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Minimum Conditions for Visible Mold Growth

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Considerable confusion and misunderstanding exists over the conditions required for visible mold growth at a surface in buildings. That is evident in papers and articles authored by engineers and other scientists, including various ASHRAE, ASTM and Canada Mortgage Housing Corporation publications. One of the major problems is that many HVAC engineers, building scientists, practitioners and others believe there exists a single critical value of the relative humidity (RH) of the indoor or ambient air well away from surfaces, below which mold will not grow on surfaces. However, that is not the case. The purpose of this article is to clarify the situation regarding what conditions are required for mold growth on building materials.

Mold growth at a surface depends on the moisture available at the surface, typically referred to as the "water activity."* The water activity denotes the amount of free (rather than bound) water available for mold growth at the nutrient surface. It depends on the water available within the surface as well as within the surrounding air (but only indirectly), and differs for different materials and different fungi. It is not the same as the moisture content of the surface material.

All microorganisms have a level of water activity they prefer to grow within, including lower limits for growth. Growth depends on the surface relative humidity (the RH of the air directly in contact with the surface rather than in the ambient air), the surface temperature and the so-called "time-of-wetness," or "TOW." The TOW represents the fraction of time (ranging between 0 and 1) during which the relative humidity in the immediate vicinity (or microenvironment) of the fungus is above a threshold level for growth.[2]

The temperature of a surface is often quite different from that in the ambient air, so the relative humidity of the air right at the surface is then distinctly different from the value in the indoor air. For example, during the winter in cold climates, the inner surface of an exterior wall can be notably colder than the ambient indoor air, especially at thermal bridges, such that the relative humidity of air right at the surface is considerably higher than that of the ambient air. Adan[2] has described a number of reasons or effects why the ambient climate and the local surface climate can be different (some of which are not at all obvious or commonly understood), including that ambient and local surface relative humidities can be as much as 50% different.

* Water activity can be defined as the relative humidity at equilibrium (ERH) divided by 100; it varies from 0 to 1.[1]

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Harriman[3] has provided excellent numerical examples that illustrate those differences. Notably, the important relative humidity is that of the air in direct contact with a particular surface at its surface temperature and *not* of the ambient air away from the surface in question. That is an important distinction regarding mold growth that is often misunderstood.

Minimum Conditions for Mold Growth at a Surface

The most widely recognized value for the minimum conditions was published in a document by the International Energy Agency (IEA) in 1990 based on many previous years of experience and testing, including extensive research of experimental data.[4] It stated, "In fact, on paints, wallpaper, wood, gypsum, dust, mould germination and growth is, in steady state RH and temperature conditions, rarely observed under 85%." They also stated, "The lower the RH (from 99% to 80%), the longer the steady state time period before mould becomes visibly present."

The key IEA finding regarding mold growth was: "the threshold RH for mold germination on materials in buildings is 80% on a mean monthly basis" (they actually specified a water activity of 0.8).

They also noted: "In fact, we know from mould research that, with very high RH, mould may germinate on a substrate after a fairly short time. In other words, we have to introduce a time scale in the RH judgement." "Basically, if the mean inside RH is over a week rather than a month, then the minimum RH increases to 89%, whereas if the mean inside RH is over one day then the minimum RH is 100%."

The conditions for growth included a surface RH condition based on the surface temperature, as well as a duration of that RH condition (guidance on duration was generally ignored prior to that time). Thus, time is a key factor. Moreover, the threshold value was presented as independent of temperature, fungal species and type of material. Nowhere in the guideline was there reference to an RH value in the ambient air. Nielsen[5] noted that measurement of indoor RH, rather than the RH at a surface, is a poor indicator of mold problems.

Much has been learned in the intervening 26 years that should be considered in determining if the 1990 criteria are appropriate today. The consensus, based on more recent experimental data from numerous studies of construction materials, appears to be that the minimum RH for mold growth (germination) on building construction materials is still about 80%.

Confusion Over Conditions Required for Visible Mold Growth

Confusion between ambient and surface relative humidity may exist because most laboratory studies expose samples to constant RH levels in sealed chambers where the humidity in the air is essentially the same as that at the surface of the material being tested. Some test authors have even used the term "ambient RH," as well as "RH of microclimate" (i.e., at the surface) to describe test results when materials are exposed to constant RH conditions in controlled humidity chambers,[6] which may have added to the confusion. Those steady-state conditions in laboratory tests are not the same as in real buildings where conditions are often changing.

