# Field Monitoring of Cold Climate Double Stud Walls with Cellulose and Low-Density Foam Insulation

Kohta Ueno<sup>1</sup>, Joseph W. Lstiburek, Ph.D., P.Eng.<sup>2</sup>

# ABSTRACT

Double-stud walls insulated with cellulose or low-density spray foam can have high R-values; compared to approaches using exterior insulating sheathing, double-stud walls are typically less expensive, and have exterior details similar to typical construction. However, double stud walls have higher risks of interior-sourced wintertime condensation damage.

Field monitoring was installed in a Zone 5A climate house with 12" thick double stud walls; assemblies included 12" open cell polyurethane spray foam, 12" netted and blown cellulose, and  $5-\frac{1}{2}$ " open cell spray foam at the exterior of the stud bay.

Data were collected for three winters. The first winter was mild (warm), and interior relative humidity levels were very low (unoccupied conditions). Sheathing moisture contents rose to peak values in wintertime; open cell foam walls peaked in the 15-20% MC range, but the cellulose wall peaked in the 20-25% range.

In the second winter, the house was occupied, and the ventilation system was not functioning; these factors combined with low air leakage resulted in high wintertime humidity levels (40-50% in December-January). The response in the wall assemblies was markedly greater wetting and high risks; condensation gauges indicated condensation occurring at all walls, but much wetter conditions in the cellulose walls.

The third winter combined occupancy with a functioning ventilation system (and thus more moderate interior relative humidity levels) with a very cold winter. Sheathing MCs were below 20%, except for the north-facing cellulose wall. Summer measurements following each winter of wetting indicated that all walls dried to safe levels.

ASHRAE 160 criteria were applied to the monitored data; all walls failed (i.e., mold growth likely). However, when the walls were disassembled at the conclusion of the experiment, the sheathing and framing showed remarkably little evidence of wetting damage or mold growth. No visible mold growth was found, nor evidence of staining or water rundown. The damage was limited to some grain raise of the interior surface of the OSB at the cellulose wall, and corrosion of fasteners.

## INTRODUCTION

Double-stud walls insulated with cellulose or low-density spray foam can have R-values of 40 (RSI 7.0) or higher. Compared to approaches using exterior insulating sheathing, double-stud walls are typically less expensive, and have exterior trim details similar to conventional construction. However, double stud walls have a higher risk of interior-sourced condensation moisture damage. Insulation outboard of structural sheathing increases the winter temperature of the sheathing, while additional insulation inboard of the sheathing decreases its temperature (Straube and Smegal 2009).

<sup>&</sup>lt;sup>1</sup> Kohta Ueno, Senior Associate, Building Science Corporation, Westford, MA

<sup>&</sup>lt;sup>2</sup> Joseph W. Lstiburek, PhD, P.Eng., Principal, Building Science Corporation, Westford, MA

If a double-stud wall is compared with a 2×6 wall with the same type of stud bay insulation and no exterior insulating sheathing, it is clear that the double-stud wall sheathing experiences less heat flow and colder wintertime temperatures. Both of these factors increase the risks of moisture-related problems (Lstiburek 2008, LePage et al. 2013). Low-density spray foam (open cell polyurethane spray foam/ocSPF, 0.5 lb/ft<sup>3</sup> or 8 kg/m<sup>3</sup>), with similar R-value to cellulose, is believed to have lower moisture risk because its superior control of air leakage reduces the risk of wetting of the exterior sheathing due to interior-source moisture. However, the insulation material is still open to vapor diffusion: a 12" (305 mm) thickness of ocSPF has a vapor permeability of 7.3 perms/419 ng/(Pa·s·m<sup>2</sup>) (both wet and dry cup; ASHRAE 2009), while 12" of cellulose is roughly 7–10 perms/402-575 ng/(Pa·s·m<sup>2</sup>) (dry and wet cup).

A moisture monitoring experiment was conducted at a new production house located in Devens, MA (DOE Zone 5A). The builder has been using double-stud walls insulated with 12" of ocSPF; however, the company has been considering a change to netted and blown cellulose insulation for cost reasons. Cellulose is a common choice for double-stud walls due to its lower cost (in most markets). However, cellulose is an air-permeable insulation, unlike spray foams. For these reasons both materials were tested as a comparison.

