Building Diagnostics: A Conceptual Framework (1985)

Pages
47

Size
8.5 x 10

ISBN
0309322715

Building Research Board; Commission on Engineering and Technical Systems; National Research Council

Building Diagnostics

A Conceptual Framework

Building Research Board
Commission on Engineering and Technical Systems
National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C. 1985

85-0040
C. 1

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

The National Research Council was established by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and of advising the federal government. The Council operates in accordance with general policies determined by the Academy under the authority of its congressional charter of 1863, which establishes the Academy as a private, nonprofit, self-governing membership corporation. The Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in the conduct of their services to the government, the public, and the scientific and engineering communities. It is administered jointly by both Academies and the Institute of Medicine. The National Academy of Engineering and the Institute of Medicine were established in 1964 and 1970, respectively, under the charter of the National Academy of Sciences.

This report was prepared as part of the technical program of the Federal Construction Council (FCC). The FCC is a continuing activity of the Building Research Board (formerly the Advisory Board on the Built Environment), which is a unit of the Commission on Engineering and Technical Systems of the National Research Council. The purpose of the FCC is to promote cooperation among federal construction agencies and between such agencies and other elements of the building community in addressing technical issues of mutual concern. The FCC program is supported by 14 federal agencies: the Department of the Air Force, the Department of the Army, the Department of Commerce, the Department of Energy, the Department of Health and Human Services, the Department of the Navy, the Department of State, the Federal Emergency Management Agency, the General Services Administration, the National Aeronautics and Space Administration, the National Endowment for the Arts, the National Science Foundation, the U.S. Postal Service, and the Veterans Administration.

Funding for the FCC program was provided through the following agreements between the indicated federal agency and the National Academy of Sciences: Department of Commerce Contract No. 50SBNB5C3528; National Endowment for the Arts Grant No. 42-4253-0091/R; and National Aeronautics and Space Administration No. NASW-4029.

For information regarding this document, write the Director, Building Research Board, National Research Council, 2101 Constitution Avenue, N.W., Washington, DC 20418.

Printed in the United States of America

BUILDING RESEARCH BOARD
1984 - 1985

Chairman

GEORGE S. JENKINS, President, Consultant Networks, Inc., Washington, D.C.

Members

ROBERT C. DOBAN, Senior Vice President, Science and Technology, Owens-Corning Fiberglas Corporation, Toledo, Ohio
DAVID R. DIBNER, Senior Vice President, Bernard Johnson Inc., Bethesda, Maryland
EZRA D. EHRENKRANTZ, President, The Ehrenkrantz Group, New York, New York
DENOS C. GAZIS, Assistant Director, Semiconductor Science and Technology IBM Research Center, Yorktown Heights, New York
PHILIP G. HAMMER, Consultant to Industry and Governments, Edgewater, Maryland, and Tampa, Florida
RICHARD H. JUDY, Director, Dade County Aviation Department, Miami, Florida
JOHN T. JOYCE, President, International Union of Bricklayers and Allied Craftsmen, Washington, D.C.
WILLIAM LE MESSURIER, President, TSC Corporation, Cambridge, Massachusetts
ROBERT P. MARSHALL, Jr., Turner Construction Company, (Retired), Cos Cob, Connecticut
DOUGLAS C. MOORHOUSE, President, Woodward-Clyde Consultants, San Francisco, California
LOUIS A. ROSSETTI, President, Rossetti Associates, Detroit, Michigan
GEORGE STERNLEIB, Center for Urban Policy Research, Rutgers University, New Brunswick, New Jersey
RALPH WIDNER, Executive Director, Greater Philadelphia First, Philadelphia, Pennsylvania

COMMITTEE ON BUILDING DIAGNOSTICS

Chairman
EZRA D. EHRENKRANTZ, The Ehrenkrantz Group, New York, New York

Members
PAUL REECE ACHENBACH, Engineer (Ret.), McLean, Virginia
PLEASANTINE DRAKE, Architectural Diagnostics, Ottawa, Canada
PAUL D. EGAN, (until April 1984), The Prudential Insurance Company of America, Newark, New Jersey
DAN INT-HOUT, Krueger Manufacturing, Inc., Tucson, Arizona
ROBERT W. MARANS, Institute for Social Research, University of Michigan, Ann Arbor
WILLIAM RUDOY (Deceased), School of Engineering, University of Pittsburgh
ARAN SAFIR, M.D., (until April 1984), School of Medicine, University of Connecticut, Farmington
NEIL SHER, Honeywell, Inc., Minneapolis, Minnesota

Liaison Representatives
GEORGE COURVILLE, Oak Ridge National Laboratory, Oak Ridge, Tennessee
KENNETH CRAWFORD, Construction Engineering Research Laboratory, Champaign, Illinois
CHARLES CULVER, National Bureau of Standards, Gaithersburg, Maryland
DAVID EAKIN, General Services Administration, Washington, D.C.
FREDERICK KRIMGOLD, National Science Foundation, Washington, D.C.
CHARLES MARKERT, Naval Facilities Engineering Command, Alexandria, Virginia
LARRY SPANGLER, Department of the Air Force, Washington, D.C.
ROBERT WALKER, Veterans Administration, Washington, D.C.

Consultants
JOHN CABLE, Hagler-Bailly and Co., Inc., Washington, D.C.
VOLKER HARTKOPF, Carnegie-Mellon University, Pittsburgh, Pennsylvania
VIVIAN LOFTNESS, Carnegie-Mellon University, Pittsburgh, Pennsylvania
FORREST WILSON, Catholic University of America, Washington, D.C.

Staff
JOHN P. EBERHARD, Director, Building Research Board
PETER H. SMEALLIE, Program Manager
ABRAM B. BERNSTEIN, Senior Staff Officer
DELPHINE D. GLAZE, Administrative Secretary
DONNA F. ALLEN, Senior Secretary

FOREWORD

This report, prepared by the Committee on Building Diagnostics of the Building Research Board, describes the concept of building diagnostics, its evolutionary development, its status today, and its future potential. Much of the groundwork for this report took place at a workshop on building diagnostics that was conducted by the committee in March 1983. A report from that workshop is available.[1]

The present report was prepared by an eight-member committee consisting largely of architects and engineers from academia and industry. The committee was assisted by a team of consultants and by liaison representatives from a number of federal agencies concerned with the design, construction, and management of government facilities.

The committee's activities were supported by the federal agencies belonging to the Federal Construction Council. The Federal Construction Council is a continuing activity of the National Research Council's Building Research Board. The purpose of the Federal Construction Council is to promote cooperation among federal construction agencies and between those agencies and other elements of the building community in addressing technical issues of mutual concern.

John P. Eberhard
Director
Building Research Board

---

[1] A Report From the Workshop on Building Diagnostics, March 1983, National Academy Press, Washington, D.C., 1983.

CONTENTS

OVERVIEW

Building diagnostics is the name given, collectively, to a set of practices that are used to assess the current performance capability of a building and to predict its likely performance in the future.

Building diagnostics can be of value at a number of stages in the life of a building. Even before construction is underway, there are diagnostic techniques that can be applied to the "virtual building" that exists in the mind of the designer and in the form of working drawings and specifications. Diagnostics can be applied during construction, when components and assemblies can, for the first time, be tested "in place." Diagnostics can be applied when the completed building is ready to be turned over to the owner for initial occupancy, in order to assess its "as built" performance capability. Diagnostics can be used for various purposes during the building's normal use. When there are indications that some part of the building is not functioning properly (e.g., when the building's climate control system is unable to maintain the desired indoor temperature without exceeding preset limits on fuel consumption), diagnostics can be used to identify the cause so that the problem can be corrected before a serious failure occurs. Diagnostics can also be of value in detecting and correcting incipient problems before they develop to the point where there is evidence of a building system failure. Finally, diagnostics can be applied in connection with a proposed conversion of the building to some other use, and in connection with its eventual demolition.

While building diagnostics cannot be said to exist today as a recognized field, many of the activities and procedures of building diagnostics are regularly practiced within various disciplines. The purpose of this report is to describe the concept of building diagnostics in a way that makes clear what the potential impact might be on the achievement of satisfactory building performance if today's practices were gathered together to form a new mode of a professional practice having diagnostics as its central element.

Four elements are essential to the practice of building diagnostics: (1) knowledge of what to measure, (2) availability of appropriate instruments and other measurement tools, (3) expertise in interpreting the measurements, and (4) a capability for predicting the future condition of the building based on that interpretation. (A fifth element that is related, but is not properly a part of building diagnostics, involves the ability to devise corrective procedures when the future condition is likely to be undesirable.)

