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INDOOR AIR QUALITY AUDITS FOR COMMERCIAL BUILDINGS

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EXECUTIVE SUMMARY

Air quality in buildings is a topic of considerable concern. Poor air quality affects the comfort, health, and productivity of building occupants. This paper describes several strategies that may be used to evaluate air quality in buildings. These different strategies have varying degrees of effectiveness in (1) evaluating air quality, (2) identifying causes of poor air quality, and (3) recommending corrective actions.

The causes of poor air quality generally can be placed in one of two major categories: contaminant sources found in the building or malfunctions of the building's ventilation system. Knowledge of contaminant sources having a significant impact on indoor air quality is incomplete. This paper discusses contaminants associated with building materials, building furnishings, and actions of building occupants. Where known, the health effects of the contaminants are summarized. Contaminants having both indoor and outdoor sources and contaminants with only outdoor sources are mentioned; however, the focus of the paper is on contaminants with indoor sources.

Dilution of indoor air with clean air using the building's ventilation system is generally the dominant mechanism for improving indoor air quality. Often, indoor air quality problems have been traced to malfunctions in the building's ventilation system. These malfunctions may be the result of several things, including design errors, improper installation, incorrect operation of the system, or poor system maintenance.

Several audit procedures are described in this report. The first, a walk-through audit, is the simplest and least expensive but also yields an audit result with significant uncertainty. A second, the evaluative indoor air quality audit, measures contaminant concentrations and reports these results. Only a minimal attempt is made to assess the causes of excessive contaminant concentrations that are found. The third audit strategy, the diagnostic indoor air quality audit, includes contaminant source observations and ventilation system performance measurements in its procedures. Each of the audit strategies can be considered as steps in an audit progression. Thus, the diagnostic audit is aimed at determining the cause(s) of IAQ problems identified in the evaluative audit, while the evaluative audit is a verification of observations from the walk-through audit.

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1. INTRODUCTION

Energy conservation priorities that mandate reductions in ventilation rates and the emergence of information about the health effects of indoor air pollution increase the need for identifying potential or existing air quality problems in buildings. This report discusses several options available for indoor air quality (IAQ) audits in commercial buildings. Issues addressed include:

1. causes of indoor air quality problems;
2. objectives of indoor air quality audits;
3. building classifications for audits and audit frequency;
4. what typical audits should encompass;
5. personnel and training required for audits; and
6. equipment required for audits.

1.1 Causes of Indoor Air Quality (IAQ) Problems

The concentration of air pollutants within a building is dependent on both the injection of pollutants into the space by internal or external sources and the efficiency of the removal processes -- usually dominated by the building's ventilation system. Excessive input of pollutants and/or inadequate removal processes lead to IAQ problems.

Providing adequate indoor air is the purpose of building ventilation systems. The amount of clean outdoor air and filtered recirculated air supplied to a building should be sufficient to dilute pollutants to an acceptable level. Pollutant sources include people and other animals (CO_2, H_2O, odors), smoking (CO, organics, particulates), building materials and furniture (formaldehyde, other organics), and miscellaneous sources such as wet-process copy machines and cleaning solvents. Inadequate pollutant removal can often be attributed to ventilation system problems such as design and installation errors, improper maintenance, and inappropriate modifications including improper attempts to reduce building energy requirements.

Characterizing possible indoor (and outdoor) pollution sources in a building and the ventilation system that removes or dilutes their emissions is a requirement of any IAQ audit. As background, this report contains sections with information on ventilation systems and pollutant sources commonly found in commercial buildings.

1.2 Objectives of Indoor Air Quality Audits

An IAQ audit will include one or more of the following objectives:

1. determine if the building has an existing or potential IAQ problem;
2. identify the type and magnitude of IAQ problem, if it exists;
3. identify cause(s) of IAQ problem, if it exists;
4. recommend solutions to existing IAQ problems;
5. recommend additional auditing, if necessary; and
6. document findings.

Each of these objectives requires specific information and thus specific equipment and auditor skills. Audit procedures and the amount of information gathered will be dictated by the degree of required confidence in the audit's results.

1.3 Types of Buildings Addressed -- Audit Frequency

Certain types and uses of buildings may have different primary causes of indoor air quality problems. Some of the methods of categorizing buildings include:

1. use: school, office, etc.
2. size: square feet of floor area, stories, etc.
3. status: new, renovated, existing, etc.
4. type of HVAC system: variable air volume, dual duct, etc.
5. processes in building: chemical laboratory, blueprinting, etc.

Buildings in each of these categories have the potential for either a source-derived IAQ problem or a ventilation system-derived problem or both. However, the availability of building information and the likelihood of different IAQ problems and causes could be different in each category. For example, comparing buildings by status (item 3 above) yields the following:

- contrary to the case in new or renovated buildings, existing buildings rarely have accurate, if any building drawings available;
- building material and furnishing sources tend to be more of a problem in new buildings;
- occupant-related sources cannot be detected before a new building is occupied;
- ventilation system installation problems are more likely in new and renovated buildings than in existing buildings;
- ventilation system maintenance problems are more frequent in existing buildings.

Issues such as these help determine both which IAQ audits are appropriate for each building category and what should be investigated first in the buildings of each category.

When conducting an audit it may be appropriate to evaluate only a portion of a building. For example, audit costs for high-rise buildings with many identical ventilation systems and similar occupancies may be reduced with only a small reduction in accuracy by evaluating representative floors. Also, in some buildings only certain areas with an identified high risk for IAQ problems, such as laboratories, may need auditing.

The timing of an audit is quite important. Air quality in a building may vary by the season, day of the week, or even time of day. Conditions such as outdoor pollution levels, processes taking place in a building, or the ventilation systems' operating mode will effect the results of audits. It may be most appropriate to conduct audits several times a year or at the time(s), when the potential for IAQ problems is identified to be at a maximum.

Audits may also be conducted as response to complaints. The audits in this report can be adapted for a complaint-response orientation, but they were not designed for this purpose.

1.4 Personnel, Training, and Equipment Required for Audits

The types of skills and training required to perform the audits described in Section Four are discussed in Section Five. Indoor pollutant monitoring is described in Section Six. Air flow measurement (for ventilation systems) equipment and techniques are discussed in Section Seven.

2. INDOOR POLLUTANT SOURCES

It is currently impossible to identify every potential indoor air pollutant and its source. Below is a list of air contaminants which have been identified in non-industrial indoor environments and some of their sources and adverse health effects. Major pollutant categories include building materials, interior decor, some specialized building utilizations, and human activity.

2.1 Building Materials

2.1.1 Asbestos. Asbestos is a term which refers to the fibrous form of a number of mineral silicates. If inhaled, these fibers can cause serious damage. Exposure to asbestos has been linked to such respiratory diseases as fibrosis, lung cancer, and mesothelioma, a cancer of the interior lining of the chest cavity (Casarett and Doull, 1975).

Asbestos is used in many building materials including thermal insulation which surrounds pipes, roofing and flooring materials, textiles and papers, filters and gaskets, cement panels, and various coating materials. In almost all cases the asbestos fibers are immobilized in strong binding materials. However, when any asbestos-containing product is disturbed during processes such as remodeling, renovation, demolition, or simply heavy use, free fibers can be released to the environment. Fibers are also introduced into the environment when asbestos is sprayed onto building surfaces for insulation or decorative purposes. Although this practice is presently banned, fibers released during past applications remain a large source of asbestos exposure in many existing buildings (National Academy of Sciences(NAS), 1981).

2.1.2 Glass Fibers. Glass fibers are currently being substituted for asbestos in many building materials including thermal and acoustic insulation, matting, and as a reinforcement in plastics. Although fibrous glass has caused mesothelioma in some animals in which fibers were implanted in the pleural cavity, no health risk has yet been demonstrated for humans (NAS, 1981).

2.1.3 Urea-formaldehyde Foam. Urea-formaldehyde foam insulation (UFFI) is currently being used as a cost-effective insulating material in many commercial buildings. (A ban prohibiting its use in schools and homes has recently been lifted.) It is installed by injecting a mixture of urea-formaldehyde resin, a surfactant, and acid catalyst under pressure (to form the foam) into the wall cavity of the structure to be insulated. Proper insulation is difficult since mixing ratios, temperature, and humidity must all be carefully controlled. If the rigorous installation conditions are not met, free formaldehyde gas can be produced during the process or later by polymer degradation (NAS, 1981). It is easy for the formaldehyde gas to enter the building through cracks and openings in the interior structure and contaminate the indoor atmosphere.

Formaldehyde has a pungent odor which can be detected by some individuals at levels in the range of 0.05 to 0.8 ppm. It is an irritant to the skin, eyes, and all areas of the upper respiratory tract, and may cause an allergenic response in up to 8% of the population (Gunby, 1980). Formaldehyde is mutagenic, and has recently been shown to cause cancer in laboratory animals (Swenberg et al., 1980).

2.1.4 Radon and Radon Progeny. The greatest source of radiation exposure in indoor environments (with the exception of certain specialized workplaces) is radon (Rn-222), an inert gas created by the alpha decay of radium in the uranium-238 series. It is believed that exposure to high levels of radon increases the risk of lung cancer in humans (UNSCEAR, 1977).

Building materials are one major source of radon indoors. Some concretes, brick, and tile have been found to contain substantial radioactivity which occurs naturally and varies by geographic location. During their formation, additional radiation can also be introduced into concretes via the use of phosphate slag and perhaps fly ash (NAS, 1981).

The soil underneath many buildings may be an even greater source of indoor radon. The gas can enter by diffusion through the concrete or by movement through any cracks or designed openings in the foundation. Many factors influence radon concentrations in indoor environments; at present actual air sampling is the only method for determining the potential for radiation exposure in commercial buildings.

2.1.5 Polychlorinated Biphenyls (PCBs) Although the manufacture of PCBs has been halted for some time, these chemicals remain as insulation fluid in the capacitors and transformers of electrical systems in many buildings. Potential occupant exposure may occur if leaks develop in the systems or if the transformer fluids are spilled during maintenance or removal. PCBs are known to cause severe skin irritation and liver damage, and are presently considered potentially carcinogenic to humans (NIOSH, 1977).

2.1.6 Uncharacterized Organics. Common building materials contain a multitude of organic solvents, polymers, and miscellaneous compounds which can be released indoors. These include aldehydes, aliphatic and aromatic hydrocarbons, halogenated aromatics, alcohols, ketones, ethers, and esters. At present little is known about the specific chemical composition of building materials and their release of organics into the environment. A partial list of organic compounds which may be be present indoors, their health effects, and potential sources are given in Table 2.1.

