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Diagnosing Envelope Problems by Field Performance Monitoring

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ABSTRACT

Over the course of several research and investigative projects, techniques have been developed to carry out field performance monitoring of exterior envelope components to diagnose performance problems.

In these projects, sensors are installed to measure the temperature, humidity, and pressure near the surface of the exterior wall, near the surface of the interior wall, and within the body or cavity of the exterior wall. Using the data obtained from these sensors, it is possible to analyze how the wall system responds to the various climatic loads placed on it. By using normalizing data analysis techniques and comparing the monitored system performance against performance factors for a properly functional wall system, one can

- *detect a variety of wall performance problems,*
- *determine the root cause of these problems,*
- *judge the significance of the problem with respect to the long-term performance of the wall system, and*
- *detect unusual environmental loading conditions on the wall system.*

It has been found that such performance monitoring provides diagnostic information that enhances information obtained using more conventional techniques, such as visual inspections, destructive test openings, or thermography.

This paper describes the performance monitoring techniques that have been developed and discusses the analytical techniques that are used to extract diagnostic information from the data collected. In addition, the paper discusses the range of applications for this diagnostic tool and provides examples of how performance monitoring can be used to develop specific remedial work plans for building performance problems with minimal destructive testing of the wall system.

INTRODUCTION

A building envelope can be considered a series of barriers separating an indoor and outdoor environment. It is subject to driving forces caused by differences in indoor and outdoor environmental conditions, such as

- differences in atmospheric pressure between the indoors and outdoors, which are caused by wind, stack force, and mechanical systems;
- differences in indoor and outdoor temperatures, which can be driven by both air temperature differences and solar effects; and
- differences in moisture conditions, whether the water is gaseous (vapor pressure or humidity), liquid (rain or runoff), or solid (snow and ice).

A successful and durable envelope system must resist the combined effect of these continuously changing driving forces. If there is a local or general condition where the envelope's barriers against heat flow, airflow, or moisture flow are inadequate or subject to premature deterioration, one has an envelope problem. It is usually easy to detect the symptoms of these performance problems by direct visual observation or using other diagnostic techniques such as thermography or internal examination through test openings. However, to determine the root cause of the problem and prescribe the most appropriate corrective measure often requires observing the undisturbed envelope's performance over a range of operating conditions.

The process called diagnostic *envelope performance monitoring* in this paper provides such data. Environmental driving forces and internal conditions in the envelope element are monitored for a period of time in which the envelope is subject to changing environmental conditions. By using a variety of analytical techniques, the effects of specific driving forces can be determined and compared to what one would expect with a well-functioning envelope system.

The techniques were originally developed in the course of research projects funded by Public Works Canada and have since been successfully applied in a number of investigative projects to obtain diagnostic information that more conventional techniques, such as visual inspection, destructive test openings, or thermography, could not provide.

MONITORING PRINCIPLES

Figure 1 shows a schematic of an exterior wall assembly with the instrumentation used in envelope performance monitoring.

In general, a wall can be considered to consist of an exterior surface or cladding, an interior surface, and a cavity in between. In cold climates, the cavity usually contains an insulating material to provide a thermal barrier and a vapor diffusion retarder on the warm side of the insulation. The components that provide the primary

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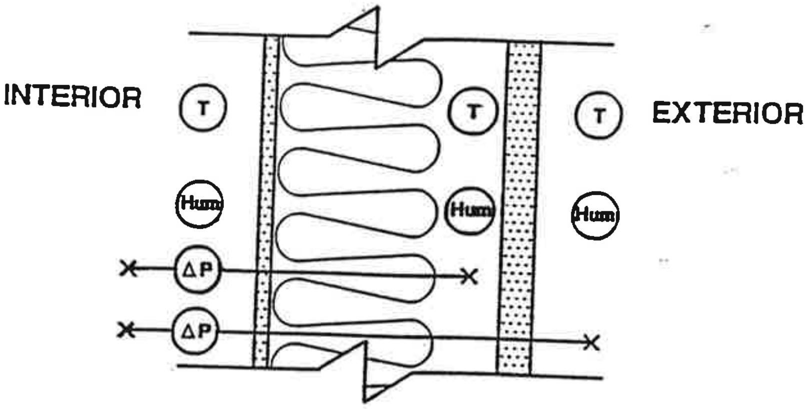

Figure 1 *Instrumentation schematic.*

resistance to airflow are usually, but not always, on the interior side of the insulation as well.

The information needed to assess environmental driving forces on the envelope consist of indoor and outdoor air temperatures, indoor and outdoor humidity levels, and the pressure difference across the envelope. To determine which layer of the wall is resisting these environmental driving forces, one can measure conditions in the cavity, including temperature, humidity, and the pressure difference between indoors and the cavity.

The key to the successful application of envelope performance monitoring is to obtain data for the range of environmental conditions to which that wall or envelope element is exposed. The simplest way of doing this is to collect continuous data for representative periods of time in different seasons. We have found that data collection periods of one or two weeks usually provide adequate temperature, humidity, and pressure variations to provide meaningful results for a particular season. Since so many of Canadian wall performance problems are associated with cold weather, a winter collection period usually proves most valuable, but comparison of winter and summer data has also proved to be enlightening.

