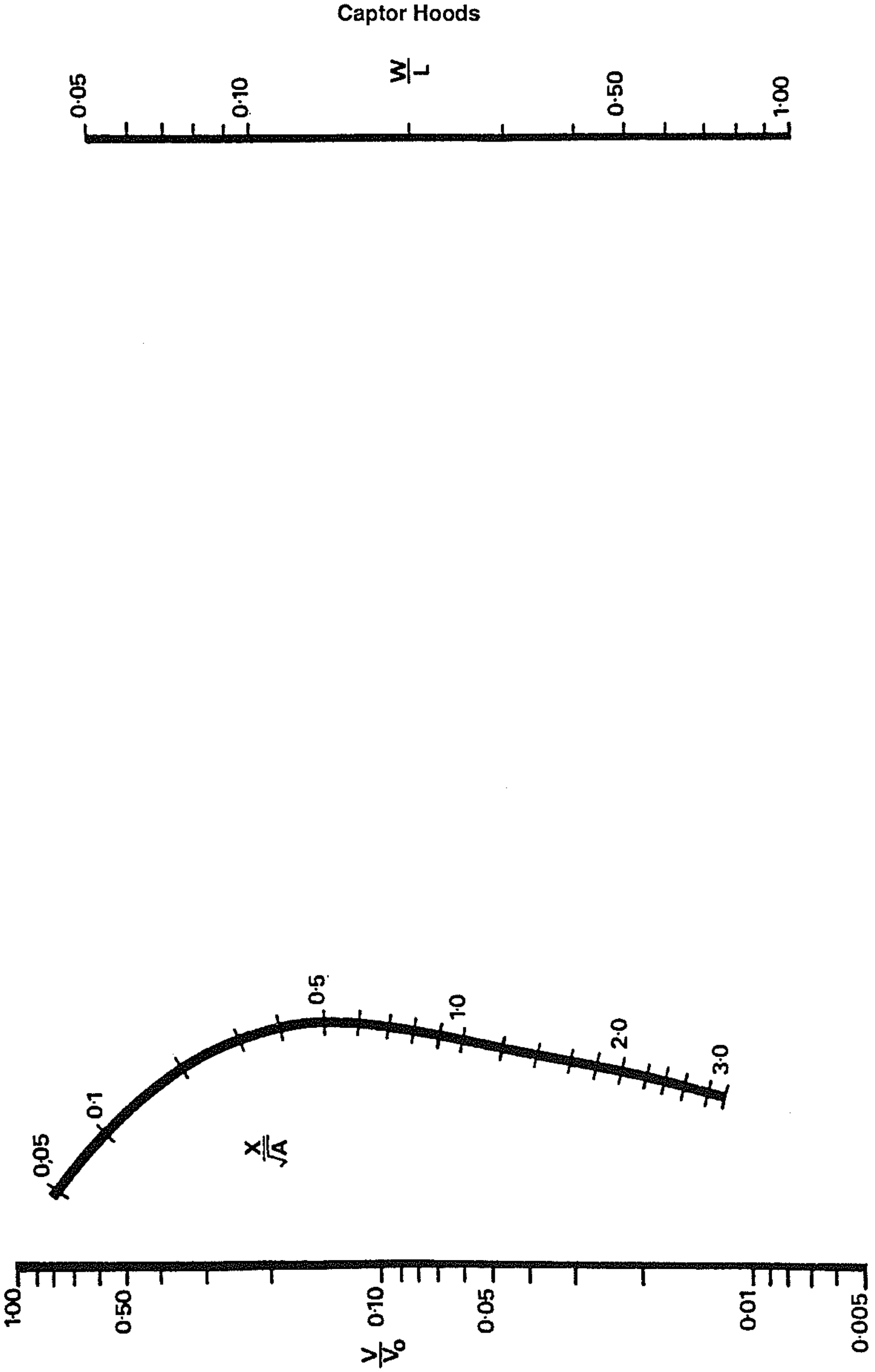


Figure 8.2
Nomogram for the calculation of centreline velocities in front of freely suspended hoods (see text Section 8.3).

Process	Capture Velocity ms^{-1}
Low velocity release into moderately still air, eg welding, dipping	0.5 - 1.0
Medium velocity release into a moderate air movement, eg paint spraying, conveying	1.0 - 2.5
High velocity release into a rapid air movement, eg shot blasting	2.5 - 10.0

The lower figure in each group should be considered as the minimum value for control. The selection of a velocity within the range will be influenced by such factors as the toxicity of the materials being handled and the air movement within the room but the upper value may also be limited by process requirements, eg the velocity must not be so high as to cause excessive solvent evaporation or powder entrainment, or to remove the gas shield during gas welding.

8.2 Captor Hood Design

The aim of the captor hood design is to produce a sufficiently high capture velocity to achieve control of a contaminant whilst at the same time extracting a minimum amount of air; the prime purpose of a local exhaust ventilation system is not to provide fresh air but to remove contaminated air. The hood should be sited as close as possible to the source. This distance may be limited by the process, the machine design or ergonomics: a hood which gets in the way of an operator may soon be removed. The hood size and shape are usually based on the source size, eg the length of a tank side, but it may also be determined by the method of working. For example the length of a slot for use in welding could be based on the length of weld which could be made with one welding rod; this would avoid repositioning of the slot during welding.