#### **PREVIOUS WORK**

Arena et al. (2013) monitored moisture contents in double stud walls insulated with cellulose in DOE Zone 5A. Walls were monitored for temperature, relative humidity, and moisture content on north and south sides. The wall thickness was 10.5" (267 mm), resulting in nominal R-40 (RSI 7.0) insulation. A vapor retarder primer was applied to the interior gypsum board. South side sheathing moisture contents peaked near 17%, while north side moisture contents peaked higher, slightly over 20%. Wintertime interior relative humidity levels were typically in the 20-30% range, with slightly higher than typical interior temperatures 72-73°F/22-23°C. The assemblies were also simulated using WUFI; correlation between measurements and simulations were difficult; the model was tuned assuming a bulk water leak at the moisture content pins, which improved correlation. The assemblies were also evaluated in terms of ASHRAE Standard 160 criteria: based on monitored data, both north and south walls fail. However, the authors have simulated other common walls using ASHRAE 160, and have found that many commonly-used walls fail this test, which suggests that the standard has overly conservative criteria for failure.

Fox (2014) monitored multiple high R-value wall assemblies in a test hut in Kitchener-Waterloo, ON (DOE Zone 6A) over one fall-winter-spring season. The walls included deep cavity walls insulated with dense-packed cellulose (double stud and I-joist), cavity walls with exterior insulation (polyisocyanurate, extruded polystyrene, and mineral wool), a closed cell spray foam wall (with 2x8 studs), and a "datum" or baseline comparison wall (2x6 with cavity insulation). After running the walls for a baseline period (October to mid-February), the walls were stressed in mid-winter (mid-February to April) by injecting interior air (at roughly 40% RH) into the insulated stud bay cavities, followed by a drying period. During the baseline period, all walls had relatively low and stable moisture contents. However, when interior air leakage was introduced, moisture contents rose sharply in the walls without exterior insulation, with many moisture contents above 20%. Overall, this work demonstrated that "thick" walls with cold sheathing (i.e., double stud and I-joist walls) are more vulnerable to interior-sourced condensation than exterior insulated walls.

## EXPERIMENTAL SETUP AND ASSEMBLIES

Three wall assemblies were instrumented; they were duplicated on opposite orientations (north and south), for a total of six test wall sections, described as follows:

- N1/S1: 12" (305 mm) 0.5 lb/ft<sup>3</sup> (8 kg/m<sup>3</sup>) open cell spray foam in double-stud wall (as per the remainder of the house). The spray foam was installed in three passes, with time allowed between the passes for cooling. The insulation is a nominal R-48 (RSI 8.1).
- N2/S3: 12" (305 mm) netted and dry blown-in cellulose in double-stud wall. The density was not directly measured, but it was reported to be 3.5 lb/ft<sup>3</sup> (56 kg/m<sup>3</sup>). Typical densities achieved for proper dense pack installations behind netting are 3.5-4.0 lb/ft<sup>3</sup> (56-64 kg/m<sup>3</sup>) (Tauer 2012). The insulation is a nominal R-42 (RSI 7.4).
- N3/S3: 5-½" (140 mm) of 0.5 lb/ft<sup>3</sup> (8 kg/m<sup>3</sup>) open cell spray foam at exterior of doublestud wall, to approximate conventional 2×6 wall construction and insulation levels, acting as a control wall (a.k.a. "shorted" bay). The insulation is a nominal R-21 (RSI 3.7).

The remainder of the walls are constructed as per the builder's conventional construction, with an oriented strand board (OSB)-based sheathing with an integrated drainage plane and taped seams (no separate house wrap), and vinyl siding. The interior finish is ½" (12.5 mm) gypsum board with latex primer and paint finish (Class III vapor retarder).

The control wall (5-½" open cell foam) is meant to represent common construction (2×6 stud frame walls); this assembly has no history or reputation of endemic moisture failures, which serves as a comparison point to the experimental bays.

