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Experimental evaluation of potential movement of airborne mold spores out of building envelope cavities using full size wall panels

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ABSTRACT: Movement of mold spores from the stud cavity to the living space is related to the capacity of the building envelope to prevent contaminants from penetrating into the indoor environment. As part of a larger collaborative research project with industry partners on experimental evaluation of hygrothermal performance of various building envelope systems, a testing program was undertaken on full-scale wood framed wall assemblies to monitor the transport, if any, of mold spores from within the stud cavity to the indoor environment. A series of tests were performed with variations of such parameters as rates or patterns of air leakage, presence or absence of insulation and vapor barrier. Experimental results for the first stage of the test runs are presented.

1 INTRODUCTION

The study reported in this paper was undertaken to investigate the capacity of wall systems to contain spores emanating from studs with 10% of their surface covered with mold.

Spores are the most known components of molds, that can be dispersed and transported in the air, and be used as an indicator of mold presence inside the walls. In addition to spores, molds produce airborne fungal components and other products such as fungal fragments, and microbial volatile organic compounds (MVOCs) (Miller, 1992; Gorny et al., 2002; Nielsen, 2002; and Hyvärinen, 2002).

The effectiveness with which the building envelope serves as a filter between the indoor and outdoor environments depends to a large extent on its integrity and resistance to air leakage. When limited amounts of molds exist within the envelope, the envelope could still limit the access of spores to the interior depending on its characteristics. There has been only limited research on this aspect.

This paper presents results from a research project undertaken to establish to what extent building envelopes of different wall configurations can contain airborne spores of molds that may exist within their stud cavities.

The initial concept and design and results from trial runs of this project were published in Fazio et al., (2005). From these initial trials, improvements were made to the test setup, material selection, and sampling methods. This paper presents the most recent experimental design and results of the spore samples.

2 TEST SETUP AND PROCEDURE

The overall approach of the project is to use full size wall assemblies of residential wood frame walls, to provide the molds on studs at a relatively consistent concentration, to subject the wall assemblies with air infiltration typical of houses in the Quebec region, and to assess possible mold movement through sampling of airborne spores and MVOCs. The parameters that are expected to influence the end results and are included in the project include the air leakage characteristics of walls (air leakage path and rate) and envelope configurations (insulation, vapor barrier and sheathing). The experimental design focused on the following aspects: envelope configuration, selection of air leakage levels,

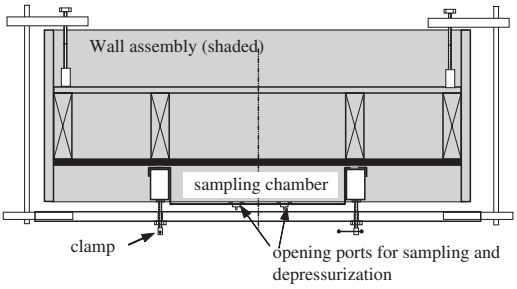


Figure 1. Experimental setup.

Figure 2. (a) View of a stud cavity; (b) View of sampling chamber installed on a wall assembly.

depressurization setup, simulation of mold source, and sampling methods.

2.1 *General setup*

Each wall assembly contained one full stud cavity to represent the walls in wood-framed residential buildings. The assemblies were built with 38 mm 2″) × 140 mm (6″) wood studs and flanked by two guarded bays of 203 mm (8″) each. A boundary made up of plywood boards contained the entire assembly, as shown in Figures 1 and 2.

A metal chamber was constructed to encase the central stud cavity of an assembly and to provide depressurization for the air infiltration. The chamber was compressed onto the drywall of the wall assembly before it was tested. The depressurization of the sampling chamber was provided by a centrifugal pump connected to an opening port on the sampling chamber. Airflow rates were regulated by a manually operated gate valve and measured by an inline flow meter (laminar flow element).

2.2 *Envelope configuration*

The wall assemblies include the following layers: drywall, vapor barrier, 38 mm (2″) × 140 mm (6″) wood studs spaced 406 mm (16″) apart, loose fiberglass insulation, and sheathing.