2.2 Sources Related to Interior Decor and Building Use

Materials used in furnishing and decorating as well as machines, laboratories, or specialized equipment within a building can contribute to indoor air contamination. Water accumulation in specialized cooling and ventilation systems can also be a source of harmful materials. Although it is impossible to cover all of the sources of toxic materials in commercial buildings because of the almost infinite variety of activities within the structures, some of the more commonly encountered pollutant sources are discussed below.

2.2.1 Furnishings and Decorating Materials. A great deal of new furniture is constructed of particleboard and/or plywood which may be covered by a veneer. These wood products are constructed with urea-formaldehyde glues and resins which can release formaldehyde gas. (The health effects of formaldehyde were discussed above.) Particleboard tends to release more formaldehyde than plywood. Wall paneling is also constructed of these materials and, as has been demonstrated in mobile homes, can be a serious source of formaldehyde in indoor air (NAS, 1981).

Many fabrics are also treated with formaldehyde, thus upholstery, draperies, and carpet may be formaldehyde sources. In addition, synthetic fabrics contain many organic compounds which may be released into the environment. Table 2.1 lists some of these compounds and their sources.

The paints, varnishes, adhesives, ceiling tiles, and wall coverings used in the interior decoration of commercial buildings are also sources of organic materials as seen in Table 2.1. Preliminary studies have shown that the number and concentrations of organic compounds in new office buildings are higher than in outdoor air (Hollowell and Miksch, 1981). The compounds most often observed in these studies were hydrocarbons, alkylated aromatics, and halogenated hydrocarbon solvents. Some latex paints have been observed to emit detectable levels of mercury vapor. (NAS, 1981).

2.2.2 Office Equipment. Many photo-copiers and other office equipment which use inks and solvents are sources of organic compounds. Most important among these are the old wet process-type copiers which release methanol vapor, signature machines which release butyl methacrylate, and carbonless copy paper which has been shown to emit formaldehyde (Kleinman and Hurstman, 1982).

Photocopy machines may also be minor sources of ozone, as are electrostatic air cleaners. Ozone is an extremely reactive and powerful oxidizing agent, and has rarely been found to be in higher concentrations indoors than outdoors (Yocom, 1982). At lower concentrations ozone can cause mild nasal and throat irritation, and as exposure increases breathing is affected and severe pulmonary edema can occur at very high levels (National Air Pollution Control Association, 1970). Poorly ventilated copy machines may produce enough ozone to cause some adverse health effects. (Wadden and Scheff, 1983).

Mentioned above are only a few of the many types of equipment used in offices today. An auditor must make careful note of such equipment if he or she is to accurately assess indoor air quality.

2.2.3 Specialized Building Use. "Commercial building" is a term covering a wide range of business activity. Besides offices, with which we are most concerned, commercial buildings can contain kitchens, darkrooms, laboratories, and retail activity.

Commercial buildings may also contain areas of light industrial activity. Most often chemical exposures in these areas are regulated by the Occupational Safety and Health Administration. Contaminants released from these areas into atmospheres surrounding non-industrial activities are of most concern to auditors.

Kitchens can contain pollutants released from gas appliances as well as the organic compounds emitted from food as it is cooking. CO, CO_2, and NO_2 are the most important pollutants released during combustion. Concentrations may vary depending on the condition of gas stoves and the degree to which they are ventilated (NAS, 1981).

It is known that exposure to high concentrations of CO can lead to carboxyhemoglobin saturation and death, but health effects from concentrations typically found during cooking are not well characterized. Moderate headaches and dizziness may sometimes occur. NO can also bind to hemoglobin but more importantly it can be oxidized to NO_2 in the environment. NO_2 is a major air pollutant released during combustion and has been associated with bronchitis and pulmonary edema at high exposure levels. At lower levels it may affect sensory perception and produce eye irritation. Chronic exposure can lead to lung tissue damage (NAS, 1981).

In general, though, combustion-generated pollutants are not considered to be a problem in the great majority of commercial buildings. Fuel-burning space heaters can emit pollutants if improperly tuned (Girman et al., 1982). In a number of cases, ventilation intake ducts have been found in or near areas of high vehicular traffic, including traffic garages leading to contaminanted indoor air (Yocom, 1982). Fuel-burning furnaces can emit toxic levels of CO if improperly operated, and heating ducts will spread the gas throughout a building.

Darkrooms contain a number of organic solvents, most importantly acetic acid. Laboratories, both chemical and biological, also contain any of a great variety of organic chemicals which can enter building air handling systems through improperly designed or operating hoods. Inorganic chemicals can also be of importance. Mercury has a high vapor pressure and may be found in laboratories and dentists' offices. Exposure to mercury vapor results in absorption through the lungs, and in some cases, the skin. Chronic exposure can result in nervous system disorders, and kidney and gastrointestinal tract disturbances have also been noted (Casarett and Doull, 1975).

The auditor must make note of any chemicals in use within the building under investigation and be aware of the resources available to him or her to determine their adverse health effects and the extent to which the chemicals may be contributing to general indoor air pollution. Consulting with building managers is one way of determining what cleaning products, odor masking agents, and pesticides may be in use.

2.2.4 Air Handling Systems. Air-conditioning and humidifying systems can be sources of indoor air pollution and can cause contaminants to be spread throughout a building. The water they contain can become contaminated with bacteria resulting in dispersion of a disease agent to many building inhabitants. Cool-mist type vaporizers and nebulizers are of most concern. Legionnaires' disease, humidifier fever, and Pontiac fever have all been reported to have resulted from contaminated air handling systems in commercial buildings, and have resulted in serious illness among many exposed. (Kreiss and Hodgson, 1984).

2.3 Sources Related to Human Activity

People working in commercial buildings can create many indoor pollutants. Tobacco smoking is perhaps the most important of these, but aerosols and cleaning products, pesticides, and human beings themselves all emit contaminants into the indoor environment.

2.3.1 Tobacco Smoking. A distinction can be made between active and passive smoking in which a non-smoker is exposed to the tobacco smoke of others. Sidestream smoke, that which comes directly from the burning cigarette, is most often considered during indoor air quality evaluations. It contains a wide variety of compounds in various physical forms (over 2,000 compounds have been identified in cigarette smoke), though particulates carrying nicotine and benzopyrene, CO, acrolein and formaldehyde are considered the most important pollutants emitted. Their concentrations are especially high in bars and restaurants and in areas with poor ventilation (NAS, 1981).

Specific adverse health effects of CO and formaldehyde were discussed above. General symptoms resulting from exposure to side-stream cigarette smoke include eye and respiratory system irritation, coughing, headaches, and nausea. Long-term exposure may cause small-airway dysfunction and an increased incidence of lung cancer. Children and the infirm are more susceptible to the effects of CO released by tobacco smoking, and may be more likely to suffer from respiratory symptoms (NAS, 1981).

2.3.2 Cleaning Products. Many of the organic chemicals listed in Table 2.1 are contained in common cleaning products and the propellants used to disperse them. Normal use of aerosols can release a variety of volatile organic chemicals as well as high levels of respirable particulate matter (Wadden and Scheff, 1983).

In addition to organic solvents (especially halogenated hydrocarbons) cleaning products can contain caustic materials such as sodium and potassium hydroxide and ammonia all of which may irritate the respiratory tract and eyes. If cleaning products are suspected of creating an indoor air quality problem, maintenance personnel should be interviewed and containers obtained to evaluate hazards.

2.3.3 Pesticides. Pesticides are used in great quantities every year to kill insects, worms, and rodents in commercial buildings. It is often intended that residues and vapors remain for long time periods. Chlordane, an organo-phosphorous compound, has been found in structures up to 20 years after its application.

Organophosphates, organochlorides, and carbamates are the three major classes of pesticides. The organophosphate and carbamate pesticides attack the nervous system resulting in symptoms listed in Table 2.1. Organochlorides are highly resistant to degradation and can be absorbed through the skin as well as inhaled. Some of them, including lindane, captan, and chlordane, have been found to cause cancer in animals. Other symptoms are given in Table 2.1 (Casarett and Doull, 1975).

2.3.4 Bioeffluents. Humans, animals, and plants all release a variety of organic compounds. Chief among these are methanol, ethanol, acetone, and butyric acid, none of which are considered to be of concern unless ventilation systems are extremely inadequate. CO_2 gas is also emitted by humans and animals, and at very high concentrations can cause headaches and dizziness. Concentrations of CO_2 often determine ventilation requirements of a building. (ASHRAE 62-81, 1981).

2.4 Summary

At present formaldehyde, organic solvents, pesticides, tobacco smoke, and various bacterial agents are considered the most likely chemical causes of indoor air quality problems. However, little research has been performed to date and much remains to be done to adequately characterize the indoor environment. An auditor must keep abreast of current research as new causes of indoor air pollution are discovered.

Table 2.1
Organic Compounds and Health Effects

Compounds	Health Effects	Sources and/or Uses
Aldehydes	Eye and respiratory irritation, may have more serious long-term health effects including sensitization, some compounds cause cancer in animals.	Out-gassing from building materials-particleboard, plywood, and ureaformaldehyde foam insulation; also generated by combustion of a variety of fuels and smoking, used in glues, plastics, perfumes and to prevent mold growth on leather
Aliphatic Hydrocarbons	Narcotic at high concentrations, moderately irritating	Gasoline, mineral spirits, solvents in building materials, fuels, aerosol propellants, glues, thinners, varnishes, and photocopiers
Aromatic Hydrocarbons		
a. Benzene	Respiratory irritation, central nervous system depressant, recognized human carcinogen.	Plastics and rubber solvents, cigarette smoking, paints and varnishes, putty, filler, stains, finishes, and cleaning fluids
b. Toluene	Narcotic, may cause anemia, muscle fatigue, liver and kidney damage	Solvents, by-product of organic compounds used in several household products, photocopiers, paints, varnishes, glues, enamels, lacquers, and dry cleaning
c. Xylenes	Narcotic, irritating, high concentrations may cause injury to heart, liver, kidney, and nervous system	Used as solvent for resins enamels, etc., also used in nonlead automobile fuels and in manufacture of pesticides dyes, and pharmaceuticals, detected near printing machines

