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16. ABSTRACT The report gives results of a literature review, conducted to survey and summarize recent and ongoing engineering research into building ventilation, air exchange rate, pollutant distribution and dispersion, and other effects of heating, ventilation, and air-conditioning (HVAC) systems on indoor air quality (IAQ). The concerns of the ventilation community and technical questions that remain to be solved were identified, as were a number of research opportunities. The ventilation-related engineering literature was divided into seven major categories: (1) pollutant transport to and into the building envelope; (2) air cleaning systems; (3) flow and pollutant dispersion; (4) room and building flow/dispersion research; (5) HVAC/building design, operation, and control strategies; (6) applied microbial research; and (7) building performance. The significance and status of ventilation-related IAQ research was summarized by research category, and research opportunities were identified within each category.

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ABSTRACT

Building ventilation and air conditioning systems have traditionally been designed and controlled to maintain occupant thermal comfort at acceptable capital and operating costs, an indoor air quality (IAQ) has not been a primary concern. Poor ventilation has contributed to many IAQ problems. A literature review was conducted to survey and summarize recent and on-going engineering research into building ventilation, air exchange rate, pollutant distribution and dispersion, and other effects of heating, ventilation, and air conditioning (HVAC) systems on IAQ. The concerns of the ventilation community and technical questions that remain to be solved were identified, as were a number of research opportunities.

The ventilation-related engineering literature was divided into seven major categories: 1) pollutant transport to and into the building envelope; 2) air cleaning systems; 3) flow and pollutant dispersion, 4) room and building flow/dispersion research; 5) HVAC/ building design, operation, and control strategies; 6) applied microbial research; and 7) building performance.

The significance and status of ventilation-related IAQ research was summarized by research category, and research opportunities were identified within each category.

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1.0 INTRODUCTION

Building ventilation and air conditioning systems have traditionally been designed and operated to maintain occupant thermal comfort at acceptable capital and operating costs. Indoor air quality (IAQ) has not been a primary concern, and some of the heating, ventilation, and air conditioning (HVAC) strategies developed to reduce energy costs have been found to adversely affect IAQ. The contribution of poor ventilation to many IAQ problems was recognized by the implementation of ASHRAE Standard 62-1989, *Ventilation for Acceptable Indoor Air Quality* (ASHRAE, 1989a), which emphasizes the importance of building ventilation for IAQ improvement and control. This standard is having a profound impact as the building industry attempts to cope with the often (apparently) competing imperatives of high energy efficiency and good IAQ. In this light, the possibilities, capabilities, and limitations of ventilation as a means to improve IAQ have become increasingly important.

The objective of this literature review was to survey and summarize recent and ongoing research into building ventilation, air exchange rate, pollutant distribution and dispersion, and other effects of HVAC systems on indoor air quality. In keeping with this objective, recent literature is emphasized. From this literature, the concerns of the ventilation community and technical questions that remain to be solved were identified and a number of opportunities for ventilation-related engineering research were generated.

Three general types of IAQ research are under way:

- Basic laboratory investigations into the characteristics of sources and processes that influence IAQ
- Applied engineering research into transport, dispersion, control devices, control strategies, and costs
- Surveys and evaluation of the energy/economic impact of IAQ and communication of research results to the users.

The ventilation research encompassed by the scope of this review largely falls in the second category. This broad category of IAQ applied engineering research was further subdivided into a number of research areas that form the framework of this review. Table 1 expands these three categories into the outline of this review. The first three topics are the laboratory work, the shaded topics are the IAQ engineering research topics that are the subject of this review, and the final topics are the survey and communication work.

Table 1. Indoor Air Research Topics

Laboratory Investigations
- Single Source/Sink Experimental Studies
- Multiple Source/Sink Experimental Studies
- Basic Biological Growth Studies

Applied Engineering Research

Pollutant Transport to and into the Building Envelope (Section 4.0)
- From source to envelope boundary (dispersion/wind transport)
- Entry into the envelope (HVAC, infiltration, doors/windows)

Air Cleaning Systems (Section 5.0)
- In-duct air cleaners
- In-room air cleaners
- Radon control by particle control

Room Airflow and Pollutant Dispersion (Section 6.0)
- Fundamental source/sink transport
- Jet and diffuser flow

Room and Building Flow/ Dispersion Research (Section 7.0)
- Single rooms and micromodels
- Multizone buildings and macromodels
- Schools, hospitals, and other special buildings

HVAC/Building Design, Operation, and Control Strategies (Section 8.0)
- HVAC system design and selection
- Innovative ventilation delivery designs
  - — Ventilated Work Stations
  - — Personally-Controlled Ventilation
  - — Displacement Ventilation
  - — Demand-Controlled Ventilation
  - — Energy Recovery Systems

Applied Microbial Research (Section 9.0)

Building Performance (Section 10.0)

Energy/Economics of IAQ
- Energy/dollar cost of getting good IAQ.
- Health effects/results of good and bad IAQ
- Productivity and other economic gains from good IAQ.
- Productivity and other economic losses from bad IAQ.
- Relationship between IAQ quality measure and productivity.

Translation to/Communication of Engineering Design Guidelines from Research

Note: Ventilation-related topics are shaded. Numbers correspond to report sections.

Literature concerned with each ventilation-related IAQ engineering area was then examined to identify major accomplishments, current status, trends, and research opportunities. The numbers in Table 1 refer to the relevant sections of this review. Section 2.0 summarizes the significant findings of this review, as detailed in Sections 4.0 through 10.0. The research opportunities identified through this review are summarized in Section 3.0.

The primary sources for the review were the IAQ literature in the form of IAQ technical meeting proceedings and published articles (Section 11.0). The annual Indoor Air Quality Conferences sponsored by ASHRAE (IAQ XX series) were particularly helpful. Also reviewed were the IAQ-related research programs of several organizations (see Appendix A, B, and C). IAQ research is international in scope, and the proceedings from international meetings were included when English translations were readily available. Similar research reported in other technical literature (the building energy literature, for example) was reviewed to fill particular needs but overall is underrepresented. This approach allowed efficient recovery of the most pertinent information. The review is drawn primarily from literature published through 1992.

2.0 SUMMARY

The significance and status of ventilation-related IAQ research is summarized in this section by research category.

Pollutant Transport

The importance of pollutant transport through the building envelope is not known. Water vapor transport through the envelope can cause microbiological problems if condensation occurs. The extent to which cross-envelope transport of contaminants affects indoor pollutant levels is seldom studied, though problems with engine exhaust and kitchen fumes are known to occur when the envelope is breached in some way. The research that has been done was primarily directed at energy conservation, and transport through the envelope as a cause of poor IAQ has not been an active research topic.

Air Cleaner Research

The common tests of particle air cleaners do not provide enough information for HVAC system designers to incorporate filters into the system rationally. No standard tests are available for gas-phase contaminant air cleaners. Research to address the test method deficiency is under way, and a body of test results must be gathered to support design.

Diffuser Research

In conventional all-air HVAC systems, improved diffusers may be a relatively inexpensive and accessible way to improve ventilation effectiveness (VE). Both experimental and modeling work are ongoing. A current focus of diffuser modeling is the design of equipment suitable for cold air ventilation systems, the importance of which is apparently increasing.

Single Room Flow and Dispersion

The movement of air and pollutants within a room or confined space is an active research area. Computational fluid dynamics modeling efforts are the most common approach. This research examines the 3-dimensional flow field in detail and is computationally intensive. A 2-dimensional model is being developed for personal computer use. Little has been done to validate any of the models.

Building HVAC Flow and Dispersion

Current measurement and analysis techniques for building HVAC flow and dispersion are expensive and difficult to relate to IAQ in most cases. Simple tracer decay measurements apply only to a small segment of time, and the long-term, multitracer studies needed to characterize a large building are difficult and time-consuming. The many different measures of ventilation adequacy within a space confuse the analysis.

Several models of building HVAC flow and dispersion have been developed. Most are computationally intensive. None of the models has been validated experimentally. In their current state, they are research tools and are unlikely to be directly useful to HVAC designers.

HVAC/Building Design, Operation, and Control

Capital cost constraints and system operating costs, particularly energy costs, are generally dominant forces in design and operation of HVAC systems. IAQ must become an important part of the design process. ASHRAE 62-1989 has at least partially accomplished that goal. To date a general study of HVAC applications and their potential effects on IAQ has not been carried out, though many of the components of such a study are known.

A number of innovative ventilation schemes are being developed, primarily in Europe and Japan. They have the potential to improve the efficiency with which ventilation air is delivered to occupants. At the current level of knowledge, however, they are essentially experimental in the United States. Sensor technology is also advancing, and improved sensors are becoming available and are being incorporated in conventional and innovative HVAC systems. Economic and performance claims are being made by developers and enthusiasts, but hard data are rare.

Applied Biocontaminant Research

Biocontaminants are known to be important causes of poor building IAQ. The general principles for their control are to reduce the nutrient loading in HVAC ducts and to reduce moisture in general and prevent condensation of water in particular. The best ways to apply these principles to HVAC design, construction, and use need to be developed.

Building Performance

Because acceptable building IAQ is not defined by physical measurements, evaluation is often qualitative. Building performance evaluation and ventilation research intersect primarily in the need for those evaluating the building to understand the building's ventilation system and to make accurate and appropriate measurements of air exchange rate, ventilation effectiveness, interzonal transfers, and similar measures.

3.0 RESEARCH RECOMMENDATIONS

Pollutant Transport

A potential research topic within the pollutant transport category appears to be the possible impact of envelope infiltration on IAQ. That is, infiltrating air may become contaminated either by building materials or materials of microbiological origin, and little research has been undertaken in this area. Infiltration is related to infiltration through the pressure distribution maintained in the building by the HVAC system. A second ventilation research topic is the effect of wind pressure fields on building ventilation in general and outdoor air exchange rates in particular.

Air Cleaner Research

The performance of air cleaners must be evaluated with tests that provide HVAC system designers the information they need to specify the air cleaners and reliably predict their performance. To this end, standard air cleaner test methods (for both particle and gas- phase contaminants) must be developed.

Diffuser Research

Development of improved models of diffuser flow (particularly for cold-air ventilation systems) and the impact of diffuser design on ventilation effectiveness would be a useful goal for a ventilation research program. Linkage of diffuser and room design data and modeling through CAD-like computer programs is a long-term goal for diffuser research.

