

# THE DESIGN AND OPERATION OF AIR QUALITY SURVEILLANCE SYSTEMS

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## CONTENTS

|  | Page |   | Page |
|--|------|---|------|
| Introduction . . . . .   | 153  | An outline of a systems approach to air quality surveillance programme design . . . . . | 163  |
| Objectives . . . . .   | 153  | Systematic surveillance site selection procedure . . . . .                              | 165  |
| Methodology . . . . .  | 153  | Methodologies in air quality monitoring . . . . .                                       | 167  |
| Background . . . . .   | 154  | Basic considerations of sampling . . . . .  | 167  |
| Air quality surveillance programmes—the total system . . . . .           | 155  | Sampling frequencies . . . . .  | 168  |
| General considerations . . . . .   | 155  | Measurement techniques . . . . .  | 169  |
| Identification of data users . . . . .                                   | 155  | Data acquisition, handling, and analysis . . . . .                                      | 171  |
| Needs of data users . . . . .  | 156  | System configuration . . . . .  | 172  |
| Other needs . . . . .  | 159  | Current limitations and summary . . . . .   | 173  |
| Outline of a systems approach to surveillance programme design . . . . . | 161  | Limitations . . . . .   | 174  |
| Introduction . . . . .   | 161  | Summary . . . . .   | 175  |
| Basic design considerations and requirements . . . . .                   | 162  | References . . . . .  | 175  |

## INTRODUCTION

The establishment of air quality standards on a regional, national, or international basis requires the continual ascertainment of air quality in a reliable and regular manner if the standards are to be maintained. The term "air quality surveillance" is used to describe the procedure for assessing the concentrations of atmospheric contaminants and other properties of the air so that air quality management requirements can be met.

### Objectives

The principles and procedures for air quality surveillance are reviewed in this chapter. The following topics are discussed:

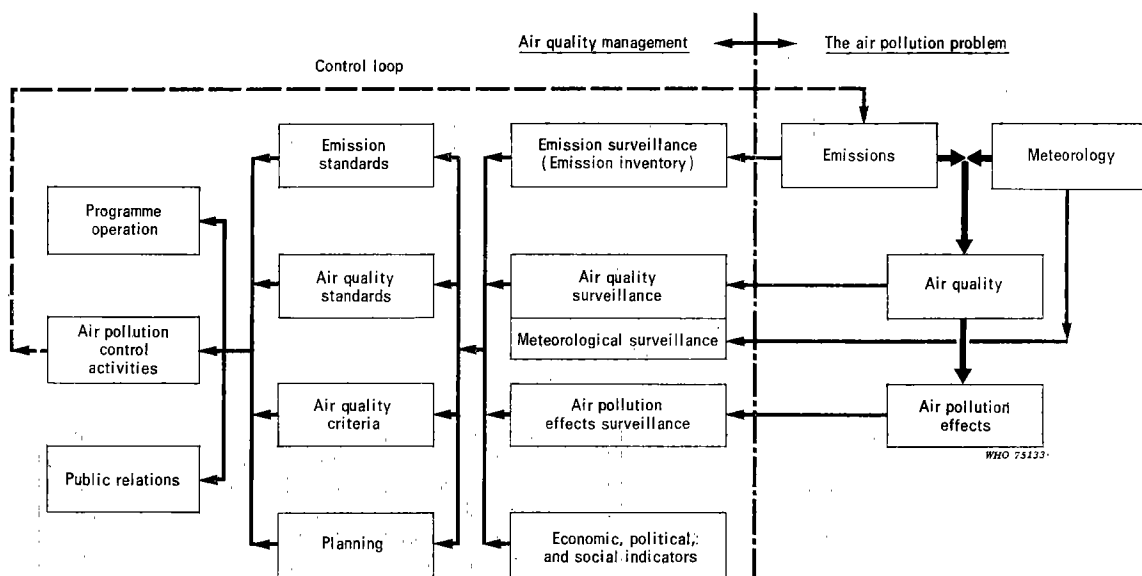
- (1) the need for a total air quality surveillance system;
- (2) the objectives of various air monitoring programmes;
- (3) methods of sampling for, and determining, air quality;
- (4) techniques for the acquisition, analysis, and display of air monitoring information;
- (5) system costs;
- (6) current limitations and needs.

### Methodology

As illustrated in Fig. 1, a surveillance system represents a subsystem of an air quality management programme and is closely associated with other subsystems in the overall programme. For example, the surveillance system should be closely linked with

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Fig. 1. Air quality management systems <sup>a</sup>

<sup>a</sup> Heavy arrows indicate material flow and light arrows indicate information flow.

data processing systems for emission inventory, registration and permits, violations and complaints, fuel use, emission reduction plans, land use, demographic projections, and urban planning (1). An orderly appraisal of the principles and procedures of air quality surveillance must include considerations of the larger system. For this reason, the logical approach to a review of surveillance requirements is first to examine the objectives of the surveillance programme within the framework of the total air quality management system. Once the objectives have been identified the remaining aspects of the surveillance programme can be characterized.

A literature search was undertaken with the stated objectives of the approach outlined above in mind to provide the historical and technical information needed to identify as many factors and parameters as possible that contribute to the design, selection, installation, and operation of an air quality surveillance programme and to characterize the support and other activities related to the system. The review showed clearly the need to consider the surveillance programme within a systems framework. As a result, certain categories were identified in which the principles and procedures for air quality surveillance could be grouped, thereby providing a framework for future systems analysis. These categories, corre-

sponding in part to those used in a systems design study of a water quality surveillance system (2), have also been suggested by Hamberg (1) and Keitz (3), and are discussed below (p. 165). The failure of many earlier systems to perform satisfactorily was a result of inadequate planning with respect to the various categories of air quality surveillance.

The particular contaminants and effects to be measured in a surveillance programme depend on the nature and extent of the problem to be studied, eliminated, or prevented. As a result, each air monitoring programme should be adjusted to suit the needs and resources of the community or agency but must also provide the basic data on which control efforts are to be based. The need for good data and the high cost of data collection and analysis are major obstacles to an air quality management programme.

### Background

Historically, air surveillance programmes have developed since the Second World War around the sampling network concept. Developments up to the present time have proceeded along the same lines with modifications being made in sensor type and data transmission and handling, the systems still

retaining the network pattern. Elaborate networks with automatic equipment and simultaneous computer displays are currently available for air pollution surveillance, and a number of these systems have been installed in the USA (5-9). Complex surveillance networks and systems installed in numerous locations in Europe have been described (10-17).

From a review of the history of air quality surveillance it seems apparent that, although much has been done to improve the design and development of surveillance networks, there has in the past been very little attempt to determine the actual atmospheric surveillance data requirements in an air resource programme from the data user's point of view. Recent work by Keitz (3) and others has indicated that frequently more data are being collected than are actually needed, or can be used, in management programmes. Thus, a critically important aspect of surveillance programme planning is determining the needs of the data user and designing the surveillance system to meet these needs. Merely to follow previous examples without closely scrutinizing data requirements, as seems to have been done in many instances, can lead to a commitment of resources disproportionate to the value of the final product of the surveillance programme.

In spite of previous efforts that have been made, knowledge about pollutants in the atmosphere is far from satisfactory, particularly with regard to long-term exposure to pollutants at low levels and to global concentrations. This represents a serious shortcoming in the approach to air quality (18), and to make good these deficiencies it is suggested that air quality surveillance should assume even greater importance in future studies.

## AIR QUALITY SURVEILLANCE PROGRAMMES—THE TOTAL SYSTEM

To conduct an air quality management programme effectively requires reliable information on air quality to be collected, analysed, and evaluated regularly and efficiently. There are several underlying reasons for this (19). First, there is the paramount need to protect man and important domestic animals and crops from damaging exposures to air pollution. Secondly, there is a desire to know the trends in air quality so that control efforts can be regulated accordingly. Air quality surveillance is undertaken to provide this information. The adop-

tion of air quality standards and the subsequent development of emission standards cannot assure improvements in air quality; the effectiveness of control programmes can only be determined through long-term monitoring of actual air quality (20).

### General considerations

In any air quality surveillance programme there are certain basic considerations, which are, in effect, constraints upon its nature and magnitude. These considerations include: (1) the needs of data users (quantity, quality, location, time); (2) available resources (funds, manpower, existing surveillance facilities); (3) legal requirements (local, regional, state, national, international); (4) available technology (equipment, techniques); (5) operational criteria (economic, social, legal, cost-effectiveness); and (6) operational responsibility.

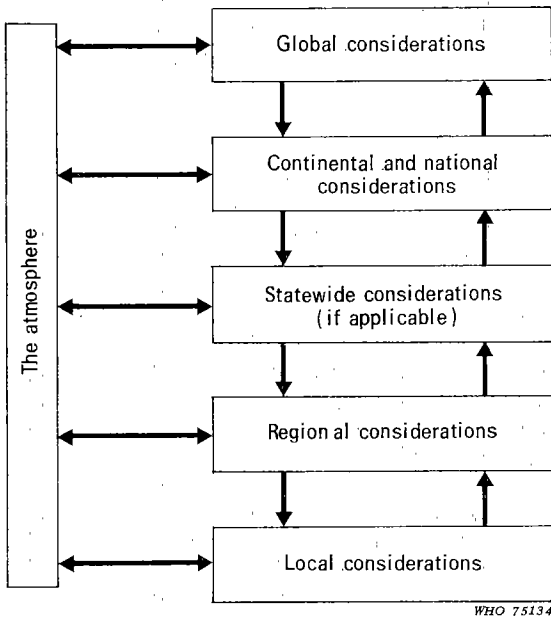
In any particular programme, one or other of these general considerations will be the primary constraint—generally, the available resources (in particular, the available funds). In the design of a programme the constraints must be ranked according to their importance as guides for selecting the best course of action.

