BUILDING ENVELOPE PERFORMANCE MONITORING

Brian Hubbs, P.Eng.[1] and Matthew Hircock[2]

INTRODUCTION

The design and construction of multi-family buildings in the Lower Mainland of British Columbia has come under increasing scrutiny due to the high incidence of water ingress and resulting decay of materials in the exterior assemblies of these buildings. Most new buildings and many of the remediated moisture damaged buildings are being built using “rainscreen” wall assemblies, on the premise that that these assemblies are more tolerant of moisture and will limit wetting to levels which can be accommodated by the building materials. Unfortunately, very little data is available to determine how these assemblies actually perform in service. As an industry, we require data on how the “rainscreen” wall assemblies, as currently being designed and constructed, will perform on a long-term basis. Better knowledge of rainscreen wall performance in service will also help identify opportunities for fine-tuning rainscreen assembly design to make them more cost effective and durable.

This paper outlines the monitoring systems used in the study. Portions of the results are presented that relate to anomalies of interest such as, the effect of overhang on wetting, the results of unexpected moisture levels in the buildings, a comparison of the different cladding systems used in the study, and a comparison of actual wind and driving rain conditions compared with current design guidelines.

At the time this paper was written the monitoring program was approximately 60% complete. Building 5 had not come online yet due to construction delays and only limited data has been obtained from Building 4. As such, this paper does not include analysis of the results from these buildings.

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[1] Brian Hubbs, P.Eng. is a Principal in the building science consulting firm of RDH Building Engineering Ltd.

[2] Matthew Hircock is an EIT in the building science consulting firm of RDH Building Engineering Ltd.

OBJECTIVES

The purpose of the monitoring program is to provide data, which will be used to assess the effectiveness of rainscreen wall assemblies. The measurements can also be analyzed to determine whether wetting has occurred in susceptible materials, and if so, under what circumstances of weather and wall characteristics. The monitoring program was designed and implemented on five buildings being constructed or rehabilitated using a "rainscreen" wall assembly. While the focus of the program to date has been on obtaining the raw data for analysis, the opportunity for the use and analysis of the data is enormous. Specific examples are:

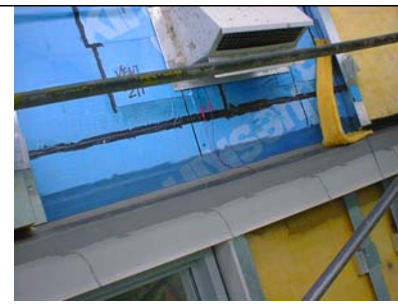
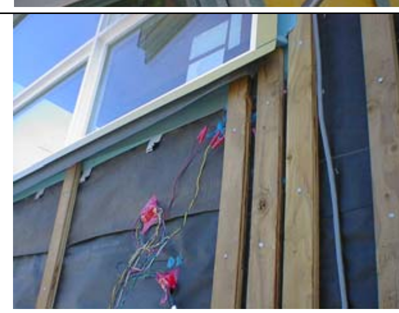
- To correlate wetting events with exposure, weather conditions, and building interior conditions;
- To determine if wetted walls dry quickly enough to resist damage, and under what conditions drying takes place;
- To provide baseline data that can be used comparatively when assessing the performance of other rainscreen buildings, when they are investigated in the future as part of warranty and maintenance requirements.

METHODOLOGY

The monitored buildings include three multi-unit wood frame residential projects, a concrete frame mid-rise residential rehabilitation project, and a new residential high rise construction project. All buildings are located in Vancouver, B.C. General building information and photographs are shown in Table 1.

The monitoring program was designed to measure temperature, wood moisture content, relative humidity, local weather conditions including rainfall, driving rainfall (rain contacting vertical walls), and pressure difference across the walls. A continuous, automatic electronic system records measurements from all sensors every 15 minutes. Five wall cavities on each building were monitored, each cavity contained 4 temperature, 4 moisture content, and 2 relative humidity sensors (Figure 1). On the non-combustible buildings, since it was not possible to take moisture content measurements on the steel studs, gold leaf wetness sensors were used to detect the presence of liquid water in these locations. The data acquisition and logging system is powered by a battery which is charged by a solar panel, this allows the system to collect data during severe storms even if building power is interrupted. Four of the five cavity locations were chosen to be representative of areas most likely to be wetted during severe weather, while the remaining 5th cavity was located in the center of the wall, away from details, to act as a control. Cavities were generally chosen on the east and south elevations at key details such as dryer vents, window sills, balcony transitions and saddle flashings where historically, high moisture levels have been observed (Figure 2).

Table 1 – Building Information

Building 1 Height: 4 stories Project Type: New Construction Frame Type/Sheathing: Wood/Plywood Insulation: Fiberglass Batt in stud cavity Moisture Barrier: 2 layers of Building Paper Cladding: Vinyl Siding on Wood Strapping		
Building 2 Height: 4 stories Project Type: Cladding Rehabilitation Frame Type/Sheathing: Wood/Plywood Insulation: Fiberglass Batt in stud cavity Moisture Barrier: Tyvek commercial wrap Cladding: Stucco on Wood Strapping		
Building 3 Height: 6 stories Project Type: Cladding Rehabilitation Frame Type/Sheathing: Concrete/Dens-Glass Insulation: Rigid Fiberglass on ext. of M.B, fiberglass batt in the stud cavity. Moisture Barrier: Self Adhesive Bitumen Cladding: Stucco on "Z" bars		
Building 4 Height: 4 stories Project Type: New Construction Frame Type/Sheathing: Wood/Plywood Insulation: Fiberglass Batt in Stud Cavity Moisture Barrier: Building Paper Cladding: Fiber Cement Board on Strapping		
Building 5 Height: 30 stories Project Type: New Construction Frame Type/Sheathing: Concrete/Dens-Glass Insulation: Polystyrene on ext. of M.B., Moisture Barrier: Self Adhesive Bitumen Cladding: Stucco on "Z" bars and Aluminum Window Wall		

