Quality Assurance Strategies for Investigating IAQ Problems

Most investigators recognize that a multidisciplinary approach is needed to identify and diagnose indoor environmental problems

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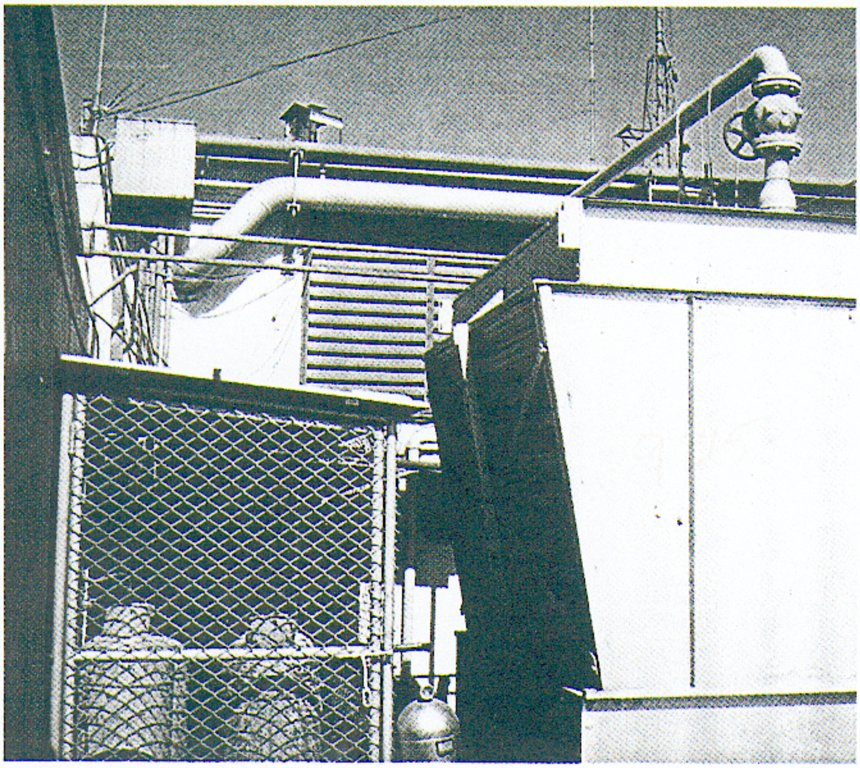
Environmental quality inside buildings has been of growing concern over the last 20 years. The deterioration of environmental quality in buildings has been associated with energy conservation actions such as reduced ventilation and increased insulation, use of synthetic materials in construction and interior furnishings, and increasing levels of outdoor air pollution.[1]

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,[2-5] private consultants,[6,7] researchers,[8,9] and physicians.[10]

Review of these strategies shows a consistency and commonalty in approach,



One cause of IAQ problems is improper location of outside air intakes, such as immediately adjacent to a cooling tower and a storage area for gas containers.

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despite differences in terminology and organization. Most of the published protocols recognize the need to employ a multidisciplinary approach to the evaluation of indoor environmental 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 when the causes of problems may be identified.

A typical phased approach

Figure 1 shows a flowchart of the approach used by the authors to evaluate building-related indoor environmental problems. This approach has evolved in part from extensive field experience and from the review of the investigative strategies used by other researchers.

The objectives of the strategy are: to determine whether an environmental problem exists; to identify the cause of the problem; to design and implement modifications to alleviate the problem by recommissioning; and to re-evaluate conditions after modifications have been implemented to test the effectiveness of the design solutions.

Phase One: Initial assessment. 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 phase is an initial assessment in which information about occupant concerns and the physical building are gathered from the following sources:

- Meetings with the building operator and occupant representatives (for example, an Occupational Safety and Health Committee or individual who coordinates complaint procedures).
- Review of available architectural and engineering plans.
- Walkthrough inspection to identify pollutant sources within and adjacent to the building (parking garages, print shops, kitchens, etc.); to inspect the design configuration and operational conditions of the building's HVAC systems (locations of air intakes and exhausts, presence of standing water, etc.); 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.[3,5,8]

As shown in *Figure 1*, a decision point is reached at the completion of Phase One (and also at the completion of any of the subsequent phases), where the question is posed as to whether the probable cause of the problem has been identified.

