Moisture Performance of a Contemporary Wood-Frame House Operated at Design Indoor Humidity Levels

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ABSTRACT

This manuscript concerns a case study involving moisture performance of a contemporary wood frame house over a series of heating seasons in Madison, Wisconsin. Over most of the heating seasons, the building was humidified to levels as calculated by methodology outlined in section 4.3.2 of Proposed ASHRAE Standard 160, Design Criteria for Moisture Control in Buildings.

Over the first two heating seasons following construction, indoor humidity levels moderately lower than design conditions were attained, even though the house was neither occupied nor humidified. The moisture source was evidently wet soil around the building foundation, a condition probably associated with roof runoff deposited near the foundation during construction. Over the third, fourth and fifth heating seasons the house was brought to design indoor humidity values with less than anticipated moisture release by humidifiers. Throughout the study, the indoor humidity levels resulted in some window condensation in cold weather, but the condensation was restricted to glass panes. Attic spaces remained dry. Painted wood-based sidings showed no staining, buckling, warping or finish failure. Stucco cladding showed cracking that, although minor, would be consistent with seasonal moisture accumulation in the sheathing. Substantial seasonal moisture accumulation was measured in the sheathing of exterior walls that did not incorporate an interior vapor retarder. Vapor retarding interior wall paint mitigated moisture accumulation, but nonetheless permitted seasonal peak sheathing moisture contents to exceed 16%. Seasonal moisture accumulation was greater in walls clad with plywood panel siding or stucco than it was in walls clad with strandboard lap siding or brick veneer. With lap siding, an air gap between siding and sheathing, even though not intentionally ventilated, reduced seasonal moisture accumulation and aided in springtime dissipation of moisture.

INTRODUCTION

A standard outlining design moisture load calculation methodology has been under development, and was recently released for public review by ASHRAE Standard Project Committee SPC 160P (ASHRAE, 2006). The document, which is a Proposed Standard, is, for brevity, referred to in this manuscript as ASHRAE 160. Interior humidity is among the important moisture loads to which a building is exposed, and ASHRAE 160 outlines three methods (of varying complexity) for estimating design interior humidity. The main objective of this study was to evaluate the effects and implications of operating a contemporary wood-frame home at interior humidity levels calculated by one of the methods in ASHRAE 160, specifically the method of intermediate complexity. This calculation methodology, outlined in section 4.3.2 of ASHRAE 160, is consistent with that described by TenWolde and Walker (2001).

Moisture is a component of spray cellulose insulation. It is needed to activate the adhesive additive, which allows complete filling of vertical cavities, and precise mechanized removal of overfill. The recommended initial moisture content for spray-applied cellulose is between 25% and 40% by weight (Burch et al. 1999). Rapid drying of the insulation after installation is desirable. Because wall cavities without a vapor retarder dry more quickly than walls with a vapor retarder, cellulose manufacturers have advocated installation

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of wet-blown cellulose insulation without a vapor barrier, even in cold climates. This recommendation was based on the assumption that the cellulose insulation's capacity to store moisture during winter would provide enough moisture buffering that the wall could cycle through the winter season without moisture damage or mold. Burch et al. (1999) investigated the validity of this assumption via computer analysis of exemplars in which a vapor retarder was omitted. Given the construction, and the boundary conditions used in their simulation runs, and given their criteria for acceptable performance, their analyses suggested that an interior vapor retarder was unnecessary in cold climates.

It can be argued that the combinations of constructions, boundary conditions, and performance criteria chosen by Burch et al.(1999) were such that their analyses provide little confidence that omitting a vapor retarder in cold climates is safe practice. The location they used as the primary exemplar for a cold climate was Boston, MA, which has a historic heating season containing roughly 5800 Fahrenheit heating degree days (65°F basis). This climate meets DOE Building America criteria for a cold climate by roughly 400 Fahrenheit heating degree days. Chicago, Detroit, Cleveland, and Denver historically experience a greater number of degree days in a heating season. The construction modeled in their simulation analyses incorporated plywood sheathing. Plywood sheathing has roughly three times the vapor permeance of oriented strand board (OSB) sheathing at 90% RH (Burch et al. 1992; Kumaran 2001). More recently, Ojanen et al. (2006) found that outward vapor transmission rate through simulated wall sections was roughly an order of magnitude slower when OSB was substituted for plywood sheathing. The methodology used by Burch et al. (1999) for calculating assumed indoor humidity levels was evidently similar to that in section 4.3.2 of ASHRAE 160, but assumed a slightly lower indoor moisture generation rate and a slightly higher ventilation (air exchange) rate. The criteria selected by Burch et al. (1999) for acceptable performance was that the sheathing (and siding) not reach fiber saturation, or alternatively that it remain at a lower moisture content than that in equilibrium with an atmosphere at 97% RH (a condition slightly drier than fiber saturation, at the verge of capillary condensation). By either of these performance criteria, decay establishment would not be anticipated in wood based material as long as it were not initially infested, (a reasonable assumption for panel products produced by hot pressing), particularly if the moisture accumulation were to occur at cold temperatures. At room temperature however, the criteria provide, at best, a narrow safety margin with regard to decay establishment, and (unless a mold inhibitor is present) no safety margin at all with regard to mold growth[1]. The more stringent of the two criteria, (moisture content below equilibrium with 97% RH), furthermore allowed for higher moisture levels than 16% mc, the level prescribed by the APA Engineered Wood Handbook (Baker 2002) as the maximum acceptable level for wood-based sheathing in service[2]. According to the formula presented by Richards et al. (1992) for OSB sorption, 16% mc is the equilibrium mc of OSB at 88% RH[3].

As indicated previously, this study was undertaken to identify issues associated with operation of a contemporary wood frame house in a cold climate (specifically a climate with approximately 7000 Fahrenheit heating degree days) at humidity levels calculated by section 4.3.2 of ASHRAE 160. One of the issues evaluated, and the issue investigated in greatest detail, was the performance of walls insulated with spray cellulose.

THE BUILDING

Description and Characteristics

The FPL Research House is a 2-story, 4-bedroom, 2200-ft^2 (204 m^2) wood-frame building, with attached garage (Figure 1). The exterior walls are framed with 2x6 (38 mm by 140 mm) studs, and sheathed with 7/16" (11 mm) oriented strand board. The exterior wall finishes are OSB lap siding, brick veneer, plywood panel siding, and cement plaster (stucco). The foundation is a Permanent Wood Foundation, constructed with pressure-treated southern pine 2x8 (38 mm by 185 mm) lumber and pressure-treated plywood. The treated lumber and plywood are of foundation-grade, and thus were kiln dried after treatment. Exterior walls, including the basement walls, were insulated with spray cellulose at a density of 2.3 lb/ft3 (37 kg/m3) (oven dry weight basis). The foundation walls are covered with painted gypsum drywall, making the basement semi-finished. With the exception of three stud spaces associated with an instrumented wall (described subsequently), no vapor retarders were installed on the interior. The garage walls and the garage ceiling are insulated with cellulose insulation and are drywalled, taped, textured, and painted. Ceilings are insulated with dry-blown cellulose insulation. The house has three attic spaces, (one over the "great room" one over approximately half the garage ceiling, and one over the second story). Each of the attic spaces is ventilated; the small attic space over the garage is ventilated with soffit vents, while the other two attic spaces have vents in both the soffits and roof planes.