### Identification of data users

A convenient way of identifying the potential users of surveillance data is to arrange the air pollution problem in a logical hierarchy, as shown in Fig. 2. Global considerations include such factors as the balance between sources and sinks and the evaluation of the effects that might possibly result from imbalance. It is necessary to know whether the background level of pollutants in the earth's atmosphere is increasing, and if so at what rate (21). International cooperation must be achieved to permit the systematic appraisal of global air pollution. Continental and national considerations are important where air pollution may be transported from one country to another and create problems of international proportions, as may happen in Europe.

Statewide considerations can be an important component in the overall air quality management programme although state boundaries are political and generally do not correspond to the pattern of the air pollution problem. In the USA, for example, the primary responsibility for air pollution control rests with state governments. Similar situations exist

Fig. 2. Logical hierarchical structure of the air pollution problem<sup>a</sup>



<sup>a</sup> Arrows indicate information flow.

in Europe where air pollution control is often the responsibility of state or provincial governments (12).

Regional considerations usually imply that the air pollution problem has been identified in a region, irrespective of political jurisdiction. The regional nature of many air pollution problems, air pollution episodes and photochemical smog occurring at the regional level, for example, generally indicates that the problem should be attacked at that level; this principle is recognized in the designation of official air quality control regions in the USA. At the lowest level in the hierarchy, local air pollution control is generally restricted to special cases where a local nuisance is involved.

On the basis of this scheme, five programme levels, corresponding to the levels in the air pollution problem, appear to represent the potential users of air quality surveillance. The hierarchical nature of the air pollution problem represented in Fig. 2 suggests a need to coordinate air quality surveillance efforts among these five programme levels. For this purpose, compatibility between local, regional, national, and international programmes is essential. The primary criteria for compatibility are the com-

patibility and standard quality of surveillance data and information.

#### Needs of data users

Information obtained in an air quality surveillance system is used in various air pollution control activities. Hochheiser et al. (22) have identified the following activities in which air quality data are used:

- (1) assessing pollution effects on man and his environment;
- (2) studying and evaluating pollutant interactions and patterns;
- (3) establishing air quality standards;
- (4) developing control strategies and regulations;
- (5) evaluating the effectiveness of control efforts;
- (6) activating emergency procedures to prevent air pollution episodes or reduce their severity;
- (7) guiding efforts to minimize the impact of air pollution by applying land use and other planning system.

Each of these activities has specific data requirements. For example, the data required for episode-avoidance procedures are quite different from those required for assessing the global pollution effects on man and his environment. In the former case, the speed of data acquisition and analysis is the overriding concern. Control actions during projected periods at heavy air pollution, frequently referred to as "episode avoidance activities", are designed to prevent ambient concentrations of pollutants from reaching levels that endanger the health, safety, and welfare of the community (23, 24). In studies of global pollution the speed at which data are collected is not as important as the quality of the data.

In order to assess accurately the effects of pollution the data must be representative of the levels of air pollution responsible for these effects. Since effects are difficult to determine, especially when they are caused by exposure to low levels of pollution, data measurement techniques are much more elaborate than those needed for episode avoidance. For each of the examples given above the cost of data collection will depend primarily on the characteristics of the particular system. Thus, the costs involved in obtaining data for episode avoidance activities lie in applying rapid collection and analysis techniques, whereas in the elaborate sampling of low level pollution the costs will probably lie primarily in the instrumentation.

Because of the considerations involving quality, quantity, location, and time the identification of data needs in air quality control is of major importance. Unfortunately, these needs have not been identified satisfactorily. In the USA, for example, the practice has been to depend almost entirely on two groups of surveillance networks—a particulate sampling network and a gas sampling network, each of limited accuracy and precision. The United States national requirements for episode avoidance procedures specify that these networks must provide data very quickly so that emergency control procedures can be set in motion to prevent air pollution episodes (25). Although these networks can satisfy the requirements for episode avoidance, they have been found inadequate for providing the data needed for other purposes. For example, current particulate network sampling networks do not measure the size distribution or respirable fraction of atmospheric particulate matter, or many of the condensable components of atmospheric pollution that cannot be collected on high-volume filters. Such information is of importance, however, when an attempt is made to evaluate air pollution effects and assess certain trends and problems.

In Table 1 an attempt is made to classify the data requirements for air quality management on the basis of data use and to suggest the programme levels that are most closely associated with particular data use. Although Table 1 represents a subjective classification, it provides an indication of the various data requirements for specific uses in the air quality management approach discussed below.

The highest data characteristics are required for assessing pollution effects and studying pollutant interactions in the atmosphere. One of the most important aspects of air pollution control is the determination of air pollution effects. These range from minor psychological upsets and annoyances, such as eye irritation and the occurrence of unpleasant odours, to possible global air pollution damage. For making these assessments, accurate and representative air quality information is required. These data are not easily obtained and surveillance efforts to obtain them should therefore be coordinated at the highest programme level. A multidisciplinary approach is essential in air quality surveillance programmes that aim to provide appropriate data for effects studies.

Coupled with the problem of air pollution effects is the fact that our knowledge of the extent and behaviour of atmospheric pollution is far from satis-

factory. Without a basic understanding of interactions in the atmosphere and the basic chemical and physical phenomena underlying the air pollution problem, control efforts cannot be properly directed towards the achievement of a clean, healthy environment. In some instances, control efforts can make the air pollution situation worse rather than better. For example, efforts to reduce particulate mass emissions have increased the emission of smaller particles. As a result, visibility indexes decreased in some areas although control programmes were making impressive gains. To obtain the best results, research and surveillance efforts must be multidisciplinary and there should be cooperation between various agencies and governments.

The data characteristics required for establishing air quality standards are determined by the nature of the air quality standards. The purpose of air quality standards is to provide goals for air pollution control programmes that, when achieved, will ensure a healthy environment. In order to establish these standards, air quality data must characterize the conditions that give rise to detrimental effects. The continual reassessment of air pollution effects requires the collection of air quality surveillance data. Recent experience in the USA illustrates the desirability of uniform and nationwide air quality standards. Geographical considerations suggest that the establishment of air quality standards in Europe should be considered on a continental basis. If this is to be done comparable air quality data must be obtained, preferably by means of cooperative and coordinated efforts.

Air quality data are needed for developing control strategies and regulations. These data will permit areas of high concentrations to be identified and, in certain cases, permit sources to be linked to particular problems. It is suggested that although data requirements are not critical the data must be obtained prior to the development of a plan to implement selected control strategies. As such, these data may be some of the first required for programme initiation.

The data requirements for evaluating the effectiveness of air pollution control efforts, while not as critical as for some of the other applications, are extremely important. A continual effort must be made to obtain air quality surveillance data that will permit the determination of progress made towards meeting air quality standards and goals. These trends and achievements should be evaluated at higher programme levels to ensure that a clear,

Table 1. Classification of possible data requirements for air quality management on the basis of data use and programme level

| Data use category   | Data characteristics required <sup>a</sup> |                                 |                     |                    |                         | Delay in obtaining results      |
|---|--|---------------------------------|---------------------|--------------------|-------------------------|---------------------------------|
|   | Quality                                    | Quantity                        | Number of locations | Sampling frequency | Level of data use       |                                 |
| Assessing pollution effects on man and his environment  | high                                       | several years                   | many                | high               | global-national         | several years                   |
| Studying and evaluating pollutant interactions and patterns, including long range atmospheric transport | high                                       | several months to several years | many                | high               | global-national         | several months to several years |
| Establishing air quality standards  | medium to high                             | several years                   | few                 | high               | national-state          | several years                   |
| Developing control strategies and regulations   | low to medium                              | several months to 1 year        | medium to many      | high               | national-state-regional | 1 year                          |
| Evaluating the effectiveness of control efforts   | low  | several months to 1 year        | few                 | medium             | national-state-regional | 1 year                          |
| Activating emergency procedures to prevent air pollution episodes or to reduce their severity           | low  | several years                   | few to medium       | high               | regional                | several months to several years |
| Guiding efforts to minimize the impact of air pollution through land use planning                       | low to medium                              | 1 year                          | many                | low                | state and regional      | several years                   |

<sup>a</sup> Data quality refers to the accuracy and precision of the data; data quantity refers to the amount of data available over a certain time span; number of locations refers to geographic coverage required; sampling frequency refers to the time scale for data collection (i.e., 1-hour averaged samples as against 24-hour averaged samples).

overall assessment is made of progress in air pollution control.

It is necessary to provide air quality data rapidly during air pollution episodes. The primary requirement is that the data should be available as soon as possible to permit action to be taken under the episode avoidance plan. If the episode plan involves forecasting, concurrent meteorological data will also be needed. In the USA, the national weather bureau (ESSA) assists by supplying the data necessary for describing the local meteorology and by issuing high pollution potential forecasts for the entire country.

The final use of air quality data described in Table 1 pertains to efforts made to guide land-use planning so as to avoid future air pollution problems. In this regard, the use of diffusion models can be an important technique in the planning function because of the importance of characterizing the air pollution levels of the region or area under consideration.

