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REVIEW OF STRATEGIES USED TO INVESTIGATE INDOOR AIR QUALITY PROBLEMS

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ABSTRACT

In the last 20 years, indoor air quality problems have been investigated in thousands of buildings throughout North America and western Europe. The evaluative strategies and protocols used by different researchers have generally been similar, despite differences in terminology and organization. Most investigators recognize the need to apply a multidisciplinary approach to identify and diagnose indoor air quality problems, including assessment of the physical building, occupant discomfort and ill health, and air quality and thermal conditions. Implementation of the various strategies has led to remarkably consistent conclusions; design and operational inadequacies with heating, ventilating, and air-conditioning systems are a principal cause of indoor air quality problems, having been shown as the cause in more than 50% of investigated buildings. As a consequence, indoor environmental criteria are now being integrated into the design and commissioning process in some North American building projects, and governments are developing specific air quality procedures and regulations for nonindustrial workplaces.

INTRODUCTION

The quality of the air inside office buildings and other nonindustrial workplaces has been of growing concern over the last 20 years. The World Health Organization has estimated that 30% of newly built or renovated buildings may have problems associated with poor indoor air quality (IAQ) and the "sick building syndrome" (WHO 1984). The deterioration in IAQ in buildings in the last 20 years has been associated with energy conservation actions such as reduced ventilation and increased insulation, use of synthetic materials in construction and interior furnishings, and increasing levels of outdoor air pollution (Collett and Sterling 1988a; Goyer and Nguyen 1989). Thousands of buildings have now been investigated throughout North America and western Europe. The evaluative strategies and protocols used by various investigators have been described in the scientific and technical literature, including those used by government agencies (Shaw 1988; Rajhans 1989; Nathanson 1990; NIOSH 1989; EPA 1991), private consultants (Sterling et al. 1987a; Lane et al. 1989; Montz 1992), research scientists (Goyer and Nguyen 1989; Gammage et al. 1989; Brooks and Davis 1992), and medical doctors (Quinlan et al. 1989).

Review of these strategies shows a general consistency and commonality in approach, despite differences in terminology and organization. Most of the published protocols recognize the need to employ a multidisciplinary approach to the evaluation of IAQ problems, an approach that views buildings as complex, dynamic systems.

The multidisciplinary approaches advocated by investigators gather information about the physical building (architectural), the mechanical systems that control indoor environmental conditions (engineering), the type and extent of occupant health and comfort concerns (medical), the objective quality of the air (industrial hygiene), and the occupants' subjective perceptions of conditions in their work environment (social science). These components have generally been organized into a series of steps or phases, with each phase extending the information gathered from the preceding phase until a point is reached when the causes of IAQ-related problems may be identified.

A "TYPICAL" PHASED APPROACH TO BUILDING EVALUATION

The investigative approach used by our research team was originally developed and tested as a three-phased strategy (Sterling et al. 1987a) with subsequent evolution into five phases (Sterling et al. 1987b). Ongoing application of this strategy in problem buildings, combined with the published experiences of other investigators, has resulted in further evolution and refinement of our protocol for building investigation.

When investigating IAQ-related concerns, our objectives are to (a) determine whether an environmental problem exists, (b) identify the cause of the problem, (c) design and implement modifications to alleviate the problem, and (d) re-evaluate conditions after modifications have been implemented to test the effectiveness of the design solutions. Our current approach consists of the following stages.

1. Initial assessment.
2. Assessment of health and comfort concerns.
3. IAQ and thermal comfort monitoring.

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4. Followup IAQ measurements.
5. Ventilation measurements.
6. Development and implementation of mitigation strategies.
7. Post-implementation assessment.

Each of the first five stages does not necessarily have to be completed before conclusions are drawn and stage 6 (development and implementation of mitigation strategies) is implemented. For example, if the cause of IAQ-related problems is determined at stage 1 (initial assessment), the investigation would immediately proceed to stage 6.

Stage One: Initial Assessment

Our investigations are normally instigated by a building owner, manager, or tenant in response to occupant complaints of discomfort or ill health that are suspected to be related to indoor environmental conditions.