A variety of instrumentation and data collection systems have been used to collect these data. A host of temperature sensors provide accurate, reliable performance in field situations, including thermocouples, RTDs, and thermistors.

Pressure transducers to measure the indoor-to-outdoor and indoor-to-cavity pressure differences must be of an appropriate range and bidirectional. While wind forces can create very high pressure differentials over a short term, it is usually the driving forces of long duration, such as stack action or mechanical forces, that cause durability problems. We have therefore found that the most appropriate pressure transducers have a range of -250 to $+250$ Pa (-1.0 to $+1.0$ in. H_2O) with a resolution of at least 1 Pa. Most pressure transducers are subject to significant zero drift, and the monitoring system design or analytical technique must recognize this. There are a number of techniques in which zero drift can be determined and data corrected. For long-term data collection projects, these should be employed. This is not usually necessary for the one- or two-week periods normally used in diagnostic projects *if* it is recognized that there may be some zero drift and the analytical technique works with variations or changes in the pressure differential rather than the absolute values.

Humidity is one of the more difficult things to measure accurately and reliably in the field, especially in freezing and/or condensing conditions. The prime variables required for the analytical techniques are the humidity ratios of the indoor, outdoor, and cavity air. These can be determined from dew-point sensors or calculated from readings of relative humidity and temperature. Both techniques have been used in past projects and both methods have their advantages and disadvantages. Dew-point sensors work very well when properly calibrated but are expensive, bulky (particularly for cavity readings), and require special care and calibration to maintain reliability. Relative humidity sensors are notoriously inaccurate in freezing and condensing conditions. Our experience has shown that either approach can be used, but again, one must use measured humidity as an indicator and look at the patterns of humidity value changes rather than the absolute values.

The most appropriate data acquisition and storage system depends on the specific project. In the original research project in which our techniques were developed, a central data acquisition system collected a whole year's data from a number of sensor locations. However, for most field diagnostic projects, this approach would be expensive and cumbersome. We have therefore developed data acquisition packages to collect data at a single monitoring location. These are based on commercially available data loggers, which are collecting and recording devices that can be downloaded for analysis onto a microcomputer. These units are very compact, relatively inexpensive, and very flexible in their application.

The datalogger modules we use have a 32-kilobyte memory. The data collection interval is set to suit the desired monitoring period. For a two-week period, intervals of 2 to 10 minutes are possible. This data set is postprocessed to obtain hourly averages for all variables. This step reduces the amount of data that has to be processed without significant sacrifice in value because most performance problems in envelope systems result from long-term effects rather than from short-term transients. Weather data such as wind speed and direction, sunshine hours, and precipitation can be obtained directly from weather records.

Choosing monitoring locations is project specific. In diagnostic projects, one focuses, of course, on suspected problem areas. The envelope construction will also affect selection of monitoring location. The cavity instrumentation should be placed where the installation will minimize disruption to the envelope systems, and it is imperative that any holes made through the air barrier systems be sealed after placement.

DATA ANALYSIS

Time-Based Data

The first step in data analysis is to review the time-based plots of recorded values and weather data looking for expected and unexpected patterns or events. For example:

- One would expect to see exterior temperatures and dew-point temperatures vary on a diurnal basis and with weather patterns. Less variation is expected with indoor conditions.
- One would expect to see cavity temperatures and humidity ratios remain between indoor and outdoor conditions. In buildings with exterior cladding of low thermal inertia and resistance, cavity temperatures can exceed outdoor temperatures when subject to solar radiation and may be slightly lower than the outdoor temperature at night.
- While one could expect indoor to outdoor and indoor to cavity pressure differences to vary with outdoor temperature, one does not expect a regular diurnal pattern. Such a pattern could be caused by operation of a building's mechanical system.

One should also explore the causes of concurrent changes in different variables. For example, in a number of buildings monitored, we found changes in the indoor to cavity pressure (ΔP_{cavity}) when there was no concurrent change in the indoor to outdoor pressure (ΔP_{out}). This would lead one to suspect that the cavity was in some way connected aerodynamically to the building's air-handling system. In one case, this was corroborated by noting that the cavity pressure change occurred at times when the indoor temperature increased in a manner indicative of raising the thermostat setpoint.

When analyzing the data, one has to take into account the accuracy of the installed instrumentation. Because of their potential for zero drift, one has to be cautious about comparing the ΔP_{out} and ΔP_{cavity} in absolute terms unless one is certain about the calibration of the instruments. However, by looking at changes in pressure readings (that is, from time to time and peak to peak), the effects of zero drift can be negated.

By examining the relationship between ΔP_{cavity} and ΔP_{out}, one can assess where in the construction airtightness is provided. In a wall where the interior surfaces of the cavity are much more airtight than the exterior cladding, one would expect ΔP_{cavity} to closely track ΔP_{out}. In a face-sealed system, one would expect the ΔP_{cavity} to be near zero.