While building diagnostics relies heavily on measurements, it is not solely a measurement science. The essence of the diagnostic process involves the formulation and testing of a series of hypotheses concerning the likely performance of a part or all of the building. The success of a diagnostic procedure depends as much on the skill of the diagnostician in formulating appropriate hypotheses and interpreting measurements as on the availability of measuring instruments.

Building diagnostics cannot be practiced without a fundamental understanding of buildings, building performance, and the causes and implications of performance failures. It is not possible to assess building conditions without first specifying the performance that is desired and the criteria for evaluating such performance. The formulation of performance requirements for a building is thus an essential early step in the building program.

Building performance requirements cover a broad range of attributes. There are performance requirements that are concerned with such structural and mechanical considerations as the building's ability to withstand environmental loads associated with wind and snow; the capacities of its electrical, mechanical, and hydraulic systems; the physical integrity of its outer shell; the ability of its climate control system to maintain desired levels of interior air quality, temperature, and humidity; and the ability of its internal traffic system (entrances, exits, loading and receiving bays, elevators, escalators, stairwells, and corridors) to accommodate the expected flow of people and goods. There are performance requirements that are concerned with health and safety considerations such as the possibility that interior materials might give forth toxic emanations; the danger of slipping and falling in stairwells and corridors; the potential for light and noise levels to impair vision and hearing; and the question of whether smoke detectors, fire alarms, corridors, stairwells, and emergency exits will permit timely evacuation in an emergency. Still other performance requirements pertain to the way in which the building contributes to or enhances the activities carried out within it and within the community in which it is located. These include both aesthetic and practical considerations, such as the harmonious blending of the building with its surroundings, the psychological impact of the building on its occupants, visitors, and passersby, and the ability of the overall design of the building to contribute to the building's purpose--productivity if it is a factory, learning if it is a school, sales if it is a retail store, treatment of the ill if it is a hospital.

Performance requirements reflect the building's purpose. If the building is to serve its purpose properly, it must be designed, built, operated, and maintained with the performance requirements as goals. This means that performance requirements must be formulated so that they can serve as useful guides for the architects and engineers who design the building, the construction firm that builds it, and the management firm that operates and maintains it. They must also be quantitatively specified so that it is possible to determine, by interpretation of appropriate measurements, whether they are indeed being met. Such determinations must then be made and the results made available to the building's owners and managers so that appropriate corrective action can be decided upon and undertaken.

To some extent this is the practice today and has been for years, although only recently coming under the label of building diagnostics. As building systems have become more complex and more automated, and as measurement technology and interpretive techniques have become more sophisticated, there has begun to emerge a sense of the possibilities of diagnostics as a field of practice in its own right. This recent interest in diagnostics traces its origin to the time, a few years ago, when concern about dwindling energy resources created a demand for expertise in assessing the energy performance of a building and devising ways to improve it. This led to the development of new applications of existing measurement technologies, such as infrared thermography, which was found to be useful in detecting thermal leaks in walls and roofs. These leaks, once located, could be patched with significant economic benefits. In many people's minds, that illustrates what building diagnostics is.

In the past, there has been a concentration of efforts on the performance of individual building components, usually assessed in the laboratory. But the way components perform under controlled conditions in the laboratory is not always a good indicator of how they will perform, in combination with other components, in an actual building that is being occupied and used. It is the performance of the building as a total system and of its component subsystems (such as heating/air conditioning systems, lighting systems, and structural systems) rather than the individual components (such as fans, condensors, or elevators) that is of ultimate concern to building owners and occupants. The assessment of total building performance is an important aspect of building diagnostics.

The purpose of this report is to describe the potential benefits that would be associated with the evolution of a field of building diagnostics that addresses all aspects of building performance. To accomplish this, the report first offers a definition of building diagnostics and describes its evolution. The report then addresses the subject of building performance requirements, considering in turn a number of building systems and components. Next it examines the steps that are, or can be, taken in design, construction, and building management to achieve performance goals, and it identifies ways in which building diagnostics could be helpful at various stages in the life-cycle of a building. The report concludes by discussing the market for building diagnostics, the motivation for building owners and managers to undertake diagnostics, and the attributes that might characterize building diagnostics as a coherent field of professional practice.

1

BUILDING DIAGNOSTICS: DEFINITION AND EVOLUTION

The fundamental purpose of a building is to provide shelter for some activity that could not be carried out as effectively, if at all, in the natural environment. Such an activity may involve people, a mix of people and machines, or--as in the case of telephone switching centers--machines alone (save for an occasional visit from a technician for maintenance and repairs). Nevertheless, all such activities require, to some degree, protection from the elements, and many such activities require a specific range of environmental conditions and a specific set of service facilities if they are to be carried out successfully.

A building provides these in four primary ways: (1) by providing a load-bearing structure that anchors the building to the ground and keeps it erect and intact, (2) by providing an exterior enclosure, or shell, that serves as a physical barrier to keep out wind, rain, marauders, and pests, (3) by providing an interior space whose configuration, furnishings, and environment (temperature, humidity, noise, light, air quality, etc.) are suited to the activities that take place within the building, and (4) by providing the service facilities--water, electricity, waste-disposer systems, elevators--that are necessary for the building's activities and for the well-being of the people carrying out those activities.

A building's performance capability reflects its ability to accomplish all of these things. Building diagnostics is the process of assessing this ability and predicting the future performance of the building and its subsystems and parts.

DEFINITION OF BUILDING DIAGNOSTICS

Building diagnostics is the name given to 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 diagnostics makes use of a variety of techniques ranging from visual inspection to sophisticated sensors, telemetering systems, and computers. The instruments of building diagnostics include a range of tools--such as interviews, questionnaires, user surveys, checklists, measuring devices, remote probes, indicating and recording devices, and computers--that are used to transform some measurable characteristic of a building into information relevant to the building's performance. The essence of building diagnostics lies not in the sophistication of the measurement instruments, but in the ability of the diagnostician to translate the measurements into an assessment of the building's present performance capability, and to extrapolate that assessment to a prognosis about the likely performance of the building in the future.

Building diagnostics is the process of judging how well a building can be expected to perform its functions. This judgment requires knowledge about the building's original purpose, its present purpose, its surroundings, and its history. It assumes that there are measurable quantities that are indicative of, or correlated with, the suitability of a building for a particular purpose, and it seeks to identify or recognize patterns in the measured values that relate to this correlation. Information obtained from the building's owners and occupants, visual observations, and measurements made by instruments provide the data on which the diagnostic assessment is based.

An essential element of building diagnostics lies in the view that the deterioration of a building or a building system usually begins with a subtle change in the structure or chemical composition of a building material, a minor malfunction in a piece of equipment, or a minor complaint from building occupants about discomfort or inconvenience. From these often imperceptible early stages the deterioration may progress rapidly or slowly. A means of identifying and assessing this early condition can clearly be of great economic value.

THE EVOLUTION OF BUILDING DIAGNOSTICS

While some building evaluation and measurement techniques have been carried on for years, building diagnostics as such had its genesis in recent developments in instrument technology and in the trend toward integration of measuring devices with microprocessors and minicomputers to provide information tailored to meet specific needs. Its first widely known practical success involved the use of infrared thermography to assess various aspects of a building's energy efficiency. Although the field of building diagnostics had its roots in measurement, it involves much more than measurement; it involves the combining of the knowledge of an expert (a professional in most cases) with a measurement process in order to make a prediction (or prognosis) of what the future performance of the building will be if the conditions disclosed by the diagnosis continue their present development with no intervention.

Today, most diagnostic services are called for because of building failures of one type or another. The initial call is usually made in response to some apparent indication of a problem, and the call is made to a specialist in the field deemed most likely to have a direct bearing on the problem. A structural engineer is called when cracks appear in load-bearing walls; a mechanical or electrical engineer when energy consumption becomes excessive, etc.

However, connecting the problem with the right expert is not as easy as it might seem. While the professional specialties that serve the building industry have developed a variety of measurement tools and procedures, most of these have been developed within specific disciplines. Yet most building problems call for a interdisciplinary approach, drawing on both physical and behavioral disciplines. For example, a number of professional skills are called into play when dealing with environmental issues that relate to working conditions and human comfort. Lighting quality, access to fresh air, and the elimination of noxious pollutants are of increasing concern. New materials are being used today, and buildings are being designed to be more air-tight in the interest of energy conservation. The effects of tightly sealed buildings and new materials on the occupants of the building and on the building fabric itself are unknown at this time.

