3952

Indoor Humidity and Human Health: Part II—Buildings and Their Systems

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ABSTRACT

This paper continues a review of the humidity effects on health as addressed in indoor ventilation and environmental standards. Part I identified a number of health-related agents that are affected by indoor humidity, common sites of contamination within buildings, and common remediation measures. Part II discusses the physical causes of moisture-related health problems in buildings, subdividing them by climate and mechanical system type. It examines studies done on moisture problems in these differing environments, showing that in most, if not all, cases the causes of the problem are only indirectly related to indoor humidity in the space. To do a better job of controlling such problems, the building- and system-specific causes of the problems should be studied. A number of specific research needs are identified.

INTRODUCTION

Health-related agents that are affected by indoor humidity include dust mites, fungi, bacteria and viruses, and nonbiological pollutants. All of these affect human health, primarily through their inhalation from the air, although some of them have lesser effects through the skin. The primary biological health problems related to higher levels of humidity are due to growth on surfaces or contaminated aerosols produced by spray humidification systems. The interpersonal transfer of biotic agents through the occupied airspace is not determined as extensively by ambient humidity. Airborne levels of nonbiological pollutants may be affected by humidity through its influences on offgassing and surface reaction rates.

Humidity in buildings is usually measured in the airspace of the occupied interior. Not all of these listed humidity/health effects are directly affected by the humidity of the air. For example, fungi depend on the moisture of the surface on which they are growing. The moisture content of this substrate may be a function of the humidity of the surrounding air or may come from totally unrelated sources. For example, field studies have shown that mildew can form at as low as 10% relative humidity (RH) in some cases, whereas in others RH values as high as 95% have not produced biological activity (Pasanen et al. 1991a, 1991b). Clearly there are other factors at work producing these observations. Even if the surface moisture is caused by air humidity alone, the relationship between these two may be a complex function of surface temperatures, materials, textures, and exposure to air movement. In addition, the surface may be in a part of the building or its mechanical system where temperatures differ from those in the main airspace, resulting in different rates of condensation/evaporation from those of the moldy surface. Intermittent operation of the mechanical system may increase this effect.

Biological agents require appropriate conditions in the building for their germination, growth, release to the air, and transport to the human host. To understand humidity/health effects, one must ideally consider the organisms and their life cycles in the context of the building, its surface materials, its mechanical system, its operation schedule, and its surrounding climate (e.g., the entire ecosystem of the organism). This is rarely done in the literature. Laboratory studies have characterized some of these pieces of the puzzle in considerable detail, but the applicability of such studies to buildings is often difficult to determine. At the other side of the experimental spectrum, field studies have often identified health-affecting agents in buildings but have not discovered or reported either the specific location of their origin or the mechanisms by which humidity influences their growth and release into the human-occupied zone. Correlations between health effects and indoor air humidity are therefore often building-specific and are risky to generalize.

In writing indoor environmental standards that use generalized criteria, there is a tendency to set restrictive limits in order to include all classes of problem cases. Restrictive limits can have the undesirable effects of increasing energy required

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for conditioning spaces and reducing options for of space conditioning. For example, in arid climates such limits affect the use of evaporative cooling, which can offset energy-intensive compressor cooling. They also directly affect a substantial fraction of the cooling load in hot, humid climates. To develop more precise standards, it is useful to examine the types of processes that lead to health problems and to categorize types of buildings, climates, etc., by how many of these processes they contain. It appears likely that the biotic/health problems at any given level of interior air humidity are different for buildings in different types of climates and for different types of environmental control systems.

In this paper the different climate types are categorized as:

- hot, dry climates (thermal flows through the building envelope are inward and water vapor flows outward);
- hot, humid climates with interior cooling and/or dehumidification (both thermal and vapor flows through the envelope are inward);
- hot, humid climates without cooling or dehumidification (thermal flows to and from the building's thermal mass); and
- cold climates (both thermal and vapor flows through the envelope are outward).