The house is heated with a sealed combustion dual firing rate condensing gas furnace. It is cooled in hot weather with central air-conditioning. The house is equipped with an energy recovery ventilator (ERV) with the incoming tempered fresh air ducted to the main return duct leading to the furnace

1. Cellulose insulation contains borate additive which inhibits combustion and mold growth, and may inhibit decay propagation as well.

2. The APA Engineered Wood Handbook assumes that higher levels may be attained by sheathing during construction, but that once the building is enclosed, the sheathing will dry, and thereafter will not exceed 16% mc in service.

3. At 24°C

Figure 1 *The FPL research house in Madison, Wisconsin.*

air handler (blower). A fresh air intake ducted to the furnace blower is a standard feature in contemporary residential construction in Wisconsin; inclusion of an ERV in such a setup is not however common. In blower-door testing, the house was found to have an ACH50 of 4.3[4]. This was in common mode testing, wherein the (weather-stripped) door between the house and the attached garage was closed, as was the door (an undercut interior passage door) between the house and the semi-finished basement, and the exhaust and intake hoods for the ERV were blocked. Although both the garage and basement are semi-finished, with walls insulated, drywalled, and painted, neither the basement nor the garage have supply or return registers. Second-story ducts are in the attic, partially buried in insulation. Effort was taken to seal ducts (mastic was used extensively), and particular care was taken on the second story to seal registers boots to their drywall cut-outs using latex foam. The heating/cooling system has two thermostats (one for the first story and one for the second story); the supply duct system is thus equipped with zone dampers. In duct leakage testing, with both zone dampers open, total (combined supply and return) leakage "to" (actually, from) the outside was 55 cfm (0.026 m3s-1) at 25 Pa. (house and ducts at negative 25 Pa. with regards to the outside). At a negative 50 Pa., total duct leakage from the outside was 86 cfm; this was roughly equivalent to 7% of the total house air leakage, measured at the same pressure differential, in blower door testing.

The building site is a gently sloping hillside, near, but not at, the crest of a knoll. The site receives no runoff from pavement; all nearby pavement is at lower elevation than the building site, or is curbed and drained to functioning storm sewers. Aside from a short (roughly 15-minute) daily public tour that occurs from May through early October, the house is unoccupied.

4. Air leakage rate with the house depressurized to 50 Pa. was 1300 cfm (0.61 m^3s^{-1}). This air leakage rate multiplied by 60 (minutes in an hour) amounts to roughly 4.3 times the (18,200 ft^3) interior volume of the house.

Construction History

Construction began in January 2001 and was completed in October of that year. Foundation wall sections were prefabricated, and were placed in below-freezing weather. The building was enclosed by May 1, at which point it had a functional (water-shedding) roof, windows and doors were installed, and the wall sheathing was covered with spun-bonded polyolefin membrane. Wall instrumentation for moisture content, relative humidity, and temperature (described more fully later) was installed by June 19. As indicated previously, above grade walls and foundation walls were insulated with spray cellulose; the insulation was placed on June 19 and 20[5]. Interior paper-faced gypsum drywall was installed in most of the house roughly ten days later; the exception was the southwest-facing wall of the attached garage. On the southwest-facing wall of the garage, drywall was not installed until August. Moisture instrumentation indicated sheathing moisture contents of roughly 20 percent in above-grade walls on June 29, the date when much of the drywall was hung. Weather conditions were conducive to drying in late June and early July, and sheathing moisture content in instrumented walls was 16% or less by the middle of July. The drywall was painted in late August with flat interior emulsion (latex) paint.

Exterior wall claddings were installed between mid July and late September. Most sections of the OSB lap siding were installed directly over the polyolefin-covered sheathing; the only airspaces behind the siding were those occurring by lap installation of the flat (un-tapered) siding. One section of OSB lap siding was installed on ¾-inch (19 mm) furring strips, but without vent openings at either the top or bottom of the wall. All OSB lap siding was blind-nailed. The section of wall clad with stucco was of single-story height and faced south-southwest. The stucco was cementitious, (consisting of portland cement, lime and sand) installed in a conventional manner in three "coats". The first (scratch) coat was installed on expanded metal lath. The stucco had vertical control joints at intervals of 78" to 92" (2.0 - 2.3 m). All cladding systems, with the exception of brick veneer, were painted after installation. Exterior paint color was off-white (Figure 1).

Roof gutters were installed at completion of construction. Landscaping, which included final grading to direct water from gutter downspouts occurred shortly after gutter installation. Monthly rain totals for June through November of 2001 are shown in Table 1. The combination of significant rainfall in August and September and lack of roof gutters resulted in significant wetting of roughly the lowest 0.3 m (12 inches) of sections of foundation wall, particularly those sections located in the lateral vicinity of roof eaves. Foundation wall-base wetting became easily observable in September; various species of molds grew on gypsum drywall within 7.5 inches (190 mm)

5. According to the simulations of Burch et al. (1999), the installation date (mid- to late-June) was virtually ideal for dissipation of spray (installation) moisture from above-grade walls in a cold climate.

Table 1. Monthly Rainfall Amounts (at MSN Airport) June—November 2001

Month	Rainfall Amount in Inches (mm)
June	5.40 (137)
July	3.09 (78)
August	7.64 (194)
September	5.53 (140)
October	2.62 (67)
November	1.59 (40)

of the finished basement floor. The mold was removed by cutting and removing the lower 195 mm of gypsum drywall, and removing the (usually wet) cellulose insulation from the lower portion of foundation walls (from the cut line down to the foundation wall plate). Insulation removed from foundation sections in the lateral vicinity of roof eaves usually gave obvious appearance of being above fiber saturation; water could sometimes be squeezed from it with moderate hand-grasp pressure, and much of it was obviously infested with the mold fungus Penicillium chrysogenum. In some locations, the insulation was so wet that water would drain from it without squeezing; insulation this wet generally was not inhabited with mold, but smelled of hydrogen sulfide, perhaps indicating infestation by anaerobic bacteria. Since the removal of the bottom 195 mm of drywall from foundation walls there has been no further occurrence of mold on the remaining drywall in the basement. The significant wetting of foundation wall bases in September of 2001 indicated that soil moisture conditions near the foundation were high at completion of construction.

