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The Philosophy of Monitoring [and Discussion]

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The philosophy of monitoring

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The paper is concerned with the efficient design of monitoring studies on a logical basis to meet stated objectives. A series of questions are posed: why monitor, what to monitor, where to monitor, when to monitor and how to monitor?

Three broad categories of monitoring can be discerned: observation, explanation and control. The first tends to be orientated towards the receptor of pollution and the last is generally the most source-orientated. The paper discusses the requirements of different types of study. It emphasizes the desirability of monitoring the specific polluting agent having a particular effect but recognizes that sometimes a surrogate may have to be accepted. When one should measure depends on the nature of the effect produced by the pollutant in question, e.g. acute effects related to short-term peaks or cumulative effects related to long-term mean exposure. Statistical sampling should be considered but may be incompatible with some basic objectives. The siting of measuring stations is considered from the global to the local scale of monitoring and the relative attractions of mobile and stationary measuring stations are discussed. The problems of measurement of gases and particles are compared and a check list is put forward for use in selecting monitoring methods or instruments.

Methods of presenting and interpreting monitoring data are briefly discussed. Modelling of the physical dispersion of emissions is recognized as crucial to the use of monitoring data in air quality control. Much more difficult is the interpretation of biological effects with respect to pollutant exposure and concern is expressed about the tendency to attribute cause and effect relations on the basis of correlation analysis. Monitoring is not to be confused with mindless measurement.

1. Introduction

This discussion meeting is concerned with a scientific approach to air pollution problems. That in turn requires a logical and systematic approach to monitoring. It is my experience that such an attitude is not always to be found even in relation to otherwise quite sophisticated environmental studies. These studies are often carried out by specialists to whom the measurement of air pollution is peripheral. At the other end of the spectrum there are those whose elaborate proposals for scientific monitoring take little account of the very real practical constraints that exist and cannot simply be wished away.

This paper offers some observations and opinions about the overall philosophy of monitoring, trying to isolate some of the factors to be taken into account in the rational design of air pollution monitoring systems. The word monitoring itself needs some definition. It implies a variety of things to different people. There is little point in being too pedantic and accepting only one narrow definition. It is more useful to recognize the various usages but to draw a clear distinction between *monitoring* of air pollution and simply *measurement*.

The term monitoring is properly applied to the measurement of air pollution (usually ambient) over time to discern any changes produced by alterations in various factors such as emissions, weather, etc. The word has a different shade of meaning when it is applied to the

measurement of air pollution (ambient concentrations, or emissions in concentration or mass terms) to demonstrate that some preset limits of quality or quantity are or are not being exceeded. Rather more questionably the term may be applied to measurements at one moment but at a number of locations to indicate spatial rather than temporal distribution. What is unacceptable is the use of the word in connection with spot measurements with no possible claim to producing representative data in time or space.

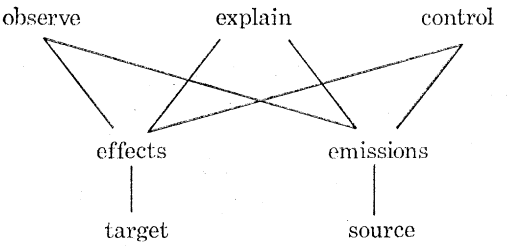

FIGURE 1. Purposes of monitoring.

2. WHY MONITOR?

The first and most important step in the logical design of an air pollution monitoring system is to set down clearly the objectives of the project. Various broad categories can be discerned.

(*a*) Monitoring may be purely speculative, looking for instance at a range of potentially harmful materials to see if there are concentrations present which should be of concern and whether there are any trends in these levels.

(*b*) Monitoring may be linked closely to studies of the effects of environmental quality factors on human health, on plants or on climate, etc., to elucidate any possible cause and effect relation.

(*c*) Monitoring of pollutants in the air or their deposition may be part of a budget assessment from source (emission) through transmission (dispersion and transformation) to sinks (immission).

(*d*) In a rather less speculative way than (*a*), monitoring may be undertaken to assess the need for emission control, e.g. around industrial sources of pollution or in streets in respect of vehicle pollutants.

(*e*) Very commonly monitoring is undertaken to provide a historical record of ambient air quality or of emissions in relation to recommended or legislated objectives or standards.

(*f*) Quite differently, monitoring may be carried out to provide the basis for real-time action to maintain emissions or air quality within regulatory limits.

(*g*) Monitoring may also be employed in relation to single or multiple sources to provide a quantitative understanding of pollutant distribution so that, for instance, the effect of developments can be reasonably predicted. This is a particularly investigative form of monitoring.

There are many other reasons for undertaking specific monitoring studies. They tend to fall into broad categories – to observe, to explain and to control. Figure 1 illustrates how various types of monitoring may be either target orientated or source orientated.

Being clear in the first place why monitoring is being undertaken goes a long way towards decisions on what to monitor, when to monitor and where, and even on how to monitor. These are not really independent questions but they can be dealt with roughly in that order.

3. What to monitor?

Why does air pollution matter? It is generally that some object or system exposed to it directly or indirectly receives a dose which has a damaging effect. Ideally, if one is interested in the relation between pollutant levels or other factors and the effects they produce, one should try to measure the effects, and the exposure to the agent or agents producing those effects. Life being what it is, however, our knowledge and our ability to measure are often so limited that we have to compromise by choosing to measure some surrogate for the effect and possibly some aspect of the pollutant which may be only indirectly related to the specific factor about that pollutant which produces the adverse effect.

