RESEARCH REPORT

Performance Monitoring of a Brick Veneer/Steel Stud Wall System

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PERFORMANCE MONITORING

OF A

BRICK VENEER/STEEL STUD

WALL SYSTEM

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ABSTRACT

The brick veneer/steel stud (BV/SS) wall system has become very popular over the last 20 years, however, the rapid adoption of this wall system has proceeded the development of adequate design and construction standards. This situation has led to concerns regarding the longterm safety, serviceability and durability of BV/SS wall systems. Therefore, Canada Mortgage and Housing Corporation (CMHC) has been evaluating BV/SS wall systems over the past several years by commissioning studies by various consultants, including Keller Engineering Associates Inc. (KEA).

This study by KEA involved the in-situ performance monitoring of a BV/SS wall system over a period of time, with respect to structural performance, air and moisture movements as well as temperature gradients. The performance of a test wall was monitored using various temperature, moisture and air pressure sensors that were connected to an automatic data logging system. The results of the study demonstrate that, even though the BV/SS wall system was generally well designed and constructed, performance problems exist that may lead to significant distress problems over the long term. The more serious performance problems are mainly due to design weaknesses, illustrating the need for improved design and construction standards.

Canada Mortgage and Housing Corporation, the Federal Government's housing agency, is responsible for administering the National Housing Act.

This legislation is designed to aid in the improvement of housing and living conditions in Canada. As a result, the Corporation has interests in all aspects of housing and urban growth and development.

Under Part IX of this Act, the Government of Canada provides funds to CMHC to conduct research into the social, economic and technical aspects of housing and related fields, and to undertake the publishing and distribution of the results of this research. CMHC therefore has a statutory responsibility to make widely available, information which may be useful in the improvement of housing and living conditions.

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DISCLAIMER

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EXECUTIVE SUMMARY

The brick veneer/steel stud (BV/SS) wall system has become very popular in Canada over the last twenty years since the wall system is both economical and attractive. However, the construction of BV/SS walls has preceeded the development of adequate design and construction standards. This situation has led to concerns among many members of the construction industry regarding the longterm safety, serviceability and durability of BV/SS wall systems. In order to address these concerns, Canada Mortgage and Housing Corporation (CMHC) has undertaken a program to evaluate the design, construction and performance of BV/SS wall systems.

This program has included many studies, several of which were carried out by Keller Engineering Associates Inc. (KEA). Among other things, these studies have surveyed design and construction practices, evaluated the in-situ performance of existing BV/SS wall systems through field investigations, and determined the "best practices" for the design and construction of BV/SS wall systems. These studies provided extensive information towards a better understanding of BV/SS wall systems. However, an evaluation of specific performance criteria over a period of time could only be obtained through detailed monitoring.

Therefore, KEA was commissioned by CMHC to develop and implement a program aimed at monitoring the in-situ performance of a BV/SS wall system over a period of time. The building selected is a seven-storey residential building located in the Ottawa/Hull region. It was decided to carry out the study using one test wall of this building. The test wall was evaluated with respect to structural performance and various building science issues, such as air and moisture movements as well as temperature gradients. In order to evaluate the BV/SS wall system under the worst combination of air pressure differences and moisture conditions, the selected test wall faced east and was on the top floor of the building.

Instrumentation was installed across the test wall that consisted of various temperature, moisture and air pressure sensors which were connected to a computer based, automatic data logging system. The test wall was monitored periodically over a 12-month period, with the monitoring periods being two to four weeks in length. Six monitoring periods were selected such that these periods would represent the differing weather conditions that occur over the year in Ottawa/Hull. The data collected was analyzed to evaluate the in-situ performance of the test wall and the findings are discussed in this report under the headings of temperature, moisture and air pressure.

While several aspects of the design did not represent best practices, the BV/SS wall system was generally well designed, as compared to standard construction today. The BV/SS wall system was inspected during its construction and workmanship was found to be of above average quality.

The results of the monitoring program demonstrate that good thermal performance can generally be expected from brick veneer/steel stud walls. However, significant thermal bridging occured at the steel studs of the test wall, due to a lack of exterior insulation. This thermal bridging is typical of any steel stud backup wall without exterior insulation.

An important finding of the monitoring program, with respect to moisture, was that the cavity of the test wall does not vent effectively and, therefore, water vapour levels within the cavity are high. As a result of this situation, condensation regularly occurs on the interior surface of the brick veneer during temperatures approaching 0°C. In addition, condensation occurs on the brick ties and minor condensation occasionally occurs on the exterior surface of the exterior gypsum board sheathing. Experience has shown that condensation on the interior surface of the brick veneer will gradually cause back spalling of the masonry due to freeze/thaw action. In addition, condensation within the cavity can lead to corrosion and eventual failure of the brick ties. Therefore, the lack of adequate cavity venting at the test building may lead to serious distress problems over the long term, in spite of the BV/SS wall generally being well designed and constructed. Note that it was also found that minor condensation regularly occurs on the interior surface of the exterior sheathing. This condition could also be detrimental to the long term performance of the wall system.

An analysis of the air pressure differences across the test wall over the different monitoring periods indicates that the air/vapour system of the test wall generally performs in a satisfactory manner. However, the results also indicate that the wall system does not function as well as desired. Firstly, pressure equalization is not fully effective and, therefore, both the brick veneer and the steel stud backup wall resist wind loads whereas it is desired to have the backup wall alone resist wind loads (once these loads are transferred through the brick ties). Secondly, minor air leakage occurs through the air/vapour barrier even though workmanship appeared satisfactory. While air leakage through the air/vapour barrier is relatively minor, air leakage is significant enough to cause a reduction in the thermal efficiency of the wall system under wind conditions.

In summary, the brick veneer/steel stud test wall was generally well designed and constructed, however, the wall system is not performing in a satisfactory manner. Condensation within the cavity may lead to serious distress problems over the long term. The observed performance problems are mainly due to a few basic design weaknesses, which include inadequate cavity venting and a lack of exterior insulation. In addition, minor construction defects cause air leakage through the air/vapour barrier. This monitoring program has further illustrated the need for improved design and construction standards since the BV/SS wall system under study likely represents "typical" construction and the wall system may experience significant distress problems over the long term.

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1. INTRODUCTION

1.1 Background

Over the last 20 years, the brick veneer/steel stud (BV/SS) wall system has become widely utilized on multi-storey buildings in Canada because it is an economical system and it is also aesthetically pleasing since it incorporates brick veneer walls. However, the construction of BV/SS walls has preceded the development of adequate design and construction standards. This situation has led to concerns among design professionals, contractors and building owners about the longterm safety, serviceability and durability of BV/SS wall systems. In order to address these concerns, Canada and Mortgage and Housing Corporation (CMHC) has undertaken a program to evaluate the design, construction and performance of BV/SS walls.

Since 1986, Keller Engineering Associates Inc. (KEA) has been involved in several studies as part of the above program. The first study, which surveyed BV/SS designers and contractors, revealed that standardization was required to ensure adequate design, construction and inspection of BV/SS walls and that further research pertaining to the longterm performance of BV/SS wall systems was required. A further study by KEA, involving a field investigation to determine the in-situ performance of BV/SS walls, found that proper detailing and construction practices were critical factors in the performance of the BV/SS walls. Specifically, it was determined that all efforts should be made to keep moisture out of the steel stud backup walls and that several common construction practices should not be allowed.

While the field study utilized visual inspections to assess the general performance of BV/SS walls, an evaluation of specific performance criteria over a period of time could only be carried out through detailed monitoring. Therefore, KEA was commissioned to develop and implement a program aimed at monitoring the performance of a BV/SS test wall over a period of time. This report outlines the monitoring program and discusses the findings obtained from evaluating the data collected during the first year of monitoring.

1.2 Scope of Work

The key objective of this project was to monitor and evaluate the in-situ performance of a newly constructed BV/SS wall system over a period of one year, with regards to air and moisture movements, temperature gradients and structural performance. The scope of work included the following tasks:

- building selection
- evaluation of design drawings
- construction monitoring
- design and installation of instrumentation setup
- data collection
- data analysis
- preparation of report.

In carrying out the above scope of work, assistance was provided by other parties for selected portions of the work, as follows:

Development of Research Program:	R.B. Platts, P. Eng. (Scanada)
Building Selection:	A.J. Garwood, P. Eng. (GSL)
Evaluation of Steel Stud Design:	T.W.J. Trestain, P. Eng. (TWJT)
Instrumentation Design, Installation and Data Collection:	A.H.P. Maurenbrecher, P. Eng. (NRC/IRC) W.C. Brown, P. Eng. (NRC/IRC) G.F. Poirier, P. Eng. (NRC/IRC)

1.3 Building Selection

Originally, it was the intent of CMHC to select a building which was designed and constructed according to current "best practice" guidelines in order to determine how a well designed and constructed BV/SS wall system would perform. During the proposal stage, KEA suggested the alternative that a building be selected based on the design being of average quality in order that the building monitored would be representative of a larger number of buildings. Thus, the research results could be interpreted for a wider range of buildings.

Initially, a number of candidate buildings were located through the cooperation of local consulting engineers involved in BV/SS construction. A list of candidate buildings was reviewed to determine which buildings would be under construction at a time suitable for the schedule of the project. Since there were few BV/SS construction projects underway in 1990, choices were limited. Another limitation was that cooperation was required from all major parties involved with the design and construction of the candidate building, namely the owner, the architect, and the builder. As was soon discovered, not all builders or owners were willing to spend the extra time required to be involved in a project of this nature without compensation. Others were concerned about potential liability issues if the research findings identified construction deficiencies and serviceability problems.

Due to the project schedule and the limited number of candidate buildings available for this project, the opportunity did not exist for KEA to select a building where this project could alter the design of the BV/SS wall system to ensure that it met best practice guidelines. Therefore, the building that was finally chosen for this project was selected mainly because its construction schedule corresponded best with the schedule of this research project and because the owner, the architect and the builder were interested in cooperating in this research effort.

2. REVIEW OF BV/SS DESIGN AND CONSTRUCTION

The scope of work included a detailed evaluation of the design drawings. The purpose of this evaluation was to identify design issues which did not meet best practice guidelines. It was hoped that the designers would be prepared to incorporate KEA's recommendations in their final design.

The brick veneer/steel stud wall system consists of:

- 90 mm clay brick masonry veneer
- 25 mm air space
- building paper
- exterior grade gypsum board
- 150 mm steel studs
- batt insulation in stud space
- 6 mil polyethylene vapour barrier
- interior gypsum board.

Pertaining to the steel stud backup wall, the following materials and methods of construction were used:

- 150 mm X 38 mm, 20 gauge steel studs with G90 hot dipped galvanizing
- adjustable, 4.95 mm triangular wire ties, with C-type connector plates, at 400 mm o.c. horizontally and 600 mm o.c. vertically
- 150 mm X 25 mm X 20 gauge bottom tracks with G90 galvanizing, ramset to slab at 600 mm o.c.
- steel studs fastened to bottom tracks with one screw on the inside
- 150 mm X 25 mm X 20 gauge top tracks with G90 galvanizing, ramset to slab at 600 mm o.c.
- steel studs fastened to top tracks using flexible ties, or "deflection plates" (Photo 5)
- lateral bridging through cut-outs at the mid-height of studs with the bridging screwed to the channel clips which were, in turn, fastened to the studs (Photos 6 and 7)
- single studs at windows, but spacing between studs was reduced to 200 mm o.c.
- all screws for steel stud walls were TEK screws.

Upon reviewing the design of the BV/SS wall system for the test building, concerns were raised about the lack of adequate detailing for construction of the exterior wall system. This concern arose from the steel stud backup wall being specified in very general terms, with few of the above details specifically outlined in the design. As such, it was recommended that the steel stud contractor be required to submit shop drawings stamped by a professional engineer with experience in steel stud design. In addition, many recommendations were made pertaining to specific steel stud and building science details. KEA's comments and concerns were discussed with the design consultants, however, virtually no changes were made and construction proceeded without the design being revised to reflect best practices.

The exception was that the steel stud contractor did commission a professional engineer to design the steel stud backup wall. While several aspects of the final design were not considered to be according to best practices, it appeared that the steel stud wall was generally well designed. The main reason that the suggested design changes were generally not implemented is that the changes would have resulted in additional construction costs that neither the owner nor the builder were willing to absorb.

Pertaining to key building science issues, the test wall does not reflect best practices since the following features were not incorporated into the wall design:

- an air space which is 50 - 75 mm wide to provide free drainage of cavity moisture and improved pressure equalization of the cavity and the exterior
- compartmentalization of the cavity for pressure equalization
- exterior insulation for improved thermal performance of the wall, particularly at the steel studs

Since the design was not revised to reflect best practices, the test building would therefore reflect an average situation and the project was continued from that viewpoint. This situation did not adversely affect the study since, as described previously, KEA felt that evaluating an average BV/SS wall system would generally represent current construction practices and, therefore, would yield more meaningful results.

Regular visits to the construction site were made during July and August 1990 to observe construction practices and compliance with design drawings and specifications. Construction was generally in compliance with the design drawings prepared by the architect and the engineering consultant hired by the steel stud contractor. Workmanship on the BV/SS wall system was generally found to be of above average quality although the BV/SS walls are not considered to meet best practice guidelines. Overall, the BV/SS walls were adequately designed and they were constructed according to current industry practices.

3. INSTRUMENTATION AND PERFORMANCE MONITORING

The key objective of this project was to monitor and evaluate the in-situ performance of a BV/SS wall system with regards to moisture movements, temperature gradients and structural performance. Therefore, the design and implementation of the performance monitoring program was a critical part of this project.

3.1 Selection of Test Wall

Air leakage out of a building and rain wetting of walls are important consequences of the effects of wind in relation to a building. In Ottawa, wind directions during the rainy spring and fall seasons are predominantly easterly while in the winter and summer, winds are predominantly from the west-north-westerly and south-westerly directions, respectively. At upper floor levels, these wind directions result in suction pressures on walls with south-east and north-east exposures, as well as on all exposures in between. These negative pressures combine with those of stack effect (for taller buildings) and the building pressurization to induce air exfiltration from the interior of the building. Since air exfiltration is the principal manner in which water vapour is transferred into the wall during winter, condensation is more likely to occur in walls with an easterly, or nearly easterly, exposure. Pertaining to the rain wetting of walls in the Ottawa area, the predominant wind-driven rains are from an easterly direction and, as such, more severe wetting conditions due to driving rains will occur on walls with an easterly exposure.

Considering the above factors as well as the building orientation and exterior wall construction, an upper floor BV/SS wall with an east-north-east exposure at the south-east corner of the building was selected as the wall to be monitored. This wall would provide the worst combination of wind and rain. The selected test wall was instrumented with sensors that measured the driving potentials that affect moisture and structural performance, i.e. temperature, moisture and air pressure. Contrary to the original plans, relative movements between wall elements were not included in the monitoring program since such measurements would not have yielded meaningful information, due to the location and the relatively short lengths of BV/SS test walls available at the building.

3.2 Instrumentation

The instrumentation consisted of various temperature, moisture and air pressure sensors which were connected to a computer based, automatic data acquisition system. For sensors within the wall, one stud region located approximately in the middle of the wall was selected for monitoring, as shown in Fig. 1. This location was selected to avoid the effects of wall penetrations from telephone and cablevision outlets as well as to ensure the test location was not immediately adjacent to columns or corners, which could affect the data recorded. Sensors were installed as the masonry work was completed in the vicinity of the selected test wall.

Instrumentation installed within the test wall was generally located at the stud on the north side of the instrumented stud region as well as at the mid-way point between adjacent studs. (Note that for the remainder of this report, instrumentation and building performance at these locations will be described as being at the stud and at the insulation, respectively). The majority of the pressure, temperature and moisture sensors within the BV/SS wall system were installed approximately 500 mm below the soffit of the roof slab (Fig. 2), which is approximately the mid-point between the top two masonry wall ties. Additional moisture sensors were installed in the wall at the floor slab level and at the soffit of the roof slab. In addition, sensors were installed within the apartment located at the test wall and at the mechanical penthouse on the roof in order to monitor interior and exterior environmental conditions. The data acquisition system and sensor accessories, such as power supplies and micromanometers, were installed in the mechanical penthouse on the roof.

The test wall instrumentation is illustrated in Figs. 1 to 6 and a summary is given in Table 1. A detailed discussion of the temperature, moisture and air pressure instrumentation is provided in the following sections.

3.2.1 Temperature

Air and surface temperature measurements were taken using thermocouples in many locations within and outside the test wall (see Figs. 3 to 5). Thermocouples were installed at several points across the wall section at the stud and at the insulation in order to determine the temperature gradient across the wall at these locations. The instrumentation points across the wall were the same at both instrumented regions (i.e. at the stud and at the insulation), except that:

- an additional thermocouple was installed at the stud location on the interior flange of the stud

- the thermocouple on the interior of the exterior gypsum board at the stud was installed on the exterior flange of the steel stud, whereas at the insulation, it was installed on the gypsum board.

A thermocouple was also installed on a triangular wire brick tie at the stud location. Other surface temperature thermocouples included sensors installed at the interior and exterior flanges of the bottom track as well as at the centre of the top track. Air temperatures were measured on the interior and exterior of the building as well as within the air space and stud space of the test wall.

3.2.2 Moisture

In order to monitor the amount of water vapour in the air on the interior and exterior of the building as well as within the test wall, relative humidity (RH) sensors were installed (see Fig. 6). The relative humidity of the exterior air was measured at the mechanical penthouse while the interior RH sensor was located approximately 180 mm below the roof slab at the stud region south of the instrumented stud region. At each of these locations, secondary exterior and interior thermocouples were installed at the RH sensor location in order that, for each RH reading, the dew point temperature of the air could be calculated. These thermocouples are described as secondary thermocouples because they were used only to measure the dry bulb temperature at the RH sensor. Interior and exterior ambient air temperatures were measured using the thermocouples described in the previous paragraph.

A relative humidity sensor was installed in the middle of the stud space slightly above the mid-height of the test wall within the instrumented stud region. The RH sensor was installed by attaching it to the north side stud such that it was positioned approximately 75 mm away from the stud. A relative humidity sensor was also installed in the air space of the test wall, slightly above mid-height. This RH sensor was installed in the stud region south of the instrumented stud region due to space limitations. The thermocouples placed within the stud space and air space described above were located at the RH sensor location.

In addition to water vapour being monitored using RH sensors, the presence of liquid water was monitored using electrical resistance sensors and, in one location, a condensation sensor. The condensation sensor was installed on the interior of the exterior gypsum board within the instrumented stud region, slightly above the mid-height of the wall. This sensor was installed to detect any condensation that may occur at this location. Electrical resistance sensors were used to detect moisture levels in the brick masonry, at the floor slab level and approximately 500 mm below the roof slab level, as well as in the air space at the shelf angle and within the stud space at the centre of the bottom track.

