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Sampling Strategies *for Airborne Contaminants in the Workplace*

BOHS Technology Committee Working Group

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CONTENTS

FIGURES

PREFACE

This Technical Guide is written to assist occupational hygienists and others responsible for sampling airborne contaminants in the workplace. It focuses on sampling strategies for contaminants which present a hazard to health and it does not consider flammable and explosive hazards or ambient air quality.

The Guide is not a working manual. It attempts to cover all the key subjects which need to be considered if a successful sampling strategy is to be implemented. The Guide also briefly discusses a number of additional topics which will need to be considered to ensure that the information obtained in any survey is to be put to maximum use. Such topics include the proper recording and reporting of survey results and other 'Quality' issues which need to be considered. Inevitably, in such a wide-ranging guide it can only provide a basis for further investigation and therefore documentation relevant to specific topics is extensively referenced.

The application of statistics is essential if occupational hygiene sampling excercises are to achieve their full potential. The use of statistical terms has however been kept to a minimum in the Guide to make it accessible to a wider audience including those hygienists undergoing training who may initially have little or no knowledge of statistics. However to obtain full value from the Guide a basic knowledge of statistics will be necessary, some of which can be gained from the quoted references.

The guidance provided is of a general nature only and does not discuss specific sampling strategies which may be included in the regulatory requirements of any country. The views expressed are those of the authors and not necessarily those of the British Occupational Hygiene Society itself.

1 FACTORS AFFECTING STRATEGY DESIGN

1.1 Introduction

Atmospheric measurements in the workplace can be used for various purposes, for instance to assess the flammability of the atmosphere or the ambient air quality. In this Technical Guide the application of atmospheric measurement is restricted to the measurement of airborne substances hazardous to health in the workplace atmosphere.

This chapter is concerned with the factors which influence airborne contaminant concentrations, the capabilities and limitations of measurement techniques and other factors that need to be considered when planning any measurement exercise. Some of these considerations are not directly linked to planning and survey strategy but are critical to its overall success.

1.2 Survey Objectives

1.2.1 General Considerations

Any occupational hygiene survey, whether quantitative or qualitative, is usually part of a decision-making process. It is therefore important when considering sampling to ask the fundamental questions "Why are the data needed?". Considering this from slightly different stand-points it may become "What questions will the data answer?", or more broadly: "How will the data generated be used?" However the question is phrased, the answer will define the aim or aims of the survey. Without a definite aim, or aims, any survey merely becomes the collection of data "for the sake of it": an ultimately futile and wasteful exercise. The overall objective of any sampling strategy is to obtain appropriate information of an acceptable quality at a reasonable cost. The need for clearly defined objectives may seem obvious, but experience suggests that measurements are all too often carried out without a clear purpose.

Surveys carried out for some specific purposes, such as comparing sampling methods, may have a very precise end-point when contrasted with measurements for health risk assessment. Whether the aims are narrow or wide, once they are defined, a structured and informed approach to achieving them has various benefits. Thus setting up and carrying out a sampling exercise to achieve defined aims can be approached as an exercise in project management. In particular the route to achieving the aims can be broken down into a series of interdependent stages each with its own objectives. There will then be an overall conceptual strategy within which individual elements will have their own strategic considerations.

The advantages of using such an approach are well recognised and include:

- Once decided it provides a basis for planning and costing.
- It builds on a firm and increasing information base, which assists in defining and following up priorities.
- It has the flexibility to allow changes of direction should this prove necessary.
- The systematic build-up of information may provide answers to the basic questions being asked at some intermediate stage in the project, which will save the expense of completing the remaining stages.

Once the objectives of a proposed survey have been clearly defined a number of other factors need to be considered before commencing any practical work. These include:

- The requirement for a qualitative risk assessment and appraisal of the workplace prior to doing any measurements.
- The need to obtain measurements other than those of airborne contaminant concentrations, *eg* wipe tests to determine surface cleanliness as a way of assessing the potential for skin contact or measurements ventilation plant performance.
- Any requirements for biological monitoring and the integration of these into the overall survey strategy.
- Any requirements for monitoring overall performance or auditing the process.
- Any other health hazards which may exist within the workplace, *eg* noise or biological hazards *etc*, which may also need to be considered.
- Any environmental or personal characteristics of the workers which may affect the measurement.

1.2.2 Purpose of Atmospheric Measurement

The most appropriate sampling strategy to employ in a given situation will depend upon the objectives of the exercise which should include:

- Health risk assessment (*eg* as part of an assessment under the U.K. Control of Substances Hazardous to Health Regulations 1988 (COSHH) (COSHH, 1988)).
- Determination of conformity or compliance with occupational exposure limits (OELs).
- Evaluation of control measures or plant performance.
- Monitoring of continued performance of control measures.
- Provision of data for epidemiological purposes.
- Compliance with legislation.
- Validation or comparison of measurement methods (sampling and analytical methods).

Health risk assessments can involve both qualitative and quantitative elements and atmospheric measurements may form part of the quantitative element. Many people see quantitative measurements as being the more important element of the two, for example, because of its traditional role in assessing conformity or compliance with published exposure limits. However, it can be argued that it is in fact the lesser of the two partners. No health risk assessment can take place without some form of qualitative evaluation. Exposure to a hazardous substance may occur by inhalation, ingestion or skin contact. The assessment process inevitably involves evaluating the potential risks which may result from each route of exposure together with an understanding of the circumstances which cause the exposure to occur. Atmospheric measurement alone cannot answer any of these aspects satisfactorily.

Measurement plays a major part in evaluating conformity or compliance with OELs. A well-planned strategy generating a large number of measurements should provide a high level of confidence in the results. This may not always be essential. Observation or limited measurements may be all that is required when workplace conditions are obviously of an unacceptable or very acceptable standard.

It is a primary duty of employers to ensure a healthy working environment for their employees and the employer needs sound and timely advice where improvements in control may be required. Whilst the occupational hygienist may require adequate data to support the case for capital spending on engineering controls, it is equally important to avoid excessive measurement which could delay the implementation of any necessary controls and involve much expenditure of time and money.

Measurement commonly forms part of the overall strategy for evaluating the effectiveness of control measures and is a means of monitoring continued plant performance. However, qualitative methods *eg* use of a dust lamp (BOHS, 1987), can often be as effective, easier to use and provide more rapid results.

Atmospheric measurements may be required as part of an epidemiological study or similar exercise. The data needed for such studies are often substantially different from those required for evaluating compliance with an OEL or the performance of control measures, and different strategies could be required.

Atmospheric measurements often have to be made to comply with legislation. For example in the United Kingdom, air sampling may be necessary under both the Control of Lead at Work Regulations 1980 (CLAW, 1980) and the Control of Asbestos at Work Regulations 1987 (CAWR, 1987). Other national legislation may also require its mandatory use *eg* for vinyl chloride monomer in the Federal Republic of Germany. Its routine use is often implied when a duty exists to demonstrate that control of exposure has been achieved as far as is reasonably practicable *eg* for carcinogenic materials or those substances where socio-economic rather than health-based exposure limits exist.

1.2.3 Limitations of Atmospheric Measurements

Measurement cannot be used as the sole indicator of occupational health performance because of some of the limitations already outlined above. However, if the data are reliable and comparable, they can be used to establish whether the risk to health due to inhalation exposure is changing with time. In many situations the data may be a poor surrogate measure of management performance.

Measurement results are not yes or no indicators of whether a risk to health exists in the workplace. Neither the results of atmospheric measurements nor the exposure limits to which they are generally compared are absolute: both suffer from shortcomings and hence caution must always be exercised in their interpretation and comparison.

Measurement cannot be used as a substitute for making decisions affecting the control of risks to health or, indeed, continually deferring such decisions until substantial exposure data are available. Measuring the concentrations of hazardous substances in the air, by itself, does not control or reduce risks to health.

1.2.4 Factors Influencing Airborne Concentrations

There is a need to understand the variability of the workplace environment in order to appreciate why there is no universal approach to measurement methods i.e. a solution is only likely to be applicable to a limited range of circumstances. The inconsistency of the workplace, in terms of density and intensity of activity, variability of activity with time and the action of uncontrolled external factors, such as draughts or wind direction and strength, means that measurements can only be related to the regime being studied at the time.

A worker's exposure invariably arises from two general sources: the background associated with the working environment and specific exposures directly associated with the person's task. This duality of exposure and the balance between the sources of exposure will affect both the measurement methods and strategies. For individuals with peripatetic jobs or jobs involving a variety of tasks the requirement to ensure that all tasks are adequately assessed is paramount as illustrated in Figure 1.1.

The task or range of tasks undertaken can dominate the exposure pattern and level. The background in the workplace environment becomes more important as task-governed exposures are more controlled in size and number or where the individual's tasks are not a direct source of exposure *eg* in offices or control rooms (Figure 1.2). In some production situations (Figure 1.3) cyclical operations may cause fairly regular peaks in exposure. The measurement methods and strategies will be affected by these differences. In the latter case it may be essential to evaluate exposure peaks as well as full-shift exposures.

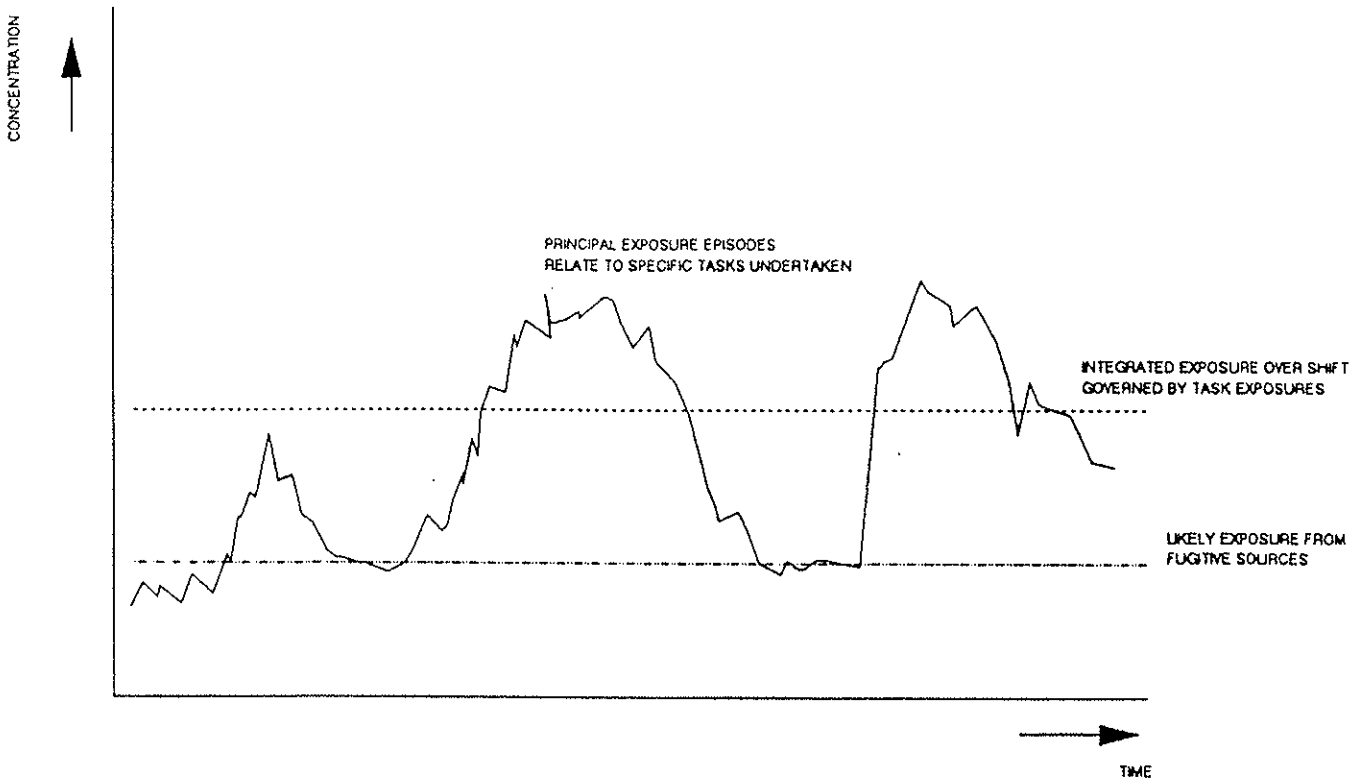


Figure 1.1
Typical exposure pattern for a peripatetic worker

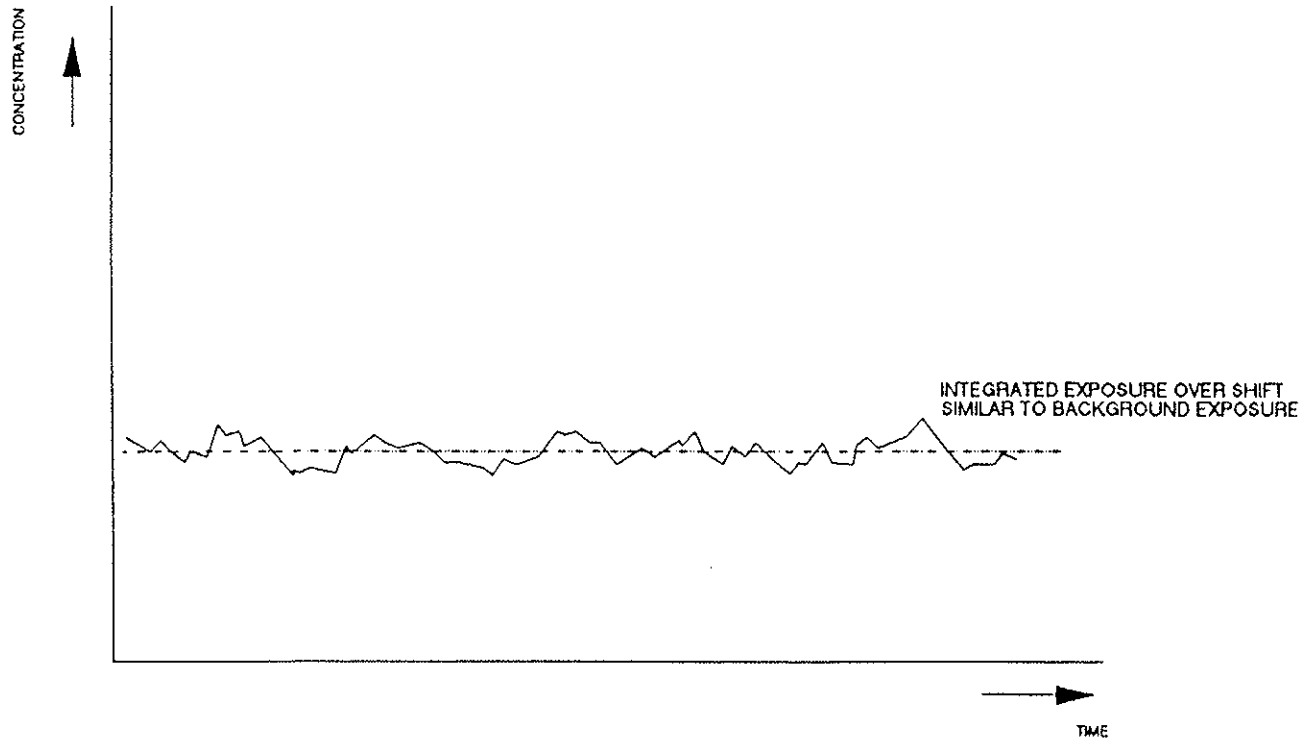


Figure 1.2
Typical exposure pattern from a well-controlled process: principal exposure sources are fugitive emissions

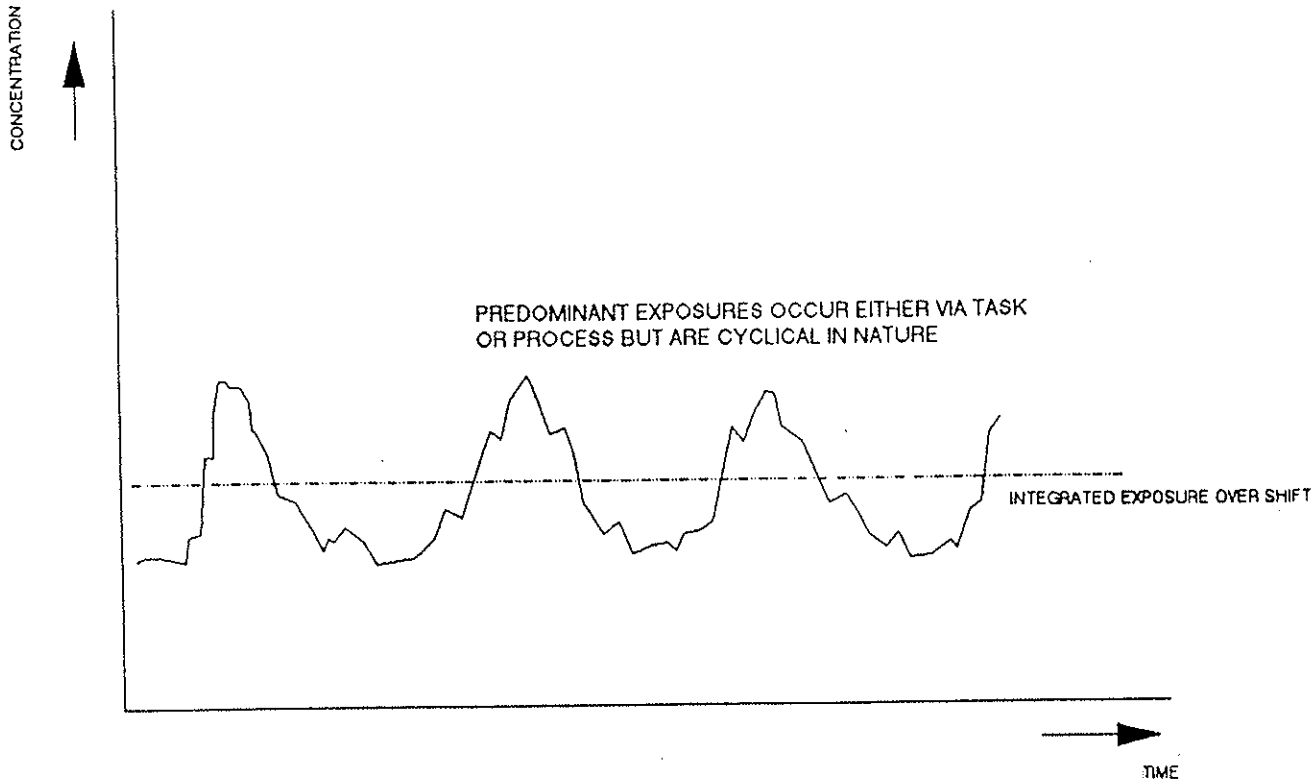


Figure 1.3
Stylised exposure pattern for a worker on a cyclical operation, *eg* filling containers

As exposure limits become more stringent and task-governed exposures come under increasing control, the contribution of the sources in the general workplace environment, for example, due to leakages from valves, flanges and pump or agitator seals, will become more important.

The contributions to exposure from the task and the workplace environment are not constant. Over time there will be changes to production rates or the workplace itself *eg* the installation of ventilation systems or modifications to process equipment. Products, product formulations or synthetic routes may also change with time. Even in a stable work environment day-to-day variations in exposure can vary considerably.

The concentration of pollutants in the workplace is therefore subject to both temporal and spatial variation and it is likely to be in a constant state of flux. This is not only due to changes in the process (number, type and position of contaminant source plus release rates) but ventilation rates and patterns can change with time *eg* the opening of doors or windows and their proximity to the contaminant source. The changes can occur minute by minute as well as daily or weekly. Seasonal variations may also occur. Climatic conditions can affect the concentration of atmospheric pollutants in a workplace. This is particularly so for outdoor work or in buildings which rely heavily on natural ventilation or which are badly designed in terms of the dispersion of airborne contaminants. Wind speeds and directions may need to be noted when undertaking atmospheric sampling programmes when any adverse relationships are known to exist or can reasonably be expected. Similarly, unusual climatic conditions which could result in elevated risks to health, *eg* atmospheric inversions, should also be considered.

The application of these general concepts within a structured approach to strategy development is discussed in more detail in Chapter 2.

1.2.5 Representative Measurements

Exposure measurements can be taken on a person and personal sampling is the truest measure of an individual's exposure. A sampling device is located within a person's breathing zone to sample the micro-environment to which the person is exposed. Some potential problems exist with this form of sampling, especially those associated with the location of the sampler at a position truly representative of the breathing zone and the aerodynamic behaviour of aerosols over body surfaces. Procedures can be introduced, *eg* dual lapel sampling, to compensate for some of the difficulties which may arise.

Samples which are not taken on the individual are generally referred to as static samples. Static samples may not correlate well with actual personal exposures (Higgins, 1970). They do, though, still have a substantive role in the general area of atmospheric measurement. They are:

- Often used to check the performance of control devices.
- Useful as a surrogate for personal exposures, when a clear correlation between the results from static samples and personal samples has been established (*eg* in UK coal mines where static samples, for compliance testing, are taken in the return roadway).
- Of use in identifying and quantifying contaminant sources in the workplace and in delineating areas of unacceptable contamination.
- Part of the process for assessing trends in baseline concentrations.
- Sometimes the only realistic means of measurement when certain types of continuous monitoring are required.
- The only realistic method of sampling high volumes of air.
- A legal or recommended requirement for some atmospheric exposure limits *eg* cotton dust in the U.K. (HSE, 1980).

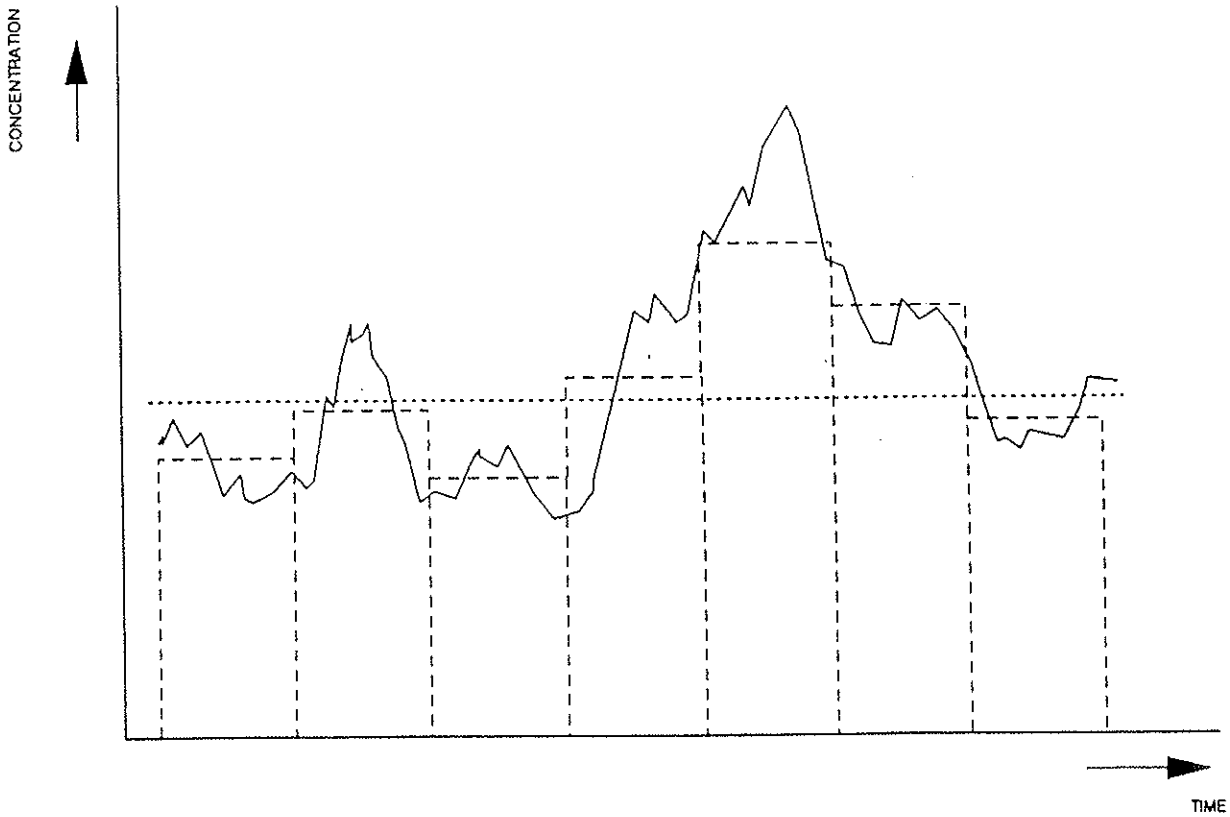
When measurements are necessary or appropriate, the measurement period needs to be considered. The measurement time may have to be a short one (in the context of the working period) where substances having acute effects are present and where the task (see Section 1.2.4) is likely to be the prime exposure determinant. However it may still be necessary to quantify exposures over the full working period, for example, to compare with an occupational exposure limit (see Section 3.7.1).

For substances which present chronic health hazards the full shift would be a more appropriate measurement period. However information could be lost on the specific tasks which are the main sources of exposure and this information would be useful when new control measures may be required. There are several options which can be considered, including the following:

- Sample the full shift or working period. This is convenient as only one sample is obtained but detail related to tasks or specific periods during the day is lost.
- Take a series of sequential measurements over the working period (Figure 1.4). The measurements give shorter time-weighted average concentrations which, with appropriate timing, will reflect the relative contributions made by the various components of a job or task.
- Take a single full-shift sample or series of consecutive samples supplemented by short-term samples (10-15 minutes) during periods of peak exposure.
- Continuously sample and analyse on a real-time basis. Such methods offer the opportunity for accruing a considerable amount of data which records the variations in an individual's exposure profile over the working period. Appropriate computing facilities are usually required to handle the large amount of data generated and continuous monitoring methods are only available for a limited number of substances.

Whatever measurement period or combination of measurements is selected, this has still only taken into account the relevance of the within-shift variation in contaminant concentration. It may also be necessary to consider the variations between individuals, even when they may be doing the same work, and the variations between shifts, or over longer time periods. It will also be necessary to consider the possible importance of exposure to a mixture of substances and the patterns of exposure that may occur (see Section 1.4.2).

The possible effects on exposure of novel shift patterns or overtime working may need to be taken into account. Sampling periods may need to be extended to cover such work routines. Alternatively, provided it can reasonably be assumed that exposures during unsampled periods are comparable with, or not greater than, those experienced during the period sampled, then the data can be corrected. The data obtained will need to be compared to OELs which have been established for the normal five-day week, eight-hour day work routine and techniques are available to do this (see Chapter 4).



NOTES : 1. CONTINUOUS MONITORING MEASURES EXPOSURE ON A REAL-TIME BASIS RESULTING IN A CONCENTRATION PROFILE ( ) ——

2. SEQUENTIAL SAMPLING MEASURES A SERIES OF (USUALLY EQUAL) EXPOSURE PERIODS TO GIVE AN EXPOSURE HISTOGRAM ( ) - -

3. SHIFT MONITORING ONLY GIVES THE AVERAGE EXPOSURE CONCENTRATION EXPERIENCED OVER THE WORKING PERIOD ( ) ···

Figure 1.4
Effects of different measurement methods on data quality

1.3 Other Factors Affecting Sampling Strategies

A number of additional factors of a practical or pragmatic nature also need to be taken into account before undertaking any measurement programme. Such factors will include the overall "quality of approach" rather than the fundamental objectives of the process.

1.3.1 Selection of Equipment

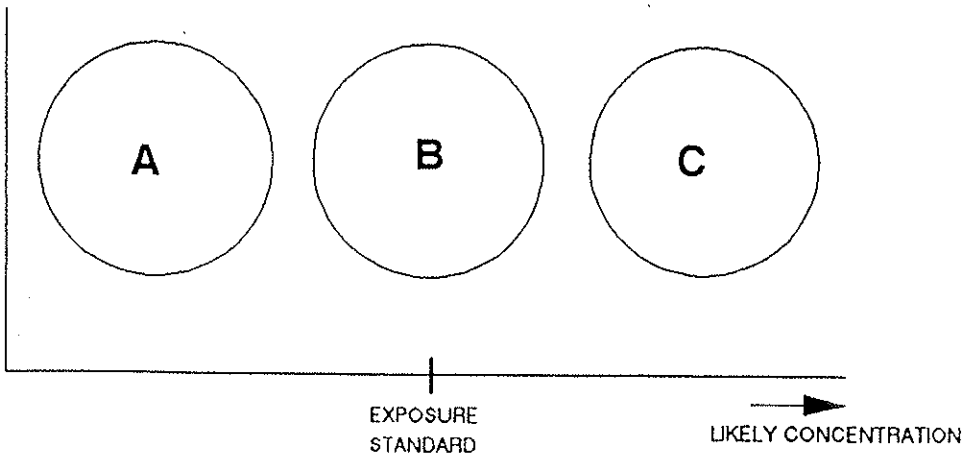
Depending upon the survey objectives, very precise and accurate measurements may not be necessary and a relatively coarse quantification could be acceptable. However, the accuracy and precision of the method will still need to be known. Figure 1.5 shows how the need for precise and accurate measurement may vary in relation to the level of exposure.

Each type of measurement has a different purpose and because of this the requirements to understand and characterise the method will differ.

Rappaport (1991) noted that the sampling and analytical methods chosen should fit the requirements of the sampling strategy and not vice versa. Ideally this should be the case but on occasions practicalities, including the nature of the environment in which the measurements are taken, will dictate otherwise.

The most appropriate sampling equipment to be used in the workplace will be influenced by factors such as:

- The intrinsic safety of equipment.
- Its wearability, spares availability and ease of maintenance.
- Flow-rate range.
- Battery performance over the sampling regime.
- The chosen sampling train must not interfere with the work in such a manner as to either introduce additional risks or influence the task in such as way that the resultant data become atypical (see Section 2.4).



NOTES :

A. METHOD GENERALLY DEMANDS GOOD SENSITIVITY AND REASONABLE SPECIFICITY. PRINCIPLE PURPOSE OF MONITORING IN THIS AREA IS TO FOLLOW TRENDS AND DEMONSTRATE ONGOING SATISFACTORY CONTROL.