The test walls were installed in second-floor bedrooms (Figure 1). The test bays are indicated by the dotted patterns, and the guard areas (non-instrumented portions) are filled with full-thickness spray foam to maintain separation between adjacent bays.



Figure 1: Test walls shown on second floor plan, with guard bay insulation for separation

The test home is not oriented directly north-south, but the southernmost and northernmost walls were used. North-facing walls experience the least solar gain, while south-facing walls receive the most. The two orientations place upper and lower bounds on the moisture problems, as solar gain is the major source of energy to dry the sheathing in well-insulated walls.

As shown in Figure 2 (right), the third bay ("control") on the north side is partially sheltered at the bottom by the sloping garage roof. No better location was available, due to the positioning of windows, bathrooms, and garage.



Figure 2: Test wall locations shown on exterior of house; south (L) and north (R) orientations

## INSTRUMENTATION

Three types of sensors are used to measure conditions within the walls; specifics of these sensors are covered in detail by Straube et al. (2002). Figure 3 shows typical sensor types and installations.

- Temperature sensors (10k NTC thermistors; accuracy ± 0.04°F/0.2°C)
- Relative humidity (RH) sensors (thermoset polymer capacitive based sensors with onboard signal conditioning (accuracy ±3%, 10%–90% RH)
- Wood moisture content (MC) (in-situ electrical-based resistance measurements between corrosion-resistant insulated pins).

In Figure 3, the left-hand image shows a temperature and wood MC sensor installed at the exterior sheathing; the right-hand image shows typical conditions mid-height in the study bay, including temperature/RH (x3), sheathing MC, and stud MC. Another sensor was a wood-based relative humidity sensor (a.k.a. "wafer" sensor), installed at the inboard side of the sheathing, to measure conditions at the likely condensation plane. This sensor can differentiate between high relative humidity levels and condensation/liquid water conditions; it is described in more detail by Ueno and Straube (2008).

Stud bays were chosen to avoid anomalies such as electrical boxes, plumbing pipes, or corners of the building. Lateral air movement at the cellulose bay is controlled by full-thickness spray foam between test bays.



Figure 3: (L) Temperature and MC sensor at sheathing; (R) sensors at mid-height of stud bay

The instrumentation plan for this research is shown in Figure 4; sensor packages are further described in the bullets below.



Figure 4: (L) Instrumentation diagram for 12" ocSPF; (C) 12" cellulose; (R) 5-1/2" ocSPF

• Sheathing moisture content is a key indicator for long-term durability; therefore, three sheathing MC/temperature sensors were installed at each wall (upper/middle/lower).

- The outermost stud MC was monitored at inboard and outboard edges.
- Temperature and RH were monitored at three depths mid-height in the stud bay (outboard/middle/inboard), which allows measurement of temperature and humidity gradients.
- The "wafer" sensor was installed at the inboard surface of the exterior sheathing, to measure surface humidity conditions at the likely condensing plane.
- A temperature sensor was installed at the interface between the insulation and the interior gypsum board.

The sensor complement is identical in the two 12" thick insulation (spray foam and cellulose) wall test bays. At the "shorted" or "control" bay (N3/S3), the sensor count is reduced. There is a "dead" air space between the interior gypsum board and the interior face of the stud bay spray foam. This is not an ideal comparison, but was required to keep the interior gypsum board in plane at this occupied house. Temperature and RH conditions within the void space are being recorded directly, for comparison with interior conditions.

The base of one of the north-facing walls  $(5-\frac{1}{2})$  ocSPF) is shielded by the garage roof (Figure 2); the sensors at the "lower" sheathing location were shifted to the lowest exterior exposure in the stud bay.

In addition to the sensors in the walls, temperature and relative humidity were measured in the north and south bedrooms, and an exterior temperature and relative humidity sensor was located within a solar radiation shield on the north side. The data logger is located in the basement; data are collected at 5-minute intervals, and hourly averages are recorded.