3.2.3 Air Pressure

Air pressure was measured at the test wall by installing pressure taps through the wall and connecting the pressure taps to vinyl tubes which were run up to the micromanometers located in the mechanical penthouse (see Fig. 6). The air pressure outside and within the building interior were measured as were the air pressure within the air space and stud space of the test wall. The pressure differentials between the interior air and the air at other positions across the wall were recorded. Therefore measurements were obtained for:

- pressure differential between interior air and exterior air (P1-P4)
- pressure differential between interior air and the air within the cavity (P2-P4)
- pressure differential between interior air and the air within the stud space (P3-P4).

In addition, the barometric pressure at the site was measured using a manometer installed at the penthouse. Airport data was used for wind speeds and directions.

3.3 Data Acquisition

Data acquisition was achieved through the use of a computer based system which read the output of the sensors and recorded the data in data files on a floppy disk. The system was setup in such a way that the floppy disk could be changed, thus creating separate data files, without interrupting the collection of data. The automatic data acquisition system read data at each sensor every minute. Every hour, the system calculated the average value of the data read at each sensor and recorded these values in the data file. In addition, the hourly minimum and maximum readings at each sensor were recorded.

The test wall was monitored periodically over a 12-month period, with the monitoring periods selected to represent the differing weather conditions that occur over the year in the Ottawa-Hull area. (The budgetary constraints of this research project prevented continuous monitoring over the 12-month period). During the coldest months of the year, i.e. December to February, there is generally a higher incidence of moisture accumulation in the wall due to warm, moist air which exfiltrates through the wall system. Brick veneer walls tend to experience more freeze/thaw cycles during the period of January to March. Moisture accumulation in the walls due to easterly wind driven rains generally occurs in the spring and fall, particularly during the months of April and November. Moisture accumulation in the wall will typically dry out during the summer months.

Considering the above weather patterns and their effects on moisture accumulations in the wall, the test wall was monitored during the following periods:

1. February 25 - March 29, 1991
2. April 6 -30, 1991
3. July 20 - August 2, 1991
4. November 17 - 30, 1991
5. December 6 - 21, 1991
6. January 4 - 18, 1992.

Raw data recorded by the data acquisition system was transferred into Lotus and Excel files so that the data could be evaluated on spreadsheets and graphs.

4. EVALUATION OF DATA

While data pertaining to all sensors were recorded during six different time periods over the 12 months of periodic monitoring, evaluating the performance of the test wall involves an analysis of only the most useful sets of data. For instance, when the thermal performance of the BV/SS wall is being evaluated, it is more useful to examine data recorded during colder winter weather than it is to examine summer data. Therefore, the evaluation of data first required that readings at key locations be summarized for each data file created. As such, Tables 2 to 7 include summaries for key temperature and water vapour data recorded during each of the six monitoring periods. In order to determine which pressure differential and brick wetness data were most relevant, each of the files were examined in detail in order to identify specific events and trends which were useful for detailed evaluations.

The evaluation of data carried out is described under the following headings:

- Temperature
- Moisture
- Air Pressure.

While the following sections generally discuss the findings illustrated by a limited number of graphs, which are included in Appendix B, these figures merely represent sample graphs which represent key findings as extensive data analysis was carried out involving all sets of data collected.

4.1 Temperature

Since the coldest exterior air temperatures recorded during the 12-month period were experienced during the monitoring period of January 4 to 18, 1992, the data recorded during this time period was examined to evaluate the thermal performance of the test wall. Since exterior air temperatures dropped to about -30°C during this period, the data recorded represents the coldest weather that the Ottawa-Hull area would typically experience over the winter.

Figure 7 illustrates the temperature profile across the wall at the insulation. This profile demonstrates that good thermal performance can be expected from a "typical" brick veneer/steel stud wall since all surfaces on the exterior of the fibreglass batt insulation are at temperatures much lower than the interior gypsum board. However, surface temperatures between the interior and exterior drywall are more widely distributed at the steel stud (Fig.8) than at the insulation. This temperature profile, caused by thermal bridging through the stud, indicates that the wall does not perform as well, thermally, at stud locations as it does at the insulation.

It was observed that the measured temperature profile of the test wall often varied significantly from the theoretical temperature profile. In-situ conditions which differ (such as wind pressures, air leakage through the wall system, wet masonry and the sun shining on the brick veneer) cause the test wall to behave differently than is assumed in a theoretical calculation of the temperature profile. In general, the measured temperature profile is more likely to correspond to a theoretical calculation if there is no wind, the temperature has not been fluctuating, the brick veneer is dry and the sun is not shining on the test wall.

Table 8 compares average hourly surface temperatures at various locations across the wall section at the steel stud and at the insulation from 7:00 to 8:00 a.m. on January 16, 1992, when the exterior temperature was approximately -29°C. As shown in Table 8, the interior surface of the interior gypsum board was approximately 3°C lower at the stud than at the mid-point between studs. Conversely, surface temperatures at the exterior gypsum board are much warmer at the stud than at the mid-point between studs due to thermal bridging. Note that a temperature differential of 3°C, due to thermal bridging at the steel studs, is often sufficient to cause dust marking on the interior surface of the drywall. Thermal bridging across the studs would be reduced significantly if exterior insulation was utilized.

4.2 Moisture

Moisture within the wall system consists of water vapour and liquid water. There is always water vapour within the wall system but its presence is most significant during colder weather when water vapour can condensate against cold surfaces, causing wetting of building elements. Therefore, water vapour within the wall system is best evaluated during periods of cold weather when there is greater likelihood that its presence will have detrimental effects on the BV/SS wall system. As such, water vapour within the wall system and the resulting condensation that can occur was also evaluated using the January 4 to 18, 1992 data since this data was recorded during the coldest weather experienced over the 12-month time period. Liquid water within the wall system is best evaluated during periods of wind driven rains since these are the times when there is a higher likelihood of larger amounts of water penetrating through the brick veneer, and possibly into the steel stud backup wall if defects exist which would allow such conditions to take place. It is also useful to evaluate moisture conditions within the wall during the summer months to determine if moisture accumulations from other times of the year are able to dissipate if they have not previously been able to do so.

Tables 2 to 7 show that the hourly average relative humidity in the cavity ranged from about 70% to nearly 100% for all monitoring periods except for the summer period. However, at similar air temperatures, the relative humidity of the exterior air was often much lower than that of the air in the cavity. This indicates that moist air is not easily vented from the 25 mm air space. Experience indicates that a wider air space would have provided better venting of the cavity, since wider air spaces are less likely to be clogged with mortar protrusions and droppings that impede air movement in the cavity. In reviewing the data files, it was observed that the dew point temperature of the air in the cavity is often much higher than the dew point temperature of the exterior ambient air (since humidity levels are high, regardless of the air temperature in the cavity). In addition, the temperature on the interior surface of the brick is often lower than the dew point temperature of the air in the cavity, particularly at exterior temperatures near or below 0°C (Fig. 9). Therefore, the monitoring work indicates that condensation regularly occurs on the interior surface of the brick masonry veneer. In addition, condensation regularly occurs on the brick ties and occasionally on the exterior surface of the exterior gypsum board sheathing.

Experience has shown that this condition could be detrimental when the interior surface of the brick falls below freezing temperatures. The resultant freeze/thaw action could cause significant deterioration of the interior surface of the masonry, a condition which is of particular concern since much deterioration may occur before it is evident on the exterior face of the masonry wall. The main concern with back spalling is that the brick masonry will deteriorate to the point that it is no longer adequately supported by the brick ties although the exterior face of the brick veneer may show little or no distress. If this condition goes undetected, sudden failure of the masonry wall could occur. While the above situation represents an extreme case, back spalling can lead to major brick replacement work as the masonry distress may not become evident on the exterior until much deterioration has already occurred. Condensation within the cavity is of concern since this condition can also lead to corrosion and eventual failure of brick ties.

In comparing the dew point temperature of the air in the stud space to the surface temperature on the interior of the exterior gypsum board, it was observed that minor condensation generally occurs on the interior surface of the exterior gypsum board at exterior temperatures of about 0°C or less (Fig. 10). The 2.5 Volt (or nearly so) readings on the condensation sensor during monitoring periods with colder weather confirm that condensation regularly occurs on the interior surface of the exterior drywall. In comparing the dew point temperature of the interior air to the surface temperatures within the stud space, it is obvious that any moist interior air which escapes into the wall space will condensate within the wall (Fig. 11). The above findings demonstrate that minor amounts of condensation will likely occur within most steel stud walls that lack exterior insulation. Therefore, the walls should be designed such that condensation which forms in the stud space and travels down to the bottom track can be drained from the stud wall rather than being trapped in the bottom track where it can cause significant corrosion over the long term. The test wall was not specifically designed to allow moisture accumulations to drain from the stud wall and, therefore, there is a potential for corrosion of the bottom tracks over the long term. In addition, the above findings provide further evidence that exterior insulation should be used to keep temperatures within the stud space as high as is reasonably and economically achievable.

The wetness of the brick surface at monitoring points M1, M2, M3 and M4 is shown in Figs. 12 and 13 for the April 1991 and January 1992 monitoring periods, respectively. Note that the electrical resistance moisture sensors in the test wall were not calibrated to determine the specific moisture content in the brick. Therefore, the readings indicate relative wetness. Higher resistance readings are obtained when the brick is drier and, conversely, lower readings are yielded when the brick becomes wetter. Figs. 12 and 13 indicate the degree of wetness for the monitoring points. Note that during freezing temperatures, freezing of water in the brick will result in higher readings, giving a false indication of the brick being drier and, therefore, this point must be kept in mind when analyzing the data.

The weather during April 6 to 30, 1992 was relatively dry, with only occasional rain or snow. Exterior air temperatures were generally above 0°C and, therefore, the data collected during this period is considered reliable. In Fig. 12, the graphs of M2 and M4 indicate that the degree of wetness on the interior face of the brick is fairly consistent when the wall is not subjected to significant exterior sources of moisture. The data also indicates that wetness levels are consistently higher near the roof level than at the fourth floor slab. The data also indicates that, at the floor slab level, the interior face of the brick veneer is generally wetter than the exterior face of the brick, even during most of the rainy weather. One reason for the higher moisture levels on the interior brick face may be from condensation which forms on the interior of the brick veneer, since the surface temperature of the brick consistently was nearly identical to the dew point temperature of the cavity air in April 1991.

Fig. 13 provides a good illustration of how major rain storms will wet the entire thickness of the brick veneer. On Day 10 (when rain fell for 24 hours, bringing 28 mm of rain, followed by snow), all monitoring points were very wet as all curves reach minimum values for the monitoring period of January 4 to 18, 1992. The data indicates that wetness levels are approximately equal on the interior and exterior faces of the brick, both at the fourth floor slab and near the roof level. The data also indicates that the brick is wetter near the roof level than at the fourth floor level. While the brick veneer was saturated during the rain storm described above, due to capilary action and wind pressures, the moisture sensor at the bottom of the air space showed only a moderate increase in wetness. Therefore, most rainwater which penetrated to the air space did not cross the cavity and the brick veneer generally acted as an effective rainscreen, although the cavity was not pressure equalized in a fully effective manner.

Immediately following the major rain storm, a cold front moved in, dropping temperatures to -30°C within 40 hours of the rain storm ending and within 30 hours of the snowfall ending. Therefore, the moisture in the brick veneer froze. The high electrical resistance values shown in Fig. 13 illustrate how the moisture sensors provide inaccurate results in freezing conditions, as discussed above, since the data indicates that the brick has dried out considerably whereas it is very likely that the moisture is frozen in the brick.

4.3 Air Pressure

Utilizing P1, P2, P3 and P4 to indicate air pressures at the exterior, the air space, the stud space and at the interior, respectively, then a wall which performs well would fulfil the following criteria under wind loading conditions:

1. P1-P4 should be significant since the wall system, particularly the air/vapour barrier, should ensure that the interior and exterior air pressures are distinctly different under most circumstances.

2. Since the exterior sheathing should not act as an air barrier in order that moisture from the interior may freely exfiltrate past this layer of sheathing, P2-P3 should be minimal since P2-P4 and P3-P4 should be virtually equal.

3. P3-P4 should be high in most cases since a large value for P3-P4 means that the air/vapour barrier is functioning adequately.

4. Variations in P1-P2 should be fairly consistent and relatively small. This criteria will be met if there is pressure equalization between the cavity air and the exterior air (by having an adequate cavity and compartmentalization) and the air barrier does not leak siginificantly. While the brick veneer initially resists the wind loads, effective pressure equalization causes the load on the brick veneer to quickly diminish and, hence, the backup wall resists the wind loads. In such cases, the value of P1-P2 would be relatively small although its absolute value is less important than trends related to how much P1-P2 varies as wind loading conditions change. Variations in P1-P2 and large values of P1-P2 would indicate that pressure equalization is not fully effective and/or that the air barrier allows air infiltration or exfiltration.

5. The thermal performance of the insulated stud wall would be consistent, regardless of variations in pressure difference across the test wall. If the wall does not perform as well during high pressure differences across the wall, this condition also would indicate air infiltration or exfiltration through the air barrier.

Specific incidents of high winds during the April and November 1991 monitoring periods are most useful to evaluate the performance of the wall with respect to air pressure during severe conditions. However, the most useful information regarding air pressure is obtained by analyzing trends in wind differentials under changing wind loading conditions, and these trends are best evaluated by examining the average wind pressures over the length of a monitoring period.

The graphs of P1-P4, P2-P4 and P3-P4 over the period of January 4 to 18, 1992, (Figs. 14 and 15) demonstrate that the test wall generally performs in a satisfactory manner since the wall meets most of the criteria outlined above. Note that, in both graphs, P1-P2 is represented by the distance between the curves of P1-P4 and P2-P4. Similarly P2-P3 is represented by the distance between the curves of P2-P4 and P3-P4. Fig. 14 illustrates the hourly average pressure differentials while Fig. 15 illustrates the daily average pressure differentials.

P1-P4 is substantial throughout the monitoring period and this finding demonstrates that, as expected, the wall system is effective at isolating the exterior air from the interior air. Note that the smaller values for P1-P4 are recorded when P1 increases due to the test wall being exposed to winds from the easterly direction (eg. Days 1 and 5). Note that the pressure differential is still negative during easterly winds, likely due to building pressurization. Similarly, higher values of P1-P4 occur when winds are from a westerly direction (eg. Days 4 and 11) and, therefore, negative wind pressures occur on the east facing test wall, which combine with the building pressurization to yield large pressure differentials between the interior and exterior air. (Note that stack effect would provide only a minor contribution to the negative pressures since the building is only seven storeys high).

Since Criteria 2 and 3 above are met by the test wall, the monitored BV/SS wall performs reasonably well in terms of air/vapour barrier placement and effectiveness. Specifically, the curve representing P2-P4 illustrates that there is a substantial pressure difference between the interior air and the cavity air and, therefore, the air/vapour barrier is effective. In addition, P2-P3 is minimal and, therefore, there is little pressure differential between the air in the stud space and the air in the cavity. This finding indicates that the exterior drywall does not act as an unintentional air barrier on the exterior of the insulation and, therefore, the test wall performs as designed in this regard.

One aspect of BV/SS wall performance that is often debated is whether:

(a) the brick veneer resists the wind load and this load is then transferred to the backup walls through connectors, or

(b) the air space within the wall acts to create pressure equalization between the air space and the exterior air, thereby enabling the brick veneer to act as a rain screen more effectively as well as causing the backup wall to resist wind loads directly (after the brick momentarily resists the loads) while the backup wall provides structural stability to the brick veneer.

Fig. 14 illustrates that the pressure differential between the cavity air and the exterior air (P1-P2) varies significantly depending on wind conditions. During easterly winds, the magnitude of all pressure differential values are reduced as positive wind pressures partially counteract the negative pressure differentials caused by building pressurization. The simultaneous increase in pressure on the exterior and within the cavity illustrates that pressure equalization does occur to some degree and that both the brick veneer and the backup wall are affected by wind pressures, and thus resist, wind loads.

However, Figs. 14 and 15 also illustrate that when wind directions change, there is a greater change in P1-P4 than in P2-P4. In fact, the pressure difference across the brick veneer generally accounts for 50% of the pressure difference across the entire wall. Since the changes in the pressure differential between the exterior air and interior air tend to be greater than changes in the pressure differential between the cavity air and the interior air, pressure equalization is not fully effective. As such, wind loads are carried by the BV/SS test wall in a manner that is a combination of points (a) and (b) above. That is, pressure equalization causes a portion of the wind load to be immediately transferred to the backup wall but since pressure equalization is not fully effective, a portion of the wind load is still carried by the brick veneer.

The magnitude of P1-P2 not only indicates that pressure equalization is not fully effective. This data also indicates that air leakage occurs through the air barrier since air leakage partially "releases" pressure on the air barrier. In order to examine air leakage on its own, pressure differences across the test wall are plotted against the ratio of the temperature difference across the insulation to the temperature difference across the entire wall (i.e. ΔP is plotted against the ratio of T_{cavity} minus $T_{exterior}$ to $T_{interior}$ minus $T_{exterior}$). If no air leakage occurred, then the above temperature ratio would be relatively constant regardless of the pressure difference across the test wall. However, the temperature ratio for the test wall decreases slightly as the pressure difference increases, indicating that air leakage does occur through the air/vapour barrier system. While it appears that only minor air leakage occurs, air exfiltration does contribute to the high water vapour levels in the cavity which lead to condensation on the brick veneer and exterior sheathing.

5. CONCLUSIONS AND RECOMMENDATIONS

The data analyzed indicates that the test wall currently is performing in an unsatisfactory manner since condensation that occurs on the interior surface of the brick masonry and within the steel stud wall may cause significant building distress problems over the long term.

