ON-SITE EXTERIOR WALL MONITORING METHODS FOR AIR LEAKAGE, CONDENSATION AND RAIN PENETRATION CONTROL PROBLEMS
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On-Site Exterior Wall Monitoring Methods for Air Leakage, Condensation and Rain Penetration Control Problems.

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Thanks are given to Can-Best Inc., a construction research laboratory in Toronto, for providing data on a field monitoring project used in this report. Specifically, Can-Best Inc. instrumented and monitored the rain penetration control performance of the precast panels on a seventeen storey building in Toronto.

Thanks are also given to Keller Engineering Associates Inc. for providing the data of a field monitoring project used in this report. Specifically, Keller Engineering Associates Inc. monitored the conditions of an exterior wall of a high-rise apartment building in Ottawa for over four years. Their monitoring observations of the condensation occurring behind the brick veneer and exterior sheathing of the exterior wall from the leakage of humid indoor air were very useful in demonstrating the Condensation Detection and Analysis Method.

Special thanks are also given to Jacques Rousseau of the Canada Mortgage and Housing Corporation for discussions about the project and for reviewing the previous drafts of this document. Jacques contributed numerous positive suggestions and his advice was invaluable in organizing the final report.

Lastly and most important, thanks are given to the Canada Mortgage and Housing Corporation for undertaking this project. This research and development project brings valuable information to the professionals in the building industry and new tools to improve the quality and accuracy of diagnostics in the investigation of building envelope problems.
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SOCIÉTÉ CANADIENNE D'HYPOTHÈQUES ET DE LOGEMENT

Canada
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Appendix "A" - Wall Cavity Physics
1.0 Introduction

Cladding and exterior wall performance problems occur on all types of buildings. These problems may range from efflorescence on bricks, to freeze-thaw damages to masonry claddings, to the corrosion of metal studs and brick ties to the rotting of wood sheathing in wood framed buildings. These problems may also include failed rain penetration control, high energy cost and poor indoor temperature control.

Wall performance problems may vary considerably from one wall type to another but they almost all involve one or more of the following wall performance deficiencies. There is inadequate or deficient exterior wall air leakage control, inadequate or deficient vapour diffusion control and or inadequate or deficient rain or melt water penetration control into exterior wall construction cavities.

Cladding and exterior wall problems are usually investigated in terms of location and severity of damage. This is necessary to develop the initial scope of the remedial repairs and to estimate first costs. However, investigative surveys do not always reveal the exact cause of the problem or damage and without the knowledge of an exact cause, the owners and the consultants may develop recommendations from an incomplete or incorrect diagnosis. This then leads to the risk of undertaking incorrect or perhaps unnecessary remedial repairs with respect to the problem under consideration. The cause of an incomplete or incorrect diagnosis is the lack of information with respect to actual field conditions.

To improve diagnostics of problem analysis, a field investigation may be expanded to include wall performance monitoring. Specifically, by instrumenting the problem location of an exterior wall with appropriate sensors, by monitoring the exterior, interior and cavity conditions of the problem area for the duration of a few hours to a few weeks, much information may be obtained about the sources of moisture and the moisture balance of the problem areas. Finally, by analyzing the monitoring data, the diagnosis of the actual cause of the problem or source of moisture may be positively identified.
CMHC recognizes that most consulting firms provide services for the design and construction of new building designs and for the design of remedial repairs in existing buildings. Design consultants are not generally oriented towards the diagnostics of building envelope problems with the exception of site visits and review of test openings. CMHC also recognizes that numerous remedial repair recommendations are conservative and at times considerably more expensive than need be. The problem is inadequate diagnostic information and this project was undertaken to provide consultants with additional investigative tools to undertake more complete investigations.

This report is an updated version of an earlier report on the monitoring of exterior walls for the IDEAS Challenge projects. The various monitoring protocols of the previous report have been updated and rearranged to better explain the basics of field monitoring and the interpretation of monitoring data. The monitoring protocol now includes three specific methods. These are the Air Leakage Detection and Analysis Method, the Condensation Detection and Analysis Method and the Rain or Melt Water Detection and Analysis Method.
2.0 Method 1 - Air Leakage Detection and Analysis

2.1 Theory

The leakage of air through an exterior wall may result in any number of wall or building performance deficiencies. These include condensation in the exterior wall cavities or materials, rain penetration into and through the exterior wall and various room temperature or humidity control problems. If any of these problems or symptoms are observed, air leakage may be suspected as one of the principal causes of the problem. To determine if air leakage is occurring in an exterior wall the following detection and analysis monitoring method may be used.

The detection and analysis of air leakage in an exterior wall may be undertaken by monitoring when there exists a temperature difference between the inside and the outside of the building and by comparing the measured temperature index of a wall cavity with the air pressure difference occurring across the exterior wall. The temperature index of an exterior wall is the fractional temperature drop that is expected at a particular location in the wall due to conductive heat losses and the thermal resistance of the wall elements. For a detailed explanation of temperature index applied to exterior walls, see Appendix A.