8.3 Prediction of Air Velocity - Fletcher's Nomogram

Suppose now that we want a captor hood for a particular application and that, having observed the process, we have determined the source size, the hood size and shape and the closest distance it can be positioned to the source. The hood face velocity (V_o) can now be found from Fletcher's nomogram illustrated in Figure 8.2. This gives the centreline velocity in front of freely suspended rectangular hoods. W, L and A are the width, length and area of the hood respectively and V is the capture velocity at a distance X from the hood. The suction volume flow rate, Q, can then be found, ie $Q = V_oA$.

This nomogram was constructed to facilitate centreline velocity calculations from the formula:

$$\frac{V}{V_o} = \frac{1}{0.93 + 8.58\,\alpha^2}$$

where

$$\alpha = \frac{X}{\sqrt{A}}\left[\frac{W}{L}\right]^{-\beta}$$

$$\beta = 0.2 \left[\frac{X}{A} \right]^{-1/3}$$

The formula was based on measurements (FLETCHER, 1977) of centreline velocity gradients made on hoods of aspect ratios (ratio of hood length to width) between 1:1 and 16:1 with areas between 25 and 900 cm^2. Average face velocities were in the range 2-30 ms^{-1}. Comparison with subsequent work (FLETCHER, 1982) shows that the nomogram and formula can be used to fit measurements made on hoods of area 6.45 cm^2 with face velocities up to 120 ms^{-1}.

The nomogram and formula illustrate two important points which should be taken into account when designing a hood:

(i) The velocity induced by suction falls rapidly with increasing distance from a hood and hence the opening should be sited as close as is practicable to the source of the contaminant if the system is to be effective.

(ii) The velocity decreases as the aspect ratio increases at a given point in front of a hood for a fixed face area and flow rate. Hence in the absence of other design limitation, the aspect ratio should be kept low, ie close to 1:1.

The importance of these design considerations can be seen clearly from Figure 8.3 which shows the variation of velocity with distance in front of a square hood and one of aspect ratio 10:1.

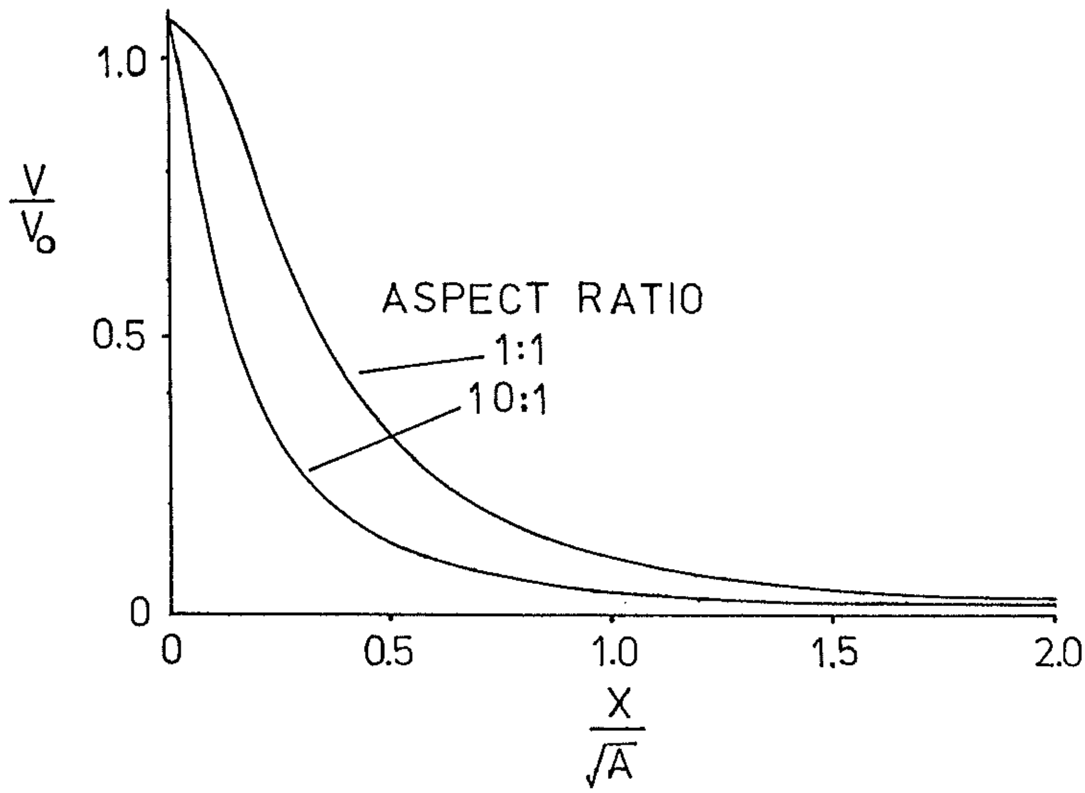


Figure 8.3
Variation of velocity with distance and aspect ratio.