Single Room Flow and Dispersion

The primary knowledge gap appears to be experimental measurements that can be used to evaluate the many available models. Once data are available, the required model complexity for various purposes can be evaluated and the performance tradeoffs examined.

Building HVAC Flow and Dispersion

The most pressing need overall appears to be improved measurement techniques, including the development of standardized methods. Development of such methods would encourage their use, ensure a supply of consistent data for model development, and hopefully increase the overall amount of performance data available. These data could then be used to validate and improve the computer models.

HVAC/Building Design, Operation, and Control

For this research area, the most immediate need appears to be gathering and organizing what we know about designing buildings and choosing HVAC systems to ensure good IAQ. This information must then be communicated to the building industry. A reasonable approach would be to determine, through a cost and energy modeling effort, the best energy/cost/IAQ design for HVAC systems to be used in different building types, in different environments, and as a function of usage.

A systematic investigation of the performance, costs, and benefits (including energy impact) of the innovative ventilation schemes would allow designers to make early use of these technologies if they are worthy. In addition, over the long run, the proper use of improved sensor technology will be very important.

Applied Biocontaminant Research

Research into two aspects of biocontamination interacts with ventilation research. HVAC maintenance practices need to be strengthened, possibly through education or maintainability standards. Second, basic research into the conditions and materials that affect microbial growth in HVAC systems is needed to evaluate design and construction practices.

Building Performance

As with the air distribution category, the primary research needs for building performance evaluation research are improved sensors, measurement techniques, and a standardized protocol. At the same time, models must be available and easy to use so the data can be interpreted. Therefore, flexible, easily used IAQ models should be developed. PC-based models would be preferable, though fast models accessible through a modem might be acceptable if their performance was superior.

4.0 POLLUTANT TRANSPORT TO AND INTO THE BUILDING ENVELOPE

Although many indoor pollutants originate indoors, some are transported into a building through infiltration, natural ventilation, or the HVAC system. Engine exhaust, stack emissions, and ambient SO_2, NO_x, ozone, and pollens are examples of outdoor pollutants that can cause problems indoors. The dispersion of any pollutant from its source to a building and then through the envelope and into the building may be an issue in an investigation of a problem building. The transport of outdoor air pollutants into a building is the subject of this section.

4.1 OUTDOOR POLLUTANT DISPERSION AND WIND TRANSPORT

The dispersion of pollutants outdoors from stationary sources and spills has been extensively studied and modeled. Outdoor dispersion is related to IAQ primarily through the effect of wind on building pressurization and consequent infiltration. The air flow around buildings has been investigated in the course of studying structural wind loads and infiltration. A source of basic information is "Air Flow Around Buildings," Chapter 14 in the ASHRAE Handbook (ASHRAE, 1989b). For the purpose of this review, the pertinent aspects of this topic are the effects of the wind field on ventilation in a building.

The effect of wind field on building ventilation is an active research subject. Wind fields can be very complex in complicated terrain or for architecturally complicated buildings. In general, the upwind side of a building develops a positive pressure and the downstream side a negative pressure. This wind pressure field interacts with the HVAC system pressure balance to cause infiltration. Wind effect appears to be a relatively well-understood variable in building models, with measurements of outside pressure generally being considered adequate for modeling purposes. Mounajed et al. (1990) described recent research into the effects of wind turbulence on ventilation. Wind is always turbulent, so the impinging flow changes in velocity and direction with variable frequency. Their model and experiment indicate that assuming a steady wind pressure (a common simplifying assumption is a constant wind at the mean wind speed and direction) in a building ventilation model is a poor assumption that can lead to substantial errors in the models. A second indication of current research interest is "Assessment of the Effects of Wind Turbulence on Natural Ventilation Air Change Rates," a research project proposed by ASHRAE Technical Committee 2.5 for funding in the 1992-1993 ASHRAE Research Plan (ASHRAE, 1992).

4.2 ENTRY INTO THE ENVELOPE (HVAC, INFILTRATION, DOORS/WINDOWS)

When poor quality outside air is delivered to all or portions of a building envelope, IAQ problems may develop if this air enters the building through infiltration, natural ventilation, and/or the HVAC makeup air systems. (Overall measurement of infiltration and air exchange rate is addressed in Section 6.0.) Within this context, the principal research areas are the following:

- Radon infiltration through slab or floor penetrations
- Entry of polluted outdoor air through the HVAC system
- Outdoor air leaks through the building envelope.

4.2.1 Radon Infiltration

Radon infiltration continues to be studied extensively. Infiltration from beneath a slab is the most common entry route, though in some circumstances the outdoor air around a building contains enough radon to be of concern. The major IAQ research programs are sponsored by the Environmental Protection Agency (EPA) and the Florida Radon Research Program (FRRP) and directed at radon. The following are recent research projects (FRRP, 1992):

- **FRRP New House Evaluations**
  — **Pressure Differential and Infiltration**. Measured pressure differences across slabs, identified causes, and observed impact of pressure differentials caused by mechanical systems.

  — **Radon-Resistant Construction Techniques**. Two programs in different parts of Florida that evaluated new slab construction criteria and sub-slab construction techniques.

- **FRRP Research Houses**
  — **Polk County Research Houses**. Work includes study of the effects of different fill soils on the radon concentrations within movable "houses." Has validated the effectiveness of "barrier" construction features.

  — **University of Florida (UF) House Dynamics and Modeling**. Recent work includes study of centralized versus ducted return, house pressure control using fans added to HVAC system, and tracer gas studies. Future work includes continued evaluation of balanced versus unbalanced HVAC for radon control, installation of air-to-air heat exchanger, and modeling using Florida Solar Energy Center (FSEC) Model 3.0 (Hintenlang, 1992).

  — **FAMU/FSU Crawlspace House and Modeling**. House has been constructed and research is just starting. Work planned includes investigation of radon entry mechanisms and possible control techniques and development of mathematical models.

- **FRRP Large-Scale Building Program**
  - **Assessment Studies**. One completed project assessed school construction practice sub-slab depressurization in schools. A second completed project assessed the scope of radon problems in large Florida buildings, identified radon entry mechanisms, and identified testing methods.
  - **EPA/FRRP Large Building Study**. Study of Deerfield Beach building to determine variables important in radon entry and relationships between the variables, develop mitigation techniques, and produce a guidance document. Additional buildings will be added to the study.
  - **EPA/FRRP Development and Demonstration of School Mitigation Techniques**. Identification of difficult-to-mitigate schools and performance of field diagnostics. Active slab depressurization (ASD) to be conducted at new school in Alachua County, FL.

Other FRRP research less directly related to ventilation includes the following:

- **FRRP Improved Floor Barriers**. Several research programs investigating various aspects of radon penetration of floor materials are under way. Included in this category is a study of floor cracks in slabs.
- **FRRP Mapping**. Work to map Florida with respect to the potential for radon problems in buildings is in progress.

Current EPA emphasis is on research to understand the radon infiltration process, low radon level mitigation techniques, and studies of radon in schools (EPA Radon Research Branch Research Plan).

The DOE radon infiltration program appears to be currently focused on participation in the modeling for other studies such as the Florida Radon Research Program (FRRP, 1992).

4.2.2 Miscellaneous Building Envelope Infiltration

The myriad smaller leaks into a building envelope through walls, windows, doors, roof, etc., have been widely studied, primarily to determine how to reduce energy losses. In most of the country, such leaks are sources of increased outside air ventilation and not causes of reduced indoor air quality. Only in the locations with generally poor outdoor air quality or strong local air pollution sources will infiltration lead to reduced indoor air quality. In addition, a properly balanced building HVAC system should keep the building at a slight positive pressure and prevent infiltration except in a strong wind field.

A great deal of research has been done, supported by a number of industry groups (construction industry, door and window manufacturers, ASHRAE, ANSI, etc.) as well as by public funding, including the Department of Energy (DOE). Design tools incorporating the results of this research are given in the ASHRAE Fundamentals Handbook (ASHRAE, 1989c). An active ASHRAE project is 763-WS, "Impacts of High-Use Automatic Doors on Infiltration" (ASHRAE, 1992).

Because the impacts of infiltration on indoor air quality are generally localized, often related to poor design or construction, and difficult to generalize, little emphasis has been placed on this topic in this review. The problems are better treated with on-site examinations by capable professionals rather than by a research program.

4.2.3 Entry Through HVAC System

Polluted air entry through the HVAC system is frequently caused by improperly positioned outdoor air intakes. References to misplaced intakes are common (Morey, 1988), as are appeals for the use of common sense in their placement. No systematic, ongoing research program was identified, although Technical Committee 2.5 of ASHRAE proposed a project titled "Urban Pollution Design Criteria for Building Ventilation Inlets and Exhausts" to ASHRAE, and the proposal was given second priority. Additionally, wind tunnel studies of physical models of existing or proposed buildings, including flows near vent stacks, have been reported. Current guidelines for design are given in the Fundamentals Volume of the ASHRAE Handbook (ASHRAE, 1989c).

Leakage in HVAC duct systems is another known infiltration route. The ASHRAE-sponsored project 308, "Investigation of Duct Leakage," was completed in 1985. Active projects ASHRAE is sponsoring include 438-RP/A, "Measurement and Rating of Air Leakage in Building Components"; 641-RP, "Duct Design using the T-Method with Duct Leakage Incorporated"; 764-WS, "Impacts of Leaks in Residential Air Distribution Systems on Energy Consumption (ASHRAE, 1992).

Outdoor air contaminant levels exceeding the National Ambient Air Quality Standards has led to the requirement (ASHRAE 62-1989) for cleaning outdoor ventilation air even when the outlet is properly positioned. Ongoing research regarding air cleaners is discussed in Section 5.0.

4.3 SUMMARY OF RESEARCH

Wind pressure effects and infiltration are the subjects of active research programs. Pollutant infiltration through the building envelope does interact with the building ventilation system, with a resultant impact on IAQ. The EPA/FRRP program appears to be covering the major radon infiltration and transport research needs. Well-integrated experimental and modeling programs are under way and producing results. The emphasis to date has been on residential construction; however, schools and larger buildings are also being included. The relationship between multistory building pressurization and radon infiltration is not clear.