Changes in the ratio $\Delta P_{cavity}/\Delta P_{out}$ with time imply some change in leakage area. For example, one of our laboratory projects monitored wood-frame wall sections with chipboard exterior sheathing. When these test sections were subjected to winter conditions and exfiltration for a two-week period, we found that the ratio $\Delta P_{cavity}/\Delta P_{out}$ was reduced as time went on. This indicated that frost or moisture was collecting on and in the exterior sheathing, sealing air leakage paths. This was confirmed by visual inspection.

Another factor to look at is the amount of time that the wall cavity spends in condensing conditions and whether this is related to precipitation patterns or exfiltration pressure. This can be done either by looking at the percentage of time that cavity humidity is at or near 100% or by examining the difference between dew-point temperature and cavity temperature. In a well-functioning cold-climate wall system, one would expect cavity humidity to follow changes in outdoor humidity unless water has collected in the cavity.

Normalizing Methods

In the plots of performance variables vs. time, there can be many factors occurring concurrently. It can be difficult to isolate the effect of particular variables. This can be done, however, by normalizing techniques and selective data review.

One of the most useful processes is to look for distortion in the expected temperatures caused by air leakage. This can be done by analyzing how the cavity temperature index varies with pressure.

We define the cavity temperature index as

$$\frac{T_c - T_o}{T_i - T_o} \tag{1}$$

where

T_c = cavity temperature,
T_i = indoor temperature,
T_o = outdoor temperature.

What makes this calculated variable useful is that it normalizes the data with respect to temperature driving force.

In an envelope element in which solar effects are ignored and heat loss is limited to conduction, the cavity temperature index will remain constant at a value that is equivalent to the ratio of the thermal resistance of the construction outside the cavity (usually just the cladding) to the total thermal resistance of the wall system. If air leakage is significant, it will change this relationship. In winter conditions, exfiltration will increase cavity temperature and the cavity temperature index. Conversely, infiltration will decrease cavity temperature and the cavity temperature index. Since the rate of air leakage depends on the pressure driving force and the leakage area, which can usually be assumed to be constant, the cavity temperature index will vary with indoor to outdoor pressure difference (ΔP_{out}). Figure 2 illustrates the expected curve of the cavity temperature index versus pressure difference in a sealed and leaky envelope section. Solar gains will also affect the cavity temperature index, but this complication can be overcome by using only night period data for the analysis.

If one assumes or knows the R-values of the wall components inside and outside the temperature measurement point, one can actually calculate the infiltration rate that is required to create the temperature index distortion by solving an energy balance equation to and from the cavity. This ability to identify and roughly quantify air leakage effects has proved invaluable in diagnosing envelope problems that could have been caused either by exfiltration-related condensation or by other water entry methods.

A similar analytical technique can be used to look at the humidity ratio index, defined as

$$\frac{W_c - W_o}{W_i - W_c} \quad (2)$$

where

W_c = humidity ratio cavity,
W_i = humidity ratio inside,
W_o = humidity ratio outside.

For cold-weather data periods when there is no moisture collection in the wall, one would expect this number to be constant and equal to the inverse of the ratio of permeance of the exterior surfaces over the permeance of the wall as a whole. Since the permeance of the wall as a whole is usually governed by the permeance of the vapor retarder at the inside surface, one would expect the humidity ratio index to be near zero in the well-sealed wall. Because of phase-change effects, the relationship is not nearly as simple and obvious as with the cavity temperature index. However, if the humidity ratio index is shown to increase with exfiltrating pressure, this would be a sign of air leakage. High humidity ratio indexes at neutral or infiltrating pressures could be indicative of exterior sources of moisture, such as rain penetration, or may be the result of previous moisture accumulation.

CASE HISTORIES

The following three case histories are provided to illustrate how wall performance monitoring has been used to diagnose the cause of envelope problems that were not evident using more traditional techniques.

Case History 1

The Building In this building of recent construction, the indoor environment is maintained at a constant 20°C,

