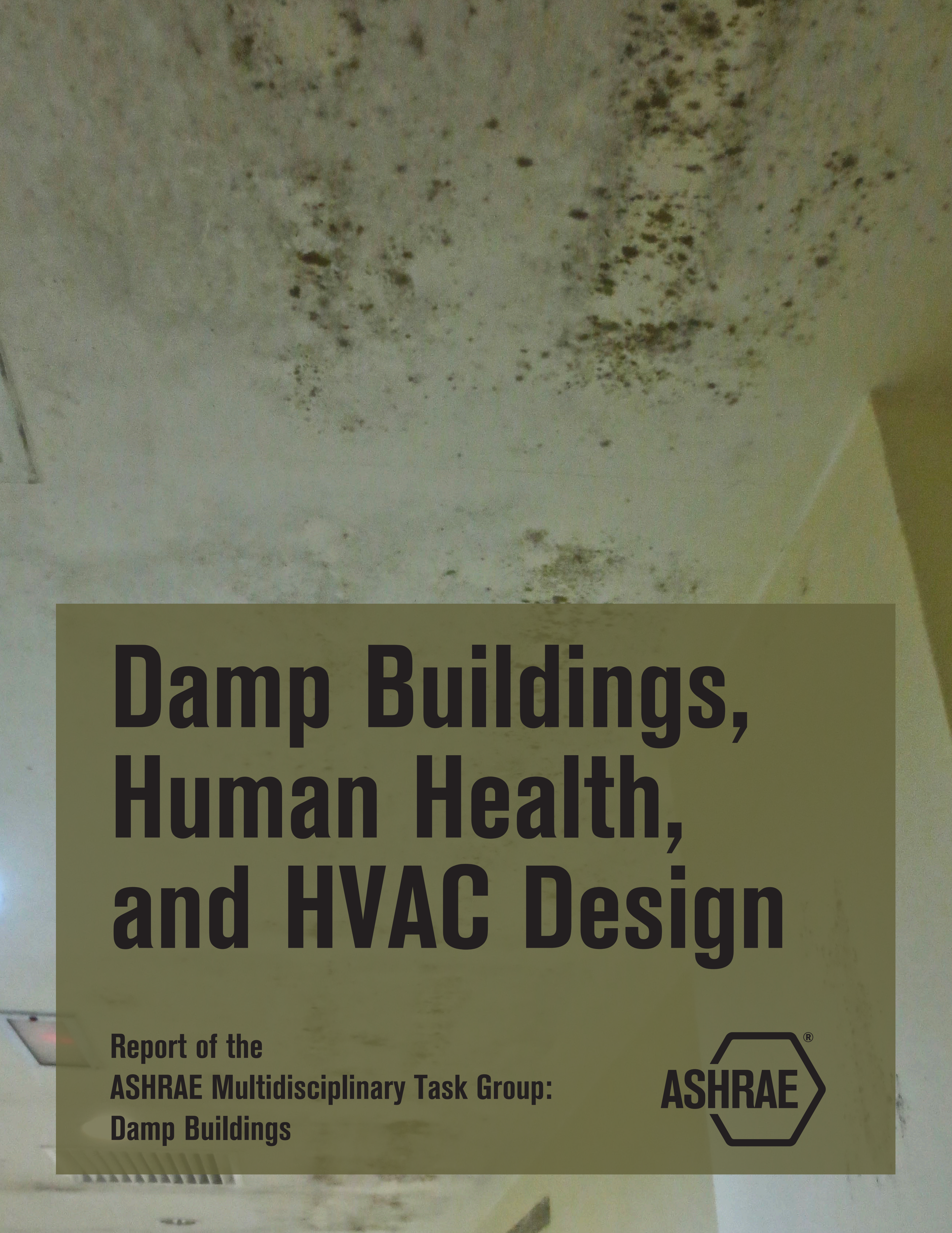

Damp Buildings, Human Health, and HVAC Design

Report of the ASHRAE Multidisciplinary Task Group: Damp Buildings

ASHRAE®

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Contents

Preface

This report provides a summary of what is understood within ASHRAE about dampness-related health risks in buildings as well as suggestions for HVAC system designers that can help avoid such risks. As readers understand, knowledge advances over time; this report summarizes the state of understanding of volunteer experts within the Society as of 2019.

Since the late 1980s in North America and increasingly around the world, moisture and humidity problems in buildings have been the subject of extensive litigation, based in part on concerns about occupant health. For example, a detailed survey of federal buildings in the United States during the late1990s noted that more than 85% of buildings surveyed had experienced moisture or humidity problems over their lifetime, and at the time of the investigation 45% were experiencing current problems (EPA 2006). In 2008, the National Association of Insurance Commissioners (NAIC 2008) reported that as of 2007, humidity and moisture-related problems in buildings accounted for 84% of the claims against the errors and omissions insurance of architects and engineers, and moisture-related damage was the single most-litigated construction defect claim against contractors.

As a Society of volunteers, ASHRAE's mission statement is broad and compelling: "To serve humanity by advancing the arts and sciences of heating, ventilation, air conditioning, refrigeration and their allied fields." Consequently, from the beginning of mold and dampness problems in modern buildings, the membership of ASHRAE has been deeply involved with these issues because of their expertise in the design, installation, and operation of HVAC systems

Initially, members were called upon to help solve the indoor air quality (IAQ) problems that result from excessive moisture, humidity, and microbial growth in buildings and HVAC systems. More recently, additional technical experts within the membership volunteered to help the industry improve building science, a subject that includes the complex interactions between buildings' HVAC systems and their enclosures. ASHRAE volunteers have formed and served on several technical committees to discuss, understand, and make recommendations to reduce the risks associated with building dampness.

As a result, over the last 20 years volunteer efforts have produced publications that can help our members and the industry develop and improve best practices with respect to humidity control and moisture management in buildings. ASHRAE publications currently available to the public on this subject include the following:

- *Humidity Control Design Guide for Commercial and Institutional Buildings* (Harriman et al. 2001a)
- *The ASHRAE Guide for Buildings in Hot and Humid Climates* (Harriman and Lstiburek 2009c)
- *ASHRAE Position Document on Limiting Indoor Mold and Dampness in Buildings* (ASHRAE 2018)
- "Moisture Management in Buildings," Chapter 36 of *ASHRAE Handbook—Fundamentals* (ASHRAE 2017b)
- "Heat, Air, and Moisture Control in Building Assemblies—Fundamentals," Chapter 25 of *ASHRAE Handbook—Fundamentals* (ASHRAE 2017b)
- "Heat, Air, and Moisture Control in Building Assemblies—Material Properties," Chapter 26 of *ASHRAE Handbook—Fundamentals* (ASHRAE 2017b)
- "Heat, Air, and Moisture Control in Building Assemblies—Examples," Chapter 27 of *ASHRAE Handbook—Fundamentals* (ASHRAE 2017b)
- "Moisture and Mold," Chapter 64 of *ASHRAE Handbook—HVAC Applications* (ASHRAE 2019c)

Although helpful to professionals who seek to avoid moisture and humidity problems, these publications do not directly address the health consequences of such problems. Therefore, in the Society's position document on this subject (ASHRAE 2018), the ASHRAE Board of Directors asked that members of our technical committees again volunteer their time and expertise to work with other stakeholders to develop a practical and inspectable description of a building that is "damp enough to increase the risks of health effects for some occupants." As of 2019, that Board request has resulted in the following:

- The formation of the Multidisciplinary Task Group: Damp Buildings, the group that produced this report, which is the result of a three-year collaboration between 2013 and 2016.
- Inspectable criteria for buildings that, based on peer-reviewed public health research reports, are similar to buildings proven to be damp enough to increase health risks.
- Indoor dew-point temperature (DPT) limited to 60°F (15°C) by ANSI/ASHRAE Standard 62.1 (ASHRAE 2019a). In mechanically cooled and ventilated buildings, the standard requires that designs include equipment and controls that are capable of keeping the indoor air dry at all times, including periods when the building is not occupied.

Readers are encouraged to obtain and make use of the guidance provided by Standard 62.1 as well as the other resources described in this report. Readers are also welcome to assist efforts to further improve guidance as volunteer members of the ASHRAE Technical Committees (TCs) that are concerned with these issues, namely TC 1.12, Moisture Management in Buildings, and TC 4.4, Building Materials and Building Envelope Performance, as well as the Environmental

Health Committee and Standing Standard Project Committee (SSPC) 62.1, Ventilation.

Finally, the publications referenced above and this report were written with commercial buildings, schools, and multifamily high-rise residential buildings as their primary focus. However, as readers can appreciate by reading the epidemiological studies of building occupants referenced in this report, the warning signs of health-relevant indoor dampness and the principles of avoiding those conditions also apply to low-rise residential housing.