B. METHOD REQUIRES GOOD SPECIFICITY AND REASONABLE SENSITIVITY. METHOD SHOULD DETECT TO ONE TENTH OF EXPOSURE LIMIT. PRIME PURPOSE OF MONITORING IN THIS AREA IS TO DETERMINE ADEQUACY OF EXPOSURE CONTROL VERSUS RELEVANT EXPOSURE STANDARD.

C. METHOD UNLIKELY TO REQUIRE GOOD SENSITIVITY OR SPECIFICITY PROVIDED DUE ACCOUNT TAKEN IN INTERPRETATION OF DATA. PRIME PURPOSE OF MONITORING IN THIS REGION IS TO CONFIRM INADEQUATE EXPOSURE CONTROL.

Figure 1.5
Variation in measurement requirements with exposure concentration

In terms of the sampling medium, account also needs to be taken of:

- Whether the medium could be adversely affected by the presence of contaminants within the working environment, *eg* the use of some absorbents in the presence of strong acids, the effect of high humidity atmospheres, the incompatibility of some atmospheres with the de sired collection medium.
- Whether the sampling medium requires remote preparation and is capable of being transported to and from the facility.
- The potential impact of the sample medium on the workplace (many aggressive collection media may not be permissible if they could adversely affect product quality).

Cost clearly is a basic consideration but generally consumable costs are small compared with those for personnel and analytical time. It is therefore important to have reliable equipment which will not fail either during sampling or subsequent procedures.

1.3.2 Measurement Method Validation

Not only must the measurement period be representative of the exposure one is attempting to characterise, but some account must be taken of any adverse effects which either the sampling or analytical methodologies may introduce. The method of obtaining a sample will depend on:

- Sampling method.
- Analytical method.

Both are subject to error. The various components, *eg* sampling equipment, sampling medium, analytical processes, must be compatible. What may be the most desirable choice from one standpoint may be less desirable from the other. The final combination is therefore often a compromise and a strong working relationship should exist between the occupational hygienist and the analytical chemist in reaching a mutual understanding of what needs to be achieved.

In terms of the sampling method, two basic considerations need to be taken into account:

- Is the sampling device (and collection medium) suitable for collecting the contaminant of interest and is the medium compatible with the subsequent analytical method?
- Is sufficient known about the dynamics of the collection process so that any variables can be accounted for in the design of the sampling programme?

A number of factors can influence the selection of the sampling device and collection medium, but in practice they are generally limited to:

- For aerosols, what is the most appropriate device to collect the size range of particles of interest? Are wall losses, either within the sampling head or train, of an order such that account needs to be taken of them?
- For mists, especially, does possible vapour loss need to be taken into account?
- For gases and vapours sampled from a mixed atmosphere does preferential sorption of one or more contaminants take place in the collection medium? Does the presence of high water-vapour levels affect sorption characteristics of the sampling medium or the presence of particulate material adversely effect the collection characteristics?
- With all contaminants, is the total capacity of the collecting medium sufficient to cope with the likely loading of the contaminant given the intended sampling rate over the proposed sampling period?

A further consideration with all contaminants is the practicality of using the selected device. For example:

- A fragile device may not be suitable in an environment where damage could occur.
- A static sampler may need a mains power supply.
- The results may need to be comparable to historical data obtained using a different device.
- A particular device may be specified in regulations or codes of practice. For example, in the UK the Approved Code of Practice for the Control of Asbestos at Work Regulations (CAWR, 1987) requires an approved method.

A basic understanding of the collection efficiency of the method is necessary (or at least assumptions concerning it must be made when interpreting the results). In all cases collection efficiencies will vary with the contaminant and collection medium. However, other contaminant-dependent variables can also affect the overall efficiency. With aerosols, it will be affected by the aerodynamic charac-

teristics of the sampling device, and possible sample loss resulting from overload. For gases and vapours, sample loss principally arises from breakthrough. Breakthrough volumes should be available from equipment suppliers for different combinations of contaminant, collection medium, temperature and relative humidity, in order that appropriate sample volumes can be defined.

Ideally the analytical method should be capable of measuring the contaminant of interest at the concentration that is presented in the sample. Whilst this may appear obvious, the same cannot be said of the process for deciding which analytical method should serve such a basic aim. Extensive literature exists (*eg* Cullis and Firth, 1981; Cralley and Cralley, 1985) which examines the major factors to be considered.

In summary, six properties of an analytical method determine its acceptability for the purpose:

- Specificity
- Sensitivity
- Accuracy
- Precision
- Recovery Efficiency
- Transport Loss/Sample Stability

Whilst each is likely to vary for a particular contaminant and its analytical method, their level of acceptability will be governed by the end use of the technique.

1.3.3 Occupational Exposure Limits

There are various types of standard available for occupational health protection. They are primarily aimed at the occupational exposure of individuals and include OELs for airborne contaminants and biological exposure indices (BEIs) as measures of total intake of a contaminant. Only OELs are of direct interest in this Technical Guide.

There may be considerable differences between OELs set by different authorities for a given substance and this may be due to:

- Differences in the data used to derive the limit.
- Regulatory and cultural differences between countries, affecting the purpose of the OEL and the philosophy underpinning it.
- Different standard-setting philosophies within a single country reflected in national standards or individual company standards.

For the most part OELs attempt to be either 'health-based' or 'pragmatic' in their derivation. Exposure for a working lifetime at or below a health-based exposure limit should not result in any adverse effect in nearly all workers.

On the other hand, exposure for an equivalent period to a pragmatic OEL cannot be assumed to offer similar protection: pragmatic standards either recognise that, for some substances exhibiting stochastic effects, any exposure may result in significant adverse effects, or they incorporate an assessment of the practicality of achieving the standard within industry. Whilst they aim at preventing adverse effects, pragmatic OELs tend to be set as less stringent values than would a 'health-based' standard for the same substance. Controlling exposures to the level of a pragmatic OEL might not prevent adverse effects in the exposed population. Because of the fundamental differences between the two types of standard, differing philosophies also apply to their application and interpretation (see Section 4.2).

Because the time base and application of an OEL can vary, care needs to be exercised when developing any monitoring strategy. The form measurements take can be influenced by OELs; the OEL may require a standardised sampling period, sampling device or analytical method. Of the three, the sampling period is the most common in that the majority of OELs are quoted as concentrations averaged over a specific reference period. However some substances require specific sampling or analytical methods, *eg* cotton, asbestos, rubber fume, mineral fibres. Similarly many substances have recommended sampling or analytical procedures associated with them. For example, within the UK the MDHS (Methods for the Detection of Hazardous Substances) series of publications by the HSE gives

such information for many substances. Comparable information sources are available for standards elsewhere (NIOSH, 1984).

1.3.4 Quality Systems

Many initiatives now exist in industry which address the overall quality of the processes which industry is reliant on to support its activities. International Standard ISO9000 addresses such considerations. In the UK, the application of this standard is described in British Standard BS5750 (BSI, 1987). In certain industrial sectors (*eg* pharmaceuticals, defence manufacturing, food processing) parallel guidance exists which governs the quality of specific aspects of product manufacture. Industry now openly embraces such principles in most of its production activities and is now turning its attention to functional support areas such as occupational health (Hoare, 1991). Therefore, the option is available either to follow the systems in operation within an organisation or to embrace those which may be available outside and which satisfy the quality requirements relating to occupational hygiene.

The procedures by which measurement methods and programmes are established and managed and samples obtained, analysed and interpreted are all suitable for incorporation into quality systems. Within the UK, the Health and Safety Executive (HSE) provides guidance on some of these considerations (HSE, 1991) and the National Measurement Accreditation Scheme (NAMAS) operated by the Department of Trade and Industry exists for such purposes. Specific quality control schemes are also supported by HSE for some analytical procedures *eg* the Workplace Analysis Scheme for Proficiency (WASP) and the Regular Interlaboratory Counting Exchanges (RICE) scheme.

Similar schemes exist elsewhere, for example, the Proficiency Analytical Testing Program (PAT Program), a collaborative effort of the American Industrial Hygiene Association and National Institute of Occupational Safety and Health, follows a similar approach (Abell and Doemeny, 1991).

Good occupational hygiene practice dictates that self-applied quality control should form part of the process regardless of the existence or otherwise of recognised quality assurance schemes (Stillman *et al*, 1991). In formulating and executing any survey, it is possible to introduce the principles of quality at most stages. For example, the measurement protocol should be agreed in advance and adhered to, and sampling and analytical variation can be assessed using blank, spiked and side-by-side samples. Indeed, many of these internal controls form an integral part of the quality schemes administered by external organisations.

However, such initiatives have until now been directed mainly at the analytical methodology. They have not been applied to sampling methodology and practice. The overall quality of the data is dependent on both; having a quality analytical procedure does not guarantee a quality approach to obtaining the sample and the subsequent interpretation of the results.

Apart from the integrity of the data there is also a need to ensure that the overall approach to the assessment and resolution of any problem is undertaken along quality lines. Any report arising from the process must contain sufficient information to arrive independently at conclusions similar to those contained in the report. Whilst it is to be expected that, by employing qualified occupational hygienists, a quality programme will ensue, this is not always realised in practice.

In terms of the 'total quality' of any survey undertaken the efficiency and proficiency of the individuals carrying out the work is critical. Technical competence is necessary but so are management and inter-personal skills, Nowadays, the expectation within industry is not only one of producing an excellent product, but also achieving it by a process which is internally efficient and responsive to the customers' expectations and demands. Similar considerations should be applied to and by those undertaking surveys. The occupational hygienist's 'customers' will range from the shopfloor to senior management.

It is essential that the interest, cooperation, active commitment and knowledge of the management, supervisors, workforce and their representatives (*eg* Trade Unions, Health & Safety Representatives *etc*) be obtained at all stages in the process. After all it is their health which may be at risk. They will also be most affected by any monitoring. Initially there are the obvious short-term effects (*eg* the "nuisance" caused and possible effects on work schedules *etc*) and the survey may indicate that changes are needed which may involve long-term cost and disruption. Everyone needs to be convinced of the need for the measurements and understand the potential benefits. An open exchange of information is essential so that a measurement programme can be developed in a climate of co-operation and trust. Morton Corn in his review of air sampling strategies (Corn, 1985) makes the following point:

"Failure to deal adequately with this aspect of the sampling strategy has resulted, for example, in accusations of my performing time and motion studies and of air pumps being suspected of being tape recorders!"

With such a lack of empathy, non-co-operation may be the least of the problems; positive sabotage and total dismissal of the results become a real possibility.

If sabotage is suspected and gross results arise which appear at odds with the expected pattern of exposures these results require further investigation. Elevated exposures cannot be dismissed simply on the basis of suspected sabotage and must be followed up with a detailed examination of how the task may have given rise to the recorded exposure. Sabotage is generally associated with one or two individuals in a work group and tends to be found only in the first one or two samples from such people. The likelihood of it arising is substantially reduced provided the workforce is made aware of the reasons for and intended outcome of any survey. However, should this situation arise, it soon diminishes if the measurement is repeated on several occasions.

If the philosophy of Total Quality Management were to be applied, any unnecessary sampling or analysis represents a failure cost. The failure may be in the planning and execution of the survey or may be fundamental and be a failure to implement adequate control measures, thereby triggering the need for a survey. Whatever the source of failure it will represent a waste of resources which should not have been incurred.

It is perhaps unfortunate that the only standards most people refer to in occupational hygiene are those which exist for atmospheric exposure concentrations. Part of the total quality approach which most health professions should aspire to are performance standards; that is, the acceptable standard is a level of health-risk control which will not result in adverse ill health or disease in either the working population or other affected communities. Attaining such a standard represents a synthesis of a number of different occupational health and hygiene factors, all of which contribute to improved performance once implemented. Conformity with exposure standards is thus only one element in such a process. Performance standards, however, are more difficult to assess in terms of achievement than straightforward numerical standards, but they are a better measure if the ultimate objective is the prevention of disease. Because performance standards focus on an organisation's ability to manage successfully risks to health, their adoption implies a process of continual review and improvement.

The Responsible Care programme promoted by the chemical industry (CIA,1992) is one example of a performance standard: a company committed to the principles of Responsible Care embarks on a process of continual review and improvement in all areas of safety, health and environmental risk. The Company's performance is judged not only by the standards it achieves today, but by the standard it aspires to and the demonstrable rate of progress towards it. As time progresses the standards themselves will be reviewed and changed.

1.3.5 Records and Reports

When developing a survey strategy it is good practice to record the strategy and its objectives. This may not be reported in detail to the 'customer' but it is a useful quality step in the overall procedure because:

- It assists in the planning process.
- It provides a record against which any subsequent proposals for changes in the strategy can be assessed.
- In long-term studies it is an essential record to prevent corruption of the original strategy. Changes may have to be made as the workplace changes and inevitably staff involved in the survey will change and word-of-mouth is not an adequate means of passing on essential information.

Adequate data recording was noted in the previous section as being a key factor in developing a quality approach to atmospheric measurements. The measurement process and the interpretation of resulting data require the application of scientific method. It is therefore crucial that relevant information about the work environment and the events occurring in the workplace which may affect the results are recorded at the time the samples are taken. Whilst this may appear common sense, in practice there are difficulties. Decisions have to be made about which events or information are sufficiently important to warrant recording and what form the records should take.

Because the workplace is dynamic and resultant exposures are dependent on many factors it is possible to note many events which may contribute. Records also need to be kept of the measurement methods used. In practice the large number of possible items of information can be reduced to manageable levels. Records must contain the key information required to reach any conclusion made and should be sufficiently comprehensive for any retrospective analysis of the results, *eg* in subsequent epidemiological studies.

The National Exposure Database (NEDB) operated by the Health and Safety Executive was established in 1986 (Burns and Beaumont, 1989). This contains exposure data, together with the relevant key information required for interpretation of the data. The database structure has been published to enable private organisations to collect and record occupational hygiene data which will be in a broadly compatible form.The requirements for what constitutes key data have recently been redefined (Beaumont and Dalrymple, 1992). Collecting and recording data in a disorganised manner may fulfil an organisation's short-term requirements, but it does not allow data to be pooled or assist their future examination. The negative consequences of such actions for occupational health, both now and in the future, are obvious. In his review of challenges still facing occupational health, Baker (1989) recognised that it was not until this aspect had been satisfactorily resolved that occupational disease recognition and control would be at a similar standard to that now achieved by communicable disease surveillance systems.

The final output from the process, the report, should be timely, understandable to the recipient, and represent value for money, giving clear conclusions, recommendations or proposed actions which are supported by the data and other information.

1.4 Exposure to Mixtures

1.4.1 Introduction

When devising a monitoring strategy it should be recognised that workers are usually exposed to a mixture of substances at work. Even ostensibly single component substances may contain isomers, congeners, stabilisers, impurities, anti-oxidants or other materials in sufficient quantities for the whole to be best regarded as a mixture. In fact it is probably rare for a worker to be exposed to a single substance, although one substance may dominate the exposure.

The aims of a survey and the basic questions underlying its need are essentially the same whether exposure is to a single substance or a mixture. Hence the questions of what the data will be used for and how they can be most effectively and efficiently obtained remain the starting point for deciding the strategy. The project management approach to the overall strategy is thus applicable. However, this has to be set into the context of the complexity of mixed exposure situations, the constraints that this puts on measurement methods and the decisions which will need to be made on how to interpret any data obtained. The answers to the questions which guide the strategy may thus be different for mixed exposures compared with single substance measurements (see Chapter 2).

1.4.2 Patterns of Exposure

Exposure to several substances can occur in one, or both, of two basic patterns: simultaneous or consecutive exposures.

- Simultaneous exposure to a number of substances can occur because of direct involvement with the work (*eg* applying adhesives) or because of contamination of the workplace by substances from several adjacent processes (*eg* in an engineering workshop there may be pollutants from machining, welding, degreasing, cleaning *etc*).

- Consecutive exposures occur when changes to a worker's local environment cause changes to the nature of the potential pollutants. This can happen by the worker moving, either between jobs (*eg* on maintenance work, or collecting QC samples on a chemical plant), or by moving between sites (*eg* peripatetic contract workers). Alternatively the nature of the contaminants may vary at different stages of a process. Sequential exposure may occur over part of a shift, a whole shift, several days, or even longer periods. The significance, or otherwise, of the temporal pattern of exposure will depend on the way the body handles the substances involved. For instance there is an obvious difference between substances which may accumulate and those with short half-lives in the body.

Which pattern of mixed exposure is occurring has significant implications for the sampling strategy used, especially with respect to the time and pattern of sampling, the sampling and analytical methods and the interpretation of the results.

1.4.3 Types of Mixture

There are various ways in which mixtures may be categorised (*eg* by composition, by source *etc*) but five categories can be envisaged which have particular significance to a sampling strategy.

These types are:

- Natural mixtures.
- Petroleum based mixtures.
- Formulated mixtures.
- Processing mixtures.
- Combined mixtures.

Thinking of mixtures in these terms highlights interesting properties of these classes which are useful in devising sampling strategies.

- *Natural mixtures.* These come from the extraction and processing of naturally occurring substances (*eg* tea, vegetable oils, mineral ores). Their composition is often not known in detail and may vary between sources, seasons, processes *etc.* Such mixtures are often defined by their physical properties or production processes. It is rare for these mixtures, or their individual components, to have OELs assigned. However, specific ill-effects of the product (*eg* respiratory sensitisation to castor beans, or animal products) or a component (*eg* dermatitis due to limonene and its oxidation products in citrus oils) are often well documented.

- *Petroleum based mixtures.* These are a sub-set of "natural mixtures" and include Special Boiling Point Solvents (SBPs), white spirit and various fuels. Some solvents which consist of mixed isomers (*eg* xylene and trimethyl benzene) also fall into this group. They are the end-result of processing a natural product, but generally much more is known about their composition than for "natural mixtures". They are again often defined by their physical properties and their detailed composition will vary with source and processing. An important difference is that these mixtures, and many of their individual components, may have been assigned OELs.

- *Formulated mixtures.* These are produced by mixing components to a pre-defined formula to give products for specific applications. Examples include paints, cleaning solutions, hard-metal dust, adhesives *etc.* Their compositions are thus, in principle, "known" (although some components may themselves be "natural mixtures" or "petroleum derived mixtures") and the composition of the product is controlled. The final "formulated mixture" is unlikely to have an OEL, but its major constituents may well have been assigned OELs.

- *Processing mixtures.* "Processing mixtures" are those which arise adventitiously from a process; frequently this involves the application of heat and consequent thermal breakdown of the substances being processed. Examples include rubber fume, welding fume, plastic fume, solder fume and fuel exhausts. These are complex mixtures whose composition may change rapidly with such factors as temperature, oxygen supply and feedstock. They contain a range of identified and unidentified substances, some of which may have OELs in their own right (for example various aldehydes are commonly found in the fume from thermal processing of organic materials). Furthermore some of these processing mixtures have been set OELs (*eg* rubber fume or welding fume).

- *Combined mixtures.* In any one workplace exposure may be to several different types of mixture and various relatively pure single compounds to give a combination of mixed exposures.

The question: "What is to be measured?" takes on a new level of significance when applied to mixtures and may guide the whole sampling strategy. Deciding on what is to be measured is dependent on two factors:

- How are the data to be used and interpreted?
- What can, or should, be measured?

1.4.4 Use of the Data

How the measurement results will be interpreted can influence the whole measurement strategy, especially in relation to achieving the basic aim of protecting workers' health. In particular the joint toxic action of several chemicals may be different from the sum of their individual effects at the same concentrations. Various theoretical approaches have been developed to estimating the combined toxicological effects (especially LD50s) of simultaneous exposure to many single chemicals. These have led to various ways of categorising these joint effects. (For the theoretical and historical background see Bliss (1939), Finney (1971), UNSCEAR (1982) and Hoel (1987)). These in turn have been extrapolated to workplace exposure and into schemes to check compliance with OELs in mixed exposure situations (*eg* ACGIH (1991-92), BFAS (1985), CIA (1993) and HSE (1992)).

For application to the workplace it is probably most useful to consider four categories of joint toxic effects:

- *Independent action.* Each component acts in an individual way in the body which is different from, and unaffected by, the effects of the other components.
- *Additive action.* The combined toxic effects are the simple sum of the toxic effects of each component acting alone.
- *Synergistic action.* The combined toxic effects are greater than the simple sum of the toxic effects of the individual components acting alone. (A special case arises when one component is essentially without a particular toxicity, but the combined toxic effects are still greater than the sum of the individual effects. This is usually referred to as potentiation).
- *Antagonistic action.* The combined toxic effects are less than the simple sum of the toxic effects of each component acting alone.

In a real mixed exposure situation several types of toxic interaction may be occurring and the information on which to judge this is usually sparse. It is therefore generally unwise to assume independent action unless there is good evidence for this and additive effects are therefore frequently assumed to be likely. When substances in the mixture have OELs the assumption of additivity means that for adequate control of exposure, or compliance with OELs, the sum of the ratios of measured exposures for individual compounds (C) to their OELs must be less than, or equal to, one. This is expressed in the so-called "additive equation" where, when "C" and OEL have the same units:

$$C_1/OEL_1 + C_2/OEL_2 + \ldots C_n/OEL_n \leq 1$$

The assumption of additivity has the advantages that it avoids the need to distinguish additive and independent systems and provides a conservative approach to the control of exposure. However, the "additive equation" must always be applied with caution:

- It was developed for application to the frequency of effects but not to the severity of graded effects. The original application was to events with a yes/no outcome (*eg* LD50s, LD10s *etc*) not to OELs which represent some "acceptable" degree of exposure on a rising scale of effect.
- The statistical treatment leading to the additive equation may, or may not, be applicable to the effects of long-term, low-level exposures, or some types of delayed effects. Again this is because the original applications were to acute effects.
- OELs are not static but evolve with knowledge and changing perceptions of "acceptable" risk.
- As previously noted (Section 1.3.3) OELs are defined in various ways in different countries and some countries have more than one type of OEL. The two types of UK OEL have different philosophical bases, different compliance interpretations and different practical implications. This makes it difficult to include substances with different OELs in an additive approach, although one approach has been suggested (CIA, 1993). Occupational hygienists in other countries will need to consider how their own criteria are to be interpreted.

- Even when substances have the same target organ their OELs may have been set on different lead toxic effects, *eg* even in an homologous series of organic chemicals some may have had OELs set on, say, liver damage and others on irritation. In recognition of this problem attempts have been made to produce Effect Specific Limit Values (ESLVs) for solvent mixtures (Scheffers *et al*, 1985; Manz and Manz, 1987). Thus, for each solvent, ESLVs were estimated for individual effects *eg* mucous membrane irritation and pre-narcotic effects and used to calculate effect-specific Exposure Indices (EIs) using the additive equation. Whilst this approach is logical it should be noted that OELs for many solvents are much lower than their ESLVs for specific effects.

To be able to consider applying such concepts as the additive equation means that the question of "What can or should be measured?" is not a trivial one when mixed exposures are involved. This question becomes even more important when designing a strategy for mixed exposure situations where there are unknown components, or components without OELs. It is further complicated by the aims of the strategy; very different strategic approaches may be chosen for testing adequacy of control compared with, for instance, obtaining data for development of a standard. The next section considers this in some detail.

1.4.5 What can or should be Measured?

There are several ways of answering this question. Which of them is chosen depends on the aims of the work, especially in the context of how the data will be used, and this determines the strategy.

There are four basic possibilities and these involve the identification and quantification of:

- All, or many, of the individual components in the worker's breathing zone.
- The total "mixture".
- A single substance, or substances, as a guide to exposure and control.
- A surrogate material as a guide to exposure.

Considering each of these in turn:

a) *Quantification of all, or many, components*

Modern measurement methods provide opportunities to identify and quantify large numbers of atmospheric pollutants. However, the desirability of doing this needs to be set in the context of the resources available and how the data are to be used.

Where the aim is to compare exposures with OELs then those substances which have been set OELs need to be measured. The availability of the data also makes it possible to apply the additive equation as necessary. Generally this is likely to be most useful where formulated mixtures, or some petroleum based mixtures, are present.

A strategy involving quantifying exposure to as many components as possible may also be necessary when the aim is to map the type and extent of exposure with a view to improving control, or obtaining data for setting OELs. This may also necessitate identifying unknowns in complex fume (*eg* where the potential formation of a carcinogen might imply the need for tighter control of exposure).

b) *Quantification of the total mixture*

There are several ways in which quantification of total exposures may be used.

- Measuring the total mixture when this has an OEL against which conditions can be compared (*eg* rubber dust, rubber fume and white spirit).
- Measuring total mixtures of dust when no OEL is available. For instance, in the UK total concentrations of any inhalable dust of 10mg/m^3 (8-hour TWA), or greater, would be regarded as "substantial" concentrations under COSHH.
- Measuring total mixed exposures as a measure of control. Examples would be the measurement of total inhalable dust for "natural mixtures".

In each case the results allow patterns of exposure to be mapped, controls to be assessed and the effects of improving controls to be seen even in the absence of OELs.

c) *Quantification of a single substance as a guide to exposure and control*

In many situations it is only necessary, or desirable, to measure a limited number of substances in the mixture. Examples include situations where:

- Measurement methods are not available for all the pollutants.
- There are many components which have no OELs.
- There are unidentified components.
- Quantification of all components would be excessively expensive in terms of money and time. (This is especially significant if the money might be better spent on control).

To resolve the situation it may be necessary to reduce the number of substances to be measured to one, or several, key components. The chosen key component(s) can then be measured alone as a guide to exposure and control. There are several criteria which can be used in guiding the choice of a key substance in any given situation *viz* the existence of OELs; the component present in the highest concentration; and the toxicity of the individual substance.

The existence of OELs

In any complex mixture it is often the case that only a limited number of the substances present have been set OELs. This of necessity means using these as the key substances for sampling when the aim of the survey is to check compliance with standards. When substances with different types of OEL are present (*eg* occupational exposure standards (OESs) and maximum exposure limits (MELs) in the UK) the differences in definition must be taken into account when deciding on key components. Thus the requirement to keep exposures as low as reasonably practicable below the MEL is likely to lead to more stringent controls than if substances with OESs are considered.

Component present in highest concentration

Where the components of an airborne mixture have OELs then the substance(s) which occurs at the highest concentration may be useful as a key component.

It is sometimes possible to predict which component will be present in air at the highest concentration from the analysis of the bulk material. However, the relative compositions of, say, a solvent mixture in the bulk liquid or air will depend on such factors as the volatilities of the individual components and any binding forces between components in the bulk phase (*eg* H-bonding). The sort of differences which can arise between bulk liquid and airborne compositions is illustrated in a CONCAWE study of exposure to gasoline (CONCAWE, 1987). Here the mean percentage of C6 hydrocarbons in a range of liquid gasolines was measured as 14.2% (range: 7.8 - 17.4%) whilst in the corresponding gasoline vapours it was measured as 6.8% (range: 1.3 - 18.1%). By comparison C4 hydrocarbons formed only 5.4% (range: 0.9 - 8.1%) of liquid gasoline, but 34.9% (range: 15.2 - 44.5%) of gasoline vapour. A method of predicting hydrocarbon distillate vapour compositions is available (BOHS, 1982).

The toxicity of the individual substances

The relative toxicity of individual components in a mixture can provide the basic criterion for choosing key compounds to measure. The essential idea is that controlling exposure to the most toxic substance(s) will ensure the exposure to others is adequately controlled. There are several aspects to this:

- Substances which may be carcinogenic (*eg* polycyclic aromatic hydrocarbons in exhausts) or respiratory sensitisers (*eg* some plasticisers or monomers in fume from thermal processing of plastics) will need to be given priority over other components.

- For non-carcinogens the relative OEL values where available can be used as a guide to choosing the key compound. For instance in mixtures of aromatic hydrocarbons the trimethylbenzenes might be suitable key components because of their relatively low OEL (25ppm 8-hour TWA) compared with toluene, xylene *etc*. In making this decision one needs to be sure that the OELs being compared have been based on similar health considerations.
- One particular substance may have such an unusual toxic effect compared to the others that this, as well as reference to the OELs, leads to it being chosen as a key component (*eg* in mixed hydrocarbons n-hexane may be chosen because this substance causes peripheral neuropathy).

- It may be possible to use OELs and/or general toxicity parameters to decide on a key component from the bulk analysis. However, the same provisos apply as when trying to use bulk composition as a guide to airborne composition (see above).

- It is advantageous in choosing a key component to consider the OELs and vapour pressures (at the temperature of use) of the substances present. This takes account of the fact that it is not merely the OEL which is significant but also the ease with which the OEL is reached in practice. Various attempts have been made to develop hazard indicators on this basis and some may be useful in deciding key components in mixtures (Langner *et al*, 1979; Pitt, 1982; Popendorf, 1984). As an example Pitt (1982) has proposed a "Vapour Hazard Index" (VHI) defined thus:

$$VHI = \frac{\text{Concentration of saturated vapour}}{(\text{OEL}) \times 1000}$$

This is of course temperature dependent, but comparison of VHIs at a given temperature can give an indication of relative hazard and hence guide the choice of key components.

d) *Quantification of a surrogate substance*

It is sometimes possible to use an easily quantified material as a surrogate measure of a component which is more difficult to quantify. Total dust measurements are frequently used in this way. There are two general approaches:

- Total dust by gravimetric analysis is kept below the concentration set for the substance with the lowest OEL in the mixture.

- When the percentage of the most active substance in the airborne mixture is known then a different situation may arise. Here the concentration of total dust can be allowed to rise to some level above the OEL of the most active ingredient without risk of exceeding this OEL provided it does not exceed 5mg/m^3 for respirable dust or 10mg/m^3 for inhalable dust.

2 SAMPLING STRATEGIES: A STRUCTURED APPROACH

2.1 Introduction

The obvious utility of a structured approach to sampling has led to various publications examining how this can be achieved, including attempts to formalise strategies into general standards. Some of the different perspectives brought to this include:

- Guidance on sampling strategies in relation to compliance with national legislation or national exposure standards. Examples include publications from the UK (HSE, 1989), the USA (Leidel *et al*, 1977), Germany (BFAS, 1984) and France (Herve-Bazin, 1989).

