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Occurrence of Mold in a Two-Story Wood-Frame House Operated at Design Indoor Humidity Levels

Carol A. Clausen
Jessie A. Glaeser
Samuel V. Glass
Charles Carll

Abstract

Mold growth was observed in limited areas in a two-story contemporary wood-frame house during the seventh heating season of operation at or near design indoor humidity levels. The house was in a cold climate (Madison, Wisconsin). Humidity levels were estimated as being exceeded in one of 10 homes at this location. Moderate amounts of window condensation were observed during each of the seven heating seasons. Areas of observed mold growth were limited to the lower extremities of windows (near the lower edge of glass panes) and the edges of lower panels of a wood panel entry door that was not equipped with a storm door. Mold growth was also present in sprayed-on cellulose insulation in close proximity to the rim joist (board) in the basement, although this mold was not visible unless the insulation was disturbed and was probably present during previous heating seasons. Mold from these locations was cultured, isolated, and identified morphologically or by DNA sequence. Seven genera of common ascomycetes and deuteromycetes were detected, all of which are commonly associated with indoor air. *Penicillium* was the most common genus, with at least six different species. The greatest variety of genera (five) occurred in samples taken from interior wood millwork (the edges of panels in the entry door and from a wood window sash). Only two genera were found in a sample taken from the interface between the rim joist board and cellulose insulation. Total spore counts taken in April revealed that on the first and second stories, mold spores were less prevalent than in outdoor air but that mold spores were more prevalent in the basement than in outdoor air.

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Keywords: mold, spore, indoor air quality, relative humidity, condensation

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Carol A. Clausen, Supervisory Research Microbiologist
Forest Products Laboratory, Madison, Wisconsin

Jessie A. Glaeser, Research Plant Pathologist
U.S. Forest Service, Northern Research Station, Madison, Wisconsin

Samuel V. Glass, Research Physical Scientist
Charles Carll, Research Forest Products Technologist
Forest Products Laboratory, Madison, Wisconsin

Introduction

Predicting operational conditions that are conducive to mold establishment has historically not been a critical consideration in house design. Mold spores that are ubiquitous in the environment require a simple food source, proper temperature, oxygen, and moisture for germination and growth to occur. Due to the ready availability of the first three requirements, moisture becomes the controllable limiting factor in the initiation of mold growth. Interior humidity is one of the most important controllable moisture sources in a house (Christian 1994). Moist building materials, such as framing lumber, wet-applied insulation, and especially recently poured concrete, can be a very significant moisture source in the first year after building construction. Following dissipation of moisture from construction materials, humidity levels during normal operation vary greatly and are primarily dependent on number of building occupants, building volume, occupant behavior, air exchange rate, water vapor content of outdoor air, and the manner in which air exchange occurs. A large potential source of indoor humidity that is not always considered is the building foundation, which is in contact with earth that commonly is damp or even wet (Christian 1994).

The Building and Its Operation

A dual-purpose research and demonstration house, located on the campus of the U.S. Forest Service Forest Products Laboratory, was constructed in 2001. The building is not occupied but generally has been humidified during the heating season to simulate occupancy. Carll and others (2007) describe the building's construction history, operation, and performance through the first five heating seasons. The primary research effort thus far has been to identify issues associated with house operation in a climate with approximately 7,000 Fahrenheit heating degree days and with high internal humidity. Relative humidity within the building was targeted to exceed the relative humidity of 9 out of 10 houses at this location. The target humidity was calculated by an ASHRAE standard (ASHRAE 2009a) based on assumed moisture release rates as affected by the number of occupants, assumed air exchange rate between the house and the outside, water vapor content of outdoor air, and an assumed indoor temperature of 21 °C (Carll and others 2007, Ten-Wolde and Walker 2001). The design relative humidity (RH) values that were calculated for this house are shown in Table 1. Design values were intentionally higher than the wintertime value of 35% to 40% often cited as risky to exceed in residential buildings of normal construction in cold climates (Powell 1994; ASTM 2008).

Table 1—Design and measured values of indoor relative humidity by month[a]

Month	Design indoor RH (%)	Measured indoor RH (%)
November 2007	50.5	54.5
December 2007	45.2	45.9
January 2008	42.4	43.0
February 2008	41.9	40.1
March 2008	47.4	44.0
April 2008	60.8	54.8

[a]Design indoor RH values are calculated according to ASHRAE Standard 160, Section 4.3.2, Indoor Design Humidity, Intermediate Method (ASHRAE 2009a), using mean monthly outdoor water vapor pressures (NCDC 2007, 2008). The calculations assume an indoor design temperature of 21 °C, an air exchange rate of 0.2 air changes/hour, a house volume of 515 m^3 (18,200 ft^3), and a moisture production rate of 15 kg/day. Measured indoor RH values are monthly averages from the living room on the first floor of the house.

For the first two heating seasons, the building was not actively humidified, but indoor humidity levels moderately close to design levels were nonetheless reached. The probable reasons for this were discussed in an earlier manuscript (Carll and others 2007). The building was humidified to