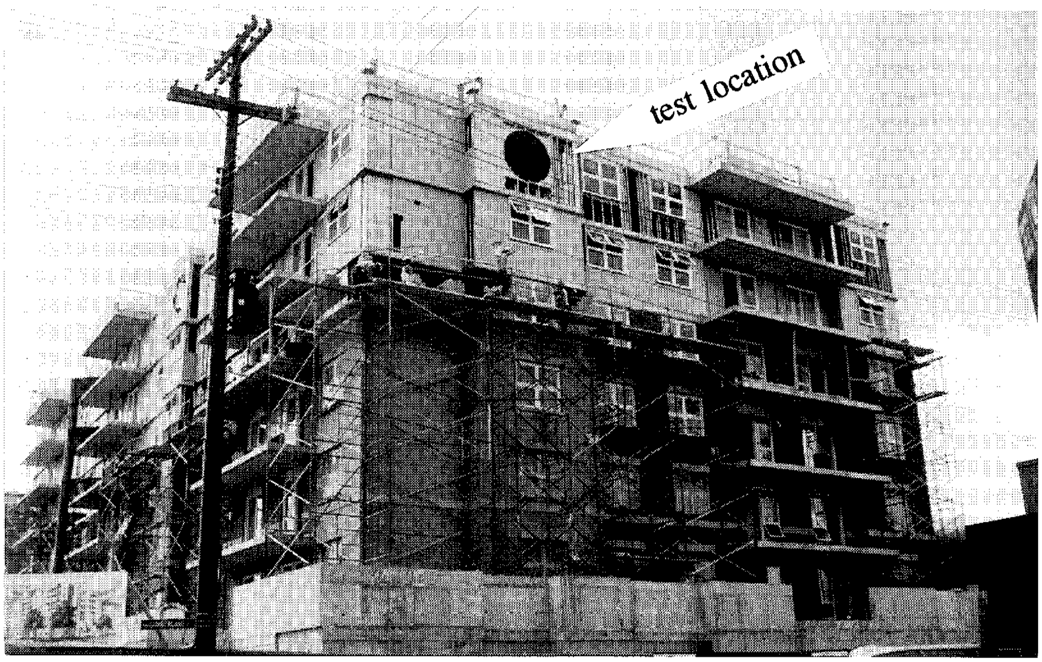
Exterior insulation would have contributed to improved thermal performance of the wall system. As such, condensation on the interior surface of the exterior gypsum board would have been prevented and the possibility of condensation forming on steel studs would have been minimized. A larger cavity would have allowed better venting of the air space, thereby reducing the buildup of water vapour in the cavity which causes condensation on the interior surface of the brick veneer in cold weather. Note that air leakage through the wall system is the main mechanism by which water vapour migrates through the backup wall until it either escapes into the cavity or condenses within the wall. Therefore, all reasonably ecomomical efforts should be made to prevent air leakage through the wall system, however, it should also be noted that minor air leakage will occur, in spite of the best efforts of the designers and contractors. As such, brick veneer/steel stud wall systems should be designed to be "forgiving" of such air leakage. To be forgiving of such air leakage, exterior insulation and good cavity venting (as mentioned above) are essential since both are important contributors to the satisfactory longterm performance of the brick veneer/steel stud wall system. Another important factor for the satisfactory performance of BV/SS walls is compartmentalization of the cavity. Proper compartmentalization results in more effective pressure equalization, a phenomenon that allows the brick veneer to act as a more effective rain screen, thus reducing the possibility of rain water penetration through the wall system.

The key finding of this research program is that the BV/SS test wall is not performing in a satisfactory manner even though it was built in accordance with existing codes, standards and construction practices. Therefore, the findings of this study clearly illustrate that improved design and construction standards are required to ensure that brick veneer/steel stud wall systems are constructed in a manner which will ensure satisfactory performance over the long term.

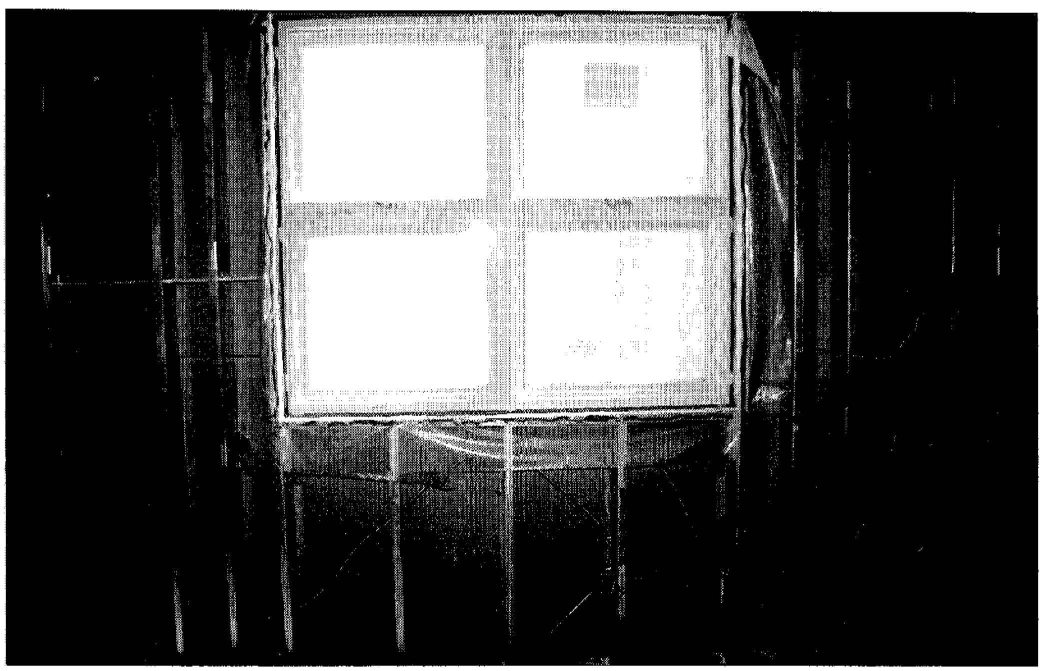
The current monitoring program has been extended so that additional data may be obtained and the performance of the brick veneer/steel stud test wall may be evaluated over a longer time period. This will be especially important in view of the known presence of moisture in the wall system due to condensation. Since presently there exists a lack of data related to the longterm performance of brick veneer/steel stud walls, continued monitoring will provide data which will be very useful to CMHC and the construction industry, especially designers. This data will be particularly important since the test wall does not represent "best practices" but, rather, represents the method by which BV/SS walls are commonly constructed today.

Finally, it is recommended that this monitoring project be expanded to include another BV/SS project built according to best practices. Excellent comparisons could be made over the long term if monitoring were carried out for both projects over a period of several years. The results of this expanded monitoring project could be used in conjunction with other research findings to develop improved standards related to the design and construction of brick veneer/steel stud wall systems.

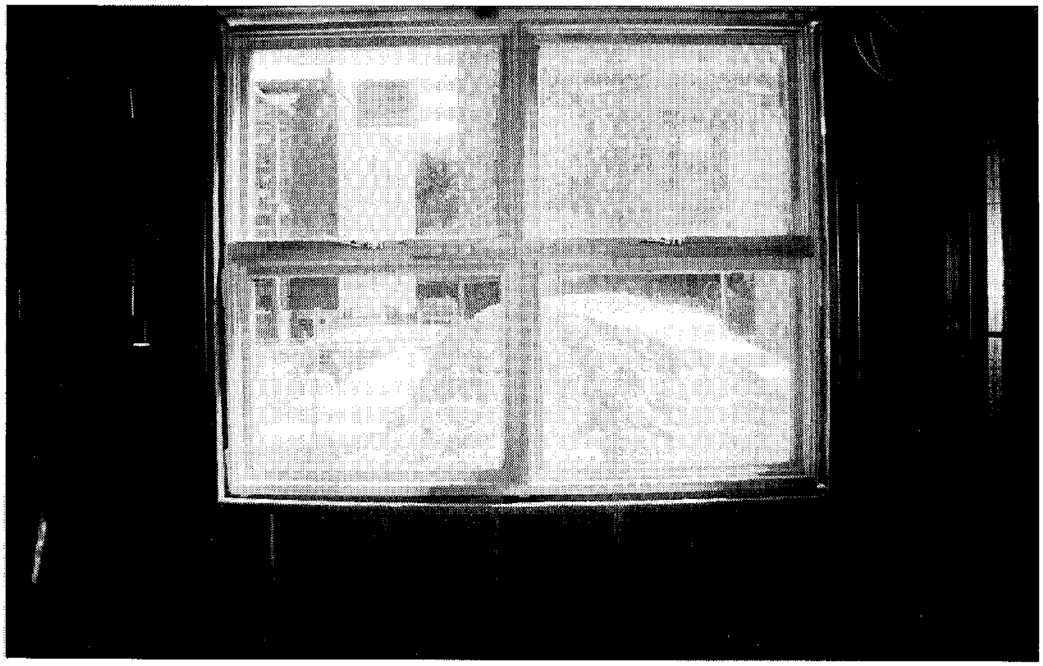
APPENDIX A: Photo Review

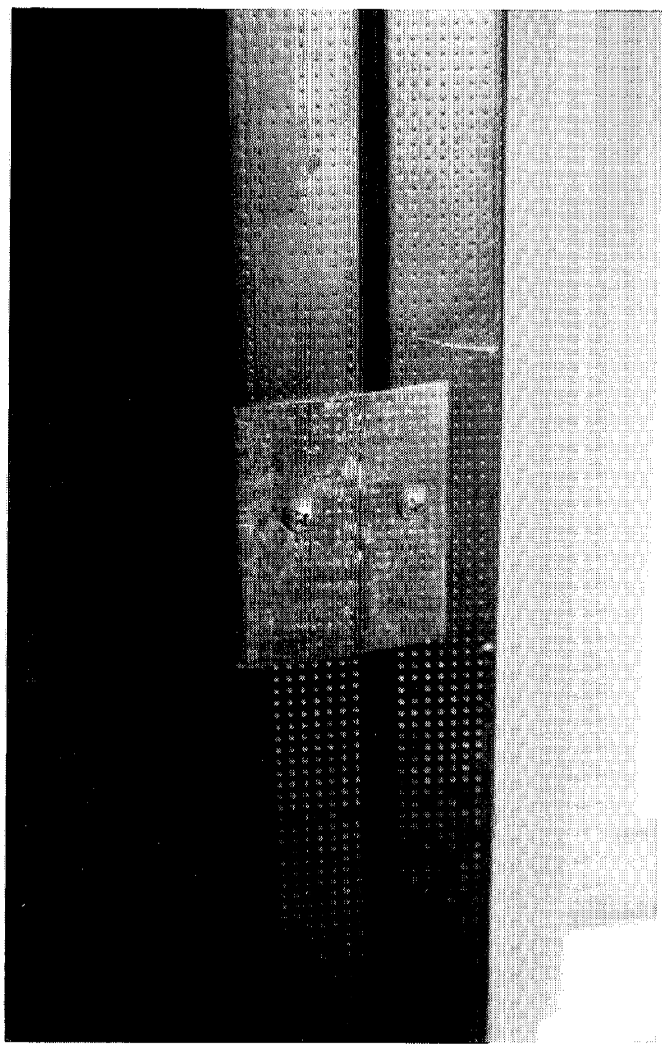


1 Showing building during construction in 1990



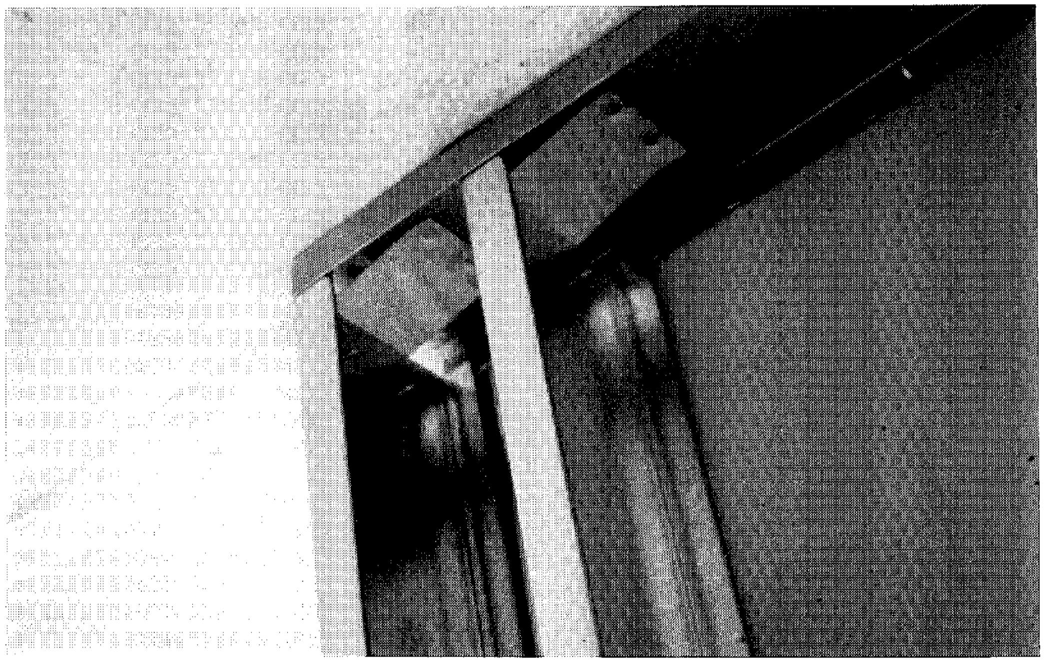
2 Interior view of typical steel stud arrangement at window opening. Note that the designer opted to use single studs at the window but that the spacing of the studs was gradually reduced.



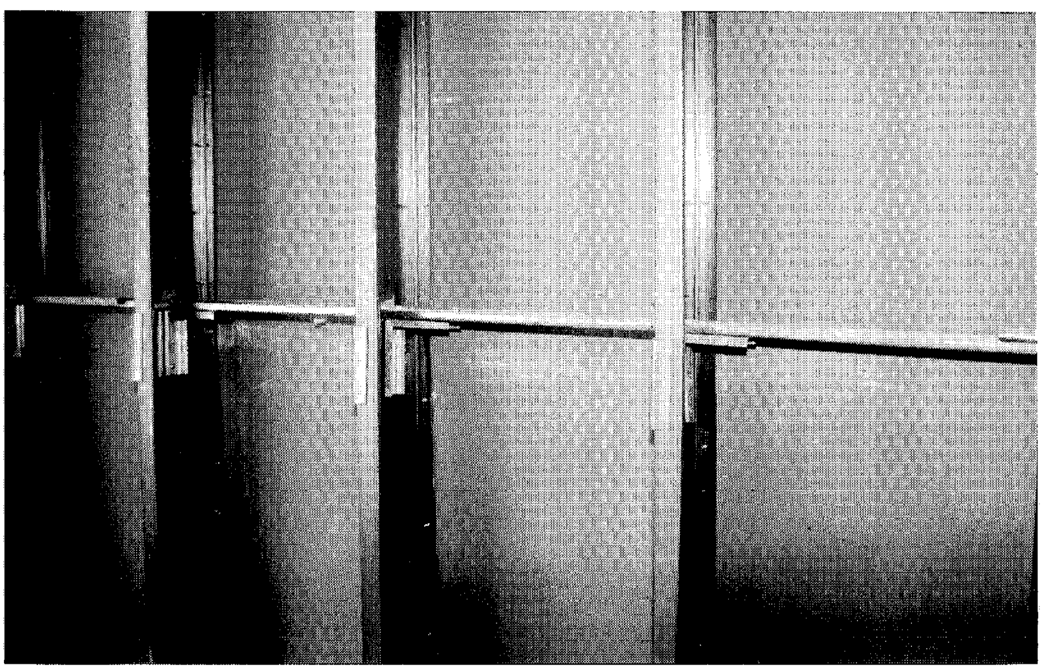


3 In this location, double studs were used at the window opening

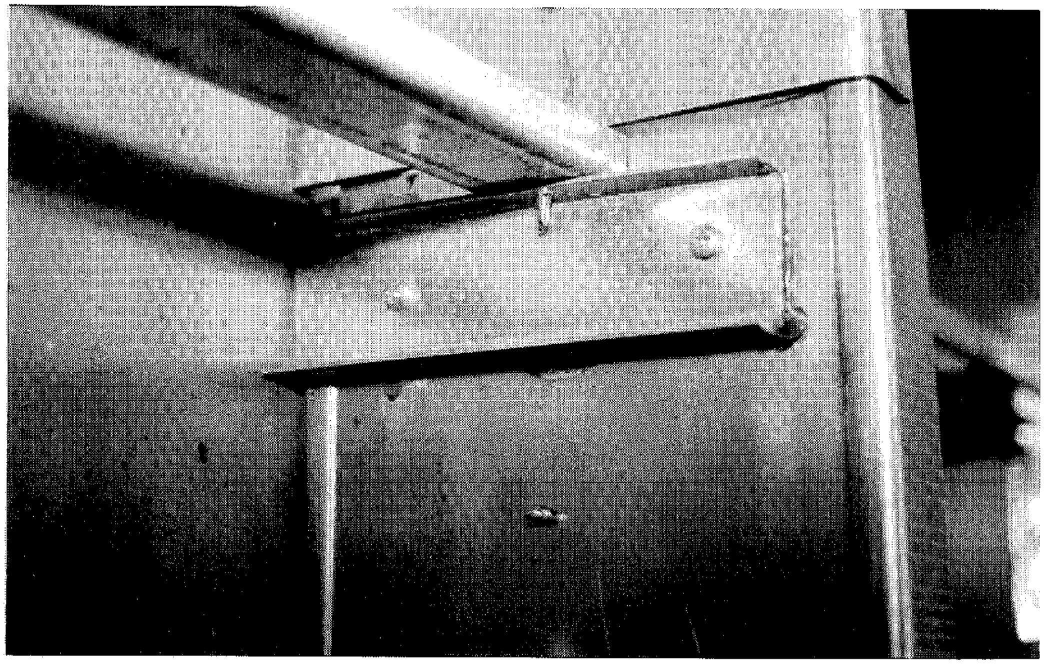
4 Showing the clip connection used to tie double studs



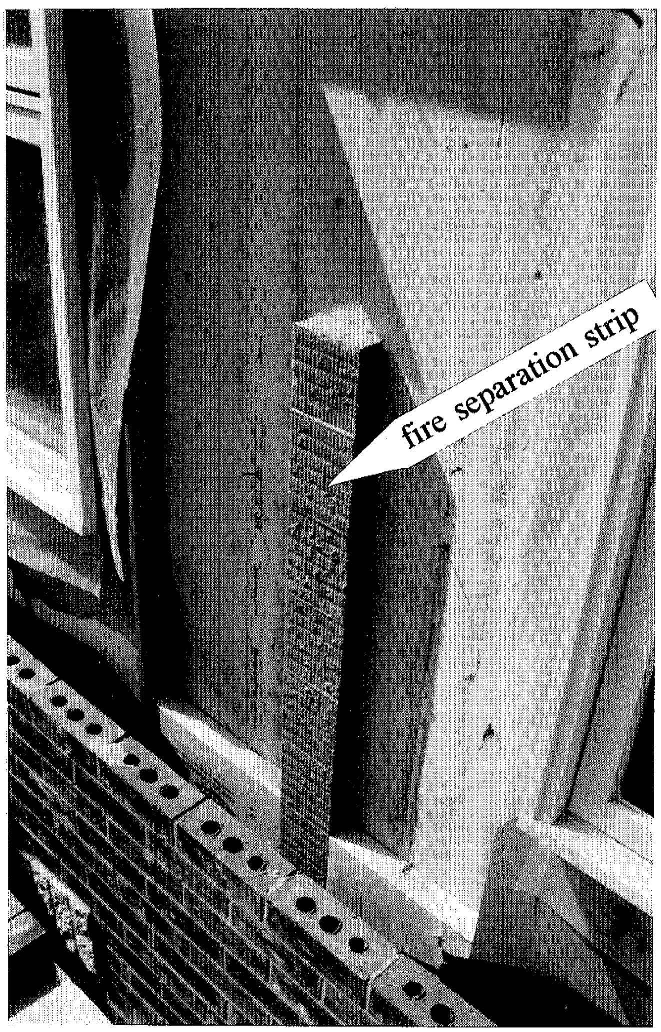
5 Showing the use of flexible ties between stud and top tracks. These types of ties have proven to be easy to install and hence economical but also very effective in transferring lateral load.



