PERFORMANCE MONITORING OF A BRICK VENEER/STEEL STUD WALL SYSTEM

- PHASE 2 RESULTS -

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ÉTUDE DE PERFORMANCE D'UN SYSTÈME DE MURS À OSSATURE D'ACIER RECOUVERTE D'UN PLACAGE DE BRIQUE RÉSULTATS DE LA PHASE 2

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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 preceded 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).

Phase 2 of this study by KEA involved a second year (1992/93) of in-situ performance monitoring of a BV/SS wall system, with respect to 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. In addition, inspection openings were made in the test wall after the 1992/93 monitoring work was completed, in order to verify the results of the data analysis. Even though the BV/SS wall system is typical of current practices and workmanship was satisfactory, the results of the study demonstrate that performance problems exist that may lead to significant distress over the long term. The more serious performance problems identified in this study 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.

This publication is one of the many items of information published by the CMHC with the assistance of federal funds.

DISCLAIMER

EXECUTIVE SUMMARY

The brick veneer/steel stud (BV/SS) wall system has become very popular in Canada over the last twenty years, however, the construction of BV/SS walls has preceded the development of adequate design and construction standards. In order to address concerns about the longterm safety, serviceability and durability of BV/SS wall systems, Canada Mortgage and Housing Corporation (CMHC) has undertaken a program to evaluate BV/SS wall systems. This program has included many studies into design, construction and performance of BV/SS wall systems.

As part of the CMHC evaluation program, Keller Engineering Associates Inc. (KEA) carried out in-situ performance monitoring of a BV/SS wall system. The performance monitoring focused on building science issues such as temperature gradients, moisture movements through the BV/SS wall, and pressure differences across the wall system. This report outlines the findings of the second year of performance monitoring.

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. 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 installed across the test wall consisted of various temperature, moisture and air pressure sensors which were connected to a computer based, automatic data logging system. For Phase 2 of this study, the test wall was monitored periodically between November 1992 and August 1993, with the monitoring periods being two to four weeks in length. Six monitoring periods were selected which would represent typical 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, air pressure and moisture.

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 results of the 1992/93 monitoring work were very similar to those found in 1991/92. In March 1994, inspection openings were made in the test wall in order that conditions across the test wall could be documented and compared to the findings of the data analysis. The inspection openings revealed that the results of the data analysis accurately predicted the wall conditions.

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 occurred 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.

In terms of acting as a rain screen, an analysis of the measured air pressure differences across the test wall indicates that the BV/SS wall system generally performs in a satisfactory manner. However, the test wall did not perform 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. In a fully pressure equalized wall, it is desired to have the backup wall alone resist wind loads. Secondly, air leakage occurs through the air/vapour barrier system even though workmanship generally appeared satisfactory. While air leakage appears relatively minor, it is enough to allow a significant amount of moist interior air to penetrate into the backup wall, as well as causing a reduction in the thermal efficiency of the wall system under wind conditions.

An important finding of the 1991/92 monitoring program, with respect to moisture, was that the cavity was unable to dry out because there was more condensation occurring due to a faulty air barrier than could be removed from natural convection movement of air through weep holes. Furthermore, the back face of the brick veneer stays wet throughout the winter season when many freeze/thaw cycles occur. In addition, minor condensation regularly occurs on the interior surface of the exterior sheathing. Due to the above conditions, building distress problems may occur over the long term.

In summary, the brick veneer/steel stud test wall was constructed in accordance with the design drawings and it meets today's standards, however, the wall system is not performing in a satisfactory manner. Moisture trapped within the cavity and in the brick veneer may lead to serious distress problems over the long term. Thermal bridging at the studs also reduces the performance of the wall. The observed performance problems are mainly due to an ineffective air/vapour barrier system, inadequate cavity venting and a lack of exterior insulation. Design weaknesses are causing the performance problems that exist, even though the wall design is of typical construction.

This monitoring program has further illustrated the need for improved design and construction standards; the BV/SS wall system under study likely represents "typical" construction, but the wall system may experience significant distress problems over the long term.