Building envelope infiltration is important to energy conservation and potentially important to IAQ. Infiltration through individual components can be measured, but the performance of the components as a unit remains a question. Test measurements for local conditions and individual components (doors, windows, wall systems, etc.) must be related to whole building performance over an entire year with real, dynamic weather and use. Leaks in HVAC ducting are also important to the overall impact of infiltration. The difference between as-designed and as-built confounds all the experimental results in this research area. Overall, we know a lot about the individual pieces of the infiltration puzzle, but not enough about how to put them together in an easily understood, generally useful way. This is essentially a modeling requirement, and a flexible model that could be used in an interactive way is a general need in the IAQ field.

5.0 AIR CLEANING SYSTEMS

In traditional HVAC design, the primary purpose of air cleaning systems was to protect the equipment downstream. Increased ventilation rates were used to improve IAQ; air cleaning for IAQ improvement was not common. Under ASHRAE 62-1989, recirculating cleaned air is an acceptable way to increase the ventilation rate within a space (ASHRAE, 1989a). Air cleaners may be desirable either because the outdoor air quality is poor and increased outdoor air does not provide IAQ improvement, or to reduce the energy costs of high outdoor air exchange rates. For these reasons particle filtration to improve IAQ is becoming more common. Gas-phase air contaminant control for IAQ improvement remains uncommon, but may increase in use under the impetus provided by ASHRAE 62-1989.

Within the vague limits of current test methods, the design and construction of air cleaners are adequate. Testing is the current weakness. The existing standard particle air cleaner tests do not measure size-dependent efficiency, relying instead on overall mass removal efficiency of a synthetic test dust or discoloration of a test filter by atmospheric aerosol (ASHRAE, 1976). Particle size measurements are not made, and the results of the test do not provide HVAC engineers with enough information to design an air cleaning system. Currently, no standard test method for gas-phase air cleaners for IAQ improvement exists, the performance of the devices is not well known, and thus no systematic design procedure is available.

Neither gas-phase nor particle contaminant air cleaners in recirculating HVAC systems need high efficiency to significantly reduce the concentration of air contaminants. The high (compared to the outdoor air rate) recirculation rates used in building HVAC systems for comfort can move enough air through moderate efficiency air cleaners to have the same IAQ impact of moving a smaller volume through high-efficiency air cleaners. Efficiencies of 40 to 60 percent can be shown to have sufficient impact to bring a building into compliance with the ASHRAE 62-1989 ventilation rate standards (Yu and Raber, 1990).

5.1 IN-DUCT AIR CLEANERS

A new test method for particle removal air cleaners designed to provide engineers with more performance information than can be provided by ASHRAE 52-76 is in the early stages of development by ASHRAE (ASHRAE 671-RP). ASHRAE (through Technical Committee 2.3) is also working with gas-phase air cleaners, for which no standard test method exists. Current public research into in-duct air cleaners is largely being supported by ASHRAE and by EPA. ASHRAE has the following active research programs, which focus on full-scale in-duct air cleaners:

- 475-RP/A, Investigation of Co-sorption of Gases and Vapors in Sorption Dehumidification Equipment.

- 625-RP/A, Matching Filtration to Health Requirements. The work is under way at the University of Minnesota. The literature search is complete and the experimental work is under way.

- 675-RP/A, Determination of Air Filter Performance Under Variable Air Volume (VAV) Conditions. The research is being conducted at Air Filter Testing Lab. The literature review is complete and experimental work is under way.

- 671-RP/A, Define a Fractional Efficiency Test Method That is Compatible with Particulate Removal Air Cleaners Used in General Ventilation. The work is under way at RTI. The literature search has been completed and recommended test methods are now being evaluated.

- 674-RP/A, Evaluation of Test Methods for Determining the Effectiveness and Capacity of Gas-Phase Air Filtration Equipment for Indoor Air Applications - Literature Review. Completed at RTI.

- 760-TRP, Investigate and Identify Indoor Allergens and Biological Toxins That Can Be Removed by Filtration. Recently awarded to RTI.

EPA's Air and Energy Engineering Research Laboratory (AEERL) is supporting tests of particle and gas-phase air cleaners at RTI through cooperative agreement number CR-817083. Currently active tasks are the following:

- Small-scale Test of Gas-phase Air Cleaners
- Particle Air Cleaner Testing
- Specification and Construction of VOC Air Cleaner Test Apparatus
- Specification and Construction of 3,000 cfm Aerosol Test Rig.

The Canadian Electric Association is supporting development of a test method for electrostatic particle air cleaners at RTI. This program is under way.

The U.S. Army, through the Chemical Research, Development, and Engineering Laboratory, has supported a number of air cleaner tests over the past decade. Although the research is directed toward chemical defense, the technology is much the same as for commercial use.

The National Institute for Standards and Technology (NIST) has developed a recommended "Standard Laboratory Practice for Assessing the Performance of Sorption Gas-Phase Air Cleaning Equipment" (Silberstein, 1991). Despite the title, this is a test of sorption media, not full-size air cleaners. It utilizes a 2-in.-diameter by 1-in.-deep test canister designed for testing radioactive gas control carbon media (ASTM, 1990).

Research topics identified by ASHRAE in their research plan though not currently funded are the following:

- Investigate and Identify Means of Controlling Virus in Indoor Air by Filtration or Ventilation. Proposed by Technical Committee 2.4 but given low priority by ASHRAE.
- Identification of Particle Contaminants That Are Air-Borne Upstream of Air Cleaning Filters. Proposed by Technical Committee 2.4 but given no priority by ASHRAE.
- Investigate and Identify Radon Decay Products and Particle Interactions That Exist Indoors and Can Be Removed by Ventilation Filtration or Source Control. Proposed by Technical Committee 2.4 but given no priority by ASHRAE.

Offermann et al. (1991) recently reported an investigation into the effectiveness of in-duct particle removal devices. Six different air cleaners were installed in a residential test house HVAC system and their performance with respect to 0.01- to 3-μm particles evaluated. Some ducted air cleaners were found to significantly reduce the levels of indoor particles, though some performed poorly. This work was conducted at Lawrence Berkeley Laboratory (LBL) and supported by DOE, EPA, and the Bonneville Power Administration (BPA). Hedge et al. (1991) report an investigation into the effects of breathing zone filtration on IAQ.

5.2 IN-ROOM AIR CLEANERS

Control of a pollutant close to its source to prevent contamination of the ventilation systems has been shown (Owen et al., 1990) to be advantageous compared to centralized air cleaners. In-room air cleaners are being marketed widely for this purpose, but their individual efficiency, suitability for various tasks, best location in a room, limits on use, overall capacity, and similar operational details are not well understood. As with the in-duct air cleaners, test methods are inadequate. The Association of Home Appliance Manufacturers (AHAM) has a room air cleaner test procedure for particle removal (AHAM, 1987). The AHAM test chamber, which is a completely mixed room-sized environmental chamber, is charged with a test aerosol at the beginning of the test. The initial concentration is measured, then the air cleaner is turned on and the decay rate of particle concentration in the chamber is measured. The initial removal efficiency for the air cleaner can then be estimated by applying the theory of perfectly mixed reactor vessels.

Conducting the AHAM test in a completely mixed room avoids one of the principal shortcomings of room air cleaners—they can only clean the air that passes through them. In some cases, they have been found to largely recycle air from discharge to suction over and over again. Their usefulness for control of indoor allergens has been vigorously questioned (Nelson et al., 1988). Offermann et al. (1985) report an evaluation of portable air cleaners for control of respirable particles indoors in a test chamber.

No approved protocol exists for testing in-room gas-phase air cleaners, though Daisey and Hodgson (1989) used an AHAM-like procedure to test nitrogen dioxide and volatile organic compound (VOC) removal by room air cleaners. An AHAM-type test should be more suitable for gases than for particles for the measurement of efficiency, but the real-world performance questions remain. The current test procedure measures initial efficiency only and gives the user no idea of how long the air cleaner will function. The efficiency of particle air cleaners as a function of particle size and the efficiency of gas-phase air cleaners in general have not been determined.

5.3 RADON CONTROL BY PARTICLE CONTROL

At various times during its decay cycle, the effects of radon may be reduced by reducing the number of airborne particles to which the radon daughters might become attached (Nazaroff et al. 1981; Sextro and Offermann, 1991; Sextro et al., 1986; Windham et al., 1978). EPA/DOE are supporting work at Clarkson University to evaluate the control of radon progeny.

5.4 STATUS OF RESEARCH

Air cleaner research is currently being conducted by EPA, ASHRAE, and commercial firms. The ASHRAE research is focused on the development of test methods that will enable air cleaners to be usefully and accurately evaluated. EPA's research efforts are intended to generate air cleaner performance data that can be used to estimate the usefulness of air cleaners for IAQ improvement. The current major research needs appear to be the development of test methods and the completion of test work to develop the engineering data required to rationally design air cleaning systems. The ongoing work interacts with ventilation research in a number of ways, and coordination with other aspects of ventilation research will ensure that the benefit of air cleaner research will be maximized.

6.0 ROOM AIRFLOW AND POLLUTANT DISPERSION

Two different aspects of ventilation airflows in rooms are addressed in this section—flow rates across sources and HVAC diffuser flows. The air velocities across sources and reversible sinks (S/RS) affect the rates at which contaminants are transferred from the sources and sinks into the room air. Diffusers determine the initial interaction of incoming ventilation supply air with the room air and hence greatly influence both comfort and contaminant distribution.

6.1 SOURCE/SINK EFFECTS AND VENTILATION

The interaction of the working, or mixed breathing-zone, air in a room and the S/RS in that room can be described as a three-step process consisting of the following:

- Transport from within the S/RS to the S/RS surface. The inclusion of this step presumes that the contaminant is bound inside the S/RS and that it must diffuse to the surface to be released.
- Transfer from the surface to the air boundary layer in contact with the surface of the S/RS.
- Transport from the S/RS boundary layer into the mixed breathing-zone (assuming complete mixing) air of the room.

The first two of these steps are only indirectly related to the building ventilation system, and therefore are not included in this review. The final step is related to the characteristics of the contaminant, its concentration in the boundary layer, and the air velocity near the S/RS surface. Increased S/RS surface velocities may lead to increased mass transfer rates, and these velocities are controlled by the amount of air entering the room, the type of diffuser, the return vent location and type, the furnishings in the room, thermal sources in the room, and similar considerations. As described below, a combined mass transfer coefficient can be used to account for all three steps in many practical applications.

