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Indoor air quality and passive solar buildings

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Abstract

Passive solar buildings are expected to provide their intended functions, safely and without adverse health effects, and at substantial energy savings compared to conventional buildings. Moreover, passive solar buildings are frequently considered as appropriate technology in parts of the world where the incidence rates of diseases associated with indoor exposures may be the highest. It is therefore critically important to understand both the health and economic consequences of applying "appropriate" passive solar technologies available today to residential, educational, health care, and commercial facilities. In this paper, environmental characteristics of buildings are reviewed; the two basic strategies of source and exposure control are examined; and a method of assuring the "health" of passive and low energy buildings is described. It is concluded in this paper that all buildings contain both active and passive systems; that acceptable indoor air quality can be achieved and maintained in passive and low energy buildings through the process of continuous accountability; and that building diagnostics procedures can be used to assure the performance of "healthy" passive and low energy buildings during their design, construction and operations phases.

INTRODUCTION

The purpose of buildings, anywhere in the world, is to provide secure, safe, and healthy conditions that facilitate productivity and well being of their occupants, owners, and managers. In this regard, buildings may be considered to consist of four primary functional categories: residential, educational, health care, and commercial/public assembly. It is now well understood that indoor occupancy in the four categories of buildings far exceeds the percentage of time that people are outside, in most parts of the world [1].

However, standards and criteria by which indoor environmental conditions are evaluated and controlled, as well as the resources available to provide that control, vary widely throughout the world. Thus, the performances of buildings intended to provide similar functions also vary widely. A significant result of these variations in performance is that improperly designed, constructed, and operated buildings can cause or exacerbate illness and disease, in the developed as well as in the developing regions of the world [2, 3]. Conversely, buildings that are carefully designed, constructed and operated can be beneficial to the health, comfort, and well being of occupants while providing their intended functions.

Passive solar buildings are subsets of the four primary functional categories, as they are intended to provide the same functions, safely and without adverse health effects, but at substantial energy savings compared to conventional buildings. Passive solar buildings are not only considered to be appropriate for application of sophisticated technology in the developed world, but are frequently considered as appropriate technology in parts of the world where the incidence rates of diseases associated with indoor exposures may be the highest [1]. It is therefore critically important to understand both the health and economic consequences of applying "appropriate" passive solar technologies to residential, educational, health care, and commercial facilities.

The objectives of this paper are two-fold: 1) to identify issues of concern in assuring acceptable indoor air quality (IAQ) in passive solar buildings while meeting the functional and energy goals of the design; and 2) to describe procedures that can be used, globally, to diagnose the environmental and economic performance of passive solar buildings. To achieve these objectives, this paper focuses on minimizing *failures* (i.e., adverse exposures and human responses) by detecting *faults* in system design, construction, and operations.

ENVIRONMENTAL CHARACTISTICS OF BUILDINGS

Indoor air quality is one of four primary environmental (i.e., exposure) parameters that determine occupant health and well being. The others are thermal (i.e., temperature, humidity, and air movement), lighting, and acoustics [4, 5]. Thus, a fundamental objective of environmental control is to provide for the desired human responses of the occupants by simultaneously controlling these exposure parameters within acceptable limits [5, 6]. If values of these parameters exceed these limits, discomfort complaints and symptoms are likely to increase.

Simultaneous control of these parameters should be provided during the design of new buildings, but it is of equal or greater importance in the existing building stock. For example, there are more than 4 million commercial, health care, and educational facilities, and 84 million residences in the U.S. These are being replaced at a rate of approximately 1 to 2% per year and another 1 or 2% per year are being added to the existing building stock. Thus, 80 to 90% of the buildings that will be in use in the U.S. by the year 2020 have already been built [7]. Similar percentages may be expected in the other developed parts of the world, but may be significantly different in developing regions.