In addition, the following building-/system-related categories are useful in examining potential humidity/health effects:

- surface properties in rooms and in heating, ventilating, and air-conditioning (HVAC) ducts, including temperature, hygroscopicity, and air movement;
- water in cooling and humidification systems;
- intermittency of operation in cooling systems; and
- moisture sources *not* resulting from the humidity in the interior air, including rain penetration into the building's structure, rising damp through foundations, and plumbing leaks.

Each of these categories represents a set of different opportunities for humidity/health effects. The various health agents will be discussed in this context. Given the complexity of the biotic/health problem in buildings and their mechanical systems, the links of humidity to biotic/health factors should be determined as explicitly as possible.

EFFECTS OF MICROENVIRONMENTS ON BIOTIC GROWTH

The surfaces that suffer biotic growth differ among building types. West et al. (1989a, 1989b) suggest that in commercial buildings, moisture-associated air quality problems commonly stem from the proliferation of microbes on moist hygroscopic surfaces within the HVAC system. In residences, mold contamination is usually found on room surfaces (Aberg 1989) and dust mites on carpeting and furnishings within the occupied space (Arlian et al. 1982). Which particular surfaces are affected depends on specific characteristics of the building's construction and operation, the climatic characteristics of the region, the type of HVAC system used, and the maintenance of the building, its system, and its furnishings.

For molds, the key issue for growth occurring on surfaces is the equivalent relative humidity (ERH) or water activity. This parameter is influenced by the following processes:

- surface temperatures and the adjacent air humidity,
- hygroscopic properties of the materials, and
- air movement at surfaces.

Although dust mites are not directly dependent on the ERH of the substrate, the fungi that some mites require for digestion of skin scales are (Flannigan, 1992; Hart et al. 1990). The mites themselves live within textiles of furnishings and carpets in microenvironments buffered from and quite different from the space environment. It is the relative humidity within these microenvironments that is most important, since mites extract water vapor directly from the surrounding air. In their studies of houses in Tucson, O'Rourke et al. (1993) observed mites most commonly in ground-floor carpets on cold slab floors. This is probably explained by the increased local relative humidity within the cooled carpet pile. If the floor is cool enough or the space environment moist enough, the dew point will be reached and condensation will occur. Even if this occurs only occasionally, the condensed water will be retained in the carpet and its backing for an extended period, providing a higher local vapor pressure and higher relative humidities in the carpet.

EQUIVALENT RELATIVE HUMIDITIES RELATED TO SURFACE TEMPERATURES AND THE HUMIDITY OF ADJACENT AIR

Thermal Gradients and Vapor Pressure Gradients

Vapor pressure is proportional to temperature. If a surface becomes cold relative to the adjacent air, its relatively depressed vapor pressure can allow water to condense onto the surface from the air. For a given type of material, the amount of water eventually condensed (and its ERH) are functions of both the surface temperature and the vapor pressure of the surrounding air. Different types of surface materials will reach different ERH values; this is described in the section on moisture absorption.

For a given temperature difference across a material, the temperature gradient is proportional to its thermal resistance and its thickness. Resistances are summed for multiple layers, as found in building wall and roof assemblies. The layers include the air films (boundary layers) at the surfaces, whose resistance (for a given air speed) is largely fixed. Thus, if a wall's solid materials have low thermal resistance, the resistance of the interior boundary layer (under still air) will be relatively high, and a substantial temperature drop may develop across this film when the wall is exposed to an overall temperature difference. The wall's surface temperature may be higher or lower than that of the interior air; when it is lower, condensation may occur on the surface as described above. This may be the situation in cold climates, where the thermal gradient across a wall is outward. It could also occur during transient conditions, such as when mechanical systems are shut down or switched to the economizer mode. In these cases, hot and humid air may come into contact with a cooled interior surface, resulting in surface condensation.

There is also a water vapor gradient across walls separating different vapor pressures. For this gradient, the resistance is the permeance of the building materials. The vapor gradient describes the vapor pressure available at various depths within the wall assembly. The thermal gradient occurring at the same time determines the saturation vapor pressure at each depth in the wall. Where vapor pressures exceed the saturation vapor pressure at a given depth, condensation will occur within the wall assembly. This is the general case of the surface condensation example given above.