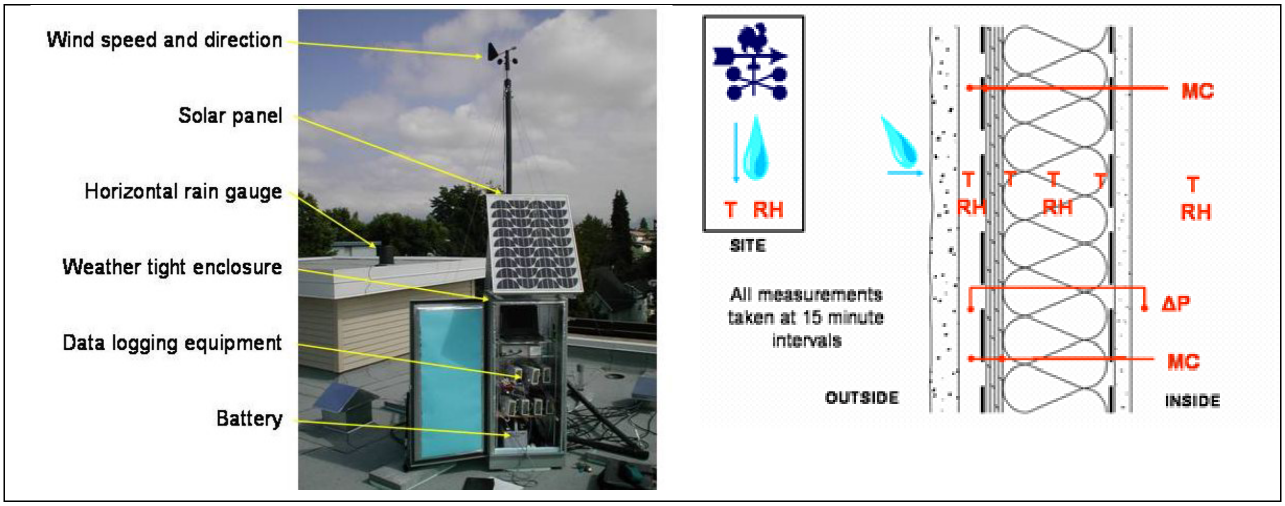


Figure 1 – Monitoring Equipment and Sensor Locations

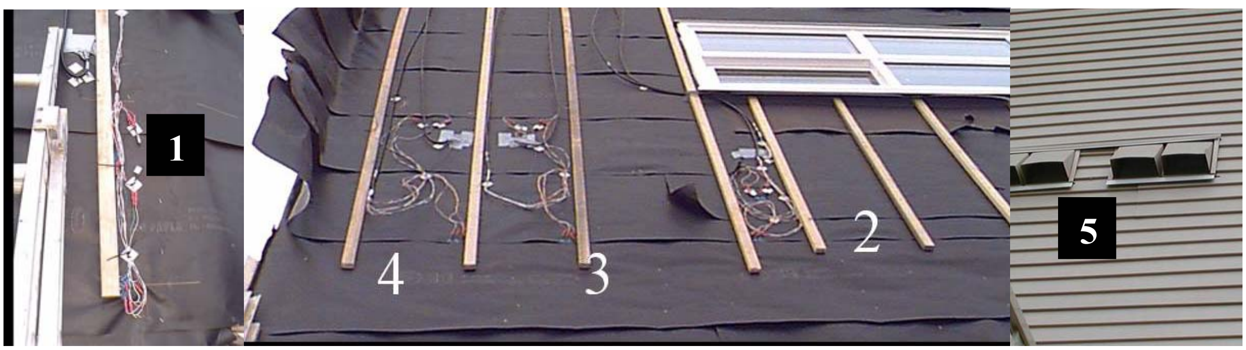


Figure 2 – Cavity Locations, Building 1
(1-Balcony saddle, 2-Window Corner, 3- Control, 4- Electrical Box, 5- Dryer Vent)

A description of the equipment and sensors is shown in Table 2.

Table 2 – Monitoring Equipment

Wood Moisture Content	Two 3/8" brass screws installed 1" apart into the sheathing (Plywood) and sill plate (Wood Frame Buildings).
Gypsum Moisture Level	Two ¾" nails installed on a 45° angle, 1" apart into gypsum sheathing. (Concrete Frame Buildings)
Temperature	Uni-Curve Thermisters part number 192-103LET-A01, by Fenwal Electronics
Relative Humidity	Honeywell HIH 3610-002
Wetness	Davis Leaf wetness Sensors (Concrete Frame Buildings)
Pressure Sensor	Setra Systems Model 265 – Differential Pressure Transducer
Rain Gauges	Vertical Rain: Davis Rain Collector II Driving Rain: Davis Tipping Bucket sensor in Custom Built driving rain collector, 1' x 1' opening for driving rain only (Does not measure water accumulation running down wall surface)
Weather Station	OMEGA WMS-22B, Wind Speed and Direction Module R.M. Young Company Wind Sensor, 05103-10A Wind Monitor
Data Logging System	Buildings 1 and 2 - Lakewood 8 Channel Chart Pac CP-X loggers Buildings 3,4,and 5 – Campbell Scientific Inc. CR10X Logger w AM16/32 Multiplexer and modem

The wood moisture content (MC) was determined by measuring the electrical resistance between the two sensors and estimating of the percent moisture content using the method developed by Straube[1] without temperature correction. Moisture level (ML) measurements in gypsum were calculated using the following formula which was derived using a multi point calibration with a Delmhorst BD10 Moisture meter:

$$ML=56.056x\ln(MC)-99.584$$

The formula for ML converts the electrical resistance measurement to the 0-100 reference scale on the Delmhorst BD10 series moisture meters. Moisture content measurements taken using the Campbell Scientific and Lakewood Logger systems were calibrated by taking readings on several samples of plywood that had reached a steady state condition at a known relative humidity, using a Delmhorst BD-10 Moisture meter. The samples were not kiln dried to determine the exact moisture content. Known humidity test cells were created utilizing a supersaturated solution of the following salts.