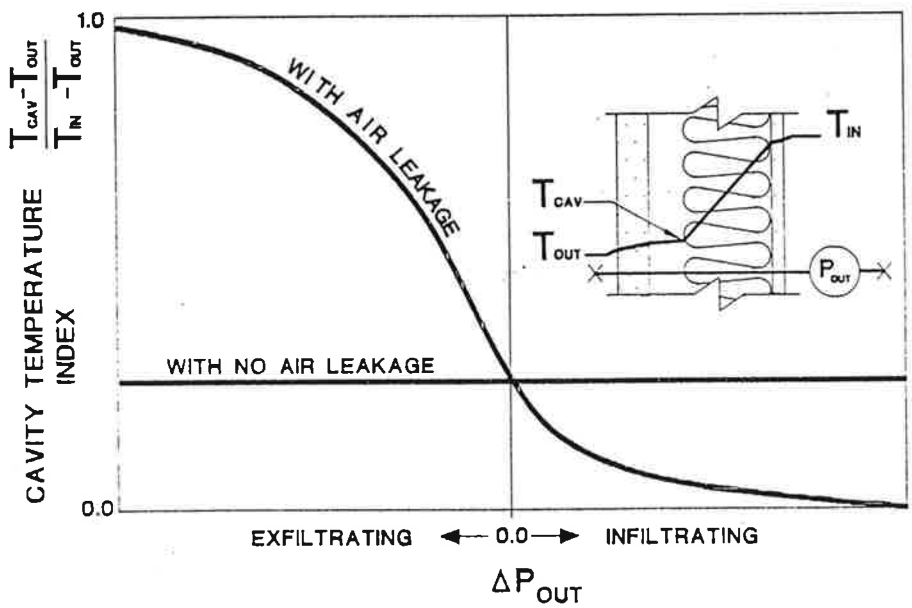

Figure 2 Cavity temperature index vs. pressure difference curves.

50% RH. The wall design was based on the rain screen principle and called for a good air/vapor barrier in the building system, which was provided, for the most part, by the use of a torch-on membrane. The exterior cladding of the building is a pale, porous sandstone. The only venting through the cladding is small drains through the mortar joints at the base courses of stone.

The Problem There was visible evidence of water collection and staining in the sandstone cladding, particularly at shelf angle locations. This created both an aesthetic problem and some concern that freeze/thaw action in the saturated sandstone could cause premature deterioration.

It was known from previous investigations that there were some imperfections in the air barrier just below the shelf angles. Exfiltration-related condensation on the stone was one suspected cause of the moisture accumulation on the stone. However, some alternative causes had been suggested, including the penetration of wind-driven rain through the stonework where it would run down to the shelf angles. Others were concerned by the small venting and drainage area provided through the cladding.

Correcting the air barrier imperfections would be a costly endeavor, and the client desired some hard evidence that exfiltration-related condensation was really the problem.

Monitoring Findings Instrument packages were installed at three different locations near shelf angles for periods of approximately two weeks during the winter of 1990-91. Results showed that the cavity temperature index versus the indoor-to-outdoor pressure curve for night data had, at all locations, the characteristics of a wall with a significant level of air leakage (Figure 3). The calculated value for the air leakage to create this distortion in the cavity temperature index curve at the measurement points was approximately 10 to 20 L/s·m^2 at 75 Pa. This was much higher than the design intent of the wall system.

Since this diagnosis, the investigation has concentrated on finding the most appropriate remedial actions for the air leakage problem. In the winter of 1991-92, three possible remedial actions were implemented in test sections. These were a complete sealing at the air barrier, adding vents at both the top and bottom of the cladding sections, and filling the cavity with polyurethane foam. Only the air sealing solved the moisture collection problem.

Case Study 2

The Building This 9-story building with a 12-story tower was built in 1920 of uninsulated stone masonry construction with complex "gothic" architecture.

The Problem The joints in the stonework have shown some signs of deterioration that could be linked to moisture damage. Furthermore, some areas of the masonry and mansard-style roof were very prone to the formation of icicles, which created a significant pedestrian hazard below.

Previous work had shown that the building had a high level of air leakage and the mechanical system was operating with a high imbalance between supply and exhaust flow to minimize cold drafts. It was postulated that exfiltration-related condensation was causing much of the stone and joint deterioration and was warming some areas of the roof but not others, which was causing the excessive icicle formation.

In 1989 a trial remedial repair was implemented in one area of the building. The exterior envelope was air sealed by using a combination of urethane foam and sealing the drywall interior finish.

Visual monitoring during the winter showed that icicle formation appeared to be reduced from previous years but still occurred. Furthermore, a thermographic survey showed that a section of the mansard roof in the trial area was very warm and there appeared to be warm air leaking out of an

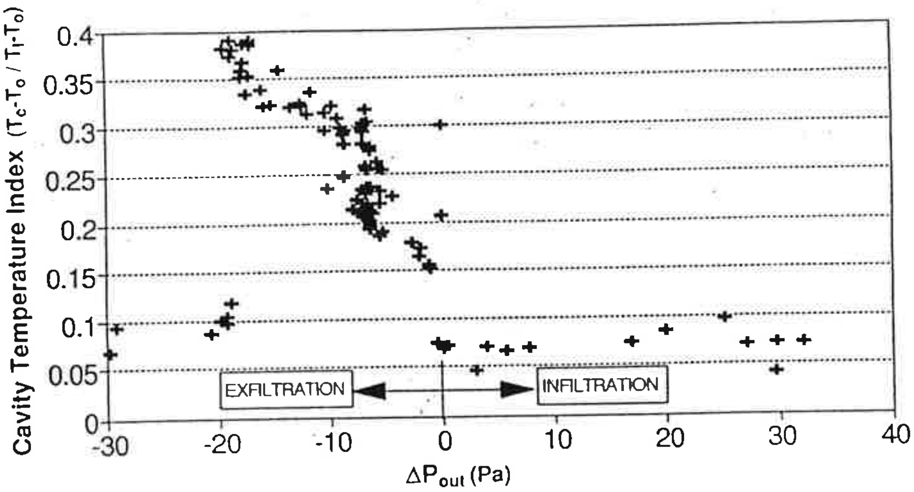

Figure 3 Temperature index (night), station 2.