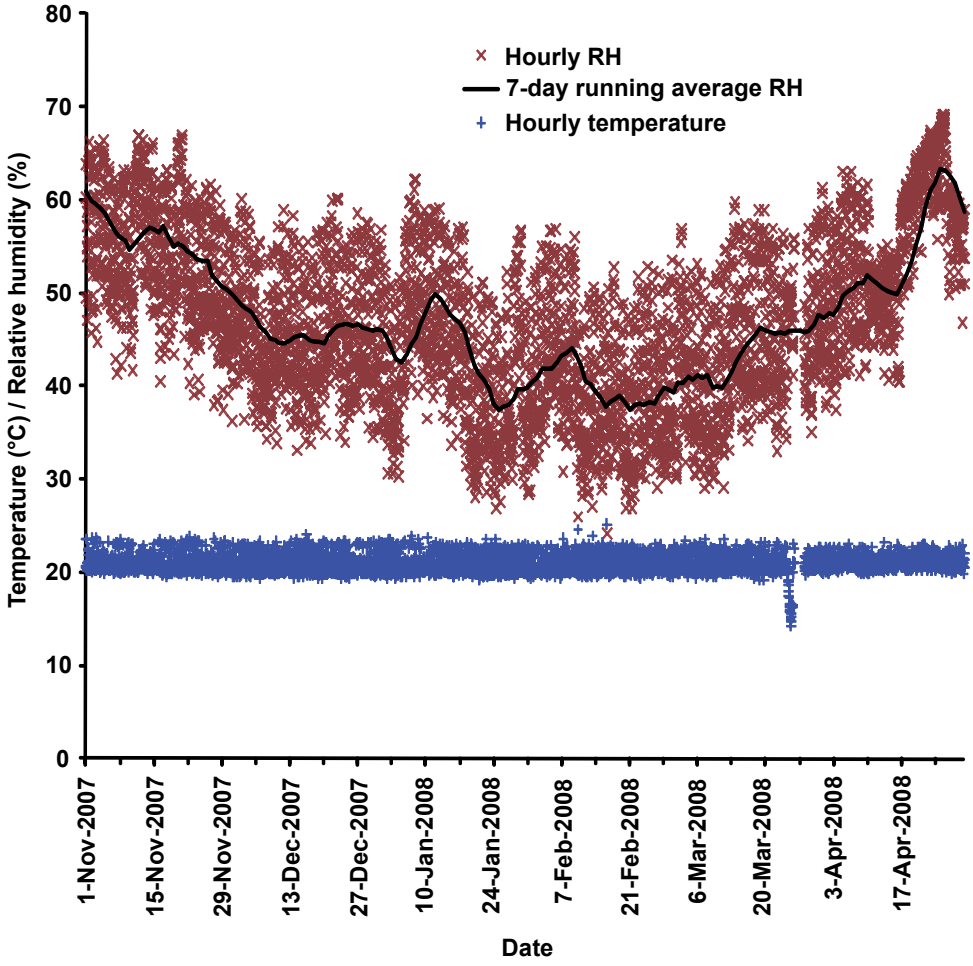

Figure 1—Temperature and RH measured in the living room on the first floor of the house from November 2007 through April 2008.

design levels for the third and fourth heating seasons, generally at substantially lower rates of moisture release from humidifiers than the assumed release rate from which design humidity levels were calculated. For the fifth, sixth, and seventh heating seasons, a set amount of moisture (10 kg/day) was released by three free-standing humidifiers placed in the first and second stories of the house. This release rate was two-thirds of the design load of 15 kg/day, based on the assumption of five occupants for the four-bedroom house, but commonly resulted in design RH levels being reached and, in some cases, exceeded. No sole-purpose dehumidification equipment was operated in the house in any season, but the house was air-conditioned in summer months and the air-conditioning undoubtedly provided some dehumidification. Humidifiers were used October through April but were inactive May through September. Hourly RH conditions during the 2007–2008 heating season are shown in Figures 1 and 2 for the house living room (great room) and basement, respectively. Figure 1 shows substantial variability in hourly RH in the living room. Monthly average RH conditions are shown in Table 1; over the course of the heating season, indoor humidity levels more or less coincided with the design levels.

Visually Observed Mold Growth

During all heating seasons, some window condensation was observed. Through the fifth heating season, we noticed intermittent window condensation during winter months but did not observe the presence of mold. In January 2008, visible mold was observed on areas of the lower portions of all windows and on areas of the building's front entry door, which faces WNW. The front entrance consisted of a six-panel wood door and was not provided with a storm door. An identical wood panel entry door on the opposite side of the same interior room was equipped with an exterior storm door and was devoid of mold.[1]

Mold growth on a window and the panels of the entry door are shown in Figures 3 and 4, respectively. The mold was restricted to edge areas of door panels or to areas on windows near the lower edge of a glass pane. Most of the windows in the house were casement windows. The window sash had

[1]Interior surfaces of the door lock hardware of the front entry door regularly showed appreciable condensation in cold weather. In contrast, we never observed condensation on the lock hardware of the rear entry door (which was equipped with a storm door).