Condensation occurs in building assemblies when thermal and vapor pressure gradients are both outward and when thermal and vapor pressure gradients are both inward. The former occurs under heating conditions in cold climates, while the latter occurs in hot and humid climates when the interior is mechanically cooled and dehumidified. Condensation does not occur when the thermal and vapor gradients are opposite, which is the case for buildings that are located in hot, arid climates and use direct evaporative cooling.

Cold Climates: Outward Thermal and Vapor Gradient

The majority of field studies of "sick buildings" have been performed in cold climates, and results linking (in particular) mold growth to space humidity are often inapplicable to building environments in hot climates. The mold found by Pasanen et al. (1991a, 1991b) during extremely dry (10% RH) heating conditions was due to leaks and condensation on cold surfaces. Many European studies have been done in older, poorly insulated housing where cold surfaces are common. Interior mold growth in cold climates is nearly always a winter effect. Becker (1984), studying mildew in masonry buildings in Israel, found no difference between rooms having high and low internal moisture generation: all the mildew problems occurred on thermal breaks in outside walls. The lowered interior surface temperatures (in winter) dominated the surface condensation process. Similarly, part of the mold effects discovered by Aberg (1989) in Angola were due to ceiling surfaces cooled by nighttime radiation to the sky. Cold-climate effects are thus possible even in the tropics, where nocturnal radiative cooling is high.

Humidity problems are exacerbated when low ventilation rates are used for energy conservation and when there is inadequate exhaust of internal humidity sources. In the Pacific Northwest, Tsongas (1991) found substantial numbers of houses experiencing humidity problems. Condensation problems occurred primarily on the inner surfaces of outside walls. Few of these buildings had functioning moisture exhausts, and the spot-check RH measurements (which found average values from 47% to 56% during the winter) may have missed cooking periods when condensation was produced. TenWolde et al. (1984) recommended that "few moisture problems will occur when a home's RH is below 40%." The discussion in the paper covered mildew in wall corners and (exterior wall) closets, condensation on windows, and decay in walls or on the underside of roof sheathing. These are all effects due to thermal transmission outward through walls and would not be applicable, for example, in summer cooling situations.

Hot, Humid Climate with Mechanical Cooling: Inward Thermal and Vapor Gradient

Gatley (1992), Shakun (1992), and Banks (1992) discussed mold problems in buildings (primarily hotels) in hot, humid climates close to the Gulf of Mexico. They all gave interior RH recommendations, although most of the effects cited were related to inward penetration (by diffusion and infiltration) of warm, humid outdoor air into mechanically cooled rooms. A major problem is that the most impermeable layer in the wall construction is a commonly used vinyl wallpaper that acts as a vapor barrier at the wrong side of the wall. Much mold growth takes place behind such coverings. The other primary problem had to do with operating the corridors at negative pressures relative to the ambient, so that humid air tended to migrate inward through the envelope or through-wall air conditioners. A recent study (Spaul 1993) found that indoor spore counts in buildings with improper vapor barrier placement could be controlled by pressurizing the building.

Chilled mass encountering warm, moist air may cause surface condensation. In humid climates, this effect can occur when mechanically cooled space is opened to natural ventilation or economizer cycle operation. It also can occur when cold-air duct systems are turned off at night and on weekends, and warm moist air can migrate in and condense on the chilled surfaces. Substantial fungal growth can occur in the ducts, particularly to unfaced fiberglass insulation inner linings. (This was described at the ASHRAE forum on humidity, Chicago, January 1993.)

Bayer et al. (1992) describes humidity/health problems in southeastern schools where RH levels were reported above 75% for the majority of the year, evidently reaching saturation on occasion. It appears as if the problems are primarily due to intermittent operation of the HVAC system, resulting in large inflows into the cool interior of air that had not been dehumidified. The problems were alleviated by providing a continuous system and keeping interior humidity levels below 70%.

Kohloss (1987) reviewed air-conditioning practice in the hot, humid tropics and suggested that the ASHRAE humidity limits of that time were too low for tropical use. He states that mold and mildew are "usually well under control as long as RH is below 70%" and recommends raising the humidity limit in ASHRAE Standard 55 so that it is 65% at the warmer boundary of the summer comfort zone, rising to 69% at the cooler boundary.