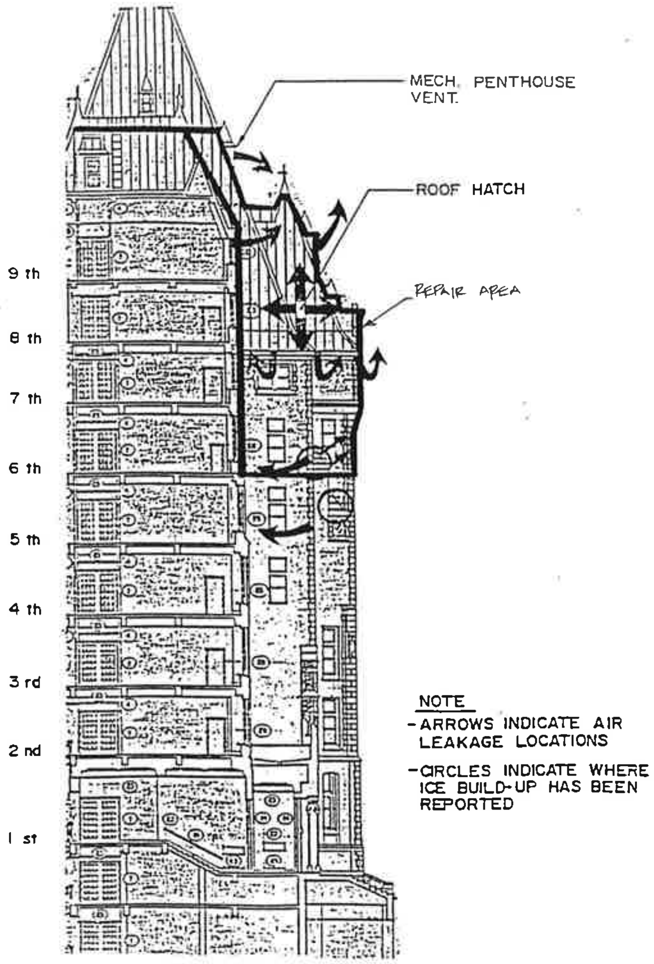

Figure 4

access hatch on the copper roof surface (see Figure 4). The air barrier and insulated surface in this area were an interior kneewall and the floor slab. The enclosed attic space was expected to be cold and isolated from the building. It seemed that the trial remedial repair was not effective in creating an air barrier in this area.

Monitoring Findings A combination of visual inspection and performance monitoring was used to try to find out what was going on in this area. Visual inspection found piping for the hydronic heating system in the "attic space" behind the kneewall, some of which had damaged insulation. However, this would not explain the apparent air leakage through the roof hatch, and no major defects in the remedial air barrier system were noted. There were no visible signs of moisture collection in the space.

Wall performance monitoring was carried out in this repaired area and at an adjacent area that had not been repaired. Plots of the cavity temperature index versus pressure difference across the interior wall for the repaired area (Figure 5) and a comparison location (Figure 6) showed that the average cavity temperature index in the area that had been repaired was significantly lower than in a comparable area that had not. However, the cavity temperature index in the repaired area was still higher than one would expect considering the ratio of the thermal insulation on the inner surface and that on the outer surface. Exfiltration could explain this, but the cavity temperature index versus pressure difference plots did not show the characteristic curve one would expect due to exfiltration in spite of some very high pressure differences across the interior wall.

The pressure difference versus time plots showed little relationship between the indoor-to-cavity pressure difference and the outdoor-to-cavity pressure difference but did show a strong diurnal cycle (Figure 7). This indicates some aerodynamic linkage between this attic space and the building's air-handling system.

Exfiltration through the interior wall could not be blamed for the problems being experienced.

Case Study 3

The Building This 16-story downtown Toronto building, approximately 30 years old, has a face of sealed metal and glass curtain wall.

The Problem In 1988 a humidification system was retrofitted into the building. Subsequently, a problem developed with moisture collection in the aluminum panel cavities and icicles formed on the exterior facade near cavity drains. Site visits found that the building was operated under a positive indoor-to-outdoor pressure difference during winter months. The obvious diagnosis was that the building was suffering from an air-exfiltration-related condensation problem.

Monitoring Results This building was one of the subjects of our original research projects in which the building was monitored to collect wall performance monitoring data for two locations on an upper floor for two-week periods in each of the four seasons.