Study of Table 1 suggests that national and international data needs are associated with the assessment of pollution effects, study and evaluation of pollution interactions, establishment of air quality standards, and evaluation of air pollution control effectiveness in terms of the national and international perspective. For programmes at the state, regional, and local levels, air quality surveillance data are needed for operational activities such as developing various control strategies, issuing air pollution alert warnings, and land-use planning. It should be noted particularly that Table 1 indicates programmes for which the data use appears to be most critical.

On the basis of this discussion, general objectives for the suggested programme levels can be partially identified. For example, Morgan & Ozolins (26) have identified and described the following objectives for regional air quality surveillance programmes:

- (1) to measure and document the region's progress toward meeting the adopted ambient air quality standards;
- (2) to determine the ambient air quality in non-urban areas of the region;
- (3) to improve the reliability of diffusion models and aid in the establishment of air pollution control strategies and long-term planning;
- (4) to provide air quality data during air pollution episodes.

For state, national, and international programme levels the primary objectives of air quality surveil-

lance can be distinguished from those at the local and regional levels, although programmes at the higher levels should incorporate the data gathered regionally and locally. For the higher programme levels the suggested primary objectives for obtaining air quality surveillance data are:

- (1) to provide air quality data that can be used to assess air pollution effects on man and his environment;
- (2) to provide air quality data for studying and evaluating pollutant interactions and patterns including the development and verification of mathematical models;
- (3) to provide air quality data for the establishment of air quality standards;
- (4) to monitor the progress of lower programme levels.

Although the specific objectives of air quality surveillance at the various programme levels differ, several of these objectives can sometimes be met by a single monitoring subsystem. If this is not possible a careful analysis must be undertaken to examine alternative means for obtaining the required data.

Under normal circumstances the specific surveillance objectives of a particular programme may change as the programme matures or unforeseen changes and developments occur. A primary factor that may cause such a change is an alteration in the level of surveillance technology available. The basic design considerations should provide for some degree of flexibility in the selection of a system. For example, mobile monitoring may be a more attractive possibility than a number of fixed surveillance systems if rapidly changing monitoring technology, meteorological forecasting, and mathematical modelling results are considered. An attempt to outline several possible surveillance system configurations is given below (p. 172).

#### Other needs

Resource availability, primarily the availability of funds, is the major constraint that determines the air quality surveillance effort at each programme level (local, regional, state, national, and international). If resources were unlimited it is conceivable that each air pollution control programme could monitor air quality to provide all the information needed from the local to the global scales. However, the limited available resources coupled with air quality data

requirements at various programme levels strongly suggests the need for cooperative air quality surveillance by the various programme elements. In the past, air quality surveillance has, for the most part, been focused on regional (and local) efforts.

At the international level there has been some cooperation in air quality surveillance. Cooperative investigations of global background pollution are organized by the World Meteorological Organization (WMO) and the problem of drifting pollution in Europe is being investigated by an international surveillance system arranged by the Organization for Economic Cooperation and Development (OECD). Latterly, the Commission of the European Communities (CEC) has been very concerned about air quality and there is a good chance that a surveillance system for Europe will ultimately develop out of their efforts.

The programme levels associated with each data use category shown in Table 1 indicate that the overall air quality surveillance effort could be subdivided into possibly five levels, and the activities of each level coordinated so that the essential data requirements for the entire system (local to global) are satisfied. Once the programme elements in the overall air quality surveillance system have been identified, it becomes possible to consider the allocation of operational criteria and responsibilities to each level. Such allocation must consider available resources and legal requirements at each level in addition to the level of available and existing technology that might be utilized in air quality surveillance.

Available resources must be identified on the basis of (1) available funds, (2) trained manpower, and (3) existing facilities at each programme level. A result of the previous emphasis on local and regional programmes is the general widespread existence of surveillance networks serving the primary needs at the local or regional levels by identifying areas of high air pollution and acting as indicators of periods of heavy air pollution. Although these systems may meet local and regional (and possibly statewide) primary requirements, in most instances they fail to satisfy the requirements of higher programme levels. This failure lies in the surveillance methods in use at the local and regional levels. In general, these methods, whether for gaseous or particulate matter, were developed when any data that could be collected were of great value. Accuracy and precision were less important than relative consistency and rapid generation (at minimum cost) of many data for a large number of representative sites. These data

have been useful in characterizing gross differences between areas and in determining initial air pollution control strategies but because of their nature it is difficult to extrapolate results into a national or international perspective.

A careful inventory of existing facilities will aid in the proper allocation of operational criteria and responsibilities at each level. In Europe, for example, much preparatory work has already been done by the international agencies concerned with air pollution (WHO, WMO, OECD, ECE,<sup>a</sup> CEC) to provide the necessary information on existing systems to determine where emphasis should be placed for obtaining the required data compatible with the whole system.

A discussion of legal requirements of air quality surveillance is beyond the scope of this paper but several important factors may be noted. Legal considerations must span the complete spectrum of air quality surveillance programmes from local to international efforts. Questions concerning the sharing and interpretation of data are of extreme importance at the national and international levels. Legal instructions and backing must be given to the statutory authority for establishing air quality surveillance systems at each programme level and for dealing with questions such as the acquisition of surveillance sites in selected areas and the admissibility of surveillance data as evidence in legal proceedings.

To summarize briefly, air quality has been reviewed within the air pollution hierarchical framework ranging from local problems to global considerations. Surveillance activities at each level in this hierarchy must be compatible and comparable if data requirements at each level are to be satisfied. In general, the data needs at each level have been identified. Prior to an allocation of operational surveillance criteria and responsibilities to each programme level consideration must be given to available resources, legal requirements, and the states of available technologies.

The rest of this chapter is devoted to an outline for a systems approach to surveillance system design, a description of the methodologies for air quality surveillance, and a consideration of the necessary data systems; in addition, possible system configurations for air quality surveillance programmes are considered briefly.

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<sup>a</sup> United Nations Economic Commission for Europe.

## OUTLINE OF A SYSTEMS APPROACH TO SURVEILLANCE PROGRAMME DESIGN

### Introduction

The design and mode of operation of an air quality surveillance system will depend on a number of technical considerations, including the types of emission source and their geographical density, as well as the potential sufferers from the resulting air pollution, and the degree of complexity of meteorological and topographical factors. Available time and resources, legal requirements, etc., must also be taken into account.

Surveillance efforts can be divided into two classes—namely, continuous air quality surveillance and special studies. Within each class, two types of monitoring activity are possible—mobile monitoring and fixed station surveillance.

Continuous air monitoring at fixed locations is the most common mode of air quality surveillance. Generally, a number of air surveillance stations are distributed in a network to characterize the air quality for a particular region. The monitoring activities of most of the air pollution control programmes in the USA and Europe are based on the network arrangement, and a number of these networks have been described (see references 5-17).

Special studies of air quality can be as important as routine surveillance activities. Rossano (4) has identified three categories of special studies—local source problems, site selection surveys, and research studies.

### *Local source problems*

Studies of local source problems usually involve specific and identifiable emission sources. Examples of this type of survey are studies of the air, water, vegetation, construction materials, and animal life in the vicinity of a phosphate fertilizer plant, aluminium reduction plant, or steel mill to determine the extent to which particulate and gaseous pollutants from the source affect local ecology. A study of the concentrations of sulfur dioxide and particulates from an isolated coal-burning electric power plant or metal refinery may be carried out to obtain data on the range of influence of such a source or the efficiency of the pollution control measures applied to the source.

### *Site selection surveys*

A practice that is unfortunately followed only infrequently is making an air pollution survey of an area prior to the selection of a site for the construction of a new industrial plant. The proper use of land in an area of expanding technological and population growth requires imaginative and thoughtful community planning and zoning. While such a practice cannot guarantee freedom from subsequent air pollution problems, it does provide an opportunity to prevent obviously undesirable situations being created unnecessarily and possibly to avoid litigation.

If the site has already been selected, a study of environmental conditions existing at the site before the plant starts to operate, as is always done for electricity generating plant in the United Kingdom, is highly desirable. This provides background data against which the pollution subsequently caused by the plant can be assessed. This knowledge is of very great value for planning other developments in similar areas.

### *Research studies*

Though impressive progress has been made in recent years, there is still a great lack of understanding of the fundamental mechanisms and processes involved in the formation, intensification, and attenuation of air pollution and its undesirable effects. In the past, community air pollution studies have increased our understanding of the basic concepts of air pollution even though their main objective was to develop control measures. The Nashville Community Air Pollution Study was one of the first surveys to be conducted principally in the interest of research (27). More research oriented air pollution surveys are needed to provide answers and explanations for the many questions inherent in the air pollution problem.

Investigations of air pollution disasters in Liège (Belgium), Donora (USA), Poza Rica (Mexico), and London (England) were special research projects carried out immediately after the pollution episode in an effort to discover fundamental facts concerning the nature and extent of the air pollution and the causative factors involved.

Other examples of area-wide studies of a research nature are the study of air pollution in the Central Valley of California in 1959 to determine the nature and contribution of pollution from agricultural burning, and the comprehensive health survey in

New York City to ascertain the impact of urban pollution on the health of a large group of selected families. Similar studies have been conducted in St Louis, where a substantial effort was made to obtain data for computer model verification (28).