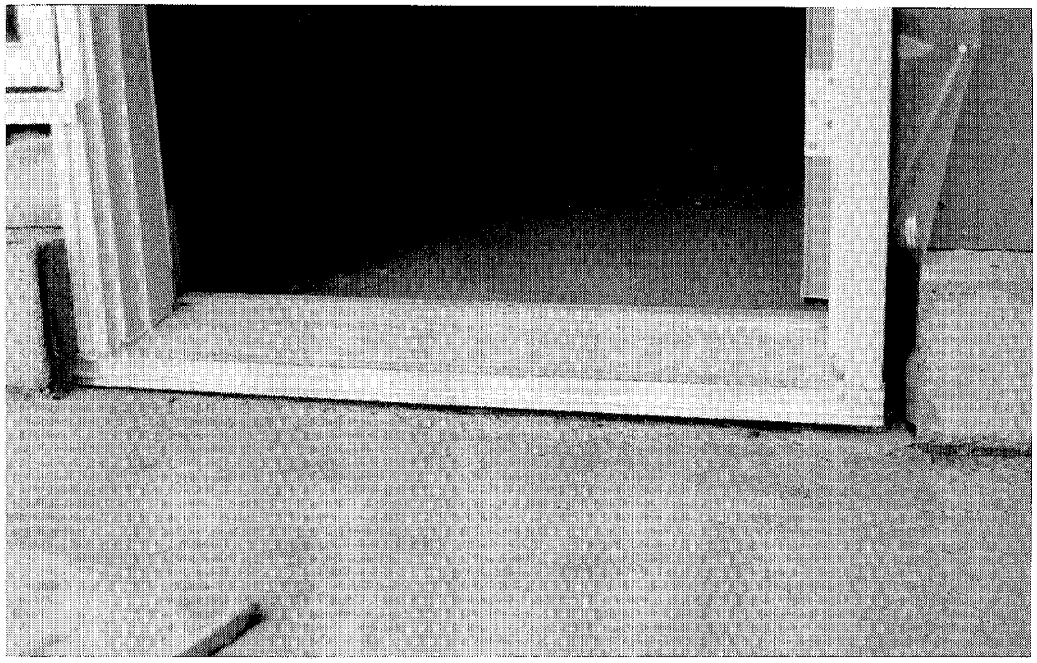
6 Typical through-the-stud bridging



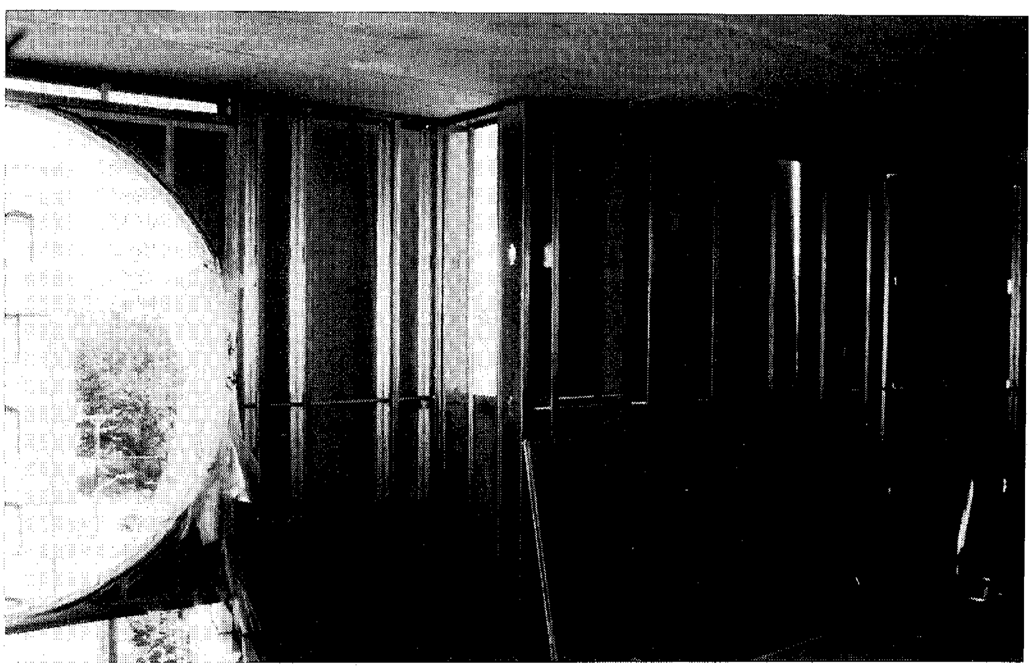
7 Closeup view showing bridging to stud connection



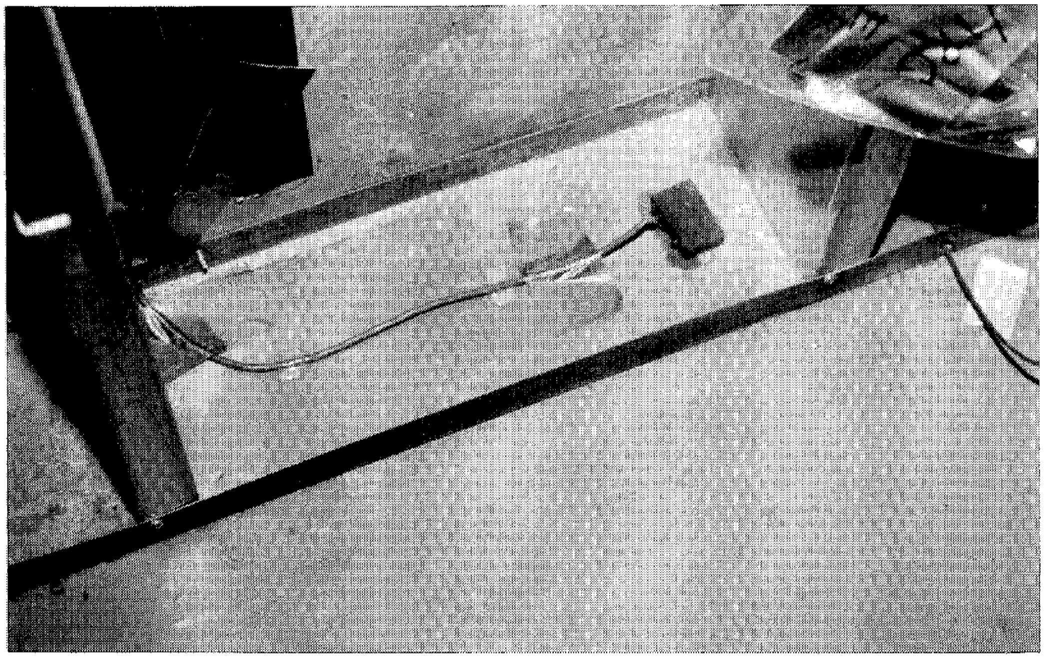
8 Showing use of rigid insulation at column locations. Note vertical fire separation strip.



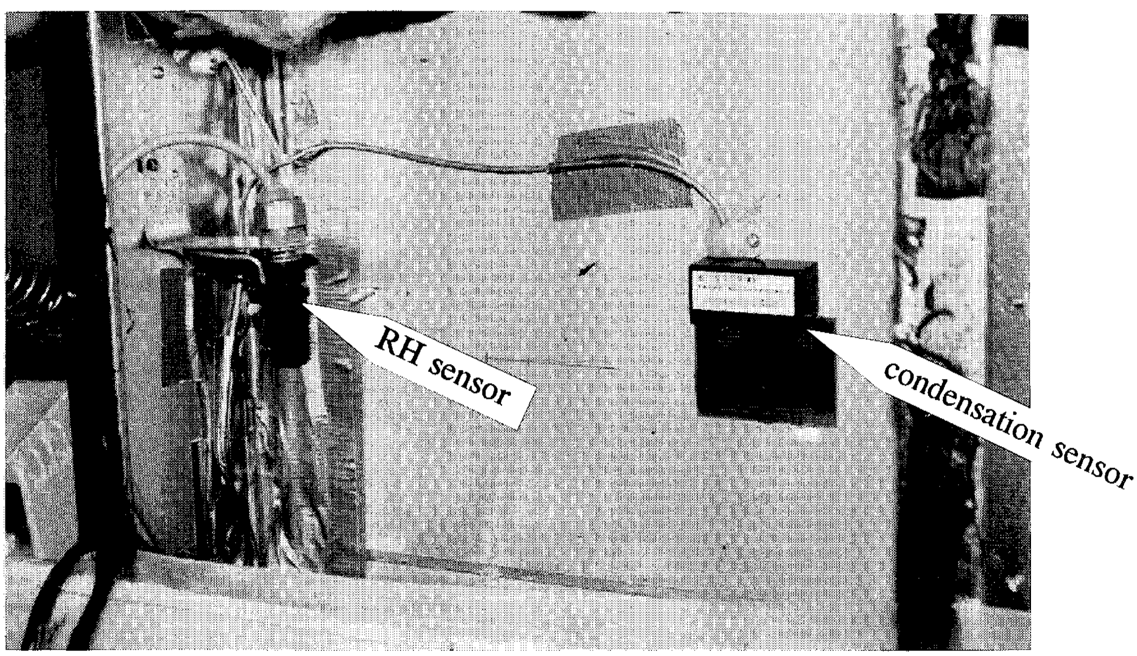
9 Showing example of poor balcony door detail. Note absence of curb. The gap below the door threshold is merely sealed with a bead of caulking which is prone to deterioration and ongoing maintenance.



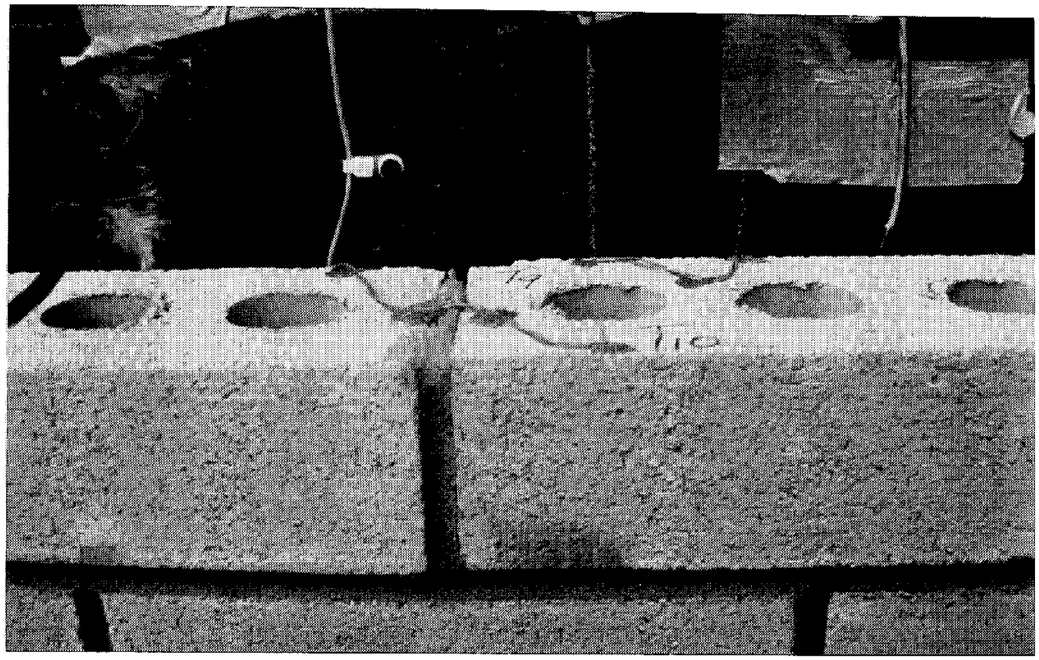
10 Interior view of test wall location



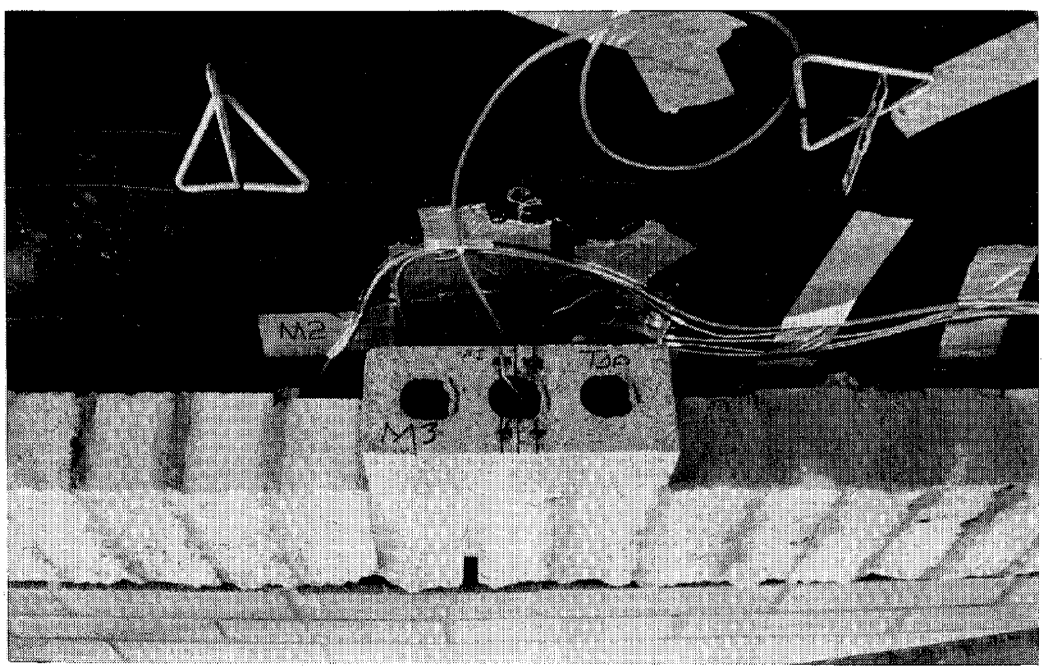
11 Showing moisture sensor in bottom track



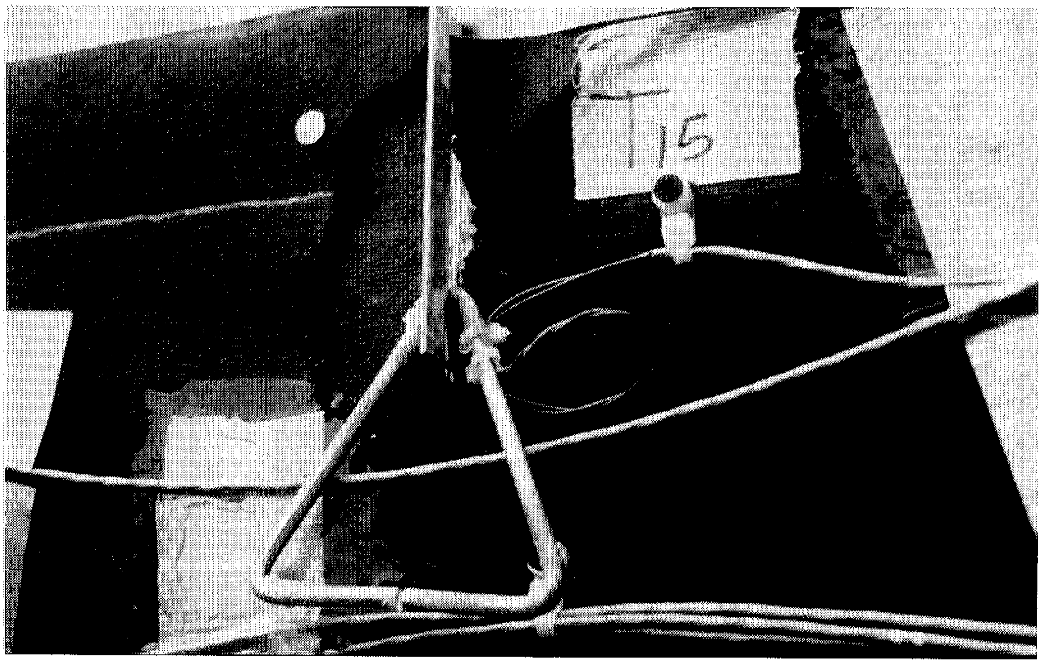
12 Showing condensation and relative humidity sensors in stud space



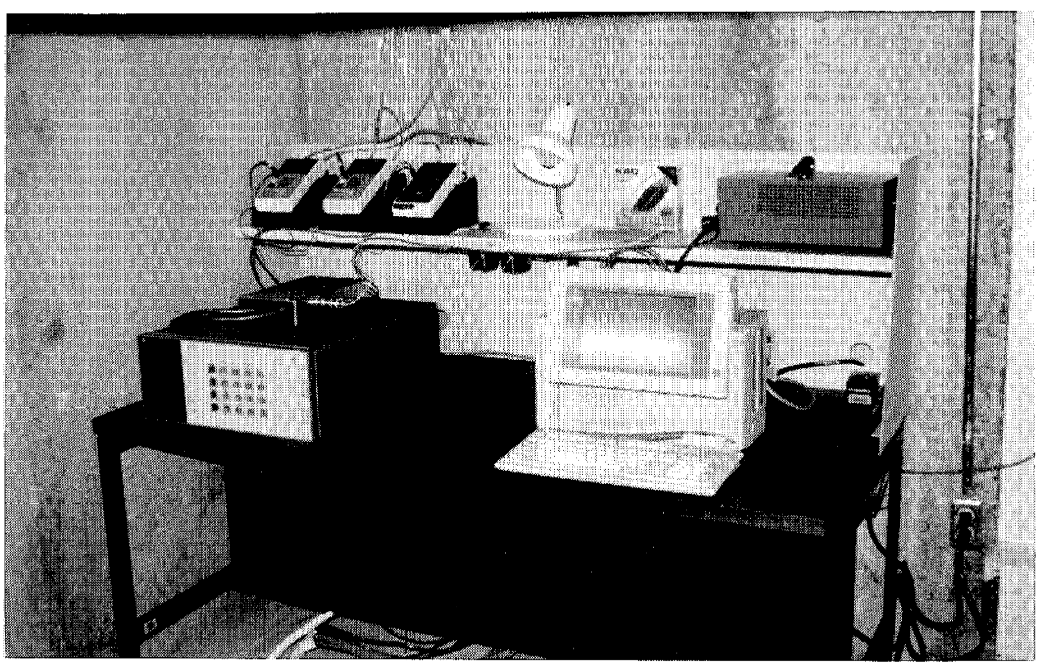
13 Showing thermocouples at interior and exterior surfaces of brick unit