1. Distilled Water, Cell 1 (100% RH)
2. Sodium Chloride, Cell 2 (75% RH)
3. Magnesium Chloride, Cell 3 (33% RH)

The calibration for plywood samples 1 to 4, using the Lakewood logger, and DensGlass gold Test # 6, using the Campbell Scientific logger is shown in tabular form in Figure 3. The calibration of Dense Glass sample 1 and 2 using the Campbell Scientific logger, is shown graphically in Figure 3.

Relative Humidity (%)	Avg. of Plywood Tests 1-4	
	Calculated (MC%)	Delmhorst BD10 (MC%)
33%	10	10
75%	19	18
100%	+40	+40
Ambient	11	10

Relative Humidity (%)	Avg. DensGlass - Test #6	
	Calculated (ML%)	Delmhorst BD10 (ML%)
33%	37	28
75%	64	62
100%	85	89
Ambient		

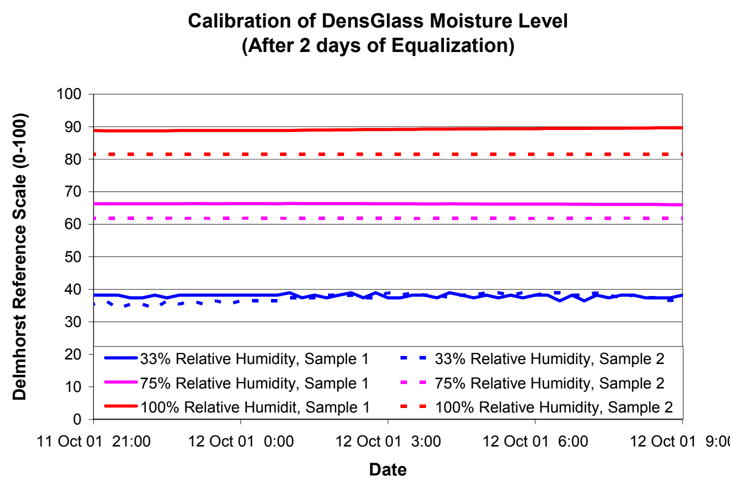


Figure 3 – Calibration of Moisture Measurements in Plywood and DensGlass

GENERAL OBSERVATIONS

The results for Buildings 1 and 2 for the period of July 1, 2001 to October 30, 2002 and for Building 3 from January 17, 2001 to October 30, 2002 are summarized in Table 3. None of the moisture readings in the wood frame buildings (Buildings 1 and 2) have exceeded 20% for an extended period of time. In most cavities, the moisture content remains below 15% for most of the year.

Table 3 – Summary of monitoring (Winter-Summer, 2002)

	Maximum %MC Sheathing Field	Maximum %MC Sheathing at Detail	Maximum %MC Strapping	Average %MC Sheathing Field	Average %MC Sheathing at Detail	Average %MC Strapping	Maximum Ext. Cavity Temperature (Celsius)	Minimum Ext. Cavity Temperature (Celsius)
Building 1	16	20	15	10.6	10.8	8.4	55	-6
Building 2	15	16	13	10	10	7.6	58	-6
Building 3*	90*	90*		55*	45*		44**	-6**

*- Sheathing is fiberglass faced gypsum board. Result is expressed as 0-100 moisture reference scale, Delmhorst BD-10/2100

** - Results are expressed as the average of the 3rd floor readings

Figure 4 shows the wood moisture content in the control cavity on Building 1. This graph is an example of the typical seasonal wetting and drying cycle that was observed in virtually all cavities, on all buildings. Generally the wood framed walls in the winter months were observed peaking at around 15% MC followed by a drying trend in the summer months. The highest wood moisture content levels were found on Building 1 in Cavity 5 (Figure 5). The higher moisture content identified by the increase in the moisture content in the sheathing directly below the exhaust vent was likely caused by an increase in water infiltration past the shedding surface at the cladding to vent interface. The large spikes throughout the year which can be seen on Figure 5 but not in Figure 4 were caused by usage of the vent itself and contact of the wall components with the warm humid exhaust air.

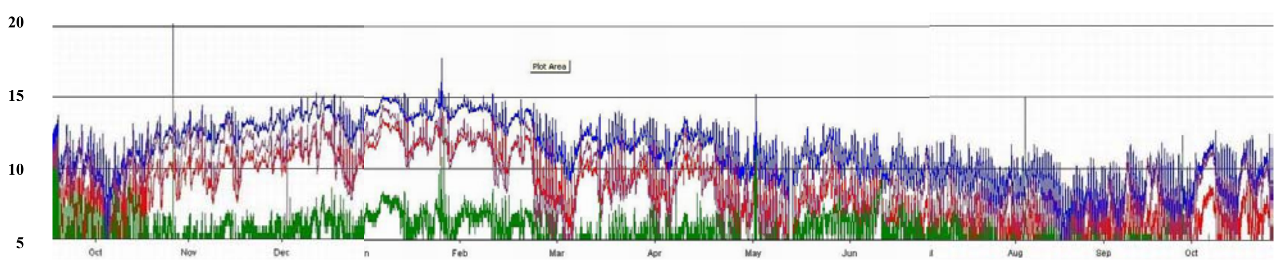


Figure 4 – Building 1, Cavity 3 (Control) Moisture Content (%), October 2001 to October 2002
Red=Sheathing in Centre of Cavity, Blue=Sheathing near strapping, Green=sill plate, Magenta=Strapping

