INDOOR AIR QUALITY DIAGNOSTIC PROCEDURES FOR SICK AND HEALTHY BUILDINGS

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ABSTRACT

With respect to environmental quality, two populations of existing buildings are apparent—those with known problems (i.e., problem buildings) and those with nonexistent problems (i.e., healthy buildings). A new discipline, known as building diagnostics, may be employed to identify and recommend solutions for problem buildings and to provide reasonable assurance that healthy buildings are not being compromised. However, the diagnostics procedures needed to address these two populations are somewhat different and present a dilemma. The accuracy of building diagnostics procedures can be evaluated by how well an actual event and the diagnosis (i.e., measurement or prediction and the occurrence of an event) agree. Two ways exist in which an actual event and the diagnosis can agree (i.e., two kinds of correct outcomes): "true-positive" and "true-negative." Similarly, there are two ways in which the event and the diagnosis can disagree (i.e., two kinds of errors): called "false-positive" and "false-negative." Building diagnostics performed for problem buildings seek to maximize the "true-positive" outcome (i.e., correctly diagnose an event) and minimize the "false-negative" outcome (i.e., fail to diagnose an event). Conversely, diagnostics performed for "buildings without known problems" (i.e., either healthy buildings or problem buildings) seek to maximize the "true-negative" outcome and minimize the "false-positive" or the "false-negative" outcome dependent on the relative risks incurred. A dilemma exists in using building diagnostics for this latter building population: Is it better to use diagnostics procedures which err toward the "false-positive" or the "false-negative" outcome?

In this paper, these two building populations are characterized, the basic concepts of building diagnostics are discussed, and the diagnostic procedures for problem buildings and buildings without known problems, respectively, are presented. Criteria used for evaluation and selection of instrumentation required for diagnostics to achieve the desired objectives are also discussed.

INTRODUCTION

Two populations of existing buildings are apparent when indoor environments are evaluated: those with known problems (i.e., problem buildings) and those without problems (i.e., healthy buildings). Based on a random survey in 1985 of 600 office workers in the U.S., it has been hypothesized that 20% of office workers (i.e., 20% of buildings) have problems which are manifested as symptoms associated with sick building syndrome (Woods et al. 1987a). Thus, in the complementary 80% of the U.S. building stock, these problems are either nonexistent (i.e., healthy buildings) or not known to exist.

A new discipline, known as building diagnostics, may be employed to identify and recommend solutions for problem buildings and to provide assurance that healthy buildings are not being compromised. Building diagnostics is described as ". . . a process in which a skilled expert draws on available knowledge, techniques, and instruments in order to predict a building's likely performance over a period of time" (Building Research Board 1985). Building diagnostics consists of four essential steps: 1) knowledge of what to measure, 2) availability of appropriate instrumentation, 3) expertise in interpreting results of measurements, and 4) capability of predicting building performance. From these steps, recommendations should follow that can improve system performance. As a derivative of building diagnostics, the two protocols (i.e., problem buildings and buildings without known problems) introduced in this paper are based on these four steps.

Building diagnostic procedures provide a mechanism to characterize a building in terms of three sets of parameters: 1) the type and location of sources of contaminants, 2) the four building elements that comprise a building system (i.e., structure, envelope, interior spaces, and services), and 3) performance characteristics during the life of the building.

The overall objective of this paper is to discuss how a common approach to building diagnostics can be used either to identify and evaluate causes of problem buildings or to provide reasonable assurance that design and operation of healthy buildings (including buildings without known problems) meet acceptable criteria. Specifically, this paper characterizes these two populations of buildings, describes