Part of the confusion about the minimum RH requirement appears to exist because some molds will grow on foods at surface RH levels well below 80%.[7] Much of the early research on mold was related to growth on foods, and early guidance for construction materials may have been influenced by that. Some further confusion may exist because leather goods in homes (e.g., leather shoes or belts in closets) will experience mold growth at RH levels well below 80%, whereas construction materials will not.

Sometimes confusion arises about the minimum RH requirement for mold growth because some publications suggest a value less than 80% is required as a safety factor to prevent mold growth. For example, an ASTM publication stated that "to prevent mold growth a 75% surface RH at room temperature appears to be a reasonable daily-average not to exceed value."[8]

One has to wonder if the authors meant a monthly average rather than a daily average, given the growth requirement of 100% RH for a daily average in the IEA criteria. Yet in that same ASTM reference, it is stated that growth can occur when the humidity level in the air immediately adjacent to the surface exceeds roughly 80%, and growth occurs rapidly when the surface RH values exceed 90%. The Canada Mortgage Housing Corporation published a much more stringent requirement of always keeping surface relative humidity below 65% to prevent mold growth.[9]

The IEA criteria was specifically stated only for mold germination rather than visible mold growth. Unfortunately, that important distinction frequently has not been made or understood. Oftentimes, the IEA criteria are presented as though they refer to visible mold growth.

In addition, modeling and test results for the minimum required RH for *mold growth* are often presented without clearly stating whether the results are for germination or for visible growth. For example, a publication by Ojanen et al.[10] states that the minimum RH is 80% for wood products, without clearly noting that is for mold germination rather than visible mold, which is what is seen in the field. The IEA did not set criteria for visible mold growth, yet it is visible mold growth that is of most concern, especially from a health concern point of view. It is tacitly assumed that mold germination is microscopic and hence not visible. So an important question is what is the minimum RH requirement for visible mold growth rather than for mold germination?

The minimum RH needed for what is often termed "mold growth" is different for spore germination, growth and reproduction (spore production). A higher relative humidity is required for spore production compared to that for mold growth, and a higher RH is required for growth compared to spore germination.[2,11] So what are the differences?

Growth can be considered detectable by microscopy or visually, with visual growth requiring higher RH values than for microscopic growth. Hukka and Viitanen[1] described the severity of mold growth on wood-based materials by the following Mold Growth index:

- 0 to 1–no growth
- 1–some growth detected only with microscopy
- 2–moderate growths detected with microscopy (coverage more than 10%)
- 3–some growth detected visually
- 4–visually detected coverage more than 10%
- 5–visually detected coverage more than 50%
- 6–visually detected coverage 100%

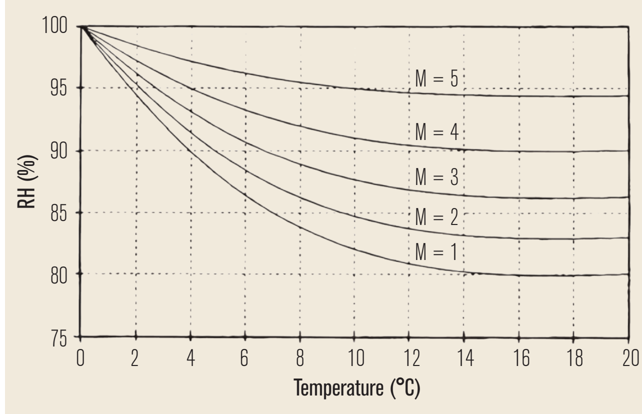
The Mold Growth index related to surface temperature and humidity is shown in *Figure 1*.

Two points regarding the graph need emphasizing. First, while microscopic growth may start at around 80%, it takes a much greater surface RH to get visible growth. That is extremely important, as it is visible growth that is seen in the field! Mold growth once initiated does not necessarily lead to visually detectable amounts of mold if the RH levels are not high enough.

Based on the Mold Index shown for wood-based materials, visible growth requires humidity levels at least 5% higher than for germination, typically above 85%. That is in complete agreement with the IEA finding that mold growth is rarely observed (i.e., visibly) at RH values of less than 85%.

The second point is that surface temperature has a relatively minor, if any, effect on the critical RH needed for mold growth at different Mold Index values at normal conditioned indoor temperatures, and especially at warm room temperatures. The curves of critical RH shown in *Figure 1* are essentially flat with temperature differences when the temperatures are above about 59°F (15°C) all the way to about 104°F (40°C) (roughly the upper temperature limit above which most molds will not grow). As temperatures drop below 59°F (15°C), the required surface RH for mold growth goes up. It thus seems reasonable that the IEA researchers decided to not make temperature a part of the threshold criteria.