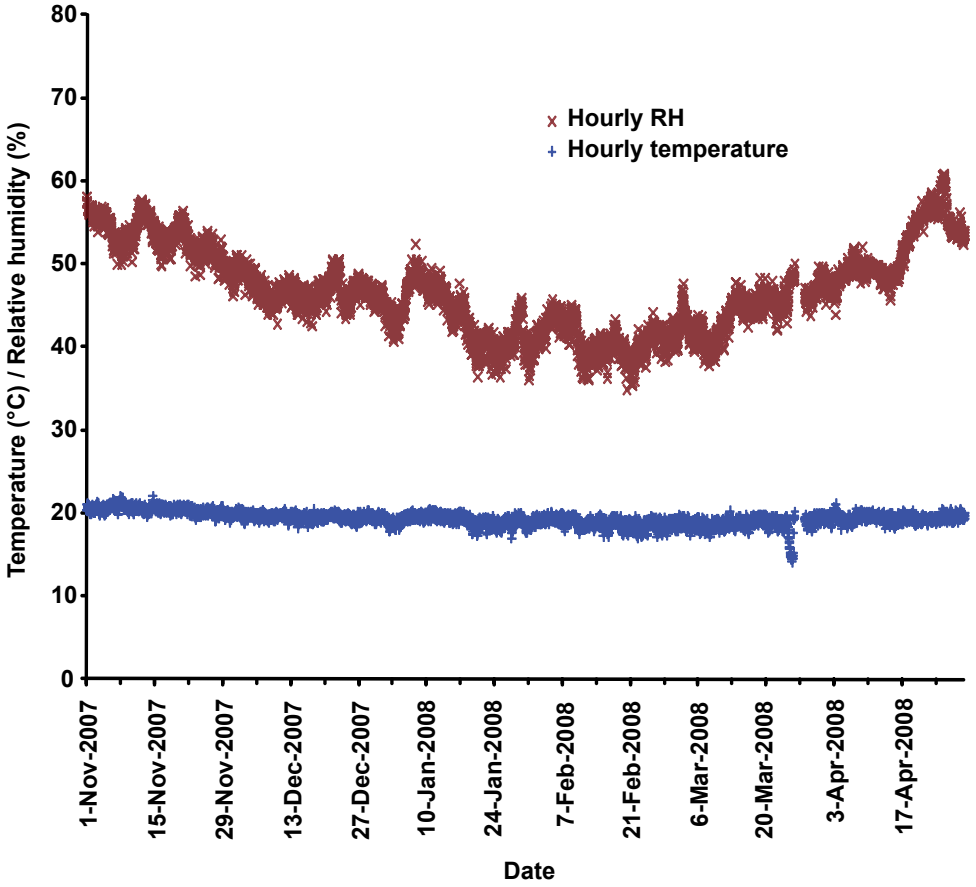

Figure 2—Temperature and RH measured in the basement of the house from November 2007 through April 2008.

wood cores, with all surfaces of the sash encased in polyvinyl chloride (PVC). These windows had interior wood stops at the sides (jambs) and top (head) that contacted the sash when it was closed and latched. At the bottom (sill) of the window was a piece of wood stop trim. This was machined with the same outer profile as the jamb and head stops but was hollow-backed to conceal the window operating hardware. The two windows in the basement were of "hopper" style—hinged at the bottom, opening inward at the top. All surfaces on these windows were PVC. The entry door was flanked on each side with a multi-lite side-lite panel. Each panel consisted of a 0.36- by 2.0-m wood sash containing five vertically stacked panes, with wood muntins between panes. All three window types showed mold growth in January 2008. In all cases, mold was visible on the window sash but was restricted to the bottom rail of the sash or to muntins between panes in the sash. In all cases, the bulk of the mold was very close (within 8 mm) to the lower edge of a glass pane.[2] Mold was also present on the sill window stop trim of the casement windows, especially at the corners where the stop trim interfaced with the jamb stops. Corridors of mold growth, which sometimes coincided with presence of condensed water, were regularly observed between the sash and the stop trim. A limited amount of mold was also present on interior wood trim below one of the basement windows, but this did not appear to be associated with run-down of condensed water from the window sash.[3]

[2]The glass in the casement and side-lite windows was insulating glass (double-pane sealed insulating glass units (IGUs) with metal edge spacers). The glass in the hopper-style basement windows was dual pane, without a seal between panes; the outer pane in these windows can be removed by removing retainer hardware. Because the basement windows did not have sealed IGUs, there were no metal edge spacers between the two panes of these windows. Although the glass in the basement windows almost certainly had higher U-value (measured at glass center) than the glass in the casement units (used on first and second stories of the building), and although the basement windows regularly showed more condensation and condensation at greater distances from the lower glass edge, the prevalence of mold on the sash of these windows was not perceptibly greater.

[3]This window had sweep weather stripping at sash stiles and at the head sash rail. It had a ridge in the window frame and a mated groove in the bottom rail of the sash. This design is probably very effective with regard to prevention of water intrusion but probably is less effective than a functional sweep or compression gasket at restricting air movement. There were no stain trails between the sash and the interior trim. The mold-growth pattern on the trim was diffuse. These observations, along with the lack of an obviously effective air seal at the sash bottom rail, led us to suspect that cooling of the trim surface by cold air infiltration below the bottom sash rail was the probable cause of the moisture that resulted in mold growth on the trim.

Figure 3 (a, b)—Mold growth on interior surfaces of lower rails of two representative vinyl clad window sash. Mold growth is most prevalent near pane edges and at corners, where condensate has collected. (Photo by Robert Munson, Forest Products Laboratory, January 10, 2008.)

Figure 4—Mold growth on the edges of panels of the front entry door. Evidence of run-down of condensate (seen as staining and mold growth) is also apparent on the rail below the panel, particularly on the profiled edge of the rail. (Photo by Robert Munson, Forest Products Laboratory, January 10, 2008.)

Table 2—Mold sampling locations

Sample ID	Structure level	Room identifier	Geographic sample location	Description	Substrate
1	Main	Living room	ESE	Window sash	PVC
2	Main	Living room	ESE	Window stop	Wood
3	Main	Front entry	WNW	Bottom door panels	Wood
4	Main	Front entry	WNW	Center door panels	Wood
5	Second	Bedroom	WNW	Window sash	PVC
6	Second	Bathroom	ESE	Window sash	PVC
7	Second	Bathroom	ESE	Window stop	Wood
8	Lower	Basement	WNW	Rim joist / insulation interface	Cellulose
9	Lower	Basement	NNE	Window sash	PVC
10	Main	Front entry	WNW	Window stop	Wood

Objective

The objective of this study was to identify mold in the different areas of the building. Identification of species is sometimes used as an indicator regarding potential health concerns. An associated objective was to document the prevalence of airborne fungal spores in indoor air compared with their concurrent prevalence in outdoor air.