Drywall with unpainted gypsum boards (13 mm thick) was used for all assemblies. The inner surfaces along the openings in the drywalls were not treated further after drilling or sawing so that capture or release of spores by the inner surfaces of cracks may occur when spores pass through them. However, the influence on this filtration process due to material types or details of crack geometry was not considered nor was the interior painting.

The *vapor barrier* (VB) is required for effective hygrothermal performance of the envelope; polyethylene placed next to the drywall is a common form in cold climates. Fifteen assemblies have polyethylene VB and the other 5 assemblies have no VB for comparison.

Insulation can influence the movement of spores, or other particulate matters, through the envelope. Existing research (such as Liu and Nazaroff, 2003) on fine airborne particulate matter (diameters 0.02 to 10 μm) concluded that fiberglass insulation used in wall cavities is very efficient in filtering out particles in infiltrating air. Assuming there are no air gaps in the insulation, nearly all particles should be filtered by the fibers in the air path through the insulation which may be several inches long. However, air gaps between the insulation and the inner surface of the stud cavity do exist. Therefore, insulation is not expected to capture all particles before they reach the air cracks on the drywall.

In this study, the *sheathing* serves to confine air infiltration to specific locations/patterns. In the results presented, the sheathing material has not been considered. However, for the second stage of the project, the wall assemblies will be saturated in humid air of 90% RH and the sheathing material may affect the results.

2.3 *Selection of air leakage parameters*

Air infiltration is the driving force that carries the spores, found within the stud cavity, through cracks on the drywall and into the living space. Two levels of air infiltration rates were applied. The low rate represents the typical air leakage load that a wall would experience and the higher rate represents the upper percentile of the distribution of air leakage rates as it varies by seasonal and daily cycles.

The average air change rate for Quebec houses is 0.2 ACH (air change per hour) (Hamlin and Gusdorf,

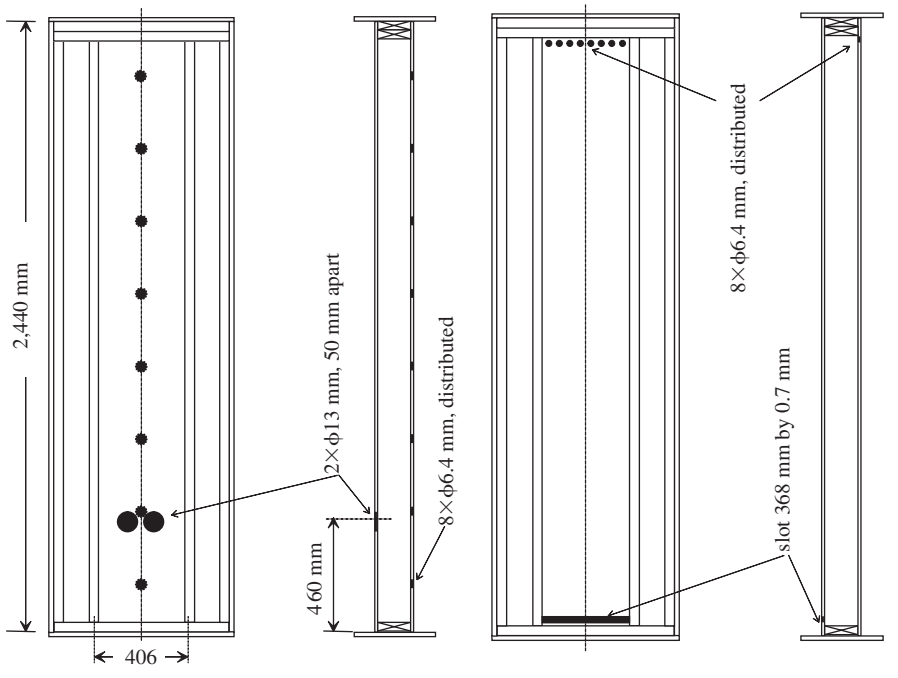


Figure 3. Air leakage openings and paths (not drawn to scale).

1997[1]). Calculations show that, assuming that 1/3 of the air passes uniformly through all exterior walls (ASHRAE 1989) and air enters on the windward wall, the air leakage rate through one full stud cavity is about 6.9 L/min (liter per minute). This rate was used as the low rate. The high rate was arbitrarily set to correspond to 0.5 ACH or 16.8 L/min, based on judgment of the authors and discussion with industry representatives.

