Title: Duration Required for Mold Growth Arising from Condensation Development on Interior Surfaces

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ABSTRACT

A strong legal precedence is driving the demand for understanding the cause, origin, and duration of mold growth within occupied buildings. Identifying a mold growth timeline resulting from overlooked condensation development can be challenging because it lacks a distinct free water release to trace back to. Mold growth that arises from condensation development is enabled by surfaces with adequate nutrient availability either sustaining a temperature below an elevated dew point, becoming over cooled, or a blend of both. Therefore a dependence exists on substrate, surface temperature, and humidity. A case-study and literary review was completed to better understand how these variables influenced the timeline required for microbial growth. Substrate locations that demonstrated vulnerability to condensation development include window frames, exterior walls, thermal breaks, thermal bridges, and air conditioning supply vents and their abutting surfaces. There were two apparent causes for decreasing interior temperature, AC cooling operation and the decrease in outdoor temperature during winter months. The likelihood of condensation development from these occurrences depended upon interior humidity levels. Case study examination revealed that negligent ventilation and/or dehumidification efforts, overcrowding, and outdoor air infiltration were popular causes for elevated indoor humidity. Theoretical and empirical data showed that the conditions which lead to condensation development and subsequent mold growth on interior surfaces require a duration of sustained elevated humidity on the order of weeks. *Cladosporium* was the most common fungal taxa identified in association with chronic condensation.

1.0 Introduction

Condensation and mold growth are patient adversaries in the built environment. The vast majority of building managers and homeowners possess a modest appreciation for when, where and why condensation occurs. The costs of condensation and mold growth damage represent unanticipated expenses to homeowners and building management companies. These damages can be linked to a sequence of events relating the moisture source and resulting microbial growth. Instances involving condensation development prolong this sequence because of the phase change required from the water.

In this paper the conditions for condensation and microbial growth were analyzed separately, correlations were identified between the two. Case studies were also analyzed and included in the conclusions made. They were limited to residences located in Florida's hot and humid climate, a favorable location for indoor condensation to form. The following discussion addresses the interrelationship between building materials, condensation and microbial growth.

2.0 Building Materials

Building materials serve as the substrate for condensation and microbial growth. The following terms describe building material properties that influence the occurrence of condensation and mold growth.

Thermal conductance characterizes a material's ability to transfer heat (Callister, Jr. 2007). The higher the thermal conductance, the greater the heat transfers across an area of material. The reciprocal of thermal conductance is thermal resistance. The thermal conductance and resistance of a building material are important considerations because the interior surface temperatures influence microbial growth and the development of condensation.

Vapor permeability quantifies the rate that water vapor passes through a given material (ASHRAE 2013). Kraft paper is an example of a material with high vapor permeability. Vapor permeability is often expressed in terms of permeance and perms, a unit that represents a material's permeability divided by its thickness. A vapor retarder is a material that has a permeance less than or equal to 1 perm (Trechsel 2001). In contrast, window glazing (glass) is vapor impermeable because water vapor cannot pass through it (0 perms). The amount of local water vapor near an interior surface influences both microbial growth and condensation development.

Moisture content is the mass (or weight) of moisture within a given volume of porous material (ASHRAE 2013). Many building components like drywall, concrete, and wood are porous and can therefore absorb moisture. However, a glass window is impermeable and contains no moisture because it is not porous. For porous materials there is a relationship between local water vapor, moisture content, and thermal conductivity. Thermal conductivity increases with moisture content; moisture content is influenced by the local water vapor pressure.

3.0 Condensation

Water vapor is present in the air around us, and is typically converted to a liquid by cooling. The energy required for phase change is formally described as latent heat, "heat required to change the state, as a solid or liquid, of a body without a rise of temperature" (Salisbury 1950). This conversion is familiar to us when we place a cold soda can on the Kitchen countertop and observe the accumulated condensate. Condensate also develops within air handling equipment as the AC system works to lower the indoor air temperature below its dew point in an effort to cool and dehumidify the space. Therefore, by either natural or mechanical means, condensation forms when a surface is at or below the surrounding air's dew point. This parameter is also referred to as the saturation temperature (Moran and Shapiro 2008). Therefore, a material's vulnerability to condensation is dependent upon dew point first, then surface temperature. A 40°F metal surface is vulnerable to condensation only when it is surrounded by air with a dew point ≤40°F. Unlike relative humidity (RH), the dew point expresses a direct correlation with the amount of water vapor in the air.

Among porous materials, conditions for condensation may exist without producing visible moisture because it is absorbed inside the material rather than appearing on the surface

(ASHRAE 2013). The occurrence of surface moisture is described as visible thin film condensation (VTFC). VTFC occurs on non-porous, vapor impermeable materials like glass, metal, and vinyl. The presence of some types of fungal growth i.e., *Cladosporium* has demonstrated a correlation with the presence of condensation within the built environment.