Table 2.1 (cont)
Organics Compounds and Health Effects

Compounds	Health Effects	Sources and/or Uses
Halogenated Hydrocarbons	central nervous system and myocardial depression, kidney and liver damage	cleaning solvents and pesticides
a. 1,1,1 trichloroethane	Subject of OSHA carcinogenesis inquiry	Aerosol propellant, pesticides, and cleaning solvents
b. trichloroethylene	Animal carcinogen; subject of OSHA carcenogenesis inquiry	Oil and wax solvents, used in cleaning compounds, vapour degreasing products, dry cleaning operations; also used an an anesthetic
c. methylene chloride (see above)		flame suppressant, degreasing agent, paint stripper, aerosols
Halogenated Aromatics	Strong narcotic, possible lung liver, and kidney damage	Used in production of paint varnish, pesticides, and various organic solvents
a. pentachlorophenol	under investigation as a potential carcinogen	pesticide, preserves wood, starches, dextrins, and glues
Alcohols	irritants; central nervous system depression resulting in excitation, ataxia, drowsiness and narcosis	aerosols, window cleaners, paints, paint thinners, cosmetics, and adhesives
a. methanol	same as above, and can cause blindness at high concentrations	paints, spot cleaners, and spirit-type duplicating machines
Ketones	central nervous system depression and pulmonary vascular dilation	lacquers, varnishes, polish removers, and adhesives
Ethers	headaches, weakness, drowsiness and disorientation	resins, paints, varnishes, lacquers, dyes, soaps, and cosmetics, certain ethers used as anesthetics
a. dioxane	skin and eye irritation, liver and kidney damage, animal carcinogen	solvent and dispersing agent
Esters	irritate eyes, nose, & throat, some cause central nervous system depression	plastics, resins, plasticizers, and laquers, flavorizers and perfumes, pesticides

Table 2.1 (cont)

Organic Compounds and Health Effects

Compounds	Health Effects	Sources and/or Uses
Pesticides		
a. organicphosphates (including ronnel, dichlorvos, malathion, diazinon, dursban)	anticholinestervase activity, causes wheezing, lacrimation, nausea, bradycardia, fatigue tremors, and headaches	pesticides
b. organochlorides (including lindane, captan, and chlordane)	animal carcinogens, cause headaches, weakness, convulsions, respiratory problems	pesticides
c. carbanates (including carbaryl and propoxcur)	same as organophosphates	pesticides
Monomers Released from Polymers		
a. acrylic acid esters	irritates skin, eyes, mucous membranes	acrylics used in blocks, plexiglas, lucite, and paints
b. epichlorohydrin	destroys mucous membranes, possible human carcinogen	floor tiles
c toluene/diisocyanate	irritates skin, eyes, respiratory tract, sensitizer, may cause asthma	polyurethane used in rubbers and foams
d. vinyl chloride	known human carcinogen, irritant, causes dermatitis, hepatitis, indigestion, ulcers, chronic bronchitis, and after long-term exposure, deafness and blindness	polyvinylchloride plastic used in building materials, household furnishings consumer goods and packaging materials
e. styrene	narcotic, can cause headaches, stupor, depression, incoordination and possible eye injury	used in manufacture of plastics, synthetic rubber and resins

Sources: Beall and Ulsamer, 1981;
Casarett and Doull, 1975;
Hollowell and Miksch, 1981; and
National Academy of Sciences, 1981.

3. COMMERCIAL BUILDING VENTILATION SYSTEMS

Ventilation systems in commercial buildings are often part of a complete heating, ventilating and air conditioning (HVAC) system. The purpose of the HVAC system is to provide a safe and comfortable environment for occupants of the building. Comfort is attained through the simultaneous control of temperature, humidity, and the amount and cleanliness of both outside and recirculated air. The Indoor Air Quality Audit is specifically concerned with the amount and cleanliness of outside and recirculated air in a building although the other factors which the HVAC system controls are often closely related.

The following terms will be used to describe a building ventilation system:

1. Supply Air: Air delivered to a conditioned space.
2. Return Air: Air removed from the conditioned space, to be recirculated or exhausted.
3. Recirculated Air: Air removed from the conditioned space and then reused.
4. Outdoor Air: Air taken from the external environment for use in the conditioned space.
5. Exhaust Air: Air removed from the conditioned space and not reused.
6. Mechanical Ventilation (Supply or Exhaust): Circulation of air by the use of a fan or other mechanical means.
7. Natural Ventilation (Supply or Exhaust): Circulation of air without the use of fans or any other mechanical means.

Ventilation may be provided in a building by one or more of the following methods: natural supply and natural exhaust, natural supply and mechanical exhaust, mechanical supply and natural exhaust, and mechanical supply and mechanical exhaust. While any of these systems may be encountered, for commercial buildings the most prevalent systems are those with mechanical supply and exhaust.

Part of an IAQ audit may involve measuring the amount of outdoor air, or combination of outdoor and clean recirculated air available to each zone in a building. Zones are defined as areas in a building serviced by one conditioning or air handling unit. Building codes typically specify required amounts of outdoor air per unit area or per occupant.

Determining the amount of outdoor air supply in a building with only natural ventilation requires analysis and/or measurement of the infiltration rates through windows, doors, and other openings in the building shell. In buildings with mechanical ventilation systems air flow can be measured in the ductwork, which is generally a more accurate and easy method than infiltration measurements in large buildings.

Figure 3.1 is a simple diagram of a typical mechanical supply and exhaust system. For this type of system the supply air, exhaust air, recirculated air, and outside air flows can be measured in the appropriate ducts for each zone. Heating, cooling, humidification or dehumidification of the air is done with different devices, both at a central unit and often at each terminal.

Indoor air quality is maintained either through dilution or dilution in combination with air cleaning. Dilution uses sufficient quantities of outdoor air to reduce the concentration of pollutants in indoor air. Air cleaning (filtration) conserves energy by lowering pollutant levels in recirculated air to maintain acceptable air quality, thereby reducing the amount of outdoor air required. Outdoor air is also filtered to remove pollutants before it is used as supply air.

Therefore, part of an IAQ audit may involve the evaluation of a building's air filtration system. As shown in Figure 3.1, filters can be located in several locations. The following are the common types of filtration systems found in commercial buildings:

1. viscous impingement filters,
2. dry filters,
3. electronic filtering systems, and
4. renewable media filters.

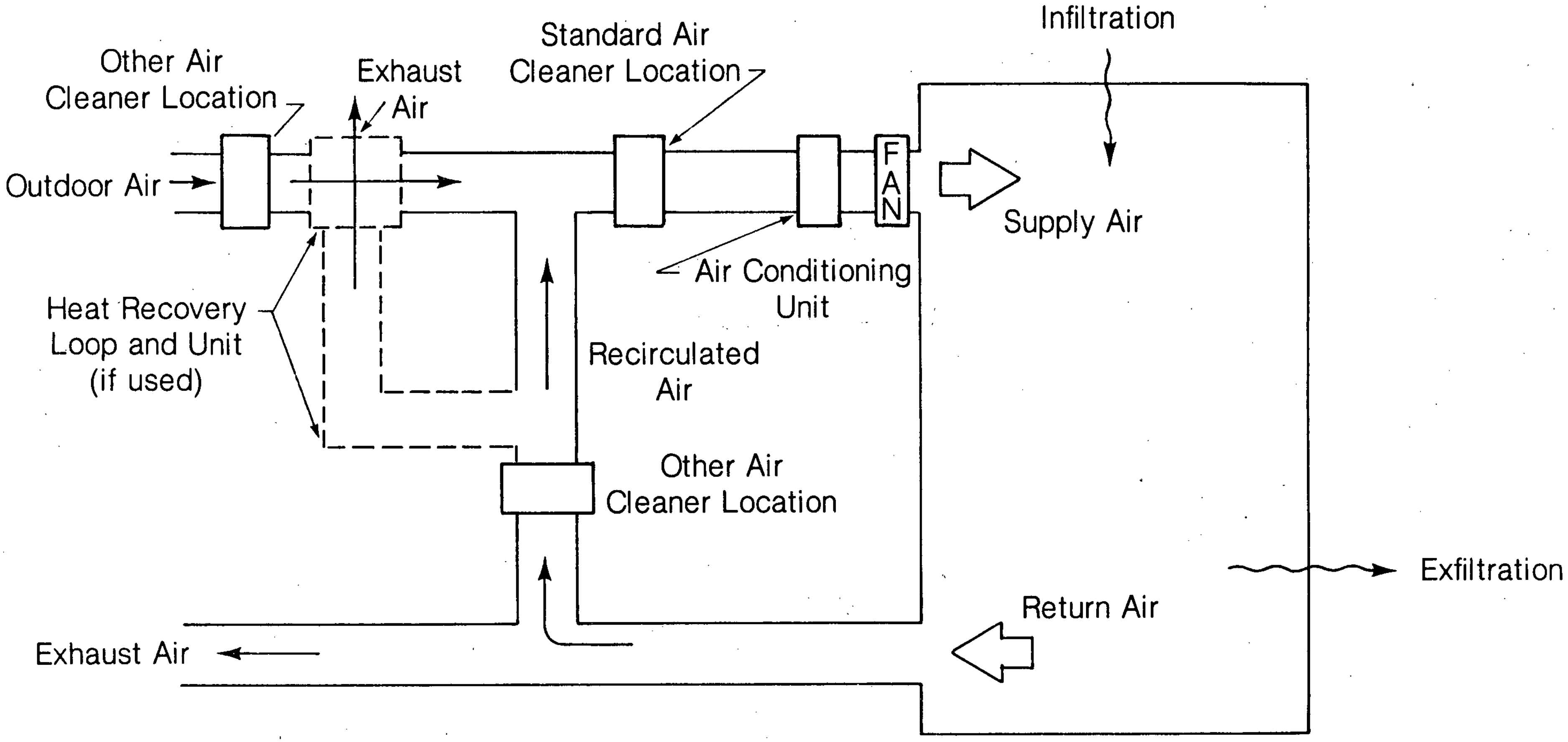

Figure 3.1 Schematic diagram of mechanical ventilation system.

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Filters are rated by their efficiency (ability of a filter to remove pollutants from an air stream), air flow resistance, and dust holding capacity. Efficiency and dust holding capacity, which are important factors for maintaining indoor air quality, are not easily measured for any type of filter. Unfortunately, visual observation is not always a complete indicator of filter condition. Usually knowledge of the filter replacement and/or cleaning schedules, as compared against manufacturer specifications, is needed to confirm that filters are operating satisfactorily.

Numerous mechanical ventilation system problems may result in poor indoor air quality. Some of these are readily observable during an audit, others require careful, time-consuming observations by experienced engineers. Still others require measurements. All possible ventilation system problems can be addressed only in a very detailed IAQ audit. The audits presented in Section 4 are not intended to ensure that all possible problems are investigated, as this would be prohibitively expensive. The options presented range from quick checks of ventilation equipment, i.e., a walk-through audit, to audits where relatively detailed measurements of air flows are made.