Diagnostics for Sick and Healthy Buildings

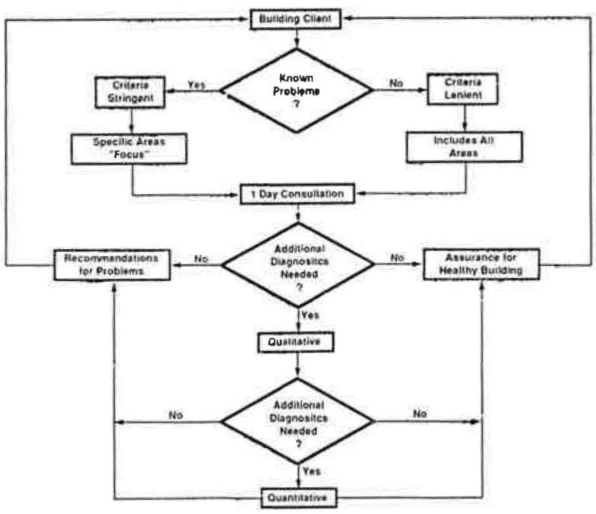

Figure 1 *Two populations of non-industrial buildings for evaluation of environmental acceptability*

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procedures for establishing evaluation criteria for diagnosing them, and highlights the similarities and differences in the respective diagnostic protocols.

CHARACTERIZATION OF BUILDING POPULATIONS

Problem Buildings

Problem buildings generally can be classified either as having occupants who are experiencing symptoms which are characterized as sick building syndrome (SBS), building-related illness (BRI), or both (Figure 1) (Woods 1988). When the complaints of a set of symptoms, including headaches, eye irritation, sore throat, fatigue, dizziness, drowsiness, and nausea, persist at frequencies significantly above 20% among occupants for periods of longer than two weeks, when the sources of complaints are not obvious, and when occupants usually obtain relief outside of the building, the building is considered to manifest SBS (Building Research Board 1987). The symptoms associated with SBS are actually related to responses of "acute discomfort" rather than frank illness (e.g., fever, infection, tissue deterioration). If symptoms of frank illness are present, the condition is often classified as BRI. Examples of this latter condition are occurrences of some nosocomial infections in hospitals (i.e., most nosocomial infections result from person-to-person transmission, rather than airborne transmission), humidifier fever, and Legionellosis.

An important difference between situations classified as SBS or BRI is that the etiology of SBS (e.g., a specific chemical contaminant) may not be necessary, as complaints are often resolved by increasing system ventilation, by discussions with the occupants, and by improved system maintenance. On the other hand, the etiology of a BRI incident usually must be determined before a solution can be implemented. In some instances, complaints registered by occupants do not exactly meet the symptoms that can be characterized as either SBS or BRI (e.g., complaints of environmental tobacco smoke). Complaints in these buildings can be characterized as "discomfort" rather than SBS or BRI.

When diagnosis of SBS or BRI reveals methods of control that can mitigate the problems, the building is then described as a "problem building" and engineering solutions are usually employed.

Buildings without Known Problems

Healthy buildings should have an absence of problems when evaluated by a building diagnosis. From a practical perspective, it is recognized that an occupied facility cannot exist without some problems. It is therefore suggested that a healthy building be characterized by three sets of criteria: human responses (e.g., no known clinical signs of BRI, and the frequency of reported SBS symptoms and discomfort complaints should be significantly below 20%); system performance (e.g., compliance with environmental criteria, uncontaminated air distribution ductwork and mechanical equipment, ease of maintenance, and proper balance of exhaust and makeup air); and service factors (e.g., periodic inspections of HVAC systems, accurate records of occupants' complaints, scheduled filter changing, and HVAC system control calibration) (Woods 1988). If problems are identified, then the building is no longer characterized as a healthy building and diagnostic procedures used in problem buildings are performed.

DIAGNOSTIC STRATEGIES

The accuracy of building diagnostics procedures can be evaluated by how well an actual event and the diagnosis (i.e., measurement or prediction of the occurrence of an event) agree. Two ways (Figure 2) exist in which an actual event and the diagnosis can agree; that is, two kinds of correct outcomes, called "true-positive" and "true-negative" (Swets 1988). Similarly, there are two ways in which the event and the diagnosis can disagree; that is, two kinds of errors, called "false-positive" and "false-negative."