8.4 Flanges

The addition of a flange to a hood or slot can have two beneficial effects: it reduces the amount of air drawn in from the usually uncontaminated regions behind the hood and improves entry conditions into the hood. The improved entry conditions result in (a) a more even velocity distribution across the face of the hood, and (b) a lower entry pressure loss and hence a reduced power requirement.

Research by FLETCHER (1978) has shown that the addition of a flange to a hood can produce a large increase in velocity in front of the hood. Figures 8.4, 8.5 and 8.6 show the effect of flange width on the velocity in front of hoods of aspect ratio 1:1, 4:1 and 16:1 respectively (D is the flange width, V_F, and V_U are the centreline velocities for flanged and unflanged hoods respectively). These show that the optimum flange width is A. As the aspect ratio increases the effect of the flange increases; velocity increases of over 55% can be produced on hoods of aspect ratio 16:1 for flanges of width A but even small flanges can make an appreciable difference to the velocity. A flange will therefore reduce the amount of air needed to control a contaminant and should be used wherever circumstances allow it.

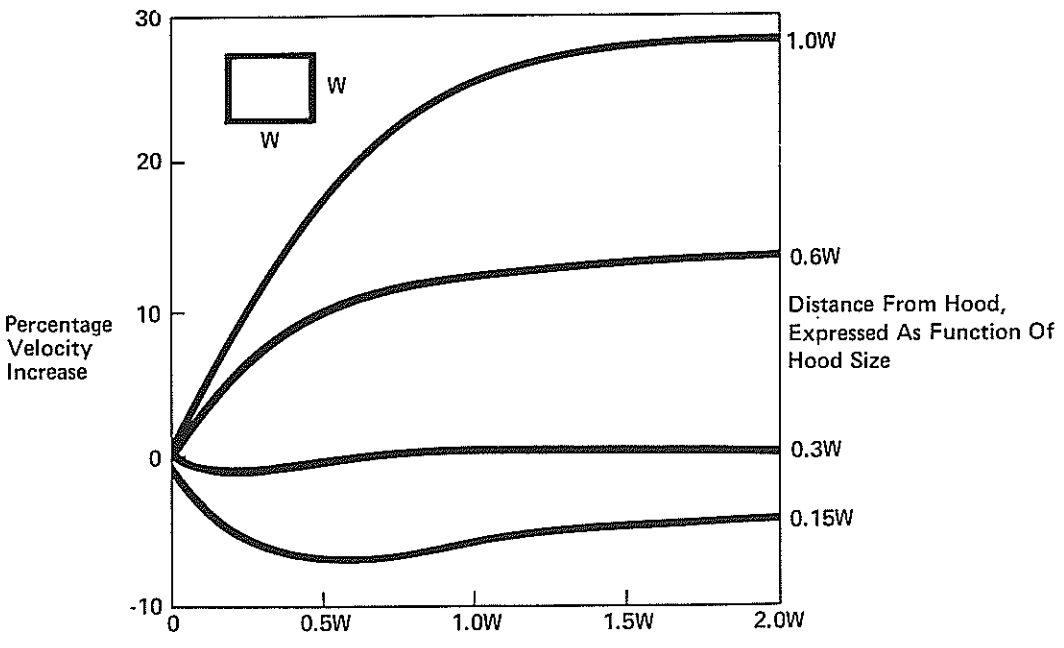


Figure 8.4
Effect of flange width on the velocity in front of square hoods (based on FLETCHER, 1978).