The following are examples of problems that may be found in mechanical ventilation systems:

- Control problems - e.g., dampers not positioned correctly, fans not started or stopped.
- Duct leakage - e.g., contaminanted exhaust air forced into buildings.
- Fan problems - e.g., fans not operating at proper speed, installed backwards.
- Damper problems - e.g., outdoor air dampers closed, installed backwards.
- Improper air flow balance - e.g., areas with insufficient or excessive air supply.
- Filter problems - e.g., wrong filters installed or not properly maintained.
- Installation errors - e.g., 100% exhaust terminal connected to return air duct, duct work contains obstructions.
- Design errors - e.g., fans too small, wrong duct sizes. to certain areas, insufficient exhaust in certain areas.
- Renovation errors - e.g., area not designed for current use, air intake located close to contamination source.

4. INDOOR AIR QUALITY AUDIT STRATEGIES

Indoor air quality (IAQ) audits can be organized in several ways. The most fundamental difference is between those that require measurements and those that do not. Audits that forego measurements minimize costs but sacrifice reliability. Measurements are required to ensure maximum confidence in the results of the audit. In this section three audit strategies are presented: (1) walk-through audits, (2) evaluative audits and (3) diagnostic audits.

1. Walk-through Audits are relatively rapid surveys that, without measurements, attempt to determine if an IAQ problem exists in a building.

2. Evaluative Audits consist of pollutant concentration measurements in a building to determine if an IAQ problem exists.

3. Diagnostic Audits include relatively detailed building inspections for pollutant sources and measurements and inspections of the ventilation system. These audits are conducted to determine the cause of an existing IAQ problem, and are only performed after an evaluative audit has been made.

These audit strategies are not exclusive. An optimal audit may combine aspects of all three. For example, the two measurement audits are done in conjunction with each other, with the evaluative audit done first to determine whether a problem exists, then the diagnostic audit conducted only if a problem is found. Also, the walk-through audit would be conducted prior to either of the measurement audit procedures.

The three types of audits described above are applicable for all types of commercial buildings because they provide the flexibility necessary to efficiently evaluate buildings. The primary example of this flexibility is in the walk-through audit checklists -- different checklists can be developed for different building types, uses, conditions, etc (Bonneville Power Administration, 1982a). The Appendix contains examples of different checklists.

4.1 Walk-through Audits

The objective of the walk-through audit is to determine quickly and inexpensively (1) if a building has an existing or potential IAQ problem, 2) the sources of the potential problem, and 3) document results.

Advantages of the walk-through audit include:

1. Low Cost -- The walk-through audit requires no equipment.

2. Minimal Time -- As no long-term measurements are required, the audit and report may be completed within one day for most buildings.

3. Simplicity -- Since the auditor will be looking for specific items in each type of building, a check list approach is

appropriate.

Disadvantages of the walk-through audit include:

1. Low Overall Accuracy -- A walk-through audit can only be used to detect obvious causes or effects of IAQ problems. Unusual problems will probably be missed due to lack of measurements, lack of time, and minimal auditor training and experience. Problems due to minimal auditor experience can be overcome if more qualified and experienced persons perform these audits.

2. No Quantification of IAQ Problem -- Since no measurements will be made it is virtually impossible to determine the absolute magnitude of any IAQ problem with just a walk-through audit.

3. Recommendations Unlikely -- Recommendations for solutions of an IAQ problem are not to be expected from most walk-through audits. Effective solutions can only be developed with a detailed understanding of a problem which usually requires measurements of air quality. A recommendation for further measurements (i.e. an evaluative or diagnostic audit) would, however, be consistent with this audit.

The recommended procedure for a walk-through audit is shown in Figure 4.1. The steps are described below; letters correspond to the steps in Figure 4.1.

A. Characterize Building Type and Use.

This audit procedure covers most commercial buildings. However, there are many types of commercial buildings, and different types may have different primary causes of IAQ problems. Buildings can be grouped into categories which will indicate what is required in the walk-through audit.

B. Select Appropriate Checklists

Sample checklists are contained in the Appendix. The checklists address evaluation of building drawings, if available, and the actual steps required to complete the building evaluation.

Ca. Drawings Checklist

New buildings, buildings undergoing a HVAC system retrofit, and some existing buildings will have accurate sets of construction drawings. These drawings can be used to calculate the HVAC system's outdoor air capacity for comparison with existing codes.

For the actual building inspection, drawings can provide a needed guide and can be compared with existing equipment to find installation errors or improper retrofits. In addition, building drawings may indicate the presence of certain pollutant sources in a building such as excessive laminated wood.

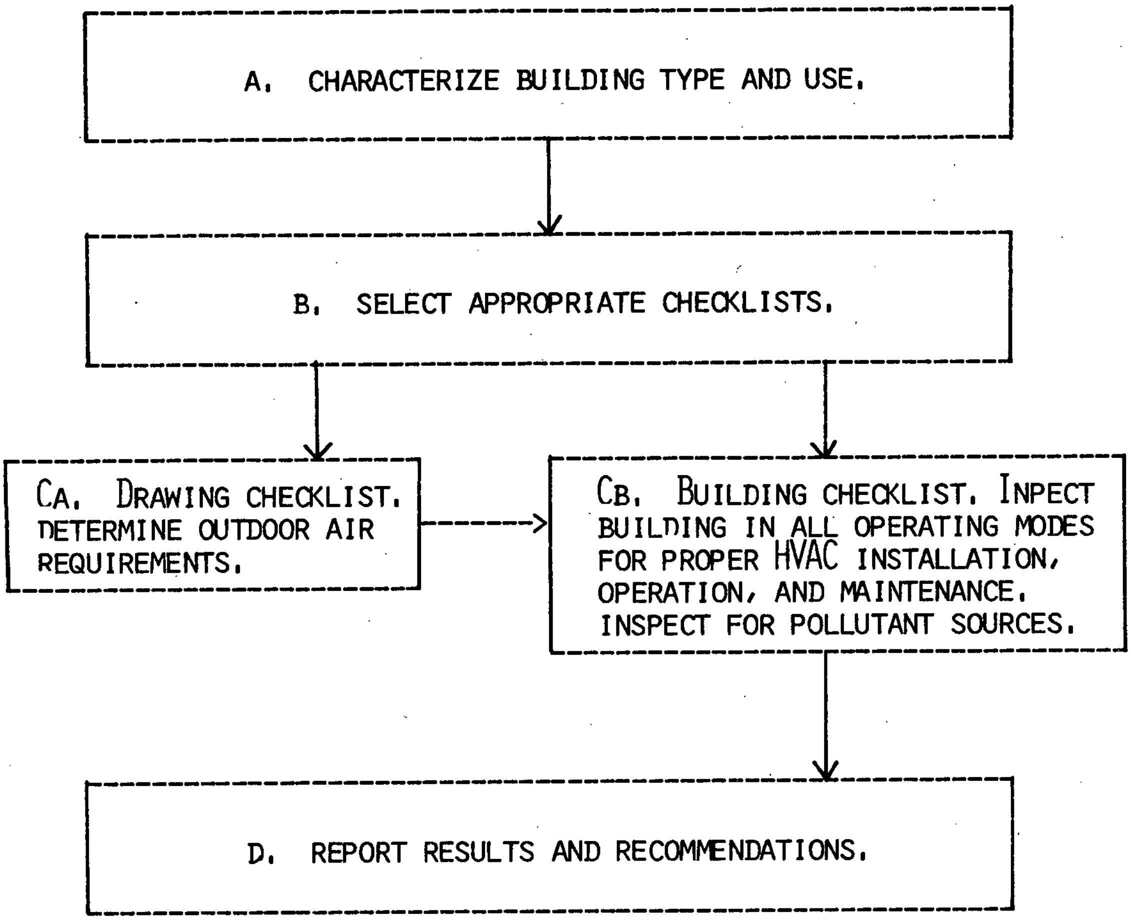
Cb. Building Checklist

Preferably using a set of drawings for reference, a HVAC system can be inspected for gross operation, installation or maintenance failures. For example, observation will verify whether:

- fans operate (broken belts, burned out motors)
- dampers operate (summer/winter position)
- air flow exists at each supply and return terminal
- filter conditions (an indication of proper maintenance).

FIGURE 4.1

WALK-THROUGH IAQ AUDIT PROCEDURE



For most buildings a cursory evaluation of ductwork and proper installation is all that is possible in a walk-through audit. Tracking all ductwork and checking each HVAC system component is a time consuming and tedious task. The building may also be inspected for pollution sources such as those given in Section Two. If drawings or design specifications do not exist, it will be assumed that the building does not have an IAQ problem if the ventilation system appears to be properly installed, operated, and maintained and excessive pollution sources are not found.

D. Report Results

A standard report will be prepared indicating the findings and conclusions of the audit.

No equipment is required for the walk-through IAQ audit. For the IAQ auditor, no particular training in making indoor pollutant measurements would be required as no pollutant measurements are required. However, the auditor should have experience with HVAC systems to evaluate building plans and thoroughly inspect ventilation equipment. Experienced auditors/engineers may be ideal for this audit as they would have the background to detect faulty HVAC system operation and/or if further investigation were necessary.

4.2 Evaluative IAQ Audit

The objective of the evaluative audit is to determine if any specified pollutants exist in a building in excessive concentrations.

Advantages of the evaluative audit are that it:

- Provides a direct indication of an IAQ problem when one of the targeted pollutants exists in an excessive concentration.
- May be non-labor intensive since passive monitors may be left and later retrieved for analysis.
- Eliminates the need for more detailed audits if excessive pollutant concentrations do not exist.

Disadvantages of this audit strategy are:

- All possible pollutants cannot be measured due to technology and/or cost constraints.
- This audit does not indicate the potential for an IAQ problem and therefore may have to be repeated on a regular basis.
- This audit may involve expensive and sophisticated monitoring equipment, requiring an experienced auditor.

- By itself the evaluative audit doesn't indicate causes of IAQ problem(s).

The recommended procedure for an Evaluative IAQ Audit is shown in Figure 4.2. The steps are described below (letters correspond to steps in Figure 4.2).

A. Note building type and use (as determined in walk-through audit.

This audit procedure covers most commercial buildings. However, there are many types and uses of buildings, and each type and use may have specific pollutants (or pollutant classes) associated with it.