Transport across boundary layers has been studied for years in chemical engineering transport studies, and workable transport equations have been developed for known flow patterns under isothermal conditions. In real rooms, the flow patterns over sources are not known, limiting the usefulness of the existing equations. Dunn and Tichenor (1988) assume a thin-film source in their model of sink effects in well-mixed emissions test chambers, effectively neglecting diffusion from within the source. Ventilation rates within the chamber were not included in the study. Experimental S/RS studies using protocols similar to those developed at AEERL-Research Triangle Park are being conducted at a number of locations (for example, AEERL [Tichenor, 1989; Tichenor, et al., 1991], Air Quality Sciences, Inc. [Black et al., 1991], and Finland [Saarela and Sandell, 1991]). Sparks et al. (1990) describe the integration of an S/RS model into a multizone building model (using an overall mass transfer coefficient to account for the complete S/RS transport process) to obtain estimates of concentrations within the rooms. Ventilation rates are not included in the mass transfer calculation. Recent work by Guo et al. (1990) treats the sorption/boundary layer transport problems as two resistances in series. Sollinger et al. (1993) present chamber emissions data that show increased total mass emissions at high air exchange rates but have insufficient data to generalize the effects.

Given the shortage of data, the combined mass transfer coefficient approach may be the best way to model S/RS behavior in rooms, provided the coefficient is measured under air flow conditions that are typical of room ventilation. Incorporation of room flow conditions into the S/RS models will require research into the detailed flow patterns in both rooms and emissions chambers.

In summary, investigation of the ventilation aspects of S/RS research is just beginning. The fundamental concepts relating transport to flow rate have been developed, but these concepts have not been widely applied to ventilation problems. The relationships between the flow rates over the surfaces of an S/RS and emissions rate have not been studied sufficiently. Nor are workable relationships between room ventilation parameters and the flow rates over the S/RS known. The details of flow in rooms are not sufficiently well known to fully use the available theoretical framework.

6.2 JET AND DIFFUSER FLOW

The final transfer of heat energy from the HVAC system to the room air takes place in air jets leaving diffusers. Diffusers are designed to ensure thermal comfort by adequately mixing the air leaving the HVAC system with room air. This has become especially important with the current development of cold-air distribution systems, which rely on colder air in the HVAC system than is now common and consequently have reduced margins of error at the diffusers. Diffusers are also required to perform adequately under variable air flows in VAV systems and are the motive source that promotes room mixing and high ventilation effectiveness.

Most of the current research appears to focus on the thermal comfort aspects of air distribution systems. However, the airflow aspects of this research apply equally to pollutant distribution in a space.

6.2.1 Computer Models

Flow in the vicinity of a diffuser is generally modeled using numerical solutions of the Navier-Stokes equations and the equation of continuity, with turbulence accounted for in equations for transport and dissipation, respectively, of turbulent kinetic energy. This is a subset of the micromodeling approach described in Section 6.2.3. Modeling diffuser flow is difficult because the rapid flow field changes that occur require a small grid size, yet a large grid size is desirable because of the large size of the room into which the diffuser is discharging. Recent research has been described by Nielsen (1989), Murakami and Kato (1989), and Kurabuchi et al. (1989). Overall, the models appear to reproduce simple experimental conditions fairly well, and their use in more complex situations is being proposed. The computer power required and the specificity of the input data appear to be the limiting factors on additional use of the models.

6.2.2 Experimental

Experimental work is being done in conjunction with the modeling work reported in the previous section. The measurements are demanding and require considerable expertise. Velocities are measured with thermal anemometers and laser doppler anemometers (LDA). Flow visualization is also important, and Murakami and Kato (1989) report use of a laser light sheet. Standard wind tunnel techniques such as smoke tracing and neutral density bubbles can also be used. Kurabuchi et al. (1989) report using an ultrasonic anemometer for flow field measurements.

6.2.3 Research Status

Diffuser flow is a key part of any indoor air micromodel. In conventional conditioned-air HVAC systems, improved diffusers are a relatively inexpensive and accessible way to improve ventilation effectiveness (VE). Research to improve diffusers can be done in a properly designed large chamber. Additionally, diffuser research will impact energy efficiency through its impact on low-temperature air distribution system acceptability. A chamber designed by Honeywell was described by Schultz and Krafthefer (1989). It is room-sized, with elaborate environmental controls.

On the modeling side, the development of more efficient computational algorithms will remain an important research subject. Current diffuser modeling is limited by computation as much as by data requirements. Linkage of diffuser and room design information through CAD-like programs seems an appropriate next step.

7.0 ROOM AND BUILDING FLOW/DISPERSION RESEARCH

7.1 INTRODUCTION

Two principal scales of flow and dispersion of air and pollutants in buildings can be differentiated: (1) flow and dispersion within a single room and (2) dispersion among rooms in a multiroom building. Within a room, the emphasis is on the detailed flow pattern as the ventilation system moves air into and through the room. Infiltration and flow through doors and windows complicates the situation. At the whole building scale, the primary concerns are the overall air movement within the HVAC system, infiltration and outside air flows, and interzonal flows.

These two scales of flow and dispersion are mirrored in the current models, which can be described as either microscopic or macroscopic. Microscopic models are set up using the Navier-Stokes equations for mass, energy, and momentum transfer, and distributed parameters. The partial differential equations are solved simultaneously by numerical techniques after choosing appropriate boundary equations. Microscopic models are used to study the details of air movement within a room or zone. They are typically computationally intensive. Macroscopic models make use of the macroscopic conservation equations of mass, momentum, and energy, which are ordinary differential equations. The macroscopic equations are written for zones having lumped parameters that are linked through transfer at known boundaries and flow paths. Macroscopic models are customarily applied to a whole building, although they can also be used in a single room by breaking the room into a series of zones.

The two modeling approaches support one another in that macromodels can provide the boundary equations to micromodels, while micromodels provide the velocity, temperature, and contaminant distribution fields useful in setting up macromodels. Conceptually, the two can be linked to provide a complete building model, though such a model is not currently practical. This division into microscopic and macroscopic models parallels experimental work with single and multiple rooms and is applicable to the following discussion. The division is useful, but should not be overemphasized. Both modeling and experimental approaches overlap to some extent.

The flow of ventilation air within a room can be visualized as falling into one of two categories:

- **Mixed Air Ventilation**. The supply air in a mixed air room is dispersed throughout the room in a mixed air ventilation system. Perfect mixing is achieved if the concentration throughout the room is uniform. Once contaminant addition has stopped, the decay in concentration of that contaminant in a mixed air room can be described by:

$$C(t) = C_0 e^{(-It)} \tag{1}$$

  where C(t) is the time-dependent concentration of the contaminant, C_0 is the initial concentration, and I is the air exchange rate. In a perfectly mixed room, I is the room volume divided by the supply air rate. Compared to perfectly mixed room, the concentration decay in an imperfectly mixed room may be faster or slower depending on the location of the source.

  Poor mixing within a ventilation system that relies on mixing is known as *short-circuiting*, in which the supply air flows directly to the return without mixing or flowing through the breathing zone.

- **Plug or Piston Flow Air**. Ideal plug flow ventilation is achieved when the supply air enters at the bottom (or one side) of a room, sweeps uniformly through the room, and exits at the top (or opposite side.) In plug flow, the ideal is rapid contaminant clearance in which the ventilation air replaces the room air rather than mixes with it. *Displacement ventilation* is an imperfect case of plug flow, in which the supply air enters near the contaminant source and sweeps the contaminant toward the return air vent.

A number of terms have been proposed as single-parameter measures of the quality of ventilation within a space. Bearg (1993) cites more than 10 different definitions of ventilation efficiency that have been proposed since 1981. Some were proposed to describe mixed air systems and thus are referenced to the perfectly mixed situations. For example, ASHRAE 62-1989 defines VE as referenced to the perfectly mixed case, so a well-mixed condition has a VE value of 1. Short-circuiting conditions give VE values less than 1, while plug flow conditions in which the ventilation air sweeps pollutants from the occupied zone can have VE values greater than 1. Other definitions are directed at pollution clearance rather than mixing and are referenced to plug flow. Within these two types, there are steady-state and transient VEs as well as Ves based on various types of concentration measures (local and various averages within the space).

7.2 SINGLE ROOMS AND MICROMODELS

The term "single room" is used here to refer to a portion of a building that can be treated as a single entity from the ventilation perspective. An office with a supply diffuser and a return vent would be a common example, as would a residential room with a supply and return through open doors. Some large rooms are too large to treat as single rooms, and extensive partitioning, unusually large thermal sources, or unusual HVAC design in a room could also preclude its classification as a single room as the term is used here. Single-room pollutant distribution studies are concerned with the transport of pollutants from a source to the rest of the room and from the HVAC diffuser to the rest of the room, the rate of pollutant removal, the extent to which ventilation air is distributed within the room, and similar concepts. Micromodels are the appropriate computational tools for ventilation in single rooms. Given appropriate inputs, such models can also be used to evaluate exposure histories to local sources and recirculating indoor pollution.

7.2.1 Micromodels

The micromodels discussed in this section are representative. Generally speaking, there are two approaches. Computational fluid dynamics (CFD) techniques can be applied to the indoor air problem in a rigorous, detailed model that must be run on a powerful computer. Alternatively, algorithms can be developed to allow solution of the equations on a personal computer. Turbulence is incorporated into the model using the k-ϵ model.

A number of researchers at universities in the United States and abroad are using what amount to CFD techniques to model flow in rooms (Jones, 1990; Kurabuchi et al., 1989; Murakami and Kato, 1989; Nielsen, 1989; among others). In all cases the flow field of the room is computed from the Navier-Stokes equations, and experimental work is used to validate the models. Outputs of the models are the velocity and turbulence fields for the rooms modeled. Baker et al. (1989) discuss the expected future impact of CFD on the design of room ventilation systems. They believe the effects of CFD will be profound. The authors (who are working on an ASHRAE research program) envision a CFD laboratory in which the flow fields in actual rooms could be modeled accurately from a few computer inputs. The laboratory would consist of an expert system environment in which the design engineer could conduct CFD experiments. A great deal of coordinated experimental and modeling effort will be required to make this vision a reality.