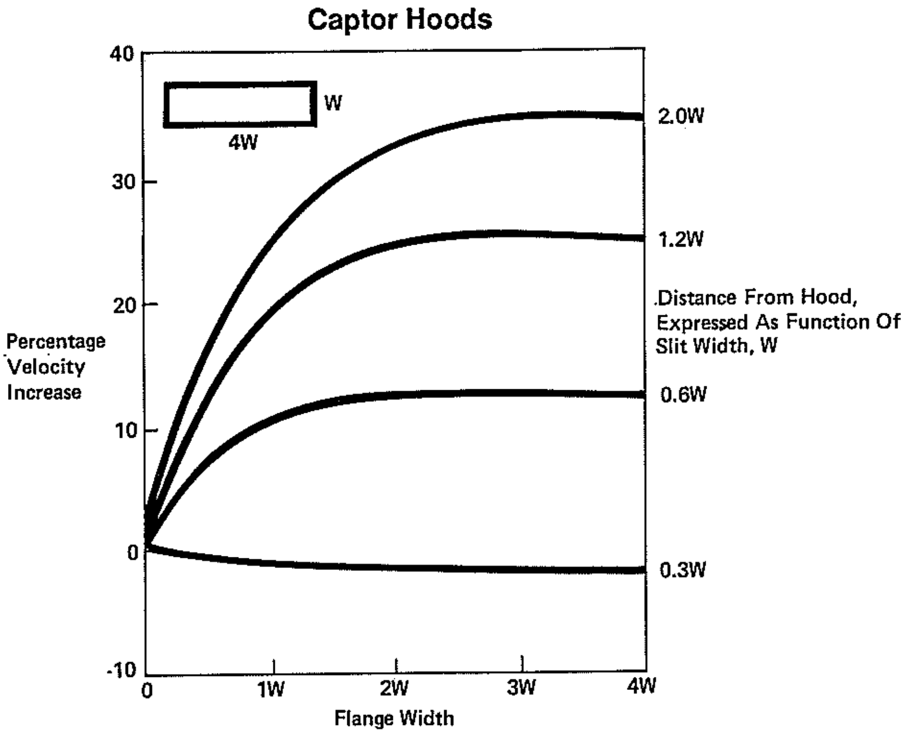


Figure 8.5
Effect of flange width on the velocity in front of a hood of aspect ratio 4:1 (based on FLETCHER, 1978).

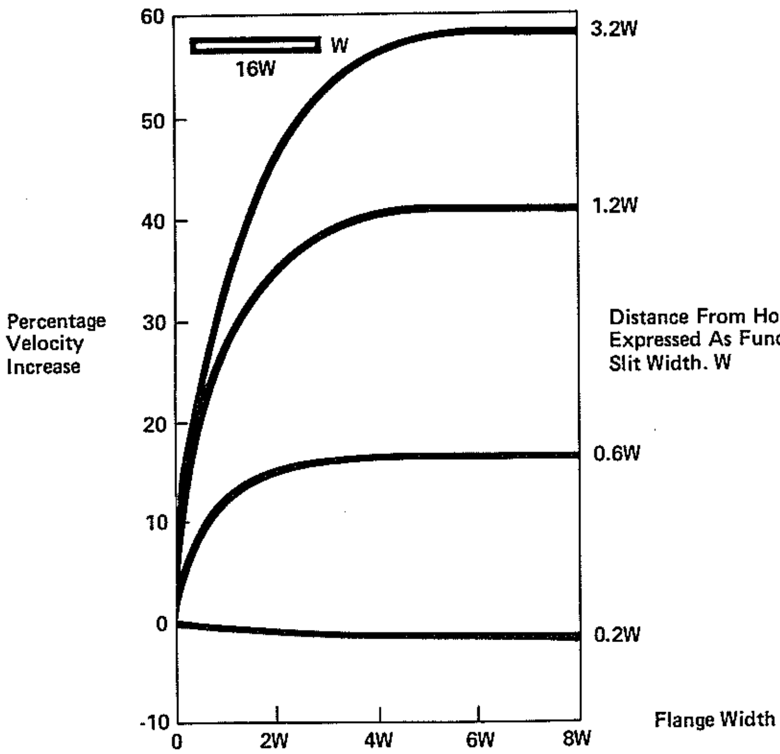


Figure 8.6
Effect of flange width on the velocity in front of a hood of aspect ratio 16:1 (based on FLETCHER, 1978).

8.5 Effect of an Adjacent Plane

When a hood rests on a solid flat surface such as a workbench, the amount of air needed to produce the same velocity at a given distance is considerably smaller than in the case of a free standing hood. Figures 8.7 and 8.8 (FLETCHER and JOHNSON, 1982) show how, in the case of a 16:1 hood, the velocity profiles are pushed farther from the hood face by the plane.

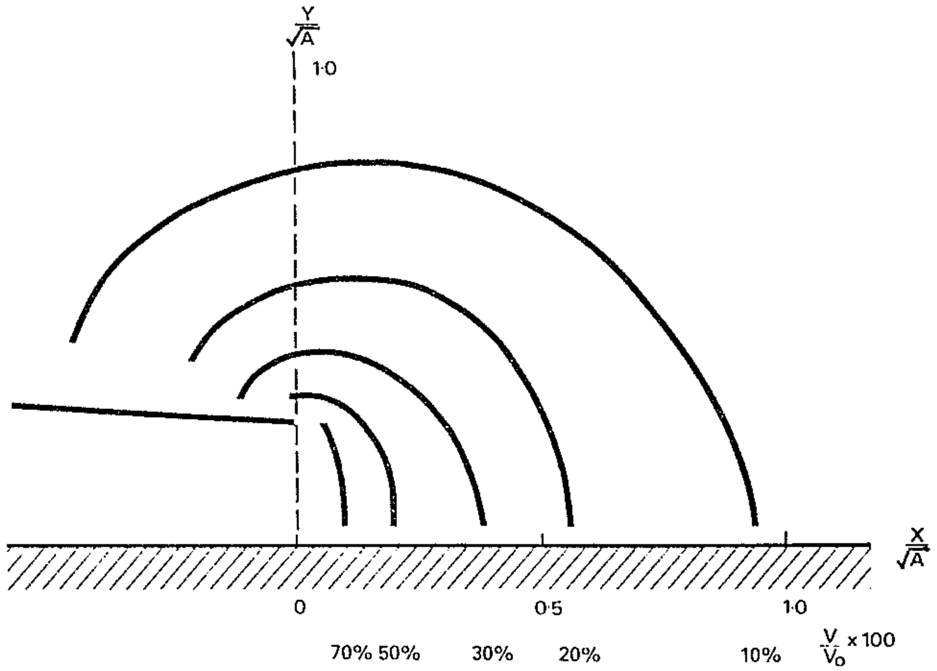


Figure 8.7
Velocity profiles in the plane bisecting the longer side of a slot of aspect ratio 16:1.