The percentage of the existing building stock that represents passive solar buildings is unknown. However, as all buildings contain some passive solar features, (e.g., thermal mass, fenestration, natural ventilation), control of these features must be considered in operating and maintaining the existing building stock, as well as in new design.

Problem Buildings

Although no definitive studies are yet available, several investigations have been reported during the last fifteen years indicating that 20 to 50% of the existing commercial, health care, and educational buildings in Western Europe and North America have deficiencies in their performances (i.e., problems) that manifest in significant percentages of occupant complaints and symptoms [3, 8-11]. Similar estimates have not yet been published for residences in developed parts of the world, but the percentages are generally thought to be about the same as for the commercial sector of buildings. Generically, these buildings are called "problem buildings."

In a study conducted by the Institute of Medicine [12], indoor allergens were reported to be associated with sick building syndrome and other specific building-related illnesses. This report also stated that more than 20 percent of Americans suffer from allergic rhinitis (hay fever) and other allergic diseases; that allergic rhinitis is the single most common chronic disease experienced by humans; that allergy plays a key but sometimes unrecognized role in triggering asthma; that 8 – 12 percent of the American population has asthma; and that among chronic diseases, asthma is the leading cause of school absenteeism.

Problem buildings in the developing world may be even more perverse. Smith reports that the largest air pollution exposures in the world apparently occur indoors in developing countries where unprocessed solid fuels such as wood, crop residues, and coal are used for daily cooking and heating, and that such exposures may result in as much as 6% of global mortality [1]. Nardell reports that "of all building-associated risks in health care facilities, tuberculosis (TB) almost certainly accounts for the greatest morbidity and mortality, reflecting its rank as the world's single most lethal infection" [3].

The classification of problem buildings may be characterized by the frequencies of occurrence and the nature of the occupant complaints. There are two basic types of problem buildings [13]:

1. Sick Building Syndrome (SBS): persistence of a set of symptoms, reported by a substantial percentage of the occupants, which are alleviated soon after the occupants leave the building, and the cause of the complaints has not been determined, and
2. Building Related Illness (BRI): frank illness or disease, reported by more than one person that is associated with exposure in the building.

Healthy Buildings

At the first Healthy Building Conference, in 1988, Berglund defined a "healthy building" as one that is: "...not just free from building-related illness and discomfort but indeed promotes well-being and health. Besides being non-hazardous, the salient features of a healthy building include thermal comfort, pleasant air quality, illumination and acoustical characteristics, support of social needs and productivity and distinguished aesthetic qualities. These features should be maintainable over the building's lifetime..."[14].

Pragmatically, some problems exist in all buildings, but those that function with minimal occupant complaints, and comply with acceptable criteria for exposure, system performance, and economic performance may be included in this category [15, 16]. However, when the number of occupants expressing discomfort and symptom prevalence becomes noticeable, but less than in problem buildings, or when other conditions are only marginal, the building or the affected zones within it should not be categorized a healthy; rather a fourth category has been described a "undetected problems" [15, 16].

Concept of Continuous Degradation

Based on the results of reports and studies during the las decade, the concept of "Continuous Degradation" ha evolved as a hypothesis that a continuum exists in th degradation of building performance [2, 15, 16]. Thi continuum, which also applies to passive solar buildings consists of four stages:

1. Healthy Buildings. It is reasonable to expect th achievement and maintenance of healthy building through proactive programs of quality assurance and con trol that begin with the planning and design of building and continue throughout their lifetimes. However, if no implemented, it is also reasonable to expect the "health' of buildings to degrade in a manner analogous to that o individuals without adequate health care.
2. First Level of Degradation (i.e., undetected problems) This level is likely to occur in most buildings at som time but, once recognized, it is relatively easy an inexpensive to mitigate and to regain the "health building" status. Conversely, if appropriate action is no taken, the performance of the building will furthe degrade.
3. Second Level of Degradation (i.e., SBS). This level o degradation is likely to occur if occupant complaints an deterioration of system performance are neglected ignored, or denied. Mitigation to regain the "health building" status is more difficult and costly. For example the cost of recovering the good will of the occupants may equal the cost of the physical mitigation. But, i mitigation is not implemented at this level, the performance of building will continue to degrade.
4. Third Level of Degradation (i.e., BRI). This level of degradation is likely to occur if neglect, ignorance, or denial of occupant complaints and symptoms, and deterioration of system performance persist. This level of degradation can result in illness, disease, or death. The cost of recovery from this level of degradation is very expensive and can exceed the cost of the building.