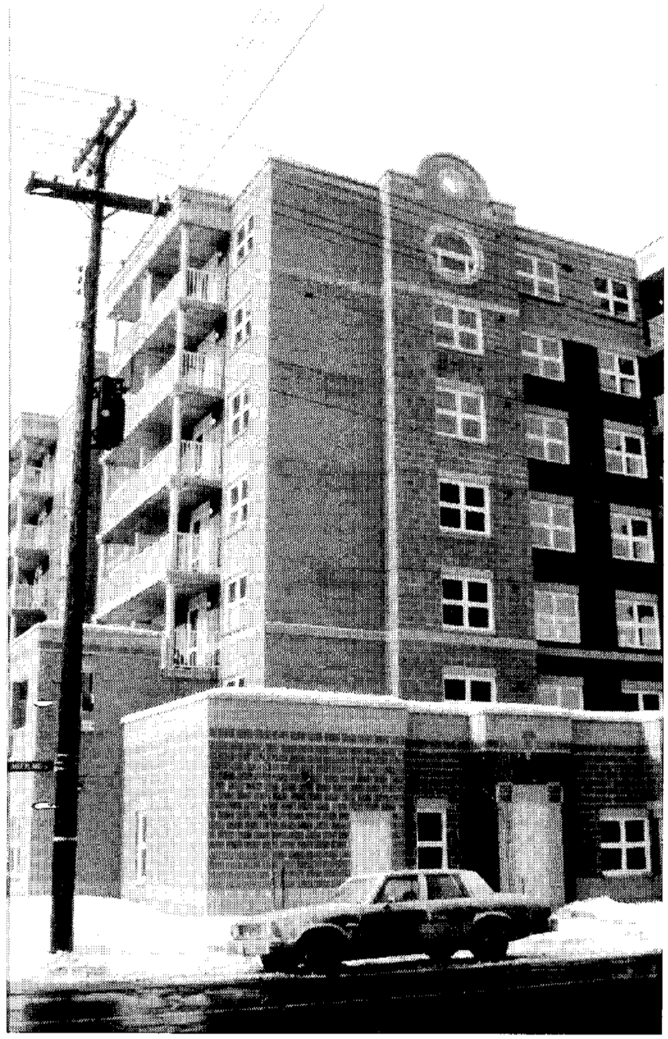
14 Showing electrical resistance moisture sensors on brick (M3) and exterior drywall (M2)



15 Showing thermocouple on brick tie



16 Data acquisition station located in mechanical penthouse room



17 View of completed structure in 1991

APPENDIX B: Instrumentation Details

Table 1 List of Sensors and Their Locations

Surface Temperature Thermocouples	
10	Exterior of brick veneer at centre of stud region
9	Interior of brick veneer at centre of stud region
8	Exterior of exterior drywall at centre of stud region
18	Interior of exterior drywall at centre of stud region
22	Interior of interior drywall at centre of stud region
13	Exterior of brick veneer at steel stud
12	Interior of brick veneer at steel stud
11	Exterior of exterior drywall at steel stud
19	Exterior flange of steel stud
20	Interior flange of steel stud
23	Interior of interior drywall at steel stud
15	Triangular wire brick tie
24	Exterior flange of bottom track
25	Interior flange of bottom track
17	Centre of web of the top track
Air Temperature Thermocouples	
14	Outside air
33	Air space at R2 (DBT2 in Lotus files)
34	Stud space at R3 (DBT3 in Lotus files)
31	Inside air
Relative Humidity Sensors	
R1	Outside air
R2	Air space
R3	Stud space
R4	Inside air
Moisture Sensors	
M1	Exterior face of brick veneer at floor slab level
M2	Interior face of brick veneer at floor slab level
M3	Exterior face of brick veneer 500 mm below roof slab level
M4	Interior face of brick veneer 500 mm below roof slab level
M5	Bottom of air space
M6	Centre of bottom track
C1	Condensation sensor at interior face of exterior drywall at centre of stud region
Air Pressure Sensors	
P1	Outside air
P2	Air space
P3	Stud space
P4	Inside air
B1	Barometric pressure at mechanical system penthouse

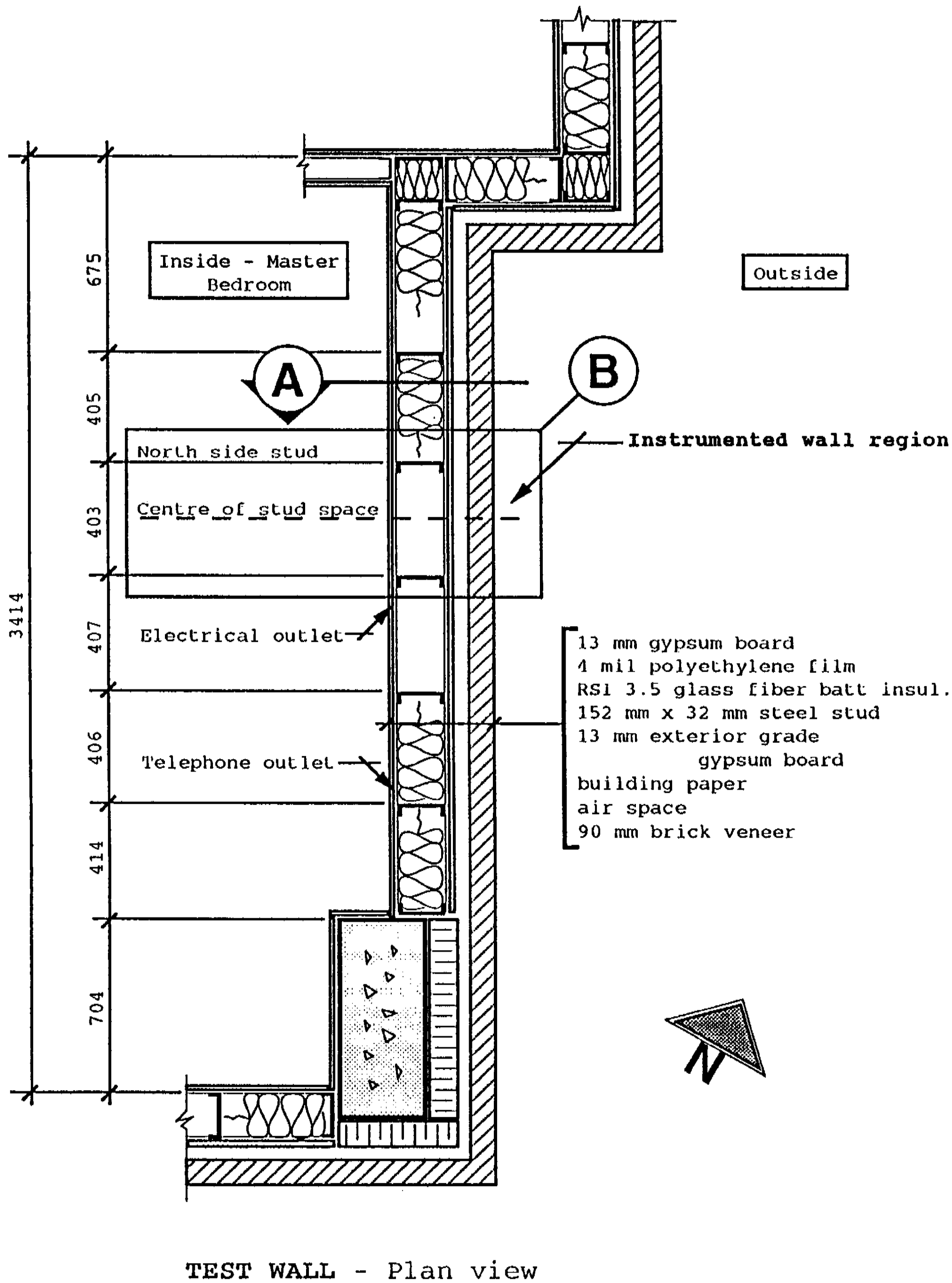


Fig. 1 Plan View of Test Wall

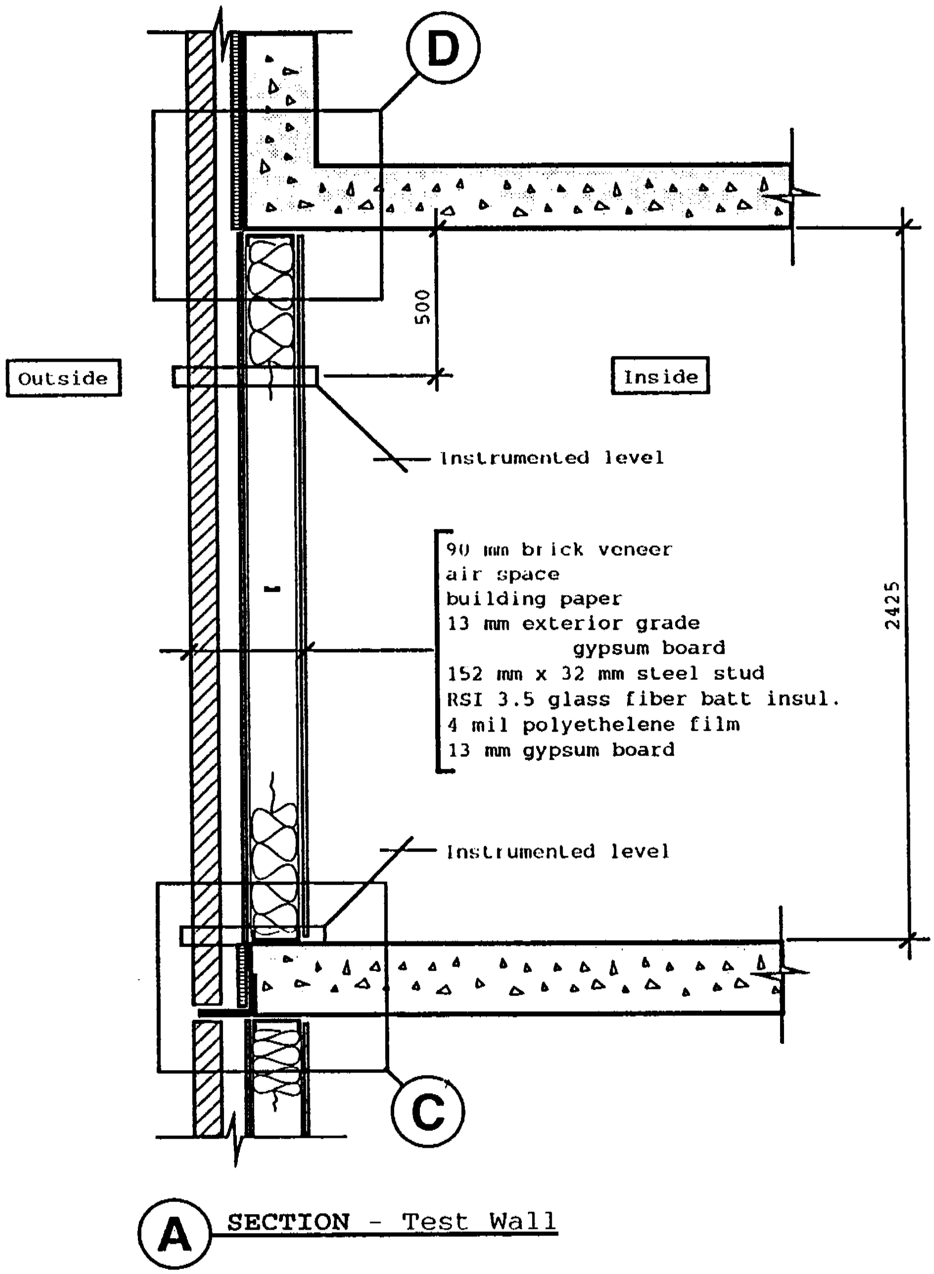
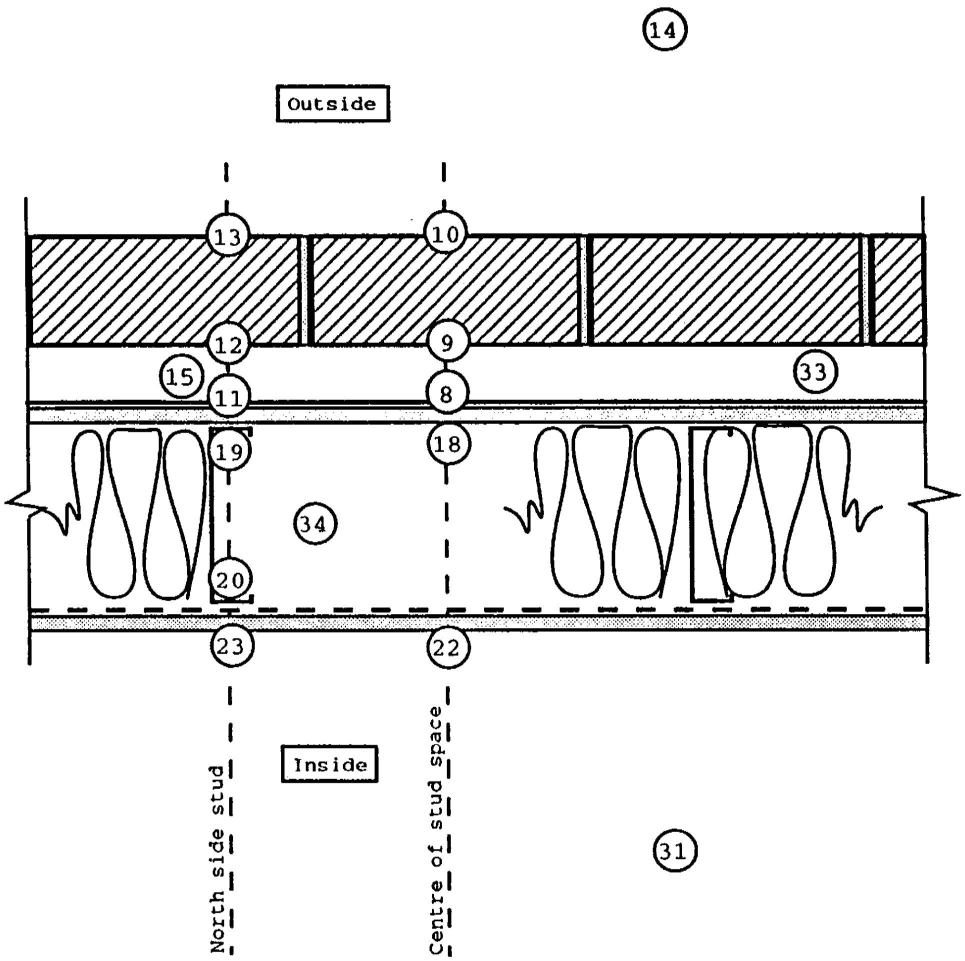


Fig. 2 Cross-section Through Test Wall



○ Indicates surface temperature thermocouple except for #14, #31, #33 and #34 which are air temperature thermocouples. Thermocouple #15 is attached to the triangular wire tie.