Summary and Recommendations

Epidemiological researchers have shown clear and consistent associations between occupancy of damp indoor spaces and increased probability of important adverse health effects such as development of new asthma, exacerbation of existing asthma, allergic rhinitis, and respiratory infections[1] (IOM 2004; WHO 2009; Mendell et al. 2011; Miller 2011; Kennedy and Grimes 2013; Miller and McMullin 2014; Kanchongkittiphon et al. 2015; Mendel and Kumagai 2017). Unlike some other health risks, illnesses triggered by damp indoor spaces are preventable.

In response to *ASHRAE Position Document on Limiting Indoor Mold and Dampness in Buildings* (ASHRAE 2018), ASHRAE's Technical Activities Committee (TAC) authorized the creation of this multidisciplinary task group to develop a simple and easily recognizable description of dampness that is sufficient to increase the probability of negative health effects and to suggest practical, quantitative tools and techniques that can alert managers to the risk of a building or an indoor space becoming "damp" to an extent that it will affect health in the future.

Toward these ends, this task group has reached consensus recommendations for a description of health-relevant indoor dampness and for quantitative tests and thresholds that can serve as early warning signs of possible health-relevant dampness in the future. These include health-relevant indoor dampness, quantitative metrics, and dampness leading to structural risk.

Health-Relevant Indoor Dampness

Indicators of health-relevant indoor dampness in a building or space include visible mold growth, moisture, damage from water or moisture, or musty/moldy/earthy odors. These indicators have each been clearly and strongly associated with increased probability of negative health effects for occupants, although no specific dampness thresholds have been established and not all individuals are equally affected.

Quantitative Metrics

Quantitative metrics, with thresholds that separately provide *early warning* of possible future health-relevant dampness, are as follows:

1. Evidence from epidemiological studies showed indoor dampness or mold were consistently associated with increases in multiple diseases (asthma development, asthma exacerbation, current asthma, never-diagnosed asthma, respiratory infections, allergic rhinitis, eczema, and bronchitis) and symptoms (lower respiratory symptoms such as difficulty breathing and wheezing as well as upper respiratory tract symptoms such as nasal, sinus, and throat symptoms and cough) (Mendell et al. 2011).

1. Persistent water activity levels above 0.75 at the surfaces of organic materials or coatings.
2. Persistent moisture content above 15% wood moisture equivalent (WME) in organic materials, coatings, and untreated paper-faced gypsum board.
3. Persistent moisture content above 90% equilibrium relative humidity (ERH) in concrete or masonry that is either coated with—or is in contact with—organic materials or coatings.
4. Persistent indoor humidity above a dew-point temperature (DPT) of 60°F (15°C) for buildings that are being mechanically cooled or above a DPT of 45°F (7°C) for heated buildings in moderately cold and mixed climates (in international climate zones 4 and 5, as referenced in Table B1-4 of ANSI/ASHRAE/IES Standard 90.1 [ASHRAE 2019b]).

In this context, the word *persistent* means that the condition has become typical because it extends for days or weeks at a time rather than being infrequent excursions of a few hours per week above these suggested thresholds followed by a return to normal levels of dryness.

Note that *any* of these quantitative metrics are indicators of abnormal conditions that can ultimately lead to moisture accumulation and health-relevant indoor dampness. The word *abnormal* is used here to describe conditions that, while they may occur with some regularity in many buildings, are seldom if ever the basis of design for durable buildings and energy-efficient climate-control systems.

Finally, note also that these quantitative metrics and thresholds are not intended to be, nor have they been documented to be, indicators of *current* health-relevant indoor dampness. Unless or until such associations are established and documented, these quantitative metrics should be considered *early warnings* of possible health-relevant dampness at some future date. They do not provide quantitative validation of current health-relevant dampness.

Dampness Leading to Structural Risk

This report deals with the issue of dampness as it relates to human health. But the committee notes that excessive indoor dampness has also been documented to reduce the load-bearing capacity of wood framing. Further, extended dampness or periodic condensation can corrode critical structural fasteners inside the walls, foundation, and roof of a building.

Under those circumstances, problems associated with excessive indoor dampness go far beyond long-term health effects, extending all the way to the risk of short-term structural failure. A thorough discussion of structural risks is beyond the scope of this committee's assignment, but we note the importance of limiting moisture accumulation and avoiding condensation not only inside the building but also inside the assemblies of its exterior walls, foundation, and roof. Prudent building design, construction, and management must avoid interstitial condensation and moisture accumulation.

Periodic moisture content measurements and/or continuous monitoring of moisture content and condensation inside building assemblies can help alert the building owner, allowing action to avoid problems that could proceed to the level of structural failure, with its obvious and significant risks to public health and safety.

Epidemiological Studies of Damp Buildings

Our task group notes that persistent dampness is not a normal indoor condition. Indoor spaces and furnishings are designed, constructed, and operated to be dry and to stay dry. If an indoor space has become damp enough to grow visible amounts of mold, or to create musty/earthy odors, or to have visible water damage or moisture, something about the way the building is designed, constructed, operated, or maintained is simply wrong. The sources and mechanisms that led to persistent dampness must be discovered and eliminated promptly to avoid increased probability of health risks to occupants.

Foundation of the Description

The description of the characteristics of health-relevant dampness is based on field research by epidemiological investigators that shows clear relationships between these dampness/mold (D/M) indicators and negative health effects. In addition, investigations show a dose-response relationship between the amount of the D/M indicator and the probability of adverse health effects. As examples of this research, consider the evidence summarized in Figures 1 and 2. (Mendell and Kumagai 2017; Kanchongkittiphon et al. 2015).

Figure 1 summarizes findings from two quantitative summaries (Quansah et al. 2012; Jaakkola et al. 2013) of many studies. The first group of four columns shows that, with any indicator of mold or dampness, the asthma odds ratio increases to 1.3. In other words, the results show that the probability of developing asthma in previously unaffected occupants was about 30% higher in the presence of any indicator of dampness or mold. Further, the probability of developing any form of rhinitis increased by 110%, and the probability of rhinoconjunctivitis was 70% higher.

The fourth column grouping shows the association established by this research between perceived dampness and negative health effects. We note, however, that the studies do not provide any means of quantifying the amount of perceived dampness that was associated with those health effects.

Figure 1 also shows that increases in probability indicated by the presence of mold odor (column grouping 2) is greater than the risks associated with the other indicators: visible mold growth, dampness, and water damage (column groupings 3, 4, and 5). From evidence such as this, we conclude that professionals should not dismiss moldy/musty odors as merely indicators of a potential future problem. Instead, those in a position to take action should recognize that odors are an indicator that the probability of negative health effects is already elevated.

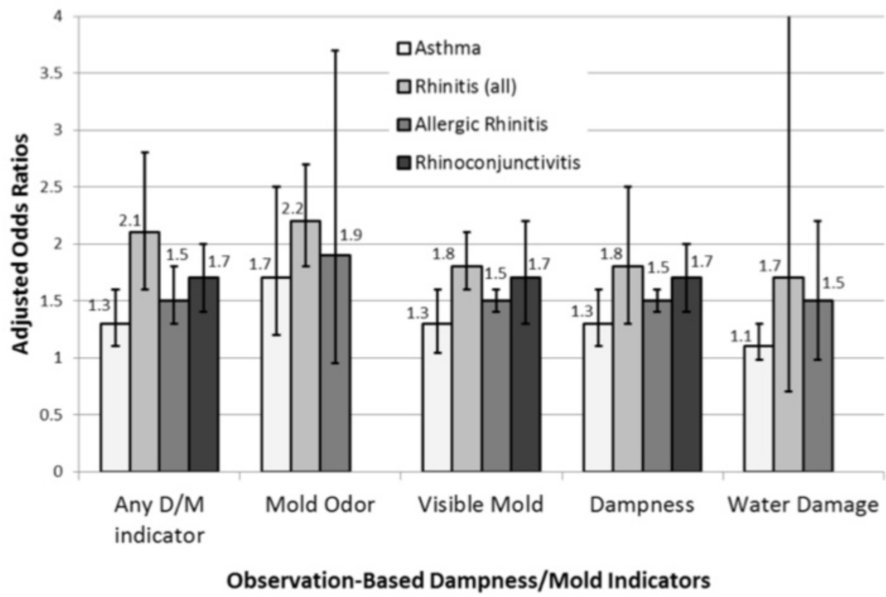

Figure 1 Summarized findings from data described in two meta-analyses of associations between health effects and dichotomous scores for dampness/mold (D/M) indicators (results reported by Quansah et al. 2012 and Jaakkola et al. 2013). Vertical bars show 95% confidence limits. An odds ratio of 1.0 indicates no increased risk with the presence of the D/M indicator; an odds ratios above 1.0 indicates increased probability of the heath effect. *(Courtesy M.J. Mendell)*

Next, consider the elevated probability of health effects shown by the three field studies summarized in Figure 2. In these studies, four easily perceptible indicators of dampness or mold were used to establish a dampness/mold (D/M) index:

1. Visible mold
2. Mold odor
3. Current water damage
4. History of visible mold or water damage

The researchers established three levels for their D/M index: none, low, and high. The criterion for an index score of none was that none of the four indicators of dampness or mold were present in the buildings examined. The general level of negative health effects for this group, without the presence of D/M indicators, was considered the reference level, with an odds ratio of 1.0.