- Attempts to produce supra-national standards. Examples include a draft European Standard (CEN, 1992) and earlier reports by the European Council of Chemical Manufacturers' Federations (CEFIC, 1984) and The World Health Organisation (WHO, 1984).

- The use of statistical techniques to rationalise and maximise information from sampling programmes. Examples include Roach (1977), Nenadic (1981), Petersen *et al* (1986), Rappaport (1991) and Rock and Cohoon (1983).

- General reviews or critiques of sampling strategies. Examples include Corn (1981, 1985), Goelzer and O'Neill (1985), Hosey (1973), Lynch (1985), Olishifski (1979), Still and Wells (1989) and a Swedish Environment Fund publication (SWEF, 1988).

- The consideration of sampling strategies and their management for particular industries or processes. Examples include studies by Rackham *et al* (1989), Damiano (1989), Lichtenstein *et al* (1983), and Lynch *et al* (1982).

When such a wide range of perspectives exists it is not surprising that authorities differ in the details of approaches to sampling strategies. (For instance, in relation to the use of personal or area sampling). However, a structured approach based on a series of steps is a common theme. Four basic elements can usually be distinguished:

- Initial appraisal.

- Basic survey.

- Detailed survey.

- Routine surveys.

The names given to these stages can vary and some schemes may have different numbers of elements (*eg* three-stage strategies are common in which the initial appraisal and basic survey are combined into one step), but the principles remain similar throughout.

Some countries have legislation which, wholly or partly, formalises this sort of approach. Occupational hygienists in different countries will therefore need to set their sampling strategies in the context of their own national laws and standards. As an example, in the UK the Control of Substances Hazardous to Health Regulations 1988 (COSHH, 1988) require that employers make an assessment of the risks to health created by the work and of the consequential measures needed to protect the workforce. This assessment will certainly involve an appraisal of the hazards and may require measurements to assess the risk and hence the control measures needed. The assessment under COSHH may thus involve all of the first three strategy elements noted above, or end after the first or second depending on the circumstances. Furthermore there are specific requirements under COSHH for routine monitoring (element four above) in some circumstances.

The four stages to the sampling strategy are examined individually in detail below.

2.2 Initial Appraisal

Since the initial appraisal of a workplace does not involve sampling *per se* there is sometimes a tendency to regard it as not really being part of the strategy. However, an appraisal of all available pertinent information is an essential first step in deciding whether or not a quantitative air sampling survey is necessary and, if it is, where it should be targeted. The objective of the initial appraisal should thus be to obtain sufficient information to answer the following questions:

- What are the potential exposures?
- Where and when do they occur?
- Can the exposures be allocated priorities in hazard/risk terms?
- Is a quantitative survey needed?
- What should the strategy be for the subsequent basic and/or detailed surveys if these are necessary?

To answer these questions a range of information is needed on factors related to the substance and to the workplace.

Deciding which substances may cause exposure in the workplace and obtaining information on them is a primary step in the initial appraisal. As previously noted (Section 1.4.1) exposure may be to a single substance or more frequently a mixture of substances which may be poorly characterised (*eg* various hot process fumes). Even in a relatively small workplace, there may be a large number of potential contaminants.

There are many ways of classifying the types of material which may be encountered in the workplace. The following, incomplete, list gives an idea of possible types of substance to which exposure can occur:

- Raw materials (*eg* ores, reagent chemicals).
- Contaminants of raw materials which may be naturally present (*eg* arsenic with other metal ores) or by-products from previous processing (*eg* historically ß-naphthylamine or benzidines in rubber chemicals).
- Ancillary chemicals (*eg* catalysts, reaction solvents *etc*).
- Intermediates which may, or may not, be isolated (*eg* in the production of pharmaceuticals and fine chemicals).
- End-products (*eg* single substances or formulations) and impurities therein.
- By-products (*eg* various useful "side-streams" may be by-products of the main reaction in a chemical production plant).
- Waste-products (examples range from reaction residues to used engine oils).
- Formulated products (*eg* paints, adhesives, cleaning agents *etc*).

- Part of the workplace (*eg* insulation).
- By-products from support processes (*eg* welding).

Once the substances present have been identified information on them needs to be collected and collated. This will consist of basic information on the substances amplified by setting it into the context of their use in the workplace. All the time the objective should be borne in mind - i.e. to form a judgment on the intrinsic hazard posed by the substances and the risk which may arise due to their presence.

Substance related factors which need to be considered include the following:

- *Physical properties*. Especially those which influence how easily the substance may become airborne; examples are boiling point, vapour pressure, saturated vapour pressure, relative evaporation rate, dustiness, particle size distribution, ability to sublime *etc*.
- *Physical form in the workplace*. Is it a gas, vapour, mist, fume, or if it is an aerosol, is it fibrous and is it of inspirable or respirable size?
- *Any indications of how hazardous the substance may be*. This could include any known toxic effects in man (both acute and chronic); other indications of toxicity (*eg* animal studies, *in vitro* tests, structural factors, *etc*); any special toxic potential (carcinogenicity, respiratory sensitisation, reprotoxicity *etc*); and any indication of increased hazard from exposure to mixtures of substances.
- *Potential routes of intake* (especially inhalation and percutaneous absorption) and their likely relative importance.
- *Any effects on skin* (*eg* corrosion, dermatitis) or mucous membranes (*eg* drying, irritation).
- *Any available OELs* and the documentation for these.

For this initial appraisal the basic information should be obtainable from container and package labels and data sheets provided by manufacturers, suppliers and importers. This can often be supplemented by reference to compilations of data such as "Patty" (Cralley and Cralley, 1985), Sittig (1985), "Sax" (Sax and Lewis, 1989) *etc*. (However, secondary sources of information must always be used with some care). For many individual substances there are other sources of information including publications from national bodies (such as the HSE in the UK; the National Institute for Occupational Safety and Health (NIOSH) and the Environmental Protection Agency (EPA) in the USA; the Canadian Centre for Occupational Health and Safety (CCOHS) *etc* and international bodies (such as the World Health Organisation (WHO)) and various specialist publications and data-bases.

To gauge the potential for, and extent of, exposure to substances in use a detailed review of the processes and procedures is required. Collection and analysis of this information needs to be approached somewhat differently from the substance information. The information required is much more based on observation and depends on watching the processes and talking to the personnel, for what happens in practice is rarely a direct implementation of written protocols.

The areas to be covered and the sort of questions to be asked include the following:

- *Production processes*. "What are the processes?"; "Are they continuous, batch, campaign *etc*?"; "What substances are used?"; "Why?" (i.e. could other materials be used instead?); "What is the throughput of chemicals?"; "What are the feedstock use rates and production rates?"
- *Workplace design*. "What is the layout?"; "Why is it like this?"; "Is the layout likely to contribute to the risk of exposure?" (*eg* by introducing extra, or unnecessary, transport/transfer processes).
- *Job functions and techniques*. "What do the workers actually do?"; "How does this influence their potential exposures?"; "How much manual handling is there?"; "How much of the work is automated, or could be?"; "Have individuals developed their own techniques and will these reduce, or increase, exposure?"; "Are there obvious ergonomic factors (*eg* size, shape, sex of the worker in relation to a job)?"

- *Patterns of work.* "Are workers dedicated to one job or do they move around?"; "What shifts are worked?"; "How do conditions vary during night shifts, close-down for maintenance *etc*?"; "Are there any unusual working patterns which may affect exposure (*eg* of maintenance personnel)?"; "Are there non-routine tasks which may be of significance to exposure (*eg* product re-working, system break-in to clear blockages *etc*)?"

- *Sources of exposure.* "What sources of exposure are present?"; "Are there manual transfer or loading/unloading processes; open tanks/containers; hot sources; *etc*?"; "How widespread is the contamination likely to be?"; "What stages of the process are most polluting?"

- *Exposure times.* "How long do workers spend at job where exposure may occur?"; "Is there a likelihood of high short-term exposures?"; "How long would these be?"; "Are there unusual work schedules (*eg* extended shifts)?"

- *Control measures.* "What control measures are in place (*eg* enclosure, containment, general ventilation, local exhaust ventilation, *etc*)?"; "Are these obviously useful/useless?"; "Do they make sense in the context of the process?"; "Are they used consistently/effectively?"; "If not - why not?" (for instance are there design/job/personnel factors which militate against their effective use?); "Is Personal Protective Equipment (PPE) supplied/used?"; "Is its use/storage/maintenance *etc* effective?"

- *Have there been previous investigations* and what were the findings?

During the initial appraisal it is very important that the adequacy of personal protective equipment, including respirators, is properly considered for several reasons including:

- When the risk is primarily from skin contact with a substance, airborne contaminant measurements will be of little value. There may be a need to improve the PPE supplied or aspects of the PPE management programme. There may be a need to consider some form of health surveillance.

- When inhalation of the substance may lead to acute toxic effects and peak exposures may exceed the maximum use concentration of the respiratory protective equipment. Also, for example, many respiratory sensitisers currently have eight-hour time-weighted average OELs which do not reflect the importance of short-term peak exposures in initiating immunological responses.

Insight into how workplace factors are affecting potential exposures may be obtained in the initial appraisal by the use of simple qualitative tests.

The most basic of these are the hygienist's senses:

- *Sight* - can dust be seen in the air at the process, is it on floors, walls, machinery, personnel, pipes, ledges *etc*? It has to come from somewhere and its dispersion may be simply controlled.

- *Touch* - do floors, walls, hand-rails *etc* feel "sticky" or stain hands/gloves? Again where is this coming from and why?

- *Smell* - what odours are noticeable and when do they occur during the process? Odour is a notoriously inadequate guide to hazard or risk, but odour may indicate escape of pollutant and a changing pattern of odour may assist in pin-pointing the cause.

The use of real-time measuring instruments or detector tubes can help to identify emission sources or employees with significant exposures. The information obtained will be very limited in both quantity and quality and should at this stage be treated qualitatively, using the information to support observations, for example.

The "dust lamp", which allows the visualisation of very fine airborne dust particles invisible under normal lighting, is a very useful qualitative tool (BOHS, 1987). This works by utilising the Tyndall effect, involving the scattering of light by fine particles. To maximise the effectiveness of the dust lamp two people are really needed, but it is excellent for identifying emission sources, studying dust dispersion and illustrating how exposures occur. Because the potential pollutant is made visible it is a very good teaching aid.

Smoke tubes, or pellets, are also useful in studying general air movements and the effectiveness of exhaust ventilation. Again these have the advantage of producing visual effects.

The basic information obtained from the initial appraisal should fairly easily cover the "What?", "When?" and "Where?" of potential exposure. The combination of this with substance-based hazard information will, with more difficulty, allow levels of risk to be defined. In practice areas of low and high risk are often easily identified, the "grey" intermediate risk areas tend to be more problematic. With respect to the risk, the perceptions of the workforce will need to be taken into account. Workers' qualitative estimates of exposure (*eg* high, medium, low, none: or good, average, poor) often agree quite well with quantitative measurements, especially where visible pollutants such as dust are involved (Woitowitz *et al*, 1970; doPico, 1982; Rom *et al*, 1983) though task misclassification is often a problem (Kromhout *et al*, 1987). However, their views on the relative importance of the exposures may well differ from those of the professional occupational hygienist, particularly when effects such as irritation at one job have to be balanced against potential long-term effects at another. (For instance, even with the intense publicity surrounding asbestos it is not uncommon for workers to consider glass-fibre products as being much worse because of their immediate and noticeable irritant effects). However, they are the major "customer" and their views will be important to the credibility of any measurements and the success of any subsequent recommendations. Once the priorities are decided, and everyone understands and is content with these, decisions can be made on whether a quantitative survey is needed, where this should be targeted and what strategy should be followed.

The initial appraisal can in many, perhaps the majority of, cases provide a sufficiently detailed assessment of hazard and risk to allow decisions to be made, *eg* that conditions are satisfactory or that additional control measures are necessary (sometimes immediately), without recourse to measuring airborne contaminants. This is an important aspect of the overall strategy, potentially eliminating the time and cost for a quantitative survey. (This aspect of the overall strategy is discussed by SWEF (1988)).

2.3 Basic Survey

Following the initial appraisal it may be necessary to obtain quantitative information on the exposure of the workforce. A basic survey is likely to be required when:

- The initial appraisal suggests that an exposure problem may exist.
- A new process is being started-up.
- There have been substantial changes to the process, operations or control measures.
- Unusual, infrequent or intermittent processes or operations are to be conducted *eg* maintenance, decommissioning of plant, special cleaning operations, infrequent batch processing *etc*.
- An occupational exposure limit has been set where one did not previously exist.

In some situations it may be necessary to follow the initial appraisal immediately with a detailed survey. This depends on what is found and the professional judgment of the hygienist. The overall strategy should be flexible enough to allow this.

A basic survey will have limited objectives but these should include obtaining sufficient information to answer the following questions:

- Does an exposure problem exist as suggested by the initial appraisal?
- Are available engineering, or other, controls adequate and likely to remain so?
- Is a more detailed survey necessary and what strategy should it follow?

Because of the limited aims of the basic survey, and in the interest of parsimony, it may be possible to obtain sufficient information without recourse to sampling. Sufficient data may be available from other sources to allow a decision to be made as to whether further work is necessary. Such information sources include:

- *Earlier measurements*. Historic measurements can be useful, but they need careful interpretation. There are several caveats to their use; for instance "Were the measurement methods used adequate by current standards?" and "Have the materials or processes or working methods changed in ways which might affect exposure?".

- *Measurements from comparable installations or workplaces*. Again careful interpretation is essential. Even where the same plant and materials are in use there may be obvious differences between sites (*eg* layout, size, ventilation). Other more subtle differences (*eg* in work practices, pattern of breaks, job sharing *etc*) may also alter the degree and pattern of exposure. For some processes (examples could be maintenance and painting) conditions are so variable that sampling results from other sites are rarely directly comparable.

- *Calculation*. Calculation or prediction of potential ambient concentrations is often possible (Leidel *et al*, 1977; Buringh and Lanting, 1991) and frequently applied to ventilation design. However, the data and techniques have got to be reliable and relevant to the situation. A combination of measurement and modelling techniques can substantially reduce that total effort needed to reach decisions on, for instance, control.

Where existing or calculable data are insufficient, measurement will be necessary. For the basic survey this will be very much a range-finding exercise to confirm, or reject, concerns about exposure and priorities raised by the initial survey. Thus it is usually not appropriate to sample the whole workforce, nor even a random sample. It is more efficient if the basic survey concentrates on identifying extreme, or "worst case" exposures. This means that the strategy chosen for a basic survey is heavily influenced by the workplace factors noted during the initial appraisal and these factors may need further analysis when deciding a strategy for a basic survey. The basic survey is heavily reliant on the skill of the occupational hygienist in setting up the survey and interpreting the limited data it produces. Inexperience may result in sampling the wrong employees, at the wrong time, or misinterpretation of the data. This could result in a health risk for some workers remaining unidentified or alternatively excessive costs imposed on the employer to control a very limited problem.

The strategy can be delineated by posing a series of questions which guide the hygienist when choosing: "Who, when, where and how to sample?"

- *Which workers are likely to have the highest exposures?*

When workers are dedicated to different jobs on a plant, or in a workshop, it is generally fairly easy to decide which of them are likely to receive the highest exposures. When a large number of workers are apparently doing the same thing this becomes more difficult. However, even in an apparently homogeneous group some workers may have higher exposures than the rest. This may happen because of individual work practices, or be ergonomically based and arise from difference in worker's anthropometric details, or work-station design. Whatever the reason, observations to pick out such situations are essential if "worst case" measurements are intended.

Although targeting the "worst case" is a good strategy for a basic survey, there is also merit in including some workers who are expected to have lower exposures. This provides some quality control over the initial appraisal and the original choice of "worst cases".

- *What period should be sampled?*

For "worst case" studies it is essential that sampling is done over an appropriate period. This will be determined by whether the exposure is continuous, or intermittent, and whether or not "peak" exposures occur. For instance, there would be no point in sampling a cyclic process outside of the peak potential exposure period. In this connection it is essential that events at the start and end of the work period are considered. Start-up often involves periods of high exposure because of increased activity levels (*eg* weighing, reactor loading, lighting of stoves or ovens with high fume emissions *etc*). Similarly the end of a shift, or batch process, may involve off-loading, emptying and shut-down procedures and ancillary work such as cleaning equipment or workshop surfaces. It may also be necessary to consider "worst cases" over several shifts. Thus personnel, processes, supervision and ambient condi-

tions can all vary from shift to shift leading to changes in personal exposure patterns. Experience also suggests that the difference between day and night shifts, and the various stages of rolling shifts, are especially marked.

- *Are the exposures associated with particular sources of contamination?*

Resources may be saved by the recognition that atmospheric pollution in a workplace is associated with a particular source. Examples include part of a plant (*eg* leaky gland), part of a process (*eg* hopper loading), a particular site (*eg* a filter-room during bag changing) and support processes (*eg* welding, painting, cleaning). Identification of the source provides a spatial element to the monitoring strategy which may assist in deciding what type of measurement is best suited to the situation. This knowledge may suggest that static measurements will provide sufficient information to allow a decision to be made on exposure and control. For instance, the initial appraisal may have identified an emission source which can be confirmed, or denied, using static measurements. Similarly static measurements may be quite sufficient to test a suspicion from the initial appraisal that certain engineering controls are not adequate. Qualitative methods mentioned earlier (*eg* dust lamp and smoke tubes) may again be useful.

- *What measurement methods are best suited to meet the needs of the basic survey?*

The selection of measurement equipment and methods is discussed in Sections 1.3.1 and 1.3.2. The information necessary for deciding which methods are appropriate would have been gathered during the initial appraisal. There will need to be a cost-benefit analysis in relation to the quantity and quality of the information needed: "Would detector tubes be adequate and even preferable to pumped sorption systems for a basic survey?" (Miller, 1989); "Would the use of a continuous recording instrument to measure operator breathing zone concentrations suffice?"; "In the case of mixed exposures would a total mass measurement provide sufficient information?" The most efficient and effective method which achieves the objectives should be first choice.

Once a basic survey has been completed there will be some data on which to decide what to do next. The decision is often guided by a comparison of exposure results with an appropriate occupational exposure limit. In essence a compliance test is made. This may be quite informal, but many regulatory bodies have formalised decision making based on compliance with OELs. (This is considered in detail in Chapter 4 - see Herve-Bazin (1989), for a wide-ranging review). However the basic survey is generally a range-finding exercise and it is used in a wide variety of situations. Hence the definition of universal criteria for making decisions from a basic survey is difficult. Indeed the mechanical application of a set decision-making procedures can, without the application of good professional judgement, be misleading.

Bearing the above in mind the basic decisions can be summarised thus:

- *Make no more measurements*. If the results from the "worst case" studies are low then a detailed survey is unlikely to be necessary. There are different ways of interpreting "low", but results of less than about 0.2 x OEL suggest that the limit is unlikely to be exceeded. The decision not to do further measurements is not necessarily a decision to do nothing. For instance the basic survey may have revealed deficiencies in control which are open to improvement.

- *Carry out immediate investigative or remedial action*. Where a basic survey reveals high exposure, installation of controls will need to be considered immediately. Unless there are good reasons to be suspicious of the results further survey work may be a waste of time and effort. However, sampling after controls have been instituted will be needed to check their efficiency.

- *Proceed to a detailed survey.*

2.4 Detailed Survey

The decision to conduct a detailed survey may be reached in several ways, some of which are similar to the reasons leading to a basic survey:

- The initial appraisal suggests that the extent and pattern of exposure cannot be reliably assessed by a basic survey and it is necessary to proceed immediately with a detailed survey.

- The basic survey reveals that exposure is very variable; that large numbers of people may be at risk; that measured exposures suggest that OELs may be exceeded; or that the results were not clear-cut enough to make a definite decision.

- Special situations arise such as starting up a new process; when there have been substantial changes to a process, operation, or control measures; when there are unusual, infrequent or intermittent processes or operations; when an OEL has been set for a substance for the first time.

A detailed survey has a precise objective: usually it is to obtain reliable measurements of personal exposures averaged over appropriate periods. However, this is not invariably the case and a detailed survey may be based on area sampling, or a mixture of both area and personal sampling. This may be appropriate when there is a need for a detailed examination of the nature and extent of a problem revealed by the initial survey.

A common aim of a detailed survey is to compare the data collected with appropriate OELs, reach conclusions about exposures and decide what steps, if any, need to be taken to exercise further control over exposure. This has an immediate effect on the strategy in ways which were not, or were less, important to the basic survey, *viz*:

- For comparison with an OEL the results will, with a few exceptions, need to be representative of personal exposures, hence personal sampling techniques should normally be used.

- The appropriate measurement period must be chosen if the results are to be compared with OELs which are defined over specific reference periods.

- All aspects of the survey need to be carefully thought through to minimise errors which may be more significant than in a worst-case situation.

- The possibility of detailed statistical analysis should be considered before beginning any survey work and, where necessary, used to guide the strategy. (See Chapter 3).

There are thus some in-built constraints on the strategy for a detailed survey which are not so critical in a basic survey. However, the essential questions of: "Who?, When?, Where? and How?" to sample remain the core guides to the strategy.

Who should be included in a detailed survey?

There are no simple universal rules to choosing who to sample; each situation needs considering on a case-by-case basis. If a small number of workers are involved it may be practicable, as well as statistically sensible, to sample all of them. Where a large number of workers fall into well defined homogeneous groups then sampling can be designed around this fact. In general this is only possible where very large workforces are involved; more often individual workers will have quite individual jobs. The selection of workers for sampling and the concept of grouping workers for sampling purposes is discussed in detail in Chapter 3. Workers within a group would normally be selected for sampling on a random basis. As a matter of judgment, however, the occupational hygienist will wish to introduce some subjective bias on top of this. For example, if observation shows that some workers are particularly careful and others particularly clumsy (assuming that the differences are not so great as to place the workers into different groups) it would be prudent to ensure that instances of both types are included in the survey. This is important, for both morally, and in most countries legally, each individual employee should be protected from the ill effects of potential exposures in the workplace. Hence both individual exposure results and group means are important. Once results begin to become available, examination of them may suggest that a group is not homogeneous and may need refining. This needs to be done with care and the guidelines laid down in Chapter 3 should be followed. When assigning workers to groups for multishift measurements temporal factors may lead to very high variations in exposures between shifts in which case each shift has to be tested as a separate group. Extreme examples can occur on three-shift systems where even the same time-based shift may find themselves doing different work on alternate days. Consider for instance a batch production process; this may be set up and run by the first shift, but the product is removed, finished and packed by the second shift. The third shift then sets the process up again for the returning workers of the first shift to remove, finish and pack.

Over what period should sampling be carried out?

If the aim of the detailed survey is to obtain accurate personal exposures for comparison with an OEL then the period of sampling will necessarily be guided by the reference period over which the OEL is defined. This doesn't necessarily mean that a sample has to be taken over the whole period. But sufficient samples of appropriate quality must be obtained to allow an accurate calculation of the worker's average exposure over the reference period.

It must be ensured that periods of high exposure are thoroughly covered and taken fully into account when calculating the time-weighted average exposure. One way of accomplishing this is to stratify sampling so that the actual regime used concentrates sampling effort on to period of probable maximum exposure. This should not be carried so far that one returns to a "worst-case" situation. However, the attention given to maximum exposure periods must be commensurate with their importance in determining the time-weighted average (TWA) exposure and in relation to designing control measures. In this respect it is, as mentioned earlier, important to include activities at the beginning and end of the work period since these may differ from those occurring during the rest of the time.

It is also important to the overall strategy to measure short-term exposures. This is not just for comparison of results with any short-term OELs which may have been assigned. The recognition and control of peak exposures play a significant role in reducing average exposure. Also control of peaks may be particularly important in controlling concentration-dependent effects, for example, known, or potential, respiratory sensitisers. In practical terms 10-, or 15-minute sampling raises some problems. There is some evidence that work practices and consequently personal exposures can be modified by the sampling programme (Bord, 1987; Gressel *et al*, 1988; Cherrie *et al*, 1991). The possibility that equipping workers with sampling equipment, or the action of observing them, may cause such changes is of real concern. In principle it seems likely that this effect will be less marked for long-term sampling than for short-term sampling. The latter is particularly disruptive of the flow of work. One way of reducing this disruption is to have workers wearing the sampling train with the pump switched off. This allows them to get used to the equipment and it is a simple matter to switch the pump on and off at the appropriate time with no real disruption. At some period of low activity the sampling train can be replaced ready for the next peak period. Special thought needs to be given to situations where exposure is intermittent. Such exposures may vary from a few hours per week (*eg* for cleaning staff) to campaign production where exposure may occur for a few weeks twice a year (*eg* pharmaceutical and bespoke chemical production). In all cases sampling periods should be designed to coincide with operations likely to produce exposure. Without this TWAs are obviously meaningless.

So far the discussion has concentrated on personal sampling, but consideration should always be given to including some carefully chosen static sites in the survey. A combination of personal and static sampling results gives a powerful tool which can:

- Help to define the area of an exposure problem.
- Assist in identifying sources of exposure.
- Check the engineering performance of any control methods being used.
- Help in recognising or confirming ergonomic effects on exposure *eg* engineering controls not designed taking into account the task to be done or the abilities of the workforce.

Although precise correlation between personal and static sampling results is unlikely at a given working position, the pattern of the exposure, as indicated by the two sets of data, should be similar. In this sense the personal and static samples also act as mutual quality controls and any extreme variations in the pattern of results is worthy of investigation. The situation will be different for peripatetic workers who may move in and out of several sources of contamination. Once all the sampling data are available the hygienist can use them, with their own observations to decide:

- *Whether further work is needed.* In particular more data may be required if the results are few in number, or highly variable. Temporal factors such as seasonal effects or shift patterns may make further information desirable although these factors should have been identified at the initial appraisal stage and been built into the strategy in the majority of cases.
- *Whether control of exposure is adequate.*

- *Whether further control measures are needed*, where these should be applied and what form they should take.

- *Whether routine monitoring should be instituted* and at what frequency.

One guide in reaching these decisions is the comparison between the measured exposure results and relevant OELs. A number of schemes have been devised to facilitate decision-making from this comparison (see examples in CEFIC (1984), CEN (1992), Herve-Bazin (1989) and Leidel *et al* (1977)). Some of these schemes are more complex than others and often depend on sufficient data being available for a sensible statistical analysis to be made (see Chapter 4).

Whatever scheme is used there are essentially three possible conclusions:

- *Exposures exceed the appropriate OEL.* In this case the reasons for exceeding the OEL need to be identified and the situation rectified as soon as possible. Once steps have been taken to control exposure a further detailed survey will be necessary to show that the controls applied have been successful.

- *Exposures are well below the OEL* and likely to remain so on a long-term basis. For exposures to remain the same the conditions at the workplace must be stable, especially in relation to the materials, processes, working practices and any controls. There will be a need to check regularly that conditions have not changed sufficiently to nullify the conclusions from the original exercise. However, periodic measurement of exposures is not needed in this situation.

- *Exposures lie somewhere between the above situations.* In this case the OEL is not being exceeded but exposures are not so low that control can always be assumed to be adequate. In this situation periodic measurements become necessary and routine surveys will need to be instigated.

2.5 Routine Surveys

Routine surveys involve periodic sampling of exposed persons and selected static sites to meet defined long-term objectives. These objectives may include:

- Checking that control measures remain adequate.

- Ensuring that OELs continue to be complied with.

- Checking possible trends in exposure levels and patterns of exposure.

- Providing data for possible epidemiological studies.

- Complying with national legislation.

Routine surveys thus provide a different type of information from that obtained from other surveys. This means that the strategies applied to routine surveys will not necessarily be the same as for any other surveys. However, any periodic monitoring strategy must take account of, and be designed on the basis of, information from earlier surveys. The Who? When? and Where? aspects of routine monitoring are similar to those for other surveys. Indeed the answers given to these questions for earlier surveys will heavily influence the strategy chosen for routine surveys. Thus with respect to "Who" to monitor, it may, with a small workforce, make sense to monitor everyone; with a large workforce this approach would be difficult and expensive, if not entirely impossible. Approaches to selecting sample populations are described later (Section 3.5).

In the context of a strategy for routine surveys the following are particularly significant:

- The frequency with which routine surveys should be made.

- The sampling methodology.

- The number of samples which need to be taken.

- The nature of the analysis to be applied to the data obtained.

Each of these are considered in turn below.

Conditions and needs can vary so widely that it is not possible to define precise rules for determining the frequency of routine surveys. Some standards have proposed set procedures for determining when and if periodic monitoring is necessary (for examples see CEN (1992) and Herve-Bazin (1989)). These usually relate frequency to level of exposure expressed as a fraction of the OEL or some other target value. However, there are always dangers in the application of purely mathematical rules to this sort of decision. In particular, both the quantity and quality of the available data must be sufficient for this to work. Either or both of these aspects of the data may be deficient. Whatever approach is used in deciding the frequency of sampling the following factors are significant.

- *How closely exposures below the OEL approach it.* The closer exposures approach the OEL the more likely non-compliance becomes. It also becomes more likely that even minor changes in conditions will result in over-exposure. Hence the closer measured exposures are to the OEL, the more frequent monitoring should be.

- *The effectiveness of the controls.* Where a process is well-controlled and the situation is likely to remain stable there may be little need for routine sampling. Hence the frequency of monitoring need not be high.

- *The consequences of control failure and the time to re-establish control if failure occurs.* The significance of these factors is closely related to the nature of the materials being handled, especially their physical form and toxicity. For instance if solids are being handled a breakdown in control may only be of significance during manual handling stages. By comparison if a volatile liquid or a gas is in use, breakdown of controls may be significant at any stage in the process. Also if a substance has a steep dose-response curve the consequence of a failure of control could rapidly put workers at unacceptably high risk. Similarly, if controls fail and the failures are of such a nature that re-establishing control may take considerable time then workers may be placed at unacceptably high risk for an extended period. If these, or similar situations, are likely to arise then a fairly frequent routine monitoring regime would suggest itself as sensible.