STUDY METHODOLOGY

Instrumentation

Eight stud spaces in above-grade walls, each of full wall height, were instrumented for measurement of sheathing moisture content and sheathing temperature, and for measurement of relative humidity and temperature close to (within roughly 4 mm of) the inner face of the sheathing. Moisture content measurements were made with pins, five pairs in each of two vertical rows, the rows at third-points between the studs. Pin leads were connected to a multi-channel instrument marketed for monitoring moisture in kiln loads of lumber in industrial lumber-drying operations. The instrument in effect measured DC resistance with a bridge circuit, but recorded values in terms of equivalent moisture content of a reference wood (Douglas-fir) at 70°F (21°C). We converted instrument moisture content readings to resistance values, and then made corrections for temperature and or the material being measured (OSB). The relationship between moisture content (mc) and resistance(R) of the OSB sheathing (at roughly 21°C) was found (by laboratory measurement) to be as follows:

$$\ln(mc) = 4.17 - 0.097\ln(R)$$

where

mc is gravimetric, expressed as a percentage

R is expressed in ohms

Correction of moisture content values for temperature was made based on an assumed straight-line relationship between the natural logarithm of resistance and temperature at constant moisture content. This assumption was based on a data plot presented by James (1968) for black ash (*F. nigra*), (at mc in equilibrium with 80% *RH*), over the range of 0°F to 120°F (-49°C to 49°C). The slope of the straight-line relationship is:

$$\frac{\Delta\ln(R)}{\Delta T} = -0.044$$

when

ΔT is expressed in Fahrenheit degrees

Conversions and corrections were performed via software, after the data had been downloaded from the instrument, first to a data collection computer located in the house, and later to a general purpose computer used for data processing. Sheathing temperatures were monitored with thermocouples, (at two locations on the sheathing in each stud space), with thermocouple leads connected to a data logger. Temperature and relative humidity near the sheathing were monitored with Vaisala HMP 233 sensors, with sensor output connected to the same data logger used to monitor sheathing temperature. Location of the RH sensor was not controlled with extreme precision; a plastic cable clamp was used to secure the sensor lead to the sheathing. The clamp was located within roughly 8 mm (axially along the cable lead) of the sensor; flex in the cable lead between the sensor and clamp could have resulted in minor sensor displacement during installation of the cellulose insulation.

Instrumented walls are listed in Table 2. It may be noted that five of the eight instrumented walls were in the garage. The normal living space of the house had an insufficient number of available uninterrupted full-height stud spaces for instrumentation. The house had many windows and inside and outside corners in the exterior walls; and the interior surfaces of some of the full-height opaque walls were covered with cabinets. This incidentally is common in contemporary residential architecture.

Table 2. Designation and Description of Instrumented Walls

Wall Designation	Orientation That Wall Faces	Stud Spacing and Wall Height	Exterior Cladding Type	Interior Vapor Retarder
H-1	302° (WNW)	24 in. (0.6 m)/10 ft (3.0 m)	Brick veneer	None
H-2	32° (NNE)	24 in. (0.6 m)/ 10 ft (3.0 m)	OSB lap siding	None
H-3	32° (NNE)	24 in. (0.6 m)/10 ft (3.0 m)	OSB lap siding (furred[2], not ventilated)	None
G-1	122° (ESE)	16 in.(0.41 m)/112 in. (2.8 m)	Plywood panel (“T-111”)	None[3] (for first four heat seasons)
G-2	122° (ESE)	16 in.(0.41 m)/112 in. (2.8 m)	Plywood panel (“T-111”)	None[3] (for first four heat seasons)
G-3	212° (SSW)	16 in.(0.41 m)/112 in. (2.8 m)	stucco	None
G-4	212° (SSW)	16 in.(0.41 m)/112 in. (2.8 m)	stucco	None
G-5 [1]	212° (SSW)	16 in.(0.41 m)/112 in. (2.8 m)	stucco	polyethylene

[1] Drywall was hung on walls G-3, G-4, and G-5 in August, more than 6 weeks after installation of the spray cellulose insulation. The polyethylene in wall G-5 was installed over three stud-spaces (G-5 being the middle of the three spaces) shortly before the drywall was hung.
[2] Furring strips were ¾-in. 19 mm thick
[3] Vapor retarding paint applied at start of fifth (2005–2006) heating season

Drywall gasket was installed around the perimeter of each instrumented stud cavity (on inboard faces of studs and of top and bottom plates) before drywall was hung. Instrumented walls did not have any electrical utilities in them, although walls G-2 and G-3 were each fitted with one non-functional (not wired) duplex receptacle in an “old work” box that clamped to a carefully cut hole in the drywall. Instrumentation lead wires exited the stud cavities through PVC thimbles at wall top or bottom plates, and thimble ends, (where lead wires emerged), were foamed shut. In essence, all instrumented stud cavities with the exception of G-2 and G-3 were airtight, and G-2 and G-3 were, if not airtight, very nearly so.

Building Operation

Because the basement is insulated and semi-finished, and because there are daily public tours of the house from May through early October, the house is operated with the basement door removed from its hinges. This allows relatively free air (and vapor) exchange between the house and the basement. As stated previously, instrumented walls G-1 through G-5 were located in the semi-finished (and insulated) garage. The garage was therefore heated for the heating seasons discussed in this manuscript. For the first four heating seasons, the door between the house and garage was left open, and the garage was heated by a combination of heat transfer through the open doorway, and use of a fan-forced electric heater. As discussed in greater detail later, for the fifth heating season, the door between the house and the garage was closed, and the garage heated with the fan-forced electric heater[6]. The essential point is that the house has never been operated in the same mode in which its ACH_{50} was determined. The basement and the garage were relatively air-leaky compared with the house. Both of these relatively leaky series-attached zones were, from an air-exchange standpoint, part of the house during the first four heating seasons. For all five heating seasons, the basement series-attached zone was part of the house from an air-exchange standpoint.

Because of the high soil moisture conditions at completion of construction, we did not humidify the building during the first (2001-2002) heating season. Despite the lack of humidification, we observed window condensation when outside temperature fell below roughly 12°F (-11°C). During the first heating season the house was heated to 60°F. We did not operate the ERV for the first heating season, but neither did we block the ERV’s outdoor air intake duct. This allowed the furnace blower to draw some outside air through the ERV core into the return duct system when it (the furnace blower) was in operation. Based on what we had observed during the first heating season, we again chose not to humidify the house for the second (2002-2003) heating season; again we observed window condensation in cold weather. The house was heated to 60°F for the first half of the 2002-2003 heating season, and the temperature raised to 70°F for the second half of the

6. There was also most likely some heat transfer by conduction through a second-story bedroom floor that was directly above part of the garage. In addition, for all heating seasons after the first one (2001-2002) the overhead garage door was seasonally covered on the outside with polystyrene foam, and the overhead door held against its jamb sweep seals by wood hand-screws clamped on the door tracks.

season. Indoor vapor pressures during the second heating season never fell below 79% of the vapor pressures corresponding with design indoor temperature and humidity values (described in following paragraphs). Vapor pressures during the second heating season were slightly, but consistently, higher in the basement than in the rest of the house, indicating that the primary humidity source for the building was associated with the basement. Spot checks of sensors in instrumented walls indicated that seasonal peak moisture contents in the sheathing of walls, except G-5, exceeded 16%. In summary, for the first two heating seasons following building construction, humidity levels moderately close to design values were attained in the house, although it was neither occupied nor humidified.