B. Monitor for pollutants.

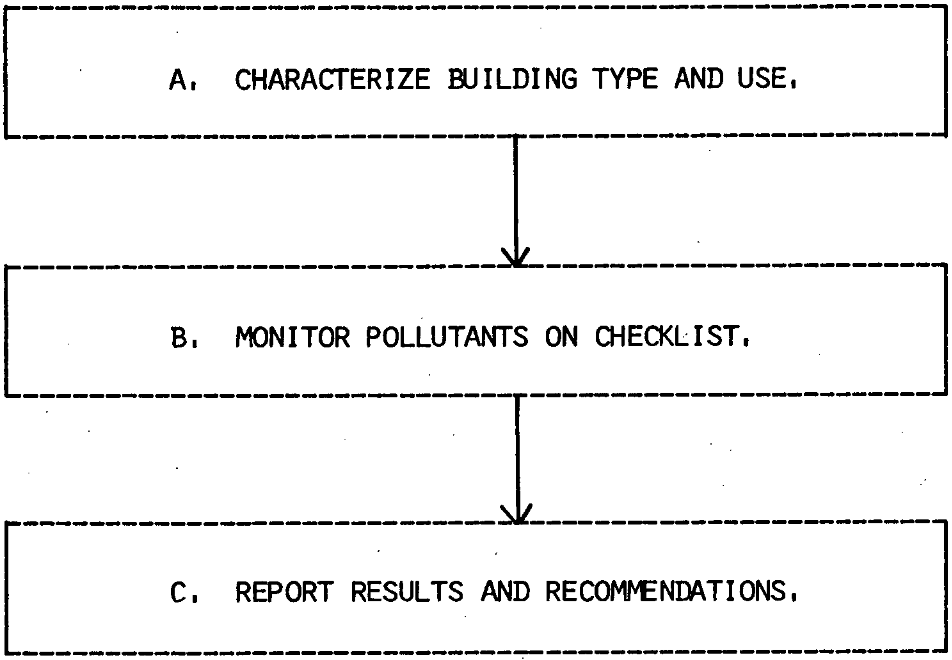
See Section Six and Checklist for evaluative audit in Appendix.

C. Report results.

If none of the pollutants measured exceed guideline values, only a report documenting the findings and conclusions is required. If one or more of the pollutants do exceed acceptable levels, then the report will indicate suspected sources and recommend that a diagnostic evaluation be conducted if necessary. (See step D of Diagnostic Audit, below).

FIGURE 4.2

EVALUATIVE IAQ AUDIT PROCEDURE



4.3 Diagnostic IAQ Audit

The objective of the diagnostic audit is to determine the cause of an acknowledged problem, and document the results.

The diagnostic audit involves thoroughly investigating a building to identify any sources of pollutants found to be at unsafe levels during the evaluative audit. In addition, HVAC systems will be investigated and measurements of outdoor air supply to areas within the building will be made. This can be done directly using a tracer gas or indirectly by measuring the flow rates of the ventilation system. Measurement techniques are discussed in Section Seven.

Advantages of the diagnostic audit are:

- More accurate than a walk-through audit because the distribution of outside air is determined and a relatively detailed investigation of the entire HVAC system is made.
- Sources of the pollutants measured in the evaluative audit are identified and detailed evaluation of the causes of an IAQ problem may be made.

The primary disadvantage of a diagnostic audit is its cost. The measurements require well-trained and experienced personnel, leading to a procedure that is time-consuming and expensive.

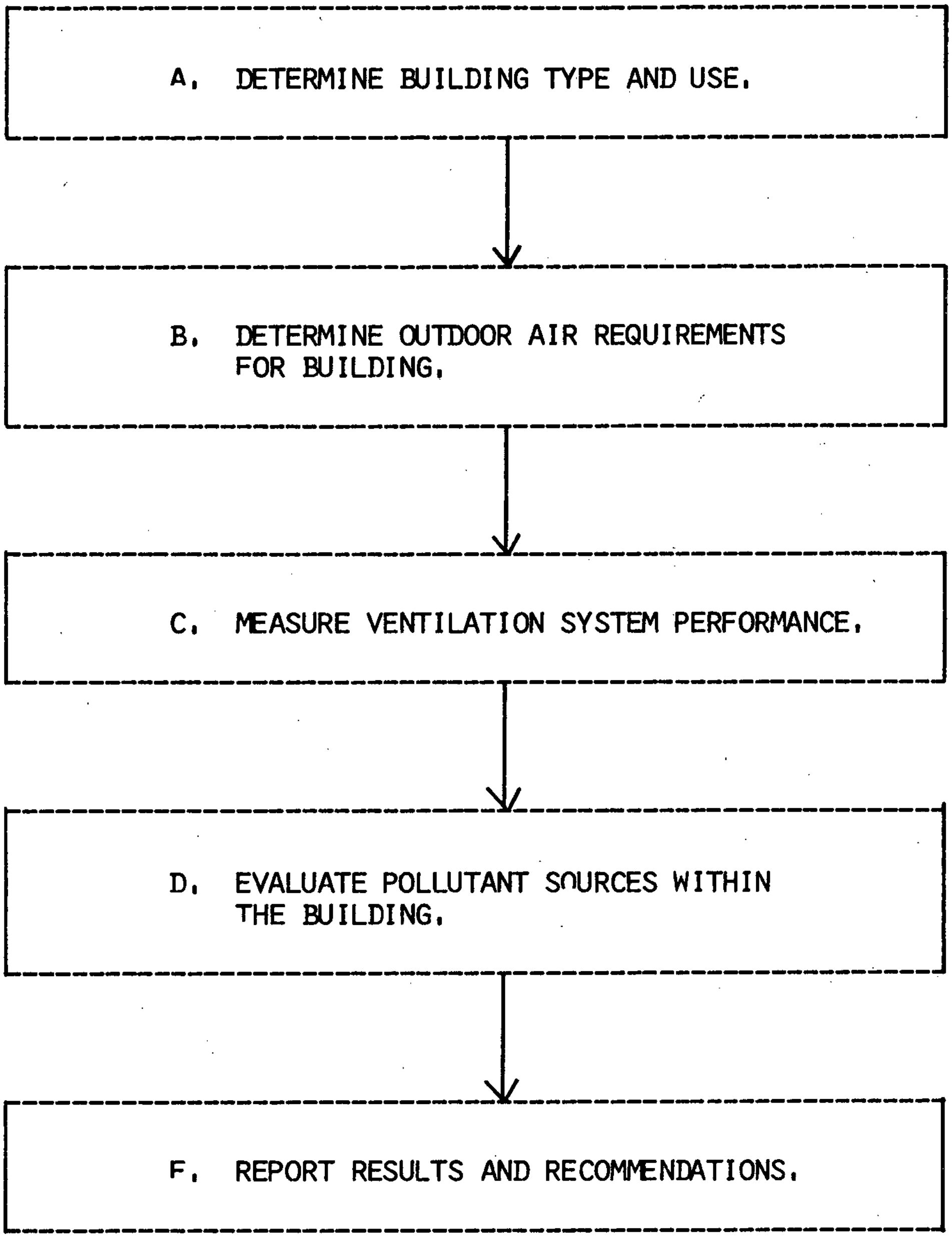
The recommended procedure for a diagnostic audit is shown in Figure 4.3. The steps are described below (letters correspond to steps in Figure 4.3).

A. Note building type and use (as determined in walk-through audit.

The type and use of the building may provide clues as to the likely causes of an indoor air quality problem.

FIGURE 4.3

DIAGNOSTIC IAQ AUDIT PROCEDURE



B. Determine outdoor air requirements for the building.

Before the amount of outdoor air supplied to a building is measured, a determination of the amount required for proper system operation should be made, preferably by zone (see "Calculated Demand for Ventilation" Checklist from walk-through audit). Once measurements are made, requirements can be compared with actual values to determine if the building has a potential IAQ problem. An example of this procedure is given in the Appendix in the "Summary of Ventilation Measurements". Outdoor air requirements will be based on existing standards (e.g., ASHRAE 62-1981 and local codes).

C. Measure ventilation system performance

Measurements of air flow will be aimed at determining the amount of outdoor air and filtered recirculation air that is supplied to some or all of the building's areas. This can be done with direct air flow measurements in each duct, with tracer gas techniques, or with other methods that identify the sources of the various air supplies.

D. Evaluate pollutant sources within the building

If one or more of the pollutants measured in the evaluative audit is in concentrations greater than what is currently considered safe, then efforts should be taken to ascertain the cause(s). Checklists from the walk-through and evaluative audits and information given in Section Two may be used to identify source, but they serve only as a basic reference. For example, if elevated carbon monoxide levels are measured in a space with no combustion sources, a possible outdoor source near the outdoor air supply should be investigated. A complete and thorough audit cannot be done from a checklist, rather it requires a well-trained and experienced auditor.

E. Report results.

A standard report would be prepared indicating the findings and conclusions of the audit.

In the diagnostic IAQ audit, air flow measurement equipment is required and the auditor should possess appropriate experience to enable him/her to determine outdoor air requirements and evaluate HVAC systems. The auditor must also be able to recognize the potential sources of the pollutants detected in the evaluative audit.

5. PERSONNEL AND TRAINING

The quality of any audit is highly dependent on the motivation and skills of the auditor(s). For each of the audits proposed in Section Four, different skills are required of the auditor. The various skills are listed under each audit in Table 5.1 and are described below. An understanding of IAQ and the objectives, constraints, and procedures of each audit will probably have to be taught to each auditor irrespective of his/her skills. Obviously, it is not necessary for every auditor to possess all of the skills listed; they can be shared among two or more auditors.

An engineering technician should have the following skills:

- Ability to read mechanical drawings.
- Understanding of all HVAC system operations.
- Experience in installation and/or maintenance of HVAC systems.
- Thoroughness and attention to detail in his/her work.

A HVAC mechanical engineer should have the following skills, in addition to those of the engineering technician:

- Complete understanding of all HVAC system operations.
- Experience in design of HVAC systems.
- Ability to interpret results of HVAC system measurements.

A chemistry technician would have the following skills:

- Ability to identify sources of indoor air pollutants.
- Familiarity with standard pollutant analysis techniques.
- Knowledge of pollutant monitoring instrumentation.
- Thoroughness and attention to detail in his/her work.

A chemist would have the following skills, in addition to those of the chemistry technician:

- Understanding of sources and health effects of most indoor air pollutants.
- Ability to interpret results of pollutant monitoring experiments.

An instrumentation engineer would have the following skills:

- Ability to operate and maintain monitoring equipment
- Understanding of limitations of equipment
- Ability to interpret results of measurements for equipment or method errors.

Technical writing skills are required to ensure that audit reports are written in a succinct manner.