Fig. 3 Location of Thermocouples Across Test Wall at 500 mm Below Roof Slab

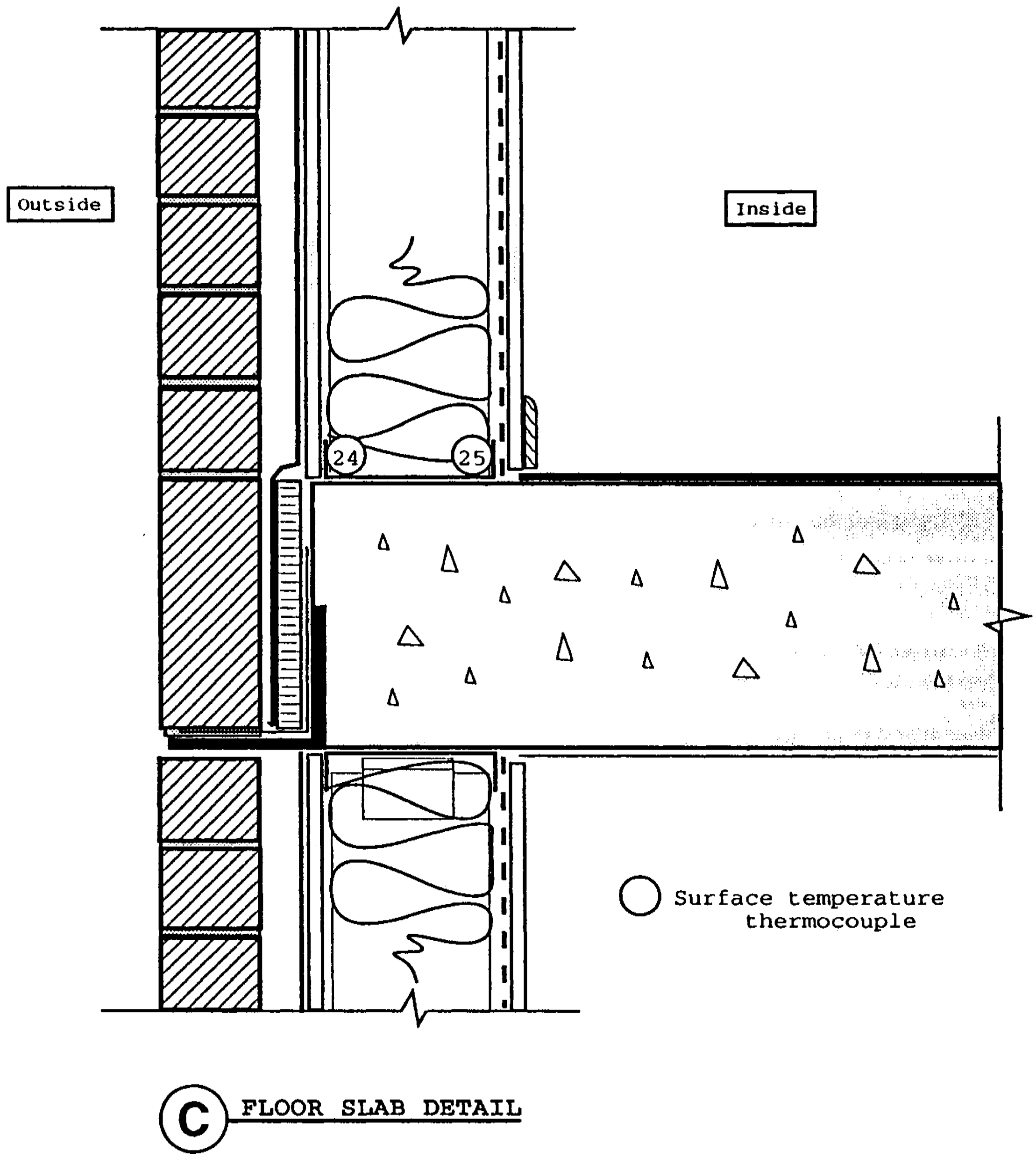


Fig.4 Location of Thermocouples at Floor Slab Level

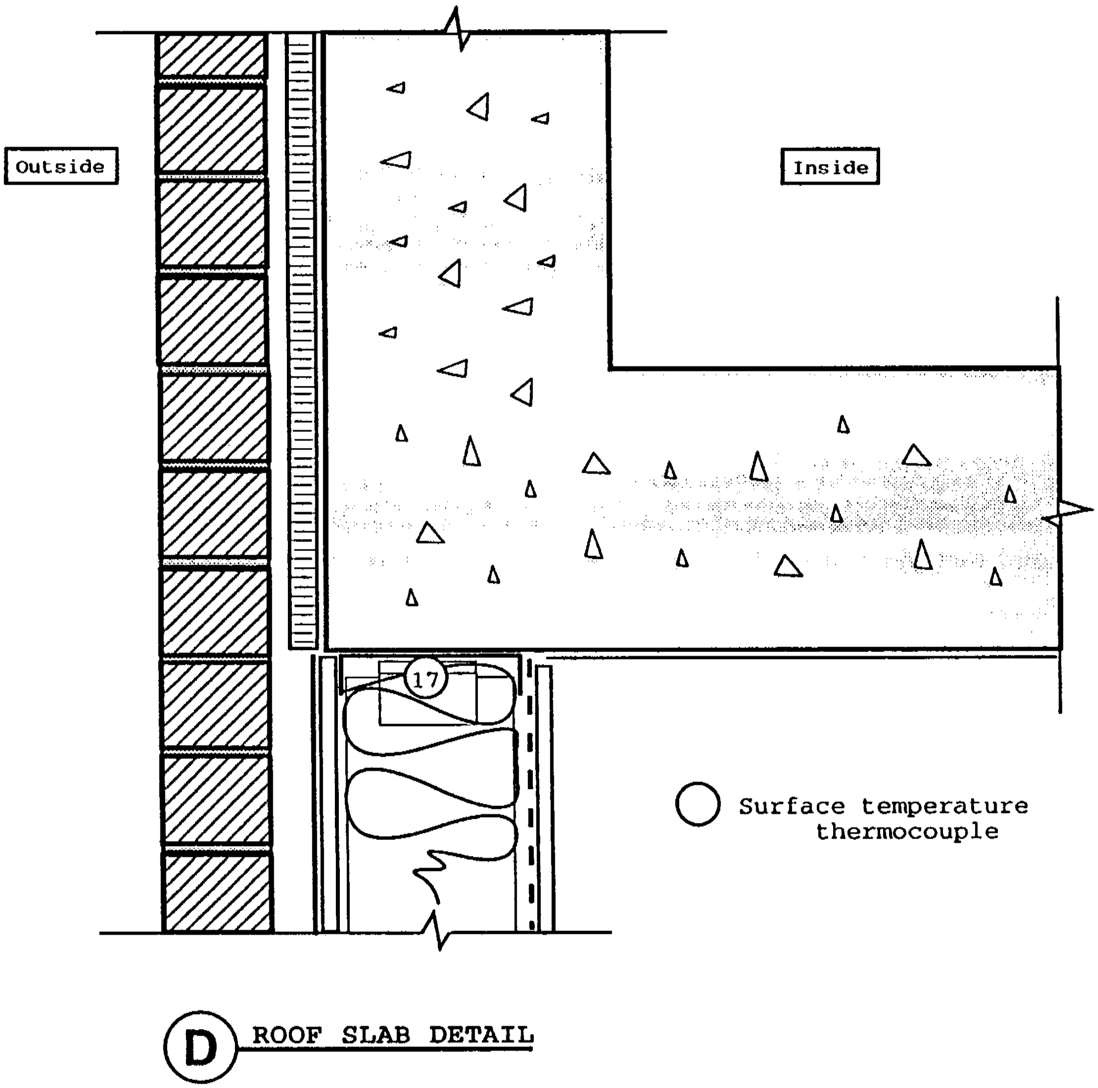
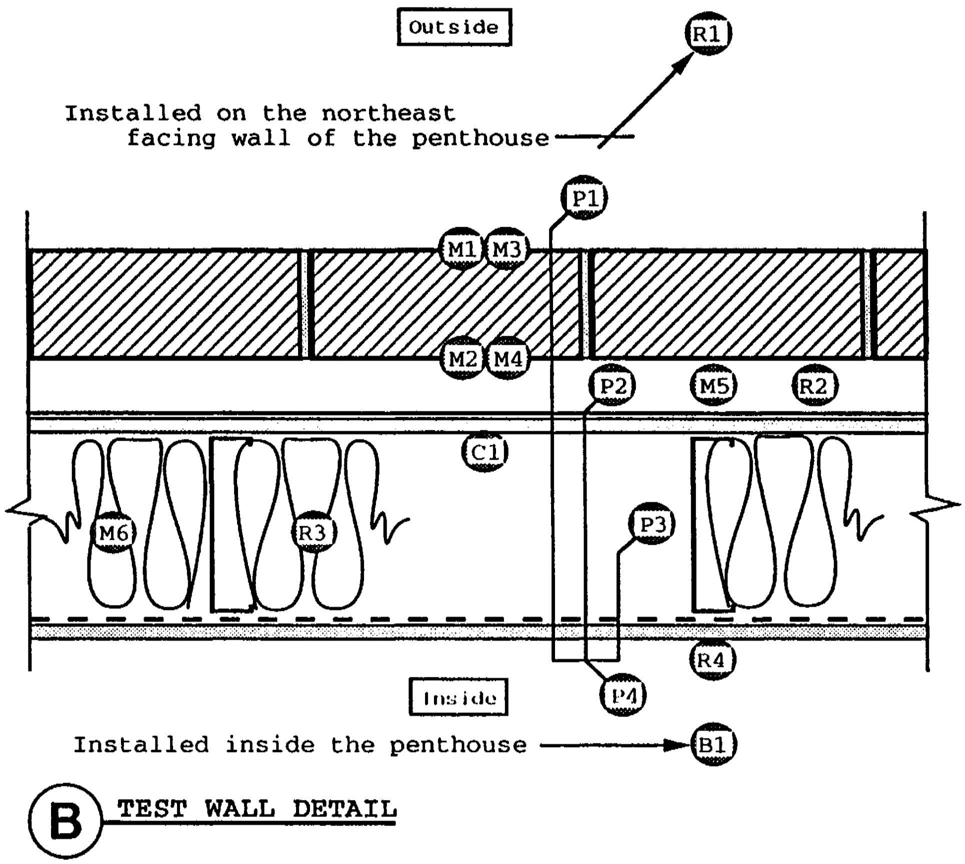


Fig. 5 Location of Thermocouple at Roof Slab Level



(C) Condensation sensor.

(M) Electrical resistance moisture 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.

(P) Pressure tap.

(R) Relative humidity sensor.

(B) Barometric pressure transducer.

Fig. 6 Location of Moisture and Air Pressure Sensors

APPENDIX C: Data Tables and Sample Graphs

Table 2 Range of Readings at Key Locations, February 25 to March 29, 1991

Reading Type	Minimum Hourly Average	Maximum Hourly Average	Absolute Minimum	Absolute Maximum
Surface Temperatures:				
· exterior of brick (10)	-11.1°C	13.1°C	-11.5°C	13.2°C
· interior of brick (9)	-8.7°C	12.8°C	-8.9°C	12.8°C
· ext. of ext. drywall at insulation (8)	-3.9°C	13.7°C	-4.0°C	13.7°C
· ext. of ext. drywall at stud (11)	2.0°C	16.3°C	1.9°C	16.3°C
· int. of ext. drywall at insulation (18)	-3.1°C	13.9°C	-3.2°C	13.9°C
· exterior flange of stud (19)	6.5°C	17.7°C	6.4°C	17.7°C
· int. of int. drywall at insulation (22)	17.6°C	26.3°C	17.5°C	26.8°C
· int. of int. drywall at stud (23)	15.7°C	23.7°C	17.2°C	24.1°C
Air Temperatures:				
· exterior (14)[1]	-14.2°C	12.3°C	-14.8°C	16.3°C
· air space (DBT2 or 33[2])	-6.2°C	13.2°C	-6.4°C	13.3°C
· stud space (DBT3 or 34[2])	9.9°C	18.9°C	9.9°C	19.0°C
· interior (31)	17.3°C	26.2°C	17.2°C	26.8°C
Relative Humidities:				
· exterior (RH1)	18%	92%	17%	92%
· air space (RH2)	82%	99%	71%	100%
· stud space (RH3)	42%	65%	42%	65%
· interior (RH4)	17%	50%	17%	68%
Condensation Sensor (C1)[3]	0 Volts	0 Volts	0 Volts	0 Volts

Notes:

1. Solar effects during sunny weather can result in readings which are up to 2-3°C higher than the actual exterior temperature.

2. The air space and stud space temperatures were measured by thermocouples 33 and 34, respectively (as shown in Fig. 3) but are listed as DBT2 and DBT3, respectively, in the spreadsheets created by NRCC/IRC when the raw data was transferred to Lotus files.

3. Readings of, or close to, 0 Volts represent dry conditions while readings of, or close to, 2.5 Volts represent wet conditions, indicating that condensation has occurred.

Table 3 Range of Readings at Key Locations, April 6 to 30, 1991

Reading Type	Minimum Hourly Average	Maximum Hourly Average	Absolute Minimum	Absolute Maximum
Surface Temperatures:				
· exterior of brick (10)	-2.3°C	27.7°C	-2.8°C	27.9°C
· interior of brick (9)	-0.8°C	25.1°C	-0.9°C	25.3°C
· ext. of ext. drywall at insulation (8)	2.0°C	25.0°C	1.8°C	25.1°C
· ext. of ext. drywall at stud (11)	6.0°C	24.6°C	5.8°C	24.8°C
· int. of ext. drywall at insulation (18)	2.3°C	24.9°C	2.2°C	25.0°C
· exterior flange of stud (19)	8.7°C	24.2°C	8.6°C	24.3°C
· int. of int. drywall at insulation (22)	16.4°C	23.9°C	16.4°C	24.0°C
· int. of int. drywall at stud (23)	15.3°C	23.6°C	15.3°C	23.7°C
Air Temperatures:				
· exterior (14)[1]	-2.4°C	26.0°C	-2.9°C	26.7°C
· air space (DBT2 or 33[2])	1.0°C	24.3°C	0.8°C	24.4°C
· stud space (DBT3 or 34[2])	10.9°C	23.9°C	10.9°C	24.0°C
· interior (31)	16.2°C	23.8°C	16.2°C	24.0°C
Relative Humidities:				
· exterior (RH1)	10%	93%	9%	93%
· air space (RH2)	84%	99%	71%	100%
· stud space (RH3)	54%	89%	54%	89%
· interior (RH4)	21%	65%	19%	74%
Condensation Sensor (C1)[3]	0 Volts	0 Volts	0 Volts	0 Volts

Notes:

1. Solar effects during sunny weather can result in readings which are up to 2-3°C higher than the actual exterior temperature.

2. The air space and stud space temperatures were measured by thermocouples 33 and 34, respectively (as shown in Fig. 3) but are listed as DBT2 and DBT3, respectively, in the spreadsheets created by NRCC/IRC when the raw data was transferred to Lotus files.

3. Readings of, or close to, 0 Volts represent dry conditions while readings of, or close to, 2.5 Volts represent wet conditions, indicating that condensation has occurred.

Table 4 Range of Readings at Key Locations, July 20 to August 2, 1991

Reading Type	Minimum Hourly Average	Maximum Hourly Average	Absolute Minimum	Absolute Maximum
Surface Temperatures:				
· exterior of brick (10)	15.8°C	42.2°C	15.7°C	42.5°C
· interior of brick (9)	17.6°C	39.1°C	17.3°C	39.2°C
· ext. of ext. drywall at insulation (8)	18.8°C	38.3°C	18.7°C	38.3°C
· ext. of ext. drywall at stud (11)	20.6°C	36.9°C	20.5°C	37.0°C
· int. of ext. drywall at insulation (18)	18.9°C	38.1°C	18.9°C	38.0°C
· exterior flange of stud (19)	21.7°C	35.8°C	21.7°C	35.9°C
· int. of int. drywall at insulation (22)	25.9°C	31.9°C	25.4°C	32.0°C
· int. of int. drywall at stud (23)	25.3°C	32.5°C	25.3°C	32.6°C
Air Temperatures:				
· exterior (14)[1]	14.4°C	38.5°C	14.1°C	39.4°C
· air space (DBT2 or 33[2])	17.9°C	38.2°C	17.7°C	38.2°C
· stud space (DBT3 or 34[2])	22.6°C	34.8°C	22.5°C	34.8°C
· interior (31)	25.9°C	32.3°C	25.4°C	31.8°C
Relative Humidities:				
· exterior (RH1)	19%	93%	16%	93%
· air space (RH2)	39%	68%	38%	69%
· stud space (RH3)	34%	65%	34%	65%
· interior (RH4)	27%	57%	24%	58%
Condensation Sensor (C1)[3]	0 Volts	0 Volts	0 Volts	0 Volts

Notes:

1. Solar effects during sunny weather can result in readings which are up to 2-3°C higher than the actual exterior temperature.

2. The air space and stud space temperatures were measured by thermocouples 33 and 34, respectively (as shown in Fig. 3) but are listed as DBT2 and DBT3, respectively, in the spreadsheets created by NRCC/IRC when the raw data was transferred to Lotus files.

3. Readings of, or close to, 0 Volts represent dry conditions while readings of, or close to, 2.5 Volts represent wet conditions, indicating that condensation has occurred.

Table 5 Range of Readings at Key Locations, November 17 to 30, 1991

Reading Type	Minimum Hourly Average	Maximum Hourly Average	Absolute Minimum	Absolute Maximum
Surface Temperatures:				
· exterior of brick (10)	-5.5°C	16.2°C	-5.7°C	16.5°C
· interior of brick (9)	-3.4°C	15.8°C	-3.6°C	15.9°C
· ext. of ext. drywall at insulation (8)	0.1°C	16.0°C	0.0°C	16.1°C
· ext. of ext. drywall at stud (11)	5.3°C	17.1°C	5.3°C	17.2°C
· int. of ext. drywall at insulation (18)	0.6°C	16.1°C	0.6°C	16.2°C
· exterior flange of stud (19)	8.7°C	17.9°C	8.7°C	17.9°C
· int. of int. drywall at insulation (22)	18.7°C	24.1°C	18.7°C	24.7°C
· int. of int. drywall at stud (23)	17.1°C	22.0°C	17.0°C	22.4°C
Air Temperatures:				
· exterior (14)[1]	-7.0°C	17.7°C	-7.3°C	18.0°C
· air space (DBT2 or 33[2])	-1.0°C	16.1°C	-1.1°C	16.2°C
· stud space (DBT3 or 34[2])	11.7°C	18.7°C	11.7°C	18.8°C
· interior (31)	18.5°C	23.9°C	8.4°C	24.8°C
Relative Humidities:				
· exterior (RH1)	32%	91%	30%	91%
· air space (RH2)	83%	93%	69%	99%
· stud space (RH3)	51%	80%	51%	80%
· interior (RH4)	29%	62%	28%	66%
Condensation Sensor (C1)[3]	0 Volts	0 Volts	0 Volts	0 Volts

Notes:

1. Solar effects during sunny weather can result in readings which are up to 2-3°C higher than the actual exterior temperature.

2. The air space and stud space temperatures were measured by thermocouples 33 and 34, respectively (as shown in Fig. 3) but are listed as DBT2 and DBT3, respectively, in the spreadsheets created by NRCC/IRC when the raw data was transferred to Lotus files.

3. Readings of, or close to, 0 Volts represent dry conditions while readings of, or close to, 2.5 Volts represent wet conditions, indicating that condensation has occurred.

Table 6 Range of Readings at Key Locations, December 6 to 21, 1991

Reading Type	Minimum Hourly Average	Maximum Hourly Average	Absolute Minimum	Absolute Maximum
Surface Temperatures:				
· exterior of brick (10)	-18.5°C	8.9°C	-18.6°C	9.2°C
· interior of brick (9)	-15.5°C	9.2°C	-15.6°C	9.2°C
· ext. of ext. drywall at insulation (8)	-9.5°C	10.4°C	-9.6°C	10.5°C
· ext. of ext. drywall at stud (11)	-2.1°C	13.2°C	-2.2°C	13.3°C
· int. of ext. drywall at insulation (18)	-8.9°C	10.7°C	-8.9°C	10.7°C
· exterior flange of stud (19)	3.2°C	15.1°C	3.1°C	15.2°C
· int. of int. drywall at insulation (22)	17.6°C	23.8°C	17.5°C	24.2°C
· int. of int. drywall at stud (23)	15.8°C	21.8°C	15.8°C	21.9°C
Air Temperatures:				
· exterior (14)[1]	-21.9°C	9.3°C	-22.2°C	9.7°C
· air space (DBT2 or 33[2])	-12.2°C	10.1°C	-12.6°C	10.2°C
· stud space (DBT3 or 34[2])	7.4°C	17.0°C	7.4°C	17.1°C
· interior (31)	17.4°C	23.5°C	17.3°C	24.1°C
Relative Humidities:				
· exterior (RH1)	44%	90%	43%	90%
· air space (RH2)	77%	92%	67%	98%
· stud space (RH3)	37%	71%	37%	71%
· interior (RH4)	25%	51%	24%	66%
Condensation Sensor (C1)[3]	0 Volts	2.5 Volts	0 Volts	2.5 Volts

Notes:

1. Solar effects during sunny weather can result in readings which are up to 2-3°C higher than the actual exterior temperature.

2. The air space and stud space temperatures were measured by thermocouples 33 and 34, respectively (as shown in Fig. 3) but are listed as DBT2 and DBT3, respectively, in the spreadsheets created by NRCC/IRC when the raw data was transferred to Lotus files.

3. Readings of, or close to, 0 Volts represent dry conditions while readings of, or close to, 2.5 Volts represent wet conditions, indicating that condensation has occurred.