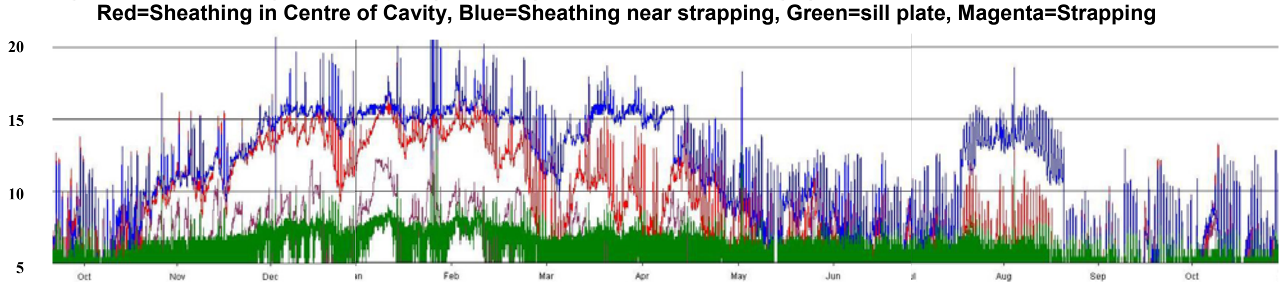


Figure 5 – Building 1, Cavity 5 (Exhaust Vent) Moisture Content (%), October 2001 to October 2002
Red=Sheathing in Centre of Cavity, Blue=Sheathing below vent, Green=sill plate, Magenta=Strapping

While the moisture content results cannot be directly compared between Building 3 and Buildings 1 and 2, the amount of moisture observed in the walls differs significantly. The moisture readings in gypsum sheathing have been calibrated to the 0-100 relative scale common to the Delmhorst BD10 and 2100 moisture meters and therefore, and cannot be compared to wood moisture content readings. Calibration of the moisture sensors performed at the start of this study indicate that moisture readings in the range of 80 to 90 in Dens-Glass Gold sheathing are indicative of exposure to conditions at or near 100%RH. In addition, during the period in February and March of 2002 when the high readings were observed, the gold leaf wetness sensors were reading levels that indicate condensation on the interior surface of the sheathing. The abnormally high humidity values can be explained by examining the wall assembly in more detail. On Building 3 an exterior insulated rainscreen assembly was used that incorporated an impermeable air/vapour/moisture barrier applied to the exterior sheathing. However, as this was a retrofit, R8 batt insulation was left in the stud space and the polyethylene vapor retarder was removed in most locations. As the temperature cools down across the batt insulation, the amount of moisture that the air can hold decreases, increasing the relative humidity. This phenomenon can be seen on Figure 6a. The calculated relative humidity at the exterior sheathing is at 100% for the majority of the period shown in Figure 6b, and small reductions in moisture content in the sheathing are observed during period of warm exterior temperatures when the calculated relative humidity drops below 100%. The high moisture levels observed in the exterior sheathing were relatively constant throughout the winter of 2002. The moisture level started dropping in mid March and was relatively dry (35-50) between May and September at which time the levels start to increase again. As of October 2002 the moisture level in the exterior sheathing was approaching 75.

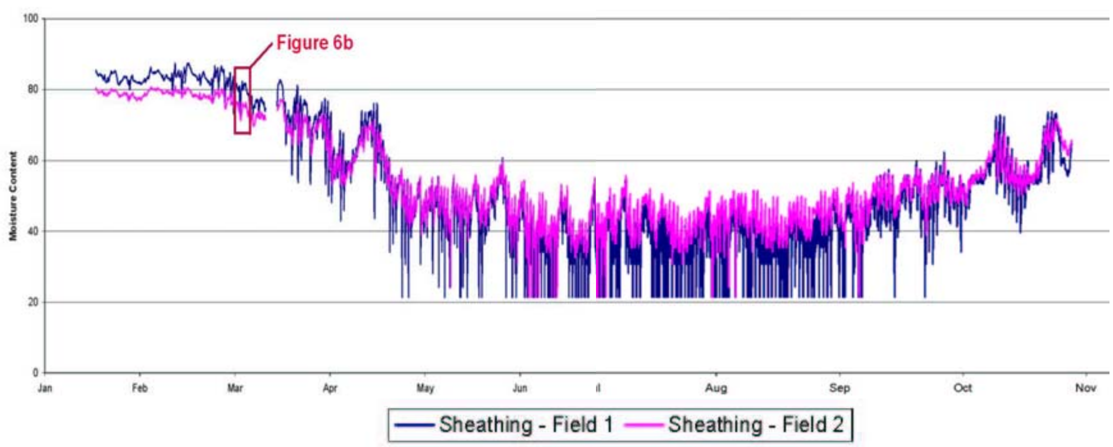


Figure 6a – Building 3 Cavity 6, Relative Moisture Level (0-100 scale)
January 15, 2002 to October 25, 2002

DRIVING RAIN AND WETTING

The relationship between overhang protection and wetting on the walls was examined for Buildings 1, 2 and 3 by dividing the total driving rain by the total vertical rainfall on each building and elevation. The results of this analysis shown on Table 4 indicate that the width of the overhang can significantly impact the amount of wetting from wind driven rain. For example the east wall on Building 2, which has an overhang of 50mm, experienced three times more wetting from driving rain than the east wall on Building 1, which has a roof overhang of 500mm.