AEERL-RTP has supported development of a three-dimensional microscopic model for use on a personal computer (Kim et al., 1990). The model, which neglected the effects of turbulence and assumed spherical airflow leaving the diffuser, was used to evaluate the effects of the air exchange rate on pollutant effects in a room. Contaminant diffusion was found to be of secondary importance. AEERL-RTP is also supporting development of a two-dimensional "ventilation helper" microscopic model at the Research Triangle Institute (RTI) (Yamamoto et al., 1991). This model utilizes a powerful algorithm that allows the model to run at reasonable speed on a personal computer. The model is user-friendly, utilizing menus and graphical data entry. It has been used to evaluate changes in ventilation effectiveness due to changes in supply duct and contaminant source location.

Lack of experimental validation is a weakness of all the micromodels. Adequate experiments are difficult to conduct, and the many different geometries and thermal conditions that can be encountered in rooms require that a large number of studies be conducted to achieve broad applicability.

7.2.2 Experimental Studies

Validation of an IAQ micromodel requires that concentrations, temperatures, and flow rates be measured at a number of points in a room under controlled flow conditions. Time-dependent measurements may be necessary in some cases. Flow visualization, which has been useful in some studies, can be used to estimate overall mixing. Simple smoke and laser light sheet flow visualization can be used, and some innovative approaches have been developed for rooms. Saunders and Albright (1989) describe a method for externally monitoring two-dimensional flow using aerosol tracers and digital imaging analysis. Farrington and Hassani (1991) utilized infrared imaging to determine the flow field in an experimental room.

Anderson (1989) describes the various methods that can be used to determine ventilation efficiency in a room. Tracer gas techniques based on Equation (1) can be readily used to evaluate the overall VE of a room per ASTM E741-83 (ASTM, 1983), but multipoint local sampling must be used to determine the concentrations at various points in a room. Therefore Anderson promotes the development of multipoint measurement techniques for detailed room analysis. Anderson also reports, based on measurements of ceiling-based slot diffuser flow patterns, that supply temperature is the most important parameter in determining the extent of short-circuiting in a room. This suggests that HVAC systems that rely on slot diffusers in the ceiling may have markedly different IAQ performance during the heating and cooling seasons.

Lagus (1989) describes the instrumentation required to make tracer gas measurements. He emphasizes the complexity of the measurements and the expertise required to perform them. Lagus also describes new analytical techniques that may improve tracer gas measurements by reducing costs and reducing instrument response time.

7.3 MULTIZONE BUILDING PERFORMANCE (MACROMODELS)

Applying an approach developed in other fields, multiroom buildings can be described as a number of elements (rooms) linked by various mass and energy transfer pathways. The overall ventilation performance factor is the ventilation rate or the air exchange rate. The multizone models discussed in this section deal primarily with IAQ. Similar models have been developed that emphasize energy use, thermal comfort, and lighting.

7.3.1 Computer Models

A number of models use mass conservation and indoor source emissions data to determine indoor concentrations. The numerous input parameters are entered in a number of different ways, some of which are not convenient. Obtaining sufficient data to run the models in a complex building is a significant burden.

Recent development of the macromodels appears to be concentrated on validation and development of improved user interfaces. Some representative examples of macromodels are the various versions of CONTAM, the California Institute of Technology (CIT) indoor models, the Multichamber Consumer Exposure Model (MCCEM), the Indoor Air Quality model for Personal Computers (IAQPC), and INDOOR, developed at AEERL. A recently developed infiltration model, developed by COMIS, could be used in an IAQ model. Models continue to grow and change as they are used.

CONTAM, the NIST General Indoor Air Pollution Concentration Model, is the prototypical macromodel based on a multizone representation of the particular environment. CONTAM allows buildings to be modeled as containing separate rooms or areas where the concentrations are uniform, allowing the different zones to account for varying concentrations throughout the indoor space. Systems of ordinary differential equations must be solved for each time interval. This method of calculating results in a program is computer-time-intensive. More than one microenvironment may be modeled if separate runs are employed. The program can be used to simulate flow processes such as infiltration, dilution, and exfiltration by specifying interzonal flows for each process (outdoors is considered a zone). To account for interzonal flows due to pressure and temperature fields, CONTAM88 incorporates a steady-state airflow program into the basic macromodel. Potential mitigation measures involving air filters, lumped sink rates in individual zones, and variations in outdoor air ventilation may be modeled. The original program, written in FORTRAN, was somewhat machine-specific and required complicated input files. Recent work has emphasized the development of a graphics-oriented, user interface, PC-based version, CONTAMps (Axley, 1990).

CIT has developed two pollution-specific models that describe the indoor air space (Nazaroff and Cass, 1986, 1989). The first predicts the concentrations of NO_x and ozone in indoor air and the second simulates aerosol size distributions. Both calculate concentrations from source emissions, ventilation rates, and filtration efficiencies. The program was written in VAX Fortran to run on a micro-VAX and several hours were required to complete routine simulations.

MCCEM estimates indoor concentrations and exposures of chemical released from consumer products used in residences with up to four zones. Time-varying emission rates for a contaminant in each zone of the residence, outdoor concentrations, and occupied zone may be input through a spreadsheet type environment that includes the option of calculating formulas. Infiltration and interzonal flow rates and zone volumes may be input or the user may specify an included data set for a specific type of house and geographic area (Geomet Technologies, Inc., 1989).

IAQPC calculates concentrations for a multizone indoor environment (Owen et al., 1989). This program is the second version of indoor air quality simulator to be developed through the continuing EPA IAQ program. It can be used to simulate many microenvironments during different simulations. The program emphasizes user-friendly menus for data entry, incorporates default values for key parameters, and features onscreen graphics of building floorplan, flows, and source and sink layouts.

The AEERL IAQ model INDOOR (Sparks and Tucker, 1990; Sparks et al., 1990) is a macromodel designed to run on a personal computer. It has been integrated with emission factors for sources and a good data set of interzonal flows and used to model concentrations throughout the EPA test house.

Little information has been published regarding the relative merits of the different models. Data are not available to validate the models, so selection on the basis of accuracy is not possible. Of the models described above, the AEERL model INDOOR appears to be the most frequently cited in the IAQ literature.

The COMIS infiltration model is a modular computer program developed by an international group of scientists (Feustel et al., 1989, Feustal, 1990). Work on the model began in 1988 at a workshop held at Lawrence Berkeley Laboratory. Although it appears to emphasize infiltration, the COMIS model could provide the room and zone distribution portions of an IAQ model. The results of using the code have not been published.

7.3.2 Experimental

A primary and practical goal of ventilation evaluations in large buildings is to determine whether observed IAQ problems are related to the air exchange rate, either overall or in particular rooms. A second goal, important to the research community, is to develop a database that could be used to validate large building models.

Tracer gas decay (or a similar analysis based on complete mixing) is the common approach to measuring air exchange rate. Persily (1986) describes the application of tracer gas experiments to measurements of ventilation effectiveness in multiroom buildings. The theory and application of the buildup and decay tracer gas methods are described, as are the results from a field test. Persily shows that the single tracer gas methods, although simple in concept, become difficult to apply, and the results somewhat ambiguous, in the rooms of a large building. Crawford and O'Neill (1989) draw similar conclusions. Determination of overall building outdoor air rates has been measured using CO_2 concentration as a tracer and by using tracer decay measurements with SF_6 (Bearg and Turner, 1989). As discussed by Bearg and Turner, both methods have advantages and disadvantages. Careful interpretation of the data by an experienced professional appears to be important. The fundamental problem with tracer gas studies in large buildings is that uniform conditions do not exist in buildings and air movement is not limited to the HVAC system.

A number of attempts have been made to deal with the experimental complexities of ventilation evaluations. The use of the passive perfluorocarbon tracer gas (PPTG) technique developed by Dietz is described by Zarker (1989). Unlike the tracer gas decay measurement, which is normally short term, the PPTG method provides a week- to months-long average rate of air exchange for different building zones. Small PPTG emitters and sorption tubes are placed in each zone, left for the duration of the test, and analyzed. From knowledge of the room size, emission rates, and temperature, and the concentration in the sorption tube, the air exchange rate can be computed. By using different tracer gases, multizone buildings and interzonal transfers can be analyzed.

Similarly, multiple tracer gases can be actively injected to evaluate flows in a multizone building (Fisk et al., 1985). The same techniques used for single tracer experiments are used for multiple tracer work, except that different tracer gases are used in different zones.

Crawford and O'Neill (1989) lay the mathematical basis for a multizone airflow measurements using a single tracer gas. The method relies on mathematical manipulation of a data matrix and requires careful experimental control with an accurate mass balance on the zones, low noise measurements, a sufficiently wide range of tracer in the different zones, and proper zone selection. This method was experimentally validated using a three-zone test facility at the University of Illinois (O'Neill and Crawford, 1990) but has not been used in an actual building.

In summary, the goal of a simple and reliable method to evaluate building ventilation and relate it to IAQ has not been met, though experienced professionals can interpret a number of measurements and often discover the cause of IAQ problems. Similarly, true verification of a multizone model is very difficult. In a complex building, model inputs such as interzonal and infiltration flows must be obtained from tracer gas studies that themselves have to be interpreted with some kind of multizone model. This situation is not satisfactory. Experimental facilities in which all flows can be controlled are needed to validate models.

7.4 SCHOOLS, HOSPITALS, AND OTHER SPECIAL BUILDINGS

Schools, hospitals, and other buildings that frequently house individuals at special risk of exposure to episodes of poor IAQ have been studied more extensively than office buildings. Schools are often under intense pressure to maintain low energy costs, which results in marginal IAQ in a number of locations; they are often single-story, which increases the radon risk in problem areas; and they are often low-bidder constructed. A symposium on school ventilation conducted at IAQ'91 in Washington, DC, demonstrated the IA community's recognition of the requirements of special buildings.

Except for the vulnerability of the user population, evaluation of special buildings such as schools is no different from other building evaluations. EPA is currently sponsoring radon research in schools. Microbiological contamination is also likely to be a problem in buildings of this type. Homeless shelters have experienced an increase in tuberculosis because of the special conditions within the shelters, and, in at least one case, ultraviolet (UV) disinfection was used to control the spread of tuberculosis (Nardell, 1988). Increased ventilation was not considered as effective a control technique as UV air cleaning. Over the next decade, control of infectious diseases may take on increasing importance because of the increasing numbers of antibiotic-resistant bacteria strains.

7.5 RESEARCH NEEDS

For the modeling aspects of building flow/air distribution research, the principal needs appear to be improved validation and thus improved confidence. This requires additional building ventilation performance data, which are currently difficult to obtain because there is no standard test protocol or even agreement on which of the available tests should be run. Currently, a very high level of skill is required on the part of the measurement team to obtain reliable data.