Two test runs were performed on each wall assembly, under the low air leakage rate first, followed by the high rate.

Two patterns of air leakage, direct and long-paths (Desmarais et al., 1998) were implemented. The direct path allows air to enter and exit the stud cavity at the electrical box level. The long-path lets air enter at the top near the header on the exterior and to exit at the bottom near the bottom plate on drywall. In this experiment, air leakage paths were provided by holes and slots in the panels. For the direct path, two ϕ13 mm (1/2″) holes (50 mm (2″) apart) were drilled on the drywall at 460 mm (18″) from the bottom and eight ϕ6.4 mm (1/4″) holes were drilled on the sheathing panel along the vertical center line of the stud cavity. For the long path, a horizontal slot of 0.7 mm (1/40″) wide by 368 mm (1′ 4 1/2″) long and spanning stud-to-stud were cut on the drywall above the bottom plate and the eight ϕ6.4 mm holes were drilled on top of the sheathing panel along the horizontal line below the top plates. Figure 3 shows the locations and patterns of the purpose-drilled/cut openings.

In addition to the air leakage patterns and flow rates, the mixing of air inside the sampling chamber was taken into consideration. When the sampling chamber is attached, only the lab background spores stay in it. As air infiltrates into the chamber and is extracted by the depressurization setup, more spores enter the sampling chamber as the lab background spores leave it. Thus the spore concentration changes until it approaches steady state. The duration of this time delay is affected by the ratio between the air infiltration rate and the volume of the sampling chamber, by how well the infiltrating air mixes with the air inside the sampling chamber, and by the complex aerobiological mechanisms of surface settling and re-suspension of particulates within the sampling chamber. The duration of this time delay is set to a value long enough for twice the volume of air in the sampling chamber to be extracted. With the assumptions of perfect mixing in the sampling

[1] Table 14 indicated that the annual averages of the natural air change rates, predicted by HOT2000 for the new conventional houses built between 1981 and 1995, had a median value of 0.2 ACH, based on field data of house characteristics and fan pressurization tests.

chamber and constant spore concentration in the wall cavity, this duration should in theory allow the concentration in the sampling chamber to reach about 86% of the final level.

2.4 *Growing molds on jack pine studs*

To provide comparable results, the initial mold sources on the studs should be relatively uniform among wall assemblies and the growth potential on all the studs should be equal.

The studs for residential construction in Canada are produced from the most common grouping: Spruce-Pine-Fir (SPF), although other species can be and are sometimes used. SPF (denoting a number of soft wood species of spruce, pine, and fir) studs are widely used. Trees of these species tend to grow in stands of mixed species. It is usually not practical to separate them into individual species during logging and manufacturing. So, all the species are harvested, processed, graded and marketed together (CWC, 2004). Shipped studs from manufacturers contain a mix of all the three species.

While SPF studs are interchangeable in terms of structural performance, the potential of growing molds are different. Our first trials on growing molds on kiln-dried SPF studs failed to produce molds on time. Even after exposing the studs to moisture for 2 months, the growth failed to produce uniform coverage on the wide faces of the studs. Visits to lumber yards indicated that it is very difficult to find studs with similar and uniform mold coverage.

The final wood studs selected came from jack pine (*Pinus banksiana* Lamb.), which is the most widely distributed pine species in Canada and its wood has a relative higher susceptibility to mold infestation. All studs used in the tests were verified by a species identification kit using two reagents (Fast blue B and sodium bicarbonate).

To grow molds, kiln-dried jack pines studs were cut into 1,220 mm segments. The current trend in North America is to use kiln-dry wood in construction. The studs were fully submerged in water for 24 hours to reach high moisture contents near the surfaces. The wet studs were then inoculated on one surface with a fresh spore water solution (1×10^6 spores/mL) of a mixture of three common molds: *Aspergillus niger, Aureobasidium pullulans* and *Penicillium citrinum*. The studs were stacked together separated by wood sticks. The top and bottom were covered with wet felts. The pile was wrapped and sealed with a plastic sheet and maintained at about 20°C. The visible mold growth on studs was observed after 2 weeks and 10% coverage was obtained at about 3 to 4 weeks.