The criterion for an index score of low was the presence of at least one of the four indicators, but not as much as the surface area amount specified for an index score of high. The criterion for an index score of high was a total of *either* visible mold greater than or equal to 0.2 m^2 in one room *or* visible mold growth plus water damage greater than or equal to 0.2 m^2 on one surface (0.2 m^2 = 2.15 ft^2).

To understand the implications of these results, consider the increase in odds ratio for upper respiratory infections (URIs) shown in Figure 2a (Biagini et al.

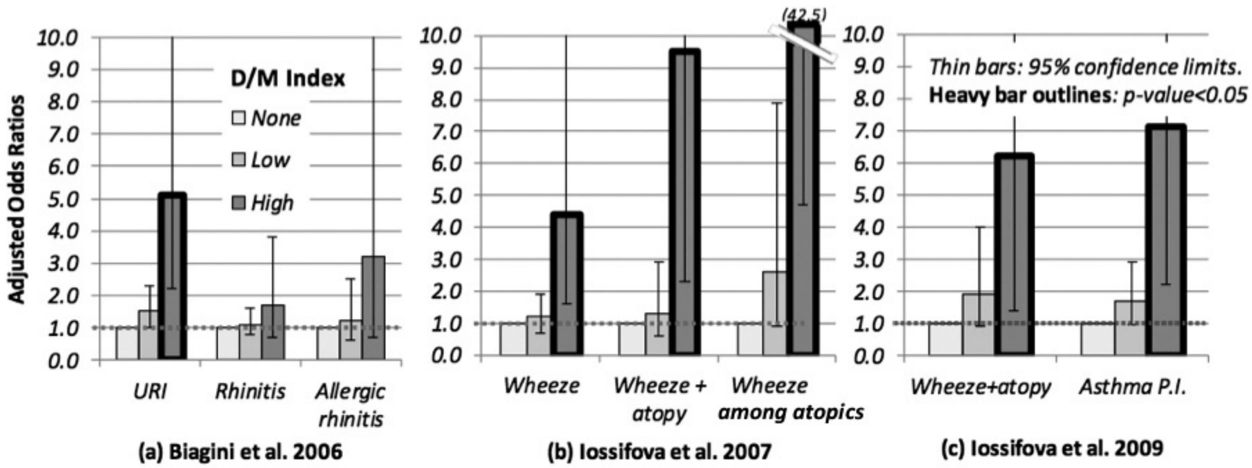

Figure 2 Summarized associations between health effects and three-level scores for mold and dampness. Results from the Cincinnati Childhood Allergy and Air Pollution Study (CCAAPS), as reported by Biagini et al. (2006) and Iossifova et al. (2007, 2009). *(Courtesy M.J. Mendell)*

2006). Researchers found approximately five times the odds of having a URI (400% increase in probability) in the presence of *either* visible mold greater than or equal to 0.2 m^2 in one room *or* visible mold growth plus water damage greater than or equal to 0.2 m^2 on one surface (0.2 m^2 = 2.15 ft^2).

Also note another important point about the findings shown in the three-column grouping for *wheeze* in Figure 2b (Iossifova 2007). The second and third columns in that set of three show that the odds ratios for developing wheezing among all the children in the study at the low and high levels of dampness were 1.2 and 4.4 (20% to 410% increase), compared to the first column (no dampness).

But even far greater effects from dampness were seen among the children who were atopic (allergic). These observations are shown in the third set of columns within Figure 2b. Note that the third set of columns, labeled “wheeze among atopics,” shows that odds ratios for wheezing increased between 2.6 and 42.5 times. Thus, in this sensitive population, even the low dampness level was associated with a 160% increase, and at the high dampness level the resulting probability of wheezing was almost 10 times the probability of that negative effect (i.e., 42.5 vs 4.5) compared to dampness effects on children who were not reported as being allergic at the time of the investigations.

From evidence such as this, we conclude that professionals should not dismiss relatively small amounts of mold growth in one or two parts of a building as merely indicators of a potential future problem. Instead, those in a position to take action should recognize that even relatively small areas of visible mold or water damage (no threshold yet determined) and/or perceptible moldy odors are associated with large increases in probability of negative health effects, for at least some percentage of the public.

Factors that May Increase or Reduce Dampness Health Risks

While these epidemiological investigations clearly show elevated probabilities of negative health effects in spaces that have visible mold, water damage, or moisture or that smell moldy, we note that the research does not confirm equal probability for all people and all types of occupancies. Factors outside of our recommended description may also increase or reduce risks for specific buildings and specific individuals, such as the factors discussed in the following subsections.

Exposure

The peer-reviewed research that establishes a dose-response relationship between the amount of moldy or water-damaged surface and the probability of health risk was conducted mostly in residences rather than in commercial buildings. The number of hours, days, weeks, and years that an occupant is exposed to dampness in a home, apartment, or bedroom is far higher than the amount of time occupants spend in hotels or airports, unless they are employees. When other factors are equal, dampness increases the probability of occurrence of respiratory health problems from spaces where people spend more time, as shown by research in both homes and offices (Park et al. 2004; Mendell and Kumagai 2017).

Individual Occupant Sensitivity

Clearly, hospital patients taking drugs that suppress their immune systems are more sensitive to any health risk, including effects of building dampness. Similarly, infants, children, and the elderly have fewer defenses against environmental insults that most healthy adults may endure without obvious harm. Also, individuals who have allergic sensitivities are less able to endure an environment that others of similar age and health status might find less risky, as shown in Figure 2. So, all other factors being equal, it is reasonable to assume that individual sensitivity is an important factor in determining health risk, and to date, this sensitivity has been difficult to quantify for specific individuals.

Dampness Description is Based on the Precautionary Principle

Based on the history of indoor air and mold investigations in North America and Northern Europe over the last 25 years, it is clear that not all occupants share the same probability for health risk in damp spaces. Further, some may elect to occupy spaces that elevate the probability for negative health effects. Adults are entitled to accept risk, absent any coercion of organizational or economic necessity, and assuming the individual is capable of informed consent, has been informed, and has in fact consented to the risk.

But given ASHRAE's stated mission, "to advance the arts and sciences of heating, ventilation, air conditioning and refrigeration to serve humanity and promote a sustainable world," we believe that the Society should inform the public of factors that we know increase the probability of negative health effects rather than waiting until we know the exact percentage of occupants that face that risk at each level of personal sensitivity or waiting until we know the exact number of hours of exposure that represent an increase in risks in each type of building.

We recommend the description of health-relevant indoor dampness stated previously, based on the precautionary principle that obvious risk factors should be eliminated when they are known, even if all the mechanisms that lead to risk are not fully understood.

Quantitative Tests with Early-Warning Thresholds

Delaying action until indoor spaces become damp is not in the public interest. Accordingly, building owners and operators need quantitative tools and tests that help them recognize the approach of future problems so they can prevent health-relevant dampness before it occurs.

But before considering the use of any quantitative tests and thresholds, readers should keep in mind some important cautions about building dampness, beginning with its dynamic bio-hygro-thermal variation over time, and the critical importance of the exact locations of measurements.

The Importance of Measurements Over Time

The real-world constraint of limited budgets creates a strong desire for simple, one-time, one-location measurements that conclusively warn or reassure managers and occupants about dampness risks. Unfortunately, risks from building dampness and microbial growth are microgeographic and constantly changing.

So any single snapshot measurement taken at any one location is simply never going to be a conclusive indicator of the presence or absence of health-relevant dampness in an entire building. Moisture, mold, and bacteria are always present in buildings. It is the excessive accumulation of these over time in specific locations that causes problems (Flannigan and Miller 2001; Li and Wadso 2012; Ojanen et al. 2010; Viitanen et al. 2001; Viitanen and Ojanen 2007).

Therefore the change (or lack of change) in exactly located measurements over time provides the best indication of the presence or absence of excessive moisture accumulation that can lead to microbiological growth. When reliable indicators are needed, investigators and building owners are encouraged to make observations and keep records of measurements over time and to document the locations of these measurements within inches of the measurement points. Photographs annotated with exact measurement locations along with the values recorded at those locations can be helpful in assessing changes over time (see an example of this recording method in Figure 8).