The first stage of investigation is an initial assessment in which information about occupant concerns and the physical building are gathered from the following sources.

1. Meetings with the building operator and occupant representatives, e.g., an occupational safety and health committee or individual who coordinates complaint procedures.
2. Review of available architectural and engineering plans.
3. Walkthrough inspection to identify pollutant sources within and adjacent to the building (e.g., parking garages, print shops, kitchens); to inspect the design configuration and operational conditions of the building's heating, ventilating, and air-conditioning (HVAC) systems (e.g., locations of air intakes and exhausts, presence of standing water); and to observe characteristics of the occupied space, particularly in those areas in which occupants report a high prevalence of health and comfort complaints (as determined in previous meetings). Checklists to guide the walkthrough inspection process have been published by several investigators (Rajhans 1989; Goyer and Nguyen 1989; EPA 1991).

Stage Two: Assessment of Occupant Concerns

In the research strategies described by different investigators, the largest variation in approach occurs when evaluating the type and extent of reported discomfort and ill health. Some investigators recommend extensive questionnaire surveys, others suggest formal medical examination, while others neglect occupant concerns, focusing solely upon objective air quality data and the characteristics of the physical building.

Our field experience suggests that the approach must be flexible, responding to the specific requirements of a particular project. A standardized questionnaire is of greatest value in building complexes with large occupant populations. The results from a questionnaire survey may be used to quantify the prevalence and type of health and comfort complaints, and also to determine the spatial distribution of complaints between and within floors. Identification of specific problem locations is important in the development of the sampling protocols used in stages 3 and 4 (IAQ assessment).

We have also used questionnaire surveys to evaluate the impact of demographic differences (age, sex) and psychosocial factors (stress, satisfaction) on the prevalence of occupant complaints (Kleven and Sterling 1989).

In investigations of smaller workplaces, or of specific floors within larger complexes, our experience has shown direct interviews to be effective in gathering data regarding occupant concerns, either through a series of structured interviews or informal discussions during the walkthrough inspection.

Interview or examination by an occupational health physician may be required in cases where specific and serious health impairment has been reported by occupants or diagnosed by their physicians. While this is not a common approach in "typical" building evaluations, it may be necessary in assessing a specific building-related illness in which a known etiologic agent such as a microbial contaminant is suspected as the cause of the problem.

Stage Three: IAQ and Thermal Comfort Monitoring

The following two stages evaluate the chemical composition and thermal condition of the indoor air. In stage three, five parameters are monitored to indicate the general performance of the HVAC systems:

- carbon dioxide as an indicator of the adequacy of the outside air supply,
- carbon monoxide as an indicator of the infiltration of combustion byproducts,
- respirable suspended particles as an indicator of filtration effectiveness and the general dust loading of the indoor environment, and
- temperature and relative humidity as indicators of thermal comfort.

Direct-reading instruments are used to gather instantaneous data at sampling locations throughout the study area and an outdoor site adjacent to the HVAC system air intakes. Sampling locations are selected to reflect different uses of a space, to incorporate all HVAC zones, and to investigate "problem" locations identified in the previous stages. Multiple sampling passes through each site are undertaken throughout a working day to evaluate diurnal variations. In addition, one or more continuous monitoring stations are set up to record trends in carbon dioxide, temperature, and relative humidity. The continuous monitors are typically placed in "worst case" locations as identified in the walkthrough inspection.

Other environmental parameters that are monitored at this stage, only if a problem is suspected from the walkthrough inspection and assessment of occupant concerns, include lighting and noise levels. Non-IAQ and thermal comfort parameters appear to have rarely been integrated into the research strategies used by other investigators.

Stage Four: Followup IAQ Measurements

Additional IAQ sampling may be undertaken as dictated by the findings from the previous stages, particularly if specific point sources of indoor pollution are identified in the walkthrough inspections or the occupants' symptomology suggests the presence of a particular contaminant. Followup measurements may include sampling and analysis for formaldehyde, airborne fungi and bacteria, total and specific volatile organic compounds, ozone, and nicotine. Evaluation of these substances typically requires integrated sampling techniques, with a known volume of indoor air drawn through a collection medium, and laboratory analyses of the collected sample.