## **RESULTS (OVERVIEW AND BOUNDARY CONDITIONS)**

Roughly 32 months of data were collected and analyzed (December 2011 through July 2014), which covered roughly three winters (one partial). Interior and exterior temperatures are shown in Figure 5. Winter 2011–2012 was exceptionally mild (5220 HDD Base 65°F/2900 HDD Base 18°C versus 6220/3445 HDD climate normal); winter 2012-2013 was closer to normal (6050/3360 HDD), and winter 2013-2014 was very cold (6730/3740 HDD). Interior winter temperatures held steady in both north and south bedrooms in the 65°-72°F (18-22°C) range, except for a period in March 2012 when the heating system was inadvertently turned off.



Figure 5: Exterior and interior (test rooms and basement) temperatures

Interior RH conditions are shown in Figure 6; in the first winter, interior RH levels fell to the 10%–20% range for much of the first winter, which are exceptionally dry conditions. There was no occupancy through the winter, and therefore no interior moisture generation (occupants, showering, cooking), explaining the low RH levels. However, drying of construction moisture was occurring during the winter. Basement RH levels were higher, as would be expected due to lower temperatures. In the second winter, the house was occupied by a family of four, and the ventilation system was not operated consistently; in addition, the house is very airtight (1.1 air change per hour at 50 Pascals/ACH50). This resulted in high wintertime humidity levels of 40-50% for most of the early winter. The ventilation system was put in operation in late winter (mid-February 2013), resulting in lower interior RHs (20-35%). The third winter had interior RHs in the 10-30% range; the spikes in basement RH levels were due to basement flooding issues.



Figure 6: Interior RHs (test rooms and basement)

Interior temperature and RH conditions were used to generate dew point temperatures (absolute air moisture content), which were plotted with outdoor dew points (Figure 7). Interior moisture conditions essentially tracks outdoor conditions in the first winter, as would be expected without interior moisture generation. But in the second winter, interior dewpoints were higher in early winter (40-50°F/4-10°C), with drier conditions after ventilation (30-40°F/-1-10°C). The third winter had dew points between these extremes.



Figure 7: Exterior and interior (test rooms and basement) dew point temperatures

## **RESULTS (MONITORED WALLS)**

Sheathing MCs for the north-facing walls are shown in Figure 8; they show the expected seasonal rise and fall, with peak MCs in wintertime. However, the different boundary conditions in the three winters resulted in different responses from the walls.



In the first winter, the north 12" ocSPF wall (N1) showed a peak wintertime sheathing MC near 12%–15%; the 5- $\frac{12}{2}$ " ocSPF wall (N3) was similar to N1, but with slightly higher peak MCs (15%–20%). However, the 12" cellulose wall (N2) showed considerably higher MCs, in the 20%–28% range. The first winter had low interior RH levels. In the following summer, MCs fell to the safe range (10-12% MC).

However, the second winter, with interior RH levels in the 40-50% range, resulted in much higher sheathing MCs. The north 12" ocSPF wall (N1) showed a peak wintertime sheathing MC near 20%–26%; the 5-½" ocSPF wall (N3) had similar behavior to N1 (24%–26% peaks). The 12" cellulose wall (N2) showed very high MCs, in the 25%–33% range. Again, in the following summer, MCs fell to the safe range (10-12% MC).

In the third winter (moderate interior RH, cold outdoor conditions), behavior was similar to the first winter. The north 12" ocSPF wall (N1) showed a peak wintertime sheathing MC near 15%–18%; the 5-½" ocSPF wall (N3) was slightly drier than N1, with peak MCs of 15%–16%. Again, the 12" cellulose wall (N2) had higher MCs, in the 15%–23% range, but much drier than the second winter. Also, all walls dried to safe levels in the summer.

The MC anomalies seen in the second winter at high MC levels (sudden jumps in MC) coincide with freezing temperatures; it is likely that freezing of bound water in the sheathing results in different electrical resistance response, and thus measured MC. The MC trends during non-freezing condition are likely more representative of actual conditions.