A considerable amount of air quality monitoring is performed principally to provide answers to the many questions inherent in the air pollution phenomena. For example, in one of the most recent efforts a team of various university and government investigators assembled from different parts of the USA, conducted an intensive 2-week study of the aerosol characteristics of smog in the Los Angeles Basin in California (29). This study has yielded information not obtainable from routine surveillance programmes which has direct implications for monitoring activities in the Los Angeles region.

Mobile sampling, as opposed to the operation of permanently located stations, is the second mode of air quality surveillance; this technique can be a very useful complement to a surveillance programme based on fixed stations. Mobile sampling is conducted by equipping a mobile unit (motor car, truck, aeroplane, helicopter, etc.) with a variety of sampling instruments and operating the unit on a selected or random basis throughout one or several regions. In the past, only limited use has been made of mobile monitoring but it is likely that future surveillance efforts will depend more heavily on this technique. Primary advantages of mobile monitoring lie in the possibility of evaluating air quality over large geographical areas in rather fine detail at a reasonable cost compared with that of operating permanent stations. Mobile units can serve as semi-fixed surveillance stations to check the accuracy of fixed stations. Mobile monitoring is also valuable in site selection surveys, such as the location of a fixed surveillance station or evaluation of special air pollution problems. The faster time response of the newer instruments makes mobile monitoring a more attractive proposition for the future. The slow response time of older sampling instruments severely limited their application in earlier mobile sampling efforts.

#### Basic design considerations and requirements

The basic design of an air quality surveillance system at any of the five programme levels identified above involves a number of steps; the selection of pollutants to be monitored, the determination of the number, mode (fixed or mobile), and location of surveillance sites required, the selection of appro-

priate instrumentation, analytical techniques and sampling frequencies for satisfactory measurement of pollutant levels and behaviour, and the development of appropriate data handling and analysis procedures (26). In addition, the basic design calls for the selected parameters to be compatible with those of the other levels in the overall system. The requirements for, and uses of, air quality data within the total system, together with practical considerations and limitations, are the primary factors that determine the design of the air quality surveillance system. The system design will in fact be a compromise between desirable objectives and available resources (30).

Essentially, the purpose of a surveillance system is to provide information. The expression "garbage in, garbage out" used with reference to the data fed into a computer applies equally well to an air quality management programme. Good surveillance data are essential if the control programme is to function effectively. Although the objectives of each programme are of primary importance in the design of a surveillance system, experience indicates that the ultimate usefulness and relevance of air monitoring systems can be greatly diminished, if not nullified, if proper attention is not given at the planning stage to a number of essential details designed to optimize the performance of the total system (3). These details include:

- (1) the reliability of the system and specification of the failure rates of components;
- (2) quality control, including quality specifications and inspection schedules;
- (3) regular maintenance programmes, minimizing the length of time equipment is out of action, reporting failures, and making repairs;
- (4) testing, both prior to the acceptance of the system from the supplier and routinely afterwards;
- (5) the manpower situation, including the availability of the special skills required at all levels of operation and maintenance, and provisions for training;
- (6) documentation—training manuals, operations and maintenance procedures, and computer routines;
- (7) systems management, which includes plans for organization, staff responsibility, lines of communication, and authority.

Because of the inherent complexity of surveillance requirements, including the considerations listed

above, a systems design approach is suggested as a means of achieving a reasonable compromise between desirable objectives and available resources.

### **An outline of a systems approach to air quality surveillance programme design**

Some indication has been given of the complexity of, and issues involved in conducting, an effective air quality surveillance programme. A systems approach can help by arranging these issues and complexities within a framework that can serve as a guide for determining the surveillance activities that are required within the total air quality control programme.

The total design requirements can be divided into 9 categories (2) as follows:

- (1) operational requirements;
- (2) systems design and performance requirements;
- (3) development and test requirements;
- (4) training requirements;
- (5) existing facilities;
- (6) episode and emergency requirements;
- (7) system effectiveness;
- (8) system support requirements;
- (9) parameters to be measured.

Taken in this order, proper consideration of each requirement will help greatly in achieving an adequate air quality surveillance system design.

#### *Operational requirements*

The operational concept relates to the manner in which the surveillance system is to be operated. It is determined for the most part by the prior allocation of operational requirements to a particular level in the overall surveillance effort. As a consequence, this category includes the description and application of the system; the organizational structure, where applicable; operational capabilities; the characteristics of the area or region where operations are planned; and the intended use of the system.

#### *Performance requirements*

This category of considerations and parameters includes those necessary for selecting the appropriate type of system configuration and operational requirements, assuming that the various demands on the system have been identified. It is essential to have a sufficient amount of data for this category so that the most suitable approach can be identified.

#### *Development and test requirements*

The development and test requirements of an air quality surveillance system provides for the validation and verification of the system with respect to the system operational requirements. The cost of this phase in relation to the overall system cost can be significant.

#### *Training requirements*

An analysis of the operation and maintenance of the system and the associated human factors is required to define the levels of skill needed to provide for efficient working. Furthermore, training may be needed for existing data users if the surveillance system is to provide data in new formats or terms, and the possible requirements should be carefully studied. Studies to determine training requirements should take into account the resources needed to provide this training. In this category, therefore, the considerations are those of manpower, skills, and selected equipment.

#### *Existing facilities*

In general, substantial facilities are required for surveillance programme activities. They include data transmission facilities; data handling, analysis, and storage facilities; analytical laboratories; monitoring stations; and mobile equipment. All these facilities can greatly affect the system acquisition and operating costs.

#### *Episode requirements*

The episode and emergency requirements category includes considerations of the surveillance system response to high levels of air pollution. Not only must the system hardware design be able to cope with conditions of heavy pollution, but the administrative and emergency procedures must be fully described and tested.

#### *System effectiveness*

An important consideration in the surveillance system design is a determination of the capacity of the system to perform assigned tasks and attain specific objectives. Further consideration must be given to the ability of the system to remain operational over the required period and to function at critical times. In general, this information will be obtained from other considerations, such as equipment specifications and selected design criteria. This category of requirements, more than any other, provides for assessing different systems and the

Table 2. Commonly measured pollutants and methods used in their determination

| Pollutant               | Method <sup>a</sup>   |
|-------------------------|---|
| Grit and dust fall      | bucket, jar, British Standard deposit gauge (monthly)   |
| Suspended particulates: |   |
| — total                 | USA high volume filter (gravimetric; 8-hourly)  |
| — smoke                 | British Standard smoke filter (soiling index; daily)<br>Tape-filter (soiling index; hourly)   |
| Sulfur dioxide          | West-Gaeke (specific for SO <sub>2</sub> ; daily or continuous)<br>H <sub>2</sub> O <sub>2</sub> followed by analysis for sulfate (specific for SO <sub>2</sub> ; daily)<br>H <sub>2</sub> O <sub>2</sub> followed by titration or determination of conductivity (net gaseous acidity; daily or continuous)<br>coulometric (specific for SO <sub>2</sub> ; continuous)<br>Stratmann silica gel (8-hourly) |
| Sulfuric acid mist      | double filtration (daily)   |
| Carbon monoxide         | non-dispersive infrared (continuous)  |
| Ozone                   | chemiluminescence   |
| Oxidants                | neutral KI (daily)  |
| Methane                 | flame ionization (continuous)   |
| Higher hydrocarbons     | flame ionization (continuous)   |
| Nitric oxide            | chemiluminescence — reaction with O <sub>3</sub> (continuous)   |
| Nitrogen dioxide        | Saltzman (daily or continuous)<br>chemiluminescence — reduction to NO, then reaction with O <sub>3</sub> (continuous)   |

<sup>a</sup> Continuous methods are those operating automatically and producing a continuous record on a recorder chart or a computer input tape. The other methods are operated manually; the frequency of sampling indicated can be varied within limits to suit requirements, e.g., a deposit gauge can be changed at 2-weekly intervals and the H<sub>2</sub>O<sub>2</sub> method for sulfur dioxide can be used over 14-day intervals if the pollutant concentration is very low.

suitability of a given system, and for making a comparison between the various possibilities.

#### System support requirements

The support features of an air quality surveillance system are of primary importance. Considered as a part of the support requirements are system maintenance, laboratories, meteorological and other services, storage facilities, data transmission facilities, data handling, storage, and reduction facilities, etc. In this regard, the system support requirements are important inputs into the determination of system effectiveness.

Clearly, meteorology is very important in the overall air pollution system. In its broader aspects, as illustrated on the right side of Fig. 1, the air pollution problem can be considered as a system with three basic components: the emission source, atmospheric dispersion and the resulting air quality, and the damage caused by the pollution. Since air quality is so closely tied to meteorological conditions, the operation of the surveillance network generally includes the measurement of atmospheric parameters that affect the nature and distribution of

pollutants. These parameters usually include wind speed and direction, turbulence, temperature, humidity, and solar radiation.

The importance of meteorology in describing the air pollution problem makes it necessary for the surveillance programme to have the services of trained meteorologists (31) whose role includes, but is not limited to, the following activities:

- (1) forecasting periods of high air pollution potential. Forecasting programmes in the USA have been described by Gross (32) and Kirschner (33);
- (2) analysing air quality surveillance data with respect to meteorological conditions;
- (3) aiding in the development of atmospheric dispersion models;
- (4) participating in air pollution surveys;
- (5) participating in site selection decisions concerned with surveillance and land-use planning.