A training course for potential IAQ auditors and supervisors should address the following topics:

- Introduction to Indoor Air Pollutants and Their Sources
- Health Effects of Common Indoor Air Pollutants
- Relationship between Energy Conservation and IAQ
- Introduction to HVAC System Operation
- Audit Objectives
- Audit Equipment
- Audit Procedures and Techniques
- Interface with Building Occupants

As with any job that requires contact with the "public," auditing requires an interpersonal communication style that will allow the auditor to minimize his/her intrusion while permitting the collection of data. Any auditing class should stress this point.

TABLE 5.1

SKILLS REQUIRED FOR AUDITS (general categories)

	Walk-through	Evaluative Audit	Diagnostic Audit
Auditor:	1,3,6	3,6	1,2,3,5,6
Supervisor:	2,4	4,5	2,4,5

1. Engineering technician.
2. Mechanical engineer.
3. Chemistry technician.
4. Chemist.
5. Instrumentation engineer.
6. Technical writer.

6. EQUIPMENT AND TECHNIQUES FOR MEASURING INDOOR AIR POLLUTANTS

This section contains information on equipment and techniques currently available for measuring indoor pollutants.

6.1 Pollutants To Be Measured

Pollutants commonly monitored in IAQ audits are given below and include those addressed in the BPA Commercial Building Environmental Assessment (BPA,1982b).

Pollutant	Level of Concern
Radon	3 pCi/l
Formaldehyde	120 $\mu g/m^3$(100 ppb)
Airborne Particles	75 $\mu mg/m^3$(annual average) 260 $\mu mg/m^3$(one-day average)
Carbon Dioxide	4500 mg/m^3(2500 ppm)
Carbon Monoxide	10 mg/m^3(9 ppm)(8hr average)
Water Vapor	------------

In addition to these pollutants, nitrogen dioxide would be measured if a major indoor source such as an unvented combustion appliance had been identified within the building of if an outside air supply intake was found to be located near an important outdoor source of NO_2.

Another major pollutant class not included in the list above general group called airborne organics. This class has recently is the been identified by the World Health Organization as an area of primary research interest (WHO,1982) although presently neither sampling nor analysis techniques for organics are well characterized. In the future, as the importance of these pollutants is better understood and as sampling techniques are developed and improved, instrumentation and protocols would be added to the standard measurement techniques section.

6.2 Instrumentation for pollutant measurements

The table below lists suggested instrumentation for determining concentration levels of the pollutants discussed above. For some of the pollutants more than one commercial device is available within the suggested instrument class. Cost, reliability, and availability should be considered when purchasing equipment.

Table 6.1. Pollutant Measuring Equipment

Pollutant	Instrument	Notes
CO	Electrochemical	Real-time monitoring. Output on stripchart recorders or data logger.
CO_2	Nondispersive I.R.	Real-time monitoring.
HCHO	Passive sampler	Sample averaged over buildings occupancy periods.
NO_2	Passive sampler	Sample averaged over building occupancy periods.
Radon	Track-Etch Passive Sampler	One-month sampling,intensive analysis.
Particulates	EPA-type flow controlled cyclone separator for RSP	Gravimetric analysis;HPLC analysis for PAH's if warranted.
Organics	Solid Sorbents	Analysis by GC or GC/MS.
Water Vapor	Passive Sampler/ Hygrometer	Gravimetric analysis/ real-time monitoring

The instrumentation given above reflects the current most cost effective state-of-the-art techniques for determining various pollutants in ambient air. Before an audit program is established, the sales market should be reviewed to identify improved sampling devices for each pollutant (e.g. passive samplers for CO are presently under development). Passive samplers, which require no pump for air sampling and give integrated time-weighted average pollutant concentrations, are convenient for indoor air sampling due to their low cost and ease of operation. They do not, however, yield real-time concentration data which may be important in evaluating acute responses to pollutants.

It must also be stressed that the performance if any passive sampler depends on the quality control exercised by the manufacturer. Quality control reports should be reviewed periodically and blanks included with every purchase of samplers. Real-time analyzers should be calibrated over the entire range of expected concentrations upon receipt of the instrument and at regular intervals to insure accuracy in field use.

6.3. Pollutant measurement protocols

6.3.1 Select Sampling Sites. Often commercial buildings contain more than one air handling system. Since it is important to sample the air supplied by each system separately, multiple sampling sites will usually be required in these audits. For example, in buildings with more than two stories, nine sampling sites could be chosen such that the lowest floor, a representative middle floor, and a floor near the top of the building each contain three sampling sites. These sites should be located in areas of human occupancy but not in locations containing any industrial activities (i.e. print or welding shops) where worker exposure to contaminants is regulated by the Occupational Safety and Health Administration.

6.3.2. Passive Samplers. Passive samplers for formaldehyde, nitrogen dioxide, and water vapor are deployed in triplicate at each sampling site. Samplers should be located at breathing heights appropriate for the occupied zones of the building, away from diffusers, returns, and open doorways. Care should be taken to avoid placing the samplers in bookshelves or other areas where the air does not mix well with occupied areas of the building. Samplers are uncapped to initiate sampling at the beginning of the workday and re-capped eight to ten hours later (when workers leave) to ensure that only actual occupant exposure to contaminants is measured. (Care must be taken to record the time every sampler is uncapped and capped.) The total cumulative exposure time of each passive sampler must be adequate to meet required minimum detection levels.

6.3.3. Radon Measurements. One Radon Type-F Track Etch detector is deployed for one month at each of the nine measurement sites. Current thinking suggests that the dominant radon source in buildings in the U.S. is the soil on which the building is found. However, few radon measurements have been made in high-rise buildings(Abu-Jarad 1982). Therefore, the radon measurement sites should not be biased toward the lower floors until it can be shown that these are the only areas of concern. It is recommended that each monthly measurement be analyzed by Terradex Corporation using their most sensitive analysis procedure to improve the counting statistics associated with the short measurement interval.

6.3.4. Real-time Analyzers. Real-time sampling is performed at all three sites on each floor for two (not necessarily consecutive) workdays during the overall test period. Sampling takes place during the regular hours of building operation. Single instruments for CO and CO_2 may be used to sample all sites on a floor in one day using a manifold which connects sampling lines from each site to the devices. Continuous sequential samples are then taken from the three sites. Data may be logged on a chart recorder or by an internal or external data logging system. Each instrument should be calibrated with zero and span gases(provided by the manufacturer) before and after each sampling period.

6.3.5. Particulate Samplers. Three separate particulate samplers are placed at each site on a floor and operated concurrently with real-time analyzers. (Two one-day measurements per site). Flow rates should be checked before and after each sampling period. The recommended EPA-type cyclone samples are measured gravimetrically and may also be analyzed for polyaromatic hydrocarbons by high performance liquid chromatography if significant combustion sources are present.

6.3.6. Volatile Organics. Volatile organics may be collected on a solid sorbent (e.g. Tenax) which is returned to a laboratory for analysis by gas chromatography/ mass spectrometry. Three pumped air samples should be taken simultaneously at each sampling site for a period between one and three hours.

7. MEASUREMENT TECHNIQUES AND EQUIPMENT FOR DETERMINING AIR FLOW RATES

Air flow measurements can be made to investigate infiltration rates, exfiltration rates, and air movement in rooms. However, the most common objective is to determine the amount of outdoor air supplied to an entire building (or individual zone). Two general methods are used for measuring outdoor air supply rates: tracer gas techniques and direct air flow rate measurements in ducts. Tracer gas techniques can be used in buildings with or without mechanical ventilation. Air flow rate measurements in ducts are only relevant for buildings with mechanical ventilation.

7.1 Tracer Gas

A tracer gas is used as a marker or tag to distinguish the air within the building from that outside. When a tracer gas is well-mixed with air within the building, outside air dilutes the tracer; the change in concentration as a function of time is an indication of the rate of entry of outdoor air.

An ideal tracer gas is (a) normally absent from both the inside and outside air; (b) safe and non-toxic; (c) inexpensive; (d) easily measured at small concentrations; (e) non-reactive (so that dilution by outside air is its only removal mechanism from the interior; (f) approximately equal to the molecular weight of air. There are no gases that meet all these criteria. However, many gases closely approximate the ideal tracer gas and have been used with success in measuring ventilation rates in buildings. The gases most commonly used are nitrous oxide, sulfur hexafluoride, carbon dioxide, ethane, and methane.

7.1.1 Tracer Gas Techniques. The concentration of tracer gas within the building changes as additional tracer is injected into the volume or as outside air enters the building to dilute the existing gas. This process is described by the mass balance equation:

$$V \frac{dc}{dt} = F - Qc \qquad (7.1)$$

where V is the volume of the building [l]
c is the concentration of the tracer
F is the injection rate of tracer into the building [l/s]
Q is the rate of outside air entering the building [l/s]

We shall examine the solution of this equation in the framework of the specific measurement procedures described below.

Tracer Decay. In this case tracer gas is injected into the building and mixed until the concentration throughout the building is uniform. At this point the injection is discontinued (F = 0)). The solution of the mass balance equation becomes:

$$c(t) = c_0 \exp[-\frac{Q}{V}t] \qquad (7.2)$$

where c_0 is the concentration at time t = 0 and the other symbols were defined in eq. 7.1.

Measurements of the logarithm of the concentration are plotted as a function of time; the slope of the straight line that results (the decay curve) has the value -Q/V. Therefore, the ventilation rate, i.e. the rate of entry of outside air into the building, is obtained by multiplying the negative of the slope of the decay curve by the volume of the building.

This procedure yields the <u>total</u> ventilation rate, i.e. the sum of the designed mechanical ventilation and any additional ventilation due to air leakage (infiltration) that occurs from pressure differences across openings in the building shell. Several assumptions are inherent in the use of this procedure and must be noted: (a) the entire volume is considered to be a single zone; (b) the entire zone is assumed to be well-mixed; (c) the ventilation rate is assumed to be independent of time during the measurement period; (d) the volume term is assumed to be the actual physical volume of the building. any of these assumptions can be questioned; the time independence of ventilation rates is the assumption that is most questionable. If the ventilation rate varies during the measurement period the decay curve will cease to be linear. (The converse is not true, i.e. non-linearity of the decay curve may occur because of mixing problems, coupling of two distinct zones, or changes in ventilation rate.) The measurement of ventilation must be considered to be an average that is expressed over the time interval of the decay curve.

<u>Constant Injection</u>. A second technique can be used to determine the rate of entry of outside air into the building. Injecting tracer gas into the volume at a constant rate, F, will eventually lead to a steady state concentration, C_s, in the building. In steady-state the left side of eq. 7.1 goes to zero and

$$Q = \frac{F}{C_s} \tag{7.3}$$

where Q is the steady-state ventilation rate [l/s]
F is the constant tracer gas injection rate [l/s] and
C_s is the steady-state concentration of tracer in the volume.