These Thresholds are not Indications of Elevated Health Risk

These recommended thresholds of concern have not been linked to current health risk from dampness. Neither owners nor occupants should treat these tests and threshold values as panic alarms.

These Thresholds do not Imply a Standard of Care

These thresholds are also not intended to imply contractual obligation, or a professional standard of care, or violation of a manufacturer's warranty, or to be a substitute for professional judgment in connection with construction defect disputes. These thresholds serve only as early warnings of abnormal conditions—those that are not in the normal range expected for most buildings that are well designed, built, and operated. If such conditions are allowed to persist, excessive moisture could accumulate over time, which in turn could lead to microbial growth and health-relevant indoor dampness in the future.

Early-Warning Thresholds of Possible Future Problems

Always keeping in mind the many cautions above, this committee has reached consensus on four test measurements along with suggested threshold values that can serve as early warning signs of future health-relevant dampness. Each of these indicators is important in and of itself, but when more than one is present in the same space, the early warning to building owners and occupants becomes stronger.

Early-Warning Test 1: Persistent Water Activity (a_W) at the Surface of Organic Materials or Coatings or Untreated Paper-Faced Gypsum Board in Excess of 0.75

For most building professionals, the term *water activity* is new and unfamiliar. Therefore, a short explanation is needed to clear up the confusion built up over the last 40 years about the relationship between relative humidity (RH), moisture content, and microbial growth risk.

In short, fungi and bacteria grow and multiply on surfaces. They may survive in air, but they grow to problematic levels only on surfaces. So surfaces, rather than air, must become the focus of any building manager's understanding of mold growth and its attendant health risks when making decisions about building management and maintenance.

Further, mold and bacteria only grow on surfaces that retain sufficient moisture over time. But not all moisture is equally available to support growth. In some materials, moisture is tightly bound to the surface and cannot be used by bacteria or fungi. In other materials, the moisture is easily accessed to support microbial growth. Microbiologists have found, after over 150 years of research, that the most reliable moisture-related metric that governs growth is the water activity at the surface of the material in question. Water activity could also be described as a measurement of the bioavailability of moisture in a material. It is in fact a measurement of the difference in water vapor pressure between the fungal or bacterial cell and the moisture in the surface on which it is located.

The 40-year confusion arises because of the way water activity is measured in laboratory settings where mold and bacterial growth has been studied and quantified. When the surface and the surrounding air are at perfect hygrothermal equilibrium (when the temperature and relative humidity of both are identical), the water activity (the relative vapor pressure difference) can be quantified by measuring the RH of the air inside the culture dish where all is at hygrothermal equilibrium. Biologists use the decimal fraction of RH to quantify water activity (i.e., an ERH of 85% is expressed as 0.85 water activity).

The confusion within the building community comes from the mistaken assumption that RH in the air is the same as RH at the surface. In fact, they are rarely the same, because of three factors: the difference between surface and air temperatures, the presence of subsurface moisture, and the minute-by-minute changes in all of those variables inside complex building assemblies.

Outside of an environmental chamber that contains fungal growth sealed in a petri dish, nothing is ever at equilibrium. In buildings, moisture and heat are perpetually moving around within as well as into and out of materials in small or large amounts, every minute. So the traditional use of RH in the air as a threshold of concern is both erroneous and misleading (Harriman et al. 2001b; ASHRAE 2009a, 2009b, 2019c; EPA 2013). Instead, investigators and building managers should focus on the more reliable risk indicator of surface water activity.

As shown in Figure 3, estimating the surface water activity can be done by plotting the result after measuring the ERH of the surface in one of two ways:

1. Attach an RH sensor to the surface in question inside an airtight cover sealed to that surface. After enough time has been allowed to achieve near equilibrium of both temperature and humidity for all components (the surface under the cover, the sensor itself, and the air inside the sensor cover), an RH measurement, converted to its decimal equivalent, is a measurement that approximates water activity and therefore helps assess microbial growth risk.
2. Measure the DPT of air as close to a surface as practical using a handheld thermohygrometer. Then use an infrared surface thermometer or a thermocouple to measure the surface temperature. Using a psychrometric chart or computer app, plot or enter the surface temperature plus the air's DPT to arrive at an RH value. The decimal equivalent of that surface RH is an approximation of its current water activity. Values above 0.75 indicate that water activity is above normal indoor levels, at least at that specific location, at that specific moment in time, on that specific surface.

Documents and logic that support this suggested threshold of concern include ANSI/ASHRAE Standard 160 (ASHRAE 2016), which recommends that in the absence of more specifically known parameters for risk of mold growth, those who model the hygrothermal behavior of building systems should be aware that risks of mold are higher when the ERH (the water activity) at the surface of an organic material or coating stays above 80% for a moving average of 30 days. That criterion is based on several long-term research efforts that are specific to real-world building systems and building materials in situ, as opposed to only laboratory studies in sealed chambers at perfect and static equilibrium with growth media engineered to be ideal for fungus and bacteria. Many comparisons between laboratory conditions and field conditions have been performed over the last 30 years in Northern Europe and North America, including those by Glass et al.

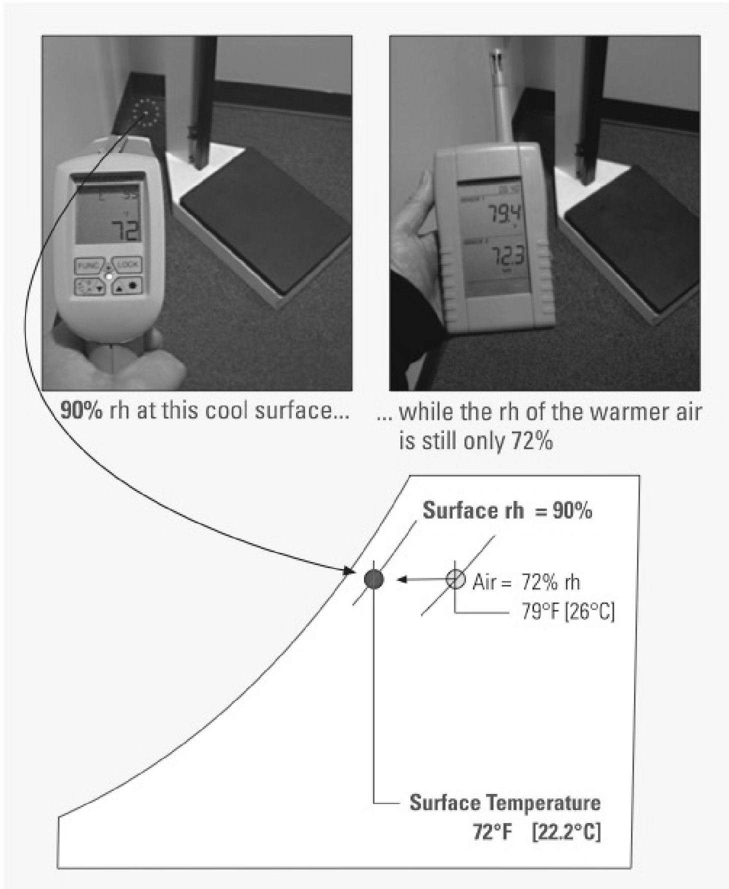

Figure 3 Measuring surface temperature and air DPT to estimate RH at the surface. Excessive moisture absorption and its persistence over time is what allows the growth of mold and bacteria. Absorption increases when the indoor DPT is high at the same time that surfaces temperatures are low. Measuring surface temperature and comparing that value with the DPT of the air allows estimation of surface RH, a value close that of water activity (a_W), which is the parameter that governs the growth of mold and bacteria at the surface.

(2015), Ueno (2015), Adan (2011), Vereecken and Roels (2012), Krus et al. (2010), Viitanen and Ojanen (2007), Neilsen et al. (2004), Sedlebauer (2001), Rowan et al. (1999), and Hens (1992).

These referenced comparisons between models, laboratory results, and field results consistently show the threshold of concern varies according the material and its exposure. For the robust materials inside, exterior walls and the very long wetting-drying cycles endured by wood framing, plywood, or oriented strand board inside exterior walls, the 30-day average 80% ERH upper limit is conservative (i.e., mold is very unlikely to grow even if that limit is not maintained and even when condensation occurs intermittently). However, these same comparison studies also show that for paper-based products indoors, such as the paper and cardboard faces of interior gypsum board, an ERH of 75% is still risky with respect to mold growth if accompanied by intermittently higher ERH or condensation, even if the time of wettedness (time above an ERH of 75%) is less than a few hours.