Consequently, the most pressing need overall appears to be improved measurement techniques, including the development of standardized methods. Development of such methods would encourage their use, ensure a supply of consistent data for model development, and, it is hoped, increase the overall amount of performance data available.

NIST is currently involved in research into many of these building evaluation topics (see Appendix C).

8.0 HVAC/BUILDING DESIGN, OPERATION, AND CONTROL STRATEGIES

8.1 HVAC SYSTEM DESIGN AND SELECTION

The HVAC system type used in a building has, in the past, generally been chosen based on cost and the expected ability of the system to achieve thermal comfort goals in the space. The recent emphasis on adequate ventilation to achieve acceptable IAQ, as codified in ASHRAE Standard 62-1989, has added a third goal for the HVAC system. One-of-a-kind buildings may be designed from the first piece of paper to meet these three goals, but commercial pressures force the design of many commercial buildings into well-worn ruts that give low capital cost at the expense of performance and flexibility. Because commercial office building owners and tenants change frequently, the use of the space also changes frequently. These changes often cause HVAC systems to be ill-suited to their use and insufficiently flexible to allow modification at reasonable cost.

Large buildings generally use either all-air (all conditioning loads satisfied by air from a central source) or air/water (conditioning loads satisfied by a combination of conditioned air and local heat exchange to tempered water in terminal induction units) HVAC systems. The two system types have inherently different capabilities with respect to achieving acceptable IAQ. Centralized air cleaning can be implemented in all-air systems as an alternative to increased ventilation with outdoor air. To use air cleaning, air/water systems must be redesigned to move additional air from the occupant to a cleaning station and back (obviating many of the advantages of air/water systems) or must rely on local air cleaning.

From the viewpoint of IAQ, unitary systems (packaged all-air systems) are similar to all-air systems in that central air cleaning and outdoor air control are possible, provided the design is sufficiently flexible. All-water systems (all loads satisfied by local heat exchange to tempered water), on the other hand, cannot be readily modified to improve IAQ in a large building.

Little research has been conducted into the inherent merits of different HVAC systems as a means of controlling IAQ. The research has concentrated on the design and construction flaws of existing systems and not on the type of system and correlations between system type and the observed flaws.

Another topic that is implicit in ASHRAE 62-1989 is modification of building operation during periods of poor outdoor air quality to prevent contaminating the building. Technical

Committee 2.3 of ASHRAE proposed a research project titled "Ventilation Strategies During Episodes of Unacceptable Outdoor Air." The project received low priority, however, and is unlikely to be funded. That the project was proposed points out that the ASHRAE community is uncertain about how HVAC systems should be operated to improve IAQ when the outdoor air quality is poor and added outdoor air will not necessarily improve IAQ.

8.2 INNOVATIVE VENTILATION DELIVERY DESIGNS

A number of innovative HVAC systems have been proposed as ways to improve IAQ in offices. Their purpose is to deliver ventilation air to the occupants or to clear contaminants more efficiently than do conventional systems. Some that have recently been discussed in the indoor air literature are addressed in this section.

8.2.1 Ventilated Work Stations

The low ventilation effectiveness that often occurs in office environments has prompted the development of ventilation systems for individual work stations. By delivering a large fraction of the ventilation air directly to the occupant, the VE can be greater than 1. This can give better IAQ with lower overall ventilation rates, and consequently reduced energy requirements.

Farant et al. (1991) describe an investigation into the design of office workstations that would optimize the amount of outside air supplied to the occupants. Both field tests in an office building and chamber tests were used to evaluate the effect of supply air temperature, type and location of diffuser, type of office, partition design, and location of the workstation with respect to the supply and return grills. Farant et al. recommend that designers test their designs, before finalizing them.

8.2.2 Personally Controlled Ventilation

Personally controlled ventilation is an active research area in the architectural and building design field. As described by Drake et al. (1991), the Advanced Building Systems Integration Consortium (ABSIC) has supported evaluations of advanced buildings since 1988. A number of advantages are cited for the systems, all of which give the users increased control over their ventilation systems.

Hedge et al. (1991) describe a system that incorporates breathing zone filtration into office furniture. The occupant has control of the system.

Drake et al. (1991) describe the improvements in ventilation and thermal comfort that can be achieved with three different types of user-based environmental control systems. Two of the systems utilize raised-floor systems with local distribution boxes; the third utilizes desk-top diffusers. In all cases, the users had control of their local environment. The authors cite comfort and productivity improvements based on occupant surveys. Further, they speculate that energy savings might be possible with such systems (by cooling only the occupied zones), but emphasize the limited nature of their studies.

8.2.3 Displacement Ventilation

Displacement ventilation, in which supply air enters occupied space near the bottom of the space and rises towards the ceiling, is common in Scandinavia. Ideal displacement ventilation utilizes a plug-flow of supply air, which carries contaminants from the occupants to the return ducts without mixing. In recent publications, Laurikainen (1991) describes the design of displacement ventilation systems and Koganei et al. (1991) discuss the applicability of displacement ventilation to Japanese offices.

ASHRAE has begun to consider displacement ventilation in the form of a research proposal from Technical Committee 2.2 titled "Effect of Displacement Ventilation on Indoor Air Quality and Thermal Comfort." However, this proposal was given no priority.

8.2.4 Demand-Controlled (Pollutant-Sensor-Controlled) Ventilation

Conventional HVAC systems are controlled by thermal sensors. Fresh outdoor ventilation air is mixed with return air at a central location, conditioned, and transported through the ducts in response to the demands for conditioned air from the thermostats. In this type of system, the ventilation air will be distributed as required by ASHRAE 62-1989 (20 ft^3/min/person) only if the thermal loads and the occupancy loads coincide. This is unlikely, and a number of approaches to better matching the HVAC system control to occupancy have been proposed.

Strindehag (1991) reports on multiyear experience with variable-volume HVAC systems controlled by carbon dioxide sensors. Low ventilation rates from poorly setup variable-volume systems have caused a number of IAQ problems, and linking their minimum flow settings through a CO_2 sensor has the potential to solve a serious shortcoming. Most forced-air HVAC systems could be controlled in the same way, though relatively few such systems have been installed.

Other approaches to delivering ventilation air in response to occupancy or pollutant loads can readily be developed as sensor technology improves. Current technology is relatively expensive, but solid-state sensors are being developed rapidly and prices will probably drop. Direct delivery of ventilation air in response to an IAQ sensor is a distinct possibility within the next decade.

8.2.5 Energy Recovery Systems

Energy recovery systems, because they indirectly contact exhaust air and incoming ventilation air, have the opportunity to transfer pollutants as well as energy. Bayer and Downing (1991) describe experience with a "total energy recovery system" based on a rotating heat-wheel heat transfer device. The system was said to recover 90 percent of the total energy exhausted from the building without detectably affecting the IAQ in the building.

8.3 RESEARCH NEEDS—HVAC/BUILDING DESIGN, OPERATION, AND CONTROL

Little systematic research has been conducted into the topics of HVAC/building design, operation, and control with the goal of improving IAQ. There are many opportunities. The most immediate need appears to be organizing what is known about designing buildings and choosing HVAC systems to ensure good IAQ and transmitting that information to the building industry. This task appears to be well under way with recent EPA and ASHRAE activity, but the impact of the basic HVAC systems has not been included in the effort. A reasonable approach would be to ask what the best energy/cost-/IAQ compromise would be as a function of the following:

- HVAC system and building type
- Environment (location, climate, outdoor air quality, etc.)
- Use (including special use—school, hospital, etc.).

A systematic investigation of the performance, costs, and benefits (including energy impact) of the standard and innovative ventilation schemes would allow designers to make rational selections. Economic and performance claims are being made by developers and enthusiasts, but hard data are scarce. The IAQ models will need to be adapted to the innovative ventilation schemes to predict performance, and energy use and cost data need to be developed. Because the designs of today will have an impact for years to come, this is an important research goal.

Development of an IAQ sensor system that simultaneously measures pollutant loadings, temperature, and humidity and can be used to control an HVAC system is a reasonable goal for the HVAC community. Although little has been published, the approach is obvious. Research is needed to establish the adequacy of such a sensor system and to develop HVAC systems that make efficient use of the technology.

9.0 APPLIED MICROBIAL RESEARCH

An HVAC system, complete with air cleaner, does not necessarily enhance IAQ. Woods (1989), for instance, gives the following estimates of the frequency of occurrence of design and maintenance shortcomings in problem buildings:

- Inadequate outdoor air - 75 percent of buildings
- Inappropriate energy management strategies - 90 percent of buildings
- Poor air distribution - 65 percent of buildings
- Contaminated duct linings - 45 percent of buildings
- Inadequate condensate drains - 45 percent of buildings
- Inadequate filtration - 55 percent of buildings
- Humidifier problems - 30 percent of buildings.

The list shows that most problem buildings have more than one shortcoming and the IAQ problems have more than one cause. Woods further states that 45 percent of problem buildings have "significant microbiological contamination." From the viewpoint of HVAC systems as contributors to poor IAQ, Woods' list identifies design, construction, and maintenance as the causes of the problems. In addition to biocontamination, HVAC systems have been found to be sources of outside air pollution (for example, Walter, 1988), and odors (Hujanen, et al., 1991). Of course, HVAC systems also spread contaminants from one space to the next once the contaminants enter the distribution system.

Morey (1988) makes the point that biocontaminants can generally be controlled by reducing the availability of water and the availability of nutrients. HVAC systems, even at a reasonable level of air cleaning, will eventually get dirty and provide nutrients for microorganisms; however, HVAC systems can be designed to stay dry. Condensate pans that do not drain and cooling coils from which water is entrained by the air are common examples of design flaws. Morey also questions the wisdom of using porous insulation inside ducts where it can become dirty and wet.

The relationships between building material moisture content and microbial growth are being investigated by EPA/AEERL-sponsored research. Foarde et al. (1992) developed a standardized environmental chamber for evaluating microbial growth on building materials and used the chamber to investigate growth on ceiling tile at a number of relative humidities (and consequent material moisture contents). They found that moisture contents substantially below those reported in the literature were adequate to allow microbial growth on building materials. The research in continuing into other building materials and conditions.