When a problem arises, it may be necessary to call in a team that includes an architect, a chemist or biologist concerned with air quality, a physiologist, and a psychologist. While the views of these individuals are related to their unique disciplines, the expertise of the team is often greater than the sum of the expertise of its individual members. Moreover, many tools and methods of measurement that were initially developed for one purpose have turned out to be applicable to other purposes as well. For example, thermographic measurements in buildings began as a way to learn where and how heat was escaping. The same technology is now used to detect roof leaks, to identify places where insulation is missing, and to determine whether electric wires are overheating.

Building diagnostics is still evolving, and a broader view of its usefulness is emerging. The original concern with individual aspects of a building (e.g., energy efficiency) is growing to encompass a concern for the performance of the building as a whole. The focus on individual physical components is expanding to include the interfaces between components and the interaction of the building with its occupants. And the earlier view of diagnostics as a tool for responding to problems is giving way to a view of diagnostics as a tool for the prevention of building failures.

Diagnostics can be of value both in the narrower context and in the broader sense. In both instances, it will be most valuable when it is firmly rooted in an understanding of the performance that is required of a building and the ways in which various building elements affect the performance that is actually achieved.

2

BUILDING PERFORMANCE[1]

For a building to serve its purpose it must first of all be physically sound. Its load-bearing walls must not collapse, its exterior enclosure or outer shell must not leak, and its mechanical and electrical systems must work. Second, the building--and especially its interior space--must be suited, in configuration and environment, to the activities carried on within it. These two areas overlap functionally in that both are essential if the building is to serve its purpose properly. They may also overlap physically when a particular building element plays a role in both areas (such as when a load-bearing column also serves to define the interior configuration).

The two requirements of physical soundness and functional suitability must be met with an eye toward economic efficiency. The building's design and construction must take into account the availability and cost of materials, fuel, and labor; the building's location and ancillary facilities must take into account the cost of transportation, communication, and security; and the building must be capable of being maintained and repaired at a reasonable cost.

All of these considerations pertain to building performance. They give rise to broadly stated performance goals. These goals are in turn transformed into specific performance requirements that serve as a guide to designers. The requirements are further clarified by defining explicit, often quantitative, criteria for determining whether or not they are met, and by establishing a range of measured values that will be considered to satisfy those criteria. For example, an air temperature between 65 and 80 degrees Fahrenheit may satisfy a temperature criterion that is one facet of the requirement for indoor comfort. This range is established by physical, physiological, psychological, sociological, and economic requirements, and is ultimately translated into standards, codes, budgets, and guidelines.

Buildings and their component systems and subsystems are thus designed to meet certain performance requirements--e.g., to support contents of a certain weight, to provide water at a certain pressure,

---

[1] For a more detailed discussion of building performance in relation to diagnostics, see "The Concept of Total Building Performance and Building Diagnostics" by Volker Hartkopf and Vivian Loftness, in Symposium on Building Preservation and Rehabilitation, American Society for Testing and Materials, 1984.

to provide illumination at a certain level, or to damp vibrations of a certain frequency. The specifications associated with these requirements are not always met, due to poor design, poor workmanship, inappropriate materials, or damage caused by environmental conditions, accidents, fires, floods, etc. It is then important to determine in what ways the building falls short of the performance that is desired as a basis for deciding how either the building or the activities carried out in it should be modified.

It is not the general case that the building's architects, engineers, designers, contractors, etc. operate under the guidance of performance criteria on actual projects. There is usually a large mix of specifically designated requirements (not necessarily performance-based) and specifications that do not define the desired performance or the means on how it is to be met. This is one of the problems in applying building diagnostics.

BUILDING ELEMENTS AND THEIR PERFORMANCE GOALS

Physically, a building is made up of a load-bearing structure, an enclosure or shell that separates the building's interior from the external environment, an interior space, and a variety of service systems. The load-bearing structure consists of the foundation, frame, load-bearing columns and walls, beams, girders, trusses, etc. The enclosure consists of the roof and exterior walls (both above and below grade) and such other features as exterior windows and doors, balconies, etc. The interior space is the usable space within the building. It is the space actually available to the building's occupants for their activities. Its configuration is defined by the interior walls, floors, and ceilings. It contains furnishings and equipment (furniture, machinery, carpets, drapes, lighting, traffic and noise barriers) that give it final definition. A portion of this space is used to house electrical wiring, ventilation ducts, plumbing, elevator shafts, and other elements of the building's service systems (e.g., heating, ventilation, air conditioning, plumbing, electric power). These systems serve both to maintain the desired environment within the interior usable space and to provide the facilities, services, and amenities needed to support the building's activities.

There are performance goals associated with each of these building elements. For example,

- The exterior enclosure, or outer shell, must not permit excessive passage of air, water, heat, or noise.

- The interior environment (temperature, humidity, air movement, air quality, illumination, noise) must be appropriate to the building's activities.

- There must be facilities and services (heating, air conditioning, electric power, communications, water, waste disposal, freight elevators) necessary for the building's activities, and the systems providing these services must function properly.

Performance goals in these different areas cannot be treated independently of each other for two reasons. First, they are related in a complex manner through their physical, physiological, psychological, sociological, and economic implications. Physical implications have to do with structural strength, resistance to forces, chemical interactions, etc. Physiological implications pertain to the physical health and safety of the building occupants and the need to protect basic bodily functions--sight, hearing, breathing, feeling, movement, etc.--from such conditions as fire, building collapse, poisonous fumes, high and low temperatures, poor light. Psychological implications have to do with supporting the building occupants' mental health through appropriate provisions for privacy, interaction, clarity, status, change, etc. Sociological (or socio-cultural) considerations involve supporting the well-being of the community within which the individuals act, relating the needs of the individuals to those of the collective. Economic implications involve the need to allocate resources in the most efficient manner in the overall goal to serve user needs.

Second, in trying to fulfill one set of performance requirements, side effects may arise that impinge upon the fulfillment of another. A ceiling light fixture may give forth heat and noise as well as light. The ventilation rate chosen to achieve acceptable air quality may adversely affect thermal and acoustic comfort. Although a particular building component may provide adequate performance in one context, it may fail in others.

Three important concepts in assessing performance are suitability, reliability, and flexibility. Suitability is a measure of the degree to which a building or a building system or component meets user needs. Reliability is a measure of the probability that a building system or component will continue to perform as intended throughout the life of the facility, given appropriate maintenance and use. Flexibility is a measure of the building's ability to accommodate changing functions and occupancies during its lifetime.

Suitability has three distinct aspects. The first involves a clear understanding of the building's purpose and an ability to design a structure and an interior space suited to that purpose. The second involves an understanding of the building's physical and social setting and an ability to design a building that will remain functional under anticipated external conditions (severe winds, earthquakes, floods, adjacent excavations) and will integrate harmoniously with its surroundings (not only aesthetically but also in terms of such social factors as transportation, commerce, and crime). The third aspect involves suitability in regard to health, safety, and the public welfare, as reflected in laws and regulations.

Reliability depends primarily on the adequacy of the design, the appropriateness of the choice of materials and construction techniques, the quality with which building components are manufactured and assembled, and the diligence with which the building is maintained.

Flexibility depends largely on the foresight of the designer in anticipating trends that might require changes in the building's use or in the way in which its intended activities are carried out.

The suitability of a building's light fixtures, for example, depends on the intensity of illumination they provide, their location with respect to ceilings, floors, walls, windows, furniture, and partitions, the occupant density and occupant activities at various times of day, the color and reflectivity of partitions and furniture, and the fixtures' interference with acoustic and thermal comfort. The reliability of the light fixtures depends upon the quality of their components--ballasts and starters, tubes and bulbs, lenses and reflectors--and the maintenance effort that can be reasonably expected, including cleaning schedules, replacement schedules, etc. The flexibility, or adaptability, of the light fixtures reflects the level of effort and resources necessary to sustain suitability when the activities carried out in the building change. New activities may require different physical arrangements of walls, partitions, and furniture, different colors of walls and carpets, different occupant densities, or different work activities (e.g., use of video display terminals), all of which may lead to different requirements for illumination.

To achieve overall acceptable performance, therefore, it is necessary first to resolve conflicts and set priorities, based on the use to which the building is to be put. Then, choices must be made using performance evaluation techniques that consider the complex interrelationships that arise in the specification, installation, and use of different materials, components, and assemblies within the building.

It is difficult to do this because the performance of individual components has traditionally been measured in isolation from other components. This is slowly giving way to integrated on-site performance measurements and assessments. The suitability, reliability, and flexibility of components and their interfaces in meeting the overall performance requirements of the building are best evaluated under occupied conditions. It is the dynamic environment created by the managers and users of buildings that provides the realistic basis for appraisal.