2.5 *Spore sampling and analysis methods*

A special type of cassette (Bi-Air cassette from Mold-Sampling.com, Placentia, CA) was selected for the spore sampling. The cassette is designed for both total spore counts and culturing on the same sample. A dual-slit filter is used to produce two distinct sample traces of 9.35 mm^2 each. The filter is cut in half to allow each sample trace to be analyzed for total fungal spores counted microscopically and for viable fungi using dilution plating techniques. A portable sampling pump was used. The flow rates through the filters sampling tube (1.0 L/min) were calibrated with a flow calibrator (DC-Lite Flowmeter by SKC Inc, Fairfield, New Jersey).

There were several trials using different sampling durations (Fazio et al., 2005). Due to abundant dust particles in the sampling chamber during depressurization, a short sampling duration of 2 minute was selected for all the air samples with 2 liters of sampled air to facilitate the counting.

After spore sampling, the cassettes were sealed, placed in a refrigerator and transported (from Montreal to the Forintek lab in Quebec City) weekly to a mycology lab for processing and analysis.

In the laboratory, half of the filter was immediately placed on a glass slide loaded with a drop of Triacetin. The slide was gently heated over an alcohol lamp until the filter became clear. The filter was then covered with a cover slip. The slide was observed under a light microscope at a magnification of 500X, and the number of spores that appeared on the filter was counted. Six areas per filter were counted and averaged and the total counts per filter were estimated by multiplying by the ratio of area counted to total area.

2.6 *Test sequence*

For each wall assembly, the construction of frames, preparation of moldy studs, test runs for sampling, and sample transport and analysis lasted 6 to 7 weeks. The test runs on all the assemblies were planned and carried out in a very tight schedule. Once the test runs on the first finished wall assembly started, four to six assemblies together with several dozen spore samples were processed every week.

The partially finished assemblies were first assembled (in Quebec City), using similar nail positions and spacing as in construction practice except that the nails were replaced with wood screws. In preparation of each assembly, all joints along the perimeter of the sheathing board, from both the exterior side and stud cavity side, were sealed with silicone caulking to eliminate air leakage from the edges of the sheathing and to limit air leakage through the predetermined paths.

Depending on the assembly configuration, either two moldy studs or two clear kiln-dry jack pine studs were installed to form the stud cavity in the assembly. Then, insulation from a newly opened bag was applied to the central stud cavity only and not to the guarded cavities on the sides of the stud cavity. A precut polyethylene sheet was then added over the entire

Table 1. List of wall assemblies tested and their parameters.

Sheathing panel		OSB				Plywood				Fiberboard			
Air leakage path		Direct		Long		Direct		Long		Direct		Long	
Cavity insulation		Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
Moldy stud	Vapor B.	11	12	13	14	19	20			22	23		
	No VB	5	6	7	8								
Clear stud	Vapor B.	9/15	16	17	18	21				24			
	No VB		10										

Note: The numbers are the wall assembly identification code. The parameters of an assembly can be read from the two left parameter columns and three top parameter rows. Wall assemblies 1 to 4 were not constructed nor tested.

assembly that called for this vapor barrier. The drywall, cut to size, was applied and screwed onto the studs with regular drywall screws. Drywall compound was then forced into cracks all along the perimeter of the drywall to achieve an airtight seal. Except for the moldy studs when required, all materials had no visible mold appearance at the time of purchase. Holes and slots were then drilled and cut according to the air leakage pattern and arrangement of the wall assembly described in §2.3. The wall assembly preparation was then complete. It usually was kept standing for one hour or, in a few cases, overnight. The stainless steel sampling chamber was then tightened to the drywall with W-shaped rubber gaskets in between for airtightness.

To sample air from the stud cavity, a thin tube (ϕ6.4 mm – inner diameter) was inserted through the sheathing into the cavity. A port was attached on the sampling chamber for spore sampling. Twenty minutes after the depressurization started at the low rate, the first set of samples, from both the stud cavity and the sampling chamber, were taken simultaneously. The depressurization was then switched to the high rate for 10 minutes before the second set of samples was taken.