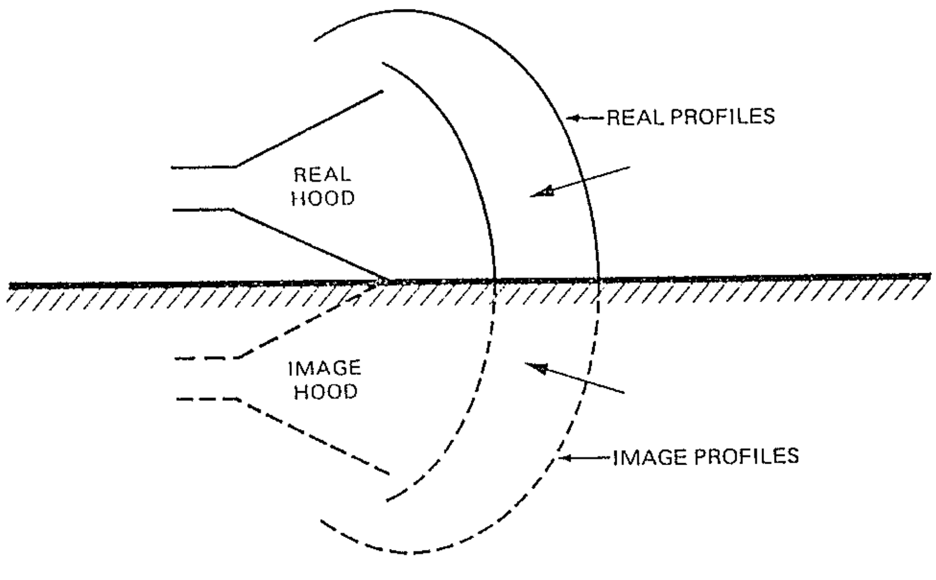


Figure 8.8
Velocity profiles around a slot of aspect ratio 16:1 when the longer side rests on a plane surface.

Captor Hoods

The method generally used to calculate the position of velocity profiles is to consider an identical image hood in the plane (shown dotted in Figure 8.8) and to take the profiles as the real half of those of a hood made up of the real and imaginary hoods. This method will give good results provided that two factors are taken into account.

(i) The area of the apparent hood (A') is twice that of the real hood (A) and this must be used to evaluate the distance of a profile from the hood, ie to find $X/\sqrt{A'}$ <u>not</u> $X/\sqrt{A}$.

(ii) The aspect ratio of the apparent hood is either twice or half that of the real hood depending on the orientation of the hood on the plane.