Building diagnostics performed for problem buildings seek to maximize the "true-positive" outcome (i.e., correctly diagnose an event) and minimize the "false-negative" outcome (i.e., fail to diagnose an event). In these buildings, problems are assumed to exist, thus diagnostic procedures are used which "focus" the evaluation on those parameters that directly impact the known problem areas and exclude other areas (i.e., diagnosis by exclusion). This diagnostic approach is different from the approach taken by investigators who attempt to utilize conventional industrial hygiene hazard evaluation techniques in non-industrial buildings. More stringent environmental criteria are established and instrumentation for obtaining data must be appropriately sensitive. For these cases, some "false-positive" outcomes are expected (Swets 1988).

Conversely, diagnostics performed for healthy buildings (including buildings without known problems) seek to maximize the "true-negative" outcome and minimize the "false-positive" outcome or the "false-negative," dependent on the relative risks incurred. In these buildings, diagnosis by inclusion is used. Thus, the "scope" of the diagnostic procedures is large (i.e., encompassing the entire building) and not "focused" on a known problem area (i.e., a specific area in the building). If it is believed more desirable to minimize the "false-positive" outcome, relatively lenient performance criteria are established and instrumentation for obtaining data may be less sensitive. If it is judged more desirable to minimize the "false-negative" outcome, more restrictive performance criteria and more sensitive sampling and analysis methods, such as those used in problem buildings, will be used.

A dilemma exists in using building diagnostics for buildings without known problems: Is it better to use diagnostics procedures which err toward the "false-positive" or the

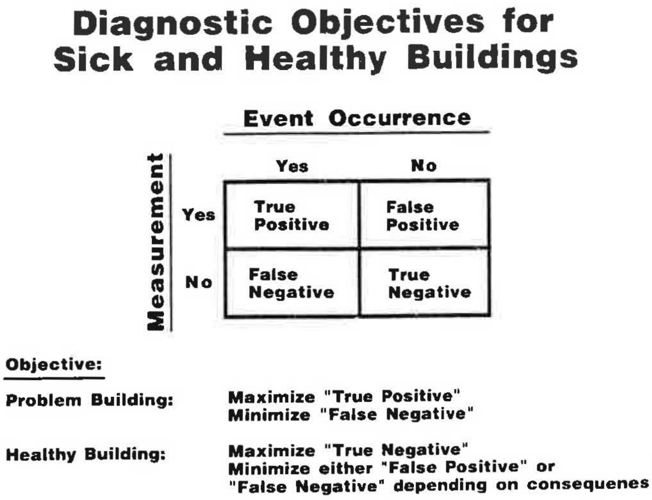

Figure 2 *Diagnostic objectives for problem buildings and buildings without known problems*

"false-negative" outcome? The answer will depend on the benefits ascribed to the correct outcomes and the costs ascribed to the incorrect outcomes. For example, predicting the occurrence of an excessive concentration of bacteria that does not occur (i.e., a false-positive) is regarded as having a cost that is small relative to the cost of failing to predict an occurrence that does occur (i.e., false-negative), so the criteria adopted for a positive diagnosis are on the stringent side. Conversely, lenient criteria are established when the cost of a false-positive outcome is disproportionately high. Take, for example, the case of an office where no SBS or BRI symptoms have been reported. If environmental monitoring is done in this office for volatile organic compounds (VOC) using sensitive techniques, and the results indicate concentrations to be in excess of stringent performance criteria, it may be difficult to justify the high cost of additional ventilation to reduce VOC concentrations in this office area considering the uncertain risk of continuing exposure at the concentrations measured.

The basic principles of building diagnostics provide guidance in resolving this dilemma. Clearly, in both classifications of buildings, the investigator has two choices: 1) take rigorous objective measurements for all possible contaminants; or 2) as a first step, characterize the building as a "system" comprised of building elements (i.e., structure, envelope, interior spaces, and services), formulate a preliminary hypothesis (i.e., evaluate the relationships between contaminant sources, symptoms, and building systems), identify preliminary recommendations, and perform additional diagnostics as necessary. Obviously, the first option is neither technically nor economically feasible. The second option is not only technically and economically feasible, but is consistent with the basic philosophy of building diagnostics (i.e., knowledge of what to measure, availability of appropriate instrumentation, expertise in interpreting results of measurements, and capability of predicting building performance).