For the third (2003-2004) and fourth (2004-2005) heating seasons, we maintained conditions close to design conditions as calculated with methodology very similar to that in section 4.3.2 of ASHRAE 160. ASHRAE 160 is a guide to use of hygrothermal simulation models and specifies that the analytic procedure used shall be transient with a maximum time step of one hour. ASHRAE 160 thus effectively mandates that interior humidity levels be calculated no less frequently than hourly. For a study such as this, it is impractical to re-set indoor humidity set-point values on an hourly basis. We instead calculated monthly indoor humidity values based on historical mean monthly outdoor vapor pressures, and, (as discussed more fully in following paragraphs), on assumed rates of interior moisture generation and of ventilation. Target indoor conditions are shown in Table 3.

ASHRAE 160 assumes that heating takes place when the daily average outdoor temperature is below 65°F, and that the heating set-point temperature is 70°F. The cooling set point is assumed to be 75°F. For October through April, (the months with humidity set-points) humidity was maintained with free-standing humidifiers in the house and in the garage.

The calculated indoor humidity values are based on a design moisture release rate of 15 liters per day (an assumed occupancy of 5 persons), and air exchange between the house and the outside of 0.2 ACH, (the default ventilation rate assumed by ASHRAE 160 for non-airtight construction). The default design air exchange ratio of 0.2 hr^{-1} is approximately equivalent to 1/20th of the measured air leakage rate for this house in standard blower door testing, and thus corresponds with the calculation cited by Bower (1995) for crudely estimating normal air exchange rate from blower door testing. For the 18,200 ft^3 volume of the combined first and second stories, an air exchange ratio of 0.2 corresponds with 60 cfm, which incidentally, is the minimum constant ventilation rate as calculated by formula 4.1a of ASHRAE Standard 62-2-2004 (ANSI/ASHRAE 2004), for providing acceptable indoor air quality for a house of 2200 ft2 floor area with 4 bedrooms.

As indicated previously, the house, basement and garage operated during the 3rd and 4th heating seasons as a single zone with regard to air exchange. In contrast, the indoor humidity values in Table 3, were based on calculations in which neither the basement nor garage were included in the house interior volume[7]. The December through February design indoor humidity values in Table 3 are moderately higher than the wintertime value of 35%-40% often cited as risky to exceed in residential buildings of normal construction in cold climates (Powell 1994; ASTM 2004). The calculation methodology is intended to yield indoor RH values that would be exceeded in one home in ten (TenWolde and Walker 2001). The design RH values are appreciably higher than what would be desirable for indoor RH, although equivalent RH values nonetheless occur with some regularity.

During the third and fourth heating seasons, the ERV was not operated, and the outside air intake port of the ERV was furthermore blocked. This was to reduce consumption of demineralized water by the humidifiers and prolong their lives. During the third heating season, and the beginning of the fourth heating season, water consumption by the humidifiers was not measured precisely, but was crudely estimated as ranging between 6 and 10 L/day. During the later half of the 4th heating season, consumption of water by the humidifiers was carefully monitored.

For the fifth (2005-2006) heating season, the door between the house and the garage was closed. The garage was heated and humidified (as during the 3rd and 4th heating seasons) to the levels outlined in Table 3, while humidifier output within the house was targeted at 10 liters of water per day, and the ERV was operated for 20 minutes of each hour[8]. Operated for 20 minutes of each hour, the ERV would result in 0.14 ACH at its nominal net flow rate of 130 cfm (where the internal house volume is assumed to be 18,200 ft3). In addition, at the start of the 2005-2006 heating season, the gypsum drywall of the wall section containing walls G-1 and G-2 was painted with a contemporary latex vapor retarding paint, at the rate of 258 ft2/gallon[9].

No dedicated dehumidification equipment is used in the building; some mechanical dehumidification however likely occurs in warm weather as a by-product of air conditioning.

Actual indoor relative humidity levels during the mid and later parts of the fourth and fifth heating seasons are shown in Figures 2 and 3 respectively. The figures indicate that conditions were usually close to targeted values. In January of 2006,

7. If the volume of the basement were included in the calculations, the indoor humidity values for December, January, and February would have been 36%, 34%, and 35% respectively.

8. ERV operation was strictly by timer and was not interlocked or coordinated with operation of the furnace blower.

9. This application rate was approximately 1.7 times the application rate specified by the paint manufacturer for smooth surfaces, (whereas walls and ceilings in the house have a sand-texture finish).

Table 3. Monthly Mean Outdoor Conditions in Madison, WI, and Corresponding Design Indoor Conditions for a 4-Bedroom, 2200 ft^2 Home with 18,200 ft^3 of Interior Volume As Calculated by Section 4.3.2 of ASHRAE 160.

Month	Outdoor Temperature (°F)	Outdoor Vapor Pressure (Pa.)	Indoor Temperature (°F)	Design Indoor RH
January	16.7	256	70	44%
February	20.6	283	70	45%
March	32.3	447	70	51%
April	46	668	70	60%
May	56.5	1032	70-75	uncontrolled
June	66.2	1499	70-75	uncontrolled
July	71.8	1816	70-75	uncontrolled
August	68.3	1777	70-75	uncontrolled
September	59.8	1355	70-75	uncontrolled
October	49.3	840	70	67%
November	35.4	541	70	55%
December	21.7	313	70	46%

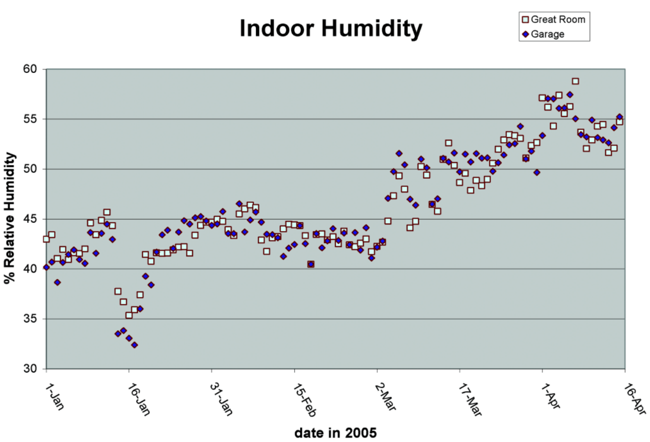

Figure 2 *Indoor humidity in the living room and garage over the period of Jan. 1 —Apr. 15, 2005 (garage and house as single zone). The dip in relative humidity between Jan. 13—18 occurred when a humidifier malfunctioned, and, (after more than one attempted repair), it was replaced.*

humidity conditions in the house (operated at roughly 10L/day release rate) generally exceeded design values.