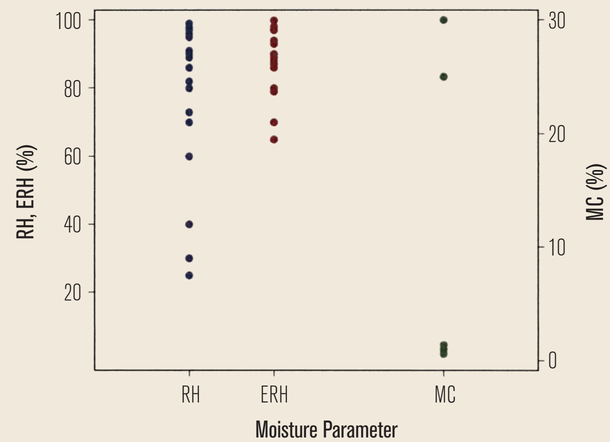
FIGURE 1 Temperature-dependent critical relative humidity needed for mold growth at different values of the mold index.



Earlier it was stated that it is visible mold growth rather than germination that is of most concern from a health point of view. Significant quantities of mycotoxins that could be responsible for adverse health effects are not produced unless surface RH values approach 95%.[5] In almost all situations, mold growth at such elevated RH levels is clearly visible. Therefore, emphasis on knowing the critical conditions for visible growth rather than microscopic germination seems reasonable in the context of possible health concerns. Furthermore, Nielsen noted that species of *Aspergillus* and *Penicillium* prevalent in the indoor environment when indoor spore levels are elevated, compared to outdoor levels, produce only relatively low concentrations of mycotoxins.

Three key moisture parameters, namely relative humidity of the ambient air (RH), the equilibrium relative humidity at a surface (ERH) based on the surface temperature, and the moisture content (MC) of the material, along with their measurement, have been described in detail by Dedesko and Siegel.[12] They performed a literature review of mold growth on gypsum drywall in laboratory and field studies with a focus on those that cited a critical moisture value, below which fungal growth will not occur (28 studies in all).

FIGURE 2 Critical moisture values to prevent fungal growth on gypsum drywall from the literature.



They found that the most frequently measured moisture parameter in the studies was RH. Forty-three, 29, and 5 critical values were recorded for RH, ERH, and MC, respectively, with several studies defining more than one critical value based on different experimental conditions (e.g., temperature). They also found that of the three moisture parameters, the surface moisture (ERH) had the least spread in values of critical moisture parameters to prevent mold growth on gypsum wallboard, as shown in *Figure 2*.

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Clearly, the air RH was not a reliable measure of the critical level to avoid mold growth. Furthermore, they explained that the spread in the various values was likely due mainly to measurement differences. Of the 29 critical ERH values almost all were greater than about 80% to 85%. The authors stated that defining a single critical moisture value to prevent fungal growth on gypsum drywall is still difficult because fungal growth is variable depending on a number of factors aside from moisture, including fungal taxa, temperature, and substrate characteristics. Yet, Adan et al.,[2] have stated, "Pragmatically, there is consensus in the scientific community that surfaces can be kept free from mold growth if the relative humidity of the adjacent air is maintained below 80%."

So based on the above findings of Dedesko and Siegel,[12] Adan, et al.,[2] and others, it appears that it is not unreasonable to select a surface ERH value of about 80% to 85% as a critical value below which most molds will not grow—at least until better evidence is available. How that critical value will be used by HVAC engineers and other practitioners will be addressed in a later section.

Time-of-Wetness

The value of the minimum surface RH required for mold growth was noted in the IEA criteria to depend on the amount of time a surface is above that threshold level. It has been well recognized that mold growth takes time, and sometimes a lot. In real buildings, surfaces are constantly wetting and drying such that there are times when conditions for mold growth may exist and times when they do not.

The time-of-wetness actually represents the fraction of time (ranging between 0 and 1) during which the relative humidity in the immediate vicinity (or microenvironment) of the fungus is above a threshold level for growth, for which usually the 80% RH value (for germination) is taken. An example to illustrate the time-of-wetness is shown in *Figure 3* (Fig. 2.7 of Adan et al.[2]).

To illustrate its effect the authors show how surface condensation, such as on porous gypsum, may adversely affect the time-of-wetness. They assumed the average indoor air RH was below 60% along with 10 minutes of surface condensation, such as with showering. That led to a surface RH above an 80% threshold for more than six hours. As a result of wetting the thin, porous surface layer, the time-of-wetness increased from less than 0.01 to 0.33. Therefore, condensation can play a major role in mold growth as a result of dramatically increasing the time-of-wetness. Clearly, time-of-wetness is an important factor in the growth of mold on surfaces.