For each test run, measurements were taken of the background spore samples in the lab, of tape-lift spore samples from the moldy studs used, of the lab temperature and RH, and of the moisture contents of the two central vertical wood studs.

3 EXPERIMENTAL RESULTS

Twenty wall assemblies were constructed with combinations of different parameters as shown in Table 1. Each assembly was tested under low and high flow rates. The results of microscope counting of the spores on half of the cassette trace are listed in Table 2, with data for wall assemblies without VB, assemblies with VB, and lab airborne spores tabulated separately. The spore count *unit* is the number of spores found on one of the two traces in a cassette.

3.1 *Vapor barrier effect*

The spore counts found in assemblies with and without vapor barriers differ significantly. Figure 4 plots data in Table 2.a for walls without VB by the circles in the middle section of the plot area, data in Table 2.b for VB walls in the left section, and data in both Table 2.a & 2.b once again in the right section. The wall assemblies without vapor barriers had higher spore counts on average in both stud cavity and sampling chamber than those with vapor barriers; both the differences are statistically significant[2] ($p = 0.00001$ and $p = 0.0002$, respectively). The spore counts for no-VB walls also had more variations among different samples from the stud cavity and sampling chamber. If data from both VB walls and no-VB walls are combined in analysis, for examples the two groups of triangle shapes in Figure 4, the average values (horizontal solid lines) of the groups are skewed by the few high values of the no-VB data points. Therefore the data for wall assemblies with VB will be examined separately in the following analysis.

3.2 *Use of moldy studs in VB walls*

For wall assemblies with vapor barriers, the spore counts are grouped by the sampling locations (stud cavity or sampling chamber) and by the use of studs (moldy or clear), as plotted in Figure 5. Basic aggregate parameters (number of data points, averages, and difference in average values between two similar groups) are also tabulated in the figure. In the stud cavities, an increase of 15.6 spores or 37% (calculated by 15.6/42.3) is observed between the averages of 14 samplings from wall assemblies using clear studs and 16 samples from moldy stud assemblies. This indicates that the use of moldy studs elevates the level of

[2] Statistical significance is determined by the hypothesis test about the difference between two population means with equal variance, using the Student's t-distribution. The level of significance is 5%.

Table 2. Microscope counting results for mold test.

a) Test runs on assemblies without VB

Wall assembly #	Low rate		High rate	
	Chamber	Cavity	Chamber	Cavity
5	65	133	89	206
6	78	118.5	213.5	239.5
7	93	124	112.5	195
8	28.5	70.5	43	70.5
10	33	30	23.5	37.5
Average	*59.5*	*95.2*	*96.3*	*149.7*

b) Test runs on assemblies with VB

Wall assembly #	Low rate		High rate	
	Chamber	Cavity	Chamber	Cavity
9	39	62.5	38.5	57
11	21	33	12	21
12	9	31.5	34.5	45
13	20.5	25	43.5	30
14	13	33	38.5	35.5
15	16	40.5	49	43.5
16	25	31.5	54	54.5
17	39.5	40.5	39	60.5
18	24	40.5	46.5	46.5
19	25.5	61.5	34.5	76
20	63	99	69	79.5
21	33	22.5	28.5	33
22	48	67.5	34.5	84
23	39	121.5	65	84
24	28.5	28	28.5	31.5
Average	*29.6*	*49.2*	*41*	*52.1*

c) Lab airborne spore counts

Wall assembly #	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**5**	**9**	**7**
Lab spore counts	36		5		22			30		48	
Wall assembly #	**6**	**10**	**24**	**19**	**22**	**20**	**21**	**23**		**8**	
Lab spore counts	36		21		26		32	45	33	24	
Average					*29.8*						

Notes:
- *Unit*: numbers of spores found on one of the two traces in individual cassettes.
- Spore counts in stud cavities and sampling chamber were averages of two sequentially taken cassettes. One cassette (or two for #23) was used to sample the lab air on the day of test runs for one to three wall assemblies.