If the answer is no (the probable cause has not been identified), the investigative approach continues into Phase Two. However, if an indoor environmentally related cause of the reported problems is identified, then the investigation progresses directly to Phase Six when mitigation strategies to alleviate the identified problems are developed and implemented.

At this stage (or at the completion of any of the subsequent phases), an investigation might also determine that the probable cause of the reported occupant problems is not related to air quality conditions, but to non-environmental factors such as ergonomics or psycho-social stressors. In this event, the investigation would focus upon the resolution of the non-indoor environmental problems.

Phase Two: Assessment of occupant concerns. If Phase One does not identify

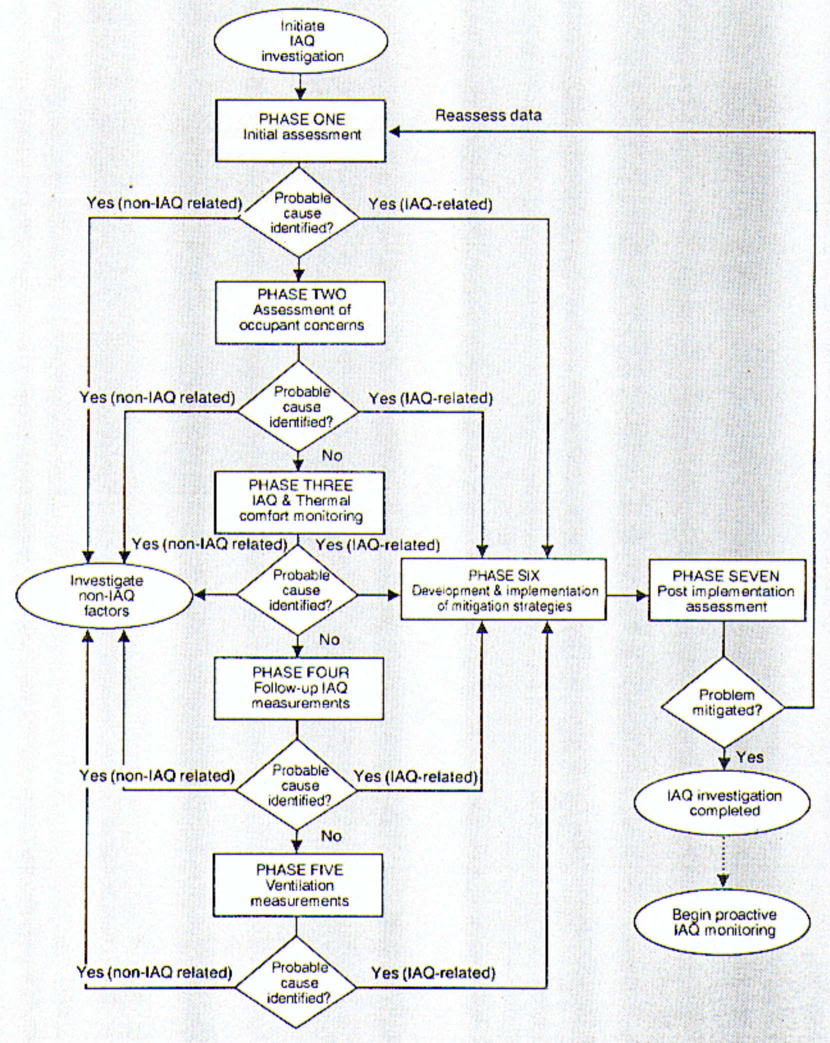

Figure 1. Flowchart to evaluate building-related indoor environmental problems.

the probable cause of the reported occupant concerns, the investigation progresses into the second phase.

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. Personal 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 Phases Three and Four (indoor environmental monitoring).

In investigations of smaller workplaces (or of specific floors within larger complexes), direct interviews are often effective in gathering data regarding occupant concerns, either through a series of structured interviews or informal discussions.

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.