For instance, records of absences from work or of deaths may have to substitute for the measurement of specific acute health effects produced by air pollution. Equally, the dirtiness of smoke and a non-specific method for determining sulphur dioxide have been used to measure the level of urban air pollution. Historically, there were good reasons for choosing to measure these things in this country in support of the Clean Air Act but we clearly recognize that it is neither the filthiness of smoke nor the concentration of sulphur dioxide in the air which is directly responsible for the effects produced by polluted urban air. For example, these measurements ignore, or are only rather tenuously related to, the presence of sulphate particles or nitrogen oxides and nitrates which may play a significant rôle in the effects of urban pollution on health.

Where possible, then, one should try to measure the precise agents and effects. Sometimes, observable effects themselves are held to be adequate indicators of the levels of specific air pollutants. Perhaps the most publicized example is the use of data on the distribution of various species of lichens to indicate levels of sulphur dioxide. This work clearly demonstrates both the advantages and the limitations of such biological indicators. Certain lichens clearly respond adversely to the presence of sulphur dioxide, either to the gas directly or to the acidity of sulphite or sulphate in water. Thus a study of the comparative occurrence of various species of lichens, whose sensitivity to sulphur pollution has been 'calibrated', may provide a relatively quick and inexpensive method of showing the distribution of such pollution over an area. It produces a useful 'snapshot'. However, sulphur dioxide is not the only pollutant to which lichens are sensitive: heavy metals and fluoride also affect them adversely. Thus lichen distribution is a clear indication of environmental quality as far as lichen health is concerned but not an unequivocal guide to levels of sulphur dioxide or to the relative effect of such environmental quality on other systems or organisms. A further limitation is uncertainty as to the extent to which the lichen distribution represents present, recent or older levels of pollution. The lichen population responds fairly rapidly to increased pollution but not so rapidly to the improvement in air quality.

Another example of an indicator is the corrosion of zinc cans. The Central Electricity Generating Boaed has carried out several country-wide surveys with the use of this relatively inexpensive technique. As a guide to the relative corrosive propensities of the atmosphere for the Board's pylons, the technique satisfies the criterion of being a measure of the precise effect in question. Although the resulting corrosion map shows considerable similarities to the distribution of sulphur dioxide levels, one can discern the effects, for instance, of sea salt and of differences in humidity or rainfall. In fact a lichen map remains a lichen map and a corrosion

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map a corrosion map. A sulphur dioxide map can be constructed only from sulphur dioxide measurements, emission data, and so on.

Depending on the objectives of the study in question, it is usually important to measure, or at least estimate, pollutant emissions – their quantity and spatial distribution, both laterally and vertically. Among related factors which should be considered for measurement are atmospheric conditions such as temperature, wind speed and direction, and aspects of the vertical atmospheric structure, such as mixing height and changes in wind speed and direction with height.

4. When to measure?

When, where and how to monitor constitute the subject of sampling. It covers some of the most important decisions and choices to be made in any monitoring system. First let us consider when to measure.

Whether one should measure all the time or only at intervals depends very much on what one wants from the data. Statistical sampling has substantial attractions. There are national or regional surveys in some countries where measurements at each site are made for as little as a few hours on one day in eight or even one day in twenty. In such systems it is sometimes possible to use mobile laboratories with more sophisticated equipment and more highly qualified staff than would be possible for continuous monitoring at so many locations. With such a régime it is possible to accumulate in time a picture of mean pollution levels over a wide survey area. But if, for instance, one of the prime objectives is to be able to link pollution levels with daily medical statistics, then continuous measurement is clearly required. Most air quality standards also require some form of continuous measurement. Another factor in deciding whether to measure all or part of the time is the broad temporal variability of the pollutant levels. A pilot study may have to be undertaken to clarify this before a decision is made for the survey as a whole.

This leads to the next question, which is the one of time resolution of the measurements. Here a basic criterion should be the link between the exposure to (or more precisely the dose of) the pollutant and the sort of effect which may occur or which it may be possible to record. Very probably a compromise will have to be reached, as in the U.K. National Survey. We fully recognize that short-term peaks within the mean daily values for smoke and sulphur dioxide may be important in terms of the effects they produce. Indeed, we have data to show the probable extent of short-term peaks within daily means in urban areas. If, on the other hand, a pollutant such as lead has a more or less cumulative effect on health, then it can be argued that integration over a long sampling time is a perfectly adequate form of monitoring. Figure 2 illustrates clearly the differences in the quality of data obtainable from different temporal régimes of sampling. Clearly a continuous measuring instrument with short time resolution will come quite close to registering the true variation in ambient concentrations. This may be important where as little as one gulp of a high concentration of a pollutant can be significant in producing health effects. Continuous sampling, but with coarser and coarser time resolution, obviously tells one less and less about the fine structure of exposure. A small amount of more detailed measurement may allow one to know with reasonable confidence what sort of ratio exists between short-term peak concentrations and longer-term means. Occasional sampling for only short intervals as shown in the fourth diagram really tells one very little about exposure to a pollutant whose concentration is highly variable.