- *The nature of the process cycle* including when normal and unusual working conditions occur. The frequency of routine surveys may need to be varied with the cyclic nature of many processes and the periodicity of some unusual events. For example in a process lasting several days some periods may require a higher frequency of monitoring than others. Also periodic events will be worthy of special consideration. With batch processes, operated on a campaign basis, the frequency of monitoring will need to reflect the frequency of exposure.

- *The temporal variability of the exposures.* In setting the frequency of monitoring account needs to be taken of potential temporal effects (*eg* seasonal and shift variations). Obviously a biased picture of conditions will be obtained if a monitoring frequency is chosen which results in the same shift being sampled again and again at the same time of the year.

- *The general variability of exposure.* Where exposure in a group is highly variable a greater frequency of monitoring could be necessary. This may be especially important where no obvious reason can be found for the variability. There is then the obvious potential for a drift to a position of over-exposure.

Consideration of all these factors can lead to a wide variation in the perceived need for routine surveys. The interval between periodic measurements may well vary from less than a week to more than a year. Whatever interval is chosen the reasoning behind the choice should be recorded and a strategy planned to meet the needs of the decision.

Planning the sampling methodology is particularly important. A programme of routine surveys can only be of real use if it is possible to compare consecutive sets of results (see Chapter 4). This means that the methodology for collecting samples must be rigorously planned and executed. All types of error need to be minimised and capable of estimation, otherwise it will be difficult to recognise genuine changes in the exposure patterns if they occur. Particular difficulties can arise if the sampling or analytical methods change. There may, for instance, be practical advantages in changing from an active sampling train to a passive system. But the relationship between results from the two methods needs to be well understood before such changes are made. Also, the effect of changing sampling protocols on the behaviour of workers is not well understood, but in some circumstances may result in

changes which affect their measured exposure. Improvements in analytical methods may allow quantification at previously unmeasurable levels. This may affect the sampling strategy. For instance, for a carcinogen the hygienist may feel that a detailed survey should be done to delineate the extent of pollution and re-evaluate the adequacy of the control measures.

The number of measurements which need to be taken during routine surveys is closely related to the question of how the data will be analysed. If statistical analysis is to be used it is important to obtain a sufficient number of measurements to ensure a reasonable degree of confidence in the conclusions. Where enough data have been obtained for statistical analysis there are several possible methods of evaluating the information against the relevant OEL (see Chapter 4). However, any statistical method has to be set into the context of the real situation in the workplace. For example, the bulk of the data may give a good fit to some theoretical distribution (*eg* normal, or lognormal) but have a few "outliers". These odd results might be dismissible on statistical grounds as random, and expected, variations. However, they might actually represent a real non-random effect associated with one person or a small sub-group of workers with routinely higher exposures. Statistical methods need to be applied with particular caution to small groups who are providing only a limited number of results.

Having cautioned against an over-reliance on a purely mathematical approach to the analysis of routine monitoring data it must also be said that where suitable data are available trend analysis is particularly useful. Thus the basic objective of routine monitoring is to detect and evaluate changes in exposure levels so that adverse trends can be corrected before over-exposure occurs. Central to this concept is that there should be an intervention or action level set so that once a significant upward trend in exposure is detected there is time to correct the situation before any individual exposures exceed the limit. The major factors to consider when setting an intervention level are:

- The time taken to implement corrective measures once the trend has been noted; this may range from a few minutes to several months.

- The existing variability in the exposure data.

The longer the time needed to respond to a change in exposure pattern and the greater the variability in the data the lower the intervention level will need to be set.

There are similarities between this and the objectives of industrial quality control programmes. Indeed Leidel *et al* (1977) have given a seven-point comparison of quality control and employee exposure monitoring programmes which emphasises this point. Because of this similarity the statistical methods developed for analysing trends and changes for quality control purposes are useful in analysing data from routine surveys. (For details of methods see Leidel *et al*, (1977), BSI (1984, 1984a), Hawkins and Landenberger (1991)).

Routine surveys will inevitably be relatively expensive and it is essential to consider their value. In the situation where the concern is that personal exposures may exceed an OEL it would be sensible to consider the cost of improving the controls which could eliminate the need for an expensive routine monitoring programme and reduce the health risk for the workforce.

Invariably routine surveys will be required for epidemiological purposes but it would be prudent to ensure that the data will be of future value. Historically epidemiological studies have been hampered by a lack of adequate exposure data. It is now relatively easy to obtain these data and a study is just as likely to be limited by problems with the human data *eg* due to worker tracking problems, small study populations or complex exposures. Particularly in the developed world there has been a shift from heavy industries employing large numbers of people who are exposed to a limited number of contaminants. New substances are being introduced into the workplace at an increasing rate and their industrial lifetime may be limited. Not only are small groups of workers exposed to a substance but workers are changing their employment several times during a working lifetime.

2.6 Limitations of the Structured Approach

2.6.1. Intermittent or Batch Processes

Intermittent or batch process operations can be investigated using basic, detailed or routine surveys, although practical problems may occur. Where intermittent exposure to a contaminant occurs fairly frequently, *eg* a few hours per week, sampling periods can be chosen to coincide with specific operations so that satisfactory time-weighted averages can be calculated. It may be possible to treat a continuously operating batch process producing a single product as a pseudo continuous process and use any one of the three strategies without difficulty. A number of industries, *eg* fine chemicals or pharmaceuticals, produce a wide range of products from an even larger range of starting materials. The

processes may operate intermittently at irregular intervals on a campaign basis. Obtaining representative exposure data can be extremely difficult for even a single substance, and obtaining data for a range of substances would inevitably be limited by resources.

Particularly where the focus is on control, various pragmatic strategies may be adopted to provide data for the assessment of control standards (CIA, 1992a). Where substances are put through common process operations the worst-case situation may be studied by selecting the substance which presents the greatest risk. This could be based purely on a hazard ranking if the various substances have similar physicochemical properties and toxicological profiles or it could include a combination of hazard, scale and frequency of usage. This is similar to one of the approaches described in Section 1.4.5 for the measurement of airborne mixtures where one component is measured as a guide to exposure and control. Depending upon the circumstances it may be necessary to select more than one substance especially where a substance is put through additional processing stages as well as the common process. When setting up routine surveys for such processes a very flexible approach will be necessary. It is quite possible that the frequency with which the process operates will define the monitoring frequency rather than any set of formal rules.

2.6.2 Sampling Substances Exhibiting Acute Toxicity

The structured approach to developing sampling strategies described in this Chapter is applicable to substances which exhibit acute toxicity. In particular, the initial appraisal and basic or detailed surveys are appropriate to the initial investigation of exposure to such substances. However, where an excursion above an OEL could cause serious, possibly irreversible, acute effects a routine survey programme (Section 2.5) using collection of the substance onto a substrate for subsequent analysis is not really appropriate. Even if an excursion is detected the data are of little value if the health of an individual is already damaged. Continuous monitoring using either self contained instruments, multipoint sampling systems or multiplexed sensors is a more appropriate approach. Depending upon the system, airborne contaminant concentrations can be measured almost instantaneously and the system used to operate an alarm and trigger any essential emergency actions. Continuous monitoring may also be appropriate for monitoring substances with less serious, reversible effects, where because of process variability or possible intermittent operations normal occupational hygiene programmes are difficult to implement.

3 SAMPLING PROTOCOLS

3.1 Introduction

The various factors which affect the choice of the most appropriate sampling strategy in a given situation together with the appropriate measurement methods were discussed in detail in the previous chapters. The major factors which will affect the sample siting, number and duration, and sampling frequency are summarised below. The prime determinant will be the survey objectives which could include:

- Health-risk assessment including epidemiological studies.
- Determination of compliance with exposure standards.
- Evaluation of control measures and plant performance.

For example, sampling to assess workers' exposures in an epidemiological study is done to help to establish a dose-response relationship. Workers with a wide range of exposures will therefore need to be sampled. This is different from compliance testing or a health-risk assessment when there is an established occupational exposure limit. In this case it may be presumed that a dose-response relationship is known and built into the limit. Workplace inspection would eliminate from the sampling programme many workers with exposures which are obviously well below the exposure limit. Similarly for workers with exposures obviously well above the exposure limit the most appropriate action may be to improve workplace controls, sampling after the improvements to determine their adequacy.

Other factors affecting the protocol include:

- The nature of the airborne contaminant and associated hazards.
- The availability of suitable sampling and analytical methods.
- Type of process and circumstances under which emissions occur.
- Spatial and temporal variations in concentration.

The last factor is of particular importance since it implies a need for statistical approaches to air sampling and decision making.

Instantaneous concentrations of air contaminant emitted from a plant or process in a work room can vary from point to point within the room and will vary with time during the course of the workshift. In addition, the average concentration for either a single point in a workroom or the average for a number of points varies from shift to shift. Within and between shift variations can be due to combinations of factors such as:

- Variation in the number of emission sources.
- Variation in the rate of emission from a given source.
- Variation in the dispersion of a contaminant from its source.

The concentrations of a contaminant inhaled by employees is governed by the above factors. Additional factors which also contribute to the variation in individual employee's exposure include:

- The employee changing position relative to the various emission sources.
- Variations in tasks amongst employees.
- Variations in working methods amongst different employees undertaking the same task.

The sources of variation outlined above may be of a random or systematic nature.

3.2 The Application and Limitations of Frequency Distribution Models

3.2.1 Introduction

For decision making on the management and control of a workplace environment or a health-risk assessment a mathematical model of the variability of time-averaged contaminant concentrations is valuable. The assessment period may be one shift, one week, one year or more. (Concern about the variability only arises when the averaging time of contaminant concentration measurements is short in relation to the assessment period). If the data could be described by a probability density function it may be possible to make statements about the probability of occurrence of any specific concentration value, or about the probability of observing concentrations above or below some criterion value.

The Central Limit Theorem (Kendall and Stuart, 1977) states that a random variate x is log-normally distributed if it is the product of a number of mutually independent random processes. The observed differences in the results of a sequence of short-term personal air samples or moment-to-moment values of contaminant concentration indicated by a continuous measuring device are not likely to arise from elemental processes which are strictly independent or indeed random. A lognormal distribution is therefore not an inherent property or inevitable consequence of such processes. For example, there may be systematic variation in levels of exposure over a work shift due to movement about the workplace or temporal variations in the process. This may have implications for the sampling strategy employed. However, where there is no time trend in contaminant concentrations due to systematic changes in one or more of the elemental processes involved, then the lognormal distribution may be an adequate descriptor of the variability of pollutant concentrations over the assessment period (*eg* an 8-hour shift).

There is better evidence in the literature (Peterson *et al*, 1966; Sherwood, 1966; Gale, 1967; Hounam, 1965; Gormar, 1976) to support claims that the variation of full-shift time-weighted averaged concentrations measured over a long assessment period, *eg* full-shift time-weighted averaged concentrations measured over a long assessment period, *eg* full-shift measurement on a weekly or annual timescale, can be adequately described for practical purposes by the two-parameter lognormal distribution. This may also often be the case with time-weighted averaged concentrations measured for groups of workers by personal sampling, where the same general pattern of work activity and process operation is repeated day after day. Again systematic changes in worker exposure may occur due to temporal changes in the process or processes being operated or to changes in the workplace, *eg* changes in ventilation patterns between summer and winter. In such cases the data may belong to more than one data set, each set being described by a different lognormal distribution. Extreme cases of such systematic changes are seen in many batch process operations such as in the fine chemical or pharmaceutical industries where not only do feedstocks and products vary throughout the workplace at a given point in time, but individual substances may be handled or produced on an intermittent basis with process conditions also subject to variation for any given product. Sampling strategies for such highly variable conditions do not readily lend themselves to a highly structured, rigid statistical approach over long time periods.

3.2.2 Appropriate Models and Goodness-of-Fit Testing

The random distribution of many (but not all) sets of occupational hygiene sampling results have a positive skew. The probability density functions which have attracted most attention are the 2-parameter and 3-parameter lognormal distributions (Aitchison and Brown, 1957). These are the basis for most of the published work on the acquisition and processing of data.

Ott and Mage (1976; 1978) suggested that the 3-parameter lognormal distribution is usually a better fit to air contaminant data. It was suggested that this provided a more flexible model which may have a much wider application than the 2-parameter model. In fact the 2-parameter model can be regarded as a special case of the 3-parameter model.

It should be noted that not all data reported in the literature necessarily fit the lognormal models and alternative skewed distributions such as the exponential, gamma or Weibull distributions may be appropriate in some cases (Weibull, 1951; Hald, 1952; Kendall and Stuart, 1977; Essenwanger, 1976). However, as noted above not all sets of occupational hygiene data are skewed and the normal distribution is more common than might be at first thought. It should be remembered that the primary purpose of fitting data to a probability function, *eg* by taking logs, log-logs, roots *etc*, is to transform the raw data so that the transformed data become normally distributed. The purpose of doing this is to allow the calculation of summary statistics which are based on the normal distribution model.

Before relying on any model for predictive purposes the goodness-of-fit of the data to the chosen probability density function must be tested. Two goodness-of-fit tests that are of general interest for this purpose are the Chi-square (Rahman, 1968) and Kolmogorov-Smirnov (Massey, 1951; Siegel, 1956; Lilliefors, 1967) tests. Unfortunately the Chi-square test requires fairly large sample sizes which has potential implications for any sampling protocol. The Kolmogorov-Smirnov test is fairly simple to apply and has been recommended for application to occupational hygiene data (Leidel and Busch, 1985). However the test is sensitive to outliers. Recently Waters *et al*(1991) have proposed a simple quantitative measure of goodness-of-fit to the log-normal model based on the ratio of two estimators of the mean of the distribution (the ratio metric). Whilst the test is simple it is applicable only to the lognormal model and if the data do not fit this model alternative tests will be necessary to test other models. A fully objective test is proposed by Filliben (1975) and discussed by Dewell (1989) which is capable of differentiating between likely distributions and providing significance levels (see Section 3.2.3).

3.2.3 Probability Plotting

Probability plotting is discussed in some detail by Dewell (1989). There are two approaches to probability plotting outlined below. The first, a graphical method, is subjective, but easy to carry out. The second method is more rigorous and provides an objective test for differentiating between distribution functions and is to be recommended.

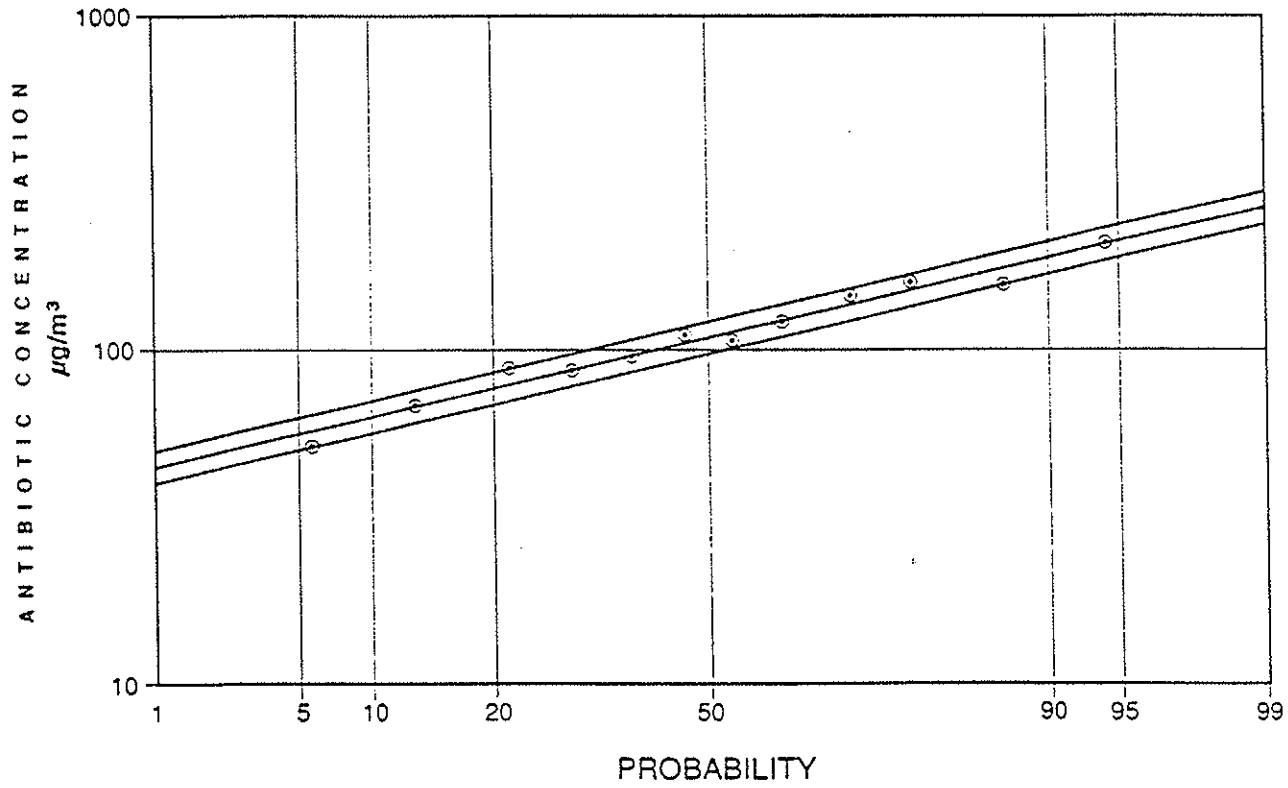


Figure 3.1

Probability plot of individual shift average concentrations of an antibiotic

A probability plot is a plot of the individual data points as a cumulative frequency curve where the percentage scale has been adjusted to produce a straight line. Probability plotting paper is available commercially (*eg* Chartwell 5575 for lognormal data; Chartwell 5571 for normally distributed data). The method can be used for relatively small sample sizes of ten to twenty results (CEN, 1992). With less than ten results scatter about the line is high and the line not well defined. With more than twenty results the improvement in precision is normally not sufficient to justify the extra measurements. Application of the technique is described in a number of publications (*eg* CEN, 1992; Leidel *et al*, 1977; Bailey and Miles, 1984). One example of data, plotted on lognormal probability paper, is shown in Figure 3.1 which shows the results for a group of workers producing antibiotics.

The slope of the line (Figure 3.1) gives a measure of the variability of the results (a steep slope indicating very variable results), and the fifty percentile concentration is the geometric mean concentration. The outer graph lines on Figure 3.1 represent the ninety-five percent confidence limits of predicted values of another random data set from the same population.

If a straight-line plot is not obtained then the data may not be lognormally distributed.

Figure 3.2 shows a line which indicates that the data may come from two different data sets, *ie* two different exposure groups (see Section 3.5). Figures 3.3 and 3.4 suggest that alternative distribution models are required or that high exposures are not being accurately measured (right truncated), *eg* measuring device saturating (Figure 3.3) or that low exposures are not being measured (left truncated),*eg* poor analytical sensitivity (Figure 3.4).

It is important to realise, that whilst a straight-line plot may indicate that the correct probability distribution model has been chosen, it is not a goodness-of-fit test. Some normally distributed data plotted on lognormal probability paper will produce what is judged by eye to be a straight line and vice versa.

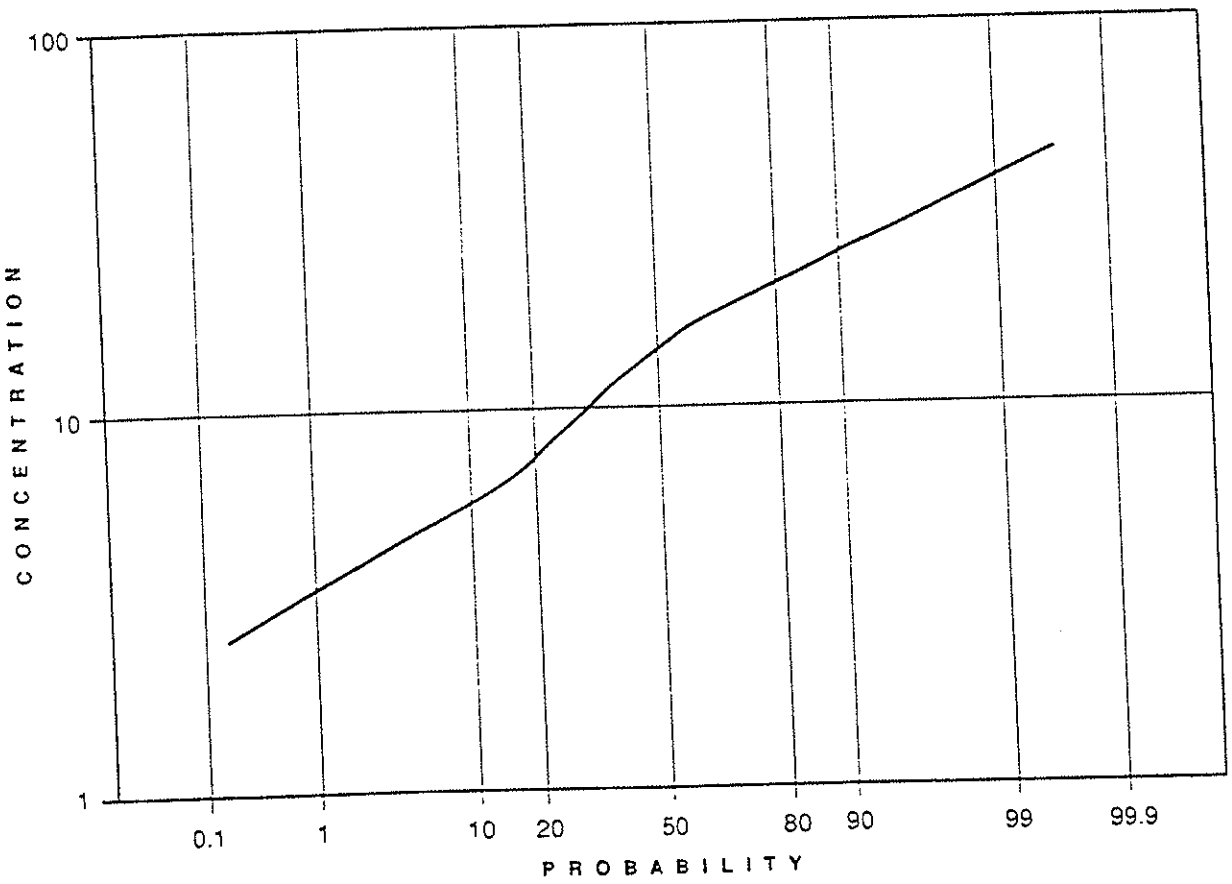


Figure 3.2

Probability plot of a mixture of two distributions

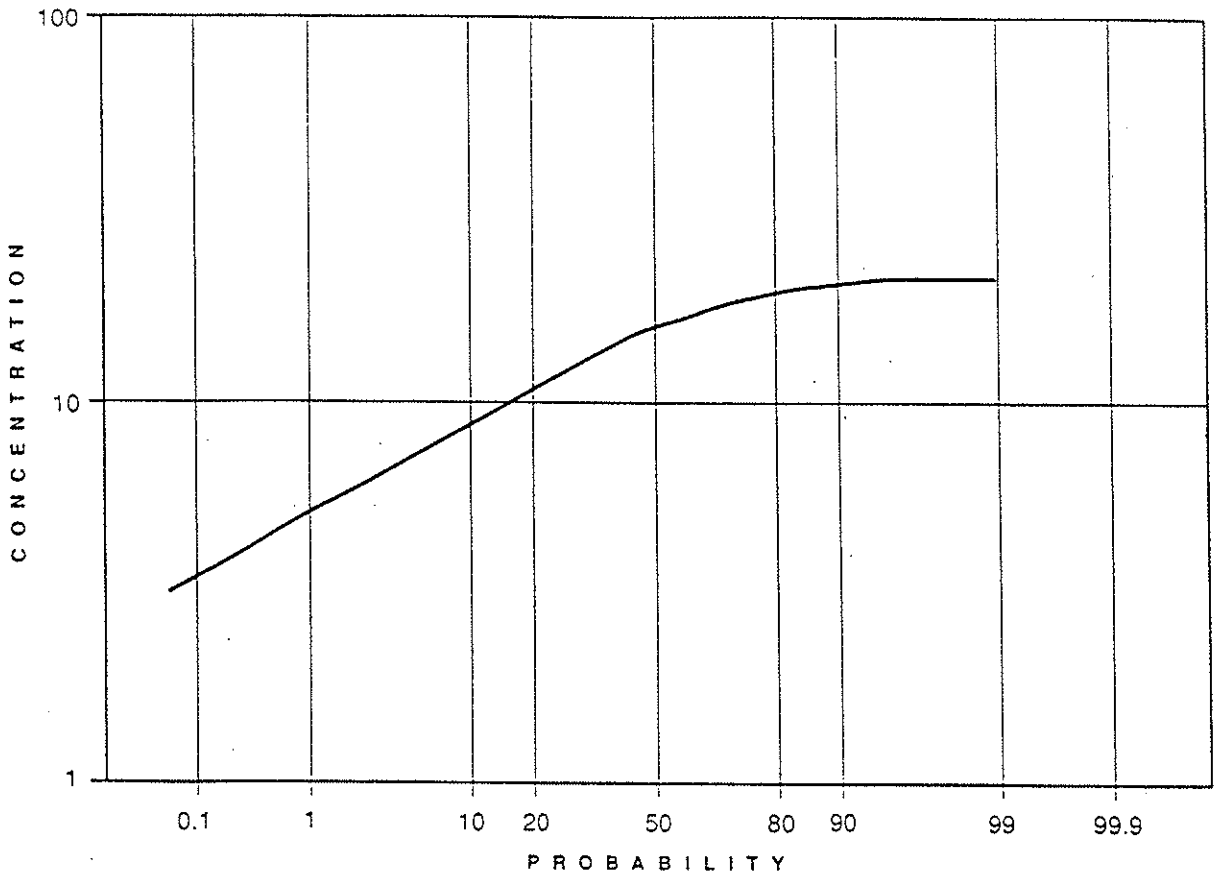


Figure 3.3

Probability plot of a right-truncated distribution

The second approach to probability plotting is to calculate first the probability plot correlation coefficients for the data, initially assuming the data to be either normally or lognormally distributed (other distribution functions could be tested if required) (Dewell, 1989). The distribution which has the higher correlation coefficient is then assumed to be the more likely one. The regression line for the data can then be calculated and the appropriate probability plot drawn. Appropriate confidence limits can then be calculated as required. Whilst all the work on the data can be done by calculation it is good practice to plot the data before progressing to the calculation of any summary statistics. For example, data represented in Figure 3.2 could produce an acceptable result in a goodness-of-fit test but observation suggests that there may be two totally different data sets (from two different groups of workers).

3.2.4 Some Consequences of Skewed Data

If airborne contaminant concentrations are lognormally distributed there are at least two potentially significant consequences. Ulfvarson (1983) noted that the relative frequency of observations occurring below the true arithmetic mean increases with increasing geometric standard deviation (Table 3.1).

Table 3.1
The area on the left of the true arithmetic means under log-normal distribution curves with varying geometric standard deviation.

GSD	1.5	2	2.5	3	3.5	4
Area	0.58	0.64	0.68	0.71	0.73	0.76

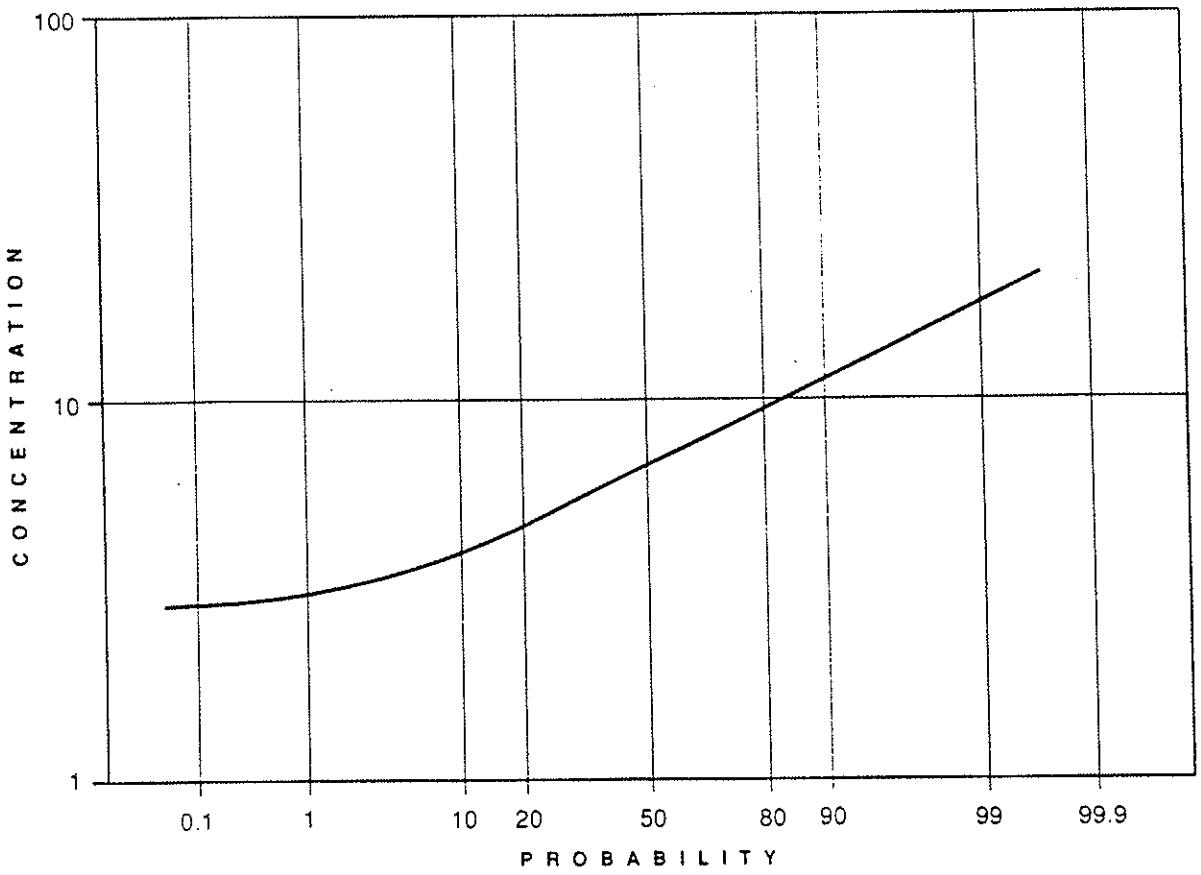


Figure 3.4

Probability plot of a left-truncated distribution

For example, with a geometric standard deviation of two there is more than a sixty percent chance in random sampling of a single measurement being below the true arithmetic mean. (If the distribution is normal this frequency is fifty percent by definition). This implies that, for a small number of measurements taken from a large population, the arithmetic mean for the data will generally be less than the true arithmetic mean. Only if a relatively large number of measurements are made will the arithmetic mean approach its true value. As discussed later the accumulated uptake of a contaminant into the human body is in principle related to the arithmetic mean airborne contaminant concentration of the period under investigation. A simple example would be an attempt to determine a worker's arithmetic mean annual exposure from a series of full-shift measurements. Taking only two or three samples at random over the year is likely to provide an estimate of the true mean that is low.