Given the low, middle, and high sheathing MC measurements, the data were examined for evidence of spatial MC relationships. The mid-height MC was noticeably higher in some cases; the upper MC was lowest in two of three cases, which would be an argument against convective airflow depositing moisture at the top of the stud bay. It is plausible that the upper sheathing is slightly shielded from night sky radiation by the roof overhang, resulting in higher sheathing temperatures; this is consistent with temperature measurements.







Figure 9: South side sheathing MCs, with exterior temperature for reference

The south walls have a similar pattern to the north walls; the 12" cellulose wall (S2) has higher wintertime peak MCs than the ocSPF walls. In the second winter, the cellulose MCs rise to the 17-30% range: this is much higher than the ocSPF walls. All walls dry to the 8% range in the summer; the intermittent data seen during summertime indicate periods drier than the measurement range of the data logger (wood electrical resistance is too high for measurement).

Other sensors were examined to confirm the sheathing MC behavior. The "wafer" sensor results for the three north-facing walls are plotted in Figure 10, which reflect conditions at the exterior sheathing-to-insulation interface.



Figure 10: North side "wafer" sensor moisture contents, with exterior temperature for reference

The response of these wood-based sensors should be understood when interpreting these results. Based on previous work (Ueno and Straube 2008), the "wafer" sensors come to equilibrium with 100% RH conditions (closed box containing water) at 28%–30% MC (blue line). However, immersing the sensors in liquid water increases their MC to the 40%–45% range.

The "wafer" response is consistent with the sheathing MC measurements. In the first winter, 12" of open cell foam remains the driest through the winter, followed by 5-½" of open cell foam. The cellulose wall shows much higher wintertime peak moisture levels, consistent with condensation occurring at the sheathing. In contrast, the open foam walls remain below the 100% RH level. During the following summer, all "wafer" sensors dry to the 9%–12% moisture content range. In the second winter, all "wafer" sensors show MC peaks well into the condensation range, with significant condensation at the 12" cellulose wall. Again, the wafer dries in the following

summer. In the third winter, similar patterns to the first winter are seen, except that 12" of open cell foam (N1) and 5-1/2" of open cell foam (N3) change order (although both are well below 100% RH). The wafer MC measurements had anomalies during freezing conditions; these anomalies are removed in the Figure 10 and Figure 11, for legibility.

The south-facing wall "wafer" results are shown in Figure 11; again, patterns are analogous to the previous sheathing MC measurements. The cellulose wall shows the highest moisture levels, but drier than the north walls. In the second winter, significant condensation is indicated in the cellulose wall; again in the following summer, the wafers return to the dry range. In the third winter, all measurements are below 100% RH-equivalent.



Figure 11: South side "wafer" sensor MCs, with exterior temperature for reference



The RH measurements further corroborate the previous results; measurements for the northfacing walls (outboard side, 1" off the sheathing) are plotted in Figure 12.



The temperatures (at the RH sensors) follow the expected wintertime pattern: N1 and N2 (12" insulation) are close to identical (tracking outdoor conditions), and N3 (5-½" ocSPF) is slightly warmer (due to reduced insulation inboard of the sensor). This results in lower RHs in N3. In the first the summer, all RH sensors at the sheathing fall to the 50%–65% range, as the temperature gradient and moisture drive are inward, away from the sheathing. In the second winter, the RHs have the same relationship, but the elevated RHs occur over an extended time period through the winter. The RH results are consistent with previous measurements: the cellulose wall has higher humidity levels at the sheathing than the ocSPF foam walls.

Framing MC levels were also checked; the relationship between walls were similar, with north walls wetter than the south, cellulose wetter than ocSPF walls, and outboard MCs higher than inboard MCs. Peak MC levels were lower than sheathing MCs; in the second winter, the north cellulose outboard framing peaked at 20-25%, while the two ocSPF walls peaked near 16-18%.