Those investigating problem buildings appear unanimous in their belief that most biocontamination problems are associated with poor maintenance (Ager and Tickner, 1983; Morey et al., 1986; Morey, 1988). Implementation of the design improvements mentioned in the preceding paragraph would help the situation, but maintenance will still be required. No matter how well a system is designed, filters need to be used and changed as they become dirty, drain lines must be kept clean, birds kept out of air intakes, and so forth.

Once a biocontamination problem has developed, the steps taken to remediate it are to identify and repair the problem, remove the biocontamination, and replace damaged materials. Within the ventilation system, different cleaning practitioners take somewhat different approaches. Three aspects of biocontaminated HVAC systems seem to be under discussion:

- Should porous materials be used inside ducts at all (Morey and Williams, 1991)?

- If porous materials are used inside a duct and they become biocontaminated, should they be cleaned and encapsulated or removed entirely. Here Morey and Williams (1991) suggest the latter while some duct cleaners follow the former practice (*Indoor Air Quality Update*, 1991). Removal of porous material is expensive.

- Should biocides be used and under what conditions? Morey and Williams (1991) state categorically that, "The use of biocides is never a solution to this problem [contaminated porous insulation]." They are concerned about the long-term effectiveness of biocides and possible toxic effects if biocides are dispersed in an HVAC system. Overall, the thrust of the discussion seems to be that a biocide that does not leave a residue is thought to be acceptable for use in the HVAC system of an unoccupied building. Continuous use of biocides in an occupied building is not recommended, though systems that inject ozone into ductwork are currently being sold. No systematic investigation of the effectiveness or safety of the commercial use of biocides in ducts has been reported.

The Environmental Health Committee of ASHRAE (with partial funding from EPA-AEERL) is currently sponsoring research project TRP-662, titled "Air Pollution Sources in HVAC Systems." Possible future ASHRAE projects are "Urban Pollution Design Criteria for Building Ventilation Inlets and Exhaust" (second highest priority) and "Evaluation of Strategies for Controlling Indoor Concentrations of Gaseous Contaminants During Construction and Renovation" (low priority). These projects will provide a good beginning and may identify additional areas for future research.

Research into two aspects of biocontamination interacts with ventilation research. HVAC maintenance practices need to be strengthened, possibly through courses, publications, etc., and possibly through standards. Second, basic research into the conditions that affect microbial growth in HVAC systems is needed to ascertain proper system designs.

10.0 BUILDING PERFORMANCE EVALUATION

Building performance is generally evaluated after problems have developed. Occupant surveys and other semiquantitative measures of performance give rough and sometimes misleading data. Quantitative evidence comes from measurements of gas-phase and particle contaminants and building ventilation parameters. A number of investigations of this type have been reported. Suggested building investigation protocols are given by Rajhans (1989) and Lane et al. (1989.)

Building performance evaluation and ventilation research intersect primarily in the need for those evaluating the building to understand the building's ventilation system and to make accurate and appropriate measurements of air exchange rate, ventilation effectiveness, interzonal transfers, and similar measures. Measurement of these parameters is discussed in Section 6.0. As stated in that section, key research needs are improved sensors, measurement techniques, and a standardized protocol. At the same time, models must be available and easy to use so the data can be interpreted. Therefore, flexible, easily used IAQ models should be developed. PC-based models would be preferable; however, fast models accessible through a modem might be acceptable if their performance is superior.

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APPENDIX A

ASHRAE VENTILATION-RELATED RESEARCH

Title	TC/TG	Cost	Time
Highest Priority (3 Stars)			
A Mathematical Model for the Determination of Laboratory Fume Hood Contaminant Criteria	TG/LS	$100K	12M
Evaluation of Gas Phase Air Filtration Equipment as Used in Common Building Applications	TC 2.3	$175K	24M
Identification and Effectiveness of Methods for and Criteria for Cleaning and Decontaminating Ducts and Other HVAC Interior Surfaces	TC 2.4	?	?
Second Priority (2 Stars)			
VAV Controls and Fume Hood Diversity	TG/LS	$75K	18M
Determine Extent to Which Poor Building Operation and Maintenance Cause Indoor Air Quality Problems	TC 1.7	$100K	12M
Effect of Temperature and Humidity on Perceived Indoor Air Quality	TC 2.1	$200K	24M
Environmental Quality in Animal Facilities—A Review and Evaluation of Alternative Ventilation Strategies	TC 2.2	$35K	12M
Urban Pollution Design Criteria for Building Ventilation Inlets and Exhausts	TC 2.5	$75K	18M
Analysis of the Combined Modes of Heat and Moisture Transport	TC 4.9	$200K	24M
Review, Evaluation, and Demonstration of Indoor Thermal Comfort Simulation Models for Assessing the Thermal Acceptability of Indoor Environments	TC 4.10	$200K	30M
Determination of Ceiling/Plenum Effect on Radiated Sound Power Levels	TC 5.3	$90K	16M

Title	TC/TG	Cost	Time
Low Temperature Air Distribution: Jets of Low Temperature Air	TC 6.9	$150K	24M
Low Priority (1 Star)			
Study of Dynamic Response in a VAV Laboratory	TG/LS	$75K	24M
Field Study of the Thermal Environment and Comfort Characteristics in Office Buildings	TC 2.1	$80K	18M
Effect of HVAC Systems on Occupant Productivity	TC 2.1	$80K	12M
Evaluation of Strategies for Controlling Indoor Concentrations of Gaseous Contaminants During Construction and Renovation	TC 2.3	$150K	24M
Ventilation Strategies During Episodes of Unacceptable Outdoor Air	TC 2.3	$100K	24M
Investigate and Identify Means of Controlling Virus in Indoor Air by Filtration or Ventilation	TC 2.4	?	?
Integration of Energy Calculation and Indoor Air Quality Analysis Methods to Encompass ASHRAE Standard 62-1989	TC 4.7	?	18M
Effects of Mechanically Induced Building Pressures on the Performance of Building Envelope Systems	TC 4.9	$150K	18M
Effect of Displacement Ventilation on Indoor Air Quality and Thermal Comfort	TC 5.3	$85K	?
Low Temperature Air Distribution: Jets of Low Temperature Air	TC 5.3	$105K	16M

Title	TC/TG	Cost	Time
No Priority (0 Stars)			
Study of the Coordinated Effects of Fume Hoods and Laminar Flow Diffusers on Room Air Distribution	TG/LS	$75K	24M
A Survey of Various Laboratory Types Regarding Containment and Disposal of Airborne Contaminants	TG/LS	$25K	6M

Title	TC/TG	Cost	Time
Investigate the Use of Low Cost Integrated Circuit Thin Film Sensors for Measurement of Low Concentrations of Contaminant Gases Inside Buildings	TC 1.2	$90K	24M
Longitudinal Study of the Environmental and Occupant Response in a Large New Office Building During Initial Occupancy	TC 2.1	$90K	24M
Assessing Models that Predict Human Responses to Their Thermal Environment	TC 2.1	$200K	30M
Human Response to Localized Ventilation	TC 2.1	$130K	12M
Effect of Displacement Ventilation on Indoor Air Quality and Thermal Comfort	TC 2.2	$120K	24M
Identification of Particle Contaminants that are Air-Borne Upstream of Air Cleaning Filters	TC 2.4	$250K	18M
Investigate and Identify Particulates and VOCs that Cause Eye Irritation	TC 2.4	?	?
Investigate and Identify Radon Decay Products and Particle Interactions that Exist Indoors and Can Be Removed by Ventilation Filtration or Source Control	TC 2.4	$50K	12M
Investigate and Identify the Particulates that may be Emitted from Hot Surfaces in Residences	TC 2.4	?	?
Assessment of the Effects of Wind Turbulence on Natural Ventilation Air Change Rates	TC 2.5	$120K	30M
Development of a Correlation for Cosorption Data	TC 3.5	?	?
Modification of Activated Carbons	TC 3.5	?	?
The Effect of Dry Air on Microbial Growth in Air Conditioning Systems	TC 3.5	?	?

Title	TC/TG	Cost	Time
A Simplified Model of Moisture Migration in Building Components and Materials	TC 4.4	$50K	12M
Development of Wetting and Drying Potential Calculation Methods for Identification of Potential Moisture Failure in Building Components and Materials	TC 4.4	$80K	18M
Development of Material Moisture Measurement Devices	TC 4.4	$100K	24M
Dynamic Comfort Index	TC 4.6	$80K	18M
Loss Coefficients for Canopy and Other Hoods	TC 5.8	$60K	12M

Status	Title	TC/TG	Cost	Time
724-URP	Moisture Diffusion in Building Materials Exposed to Combined Humidity and Temperature Gradients	4.4	$159K	24M
759-WS	Identification and Effectiveness of Methods for and Criteria for Cleaning and Decontaminating Ducts and Other HVAC Interior Surfaces	2.4	Est $275K	24M
662-TRP	Air Pollution Sources in HVAC Systems	EHC	Est $300K (50% from EPA)	24M
740-WS	An Evaluation of the Effect of CO_2 Based Demand Controlled Ventilation Strategies on Energy Use and Occupant Source Contamination Concentration	1.4	Est $120K	18M
745-WS	Identification and Characterization of Cooking Effluents as Related to Optimum Design of Kitchen Ventilation Systems	9.8	Est $200K	18M
627-WS	Hospital Operating Room Air Distribution	9.8	Est $150K	24M
687-WS	Minimum Air Flow Rates with VAV Systems	9.1	Est $90K	12M
700-WS	Effect of HVAC Systems on Occupant Productivity	2.1	Est $200K	24M
715-WS	Develop a Practical Method for Control of Indoor Air Quality	TG4/CCD	Est $200K	24M
729-WS	A Survey of the Various Laboratory Types Regarding Containment and Disposal of Airborne Contaminants	TG9/LS	Est $60K	6M
703-RP/A	Room Air Movement Data for Validating Numerical Models	4.10	$120K	22M

Status	Title	TC/TG	Cost	Time
705-RP/A	Low Temperature Air Distribution: Jets of Low Temperature Air	6.9	$90K	24M
675-RP/A	Determination of Air Filter Performance Under Variable Air Volume (VAV) Conditions	2.4	$95K	24M