When the outdoor temperature falls below the indoor temperature, a temperature drop will form across the cladding and exterior wall of a building. This temperature drop will arrange itself as a temperature gradient through the wall in proportion to the thermal resistance of the wall elements. When indoor air exfiltrates through a wall to the outside, the leakage air also transports heat to the outside. This heat loss tends to warm up the wall components and construction cavities above the normal thermal balance caused by conduction losses alone. In other words, the measured temperature index would be higher than the nominal temperature index at the same location. Similarly, if the outdoor air infiltrates through the wall to the inside, it is likely that the construction materials and cavity temperature will decrease to yield a temperature index that is lower than the nominal temperature index for the same
location. Since air leakage is driven by an air pressure difference and occurs along a flow path, comparing the measured temperature index with the monitored air pressure difference, will confirm if air leakage is occurring and reveal the severity of the air leakage problem.

2.2 Cladding and Wall Systems

The leakage of air may occur through any type of cladding and exterior wall system. To demonstrate the air leakage detection and analysis monitoring method, a residential building in Montreal was instrumented and monitored to determine if air leakage occurred. The exterior wall consisted of a brick veneer, a cavity, construction paper, a layer of mineral fibre insulation over an exterior sheathing fastened to a 6" steel stud system. There is additional glassfibre insulation in the steel stud cavity, a vapour barrier and an interior gypsum board finish. The building elevation, floor plan and wall section showing the location of the monitoring station will be found in Figures 1, 2 and 3 at the end of this chapter.

2.3 Monitoring Equipment

To detect and analyse air leakage through an exterior wall, various conditions must be measured. Specifically, the air temperature near the inside wall surface, near the outside wall surface and in a cavity of the exterior wall. Also, the air pressure difference between the inside and the outside of the building must be measured.

To illustrate the wall monitoring setup for air leakage detection examine the equipment monitoring plan in Fig. 4 at the end of this chapter. In this example plan, there are 3 temperature sensors; T1, located on the inside of the building; T2, in the steel stud insulation cavity and T3, on the outside of the exterior wall. There is also an air pressure tap (plastic or metal tubing) installed. The tube must penetrate the wall completely from inside to outside. The inside end of the tube is connected to a pressure transducer. The pressure tap may be fabricated with 6 mm diameter copper tubing with the outside end protruding about 15 mm to 20 mm from the cladding surface. There are several types of pressure transducers available, however, the Setra model 264, +/- 0.5" WC, 12-28 VDC performs quite reliably. The reference side of the transducer must be open to the inside of the building.
There are numerous types of equipment for the recording and logging of field data. For convenience and simplicity, we recommend the use of ACR data loggers or equivalent. ACR data loggers are portable units, approximately 100 mm long x 70 mm wide by 20 mm thick, having 2 to 6 channels and an internal battery. Various type of sensors are attached to the ACR loggers to include temperature sensors, relative humidity sensors and pressure transducers. The loggers are programmable to a wide range of frequencies and may store up to 32768 readings per monitoring cycle or in a continuous loop. We refer to the sensors and data loggers for a single area of exterior wall as a monitoring station.

The sensors should be carefully installed and their exact location noted for future reference. The sensors must be calibrated before installation. The sensors should then be connected to various data loggers and commissioned into operation. It is prudent to verify the operation of the loggers by downloading several hours of monitoring data prior to the planned monitoring period.

2.4 Monitoring Intervals

The heating or cooling of a construction cavity by air leakage is not a rapid process. It is dependent on the air pressure difference acting across the exterior wall and the area of the flow path. The air pressure differences result from stack effect, fan pressurization or wind. With the exception of fan pressurization, average wind and stack effect pressurization changes are slow to occur but usually noticeable within the hour. For this reason, data logging at 15 min. Intervals is quite adequate for detection and analysis of air leakage effects. Data logging for 1 to 2 weeks with downloads occurring weekly should provide sufficient data for the intended purpose.

2.5 Data Analysis and Interpretation

The data collected during the monitoring period should be organized in tabular format on Excel or Quatro Pro (for Windows) spreadsheet for easy analysis and hard copy production. In addition, the information should be plotted on graphs to include temperature related information and pressure related information. This should be undertaken for each weekly period downloaded.
From the data obtained by the monitoring process, plot the temperature performance of the exterior wall vs. time. The plot should include the indoor temperature, the outdoor and the cavity or inter layer temperature (see Fig. 5A at the end of this chapter). From the monitored data, compute the measured temperature index for the wall at each recording interval and record in the spreadsheet.

The next step involves reducing the monitoring data to select time periods. As daytime temperatures also involve solar conditions which also affect wall temperatures, various people activities which may affect pressure differences, it is recommended that the analysis be completed with nighttime data only, that is, data from 12:00 am to 6:00 am. This is undertaken by copying the desired data blocks from the main spreadsheet to an auxiliary spreadsheet. Using this reduced data, plot the actual temperature index versus the air pressure differences. Where air leakage occurs, this analysis will appear similar to Fig. 2B at the end of this chapter.