RÉSUMÉ

Au cours des vingt dernières années, les murs à ossature d'acier recouverte d'un placage de brique (OA-PBr) ont acquis une grande popularité au Canada. Cependant, on a commencé à construire ce genre de mur avant même d'avoir mis au point des méthodes et des normes de construction appropriées. C'est dans ce contexte que la Société canadienne d'hypothèques et de logement (SCHL) a entrepris un programme d'évaluation des murs OA-PBr dans le but de donner suite aux préoccupations que ces murs soulèvent en matière de sécurité, de tenue en service et de durabilité à long terme. Ce programme a donné lieu à de nombreuses études qui ont porté sur la conception, la construction et la performance des murs OA-PBr.

Dans le cadre du programme d'évaluation de la SCHL, la firme Keller Engineering Associates Inc. (KEA) a étudié la tenue en service d'un mur OA-PBr. Les chercheurs s'intéressaient à des questions de science du bâtiment comme les gradients de température, les mouvements d'humidité à travers le mur OA-PBr et les différences de pression le caractérisant. Le présent rapport fait état des résultats de la seconde année de l'étude de performance.

Le bâtiment choisi est un immeuble résidentiel de sept étages situé dans la région d'Ottawa-Hull. Afin d'évaluer les pires conditions d'humidité et de différence de pression, les chercheurs ont choisi un mur donnant sur l'est et situé au dernier étage de l'immeuble.

Sur le seul mur étudié, les chercheurs ont installé des capteurs de température, d'humidité et de pression d'air qu'ils ont raccordés à un système informatisé d'enregistrement automatique de données. Pour la phase 2 de cette étude, le mur a été contrôlé de façon périodique entre les mois de novembre 1992 et d'août 1993, les périodes de contrôle variant de deux à quatre semaines. Les chercheurs ont choisi six périodes de contrôle représentatives des conditions climatiques typiques que peut connaître la région d'Ottawa-Hull au cours d'une année. Les données recueillies ont été analysées afin d'évaluer la tenue en service du mur d'essai et les résultats sont commentés dans le présent rapport dans les sections traitant de la température, de la pression d'air et de l'humidité.

Même si plusieurs aspects de la conception ne sont pas conformes aux règles de l'art, le mur OA-PBr mis à l'essai est relativement bien conçu par rapport aux ouvrages actuels. Ainsi, les résultats de l'étude de performance de 1992-1993 sont très similaires à ceux obtenus en 1991-1992. En mars 1994, des ouvertures d'inspection ont été ménagées dans le mur d'essai afin de documenter l'état du mur et de le comparer avec les résultats de l'analyse des données. Les ouvertures d'inspection ont révélé que l'analyse des données permettait de prédire l'état du mur de façon précise.

Les résultats du programme de contrôle montrent qu'on peut généralement s'attendre à une bonne performance thermique des murs à ossature d'acier recouverte d'un placage de brique. Cela dit, il faut mentionner que des ponts thermiques importants surviennent au niveau des poteaux d'acier du mur d'essai à cause du manque d'isolation extérieure. Ce phénomène est courant pour les murs à ossature d'acier dépourvus d'isolation extérieure.

Pour ce qui est de son rôle d'écran pare-pluie, la mesure des différences de pression d'air du mur d'essai indique que le mur OA-PBr se comporte généralement de manière satisfaisante. Toutefois, le mur d'essai a déçu en termes de performance. D'abord, l'équilibrage de la pression n'est pas tout à fait efficace, ce qui fait que le placage de brique et l'ossature en poteaux d'acier résistent ensemble aux charges dues au vent. Or, dans un mur à pression entièrement équilibrée, il faut que l'ossature seule offre une résistance à ces charges. En outre, les chercheurs ont observé des fuites d'air dans le pare-air/pare-vapeur malgré le fait que la qualité d'exécution semblait généralement satisfaisante. Quoique relativement mineures, à prime abord, ces fuites sont suffisantes pour permettre le passage d'une quantité importante d'air intérieur humide dans l'ossature, provoquant ainsi une diminution de l'efficacité thermique de l'ensemble du mur lorsqu'il vente.