Initially the results were quite confusing, including such oddities as the following:

- There appeared to be no relationship between the cavity temperature index and the indoor/outdoor pressure difference (Figure 8).
- The interior to cavity pressure difference did not appear to be directly related to the indoor-to-exterior pressure difference. In fact, there were occasions where they went in opposite directions. Both pressure differences showed a strong diurnal cycle (Figure 9).
- In winter, the humidity ratio in the cavity tended to follow variations in the humidity ratio of the exterior environment (Figure 10). However, in the summer, the cavity relative humidity readings and humidity ratios appear more closely linked to the indoor environment, not the exterior (Figure 11).

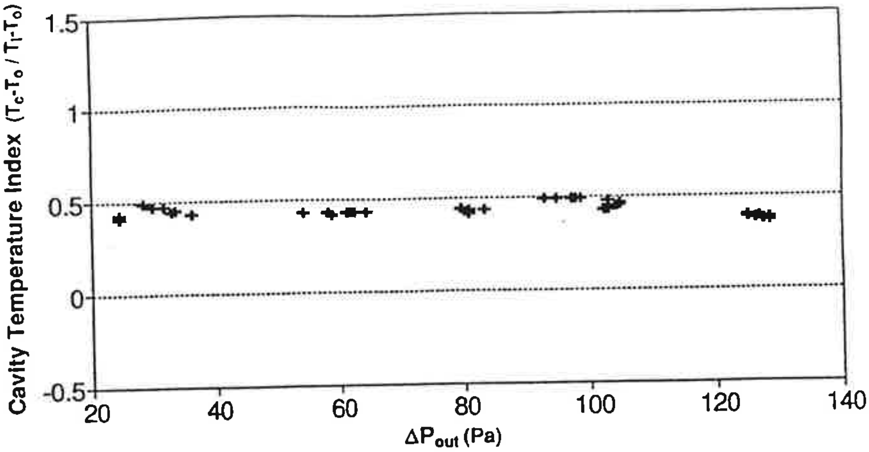

Figure 5 *North roof, location 1, night.*

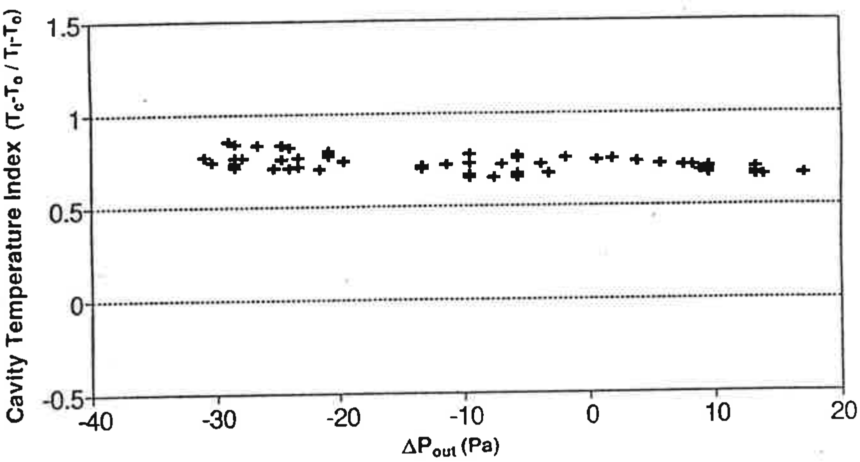

Figure 6 *South roof, location 2, night.*

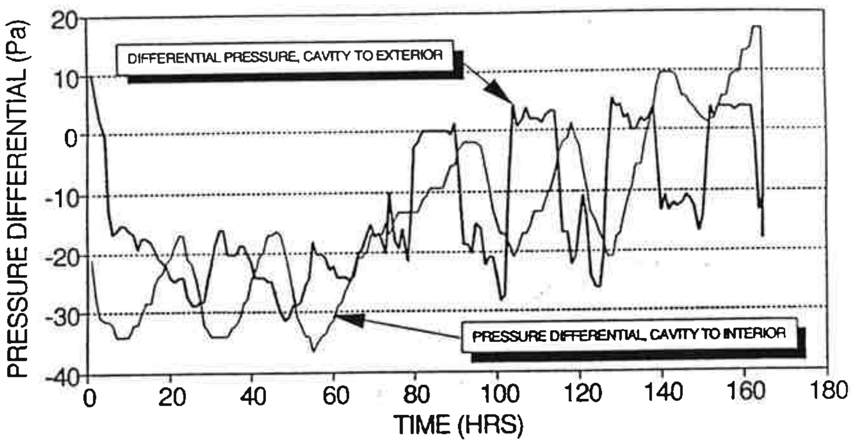

Figure 7 *South roof, location 2.*

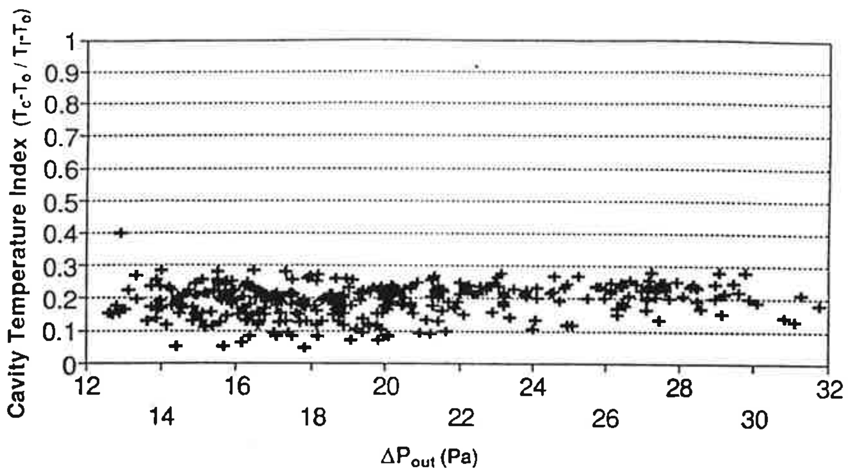

Figure 8 *Winter: temperature gradient vs. exterior PD,B.*

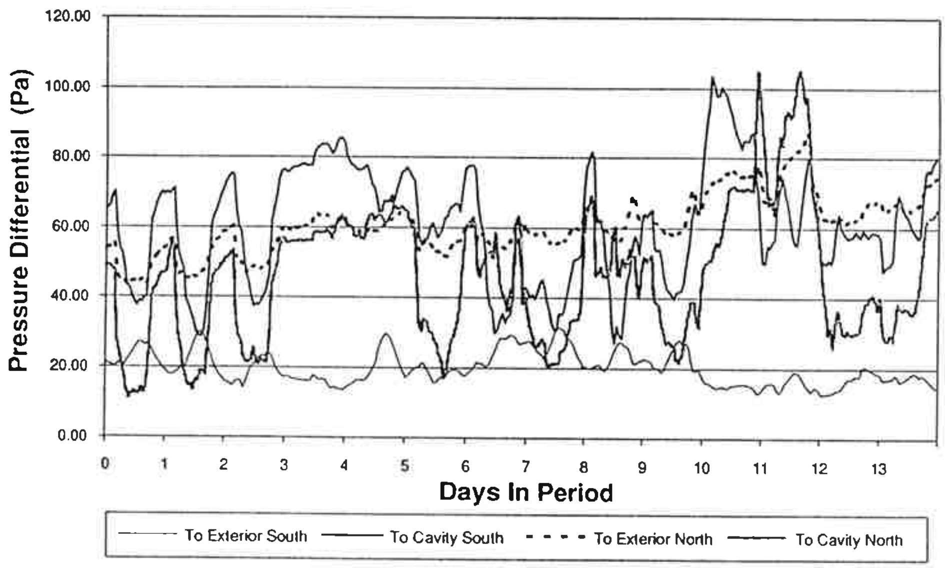

Figure 9 *Winter season (11/22/89 - 12/5/89) pressure differential measurements.*