It can be seen from Fig. 2B that the actual temperature index increases with negative (exfiltration) air pressure difference and decreases with positive (infiltration) air pressure difference. This indicates that the exterior wall is leaking air and the spread of the index change over the pressure difference range is indicative of the magnitude of the leakage problem. If the exterior wall were air tight, the pressure difference would not induce air leakage and therefore changes in cavity temperature and the temperature index would be minimal or remain constant.

2.6 Deliverables and Estimated Cost

If this method of monitoring is undertaken as part of an investigation for a CMHC project, the consultant will be required to prepare various deliverables for this assignment. These deliverables shall include a photographic record (slides preferred) of the building elevation, the exterior wall construction, the location and type of sensors and a plan of the data logging station. Following the monitoring period, the consultant will also provide, visual observations of the performance symptoms to be analyzed, the monitored data on Excel or Quatro Pro spreadsheet file, a hard copy of the data and the data plotted on graphs as noted above. The consultant shall prepare a brief report outlining the method, observations, analysis, conclusions and conceptual recommendations for repair where applicable.
The costs of this monitoring method will vary from project to project and must be determined for each case. However, for estimating purposes, the following costs are a reasonable estimate of fees and expenses for a consultant or specialist in Canada in 1999 to undertake this monitoring assignment.

1) purchase of sensors, transducers, ACR loggers and accessory hardware, $ 3000.00
2) installation of sensors, programming data loggers, downloading and re-installation $ 1500.00
3) documentation, analysis, graphs and reports $ 3500.00

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) purchase of sensors, transducers, ACR loggers and accessory hardware</td>
<td>$ 3000.00</td>
</tr>
<tr>
<td>2) installation of sensors, programming data loggers, downloading and re-installation</td>
<td>$ 1500.00</td>
</tr>
<tr>
<td>3) documentation, analysis, graphs and reports</td>
<td>$ 3500.00</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>$ 8000.00</strong></td>
</tr>
</tbody>
</table>
FIGURE 1
Elevation - Montreal Building

Wall location "B" to be monitored
FIGURE 2
Plan Location of Wall Monitoring Station B

Wall location "B" to be monitored

Wall location "A" to be monitored
**FIGURE 3**
Wall Section A or B
Montreal Building

- Solin métallique prépeint
- Bâti de bois de type hydrofuge, rempli d'isoant en natte

Approximate height of sensors in exterior walls (see plan - Fig. 2)
FIGURE 4
Air Leakage Detection and Monitoring Station

Temperature sensors
Pressure taps
Pressure transducers

Logger A
Logger B
Logger C

T1
T2
T3
P1

Ref.
FIGURE 5
Air Leakage Detection Analysis
Montreal Building

Figure 1A - Wall Cavity Temperatures

Figure 1B - Wall Cavity Temp. Index

Nominal Temp. Index = 0.5

Actual Temp. Index
3.0 Method 2 - Condensation Detection and Analysis

3.1 Theory

Condensation in exterior walls may lead to various types of moisture problems. These problems include efflorescence on bricks and mortars, freeze-thaw damage to masonry units, paint peeling on sidings, corrosion of metal fasteners and the rotting of wood sidings, sheathings and studs. To determine if condensation is the primary cause of a moisture problem, the following detection and analysis method may be used.

Condensation is generally associated with cold weather. It occurs primarily in winter although summer condensation also occurs. Condensation also tends to occur in the outer most construction cavities or construction layers in winter and the inner most layers in summer. For example, when condensation occurs on the back side of a brick veneer, it is because the dewpoint temperature of the cavity air has risen to equal or exceed the surface temperature of the backside of the brick. The condensation detection and analysis method is a study of the dewpoint temperature of the cavity air and the surrounding surface temperatures of exterior wall construction cavities.

If condensation is the suspected source of moisture, it may be detected and analyzed by measuring the following wall conditions. The outer most cavity (or innermost for summer condensation) of the wall must be instrumented to measure the temperature and relative humidity of the cavity air and the surface temperature of the outer most or colder surface of the cavity. The air temperature and relative humidity conditions are then converted to dewpoint temperatures and are compared with the cavity surface temperature. If the dewpoint temperature is equal to or higher than the cavity surface temperature for prolonged periods of time, condensation is probably occurring.

To illustrate the condensation detection and analysis method for an exterior wall, the field monitoring data of a brick veneer steel stud wall system from a medium rise apartment building is presented and discussed.
3.2 Cladding and Wall System

Koller Engineering Associates (KEA) Inc. has been involved in exterior wall monitoring for several years. Upon request, KEA provided example monitoring data for an exterior wall (known as a brick veneer steel stud wall or BVSS system) known to experience condensation in the wall cavity behind the brick. The wall monitoring was undertaken in a building in Ottawa in December of 1996.