En 1991-1992, le programme de contrôle avait permis de faire une découverte importante au sujet de l'humidité. En effet, la cavité ne pouvait pas sécher parce que le mouvement d'air naturel, par convection à travers les chantepleures, ne venait pas à bout de la condensation anormalement élevée qui se formait à cause d'un pare-air déficient. Qui plus est, la face intérieure du placage de brique restait mouillée tout l'hiver et devait subir de nombreux cycles de gel et de dégel. De plus, une légère condensation se produisait régulièrement sur la surface intérieure du revêtement extérieur. Dans ces conditions, ce bâtiment est sans aucun doute voué à présenter des problèmes à long terme.

En résumé, le mur d'essai OA-PBr a été construit conformément au plan d'étude et répond aux normes actuelles, mais il n'offre pas la performance escomptée. À longue échéance, l'humidité emprisonnée dans la cavité et le placage de brique pourrait entraîner de graves problèmes. Les ponts thermiques qui se forment au niveau des poteaux d'ossature diminuent aussi la performance du mur. Les problèmes de performance observés sont surtout le fait de l'inefficacité du pare-air/pare-vapeur, d'une mauvaise aération de la cavité et de l'absence d'isolation extérieure. Ces faiblesses conceptuelles entraînent des problèmes de performance en dépit du fait que le mur a été construit selon les normes.

Le programme de contrôle confirme la nécessité d'améliorer les normes de conception et de construction puisque le mur OA-PBr à l'étude, représentatif de ce genre d'ouvrage, risque de présenter d'importantes déficiences à long terme.

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- PHASE 2 RESULTS -

1. INTRODUCTION

The brick veneer/steel stud (BV/SS) wall system has become widely utilized over the past 20 years, however, the construction of BV/SS walls has preceded the development of adequate design and construction standards. This situation has led to concerns in the construction industry about 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 walls. For several years, Keller Engineering Associates Inc. (KEA) has been involved in various studies, including an industry survey[1], a Canada-wide survey of buildings[2], laboratory research[3], the preparation of an Advisory Document[4], and the performance monitoring of a typical BV/SS wall system in service[5]. This report outlines the findings of the second year of performance monitoring.

The key objective of this project was to monitor and evaluate the in-situ performance of a newly constructed BV/SS wall system with regards to air and moisture movements as well as temperature gradients. The BV/SS test wall was first evaluated during 1991/92 and the findings were outlined in a report dated June 4, 1993. The current report discusses the Phase 2 results of the study, including the findings from the 1992/93 performance monitoring and the March 1994 inspection openings. It is hoped that this project will continue for years to come in order that longterm performance data may be collected regarding the in-situ performance of the BV/SS test wall.

The design and construction of the BV/SS wall system was evaluated as part of the 1991/92 monitoring program. It was found that the BV/SS wall system was generally well designed, according to current standards, but the design did not reflect best practices. In addition, construction review indicated that workmanship was generally satisfactory. Therefore, the test wall monitored likely represents an average situation as design and construction were according to typical current practices.

2. INSTRUMENTATION AND PERFORMANCE MONITORING

2.1 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 driven rains tend to be from an easterly direction, and therefore, east facing walls are more severely wetted by precipitation. Due to stack effect, outward wind pressures are typically most severe at the upper floor level of a building. Accordingly, air exfiltration through the exterior wall system is typically most severe on the top floor of a building. Also, winds during the winter tend to be westerly in the Ottawa area. Accordingly, air leakage due to suction pressures will most frequently occur on the east elevation of a building. Since air exfiltration is the principal manner in which water vapour is transferred into the exterior wall during winter, condensation is more likely to occur in east facing walls on the upper floor levels.

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 for monitoring. This wall provides the worst combination of precipitation and air exfiltration. The selected test wall was instrumented with sensors that measure the driving potentials that affect the wall's performance with respect to temperature gradient, moisture migration and air pressure differences.

2.2 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 that the test location was not immediately adjacent to columns or corners, which could affect the data recorded. Sensors in the brick veneer were installed during the brick laying process.

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.

2.2.1 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.

Surface temperature thermocouples were also installed on a triangular wire brick tie at the stud location, 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.

2.2.2 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 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. The thermocouples placed within the stud space and air space described above were located at the RH sensor location.