The results of the monitoring conducted during stages 3 and 4 are compared to available standards and guidelines, such as the standards developed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), including *Standard 62-1989, Ventilation for Acceptable Indoor Air Quality*, and *Standard 55-1992, Thermal Environmental Conditions for Human Occupancy* (ASHRAE 1989, 1992). Comparison is also made with IAQ consensus guidelines that identify IAQ concentrations "of concern" and "of limited or no concern" (WHO 1984). In addition, we compare data gathered in a particular building with data from both problem and nonproblem buildings archived into an in-house building performance data base (Collett et al. 1987).

Stage Five: Ventilation Measurements

If inadequate HVAC system performance has been implicated as a cause of IAQ-related problems in the previous stages, but has not been fully confirmed, quantification of ventilation performance parameters may be necessary. Actions include airflow measurement to determine flows through the ductwork and supply and exhaust vents, and tracer gas evaluation to determine air exchange rates on specific floors or the overall building. Sulfur hexafluoride (SF_6) has been widely used as a tracer in office buildings. Some of the published protocols for IAQ investigation suggest the use of carbon dioxide (CO_2) as a tracer, as a simplified, less costly method than SF_6 (Goyer and Nguyen 1989). However, while CO_2 provides a useful general indicator of the adequacy of the outdoor air supply and IAQ, the accuracy of the use of CO_2 as a tracer gas may be questionable due to the difficulty of achieving the assumptions associated with the CO_2 method under field conditions (Levine et al. 1992).

Tracer gas, such as SF_6, may also be used to investigate the patterns of airflow within a building, for example to determine whether air from a parking garage is infiltrating other areas within a building.

Stage Six: Development and Implementation of Mitigation Strategies

When conclusions have been drawn from the implementation of one or more of the preceding stages and the cause(s) of the IAQ problems have been determined, retrofit actions to rectify the problems and improve indoor environmental conditions must be developed and implemented. Typically, the recommended retrofit actions are communicated to the building owner or operator in a written report of findings.

Stage Seven: Post-Implementation Assessment

A final, but important, stage is followup assessment to determine the effectiveness of the retrofit actions. Ideally, the assessment should include objective measurement of IAQ and thermal parameters. However, detailed followup assessment is rarely possible for private consultants due to budgetary constraints. In our field work, post-implementation assessment most often consists of followup conversations with clients and occasional site visits and meetings.

One exception was the re-evaluation of two office buildings using a standardized questionnaire (Collett and Sterling 1988b). In this project, IAQ problems were identified in both buildings and retrofit actions were recommended. The retrofits were completed in one building, while changes were not implemented in the second building. A followup survey of the populations of the two buildings showed a significantly reduced prevalence of reported discomfort and ill health in the retrofitted building and no change in the nonretrofitted building.

FINDINGS FROM IAQ INVESTIGATIONS

The results of the implementation of research strategies have been reported by government agencies and private consultants. Table 1 summarizes the results from 1,891 investigations conducted by the U.S. National Institute of Occupational Safety and Health (NIOSH 1989) and Health and Welfare Canada (Kirkbride et al. 1990).

The findings of the U.S. and Canadian agencies are remarkably similar. In more than 50% of investigated buildings, inadequate ventilation was identified as the primary cause of IAQ problems. The term "inadequate ventilation" refers to a range of HVAC-related inadequacies, such as lack of outside air, poor air distribution, poor thermal control, and inadequate maintenance procedures (Collett and Sterling 1988a).

Other identified causes include contamination from specific indoor sources (12% to 15% of investigated buildings), infiltration of outdoor contaminants (9% to 10%), contaminants from building materials and interior furnishings (2% to 4%), and microbial contamination (1% to 5%).

An illustration of the complexity of investigating IAQ problems is the finding that the cause could not be determined by the investigators in between 13% and 24% of the buildings being investigated.

The experience of other researchers has been similar, with inadequate ventilation consistently having been identified as the major cause of IAQ-related problems in offices and other nonindustrial work environments (Robertson 1988; Rask and Lane 1989; Nathanson 1990).