CONTROL PRINCIPLES AND STRATEGIES

To achieve and maintain healthy buildings, the fundamental objective of environmental control must be assured (i.e., to provide for the desired human responses of the occupants by simultaneously controlling the four exposure parameters within acceptable limits). A rational model that relates human response, exposures, systems, sources or loads, and economics is shown in Figure 1 [5].

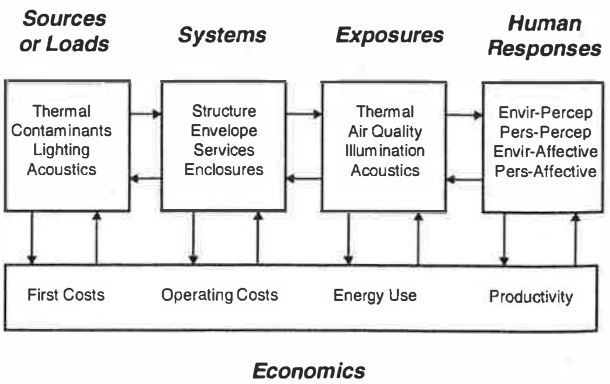

Figure 1.Rational model relating human responses to indoor environmental factors [from 5].

In this model, the desired human responses [6] are provided for by simultaneously controlling the values of the set of exposure parameters with systems that mediate the loads imposed on the occupied spaces from indoor and outdoor sources. This model also recognized that this control must be achieved within a set of economic parameters, including the goals of passive and low energy design.

Environmental control within occupied spaces primarily relies upon three control mechanisms: conduction, radiation, and convection; and two basic control strategies: source control and exposure control.

Control Mechanisms

Conduction is an important mechanism for control of heat, noise, and vibration transmission through the physical elements of the building. However, it is less important in energy transfer between the occupants and the indoor environment because most of the body's heat dissipates by radiation and convection [17]. In the selection, placement, and care of thermal and acoustical insulation, it is important to consider the risk that insulation can become a secondary source of microbiological contaminants by accumulation, adsorption of water vapor and dust [18,19].

Radiation within the visible spectrum is the fundamental mechanism for controlling light. Long-wave radiation is the primary mechanism for control of acoustics. Infrared radiation is an important mechanism for control of sensible heat transfer from occupants located near surfaces with temperatures different than the body or clothing surfaces of the occupants [17].

Convection is of equal importance to infrared radiation for control of sensible heat transfer from occupants [17]. Moreover, it is the primary indoor mechanism for transfer of latent heat, particulates and bioeffluents, and gases and vapors from occupants, indoor processes, and building materials.

Basic Control Strategies

A simple, one-compartment model of a uniformly mixed occupied space, shown as Figure 2, serves to illustrate the two basic strategies for controlling occupant exposure to thermal and contaminant stressors: *source control* and *exposure control.*

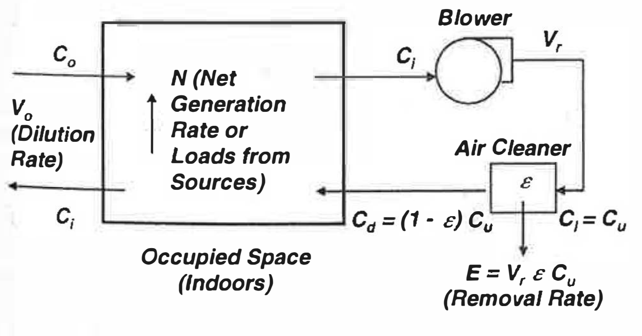

Figure 2. One-compartment, uniformly mixed, steady-state model for indoor air quality control [adapted from 5].