Methodology

Mold Sampling and Culturing

Following observation of mold on window sash and trim and on the front entry door in January 2008, mold was isolated from the entry door and from at least one window on each level of the building. Sampling locations are listed in Table 2. In addition, mold was sampled from one location that was associated with neither a window nor the front entry door; this location was at the interface between a rim joist board (in the basement) and spray cellulose insulation that had been installed over it.

Sampling was performed with sterile cotton swabs. Swabs were streaked on 2% malt extract agar (MEA) in sterile Petri plates and incubated at 27 °C and 80% RH. Fungal growth was monitored daily. When individual colonies were visible, they were subcultured until pure and incubated at 27 °C and 80% RH.

Mold Identification

Microscopy

Fungal cultures were identified using light microscopy to analyze morphological characteristics, including the size and shape of spores and spore-bearing structures (Samson and others 2000, Wang 1990). If cultures contained more than one spore type or colony morphology, cultures were subcultured on 2% MEA (Difco, Detroit, Michigan) until pure. Identification keys by Samson and others (2000) and Wang (1990) were useful for identifying most of the fungi to the species level. *Penicillium* isolates that could not be identified microscopically were placed into morphological groupings based on growth characteristics on four differential media—Czapek Dox agar, Creatine sucrose agar (CREA), Czapek yeast extract agar (CYA), and yeast extract sucrose agar (YES) (Samson and others 2000). Representatives of each morphological grouping were then identified using DNA sequencing.

DNA Analysis

Selected *Penicillium* cultures that could not be identified microscopically were subjected to DNA sequencing analysis, following the protocol of Lindner and Banik (2008). Small pieces of mycelium from MEA plates were prepared for DNA extraction by grinding in a cell lysis buffer. DNA was cleaned using GeneClean III kits (Qbiogene, Carlsbad, California) and internal transcribed spacer (ITS) sequences were amplified by polymerase chain reaction (PCR) using the fungal-specific primer pair ITS1F and ITS4. PCR products were cleaned using ExoSap (USB Corporation, Cleveland, Ohio), followed by sequencing using the BigDye sequencing protocol (ABI Prism). Sequencing products were analyzed at the University of Wisconsin Biotech Center (Madison, Wisconsin) and final sequences were aligned using Sequencher 4.2 (GeneCodes Corporation, Ann Arbor, Michigan). Sequences were assigned a putative identification based on BLAST comparisons to GenBank (NCBI) sequences.

Quantification of Airborne Spores

Each level of the structure was sampled three times consecutively at five locations for total spore counts using a VersaTrap® Spore Trapping Cassette (SKC, Eighty Four, Pennsylvania) in conjunction with a bioaerosol QuickTake® sampling pump (SKC, Eighty Four, Pennsylvania). The sampling pump pulls a sample of air through a narrow slit in the spore trapping cassette and deposits particles onto a clear glass slide coated with an optically clear sticky collection substrate. The sampling pump operated at 15 L/min for 2 min. Collected particles are held by the substrate in a well-defined rectangular-shaped particulate deposition trace. After sampling, the glass slide is removed from the cassette and examined microscopically. Sampling occurred near the conclusion of the heating season in April 2008. Three consecutive samples were collected immediately following the interior sampling at each of five exterior locations to establish a background spore count. Based on a defined field area and defined sampling area(s), a multiplier defined as the ratio of the total field area (μm^2) to the total sampling area (μm^2) divided by total volume (L) of air was determined. The resulting multiplier (1.17) was used to estimate the average spore count for each location, which was expressed as colony forming units (CFU) per unit volume (m^3) of air.

Results

Mold Culturing

All areas of visible mold growth are described in Table 2 and defined according to the structure level, room description, geographic direction, product description, and substrate material. Figures 3 and 4 are representative of the extent of the mold growth. Mold was cultured from visible locations on all three levels of the house from window and door surfaces facing all geographic directions. Substrates supporting mold growth included PVC, cellulose insulation, and wood. Mold is capable of growth on virtually any substrate under favorable moisture conditions by using nutrients from detritus that has collected on surfaces, or in the case of cellulose-based building materials, by digesting simple sugars found in the wood component. Mold fungi can also adhere to, colonize, and change the physiochemical properties of plastic polyvinyl chloride (Bochkareva and Orchinnikov 1977; Webb and others 1999, 2000).

Mold Identification

Table 3 summarizes the genus and species of each isolate cultured. A total of seven genera were identified that generally represent commonly isolated mold genera from homes. *Penicillium* and *Aureobasidium* were most frequently isolated, followed by *Alternaria* and *Aspergillus*. In a report on mold biodiversity in homes, *Cladosporium, Penicillium,* and *Aspergillus* were the most frequently encountered genera (Beguin and Nolard 1994). In a study of Danish homes infected with mold, *Penicillium chrysogenum* was found to be dominant in spring and autumn, followed by fewer numbers of *Aspergillus versicolor. Cladosporium* was commonly isolated during summer (Bech-Anderson and Elborne 2003). *Aureobasidium pullulans* was detected in most samples throughout the house. This is a very common fungus in most homes and is often associated with high moisture areas, including bathrooms, kitchens, and windowsills. The six species of *Penicillium*, identified by DNA sequencing, are all common species frequently associated with indoor air (Samson and others 2000). Isolate 8-2, *Penicillium chrysogenum*, matched the identification of a yellow mold isolated from wet cellulose insulation in the basement of the structure in 2001. The isolate was designated PH02 (Clausen and Yang 2003).