Therefore, the logic for a setting a threshold level lower than 80% surface ERH [0.80 a_W] is the same as for any safety factor used when the goal is to reduce risk in systems that have many unknowns. In short, the research shows conclusively that above 0.8 surface water activity (80% ERH) there is a risk of mold growth within 30 days. Therefore, this task group recommends using a threshold of concern known to be above normal levels but also below the level of known risk: namely, a water activity of 0.75.

Early-Warning Test 2: Persistent Moisture Content above 15% WME in Organic Materials or Coatings or Untreated Paper-Faced Gypsum Board, as Measured with a Resistance (Pin) Moisture Meter

High moisture content measurements in building assemblies frequently (but do not always) correlate well with characteristics that describe a building or space that exhibits health-relevant dampness (Macher et al. 2015, 2016). Furthermore, wood-based moisture meters are easily available, inexpensive, easy to use, and in general are also reliable enough and accurate enough to identify locations with excessive moisture accumulation.

The caution when using moisture meters that a resistance-type or *pin meter* should be used to make decisions about moisture content reflects the fact that measurements made with capacitance (nonpenetrating) meters are less consistent than those made with resistance measurements. Such nonpenetrating meters are very useful for quickly locating areas of concern without the need to puncture a surface. However, meters that measure capacitance, or impedance or radio frequency, read out on many different scales, all of which are incompatible with each other and most of which are relative values rather than the broadly comparable—and therefore more useful—WME scale. So after fast scans with nonpenetrating meters help the investigator locate areas of concern, a pin-type meter will ultimately be more reliable for making decisions about whether a specific location has a moisture content that is within a normal range or is abnormally high.

Documents and logic that support this suggested threshold of concern are that when building materials made of soft wood fibers (such as oriented strand board, paper, cardboard, and cellulosic ceiling tile) come to equilibrium with air at 75% relative humidity, their moisture content is approximately 14%–15% of their dry weight. The exact relationship between WME and ERH varies with the product and its fiber type, manufacturing processes, mechanical and sorption-desorption characteristics, adhesives, coatings, and possible conductive additives (Kumaran et al. 2006). But the general relationship is similar to that of intact soft wood lumber, as shown in Figure 4 (Glass and Zelinka 2010). Given that the biological availability of water in materials increases to levels of concern above 0.75 water activity, 15% moisture content is appropriate for use as the threshold of concern for moisture content of organic materials when measured by a moisture meter that is calibrated for wood.

Temperature		Moisture content (%) at various relative humidity values																		
(°C	(°F))	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%	65%	70%	75%	80%	85%	90%	95%
−1.1	(30)	1.4	2.6	3.7	4.6	5.5	6.3	7.1	7.9	8.7	9.5	10.4	11.3	12.4	13.5	14.9	16.5	18.5	21.0	24.3
4.4	(40)	1.4	2.6	3.7	4.6	5.5	6.3	7.1	7.9	8.7	9.5	10.4	11.3	12.3	13.5	14.9	16.5	18.5	21.0	24.3
10.0	(50)	1.4	2.6	3.6	4.6	5.5	6.3	7.1	7.9	8.7	9.5	10.3	11.2	12.3	13.4	14.8	16.4	18.4	20.9	24.3
15.6	(60)	1.3	2.5	3.6	4.6	5.4	6.2	7.0	7.8	8.6	9.4	10.2	11.1	12.1	13.3	14.6	16.2	18.2	20.7	24.1
21.1	(70)	1.3	2.5	3.5	4.5	5.4	6.2	6.9	7.7	8.5	9.2	10.1	11.0	12.0	13.1	14.4	16.0	17.9	20.5	23.9
26.7	(80)	1.3	2.4	3.5	4.4	5.3	6.1	6.8	7.6	8.3	9.1	9.9	10.8	11.7	12.9	14.2	15.7	17.7	20.2	23.6
32.2	(90)	1.2	2.3	3.4	4.3	5.1	5.9	6.7	7.4	8.1	8.9	9.7	10.5	11.5	12.6	13.9	15.4	17.3	19.8	23.3
37.8	(100)	1.2	2.3	3.3	4.2	5.0	5.8	6.5	7.2	7.9	8.7	9.5	10.3	11.2	12.3	13.6	15.1	17.0	19.5	22.9
43.3	(110)	1.1	2.2	3.2	4.0	4.9	5.6	6.3	7.0	7.7	8.4	9.2	10.0	11.0	12.0	13.2	14.7	16.6	19.1	22.4
48.9	(120)	1.1	2.1	3.0	3.9	4.7	5.4	6.1	6.8	7.5	8.2	8.9	9.7	10.6	11.7	12.9	14.4	16.2	18.6	22.0
54.4	(130)	1.0	2.0	2.9	3.7	4.5	5.2	5.9	6.6	7.2	7.9	8.7	9.4	10.3	11.3	12.5	14.0	15.8	18.2	21.5
60.0	(140)	0.9	1.9	2.8	3.6	4.3	5.0	5.7	6.3	7.0	7.7	8.4	9.1	10.0	11.0	12.1	13.6	15.3	17.7	21.0
65.6	(150)	0.9	1.8	2.6	3.4	4.1	4.8	5.5	6.1	6.7	7.4	8.1	8.8	9.7	10.6	11.8	13.1	14.9	17.2	20.4
71.1	(160)	0.8	1.6	2.4	3.2	3.9	4.6	5.2	5.8	6.4	7.1	7.8	8.5	9.3	10.3	11.4	12.7	14.4	16.7	19.9
76.7	(170)	0.7	1.5	2.3	3.0	3.7	4.3	4.9	5.6	6.2	6.8	7.4	8.2	9.0	9.9	11.0	12.3	14.0	16.2	19.3
82.2	(180)	0.7	1.4	2.1	2.8	3.5	4.1	4.7	5.3	5.9	6.5	7.1	7.8	8.6	9.5	10.5	11.8	13.5	15.7	18.7
87.8	(190)	0.6	1.3	1.9	2.6	3.2	3.8	4.4	5.0	5.5	6.1	6.8	7.5	8.2	9.1	10.1	11.4	13.0	15.1	18.1
93.3	(200)	0.5	1.1	1.7	2.4	3.0	3.5	4.1	4.6	5.2	5.8	6.4	7.1	7.8	8.7	9.7	10.9	12.5	14.6	17.5
98.9	(210)	0.5	1.0	1.6	2.1	2.7	3.2	3.8	4.3	4.9	5.4	6.0	6.7	7.4	8.3	9.2	10.4	12.0	14.0	16.9
104.4	(220)	0.4	0.9	1.4	1.9	2.4	2.9	3.4	3.9	4.5	5.0	5.6	6.3	7.0	7.8	8.8	9.9			
110.0	(230)	0.3	0.8	1.2	1.6	2.1	2.6	3.1	3.6	4.2	4.7	5.3	6.0	6.7						
115.6	(240)	0.3	0.6	0.9	1.3	1.7	2.1	2.6	3.1	3.5	4.1	4.6								
121.1	(250)	0.2	0.4	0.7	1.0	1.3	1.7	2.1	2.5	2.9										
126.7	(260)	0.2	0.3	0.5	0.7	0.9	1.1	1.4												
132.2	(270)	0.1	0.1	0.2	0.3	0.4	0.4													

Figure 4 Wood moisture content of Douglas fir, measured gravimetrically, when at static hygrothermal equilibrium with the stated air temperature and RH (Glass and Zelinka 2010, Table 4-6b).

Further support for the 15% WME threshold of concern is that recommended installation moisture content for interior wood trim, cabinetry, and floors is 9% in dry climates and 11% in humid coastal areas, with recommended maxima for any individual board of 10% and 13%, respectively (Bergman 2010). Therefore, 15% would be abnormally high for interior woodwork in any climate. The relationship between the RH of the air and the moisture content of wood is shown in Figure 4. Keep in mind, however, that unlike paper surfaces, wood with finished surfaces takes a long time to come to equilibrium with the surrounding air. In contrast, paper and cardboard, which both provide moisture content measurements similar to those of wood, respond far more quickly.

Gypsum board is a material of much greater concern, because it is present in buildings in far larger amounts than wood products and its paper face and cardboard backing are much more easily digestible by fungi than are intact wooden surfaces. The moisture content of gypsum board leaving the factory is below 1% of its dry weight, and the initial moisture content of cellulosic acoustic tile is below 6% of dry weight. In both cases, at those levels of actual moisture content, meters calibrated for wood (WME scale) are not likely to be able to read any moisture at all.