Much of the literature understandably focuses on problem buildings. On the other side, it might be instructive to observe existing practice in acceptable spaces. A recent informal sampling of many air-conditioned spaces in Singapore found no RH values below 65%, with many above 80%. The spaces were well maintained, showed no superficial evidence of biological contamination, and were considered acceptable by their occupants (Arens 1994).

Hot, Humid Climate Without Mechanical Cooling or Dehumidification: Temperature Gradients to Thermal Mass

Surface condensation can occur in passively or naturally ventilated buildings when moist air encounters a thermally massive building element cooled by previous climatic conditions. It can also occur (rarely) during thunderstorm passage in cool weather. Because neither daily air temperature nor mass temperatures fluctuate significantly in humid climates, naturally occurring condensation due to thermal capacitance is not large. In dry climates, mass may be cooled substantially below daytime temperatures by nocturnal ventilation, but this mode of cooling is unlikely to reduce the mass temperature below the subsequent day's dew-point temperature unless a humid air mass moves in outside or much moisture is generated indoors. In a lightly insulated structure, radiant cooling to the night sky can cause interior surfaces to drop below the dew point and condense water (Aberg [1989], as discussed above).

EQUIVALENT RELATIVE HUMIDITIES RELATED TO SORPTION ONTO SURFACES

Moisture Sorption Processes

The amount of moisture adsorbed to or absorbed into (the nonspecific term is "sorbed") a material depends on the physical and chemical characteristics of the material. In general, water can be held to surfaces by chemical or physical bonds or by mechanical attachment. Water that is *chemically* bonded to the surface (usually by covalent bonds, water of hydration) is too strongly attached to the surface to be useful to biological growth. Water held by *physical* (van der Waals) bonds coats smooth surfaces in single or multiple molecular layers. These bonds are roughly one-tenth the strength of chemical bonds and some layers may be available for biological growth. *Mechanically attached* water has no bonding but is attracted by surface tension effects in pores and capillaries. Most of this is available to biological organisms.

Wong et al. (1990) categorized building materials that physically bind water into three types of media: nonporous, hygroscopic porous, and capillary-porous.

- In nonporous media, condensation of liquid water can only occur at the surface. Examples given by Wong are (clean) smooth plastics, glass, glazed surfaces, and sheet metal.
- Hygroscopic porous media have very small pores (micro-capillaries). These pores are capable of exerting a powerful mechanical attraction on atmospheric moisture because once the pores of small diameter begin to fill, their liquid surface area is a strongly concave meniscus. This has the effect of depressing the vapor pressure at the surface of the water, allowing the liquid pockets to remain in equilibrium at lower ambient vapor pressures than could a plane surface of water. Hygroscopic porous media tend to swell and shrink as water is gained or lost. Examples given are wood, natural textile fibers, and clay.
- In capillary-porous media, pores are visible and the amount of physically bound water is negligible. These do not have lower surface vapor pressures to attract moisture and do not shrink or swell. Examples are bricks, concrete, gypsum board, and packings of sand.

In principle, hygroscopic porous media might appear to permit fungal hyphae access to condensed water at lower ambient RH values than would be possible on plane surfaces. However, the reverse seems to be true at least for dry wood, where water condensing in pores is adsorbed by cellulose molecules in the cell walls and becomes unavailable for fungal use (Wilcox 1994). Because of this, the hygroscopic nature of dry wood actually reduces the availability of water to molds that would normally form on surfaces when the ambient RH is 100%. This is a temporary effect, in that permanent exposure to 100% RH would eventually bring the wood to its fiber saturation point, where it loses hygroscopicity. However, wood paneling has been found to adsorb/desorb large amounts of humidity on a diurnal cycle without surface condensation occurring (Kubler 1982; Okano 1977). Ikeda et al. (1993) found that the addition of 24 mm of hygroscopic material to a wall exposed daily to several hours of 100% RH reduced the room RH by 4% to 10% and prevented surface condensation for periods as long as 60 days.