A further complication arises when one building component or assembly serves a dual function--e.g., when a load-bearing structure serves both as exterior enclosure and as interior definition, or when servicing assemblies such as ducts and elevator shafts provide interior definition or exterior enclosure. What is critical to the concept of total building performance is the understanding that the various building components are often designed only to meet their individual component performance requirements, resulting in an inability of the building as a whole to meet all of its total performance goals. For example, a roof membrane carefully designed to roofing component performance specifications may itself be watertight, but the elevator shaft--designed to other component specifications--may penetrate the membrane without adequate detailing to guarantee the air, vapor, or water seal required to withstand differential expansion and contraction and to prevent air and water leakage.

Many kinds of interactions must be taken into account. For example, guidelines, codes, and standards have been developed to protect people from excessive noise. To prevent physiological hearing loss, criteria for sound intensity and duration are established. To reduce psychological discomfort, sound frequency (even below the known hearing threshold) is measured to evaluate possible distractions outside of the acceptable range of low frequency rumbles and high frequency hisses. To enhance personal and social satisfaction, consideration is given to speech articulation and to ensuring privacy in offices and apartments. All of these aspects of the auditory environment are important in setting requirements for sound insulation and in choosing carpets, drapes, and ceiling tiles that will create the desired acoustic character within the building.

Finally, the availability of resources (financial, technical, and material) imposes another layer of requirements, establishing limits of feasibility alongside the limits of acceptability. Decisions must be tempered by a full understanding of the need to manage resources over time, evaluating allocations for initial outlay, operating costs, maintenance costs, eventual replacement or conversion costs, and associated personnel costs.

Particular requirements may often be achieved in a number of different ways, involving a variety of technical and economic factors. For example, the ability to maintain the desired interior temperature at minimal cost may depend on the degree to which the building is climate-responsive, the effectiveness of the building's heating and ventilation system, the adequacy of its insulation, and the building's freedom from leaks in heating ducts and around window and door frames. Depending on the relative cost of fuel, insulating materials, and labor, it may be most advantageous to maintain the desired temperature range by consuming more fuel, by installing more insulation, or by having repair crews regularly seal all leaks.

USING DIAGNOSTICS TO ASSESS BUILDING PERFORMANCE

Performance goals and requirements in areas such as those listed above must be translated into specific, usually quantitative, performance specifications that can serve as a guide to designers, builders, and building managers. These performance specifications must be so expressed that it is possible, by some process of measurement, analysis, and interpretation, to ascertain whether they are being met. Building diagnostics can then be used:

- To assess the degree to which each individual requirement is being met (e.g., is the heating system capable of maintaining a temperature at 64° F in all parts of the building on a day when the outdoor temperature is between 5° and 15°?);

- To assess the degree to which the performance of the building as a whole meets the requirements set for it (e.g., do aspects of the building itself detract from employees' ability to maintain specified productivity goals, or is the building responsible for employee illness in excess of a specified rate?);

- To evaluate the implications for the building's owners, occupants, and users of any present or incipient deficiencies in performance (e.g., can it be expected that there will be a certain number of health problems each year among the building occupants, or a need to close the building for a certain number of days while repairs are carried out?); and

- To determine the causes of any deficiencies as a basis for deciding on remedial actions (e.g., is the failure to maintain desired indoor temperatures due to an inefficient furnace, malfunctioning thermostats, or gaps in the insulation?).

MEASUREMENT TECHNIQUES

The measurement techniques of building diagnostics can be destructive, intrusive, or non-intrusive. Destructive techniques use a sample of material that is itself destroyed in the process. Destructive testing is of value when a small sample can be considered representative of an entire system or subsystem. Intrusive techniques may temporarily affect the performance of a system, after which the system's original performance returns (e.g., a dye can be injected into a water system to locate a blockage; after the system returns to normal no trace of the dye is left). Non-intrusive techniques do not interfere with system performance at all; these can include photography, infrared thermography, etc.

Diagnostic measurements can also be characterized as observational, physical, and behavioral. Observational measurements are typically made in the course of a walk-through of the building by an expert; they depend on skillful use of the senses of sight, hearing, touch, smell, and taste. Physical measurements can be made using either hand-held instruments, larger but transportable equipment, or sensors embedded in the building; they can be made "in place" in the actual building or in physical models or mock-ups of the building. Alternatively, portions of the building can be removed and taken to a laboratory where a variety of physical and chemical measurements can be made. Behavioral measurements are made by conducting interviews, evaluating questionnaires, and analyzing written records.

Interpretation of the measurements can also be carried out in a number of ways. Up to a point, intuition and "informed judgment" can provide the insight needed to do this. But as buildings and their component systems and subsystems become more complex and sophisticated, and as performance requirements become more stringent, equally complex and sophisticated means will be needed to assess the building's ability to perform as desired. Statistical methods, pattern-recognition techniques, and complex computational procedures may be needed.

A typical building diagnostics assessment for a total building might ideally consist of the following series of steps:

(1) Visual examination of the building, supplemented by questioning of its occupants and maintenance personnel, to classify it and identify any obvious flaws, system failures, and significant positive attributes.

(2) Assessment of the performance requirements that the building must meet. These may be the original design requirements or requirements derived from a proposed use to which the building will be put.

(3) Selection of the initial set of diagnostic procedures to which the building will be subjected, based on the results of (1) and (2). Ideally, these initial screening procedures will be chosen so that if they do not reveal any areas of inadequate performance, no further diagnosis is needed because the building's condition is judged satisfactory.

(4) Selection of additional diagnostic procedures designed to pinpoint the problem and forecast the future condition if the results of (3) reveal areas of poor performance. This step makes use of those results, together with those of (1) and (2). The additional procedures selected are intended to provide a basis for suggesting remedies. Often these procedures will be more than minimally intrusive and they may be expensive.

These procedures can also be followed for assessment of localized problems where the total building is not in question. Most diagnostic applications involve assessments of particular problems (which may or may not lead to other larger problems.)

Too often, however, only one or two of these steps are taken, without any attempt to follow a logical sequence. This can have serious and expensive consequences if it leaves the cause of a problem only partially understood.

Diagnostics may reveal problems. It may also reveal that in some ways the building is "overdesigned," i.e., capable of performing better than is necessary for a particular use. If this is so, it may be possible to use the building in a different way than was originally intended (e.g., a factory may be able to use heavier machinery than it is currently using, or machinery requiring more precise climate controls). Such positive feedback from the diagnostics team to the user may have as much economic significance as information concerning incipient failures.

3

DIAGNOSTICS AT VARIOUS STAGES IN THE BUILDING LIFE CYCLE[1]

Diagnostics can be applied at various stages in the life cycle of a building, from initial conception and planning to eventual demolition. During the early stages (before there is an actual building) diagnosis can be applied to the "virtual building"--the one that exists first in the mind of the designer, and then in the form of working drawings or models (including computer models)--but the methods used and the instruments available for that purpose are different than the ones used in an actual building.

THE BUILDING LIFE-CYCLE

The life cycle of a building falls into four major periods. First is the pre-construction period, during which the building's purpose is identified, a site is selected, feasibility studies are undertaken, financing is provided, the building is designed, specifications are developed, working drawings are prepared, and bids for construction are tendered. Next is the construction period, concluding with acceptance, fit-up, and initial occupancy of the completed building. This is followed by an extended period of long-term occupancy and use. Finally, there is a period of adaptive re-use and eventual demolition, during which the building may be renovated and put to a different use for a period of time, and is ultimately demolished. Building diagnostics plays a different role during each of these periods.

THE PRE-CONSTRUCTION PERIOD

During the pre-construction period there is no actual building on which to perform diagnostics, but there is a "virtual building"--one that exists initially in the mind of the designer, then in a

---

[1] For further discussion of the building life-cycle and its relation to diagnostics, see "The Project Delivery System of Public Works Canada," Public Works Canada, October 1978, and "Preventive Medicine" by Thomas Vonier, Progressive Architecture, April 1983.

preliminary design form, and eventually in some detail in working drawings and specifications. The virtual building is real enough to be inspected for conformance with building code requirements. Some diagnostic techniques, such as computer modeling, can be used at this time to assess the likely performance of the building when completed.

Building diagnostics at the virtual building stage is potentially one of the most productive applications of the diagnostic approach. It is at this stage that the exercise of diagnostic techniques constitutes one of the few opportunities when diagnostic feedback can improve total building performance. After this stage, when essentially all significant decisions of the future physical environment should have been made, the diagnostic analysis can only reveal the degree of change (or degradation) from the original total building performance level.

The design stage offers the greatest opportunities for ensuring the total building performance that is ultimately desired. Probably the most critical step toward achieving this is the creation of an interdisciplinary design team, including a professional in each performance area critical to the building. The team might, for example, include experts in architecture, mechanical engineering, civil engineering, energy, illumination, acoustics, behavioral and functional comfort, construction, and building operation and maintenance. It is critical that the interdisciplinary team be in a position to make design decisions from the point of initial conception, since image, siting, massing, and orientation are early decisions with significant implications for meeting many performance requirements.