If an air-quality standard is expressed in daily levels not to be exceeded more than x days

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per year then at least 24 h resolution of continuous measurements is required. If the standard involves a figure not to be exceeded for more than 1 h per month or year, then obviously hourly resolution is demanded. The monitoring implications of some countries' air quality standards are a not inconsiderable part of the cost of implementing them. Indeed, I would go so far as to say that the cost of monitoring should be considered in the process of defining mandatory air-quality standards.

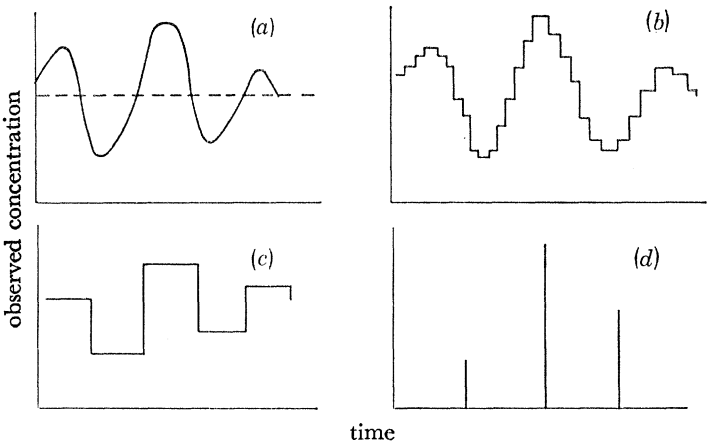

FIGURE 2. The effect of time resolution on monitoring the same air pollution event. (*a*) continuous sampling, short time resolution; (*b*) continuous sampling, medium time resolution; (*c*) continuous sampling, long time resolution; (*d*) discrete sampling, short time resolution.

5. WHERE TO SAMPLE?

On the question of where to sample air pollution, some of the major differences begin to appear between various scales of monitoring.

On the *global* scale, monitoring is usually concerned with long-term changes in background concentrations of pollutants such as particulates or carbon dioxide, which is being relentlessly produced by man's combustion of carbonaceous fuels. Alternatively, the aim may be to discern large-scale spatial variability, say between the tropics and high latitudes. Another understandable global monitoring activity is the constant watch, largely under I.A.E.A. auspices, of nuclear isotopes in precipitation. The principal siting requirement is that the places should be truly representative of background or 'baseline' conditions and not distorted by even small contributions to the levels of the relevant pollutants from specific local sources. Not all of the small number of the World Meteorological Organization's sites in this important category can match up to the basic criterion.

Elsewhere in this Discussion, reference has been made to monitoring the stratosphere. It is arguable that most of the measurements made to date do not amount to monitoring as defined in this paper. Continuous satellite measurements seem likely to provide true monitoring data.

At the *regional* level in studies, such as that carried out on long-range transport of air pollutants (L.R.T.A.P.) by O.E.C.D. countries, similar siting criteria are desirable but even more difficult to fulfil in highly developed areas such as NW Europe. In the L.R.T.A.P. project the distance and direction of 'local' pollutant sources were carefully noted for each monitoring station. If monitoring is carried out with sufficient time resolution to distinguish measurements made

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during different wind directions, which are also recorded, then the effects of local sources may at least be distinguished and often be allowed for.

In *national and local* surveys additional or alternative criteria may be appropriate. One may want principally to monitor the areas where pollution is highest, or likely to exceed preset limits, rather than to cover all areas. In the case of very local surveys one may wish to have sites in the area of maximum impact of an individual chimney, perhaps 10–30 stack heights from the source.

The required density of a network should be considered in terms of the level of detail and accuracy required. As one moves from a rural situation into an urban multi-emitter situation, the spatial variability for many pollutants becomes much greater. It is common for sulphur dioxide and smoke levels in towns to differ substantially over distances of as little as $\frac{1}{2}$ km. Let me say, however, that I am not generally advocating dense networks. Interpolation and extrapolation are possible if one studies the spatial representativeness of monitoring sites and the broad relation between the distribution of ambient concentrations and the distribution of emissions. This approach has been used in the U.K. in the production of national pollution maps. Without such a basic understanding a network containing 5–10 times as many monitoring locations would have been necessary.

Just as the spatial variability of primary pollutants, such as sulphur dioxide, is less in rural areas with greater times and distances for dispersion from the urban points of emission, so the spatial variability of secondary pollutants such as sulphate and ozone can be even less except where there are local removal mechanisms, such as the reaction of nitric oxide emissions with ozone, which has the effect of rendering local levels of ozone much lower.

The distribution of motor vehicle generated pollutants in streets provides a good example of very fine spatial and temporal variability which makes representative sampling very difficult. Depending on wind direction, concentrations of primary pollutants, such as CO, NO or Pb, on one side of a 'canyon' street can be ten times those on the other side. Considerable variability also exists in the vertical direction along the street. The concentrations of these pollutants at the street level are usually completely unrepresentative of conditions in the general atmosphere above roof-top level and at locations not immediately adjacent to the street. Referring back to §4, the monitoring and understanding of the levels of various pollutants at the kerbside is complicated by the fact that practically every pollutant has a different diurnal pattern depending on source configurations, local dispersion characteristics and even on atmospheric chemistry, as in the case of secondary pollutants such as nitrogen dioxide.