Total Spore Count

Total interior spore counts for each level of the structure are compared to the exterior spore count in Table 4. Five sampling locations per structural level revealed small variations

Table 3—Mold isolate identification

Sample ID	Isolate number	Identification
1 (Window sash)	1	*Aureobasidium pullulans* var. *melanogenum*
	2	*Aureobasidium pullulans*
	2a	*Aureobasidium pullulans* var. *pullulans*
	2b	*Penicillium glabrum*
	3	*Aureobasidium pullulans* var. *melanogenum*
2 (Window stop)	1	*Aureobasidium pullulans*
	2	*Penicillium funiculosum*
	3	*Penicillium funiculosum*
	4	*Penicillium funiculosum*; *Byssochlamys nivea*
	5	*Byssochlamys nivea*
3 (Bottom door panel)	1	*Penicillium corylophilum*
	3	*Penicillium corylophilum*
	3a	*Penicillium corylophilum*
	3b	*Aureobasidium pullulans* var. *pullulans*
4 (Center door panel)	1	*Penicillium corylophilum*
	2	*Penicillium corylophilum*
	3	*Aureobasidium pullulans*; *Penicillium corylophilum*
5 (Window sash)	1	*Cladosporium cladosporioides*
	2a	*Aureobasidium pullulans* var. *pullulans*
	2b	*Aspergillus niger*
	3	*Aspergillus niger*
	4	*Alternaria alternata*
	5	*Aureobasidium pullulans* var. *melanogenum*
6 (Window sash)	1	*Penicillium corylophilum*
	2	*Aureobasidium pullulans* var. *melanogenum*
	3a	*Aureobasidium pullulans* var. *pullulans*
	3b	*Penicillium purpurpogenum*
	4	*Byssochlamys nivea*
7 (Window stop)	1a	*Penicillium* sp. A
	1b	*Aspergillus niger*
	2a	*Penicillium mineoluteum*
	2b	*Penicillium mineoluteum*
8 (Rim joist)	1	*Phialemonium dimorphosporum*
	2	*Penicillium chrysogenum*
9 (Window sash)	1	*Penicillium corylophilum*
	2	*Aureobasidium pullulans* var. *melanogenum*
	3	*Cladosporium cladosporioides*
	4	Bacteria and/or yeasts
10 (Window stop)	1	*Penicillium corylophilum*
	2	*Alternaria alternata*
	3	*Aureobasidium pullulans* var. *melanogenum*
	4	*Alternaria alternata*
	5	*Aureobasidium pullulans* var. *melanogenum*
		Cladosporium cladosporioides
		Penicillium sp. B
	6	*Alternaria alternata*

in spore count estimations. The structure is conditioned, so windows remain closed and only the front entry door is routinely opened for access to the structure. While five of the eight genera were cultured from the front entry door and side-lite windows, the main level had the lowest average spore count (251 CFU/m^3) compared with the exterior spore count (499 CFU/m^3). The indoor/outdoor ratio of spores, an indicator of indoor air quality, was 1.52 for the basement level, 0.50 for the main level, and 0.66 for the second level. Ideally, the ratio for indoor to outdoor spore levels should be less than 1.0 and a problem is indicated for a ratio well over 1.0.

Numeric standards for acceptable concentrations of mold spores in the home environment are currently lacking (Stetzenbach and others 2004). Likewise, environmental sampling methods are not capable of characterizing the sequence of events resulting in mold growth. Rather, they are intended to provide data at a given moment in time. In the absence of numerical guidelines, sampling data provide an indication of humidity loads, indoor/outdoor ratios of fungal concentrations, and the presence of a species that may indicate a health concern.

Discussion

Two factors provide a likely explanation for the presence of noticeable mold growth in the 2007–2008 heating season. The first factor is progressive accumulation of airborne detritus over time that would serve as a nutritional source for the mold growth. The second factor is that surface temperature and RH conditions in the 2007–2008 heating season were more conducive to mold growth than they had been in previous heating seasons (discussed below).

Mold was present on the lower portions of the sash of every window in the house by January 2008. Because the overwhelming majority of windows had sash with PVC surfaces, much of the observed mold occurred on PVC surfaces. Even without the presence of detritus as a food source, mold growth can occur on inert surfaces (Bochkareva and Orchinnikov 1977; Webb and others 1999, 2000). In cases of prolonged high humidity or condensation, some species of *Penicillium*, *Aspergillus*, and *Alternaria* can grow on glass and plastic (Zabel and Morrell 1992). The house was unoccupied, although it was entered periodically for tours and research work. A large amount of particulate matter was found in the basement air samples. The duct system for the house is equipped with an electrostatic filter. The ducts in the basement are sealed with a combination of metal foil tape and mastic; the basement has neither supply nor return registers. The first and second stories of the building appear to be realizing a beneficial effect from the electrostatic filter. In contrast, the basement, by reason of its isolation from the duct system, apparently realizes no or minimal removal of airborne particulates by the filter.

Dust accumulation on window sashes on the first and second stories was largely imperceptible. Some progressive collection of airborne detritus on them would nonetheless be expected over time, even if the accumulation was not readily observable. In contrast to the interior surfaces of window sashes, those portions of sash edges that were outboard of the weather strips collected noticeable amounts of dirt, silk cocoons, and dead insects over time.

Table 4—Total airborne spore count by location

	Airborne spore count at five sampling locations[a]					
Structure level	1	2	3	4	5	Average (S.D.)[b]
Interior						
Basement	761	570	566	665	671	756 (95)
Main	225	245	191	221	191	251 (27)
Second	251	296	341	270	251	329 (44)
Exterior	420	405	341	530	440	499 (80)

[a]Expressed in CFU/m^3, colony forming units per cubic meter of air.
[b]Average of five sampling locations per structure level, $n = 3$; S.D., standard deviation.

