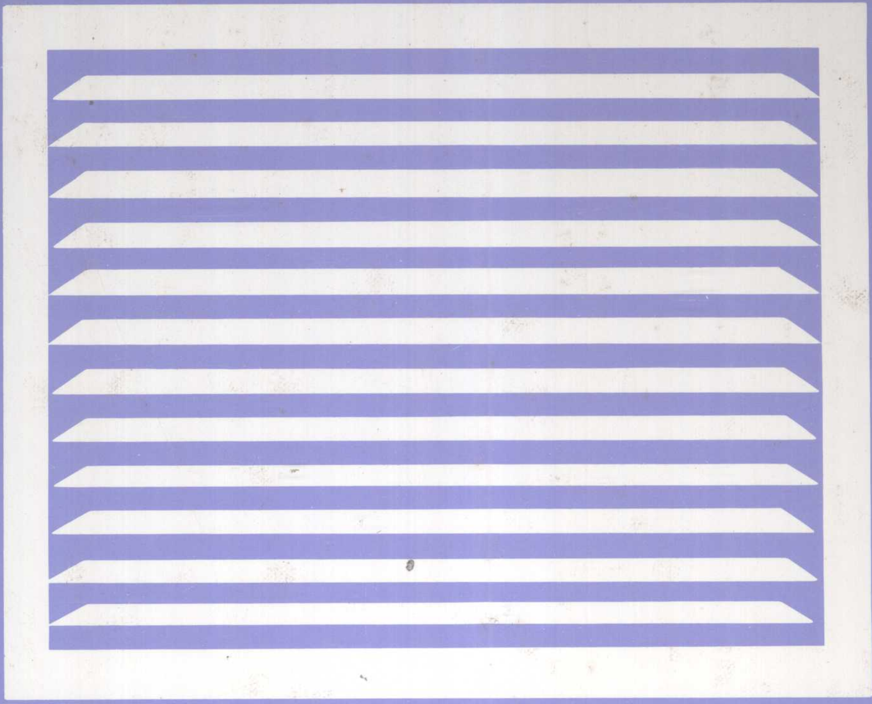

Design and Protocol for Monitoring Indoor Air Quality

Nagda/Harper, editors

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Foreword

This publication, *Design and Protocol for Monitoring Indoor Air Quality,* contains papers presented at the Symposium on Design and Protocol for Monitoring Indoor Air Quality, which was held in Cincinnati, Ohio, 26–29 April 1987. The symposium was sponsored by ASTM Committee D-22 on Sampling and Analysis of Atmospheres in cooperation with the Air Pollution Control Association and the American Industrial Hygiene Association. Niren L. Nagda was the symposium chairman and Jerome P. Harper and James E. Woods presided as symposium co-chairmen. Drs. Nagda and Harper have edited this publication.

Contents

Overview

The ASTM Symposium on Design and Protocol for Monitoring Indoor Air Quality was prompted by the growing concern for air quality in homes, offices, and schools and the need for better design of investigations so that causes of indoor air quality problems and their solutions are clearly understood. Numerous chemical and physical factors influence the indoor concentrations of contaminants. Source characteristics, chemical and physical sinks, rates of air exchange, indoor airflow patterns, and occupant activities are some of the factors which need to be considered or measured when monitoring indoor air quality.

The multiplicity of these factors makes the investigation design process complex. Determining the parameters to be measured as well as defining the extent of measurement are critical aspects of designing a study. The process is further complicated by the fact that individuals drawn to such efforts are of diverse professional and educational backgrounds—environmental scientists, chemists, industrial hygienists, architects, mechanical engineers, and public health professionals, to name a few. Thus a common understanding of the basis for conducting indoor air quality measurements is required. Well-conceived designs and protocols form a crucial starting point for successful measurement programs.

Before summarizing the symposium and the papers included in this volume, definitions of the words *design* and *protocol* are in order. *Design* of a study or investigation relates to developing a general strategy or approach. This involves a specific statement of goals for the study and translation of these goals into measurement objectives. The measurement objectives, at minimum, need to specify measurement parameters and statistically justifiable sample size.

Protocol refers to specific procedures to be followed in conducting a study. To implement the design, detailed procedures need to be developed to guide sample selection, monitoring, quality assurance, and data analysis. The documentation of such procedural items forms a written protocol for the study.