But both these materials absorb moisture in transit, and again during installation and normal building operation, eventually reaching moisture content levels

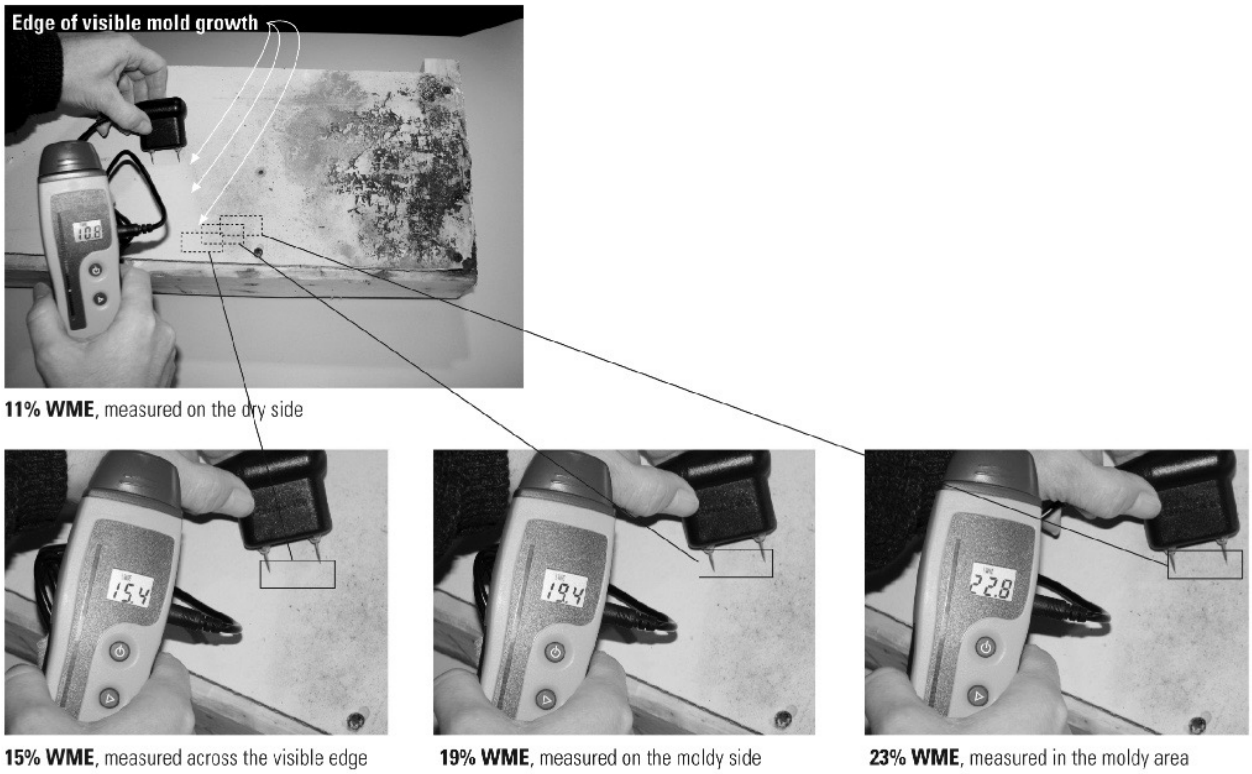

Figure 5 Gypsum board moisture content often varies widely across short distances. Consequently, it is important to note the exact locations from which measurements are taken. Also, moisture readings between instruments from different manufacturers seldom correlate. For consistent interpretation of mold and moisture risk, record the instrument make and model number and which of its several moisture scales was used to take the readings.

that allow reading with a wood-based meter. Even in humid climates, normal WME readings for gypsum board and acoustic ceiling tile are rarely above 12% WME. Therefore, as with other wood-based products, if the moisture content of interior gypsum board or acoustic tile is above 15% WME, it is an indication that at least the surface of the material has come to equilibrium with a very high RH (above 75%). Therefore, something about the building's design, construction, or operation is definitely above normal levels. So a WME reading at or above 15% can be recognized as a warning of future problems if that moisture level persists over time (see Figure 5).

Early-Warning Test 3: Persistent Moisture Content Above 90% ERH in Concrete or Masonry that is Either Coated with or Is in Contact with Organic Materials, Adhesives, or Coatings

To develop its full strength, concrete requires a great deal of water. Although normal and expected, excessive moisture must be allowed to dry out before moisture-sensitive materials are installed over concrete or masonry after construction.

Adequate drying can take weeks or months, depending on the mix, thickness, and environmental conditions (Hedenblad 1997). While the material itself resists microbiological growth, it is rarely uncoated and is often in direct contact with moisture-sensitive materials such as gypsum wall board, carpet, and tile adhesives and paint. Excessive moisture in the concrete (and masonry) will migrate to organic material, perhaps raising its surface water activity to levels that support microbial growth. Consequently, avoiding microbial growth requires that concrete and masonry be dry enough to limit moisture transfer to nearby materials and coatings.

Each manufacturer of coatings and adhesives has different recommendations (or indeed warranty requirements) for dryness of concrete and masonry to avoid excessive moisture transfer that could damage the product or interfere with adhesion, coating cure, or service life. Manufacturers of gypsum board are less specific. But it seems prudent to assume that if concrete is too wet to accept a coating or an adhesive, it is also too wet to be in contact with untreated paper-faced gypsum board.

This task group notes that, given the widespread use of paper-faced gypsum board in all parts of the world, plus the fact that it is often in contact with concrete and masonry, published research concerning acceptable and inspectable levels of moisture in concrete and masonry is missing from the literature and would be useful to the public and to building professionals.

Three methods are commonly used to assess the moisture levels of concrete and masonry. Each of these methods is effective for specific purposes, and each method uses a different system of units to define the condition of concrete that is dry enough to avoid significant risk.

Equilibrium RH test.
Threshold of concern: 90% ERH or above

This test, illustrated in Figure 6, is often the preferred choice for coating and flooring manufacturers. The fact that it is not limited to horizontal surfaces provides a strong advantage over the moisture vapor emission rate (MVER) test (discussed below). Also, this test measures moisture content, whereas the MVER test measures emission rate. But the fact that this test requires both 72 hours and drilling holes in the substrate often rules it out for use on floors and walls that cannot or should not be drilled.

One advantage of this test is that it provides conclusive measurements of moisture content supported by robust manufacturer infrastructure and procedures defined by ANSI/ASTM F2170, *Standard Test Method for Determining Relative Humidity in Concrete Floor Slabs Using in situ Probes* (ASTM 2011). Also, the test can be used for any thickness of concrete or masonry at any vertical, inclined, or horizontal orientation.

The limitations of this test are that it requires drilling holes in the concrete or masonry (three holes for the first 1000 ft^2 [100 m^2] of concrete surface, thereafter one hole per additional 1000 ft^2 [100 m^2]) and requires a full 72 h at the service temperature to reach relevant hygrothermal equilibrium. Additionally, the cost of sensors is significant, and each has limited life. Measurements that are fully compliant with ASTM F2170 (2011) also require sensors to be calibrated before each test. Further, the composition of concrete is not uniform. Often, compounds that

Figure 6 Equilibrium RH test to measure moisture content in concrete and masonry block. The ASTM F2170 (ASTM 2011) moisture content test is generally considered conclusive. One measurement is taken at the center of every 1000 ft^2 (100 m^2) of concrete surface. Each test location requires drilling a hole, cleaning it out, and inserting and sealing the RH sensor into the hole. Then you must allow 72 hours for the concrete around the hole, the air inside the hole, and the sensor body to come into hygrothermal equilibrium.

act as desiccants are part of the mix, which can greatly affect the RH readings in drilled holes. Also, if vapor barrier coatings such as curing coatings are applied to the concrete or masonry, the fact that moisture content is elevated may present no risk to nearby organic materials, adhesives, or coatings.

Documents and logic that support this suggested threshold of concern are that each coating and flooring manufacturer has specified limits for moisture content of concrete before installation (MFMA 2011). Some require as low as 75% ERH, and others tolerate ERHs of 85% or even 95% for specialized coatings designed to be vapor barriers (Kanare 2005). But our purpose in suggesting the limit of 90% is to provide a metric that allows for the fact that complete hydration (curing) requires and internal RH of 85% and that later in service only very rare circumstances call for a long-term ERH of 90% or above.

Capacitance-based concrete moisture meter. Threshold of concern: 3% or above

Measurements taken with these instruments are most useful for a quick scan to locate areas of significant moisture differences and as early warnings of extreme moisture. This technique, illustrated by Figures 7 and 8, is also referred to in the literature as *impedance* measurement.

The advantages of this method are that it provides instant readings and is low cost, and it is accurate enough for prompting concern and action to dry the material before coating or applying adhesives and before attaching vulnerable materials.