One interesting feature of eq. 7.3 is the absence of a term involving the volume. This means that any uncertainty about the physical volume actually participating in the ventilation process does not affect the outside air measurement.

A practical problem associated with this procedure is the length of time required to achieve steady state. Typically, this is of the order of five time constants where the time constant for this process is of the order of V/Q, the volume divided by the ventilation rate. The ventilation rate can be approximated by solving eq. 7.1 explicitly for Q:

$$Q = \frac{F}{c} - \frac{Vdc}{cdt}$$

A variation of this procedure is obtained if the tracer gas is injected directly into the outside air intake of the building. In steady state the result obtained is identical to eq. 7.3, i.e., the ventilation rate is equal to the ratio of the tracer injected into the outside air intake and the steady state concentration in the building.

Modified Approaches. Two special cases of the procedures described above are useful to note, the use of CO_2 as the tracer gas (Turiel, 1982) and a long-term integrating measurement procedure using a perfluorocarbon tracer gas (Dietz, 1982).

Carbon dioxide is the earliest known tracer gas (Pettenkofer, 1858). However, since CO_2 is exhaled by occupants in varying amounts and is also present in outside air, it has not been used extensively as a tracer gas in occupied buildings. Turiel and Rudy noted, however, that in many commercial buildings, occupancy changes sharply late in the day when the work force leaves. In this situation, the building contains an initial concentration of CO_2 well above that of the outdoor background concentration, but the injection rate from the building occupants has disappeared. Consequently, the concentration of CO_2 decreases exponentially with a time constant given by V/Q as in eq. 7.2. This measurement procedure obviously is limited to a single measurement period each day but can provide a useful check on other techniques.

The use of a perfluorocarbon tracer technique has been developed by Dietz and co-workers to provide long-term averages of infiltration in residences. The technique is also suitable for commercial buildings. The procedure is similar to the constant injection rate technique. The tracer gas, however, is collected using a passive diffusion-tube sampler that collects a small volume of air steadily during the measurement periods by adsorption. After completing the measurements, the sample is analyzed by measuring the amount of tracer collected using a gas chromatograph. The system is extremely sensitive; concentrations of the order of parts in 10^{12} to parts in 10^{15} are capable of detection.

Measurement Problems. The discussion to this point has neglected the topic of ventilation efficiency. This is the term that describes the effectiveness of mixing the outside ventilation air throughout the occupied space. Ventilation standards such as ASHRAE 62-1981 are written assuming that the ventilation rates specified reach all occupants equally. Many features of actual ventilation systems may prevent that ideal from being reached. Using tracer gases to measure the distribution of outside air throughout the occupied space is an important area of current research. Future audit procedures will likely include a protocol for these measurements. It is premature at this time, however, to present a procedure for use.

7.1.2 Tracer Gas Measurement Equipment. The most important instrument for tracer gas measurements is the analyzer used to determine the tracer concentration. These instruments generally fall into two categories.

A non-dispersive infrared analyzer (NDIR) is an instrument that measures the absorption of infrared energy of a particular wavelength by a gas sample and converts this to a measurement of concentration. These instruments, costing between \$2000 and \$6000, typically are sensitive to concentrations in the parts per million to hundreds of parts per million range. Unless the tracer sampled is CO_2 produced by the occupants, this limitation in sensitivity restricts the application of these instruments to residences and other small buildings. NDIR instruments can be used to measure concentrations of each of the tracer gases listed previously (CO_2, N_2O, SF_6, CH_4, and C_2H_6).

An alternate technique using a gas chromatograph with an electron capture detector can be used to measure concentrations of SF_6 and freons in the concentration ranges of 10^{-6} ppm to 1 ppm. This sensitivity means that a building with a volume of 10^6 ft^3 requires only about 10^{-3} ft^3 (27 cm^3) of tracer gas at standard temperature and pressure to initially fill the volume for subsequent measurement. This instrumentation costs on the order of \$10,000 and, because the gas sample must be separated by a GC column, does not produce a continuous output. However, the characteristic time constants of most ventilation processes is of the order of minutes or tens of minutes so that this restriction is not serious.

7.2 Measuring Air Flow in Ventilation Ducts

In this section the methods and equipment used for determining the supply rate of outdoor air to an entire building or particular rooms are discussed. These methods are only applicable to buildings with mechanical ventilation. The measurement techniques discussed are specifically aimed at buildings with both mechanical supply and exhaust, although they would also apply for buildings which have only mechanical supply or exhaust.

7.2.1 Measurement Techniques. For buildings with only mechanical ventilation, the outdoor air supply to the entire building is determined by measuring the volumetric air flow rate in the outdoor air supply duct of each HVAC unit. Figure 7.1 shows a simplified HVAC system. In this figure point 4 is the measurement point for determining outdoor air supply. In some systems this can be a difficult measurement because access to the duct may be limited and insufficient lengths of straight duct may exist (Wexler and Schiller, 1983).

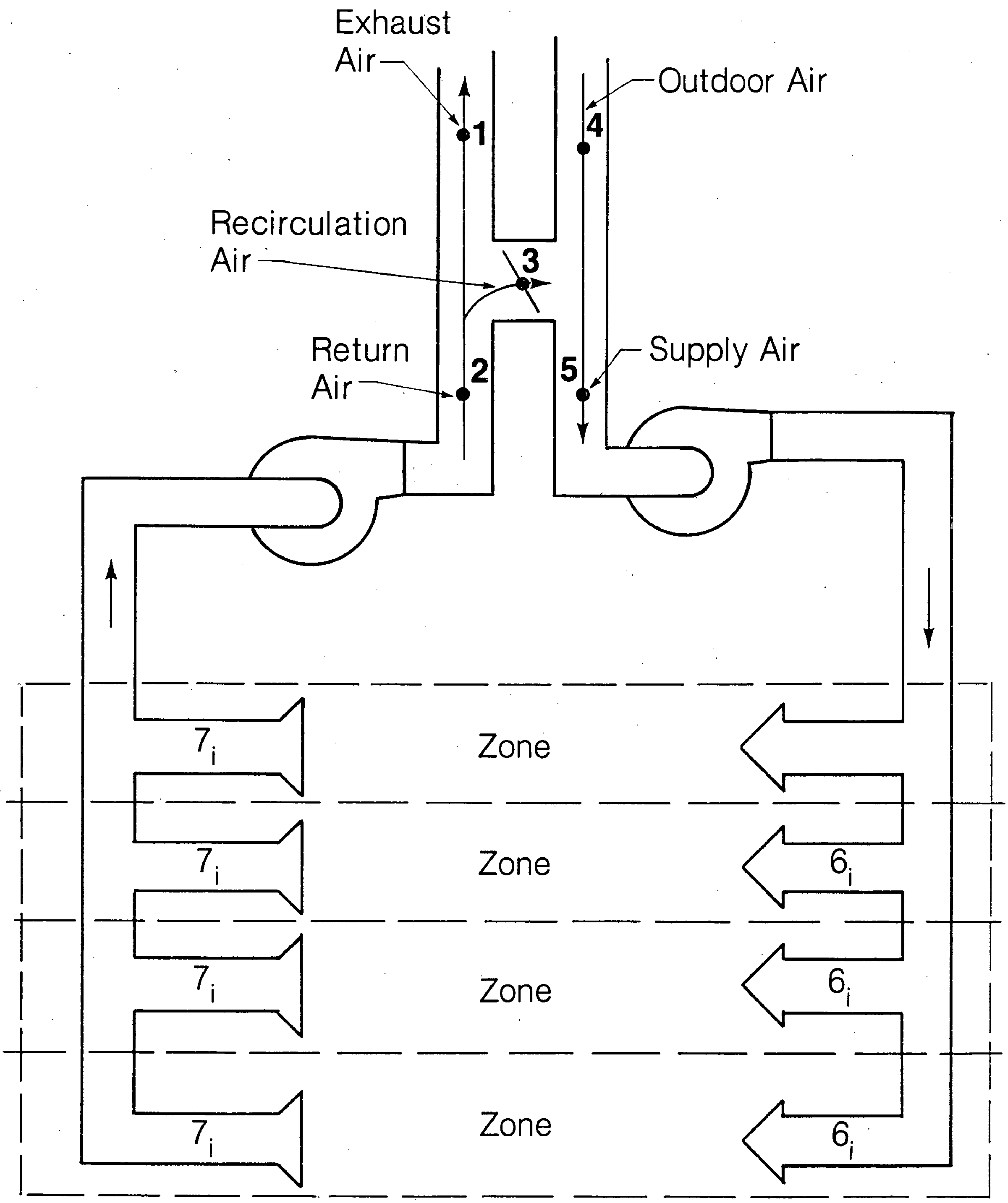


Figure 7.1 Details of a simplified HVAC system. XBL839-854

To determine the amounts of outdoor and recirculated air supplied to each area in a building requires additional measurements. First, the air flow rate from each supply terminal (points 6i in Figure 7.1) must be measured. After this is completed, the percentage of outdoor and recirculated air in the ductwork supplying their terminals is determined. This is done by measuring the volumetric air flow rate at any two of the following three points (shown in Figure 7.1):

point 3: recirculation air,
point 4: outdoor air, and
point 5: supply air.

and using the following relationships:

$$\%\ \text{outdoor air} = \frac{Q4}{Q5} \times 100 \quad \text{and}$$

$$Q5 = Q4 + Q3$$

Here Qn is the volumetric air flow rate at point n.

The outdoor air supply at terminal 6i is therefore the product of the percent of outdoor air and the flow rate at point 6i.

$$\text{outdoor air supply for zone(i)} = (\text{percent of outdoor air}) \times Qi$$

As an alternative to this procedure for determining the percent of outdoor air supplied by the HVAC unit, temperatures can be measured at locations 3, 4 and 5. Then, using the following relationships, the percentage of outdoor air supplied by the HVAC system can be calculated.

$$(Q5)\ (T5) = (Q4)\ (T4) + (Q3)\ (T3)$$

$$Q5 = Q4 + Q3$$

$$\%\ \text{outdoor air} = \frac{T5 - T3}{T4 - T3}$$

Because air turbulence assists this approach and because duct access requirements are reduced, the temperature method may be the best and easiest method of determining the percentage of outdoor air. A sizable difference in return air and outdoor air temperatures is desired for greatest accuracy.

It should be noted that these calculations and the required measurements are only meant to indicate average, steady-state values. Instantaneous values are both difficult to measure and unnecessary for IAQ audits.