CONSTRUCTION AND INITIAL OCCUPANCY

Diagnostics can be used to assess the degree to which the completed building, at the end of construction or renovation, meets the performance requirements set for it. This use of diagnostics can be thought of as acceptance testing. It is carried out to identify any flaws that may be present and to make a prognosis about the future performance of the building or building element.

Diagnostics need not wait until construction is completed; it can be applied to various elements of the building while construction is going on. In fact, if present trends continue, the construction stage may ultimately be the principal period of use of new diagnostic equipment and procedures. The most obvious application is for testing components and assemblies in place, removing the inaccuracies of laboratory testing, which is often incapable of simulating component-to-component interactions. Diagnostics can be useful to the architect and site supervisor in ensuring that specifications are being met, to the construction manager in ensuring that materials and assemblies are being appropriately installed, and to the owner in ensuring building competence on all performance levels before acceptance.

Diagnostics can also be used to assess the safety and health aspects of working conditions for those involved in the construction process.

Directly following acceptance of the completed building, after initial fit-up and occupancy, it may be necessary to reevaluate building performance. Fit-up encompasses the installation of interior finishes and furnishings and the modification or balancing of systems to serve specific occupant needs. In many buildings this is a haphazard process left to the individual divisions or renters, often resulting in the inability of the building to meet the various users' performance requirements despite the satisfactory quality of the building at the completion of construction.

For this reason, three steps should be undertaken by the building owner at the time of fit-up and initial occupancy. First, appropriate finishes and furnishings should be selected and installed, and a comprehensive balancing of all systems should be undertaken to ensure that the performance requirements associated with specific functions throughout the building are met. Second, interdisciplinary diagnostics (diagnostic testing of all performance areas simultaneously) should be undertaken to actually measure the in-situ performance of the individual materials, components, and assemblies. Third, training of personnel (managers and occupants) should be undertaken to increase the likelihood of continued satisfactory performance over time. This training should provide an understanding of system control operation and maintenance, an awareness of the potential for conflicts between performance requirements if occupancy conditions or components are modified (e.g., if acoustic partitions are brought down to the floor so that air circulation is cut off, if walls are repainted with dark colors so that light levels are reduced, etc.), and an understanding of how improvements or greater flexibility could be achieved through additional investment. All three of these steps could be undertaken by an initial occupancy evaluation team, utilizing both behavioral and physical diagnostic tools and procedures.

LONG-TERM OCCUPANCY AND USE

There are three distinct ways in which diagnostics can be of value during the lengthy period in which a building is occupied and used: it can be used for routine or periodic checkups, for troubleshooting when problems occur, and as an aid to building operation and maintenance.

The deterioration or change in condition of the building's component systems and subsystems can affect the overall performance of the building. This may come about as a result of normal deterioration of materials or their performance with time, or as a result of abuse of the system, accidents, occurrences that subject the building to greater than design stresses (e.g., excessive snow on the roof), or changes in environmental conditions (e.g., increasing water pollution that results in accumulations of contaminants that clog pipes; increasing atmospheric turbidity due to air pollution that reduces the available natural illumination; increasing outside noise that exceeds the building's capacity for noise insulation). Diagnostics can be used throughout the life of a building to determine how far its performance has departed from its initial state. The results can be used as a basis for modifications either to the building or to its use. This use of diagnostics can be thought of as routine periodic reassessment, and can often detect incipient problems before signs of failure are evident.

At times some aspects of a building's performance suffer acute deterioration because of a specific breakdown: a break in a water pipe, a leak in a roof, failure of a particular structural member. Sometimes the breakdown is obvious (e.g., a broken window); at other times only the symptom is apparent (e.g., a sudden increase in fuel consumption). Diagnostics can be used to locate and identify the system or subsystem failure that is responsible for the symptom. Once the failure is located, the remedy is often obvious. This use of diagnostics can be thought of as system failure detection.

Diagnostic tools and procedures can also assist in building operation and maintenance. Much of the diagnostic equipment currently available, ranging from computer software to photocells and thermostats, is in fact designed to operate buildings efficiently. New developments in diagnostic equipment and procedures could make it possible to anticipate the maintenance needs of a building (e.g., the use of acoustic noise level meters or thermography to assess wear in fans and other moving parts). Investment in such maintenance diagnostic tools could have significant benefits in both operation and replacement of building equipment and building components. The continuous use of such building diagnostic equipment could eventually allow the operators of buildings to set up preventive maintenance procedures suited to the materials, components, and systems within the building.

An additional value of diagnosing performance in operation and maintenance is that it makes it possible to undertake a long-term program of feeding back information to the teams responsible for the programming, design, and procurement of buildings. Without such feedback, building performance inadequacies and failures will continue, along with occupant and owner dissatisfaction and associated costs.

ADAPTIVE RE-USE AND DEMOLITION

When a major change in the use of a building is contemplated (e.g., when a warehouse is to be converted to a theater), a new set of performance requirements must be drawn up, and diagnostics can be used to determine whether the building meets these new requirements or whether modifications are necessary. This use of diagnostics may be thought of as conversion testing.

There is a final stage in a building's life when it is no longer suitable for its original purpose--either because of deterioration in its performance or because of a change in the way that purpose is carried out. Diagnostics can then be used to determine whether the building is suitable for any other purpose or whether it should be demolished and, if the latter, whether any of its component systems can be salvaged and used for some other purpose. This use of diagnostics may be thought of as salvageability testing.

When the building is finally scheduled for demolition, diagnostic procedures can be used to identify vulnerable points in the structure and fabric of the building as a basis for selecting appropriate demolition techniques. This use of diagnostics may be thought of as serving demolition safety.

4

THE MARKET FOR BUILDING DIAGNOSTICS

The analytical tools and assessment procedures of building diagnostics already have a market, and are contributing significantly to the quality of buildings. How large and how significant that market will become remains to be seen. The impact that diagnostics will ultimately have throughout the life of a building--from conception, commissioning, design, construction, and fit-up to operation, retrofit, and destruction--is still unknown. It is possible, nonetheless, to offer some thoughts about the growth in the demand for building diagnostics that can be expected over the next few decades. This growth falls into two categories: (1) the growth that can be expected as a result of increasing concern about the adverse effects of poor building performance, and (2) the growth that can be expected to stem from changing attitudes and new technological developments.

THE ADVERSE EFFECTS OF POOR BUILDING PERFORMANCE

With the growing number of megastructures being built today, enclosing communities of thousands of people, and with the increasing interest in building rehabilitation and adaptive reuse, building performance is becoming a major market concern. This concern has three primary elements: concern about the occurrence of serious structural failures for which designers, builders, owners, and operators may bear legal liability; concern about occupant health and productivity; and concern about the increasing costs of maintenance and operation.

Structural Failures and the Associated Publicity and Litigation

Whether or not the actual number of structural building failures has increased, the publicity surrounding them has grown to such proportions that on-site diagnostic procedures are critical to the building owner today. Serious building failures--such as glass and facia panels falling to the street below, roofs caving in, internal bridges collapsing, fires overwhelming the systems intended to contain them, and even stairs degrading to a hazardous level--have resulted in lawsuits that have had a significant impact on the building profession. Building owners and managers know that they must have the tools to anticipate all failures that may result in serious liability. The resulting demand for diagnostic tools has already resulted in the development of a variety of testing procedures using behavioral, visual, portable, and laboratory scale equipment.

Impacts of the Building Environment on Health and Productivity

The growing sensitivity to measurable occupant stress has also contributed to the demand for diagnostic tools and procedures. Awareness of the health ramifications of buildings and their component systems, both in the health professions and among the public, has vastly increased in the past few years. This has ocurred in direct relation to the increasing complexity and scale of new construction and the speed with which new building materials and technologies are being introduced. Health issues concerning asbestos, outgassing, air quality, eyestrain, and hearing failure are matched by a concern for the impact on productivity of visual and acoustic distractions caused by vibration, fluctuating thermal conditions, poor ergonomic design (resulting in fatigue or pain), and inefficient placement of building systems in relation to each other. The growing sensitivity of individual workers and their unions to these issues, along with employers' growing awareness of the way that the building environment contributes to productivity, is likely to lead to an increasing demand for diagnostic tools and procedures.