#### Parameters to be measured

The number of potential air pollutants is practically unlimited. Historically, however, only certain

pollutants have been considered important (see Table 2) on account of their pervasiveness in the ambient air and the detrimental effects they produce. Generally, it will be necessary to monitor air quality levels of those pollutants for which ambient air quality standards have been established. In addition, the surveillance system must respond to other pollutants that could become important in the future. This response must allow air quality standards to be determined from the surveillance results. Thus, although the number of pollutants for which standards have been set may be small, the number of pollutants that should be considered in determining surveillance system requirements may be quite large.

In selecting pollutants to be monitored by the local or regional surveillance system, consideration should be given to regional characteristics such as fuel usage, industrial activities, and special problems, in addition to the existing air quality standards. Data from the emission inventory can be a useful indicator of the pollutants that may be present and should be monitored. Before a final selection of pollutants is made, special studies should be conducted to determine the actual surveillance requirements.

The aspect of building up a surveillance capability over a period of years is attractive for reasons connected with budget and manpower. The selection of pollutants for monitoring under these circumstances should generally attempt to focus on the pollutants that are most important in the study region rather than meet general requirements. However, the actual selection of pollutants for measurement should be based not only on their immediate toxicity, but also take into account any implications they may have for health in the overall pollution picture from the perspective of national or international programmes (34).

Consideration should also be given to the meteorological parameters that will be measured in conjunction with air pollutants. The most common meteorological observations are wind speed and direction; other measurements include atmospheric stability, temperature, pressure, humidity, and solar radiation.

#### Systematic surveillance site selection procedure

One approach to surveillance system design has been suggested by the United States Environmental Protection Agency in a recent publication describing

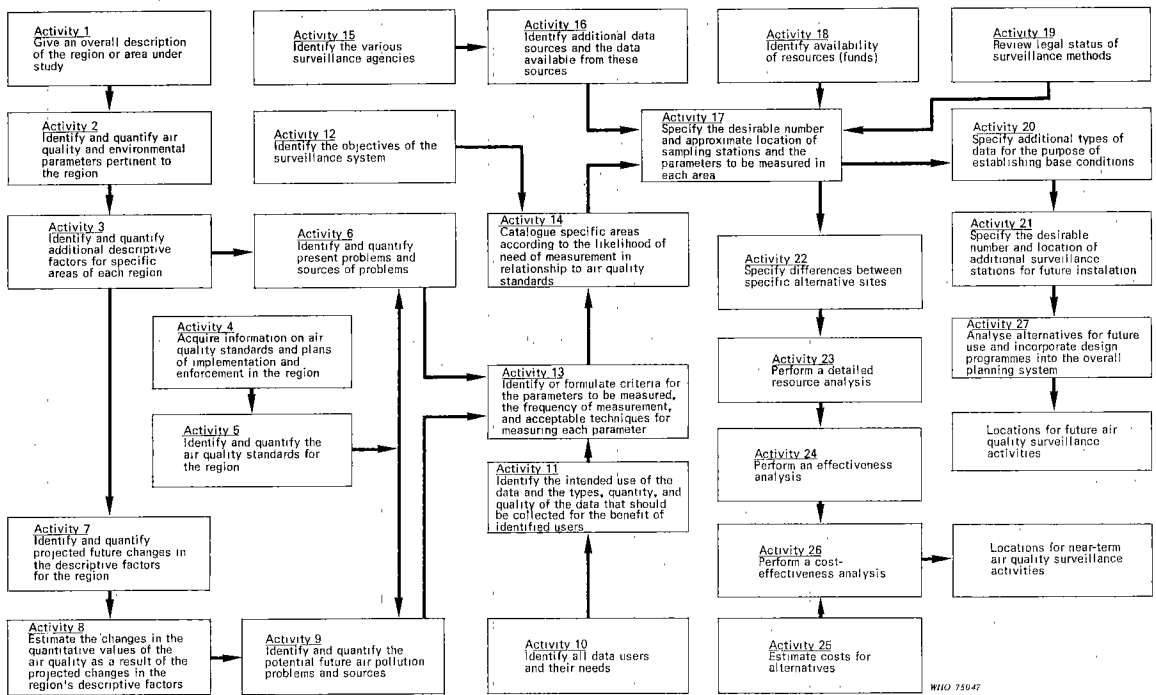
minimum surveillance requirements as a function of regional population and/or existing ambient concentrations and regional areas (36). Based on qualitative evaluations of cities of different population classes in the USA in terms of their existing facilities, pollution patterns, and geographic structures graphical and mathematical methods were developed for estimating minimum requirements for sulfur dioxide and particulate surveillance networks (the method is stated to be suitable for other pollutants also). The development of this approach, although partially mathematical, has been the result of empirical studies of a limited nature in the USA and it is highly unlikely the same expressions would be suitable for other countries. Furthermore, this method apparently fails to include any consideration of other sampling systems (mobile) or other possible sources of data. As such, the approach cannot be used to define comprehensive requirements satisfactorily and serves only to meet existing legal requirements in the USA (25).

The complex design process needed to achieve an effective compromise between desirable objectives and available (and limited) resources suggests the use of the systems approach that has already been described. In applying this approach, the design proceeds through a series of activities, which, if carefully followed, will help to assure that the design objectives are reached. Charlson et al. (19) have suggested the rudiments of such an approach by identifying three major considerations in the siting of surveillance stations—namely, (1) consideration of the surveillance system objectives, (2) consideration of the physical surroundings (meteorology, geography, topography, etc.), and (3) consideration of the specific decisions that must be made at each site location, such as sampling probe height, probe size, and flow rate. Keitz (3) elaborated a modified systems approach in developing the data requirements and primary performance characteristics for air quality monitoring networks while Hamberg (1) used a systems approach in outlining basic surveillance system design considerations.

Expanding these considerations, the activity list set out in Fig. 3 provides a possible framework for surveillance system analysis, from the definition of system objectives to the identification of the optimum location of the surveillance sites (2). The framework embodies a sequential step-by-step series of activities that, when accomplished, will yield the required system design.

The key to this analysis is that the approximate

Fig. 3. Framework for the selection of locations for surveillance sites (2)



WHO 75047

surveillance requirements are first determined by factors such as regional characteristics, air quality conditions and standards, intended data uses and surveillance objectives. More specific surveillance possibilities that satisfy these requirements are then compared through cost-effectiveness analysis of other factors, such as available resources, performance characteristics, accessibility, and existing facilities.

Fig. 3 illustrates the necessity of considering the specific air pollution problems of each region in selecting suitable surveillance sites. Certain activities in the sequence require a high degree of coordination between various programmes if a wide range of comparable data are to be obtained. Cooperation and coordination with other agencies in the following activities (Fig. 3) are essential:

- activity 4 — information on air quality and other standards;
- activity 7 — identification of projected future changes;
- activity 10 — identification of data users and needs;
- activity 12 — identification of surveillance system objectives;

- activity 13 — identification of criteria for measurement and sampling;
- activity 15 — identification of various surveillance agencies and future plans;
- activity 16 — identification of additional data sources.

The responsibility for coordination must rest with higher programme levels (i.e., state, national, and international) (37). Initial efforts in this direction include the WHO compilation of air quality standards on an international basis (18). Economic planning organizations, such as OECD in Europe, as well as general planning agencies, can provide projections of future economic and other possible changes and they appear to be anxious to aid in these efforts. The general identification of data users and needs has been discussed earlier (see p. 155). In this regard, there is a definite need to specify more fully the actual data users (by agency) and data requirements at each programme level. The general objectives of each programme level identified must be defined more specifically and the objectives of each programme balanced with those of the overall surveillance effort.

## METHODOLOGIES IN AIR QUALITY MONITORING

Apart from surveillance site location, the representative qualities of air quality surveillance data will depend on the sampling and analytical procedures selected for monitoring activities. Three important considerations include (1) sampling procedures, (2) sampling frequency, and (3) analytical techniques.

### Basic considerations of sampling

There are four basic considerations for minimizing sources of error and optimizing efficiency in air sampling.

(1) The sample to be collected must be representative in terms of time, location, and the condition to be studied or documented.

(2) A large enough sample of air must be collected to permit accurate analysis. The volume will depend on the expected contaminant concentration as well as on the sensitivity of the analytical method.

(3) The sampling rate must be chosen to provide maximum collecting efficiency. In sampling particulates by means of membrane filters the choice of flow rate may be limited by the fact that the pressure drop through the filter increases exponentially with face velocity, thereby introducing a severe design requirement for the sampling pump.

(4) The duration of the sampling period and the frequency of sampling should accurately reflect the occurrence of fluctuations in pollution levels, in so far as these are required to be known.

Air quality sampling procedures must meet certain criteria if data are to be comparable and representative of the state of the air. However, generally accepted specifications design details of air quality surveillance stations unfortunately have not yet been rigidly defined and there is a serious lack of standardization among different monitoring networks, and frequently within a single network.

Charlson (38) pointed out that the Continuous Air Monitoring Programme (CAMP) stations operated by the United States Government in a limited number of cities use "nose-level" sampling points, whereas in California sampling is performed 15-30 m above the ground. Obviously, comparisons of air quality data from geographically different areas obtained with these different techniques are

difficult to justify unless it can be shown that pollution is little affected by height above the ground.

Yamada (39, 40) surveyed monitoring practices in the USA and found that the location specifications of monitoring stations differ significantly. He also noted that most differences, as well as potentially erroneous practices, are connected with details such as type, size, length, and condition of sampling tubes. His findings suggest that numerous errors could occur as a result of the wind channelling effect of adjacent tall buildings and nearby hills, and the proximity of the sampling tubes to local sources. In another paper, Yamada & Charlson commented further on the latter point (41). The importance of proper sampling procedures has recently been illustrated by Butcher & Ruff (42), who indicated possible errors in the analysis of atmospheric nitrogen oxides and ozone on account of chemical reactions in the sampling probe if residence times are long (i.e., more than about 5 seconds).