3.2.5 Autocorrelation

The distribution of exposures received by a worker (or homogeneous group) can be described by the mean and variance. These parameters do not provide any information concerning the correlation of exposure measured at different times. This is given by a third characteristic of the distribution, the autocorrelation function, p(h), which defines the relationship between air concentrations separated by h intervals of time, where h is referred to as the lag. Autocorrelation is important because it affects the independence of samples which are collected during surveys. If a high degree of autocorrelation occurs, then it may not be possible to draw valid inferences about the underlying population of exposures. For a purely random series p (h) = 0 for all lags and for a perfectly correlated process p (h) = 1 for all lags (Rappaport and Spear, 1988; Francis *et al*, 1989; Buringh and Lanting, 1989).

A reasonable estimate of p(h) over the first 10-12 lags requires the measurement of at least 50 sequential exposures (Box and Jenkins, 1976). Unfortunately hygienists rarely collect this quantity of data to allow autocorrelation functions to be analysed.

The evidence for autocorrelation of actual exposure measurements is mainly anecdotal. Francis *et al* (1989), in the only study to directly investigate the question, found little evidence of autocorrelation in three sets of sequential shift-long air concentrations extending from 36 to 730 days. If Francis' findings are typical of the autocorrelation observed from day-to-day in most workplaces, then it may be possible to estimate the distribution of shift-long measurements on the basis of discrete campaigns of only a few days' duration.

Little work has been done on the levels of autocorrelation of intra-shift variations in exposure. Coenan (1971, 1976) observed a high degree of autocorrelation for dust concentrations and also vinyl-chloride concentrations measured continuously at fixed locations.

Roach (1977), Spear *et al* (1986) and Rappaport and Spear (1988) used air-exchange rates to estimate short-term autocorrelations which may exist in environments where mass transport of the contaminant is governed by turbulent diffusion. Autocorrelation was low with high air-exchange rates (10 air-changes per hour) and high with low exchange rates (1 air-change per hour). If the exchange rate is low, periods of hours between measurements may be required if unbiased estimates are to be obtained (Rappaport, 1991). Serial measurements to predict frequencies of excursions to STELs should therefore be used with caution if the air-exchange rate is low. However a workplace with low air-exchange rates is likely to be unsatisfactory for a number of reasons and obtaining improved ventilation performance is likely to be more important than any concerns about autocorrelation.

3.2.6 Effects of Averaging Time

As the averaging time of consecutive air samples covering the whole of an assessment period is increased, it is found that there is a smoothing of the variation in the measurements. Provided that conditions remain stable (stationarity) several investigators (Roach, 1966, 1977; Coenen, 1976; Spear *et al*, 1986; Preat, 1987) have shown that the arithmetic mean value is constant and independent of the averaging time, whereas the variance decreases with increasing averaging time (LeClare *et al*, 1969; Coenen, 1971). If the variance changes, then the geometric mean also changes. The exposure distribution therefore changes with averaging time even when taken from the same environment and all samples need to be collected over the same averaging period. However, minor variations are unlikely to have significant effects. The precision of the estimated mean increases with increased averaging time and if, for example, there is little autocorrelation between shifts, the variance of the estimated arithmetic mean measured over one week would be one fifth of that based upon measurements of single shifts, favouring long-term sampling for assessment of chronic health risks. Equally, if an estimate of the time-averaged concentration for an assessment period of T hours is made by obtaining air samples of time, t, at random or systematic intervals so that there are unsampled gaps within the assessment period. The precision of estimation improves as the size of the ratio T/t decreases towards 1.

However, smoothing of the variation in measured concentrations by increasing the averaging times may mean that valuable information is lost. For example, transient patterns of change, more persistent time trends in the worker's exposure or changes in process emission levels may be of considerable interest to the occupational hygienist or engineer concerned with evaluating the performance of control measures. The averaging time is therefore an important factor to be considered when deciding upon the overall strategy to be used for a particular survey or sampling programme.

3.3 Data Variability: the Contribution from Measurement Errors

Measurement errors can contribute to significant differences between, for example, repeated measurements of concentrations at the same location or between measurements made using different techniques and equipment. The need to use properly validated methods and to establish the compatibility of measurements when changing the methods has already been discussed (Chapter 1). Use of a recognised method or the achievement of a given performance standard within a laboratory may still produce unsatisfactory results if there is an undetected bias in the method.

Systematic error in measurements of contaminant concentrations can easily be overlooked although it can sometimes be a more serious problem than random errors which tend to cancel out as the number of measurements made in a particular situation increase. For example, two laboratories using nominally the same sampling and analytical methods can individually achieve the same degree of precision in repeated measurements of a particular pollutant but the mean value determined by each laboratory may be substantially different from the other. The mean value from each laboratory may also differ from the true concentration. Systematic errors should not be present or at least an estimate of their magnitude made so that appropriate correction factors can be applied. Membership of an appropriate interlaboratory proficiency testing scheme will assist in eliminating the potential for systematic errors in measurement.

Random error affects the precision of repeated measurements of a non-varying contaminant concentration. For an individual measurement x_i then:

$$x_i = x_o + e_i$$

where x_o is the true concentration and e_i is the measuring error, which is assumed to be a normally distributed random variable (population mean of zero).

In the case of a non-varying concentration the precision of the estimate of the true concentration would depend on the error variance and the number of measurements. The random error variate, e, is likely to be the sum of a set of independent components such as sampling pump flow rate error, loss of contaminant from collection medium, fluctuations in analytical instrument performance *etc* and the assumption of normal distribution is not unreasonable.

In the working environment the concentrations of contaminants vary with time. If the time-averaged concentration of a contaminant over an assessment period were estimated by making n short-term measurements at random during the period, the precision of the estimate of the true concentration would depend on the actual variability of the instantaneous or short-term averaged concentrations as well as the number of samples, n, and measuring error. If the number of samples, n, is large or the variability of contaminant concentrations at the sampling position is considerably greater than the measurement error, which is usually the case, the effect of measurement error would be negligible and could be ignored. However, precision would still be dependent upon the number of samples taken and would improve with the greater the number of samples taken.

On the other hand, if either m consecutive time-averaged measurements covering the full assessment period were made, or if m simultaneous full-period measurements were made, then the measuring error variance would become the source of uncertainty together with the number of measurements made.

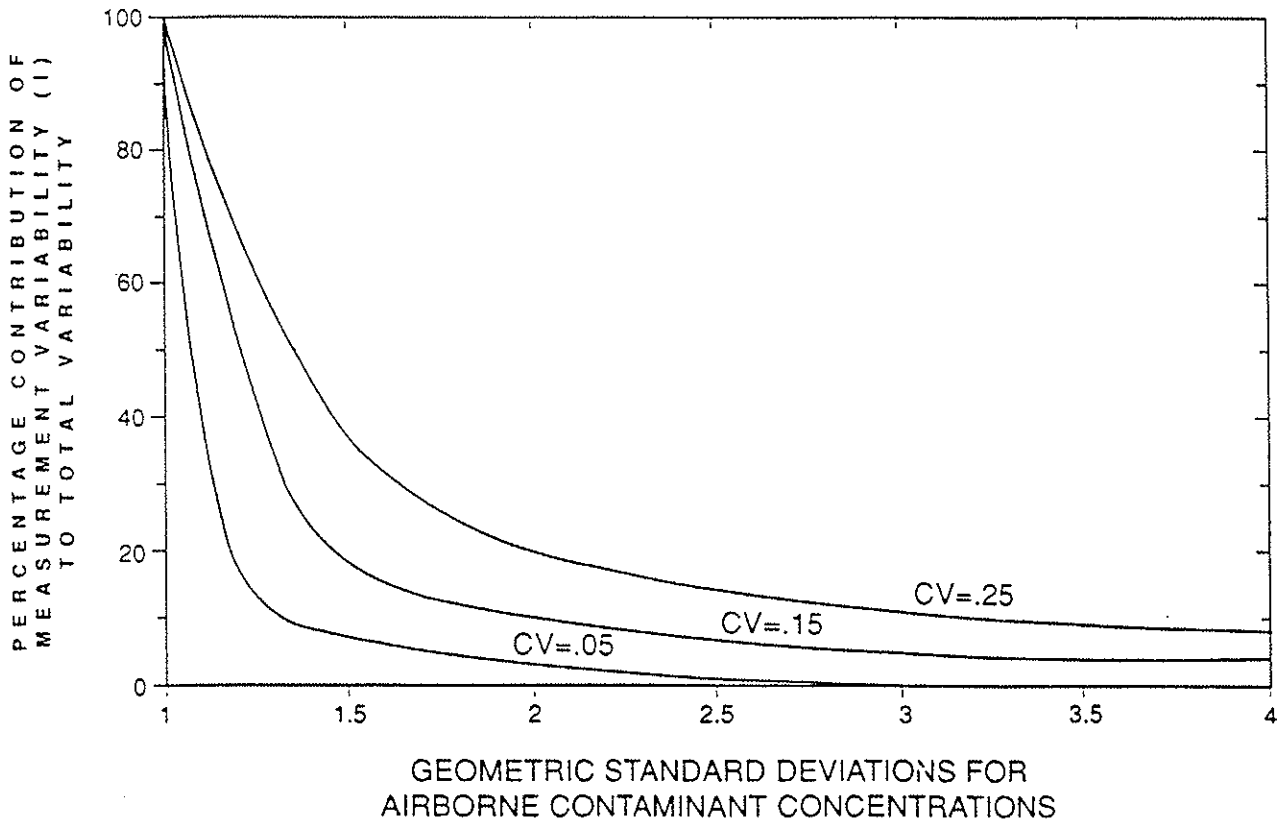


Figure 3.5

The percentage contribution of analytical variability to total variability in measurements of 8-hour time-weighted averages

Nicas *et al* (1991) has recently looked at the contribution of measurement variability to the total variability of 8-hour time-weighted average measurements. Figure 3.5 shows the percentage contribution (I) of the measurement variability for various coefficients of variation (CV) as a function of the geometric standard variation (GSD) for the airborne contaminant concentrations.

If a typical CV for a measurement method is less than or equal to 15 percent and a typical geometric standard deviation (see Section 3.6.2) is greater than or equal to 1.5 then the percentage contribution of the measurement method is less than 13 percent of the total variability. In many cases the contribution will be much less.

3.4 Biological Considerations

3.4.1 Introduction

As noted previously, exposure assessment for epidemiological studies is significantly different from that used for compliance assessment or assessment of workplace controls. A primary objective for epidemiological purposes should be to link tissue dose of a toxic agent, not just exposure, to effect. The pharmacological processes that causally relate exposure to adverse health effect should therefore be taken into account when determining an appropriate sampling strategy. For any given toxic substance the physicochemical properties and potential routes of exposure will affect the choice of sampling methods. The toxicokinetics and pharmaco-dynamics of the substance will control the selection of sample averaging time and total period of interest. In practice it is found that there is no single expression for a dose-response relationship that will fit all toxic substances and there is no single form of dose expression, *eg* cumulative dose (expressed as exposure multiplied by duration), which is suitable for quantifying all occupational exposures (Atherley, 1985). Other limiting factors include the lack of suitable human toxicokinetic information for a large number of hazardous substances and limited knowledge about damage mechanisms or the kinetics of repair processes.

3.4.2 Chronic Effects

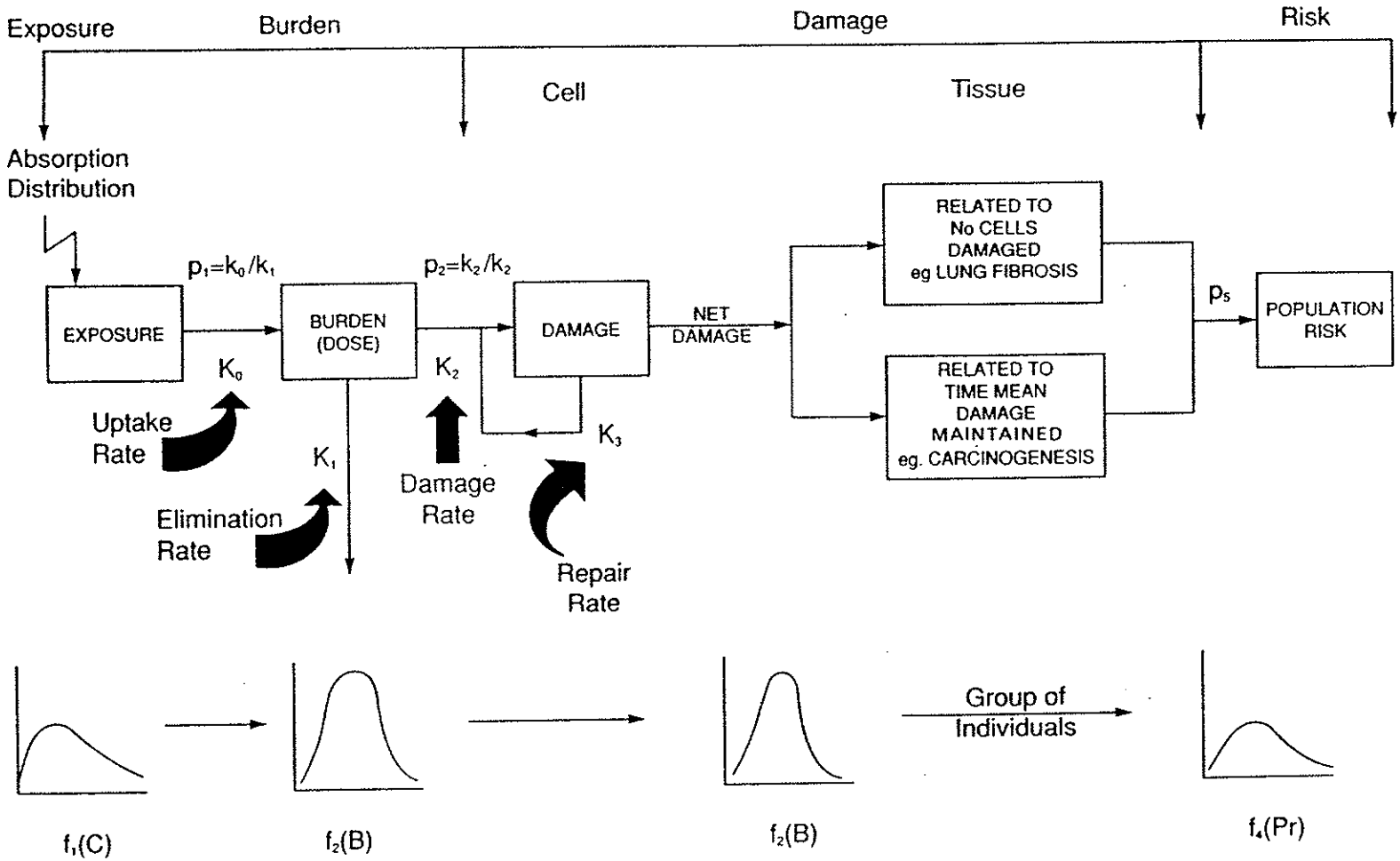
A conceptual model, Figure 3.6, has been developed linking exposure to dose, damage and risk of disease (Roach, 1977; Rappaport, 1991). The model indicates that exposure variability must be transmitted through to body burden and damage if it is to affect the risk of disease.

The model allows for two mechanisms for damage accumulation at the tissue level. It predicts that the transmission of day-to-day variations in exposure into damage diminishes rapidly when the biological half-life ($T_{½}$) of a substance is $10 < T_{½} < 100$ hours such that less than half of the variability is expected to reach the tissues when $T_{½} > 40$ hours. Rappaport (1991) proposes this as a strategic benchmark above which day-to-day variations in exposure are unimportant. Similarly, short-term transient exposures would be of little consequence to the development of cell/tissue damage and chronic health risk if $T_{½} > 2$ hours (the model assumes a minimum of 1 air-change per hour in the breathing zone). These damping effects on exposure variability may be increased by slow repair mechanisms.

Assuming linear kinetics the model indicates that chronic tissue damage is proportional to the mean exposure and that transient fluctuations or 'peak exposures' are of no consequence beyond that which their contribution to the mean would allow when $T_{½} > 40$ hours (peak exposure referred to a single event over a period of one shift or less). Tissue damage should then be related to the mean exposure and time. Advantage can be taken of this fact to minimise the number of samples required providing that the exposure range allows the kinetic processes to remain linear. Non-linear kinetics in the translation of exposure to damage may occur, from synergistic or antagonistic effects related to concurrent exposures to other agents, from allergenic responses to sensitisers or from an upward curving burden - damage relationship associated with episodes of intense exposure (*eg* due to saturation of normal clearance processes). It is thought that the latter case would be fairly rare in the industrial situation.

Even when large transients are effectively transmitted and a threshold effect exists, the quasi log normality of the exposure distribution suggests that individual risk is maximally related to the mean exposure received over a period of time.

For substances which exert primarily chronic effects, long-term average exposures could be measured and samples could be taken over several days or one week instead of multiple samples taken over 8-hours. This would minimise the number of samples taken without loss of any information, at least for epidemiological purposes. Information relating to specific parts of the process could be lost however, and short-term measurements will still be important for analysing the performance of control measures. Also, the vast majority of OELs relating to chronic toxicity are based on an 8-hour standard and regulatory bodies would require appropriate samples to be taken to demonstrate compliance with these OELs.



K_0-K_3 represent first order rate constants; P_0- $P_5$are proportionality constants resulting from linear transfer functions between succeeding series. $f_1(C)$, $f_2(B)$, $f_3(D)$ and $f_4(Pr)$ represent the distribution functions for exposure, burden,cellular damage and population risk. Assuming the exposure concentration remains constant with time, the model processes will eventually reach dynamic equilibrium after some period of time, dictated by the various rate constants

Figure 3.6

A conceptual model relating exposure, dose, damage and risk of disease

3.4.3 Acute Effects

Rate constants for biological elimination or repair range from seconds to a few hours for many acute toxicants or irritants. Translation between exposure and damage occurs within the timescale of one shift and transmission of exposure variability to tissue damage is likely to be very efficient. Many acute responses are also non-linear. The variation in acute responses ranges from the potentially irreversible, *eg* pulmonary oedema, to temporary effects, *eg* irritation, and the hazard spectrum is wide.

The risk factors associated with processes can also vary widely. A continuous process with good standards of containment and little manual intervention will show little variation in emissions to the workplace atmosphere and is readily characterised. Intermittent or batch process perhaps with significant manual intervention are potentially highly variable and difficult to characterise. It will therefore be difficult to develop a general strategy for evaluating short-term exposures.

As the regulatory bodies set short-term limits it is essential that sampling is undertaken to demonstrate compliance with these limits and also to aid in the development of adequate control measures where these are not present. However, an occupational hygiene programme using sample collection on a filter or absorbent medium followed by analysis is not adequate for routine identification of excursions above the OEL which could result in serious acute effects. Even if an excursion is detected the event is past and the data primarily of historical interest. Continuous monitoring, as described in Section 2.6.2, could be more appropriate.

3.4.4 Linking Exposure Measurements with Biological or Clinical Effects

In the previous section the work of Rappaport (1991) and Roach (1977) was outlined, showing that sample averaging time must be matched to the contaminants toxicokinetics, certainly for epidemiological purposes. Similarly, toxicokinetic models have been used to link the temporal variations in occupational exposures and tissue concentrations as an aid to interpreting biological monitoring data (Fiserova-Bergerova, 1983).

In setting up an epidemiological study an optimum approach, based on toxicological or pharmacological factors, can be applied to link exposure measurements by various means, *eg* airborne contaminant concentrations, biological monitoring with biological effect or clinical effect measurement, provided that the relevant information is available for target tissues, mechanisms of effect and kinetics data. A good example of this approach was described by Smith (1985) for a follow-up study on male reproductive effects observed in shipyard painters exposed to 2-methoxyethanol. In the initial study a decreased sperm count was noted which did not correlate with urinary levels of the major metabolite, methoxyacetic acid. A consideration of the possible mechanism for the effect suggested stem cells as the target tissue. With a 76 day sperm production cycle there is an approximate lag of 80 days between reduced spermatogenesis and reduced sperm count. Animal studies indicate that complete cell repair takes 120 days (repair half-life approximately 20 days). From the information it could be determined that the exposure characterisation period need not exceed 100 days and that it should precede obtaining semen samples by 76 days.

A single compartment model of glycol ether uptake, metabolism and elimination was set up based on three reasonable assumptions: that the glycol ether and its acid metabolite were uniformly distributed throughout the body fluids, that the glycol ether was eliminated solely as the acid and that the acid was excreted exclusively in the urine. The model was used in an exposure simulation and showed that tissue glycol levels closely followed the hourly airborne exposure levels and were sensitive to high exposures. Peak levels may be important as a non-linear response to the toxicant may be involved (the methoxyacetic acid or intermediate aldehyde). Acid levels were not sensitive to hourly peaks but reflected the daily time-weighted average exposures and acid levels in morning urine samples would be related to the previous days exposure by all routes. Exposure could be by inhalation or skin absorption. Glycol concentrations in exhaled breath are related to blood levels and exhaled breath analysis could be used as a measure of transdermal exposure. A sampling strategy would therefore need to provide data for the estimation of 2-methoxyethanol and methoxyacetic acid in tissues, the time-weighted average exposures and the frequency of peak exposures higher than a threshold which may trigger non-linear effects. It would be necessary to identify workers with a range of glycol ether exposures who were without potential confounding exposures, *eg* significant usage of paints with alternative solvent bases. The data gathered would be used to develop dose indices, calculated from each subject's exposure estimates.

Demonstration of an exposure-effect relationship is dependent upon the precision of both the exposure and effect measurements. In this example as sperm count is highly variable it would be necessary to have a large cohort to detect any effect.

3.5 Selection of Sample Populations

3.5.1 Introduction

Regardless of the survey objectives, *eg* an industry-wide prospective epidemiological study over several years or a one-off exercise covering a few workers in a single company, any data gathering should be to a strategy which recognises the inherent statistical nature of assessing exposure.

Sampling of every employee with potential exposure to a particular contaminant is not usually a viable proposition.

Several approaches are available for selecting sample populations. It is an area which is still fairly contentious and each method has its strengths and limitations. Selection of the appropriate method will be governed by particular survey objectives and resources.

Where there is a requirement to demonstrate compliance with a legal standard, regulatory organisations may promulgate their own mandatory sampling strategies and these may differ significantly from the approaches outlined below. Specific national or international compliance sampling strategies are not described here because of their potential variety and limited application. Reference should be made to the relevant legislation if such mandatory methods have to be used.

3.5.2 Prospective Employee Grouping

Grouping of employees into homogeneous exposure groups or hazard classes was described by Woitowitz *et al* (1970). The authors separated a factory into hazard classes by observation of the various jobs and activities. Validity of the proposed groupings was subsequently confirmed by sampling. This concept was developed by Corn and Esmen (1979) for prospective employee grouping (zoning) as the basis of a stratified measurement strategy. A homogeneous group was one in which all persons had a similar exposure level and profile and the resultant data distribution could be fitted to a statistical model. This approach was developed for epidemiological purposes but it is readily adaptable for any measurement programme.

As described by Corn, exposure zoning involved the following steps:

(i) Preparation of a chemical inventory for the facility and determination of chemical utilisation by plant area.

(ii) Identification of those chemicals in the inventory which are of particular concern because of their hazardous nature.

(iii) Matching of the chemicals of concern to plant areas and the employees who come into contact with them. Employees are then allocated to exposure zones based on the following criteria:

  (a) similarity of tasks (not necessarily exactly the same job)

  (b) exposure to the same range of airborne contaminants (including byproducts and intermediates)

  (c) similarity of environment, *ie* process equipment, exposure sources and ventilation arrangements

  (d) identifiability.

When a sufficient number of employees are sampled in each zone, the information contained should describe the exposure concentrations for all employees in the zone within a predetermined interval variation and statistical confidence. Zones are not necessarily single definable geographic areas.

Generalised criteria for task classification are discussed by Esmen (1979) and may be used as an aid to zone selection. It was recognised that not all employees could be fitted into appropriate zones and some flexibility was required to accommodate these individuals.

Criterion (b) above is potentially flexible to suite the survey objectives. If exposure to a single substance is the prime concern or alternatively all agents of interest are used in all areas, the criterion for agent similarity is automatically satisfied. When measuring exposure to multiple agents and substance use varies throughout a facility, the criterion for agent similarity should be satisfied by ensuring that all persons included in a zone are liable to have the same exposures to the same substances.

Criterion (d), identifiability, was a restriction originally placed on the concept to ensure that a worker was not allocated to more than one zone. It required that workers could be selected anonymously on a random basis. If name, personnel number *etc* were required for selection purposes, then the value of zoning was diminished in the original scheme.

The skill and knowledge of the occupational hygienist and other professionals involved, *eg* plant managers, is a major factor in successful zoning. A thorough knowledge of tasks, working techniques, agents, processes and personnel records is required.

When the group sizes in each zone are known, the number of workers to be sampled can be determined. Sufficient samples will normally be required to ensure that the range of exposures in the group are covered or can be defined with sufficient accuracy. This is discussed further in Section 3.6 on sample sizes.

The value of grouping is that the variability of the sampling results should be smaller for a well defined group than for the exposed workforce as a whole and there would be greater likelihood of being able to describe the variability by means of a theoretical model. The practical advantages are that resources can be concentrated on those groups at maximum risk or those with the highest exposure if the objective is to improve control. The most efficient scheduling in introducing control measures would be to remove the largest number of workers from a risk to a non-risk situation.

After completion of a sampling exercise the plant may be re-zoned for a subsequent survey but this should not be done retrospectively based on the results. Retrospective zone adjustments may lead to violations of one of the four criteria previously outlined. Prospective re-zoning utilises the knowledge from previous surveys to determine whether the number of zones needs to be increased or decreased and the results from previous surveys are useful in determining those zones where the bulk of the sampling effort should be directed in future surveys.

When analysing the results and the initial zone allocations the high results are usually of particular interest. It needs to be determined whether these are genuinely due to random variation in the results from a homogeneous group or whether they are due to non-random effects from a non-homogeneous grouping. An initial grouping may contain an initially unrecognised sub-group of individuals with consistently higher exposure patterns than the rest of the group. A useful rule-of-thumb is that no individual's exposure should be less than half or greater than twice the group mean (HSE, 1989) (see Section 3.5.3). If it is, the individual should be allocated to another group or treated separately.

3.5.3 Retrospective Employee Grouping

Rappaport (1991) proposed that random sampling of an exposed population with retrospective grouping was the most satisfactory way of obtaining data for the assessment of long-term exposures to hazardous substances, *eg* for epidemiological purposes. When substances present a chronic health risk the objective of the sampling programme is to allow inferences to be drawn concerning the degree of exposure of the individual or group over periods of months or years or to determine whether exposures are acceptable relative to particular OELs.

Multiple measurements are required to determine the within-worker and between-worker components of exposure as first expounded by Oldham and Roach (1952) and also described by Spear *et al* (1987), Kromhout *et al* (1987) and Boleij *at al* (1987). It was suggested that data acquisition could be maximised because the sampling could be performed by technicians with the hygienist's time being devoted to data analysis. This could also be enhanced by using sampling techniques, *eg* diffusive samplers, which did not require complex or expensive equipment which took time to fit onto operators.

However, in many situations the occupational hygienist is primarily concerned with ensuring that the health and well-being of the workforce is protected and that adequate control measures are in place. This usually requires a detailed knowledge of the workplace, process and operational tasks supported by adequate monitoring data and not vice versa. The use of a totally random sampling strategy would generate unnecessary data from process operations which were under acceptable control.

Rappaport recognised that some stratification, *eg* zoning, of the sampling, may be necessary in practice for epidemiological purposes to assist in the control of total sample numbers.

If a random sampling strategy were utilised, the whole of the potentially exposed workforce would be treated as a single cohort and the numbers to be sampled would be selected as described in Section 3.6.

Models for Defining Groups:

These are based on the assumption that the exposure data are lognormally distributed. A data set obtained from a sampled population will have an arithmetic mean (μ_c) and a geometric standard deviation ($\sigma_{g,t}$) for the "total distribution". Each individual in the group has a personal day-to-day distribution which may differ significantly from the group's. This within-worker distribution can be characterised by the individual arithmetic means ($\mu_{c,i}$) and geometric standard deviations ($\sigma_{g,i}$). The

distribution of the individual means can be plotted and should be lognormal with the same mean (μ_c) as the distribution for the total population but a different geometric standard deviation ($\sigma_{g,B}$), the between-worker geometric standard deviation.