The BVSS wall system was originally designed as a rainscreen system with vent and drains, a pressure equalization cavity, construction paper, sheathing, glassfibre insulation, a vapour and air barrier system (see Figures 6 and 7 at the end of this chapter). If rain water or condensation penetrated into the brick cavity, it was designed to drain and vent the condensation or rain to the exterior.

3.3 Monitoring Equipment

The brick veneer steel stud wall of the Ottawa Building was instrumented with various sensors to record temperature, relative humidity, pressure and moisture (see Figures 8 and 9 at the end of this chapter). There are numerous sensors installed at various locations in the exterior wall. Not all of the sensors shown in Figures 8 and 9 are required. For the purpose of condensation detection and analysis, the only sensors required are T8, T9, T33, and Rh2 for the brick cavity or T20, T34, T11 and Rh3 for the insulation cavity.

If the condensation detection and analysis method also requires identification of the source of moisture, temperature sensors T31 and T14 will provide a better understanding of the indoor and outdoor temperature conditions. Also a pressure tap (tube) and transducer should be installed to monitor the indoor/outdoor air pressure difference and direction. There are several types of pressure transducers available, however, the Setra model 264, +/- 0.5" WC, 12-28 VDC perform quite reliably.

There are numerous types of equipment for the recording and logging of field data. For convenience and simplicity, we recommend the use of ACR data loggers or equivalent. ACR data loggers are portable units, approximately 100 mm long x 70 mm wide by 20 mm thick, having 2 to 6
channels and an internal battery. The loggers are programmable to a wide range of frequencies and may store up to 32768 readings per monitoring cycle or in a continuous loop. We refer to the sensors and data loggers for a single area as a monitoring station.

The sensors should be carefully installed and their exact location should be noted for future reference. The sensors must be calibrated before installation. The sensors should then be connected to the data loggers indicated and commissioned into operation. It is prudent to verify the operation of the loggers by downloading several hours of monitoring data prior to the actual planned monitoring period.

3.4 Monitoring Intervals

Condensation production is not a rapid phenomenon but it may occur continuously for hours or days depending on the indoor humidity conditions and the outdoor temperature. For detection purpose, it is recommended that the data monitoring interval be set to 30 minutes. The data should be downloaded once per week. It is also recommended that monitoring continue for 3 weeks as a minimum as several climatic conditions and combination thereof are required for a complete analysis. The data obtained during the monitoring period should be downloaded to a spreadsheet program (Excel or Quatro Pro for Windows) for easy analysis and the production of graphs and charts.

3.5 Data Analysis and Interpretation

From the data obtained by the monitoring process, the temperature, relative humidity and optional air pressure difference information should be analyzed and presented as follows. From the temperature and relative humidity data collected, plot the temperature and RH data of the cavity vs. time (see Figures 10A and 10B at the end of this chapter). Convert the cavity temperature and RH to a dewpoint temperature and plot a 3rd graph that compares the surface temperature of the inside surface of the brick cavity with the dewpoint temperature and the outer surface temperature of the brick cavity (see Figure 11A at the end of this chapter). Finally, subtract the dewpoint temperature from the surface temperature of the backside of the brick and present as an area graph for easy viewing analysis (see Figure 11B at the end of this chapter).
The solid area of Figure 11B illustrates the difference in temperature and the duration of this difference where the dewpoint temperature of the cavity is consistently higher than the backside temperature of the brick veneer. This indicates that condensation is occurring but more important, that moisture is supplied constantly to the cavity throughout the 14 day period. This suggests that air exfiltration is occurring and indoor humidity is supplied constantly to the cavity air. This hypothesis was confirmed by examining the air pressure difference across the wall. It was noted that the air pressure difference was outward and constant at 10 to 20 Pa. In turn the pressure was induced by the stack effect during this winter period. It is these kinds of observations and analysis that provide direct evidence of the condensation phenomenon and its principal cause.

### 3.6 Deliverables and Estimated Cost

If this method of monitoring is undertaken as part of an investigation for a CMHC project, the consultant will be required to prepare various deliverables for this assignment. These deliverables shall include a photographic record (slides preferred) of the building elevation, plan and sections of the exterior wall construction, the location and type of sensors and a plan of the data logging station. Following the monitoring period, the consultant will also provide, visual observations of the problem symptoms, the monitored data on Excel or Quatro Pro spreadsheet, a hard copy of the data and the data plotted on graphs as noted above. The consultant shall also prepare a brief report outlining the method, observations, analysis, conclusions and conceptual recommendations for repair where required.

The costs of this monitoring method will vary from project to project and must be determined for each case. However, for estimating purposes, the following costs are a reasonable estimate of fees and expenses for a consultant or specialist in Canada in 1999 to undertake this monitoring assignment.