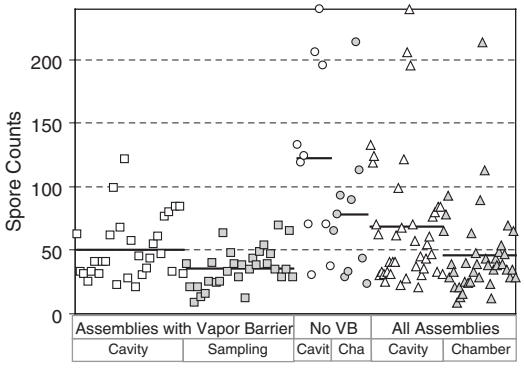


Figure 4. Vapor barrier had an effect on the spore counts.

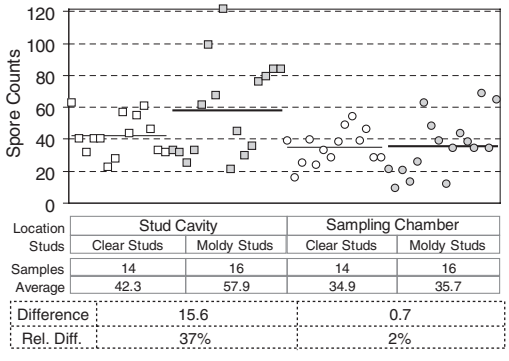


Figure 5. Influence of moldy studs on assemblies with VB.

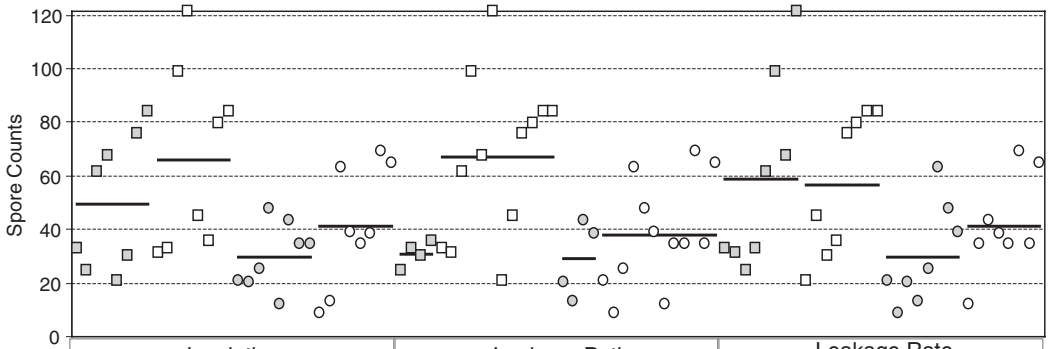
the airborne spores in the stud cavity. This increase in airborne spores in the stud cavity due to use of the moldy studs is statistically significant ($p = 0.04$).

In the sampling chamber, however, there is only a very small increase in the average spore counts when moldy studs were used. This increase is not statistically significant at the 5% level. Therefore, based on the test setup, the initial experimental data does not support that the use of moldy studs with 10% coverage leads to an increase in the amount of spores out of the stud cavity under the two above air leakage rates through the purposely provided openings on the drywalls and vapor barriers.

3.3 *Effects of cavity insulation and air leakage*

The data for wall assemblies *using moldy studs* and with vapor barriers are separately grouped according to insulation, air leakage path, and air leakage rate and are plotted in Figure 6. Data of moldy stud assemblies in Table 2.b are plotted three times, once in each of the three horizontal sections of Figure 6.

With *insulation* in the stud cavity, the average airborne spore counts in both the stud cavity and sampling chamber are lower compared to those for wall



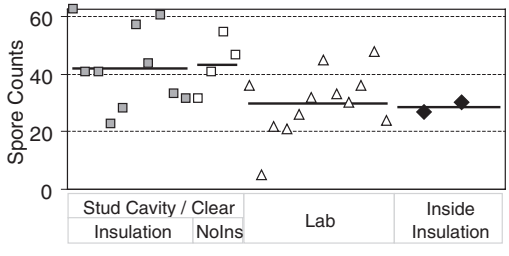
Samples	8	8	8	8	4	12	4	12	8	8	8	8
Average	49.8	66.1	29.9	41.4	30.9	67.0	28.9	37.9	59.0	56.9	29.9	41.4
Difference	16.4		11.4		36.1		9.0		-2.1		11.6	
Rel. Diff.	33%		38%		117%		31%		-4%		39%	

Figure 6. Influences of insulation, air leakage path and air leakage rate for data on wall assemblies *with moldy studs and VBs*.

assemblies without insulation. This can be seen in the left 1/3 of Figure 6, where the averages of non-insulated walls have 16.4 and 11.4 more spores than the insulated assemblies, in the stud cavity and sampling chamber, respectively. It seems that the cavity insulation attenuates airborne spores to some extent.