RESULTS

Building Performance

Over the five heating seasons, no interior mold growth occurred on walls or ceilings, even in (largely empty) closets. As indicated previously, window condensation occurred during the first two heating seasons, (when no humidifiers were operated, and indoor vapor pressures were 3%-21% below design levels). In the subsequent heating seasons, (when the building was humidified), window condensation was somewhat more noticeable. It was however always restricted to glass panes; condensation did not drip off panes onto window sash, frames, or trim. Most of the windows in the house had gas-filled insulating glass units (IGU's) with panes coated with low emissivity coatings. These were rated as having a U-factor of 0.34, and on these units, condensation was always restricted to the lower margins of the panes. It thus appears that windows with equivalent U-factors would probably withstand design interior humidity conditions indefinitely. The side-lite windows on either side of the front entry door contained IGU's of un-identified U-factor[10]. The (two) windows in the basement were of single-pane design, but each also had a factory-supplied (but not factory-installed) outer pane that inserted into the sash. Condensation was distinctly heavier on the entry-door side-lite and basement windows than on other windows. On side-lite and basement windows, condensation at pane center was common in cold weather, but after five heating seasons, the sash, frames and trim of these units nonetheless showed no water staining or mold. It is not however clear whether the sash of the side-lite or basement windows would remain free of staining under design interior humidity conditions over the course of a decade or longer.

No observable moisture accumulation occurred in vented attic spaces. Spot checks taken in mid February and March indicated truss lumber to be at roughly 10% mc. Beaded tongue-and-groove (pattern) lumber on a portion of the exte-

10. The space between the glass panes in side-lite IGU's was roughly 6 mm.

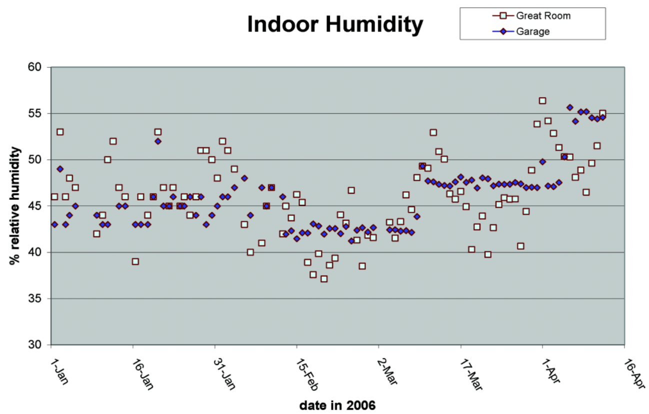

Figure 3 *Indoor humidity in the living room and garage over the period of Jan. 1—Apr. 12, 2006 (garage and house as separate zones). Humidity values in garage are stable at very close to set-points after Feb 15. Humidity levels in the living room vary inasmuch as humidifiers in the house were controlled for daily moisture release, rather than for humidity set-point.*

Figure 4 *Buckled flat-grain pine pattern lumber on porch ceiling in late December of 2005. In contrast to lumber on ceiling, OSB lap siding on adjacent wall is not buckled. Buckled lumber is not defaced by mold or mildew.*

rior porch ceiling was however seasonally wetted, causing buckling and permanent distortion (Figure 4). The pattern lumber was not back-primed. It was nailed to the lower flanges of wood I-joists that cantilevered beyond first story walls; the I-joists supported a second-story bedroom floor that cantilevered beyond the first-story walls. There was no blocking between I-joists where they rested on the top plate of the first-story wall. Outside of the first-story walls and below the second-story bedroom floor, the spaces between I-joists had been packed full of dry-blown cellulose insulation, (using netting to hold the insulation in place). The porch ceiling extended outward beyond the second story bedroom floor to a ventilated soffit. Buckling was restricted to that portion of the ceiling below the bedroom floor (the portion packed with insulation — and not ventilated). Buckling was most extreme near the first story wall. The buckled lumber was of pine sapwood, which has limited mold resistance, but it showed no mold or mildew growth, suggesting that moisture accumulated during the winter was dissipated by the time temperature conditions were conducive to fungal growth[11].

Over five years, the cladding systems showed, at worst, minor distress. The brick veneer cladding, OSB lap siding, and plywood panel siding showed no distress. The OSB and plywood sidings showed no warping or buckling, no staining, and no paint peeling, blistering, or cracking. The stucco cladding showed no finish problems, (indicating that little or no efflorescence had occurred), but it developed some (modest) cracking. The cracking was consistent with dimensional movement of the sheathing, which would correspond with seasonal change in moisture content.

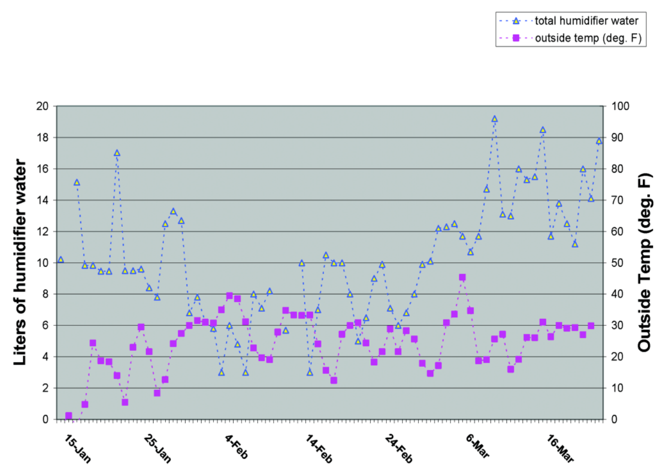

Figure 5 *Daily consumption of humidifier water, plotted with outdoor daily average on-site temperature over the period of mid January through late March of 2005.*

Over the later half of the 4th heating season, (when water consumption of the humidifiers was carefully measured), the combined consumption (in the house and the garage) was, on most days, considerably less than 15 liters per day (Figure 5). Humidification at very close to design levels was thus being attained, usually at much less than the anticipated moisture release rate, despite the fact that the house ACH_{50} value was not particularly low, and, as indicated previously, the house, garage and basement were being operated as a single zone with respect to air exchange. The low measured water consumption by humidifiers was consistent with the crude

11. It is also plausible that the borate additive in the cellulose insulation leached to some degree from the insulation and thereby inhibited mold growth on the lumber.

Table 4. Daily Average Sheathing Moisture Contents and Relative Humidity Values Near Sheathing on Selected Days in 2004, 2005, and 2006.