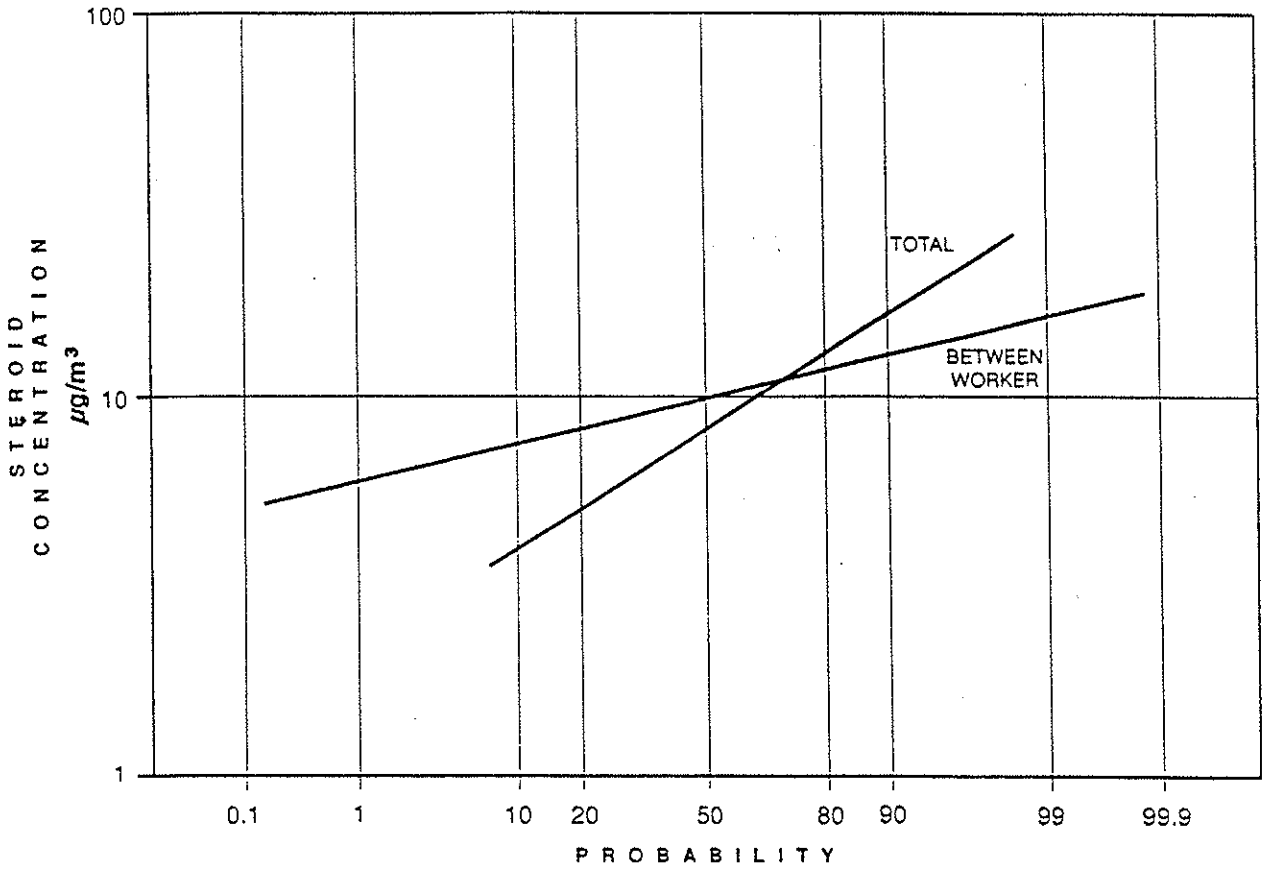


Figure 3.7

Log-probability plots of typical total and between-worker distributions

Figure 3.7 shows by the difference in slopes that the geometric standard deviation ($\sigma_{g,t}$) for the total group is greater than that for the between-worker distribution ($\sigma_{g,B}$). This is to be expected as $\sigma_{g,t}$ represents both the within- and between-worker exposure variability components. Rappaport (1991) used the distribution of individual means, the between-worker distribution, to define a monomorphic group.

A monomorphic group was arbitrarily defined as one in which 95% of the individual mean exposures comprise a single lognormal distribution and lie within a factor of 2. This implies that the ratio of the 97.5 to 2.5th percentiles ($R_{0.95B}$) is not greater than 2 and would have a between-worker geometric standard deviation ($\sigma_{g,B}$) less than or equal to 1.2. Alternative factors could be chosen to provide more or less stringent definitions of a monomorphic group.

This approach to grouping is implied in the HSE Guidance Note EH42 (HSE, 1989) where it is recommended that individual (mean) exposures should be within a range 0.5-2 times the group mean (a monomorphic group with $R_{0.95B} < 4$ and $\sigma_{g,B} < 1.4$). If exposures were outside this range it was suggested that jobs should be re-evaluated and workers assigned to more appropriate groups.

Rappaport suggests that a low $R_{0.95B}$ value indicates that the exposure variation is governed by the process and environmental conditions and a large value for $R_{0.95B}$ indicates major contributions from individual tasks or working practices, *ie* a systematic component to the exposure variation between individuals. It was suggested that, where worker practice significantly contributes to exposure, then observation is a poor way of assigning workers to groups by the prospective method. Given that initial walk-through surveys to assign groupings cannot usually devote much time to the observation of work-

ing practices for all individuals this is an important point for consideration. However, the occupational hygienist should be able to separate the potentially low $R_{0.95B}$ groups (zones) from the high $R_{0.95B}$ groups by recognising the potential for variations in worker practice.

3.6 Number of Measurements

3.6.1 Rules of Thumb

Having selected a cohort for sampling, by whatever method, it is necessary to decide on the number of samples to be collected. This can be done on a statistical basis as described below, in which case sample numbers can become extremely large and resources may not be adequate for such an extensive exercise. These large sample sizes result from the fact that workplace exposures are highly variable with respect to time and space. This contrasts with the much lower order of variation in the performance of the sampling or analytical methods which consequently require few measurements to be taken for method validation purposes.

It is suggested that from any given cohort that at least 1 in 10 are sampled (HSE, 1989; Rackham *et al*, 1989). Corn (1985) suggested that at least 3 samples should be taken before any statement of results is made and that additional samples should be taken if the results exceed a 25% spread. Such rules of thumb should be used with care as they could significantly affect data quality. Reductions in sample numbers will reduce confidence levels and increase standard deviations. In small populations, sampling the whole population should be considered to minimise any uncertainties.

3.6.2 Use of Estimated Mean and Standard Deviation

One method of determining the number of measurements to make requires prior knowledge of an estimate of the standard deviation. This could come from a preliminary survey or previous experience in similar circumstances. Leidel *et al* (1975) noted that the median category of geometric standard deviations for particulate sampling data was 1.60 to 1.69 and the median category geometric standard deviations of gas and vapour sampling was 1.50 to 1.59. However, geometric standard deviations can vary from about 1.3 to about 3 (Ayer, 1988).

In the absence of a preliminary survey or previous knowledge, a figure of approximately 2.0 can be used to provide an initial estimate of the geometric standard deviation. Providing an initial estimate of the mean in the absence of a preliminary survey could be more difficult but may be possible in some circumstances, *eg* previous experience or use of published data from similar studies.

As the samples collected during a preliminary survey would usually form part of the total number of samples to be collected, carrying out a preliminary survey is the preferred option. With an estimate of the mean and standard deviation the total number of samples required, n, can be calculated using the formula:

$$n = (t.CV/E)^2$$

where:

CV is the coefficient of variation (σ/μ_c)

E is a level of error (acceptable or chosen)

t is read from the table of t-distribution values for some chosen confidence level (n_o-1) degrees of freedom where n_o is the number of samples in the preliminary survey. In the absence of a preliminary survey infinite degrees of freedom can be chosen to provide an initial estimate for n.

The equation assumes that the population from which the sample is to be drawn is infinite, or approximately so (Dewell, 1989).

Example

Using an estimate for the mean and standard deviation based on experience (no preliminary survey and n_o not known):

For a set of normally distributed data with arithmetic mean, μ_c = 100mg/m^3, standard deviation, σ = 30mg/m^3, chosen error limit 10% and 95% confidence level, t = 1.960 (degrees of freedom = ∞)

$$n = \left(\frac{1.960 \times 30/100}{0.1}\right)^2$$

$$= 34.57 \text{ or } 35 \text{ to nearest integer}$$

That is, in order to estimate the population mean of the concentrations so that with 95% confidence the estimate would be within 10% of the 'true' mean, 35 full-shift (or 10-minute) samples would be required. Extension of this method to lognormally distributed data is discussed by Dewell (1989).

In occupational hygiene many of the populations to be sampled are relatively small. In this situation the following formula can be used to calculate, n, the number of samples required when $10n > N$, where N is the size of the population to be sampled.

$$n\frac{(N-1)}{(N-n)} = (t.CV/E)^2$$

Whilst the formula looks more complex than the previous one it does result in the prediction of smaller sample numbers from a finite population.

Example:

Using the figures quoted in the example above and a total population of 200 (approximate number of working days per year).

$$n\ \frac{(200-1)}{(200-n)} = \left(\frac{1.960 \times 30/100}{0.1}\right)^2$$

$$n = 30 \text{ to the nearest integer}$$

Whether the number of samples to be collected is initially estimated using information derived from a preliminary survey or previous experience, as data are accumulated during the survey, better estimates of the mean and standard deviation should become available. This will allow a better estimate to be made of the number of samples required. Depending upon the size of the survey this process may be repeated several times to optimise the number of samples collected.

3.6.3 NIOSH Method

If the relevant standard deviation is not known and assumptions cannot be made, provided the data are normally or lognormally distributed, an alternative method of determining sample size is the NIOSH method (Leidel *et al*, 1977). Here an initial decision is made that at least one result in the sample to be taken from a population should be in the top T% with C% confidence.

The population (cohort) size is known and presumed to be homogeneous, *eg* group of workers doing the same job or the 48 consecutive 10-minute samples which can be taken during an 8-h workshift assuming uniform exposure throughout the day (see Section 3.7).

For example an homogeneous group of size N = 30 exists, and it is required that at least one sampling result should be in the top 10% (*ie* one of the highest 3 results from 30) with 90% confidence). From Table 3.2 the required number of samples, n, would be 16. Conversely, it should be remembered that there is a 10% probability of missing all the workers in the top 10%.

TABLE 3.2

Number of samples required to ensure one result in the top 10% with 90% confidence

Group Size N	8	9	10	11/12	13/14	15/17	18/20	21/24	25/29	30/37	38/49	50+
Number of samples, n	7	8	9	10	11	12	13	14	15	16	17	18

Technical Appendix A of the NIOSH Occupational Exposure Sampling Strategy Manual (Leidel *et al*, 1977) gives tables for alternative criteria (sample size for top 10% and 95% confidence; sample

size for top 20% with 90 or 95% confidence). Dewell (1989) recently recalculated sample sizes for group sizes up to 50 and the tables presented in this reference have some minor differences.

3.6.4 Sample Numbers: Testing Mean Exposures Against OELs

An alternative method of selecting the number of samples to be taken is available when it is required to determine a given standard of compliance with an OEL, action level or other standard with a certain level of confidence. The idea that for chronic effects exposure should be evaluated in terms of the mean airborne contaminant concentration goes back to the early 1950s (Oldham and Roach, 1952). More recently work has focussed on statistical methods for testing the means of lognormally distributed exposures relative to limits (Coenen and Riediger, 1978; Galbas, 1979; Rappaport and Selvin, 1987; Evans and Hawkins, 1988). Strategies for evaluating mean exposures relative to OELs have been applied to underground mines in the USA (Corn, 1985; Corn *et al*, 1985) and for monitoring exposures to long-term limits in the Federal Republic of Germany (Heidermans *et al*, 1980; Riediger, 1986). Rappaport and Selvin (1987) developed an expression which linked sample-size requirements to test the arithmetic mean exposure, μ_c, against the OEL. Table 3.3 gives examples of the number of samples required to test compliance with an OEL at a 95% significance level and with 90% power.

Table 3.3

Approximate sample-size requirements of the test of the mean exposure (95% significance; 90% power)

	Sample Size n				
μ_c/OEL	σ_g = 1.5	2	2.5	3	3.5
0.1	2	6	13	21	30
0.25	3	10	19	30	43
0.5	7	21	41	67	96
0.75	25	82	164	266	384

σ_g is the geometric standard deviation

3.6.5 Random Sampling

Whichever of the above, or other, methods of selecting the sample-size from the population to be sampled is chosen, the selection of individuals for sampling should be on a random basis. Random number tables are available in various standard texts. Alternatively a computer with a random number generator can be used.

3.6.6 An Approach to Limiting Short-Term Measurements

If exposure data are lognormally distributed then the arithmetic mean, μ_c, and the variance are not independent (unlike with the normal distribution). One consequence of this is that it is possible to predict the frequency with which a particular concentration in the right tail of the distribution would be exceeded. The most obvious concentration of interest would be the 8-hour time-weighted average OEL. However since the arithmetic mean is independent of the averaging time of the measurements it is possible to evaluate the frequency with which a short-term limit may be exceeded based solely on a knowledge of the arithmetic mean (Rappaport *et al*, 1988). This can potentially eliminate a requirement for additional short-term sampling provided full-shift data are available. For example, if it can be demonstrated that μ_c < STEL/4 then no more than 5% of the short-term exposures are expected to exceed the STEL regardless of the variance of the distribution (see Table 3.4). Knowing the frequency with which a limit is exceeded may be of value in determining compliance with a short-term limit, particularly if exposure is essentially uniform throughout the day with only random variations around the mean.

Tasks or jobs which have systematic variations in exposure could still require short-term samples to be taken to identify those parts of the work which consistently give rise to elevated short-term airborne concentrations.

Knowing the excursion frequency does not give any indication of the airborne concentrations obtaining during the excursions and these data may be important in determining whether a health risk exists during those periods when exposures are above the STEL. STELs are frequently set to control acute effects (which are often concentration dependent) and safety margins could be relatively small.

Table 3.4

Maximum frequencies with which exposures from a lognormal distribution can exceed an exposure limit (OEL/STEL)

Maximum frequency	Exposure Limit/μ_c
1	15.0
2	8.2
3	5.8
4	4.6
5	3.9
10	2.3
20	1.4
40	1.03

3.7 Measurement Strategies

3.7.1 Exposure Patterns and Selection of Sampling Patterns

The pattern of sampling may be influenced by a number of practical issues as previously indicated (see Sections 1.2.5 and 1.4.2). These would include:

- Sampling and analytical resources available.
- Availability of staff to take samples.
- Location of employees and work operations.
- Occupational exposure variation (intraday and interday).
- Precision and accuracy of sampling and analytical methods.
- Number of samples needed to attain the required accuracy of exposure measurement.
- Type of measurements required, *ie* short-term, 8-h TWA, long-term *etc* or combinations thereof.

Figures 3.8 - 3.10 illustrate some possible exposure patterns, based on a normal 8-hour working day.

Sampling patterns need to take account of the exposure pattern if representative data are to be obtained. Possible sampling patterns are outlined below for determination of an 8-hour average exposure.

Full Period Consecutive Samples

These would normally cover the full period of the relevant standard, *eg* 8-hours for an 8-h TWA or 10-15 minutes for a STEL. The samples provide the second best estimate of the average exposure over the period of interest.

One or several samples of equal or unequal timespan are obtained during the entire period of the appropriate standard, *eg* 4 x 2 hour or 1 x 6 hour + 2 hour for an 8-h TWA. This methodology provides the 'best' results in that it gives the narrowest confidence limits on the estimated exposure during the period. The sampling periods can be chosen to cover task changes, thereby providing some data relating to the variation in exposure levels during the total period sampled.

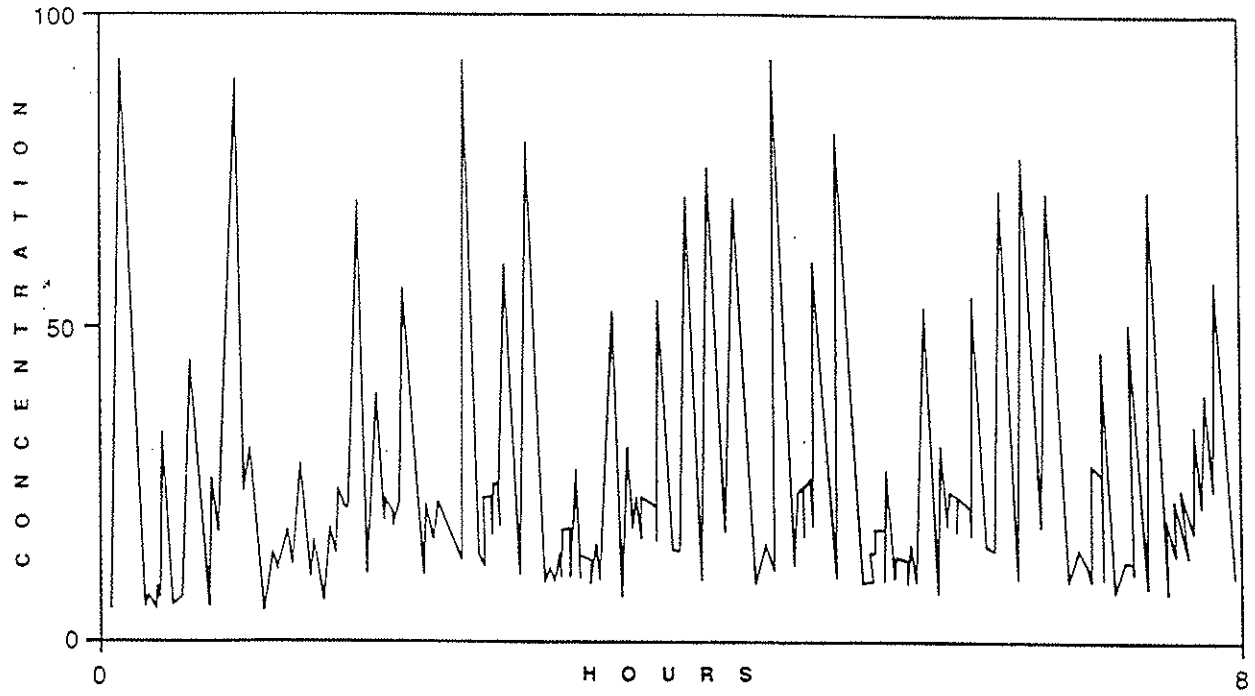


Figure 3.8

Continuous exposure with random variation around the mean, *eg* routine repetitive task

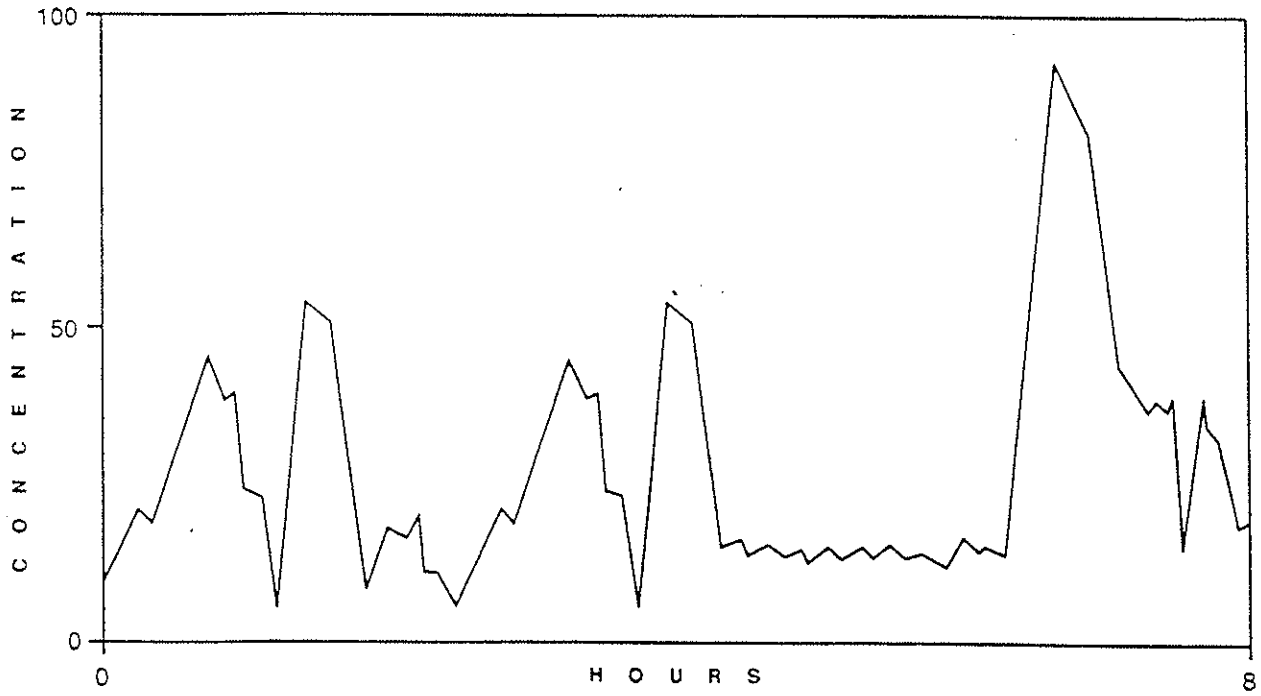


Figure 3.9

Non-continuous exposure with marked systematic variation, *eg* job with a variety of tasks lasting less than a full workshift

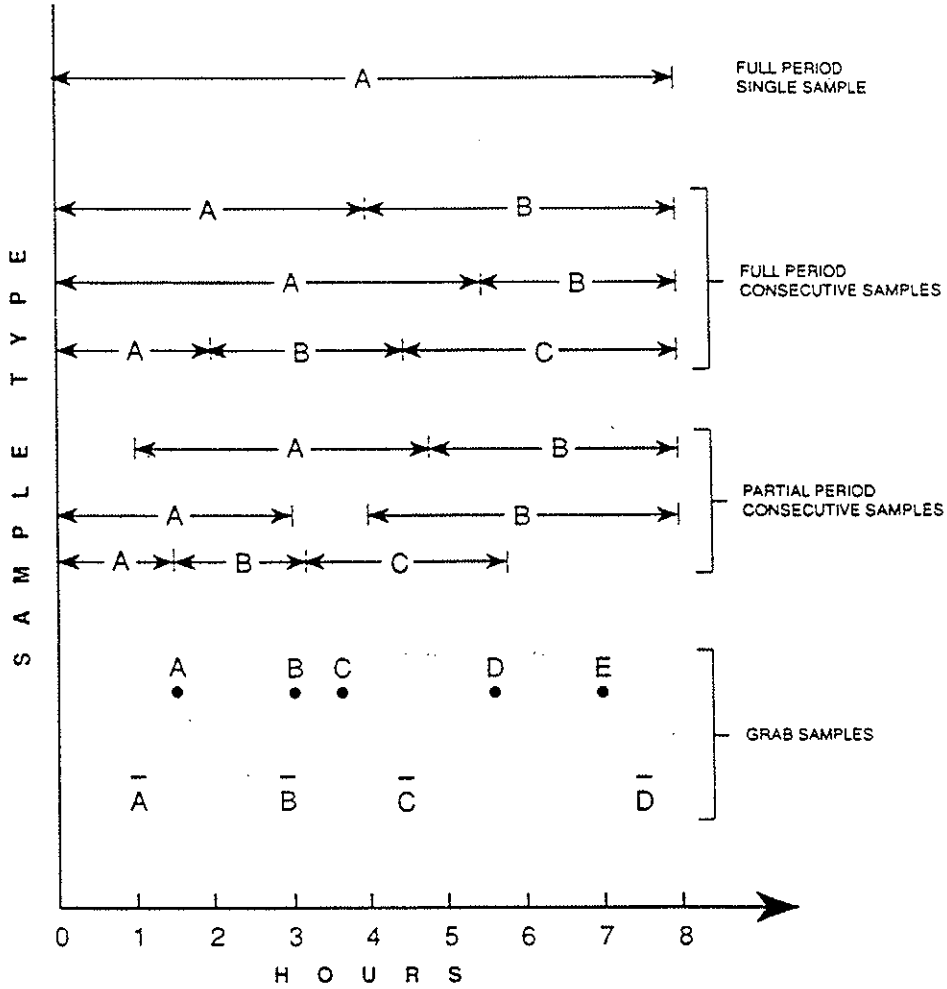


Figure 3.10

Sampling patterns applicable to an 8-hour workshift and 8-h TWA OEL taken from Leidel *et al* 1977

Partial Period Consecutive Samples

One or several samples of equal or unequal duration for only a portion of the period of interest. This approach is perhaps third in preference. The major problem is how to handle the unsampled periods. Professional judgment may allow inferences to be made about the unsampled periods provided reliable knowledge is available concerning the tasks or process. NIOSH (Leidel *et al*, 1977) recommend that at least 70-80% of the full period is sampled.

Grab Samples

Grab samples, usually lasting only a few minutes or seconds, are taken at random intervals over the period of interest. The minimum number required for a homogeneous exposure period may be established by statistical analysis (Leichnitz, 1980). The number of samples required would be substantial and would increase as the sample time decreased.

As an alternative, Table 3.5 may be used as a guide (CEN, 1992). This is based on the assumption that approximately 25% of the exposure duration should be sampled, provided that the working period does not have significant systematic variations in exposure. With very short sample durations this would still require a large number of samples, *eg* 720 for a 10-second sample duration. This is not practically feasible (without real-time data logging) and sufficient statistical stability is reached with 30 samples per shift taken at random times. This derives from the relationship between sample size, n, and standard deviation, σ, or geometric standard deviation σ_g. The greatest rate of change for each measure of dispersion with respect to sample size occurs at $n < 30$ (Harvey, 1980).

Table 3.5

Minimum number of samples as a function of sample duration

Sample duration	Minimum number of samples per shift
10 sec	30
1 min	20
5 min	12
15 min	4
30 min	3
1 h	2

Where systematic changes in exposure level occur during a period of interest a stratified random sampling exercise could make best use of the available resources. Stratified sampling consists of sharing the total number of measurements among the periods of differing exposure (each of which is fairly homogeneous) so that the number in each is proportional to the length of time involved, the measurements in each stratum being made in a random manner. Simple random sampling under the same circumstances might place undue emphasis on one phase or stratum so that a source of sampling error would be introduced. The standard error of the sample would be higher, therefore, than that of the corresponding stratified sample of the same size.

Systematic sampling, *ie* making measurements at equal time intervals over the full assessment period can be used where there is no systematic variation of contaminant concentration over that time *ie* there is no risk of coincidence effects occurring. Neither systematic nor stratified sampling methods are appropriate where there is relatively high frequency cyclic variation in contaminant concentrations.

A detailed treatment of the three methods of statistical sampling that have been described here can be found in specialised texts (Barnett, 1974; Cochran, 1963).

The foregoing discussion also applies in principle to exposure patterns and sampling patterns with different time scales, *eg* the problem of estimating, for epidemiological purposes, the average exposure level of a population of employees over a much longer assessment period by measuring 8-hour time-averaged exposures of a selection of them for a number of shifts within that period. Timing of the sampling exercise could be random, stratified random or systematic. In practice, the last approach is likely to be the most convenient approach to use. Due care is necessary in this case to ensure that sampling periods do not coincide with systematic, *eg* seasonal, changes in pollutant concentrations.

3.7.2 Routine Monitoring Frequencies

A number of schemes have been developed which link the monitoring frequency to the extent by which measured exposures differ from the 8-hour time-weighted average OEL. Some of these are presented in Section 4.5.

If the measurement programme is not constrained by such considerations it may be convenient to plan long-term sampling programmes on an annual basis. There is thus a finite population of N 8-hour time-averaged exposures where N is the number of shifts during the year times the number of employees in the group to be studied. Frequency of sampling can be expressed by deciding what annual sample size, n, is sufficient to obtain good estimates of the parameters of the finite population where

$$n = rK$$

where r is the number of persons selected for each trial and K the number of trials per annum.

For some purposes the parameter of interest might be the annual arithmetic mean contaminant exposure level (estimated from a set of 8-hour measurements), estimated over several years. Under the Central Limit Theorem (Kendall and Stuart, 1977) the probability distribution of the means of random samples is normal, or approximately so. For compliance monitoring or other epidemiological purposes an alternative model, *eg* lognormal, may be appropriate with the need being to estimate the mean and variance of that distribution.

Whatever the purpose and model, it is likely that a pilot exercise will be required to ensure that the two components of the total variance of 8-hour time-averaged exposures are known with adequate reliability (cf. Section 3.6 on selection of sample population size). The two components are variance between members of the study group within shifts, and the between shift variance, which in general is considerably larger.

The pilot survey would need to extend over a number of shifts covering any periods of known, systematic, shift-to-shift variation. With provisional estimates of the mean and variance an acceptable level of error can be chosen and the formulae given in Section 3.6.2 used to calculate the number of measurements required. Adjustment of the sample population size may need to be made as the programme progresses and more data are accumulated, providing better estimates of the mean and variance. Calculations to predict sample population sizes are based on the assumption that the mean, variance and autocorrelation functions do not change over the time period of interest, *ie* that there are no changes in the process or workplace conditions. If changes do occur the strategy may need to be modified and in any long-term programme the strategy needs to be reviewed periodically.

Petersen *et al* (1986) have described the application of a pilot study to the development of a monitoring strategy. From an initial data set, obtained from 5 cement plants, estimated variance components (Henderson, 1953) for job, subject and random error were analysed. Intersubject variability was found to be negligible. The approach to selecting sample numbers for the major follow-up study was based on being able to estimate the mean for a plant/area combination with an acceptable level of accuracy. The criterion used to select the number of samples to take was based on twice the standard error of the mean for the plant/area. This represents half the approximate confidence interval of the true mean, *ie* the halfwidth. Halfwidths were calculated for various combinations of number of measurements per job and number of jobs selected. An acceptable accuracy (halfwidth) for the measurements was determined and from this appropriate combinations of job numbers and number of measurements were determined.

4 RESULTS: INTERPRETATION AND ACTIONS

4.1 Purpose of Sampling

The interpretation of any set of measurements depends on the purpose of the sampling exercise. Before any measurements are made it is essential that the objectives of the exercise are clear. The various purposes of monitoring were reviewed in Chapter 1 and are summarised below. They are:

- As part of a health-risk assessment.
- Evaluating conformity or compliance with an OEL.
- Evaluating the effectiveness of control measures or monitoring plant performance.
- As part of an occupational health performance assessment and monitoring any changes with time.
- To provide data for epidemiological studies.
- When specifically required by legislation
- Validation or comparison of measurement methods.