The need for as much standardization as possible in specifications dealing with the design of networks and station details is obviously urgent because many important conclusions and decisions in air quality management will eventually be based on data obtained from monitoring network operations. Furthermore, valid comparisons of air quality data, as well as exchanges of information on exposure-effect relationships between cities or countries, cannot be justified until air quality data are more representative (43).

Judging from the studies cited above, insufficient consideration has been given to surveillance station design; it is suggested that a set of criteria should be developed dealing, among other things, with:

- (1) sampling probe height;
- (2) sampling probe diameter;
- (3) sampling probe flow rate;
- (4) possible meteorological obstructions;
- (5) delay times between sampling and analysis;
- (6) chemical reactions and absorption in the sampling lines;
- (7) other possible changes that could influence the sample—temperature, humidity, pressure, etc.

Agreement to standardize these criteria appears imperative if comparability and consistency in the interpretation of data are to be achieved.

The Oregon-Washington air quality monitoring criteria experience in the USA (44) is an example of

agreement between states in developing monitoring programmes. The purpose of formulating joint criteria for air quality sampling was to insure that the overall operations conducted by both states, especially in the border areas, would produce comparable and compatible results and policies. Briefly, the proposals established sampling criteria and defined the following types of monitoring station.

- (1) Primary air mass station;
- (2) Primary ground-level monitoring stations including: (a) primary fixed stations, and (b) primary mobile stations;
- (3) Special stations: (a) special source stations, and (b) special air mass stations.

The criteria include requirements for probe height, surrounding area characteristics, environmental conditions, and critical construction materials. By establishing these criteria, comparisons were limited to data taken from the same type of monitoring station, thereby helping to assure comparability and compatibility.

### Sampling frequencies

An important decision concerning the development of monitoring procedures concerns the frequency of sampling. In short, the sampling frequency, with regard to both the duration of sampling and the interval between successive measurements, should be selected to provide the information desired for a particular set of surveillance objectives.

Air pollution concentration levels fluctuate, and in order to protect potential receptors against air pollution damage it is generally necessary to measure the changing pollution levels, particularly during periods of high concentrations. Although the sampling time does not affect the mean value over a long period, it does affect the ranges of concentration recorded. Larsen (45) studied this empirically and related the sampling time to the value of the standard geometric deviation. Saltzman (30) used an analytical approach for the same purpose. The results of these studies indicate that if random sampling techniques are used, the number of samples required will increase as the standard geometric deviation increases. In other words, the greater the fluctuation of the pollutant level, the more numerous the samples that must be taken to assure statistical accuracy. Saltzman (47) has shown that in order to observe the entire variance structure in a fluctuating pollutant concen-

tration, the sampling interval must be at least 10 times shorter than the cycle time of the fluctuation. For example, to follow the changes in concentration of a pollutant that varies with a period of 24 hours, roughly 12 samples, each averaged over 2 hours, will be required.

In order to select the optimum sampling time it is necessary to know which pollutant fluctuation periods are of biological, psychological, or physical importance (47, 48). Assuming that this information is available, the sampling period would be established in such a way that the important variations could be detected.

Since the surveillance information will in many cases be used to characterize an air pollution problem, the sampling frequency must be chosen in such a way that the air quality fluctuations can be defined. These changes are related to cyclic occurrences that influence air quality, such as routine human behaviour and climatic seasons, and to random influences. The latter are, for the most part, associated with meteorological and manufacturing events. The cyclic activities generally have a duration of 2-3 hours or more; examples are the peaks of pollution concentration that occur as a result of the morning and evening rush-hour travel to and from work and the general daily cycles of human activity. These activity cycles can also influence diurnal concentration patterns of secondary pollutants formed in photochemical smog, such as oxidants and nitrogen dioxide. Random fluctuations can last almost any length of time but because of atmospheric mixing characteristics these periods are seldom less than 1-5 minutes in duration (fumigation is an example of random fluctuation).

Thus, although an instantaneous record of air quality may be desirable for some special purposes, it is not a necessary requirement for characterizing fluctuations in air quality. If a short sampling time is selected it will be necessary to record and store very large amounts of data that in most instances will be averaged over longer periods prior to decision-making.

The number of samples needed to define fully the air quality of a given region depends on the variability of the parameters concerned. Advanced knowledge of the variability of the parameters to be sampled in relation to the precision required in the final results is therefore necessary. To obtain this information, intensive field studies may have to be undertaken. Existing data in the form of meteorological studies and routine reporting, as well as other

Table 3. Air quality standards reference methods in use in the USA (11)

| Pollutant                         | Averaging time         | Reference method   | Principle of detection |
|-----------------------------------|------------------------|--|------------------------|
| SO <sub>2</sub>                   | 1 h, 3 h, 24 h, annual | pararosaniline   | colorimetric           |
| Particulate matter                | 24 h, annual           | high-volume sampler  | gravimetric            |
| CO                                | 1 h, 8 h               | non-dispersive infrared spectrometry   | infrared               |
| Photochemical oxidants (ozone)    | 0.5 h, 1 h             | gas phase O <sub>3</sub> -ethylene reaction (calibrated against neutral buffered KI) | chemiluminescence      |
| Hydrocarbons (other than methane) | 3 h                    | gas chromatography   | flame ionization       |
| NO <sub>2</sub>                   | annual                 | gas phase  | chemiluminescence      |

records, can be extremely useful for estimating the variability of many of the parameters.

### Measurement techniques

An important decision in surveillance system design concerns the selection of measuring instruments. The accuracy of the air quality determination and the delay in obtaining the results will depend upon the characteristics of the measurement methods selected. For some pollutants, measurement techniques are well established and sufficiently precise and accurate to produce high quality data for widespread application. For other pollutants, however, satisfactory measurement techniques have not been developed and the methods in use provide only crude estimates of actual concentrations (22).

A number of reviews have been published on various analytical techniques, including those of Katz (49), Altschuller (50), Stevens (51), and others (52, 53, 54, 56). Mueller et al. (55) have discussed and reviewed the various analytical chemistry techniques concerned with air pollution that were available in 1969/70, including the sampling, physical properties, and chemical composition of particulate matter. These reviews indicate the rapid development of air quality monitoring instrumentation.

However, analysis of the chemical and physical properties of the atmosphere is still quite difficult for several reasons. First, as noted earlier, the number of compounds and substances that can be present in the air is very large, and the analysis for specific compounds and quantities in this mixture may require very elaborate instrumentation. Secondly, the concentrations of air pollutants are generally very low,

often less than 1 mg/m<sup>3</sup>. As a result, the methods and instruments for measuring air pollutants in these mixtures and at very low concentrations must be carefully selected, evaluated, and standardized.

Criteria for selecting methods and instruments must include the following factors: specificity; sensitivity and range; stability; precision and accuracy; sample averaging time; reliability and feasibility; drift and calibration characteristics; response lag; rise and fall times; effects of environmental influences such as temperature, pressure, and humidity; maintenance requirements; and data output compatibility. A careful analysis of the uses to which the data are to be put is necessary for determining the importance of the various criteria.

In establishing air quality standards the measurement method must be specified. The method, preferably the most accurate and precise of those available, serves as a reference standard against which other techniques can be compared for equivalence. As indicated in Table 3, reference methods have been established in the USA for 5 pollutants. At the present time, however, these and other techniques are undergoing intensive review by the United States Government and a committee composed of representatives from national professional health, air pollution, and testing societies. The major part of the capital cost of an air pollution survey lies in the cost of equipment and instruments. While the cost of the simplest type of deposit gauge is negligible, each instrument for the daily manual determination of smoke and sulfur dioxide, or any of the other common pollutant gases, costs about US\$120. A non-dispersive infrared recorder for carbon monoxide costs about US\$2 500, and the usual sulfur

dioxide recorder a little more, say, US\$3 500. The present generation of instruments, such as those based on chemiluminescence, cost US\$7 000–10 000 each.

Atomic absorption instruments or mass spectrometers are now finding increasing application in air pollution analysis; the cost of these instruments may be as much as US\$100 000, or even more. The cost levels for the more elaborate techniques strongly suggest the need for cooperation or sharing of facilities with other agencies or programmes, even on an international level, especially if research programmes are being conducted (57). While the prices quoted above were reasonably correct at the end of 1974, the effects of continuing inflation must be borne in mind. However, as they stand, these prices provide a scale for estimating the cost of a survey and also indicate the relative costs of different types of instrumentation.

In selecting sampling and analytical techniques for air quality surveillance consideration must be given to some important factors.