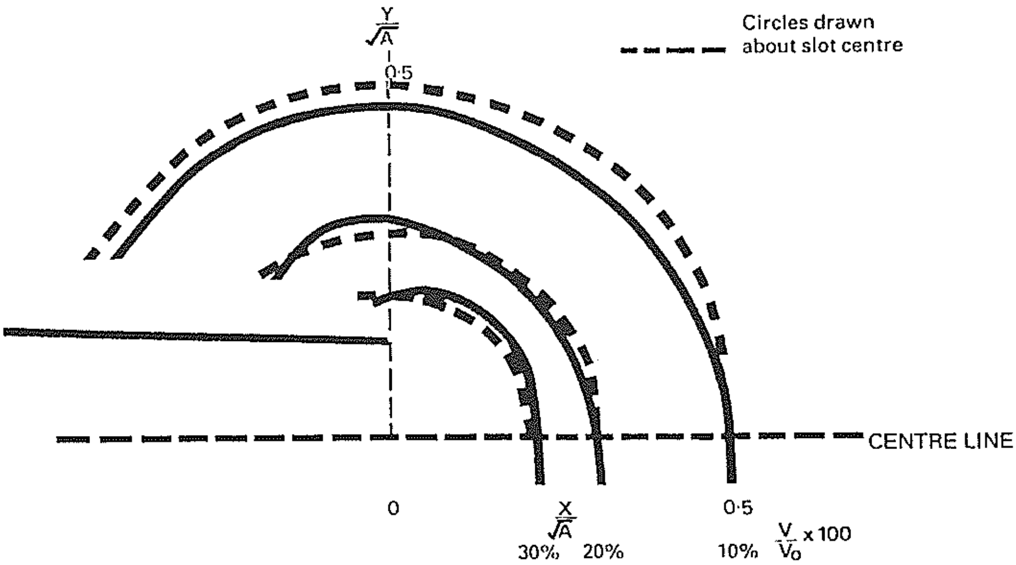
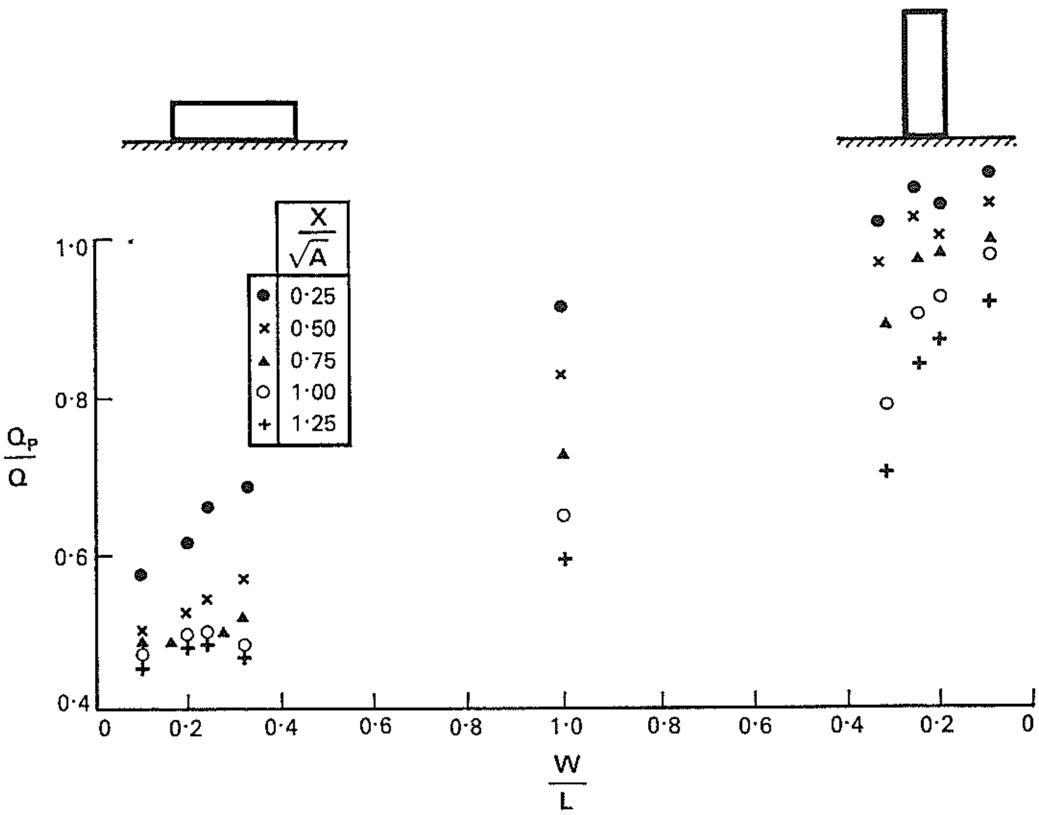


Figure 8.9
Velocity profiles around a hood placed against a flat surface (see text Section 8.5).

As an example, suppose that we wish to find the distance of the 10% velocity profile from a hood of aspect ratio 16:1 which rests with its longer side on a plane work surface. We would take W/L to be 2x1/16=0.125, ie the apparent hood would have an aspect ratio of 8:1. From the nomogram we would then get $X/\sqrt{A'}=0.62$. But A'=2A and therefore $X/\sqrt{A}=0.88$. Figure 8.7 shows that this calculated value agrees with the measured value. For the hood freely suspended the 10% profile lies at $X/\sqrt{A}=0.5$.

The above method produces slightly conservative estimates of $X/\sqrt{A}$ and hence "fails safe". However, a different approach is required to find the air extraction rate, Q_p, of a hood resting on a plane, needed to produce a pre-determined control velocity at a given distance from the hood. Figure 8.10 shows some results of measurement of Q_p/Q for hoods of various aspect ratios for values of $X/\sqrt{A}$ between 0.25 and 1.25 (FLETCHER, 1985) where $Q=V_0A$. For a specified hood and distance from the hood, a value of Q_p can be obtained. Again this gives a conservative estimate.



Variation of Qp/Q with aspect ratio, hood orientation and distance from the hood face.

Figure 8.10
Variation of Qp/Q with aspect ratio, hood orientation and distance from the hood face.

For example: A hood 80 x 5 cm rests with its longer side on a plane surface. What volume flow rate is required to give a velocity of 1.0 ms^{-1} at 10 cm from the hood?

$X/\sqrt{A} = 0.5$ and $W/L = 0.0625$
From Figure 8.10, $Q_p/Q = 0.48$
From the nomogram, $V/V_o = 0.1$
ie $V_o = 10\ ms^{-1}$ and so $Q = 0.4\ m^3s^{-1}$
Therefore $Q_p = 0.19\ m^3s^{-1}$
Check: with the plane $V/V_o = 1.0/4.8 = 0.21$

Figure 8.9 shows this to be a slightly conservative estimate.

The empirical design equations given above can be used to determine centreline velocities in the case of free standing and flanged hoods, and the velocity close to the surface in the case of a hood resting on a plane. Full velocity profiles have also been determined for these cases.