A common explanation for the greater risks associated with double stud walls is that the sheathing is colder, due to the increase in insulation. In a steady-state analysis of the temperature drop through a double stud wall assembly (outdoor 7°F), the sheathing temperature difference between 12" ocSPF and 5-½" ocSPF is 0.8°F (0.4°C): a minimal difference that only occurs under extreme conditions. The sheathing temperatures of the 12" ocSPF and 5-½" ocSPF walls were compared: minimal differences were found, with the largest discernable differences in the 1°F/0.5°C range (5-½" ocSPF warmer). This implies that instead of sheathing temperature being the key difference, durability is likely most affected by the relative amounts of heat/drying energy passing through the sheathing

#### WALL DISASSEMBLY

At the conclusion of this monitoring experiment, the test walls were temporarily disassembled to examine conditions, relating the monitored data to actual damage and conditions. The south-facing walls are shown in Figure 13.



Figure 13: South-facing test walls (L) test bays and insulation; (R) wall sheathing conditions

The sheathing was removed on north and south orientations; disassembly pulled "divots" of adhered ocSPF out of the stud bay insulation. The sheathing condition was surprisingly good on both orientations, considering that all measurements indicated liquid water condensation for extended portions of the winter, especially in the cellulose wall. There was no visible mold growth, staining, water rundown evidence, or delamination at the sheathing or the framing. Minor evidence of damage included slight grain raise at the cellulose wall (compared to the ocSPF walls), and minor rusting of nails and staples. The dense-pack cellulose all remained in place during the disassembly; no evidence of settling was seen at the opening. All materials were dry to the touch. The moisture content "wafers" at the insulation-sheathing interface had slight discoloration consistent with wetting, but no visible signs of mold growth.

#### **OVERVIEW OF RESULTS AND ASHRAE 160 ANALYSIS**

The sheathing moisture contents can be used to indicate failure risk. Traditional guidance is to keep wood MC below 20%; mold growth will not occur below this level (Carll and Highley 1999),

and optimum growth occurs in the 25%–30% MC range. Decay fungi become active at MC levels above 28% (Straube and Burnett 2005).

The boundary conditions varied strongly between the three winters, which is the key to understand the response of the assemblies. In the first winter (low RH, mild exterior temperatures), sheathing MCs peaked over 20% in the north-facing cellulose (N2) and 12" ocSPF (N1) bays, with indications of sheathing condensation in N2. In the second winter (high RH, exterior temperatures) many walls peaked over 20% MC, with extended periods of condensation in the cellulose wall. In the third winter (normal RH, cold exterior temperatures), only wall N2 peaked over 20% MC. In each summer after wintertime wetting, moisture contents fell to safe (10-12%) levels.

However, these moisture conditions should interpreted with temperatures in mind. Biological activity is inhibited at low temperatures, so high MCs in mid-winter pose less risk than in warmer seasons. Sustained high MCs at moderate temperatures pose the greatest durability risks. One metric accounting for both temperature and moisture is ASHRAE Standard 160 (ASHRAE 2009). It has failure criteria (defined as the risk of mold growth) of a 30-day running average surface RH < 80% when the 30-day running average surface temperature is between 5°C (41°F) and 40°C (104°F). As noted earlier, other practitioners (Arena 2013) have found ASHRAE 160 criteria to be excessively stringent/conservative.

The collected data were analyzed using ASHRAE 160 criteria; the relative humidity at the sheathing-insulation interface was calculated from measurements. The results show that all three walls fail ASHRAE 160 requirements for extended periods during all three winters, and that the cellulose wall (N2) has the worst performance according to these criteria. In addition, winter 2012-2013 (high humidity winter) has more failing hours: the cellulose wall (N2) fails ASHRAE 160 from mid-September through mid-November, and then April through late June. It is interesting to note that failures occur in the walls in fall and spring. During the winters, sheathing temperatures drop below the 41°F/5°C lower limit, even though the RH criterion is exceeded. Based on an ASHRAE 160 analysis, the walls do not dry rapidly enough to avoid problems. The numbers of failing hours for the entire data set are shown in Table 1.