1) purchase of basic sensors, ACR loggers and accessory hardware, $2000.00
2) optional temperature sensors, transducers and loggers, $2000.00
2) Installation of sensors, programming data loggers, downloading and re-installation $1500.00
3) documentation, analysis, graphs and reports $2500.00

**TOTAL** $8000.00
FIGURE 6
Plan View of Test Wall
Ottawa Building

- 13 mm gypsum board
- 4 mil polyethylene film
- RSI 3.5 glass fiber batt insulation
- 152 mm x 32 mm steel stud
- 13 mm exterior grade gypsum board
- building paper
- air space
- 90 mm brick veneer
FIGURE 7
Cross-Section Through Test Wall
Ottawa Building

- 13 mm gypsum board
- 4 mil polyethylene film
- RSI 3.5 glass fiber batt insulation
- 152 mm x 32 mm steel stud
- 13 mm exterior grade gypsum board
- building paper
- air space
- 90 mm brick veneer
FIGURE 8
Condensation Detection and Monitoring Station

OUTSIDE

T14

T10

T12

T13

T11

T9

T33

T30

T8

T18

T34

T20

T22

T23

T31

LEGEND

T14 Air or surface temperature thermocouple
- T14, T33, T34 & T31 are for air temperatures
- remainder are for surface temperatures, as shown,
  with T15 on a triangular wire tie
FIGURE 9
Condensation Detection and Monitoring Station

<table>
<thead>
<tr>
<th>OUTSIDE</th>
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<tbody>
<tr>
<td>RH1</td>
</tr>
<tr>
<td>M1</td>
</tr>
<tr>
<td>M3</td>
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<tr>
<td>P1</td>
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<table>
<thead>
<tr>
<th>INSIDE</th>
</tr>
</thead>
<tbody>
<tr>
<td>M6</td>
</tr>
<tr>
<td>M2</td>
</tr>
<tr>
<td>M4</td>
</tr>
<tr>
<td>RH2</td>
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<td>M5</td>
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<td>RH3</td>
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<tr>
<td>P3</td>
</tr>
<tr>
<td>M6</td>
</tr>
<tr>
<td>RH4</td>
</tr>
<tr>
<td>P4</td>
</tr>
</tbody>
</table>

LEGEND
- Electrical resistance sensor. Sensors M1 and M2 are at the first brick course and M3 and M4 at the 23rd course above the soldier course of concrete brick. Sensor M5 is sitting at the bottom of the air space and M6 is glued to the bottom track.
- P1 - Pressure top
- RH1 - Relative humidity sensor
FIGURE 10
Wall Temperature and RH Data
Ottawa Building

Fig. 10A - Brick Cavity, Ottawa Bldg.
Cavity Temperature, Hourly data

Fig. 10B - Brick Cavity, Ottawa Bldg.
Cavity Relative Humidity, Hourly data
FIGURE 11
Dewpoint & Outdoor Temperatures
Ottawa Building

Fig. 11A - Brick Cavity, Ottawa Bldg.
Cavity Surface & Dpt Temperatures

Fig. 11B - Brick Cavity, Ottawa Bldg.
Cavity Condensation potential
4.0 Method 3 - Rain and Melt Water Detection and Analysis

4.1 Theory

The leakage of rain or melt water through exterior walls and windows is usually evident when water appears on a floor or ceiling below the leakage entry point. However, not all rain or melt water penetration appears in the building. Most often when leaks are small they penetrate into the wall construction to eventually drain or dry out. On occasion, rain or melt water penetration may not drain or dry out and result in severe moisture damage to a wall construction by the time an exterior symptom may appear. These moisture damages are usually local but they include spalled masonry, peeling paint, rotted sheathing and studs, corrosion of metal fasteners and wetting of sheathings and insulation.

When rain or melt water accumulates in a wall construction, it may be absorbed by wood studs and sheathings or it may sit in a pocket where it will gradually evaporate to spread humidity to all parts of a wall cavity. When the latter occurs, the moisture content of the construction materials may rise and the relative humidity of the cavity air will also rise.

It is not unusual for construction cavities to increase in relative humidity during a rain storm. When rain or melt water penetrate into a construction cavity, the cavity relative humidity may remain high for an extended period of time. For example, it was found during a research project on rainscreen systems that when the glazing cavity of a metal and glass curtain wall system was wetted with 50 ml of water, the cavity required more than 2 weeks to dry out completely (see Figure 16 at the end of this chapter) even though it was well drained and vented.

If rain or melt water is the suspected source of moisture in a wall moisture problem, it may be detected and analyzed by using the following method. The cavity or area of most severe damage must be instrumented to measure the temperature and relative humidity of the cavity air facing the damaged area. Position additional sensors to monitor the indoor and outdoor temperature and relative humidity. As an
option, it is also recommended that the wall cavity be instrumented with pressure taps to observe the effect of pressure difference during wind driven rain. If the cavity’s relative humidity or material moisture content rises following a rainstorm or melt water event and remains high for days or even weeks, it is reasonably certain that rain or melt water has penetrated the wall construction and that it is not draining or drying out adequately. Monitoring should be undertaken through one or two rain or melt water events for conclusive evidence.