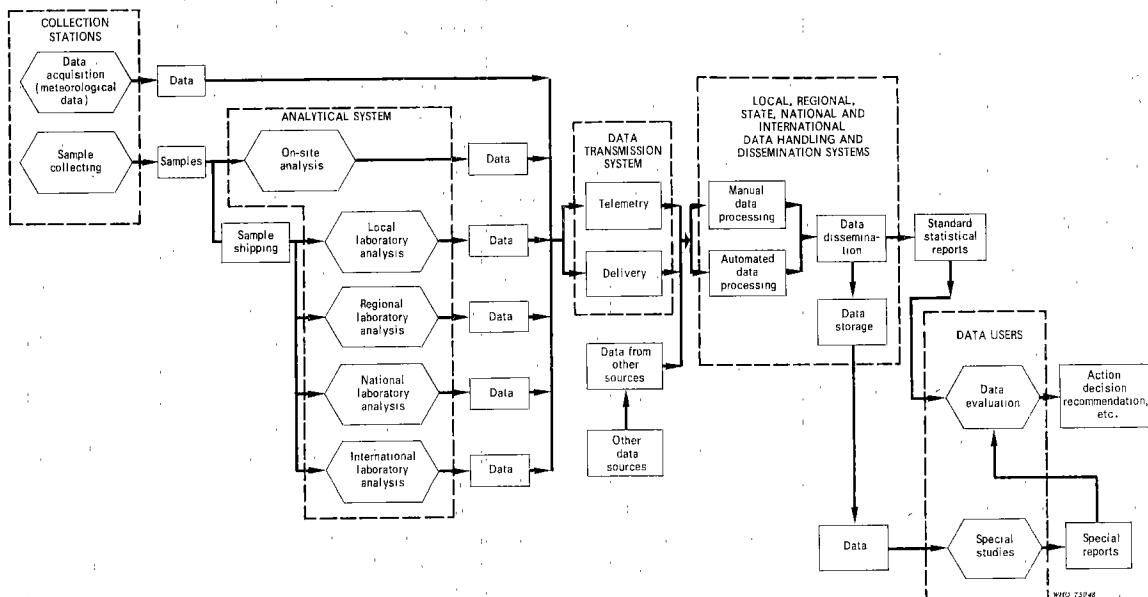
*Support facilities.* In general, the operation of a surveillance system will require various laboratory facilities, maintenance services, storage areas, etc.

The complexity of these facilities is decided by the objectives of the programme and the depth of the surveillance effort.

*Manpower needs.* The skills and training of manpower resources needed for surveillance system operation depends on the characteristics of the monitoring system. Daily samplers for smoke and the various pollutant gases, high volume aerosol samplers, and so on, do not require highly trained personnel for routine collection and operation although the subsequent laboratory analysis of samples involves chemists or highly trained technicians. On the other hand, requirements for trained manpower to operate automatic equipment are generally high.

*Calibration procedures.* The continuous production of valid and useful data requires careful maintenance of the analytical equipment and instruments. This includes calibration prior to installation and on a routine basis thereafter. For automatic analysers, dynamic calibration techniques should be used. Manpower requirements and the use of recognized reference methods must be considered in defining calibration procedures. These procedures should be standardized on a broad basis.

Fig. 4. Data flow in the surveillance system (2)



*Flexibility.* Because of the high cost of air quality monitoring instrumentation it is necessary to analyse carefully the system needs relative to surveillance objectives and to specify a degree of flexibility in the programme design phase. For example, mobile monitoring may eliminate the need for fixed monitoring stations, thus offering the possibility of making large savings in initial capital expenditure as well as providing a system that can easily be modified as new sampling and analysis become available.

### Data acquisition, handling, and analysis

A major consideration in surveillance system design concerns the flow of data from the monitoring stations to the ultimate data user. The various factors are shown in Fig. 4 and include collection stations, the analytical system, the data transmission system, the data handling and dissemination system, and the data users. It can be seen that the data flow system links together the various elements of the surveillance programme. Historically, the lack of proper planning of the data system has resulted in serious deficiencies in the capability of air monitoring programmes to produce valid data in a useful form.

Collection station activities can be divided into two categories. The usual mode of operation is the collection of samples at the monitoring station: these air samples can be used for chemical analysis, meteorological measurements, etc. The alternative is to collect data from other sources, public or private, to compliment the other data.

The analytical system is one of the critical elements in a data system. Lack of accuracy and precision at this stage will propagate errors throughout the entire surveillance programme. The analysis phase consists of either on-site analysis, as represented by monitoring instruments installed at the surveillance site, or analysis of samples sent to central laboratories for evaluation. At the present time the former approach is generally used for gaseous analysis, while particulate samples are handled by the latter technique. The use of standardized methods of analysis, quality assurance, and uniform data reporting is mandatory in the analysis phase, not only to assure the comparability of the data, but also for the subsequent use of the data within the system. To assure the proper identity and accuracy of the analytical data certain checks should be incorporated in the surveillance process at each level of data handling. These checks are most easily

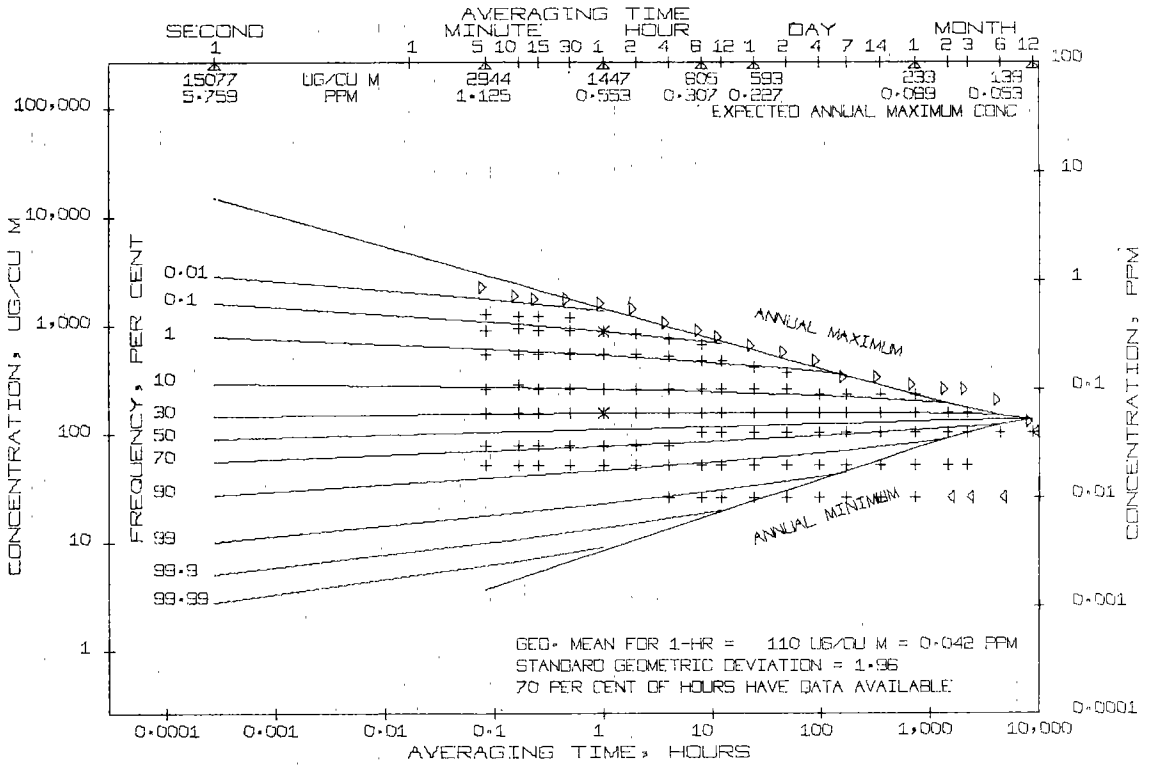
made at the analysis level and become more difficult subsequently on broader and higher levels within the overall programme.

In the design of the surveillance system, certain data transmission priorities have to be established. To determine these priorities, consideration must be given to the need for the data in a certain time frame, the ability of various transmission systems to accomplish the required task in that time frame, and the cost of each mode of transmission. The high speed data transmission offered by telemetry may be useful for activities concerned with the avoidance of air pollution episodes. Justification for telemetry, as opposed to data delivery, must be determined by analysing the costs involved, the data requirements, and the requirements and availability of manpower skills for the operation and maintenance of transmission facilities (1).

Various techniques have been used for data processing and the closely related question of data presentation. In general, the purpose of the data processing activity is to condense a great amount of data into information that can be utilized by the decision-makers. The most common reporting parameters of air quality data are instantaneous values, mathematical means and variations, including running averages, and time values indicating the length of time a given measurement was above a certain level. Graphical presentations in the form of arrow-head charts (Fig. 5) are used to present the frequency with which a sample of a certain averaging time exceeds a given concentration. Brasser (46) has used log-normal representations of surveillance data to plot isopleths of the time certain concentrations are exceeded on a map of the region being monitored. These maps reveal the extent of the air pollution problem and the variation in concentration levels of pollutants with time throughout the region. The standard and special reporting performed in conjunction with the data handling and dissemination system must fulfil the needs of the data users at all programme levels. Thus there is a need to standardize reporting formats as well as to establish certain data quality criteria (57). One example of a centralized system is SAROAD, i.e., Storage and Retrieval of Aerometric Data (35).

As a final element in the data system, storage requirements must be examined in surveillance system design. As the numbers and types of data users increase demands will be made for previously recorded data, which must be extracted for a variety of broad or specialized uses. The use of automated

Fig. 5. Computer plot of concentration against averaging time and frequency for sulfur dioxide at site 256, Washington, DC, USA, 1 December 1961 to 1 December 1968 (45)



storage and retrieval techniques can greatly speed up, and often reduce the cost of, such activities.

**System configuration**

It is clear that the range of possible surveillance system configurations is limited by considerations of available resources. The variable factors that determine the system configuration have already been described; they include:

- (1) number of stations (including mobile capabilities);
- (2) station locations;
- (3) types of sensor installed at stations (determined by pollutants to be monitored);
- (4) analytical techniques to be used;
- (5) data handling facilities to be used;
- (6) meteorological measurements to be made at stations.