Measurement of Surface Relative Humidity

Directly measuring the surface equilibrium relative humidity in the field is time consuming and impractical. A faster and relatively easy method to determine the surface RH *in situ* is to measure the temperature and RH of the ambient air with a handheld thermo-hygrometer. Then, measure the surface temperature with an IR thermometer. Using a psychrometric chart, draw a horizontal line from the indoor air temperature and RH condition to the surface temperature and read off the surface RH. Then one can check to see if the surface RH is below 85% to determine if there is a risk of mold growth. This process is described in more detail in Harriman.[3] The downside of trying to use this approach is that surface conditions can vary widely, such as on walls, so using it to check all wall surfaces may be impractical.

Dew Point as an Indicator of Mold Growth Risk

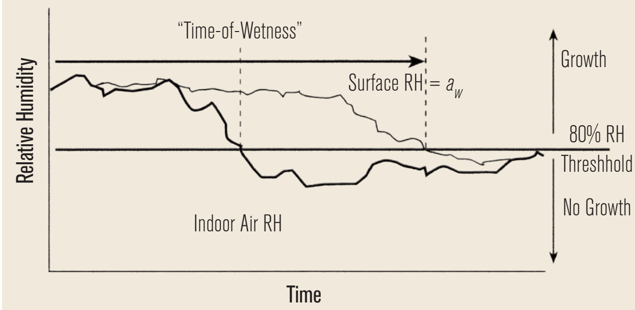
Harriman[3] has pointed out that rather than measuring surface RH conditions, it may be more practical to check the dew-point temperature of the indoor air by measuring the indoor air temperature and RH and determining the corresponding dew-point conditions from a psychrometric chart or available software program. (Drawing a horizontal line on the chart from the indoor air condition to the saturation line gives the dew-point [saturation] temperature.)

Then determine if the dew-point condition is below a critical dew point. The critical dew point is the maximum condition that has been selected below which most moisture problems will be avoided, including mold growth. Specific values for various building and HVAC system types as well as climatic conditions will be discussed in the next section.

Mold Growth Conditions in ASHRAE Publications

ANSI/ASHRAE Standard 160-2009[13] provides criteria for moisture control design analysis in buildings and for

FIGURE 3 Schematic presentation of the time-of-wetness.



acceptable performance. Section 6 presents moisture performance evaluation criteria, including conditions necessary to minimize mold growth. The required surface RH conditions are essentially those IEA guidelines described earlier with added temperature criteria.

Recent field investigations compared the mold growth in long-term-weathered building assemblies with hygrothermal mold growth modeling predictions based on the IEA guidelines. After taking apart several walls in different climates, it became apparent that the IEA guidance of 1990 is overly conservative for some materials, because it did not recognize the difference in biological growth on building materials that have different nutrient value and different water-retention characteristics.

Consequently, in 2016 ASHRAE Standard 160 is being amended[14] to recommend modeling based on four classes of building materials with different upper limits for very sensitive materials such as pine sapwood versus sensitive materials such as paper-coated products versus medium-resistant materials such as concrete versus resistant materials.[10]

The amendment also takes into account the difference between starting out wet versus starting out dry when modeling mold growth over the 30-day period. That is in keeping with reducing the health-related risk of visible mold growth rather than mold germination noted in the IEA guidelines. Mold that germinates does not necessarily lead to visible growth.

The *2015 ASHRAE Handbook—HVAC Applications* has a new Chapter 62, "Moisture Management in Buildings." It includes details regarding water activity and its measurement, as well as measuring the moisture content of a building material such as wood as an indicator of relative dampness. Wood in equilibrium (i.e., not changing its condition) at 85% surface RH and temperatures typical of indoor building conditions has a moisture content of about 18%.[15] Therefore, if the measured wood moisture content is less than about 18%, there is minimal risk of visible mold growth.

ASHRAE Multidisciplinary Task Group (MTG) Building Dampness has prepared a draft document for external comment[16] that has recommended that persistent moisture content above 15% wood moisture content equivalent (WME) in organic materials, coatings, and untreated paper-faced gypsum board provides early warning of possible future health-relevant dampness (increased probability of negative health effects for occupants).