The goals of the symposium were to provide information on designs and protocols used in different types of indoor air quality monitoring studies and to provide learning opportunities through shared experience. Three types of sessions were organized to meet these goals:

1. *Case Studies*—A limited number of studies were selected to provide an in-depth view of designs, protocols, and their relationships to study results. A 2-h session was devoted to each case study. The studies were chosen through a peer-review process.
2. *Technical Papers*—Papers representing state-of-the-art developments or offering valuable practical experience in areas related to indoor air quality monitoring were presented. Both solicited and unsolicited papers were included.
3. *Workshops*—Key areas related to design and protocol were selected for workshop sessions. Presentations on relevant topics were included in each workshop, but the emphasis in these workshop sessions was on sharing knowledge through questions and answers.

TABLE 1—*Distribution of papers in STP 1002.*

Session Type \ Technical Area	Commercial and Office Building Investigations	Residential Building Research	Instrumentation and Monitoring Methods
I. Case Studies	• Weschler et al. • Persily et al.	• Hawthorne et al. • Koontz and Nagda	
II. Technical Papers	• Seppänen and Jaakkola • Gorman and Wallingford • Woods et al. • Levin and Phillips • Allard	• Traynor • Harkov et al. • White	• Bayer and Black • Hodgson and Girman • Alevantis • Waters et al. • Fortmann et al.
III. Workshops	• Turner	• Kollander • Lebowitz	• Lewis and Wallace

Presentations covered three areas in the symposium: (1) indoor air quality investigations of commercial and office buildings, (2) residential buildings research, and (3) instrumentation and monitoring methods. The distribution of papers included in this volume is shown in Table 1 in terms of the relevant technical area and type of session.

Commercial and Office Buildings

Two case studies (Weschler et al. and Persily et al.) represent two almost opposite ends of the spectrum of research and investigative efforts involving large buildings. The paper presented by Weschler et al. focuses on the effects indoor environmental conditions have on telephone equipment. In order to assess these effects, the influence of ventilation, filtration, outdoor sources, and indoor sources on the composition of indoor air were measured in representative telephone office buildings. Persily et al. used a case study of a Washington, D.C. office building with a long history of complaints in which 20 unsuccessful investigations have been conducted to illustrate the complexity sick building studies can have. The prior investigations summarized by Persily et al. represent work done in a reactive mode to occupant complaints with limited opportunities for design. This situation sharply contrasts with the Weschler et al. study, where the design and protocols were developed prior to the initiation of monitoring. Both studies, however, offer valuable insights into how and how not to conduct monitoring in large buildings.

Seppänen and Jaakkola found, as did other investigators, that concentrations of contaminants in sick buildings are often well within generally acceptable limits but identified temperature as the best variable to explain occupant complaints. Gorman and Wallingford described the protocol the National Institute for Occupational Safety and Health (NIOSH) has developed from the numerous investigations conducted by that agency. Several specific steps, ranging from gathering background information over the telephone to closing conferences, were described. Woods et al. have described an alternative engineering-oriented approach, beginning with qualitative diagnostics and followed by quantitative diagnostics, as necessary. They emphasize that measured data may not be always needed but a clear understanding of the relationships between the building environment, support systems, and occupants is necessary for evaluation of indoor air quality problems. The complex nature of these relationships are well illustrated in investigations of energy-efficient office buildings described by Levin and Phillips. The paper by Allard confronts this complexity and focuses on how field investigators can help various parties involved in building investigations to better understand the subtle interactions and potential causes of indoor air quality problems.

In conducting building investigations, the first questions is: Why should data be collected? Then, if data collection is necessary, the following questions need to be addressed: What are the measurement parameters? When and where should sampling be done? How should the data be collected? What are the quality control and quality assurance aspects of such data collection? How should the data be interpreted?

The commercial and office buildings workshop, chaired by Turner, presented and discussed these questions with particular reference to evaluating the history of complaints, mechanical systems and their operations, air movement pathways, and contaminants and their sources. As part of the same workshop, two special presentations focused on data collection related to bioaerosols and building air exchange. Preassessment of buildings for microbial aerosols was emphasized by Burge. She also discussed special elements of design and sampling techniques. In discussing tracer gas techniques for studying building air exchange, Persily highlighted factors that are important in air exchange evaluation. Testing procedures that were covered include determination of sampling locations, estimation of effective volume, and measurement of airflows and percent recirculation.