Increasing Costs for Maintenance and Operation

Finally, growth in the costs of operating and maintaining buildings is forcing clients and building owners to rethink building performance in such areas as thermal, lighting, acoustic, and functional comfort, air quality, and building integrity. This rethinking includes consideration of larger initial investments to achieve building performance in lieu of long-term remedial measures that result in high operation, maintenance, and retrofit costs. It also includes consideration of more efficient ways of achieving the desired performance. Resource constraints involving energy, money, and even water are causing building clients, owners, and managers to place greater emphasis on the efficient performance of buildings over time. This is leading to a greater willingness to provide the resources necessary to maintain the desired performance. This in turn requires diagnostic tools and procedures to estimate performance during the design stages, to monitor materials and assemblies during the construction phase, to fine-tune systems and subsystems in the course of routine operation and maintenance, and to determine the comparative advantage of retrofit or adaptive reuse over new construction.

CHANGING ATTITUDES AND NEW TECHNOLOGIES

Several trends have developed over the last few years that could escalate the demand for building diagnostics far more than concern about the adverse impacts of poor performance. The most prominant of these trends are the growth of occupant awareness, the rapid introduction of new technology, and the increasing use of flexible environmental control systems.

Occupant Awareness

One of the most potent forces affecting building management today is the increasing occupant awareness of the potential adverse impact of poor building conditions, combined with the growing realization of the power that organized groups can exercise to induce change. To begin with, there is an increasing sensitivity among employee groups to the harmful effects of questionable working conditions, with particular emphasis on the impact of air quality on health, the impact of building degradation on safety, and the impact of thermal, acoustic, lighting, and functional conditions on comfort. The level of expectation of both employers and employees is being raised, leading to such new building performance requirements as better energy consumption, lighting matched to function, maintenance of building appearance over time, etc.

Of critical importance in this regard is the power of employee unions to bring about changes in the conditions within buildings, especially when teamed with corporate building owners who operate large numbers of buildings and have an economic stake in occupant satisfaction. These two groups could have a significant impact on the development of the field of building diagnostics by demanding diagnostic procedures and tools for improved design, construction, operation, and retrofit of buildings.

New Technology

The second trend that may lead to a rapid development in building diagnostics is the introduction of new technologies and instruments. While the computer in its many guises may be the greatest catalyst, new diagnostic instruments and environmental control devices can also contribute significantly to an improved capability for achieving desired building performance, and a consequent demand for achievement of what is potentially possible.

The increased use of computers affects building performance in two distinct ways. Personal computers and computerized production machinery have created new, unexpected environmental stresses. Traditional lighting, temperature, and humidity control systems are incapable of accommodating the visual requirements of the computer screen or the stresses due to computer-related heat generation and static. On the other hand, computerized control systems offer significant improvements in the efficient management of these same lighting, heating, and cooling systems, and can incorporate direct feedback from the occupant as to their effectiveness. At some future time, the individual computer could even become a human comfort sensor itself, at a very minimum assessing temperature, lighting, and acoustic levels, and perhaps air quality.

New diagnostic technology is also finding a significant market. Small "tattletale" gadgets (such as streamers for air diffuser testing, color-changing desk thermometers for temperature assessment, and smoke pencils for infiltration testing) for intrusive testing of existing buildings and of mock-ups and models are finding a growing demand along with sound-level meters, air quality testing equipment, light meters, flow meters, thermographic cameras, spot radiometers, moisture meters, and so forth. Large facilities incorporating laboratory equipment for intrusive and destructive testing of existing and mock-up building components and systems are being set up throughout the country.

Flexible Environmental Control Systems

The third development that is likely to promote the demand for building diagnostics is the widespread use of devices that permit flexible, individual control of the interior environment and compensation for a variety of present day performance failures. These "control" devices include step and continuous dimmers for achieving lighting comfort in the face of changing functions or changing outside conditions; individual convective and radiant heaters, humidifiers, fans, and unit air conditioners for achieving thermal comfort; ionizers for air quality; and partitions and earphones for acoustic comfort. To the extent that these devices improve the local environment for some individuals at the expense of others, or at a too great cost in terms of energy, they will provide an incentive to make the "whole environment" work better for everyone.

THE FUTURE MARKET FOR BUILDING DIAGNOSTICS

We foresee a substantial future market for relatively low-cost multifacet tests and analytical procedures that will contribute to assessments of a building's performance capability. Justification for the costs of these procedures will come from the creation of a better environment for people using the building, resulting in increased productivity. Potential trouble spots will be found early and repaired cheaply, resulting in lower operating and maintenance costs. Monitoring of the physical fabric of the building will make it possible to spot potential structural damage (from moisture corrosion, for example) before large-scale remedial work is necessary. If these activities are coordinated in an effective manner, the overall cost for each building will be sufficiently low, and the use of ongoing diagnostic procedures will become feasible and economic.

The ability to test and analyze a building's potential performance can provide a basis for acceptance testing. It will become possible to increase the number of items that are checked for performance before the building is handed over. Later, it will be possible to check the levels of degradation that occur with use over time. Information about a building's potential degradation over time can indicate in advance where frequent testing and ultimate remedial action might be necessary.

During the course of this study the committee attempted to obtain information about the costs that building owners, developers, and government managers might be willing to incur for different diagnostic services. No consensus currently exists about the willingness to pay for preventive diagnostic services. However, diagnostics for crisis response in such areas as energy conservation and building facade analysis are employed on a substantial scale, either because they are required by regulatory agencies or because there are opportunities for a quick return on investment. In every case, separate groups of experts, knowledgeable in their own specialties, perform the services.

The market for these activities is increasing. Some techniques, such as thermography, are beginning to be employed in large numbers of buildings for preventive maintenance. Professionals using thermographic instruments, for example, can spot potential roof leaks or weaknesses in the insulation system of the building.

Although building diagnostic activity is increasing, it is developing without a coordinated focus. Diagnostic efforts occur in response to special, more urgent concerns, such as energy conservation over the last few years. A building's health, however, depends on a much broader range of interests. New problems have emerged in buildings that appear likely to spur new developments. New insulating materials make it possible to have tightly sealed buildings, which promote energy conservation, but which, in some cases, result in outgassing of noxious emissions that affect occupants' health. The widespread use of video display terminals increases productivity, but the "luminous environment" then becomes a matter of concern and an issue in labor negotiations.

Productivity, health, life-cycle costing, and maintenance of the fabric of the building are all tied to the development of a capacity for assessing how well a building performs and how it may be upgraded when necessary. The ability to establish performance requirements that can be delivered at reasonable cost is critical. Norms based on cost and performance are needed for this process to occur. In the future, we anticipate higher levels of diagnoses and the emergence of "smart" buildings which, in effect, tell us when something is wrong.

A critical issue in the development of building diagnostics is the ability to obtain substantial data at low cost. The growth of a market for preventive diagnostics is likely to depend on the ability to perform multiple tests quickly and effectively. Test procedures can be expensive, and building owners will, at the outset, be most likely to undertake diagnostic testing only in response to building failure or impending failure. A client's call to look at a single item should result in a measurement program yielding data that can be interpreted and used by competent specialists from any number of different disciplines. In this manner the cost of diagnostic testing will go down and the benefits of diagnostics will increase.

5

BUILDING DIAGNOSTICS: POSSIBILITIES FOR THE FUTURE

Homeowners, office building owners, facility managers, architects, and engineers have all practiced forms of building diagnostics when confronting problems such as leaking roofs and faulty heating systems. Often, however, the fact that something is wrong becomes apparent only after significant damage has been done, and analysis, prognosis, and remedial action are a blend of custom, tradition, previous experience, and trial and error.

Today, spurred largely by the energy crisis and the growing interest in restoration and reuse of buildings, sophisticated means have been developed for assessing a building's condition. A number of practitioners and private and public organizations are actively involved in some element of measuring and assessing buildings. These include private testing laboratories, university research centers, independent and municipal building inspectors, building product manufacturers, construction and maintenance contractors, in-house facility managers, architectural and engineering firms, and other consulting organizations.

The nucleus of a building diagnostics profession has begun to form. This chapter discusses some possibilities for the future practice of building diagnostics.

FORCES TENDING TOWARD THE EVOLUTION OF BUILDING DIAGNOSTICS AS A FIELD OF PRACTICE

Building diagnostics is an evolving professional practice that is, however, growing without a cohesive focus. Its growth is characterized by unrelated activities that have developed in response to specific needs and particular financial incentives. It is an unbalanced pattern of growth, a "crisis-oriented" response to problems rather than a planned, holistic, preventive approach. Operating in a context of response to impending building failures, professionals in different disciplines, working in different kinds of organizations, tend to see the same problem from different viewpoints. Unless these different viewpoints are integrated in some systematic manner, those responsible for building performance will continue to face a situation in which they themselves must carry out enough of a preliminary diagnosis to know which expert to call--a task that most building managers and owners are not adequately equipped to perform.