For modelling air pollution distribution and for other detailed studies it may be valuable to have pollution measurements at height as well as at ground level, since there may be significant gradients within the mixing layer; it may be even more important to know the height of the mixing layer itself. Particularly in meteorological conditions adverse for the dispersion of low-level emissions, high-level emissions from power stations may penetrate above the mixing layer and make little or no contribution to local ground-level concentrations. In such area studies it is necessary to have data on the differences in concentrations on hill tops and in valleys, e.g. to show the influence of plume impact.

Personal monitoring, i.e. where sampling devices are fitted to individuals, is, of course, very common in occupational hygiene work and it has the clear merit of representing accurately the exposure of a moving target. In much of our ambient monitoring we are dealing with stationary targets, in vegetation, buildings, etc., but with humans the picture is more complex. The

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exposure of an urban dweller is compounded of the periods he spends out of doors, possibly in significantly different parts of the area from a pollution point of view, and the time he spends indoors, at work and at home. Obviously we cannot have personal monitors on a wide scale but we should look critically at the normal practice in epidemiological work of relating the health of large populations simply to out-of-doors monitoring results. We must recognize that for most pollutants, indoor levels are much lower than those outside and therefore people spending different proportions of their time indoors and out of doors have quite different exposures. For a few pollutants, levels in certain parts of the home may exceed outdoor levels and the situation is reversed. Furthermore, over time the general habits of the population may change so that the indoor: outdoor ratio changes, and thus the relation of outdoor measurements to potential health effects may alter. There may for certain studies be a case for monitoring at selected indoor sites as well as out of doors.

6. Monitoring emissions

Where to measure as far as emissions are concerned may seem fairly simple on the face of it. A few points are worth making partly on where and partly on when to monitor emissions:

(*a*) It may not be necessary to monitor some emissions at all. For instance, sulphur dioxide emissions from fuel burning are naturally related to fuel composition and so the rate of fuel consumption can represent the rate of emission. If, however, flue gas scrubbing has to be fitted to abate SO_2 emissions, they become a potentially variable process effluent and monitoring by direct measurement may become necessary.

(*b*) Most industrial emission monitoring is decided by what is legally required: the frequency and duration of tests and whether concentration or mass emission is to be reported. Because of cost and the limited availability of techniques or robust equipment, the imposed requirements in the U.K. are usually confined to short-term measurements at quite infrequent intervals. The bulk of the measurements are made by industry itself, while the controlling Inspectorate only occasionally checks with its own independent tests. It is clearly the case that such a system cannot expect often to catch the periods of highest emissions and, human nature being what it is, measurements will sometimes be arranged to positively avoid periods of high emission. But what is the practical alternative? We cannot really contemplate an army of resident inspectors making frequent independent measurements, save in the most exceptional cases. Where there are reasonable grounds for concern, the approach to be pursued is the development of a continuous monitor, recording not merely overall emissions but giving detail over short time intervals. The Alkali Inspectorate has long indicated its attraction to a reliable 'Black Box', like an aircraft flight recorder, for problem industries.

(*c*) Remote sensing techniques are being developed which measure pollutant emissions after they leave the stack. This makes unheralded inspection of industrial emissions much more positive. It is too early to say whether the accuracy of such measurements will make them acceptable for regulatory purposes.

(*d*) Good emission data are vital to modelling studies.

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7. How to monitor/sample?

There are two distinct classes of material being monitored in the air: gases and particles. They can be examined either *in situ* or on an extracted sample.

Relatively few methods exist for truly *in situ* examination, e.g. long-path spectroscopy or simple visibility measurement. Most measurement methods involve the extraction of a sample and it is here that the differences between dealing with gases and particles begin to appear.

Gases

There is not usually much difficulty in extracting a *representative* sample of air for the measurement of a gaseous constituent, at least if it is not too reactive and ephemeral.

Direct reading instruments operating on an extracted sample or gas stream can provide good time resolution of measurements although they do not quite measure instantaneous values. Where a sample is extracted continuously (or intermittently) and accumulated for subsequent analysis we begin to encounter the familiar problem of trade-offs between sampling rate, sampling time, sensitivity and cost which are dealt with in the section on selection of methods.

Particulates

It is worth expanding a little on the subject of particulate pollution. The accurate and meaningful sampling and measurement of particulate pollution in and from the air presents a difficult problem. Particulate pollution differs fundamentally from pollution by gases in that the effects of gaseous pollutants stem almost wholly from their chemical or biochemical properties, while the effects produced by particulates are often compounded of an intimate mixture of their chemical properties with their physical properties such as size, shape, colour and density. In the assessment of particulate pollution, the relation of monitoring measurements to effects is extremely complex and may vary from constituent to constituent of the particulate material present in the air.

Breathed dust

Some types of fine, insoluble and normally chemically inert particles, if respired deep into the lungs, can have serious long-term effects on health. Equally fine but soluble particles may have a quite different and more immediate effect in the lungs. If these materials subsequently get into the blood stream, their effects will depend on their toxicity in or from that medium.

Sampling of air for really fine particles is no problem but even then the sample represents the total air burden of particles in this size range and cannot itself take account of the effect of exhalation on retention, nor of such factors as the possible extent of aggregation or growth of some particles within the respiratory system which can in turn affect their aerodynamic performance in the lungs.