Residential Buildings

Two case studies—one involving a field survey of 300 homes (Hawthorne et al.) and the other examining a pair of research houses (Koontz and Nagda)—were presented. The study conducted by Hawthorne et al. is a good example of a comprehensively designed indoor air quality field study. Eight groups of houses were selected based on presence or absence of cigarette smoking, wood stoves, and kerosene heating. Initial results relating to a large number of indoor contaminants such as respirable particles, radon, formaldehyde, polynuclear aromatic hydrocarbons, and airborne microorganisms were included.

In contrast, the Koontz and Nagda study is a good example of a controlled experimental study examining a limited number of contaminants but provided a basis for detailed evaluation of air infiltration, energy, and indoor air quality relationships. This study, conducted at two heavily instrumented research houses, involved continuous monitoring of a broad range of parameters: indoor and outdoor concentrations of radon, radon progeny, carbon monoxide, and nitrogen dioxide; infiltration rates measured by tracer gas decay; and various energy use parameters. A dual approach of statistical analysis and modeling was used in the analysis of data. In addition to providing the rationale for details of the experimental design, Koontz and Nagda provided a self-critique so that future investigations could benefit from this study.

The Traynor paper identifies key parameters that affect indoor air pollutant levels from combustion sources and suggests protocols for measuring these parameters. Indoor combustion sources and modeling were discussed in order to focus on key parameters such as air exchange rates, source usage, emission rates, source venting, and pollutant reactivity rates. Traynor provides specific guidance on techniques to measure these parameters and also discusses sample size considerations.

The Harkov et al. and White papers presented different aspects of indoor air quality assessments. The White paper focuses on analysis needs as they relate to extrapolating a set of measurements to predict short-term peaks and long-term average indoor air pollutant concentrations. Harkov et al. outline the basic design for a limited survey preceding a total human environmental exposure study of benzo(*a*)pyrene to be conducted in New Jersey. The paper described selection of a study area and selection of homes within the study area. Measurement methods to be used in the initial survey were also summarized.

In the workshop on design of survey studies, chaired by Kollander, he and his co-presentors Whitmore, Wallace, and Brenner emphasized the statistical aspects of design. The statistical protocol elements discussed included the development of survey objectives, data analysis plans, interviewing methods, and questionnaire construction. Sampling protocols, which define statistical procedures for identifying study respondents and determining the required numbers of such participants, were critically examined.

The development of questionnaires and survey instruments is an important aspect of both the design and measurement. This workshop chaired by Lebowitz discussed questionnaire development and administration beginning with identification of factors influencing indoor air quality. Questionnaires used in various field studies were examined in terms of the ability to explain variations in indoor pollutant concentrations. Lebowitz and his co-presentors Quackenboss, Soczek, Colome, and Lioy articulated specific aspects of questionnaire design and explored development of standard questionnaires for indoor air quality studies.

Instruments and Methods

Methods and instruments to measure levels of indoor air contaminants were critically reviewed in the workshop co-chaired by Lewis and Wallace. This review covered biological aerosols, carbon monoxide, nitrogen dioxide, respirable particles, formaldehyde, pesticides, polynuclear aromatic hydrocarbons, volatile organic chemicals (VOCs), and radon. Methods were examined from the perspectives of operating principles, field experience, and needs for further development.

Bayer and Black examined the feasibility of using a laboratory system comprising an environmental chamber coupled with capillary gas chromatography to quantify VOC emissions. Reproducibility of the results was excellent. For measurement of VOCs in building investigations, Hodgson and Girman describe the application of multisorbent sampling techniques. This method was evaluated in a laboratory setting and under field conditions. A doubling of VOC emissions with a six-fold increase in ventilation rates was noted.

The final three papers present methods for measurements of air exchange rates and interzonal airflows. The paper by Alevantis describes a computer-controlled system for measuring air exchange rates in large buildings. The system used well-established tracer gas decay methods to monitor ventilation rates in up to sixteen different locations, and incorporates automatic self-calibration. Waters et al. also describe a computer-controlled tracer gas monitoring system designed for larger single-cell structures such as sports arenas and industrial buildings. The impracticality of obtaining uniform mixing of a tracer gas in such environments was recognized by the authors and was addressed in the design of their measurement system.

Airflows between different zones of a dwelling can vary substantially over time. The paper by Fortmann et al. describes a method employing constant injection of multiple tracer gases along with a continuous measurement system to measure time-related details of interzonal flows.