4.0 Microbial Growth

Fungal spores are ubiquitous in both natural and most built environments. The requirements for mold growth are moisture, availability of viable fungal spores, nutrients (e.g., simple or complex carbohydrates), appropriate temperature, and an aerobic environment. Among these requirements, moisture control is the most effective tool to mitigate and prevent mold growth (EPA 2010; Harriman and Lstiburek 2009; IICRC 2008). Moisture control of fungal growth means more than just moisture content; it requires an understanding of "water activity."

Water activity (a_w) is a precise parameter that describes the moisture requirements for mold. Its values range between 0.0 and 1.0. Unlike moisture content, water activity is material independent measurement. Non-porous, vapor impermeable materials (like metal or ceramic) can express a substrate water activity, yet contain no moisture. The water activity range for various fungi is broad. Some fungal species can grow with an $a_w < 0.65$ while many filamentous fungi require an $a_w > 0.90$ (Flannigan, et al. 2011).

5.0 Condensation and Microbial Growth

Condensate formation on a surface and microbial growth can be related to an extent because they depend upon similar scientific principles (e.g., heat and moisture transfer). Condensation can develop from a number of moisture sources and manifest within a limited variety of environmental conditions. Of all the exterior building surfaces, windows have frequently demonstrated a susceptibility to condensation. Let's examine the conditions in a home that favor condensate development.

5.1 Modeling and Interpreting Condensate Development

5.1.1 Moisture Sources and Management

Buildings are dynamic because they are in a constant state of change whether they are occupied or not. Air and water vapor find their way through buildings from people (occupant traffic, opening and closing windows and doors), mechanical systems (AC fan operation, exhaust fans, dryers), and building penetrations (leakage through cracks and gaps) that enable infiltration.

Common interior sources that raise moisture levels include occupants (perspiration and respiration), their activities (cooking and sanitation), and free water releases (plumbing leaks). The interior surfaces typically vulnerable to condensation development include AC components (leaky ductwork or casings, supply vents, condensate and refrigerant lines), the window assemblies or light fixtures in poorly vented bathrooms, kitchens, overcrowded rooms, and exterior walls, especially those with thermal bridges and thermal breaks. However, no two moisture sources and their scenarios are exactly the same. Each instance that leads to

condensation and microbial growth has its own conditions that create a means for interpreting duration, often extending those prescribed in this paper.
Despite the origin of the moisture sources, the AC system works to manage the sensible and latent heat loads during cooling operation. These factors underscore the importance of understanding the building's usage, history, and operation when trying to identify the cause for elevated humidity. In addition to the moisture source and dew point, surface temperature is the final critical element in residential condensate formation.

5.1.2 A Glimpse at Condensation Modeling

Second to dew point, the surface temperature demonstrates a material's vulnerability to condensation. Two conditions routinely decrease the interior surface temperatures of a residence: (1) HVAC cooling mode operation and (2) the influence of low outdoor temperatures during the heating seasons. Understanding thermal conductance of building materials becomes particularly important because the building envelope is a buffer between the outside environment and the interior living conditions. Windows often have a higher thermal conductance compared to walls and roofs. In Florida, for example, the thermal conductance of a 2004 Building Code compliant window is 6 times greater than a mass wall (0.75 and 0.123 BTU per $h \cdot ft^2 \cdot °F$, respectively). Consequently, windows have a greater vulnerability to condensation and heat transfer during the colder seasons. These conditions illustrate the importance of maintaining proper interior humidity levels when the building envelop is subject to cool outdoor temperatures.

A series of condensation estimations were completed to create a relevant scale for investigators to reference when interpreting field conditions. Condensation can be predicted using several methods. However, the Nusselt number is the basis for thin film condensation estimations on vertical surfaces with a high empirical reliability (less than 3% error) (ASHRAE 2013; Incropera, et al. 2007). The Nusselt number is derived from the average of the surface and saturation temperatures (dew point) and the properties of water at the film and saturation temperatures.

Due to their condensation vulnerability, the estimations were completed on a surface symbolizing window glazing. To achieve this the surface was characterized as 3 ft. by 3 ft. impermeable surface. The model examined several different surface temperatures with exposure to air at varying dew points (**Table 1**). For the purposes of full disclosure, the model assumes the following conditions: two-dimensional analysis, uniform temperature for each substance referenced, the substrate surface was clean and exposed to a pure vapor equal to the saturation temperature, a laminar or partially laminar film developed, constant material properties, the surrounding moist air was immobile, steady-state conditions existed as well as an infinite moisture source, , shear stresses were negligible as were momentum and energy transfer by advection, and heat transfer to the liquid-vapor was limited to condensation and through the film by conduction (Incropera, et al. 2007; Shu 2012).Dimensionless numbers were included in the table for third-party analysis of the estimation results.