Wall	# Failure Hours	% Time Failure
N1-12" ocSPF	2790	12%
N2-12" cellulose	5484	24%
N3-5-1/2" ocSPF	2913	13%
S1-12" ocSPF	1657	7%
S2-12" cellulose	2646	12%
S3-5-1/2" ocSPF	2273	10%

Table 1: Hours and percent of monitored period failing ASHRAE 160 criteria

#### ASSEMBLY VAPOR PERMEABILITY PROPERTIES

As shown above, the ocSPF walls (both 12" and 5-1/2") have lower moisture contents than the cellulose (12") wall. These materials are both regarded as "vapor open," which allow drying to the interior. All of the walls have a relatively vapor open Class III vapor retarder (latex paint on gypsum board) as the interior vapor control layer.

One difference is the vapor permeability of the assembly inboard of the condensing surface (OSB sheathing). Although ocSPF is generally thought of as vapor permeable, at the thickness applied at the double-stud wall here, there is significant vapor resistance. Table 2 shows the vapor permeability of the insulation layer alone, as well as in series with a 10 perm/575

ng/(Pa·s·m<sup>2</sup>) vapor retarder (Class III vapor retarder), or latex paint on gypsum board.

It appears that at the thicknesses applied here, the ocSPF used here provides reasonable vapor control from interior-sourced moisture. Note that the spray foam values are taken from manufacturer's data, so they are not identical to the ASHRAE value stated earlier. The vapor permeance of the latex painted and primed gypsum was not measured; however, measurements at previous sites showed results in the 7–12 perm (dry cup) range, consistent with the value used for a Class III vapor retarder (10 perm). Schumacher and Reeves (2007) reported permeance measurements of 8 perms for drywall with two coats of latex paint, and 30 perms for drywall samples finished with a knock-down coating. NAHB Research Center's (2010) testing yielded much higher permeability values, measuring 40 perms for drywall with two coats of latex paint (dry cup).

Wall ID	Insulation Material	Vapor Permeability (Insulation Only)	Vapor Permeability (Add Class III Vapor Retarder)
N1/S1	12" ocSPF	1.8–2.5 perms (105-144 ng/(Pa⋅s⋅m²))	1.5–2.0 perms (86-115 ng/(Pa⋅s⋅m²))
N2/S2	12" cellulose	7.0–10 perms (402-575 ng/(Pa⋅s⋅m²))	4.0–5.0 perms (230-288 ng/(Pa⋅s⋅m²))
N3/S3	5-1/2" ocSPF	4.0–5.5 perms (230-315 ng/(Pa⋅s⋅m²))	2.9–3.5 perms (166-201 ng/(Pa⋅s⋅m²))

For reference, the use of a Class III vapor retarder is allowed by code in conventional construction, assuming a vented cladding (ICC 2009). In Zone 5, allowable assemblies include vented cladding (such as vinyl siding) over OSB, plywood, fiberboard, or gypsum sheathing. However, a double-stud wall has different behavior than conventional (2×4 or 2×6) construction.

#### **PROTECTIVE MECHANISMS OF CAVITY INSULATION**

Based on the monitored data, calculations, and analysis, all three walls should be at high risk of failure. High moisture contents and condensation were measured, especially during the second (high humidity) winter. However, disassembly of these walls indicated no sign of any significant failure: no visible mold was seen, and no significant staining or water rundown was seen in the wall cavity. This suggests that the walls, at least in the configurations tested, are far more robust than current analysis tools would indicate.

One theory to explain this behavior was that although the walls undergo significant wetting in the winter, they dry before damage can occur. However, based on the data and ASHRAE 160 analysis, wet conditions continued into the spring, resulting in conditions warm enough to suport mold growth, especially in the cellulose wall.

Another possibility is that the cavity insulation materials provide a degree of protection to the OSB sheathing surface. For instance, cellulose is treated with borate salts as a preservative and fire retardant. Borates are highly effective at inhibiting mold growth; they appear to leach into adjacent materials (e.g., gypsum board and wood sheathing), providing some protection to them. Rose and McCaa (1998), Carll et al. (2007), and Clausen et al. (2009) described situations where high moisture conditions occurred in building assemblies, but some protection against mold growth was provided by cellulose cavity-fill insulation. The literature suggests that

although cellulose treated with borates can increase mold resistance of walls, it is by no means a panacea; the resistance can be overcome with a sufficient loading of moisture. However, it might explain the lack of damage seen in this work.