4.2 Cladding and Wall Systems

A precast concrete rainscreen wall on a renovated 17 storey building in Toronto was made available for the purpose of detecting and analyzing the rain penetration control performance of the new rainscreen wall system. The instrumentation and monitoring was undertaken by Can-Best Inc., a construction testing laboratory in Toronto.

The precast wall system consisted of a stone veneer precast panel outer wythe, a drained and vented cavity, 3 inches of glass fibre insulation and an inner wythe of precast concrete. The rainscreen precast panels were entirely fabricated off-site and installed on the building as a complete exterior wall. The elevation, floor plan and wall section will be found as Figures 12, 13 and 14 at the end of this chapter.

The precast wall panel was designed as a rainscreen system with a vent at the window jambs and drains at the window heads behind the exterior precast panels. If rain water penetrated the precast rainscreen cavity, it was designed to drain to the exterior at the window heads and to vent dry from the window jambs. On-site monitoring was undertaken to verify the rain penetration control of the new precast panel system design.

4.3 Monitoring Equipment

To detect and analyse rain or melt water in the precast panel rainscreen cavity, the precast wall was instrumented with various sensors to include a temperature and relative humidity probe in the air cavity behind the stone veneer of the precast panel, a temperature and relative humidity probe in the room adjacent to the exterior wall and a temperature and relative humidity probe on the outside near the surface of the exterior wall. In addition, the monitoring station was also equipped with a tipping bucket.
rain gauge to measure and record rain events. This is an optional sensor which is useful but not necessary to this method.

In Figure 15 (at the end of this chapter), the precast wall sensor locations and data logger requirements are presented. The sensors include T1, T2 and T3 for the inside, the cavity and the outside air temperature respectively. There are also 3 relative humidity sensors, H1, H2, and H3 to detect and measure local ambient relative humidity. In addition to the above, it is also recommended that the cavity and exterior be instrumented with pressure taps and pressure transducers to record and measure air pressure difference during wind driven rain events. This may be useful in discriminating between rain penetration by gravity and rain penetration by wind driven rain. Pressure taps may be fabricated with 6 mm diameter copper tubing. There are several types of pressure transducers available, however, the Setra model 264, +/- 0.5" WC, 12-28 VDC perform quite reliably.

There are numerous types of equipment for the recording and logging of field data. For convenience and simplicity, we recommend the use of ACR data loggers or equivalent. ACR data loggers are portable units, approximately 100 mm long x 70 mm wide by 20 mm thick, having 2 to 6 channels and an internal battery, to which various sensors are attached. The loggers are programmable to a wide range of frequencies and may store up to 32768 readings per monitoring cycle or in a continuous loop. We refer to the sensors and data loggers for a single area as a monitoring station.

The sensors should be carefully installed and their exact location should be noted for future reference. The sensors must be calibrated before installation. The sensors should then be connected to the data loggers indicated and commissioned into operation. It is prudent to verify the operation of the loggers by downloading several hours of monitoring data prior to the actual planned monitoring period.

4.4 Monitoring Intervals

Wetting of an exterior wall by rain or melt water penetration may occur rapidly but it is impossible to predict the occurrence of the rain or melt water event. For this reason set the monitoring schedule to 10 minute intervals but also set the data loggers to continuous loop recording. This method of recording retains the last 25 days of data. When a rain or melt water event occurs you may retrieve the data within 25 days of its
occurrence. It is prudent to record 2 to 3 rain or melt water events as each event may exhibit variations in rain intensity and wind effect.

4.5 Data Analysis and Interpretation

The data obtained during the rain or melt water monitoring event of the Toronto building was recorded and plotted as graphs. The data should be of suitable format for import into Excel or Quatro Pro (for Windows) spreadsheet and for easy analysis and hard copy production. In addition, the information should be plotted on graphs to include temperature, relative humidity and optional air pressure differences. This should be prepared for each rain or melt water event and extend from 2 to 7 days after the rain or melt water event.

From Figures 17 and 18 (at the end of this chapter), it can be seen that prior to a rain event, the outdoor humidity ratio (dewpoint temperature) climbs steadily until it reaches air saturation, remains high for the duration of the event and fall almost as rapidly following the storm. The cavity humidity ratio can be seen to climb slightly but not as high as the outdoors and it also fall back after the rain event. The indoor humidity remained constant throughout the rain events.

In Panel 101, Figure 17, it can be seen that the humidity ratio of the cavity increases and decreases with the outdoor humidity ratio. Even when the outdoor humidity ratio fall below the indoor humidity ratio, the cavity humidity ratio follows the outdoor conditions. This is indicative of a dry cavity and that no rain penetrated during this event.