An agreeable humid condition had to be defined for modeling purposes. A 62.5°F dew point was chosen as the analysis starting point because it was above the upper limit recommended by ASHRAE Standard 55 for seated or slightly active occupants (0.012 lbs. of water vapor per lb.

dry air, 62.2°F dew point). According to these conditions, more than 1 in 5 people would find the environment uncomfortable after a 15 minute minimum occupancy. The 62.5°F dew point is also above the 55°F recommendation for mitigating condensation risk (ASHRAE 2015). For these reasons, the authors believed dew points at or above 62.5°F qualified as a humid and functionally undesirable environment.

Table 1: The Nusselt number based estimations for thin film condensation.

Dew Point (°F)	**Surface Temp. (°F)**	**Maximum condensation film depth (mils)**	**Total condensation rate (oz./min.)**	**Jakob number (# x 10^3)**	**Prandtl number**	**Reynolds number**
62.5	40.0	7.54	34.8	2.07	8.97	59.51
62.5	60.0	4.27	7.04	2.36	7.69	13.81
65.0	60.0	5.03	12.0	4.73	7.38	24.43
67.5	60.0	5.57	16.3	7.09	7.41	33.00
82.5	60.0	7.17	40.2	21.5	6.62	90.11
85.0	60.0	7.10	47.1	23.9	5.49	124.8
87.5	60.0	7.22	51.5	26.3	5.31	140.7
82.5	80.0	4.04	7.74	2.39	5.76	19.66

5.1.3 Interpreting the Condensation Model

The estimations provided in **Table 1** were presented for illustrative purposes only. Due to their assumptions and boundary conditions they are not claimed to be exact representations of real-world circumstances. However, the data reveals the general expectation that increased differences between the dew point and a lower surface temperature correlated to an increased condensation rate.

Second, the analytical model provides an opportunity to interpret duration. Residences are not equipped with an infinite moisture source as the model presumes. The following example demonstrates the magnitude of interior humidity that can be realistically encountered within a residence., An 8,000 ft^3 conditioned space (1,000 ft^2 area with an 8 ft. floor to ceiling height) with a 62.5°F temperature and dew point (100% relative humidity) contains approximately 14 ounces of water vapor dissolved in the air (standard air properties applied).

Therefore, when conditions exist to create a 1/16th inch thick condensation film on multiple window interiors, it suggests a chronic underlying humidity problem. The matter of greater significance is the moisture source and its time dependent influence on the indoor environment. Time was required for multiple occurrences to take place prior to the observed condensation: time elapsed during moisture generation or intrusion, then humidity had to flow through the space from the source to the window(s) vulnerable to condensation development, and local conditions had to persevere against the building's dynamic environment long enough to enable condensation.

5.2 Modeling and Interpreting Mold Growth Duration

There are several relevant assumptions in the opinions of mold growth timelines. First, a mold growth timeline assumes that the substrate had no previous microbial growth or prior susceptibility to microbial growth in its final configuration. Second, the mold growth timeline study was completed in a setting that limited environmental variables to provide a more predictable outcome. Third, the test conditions cannot represent every possible scenario that could encourage mold growth. Finally, it has proven difficult to model for all variables that affect building dynamics and their relationship to mold growth (Vereecken and Roels,). Despite these limitations, mold growth studies provide a starting point to interpret findings from real world conditions. One such starting point is that indoor mold growth arising from sustained elevated humidity can occur on building materials during a summer season at 70% RH and within a week at 85% RH (ASHRAE 2015). For condensation, an additional step can be taken to understand the fungal genus *Cladosporium*.

5.3 Cladosporium, a "Condensation" Fungal Genus

Cladosporium grows on non-porous condensing surfaces and is secondary colonizer with a water activity requirement of between 0.80 and 0.90 (**Table 2**, Goldstein 2011, Flannigan, et al. 2011; Petty 2013). Several findings imply that visible *Cladosporium* growth requires a 7 to 14 day duration of consistent moisture availability. A clinical publication showed that the time required to detect *Cladosporium* from incubated fungal cultures required an average of 7 days and a maximum of 14 days (Morris, et al. 1996). A review of individual laboratory studies that cultured *Cladosporium* revealed growth diameters ranging from 0.008 to 48mm in two weeks and from 32 to 64 mm after one month, depending upon environmental conditions (Bensch, et al. 2012). Lastly, a gypsum board wall assembly study detected *Cladosporium* growth after 14 days of continuously elevated moisture exposure (Moon, et al. 2012). A common denominator amongst these studies was the establishment of an adequate moisture source for microbial growth at the onset of the study. A properly functioning, conditioned indoor environment requires an event or series of events before obtaining elevated moisture. Moreover, an additional latent time period is required before condensation develops. Lastly, experimental studies represent either ideal or worst-case real world conditions at best. Therefore, these conditions can justify extending the timeline interpreted from experimental analysis.