In steady-state, an energy or mass balance for this model may be expressed as:

$$C_i - C_o = (N - E)/V_o$$

In this Equation, C_i represents the acceptable thermal or mass concentrations (e.g., temperature, humidity ratio, particulate concentration) to be maintained indoors, C_o represents the comparable outdoor concentrations, N represents the net generation rates, or loads, from thermal or contaminant sources, E represents the rates of removal of the thermal or mass concentrations from the occupied space, and V_o represents the rate of dilution with outdoor air, by infiltration, natural or mechanical ventilation.

This Equation illustrates the relationship and priority of control strategies that should be employed in passive solar as well as in conventional buildings:

1. Source control, through which the generation rates, N, are minimized, should always be considered, first, then
2. Exposure control methods can be selected, through which the rates of removal, E, and dilution, V_o, are optimized against *energy requirements* to achieve the desired values of C_i when the outdoor concentrations are constrained at C_o.

An excellent example of this relationship was recently given by Smith [1]: "a typical unvented cookstove in a village kitchen burns one kilogram per hour of wood and produces sufficient particle emissions to require a 100 km/h wind through a one square meter window to bring indoor concentrations down to something close to current outdoor health standards." Obviously, the solution is to replace the stove rather than to try to ventilate or remove the pollutants.

Another critically important source control strategy is to minimize the potential for microbial growth indoors by minimizing the pathways for moisture to condense or migrate onto surfaces within buildings, especially dark cavities where dust, dirt or other nutrients may accumulate [18, 19]. This strategy is particularly important in passive solar buildings as the selection of construction materials and furnishings and the design of natural ventilation pathways are critical to the successful performance of these buildings.

Building Energy Efficiency

As shown in Figure 1, an important factor in environmental control is the ability to provide acceptable exposures at reasonable energy and economic costs. Passive solar buildings are intended to provide these exposures at substantially reduced energy consumption and life-cycle costs when compared to conventional buildings within the same functional categories. A control strategy to achieve these objectives, was introduced in 1984 [20]. It focuses on design alternatives that minimize *energy requirements* to achieve acceptable exposures and that minimize *energy wastes* (i.e., the difference between energy consumption and energy requirements). This control strategy is shown, schematically, in Figure 3.

In this scheme: the *energy requirement* is the amount of supplemental energy needed to balance the envelope and internal loads so that acceptable exposures are provided within the boundaries of the enclosure being controlled; *energy consumption* is the amount of energy needed to supply the energy requirement and offset the parasitic losses (i.e., energy waste); and *energy efficiency* is the ratio of energy requirement to energy consumption for a given period of time.

Energy requirement and *energy efficiency* are time-dependent functions of weather and building use, and their values may be derived in terms of enthalpy or entropy. "First Law" energy efficiencies have been shown to range from 40 to 100% over an annual period in conventional buildings [20]. For a passive solar building within a functional category, a reasonable control strategy is to achieve an annual energy requirement of 50% or less of conventional alternatives, and an "First Law" annual energy efficiency of 80% or more.

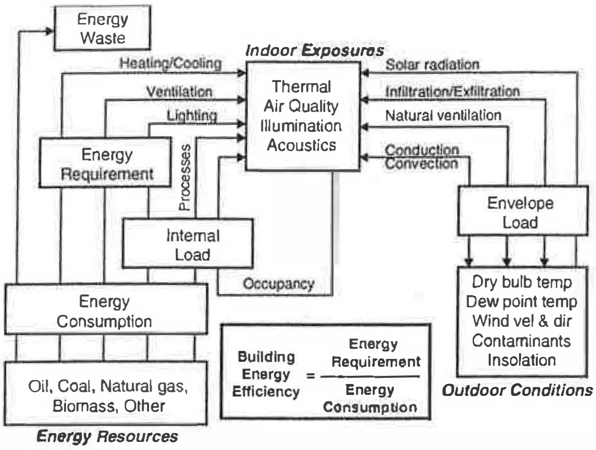

Figure 3. Concept of Building Energy Efficiency.