While the reported findings from NIOSH and Health and Welfare Canada provide an important insight into the causes of IAQ problems, the summary tables may oversimplify the field situation. The data in Table 1 summarize one primary problem for each investigated building. However, our field experience rarely identifies a single problem in a building. Typically, several inadequacies that contribute to occupant discomfort and ill health are identified within a building.

Table 2 summarizes our research group's findings based on the implementation of the investigative strategy described above. To date, this strategy has been used to investigate 85 buildings in Canada, the United States, and South America. The table shows specific causes that have been identified as contributing to IAQ-related problems.

Unsurprisingly, our findings are generally similar to those of the government agencies and private sector researchers. The identified causes of IAQ-related problems can be broadly categorized into two types: design and operational inadequacies of HVAC systems and the presence of specific contaminants from a variety of sources. These two categories are not mutually exclusive. For example, the presence of elevated formaldehyde concentrations resulting from offgassing from interior furnishings may be diluted by adequate ventilation or intensified by a lack of outside air or poor air distribution. From our experience, the identified causes of IAQ problems do not generally lead to chronic health impairment of a building's population. Most often, occupants complain of discomfort (e.g., too hot, too cold, stuffiness, lack of fresh air) and a series of short-term acute symptoms (headache, fatigue, mucous membrane irritation), which are typical of the sick building syndrome (Woods et al. 1987).

Ventilation Control

In our experience, the single most frequent cause of complaint is inadequate control of the indoor environment by the mechanical ventilation system (36% of all identified causes). Problems of an inadequate outside air supply and poor air distribution within a space can be related to both the design and operational characteristics of the HVAC system. Design problems may be a function of the design parameters of a building with low outside air ventilation rates designed for optimum energy efficiency. Operational deficiencies include building operators closing outside air dampers (again for energy efficiency), inappropriate minimum damper settings (particularly in variable-air-volume systems), unbalanced air distribution systems, and the presence of barriers to effective air movement, such as partitioning of a space or blocking of diffusers by occupants.

Mitigation of design-related inadequacies is generally capital intensive, such as the replacement of air-handling units. However, operational deficiencies can often be rectified by inexpensive "fine tuning" of the HVAC system.

Thermal Control

Nineteen percent of the IAQ problems identified in our building investigations are the result of inadequate thermal control. Similar to the ventilation-related problems, thermal control inadequacies are the result of both design and operational deficiencies. Design problems occur in buildings in which heating and cooling capacities were determined at a time before the proliferation of electronic equipment in the work environment. Typically, some older buildings do not have adequate cooling capacities to control indoor temperatures.

However, operational parameters are more often the cause of thermal control problems. Indoor environmental conditions can be improved by providing appropriate thermostat points, moving a thermostat to a location more representative of the area that it is controlling, and educating occupants as to the operation of the thermostat. Too often, occupants are either "scared" to adjust thermostats or they adjust them to less than optimum setpoints.

Ventilation Infiltration

Infiltration of contaminants through the outside air intakes represents 10% of the causes of IAQ-related problems in our investigations. Such infiltration is generally a function of the location of the outside intake immediately adjacent to pollutant sources such as loading zones, bus stops, and exhaust outlets. These are clearly design-related problems and mitigation is often costly, including relocation of the intake or addition of specialized filtration, such as activated carbon.

Cross-Contamination

Eleven percent of the causes identified in our investigations are associated with cross-contamination, with the migration of contaminants from one area of a building to another. The most common sources of cross-contamination are underground parking garages and printing facilities. In one building, a problem of the migration of environmental tobacco smoke from a designated smoking area into

TABLE 1
Causes of IAQ Problems in 1891 White-Collar Workplaces
Investigated by North American Government Agencies

	NIOSH 529 Buildings (1971-88) NIOSH (1989)		HWC 1362 Buildings (1984-89) Kirkbride (1990)	
Problem Type	Number	Percent	Number	Percent
Inadequate Ventilation	280	53	710	52
Indoor Contaminants	80	15	165	12
Outdoor Contaminants	53	10	125	9
Building Fabric	21	4	27	2
Biological Contamination	27	5	6	0.4
Unknown	68	13	329	24