Table 5—Mean outdoor temperature and number of heating degree days for the three-month period from December through February[a]

Period	Mean outdoor temperature (°C)	Heating degree days[b]
December 2001–February 2002	–1.3	3,159
December 2002–February 2003	–6.0	3,912
December 2003–February 2004	–5.5	3,880
December 2004–February 2005	–4.0	3,595
December 2005–February 2006	–4.1	3,612
December 2006–February 2007	–5.0	3,753
December 2007–February 2008	–7.5	4,211
30-year average (1971–2000)	–6.2	3,991

[a]Calculated from NCDC (2007, 2008) data.
[b]65 °F basis.

Outdoor temperatures during the various heating seasons are compared in Table 5. The table shows the mean outdoor temperature and number of heating degree days for the three-month period from December through February for each of the years since the house was constructed. Corresponding values from monthly climate normal data for the period 1971–2000 are shown for reference. It is apparent from the table that the first six winters were milder than the 30-year average, whereas the seventh winter (2007–2008) was colder than average. Further examination of the weather records (not shown) indicates that the 2007–2008 heating season was consistently cold; each of the months from November 2007 through March 2008 ranked as the coldest or second coldest of the seven heating seasons.

The surface temperature on the interior edges of the front entry door panels was calculated from hourly measured values of indoor temperature and outdoor temperature. The interior surface RH was then calculated from hourly indoor vapor pressure, based on indoor temperature and RH measured in the living room, and from hourly calculated surface temperature. The combination of surface temperature and RH were supportive of mold growth.

The panels in the entry door were 8 mm thick at their edges; the thermal resistance of the panels was thus low, particularly at their edges. As a consequence, calculated values of

Table 6—Conditions necessary to minimize mold growth as outlined in ASHRAE Standard 160 (ASHRAE 2009a)

Period for running averages	Running average surface RH (%)	Running average temperature
30 days (720 hours)	<80	Between 5 °C and 40 °C (41 °F and 104 °F)
7 days (168 hours)	<98	Same as above
24 hours	<100	Same as above

interior surface temperature are largely dominated by the thermal resistance of the air layer in contact with the exterior surface of the panel. This in turn depends on the local air speed, for which we lacked measurements. We therefore considered two extremes: (1) we assumed the thermal resistance of the exterior surface film to be the value for still air, the "high exterior thermal resistance" case; (2) we assumed the thermal resistance of the exterior surface film to be the value corresponding to air moving at a speed of 3.4 m s^{-1}, the "low exterior thermal resistance" case. The value of 3.4 m s^{-1} was the average wind speed from November 2007 through April 2008 measured at the nearest National Weather Service (NWS) station at a height of 10 m (NCDC 2007, 2008). The NWS station was 10 km from the house. The wind instrument at the NWS station is in an open, unshielded location. Further details of the calculation methodology are given in the Appendix. Figures 5 and 6 show calculated temperature and RH values at the interior surface of the wood panel door from November 2007 through April 2008 for high and low exterior thermal resistance cases, respectively.

Figures 5 and 6 indicate that at either assumed extreme estimate for local wind conditions, there would have been prolonged periods during mid-winter when surface temperature and RH conditions failed to meet the criteria listed in ASHRAE Standard 160 (ASHRAE 2009a) as "necessary to minimize mold growth." ASHRAE Standard 160 lists three sets of conditions, each consisting of a temperature and surface RH combination, coupled to a time duration (Table 6). Under the high exterior thermal resistance case, two of the three sets of conditions were not met (conditions over 30 days and 24 hours). Under the low exterior thermal resistance case, all three sets of conditions were not met.