The final cost of the surveillance system, including both capital and operating costs and the quality and usefulness of the data obtained will depend primarily on the choice of these variables. To determine the optimum values for the system configuration variables, the cost of obtaining the data must be balanced against the desired quality and quantity of these data.

Unfortunately, procedures for designing air quality systems have not yet developed to the stage where a compromise can easily be made between system objectives and system constraints in order to arrive at an adequate design. It must be recognized that final decisions about the assignment of practical values to the configuration variables will have to be made largely on the basis of experience and technical judgement. The use of a systems design approach can usually help in reaching a decision by providing a rational procedure for problem analysis.

Although the range of possible surveillance

systems is large, fixed stations, generally with uniform instrumentation at each site, have been chosen in the past for the majority of programmes. For the more elaborate systems the network stations have been linked to a central computer for automatic data collection and preliminary analysis. A range of possible fixed station configuration has been investigated by Skinner et al. (58). The results of the analysis show that the product of the number of sampling sites ( $L$ ) and the number of sensors per site ( $S$ ) roughly fixes the total system cost. As the number of stations and sensors increase, the use of automatic systems becomes more attractive than manual operation (on the basis of United States conditions and data). Conversely, with small  $L \times S$  values the costs of an automatic system will have to be carefully balanced against those of the manual system.

Experience with automatic systems in the USA has been variable. Often, costs and delays have been much higher than anticipated because long "running-in" periods were required, personnel were inadequately trained for the complex task of continuing calibration and maintenance, and no results were obtained during long periods on account of the malfunctioning of the equipment. Operationally, these costs are very important and greatly inflate the cost of the automatic system. Hamberg (1) recommends air pollution control agencies that are considering installing automatic telemetering surveillance equipment to hold discussions with other agencies that have already obtained some experience with automatic systems.

It appears that the range of choice of fixed monitoring stations under the constraint of limited funds lies between the establishment of one or two high quality stations and the establishment of a large number of medium or low grade stations. The initial development of most existing surveillance networks appear to have followed a middle-of-the-road policy between these two extremes by using automatic equipment and establishing as many surveillance stations as possible. The limiting feature of these systems lies in the sensors installed at each station. When new monitoring technology is developed, the investment required to re-equip many monitoring stations becomes prohibitive, especially as the new instrumentation is likely to cost more than the old.

In short, although monitoring equipment may become obsolete within a short time (possibly in less than 5 years), the cost of replacing the equipment may be equal to, or even greater than, the initial cost

of the system. These considerations give rise to the dilemma that investment in a limited number of high quality, reliable, and accurate surveillance systems does not provide adequate area coverage while a widespread system does not provide reliable and accurate data because of compromises in instrumentation.

It seems possible that the dilemma could be resolved by using mobile monitoring equipment in conjunction with a few (1 or 2) high quality fixed surveillance stations. Unfortunately, this system has not been adequately investigated with respect to costs and effectiveness. This suggests that an intensive analysis should be made of the use of high quality mobile sampling in conjunction with the operation of one or two first-class fixed monitoring stations for regional surveillance.

For the higher programme levels (national and international) the alternative approaches appear to be special studies (both long- and short-term) and the long-term monitoring of global or other widespread pollution phenomena. The development of these programmes should follow the systems design approach in selecting possible alternatives to surveillance activities. The extensive geographical areas and wide range of climatic conditions that must be investigated suggest that for this application also a mobile system may be more effective than the construction of a large number of remote, simple surveillance networks.

## CURRENT LIMITATIONS AND SUMMARY

The air quality management approach to air pollution control is a complex undertaking. The complexity arises from the need to understand both the causes of air pollution produced by emission sources and the detrimental effects of pollution on man and his environment. A fundamental requirement for understanding the mechanism of air pollution is the regular and accurate assessment of air quality. Air quality surveillance is the procedure of monitoring the state of the atmosphere in order to provide the basic information needed for the air quality management. This chapter emphasizes that a systematic appraisal of surveillance requirements is necessary for local, regional, state, national, and international management programmes.

## Limitations

At the present time serious limitations stand in the way of effective air quality surveillance; as a result, an overall air quality management programme is inhibited. These shortcomings can be grouped into the following categories:

- (1) organizational;
- (2) operational;
- (3) analytical.

The resulting limitations in each of these categories arise from the lack of available resources and information, and time constraints. The impact of these limitations directly influences the basic design considerations of air quality surveillance systems.

The close interrelationships of the various systems within the air quality management approach requires a high degree of organizational detail in the programme. For instance, for effective functioning of the overall system each programme element should be on approximately the same level of technical development. An elaborate surveillance system would be ineffective if it were linked with simpler air quality management programmes. The organizational requirements for a sound air quality management programme have not yet been properly developed and it is unreasonable to invest considerable resources on surveillance system design and development if the system cannot utilize the monitoring data and results effectively. Prior planning for the total programme is therefore essential.

Another major limitation in the organization category is the need to define system-wide data needs and requirements. Although some basic considerations have been described, there is a considerable gap in our knowledge about specific data requirements. Since these needs are closely associated with the programme levels of the various data users, a substantial effort will have to be made to examine the whole framework of air quality management from local to international levels so that data needs can be identified with the necessary precision to permit the design of a surveillance system.

Organizationally, the limitations described above suggest that until specific information is available, a modest approach to air quality surveillance may be desirable and that the quality of the data is more important than the quantity. In any case, a closer examination of surveillance system requirements should be undertaken before the system is designed, and a consideration of the overall air quality man-

agement programme should be included in this examination.

At the operational level, a considerable number of limitations stand in the way of effective quality surveillance. In the design phase, it appears obvious that in many circumstances the complex surveillance system design procedures outlined here will be beyond the limited resources and time available for many programmes. Although voluminous coverage could be given to each topic of the design considerations, in most cases the information needed to meet basic design requirements will not be available. For example, the objectives of the surveillance system may not be clearly defined in some instances or the regional characteristics of the area under consideration may not be known well enough to permit a comprehensive planning effort to be undertaken. Attempts should be made to identify actual design criteria, and if critical information is lacking special efforts should be made to obtain the data before the design procedure begins.

Also at this level it is necessary to balance the various components in the surveillance system. A highly automated data acquisition system coupled to ineffective sensors will not provide data of optimal accuracy and usefulness. Conversely, complex instrumentation will not be utilized effectively if the provision of trained manpower and use of data-interpreting techniques are not considered. The need to blend the various system components into an effective surveillance programme is a major obstacle in the design phase of air quality management.

Faced with the operational limitations described above, a high degree of flexibility should be maintained in the overall surveillance system design if specific information and data are not available. In addition to flexibility, the operational design criteria should provide for uniform data quality rather than quantity in the systems design.

Special consideration should be given at the operational level to the use and role of mathematical modelling (or other simulation techniques) in the surveillance effort. Although modelling can be used to extrapolate certain surveillance data, the use of models does not preclude the need for continual routine surveillance activities. However, modelling techniques can be useful in many surveillance programme activities. The advantages and limitations of these techniques should be investigated in conjunction with the design of the surveillance programme.

Current limitations in analytical techniques appear to be one of the major constraints in air quality

surveillance system design. Monitoring techniques have not been developed for many pollutants and reference methods and standard procedures for a great many other pollutants are either lacking or under review. The resulting uncertainty about analytical techniques and the high cost of newly developed sensors will mean that the selection of analytical methods in the surveillance programme design will be of critical importance. Tested and recommended techniques must be studied to ensure that they will provide data meeting the specifications for accuracy, precision, and stability, and that data from different programmes will be comparable.

Sampling systems and techniques must be considered as an inherent part of the analytical system. The lack of standardization in sampling techniques represents a serious obstacle to the comparison of data from different sources and seriously reduces the value of the data for higher programme levels. Sampling procedures should be standardized on an international basis or reference techniques specified so that results obtained by different methods can be compared analytically.

Associated with analytical limitations is the need to develop standard formats for the reporting and presentation of air quality data. In addition to standard formats, techniques must be developed for estimating the accuracy of, or errors in, reported data. The application of standard methods will greatly facilitate comparisons of data and make for system-wide compatibility.

### Summary

While the limitations discussed above present a formidable challenge to the successful design and operation of an air quality surveillance programme, the overriding need to know the effects of man's activities on his environment in a timely and precise manner makes some form of air quality surveillance essential. A systems approach has been suggested to cope with the many problems inherent in the development and operation of an air quality surveillance programme. For this approach to be effective, cooperation is required at all levels and must extend from the standardization of surveillance procedures and techniques to the development of comprehensive objectives for each level in the overall programme.

Previous experience, particularly with regard to surveillance programmes in the USA, suggests the need for considering the quality rather than the quantity of data. The high cost of analytical sensors

that provide quality data and other requirements of the surveillance programme indicate that use of mobile monitoring techniques may be more effective than the establishment of fixed network. A careful study will reveal which approach is likely to be more effective in meeting the objectives of specific surveillance programmes.

The complexity of the principles and procedures for air quality surveillance coupled with the limitations mentioned above suggest the need for considerable restraint in system planning and development. Many basic questions and issues remain to be resolved prior to the actual design of a monitoring system. Careful study and cooperative efforts are necessary to assure the resolution of these issues and achieve an effective air quality surveillance programme.

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