TABLE 2
Specific Causes Identified as Contributing to IAQ-Related Problems in 85 Buildings

Cause of Problem	# of Times Cause Was Identified	% of Times Cause Was Identified
VENTILATION CONTROL — lack of outside air — poor air distribution	57	36
THERMAL CONTROL — inadequate capacity — operational deficiencies	30	19
VENTILATION INFILTRATION — outside air intake location	16	10
CROSS CONTAMINATION — parking garage — print shop — smoking lounge	18	11
INDOOR SOURCES — interior furnishings — fiberous insulation	14	9
MICROBIAL CONTAMINATION — poor maintenace — water leakage	11	7
SITE INFILTRATION — adjacent industry — underlying soil	4	2
UNDETERMINED CAUSE	9	6

adjacent nonsmoking areas was identified. In this case, operational problems were found with an air cleaner and dedicated exhaust fan. Correction of these deficiencies mitigated the problem.

In general, cross-contamination problems can be mitigated through initial determination of the pressure relationships between locations within a building (air flows from positively pressurized to negatively pressurized spaces). Adjustment of these relationships, for example, by the provision of local exhaust systems can minimize the potential for contaminant migration.

Indoor Sources

Contamination from specific indoor sources has been identified as causing 9% of the IAQ problems in our investigations. Sources include offgassing of formaldehyde and volatile organic compounds from furnishing materials, fibrous insulation in ceiling plenums, and excessive dust loading due to poor housekeeping and janitorial procedures. In buildings where offgassing problems have been identified, ventilation control problems have also been recognized, particularly with a lack of outside air not effectively diluting and removing the indoor-generated contaminants.

Microbial Contamination

Seven percent of identified causes are the result of microbial contamination occurring from two principal sources: the presence of standing water within one or more components of the HVAC system (e.g., a blocked condensate drainage tray) and an episode of water leakage or flooding. The presence of standing water in an HVAC system suggests that regular inspections are not occurring and can be mitigated by an improved preventive maintenance program. If not rectified, microbial problems can be distributed widely throughout a building, creating the potential for serious health impairment and requiring extensive and costly decontamination.

Site Infiltration

In four investigated buildings, contamination from adjacent industrial plants and infiltration of pollutants from the underlying soil were identified as causes of the indoor IAQ problems. Pollution from the industrial source was determined to be a "chance" occurrence, with pollution control problems experienced at the industrial site (which were rectified) combined with unusual climatic conditions. The problem of infiltration of soil gas was mitigated by improved sealing and caulking of cracks and joints in the ground slab.

Undetermined Causes

As has been reported by other building investigators, specific causes of IAQ problems and the resultant occupant complaints of discomfort and ill health could not be determined in nine of the buildings investigated by our research group. In these buildings, considerations of other non-IAQ-related issues, e.g., psychosocial factors, were not within the scope of evaluation.

DISCUSSION

An effective strategy for the investigation of IAQ-related problems in nonindustrial workplaces must be both thorough and practical. A thorough evaluation should recognize the complexity of factors that can affect indoor environmental conditions. A practical evaluation should be easily implementable with reasonable cost without excessive time required for completion.

Review of the research strategies that have been described in the scientific and technical literature shows a similarity in approach, with a general recognition that a multidisciplinary approach is necessary to initially identify and then mitigate IAQ-related problems. The findings from the research groups employing these strategies are also similar, with HVAC system design and operational problems consistently identified as a primary cause of IAQ problems. Clearly, the design issues, which constitute a significant portion of all problems, could have been avoided in the original design of a building.

Fortunately, lessons have been learned from past mistakes, and IAQ issues are now being considered in the conceptual and design stages of some building projects. For example, indoor environmental criteria have been integrated into the development process of several North American projects (Sterling 1992; Burt 1992) and into the HVAC commissioning process (Sterling et al. 1992). In addition, several U.S. states, such as Washington, are currently developing IAQ regulations to be embedded into state laws. The proposed state regulations are generally based on the application of a phased, multidisciplinary approach.

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