7.2.2 Air Flow Measurement Equipment. Four types of instruments are commonly used for measuring air flow rates in ducts. These are:

- heated probe transducers,
- vane anemometers (revolving and deflecting vanes types),
- pitot tubes, and
- balancing cones.

All of these devices, except the balancing cones, measure point velocities. To accurately determine a volumetric flow rate in a duct requires the weighted averaging of several point velocities. Thus a traverse of several measurements should be made of air velocities in a duct. Some sources recommend as many as 16 to 64 measurements for complete accuracy, but usually only two or three are made due to time restrictions. The accuracy of an air flow measurement should include the inaccuracies introduced into the measurement when calculating the volume flow rate from one or more point velocity measurements. An additional consideration for air measurements is to make sure the measurement is not taken near flow disturbances, e.g. elbows. Pitot tubes are especially sensitive to flow disturbances.

Temperature probes can be used to indirectly, but often more accurately, determine flow rates as described in section 7.2.1 The best type of temperature probes for this type of measurement are thermocouples, thermistors, or RTDs connected to direct read-out devices.

Heated Probe Anemometers. These non-linear devices, which come in a wide variety of probe sizes and shapes, operate on the principle that the rate of heat transfer from the probe is directly related to the mass flow rate of air over the probe. The probe's heat transfer rate is measured with one of two techniques. The first technique involves heating the probe with a constant heat input and then measuring the probe's temperature. The second technique involves a feedback loop that keeps the probe temperature fixed. The amount of power required to keep the probe at this constant temperature is measured.

Heated probe anemometers are rugged, reliable and easy to use. In addition, well made and calibrated probes can provide accurate readings across a wide range of air flow rates. The most accurate heated probe anemometer, hot wire anemometers, are unfortunately quite delicate and expensive and thus not recommended for field measurements.

Vane Anemometers. There are two general types of vane anemometers: revolving and deflecting vane. Deflecting vane anemometers (DVAs) typically are not used for measuring flow rates in ducts, but are used more commonly for determining the speed and direction of air flows in rooms. Revolving vane anemometers (RVAs) are used for measurements in ducts.

The DVA has a pivoted vane enclosed in a case. Air passing through the case exerts a pressure on the vane proportional to air velocity. The distance the vane deflects, against a calibrated spring, is indicative of air speed. This device requires periodic calibration.

The RVA has a propeller shaped sensor which rotates at a speed proportional to air velocity when placed perpendicular to an air stream. The speed of the propeller is transmitted, either by mechanical gear train or an electric pick-up, to a display device. Accuracy of RVAs is determined by the quality of the transducer (particularly its guide bearings), the air velocity, and how often it is calibrated. Typically accuracy falls off substantially at flows near the bottom of an RVA's range.

Pitot Tubes. The pitot tube mechanism is based on Bernoulli's principle that the source of fluid velocity is proportional to the square of the difference between the total pressure and static pressure in a fluid stream. Total pressure is measured with a pressure tap that faces the air stream and the static pressure is measured with a tap perpendicular to the flow stream. The pressure difference is measured to determine air velocity. Single pitot tubes indicate a point velocity. Pitot tube arrays measure pressures at several points to determine an average duct velocity.

If properly installed, with flow straighteners and in a proper configuration, pitot tube arrays will provide an accurate indication of volumetric air flow rates. To measure the difference between static and total pressure requires a pressure transducer, e.g., a manometer or magnehelic gage. The proper installation of pitot tube arrays is much too time consuming and expensive for IAQ monitoring. However, some large HVAC systems will have pitot tube arrays installed in critical locations which can be used.

Balancing Cones. Balancing cones, which have a variety of trade names, consist of a collector section which fits over an air inlet or outlet, a pitot tube array for measuring flow rates, and a transducer/display device for indicating volumetric flow rates. The collection section is simply fit over an inlet or outlet vent and within a few seconds the display device indicates a steady state flow rate. The collector sections and pitot tube arrays come in a range of sizes for measuring various flow rate ranges and sizes of vents.

Usually purchased as a package with several different sizes, the balancing cones provide an accurate measurement of air flow into or out of a room or zone.

Hand-Held Tachometers. Another method for determining air flow rates is through a determination of a fan's rotation speed and the differential pressure change across the fan. This information can be used with the fan's characteristic curve to indicate the volumetric flow rate. Differential pressure can be determined with pitot tubes, as described earlier. Fan speeds can be measured with a hand-held tachometer. These devices attach to the fan's shaft in a number of ways and directly indicate the number of rotations. This information combined with a stop watch indicates fan speed. Hand-held tachometers cost between $40 and $200.

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Appendix

Table of Contents

Sample Checklists

Walk-through Audit

Evaluative Audit

Diagnostic Audit

SUMMARY BUILDING INFORMATION

IDENTIFICATION:

Audit Identification Number ____________ Date of Report ____________

Day, Date and Time of Audit ____

Auditing Organization Name and Address ______________________________

Name of Auditor ______________________ Telephone No. ______________

Building Name ____

Address ____

Principal Contact ____________________ Telephone No. ______________

Address ____

Building Owner _______________________ Telephone No. ______________

Address ____

Reason for Conducting Audit ____

BUILDING CHARACTERISTICS AND COMPONENTS:

Use(s) ____

Occupancy Schedule with Average No. of Occupants ___________________

____

Age _________________ Expected Remaining Life _____________________

Building Floor Area _______________ Number of Stories ______________

Description of Site ____

Type of Ventilation System(s) ______________________________________

Construction Drawings Made Available to Auditor? Type? ______________

____

Future Plans for Changes in Use, Construction, or Demolition _________

____

____

SUMMARY OF WALK-THROUGH AUDIT FINDINGS

BUILDING NAME:
AUDITOR'S NAME:

AUDIT IDENTIFICATION NO.:
DATE:

VENTILATION SYSTEM

Amount of outdoor air supply:

Condition of ventilation equipment:

Operation of system:

Maintenance of system:

POLLUTANTS

The following potential sources of pollutants were found in the building:

RECOMMENDATIONS

The following actions are recommended:

BUILDING DRAWINGS

BUILDING NAME:
AUDITOR'S NAME:
AUDIT IDENTIFICATION NO.:
DATE:

DRAWINGS INFORMATION

Type ______________________ Date ______________________

Current? yes __________ no __________ unknown __________

Condition? ____

VENTILATION SYSTEM DESCRIPTION

Ventilation Equipment:

Unit No.	Location	Description
1		
2		
3		
4		

CALCULATED DEMAND FOR VENTILATION

BUILDING NAME:
AUDITOR'S NAME:
AUDIT IDENTIFICATION NO.:
DATE:

Source of outdoor air requirements: ASHRAE 62-1981 ________ other ________

Area No.	Description	CFM Requirement	Minimum Outdoor Air Flow Required
1			
2			
3			
4			
5			

TOTAL OUTDOOR AIR FLOW REQUIRED: ____________

* If fresh supply air requirements are to be partially met with clean, recirculated air, indicate minimum outdoor air required and minimum recirculated air required based on assumed efficiency of air cleaning equipment.

Assumed air cleaning efficiency: ____________

VENTILATION SUPPLY

BUILDING NAME: AUDIT IDENTIFICATION NO.:
AUDITOR'S NAME: DATE:

Source of outdoor air supply data: drawings _________ calculations _________

Unit No.	Operating Mode	Unit's Total Air Volume Flow Rate	Unit's % Outdoor Air Flow Rate	Outdoor Air Supply to Areas*				
				1	2	3	4	5
1								
2								
3								
4								
TOTALS OPERATING MODE								

---

* If clean, recirculated air system is used, indicate amounts of clean recirculated air supplied and outdoor air supplied.

OBSERVED VENTILATION SYSTEM PERFORMANCE AND POLLUTANT SOURCES

BUILDING NAME:

AUDITOR'S NAME:

AUDIT IDENTIFICATION NO.:

DATE:

Area No.	Location	Smoking(a)	Ventilation(b)	Pollutants(c)	Notes
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					

(a) smoking: none - N; moderate - M; substantial - S

(b) check ventilation for the following:
air movement out of supply registers
air movement into return or exhaust registers

(c) check for evidence of pollutants:
(i.e., recognized sources, adverse health effects)

VENTILATION EQUIPMENT

BUILDING NAME:
AUDITOR'S NAME:

AUDIT IDENTIFICATION NO.:
DATE:

VENTILATION UNIT INFORMATION

Number ______________ Location ______________________________

Type ____

Overall Condition ______________________________________

____

Filter Types ______________________________________

Filter Locations ___________________________________

OPERATING MODES

Mode	Status	Position of Outdoor Dampers (% OA)	Position of Recirc. Dampers (% recirc. air)	Supply Fan Speed (% of design)

CONDITION OF VENTILATION EQUIPMENT

BUILDING NAME: AUDIT IDENTIFICATION NO.:
AUDITOR'S NAME: DATE:

Component	Condition Good	 Minor Problem	 Major Problem	Description (if minor or major problem)
Controls:				
Ductwork:				
Insulation:				
Dampers:				
Filters:				
Fans/Fan Motors:				
Exhaust Unit:				
Maintenance Schedule:				

BUILDING MAINTENANCE

BUILDING NAME:
AUDITOR'S NAME:

AUDIT IDENTIFICATION NO.:
DATE:

Procedure	Frequency	Materials

SAMPLING SITE DESCRIPTION

BUILDING NAME:
AUDITOR'S NAME:

AUDIT IDENTIFICATION NO.:
DATE:

			Description		
Site I.D.	Floor	Type	Occupancy	Pollutant Sources	Air Handling Systems

SAMPLING WORKSHEET

BUILDING NAME: AUDIT IDENTIFICATION NO.:
AUDITOR'S NAME: DATE:

Pollutant ____________________ Site I.D. ____________________

Instrument calibration (if any) ____

Sampler	Location	Day/Time

Notes

SUMMARY OF EVALUATIVE AUDIT FINDINGS

BUILDING NAME:
AUDITOR'S NAME:

AUDIT IDENTIFICATION NO.:
DATE:

Site No.	Pollutant	No. of Measurements	Average Concentration	Exceeds Guidelines

SUMMARY OF VENTILATION MEASUREMENTS

BUILDING NAME:
AUDIT IDENTIFICATION NO.:
AUDITOR'S NAME:
DATE:

Air handler #: ____________________

Percentage of outdoor air at minimum setting: ____________________

Measured Airflows

Location	Type	Measured Flow	Designed Flow
1.			
2.			
3.			
4.			
5.			
6.			
7.			
8.			
9.			
10.			
11.			
12.			
13.			
14.			
15.			
TOTAL		____________	____________

DIFFERENCE ____________

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