The inhalation of larger particles presents quite a different picture. Again some may be exhaled; some may deposit in the nose and end up in a handkerchief; others will be swallowed into the stomach. Inert particles of the same chemical constitution as those which produce serious lung effects when in fine particulate form, may produce no effects at all when swallowed but simply be excreted. Chemically reactive or soluble materials, on the other hand, may produce toxic effects by being absorbed from the digestive tract.

So we must recognize the diversity of factors involved in describing the significance of *exposure* to larger particles in air. In addition, we find substantial problems in actually *measuring* the

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air's content of larger particles. And the sampling problem is more difficult in ambient air subject to normal wind movements than in the relative stillness of air in most work places, which are the primary concern of the occupational hygienist.

The normal method of trapping particulates from an air sample is to collect them on a filter medium through which a known volume of air is drawn. The problem is to get the larger particles in the air to follow the path of air being sucked on to the filter. This is because of the particles' inertia. Isokinetic sampling of ambient air along the lines used in sampling emissions is too sophisticated and expensive for general use.

Work is being done and more is required on devices which will accurately sample the air for all sizes of airborne particles and, moreover, split the sample into two or more size fractions which may have different types of significance to health.

It has been mentioned that the pollution effect of airborne particles frequently involves both their physical and chemical properties. Thus characterization of a monitoring sample in terms of mass, blackness or obscuration power is not always enough. Chemical characterization may also be important. But how is this to be done? Sometimes the elemental or ionic composition of the whole sample will suffice. At times, however, the potential toxic effects may vary significantly depending on, say, the solubility of the actual compound of a heavy metal present as discrete particles in the sample. Electron scanning and other techniques are being applied with increasing precision to this problem of characterizing individual particles.

One more potential difficulty with particulates is worth mentioning. How is one to be certain that the particles in the collected sample are the same as those which were in the air? The possibility exists for the chemical and physical nature of particles caught on a filter to be subsequently changed by their being exposed to reactive gases and vapours passing through the filter or to liquid particles such as acid droplets also caught on the filter. This sort of transformation is possible especially for samples collected over long periods. For instance, a particle of chalk reacting with a sulphuric acid droplet would result in the species finally found on the filter being calcium sulphate. The problem applies also to deposit gauges.

Deposited particles

Representative sampling of particles being deposited from the air poses separate but somewhat similar problems. No deposit gauge can measure the real rate of deposition of particles of various types on to different surfaces, e.g. tarmac/grass/trees. Furthermore, different deposit gauges can show quite different efficiencies of capture for a given spectrum of particle sizes in other than calm conditions and each deposit gauge shows variability in its efficiency of capture of different sized particles with change in wind speed.

Figure 3 shows some of the results of wind-tunnel tests at Warren Spring Laboratory (C. F. Barrett & M. O. Ralph, unpublished work) on various designs of deposit gauge, the normal BS gauge (BS 1747, Part 1), the same gauge modified with a simple baffle in the receiving bowl, a simple gauge from the Norwegian Institute for Air Research (N.I.L.U.) and a rather similar design which has been proposed for consideration as an I.S.O. standard. It can be seen clearly that at a given wind speed there are large differences in the efficiency of capture for different particle sizes with each gauge and that there are substantial differences in performance between the various designs of gauge.

If ever it is suggested that there should be environmental standards for deposition rates there will not only be a problem in defining the logical basis for such standards – health or amenity –

but the choice of a standard gauge will be of real importance. Sometimes a deposit gauge is designed *not* to give a good capture over the whole range of particle sizes or wind conditions. The BS directional gauge (BS 1747, Part 5), which derives from a design by the Central Electricity Research Laboratory (C.E.R.L.), has vertical receiving slots instead of the normal horizontal receiving orifice. Thus its efficiency in a calm is theoretically zero and in winds its efficiency for capture of fine dust can be much higher than that of normal deposit gauges. This was the expressed intention of C.E.R.L., who found that the normal gauges underestimated or did not properly represent the fine deposited particulate pollution around power stations. Moreover, the recommended way of assessing the material collected in the C.E.R.L. gauge is well matched to the nature of the nuisance being studied, namely the covering of windows, walls and ledges with a fine film of dust. The particles collected in the gauge are suspended in water and the final measurement is one of the cloudiness produced in the water.

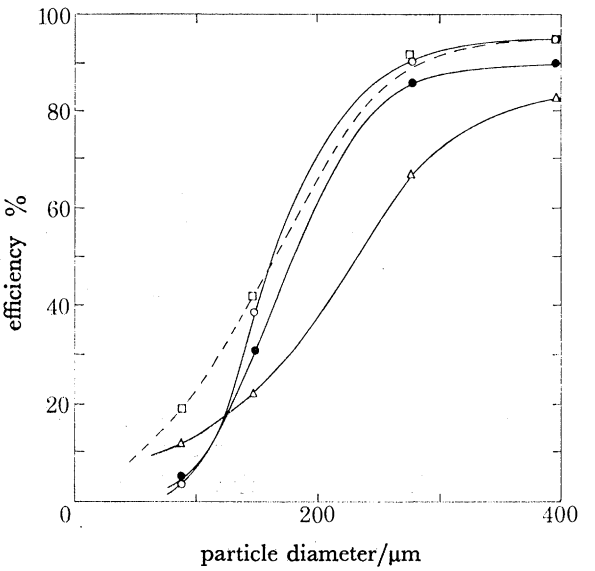

FIGURE 3. Collection efficiency of horizontal dust gauges for wind speed of 2.5 m s^{-1} at gauge height (approximately corresponds to annual mean wind speed). △, BS 1747, Part 1; □, BS modified; ○, draft I.S.O.; ●, N.I.L.U.