Depending on the objectives of the measurement exercise a suitable strategy should be selected using the structured approach laid out in Chapter 2. In all cases an initial appraisal of the workplace would be required and the appropriate survey type selected from the basic, detailed or routine types of survey.

The design of the monitoring strategy dictates the data analysis strategy that should be adopted and hence affects the interpretation that may be placed on any set of results.

Leidel and Busch (1985) have taken a similar approach, identifying nine typical objectives for occupational hygiene investigations along with possible study design strategy and data analysis strategy (Table 4.1).

It is always important to remember that a set of measurements, collected for whatever purpose, is only really meaningful when it is placed in context. The context in this case, according to Hurley *et al* (to be published), is the information which defines the conditions under which the measurements were obtained. This would include details such as the controls in use at the time the samples were collected, the quantities of substances being used, the number of people working and so on. This type of contextual information is essential if the monitoring data is to have the potential to be used other than for the immediate purpose of the measurement exercise.

Table 4.1

Sampling and data-analysis strategies

Objectives		Study Design Strategies						Data Analysis Strategies					
		A. Workplace observations	B. Estimate possible airborne levels from material usage rates etc.	C. Worst case exposure measurements	D. Limited monitoring program to identify higher risk target populations for additional monitoring	E. Quantify exposure distributions of target populations	F. Quantify determinant variables for exposure level distributions	G. Use Action Level as a screening cut off to identify target populations for additional monitoring	H. Control chart for daily TWA exposure levels and distribution parameters	I. Probability charts	J. Inferential statistical methods: Hypothesis testing Confidence limits and intervals Tolerance limits and intervals	K. Linear regression analysis: Simple (2 variables) Multiple (3 or more variables)
1.	Initial risk assessment	●	○									
2.	"Worst case" monitoring	○		●	○	○	○			○	●	
3.	Control method evaluation			○			●			●	●	○
4.	Exposure screening programs				●			●	○		○	
5.	Exposure distribution monitoring programs					●			●	●	●	
6.	Regulatory monitoring programs				●	○	○	●	●	○	○	
7.	Epidemiological studies					●	●			●	●	●
8.	Measurement methods comparison					○	○			○	●	●
9.	Measurement method validation									○	●	

Note: ● Primary strategy, ○ secondary strategy

4.2 Criteria for Compliance Evaluation

Many of the objectives identified in the previous section are associated with comparison of measured exposures with occupational exposure limits. In most countries occupational exposure limits now have a legal status which entails a definition of their meaning. In the UK most limits are covered by the Control of Substances Hazardous to Health Regulations 1988 (COSHH, 1988). These regulations define two types of occupational exposure limit: maximum exposure limits (MELs) and occupational exposure standards (OESs).

Regulation 7(1) of the COSHH Regulations states that:

> "Every employer shall ensure that the exposure of his employees to substances hazardous to health is either prevented or, where this is not reasonably practicable, adequately controlled."

The meaning of what is adequate is further defined for substances with an MEL in paragraph 4 of Regulation 7:

> "Where there is exposure to a substance for which a maximum exposure limit is specified, the control of exposure shall, so far as inhalation of that substance is concerned, only be treated as adequate if the level of exposure is reduced so far as is reasonably practicable and in any case below the maximum exposure limit."

It could reasonably be argued that this Regulation requires that where a substance has been assigned a maximum exposure limit the exposure of all the workers must always be below the MEL. However, as we have discussed earlier, the exposure of groups of workers or individuals is not a constant value but is a variable following some form of statistical distribution. These distributions are not limited at the higher concentrations and so there are likely to be some measurements in the tail of the distribution which are far from the mean concentration. The official guidance for the COSHH Regulations recognises this by stating that where the limit is expressed over an 8-hour day, it is sufficient to demonstrate that the MEL is "not normally exceeded, *ie* that an occasional result above the MEL is without real significance and is not indicative of a failure to maintain adequate control".

For substances with an OES Regulation 7 also defines how this should be interpreted:

> "where there is exposure to a substance for which an occupational exposure standard has been approved, the control of exposure shall, so far as inhalation of that substance is concerned, be treated as being adequate if:
>
> (a) the occupational exposure standard is not exceeded, or
>
> (b) where the occupational exposure standard is exceeded, the employer identifies the reasons for the standard being exceeded and takes appropriate action"
>
> *COSHH Regulation 7(5)*

The interpretation of this wording is further amplified in the COSHH Approved Code of Practice (ACOP, 1991), where it says:

".. exposure by inhalation should be reduced to that standard.."

COSHH ACOP para 28(a)

The wording in these paragraphs is clearly different from that for the MELs and it could be argued that it implies that a different approach should be adopted for assessing compliance. Where the exposure should be "reduced to" the OES then it could be argued that it is the average exposure that should be controlled rather than some upper quantile.

The concept of using the mean exposure for comparison with exposure limits is not new. Oldham and Roach (1952) argued that, because of the inherent variability in exposure, both within a working day and between days, the only suitable measure which could be used to correlate with disease was the long-term average exposure. Others have followed a similar argument, particularly when dealing with chronic hazards. Corn (1985) has advocated using the mean exposure to coal-mine dust in underground mines in the USA and Riediger (1986) for monitoring hazardous substances in Germany.

Rappaport (1991) has commented on the system operating in the USA. He notes that when new occupational exposure limits are developed by the Occupational Safety and Health Administration (OSHA) they have to assess the risk associated with the proposed limit and determine if it is feasible. When making their risk assessment they use the average exposure of a worker, or a uniformly exposed group of workers, over 45 years. This is based on the assumption that for chronic agents the mean exposure is the best predictor of risk. These limits are therefore set on the basis of average exposure although the compliance testing that is carried out aims to ensure that all exposures are below the limit.

4.3 Assessment of Compliance with Exposure Limits

There is no clear universally accepted way of assessing compliance with occupational exposure limits. The principal difficulties arise because of the inherent variability of personal exposure data, either because of measurement error or more importantly because of variation in personal or environmental factors. For example, in a group of workers using solvents, where measurements were made over six days when the same work was going on, one person's measured concentrations ranged from 13ppm to 78ppm (Cherrie *et al*, 1991). There were no obvious reasons for these differences, such as changes in production rate or the way in which the work was undertaken. In addition the vague way in which the legal definition of exposure limits deal with this inherent variability compounds the problem. The following sections set out a range of possible approaches to compliance testing.

4.3.1 A Simplistic Approach

The simplest approach would be to require all measurements to be less than the occupational exposure limit. This is a poor basis to assess compliance. In this situation the larger the number of samples collected the higher the probability that one measurement will exceed the exposure limit. For example, assuming a lognormal distribution, with a geometric mean of 50ppm and a geometric standard deviation of 2, then the probability of obtaining a measurement above the OEL of 200ppm is given in Table 4.2 below.

Table 4.2

Probability of exceeding an OEL of 200ppm with geometric mean 50ppm and geometric standard deviation of 2

Number of measurements	Probability of one sample being greater than the OEL
0	0.0%
1	2.0%
2	5.0%
5	10.0%
10	19.0%
20	36.0%
50	75.0%
90	99.1%

Clearly the best way of ensuring compliance would be to take no samples! If sufficient samples are taken, it is almost certain that one of the measurements will be above the exposure limit.

A modification of this approach is to allow occasional excursions above the limit value. This also suffers from the inherent disincentive of discouraging measurements and hence encourages decisions to be made with poor quality information (or none). This is unfortunately the approach implicit in the wording of the legislation in the UK and other countries. The COSHH Regulations state that, where there is an MEL, control of exposure shall only be adequate if:

"the level of exposure is reduced so far as is reasonably practicable and in any case below the MEL."

COSHH Regulation 7(4)

The Approved Code of Practice further qualifies this by saying:

"an occasional result above the MEL is without real significance and is not indicative of a failure to maintain adequate control."

Assessment of compliance clearly requires some more formal statistical assessment.

4.3.2 A Pragmatic Approach

In annexes to a draft European Standard entitled "Workplace Atmospheres - Guidance for the Assessment of Exposure to Chemical Agents for Comparison with Limit Values and Measurement Strategy" (CEN, 1992) two alternative approaches are set out. The first method is a pragmatic set of rules, the second a more formal statistical method.

In the former approach the measured concentration (C) is divided by the limit value to produce a so-called dimensionless index of exposure.

$$I = C / OEL$$

A series of decision criteria is then applied to a set of measurements collected during 1, 2 or 3 working shifts. The approach is only valid for stable conditions where there are no unacceptably high peak exposures. The decision rules used in this approach are shown in the flowchart (Figure 4.1). This closely parallells the system developed by Leidel and his co-workers at NIOSH in the USA.

Tuggle (1981) has reviewed the NIOSH scheme and has concluded that it is inefficient because, in high-risk situations, where there is a high degree of variability it may give incorrect conclusions with unacceptably high probability. It is likely that similar considerations would apply to any pragmatic approach.

Furthermore the requirement for exposure measurements from 3 different shifts, without specifying the way in which these are chosen, leaves open the possibility for bias of the assessment, *eg* due to sampling coinciding with the high exposure shifts of a cyclical process.

4.3.3 Estimated Frequency of Non-Compliance

The second approach, set out in the draft European Standard annexes (CEN, 1992), relies on a statistical assessment of between 15 and 20 measurements within an occupational group. It is clearly therefore aimed at the detailed survey rather than a basic survey. A suitable distribution is then fitted to the data. In many cases the lognormal distribution provides a good fit. The probability of a measurement exceeding the exposure limit is then calculated. Depending on the probability there are three possible conclusions:

- If the probability is less than, or equal to, 0.1% then the situation is in compliance and no further action is necessary unless there are changes to the process.
- If the probability is greater than 0.1% but less than, or equal to, 5% then the situation is probably in compliance but this needs to be confirmed by periodic measurements.
- If the probability is greater than 5% then the situation is out of compliance and action must be taken to bring it into compliance. A new set of measurements should be collected after the improvements have been made.

This is known as a *one-sided-tolerance test*. For a lognormal distribution, it can be described analytically, if we define T_u the test statistic:

$$T_u = X_L + Ks_L$$

where X_L is the mean of the log transformed exposures, s_L is the standard deviation of the log transformed exposures and K is a factor (the *tolerance interval coefficient*) determined by the level of confidence required in the test, the number of measurements and the percentage of measurements required to be within the tolerance interval.

If $T_u < \ln (OEL)$ then the measurements are in compliance.

We are in essence using the mean and variance of the distribution of exposures to determine compliance. The test may be interpreted as addressing the question "are less than P% of exposures above the OEL". (P is frequently chosen to be 5% and the confidence level set at 95%.)

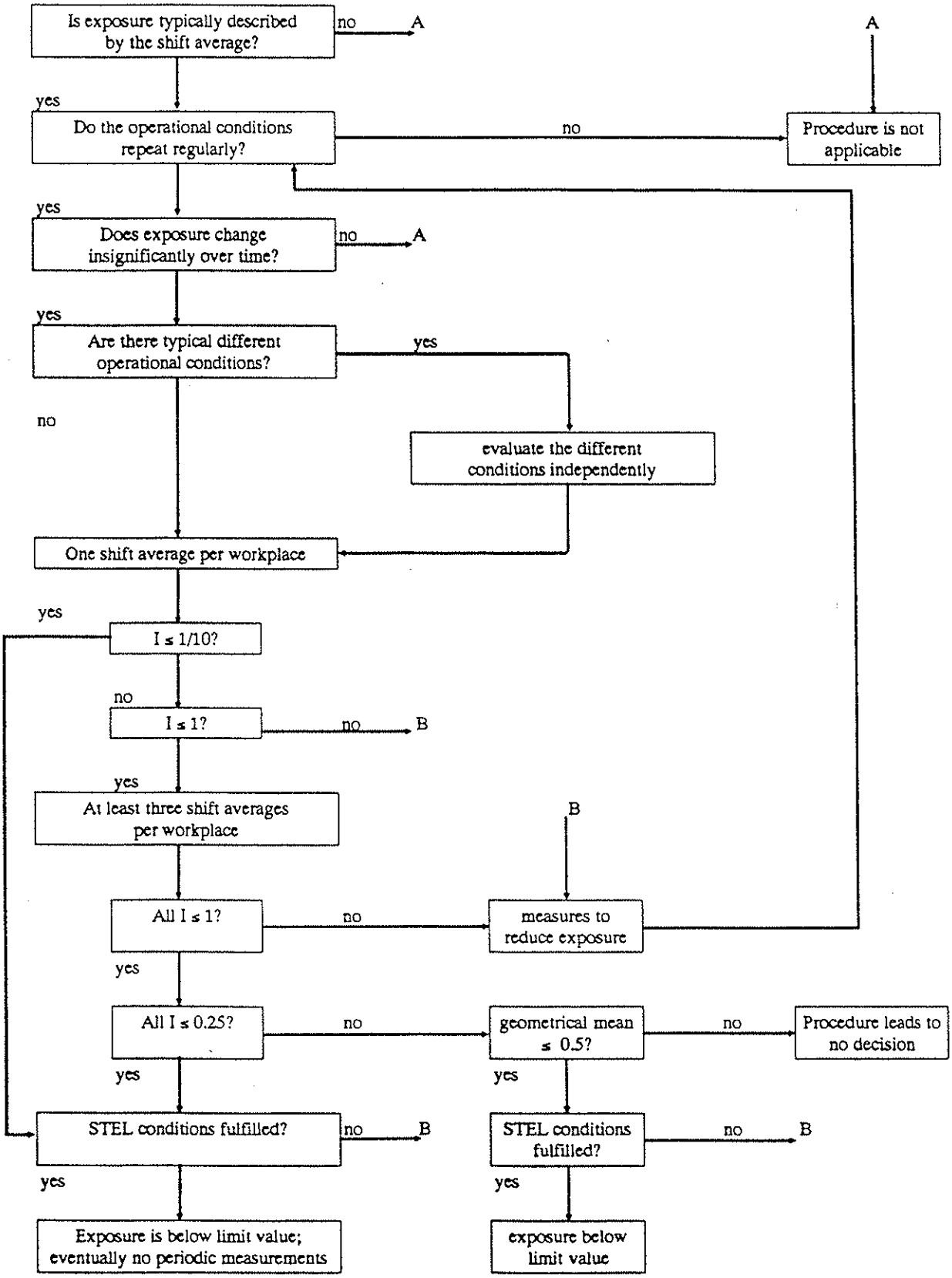


Figure 4.1

A pragmatic procedure for assessing occupational exposure measurements (CEN, 1992)
(With permission from a draft document; subject to change and should not be used in its current form)

The main problem with one-sided-tolerance tests is that the number of samples required to assess compliance increase rapidly as the proportion of samples with results above the OEL increases. Table 4.3 illustrates the situation for 95% confidence that less than 5% of all exposures are above the OEL.

Table 4.3

Number of measurements required to reach a decision on compliance

Fraction of exposures above OEL	Number of measurements required to come to a decision
0.001	8
0.01	22
0.02	50
0.03	approx 133
0.04	approx 600

4.3.4 Testing the Mean Exposure

Roach and others (Oldham and Roach, 1952; Roach, 1953; Rappaport, 1985) have argued that the most appropriate index of risk for chronic hazards is the mean exposure. Rappaport and Selvin (1987) have proposed a method of testing compliance based on the hypothesis that, if the mean exposure is above the OEL, or some defined fraction of it, the situation is out of compliance.

The test statistic they use is:

$$T_m = (X_c - OEL)/s_{xc}$$

where X_c is the maximum likelihood estimate of the mean concentration, based on the assumption that the concentrations are drawn from a lognormal distribution, and s_{xc} is the standard error of X_c.

$$X_c = \exp (x + 0.5\, s^2)$$

where x is the mean of the log transformed measurements and s^2 the variance.

$$S_{xc} = [\mu_c^2 (s_L^2 + 0.5 s_L^4)/(n-2)]^{1/2}$$

where μ_c = OEL.

The test statistic has a distribution which approximates to a "t" distribution, with n-1 degrees of freedom. For compliance $T_m < t$ (where t is obtained from a table of "t" values for the chosen confidence level).

Rappaport and Selvin (1987) give an expression for the approximate sample size required to test compliance, and as with the previous test the required number of samples increases with increasing mean and variance in the measurements. Table 3.3 (Section 3.6.4) illustrates this for the case where the significance of the test is at the 5% level and the power is 90%.

An alternative, graphical, method (Figure 4.2) of determining whether the mean of a set of measurements exceeds a limit value has been presented by Coenen and Riediger (1978). There are two figures and on each there are several pairs of curves for different sample sizes. The vertical axis shows the ratio of the geometric standard deviation to the limit value and the horizontal axis shows the geometric standard deviation.

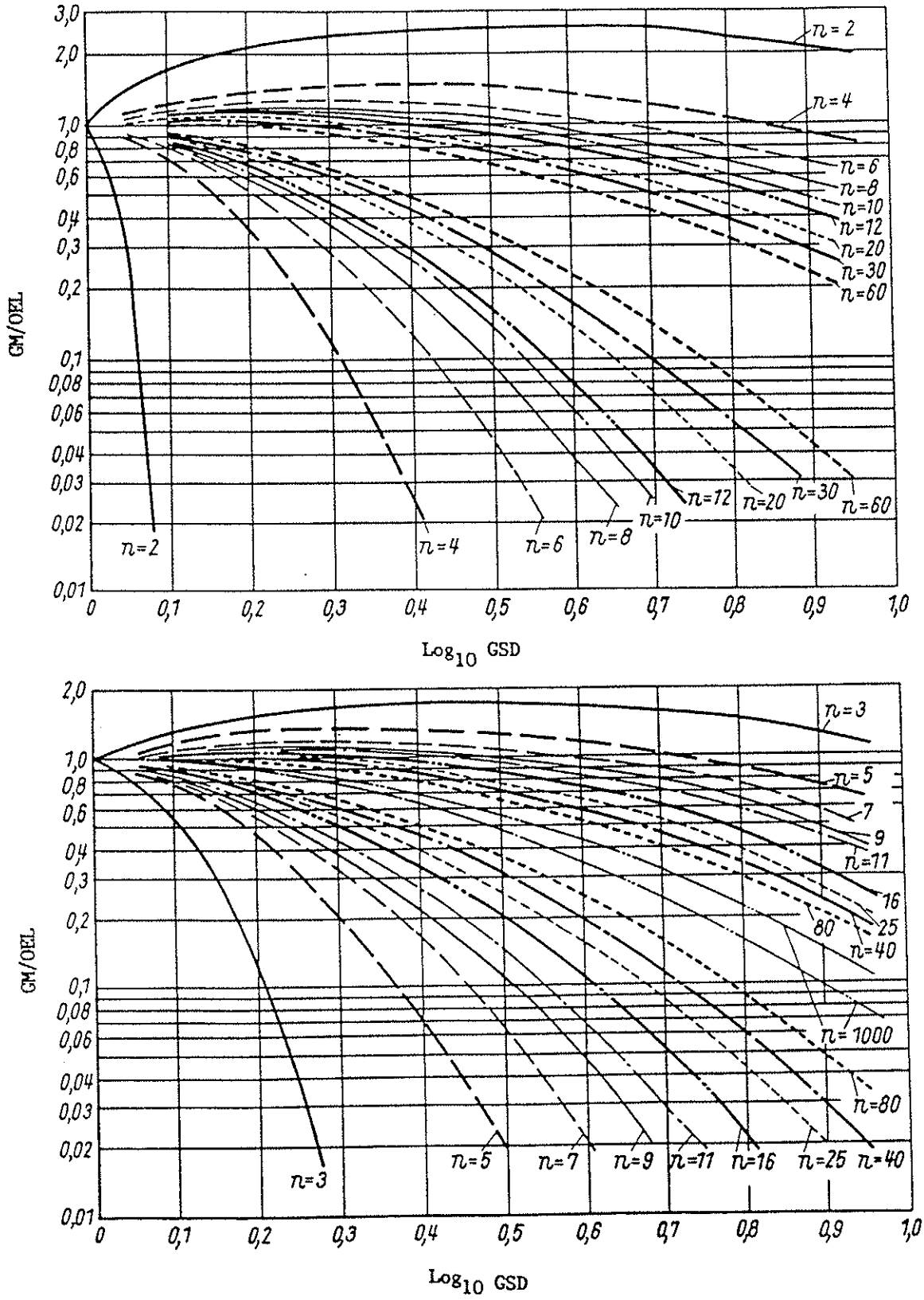


Figure 4.2

Graphs for determining if the mean of a set of measurements exceeds an OEL (Coenen & Riediger, 1978)

There are three possible outcomes for any particular set of data when the summary statistics are plotted on the graphs:

- The point is below the lower boundary curve for the sample size in question. In this case the average is less than the limit, with 95% confidence.
- The point lies above the upper boundary curve. In this situation the limit value was exceeded by the average, again with 95% confidence.
- The point lies between the two curves for the given sample size. This corresponds to there being insufficient information to decide if the average concentration is either above or below the limit value.

4.3.5 Dealing with Measurements below the Limit of Detection

The calculation of summary statistics is open to error when part of the data set is unquantified, for example because some of the measurements were below the limit of detection of the analytical technique. It can be said that the distribution of measurements is *censored*. The most commonly used method is to assign a value which is one-half of the detection limit to all of the data points which are less than the limit of detection . The assumption that is implicit in this process is that there is a uniform distribution of data points between zero and the detection limit and the method is best suited to data which is normally distributed. For a lognormal distribution, measurements can be assigned a value of two-thirds or $\sqrt{½}$ (= 0.707) of the detection limit as discussed by Waters *et al* (1991). For most situations these simple compensation methods should be adequate. More rigorous methods for computing censored data values have been reported, for example, by Hald (1952), Cohen and Ryan (1989) and Perkins *et al* (1990).

4.3.6 Graphical Data Presentation

Large sets of measurements present a particular difficulty to the hygienist. Faced with twenty or thirty measurements it is almost impossible to discern any pattern. The data must be summarised and displayed before the trends are seen. Indeed it can be argued that, before any summary statistics are calculated or any comparisons made with exposure limits, the data should be examined graphically. In this way an initial appreciation of the underlying distributions of the data may be gained. Probability plots were discussed in Section 3.2.3. They can provide a simple way of assessing whether a set of data conforms to an underlying distribution. They are a special form of cumulative frequency plot where the percentage scale is non-linear. The non-linearity corresponds to the probability density function of the normal distribution so that a normal distribution would correspond to a straight line. If the other axis of the plot has a logarithmic scale then a lognormal distribution would appear as a straight line.

Figure 4.3 shows benzene air concentration measurements obtained from a petro-chemicals plant, using 3M diffusive samplers (Tindle, 1984).

From such plots various summary statistics can be estimated, for example the geometric mean (50% point) on the benzene data plot is 0.2ppm and the 95% point is 2ppm. It is also possible to estimate the geometric standard deviation (GSD).

$$\text{GSD} = \text{84th percentile/50th percentile}$$

In the example data set the geometric standard deviation is 5, (*ie* 1.0/0.2).

Bailey and Miles (1984) describe the construction of probability plots and their application in occupational hygiene. They cite the main advantages of using probability plots as:

- Groups of workers with the same exposure distribution can be defined.
- All of the results are displayed in a form that is easily explained to non-professionals.
- The statistical distribution of the results is implicitly tested.

However, as described in Section 3.2.3, graphical plotting of the data and fitting a line to the data by eye is not a goodness-of-fit test. Lognormal distributions with low geometric standard deviations (less than approximately 1.3) look very similar to normal distributions and under such circumstances normally distributed data could plot as a straight line on lognormal probability paper. If any statistical tests are to be applied to the data then a goodness-of-fit test should be done (Section 3.2.2).

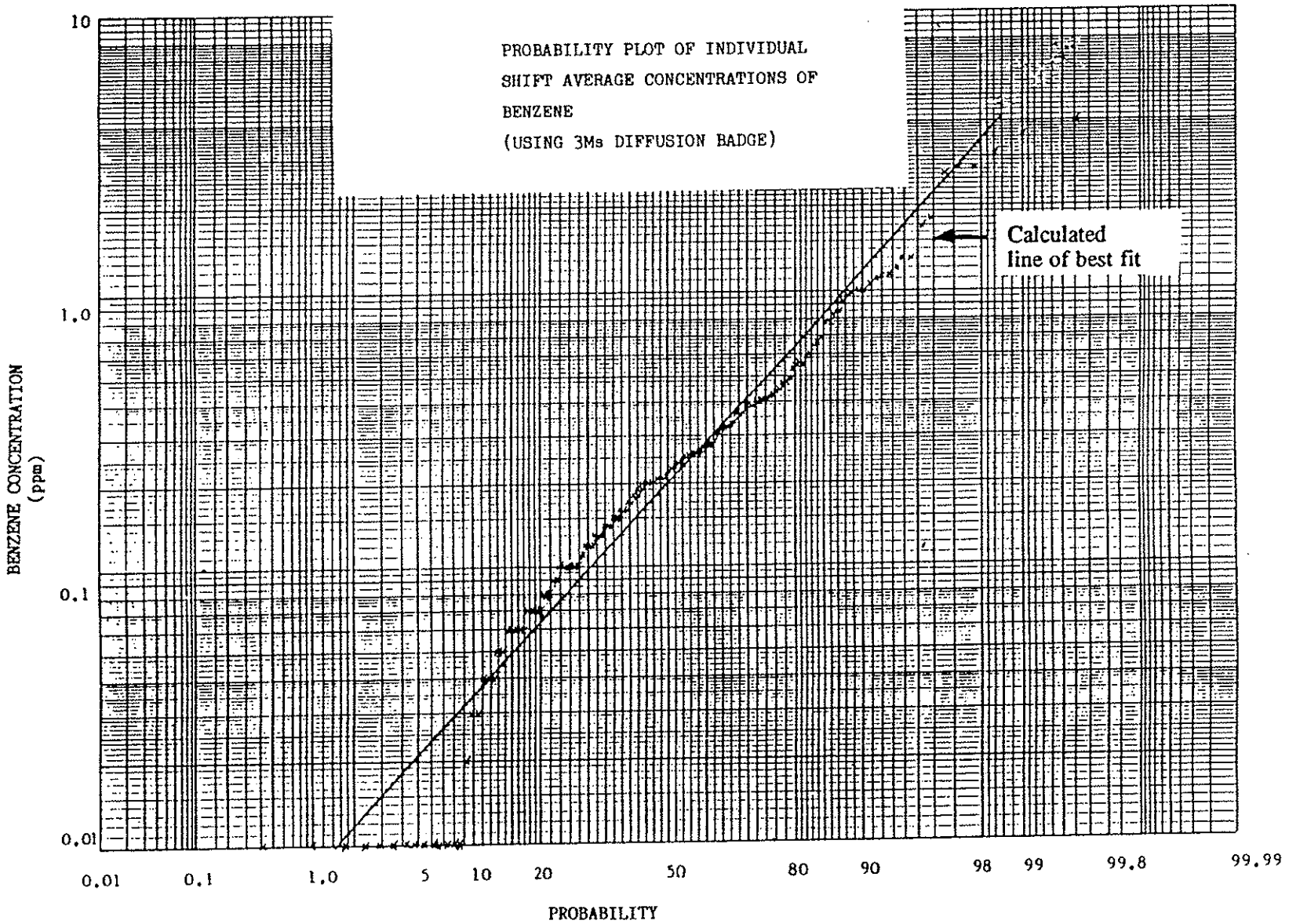


Figure 4.3

Probability plot of individual shift average concentrations of benzene (Tindle, 1984)

4.4 Control Charts

The use of a control chart will enable the movement in measurements to be tracked over periods of time. Past monitoring results are used to establish a base line against which to assess current results and look for trends thereby detecting possible changes in workplace conditions. The collection of data needs to be tightly controlled as described in Section 2.5 for routine surveys. The technique can only be used where conditions in the workplace are fairly stable. When conditions are changing fairly quickly, *eg* because new control measures are being introduced, then control charts are not appropriate. The basic techniques only work well with large numbers of samples. For these three reasons very little hygiene data currently fit the criteria for using control charts and there are few, if any, published examples.

A control chart is a plot of a summary statistic from a set of data collected sequentially in time. There are many different forms of control chart which have been devised. The method examines two characteristics of the distribution, the central tendency (usually the mean level) and the dispersion (as measured by the variance, standard deviation, or a surrogate such as range) against acceptable control limits. Control charts are based on the data having a normal distribution. They can be applied to occupational hygiene results because in the majority of cases the means of samples taken from a population themselves have a normal distribution irrespective of the distribution function applying to the population. Departures from normality for the distribution of the means can occur in some situations, particularly when sample sizes are small (which is common in occupational hygiene). The use of control charts in occupational hygiene is discussed by Hawkins and Landenberger (1991), particularly the use of charts for the mean and range. It is important to use the charts in pairs. Even if the mean remains steady it is possible that the range of the results will vary. If the measure of dispersion changes then so will the control limits for the mean which are based on multiples of the standard deviation. A change in the range of the results outside acceptable limits will also indicate that there is a potential change in workplace conditions. Control limits can be set as upper and lower warning levels (usually chosen as plus and minus two standard deviations) and upper and lower action levels (usually chosen as plus and minus three standard deviations).

Figure 4.4 shows control charts for the mean values from several sets of sampling results together with the corresponding chart for the ranges. Whilst the "means" chart suggests the workplace is under effective control, the range chart indicates that this may not be the case.

More advanced techniques are available which require less structure in the sampling plan and which can be used with fewer sampling results. The cumulative sum chart (CUSUM Chart) is one such method (BSI, 1984, 1984a) which utilises a running average for a sequence of measurements, plotted as a time sequence. The technique is not easy to apply and advice from a statistician may be needed.

4.5 Conclusions from Sampling and Periodic Monitoring

The earlier sections have shown that there is no single type of sampling exercise nor is there any single best way of comparing exposure measurements with occupational exposure limits. In cases where we are interested in compliance with limits there are three basic conclusions that can be reached:

- Exposures are above the occupational exposure limit. In this case the reasons for the results should be identified and steps taken to control the workers' exposure.
- Exposures are well below the limit value and no further action is needed at this time.
- There is insufficient information to decide unambiguously if exposures are either above or below the occupational exposure limit. Either more information is necessary or prudent action should be taken to reduce the exposure of the workers.