Where the geometry is more complex, there are several possible methods for approximating the airflow patterns into hoods (GARRISON, 1983). These graphical and mathematical concepts should form a useful design tool as computer technology and programming advances make the techniques more readily available.

8.6 The Low-Volume High-Velocity Exhaust System (LVHV)

The LVHV system is a special application of the captor hood; it is a system in which a high capture velocity (50-100 ms^{-1}) is achieved by the use of small hoods or apertures (typically 6 cm^2 or less in area) placed very close to the source of the contaminant. In this way only a low volume flow rate of air is required. These hoods are used to capture dust or grit generated at high velocity, for example, during grinding, chiselling or sanding; or vapour or gases released over a very small area, for example, during welding or soldering. When LVHV is used with portable hand tools, the hood should be an integral part of the tool design; devices added as an afterthought usually make the tool cumbersome and unbalanced. The hoses should be light-weight and of small diameter but capable of withstanding a high partial vacuum; in order to produce the high velocities required, typical static pressures would be in the range 8-20 kPa. Such suction pressures cannot be produced by the normal single-stage fan used in exhaust ventilation but will require multi-stage exhausters or vacuum pumps.

For the LVHV method to be successful, it must be:

(i) Ergonomically designed; it should be unobtrusive in use.

(ii) Correctly adjusted; the apertures are very small and their sizing and positioning must be accurate.

(iii) Regularly maintained.

These conditions are not easily met except in a few applications such as welding and soldering. For an example of the development of a well designed system applied to soft electrical soldering which has found widespready acceptance amongst workers and management see DALRYMPLE (1986). The effectiveness of the LVHV integral to the soldering "gun" is shown in Figures 8.11 and 8.12. Research is continuing (see REGNIER et al, 1985) and, in the case of sanders, very high dust capture efficiencies can be obtained. However in practice LVHV has proved to be a difficult method of control to apply satisfactorily and its range of applications may not be as wide as was once hoped.

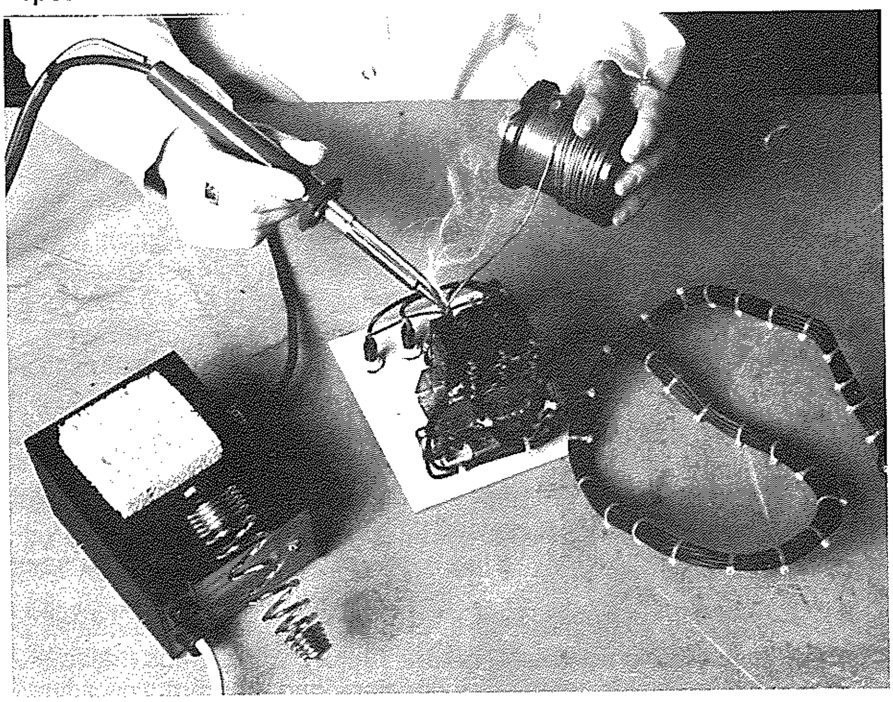


Figure 8.11
LVHV exhaust ventilation applied to an electrical soldering ion (suction off).