Figure 7 Capacitance instrument to estimate moisture content in concrete and masonry block. Although not considered conclusive, capacitance moisture meters are often used to approximate moisture content. The technique does not require drilling holes or a 72 h waiting period. It can be used to take many measurements quickly, allowing construction of a visual moisture map, as shown in Figure 8.

Figure 8 A moisture map provides visual documentation of locations and the extent of excessive moisture. Using a capacitance-based moisture meter, sticky notes, and a marker, an investigator can document the extent and locations of excessive moisture in a display of “moisture geography” that helps managers locate and eliminate a problem at its source.

The limitation of this method is that accuracy can vary depending on the conductivity of the aggregate and the operators' hand pressure. A single manufacturer makes the most widely used instrument, and two other manufacturers use different and widely varying scales for moisture content. Readings for the same moisture content differ widely between meters from different manufacturers and can even vary between different models from the same manufacturer.

As reported by Lee (2016), the 3% reading on the meters used most frequently in the United States is by no means a signal that the concrete is dry enough to allow installation. It serves instead as a useful warning signal that in one specific location the material is probably too wet to allow installation of moisture sensitive coatings, directly attached gypsum board, or water-based adhesives.

Moisture vapor emission rate (MVER). Threshold of concern: 3 lb/1000 ft^2 [100 m^2]/24 h or above

This is a well-known test that is often the basis of warranties for flooring, adhesives, and coatings. In the past, when warranty issues were in question, this test (or the ERH test) was relied upon to provide the most credible results. This test is supported by robust manufacturer and service-company infrastructure and by procedures defined by ASTM F1869, *Standard Test Method for Measuring Moisture Vapor Emission Rate of Concrete Subfloor Using Anhydrous Calcium Chloride* (ASTM 2016).

One advantage of this method is that it is a direct measurement of the rate of water vapor migration out of concrete, which is the most relevant factor for assessing the relative risk of mold growth in nearby materials or coatings. It is also relatively low in cost. It is a simple procedure that has been used for decades to ensure the level of moisture is safe for installation of flooring adhesives and finish flooring. Finally, it does not require drilling holes or chipping out test samples from the concrete surface.

The limitations of this method are that it requires three test kits for the first 1000 ft^2 (100 m^2) of surface plus one test kit for every additional 1000 ft^2 (100 m^2). Kits are not reusable. It also requires a full 72 hours at service temperature for reliable results. As a practical matter, the test can only be performed on horizontal surfaces. Results, while generally consistent, are subject to technician errors in installation or in the before-after weight measurements and in the arithmetic calculations that follow these time-weight change measurements.

Documents and logic that support this suggested threshold of concern are that each coating, adhesive, and flooring manufacturer sets limits for moisture content of concrete or masonry. In the absence of more specific limits, we can look to their industry associations and a recent survey of manufacturers' specified limits for a useful default high limit.

The suggested threshold of concern of 3 lb/1000 ft^2 [100 m^2]/24 h comes from the Resilient Floor Covering Institute as referenced in Engineering Bulletin 119 (Kanare 2005) published by the Portland Cement Association. This publication, often referenced in specifications within the flooring industry, suggests that at emission rates at 3 lb/1000 ft^2 [100 m^2]/24 h or below, most tile adhesives and most flooring materials will tolerate moisture absorption without damage.

Early-Warning Test 4: Persistent Indoor Air Humidity above a DPT of 60°F (15°C) for Buildings that are Mechanically Cooled or Above a DPT of 45°F (7°C) for Heated Buildings in Moderately Cold and Mixed Climates (in Climate Zones 4 and 5)

Mechanically Cooled Buildings

Buildings cooled by natural ventilation alone have very low HVAC-dependent risk of microbial growth. In contrast, mechanical cooling creates higher risks, because it creates cold surfaces. Cold surfaces increase risk of persistent dampness, because they encourage absorption of moisture from the air while at the same time impeding the release of that moisture back into the air. Further, the greater the mass of water vapor in the air, the greater the risk of absorption and persistent dampness when surfaces become cool. The indoor-air DPT is a reliable measurement of the mass of water vapor available for absorption and therefore potentially available to support microbial growth.

Consequently, designers, builders, and operators need to be aware that although cooling systems do remove moisture from the air, they also create a significant risk of excessive accumulation of moisture on cold surfaces, both in the building and inside the cooling system itself. Designers and building owners may benefit from a description of what is meant by *normal* and *abnormally high* indoor DPTs and the logic for selecting the recommended values.

Distinguishing between Normal and Abnormally High Indoor DPTs

Typical HVAC design practice sets a target indoor condition at or near a temperature of 75°F (24°C) and an RH of 50%. That means that most designers' intended indoor DPT is at or near 55°F (12.8°C). While it may often be the case that cooling systems fail to maintain that level of humidity as a firm upper limit, it is rarely the case that an owner or designer intends the indoor RH to be above 60% as the basis of design. Said another way, if the DPT inside the building is above 60°F (15°C), it is an indication that something about the design, construction, or operation of the cooling system is not normal and can therefore serve as a warning of excessive indoor moisture and possible future microbial growth.

Using DPT rather than RH as the Primary Dampness Risk Indicator

Using a 60°F (15°C) DPT as the threshold of concern is much more reliable than using 60% RH as a risk indicator. Condensation is the principal risk, followed by the risk of moisture absorption during unoccupied hours. Relative humidity measured at the thermostat does not alert the building manager to these risks.

Figure 9 shows an example that illustrates why monitoring the DPT provides a more reliable risk indicator than monitoring the RH. Both air and surface temperatures throughout the complex spaces of any building vary widely above and below the thermostat set-point temperature. Using RH in the air as a metric of concern is highly misleading. Focusing on an RH limit leads to needless concern when the temperature of the air is cool, as in the case of supply-air temperature during cooling operation. An RH focus also allows an unwarranted sense of safety when the air temperature is above normal, such as in a school during summer vacation, when the indoor temperature may be quite high.

Documents and Logic that Support a 60°F (15°C) DPT as a Threshold of Concern

A more detailed discussion of the logic for setting either a 55°F or a 60°F (a 12.8°C or a 15°C) DPT as a prudent limit for normal indoor humidity (and as a reasonable compromise with respect to energy use to maintain building dryness) can be found in *Humidity Control Design Guide for Commercial and Institutional Buildings* (Harriman 2001a), *The ASHRAE Guide for Buildings in Hot and Humid Climates* (Harriman and Lstiburek 2009c), Chapter 64 of *ASHRAE Handbook—HVAC Applications* (2019c), and *Moisture Control Guidance for Building Design, Construction and Maintenance* (EPA 2013).

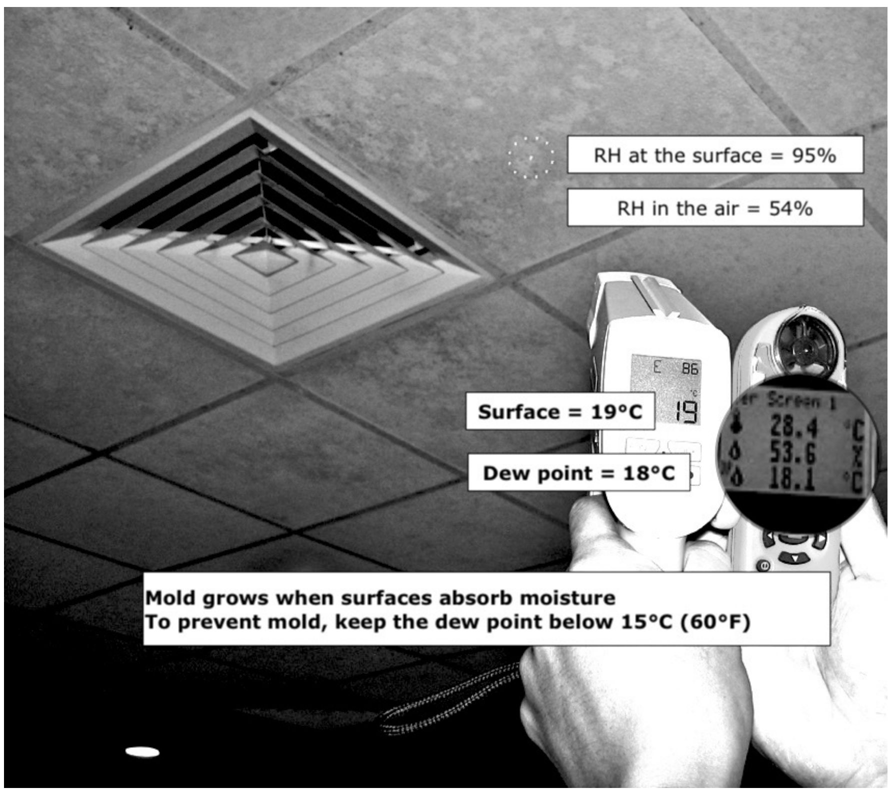

Figure 9 Moisture absorption and mold growth often result from a high indoor DPT combined with periodic cooling of surfaces. The RH in the air is rarely the same as the RH at the surface. This is particularly true near cold supply-air diffusers. In this building, the indoor DPT stayed high over months whenever air-conditioning systems were turned off. The persistent high DPT allowed excessive moisture absorption and mold growth on the surfaces of acoustic ceiling tiles near supply-air diffusers. Keeping the indoor DPT below 60°F (15°C) at all times greatly reduces the amount of indoor humidity available to support mold growth. This maximum is a design requirement for systems in mechanically cooled buildings (ASHRAE 2019a).