Conclusion

The presentations at the symposium addressed a variety of monitoring situations and offered attractive strategies for design along with practical details for protocols. The information cummunicated through presentations was further supplemented by questions and answers. On a procedural note, the three different types of sessions provided a balanced framework for exchange of ideas and information, and the audience reaction was favorable.

It is hoped that these papers not only convey important aspects of various design and protocol issues but also serve as catalysts for continual improvement in the state of the art of monitoring indoor air quality.

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Commercial and Office Buildings

C. J. Weschler,[1] *H. C. Shields,*[1] *S. P. Kelty,*[1] *L. A. Psota-Kelty,*[2] *and J. D. Sinclair*[2]

Comparison of Effects of Ventilation, Filtration, and Outdoor Air on Indoor Air at Telephone Office Buildings: A Case Study

REFERENCE: Weschler, C. J., Shields, H. C., Kelty, S. P., Psota-Kelty, L. A., and Sinclair, J. D., **"Comparison of Effects of Ventilation, Filtration, and Outdoor Air on Indoor Air at Telephone Office Buildings: A Case Study,"** *Design and Protocol for Monitoring Indoor Air Quality, ASTM STP 1002,* N. L. Nagda and J. P. Harper, Eds., American Society for Testing and Materials, Philadelphia, 1989, pp. 9–34.

ABSTRACT: Environmental contaminants can cause failures in telephone switching systems, computers, and other sophisticated electronic equipment. Unfortunately, energy conservation measures frequently increase the indoor concentrations of such contaminants. For almost six years we have been conducting detailed air sampling programs at telephone offices across the United States. This paper outlines the design and procedures used to monitor indoor air quality at these sites. The goal has been to assess the effects of ventilation, filtration, outdoor sources, and indoor sources on the composition of indoor air at representative telephone office buildings. These studies provide direction so that energy conservation measures can be implemented in such a way as to minimize resulting environmentally related failures, and, thereby, the labor and parts needed to correct such failures.

KEY WORDS: aerosols, airborne particles, calcium, coarse particles, deposition velocity, energy conservation, filtration, fine particles, HVAC, indoor air, inorganic gases, ionic compounds, mass balance model, particulate organics, sulfate, trace elements, volatile organic compounds

Objectives and Design

Origin of Study

Starting in the middle 1970s, the rising costs of fuel and electricity provided strong economic incentives for the pre-divestiture Bell System to reduce its energy usage. This usage had reached 8.4×10^{13} Btu/yr by 1980. Thirty-eight percent of the total energy consumed was used to control the environment within telephone buildings. The remaining energy use was distributed among motor vehicles (25%), manufacturing/recycling (19%), and telephone power (18%).

By the end of 1981, a building energy conservation program had been implemented in about 40% of the Bell System's 16 000 telephone office buildings across the United States. Under this program a building was not heated if the indoor temperature was above 18°C (65°F) or cooled if below 27°C (80°F). The building fans were operated only when necessary to bring the temperature within allowable limits, rather than continuously. Compared with

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energy usage when the temperature was maintained between 21 and 24°C (70 and 75°F), usage decreased approximately 30% under this program. For the installations where the energy conservation measures had been implemented, this translated to a total annual energy cost savings of about 38 million dollars, based on 1981 energy costs [*1*]. However, there was concern that this program might lead to increased infiltration of outdoor dust, since the buildings had no positive pressurization when the air-handling fans were not operating.

Goal of Study

The initial goal of this study was to assess the effect of building fan operation on the infiltration of fine and coarse particles at several representative telephone office buildings. As the study evolved (see below), so also did the objectives. It became evident that energy conservation measures affect not just the concentration of airborne particles but also their size-distribution and chemical composition. These measures also affect the composition of vapor phase species, both organic and inorganic. It was recognized that deterioration in indoor air quality could prove costly in terms of extra monitoring and maintenance of both switching and computing equipment. Money saved on energy might be lost to increased costs associated with diagnosing and repairing failures in the sensitive electronic equipment housed within these buildings. Current hardware trends in switching and computing have rendered selected components even more susceptible to environmental contaminants [*2,3*], especially connectors and disk drives. Hence the study began to address broader questions:

1. How can heating, ventilating, and air conditioning (HVAC) costs be reduced and at the same time minimize deterioration of indoor air quality?
2. At what point in the implementation of energy conservation programs is the sum of energy costs and maintenance costs a minimum?
3. Can we develop a model that permits us to predict the resulting composition of indoor air when various HVAC parameters are changed?