		Moisture Content on				RH Near Sheathing[1] on			
Wall	Year[2]	2/14	3/15	4/15	6/1	2/14	3/15	4/15	6/1
H-1 (brick)	2004	15	17	16	13	86	89	85 t	75 t
H-2 (lap)		17	19	19	16	83	86	86 t	80 t
H-3 (furred lap)		15	17	16	13	85	87	85 t	74 t
G-1 (plywd panel)		22	24	24	17	95	96	94 t	77 t
G-2 (plywd panel)		22	23	24	17	90	90	88 t	71 t
G-3 (stucco)		22	24	25	17	88	90	89 t	76 t
G-4 (stucco)		22	24	25	18	88	89	88 t	73 t
G-5 (stucco)		12	12	12	12	67	66	59 t	63 t
H-1	2005	19	19	18	13	90 t	90	90 t	69 t
H-2		21	21	23	17	87 t	87	90 t	80 t
H-3		18	18	19	13	87 t	87	88 t	67 t
G-1		26	27	26	17	96	96	95 t	76 t
G-2		25	27	27	17	89	90	89 t	74 t
G-3		27	28	27	17	91	91	91 t	78 t
G-4		27	27	28	18	90	90	90 t	78 t
G-5 (polyethylene)		14	14	13	12	69	70	65 t	62 t
H-1	2006	17	20	17	12	89 t	91	86 t	64 t
H-2		22	23	23	15	87	89	88 t	75 t
H-3		19	20	19	12	86 t	88	88 t	63 t
G-1 (VR paint)		20	20	18	14	91 t	90 t	80 t	71 t
G-2 (VR paint)		21	22	20	15	85 t	86 t	74 t	69 t
G-3		28	30	33	18	90 t	92	78 t	83 t
G-4		28	30	33	20			76 t	
G-5 (polyethylene)		13	13	12	12	66 t	67	62 t	60 t

[1] A designation of "t" following the RH value indicates that daily average temperature at the RH sensor exceeded 5°C (41°F).
[2] The number of Fahrenheit heating degree days for the 2003-2004, 2004-2005, and 2005-2006 heating seasons were 6970, 6545, and 6530 respectively.

estimates of moisture release made the previous heating season, and the (rather high) indoor vapor pressures that had been observed during the first two heating seasons (when no humidifiers were operated). It was also consistent with the over-shoot of design humidity levels in the house in January of 2006 (at a targeted moisture release rate of 10L/day).

Wall Moisture Conditions

In all instrumented wall cavities, except the one with the interior polyethylene vapor retarder, moisture conditions showed distinct seasonal variation. The seasonal peak in sheathing moisture content occurred in late March or early April. Sheathing moisture contents and relative humidity levels within walls near the sheathing are shown in Table 4 on selected days between mid February and early June in 2004, 2005, and 2006.

Like Rose and McCaa (1998), Cautley (2004), and Murray and Tichy (2006), we found that an interior vapor retarder was very effective at controlling moisture conditions in walls during winter and early spring. Table 4 indicates that the only instrumented wall in which sheathing consistently remained below 16% mc during the heating season was wall G-5, the wall with interior polyethylene sheet. Wall G-5 was also the only wall in which relative humidity near the sheathing in the insulated cavity did not exceed 70%. In contrast, in the other walls with the same cladding system as G-5, (G-3 and

G-4), sheathing seasonal peak mc's reached 25% or more, and seasonal peak cavity RH's reached 89% or more. The influence of vapor retarding paint can be seen in walls G-1 and G-2, when conditions in these walls are compared over the three successive winter/spring periods in Table 4. As indicated previously, the vapor retarding paint was applied early in the 2005-2006 heating season. Sheathing mc and cavity RH in G-1 and G-2 were consistently lower from January through early June of 2006 than the corresponding values over the same periods in 2004 or 2005. The vapor retarding paint was not quite able to keep seasonal peak sheathing mc from exceeding 20%, or seasonal peak cavity RH from exceeding 90%. It was obviously insufficient to keep seasonal peak sheathing mc values from exceeding 16%.

Walls with cladding that incorporated some type of airspace between the cladding and the sheathing (H-1, H-2, and H-3) showed less seasonal moisture accumulation than walls with cladding that did not incorporate such a space. Table 4 indicates that sheathing moisture contents were consistently lower in walls H-1 through H-3 than in walls G-1 through G-4 in the winter/spring of 2004 and 2005. As indicated previously, RH sensors could have been displaced slightly during installation of the cellulose insulation; this justifies caution in comparison of cavity RH values between walls. This being so, it is also evident that cavity RH data were not influenced as consistently by wall cladding systems as were sheathing moisture content data. In the late winter of 2004 (and again in 2005), walls H-1 through H-3 showed lower recorded cavity RH values than walls G-1 through G-4, but by June 1st, the recorded cavity RH value in wall H-2 exceeded that in walls G-1 through G-4. The beneficial effect of cladding spacing is not as readily apparent in the data for the winter/spring of 2006 as in the data for the previous two winter/spring seasons. Walls G-1 and G-2, owing to their incorporation of vapor-retarding paint during the fifth heating season, cannot be compared with walls H-1 through H-3 over that season. In addition, in the winter/spring of 2006, the house and garage were, (as indicated previously), operated as separate zones, and interior humidity in the house generally exceeded that in the garage during the winter (Figure 3). Sheathing moisture contents in the spring of 2006 in walls G-3 and G-4 were nevertheless consistently higher than in walls H-1 through H-3.

In walls where the airspace between the cladding and the sheathing was continuous (walls H-1 and H-3), sheathing moisture contents were consistently lower than in the wall where the spacing was not continuous (wall H-2). In addition, springtime reduction in cavity RH was noticeably and consistently more rapid in walls H-1 and H-3 than in wall H-2.

DISCUSSION

Mold Growth Potential

Section 6.1 of ASHRAE 160 outlines three time/temperature/surface relative humidity criteria for prevention of mold growth. The criteria are summarized in Table 5. Failure to meet any one of the criteria represents a mold growth risk.

Table 5. Mold Prevention Criteria as Outlined in ASHRAE Standard 160

Running Average Surface RH	Running Average Temperature	Period for Running Averages
<100	Between 5°C and 40°C (41°F and 104°F)	24 hours
<98	Same as above	7 days (168 hours)
<80	Same as above	30 days (720 hours)

Table 4 indicates that in all walls except G-5, cavity RH values in the vicinity of the sheathing exceeded 80% for extended periods in the late winter and early spring, and suggests that corresponding temperatures rose above 5°C between March 15 and April 15, (and remained above that level thereafter). Table 6 shows 30-day moving average RH and temperature values near the sheathing for selected days in 2005[12]. The ASHRAE 160 criterion of <30 days when running average surface RH is 80% or higher (with running average temperature exceeding 41°F) was appreciably exceeded at the insulation/sheathing interface in all walls except G-5. Mold infestation in all walls (except G-5) would thus be anticipated at the insulation/sheathing interface, unless the borate additive in the cellulose insulation suppressed it. Based on the previous experience of Rose and McCaa (1998)[13], it seemed unlikely that the borate additive could completely prevent within-wall mold growth.