Table 7 Range of Readings at Key Locations, January 4 to 18, 1992

Reading Type	Minimum Hourly Average	Maximum Hourly Average	Absolute Minimum	Absolute Maximum
Surface Temperatures:				
· exterior of brick (10)	-25.0°C	5.2°C	-25.1°C	5.6°C
· interior of brick (9)	-21.8°C	5.5°C	-12.9°C	5.6°C
· ext. of ext. drywall at insulation (8)	-14.4°C	7.2°C	-14.5°C	7.3°C
· ext. of ext. drywall at stud (11)	-6.5°C	10.7°C	-6.6°C	10.7°C
· int. of ext. drywall at insulation (18)	-13.6°C	7.5°C	-13.7°C	7.5°C
· exterior flange of stud (19)	-0.2°C	12.9°C	-0.2°C	12.9°C
· int. of int. drywall at insulation (22)	16.0°C	23.3°C	15.9°C	23.5°C
· int. of int. drywall at stud (23)	13.4°C	21.0°C	13.2°C	21.0°C
Air Temperatures:				
· exterior (14)[1]	-29.2°C	4.3°C	-29.6°C	4.6°C
· air space (DBT2 or 33[2])	-18.1°C	6.7°C	-18.3°C	6.8°C
· stud space (DBT3 or 34[2])	4.3°C	15.0°C	4.3°C	15.1°C
· interior (31)	15.9°C	23.3°C	15.8°C	23.4°C
Relative Humidities:				
· exterior (RH1)	39%	88%	38%	89%
· air space (RH2)	71%	91%	66%	97%
· stud space (RH3)	35%	68%	33%	69%
· interior (RH4)	21%	56%	20%	62%
Condensation Sensor (C1)[3]	2.3 Volts	2.4 Volts	2.3 Volts	2.4 Volts

Notes:

1. Solar effects during sunny weather can result in readings which are up to 2-3°C higher than the actual exterior temperature.

2. The air space and stud space temperatures were measured by thermocouples 33 and 34, respectively (as shown in Fig. 3) but are listed as DBT2 and DBT3, respectively, in the spreadsheets created by NRCC/IRC when the raw data was transferred to Lotus files.

3. Readings of, or close to, 0 Volts represent dry conditions while readings of, or close to, 2.5 Volts represent wet conditions, indicating that condensation has occurred.

Table 8 Surface Temperatures at Stud and Insulation, January 16, 1992, 7:00 - 8:00 A.M.

Reading Type	Sensor Reading
· exterior air temperature (14)	-29.2°C
· interior air temperature (31)	19.8°C
· exterior of exterior drywall at insulation (8)	-14.2°C
· exterior of exterior drywall at stud (11)	-6.3°C
· interior of exterior drywall at insulation (18)	-13.4°C
· exterior flange of stud (19)	0.0°C
· interior of interior drywall at insulation (22)	19.8°C
· interior of interior drywall at stud (23)	16.7°C

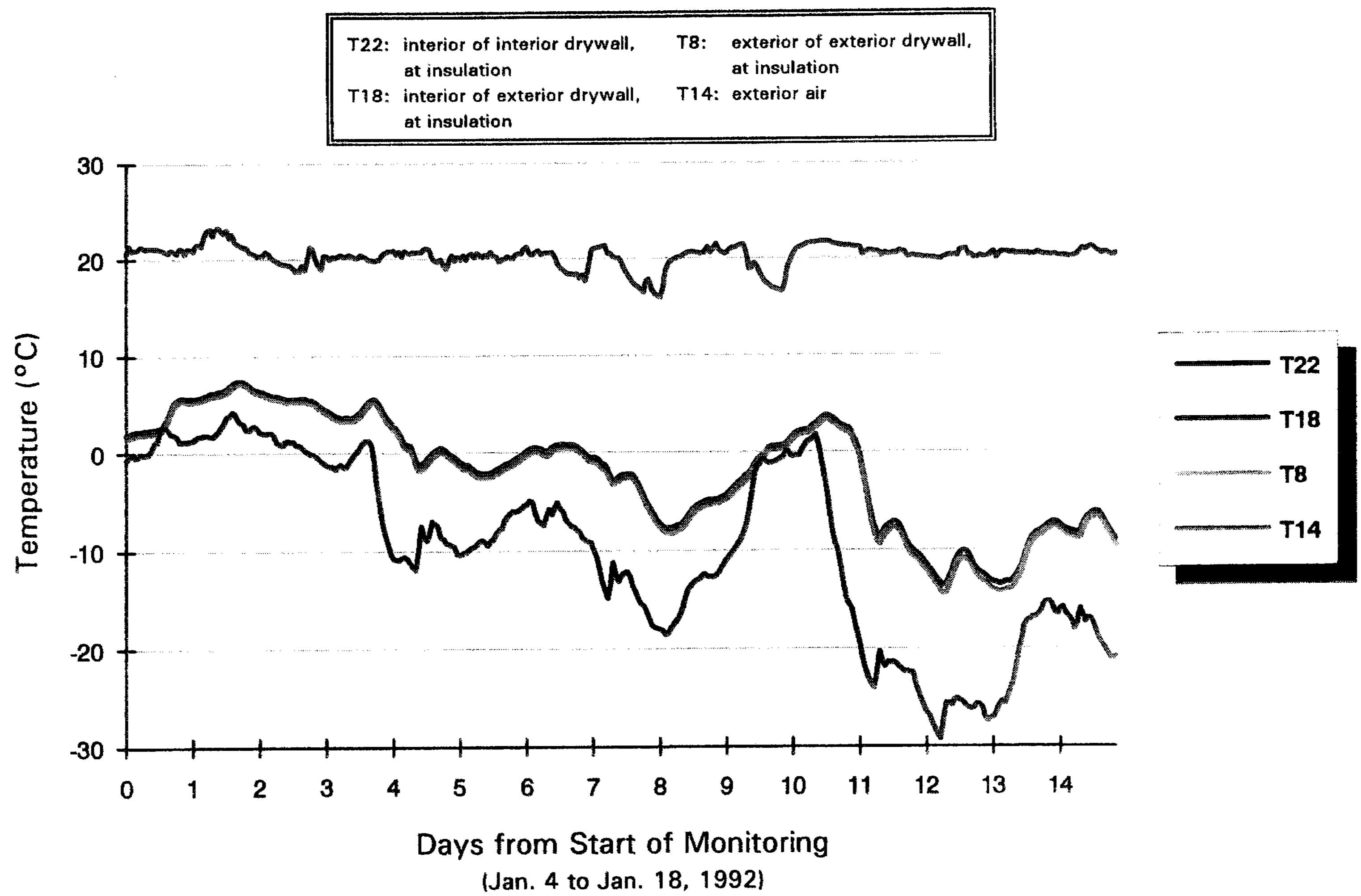


Fig. 7 Temperature Profile Across Test Wall at Insulation

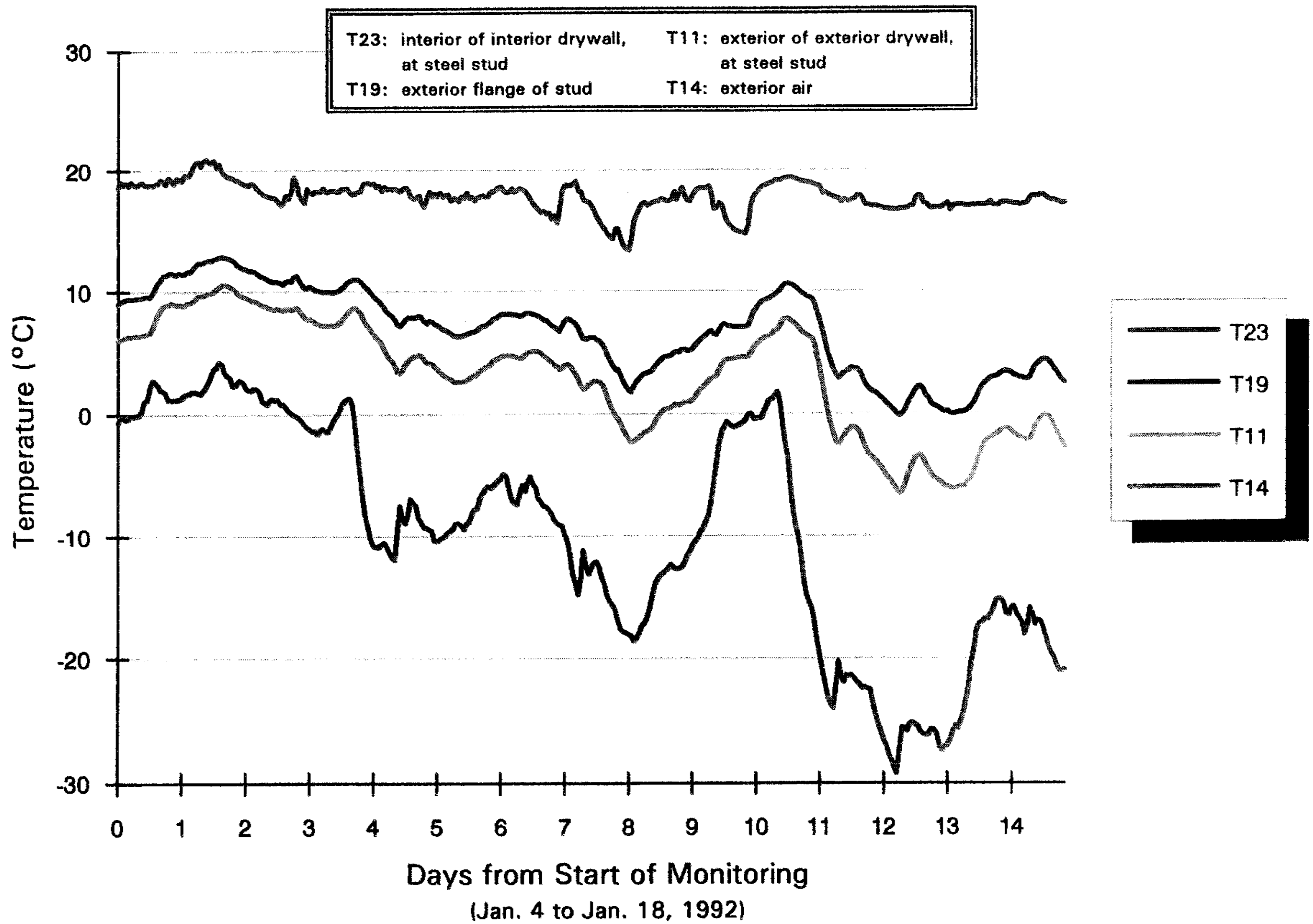


Fig. 8 Temperature Profile Across Test Wall at Steel Stud

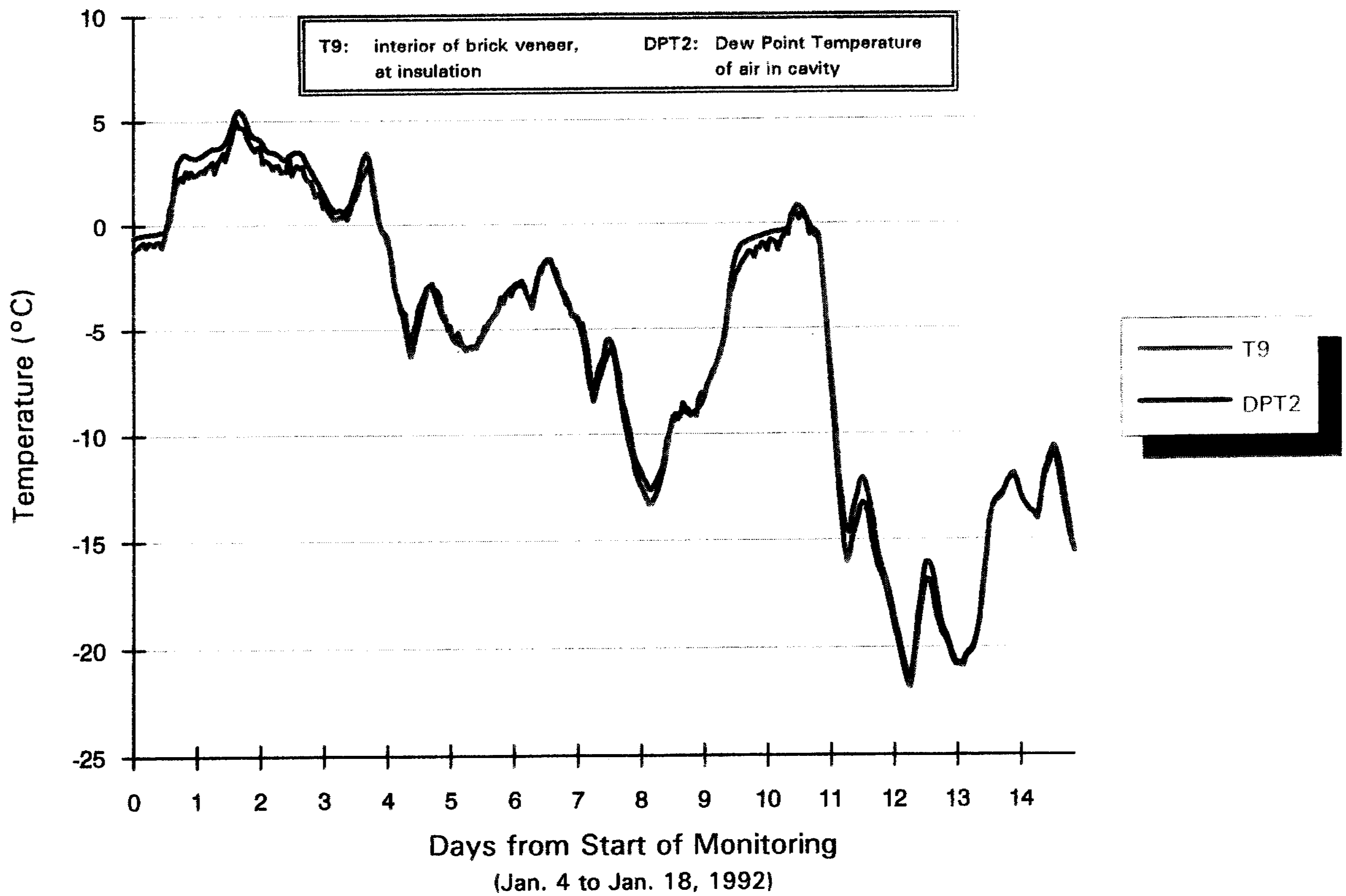


Fig. 9 Comparison of Surface Temperature on Interior Face of Brick Veneer to Dew Point Temperature of Cavity Air

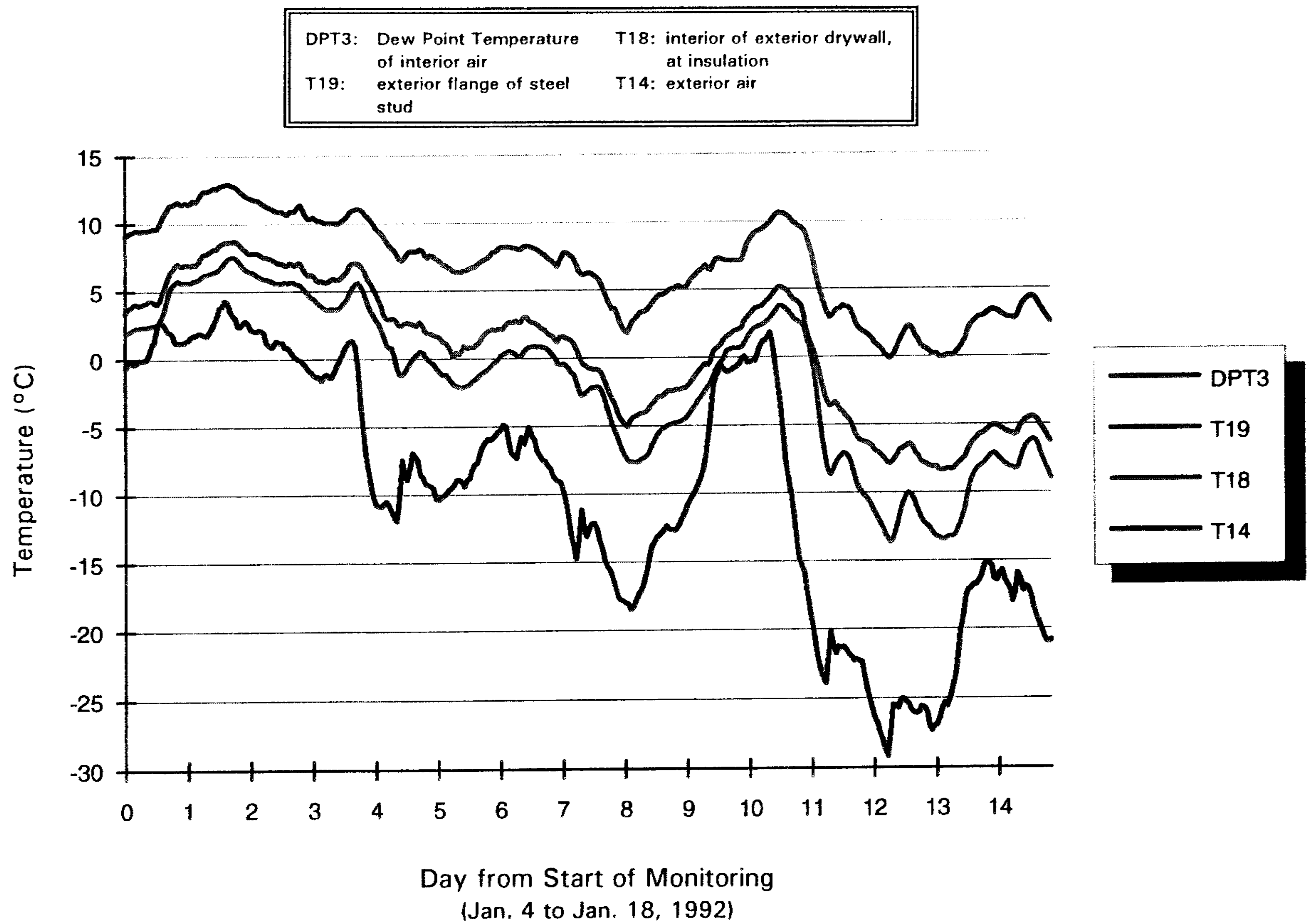


Fig. 10 Comparison of Surface Temperatures at the Exterior Drywall to the Dew Point temperature of the Air in the Stud Space