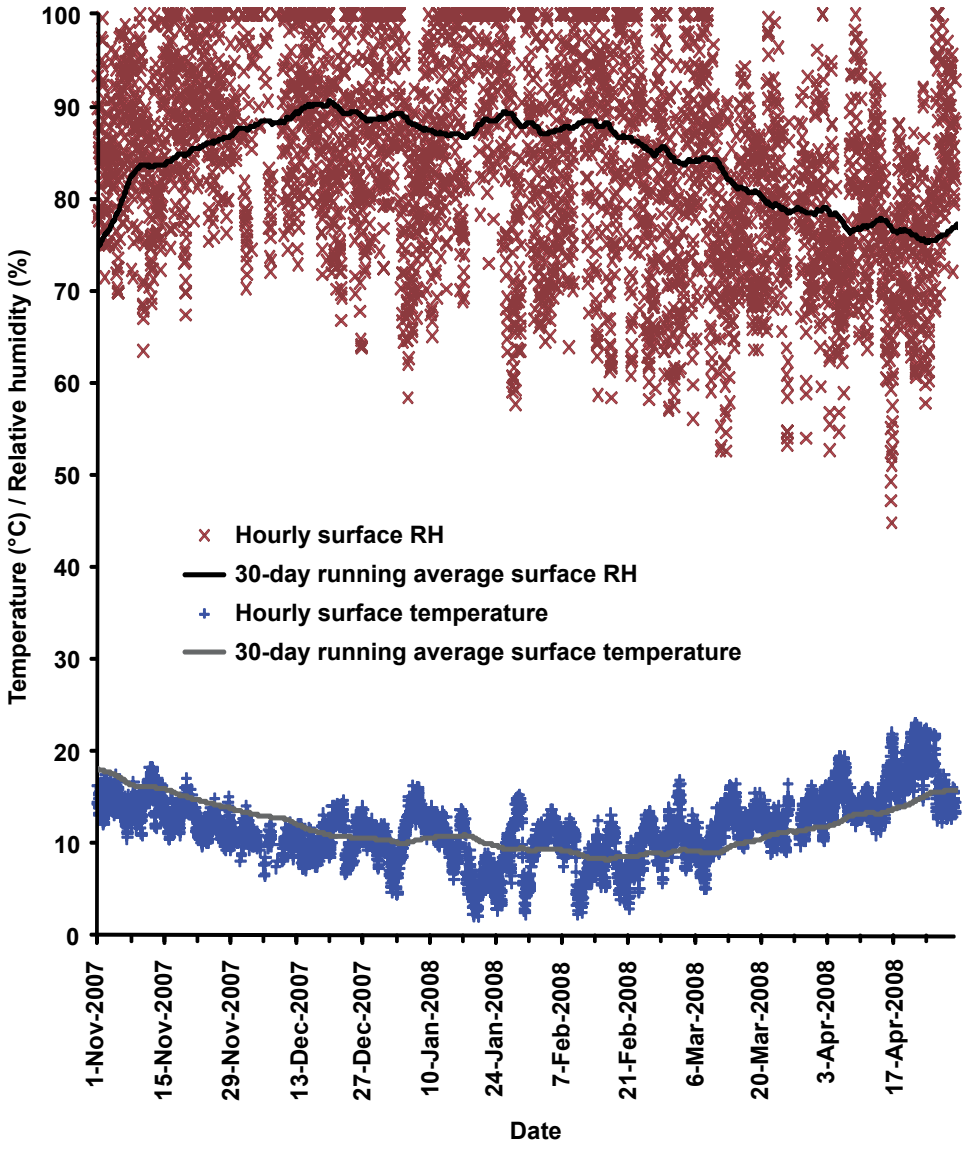

Figure 5—Calculated temperature and RH at the interior surface of a panel edge in the entry door from November 2007 through April 2008 for the case in which high exterior thermal resistance is assumed.

The rim joist area has been identified as an area that, along with windows, is subject to condensation during cold weather (Cautley 2004). The spray cellulose insulation was not covered with an interior vapor retarder, increasing the susceptibility of the rim joist area to moisture accumulation during the heating season. The rim joist board is a composition rim board (essentially an oriented strandboard (OSB) of approximately 30 mm thickness) of the same depth dimension as the I-joists. There was mold on the surface of the rim board and the insulation that contacted it. Mold was cultured from a sample of the insulation. We suspect that mold was present in previous heating seasons based on its presence within the insulation of a wall that was opened for inspection during the fourth heating season (Carll and others 2007). This wall, like the rim joist area, did not incorporate an interior vapor retarder.

Borate additive in cellulose insulation has been postulated as inhibitory to mold or to possibly select for certain mold species (Carll and others 2007). Borates at high loadings have been found to be marginally effective at inhibiting growth of mold fungi (Barnes and others 1989). Clausen and Yang (2003) reported that 5% disodium octaborate tetrahydrate (DOT) did not substantially inhibit *Penicillium chrysogenum*, *Aspergillus niger*, or *Trichoderma viride*. They estimated a minimum fungicidal concentration (MFC_{90}) of 3.7 mg/mL for boric acid (Clausen and Yang 2005). Micales-Glaeser and others (2004) reported that 8.5% DOT controlled growth of *A. niger*, but 15% DOT provided only sporadic control of *Penicillium brevicompactum*, *Stachybotrys chartarum*, and *Cladosporium cladosporioides*. Too few samples were taken in this study to draw conclusions about mold diversity or selectivity on various substrates.