The authors believe the information presented in this paper can be consolidated into this statement: *Cladosporium* growth arising from condensation development on interior building surfaces requires a two-week minimum duration of elevated moisture exposure. This duration includes the time required for moisture accumulation and mold growth.

Table 2: A case study summary of residential microbial growth from condensation on non-porous surfaces.

CRA Project Ref.	Sample Location	Microbial Results						
		Acr. / Gli.	**Asp.**	**A.- P.**	**Cla.**	**Coe.**	**Pen.**	**Ulo.**
Naples Florida. November 14, 2013.	Evaporator coil				X			
Bonita Springs Florida. November 22, 2013.	Extra floor tiles in AC closet		X					
Bradenton Florida. December 12, 2013.	Metal table		X					
Ocala Florida. January, 2014.	Kitchen window blinds		X		X			
	Family Room window sill	X		X	X			
Orlando Florida. March 4, 2014.	Bedroom window sill				X			
Lady Lake Florida. March 13, 2014.	Bedroom window frame				X			
Port Charlotte Florida. March 26, 2014.	Bedroom window frame				X			
Seminole Florida. August 19, 2014.	Bedroom AC vent				X		X	
	Kitchen AC vent				X			
	Family Room AC vent				X			
	Bedroom window frame				X	X		
Lakeland Florida. October 27, 2014.	Bathroom AC vent				X			
Jacksonville Florida. February 25, 2015.	Bedroom window blinds				X			
	Bedroom window				X			
Tampa Florida. March 9, 2015.	Bedroom window	X			X		X	
Orlando Florida. April 10, 2015.	Bathroom window				X			
Orlando Florida. April 24, 2015.	Bedroom window				X			
Tampa Florida. March 12 and April 22, 2015.	Bedroom window				X			X
Beverly Hills Florida. May 1, 2015.	Bedroom AC duct				X			
Presence in Total Sample Population		10%	15%	5%	90%	5%	10%	5%

Abbreviations: Acr./Gli = Acremonium/Gliomastix, Asp. = Aspergillus, A. – P. = Aspergillus – Penicllium Like Spores, Cla. = Cladosporium, Coe. = Coelomycetes, Pen. = Penicillium, Ulo. = Ulocladium, Ref. = Reference

6.0 Limitations and Future Work

The conditions for applying an interpretation of two-week duration are limited to residential construction located in the hot and humid climate of the southeastern United States. Non-commercial activity and typical residential/household occupancy are also included in the applicable conditions. Lastly, the primary method for cooling and dehumidifying the residence must be provided by an AC system (unitary, split system, or chilled water).

There are a multitude of possibilities for future work. First, establishing a reference for experimentally verified condensation rates on a variety of different building material and humidity level combinations could provide additional data for the forensic community to incorporate. On a case by case basis, hygrothermal analysis of the wall assembly in question would provide insight to the construction layers and/or environmental conditions that enabled condensation development. Software exists that allows for computing transient hygrothermal behavior. This would provide additional support for the opined timeline. Lastly, the implementation and development of practices and standards such as “ANSI/ASHRAE Standard 160: Criteria for Moisture-Control Design Analysis in Buildings” can help create commonplace assessment, interpretation, and reporting techniques related to building moisture examinations.

7.0 Conclusions

The litigious fabric of our society places us among a few developed nations that identify indoor air quality concerns as a priority. When water damage occurs and responsible parties identified, there are numerous avenues to recover financial losses associated with air quality testing, damaged material removal and reconstruction, business interruption expenses, engineering and architectural fees, and medical expenses (Senn 2014; Spicer 2013; USEPA 2013). During the past 20 years these costs have exceeded $100 million in settlements and awards (Cooper 2004; Petty 2013; Senn 2014).

Experts recommend controlling and managing moisture sources to prevent mold growth from arising. In the event fungal growth develops the forensic investigator is tasked with interpreting the complex dynamics of a built environment. Situations involving condensation development feature a sequence of events and/or failures that permitted elevated humidity within an otherwise conditioned space. During this study the most common condensation based fungal genera found on impermeable surfaces within a residence was *Cladosporium*. With conditions, the authors believe a two-week minimum duration is required for *Cladosporium* growth arising from condensation development on interior surfaces. Included in these conditions is its tentatively sole applicability to residences located in the hot and humid climate of the United States. We encourage additional work to develop this interpretation.

8.0 References

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