ASSURING ACCEPTABLE IAQ

As a means to intercept the process of continuous degradation, the concept of "continuous accountability" was introduced in 1990 [21]. And, to implement this concept, the principles of "building diagnostics" were applied [13, 22]. Both of these concepts are based on the definition of measurable and controllable criteria, and both are directly applicable to assuring the performance of passive solar buildings.

The principles of building diagnostics are similar to those of medical diagnostics, a mature discipline taught in medical schools, as they contain the same four essential steps: 1) knowledge of what to measure; 2) availability of appropriate instrumentation; 3) expertise in interpreting results of measurements; and 4) capability of predicting likely performance over time [22]. These procedures can be used to diagnose both sick and healthy buildings, and can be used in all four phases of a building's "life" (i.e., planning and design, construction, operations for long-term occupancy; and adaptive reuse or demolition) [21].

Continuous Accountability

By incorporating building diagnostic procedures into the four phases of a building's life, building performance can be assured through a process of continuous accountability. The following are the five steps initially described in 1990 and adopted for proposal by OSHA in 1994 [16, 21, 23]:

1. During the planning and conceptual design phases, the building owner, financiers, and designers are accountable for establishing basic performance criteria that are consistent with codes, statutes, and regulations. These criteria should be measurable and should not be changed unless the function or requirements of the building change during its lifetime.
2. During the detailing phase of design and during the construction process, the performance criteria are translated into compatible prescriptive criteria. Those responsible for designing and constructing the facility are held accountable for compliance with the prescriptive criteria and for achieving consistency with the performance criteria.
3. During the commissioning phase (i.e., also part of the detailing and construction phases), the performance of the building is evaluated before occupancy, by an independent firm or agency, for compliance with the original performance criteria. Designers and builders are accountable for the successful commissioning of the building.
4. Periodically, during the operational life of the buildi and especially when modifications are anticipated, performance of the building, including the anticipa changes, is evaluated by qualified professionals compliance with the performance criteria. If changes function or occupancy have occurred, they should analyzed for impact on system performan Accountability at this stage returns to the building own who should provide assurance to the occupants that building is performing in accordance with characteristics of a "healthy building."
5. During the intervals between inspections, accountabil must also be shared between the managers of t occupied spaces and the occupants. If activities tl exceed the capabilities of the system are allowed with the occupied spaces, or if tampering with the system allowed, the probability of degrading system performan will increase.

Commitment

Continuous accountability enables interception of tl process of continuous degradation *before* the onset "problem buildings." However, to achieve continuo accountability, three critical commitments are needed [2, 1 23]:

First, an *accountable person* must be explicitly identifie at each step of the continuous accountability process. Th commitment presumes a "chain-of-custody" by whic accountability can be passed to the appropriate person at th subsequent step of the process.

Second, the accountable person must be *empowered* wit authority to take appropriate corrective action to assure th building is performing in accordance with the establishe evaluation criteria.

Third, the accountable person must possess th *professional education and training* necessary to assur adequate building performance as well as protection o occupant health and well being.

Building Diagnostics

Building diagnostic procedures are commonly conducted ir three phases [24, 25]: *observation* (Phase I), which leads tc formulation of preliminary hypotheses and preliminary recommendations; *system analysis* (Phase II), which focuses on validating or refuting the preliminary hypotheses by evaluation of environmental loads, system capacities and controllability, and energy and economic performance at peak and part load conditions; and *exposure analysis* (Phase III), which allows for quantitative analysis of human response, exposure, system performance and economic performance.