The decision about whether or not periodic monitoring is justified must be based on the results of the initial sampling plus the characteristics of the work and the work environment. Factors which should be taken into consideration are:

- Process cycles.
- Reliability of controls.
- Data variability and closeness of exposures to limits.
- Time needed to take remedial action.

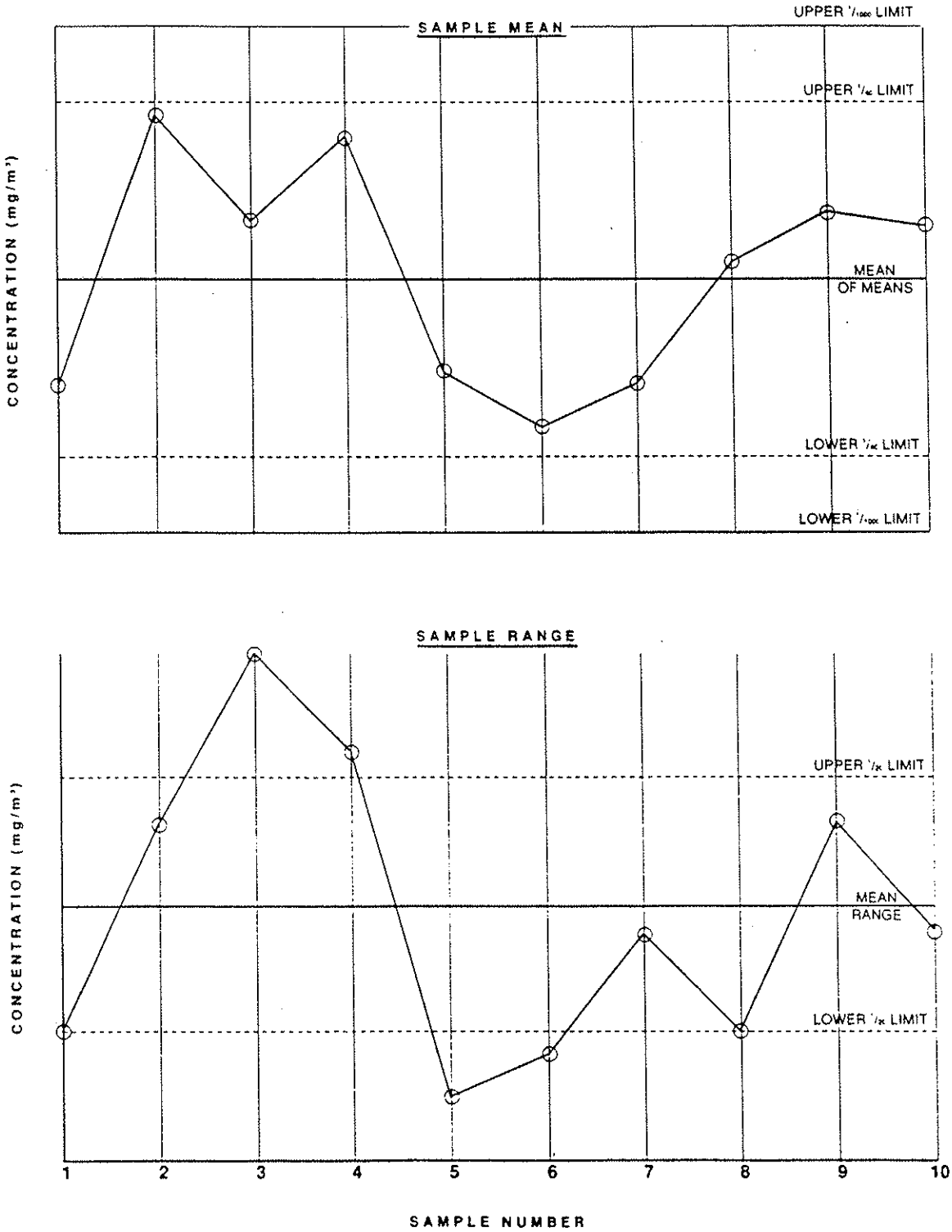


Figure 4.4

Control charts for means and ranges (See Hawkins and Landenberger, 1991)

There are a number of publications which offer guidance on the frequency of monitoring depending upon how far the measurement results are from the OEL. Roach (1977) suggests the minimum frequencies given in Table 4.4. The approach focuses the sampling effort on those employees whose exposure is close to the OEL where good-quality data are required. There is little to be gained, for example, from frequent, repeated measurements when employees' exposures are below one-tenth of the OEL or above twenty time the OEL.

Table 4.4

The minimum time to be spent on regular monitoring of personal exposure - suggested by Roach (1977)

Man-shifts covered by sampling (per 10 employees)*	Personal exposure/OEL
1/month	1 - 2
1/quarter	0.5 - 1 or 2 - 4
1/annum	0.1 - 0.5 or 4 - 20
None	<0.1 or >20

*If < 10 employees/shift - assume 10

The annexes to the draft CEN standard on monitoring strategies (CEN, 1992) present two alternative schemes.

In one scheme an initial time period (< one week) is set depending on several factors, including:

- The work routine.
- Response time of the analytical laboratory.
- The type of OEL (STEL or 8-h TWA).

The basic measurement periodicity is then set at 8 time units. Depending on the results of previous measurements of exposure the schedule is then modified, as shown in Table 4.5, by reference to four Action Levels, N1 to N4, with the following values:

N1 = 0.4 OEL
N2 = 0.7 OEL
N3 = 1.0 OEL
N4 = 1.5 OEL

The second CEN scheme is as follows:

- The first periodic measurement is carried out within 16 weeks after the need for periodic measurements has been established. The maximum time interval to the next result depends on the result of the previous measurement.
- The interval is 64 weeks if the exposure concentration is less than 0.25 OEL
- The interval is 32 weeks if the exposure concentration exceeds 0.25 OEL but is less than 0.5 OEL
- The interval is 16 weeks if the exposure concentration is between 0.50 OEL and the OEL

The choice of a 64 week baseline period in this scheme ensures that over a period of time the repeat measurements do not fall on the same week of the same month every year, reducing the risk of obtaining biased data due to seasonal effects.

Table 4.5

Measurement frequencies related to action levels N1-N4 (CEN, 1992)

Situation	Measurement Result	Decision
1	C<N1 twice consecutively	Omit the following 3 measurements
2	C < N2	Continue basic schedule
3*	N2 < C < N4	A new measurement is taken during the next time unit
4*	N2 < C < N4 for 2 consecutive time units	An additional measurement is done in the 4 subsequent programmed intervals. If this interval is one time unit immediate action should be taken to reduce exposure
5	N3 < C < N4 twice consecutively	Take immediate action to reduce exposure
6	C > N4	Immediate action to be taken to reduce exposure

* In 3 and 4 if C > N3 appropriate measures to improve control should be identified and implemented.

It is important to realise that a pre-requisite of any periodic monitoring is that the monitoring techniques and strategy are the same for each exercise, otherwise there is no basis for comparing successive sets of measurements.

The main purpose of any periodic monitoring is to check the continued performance of the controls. Where there is strong evidence to suggest that the situation is effectively controlled then such monitoring can be reduced or phased out. Both of the CEN schemes could result in large numbers of samples being collected in open-ended routine monitoring schemes with no direct benefit to the workforce. A decision must be made on whether the money could not be better spent on improving the performance of the control measures.

4.6 Adjusting Exposure Limits for Different Periods of Work

There are several suggestions for making adjustments to exposure limits for work days which are either longer or shorter than the norm. This has arisen because of the changes in the pattern of work which have occurred in the last 20 years. More people now work longer each day and to compensate they work less days per week, *eg* four 10-hour days in each week. There are many potential problems in such unusual work schedules and one of these is the difficulty in applying exposure limits which have been devised for more conventional schedules (8 hours per day, 5 days per week).

The principal reason for adjusting exposure arises because the longer working day results in a shorter recovery period between each exposure. If the biological half-life of the substances in question is of comparable duration to the normal recovery time (*ie* 16 hours) then this could result in a greater build-up of the chemical in the body than might be expected.

The original suggestion on how to adjust exposure limits was put forward by Brief and Scala (1975). They suggested a simple formula for adjusting the limit value to compensate for longer or shorter working days. This adjustment is in addition to calculating the actual exposure over an 8-hour day. Their formula is:

$$\text{OEL reduction factor} = \frac{8}{H} \times \frac{(24-H)}{16}$$

where H is the number of hours worked per day.

For example, workers are exposed to a substance with an exposure limit of 200ppm (8-h TWA) for 12 hours each day for four days each week. The reduction factor (RF) is given by:

$$RF = \frac{8}{12} \times \frac{12}{16} = 0.5$$

So the OEL should be reduced to 100ppm.

If the workers were exposed to 150ppm over the full twelve hours then their exposure would be greater than the adjusted exposure limit (100ppm).

The procedure clearly has limitations which the authors point out. The main limitations were as follows:

- When the work schedule involves 24-hour continuous exposure, the formula would not apply.
- When people work less than 7 to 8 hours per day or 35 hours per week, the formula would not apply.
- The formula should not be used to modify exposure limits for acute toxicants when the effect is concentration-dependent *eg* irritation by ammonia. The formula could be used for acute affects which are time- and concentration-dependent.

More sophisticated approaches to adjusting exposure limits, using pharmacokinetics, have been published recently by Andersen *et al* (1987), Saltzman (1988), Eide (1990) and others. These authors make use of mathematical models of the kinetics of the substance or its metabolites in the body to determine the appropriate adjustment factor which should be applied to an exposure limit.

Andersen *et al* (1987) use a physiologically based pharmacokinetic model, comprising five compartments: fat tissue, muscle tissue, richly perfused tissue, liver metabolising tissue and lung blood. They use their model to make recommendations for adjusting the exposure limits for styrene and methylene chloride. Data for the model were derived from animal and human studies. The model was validated against available experimental data.

Central to the use of this type of model is the establishment of an appropriate risk index, *ie* the model parameter which most closely correlates with the disease process. For methylene chloride Andersen and his co-workers identified blood carboxyhemoglobin (HbCO) as the critical risk factor. In their model they developed exposure limits so that the HbCO concentration was no higher than in the normal work regime. The adjusted exposure limits were 85ppm for 10 hours and 78ppm for 12 hours (OEL for 8 hours being 100ppm).

This approach is more sophisticated than the simple approach of Brief and Scala and yet it is still limited in its application. One must question the validity of using scaled-up animal data in a model intended to represent humans and, in situations where there is less understanding of the disease mechanism, the choice of risk parameter is important. The pharmacokinetic models require a great deal of detailed data about the passage of the substance in question through the body. This information is not readily available for most substances.

5 DEVELOPMENT OF A SAMPLING STRATEGY: AN EXAMPLE

5.1 Introduction

The following example of a structured approach to strategy development relates to welding in a coal-fired power station.

Welding was one of the key operations carried out as part of the general maintenance work in the power station which may expose workers to a variety of hazardous substances. There were thirty welders employed full-time, mostly repairing the large ball mills used to pulverise the coal prior to combustion. The welders were equally likely to work in one of three situations:

a) in the welding workshop

b) inside the ball mills

c) on other fixed plant within the power station, *eg* inside coal chutes, on boilers *etc.*

The work comprised cleaning the area before welding (most items are covered in coal dust and pulverised fuel ash), cutting metal using an oxyacetylene set, cleaning metal to be welded using portable grinders and finally manual metal arc welding. All of the metal being welded was mild steel.

5.2 Description of the Work Locations

The welding workshop was located at one end of the power station. It was about 40m square and 5m high. There were three purpose-built welding benches with integral local exhaust ventilation. Most welding was done at these benches, although some larger items of equipment required repairing in the centre of the workshop.

The ball mills were situated in the basement of the power station. There were thirty mills in total. Each mill was about 8m high and about 3m in diameter. The chamber where the balls were located was about 1.5m high and covered the full width of the mill. This was the area where most abrasion from coal particles occurred and hence was where most of the welding repairs were needed. When welding was in progress the men used a portable local exhaust ventilation system, which could be positioned close to the work location.

The remaining work was carried out in almost any other location within the station. Most welding was however associated with coal handling and as such tended to be in relatively confined spaces. Local exhaust ventilation was again available for these jobs.

5.3 Aim of the Sampling Exercise

A COSHH assessment had been carried out and the main conclusion of this exercise was that exposure to coal dust, coal ash and welding fumes and gases may exceed the relevant occupational exposure limits. It was decided that a sampling exercise should be carried out to determine the actual exposures. The main aim of the sampling exercise would be to determine whether the welders' exposure to hazardous substances was in compliance with Regulation 7 of the Control of Substances Hazardous to Health Regulations. Subsidiary objectives were:

- To determine which of the many possible exposures would be likely to exceed the appropriate occupational exposure limits.
- To determine if exposure to selected hazardous substances exceeded their exposure limits.

5.4 Description of the Sampling

5.4.1 "Worst Case" Sampling Strategy

The first stage was to carry out some measurements during a worst case situation. Personal samples were collected from representative welders from each of the three groups: workshop, mills and elsewhere. The "worst case" was judged to correspond to continuous work involving welding throughout an 8-hour shift. Only welders who were expected to be welding throughout the shift were chosen. Representatives were chosen from each group, even though it was unlikely that the workshop would produce high measurements.

Measurements were carried out over a full shift for total inhalable dust, oxides of nitrogen and ozone. The nitrogen monoxide and nitrogen dioxide were sampled using tubes containing coated molecular sieve and then analysed colorimetrically. The ozone was sampled using micro-impingers containing 1% potassium iodide solution and subsequently analysed using a colorimetric technique. The dust samples were weighed and then analysed for their metal content using atomic absorption spectrophotometry.

From the description of the work tasks it was expected that the welders in the workshop and the mills would have relatively small variation between samples. The welders employed elsewhere within the station might be expected to have slightly greater variation between samples.

Based on these assumptions ten samples were obtained per group.

5.4.2 Results from the Initial Sampling

The results are presented in Table 5.1. The data from the mills and the workshop are also shown in Figures 5.1 and 5.2, as log-probability plots with the concentrations normalised to the OEL.

Table 5.1

Personal airborne concentrations
geometric mean (geometric standard deviation)

	Dust (mg/m^3)	Fe_2O_3 (mg/m^3)	NO_2 (ppm)	NO (ppm)	O_3 (ppm)
Mills	43.0 (1.8)	2.2 (1.8)	0.16 (2.2)	1.3 (3.0)	0.35 (4.0)
Workshop	4.2 (3.3)	0.1 (1.8)	0.16 (1.7)	0.4 (2.6)	0.06 (1.9)
Elsewhere	35.0 (2.9)	1.9 (2.5)	0.2 (2.5)	1.2 (3.0)	0.2 (2.8)
O.E.L.	5.0	5.0	3.0	25.0	0.1

Note: There are ten personal exposure measurements for each group

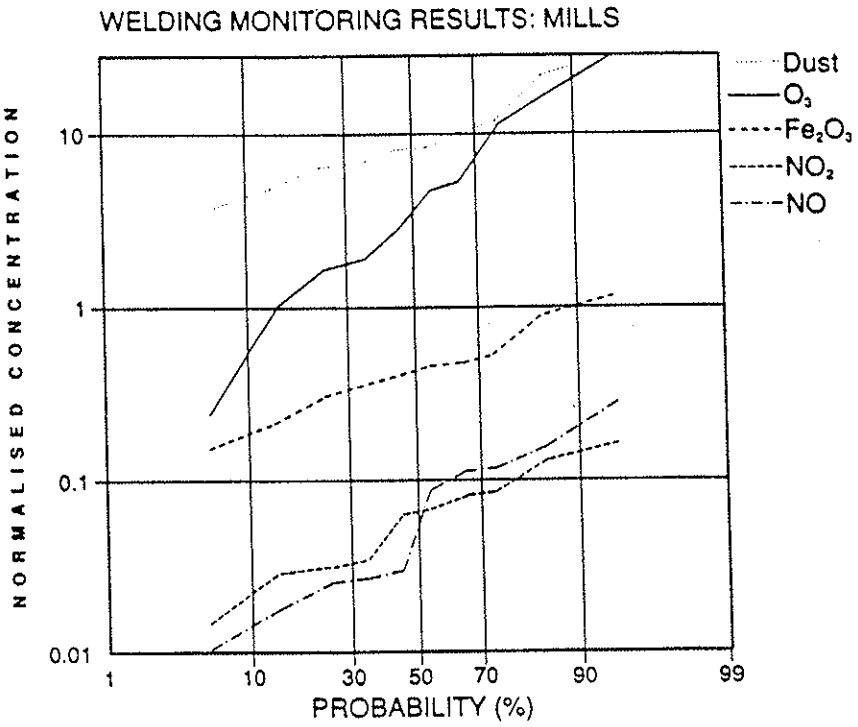


Figure 5.1

Welding sampling results: mills

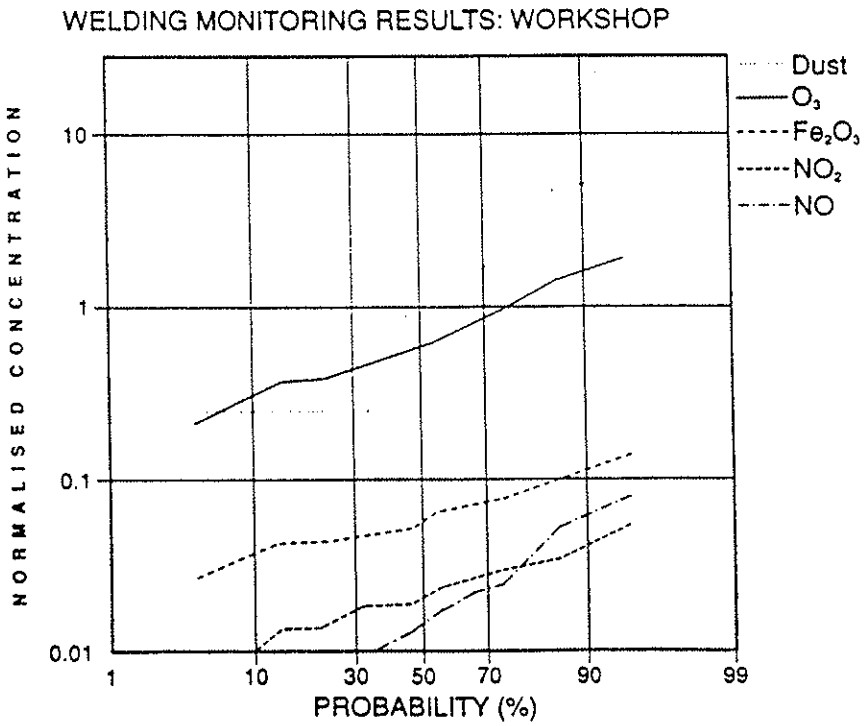


Figure 5.2

Welding sampling results: workshop

5.4.2.1 Mills

The data from the mills show that the total inhalable dust concentrations were very high, with all of the measurements in excess of the OEL for welding fume. The ozone concentrations were also apparently above the OEL. However the technique used to measure the ozone is prone to interference from other oxidising agents which may be in the air, *eg* sulphur compounds. Selected measurements with a direct-reading ozone analyser showed that the concentration of ozone in the welders' breathing zones was no greater than the background concentrations. The personal ozone measurements were therefore probably unreliable and have not been considered further.

The iron oxide concentrations in the mill area were much lower than the total inhalable dust concentrations, as must be expected; on average they were about 4% of the total mass collected (see Figure 5.3). It seems reasonable to conclude that the majority of the particulate in the air is not welding fume but coal dust or ash.

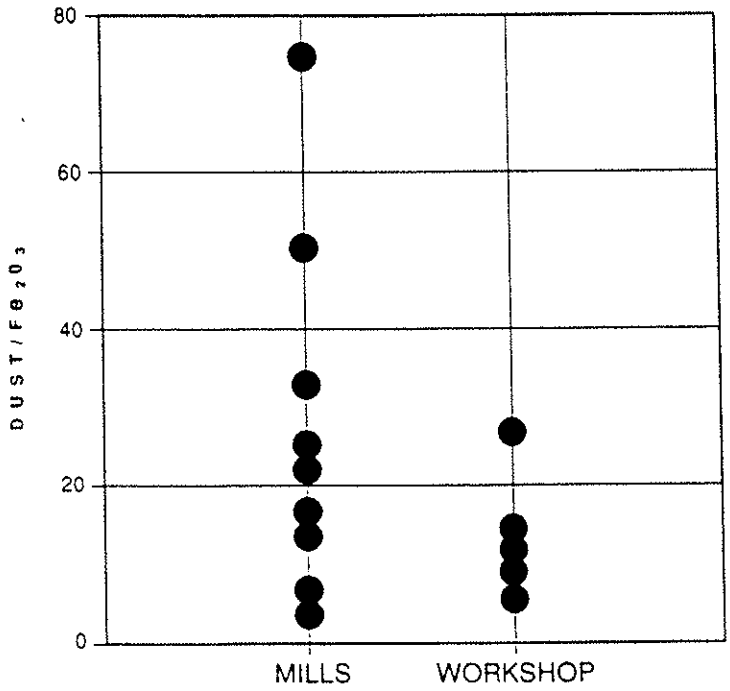


Figure 5.3

Ratios of total inhalable dust to iron oxide concentrations

The concentrations of nitrogen monoxide and nitrogen dioxide are far below their respective OELs and there seems little probability that they will exceed their limits.

5.4.2.2 Workshop

The pattern of concentrations found from samples collected in the workshop was similar to that for the mills, although the levels were generally lower. Ozone was again elevated, but measurements with the direct reading instrument again suggested that the actual levels were much lower than those measured using the method described in Section 5.4.1.

A small proportion of the total inhalable dust concentration measurements exceeded the welding fume OEL. The iron oxide concentrations were again lower than the total inhalable dust concentrations, although the difference was smaller than in the mill area and the ratio of the dust to iron oxide concentrations was less variable. It seems reasonable to conclude that a greater proportion of the particulate material in the workshop air was welding fume. However, bearing in mind that these data are from a "worst case" scenario there seems little probability that the welding fume OEL is exceeded.

5.4.2.3 Elsewhere within the Power Station

The results from these areas were similar to those from the mills, although as expected a little more variable. These data are not discussed separately.

5.4.3 Conclusions from the Basic Survey

There are a number of conclusions which can be made after the initial sampling. These are:

- The exposure of welders to coal dust and ash during welding on mills and elsewhere within the power station is probably unacceptable and above the OEL.
- The exposure of these men to welding fume, as measured by iron oxide concentrations, is probably not above the OEL.
- The welders' exposure to oxides of nitrogen and probably ozone are well below the appropriate OELs, even in the "worst case" situations measured in this exercise.

Based on these measurements there seems little point in proceeding directly to try and test compliance. It is clear that the greatest problem lies with the coal dust and ash which contaminate the work area. The most obvious remedy for this is to instigate a more rigorous cleaning regime and to improve the welders' understanding of the risks from these dusts.

5.4.4 Strategy for a Detailed Survey

Following the implementation of improved cleaning procedures and an education programme a second survey was planned to test compliance for the welders' exposure to coal dust and ash. This time there was no special selection of men, other than the stratification into the three groups. The data from the first survey were not used as they were collected using a biased strategy, *ie* a "worst case" scenario.

In this survey the substances in questions were the coal dust, ash and the quartz which might be present as a component within the coal. The appropriate sampling strategy in this case was to collect respirable dust using a cyclone dust sampler. Total inhalable dust samples were also collected. These samplers were located on the workers' lapels and the samples were collected over a full shift.Twenty pairs of samples were collected from each group over a six month period. The extended duration for the sampling exercise was chosen for convenience and to allow for possible seasonal variations in the welders' workload.

The aim of this exercise was to determine if the welders' exposures to coal dust and ash or quartz exceeded the relevant OELs.

5.4.5 Results from the Second Survey and Conclusions

The results from the respirable dust measurements made during the second survey are summarised in Figure 5.4. There was no quartz detected on any of the samples.

The respirable dust concentrations ranged from 0.05mg/m^3 to 2mg/m^3 in the workshop, to 5.5mg/m^3 in the mill area and 12mg/m^3 for those working elsewhere. If we were to assess compliance for these data we might first want to look at the proportion of measurements which exceeded the OEL. In the mill area there were six measurements out of thirty above the coal OEL; one measurement from the welders in the workshop and eight from those working elsewhere were also above the limit. Clearly neither of the groups outside the workshop could be considered in compliance if we required 95% of the results to be below the limit. In the workshop there are about 3% of the results in excess of the OEL. A formal test of compliance using the above criteria shows that this situation is in compliance.

Alternatively if we wish to test compliance using the mean exposure, then using the graphs provided by Coenen and Riediger (1978), it can be seen that the measurements for the workshop welders are again in compliance. The results for the mill welders are just on the borderline between compliance and being unable to make a decision. The welders working elsewhere are clearly in the area where neither compliance nor non-compliance can be demonstrated.

An explanation for these data not being in compliance can be found by looking at the measurements in the time sequence they were collected over. These data are shown in Figure 5.5. The concentrations show a consistent rising trend throughout the time. This may indicate that there has been a deterioration in the housekeeping, or decrease in the local exhaust ventilation, or some other cause. This can only be determined by observations and measurements in the power station. The most likely cause is deteriorating housekeeping.

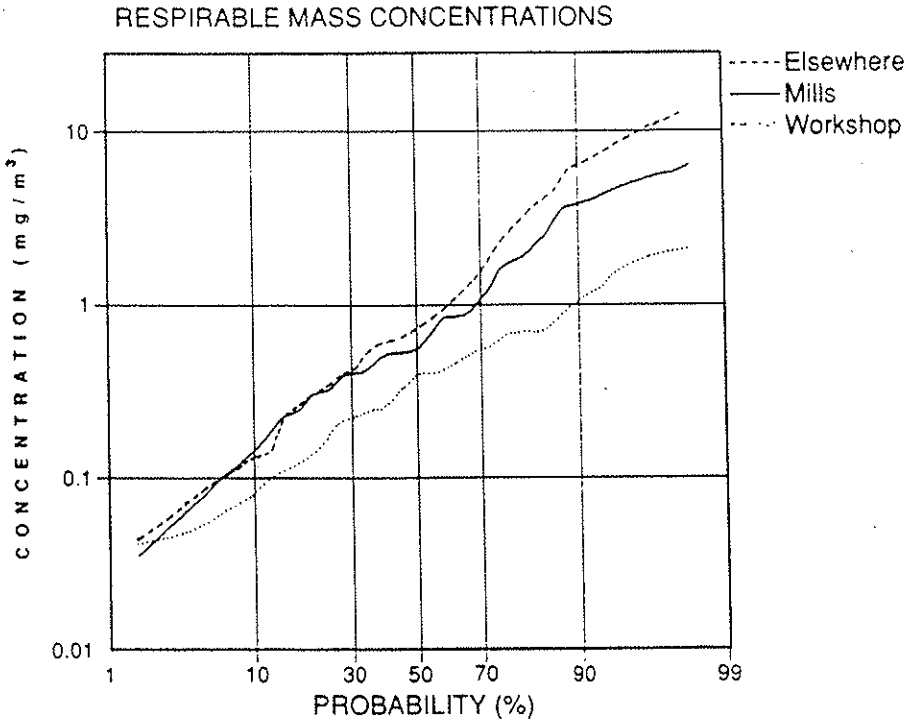


Figure 5.4

Respirable dust concentrations: all areas

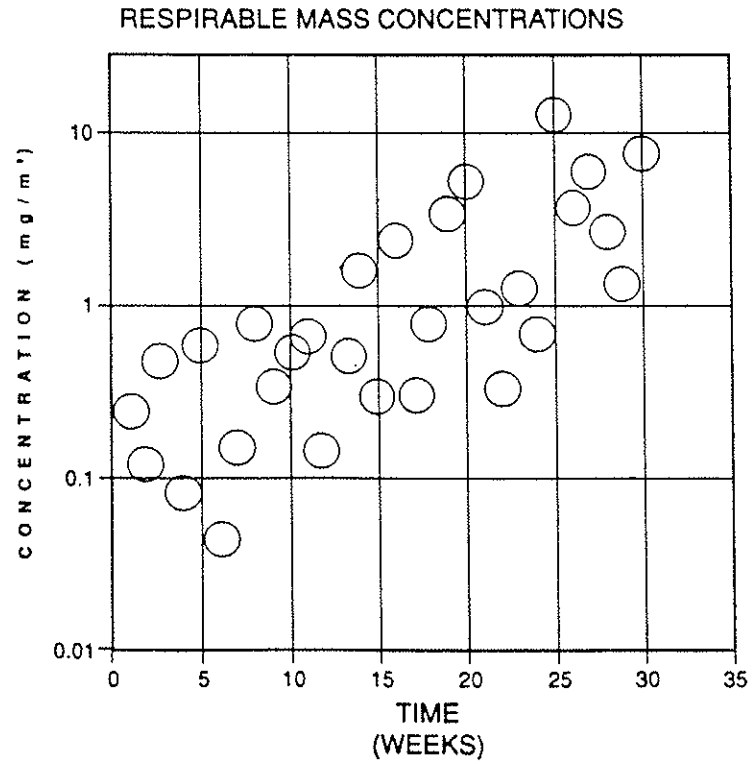


Figure 5.5

Changes in measured respirable dust concentrations with time

The total inhalable dust concentrations are higher than the respirable dust concentrations, as expected, by approximately one order of magnitude. Under the COSHH Regulations these inhalable concentrations should be less than 10mg/m^3. This is not the case. None of the testing strategies would show these data in compliance.

It is difficult to compare these measurements with the earlier data, because of the different strategies used. It is probable that they represent improved conditions, however, there is clearly a need for further improvements in control to reduce the total inhalable dust levels. Any subsequent survey would need to use the procedures utilised in this second Detailed Survey if any improvement in control is to be demonstrated.

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