Both air leakage path and rate affect the spore counts in the stud cavity and sampling chamber. For the two *air leakage path* patterns depicted in Figure 3, the stud cavities in walls with the direct path have 36.1 or 117% more spores than the assemblies with the long path. The longer the air passage path inside the stud cavity, the less the spores collected from the stud cavity. For the sampling chamber, the direct-path assemblies also have more airborne spores (9.0 spores) than the long-path ones, but to a lesser extent, only 31% difference. For the two *air leakage rates*, the test runs using the high rate generate more spores (11.6 spores or 39%) in the sampling chamber. More spores are agitated and/or moved into the sampling chamber by the higher air leakage rate. It is noted that since all high rate test runs were performed after the low rate runs, the sequence and/or the timing of the test runs may have some influence that could not be estimated from the data. In the stud cavity, the higher air leakage rate did not increase the sampled spores; rather it decreased slightly the spore counts by 4% as compared to the count in low rate.

In summary, for wall assemblies with moldy studs and vapor barriers, the spore counts in the stud cavities increase when no cavity insulation is used or when direct air leakage paths are present. In the sampling chamber, higher spore counts are found for the wall assemblies with no cavity insulation, with direct air leakage path, or with high leakage rate. However, further subdivisions of data reduced the numbers of data points in the six comparison groups of Figure 6. The statistical significance was found only for the comparison of air leakage paths in the stud cavity ($p = 0.02$, the third pair in Figure 6). Additional data are needed to affirm or negate these observed differences or lack of due to cavity insulation and air leakage.



NoIns denotes "no insulation"; Clear means "clear studs"

Figure 7. Spores sampled in insulation, lab air and stud cavity & sampling chamber of assemblies *with clear studs*.

3.4 *Spore counts in background*

Background spores were found in the lab air and in newly-opened fiberglass insulation. The lab air samples taken during the test runs (as listed in Table 2.c) show an average of 29.8 spore counts. Two spore cassettes, taken one after another from fiberglass insulation in its original plastic bag that was just opened before the samples were taken, gave 27 and 30 spore counts with an average spore count (28.5 spores)

slightly lower than the average count in the lab air. Figure 7 plots the spore counts in the stud cavity for wall assemblies using clear studs (both with and without the insulation) against the above airborne spores in the lab air and inside the insulation. It can be seen that the average spore counts in the stud cavity are higher than those found in the lab air. This difference is found to be statistically significant ($p = 0.05$), based on the data presented in Figure 7. For this difference to exist, the spore sources must include spores which may exist on material surfaces in the stud cavity. These materials include the sheathing, clear studs, vapor barrier, and drywall.

The existence of background mold spores in the lab air, inside the insulation, and on the material surfaces in the cavity, in addition to the large variations due to the nature of airborne spore sampling, may contribute to variations in the results of airborne spore counts. As a result, the data analysis in the previous sections was based on comparisons of averages from several test runs. Statistical analysis was used to determine the statistical significance of specific data sets. The randomness in the spore count variations prevents comparisons of data from individual test runs that differ only in terms of one parameter listed in Table 1. Further tests are needed to estimate the specific influences of these parameters.

4 CONCLUSION

A new protocol has been implemented to evaluate the potential movement of airborne mold spores out of building envelope cavities when studs with 10% of the surface covered with mold are used. The data presented for full size wall assemblies with vapor barriers indicate that the use of moldy studs in the wall assemblies leads to a significant increase in airborne spores in the stud cavities, but no significant increase in the airborne spores out of the stud cavities and into in the sampling chamber. Conclusions on the test results presented herein should be treated cautiously till further tests are carried out.

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