These procedures generally lead to identification of discrete or total *failures* of components or systems, but they are limited in diagnosing marginal or cumulative malfunctions or *faults*. In 1994, a modified diagnostic procedure was introduced that focuses on identifying *faults in system or economic performance* that are likely to precede *failures in exposure or human responses* [26]. In 1996, two sets of criteria were introduced to maximize the probability of achieving "true positive" *or* "true negative" outcomes while minimizing "false negative" *and* "false positive" errors [27]: *evaluation criteria* with which to compare measured data, and *classification criteria*, with which to increase analytical power in formulating and testing hypotheses. In 1997, the use of these procedures as a management tool for assuring the performance of buildings during design, construction, and operations was demonstrated [28]. As will be shown here, these procedures are also relevant for diagnosing the performance of passive solar buildings during the design, construction and operation.

EVALUATION CRITERIA

Evaluation criteria consist of a *set* of measurable and controllable parameters and their corresponding values [5, 27]. Human response and exposure criteria are considered *mandatory*, as they define parameters that directly affect the occupants (e.g., percent occupants dissatisfied, operative temperature, relative humidity, PM10 concentrations, TVOC concentrations). Non-compliance with mandatory criteria is considered a *failure*, and changes in design, construction, or operations are required to achieve compliance. System and economic performance criteria are considered *flexible*, as they define parameters that may indirectly affect the occupants (e.g., capacity to load ratio (C/L), building energy efficiency, life-cycle costs). Non-compliance with flexible criteria is considered a *fault*, and changes may be made either to these criteria or to the design, construction or operations of the systems to achieve compliance.

Table 1 is an example of evaluation criteria for a Phase III building diagnostics, in which quantitative values are set for each parameter [27]. Only qualitative values are set for Phase I building diagnostics, and a combination of qualitative and quantitative values are set for Phase II diagnostics. Thus, Phase I and II criteria are relevant for diagnosing conceptual design alternatives and for initial diagnosis of building operations. However, Phase III evaluation criteria are needed for load calculations, for diagnosing performance of a building at the time of commissioning, and for comprehensive diagnosis of building operations.

The *parameters* of the evaluation criteria apply equally to passive solar and conventional buildings, as both are expected to provide safe and healthy conditions while facilitating their intended functions. The *values* of the mandatory criteria should also be the same for passive solar and conventional buildings, but the values of the flexible criteria for passive solar buildings should reflect lower energy requirements, higher energy efficiency, and lower life-cycle costs than conventional buildings.

Table 1. Evaluation criteria for Phase III diagnostics: an example for passive solar buildings [adapted from 27].

Factor	Measurable Parameter	Value
Human Response	• Incidence of clinical signs of illness	< 2
	• Percent occupants reporting > 2 symptoms	< 20%
	• Percent occupants rating overall environment as acceptable	> 80%
Exposure	• Operative temperature	23.0 ± 0.5 C
	• Relative humidity	45 ± 15 %
	• Air velocity	< 0.25 m/s
	• Particulates (PM10)	< 50 µg/m^3
	• CO_2	< 1800 mg/m^3
	• TVOC	< 3.0 mg/m^3
System Performance	• System Capacity	$(C/L)_p = 1$
	• System Control	$(C/L)_m = 1$
Economic Performance	• Energy Requirements	Negotiated (e.g., 50% of conventional building)
	• Energy Efficiency	Negotiated (e.g., "First Law" annual average of 80%)
	• Life cycle costs	Negotiated (e.g., 80% of conventional building)

CLASSIFICATION CRITERIA

To minimize the probability of making "false-negative errors" (i.e., failing to detect problems that exist) and "false-positive errors" (i.e., detection of "problems" that do not exist), the four categories described in the concept of continuous degradation have been compressed into three categories: *Healthy*, *Marginal* and *Problematic* [26]. And to further improve the hypothesis-forming power of this building diagnostics procedure, *classes* within the categories have been introduced [27]. The resultant classification criteria, shown in Table 2, apply equally to passive solar and conventional buildings.