In Panel 99, Figure 18, the humidity ratio of the cavity in this panel is slightly different than in panel 101 after the rain event. Panel 99 probably experienced light rain penetration as the humidity ratio of the cavity exceeded the outdoor conditions and remained above the outdoor conditions for several days.

This monitoring method will detect and confirm that rain or melt water is the source of moisture that has penetrated the exterior wall and is the cause of a moisture problem. It is easy to calibrate by injecting a known volume of water into a construction cavity and comparing the drying rate from the injected water with the observed results from the natural rainstorm or melt water event.
4.6 Deliverables and Estimated Cost

If this method of monitoring is undertaken as part of an investigation for a CMHC project, the consultant will be required to prepare various deliverables for this assignment. These deliverables shall include a photographic record (slides preferred) of the building elevation plans and sections of the exterior wall construction, the location and type of sensors and a wall section showing the sensors and data loggers. Following the monitoring period, the consultant will provide, visual observations of problem symptoms, the monitored data on Excel or Quatro Pro spreadsheet, a hard copy of the data and the data plotted on graphs as noted above. The consultant will be required to prepare a brief report outlining the method, observations, analysis, conclusions and conceptual recommendations for repair where required.

The costs of this monitoring method will vary from project to project and must be determined for each case. However, for estimating purposes, the following costs are a reasonable estimate of fees and expenses for a consultant or specialist in Canada in 1999 to undertake a field monitoring assignment using this method.

1) purchase of sensors, transducers, ACR loggers and accessory hardware, $4000.00
2) Installation of sensors, programming data loggers, downloading and re-installation $1500.00
3) documentation, analysis, graphs and reports $3500.00

TOTAL $9000.00
FIGURE 12
Elevation - Toronto Building

Top of building

Location of panels 99 and 101
FIGURE 13
Floor Plan - Toronto Building
FIGURE 14
Wall Section - Toronto Building
FIGURE 15
Rain & Melt Water Detection Monitoring Station

![Diagram of a rain and melt water detection monitoring station with various sensors and loggers labeled.]

- Temperature sensors
- Pressure taps
- Moisture sensors
- Pressure transducers
- Humidity sensors
- Rain gauge
FIGURE 16
Glazing Cavity Dry Out Test

Curtain Wall Rabbet Cavity
Relative Humidity Observations

- Wet Cavity  – Dry Cavity

Relative Humidity (%)

0  20  40  60  80

Time (days)

0  5  10  15  20  25

June 17, 1999
Figure 17: Rain Penetration Monitoring Data
Toronto Building

Figure (3): Air Humidity Ratio Inside and Outside Wall Cavity
Canada Life Building, 12th Floor, West Elevation
Centre Panel #101

124 mm/15 min. Rainfall intensity on panel

Humidity Ratio (%) versus Exposure time (yr)

Elapsed Time (hrs.), Starting Midnight May 31, 94

- Outside Ambient
- Cavity (litos of panel)
- Inside Ambient
- Rainfall Event
- Max. Vapor Contribution
FIGURE 18
Rain Penetration Monitoring Data
Toronto Building

Figure (4): Air Humidity Ratio inside and Outside Wall Cavity
Canada Life Building, 12th Floor, West Elevation
Panel #99

205 mm Rainfall Intensity on panel

Elapsed Time (hrs.), Starting Midnight May 31, 1994

- Outside Ambient
- Cavity (6mm of panel)
- Inside Ambient
- Collected Rain
- Max. Vapour Contribution

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5.0 Discussion and Conclusions

The diagnosis of moisture problems with claddings and exterior walls is complex. This, in part, is because there are numerous sources of moisture and over a dozen ways in which moisture can penetrate into and through exterior walls.

In the spring, summer and fall, the most likely source of moisture entering exterior walls is rain penetration. However, rain penetration may also occur all year round in the southern latitudes. In the northern latitudes, in winter, the most likely source of cavity moisture may be condensation. However, condensation in walls may also occur in all seasons including the summer during the air conditioning season. Snow and ice melt water may also drain into cavities during winter and spring and plumbing leaks and landscape watering are sometimes the source of moisture problems.

The most effective way to control a rain penetration problem is to correct the method of moisture transport into the wall cavity. Rain penetration includes direct entry, entry by gravity flow, entry by capillary action and entry by air pressure difference. Melt water entry is primarily by gravity flow but it may also enter by capillary action.

Condensation problems originate with high humidity conditions on the inside or the outside of the exterior wall and a temperature gradient across the wall caused by seasonal temperature changes or air conditioning in summer. Humidity may migrate into a wall cavity by diffusion, by convection, by air leakage, by atmospheric pumping and by thermal pumping. By far, air leakage is the most frequent cause of condensation in wall cavities. Air leakage occurs when there is a flow path through an exterior wall and an air pressure difference. The air pressure difference may be caused by wind, stack effect or fan pressurization. The most significant causes of pressure difference is stack effect and fan pressurization. The most significant cause of a flow path through an exterior wall is the absence of an air barrier system.