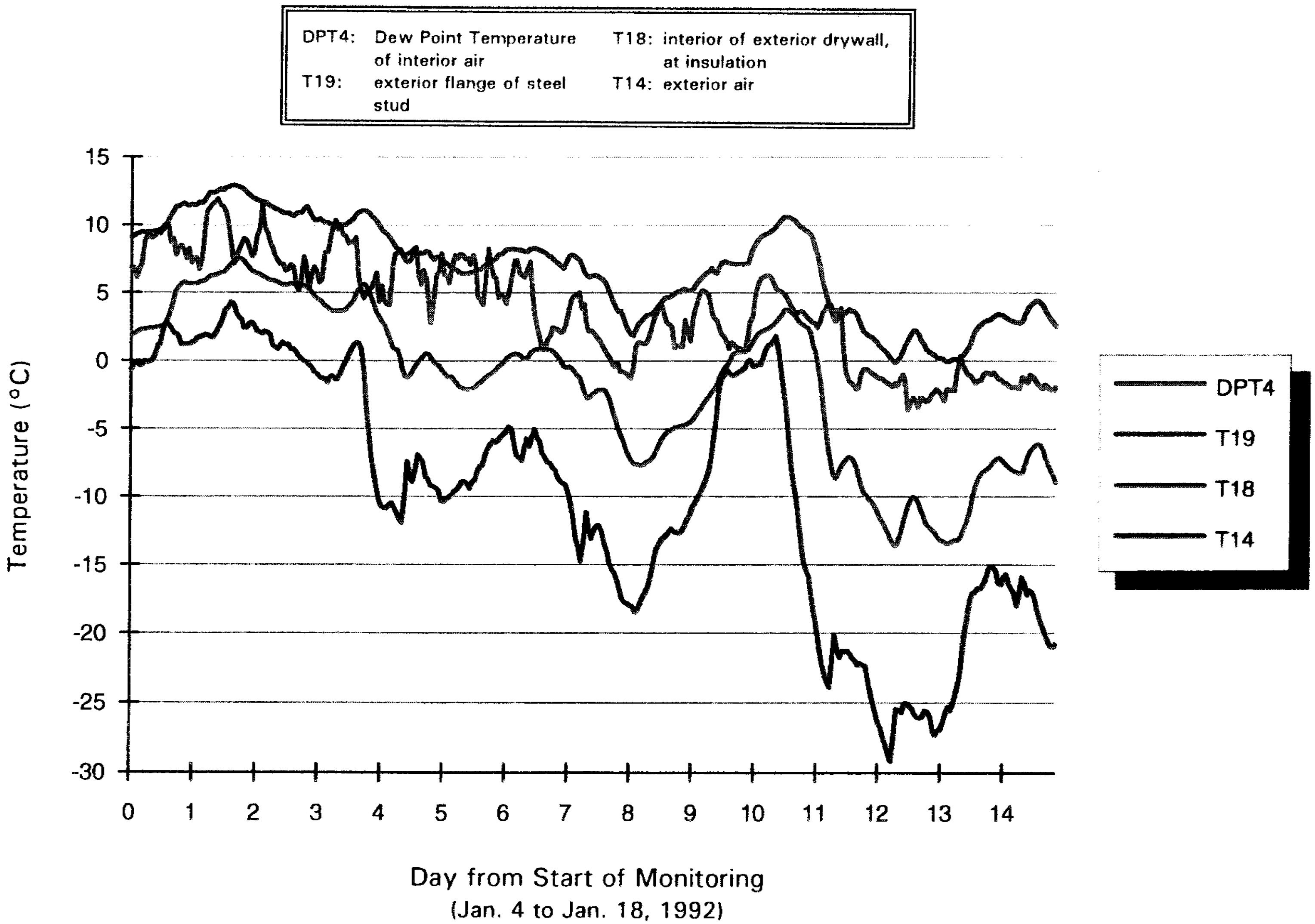


Fig. 11 Comparison of Surface Temperatures at the Exterior Drywall to the Dew Point temperature of the Interior Air

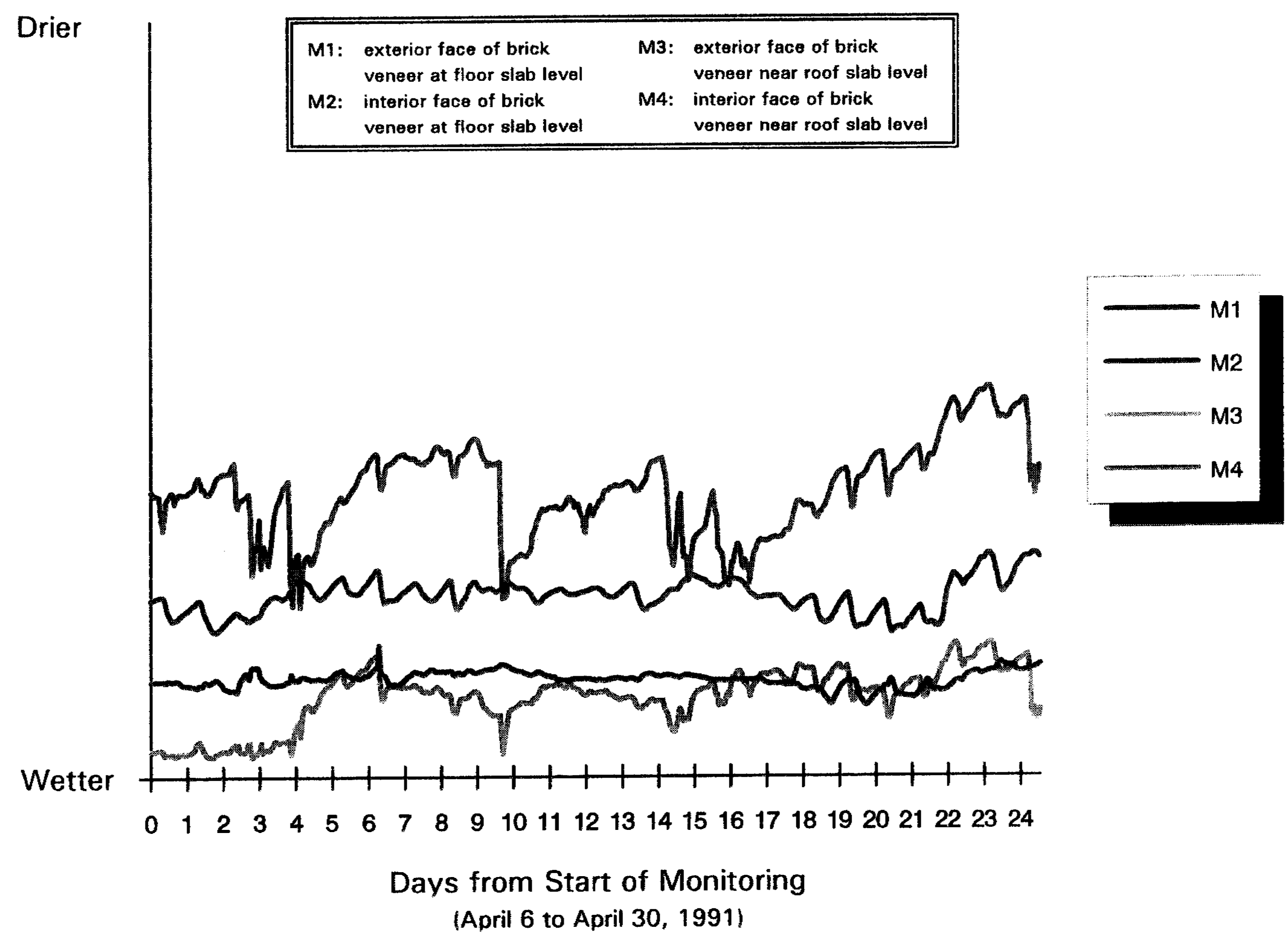


Fig. 12 Comparison of Wetness Levels at Different Monitoring Points on the Brick Veneer

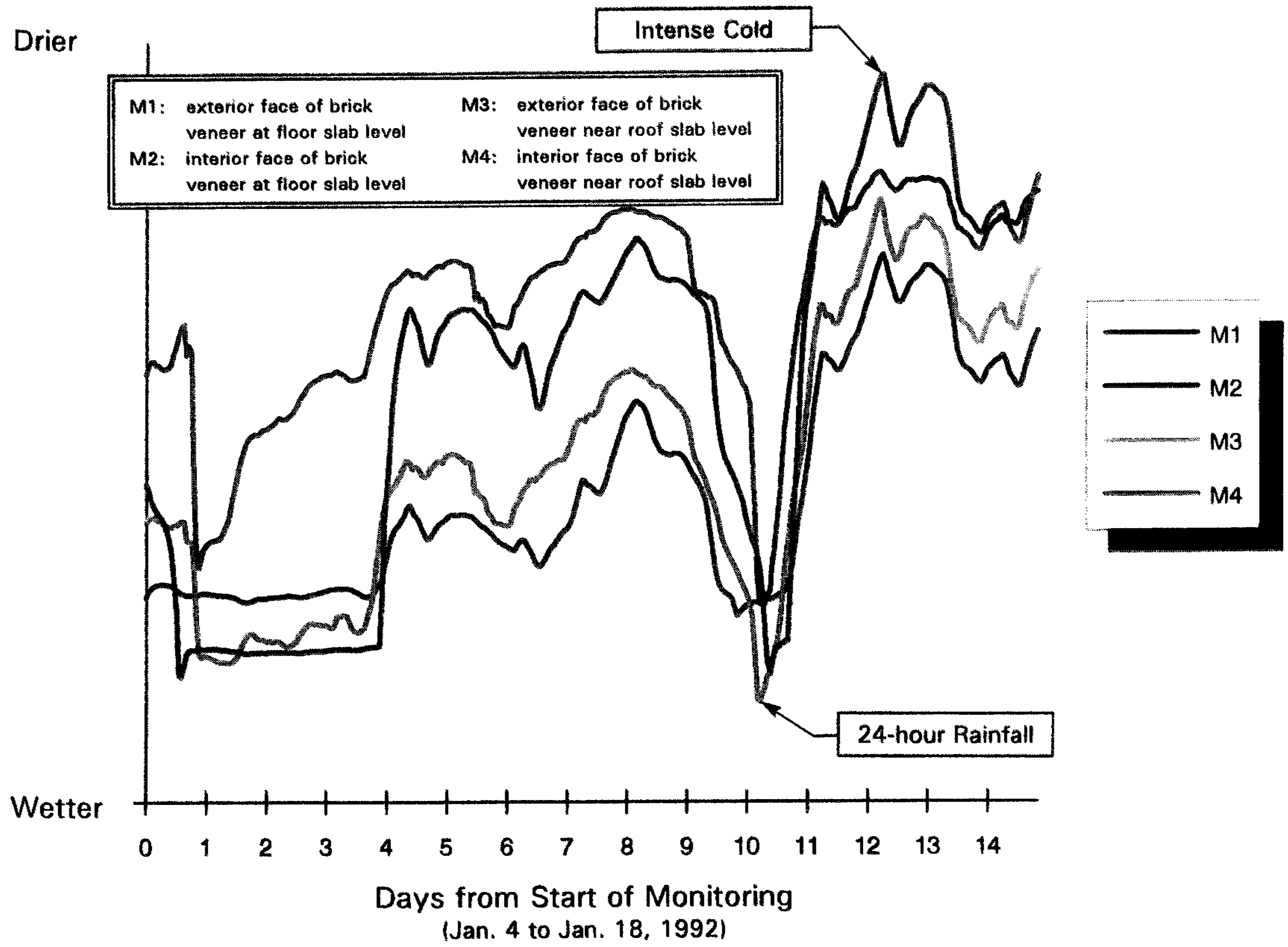


Fig. 13 Comparison of Wetness Levels at Different Monitoring Points on the Brick Veneer

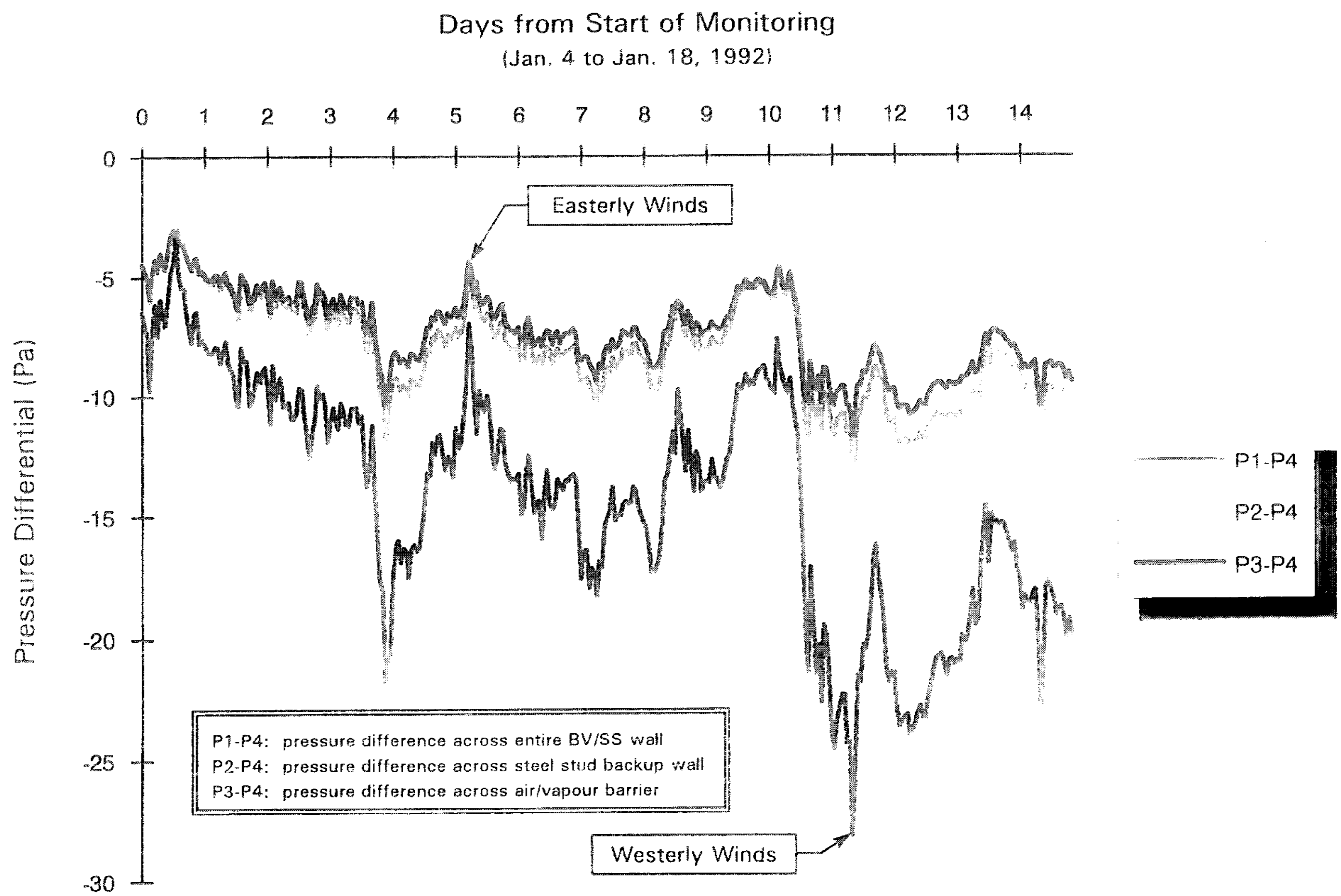


Fig. 14 Hourly Average Pressure Differentials Across Test Wall

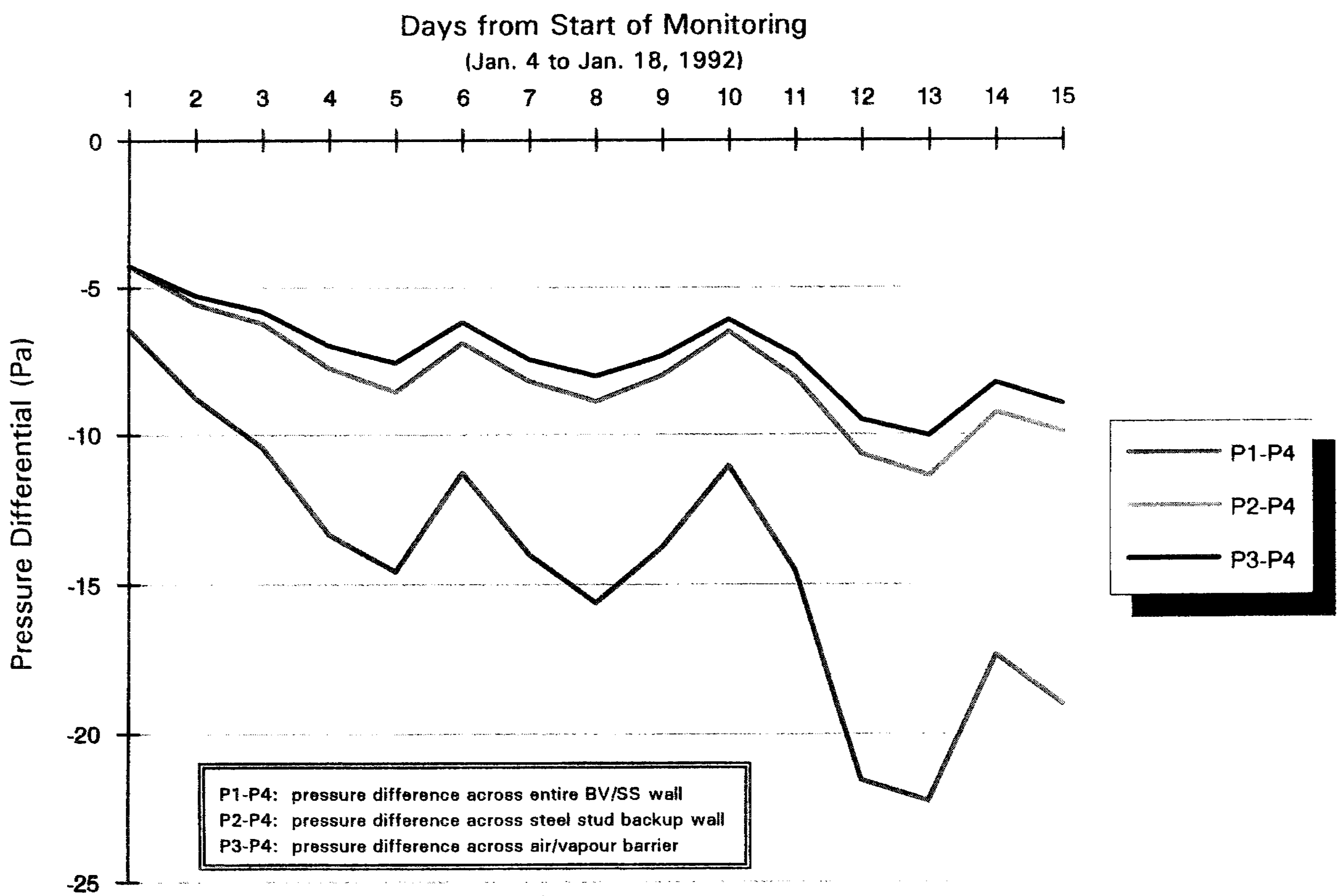


Fig. 15 Daily Average Pressure Differentials Across Test Wall