Phase Three: Air quality and comfort monitoring. If the probable cause of the problem is not identified during the second phase, the following two phases evaluate the chemical composition and thermal condition of the indoor air, and the acoustical and lighting conditions in the indoor environment.

In Phase Three, seven parameters are monitored to indicate general building performance:

- *Carbon dioxide* as an indirect indicator of the adequacy of the outside air supply and ventilation effectiveness.
- *Carbon monoxide* as an indicator of the infiltration of combustion byproducts, primarily from outdoor sources.
- *Respirable suspended particles* as an indicator of filtration effectiveness and the general dust loading of the indoor environment.
- *Temperature* and *relative humidity* as indicators of occupant thermal comfort.
- *Noise* and *illuminance* as indicators of acoustical and visual comfort.

Direct reading instruments are used to gather data at sampling locations throughout an indoor study area and outdoors 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 phases. Multiple sampling passes through each site are undertaken throughout a working day to evaluate diurnal variations.

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In addition to the sampling passes through a building, 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.

Phase Four: Follow-up air quality measurements. Additional indoor air quality sampling may be undertaken as dictated by the findings from the previous phases; in particular, if specific point sources of indoor pollution are identified in the walkthrough inspections, or if the occupants' symptomology suggests the presence of a particular contaminant.

Follow-up 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 Phases Three and Four are compared to available standards and guidelines, such as *ASHRAE Standard 62-1989, Ventilation for Acceptable Indoor Air Quality*, and *ASHRAE Standard 55-1992, Thermal Environmental Conditions for Human Occupancy.*[11,12] Comparison is also made with IAQ consensus guidelines[13] that identify contaminant concentrations "of concern" and "of limited or no concern."

Phase Five: Ventilation measurements. If inadequate HVAC system performance has been implicated as a cause of IAQ-related problems in the previous stages through comparison with existing standards and guidelines, but has not been fully confirmed, quantification of ventilation performance parameters may be necessary.

Actions include air flow and pressure measurements 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.

For example, sulfur hexafluoride (SF_6) has been widely used as a tracer in office buildings. Some of the published protocols for IAQ investigation also suggest the use of carbon dioxide (CO_2) as a tracer, because it is a simplified, less costly method than SF_6.

However, while CO_2 may provide 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 to quantify ventilation rates is questionable. This is due to the difficulty of achieving the assumptions associated with the brass balance CO_2 method under field conditions.[14,15]

Phase 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 causes of the indoor environmental problems have been determined, retrofit actions to mitigate design-related problems and recommendations to improve operational and maintenance parameters to rectify the problems and improve indoor environmental conditions must be developed and implemented. This often includes comprehensive HVAC system or even total building recommissioning.

Phase Seven: Post-implementation assessment. A final, but important, stage is a follow-up assessment to determine the effectiveness of the retrofit actions. Ideally, the assessment should include objective measurement of indoor environmental parameters. However, in practice, a detailed follow-up assessment is rarely conducted.

One exception was the re-evaluation of two office buildings using a standardized questionnaire.[16] In this project, indoor environmental 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 follow-up survey of the two buildings' populations showed a significantly reduced prevalence of reported discomfort and ill-health in the retrofitted building and no change in the non-retrofitted building.

If the post-implementation assessment verifies that the mitigation strategies have been successful, the investigation of indoor environmental problems is completed. At this stage, prudent building owners and operators should implement a program of proactive monitoring to verify that the acceptable indoor environmental conditions are maintained over time. This type of proactive surveillance can be integrated into existing preventative maintenance programs.