Spray foams appear to provide some resistance to mold growth at the insulation-substrate interface. Several theories have been posed for how the installation of spray foam might protect the sheathing; they are covered below, with further descriptions of their plausibility.

- **Oxygen restriction:** the air-impermeable nature of the spray foam might restrict the flow of oxygen to insulation-OSB interface, thus limiting mold growth. However, the food science literature inidicates mold requires minimal oxygen for growth. In addition, the open-cell structure of ocSPF would likely allow slow diffusion of oxygen to mold spores.
- Flash heating: the installation of spray foam is highly exothermic, resulting in high temperatures at the interface. It is plausible that this heating "sterililizes" the substrate surface, killing the mold spores. At that point, the substrate is isolated from innoculation with new spores, due to the spray foam. However, the food science literature indicates much longer times (circa 30 minutes) at elevated temperatures are required for sterilization of typical mold species. These time-temperature requirements, though, are likely on the conservative side, given the requirement to kill microbes in food products.
- Surface treatment (film formation): during application, spray foam forms a film of polyurethane on the substrate, and then expands. It is plausible that this film makes the substrate less amenable to mold growth. Pure polyurethane is not known to be a food source for mold; in addition, unreacted additives or reaction by-products could also render the foam matrix less conducive to mold growth. However, no further literature was found to support or refute this theory.
- **Capillary redistribution:** open cell foams are known to pass liquid water through the field of the foam. It is possible that the open cell structure allows for storage of liquid water by capillarity, and redistributing the water away from the sheathing. However, no further literature was found to support or refute this theory.

## **RECOMMENDATIONS AND FURTHER WORK**

Based on the monitoring, both ocSPF and cellulose double stud walls will experience worryingly high moisture levels in Zone 5A, during high interior wintertime RH loadings (40-50% RH), with a Class III vapor retarder (latex paint). However, disassembly demonstrated that the walls were largely unaffected by this wetting. But for the purposes of recommendations for industry, a more conservative approach is warranted. This is particularly true because it appears that the test walls were protected by some mechanisms of the specific cavity fill insulation or sheathing.

The cellulose walls clearly showed the highest moisture accumulation: the use of interior vapor control more restrictive than Class III (latex paint) is recommended. A Class II vapor retarder (1 perm to 0.1 perm; e.g., variable permeability membrane or vapor retarder paint) will reduce moisture risks to more reasonable levels. However, it is entirely likely that there are many double stud walls insulated with cellulose with only Class III vapor control that are providing fine service. A Class I vapor retarder (polyethylene) is not recommended, due to the complete elimination of inward drying.

The ocSPF walls had less moisture accumulation than the cellulose walls; it is a marginal judgment call whether a Class II vapor retarder is needed or warranted. The ocSPF material, at the thickness applied, provides reasonable vapor control, albeit lower than code requirements (2.0 to 2.5 perms in 12"). The use of a Class II vapor retarder would definitely be conservative, but the double stud walls insulated with ocSPF in this builder's houses have a history of

providing excellent performance.

These recommendations are based on this field research in Zone 5A; in colder climate zones (Zone 6 or 7), different materials or assemblies might be required.

A functional mechanical ventilation system is critical for enclosure durability in modern high performance construction in cold climates, especially if more vapor permeable interior finishes are used. Given the greater risks in high performance construction—as demonstrated in this project (airtightness, high occupancy, inoperative ventilation) —erring on the conservative side for wall design may be prudent.

As demonstrated in the literature and recent research (Fox 2014), the use of insulation outboard of the sheathing substantially reduces risks of interstitial condensation due to interior-sourced air leakage, or vapor flow (with more vapor-open interior finishes such as latex paint). Exterior insulated walls have much higher intrinsic moisture safety than thick cavity walls, such as double stud walls.

An area worth further study is the mechanisms that reduce mold risks when using open cell spray foam and cellulose cavity insulations. More specifically, quantifying their increased resistance to mold growth would be useful for expanding the failure threshold used in standards such as ASHRAE 160.

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