IMPLEMENTATION

This building diagnostics protocol can be used as a proactive (e., design, preventive maintenance) or as a reactive (e.g., investigation) procedure. In either case, the building is evaluated with respect to predetermined mandatory and flexible criteria and by linking systems, sources, and systems in a hypothesis [27, 28]. The three categories and seven classes in the classification criteria increase the analytical power in formulating and testing a hypothesis at any stage of the building's life cycle. Moreover, they allow for prioritization of mitigation in design, construction, and operations.

Table 2. Classification criteria for passive solar and convention buildings or zones within them [from 27].

Category	Class	Description
Healthy	H	Compliance with all evaluation criteria
Marginal	M3	Compliance with all evaluation criteria except economic performance criteria
	M2	Compliance with human response and exposure criteria, but not with system performance criteria
	M1	Compliance with human response criteria, but not exposure criteria
Problematic	P3	Compliance with clinical signs and symptoms criteria, but not with acceptability criteria
	P2	Compliance with clinical signs criteria, but not with symptoms criteria
	P1	Non-compliance with clinical signs criteria

After diagnostics, the classification criteria can also be used as a management tool that allows for prognostics of the building or zone performance [27, 28]. This tool is applicable for passive solar and low energy as well as for conventional buildings. By considering the hypotheses and, therefore, the placement of the building or zone on the classification scale at various times of the building's life-cycle, it is possible to predict the rate of continuous degradation, identify health and economic risks, and determine feasible, alternative goals for future performance of that building or zone. Figure 4 indicates how this classification scheme can be used as a management tool to:

1. Benchmark the performance of the building or zone, over time, by developing a history of its performance from a review of available data (e.g., at completion date of conceptual design, at bid date, at substantial completion of construction (SC), at completion of warranty (W) and at other times (X)).
2. Assess the current status of the performance of the building and its systems (e.g., M2 at time t_x).
3. Estimate the rate at which the performance is degrading (e.g., (M3 - M2) / (t_x - t_w)).
4. Plan the type of proactive intervention and time for it to be completed to achieve a classification that assures acceptable performance (e.g., H at t_x + t).

In the example shown in Figure 4, M2 was chosen as the threshold class, below which a reactive procedure would be initiated to assure acceptable performance. Also note in this example, that the classes remain constant, but adjustments in flexible criteria will reflect in a better performance.

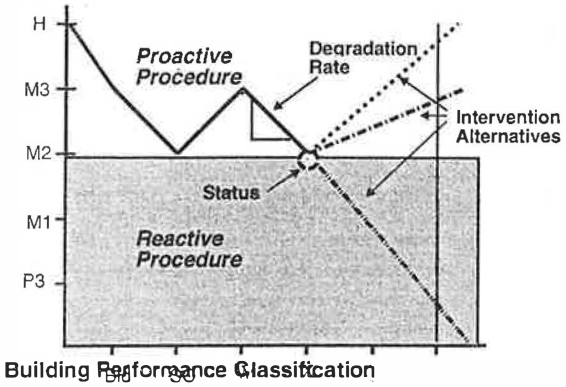

Figure 4. Chronology of Building Performance [from 28].

CONCLUSIONS

1. All buildings contain passive and active components that affect the four primary environmental exposures. However, passive solar buildings are special cases or subsets of the four functional categories of buildings and are intended to provide the same secure, safe and healthy conditions as conventional buildings, but with substantial energy and cost savings.
2. Acceptable indoor air quality can be achieved and maintained in passive solar and low energy buildings in developed and developing regions through the process of continuous accountability.
3. Control strategies should always prioritize source minimization before exposure control.
4. Building diagnostics procedures that rely on measurable and controllable criteria can be used to evaluate and assure the performance of "healthy" passive solar and low energy buildings during their design, construction and operations phases.

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