On March 31, 2005 we opened a non-instrumented section of wall on the second story to look for mold. The wall faced east-southeast, and was clad with plywood panel siding; in these regards, the wall section was similar to walls G-1 and G-2. The wall section was fitted with electrical and video cabling and outlet boxes, and it did not incorporate drywall gasket between stud faces and drywall; in these ways it differed from instrumented wall sections G-1 and G-2. In the opened wall section, insulation near the sheathing was inhabited with mold. The mold species was not identified, but it had the same distinctive yellow cast observed in mold-infested insulation removed from the bases of foundation walls in September of 2001. Borate additive in the cellulose insulation obviously did not completely prevent mold growth, but the fact that the mold was all of the same distinct color suggests that the borate inhibits some mold fungi while still permitting others to propagate. The observation of mold in the opened

12. In all calendar years, we experienced some intermittent malfunctions of the data acquisition system. The year in which the data acquisitions system performed most dependably over the winter and spring was 2005.

13. The study by Rose and McCaa, was performed in a climate with fewer heating degree days than Madison. In their study, mold was observed at the insulation/sheathing interface in cellulose insulated walls without an interior vapor retarder after three heating seasons. Interior humidity conditions in their study were, compared with those in this study, relatively dry (40% RH for entire heating season) for two of the three heating seasons.

Table 6. Running Averages of RH and Temperature Near the Sheathing for Selected Days in 2005

Wall	30-Day Running Averages of RH and Temperature at 12:00 on			
	March 15, '05	April 15, '05	May 15, '05	June 1, '05
H-1	90% / 37°F (3°C) (too cool)	91% / 51°F (11°C) (mold risk)	85% / 57°F (14°C) (mold risk)	77% / 62°F (17°C) (too dry)
H-2	86% / 35°F (2°C) (too cool)	89% /49°F (9°C) (mold risk)	89% / 56°F (13°C) (mold risk)	85% /61°F (16°C) (mold risk)
H-3	86% / 36°F (2°C) (too cool)	89% / 50°F (10°C) (mold risk)	83% /56°F (13°C) (mold risk)	76% 61°F (16°C) (too dry)
G-1	96% / 38°F (3°C) (too cool)	96% / 53°F (12°C) (mold risk)	92% / 57°F (13°C) (mold risk)	85% / 61°F (16°C) (mold risk)
G-2	89% / 37°F (3°C) (too cool)	90% / 53°F (12°C) (mold risk)	88% /57°F (14°C) (mold risk)	83% / 61°F (16°C) (mold risk)
G-3	91% /37°F (3°C) (too cool)	91% /52°F (11°C) (mold risk)	89% /56°F (13°C) (mold risk)	84% / 61°F (16°C) (mold risk)
G-4	89% / 37°F (3°C) (too cool)	90% /52°F (11°C) (mold risk)	89% / 56°F (13°C) (mold risk)	85% / 61°F (16°C) (mold risk)
G-5	69% / 38°F (3°C) (too dry and too cool)	66% /53°F (12°C) (too dry)	67% / 56°F (13°C) (too dry)	64% / 61°F (16°C) (too dry)

wall suggests that mold presence is likely in other walls in the building, although for reasons discussed later, the observation does not conclusively prove that mold was present in the instrumented walls.

Spatial Variation In Moisture Conditions

The sheathing moisture content values shown in Table 4 are average values for multiple pin pairs, and thus do not address spatial variation in moisture conditions. Over winter/spring periods, the instrumentation sometimes indicated variation in sheathing moisture content within the plane of the sheathing. When this was the case, the sheathing at mid-wall height tended to read relatively wet compared with that near the top or bottom of the wall.

In the second story wall section that was opened for observation in the spring of 2005, handheld moisture readings indicated that sheathing in the lower portions of wall cavities was consistently wetter than that in upper portions of the wall. This pattern was also observed gravimetrically, by cutting plugs from the sheathing. The plugs were also cut in half at mid-thickness to identify if there was a moisture gradient across the sheathing. The inner halves of plugs had moisture contents ranging from 28% to 58% mc, while the outer plug-halves had moisture contents ranging from 19% to 24% mc; there obviously was a moisture gradient across the sheathing. Handheld meter readings and gravimetric measurements were higher than peak seasonal moisture content readings made in walls G-1 and G-2 in the spring of 2004 or 2005 (Table 4). For this reason, presence of mold in the opened wall cannot, (as indicted previously), be taken as conclusive proof that mold was present in instrumented walls. The relatively high handheld meter and gravimetric values observed in the opened wall suggest that sheathing moisture contents in instrumented walls were at least as high as the values shown in Table 4 (in other words, that the mc values in Table 4 were not erroneously high).

There is obvious discrepancy between the observed spatial variation in sheathing moisture content (from top to bottom of the wall) in the wall that was opened and the spatial pattern that apparently existed in instrumented walls. Moreover, either of the spatial patterns observed in this study differ from the pattern observed by Rose and McCaa (1998). The pattern observed in the opened wall is similar to that observed by Cautley (2004) in a wall insulated with glass fiber insulation. The reasons for the various discrepancies in spatial patterns are unclear, but may be associated with air movement. As indicated previously, in this study, the opened wall differed from instrumented walls with respect to presence of wired utilities, and absence of drywall gasket. In this study, and the study by Cautley, the wall sheathing was covered with polyolefin membrane, and had no cuts through it, whereas in the study by Rose and McCaa, vinyl siding was installed directly over OSB sheathing, and there were friction-fit plugs cut in the sheathing (for periodic gravimetric determination of moisture content). Inasmuch as none of the studies, (including this one), examined air leakage characteristics of the instrumented wall cavities, there is little chance of accurately analyzing hypothetical reasons for the differing spatial patterns observed.

The obvious moisture gradient across the sheathing, (identified in the wall that was opened in the spring of 2005), indicated that the sheathing was impeding outward migration of condensed water. Although moisture content in the outer half of the sheathing was always in excess of equilibrium moisture content at 93% RH (Richards et al. 1992; Kumaran

2001), it nonetheless remained below fiber saturation, even if barely so. The fact that we observed no staining or paint failure on wall sections clad with painted plywood panel siding, despite high sheathing moisture contents, would be consistent with the outer surface of the sheathing remaining below fiber saturation.

Summertime Moisture Conditions

In hot weather, the on-site data collection computer regularly experienced communication problems with the measurement instrumentation. The reason for this is not known with certainty, but is likely associated with electrical noise, either from operation of the air-conditioning unit, or from an underground high-voltage distribution line that is within 30 ft. (9 m) of the house. We thus have some, but not extensive, summertime data. The limited data that we have indicates that the interior polyethylene sheet did not have a noticeably detrimental effect on summertime moisture conditions in wall G-5, even though the wall was clad with stucco. Sheathing moisture content in wall G-5 was roughly 11% in mid-August of 2006, with a corresponding cavity RH value of roughly 63%. These moisture conditions are appreciably too dry for propagation of either mold or decay fungi. Comparable conditions in walls G-3 and G-4 were approximately 10% mc and 48% cavity RH. The interior polyethylene sheet in wall G-5 thus obviously resulted in summertime within-wall moisture conditions that were relatively less dry, but nonetheless dry. It is worth noting that the stucco-clad wall was of single–story height, was reasonably sheltered (by topography) from wind-driven rain, was painted white, showed only minor cracking, had no window or door penetrations, and was shielded from roof runoff or splash by a functioning gutter (and thus was reasonably well-protected from water absorption).