In general, the effects of hygroscopicity on mold growth are not well described in the literature. Data on ERH requirements of biological organisms are being developed, as discussed in part I of this paper. Wilcox (1994), on the other hand, maintains that liquid water on the surface, at least intermittently, is a requirement for mold growth on that surface. There does not appear to be much information on the relationship between surface condensate, ERH, and the RH of the adjacent air for common building materials. In particular, it would be useful to have the characteristics of various types of paints, since they cover such a large fraction of building interior surfaces. It has also been noted that older indoor surfaces may be covered with deposited aerosols, affecting their moisture-absorption characteristics (Fisk 1994).

Moisture Sorption on Walls and Duct Surfaces

A study of mold growth on surfaces of bakeries done by Coppock et al. (1951) found that nonporous brick had more surface condensation than porous brick, with mold growth beginning at 80% RH, whereas no mold was found on natural brick until 88% RH. However, porous materials might accumulate more nutrients over time from atmospheric dust. Whitewash over natural brick caused mold growth above 80% RH, perhaps because of nutrients in this paint. A glossy painted wood grew nothing at all in the range of 70% to 95% RH. Coppock et al. recommended that, for mold control on all types of surfaces, RH should be kept below 70%.

Other researchers have noticed differences in the mold susceptibility of latex as opposed to other paints. For example, Becker (1984) found less mold growth on inorganic paints (whitewash) than on latex emulsions. Hens (1985 [as cited by Aberg]) exposed painted plasterboard panels with latex and oil paints to 75% and 95% RH at 20°C for 50 days. No growth was detected on either type of paint at 75% RH. At 95% RH the latex showed mold while the oil paints did not. It may be unwise to generalize from these studies in that many paints contain fungicidal additives that could be determining the results more than the paint's intrinsic characteristics.

Foarde et al. (1992) inoculated acoustic ceiling tiles with *Penicillium aragonense* and exposed them to RH levels from 33% to 97% for a two-week period. As long as the moisture content of the tiles remained below 3% the inoculated colonies did not grow. This occurred for all humidities, including 85% RH. At 97% RH the colonies grew. Foarde et al. also did a variant of the experiment in which they soaked the blocks initially (as with a roof leak) and then exposed them to the same humidities with and without fan-supplied air movement to dry the blocks. They found that if the moisture content could be restored to less than 3% within three days, microbial growth was contained. This drying rate was achieved with the fan for all but 85% and 97% RH levels. Without the fan, none of the humidities dried the sample adequately.

The fibers and/or binder in unfaced fiberglass duct insulation is hydrophobic *per se* and does not adsorb or absorb atmospheric moisture. However, once dirt has accumulated or mold has become established (as after a single flooding), then it becomes hydrophilic. Quoting Burge (1987), "Fiberglass-lined ductwork cannot be effectively cleaned if mold growth on the fiberglass itself has occurred (as opposed to dust and spore accumulation). Microbiologically, fiberglass exposed to humid air in the supply airstream is not a good idea. Fiberglass lining should not be used in areas of high humidity or where water air washers are part of the system." Morey et al. (1991) and West et al. (1989a, 1989b) also comment on the hygroscopicity of organic dirt on fiberglass.

Surface Treatments

Nikulin et al. (1993) found that the boron fire retardant added to cellulose insulation prevented fungal growth (*S. atra*) at high humidities (100%) where cellulose would normally have been a natural substrate at humidities above 84% RH. The preventive mechanism was not discussed, but boron is known to be an exellent fungicide and insecticide. A number of surface treatments are available for dust mites, as discussed in part I of this paper.

AIR MOVEMENT IN SPACE: VELOCITIES AT SURFACES

Air movement near the surface increases the mass transfer of moisture to and from the surface. It appears that mold growth is suppressed in many typical building situations by the architectural provision of air movement over surfaces. For example, it is common practice in naturally ventilated buildings in Hawaii and elsewhere to use louvered closet doors to eliminate mildew on the clothes inside. If this is not done, mildew is known to occur. The occupied spaces in Hawaiian buildings tend to be open and mildew is uncommon. There is not much specific information available on this subject in the literature. It is possible that air movement has its primary effect by periodically desiccating organisms on the surface and thereby disrupting their growth.