The current goal of this study is to assess the effects of ventilation, filtration, outdoor sources, and indoor sources on the composition of indoor air at representative telephone office buildings. This study provides direction so that energy conservation measures can be implemented in such a way as to minimize consequent environmentally related failures and the labor as well as replacement parts needed to correct such failures.

Study Design

Duration of Sampling at a Given Site—Because of equipment and personnel limitations, we chose to conduct detailed sampling at a small number of typical telephone office buildings representative of different locations or HVAC systems. At each building the sampling was conducted for a sufficient period of time to establish confidence in the correlations obtained.

To date, the study has been conducted at four sampling locations: Wichita, Kansas; Lubbock, Texas; Newark, New Jersey; and Neenah, Wisconsin. The initial sampling at Wichita and Lubbock concentrated on the effect of building fan operation on the concentration of indoor airborne particles. It was decided to operate for two-week intervals in two different modes: fans on or fans off. Two-week intervals ensured that the time required to achieve steady-state concentrations of airborne particles would be small compared to the total time in a given mode. At both the Wichita and Lubbock sites sampling was planned for a minimum of three complete cycles (one cycle = 2 weeks fans on + 2 weeks fans off).

Sampling would have been extended if, at this point, there was no significant difference between the data sets. At neither site was an extension necessary.

At Newark, it was not possible to operate the building fans on a cycle similar to what had been done at Wichita and Lubbock. Their operation was controlled by the building thermostats. To establish correlations between fan operation (and other HVAC parameters) and the composition of the indoor air, a much longer sampling period was required. Consequently, the sampling was conducted for 60 weeks. This provided some data sets with only a few hours of fan operation and other data sets with almost continuous fan operation—an aid in analyzing the data. However, the majority of the sets lay between these extremes.

The study at Neenah has been ongoing for more than a year. The HVAC parameters vary in response to indoor and outdoor sensors (see below). In future monitoring, for selected one week intervals these sensors will be overridden, providing periods of extreme HVAC operation and facilitating the calculation of selected parameters in a mass-balance model.

Preparation and Weighing of Filters—The dichotomous samplers use 37 mm Teflon membrane filters. Accurate weighing of these filters, before and after sample collection, has been a cornerstone to the successful implementation of this sampling program. Since a fraction of the samples are analyzed for organic compounds and another fraction for water soluble ionic species, the virgin filters are washed before sampling to reduce the background level of these compounds in filter blanks. This is accomplished through six successive ultrasonic washes (30 min each), first in methanol, then water, then methanol, etc. The washed filters are equilibrated at an ambient equivalent to that of the weighing room for a minimum of three days before the pre-sampling weighings. The weighings are made on a six place Mettler microbalance contained in a dedicated weighing room. The room (1.2 by 1.5 by 3.3 m) is kept at controlled temperature and relative humidity; lights within the room are on continuously to minimize temperature fluctuations. The balance itself sits on a marble weighing table. To reduce electrostatic problems during the weighing process, the room contains a negative-ion generator; the operator wears a grounding strap connected to the building's copper plumbing; and a polonium source sits ~3 cm from the balance pan. All weighings of both virgin and loaded filters are repeated three to five times, and means calculated. The resulting standard deviation generally lies between 2 to 5 μg. Since the net weight on certain loaded indoor filters can be less than 100 μg, the need for such weighing precautions is obvious.

Surface Sampling—Part of this progam involved the sampling of vertical and horizontal equipment surfaces for accumulated water soluble anions and cations so that deposition velocities could be calculated. The surfaces sampled were zinc and aluminum structural pieces associated with the electronic equipment frames. These surfaces were undisturbed over the lifetime of the equipment at these locations. The determined accumulation rates are average annual accumulations based on exposures on the order of ten years. Details and validation of the procedure are given elsewhere [*4*]. In brief, surface extractions were accomplished with pieces of pre-cut Whatman 542 filter paper wet with deionized water. The moistened papers were placed on flat surfaces in either a horizontal or a vertical plane and were removed from the surfaces after drying (drying time varied with ambient humidity). This procedure was repeated three times on each sampled area to ensure complete removal of water-soluble contaminants. One hundred twenty surface samples were collected at both the Wichita and Lubbock locations. There was a large scatter in deposition velocities calculated from the analyses of these samples, especially for ions in the fine particle fraction. The amount of data collected at these initial sites was insufficient to determine if the scatter was of experimental origin or was an indication of real differences among the various ions.