Murray and Tichy (2006) reported that an interior polyethylene vapor retarder slowed springtime moisture dissipation in south-facing stucco-clad walls in a marine climate. They did not however report problematic conditions as a result of the slower drying. In the study by Murray and Tichy, (as in this study), stucco-clad walls were protected from roof splash by a functioning eaves gutter. In contrast, Straube and Burnett (1998) observed substantial (although not necessarily problematic) summertime moisture accumulation in a climate similar to Madison in framing of walls that incorporated an interior vapor retarder and were clad with brick veneer. They indicated that the summertime moisture accumulation resulted from inward movement of water vapor whose origin was absorbed water in the brick cladding. It should be noted however that the walls, (in which Straube and Burnett observed summertime moisture accumulation), had limited protection from wind-driven rain, were not protected from roof splash, and were constructed with very vapor permeable layers between the framing and the brick cladding (gypsum sheathing and mineral fiber insulation board).

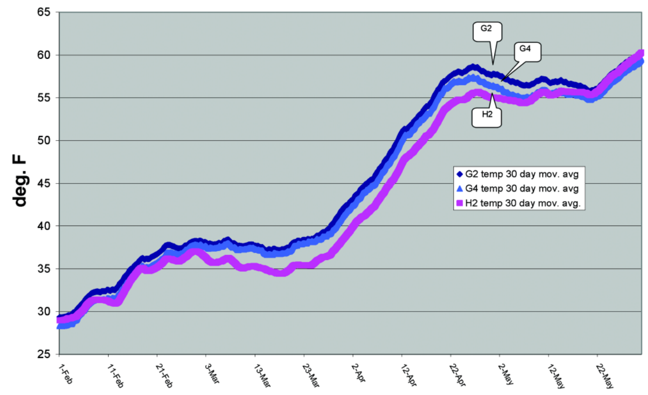

Figure 6 *Temperature near the sheathing in three selected wall cavities during the winter/spring of 2005.*

Effect of Cladding System and Spacing

It is fairly clear that the more benign winter/spring moisture conditions in walls H-1, H-2, and H-3 than in walls G-1 through G-4 are associated with characteristics of the cladding systems. All the instrumented walls in the garage, owing to the directions that they faced, received more solar warming during winter and early spring than did the instrumented walls in the house. Plots of temperature (measured near the sheathing) for selected walls are shown in Figure 6.

Despite the consistently higher outer-cavity temperatures seen in Figure 6 in the walls facing ESE or SSW (walls G-2 and G-4) than in the wall facing NNE (wall H-2), the wall facing NNE showed less sheathing moisture accumulation, and (at least until early-spring) tended to show lower RH in the insulated cavity (Table 4). The primary reason for superior moisture performance of the walls clad with brick veneer or lap siding is probably air exchange between the exterior and the space(s) behind the cladding. Our observations concur with those of Murray and Tichy (2006), who observed drier conditions in walls clad with fiber cement lap siding than in walls clad with stucco[14]. By algebraic calculation, Straube and Burnett (1998) evaluated the theoretical benefit of cladding ventilation, and concluded that the benefit was likely substantial even when ventilation rates were modest.

As also indicated previously, of the two walls clad with OSB lap siding, the one on which the siding was installed on furring strips showed more favorable moisture history than the one on which the siding was not furred, even though the furred space was not provided with inlet or outlet vents. The difference in moisture history is clearly visible in the sheathing moisture data (Table 4). In contrast to the effect on sheathing moisture content, there appears to be essentially no effect

14. Murray and Tichy included one wall clad with a furred stucco system. They found that moisture performance of this wall was as good as walls clad with fiber cement lap siding.

on relative humidity within the insulated cavity until approximately April 15. Between April 15 and June 1 however cavity RH drops noticeably faster in the wall clad with siding installed on furring (Tables 4 and 6). The observed benefit of installation of lap siding on furring strips is consistent with the observations of Bassett and McNeil (2005) who found that measurable ventilation occurred behind furred siding, even when inlet vents were small and outlet vents were not intentionally provided.

CONCLUSIONS

In this case study, the house could be brought to design humidity levels at lower than anticipated indoor moisture release rates. Furthermore, for the first two heating seasons following construction, indoor humidity levels were moderately close to design conditions with no moisture release by humidification equipment. This appears to have been the result of high soil moisture levels near the building, which in turn appears to be related to the common practice of installing roof gutters near or at the end of construction. It thus appears that soil moisture may be a significant moisture source in new construction, (or in buildings with no or poorly-functioning roof gutters).

Operation at design humidity levels resulted in a few readily observable performance problems, none of which were particularly troublesome or expensive to remedy. These problems were: 1) window condensation in cold weather, (apparently insufficient to cause window damage), 2) minor cracking of stucco cladding, (probably associated with seasonal moisture accumulation in sheathing), and 3) buckling of flat-grain lumber in the unventilated portion of a porch ceiling. Interior mold growth was not observed. Neither were performance problems with contemporary wood-based siding. Neither was attic moisture accumulation.

Omission of a vapor retarder in this test house in a 6700 Fahrenheit HDD (3700 Kelvin HDD) climate and operated at design humidity levels resulted in significant seasonal moisture accumulation in OSB wall sheathing. The accumulation was consistently sufficient to cause seasonal peak moisture levels to exceed 16%, and sufficient to cause humidity conditions at the insulation/sheathing interface to exceed at least one criteria of ASHRAE 160 for mold growth risk. Although interior vapor retarding paint limited moisture accumulation in the sheathing and cavity RH near the sheathing, it was not sufficient to keep sheathing mc from seasonally exceeding 16%. Destructive investigation of a wall section that had no vapor retarder (neither polyethylene sheet nor vapor retarding paint) showed that mold was present near the insulation/sheathing interface. Based on these observations, we suggest that omission of the interior vapor retarder in cold climates is risky. Conversely, the instrumentation gave no evidence that an interior vapor retarder resulted in troublesome moisture accumulation during the summer, even in a southwest-facing stucco-clad wall.

The cladding system had a clear influence on seasonal moisture accumulation in insulated walls. Cladding systems that incorporate some type of airspace limited seasonal moisture accumulation, and (for the most part) aided in springtime moisture dissipation. Performance was noticeably better if the airspace was continuous, even if the continuous airspace was not provided with vent openings.

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