The *smoothness of surfaces* affects the air movement within the boundary layer of the surface. This may be a factor in the fine texture of paints and other surfaces but is particularly important at the larger scale offered by carpets, furniture, bedding, and the unfaced fibrous insulation mentioned above. The protection offered by the roughness of the fibers buffers the surface microclimate and substantially reduces the transfer of both moisture and heat to and from the surface. The resulting stability is an advantage to biological organisms such as mites, which tend to be most populous in carpets and carpet backings. This may also be true for molds but evidence was not found in the literature. Another effect of roughness is the increased trapping of particulate air pollutants. As with the topic of air movement within buildings, there is not much empirical literature on the microenvironments at and within building surfaces and on the ways in which microclimatic fluctuations influence the growth and spread of biological pollutants.

The dynamic behavior of air humidity in rooms, walls, and wall cavities can be modeled numerically. El Diasty et al. (1992) demonstrate a simulation of indoor humidity levels, moisture transport, moisture absorption/desorption, and surface condensation/evaporation for different wall types. They also provide references to other such works. Such models could be used to predict the moisture conditions available for microorganisms over typical daily and seasonal cycles of indoor temperature and humidity. In the future, they could form a basis for designing and evaluating biological tests and also for developing more sophisticated criteria and standards for indoor humidity.

WATER IN ENVIRONMENTAL CONDITIONING SYSTEMS

Humidifiers: Steam vs. Spray

Aerosol-generating ultrasonic and spray-based humidifiers have been implicated in spreading diseases such as humidifier fever (caused by allergens from humidifier water protozoans and bacteria). British studies have also linked them to increased sick building syndrome symptoms (Fisk 1994). Aerosol-generating humidifiers are generally discouraged in the literature and steam humidifiers are recommended instead because they do not form aerosols.

Evaporative Coolers: Solid Medium vs. Spray

There are few studies on the air quality effects of direct evaporative coolers. Since most systems use a recirculating water reservoir, there is a potential for biological growth within the reservoir and on the evaporative pads. However, since the systems are designed to have relatively low air velocity across the pads, the water evaporates into the air without creating an aerosol, and biological contaminants should, in theory, not become airborne. This seems to be supported by field observations (O'Rourke et al. 1993; Macher et al. 1990) as discussed in part I of this paper.

Industry guidelines for evaporative coolers using the new synthetic solid media suggest a bleed rate from the reservoir equal to 30% of the recirculation rate, regardless of the loss to evaporation (ASHRAE forum on evaporative cooling, Denver, June 1993). Although the bleed is primarily to prevent salt buildup, making its rate constant presumably also acts to control the amount of growth within the reservoir. A similar industry suggestion is that evaporative cooling systems should completely drain their sumps daily, which would also act to control growth.

It is possible to evaporatively cool incoming supply air with aerosol-generating sprays. The authors have heard of examples of this in commercial buildings but have no experience with any of them, either directly or in the literature. Such systems could presumably present the same health hazards as spray humidifiers and appear to be discouraged in the industry. (This sentiment appeared to be the consensus at the June 1993 ASHRAE forum on evaporative cooling.)

Cooling Coils in Air-Conditioning Systems

Under dehumidification, the cooling coil becomes coated with a film of condensate from the incoming airstream. This condensate is led to the drain via the drip pan. The drip pan can be a major source of health problems when improperly drained. The standing water is often contaminated with bacteria and protozoa and, since its liquid surface is in direct contact with the supply airstream, it has the potential to contaminate the building. The literature cites this as a cause of a number of observed cases of sick building syndrome. The exact mechanism by which the pollutants are injected into the airstream does not appear to have been described.

Aerosols containing pollutants can enter buildings through outside-air inlets positioned near aerosol-forming cooling towers. Since cooling towers contain warm water, *Legionella* is often present. Cooling tower mist was the cause of the large original outbreak in Philadelphia and appears to have been the cause of other outbreaks as well.