The establishment of a more coherent, integrated field of practice should make it possible to realize increased economic benefits and increased industry participation in both a preventive and failure-response mode. The orderly evolution of a building diagnostic discipline will stimulate the development of procedures that have a variety of applications, leading to analyses of test results that may go beyond the immediate problem at hand. Such a comprehensive diagnostic capability would allow for testing in areas for which there is no economic justification for separate tests.

There are other, non-economic reasons for the development of a coherent building diagnostics discipline. These include the increasing necessity to conduct tests to confirm compliance with regulatory requirements, the ramifications of legal liability in the event of a building failure, and the growing concerns of unions and similar organizations for the health and well being of building occupants. As more is learned about potential hazards associated with a building's indoor environment (such as the possible health effects of poor air quality in buildings that are tightly sealed to promote energy efficiency) there is likely to be a demand for both better measurement procedures and more stringent regulations. It is important that the two go hand in hand; that we not require a level of performance that we cannot verify by measurement and, at the same time, that we not let the availability of measurement techniques lead to regulations that are so stringent that they go beyond what the industry can afford. An organized and recognized diagnostic profession can do much to foster the integration of a variety of demand factors in a rational way so that regulations are determined by reason rather than by accident. A coordinated approach can provide a basis for developing and using decision-making tools to enhance building performance in an environment that makes the best use of available resources for the intended purpose.

Today's diagnostic activities encompass programming and design issues; construction and acceptance procedures; building operation, maintenance, and use; and assessment of a building's capacity for continued use under differing conditions. Many different experts are involved, from disciplines concerned with health, fire, engineering, architecture, construction, and other areas related to a building's well-being and its capacity to support the activities which it must house.

Our increasing knowledge about the many aspects of building performance, and about the ways in which their interactions affect human activities, has created a context within which building diagnostics can and should be recognized as a discipline of its own. This makes it possible to take advantage of the vast body of knowledge and expertise that is continuously being created in a variety of separate disciplines. The ability to focus on the mission for which a building is constructed and used--and then to draw upon a variety of different disciplines whose knowledge and skills are required to provide for the effective performance of that mission--has reached the point where its further development requires a more coherent focus. It is with this in mind that we look toward the development of a diagnostic discipline that is based on capabilities that are in hand today, but that focuses these capabilities in the direction of more comprehensive programs related to how people live in, use, and work in buildings.

More specifically, there is a need to focus attention on assessing total building performance by evaluations carried out in the building under conditions of actual use. Our ability to conduct laboratory tests and assure the performance of individual components is well developed, but quality in the components does not assure quality in the overall building. It is the building whose performance is of ultimate concern, not the components. Evaluating building performance is of necessity a multidisciplinary activity, and one that is most liekly to be successful in the context of a comprehensive diagnostics profession.

POSSIBILITIES FOR FUTURE PRACTICE

We see a range of possibilities for the future of building diagnostics, extending from a simple continuation of present practice to the creation of a new professional field in its own right. In order to assess the advantages and disadvantages of various approaches, we have identified four specific possibilities that seem to be likely if the right incentives are provided. They are:

- Within the context of present practice, each discipline and specialty continues to develop new tools and testing capabilities, and continues to provide its present services.

- Each discipline continues its present practices, including the development of new tools and testing capabilities, but with a new emphasis on developing tests and procedures that can be applied by technicians rather than professionals. This will permit a future coalescence of the activities of different disciplines by trained technicians.

- A new service field is created, centering on the establishment of field tests and laboratory services that provide information to specialists in the various disciplines in a manner similar to medical testing laboratories. This would enable a comprehensive set of tests to be conducted at one time, each of which would be interpreted by a specialist in an appropriate discipline.

- A new, comprehensive, multidisciplinary field of building diagnostics is created to replace the activities currently conducted within individual disciplines. This would go beyond testing to encompass a more comprehensive assessment of the performance capability of a building.

Each of these alternatives has advantages and disadvantages that could affect its ultimate impact on the building industry. For example, if diagnostic services are expanded within existing disciplines, the high cost of applying each separate diagnostic activity on an individual basis will emphasize the use of diagnostics for critical or emergency events rather than for long-term preventive measures.

If greater emphasis is placed on the development of new tests and procedures of such a nature that field work can be performed by technicians who do not have to be highly skilled in a single discipline, emphasis could be placed on the economic viability of current methods and procedures, and the use of less-skilled people in the field, thereby reducing costs.

If a new professional field of comprehensive diagnostic testing and interpretation is developed, there could be centralized responsibility for measurement and analysis on a comprehensive basis dealing with buildings in their entirety, rather than with components and sub-systems, along with a capability for measurement and interpretation in areas that are not perceived as meriting such activities now. This could lead to a greater emphasis on preventive maintenance in addition to responding to emergencies or single areas of high economic return, carved out by interdisciplinary teams that come together on a regular basis. These teams could include many types of architects, engineers, environmental researchers, behavioral scientists, facility managers, organizational and information system specialists, among others. On the other hand, segments of the industry that are now involved in diagnostic activities would face the possibility of displacement by new entities. This could lead to conflict with current industry-consultant relationships (e.g., professionals' work would be subject to checking by diagnostic organizations), and it could be difficult to attract qualified people to work as diagnosticians if that work is seen as conflicting with the work of designers. There is also the possibility that tests will be developed based on what <u>can</u> be tested, rather than what <u>needs</u> to be tested in order to ensure satisfactory performance. This could result in more stringent regulations in the building industry.

It is unlikely that anything other than a modest extension of current practice will transpire without inducements in two areas: (1) pressure from major client organizations and standards organizations, and (2) development of new areas in the education and training of building professionals.

Major client organizations such as government agencies and large corporations can, by requiring certain diagnostic practices or by providing certain diagnostic capabilities, do much to foster the growth of diagnostic practices and the development of a diagnostic profession. Professional organizations can, by developing appropriate standards, provide a frame of reference within which diagnostic procedures can be used and their value can be recognized. Governmental entities, labor unions, and insurance companies can, through regulations and contract provisions, require either specific levels of performance or specific diagnostic procedures. For any of these enhancing activities to be truly effective without imposing undue constraints on the industry, it must incorporate the viewpoints of these who take a broad view of what building diagnostics can contribute, as well as the viewpoints of the many already-established special interest groups that make up the building community.

LOOKING AHEAD

This report has described the field of building diagnostics in its embryonic form. While the concepts and potential are there, the field needs to be further developed before a mature mode of practice will be feasible. The essence of building diagnostics lies in the ability of a professional to recognize factors and patterns, perform needed tests and analyses, and develop a prognosis of the future condition likely to prevail in the absence of significant interventions. This requirement for a combination of measurement devices and expert knowledge suggests that the growth of the field will depend in large part on the development and dissemination of both techniques and understanding. Some ways in which this might be accomplished are set forth below. Steps such as these should do much to set the stage for a fully developed building diagnostics field without trying to create it by fiat or governmental decree, when neither the building industry nor the engineering community is technologically prepared to implement it or is convinced of its potential value.

Research, Development, and Technology Transfer

To expand the basic inventory of building diagnostic tools, it is important to continue to develop new techniques, improve existing ones, and adapt techniques developed for, or now used in, other fields. Many of the advances that have been made thus far have come about when professional firms engaged in diagnostics have encountered new situations and have developed new techniques for addressing them. As these techniques undergo repeated use and refinement, they gradually become accepted into the diagnostic repertoire. Often they lead to requirements for new instruments or new analytic methods. These are provided either by modifying existing diagnostic tools or by developing new ones specifically tailored to meet the identified need.

This process will undoubtedly continue. However, most diagnostic firms are small and do not have extensive capabilities for research and development. Even now, problems that appear to be generic to a class of buildings or a class of activities tend to be addressed by research programs in government laboratories and in universities. Present efforts would be enhanced by a systematic program of research, development, and technology transfer, undertaken by manufacturers of diagnostic equipment and by public and private research institutions.

Demonstration Projects

In addition to research, the systematic conduct of demonstration projects would do much to foster an awareness within the building community of the realizable benefits of building diagnostics. Public agencies, both at the national and local level, might conduct one or two projects each year that demonstrate particular aspects of diagnostics.

Education and Information Programs

To be useful, the knowledge and understanding on which diagnostics is based must be lodged either in the mind of the diagnostics professional or in an "expert" information retrieval system. The development of expert systems for this purpose should be encouraged, but the state of the art for such systems means that it will be some time before the field can center on their use.