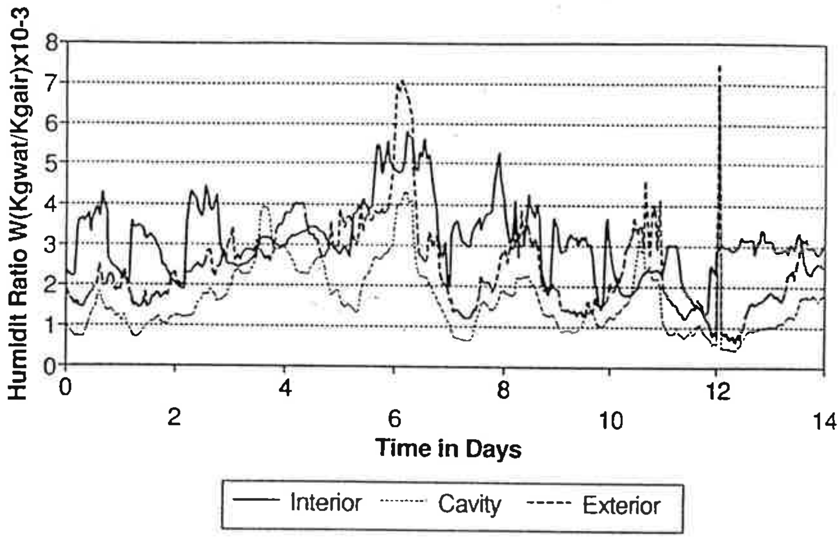

Figure 10 *Winter: humidity ratios vs. time, Wall B.*

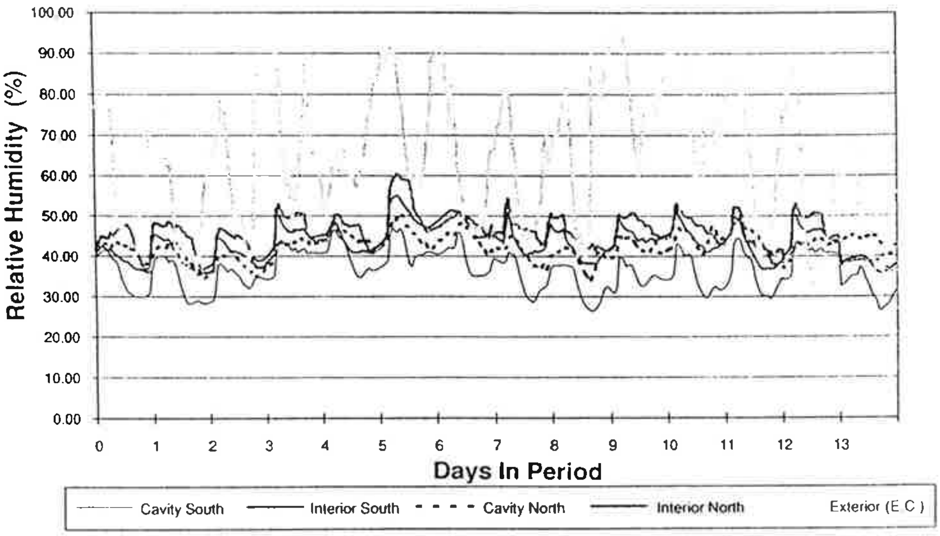

Figure 11 Summer season (7/17/89 - 7/30/89) relative humidity measurements.

This did not appear to be a classic exfiltration-related condensation problem. One diagnosis that accounts for all the above factors is that there is a circulation of indoor air into the wall cavities and then back indoors. This could be created by a connection to the building mechanical system. By looking at the wall section details (shown in idealized form in Figure 12), one can postulate that suction forces created in the ceiling return air plenum are drawing air through the wall cavity from the space above. The light-weight conductive exterior cladding effectively remains at outdoor temperatures. During the winter, it acts as a condensing surface, and any water collected would drain down to the spandrel section drain tubes and freeze into icicles.

During winter, the cavity humidity ratio would be directly related to outdoor temperature, as is the exterior air humidity ratio. In the summer, no modification in the cavity humidity ratio could be expected, so the cavity humidity ratio matches indoor conditions.

CONCLUSION

As these case histories show, performance monitoring can provide diagnostic data that can help find the root cause of many building envelope problems. To do this requires (1) reviewing time-based data over a variety of operating conditions and (2) techniques of reviewing the data that can isolate the effects of specific driving forces.

With the availability of inexpensive and reliable data-logging modules, diagnostic performance monitoring can be readily applied in many field problem investigations where it complements other investigative methods such as thermography and visual inspection.

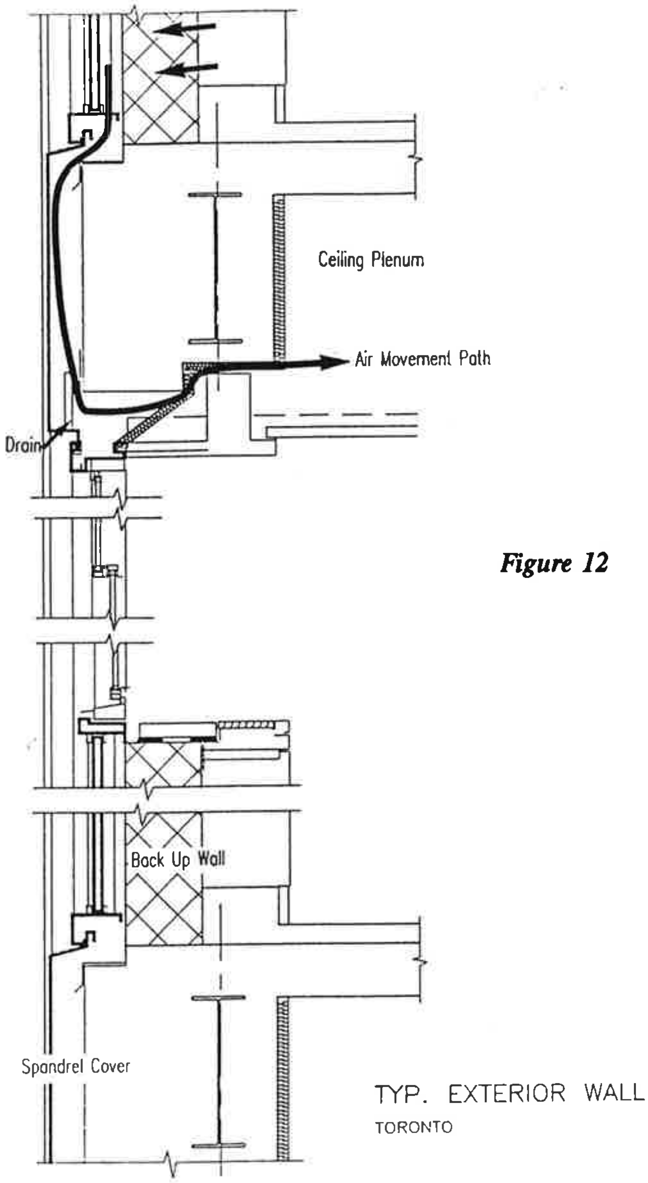

Figure 12