8. SELECTION OF METHODS AND INSTRUMENTS

To try to bring together some of the many strands involved in deciding on monitoring systems it may be useful to consider a sort of check list for use in the selection of methods and instruments for monitoring.

(*a*) *Sensitivity and limits of detection*. What is the lowest concentration or quantity of the pollutant which the method can measure with reasonable accuracy? What is the maximum concentration which the instrument reads? Is the range suitable for the situation?

(*b*) *Time resolution*. Closely linked to sensitivity. Over what sampling period or periods will the method/instrument operate? Are these consistent with the project's objectives? It is usually more expensive to measure low pollutant concentrations over short periods. A method which can be used to measure a particular level of a pollutant but requires a week-long sampling time to achieve this sensitivity is of no use if the pollution effect of interest is produced by short-term

occurrence of such levels. Sometimes it may be necessary to employ two methods, one to locate and measure peaks and the other to determine the much lower longer-term mean pollution.

(*c*) *Accuracy and precision*. Are the measured results acceptably close to the real pollutant concentrations as given by a reference method and does the method give similar values on repeated measurements of the same actual concentrations of the pollutant?

(*d*) *Specificity*. Does the method measure solely the particular pollutant of interest or are the results influenced significantly by the presence of other materials in the concentrations at which they might be present in the air being sampled?

(*e*) *Reliability*. How often does the equipment need calibration or maintenance? Will it in other words operate trouble-free and accurately for long periods without attention? It is important that it should be functioning accurately throughout the period. Few people would be impressed if they bought a clock which needed winding only every three months but could well be six hours fast or six hours slow on individual days. Instruments may have automatic calibration, zero corrections and span checks but these are not provided free. Is the method or instrument sensitive to environmental conditions (heat, light, humidity, etc.) such that it might need special housing? Is it affected by voltage fluctuation?

(*f*) *Field or laboratory analysis*. Is the method one where the results are obtained, or can be obtained, at the monitoring site or must the samples be brought to a well equipped laboratory for analysis? Do the unit analysis costs fall with increasing numbers of measurements?

(*g*) *Versatility*. Can the sampling or measuring equipment be used for more than one pollutant if desired? Some methods are being developed which offer this facility.

(*h*) *Staff* (*operation and servicing*). What numbers and type of staff would the monitoring require and how does this compare with what can be obtained? Can an instrument be serviced by the monitoring system's own staff (possibly with the use of replacement parts) or does one have to have a complete spare unit when the faulty instrument has to be returned to the makers? How highly is the completeness of data valued? Can one tolerate gaps in data due to instrument downtime?

(*i*) *Data output*. Does an instrument provide results in a form or with a frequency compatible with the other data being collected and with the user's needs?

(*j*) *Price*. This has to be considered in relation to all the foregoing and also in relation to other factors such as what network density it will be possible to afford as a result.

It is not possible to propose a specific order for going through these check list items. In some circumstances cost and staff may be the most critical determinants; in others accuracy and specificity, for instance, may outweigh most other considerations. Then again it may be crucial to measure several pollutants concurrently. The main thing to bear in mind in considering each item is the overall objective of the monitoring. Mindless measurement is pointless if it serves no useful purpose.

9. What to do with the data

Even a summary consideration of monitoring would be seriously incomplete without something about the interpretation, presentation and utilization of monitoring data. This goes full circle back to the point at which the question – why monitor? – was asked, and in each successive section the importance has been stressed of getting the monitoring system and its results to satisfy the objectives of the study. These objectives can be so widely diverse that it is not practicable to deal with interpretation in any detail here.

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It was mentioned earlier that surveys tend to be in the spectrum from observing through explaining to control in their main intentions and the position of a survey in this spectrum tends in turn to influence whether it is primarily target or source orientated, i.e. whether it is primarily interested in effects or in emissions. In principle, linkage of ambient monitoring to emissions is relatively simple (although in practice it is rarely at all simple). One is concerned with the physics which brings a fraction of the material emitted from a single source or multiple sources to be present as a particular concentration at a particular point at a certain time. One has to deal with the concepts of diffusion and dispersion, with atmospheric structure and meteorology, and to link all of these in a credible physical model of the process of transmission from emission to what our German colleagues will insist on calling immission, i.e. the receipt of the pollution by a potential target. The simplest case will be accounting for the distribution of a pollutant arising from a single emitter which is the only significant source of that pollutant. Much more complex are the cases where the pollutant arises from a multiplicity of sources distributed both laterally and vertically as in the case of urban SO_2 or smoke. Moreover, it may be important to distinguish clearly between the contributions from various source categories to provide the basis of plans for control.