Status	Title	TC/TG	Cost	Time
661-RP/A	Field Verification of Problems Caused by Stack Effect in Tall Buildings	TG9/TB	$35K	12M 9
671-RP/A	Define a Fractional Efficiency Test Method That Is Compatible with Particulate Removal Air Cleaners Used in General Ventilation	2.4	$104K	22M
674-RP/A	Evaluation of Test Methods for Determining the Effectiveness and Capacity of Gas Phase Air Filtration Equipment for Indoor Air Applications - Literature Review	2.3	$27K	6M
625-RP/A	Matching Filtration to Health Requirements	2.4	$115K	46M
652-RP/A	Optimum Airflow Velocity in Cleanrooms	9.2	$52K	15M
610-RP/A	Control of Legionella Strains in Reservoirs	EHC	$158K	37M
623-RP/A	Testing Grease Hoods	9.7	$55K	24M
518-RP/A	Human Response to Cooling With Air Jets	2.1	$115K	13M
586-RP/A	A Study to Evaluate the Efficacy of Biocides Against Legionella in Open Recirculating Cooling Systems	3.6	$99K	24M
695-TRP	Effects of Temperature and Humidity on Perceived Indoor Air Quality	2.1	Est $250K	36M
744-TRP	Influence of Space Air Movement on Exhaust Hood Performance	5.8	Est $90K	18M

Status	Title	TC/TG	Cost	Time
760-TRP	Investigate and Identify Indoor Allergens and Biological Toxins That Can Be Removed by Filtration	2.4	Est $150K	12M
438-RP/A	Measurement and Rating of Air Leakage in Building Components	4.3	$69K	48M
464-RP/A	Calculation of Room Air Motion	4.10	$119K	36M
475-RP/A	Investigation of Co-Sorption of Gases and Vapors in Sorption Dehumidification Equipment	3.5	$334K (ASHRAE $50K)	36M
496-RP/A	Investigation of Water Vapor Migration and Moisture Storage in an Insulated Wall Structure	4.4	$58K	44M

RP No.	Title	TC/TG	Cost	Completed
12	Air Sterilization by Solid Sorbents			1958
17	Ventilation Requirements		$5.8K	?
27	Gas Diffusion Near Buildings		$4.9K	1960's
28	Habitability of Survival Shelters	TG/SS	$11.2K	1962
35	Abstract on Odors	TC 1.6	$20.3K	1960's
43	ASHRAE Environmental Studies	TC 1.4	$211K	1972
60	Soiling of Surfaces by Fine Particles	WS TC 9.4	$5.6K	1966
70	Dev. of Criteria for Design, Selection & In-Place Testing of Laboratory Fume Hoods & Laboratory Ventilation Air Supply	WS TC 5.8	$26K	1978
74	Odor Identification in Occupied Spaces	WS TC 1.6	$13K	1969
86	Field Study of Air Quality in Air Conditioned Spaces		$20K	1970
88	Room Air Distribution	TC 4.1	$25K	1971
90	Soiling of Surfaces	TC 9.4	$51K	1972
91	A Study of Comfort, Health and Learning in Schools with Differing Therman Conditions	TC 1.4	$26K	1970
93	Effects of Air Conditioning Equipment on Pollution in Intake Air	WS	$16K	1970
96	Odor Identification in School Room Environments	TC 1.6	$10K	1969
97	A Study of Techniques for Evaluation of Airborne Particle Matter	TC 2.4	$42K	1975

RP No.	Title	TC/TG	Cost	Completed
99	Study of Air Pollution Caused by Residential and Commercial Heating Systems	TC 3.5	$10K	1970
108	Perception of Odor Intensity and the Time-Course of Olfactory Adaptation		$13K	1973
130	Development of Monographs for Practical Application of ASHRAE Research on Thermal Comfort and Air Distribution	SRP R&T	$3K	1972
136	Contamination of Building Air Intakes from Nearby Exhaust Gas Vents	URP TC 5.8	$10K	1975
142	Relating Indoor Pollutant Concentrations of Ozone and Sulfur Dioxide to Those Outside	TC 2.3	$21K	1979
144	Comfort, Discomfort in Thermal Warmth	TC 2.1	$28K	1976
169	Destruction of Ozone	TC 5.4	$20K	1976
183	Organic Contaminants in Indoor Air and Their Relationship to Outdoor Contaminants	TC 2.3	$93K	1981
223	Contaminant Level Control in Parking Garages	WS TC 5.9	$98K	1979
227	Analysis of Exhaust System	URP TC 1.7	$25K	1983
238	Tobacco Smoke Odor Control Development of a Test Method	TC 2.3	$37K	1982
254	Latent Loads in Low Humidity Rooms Due to Moisture Infiltration	WS TC 9.2	$52K	1982

RP No.	Title	TC/TG	Cost	Completion
268	Development of Test Method for Gaseous Contamination Removal Devices	WS TC 2.3	$73K	1984
308 (SP4)	Investigation of Duct Leakage	WS TC 5.2	$105K	1985
312	Minimum Exhaust Air Rates for Hospitals	WS TC 9.8	$33K	1984
313	Design Criteria and Methods of Removal and Control of Certain Potentially Hazardous Gases and Vapors in Hospitals	WS TC 9.8	$28K	1982
352	Analysis of Indoor Air Acceptability Data Collected in the TRC/LBL Project on Energy Conservation in Buildings	URP TC 2.3	$8K	1983
353	A Study to Determine Subjective Human Response to Low Level Air Currents and Asymmetric Radiation at Lower Boundary of Human Comfort	WS TC 2.1	$55K	1986
354	A Study to Determine a Replacement for the Dust Spot Test Method of Determining Air Filter Efficiency	WS TC 2.4	$52K	1984
397	The Effect of Indoor Relative Humidity on Survival of Airborne Microorganisms and the Related Absenteeism in Schools and Hospitals	URP TC 2.1	$51K	1985
421	Thermal Comfort of the Elderly: Effect of Indoor Microclimate, Clothing, Activity Level and Socioeconomics	URP TC 2.1	$44K	1984
448	Building Pressure Distribution for Natural Ventilation Calculations	WS TC 4.7	$34K	1987

RP No.	Title	TC/TG	Cost	Completion
464	Calculation of Room Air Motion	WS TG/IEC	$119K	1990
475	Investigation of Co-Sorption of Gases & Vapors in Sorption Dehumidification Equipment	WS TC 3.5	$50K	1991
496	Investigation of Water Vapor Migration and Moisture Storage in an Insulated Wall Structure	WS TC 9.6	$58K	1989
518	Human Response to Cooling with Air Jets	WS TC 2.1	$115K	1991
525	Indoor Air Quality Evaluations of Three Office Buildings	URP EHC	$71K	1989
586	A Study to Evaluate the Efficacy of Biocides Against Legionella in Open Recirculation Cooling Systems	WS TC 3.6	$99K	1991
590	Control of Outside Air and Building Pressurization in VAV Systems	WS TC 9.1	$94K	1990
594	Test of Blower-Door Building Pressurization Devices	WS TC 4.3	$15K	1989
623	Testing Grease Hoods	WS TC 9.7	$55K	1991
625	Matching Filtration to Health Requirements	WS TC 2.4	$17K	1990
652	Optimum Airflow Velocity in Cleanrooms	WS TC 9.2	$52K	1991
671	Define a Fractional Efficiency Test Method that is Compatible with Particulate Removal Air Cleaners Used in General Ventilation	WS TC 2.4	$104K	1992

RP No.	Title	TC/TG	Cost	Completion
674	Evaluation of Gas Phase Air Filtration Equipment as Used in Common Building Applications	WS TC 2.3	$27K	1991
675	Determination of Air Filter Performance Under Variable-Air-Volume (VAV) Conditions	WS TC 2.4	$95K	1991
702	Field Study of Occupant Comfort and Office Thermal Environments in a Hot-Humid Climate	WS TC 2.1	$143K	Not Complete
703	Room Air Movement Data for Validating Numerical Models	WS TC 4.10	$120K	Not Complete
705	Low Temperature Air Distribution: Jets of Low Temperature Air	WS TC 6.9	$90K	Not Complete
730	Development of Ventilation Rates and Design Information for Laboratory Animal Facilities	WS TG/LS	$104K	Not Complete

APPENDIX B

DOE VENTILATION-RELATED RESEARCH

Environmental Measurements Laboratory, NY
Annual Report - Calendar Year 1991
EML-545, April 1992.

- Intercomparison of a modified microorifice uniform deposit impactor and a high volume screen diffusion battery for radon progeny particle size measurements. Investigator: K-W Tu.

- A study of variables affecting surface deposition of radon progeny. Investigators: G. Klemic, E.O. Knutson, and C.V. Gogolak.

- DOE-CEC Particle Size Measurement Intercomparison. Investigators: E.O. Knutson and A.C. George.

Indoor Air Quality, Infiltration, and Ventilation Program
at Lawrence Berkeley Laboratory

- Healthy Building Study at National Renewable Energy Laboratory (Sandia)

APPENDIX C

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY FY 1992 VENTILATION-RELATED RESEARCH

Field Assessment of Ventilation for Indoor Air Quality. Development of automated system for monitoring ventilation system performance and local ventilation conditions.

Airflow and Pollutant Transport Modeling in Multizone Buildings. Apply computer simulation model, CONTAM88, to study multizone airflow and contaminant dispersal problems.

Indoor Pollutant Levels and Ventilation System Performance. Field measurements to study the relationship between indoor pollutant levels and ventilation system performance, e.g., carbon dioxide, particulates and ozone.

Building and HVAC Characterization for IAQ Evaluations. Develop parameters for characterizing building and HVAC features in conjunction with studies of indoor air quality in commercial building. (w/EPA)

Field Measurements of Ventilation Effectiveness. Develop and apply tracer gas methods for quantifying ventilation effectiveness in mechanically ventilated buildings. (w/DOE)

Three-Dimensional Modeling of Room Air Motion. Apply computer models to study effects of ventilation rate, temperature, thermal load and supply/return vent configuration on room air motion, comfort, ventilation effectiveness and contaminant dispersal. (w/DOE)

Indoor Air Quality in New Office Buildings. Long-term, automated measurements of ventilation and contaminant levels in a new Federal office building in Overland, MO. (w/GSA)

Comparison of Ventilation Measurement Techniques. Comparison of tracer gas decay, direct airflow rate measurements, and temperature and tracer gas balances in BPA Building in Portland, OR; assessment of BPA building ventilation rates 2 years after NIST study. (w/BPA)

Presentation by A. Persily, August 1992.