However, if the post-implementation assessment determines that indoor environmental concerns still exist after the implementation of the mitigation actions, then reassessment of the indoor environment may be required. This is shown by the feedback loop of the flowchart in *Figure 1.*

Findings from past 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 US National Institute of Occupational Safety and Health[4] and Health and Welfare Canada.[17]

The findings of the US and Canadian agencies are remarkably similar. In over 50% of the investigated buildings, inadequate ventilation was identified as the primary cause of indoor 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.[1]

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Table 1. Causes of IAQ Problems in 1,891 White Collar Workplaces*

Problem Type	NIOSH 529 Buildings[4] (1971-88) Number	NIOSH Percent	HWC 1,362 Buildings[17] (1984-89) Number	HWC 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

**Investigated by North American government agencies.*

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Table 2. Specific Causes Contributing to IAQ-Related Problems in 85 Buildings

Cause of Problem	Number of Times Cause was Identified	Percentage of Times Cause was Identified
Ventilation Control	57	36
Lack of outside air		
Poor air distribution		
Thermal Control	30	19
Inadequate capacity		
Operational deficiencies		
Ventilation Infiltration	16	10
Outside air intake location		
Cross-contamination	18	11
Parking garage		
Print shop		
Smoking lounge		
Indoor Sources	14	9
Interior furnishings		
Fibrous insulation		
Microbial Contamination	11	7
Poor maintenance		
Water leakage		
Site Infiltration	4	2
Adjacent industry		
Underlying soil		
Undetermined Cause	9	6

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 indoor environmental problems is the finding that the cause could not be determined by the investigators in between 13% and 24% of the buildings being investigated.

While the reported findings from NIOSH and Health and Welfare Canada provide an important insight into the causes of indoor environmental problems, their summary information may oversimplify the field situation.

For example, the data in *Table 1* identifies only one cause of problems in each investigated building. However, field experience rarely identifies a single cause of indoor environmental problems in a building. Typically, several inadequacies are identified within each building that contribute to occupant discomfort and ill-health.

Table 2 summarizes our research group's findings based on the implementation of the investigative strategy described above. This strategy has been used to investigate buildings in Canada, the United States, western Europe and South America. The table shows specific causes that have been identified as contributing to indoor environmental problems.

The findings are generally similar to the government agencies and other private sector researchers. The identified causes of indoor environmental 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.

Ventilation control. The single most frequent cause of occupant complaint is inadequate control of the indoor environment by the mechanical ventilation system. Problems of 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 or minimum code requirements.

Operational deficiencies include building operators closing outside air dampers (again for energy efficiency), inappropriate minimum damper settings (particularly in VAV systems), unbalanced air distribution systems and the presence of barriers to effective air distribution (such as partitioning of a space or occupant blocking of diffusers).

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. Thermal control inadequacies, similar to the ventilation control problems, 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. Such buildings may not have adequate cooling capacities to control the increased heat load from equipment. 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.

Ventilation infiltration. Infiltration of contaminants through the outside air intakes and other openings in the building envelope has been identified in several buildings.

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. The migration of contaminants from one area to another is a frequent concern in buildings. Common sources of cross-contamination are underground parking garages, printing facilities, designated smoking areas and restaurants.

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 a problem in buildings. Sources include offgassing of formaldehyde and volatile organic compounds from furnishing materials, environmental tobacco smoke, 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. Microbial contamination occurs from two principle sources: the presence of standing water within one or more components of the HVAC system (a blocked condensate drainage tray) or an episode of water leakage or flooding.

The presence of standing water in an HVAC system suggests that regular inspections are not occurring. This problem can be mitigated by an improved preventative maintenance problem.

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. Population pressure in many urban centers is causing the reuse of previous industrial sites (which may contain toxins and other waste materials) as commercial and residential sites. Accordingly, soil contamination is becoming an important cause of indoor environmental problems. To alleviate this, the site must be recommissioned (cleaned) prior to reuse.

Contamination from adjacent industrial plants and infiltration of pollutants from the underlying soil have also been identified as causes of the problems in several investigations conducted by the authors.

Conclusion

An effective strategy for the investigation of environmental problems in non-industrial 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.

A 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 indoor environmental problems.

The findings from the research groups employing these strategies are also similar, with HVAC system design and operational problems consistently identified as primary causes of indoor environmental problems.

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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 practices, and indoor environmental 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 and European projects,[18] and into the HVAC commissioning process.[19]

In addition, state and federal government agencies (such as the US Occupational Safety and Health Administration) are developing indoor air quality regulations. These proposed regulations are generally based on the application of a phased, multidisciplinary approach to the resolution of IAQ concerns. ■

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