One cannot control air quality simply through having quality objectives and ambient measurements. Control has to be effected on the emissions and for cost-effective control one therefore has to know a lot about how to interpret ambient monitoring data in relation to emissions. So the modelling of the physical process of dispersion is crucial. These are the easier forms of pollution phenomena to interpret and explain. The real difficulties arise when one is concerned with effects.

The effects of air pollutants on human health or living systems are rarely unique and unequivocal. Responses, as for most biological systems, will vary widely with similar exposure to a pollutant. Furthermore, there may be unmeasured variations in other environmental conditions or constituents which may also influence response. The prehistory of the exposed organism may also be important. This is only to state the obvious about all biological research. The point being raised here is a cautionary one. The interpretation of biological research data must necessarily involve statistical analysis of large numbers of pieces of information. One must not get carried away with the cult of the correlation coefficient in attributing cause and effect relations to factors seemingly linked by the existence of a high degree of correlation. There is an apposite story which Sir Edward Appleton was supposed to have told to the teetotal King Gustav of Sweden when Sir Edward was receiving his Nobel prize. This was that people get drunk on whisky and soda, brandy and soda, rum and soda, vermouth and soda and one is tempted to draw the conclusion from the data that it is soda, the highly correlated factor, which makes people drunk. The drawing of such conclusions as to cause and effect is rife in environmental studies. This is not to say that many of the conclusions are necessarily wrong. They are simply not justified by the data on their own.

While one has to be cautious in interpreting monitoring data, one should at least be as helpful as possible in presenting monitoring results. There is frequently the need to produce simple summaries of large numbers of measurements (see table 1).

In publishing summary tables for the U.K. National Survey, the general procedure has been to provide for each site the annual, summer and winter mean values and, at the monthly level, the mean value, the highest daily value and the number of days over certain levels, some of which are reckoned by the medical experts to be of significance to health. By these criteria it has been

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Table 1. Extract from the Annual Digest of Results

(Smoke and sulphur dioxide, April 1975 to March 1976; micrograms per cubic metre.)

site name and no.	class code		smoke av.	smoke h.d.	no. of days exceeding 250	500	1000	2000	3000	SO_2 av.	SO_2 h.d.	no. of days exceeding 250	500	1000	2000	3000	smoke/SO_2 ratio
Runcorn 8	A2/E	A 75	N	104						N	175						N
		M 75	28	56						84	154						0.33
		J 75	no results received							no results received							
		J 75	17	26						69	181						0.25
		A 75	21	53						63	180						0.33
		S 75	28	56						64	152						0.44
		O 75	54	155						89	168						0.61
		N 75	60	185						96	211						0.63
		D 75	71	157						95	208						0.75
		J 76	34	77						66	135						0.52
		F 76	57	126						94	211						0.61
		M 76	44	141						103	202						0.43
		mean summer	N							N							N
		mean winter	53							90							0.59
		year	N							N							N
Runcorn 9	B3/E	A 75	19	36						65	145						0.29
		M 75	N	33						N	146						N
		J 75	15	33						62	141						0.24
		J 75	14	31						41	167						0.34
		A 75	17	40						36	81						0.47
		S 75	15	41						37	96						0.41
		O 75	34	83						56	155						0.61
		N 75	52	126						74	125						0.70
		D 75	N	235						N	217						N
		J 76	N	87						N	183						N
		F 76	34	83						111	240						0.31
		M 76	N	143						N	261	1					N
		mean summer	16							50							0.32
		mean winter	44							92							0.48
		year	29							70							0.41

N, insufficient results received.

possible for local authorities to assess the priority that they should accord to smoke control or to suphur dioxide in the context of broader issues of development. Annual trend figures can be produced for individual sites, for cities, regions and for the National Survey as a whole. Care has to be taken in the selection of sites having the continuity of measurement to make their use valid in trend estimation. Interpretation of these annual trends has also to be approached cautiously since weather, for instance, can have a marked influence on the values for any one year. A run of perhaps five years is needed to eliminate the possible influence of extraneous factors.