HUMIDITY/HEALTH IMPLICATIONS FOR EVAPORATIVE COOLING OF BUILDINGS IN A HOT, ARID CLIMATE

Direct-evaporative coolers operate with high rates of outside air supply—at least three times that of a typical air-conditioned building. In general, high rates of outside air ventilation should reduce the buildup of indoor-generated pollutants. Various studies of office buildings have shown fewer complaints when they are naturally ventilated (Mendel 1993). However, if outdoor air pollution is worse than inside, once-through ventilation would increase the pollutant levels indoors. This was the case for ozone in the comparison of evaporatively cooled houses in El Paso to air-conditioned houses in Houston (Stock et al. 1993).

Direct-evaporative coolers operate with the thermal gradient inward while the humidity gradient is outward. Only one paper was found addressing the problems of biotic factors in such buildings. This paper, a field study of mites in 190 houses in Tucson, Arizona, 96% of which were evaporatively cooled, showed populations of *Dermatophagoides farinae* varying with season but present in more than half the houses (O'Rourke et al. 1993). Molds were not discussed, but personal communication with the author added that, when present, mold appeared to be primarily a result of ubiquitous leaks coming from the roof-mounted evaporative cooling units.

O'Rourke et al. also said that the great majority of the Tucson houses were cooled by old direct-evaporative "swamp coolers," even during the high-humidity "monsoon" (July through September), during which evaporative cooling is pushed to its capacity.

Evaporative cooling produces maximum indoor RHs of around 80% during operation. Wu (1990) measured (by weighing) substantial adsorption/desorption in the furnishings and structure of the space during the cyclical operation typical of summer cooling. The adsorption/desorption did not result in major changes in the space temperature under the ventilation rates used. The moisture gained during the cooling period was evaporated during off-cycle periods. Kubler (1982) calculated more than 20 gallons of daily adsorption/desorption for a wood house whose interior cycled between 60% and 80% RH. This could represent a quarter to a third of the total daily moisture added to the supply air by an evaporative cooler. The higher adsorptivities by hygroscopic materials provide a substantial effect in preventing intermittent surface condensation (Ikeda et al. 1993).

DISCUSSION: HUMIDITY/HEALTH IN STANDARDS AND DESIGN PRACTICE

Comfort standards (ASHRAE 1992; ISO 1984; DIN 1946) are based on measurements of temperature and humidity in the occupied space only. The humidities specified on the warm side of the comfort zone range between 60% and 70% RH. The difference between 60% and 70% RH at this temperature is important in cooling system design and affects the viability of direct-evaporative cooling.

The current ventilation standard (ASHRAE Standard 62 [ASHRAE 1989]) is based on air change rates, with guidance language concerning humidity limits in the occupied space (60% RH) and in ducts (70% RH). (At the time of this writing, it appears as if the 70% requirement is going to be removed in the Standard 62 revision for being impractically restrictive.)

To directly address biological *health* influences, an air quality standard should be expressed in terms of surface temperatures and humidities throughout the building and its mechanical system (i.e., walls, ducts, and drip pans), as well as the air temperatures and humidities in the occupied space. In this way the ERH can be determined for surface materials where biological growth is a possibility. For this type of specification, procedures will be needed to assess surface moisture properties by measurement and/or calculation.

TenWolde and Rose (1994) recommended a set of interim performance criteria for humidity inside the building as well as within the building envelope. Included in their recommendations is the IEA (1991) guidelines that the monthly mean ERH at all interior building surfaces, including building envelope cavities, be less than 80% (for concurrent surface temperatures between 0°C and 40°C). Washable nonporous surfaces such as glass and tiles might have the looser criterion of stating that prolonged surface condensation should be avoided, and special provisions might be instituted for dust mite control. These recommendations are not contradicted by evidence reviewed in this paper.