In both populations of buildings, the first step in building diagnostics is to determine evaluation criteria. Next, the building is characterized as a complete "system." In problem buildings, only those relationships that impact the problem area are evaluated (i.e., a limited scope of the problem). In buildings without known problems, the interaction of building systems in the entire building is characterized until all existing or potential problem areas are identified and evaluated for compliance with criteria. Once problem areas are identified, diagnostic procedures for both building populations are similar. Next, the evaluation focuses on specific possible contaminant sources, symptoms, and system interaction in the problem area(s) by formulating a "preliminary hypothesis." Finally, the evaluation validates or modifies the preliminary hypothesis by obtaining only the objective and subjective data which are necessary to validate the hypothesis.

Diagnostic procedures performed in the initial stage of building evaluation provide the mechanism by which a "trained" diagnostician can "qualitatively" (i.e., without measuring data) determine, with reasonable confidence, the acceptability of the indoor environment and evaluate the need for additional diagnostics. Philosophically, the same diagnostics procedures can be used in both problem buildings and in buildings without known problems. The primary difference between the two populations of buildings is that the "scope" of the initial step in the evaluation is larger in buildings without known problems than in problem buildings. However, more rigorous diagnostic procedures (i.e., establishing additional criteria and obtaining objective and subjective data) are not employed until an initial qualitative evaluation is performed and a need for quantitative diagnostics is identified.

OUTLINE OF PROTOCOLS

As a derivative of building diagnostics, the two protocols (i.e., problem buildings and buildings without known problems) introduced in this paper are based on the four steps of building diagnostics (Figure 3). These protocols utilize both engineering principles for system analysis and scientific principles for measurements of contaminant concentrations and for human responses (Woods et al. 1987b). They take advantage of the understanding required to evaluate compliance with both prescriptive and performance criteria for acceptable indoor air quality.

A fundamental aspect of both protocols is that knowledge is required of the relationships that exist among the building, its systems, and its occupants. For problem buildings and buildings without known problems, diagnostics are performed by a three-phase procedure.

Problem Buildings

Phase 1: Consultation. The objective of this phase is to focus diagnostic procedures on the problem area(s). In this phase, the building is characterized in four categories: 1) structure, 2) envelope, 3) occupied spaces, and 4) building services. The structure and envelope (e.g., foundation, load-carrying elements, exterior walls, windows, doors, roof, etc.) are inspected. Available plans and construction documents are reviewed to characterize heat transfer rates through the envelope and routes of contaminant transport from outdoor sources. This characterization includes identification of potential contamination of makeup air intakes; integrity of vapor barriers in walls and roofs; and deficiencies in the foundation, structure, and envelope which allow transport of moisture and other contaminants into the building. The scope of the investigation and its objectives are defined, a preliminary hypothesis may be formulated, and preliminary recommendations may be presented to the client. "Measurements" during this phase consist of "professional observations" by the investigators. A preliminary determination of what subsequent measurements may be required to better characterize the building is also made during this phase. The scope of the problem may be one specific area of the building or the entire building.

Phase 2: Qualitative Diagnostics. If this phase is needed to test the preliminary hypothesis or to validate the preliminary recommendations, it will be accomplished primarily through engineering analysis techniques. In this phase, additional performance criteria for the various functional areas of the building will be defined. If health problems are not