Figure 7 shows this information graphically for the east elevation. It should be noted however, that Figure 7 is based on a very small sample size, with differing external factors that can also

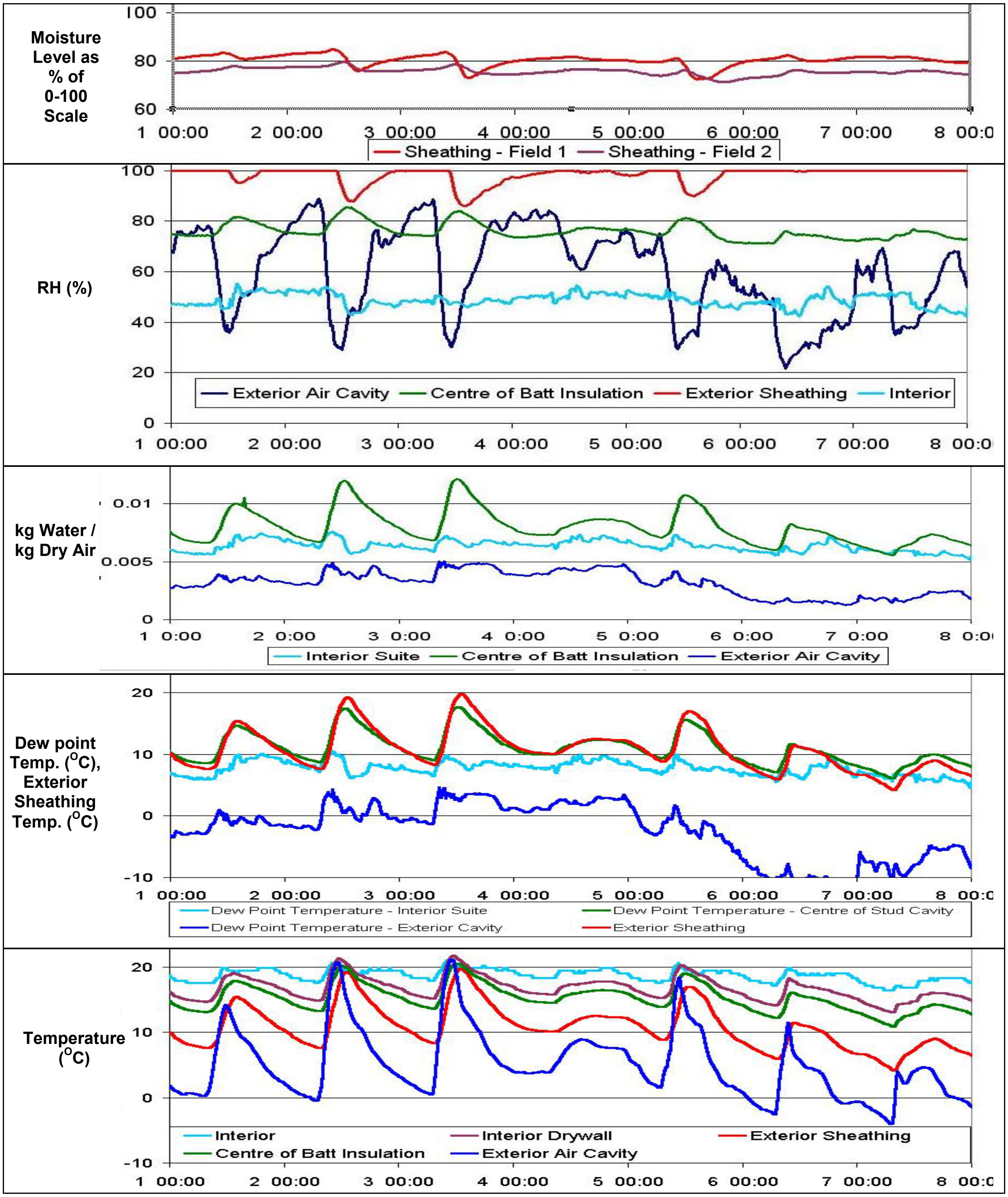


Figure 6b – Relative Moisture Level (0-100 scale), Relative Humidity (%) and Temperature (°C) Building 3 – Cavity 6 (control), March 1 – March 8, 2002

influence wetting. The monitoring of many more buildings in similar climactic conditions would be required before an accurate relationship between overhang and wetting can be developed.

Table 4 - Effect of Overhang on Wetting (winter 2002 -summer 2002)

	Location of driving rain gauge (meters from roof line)	Overhang (mm)	Driving Rain (% of Vertical) East Elevation	South Elevation
Building 1	4	500	3%	1%
Building 2	4	50	10%	4%
Building 3 - Floor 3	10	0	5%	
Building 3 - Floor 6	3	0	13%	

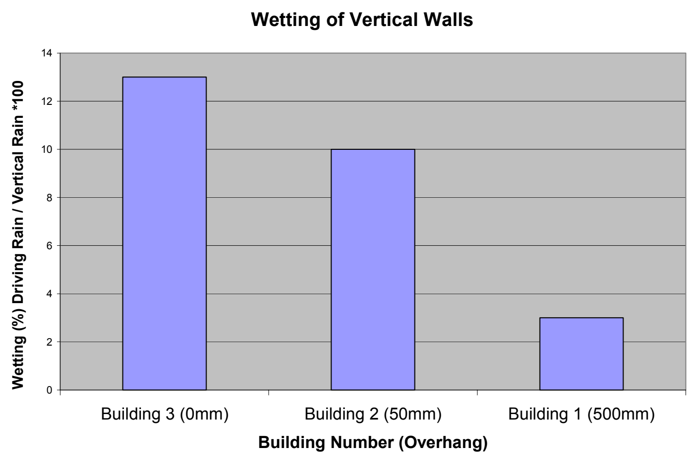


Figure 7 - Driving Rain vs Overhang Width

A significant variance in the wetting of the walls was observed on the six-story Building (Building #3) between the 2 locations monitored. On this building the 3rd floor was exposed to only 38% of the driving rain that was recorded on the 6th floor. The reduced level of driving rain on the lower level may be explained by local exposure factors such as the location of adjacent buildings which protect lower portions the east elevation, and the natural wind patterns on mid to high rise buildings which generally result in more wetting at the top of a building than in the centre.

In Vancouver the primary direction of wind driven rain is from the east. On Buildings 1 and 2 the driving rain gauges on the east elevation measured three times more wind driven rain than those on the south elevation.