Beyond the issues of building dampness and microbial growth, there is also the matter of thermal comfort for occupants. ANSI/ASHRAE Standard 55, *Thermal Environmental Conditions for Human Occupancy* (ASHRAE 2017a), warns that holding other factors equal, it is useful to maintain the DPT below 62°F (16°C) if the goal is to satisfy the thermal comfort for 80% of occupants. The "center" of the summertime humidity comfort range (that which is likely to satisfy more than 80% of occupants) is a DPT of 45°F (7°C). So, for most HVAC designs, while excursions above a 60°F (15°C) DPT in a mechanically cooled building may happen, these are neither normal nor intended to be normal by either owners or HVAC designers. Additionally, a high DPT represents a direct measurement of the degree of risk of moisture absorption or condensation on cool surfaces. Therefore, a persistent DPT above 60°F (15°C) is a useful indicator that there is an elevated risk of future microbial growth in hidden spaces in buildings that are mechanically cooled.

Heated Buildings in Moderately Cold and Mixed Climates

Excessive indoor humidity is a well-known risk factor for buildings in cold and mixed climates. Much has been published in North America and Northern Europe about the problems, which have ranged in severity from the annoying window condensation shown in Figure 10 to mold growth to exterior wall failures to corrosion of structural fasteners that has led to death (ASHRAE 2017c; Heselmans and Vermeij 2013; Mecklenburg 2007; O'Brien and Patel 2011; Trechsel and Bomberg 2009).

Cold-climate dampness and health issues in housing in North America and Europe have also been widely reported. For housing, the problem of condensation and its health implications are complicated by issues of management, overcrowding, finance, public policy, and energy. These issues have been the subject of extensive multinational research by the International Energy Agency over decades (Hens 2002).

This report proposes an indoor-air DPT of 45°F (7°C) as a prudent upper limit for existing, conventionally constructed buildings being heated in moderately cold or mixed climates (international climate zones 4 and 5).

At the same time, it must be admitted that the optimal upper limit depends on many factors that are difficult to predict. To be clear, at present there is no authority that backs up the proposed 45°F (7°C) DPT as a threshold of concern beyond the anecdotal experience of a limited number of building science professionals. To date, experts from cold climates who are members of ASHRAE Technical Committees (TCs) 1.12, Moisture Management in Buildings, and 4.4, Building Enclosures, are uncomfortable with any standard or regulation establishing a single maximum indoor humidity limit for all types of buildings in all climates. The appropriate maximum is an especially difficult question in the coldest climates (international climate zones 6 through 8). So to allow readers to set a wise limit for their projects and buildings, it will be helpful to elaborate the logic for the upper limit proposed by this report, which applies to the mixed and moderately cold climates of climate zones 4 and 5.

The goal of limiting the indoor DPT in winter is to limit the amount of condensation that inevitably occurs inside exterior walls during winter months. Some layers of exterior walls in cold climates will become wetted during the winter, but they generally dry out during the summer. To reduce health risks by avoiding winter condensation, an appropriate strategy is to set an indoor humidity limit that avoids extreme wetting (i.e., a limit that minimizes condensation and absorption of moisture to an amount that the building can tolerate without growing mold and bacteria during winter and swing seasons and that will dry out during warmer weather).

A building's moisture tolerance depends on its materials and the exact configuration of all the layers, gaps, cracks, and holes in its enclosure (which sometimes differs substantially from the designers' intentions). Additional factors include the average wind pressure and velocity across the outdoor surfaces of the building and the outdoor and indoor air and surface temperatures. Therefore, especially for buildings in the coldest climates, selection of a single number as a prudent upper limit for DPT in winter is, to say the least, optimistic. A prudent limit will be specific to each building enclosure as well as the microclimate variations at the site in question. ASHRAE provides guidance for analyzing the moisture tolerance of any specific enclosure assembly in ANSI/ASHRAE Standard 160 (ASHRAE 2016).

But for less severe climates, in the absence of more certain knowledge of all the relevant variables, a 45°F (7°C) DPT seems a plausible default upper limit if that level is intended by the owner or designer to be *persistent* (as defined at the beginning of this report).

Factors that could adjust that level up or down include enclosure airtightness and the lowest R-value of any component or assembly that spans the entire exterior wall from inside surface to outdoor surface. If the enclosure is airtight as defined by ASHRAE/IES Standard 90.1 (ASHRAE 2019b)—leaks less than 0.4 cfm/ft^2 (2.03 L/s·m^2) of air barrier surface at 75 Pa—then the building may resist condensation at levels higher than the suggested 45°F (7°C) indoor-air DPT, provided that any thermal bridging is also avoided by the design and its installation. If the building leaks more air, or if it has thermal bridges, then a lower indoor DPT would be more appropriate.

As an example, consider the condensation evident below the museum window shown in Figure 10. In this museum, located in climate zone 6, the indoor air was continually humidified to 50% RH at 70°F (21°C). Condensation was a constant issue over many weeks in this cold climate because of the high DPT versus the low R-value of the glazing and the even lower R-value of the window frame. Such problems have been common in museums even in more moderate climates, such as Washington, DC (Renaud and Rose 2019).

For further guidance, members of ASHRAE TCs 1.12 and 4.4 and this multidisciplinary task group encourage readers to consult ASHRAE Standard 160 (ASHRAE 2016) and the many building enclosure modeling programs available to engineers and architects.

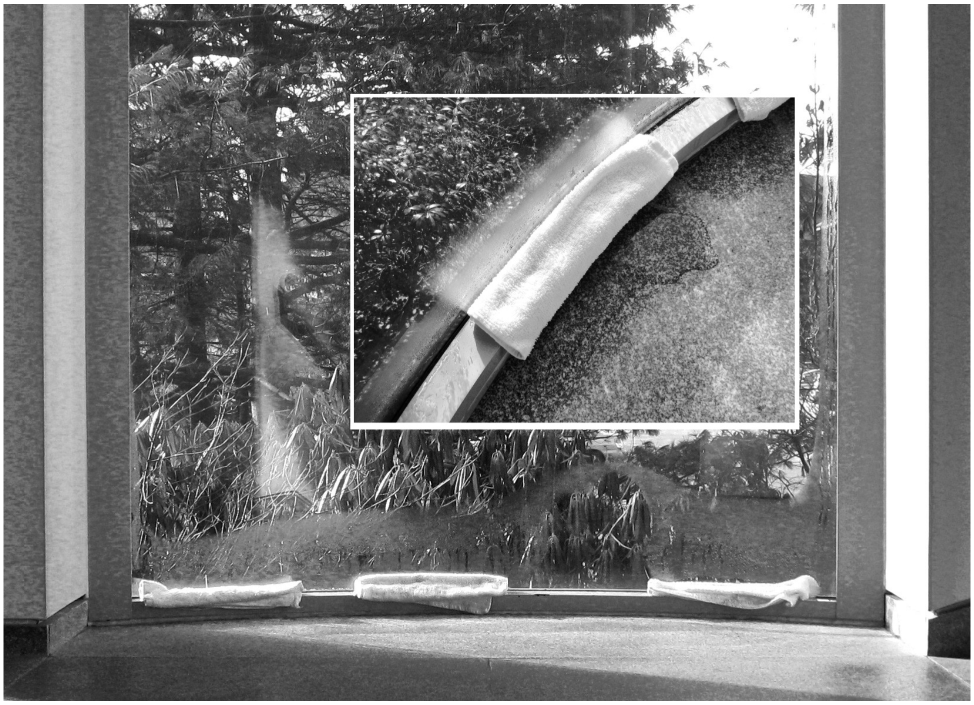

Figure 10 Museum window in a cold climate (climate zone 6). The prudent humidity limit to avoid condensation depends on airtightness and the R-values of all the components, including window frames. In this building, the 50°F (10°C) DPT was too high to avoid persistent condensation. *(Courtesy Mason-Grant Consulting)*

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