CONCLUSIONS

General Observations

- To date, the influence of high humidity on health has not been addressed in a way that considers all the relevant characteristics of building environments. None of the several types of buildings and environmental control systems has been comprehensively assessed, least of all the subset of evaporatively cooled buildings. Where health effects are noted, the specific causes are usually not determined. This situation impacts our ability to set rational standards and building specifications pertaining to high levels of humidity.
- Most of the identified biological health agents grow on or within surfaces of the building, its systems, and its furnishings or in standing water within or outside the building. None of the agents grows in the air of the occupied space or the mechanical system. Their growth is therefore only indirectly related to the atmospheric humidity measured in the occupied space or the ducts of its mechanical system. To control these, one needs to ensure that the surfaces remain dry. There are a number of ways to achieve this in the design, furnishing, and operation of buildings. It is also necessary to avoid producing aerosols of water from the mechanical system or humidifiers. How this is done is independent of the level of indoor air humidity.
- In general, molds do not become an issue below 70% or even 80% RH unless there are other factors influencing their growth on building surfaces. In setting a maximum limit to air humidity in the space, there is little if any evidence from field studies that provides a reason for distinguishing 60% relative humidity from 70%. Reported problems at lower RH values appeared to be due to causes other than space RH, such as rain penetration or thermal bridges in the envelope. The results tend to support TenWolde and Rose's recommended humidity criteria, which extend to 80% in winter and 70% in summer, with possible special provision for dust mite control.
- In general, the principles and practices of moisture control in buildings are known and available in the professional literature (Lstiburek and Carmody [1993] is a good example). This knowledge has often been neglected in practice, and the results are well documented in the literature of both health and biodeterioration. Water deposited within buildings by leaks and inadequate vapor control will result in mold problems almost completely independent of the level of indoor air humidity.
- Evaporative cooling in hot, arid climates is biologically relatively benign, since building surfaces are warmer and drier than conditioned air. Exceptions may be (1) lightweight furnishings that are permeated by the temperature and relative humidity of the interior air, providing a habitat for mites, and (2) floor slabs that are cooler than the interior because of direct coupling to cooler earth temperatures. This latter effect has been suggested for both mites and molds but as yet has not been experimentally proven.
- Direct-evaporative cooling through porous media also appears to be benign in that biological organisms in the cooling water do not seem to be aerosolized or transmitted downstream in significant concentrations. The wet pads may have benefits over dry filters in removing incoming pollutants. However, this needs to be experimentally investigated. In addition, the higher outside ventilation rate required by such systems should act to dilute the concentration of indoor-generated pollutants, including airborne infectious organisms.
- For evaporatively cooled building designs, smooth floors should be substituted for wall-to-wall carpets in the homes of mite-susceptible individuals. These floors are easier to clean. In addition, for cool floor slabs, the smooth surface reduces the temperature difference between the room temperature and the surface and reduces the ERH at the surface due to increased convective evaporation.
- Carpet treatment with biocides appears to be well-established in Europe, although the long-term health effects of such treatment are unknown. One treatment, based on the acaricide benzyl benzoate, is now approved for 49 U.S. states.
- Fiberglass-lined ducts lose their hygrophobic properties after a single immersion and are thereafter hygrophilic. The accumulation of organic dust adds to this undesirable

effect. The widely cited opinion of building health professionals is that these should be avoided in the future or sealed in some manner from the airstream.

Specific Needs Identified

- ERH (or water activity, a_w) needs to be determined in typical building situations and its relationship to atmospheric humidity tabulated for a range of temperatures. Field studies should attempt to locate the specific sources of biological agents and quantify the characteristics (temperature, ERH, material properties) of the surfaces on which they are growing.
- Information on the local RH within the carpet boundary layer is needed for studying mites. Such measurements would be analogous to ERH for molds but on a larger physical scale.
- In the literature, intermittent moisture exposure is almost never addressed yet is probably the most common condition in building systems. The effects on organisms of periodic moistening and drying out (mites and molds) influence their growth and survival. Information is needed on the effect of daily and longer-term moisture cycles on surface moisture, ERH, and on the organisms themselves. Information is also needed on how such cycles are affected by the operation of the building and its mechanical system. Dynamic moisture models might be used in conjunction with experimentation to provide such information.
- Data are needed on the hygroscopic properties of indoor paints. The studies showing latex emulsions being relatively prone to mold growth were done some years ago, probably before the development of latex acrylics and other current paints. The recent replacement of oil-based paints and even varnishes with water-based versions suggests that typical indoor finishes are very different than in the past. The effects of fungicidal additives should also be determined.

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