The effect of significant driving rain events can be seen on Figure 8, during the period shown there were 2 significant driving rain events. Each driving rain event was followed by a corresponding increase in the moisture content in the strapping. This was followed again by a corresponding peak in the moisture content of the sheathing, at the same time as there was an increased potential for condensation on the back surface of the sheathing. After both rain events the elevated moisture content quickly returned to normal seasonal levels. The condensation potential in Figure 8 was derived by subtracting the calculated vapour pressure at the backside of the sheathing from the saturated vapour pressure at the same location. When the calculated value is greater than zero there is a potential for condensation at this surface. Wind driven rain increased moisture content of strapping quickly, but took longer to affect sheathing. In many cases when storm duration is small, sheathing moisture content was unaffected by the driving rain.

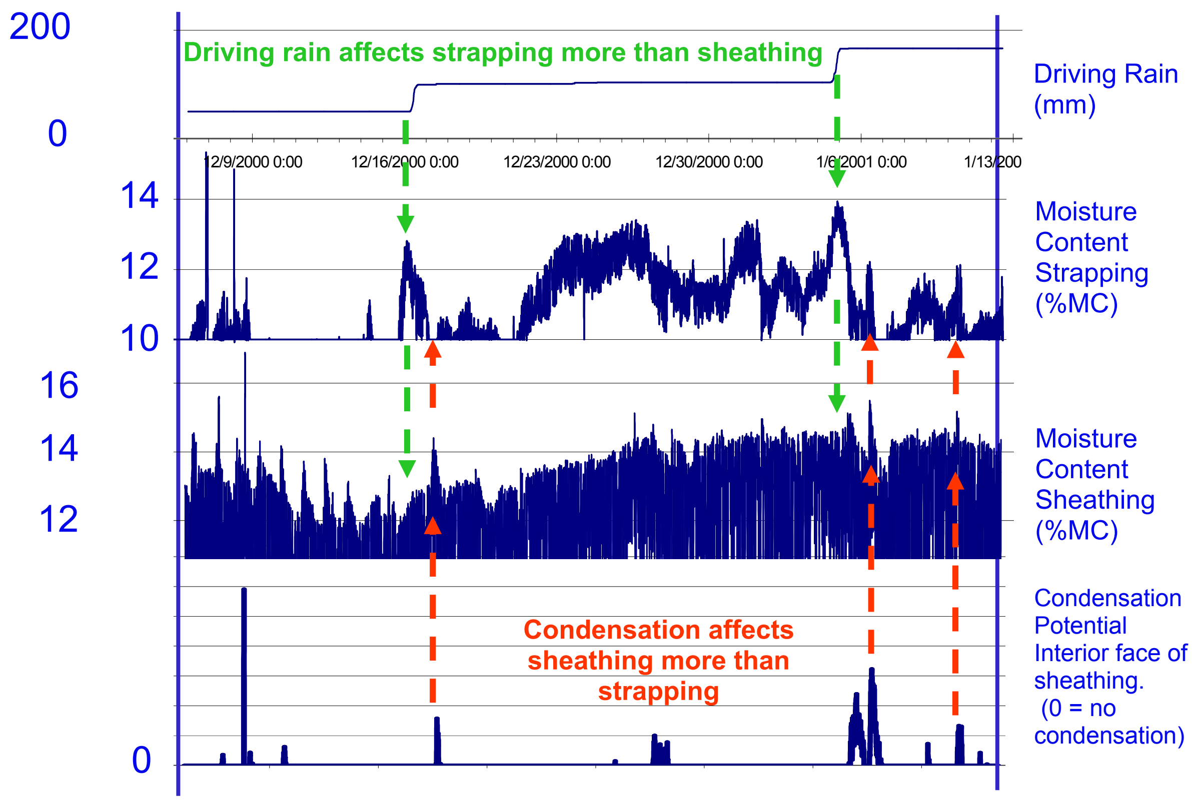


Figure 8 - Condensation Impact on Moisture Content (Winter)
Building 1, Cavity 2 December 6, 2000 to January 12, 2001

VAPOUR DRIVE

The data was reviewed to examine the effect of inward vapour drive on the moisture content of the sheathing and strapping in Buildings 1 and 2. Sample winter and summer conditions were reviewed in detail to examine the possibility of inward vapour drive. Figure 9 shows the vapour pressure at the exterior side of the polyethylene for a typical hot summer period without precipitation in 2001 between June 10 and July 12. In this period the vapour pressure curve did not touch the saturated vapour pressure curve indicating that no condensation occurred on the exterior of the polyethylene sheet from inward vapour drive. When both buildings are compared, it appears that the vinyl building is more resistant to inward vapour drive than the stucco building. This is likely a result of the higher temperatures generally recorded on the stucco building and possibly the greater water storage capacity of the stucco (Figure 11).