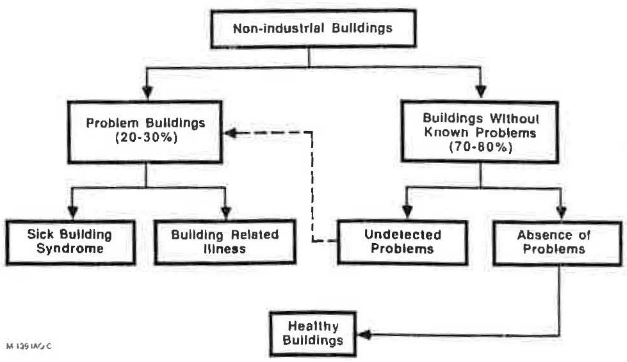

Figure 3 Diagnostics flow chart

suspected, analysis of system performance will be initiated, and measurements will be limited to those required to evaluate the system servicing the problem area(s). Thermal and contaminant loads that are generated within these areas are estimated for subsequent analysis of system performance. The services are characterized by inspection, objective measurements, and review of plans and construction documents. The capacities of the HVAC systems are evaluated in terms of their capabilities of meeting the thermal and contaminant loads imposed on them. Control strategies and systems are evaluated to determine their effectiveness in providing the required energy-efficient and cost-effective environmental conditions within the occupied spaces. However, if health problems are suspected (BRI), immediate medical attention will be recommended for the affected occupants. Based on results of the medical evaluation, specific pollutants may be identified, and airborne and bulk samples of suspected pollutants will be obtained, as described in Phase 3.

An important aspect of this phase is that measured data are not always essential to identify and solve problems.

Phase 3: Quantitative Diagnostics. If further investigation is needed to test the hypothesis or to validate the recommendations, quantitative measures of airborne contaminant concentrations, bulk samples, and other environmental parameters will be acquired through a systematic format. Also, a thorough quality assurance/quality control program will be implemented. In this phase, both objective measurements of the physical environment and subjective responses of the occupants are obtained. To characterize the interior spaces, a systematic, efficient procedure is followed to identify "areas of maximum and minimum potential exposures" within each functional category of the building. Objective measures of thermal, acoustic, lighting, and air quality may be obtained in these areas and in the outdoor air by use of instrumentation specifically adapted and standardized for this purpose. Simultaneously, subjective measures of occupant responses (i.e., perceived responses, symptoms, and demographics) may be obtained in these areas by use of questionnaires developed and standardized for this purpose.

Buildings without Known Problems

The diagnostics procedures for buildings without known problems are similar to those used in problem buildings, with two exceptions. First, the scope of the procedures used in the first phase (i.e., consultation phase) is greater since the entire building must be characterized and not just problem areas. Second, the procedures provide the building owner or occupants with a choice of two "levels" of assurance (i.e., confidence level) that problems do not exist: 1) a "reasonable" level of confidence based on qualitative evaluation of the building characteristics (i.e., qualitative assurance), or 2) a greater level of confidence based on the results of obtaining objective data (i.e., quantitative assurance). In either procedure, criteria are first established for the three components that characterize a healthy building: 1) the overall indoor environment (i.e., thermal, lighting, acoustic, and air quality), 2) the system performance (i.e., ventilation efficiency, adequate outdoor air, proper air balance and distribution, supply and return air ductwork that is not conducive to contaminant accumulation, and ease of maintenance), and 3) the service factors (i.e., periodic inspections of all components comprising the HVAC system, scheduled filter changing or cleaning, scheduled control calibration, scheduled air and hydronic balancing of the system, structured preventive maintenance program, and proper records to document occupant complaints and symptoms. If the qualitative assurance procedure is chosen, compliance with criteria is based on observing the general conditions (i.e., characterization) of the facility that exist during the time that the evaluation is performed (i.e., professional judgment). No objective or subjective measurements are obtained. This evaluation procedure results in a "reasonable" level of confidence that the environmental quality, system performance, and service factors comply with selected criteria; however, no record of actual indoor air quality data is provided. If the quantitative assurance procedure is selected, areas with maximum potential for indoor air quality problems are selected. Objective and subjective data are obtained in these areas and evaluated for compliance with criteria. The objective of either evaluation procedure is to identify any existing or potential problem areas with reasonable confidence and develop preliminary recommendations as necessary. If no problems are identified, the building can be considered "healthy."

CONCLUSIONS

Two primary conclusions can be derived from the concepts of building diagnostics presented here:

1. The same principles of building diagnostics developed for investigating problem buildings are also useful for ensuring the performance of healthy buildings; however,
2. The scope of the investigation and the criteria used for compliance evaluation differ for these two populations of buildings (i.e., the investigation of a healthy building is more inclusive, but the criteria may not be as stringent).

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