APPENDIX

BIOGRAPHICAL SKETCHES OF COMMITTEE MEMBERS AND CONSULTANTS

THE COMMITTEE

EZRA D. EHRENKRANTZ (Chairman) is president of The Ehrenkrantz Group, an architectural firm dealing with building systems technology including energy and restoration technology. Mr. Ehrenkrantz is an architect and specialist in building systems, energy-sensitive design and illumination. He was awarded a Fulbright Fellowship to study building climatology at the Building Research Station, England. He has taught architecture at the University of California, Berkeley. Mr. Ehrenkrantz received his B.A. in architecture from the Massachusetts Institute of Technology and his Master of Architecture from the University of Liverpool, England. He is chairman of the BRB Committee on Building Diagnostics and also serves on BRB's Board.

PAUL R. ACHENBACH is currently a consultant to the Department of Energy on energy conservation research and development on building envelopes, and to the Department of the Navy on moisture control in buildings. In 1979 he completed a 40-year career at the National Bureau of Standards where he specialized in the performance of heating, ventilating, air-conditioning, refrigeration and plumbing systems. Mr. Achenbach holds degrees in mechanical and electrical engineering.

PLEASANTINE DRAKE is principal of Architectural Diagnostics and specializes in functional programming, architectural and man-environment research, and building diagnostics. Her recent work has focused on office environments and on the role of functional diagnostics as a basis for the planning, programming, and design of new and existing facilities. She has participated as part of the Building Diagnostics, Inc. team consulting to the Architectural and Building Sciences Directorate, Public Works Canada, in the development and application of building diagnostics procedures.

PAUL D. EGAN is vice president of property development for the Prudential Insurance Company and his areas of expertise are business administration and real estate investment. His responsibilities include the negotiating and underwriting of mortgage loans, property development, and acquisitions related to office buildings, hotels/motels, garden apartments, industrial complexes, and shopping centers. Mr. Egan serves as corporate development director based in Newark, New Jersey. He received a B.A. in business administration from Tarkio College and an M.B.A. from the University of Missouri.

DAN INT-HOUT is director of research with Krueger Manufacturing, Inc. in Tucson, Arizona. Until 1982 he was with the Product Testing Laboratory of Owens-Corning Fiberglas Corporation. He is a member of the American Society for Testing and Materials, the American Society of Heating, Refrigerating and Air-Conditioning Engineers, and is chairman of the ASHRAE Committee, "Physiology and Human Environment,", and vice chairman, ASHRAE task group, "Environmental Calculations." Mr. Int-Hout received his B.A. in biology from Denison University and M.A. in Management from Central Michigan University.

ROBERT W. MARANS is program director of the Urban Environmental Research Program, Institute for Social Research, and professor, College of Architecture and Urban Planning at the University of Michigan. He was formerly architectural engineer and intermediate city planner for the Detroit City Planning Commission and associate, Architectural and Planning Practice, Michigan and Ohio. Dr. Marans was head planner and urban designer, Blair Associates; instructor, Regional Planning, Technion-Israel Institute of Technology, Haifa. He received a Master of Urban Planning from Wayne State University and Ph.D. in Urban and Regional Planning from the University of Michigan.

WILLIAM RUDOY was associate dean and professor in the School of Engineering at the University of Pittsburgh before his death in June 1984. He had been active in HVAC and energy utilization as a researcher and as a teacher and both in industry and in academia. He has served on national technical committees in ASHRAE for energy estimating, load calculations and its handbook committee.

ARAN SAFIR, M.D., teaches at the School of Medicine, University of Connecticut at Farmington. Prior to that he was Professor of Ophthalmology at the Louisiana State University Eye Center in New Orleans. He served as Director of the Mt. Sinai Institute of Computer Science at the Mt. Sinai School of Medicine in New York City; and as a member of the doctoral faculty of the Biomedical Sciences Graduate School, City University of New York. He is a Fellow of the American Academy of Ophthalmology, and a Fellow of the American College of Surgeons. He holds a B.A. in English and his M.D. from New York University.

NEIL SHER is director of technology and staff executive of the Honeywell Commercial Buildings Group at Honeywell Corporation. He was formerly a staff engineer with Allis-Chalmers. He is a member of the American Nuclear Society and the American Institute of Chemical Engineers. Mr. Sher received a B.S. and M.S. in chemical engineering from the University of Minnesota.

THE CONSULTANTS

JOHN H. CABLE is currently vice president of Hagler-Bailly, a consulting firm in Washington, D.C. Prior to that, he was the director of research and technical services of the Washington, D.C. office of the Ehrenkrantz Group. He directed activities in the area of energy-sensitive design and development. Formerly, he was director of the Buildings Division of the U.S. Department of Energy, where he created and directed conservation research programs addressing energy efficiency in buildings. The programs achieved major technical advances in the areas of daylighting, window design, envelope systems, thermal mass, insulation, energy estimating, ventilation and indoor air quality, air infiltration, energy auditing and building diagnostics. Mr. Cable is a registered architect in South Carolina, New York, and the District of Columbia, and holds an NCARB Certificate.

VOLKER HARTKOPF is currently working with the Architectural and Building Sciences Division of Public Works Canada in Ottawa. He is also an associate professor of architecture and associate director of the Institute of Building Sciences at Carnegie-Mellon University. Mr. Hartkopf has undertaken numerous research projects on subjects such as energy conservation, energy monitoring, building diagnostics and housing in Third World countries. Mr. Hartkopf has a Masters in Architecture from the University of Texas.

VIVIAN LOFTNESS has been actively involved with design and research in areas such as energy conservation, passive solar heating and cooling technologies, and survey and evaluation of climatic data. She has worked as a project architect in West Germany, an energy consultant in Greece, a project manager with Dubin-Bloome Associates in New York, and a project manager at the AIA Research Corporation in Washington, D.C. Ms. Loftness holds a B.S. and Masters in Architecture from the Massachusetts Institute of Technology.

FORREST WILSON is a professor of architecture at the Catholic University of America. He currently teaches a class on building diagnostics. Prior to this, he was the editor of Progressive Architecture. Mr. Wilson is an author and illustrator and has published many books and articles. He is currently writing a book on Building Diagnostics for John Wiley and Sons.

LIAISON REPRESENTATIVES FROM FEDERAL AGENCIES

GEORGE COURVILLE is currently responsible for building envelope systems research and building diagnostics research at Oak Ridge National Laboratory. Prior to Oak Ridge, he was a professor of physics at Fairleigh-Dickinson University. Dr. Courville spent two years as a program manager in the Building Community Systems Office at the U.S. Department of Energy. Dr. Courville received his Ph.D. in physics from Stevens Institute.

KENNETH H. CRAWFORD is currently an operations research analysis for the U.S. Army Corps of Engineers at the Construction Engineering Research

Laboratory where he is a principal investigator on the Computer-Aided Engineering/Architectural Design System development team. He is a visiting professor of computer-aided design at the University of Illinois School of Architecture. Other positions held include principal research programmer, Office of Institutional Research, University of Illinois, professor of computer science, Illinois State University; and chairman of the Department of Data Processing, Parkland College.

CHARLES G. CULVER is deputy director of the Center for Building Technology, National Bureau of Standards, Dr. Culver guides supervisory and research personnel both in planning future research and in conducting day-to-day activities. He works with other federal agencies, professional organizations, design professionals, industry representatives and building officials at the national, state and local level to insure the implementation of NBS research results. Dr. Culver has been involved in conducting and managing engineering research for over 20 years. Prior to joining NBS in 1972, he was on the faculty of Carnegie-Mellon University where his research led to the establishment of a national specification for the design of highway bridges.

DAVID B. EAKIN is currently the energy program coordinator for the Office of Design and Construction of the U.S. General Services Administration. He has been involved in technical review and coordination with the National Bureau of Standards in developing the building envelope diagnostics program for GSA. Mr. Eakin is a mechanical engineer with a degree from the University of Maryland.

FREDERICK KRIMGOLD is currently associate dean for Research and Extension at Virginia Tech's, College of Architecture and Urban Studies. Prior to that, he was program director for construction engineering and building research at the National Science Foundation, where he was responsible for management of research in construction, construction management, architecture, building science, transportation, and infrastructure. Prior to this, he was a research associate in the Department of Civil Engineering at the Massachusetts Institute of Technology. He has also worked with the Swedish National Building Council and the Swedish International Development Authority. Dr. Krimgold received his B.A. in Architecture from Yale and his Ph.D. in Technology from the Royal Institute of Technology in Stockholm.

ROBERT A. WALKER is chief of an air conditioning division of the Veterans Administration where he has served since 1965. From 1948 to 1965 he worked for various consulting engineers. Mr. Walker is a registered professional engineer in the state of Texas. He received his B.S. in mechanical engineering from Southern Methodist University.