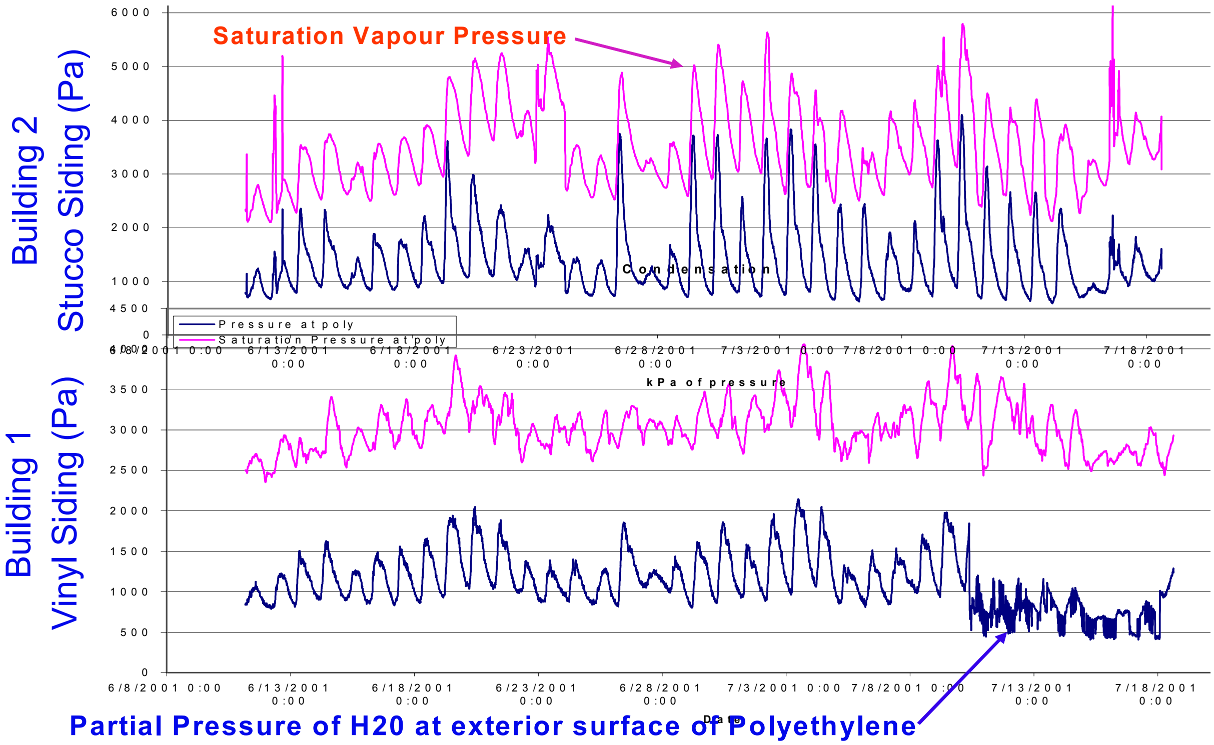


Figure 9 – Buildings 1 and 2 - Inward Vapour Drive Potential (June 10, 2001 to July 12, 2001)

Conversely, when driving rain is present inward vapour drive does occur, having a more significant short term effect on the sheathing moisture content than driving rain alone. In Figure 10 the sheathing moisture content increased slowly during the period when the cladding was wetted from driving rain at a relatively low temperature. From April 10 to the 14th during the heavy rains the moisture content of the sheathing increased from 7% to 12%. However, a much larger and shorter spike in moisture content occures on April 18th, which was a hot dry day that followed the several days of driving rain. As the wet cladding was heated, the wood moisture content in the sheathing peaked at 15%. The increase in moisture content lasted while the temperatures were elevated but quickly returned to normal with the temperature.

TEMPERATURE COMPARISON

The temperature for the warmest south elevation cavity, during one of the warmest weeks in 2002, is shown for building in Figure 11. In general, the measured temperatures at Building 2 are higher than Buildings 1 and 3. This cannot be explained by colour of the cladding as all buildings have similar colour tones. Slight differences in building orientation, shading from overhangs and trees may be partly responsible for this discrepancy. However, it is suspected that the additional ventilation inherent in the vinyl siding on Building 1, and the larger drainage cavity and conductive metal Z bars behind the stucco cladding on Building 3 also contribute to the measured differences.