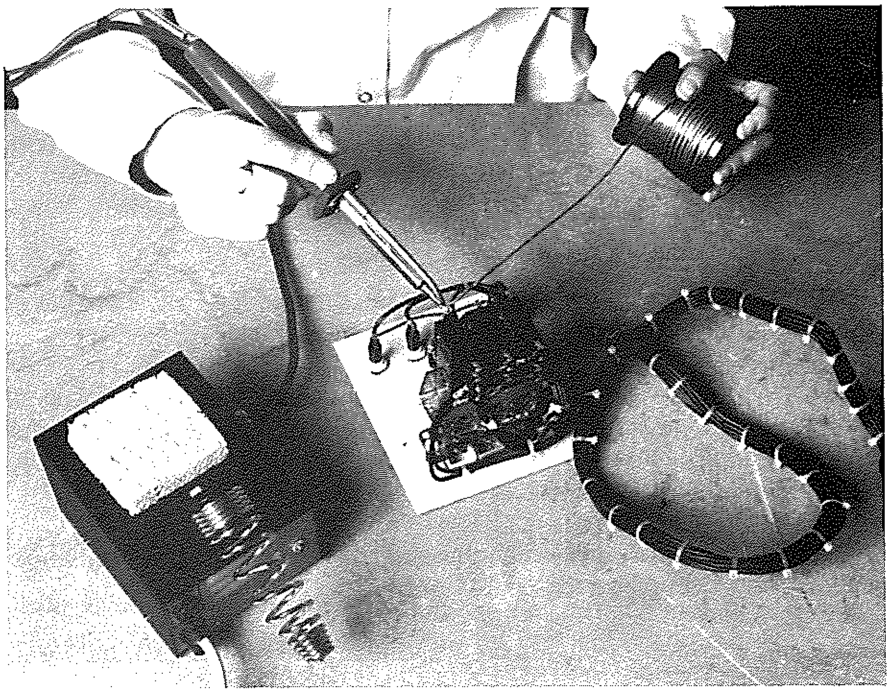


Figure 8.12
LVHV exhaust ventilation applied to an electrical soldering iron (suction on).

8.7 Captor versus Receptor Hoods

Because the process takes place outside the hood, captor hoods as compared with receptor hoods are particularly susceptible to draughts and increases in general air turbulence. They also require a greater volumetric flowrate for equivalent effectiveness as is illustrated in Figure 8.13.

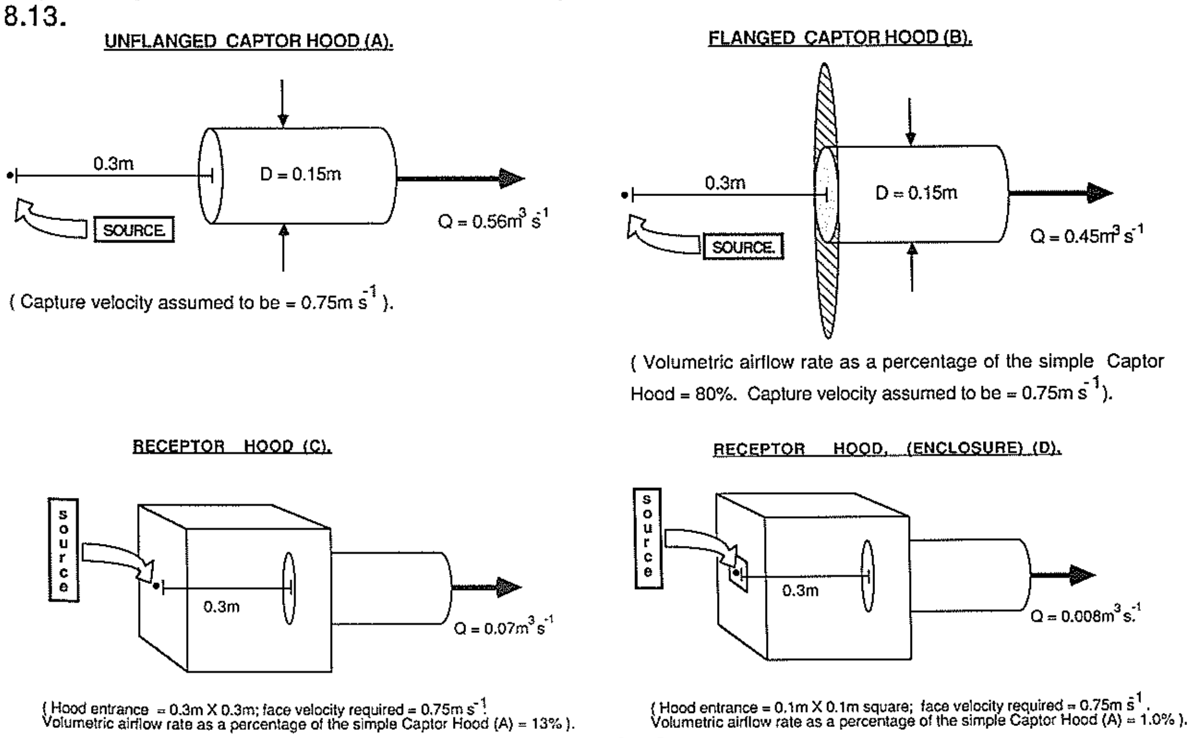


Figure 8.13
A comparison of captor and receptor hoods (based on HSE, 1975).

Captor Hoods

As receptor hoods surround the process they can physically get in the way of the operator or obscure his or her view of the process. This interference can be minimised at the prototype design stage, by cutting away parts of the hood and by judicious use of laminated glass and internal hood lighting. Captor hoods may be the only option which can be applied to a process and yet not impede operator access or use (eg LVHV). Usually this is not the case and every attempt should be made to convert captor hoods into receptor hoods by adding a flange and side curtains and generally boxing in the process as much as possible.

8.8 References

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