Chapter 62 of the *2015 ASHRAE Handbook—HVAC Applications* covers both residential and commercial buildings, including HVAC systems. It has a useful section for mechanically cooled buildings in hot or humid climates. The chapter advocates keeping the dew point of indoor air below 55°F (13°C) to avoid mold growth. However, the chapter does not discuss buildings cooled by natural ventilation instead of mechanical systems, nor does it address the question of an upper dew-point limit to avoid condensation and mold in buildings when they are heated during cold weather.

Although it is not yet a guideline, a preliminary report to ASHRAE's Technical Activities Committee from the MTG suggests that a 60°F (16°C) dew-point temperature can be used as a "prudent upper limit" that describes the normal behavior of well-designed and maintained mechanically cooled buildings in any climate during the cooling season. The report is less certain about an upper limit during the heating season, apparently because of the tremendous variations between the duration of temperature differences in different climates, and the worldwide variations in building envelope construction. For buildings such as housing without mechanical cooling, no upper dew-point limit has been determined at this time.

Finally, a non-ASHRAE reference document, the U.S. EPA's "Moisture Control Guidance for Building Design, Construction and Maintenance,"[17] also suggests the 55°F (13°C) dew point as a target for mechanically cooled buildings during humid weather, and an upper limit of a 35°F (1.7°C) dew point when outdoor temperatures fall below freezing.

The advantage with many commercial and other buildings with mechanical cooling systems is their controls can set a maximum dew-point condition. On the other hand, residential cooling systems typically do not have such a control capability. Furthermore, for residences without mechanical cooling, there is no opportunity to set a maximum dew-point temperature to help avoid mold growth. In those residential housing cases without dew-point control, one could still check indoor dew-point conditions, along with surface temperatures, to check surface RH values and maintain them below the 85% surface RH threshold.

Conclusions

Whether or not mold will grow on a surface depends on the conditions right at the surface (the source of the food and water for a fungus), including the surface water activity or the relative humidity of the air at the surface at its temperature, along with the duration of wetting. In 1990 the International Energy Agency (IEA) set the minimum conditions for mold growth on the surfaces of building materials.

Notably, nowhere in the literature we reviewed did we find any author or evidence that disagreed with the original 1990 IEA criteria to any meaningful extent. Given that the 1990 IEA criteria was specifically for mold germination, it seems reasonable to conclude that a more appropriate criteria for building materials should be for visible mold growth rather than mold germination, which is not visible and may never be.

Based on the review performed for this article, the authors believe it is reasonable to conclude that for most sensitive indoor surfaces, the relative humidity of the air in contact with that surface must exceed a 30-day running average of 85% for mold growth to be visually apparent. That is provided that the surface did not start out wet at the beginning of any consecutive 30-day period.

Unfortunately, use of the term "mold growth" without distinction whether the growth is invisible germination or actual visible growth, especially by many researchers, has led to confusion whether one should use the 80% or the 85% critical value. The authors strongly recommend that in the future researchers and all others use either the terms "mold germination" or "visible mold growth," rather than just "mold growth." Furthermore, when assessing time of wetness, it would seem best to set the critical value as 85% for visible mold growth rather than the 80% value for germination.

One approach to determining if there is a risk of visible mold growth is to measure surface RH values and see if they are above that 85% minimum condition, although that may be impractical given the wide variance in interior surface temperatures that can exist in buildings.

A more practical and simpler approach is to check the dew-point temperature of the indoor air and compare it to a critical maximum dew-point value. Such values have only been suggested for mechanically cooled buildings in hot and humid climates and in other U.S. climates during the cooling season, along with for buildings with mechanical cooling that are heated during freezing weather. For buildings with mechanical cooling but during other heating conditions, as well as buildings such as housing without mechanical cooling, alternate maximum indoor dew-point temperatures to avoid risk of mold growth have not yet been determined.

Finally, while some engineers, scientists and practitioners have the impression there is a single critical level of the relative humidity of indoor (ambient) air below which there is no risk of mold growth, that is simply incorrect for almost all real-life conditions. Further, indoor air temperature is seldom, if ever, the same as surface temperatures, so the relative humidity of the indoor air is not the same as the all-important relative humidity of the air right at a surface. Consequently, efforts to minimize or eliminate mold growth through control of the indoor air relative humidity alone will likely not guarantee that result.

Keeping the dew point low will reduce risks, as will the recognition that when things get wet, they need to be dried out quickly. Moreover, it is believed by some that mold will grow if elevated surface or even indoor air RH is found to exist at any one point in time. That, too, is incorrect, as isolated spikes in RH will not necessarily result in mold growth. Mold growth takes time, and typically lots of it.

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