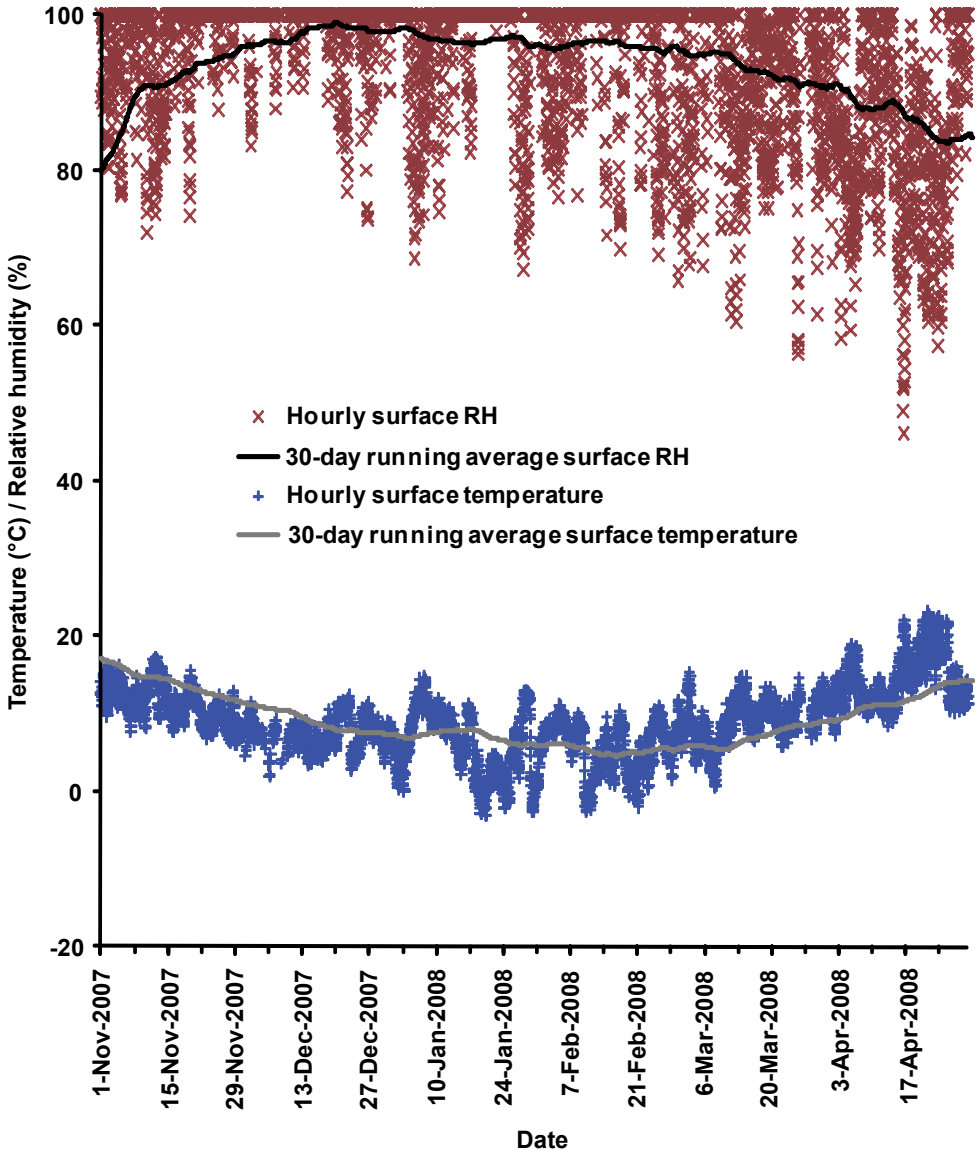

Figure 6—Calculated temperature and RH at the interior surface of a panel edge in the entry door from November 2007 through April 2008 for the case in which low exterior thermal resistance is assumed.

Conclusions

Mold growth occurred in an unoccupied wood-frame house in a cold climate after roughly 6-1/2 heating seasons of operation near or at design indoor humidity levels. The sites were primarily areas where intermittent condensation had been observed through all previous heating seasons, specifically on windows in close proximity to the lower edges of window panes. The other areas were in places where condensation had not previously been noted but where it probably had nonetheless occurred. These areas included the edges of lower panels on a wood panel entry door that was not equipped with a storm door and in the rim joist area in the basement. Seven genera of common mold fungi were isolated and identified. The diversity of species was similar on wood interior millwork (12 species in five samples) and PVC (10 species in four samples). Two mold species were isolated from the single sample of cellulose insulation. The indoor/outdoor ratio of fungal spores, measured in April, was appreciably below 1.0 in the normal living areas of the house where supply and return registers for a forced-air heating and cooling system were present. These parts of the house received conditioned air that was filtered through an electrostatic furnace filter. In contrast, the indoor/outdoor ratio of fungal spores was 1.5 in the basement. The basement had neither supply nor return registers, and the ducts in the basement were sealed. Minimal circulation of basement air through the furnace filter would thus have been expected. The presence of general particulate matter, as well as spore concentration, was distinctly higher in basement air than in air on first- and second-story levels.

Weather conditions were colder during the seventh heating season than they had been during all the previous heating seasons experienced by the house. Calculations indicated that at the edges of wood panels in the entry door, which was not equipped with a storm door, the combination of outdoor temperature and indoor humidity levels would have resulted in conditions supportive of the observed mold growth.

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Appendix—Surface Temperature and Relative Humidity Calculations

The temperature T_{surf} at the interior surface of the wood panel door at its location of least thermal resistance (its narrowest profile) is calculated as follows:

$$T_{surf} = T_i - (T_i - T_o)\left(\frac{R_{surf,i}}{R_{total}}\right) \quad \text{(A–1)}$$

where T_i and T_o are the hourly measured indoor and outdoor temperatures, respectively; $R_{surf,i}$ is the thermal resistance of the interior surface film; and R_{total} is the sum of the thermal resistances of the interior surface film, the wood panel, and the exterior surface film.

The following assumptions are made in calculating T_{surf}:

1. The thermal resistance of the interior surface film $R_{surf,i}$ is the value for still air, 0.12 m^2 K W^{-1} (ASHRAE 2009c).
2. The thermal resistance of the wood panel door at its narrowest profile, having a thickness of 8 mm, is 0.063 m^2 K W^{-1}, as calculated from equation (3–7) of the *Wood Handbook* (FPL 1999) for an assumed moisture content of 12% and an assumed specific gravity of 0.45.
3. In the "high exterior thermal resistance" scenario, the thermal resistance of the exterior surface film is the value for still air (same as $R_{surf,i}$).
4. In the "low exterior thermal resistance" scenario, the thermal resistance of the exterior surface film is 0.052 m^2 K W^{-1}. This value corresponds with an air speed of 3.4 m s^{-1} (ASHRAE 2009c).

The relative humidity RH_{surf} at the interior surface of the wood panel door is calculated as follows:

$$RH_{surf} = \frac{p_i}{p_{sat}(T_{surf})} \times 100\% \quad \text{(A–2)}$$

where p_i is the indoor water vapor pressure and $p_{sat}(T_{surf})$ is the water vapor saturation pressure corresponding to temperature T_{surf}. Values of $p_{sat}(T_{surf})$ are calculated using standard psychrometric relationships (ASHRAE 2009b). Values of p_i are calculated from hourly measured values of indoor temperature and relative humidity.

The following assumptions are made in calculating RH_{surf}:

1. The water vapor content of air at the interior surface of the door is equivalent to that measured in the living room on the first floor.
2. The finish coating on the interior surface of the door is impermeable and non-hygroscopic; that is, water vapor does not diffuse into the door.
3. When the surface reaches a condition of 100% RH, condensation is not tracked. Accumulation, runoff, and evaporation of condensate are ignored. Similarly, the effect on T_{surf} of the enthalpy of vaporization is ignored. RH_{surf} may drop below 100% at the next hour simply from changes in indoor or outdoor conditions.