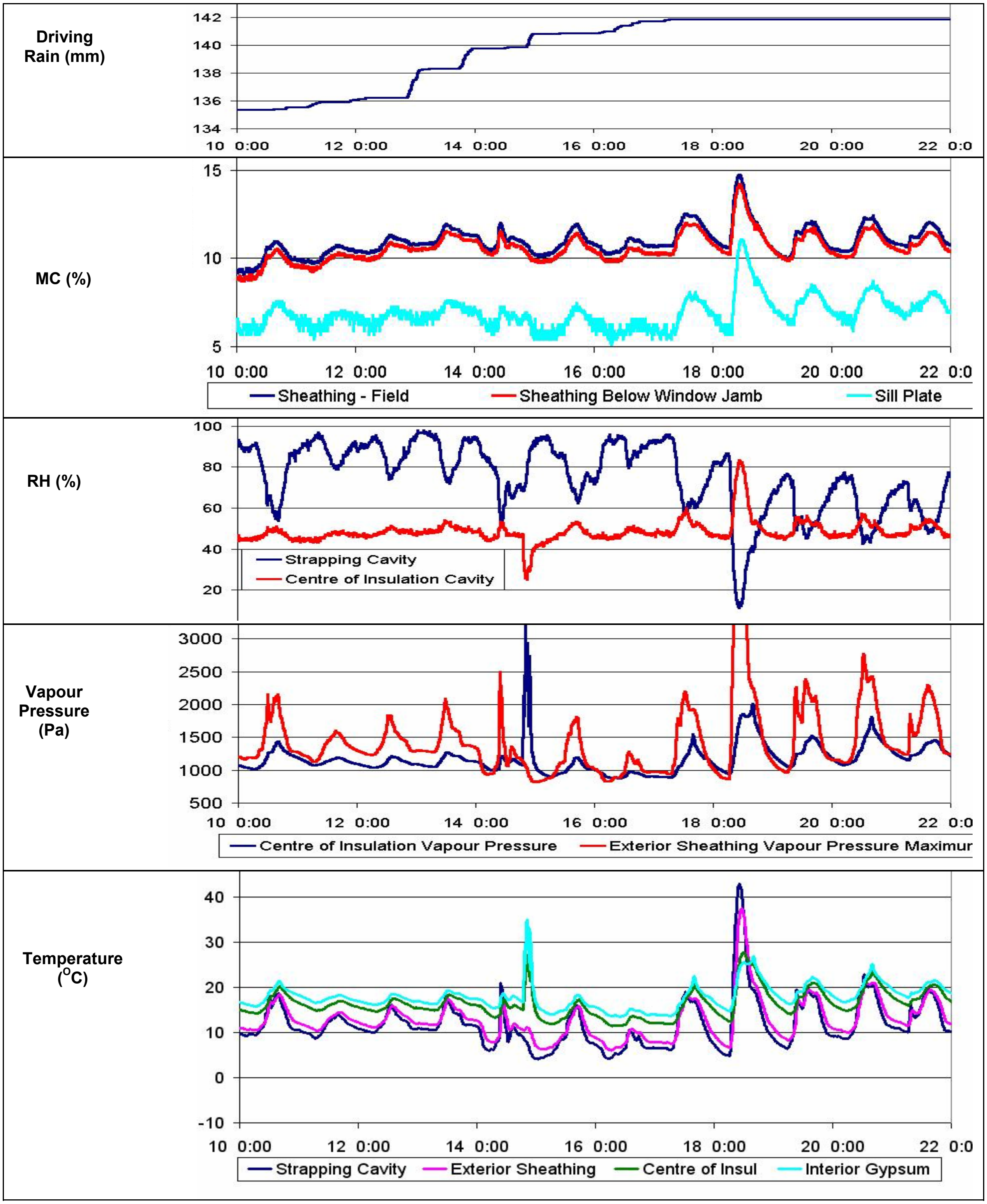


Figure 10 –Large Driving Rain Event followed by High Temperature Event
Building 2 – Cavity 4, April 10-21, 2002

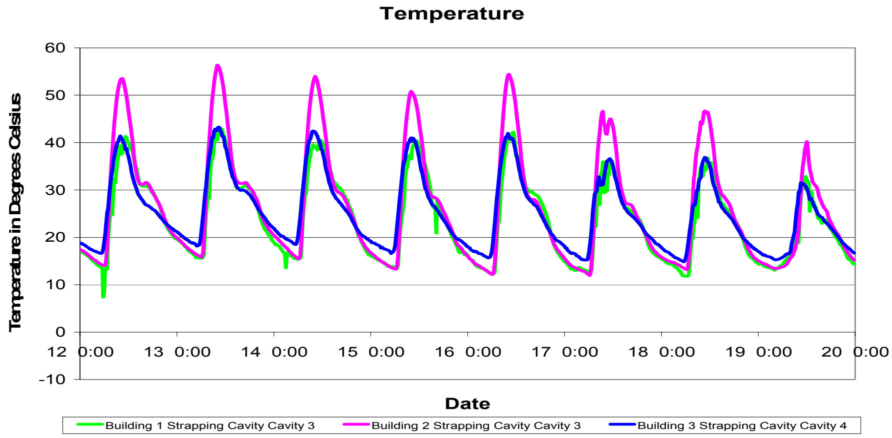


Figure 11 – Cavity Temperature Comparison
August 12, 2002 to August 19, 2002

EFFECT OF WIND SPEED ON BUILDING PRESSURIZATION

The maximum recorded wind speed and direction on buildings 1, 2 and 3 was 67 km/hr WSW, 62 km/hr W and 100 km/hr SE respectively. The maximum pressure difference recorded across the building envelope is 37, 146 and 62 Pascals positive pressure (infiltrating) for buildings 1, 2 and 3 respectively. The minimum negative pressure was 83, 124 and 83 Pascals for buildings 1, 2 and 3 respectively. Pressure differential was measured from the exterior cavity to the interior stud space. In general the maximum pressures experienced on the building envelope were lower than expected structural loads or even typical window test pressures. One reason for lower than expected readings could be the sharing of wind loads over the cladding, interior gypsum board and interior partition walls. In addition, since one reading was taken every 15 minutes, it is possible that some higher wind gusts were not recorded.

CONCLUSIONS

The moisture content in the sheathing and strapping on the wood framed buildings generally stayed well below levels that can accelerate deterioration and promote fungi growth and decay. This finding indicates that wall systems currently being utilized in the Lower Mainland can perform successfully.

The findings also support the use of caution when utilizing exterior insulated wall assemblies with a waterproof membrane on the exterior of the sheathing, in conjunction with conventional insulation in the stud cavity. More research on this wall type is required before conclusions can be made regarding its performance.

In addition to the primary goal of assessing performance, the monitoring program continues to provide information on how the building envelope reacts to weather and interior environmental conditions in a real world environment. Conclusions that can be made from the data collected to date include:

- Overhangs reduce wetting of walls in proportion to their size and ratio to wall height.
- Condensation at the interior poly vapour retarder from inward vapour drive during hot clear days in the summer was not observed.
- Condensation from inward vapour drive was measured at the exterior sheathing following some heavy rain events in the winter and spring.
- Outwards vapour drive in the winter increases the moisture content of the exterior sheathing.
- Wind driven rain increases moisture content of strapping quickly but takes longer to affect sheathing. In some cases when storm duration is small, sheathing moisture content is unaffected.

FUTURE WORK

After the determination of the basic effectiveness of the rainscreen walls, the comparative analysis of wetting and drying on the different cladding assemblies offers the best opportunity for further research and knowledge. In order to obtain data that will be useful in a comparative analysis the simultaneous monitoring of all 5 buildings must continue through the same seasonal wetting cycle. As this has not occurred to date, we are recommending that the monitoring be continued for an additional year past the fall of 2002 when Building 5 comes on line.

The following are opportunities for future research utilizing the data obtained, or the monitoring system prior to decommissioning at the conclusion of the study:

- Compare results with data from a non-rainscreen building with active water infiltration problems during the same time period.
- Perform simultaneous wetting (water testing) on all buildings (stucco, vinyl and hardboard claddings) to examine and compare wetting and drying response times.
- Compare the results from the monitoring with a commercial software applications such as WUFI.

More information is also required on the Hygothermal behavior of fiberglass faced gypsum sheathing.

REFERENCES

[1] Straube, J., *Measuring Wood Moisture Content Using the Electrical-Resistance Method*, Copyright, Copyright John Straube 1997.

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