Monitoring the conditions of an exterior wall and interpreting the exposure conditions of wall cavities is a relatively new science. It has evolved
significantly over the past 10 years and much has been learned with respect to wall performance and wall dynamics.

The diagnosis of the cause of an exterior wall moisture problem is considerably improved with wall monitoring. With accurate information on actual wall performance and comprehensive analysis, consultants and specialists should be able to develop repair recommendations that are more effective and better suited to the moisture problems under consideration.

Quirouette Building Specialists Ltd.

Rick Quirouette, B. Arch.
Appendix
"A"

Wall Cavity Physics
The Wall Cavity Temperature Index

In an insulated wall, all materials and air cavities contribute a measure of thermal resistance to the total "R" value of a wall. To be effective, the insulation materials must be correctly installed and one surface must be in contact with another. Also, insulation materials are generally stable over long periods of time and provide a constant thermal resistance. It is these assumptions that leads to the development of the wall cavity temperature index.

For example, consider a wall system having the following description:

<table>
<thead>
<tr>
<th>Description</th>
<th>Layer</th>
<th>RSI Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>air film</td>
<td>R₁</td>
<td>0.12</td>
</tr>
<tr>
<td>gypsum board</td>
<td>R₂</td>
<td>0.09</td>
</tr>
<tr>
<td>poly</td>
<td>R₃</td>
<td>0.00</td>
</tr>
<tr>
<td>insulation 1 (glass fiber)</td>
<td>R₄</td>
<td>2.11</td>
</tr>
<tr>
<td>insulation 2 (polystyrene)</td>
<td>R₅</td>
<td>1.32</td>
</tr>
<tr>
<td>cavity</td>
<td>R₆</td>
<td>0.18</td>
</tr>
<tr>
<td>brick</td>
<td>R₇</td>
<td>0.09</td>
</tr>
<tr>
<td>air film</td>
<td>R₈</td>
<td>0.03</td>
</tr>
</tbody>
</table>

As each layer of material has a thermal resistance, the total resistance of the wall is simply the sum of its individual thermal resistance. In the example wall above, the total thermal resistance of the wall may be written as:

\[ R_{\text{total}} = R₁ + R₂ + R₃ + R₄ + R₅ + R₆ + R₇ + R₈ \]  or  RS1 3.94.

If the wall is then exposed to a typical outdoor winter temperature, for example, -18°C and the indoor temperature is 22°C, the wall would be subject to a temperature drop of 40°C. This temperature drop would appear as a temperature gradient in the wall in proportion to the thermal resistance of each layer. For example the temperature in between any of the layers may be found by dividing the sum of the R values of each layer from the inside of the wall to the layer of interest by the total R value of the exterior wall and multiplying by the temperature difference. This number is then subtracted from the indoor temperature to find the wall temperature. Thus, the temperature drop (Δtx) to the plane between insulation R₄ and R₆ is:
\[ \Delta t_x = \Delta T \times \frac{(R_1+R_2+R_3+R_4)}{R_{\text{total}}} \]

Note that \[ \frac{\Delta t_x}{\Delta T} = \frac{(R_1+R_2+R_3+R_4)}{R_{\text{total}}} = \text{Constant} = T_1 \]

We refer to the expression \( \frac{\Delta t_x}{\Delta T} \) as the temperature index \( T_i \) for a particular location in the wall. Therefore, the temperature index \( T_i \) for the wall location between insulation layer R4 and R5 is:

\[
T_i = \frac{(R_1+R_2+R_3+R_4)}{R_{\text{total}}}
\]
\[
= \frac{(0.12+0.09+0.0+2.11)}{3.94}
= 0.59
\]

Alternately, to find the temperature of the cavity or between material layers at the wall location \( T_x \) between R4 and R5, subtract the product of the temperature drop \( \Delta t_x \) and the temperature index \( T_i \) from the indoor temperature \( T_{\text{ind}} \):

\[
T_x = T_{\text{ind}} - \Delta t_x \times T_i
\]
\[
= 22 - 40 \times 0.59
\]
\[
= -1.6^\circ C
\]

The wall temperature index is most useful in performance analysis. For example, on a day when there is a significant difference in temperature, the monitored index (measured cavity temperature) may be compared to the nominal index to determine if the wall leaks air. If the wall is air tight and the temperature index, \( T_i \), is plotted against the pressure difference \( \Delta P \) of the exterior wall, there should be no appreciable difference between the nominal temperature index and the monitored temperature index. However, if the air barrier of the exterior wall is leaky and there is exfiltration of air (and heat) into the wall cavity, the temperature index will rise from its nominal or constant value due to a more heated cavity.

In addition, if the measured temperature index at zero pressure difference is not equal to the nominal temperature index, there may be a false assumption about the insulation materials or the layers are incorrectly installed.