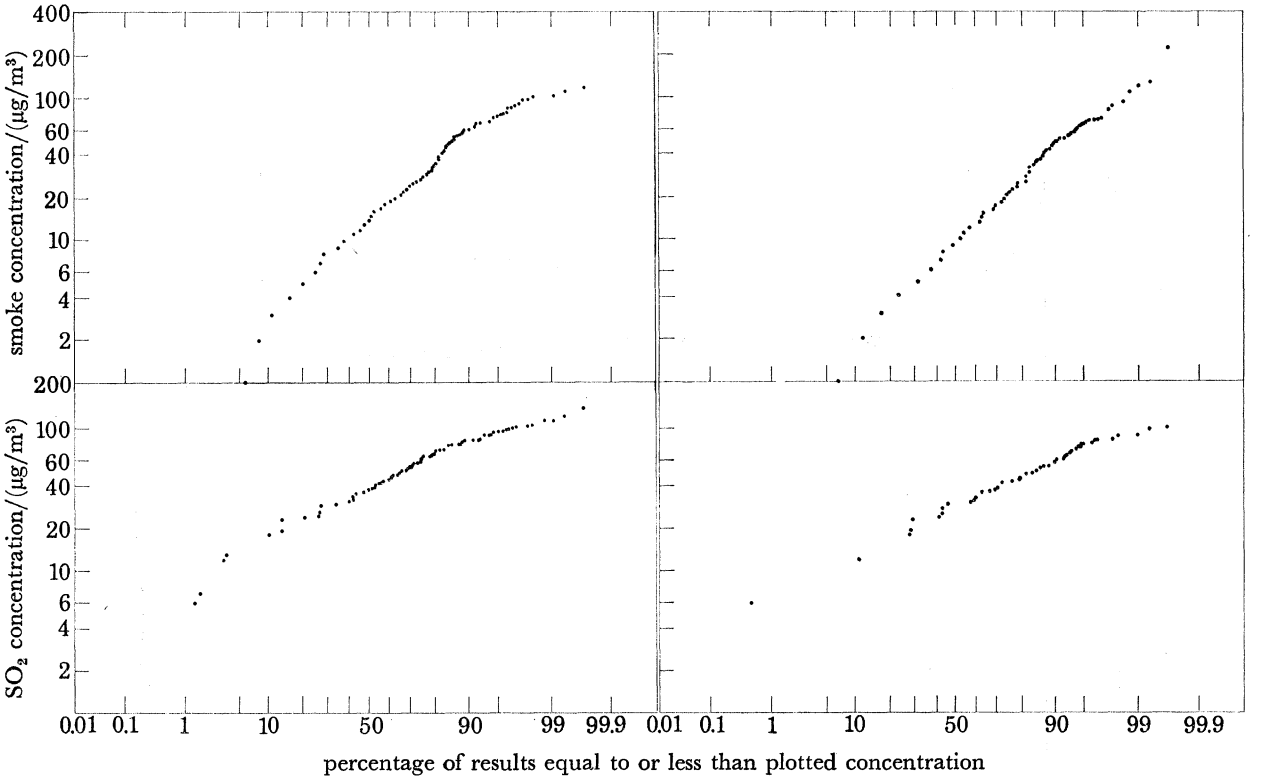

FIGURE 4. Example of cumulative frequency distributions.

Other forms of data presentation are coming into more frequent use. The annual cumulative frequency distribution curve for daily levels packs a lot of information into one diagram (see Figure 4). At the same time it cannot show when certain high values occurred to the extent seen in the normal summary tables. The two forms of presentation are complementary. The frequency distribution curve allows a quick assessment of the extent to which any value of interest is exceeded and the relation of certain percentile values to mean or median levels. Yet another form of data analysis which can be of interest from a medical point of view is the persistence of high pollution levels, e.g. the number of consecutive days when levels of smoke or sulphur dioxide, or both, exceeded particular values. Information on persistence of high pollution for two, three or more days is also important in considering the practical significance of taking temporary control measures. This sort of analysis can be readily performed on computer-stored data. With details of site location stored on the computer, computer mapping of pollution distribution is an attractive possibility. We find, however, that even with as many sites as we

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have in the U.K. National Survey, contour mapping cannot be reliably performed with the use of survey measurements alone. Mention was made in §5 that interpolation and extrapolation are needed and these require an understanding of the broad relation between the distribution of ambient concentrations and the distribution of emissions.

These brief references to data presentation and interpretation are purely by way of examples. It is to be hoped that they will stimulate thought on this aspect of monitoring.

More than anything else the intention of this paper is to convey the message that monitoring is not simply a hack job which can be left to a few junior staff to conduct. It is an important integral part of environmental research and control. More attention needs to be paid to designing monitoring systems to meet specific objectives, and further research and development are needed before monitoring techniques can, in fact, match the requierments of some environmental studies. At the same time there is no intention to advocate a monitoring explosion. A little good monitoring is usually worth more than a great deal of poor monitoring.

Discussion

D. T. Swift-Hook (*Central Electricity Research Laboratories, Kelvin Avenue, Leatherhead, Surrey KT22 7SE, U.K.*). As the understanding of pollution pathways improves, greater and greater sophistication is required in the measurement of more and more species. If monitoring is not to become unbearably costly, the sophisticated equipment that has to be developed must be useful for a wide range of different pollutants in different places. That philosophy is being adopted in this country.

There is a substantial programme of research at C.E.R.L. and elsewhere in the U.K. (including N.P.L. and Hull University) on remote sensing in the lower atmosphere, with some funding from the E.E.C. A major area of expertise is mobile differential absorption lidar, which enables concentrations as low as a few parts/10^9 to be measured over ranges of a few kilometres with resolutions down to a 100 m or so. By using a tunable laser, different frequencies can be scanned which cover a very large number of pollutant species with a single (albeit expensive) instrument.

We also believe that it is important to develop techniques for measurement *in situ*. Several countries, including ourselves, are becoming interested in model aircraft as a cheap way to take samples over extended periods. Not only is it desirable to complement remote scanning measurements with confirmatory spot checks, but also collection is necessary to study particulate compositions and heterogeneous reactions or catalysis that may be taking place on particle surfaces.

From the papers and discussions at this meeting it is clear that free radicals such as OH and HO_2 are becoming increasingly important. The remote laser techniques I have mentioned can, in principle, be applied to free radicals by tuning to appropriate lines. Collection techniques are much more difficult but we are attempting to apply free-radical chemistry methods used in the laboratory – cryogenic capture and subsequent spectroscopy, laser, n.m.r., e.s.r. or other methods of analysis – to air-borne sampling.