At the time that the second phase of data collection began, the RH sensors had been in service within the test wall for nearly two years, yet these sensors should be re-calibrated every year. Since the sensors could not be re-calibrated at the start-up of the 1992/93 monitoring, it was expected that loss of calibration would occur. As such, it was decided that the sensors would be retrieved at the end of the 1992/93 monitoring phase and recalibrated in order that the data collected by the RH sensors during this period could be "corrected" to account for the loss of calibration. In March 1994, the sensors were retrieved from the test wall and re-calibrated while new sensors were installed within the test wall. (Replacing the RH sensors was only done for convenience as this approach enabled calibrated sensors to be installed immediately after removing the original RH sensors and the original sensors were then recalibrated at a later date). Corrected data was produced in June 1994 and preliminary analyses made using the actual data collected were adjusted to account for the corrected relative humidity data. The need to recalibrate the RH sensors also provided an excellent opportunity to visually examine the test wall and document its condition at inspection openings. The findings from the inspection openings are discussed in Section 4.

In addition to water vapour being monitored using RH sensors, the presence of liquid water was monitored using electrical resistance moisture sensors. 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. During the 1991/92 monitoring period, a condensation sensor was also installed in the test wall, on the interior of the exterior gypsum board slightly above the mid-height of the wall. This sensor was installed to detect any condensation that may occur at this location. However, the condensation sensor was not used in the analysis of the 1992/93 data as it was significantly off calibration, thereby providing unreliable results. The condensation sensor was replaced in March 1994 when the RH sensors were replaced.

2.2.3 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 differences between the interior air and the air at other positions across the wall were recorded. Therefore, measurements were obtained for:

- pressure difference between interior air and exterior air (P1-P4)
- pressure difference between interior air and the air within the cavity (P2-P4)
- pressure difference 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 weather data was used for wind speeds and directions, precipitation occurrences and sunshine information.

2.3 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 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 an 8½-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 did not allow for continuous monitoring over the 8½-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 accumulation in the wall, the test wall was monitored during the following periods:

1. November 28 - December 25, 1992
2. January 16 - 29, 1993
3. February 20 - March 19, 1993
4. April 3 - 19, 1993
5. May 1 - 14, 1993
6. July 24 - August 6, 1993.

Raw data recorded by the data acquisition system was transferred into spreadsheet files (using Excel 4.0) so that the data could be evaluated.

3. EVALUATION OF DATA

While data pertaining to all sensors were recorded during six different time periods over the 8½ months of periodic monitoring, evaluating the performance of the test wall pertaining to each particular criteria 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 difference and brick wetness data were most relevant, the data within each of the files was examined to identify specific events and trends which were useful for detailed evaluations.

The findings outlined in the June 1993 report are summarized in Section 3.1 while the evaluation of data collected during 1992/93 is described in subsequent sections. While all findings of the data analysis are discussed in Sections 3.2 to 3.4, only a limited number of graphs are included in Appendix B. These figures merely represent sample graphs which illustrate key findings as extensive data analysis was carried out involving all sets of data collected. In general, the findings relating to the 1992/93 data are very similar to the findings obtained from analyzing the 1991/92 data.

3.1 Summary of 1991/92 Findings

The results of the first year of monitoring demonstrated that good thermal performance can generally be expected from brick veneer/steel stud walls. However, significant thermal bridging occurred at the steel studs of the test wall, due to the absence of exterior insulation. This thermal bridging is typical of any steel stud backup wall without exterior insulation.

An analysis of the air pressure differences across the test wall over the different monitoring periods indicated that the air/vapour barrier system of the test wall generally performed in a satisfactory manner, although marginally so. Firstly, pressure equalization was not fully effective, and therefore, both the brick veneer and the steel stud backup wall resisted wind loads whereas it is desired to have the backup wall alone resist wind loads. Secondly, minor air leakage occurred through the air/vapour barrier even though workmanship appeared satisfactory. While air leakage through the air/vapour barrier appeared relatively minor, air leakage was enough to allow a significant amount of moist interior air into the backup wall, as well as causing a noticeable reduction in the thermal efficiency of the wall system under wind conditions.

An important finding of the 1991/92 monitoring program, with respect to moisture, was that the cavity was unable to dry out because there was more condensation occurring due to a faulty air barrier than could be removed from natural convection movement of air through weep holes. (The brick veneer contains only weep holes, there are no vents at the top of each floor level). As a result of this situation, condensation regularly occurred on the back face of the brick veneer during temperatures of about 5°C or lower. In addition, condensation occurred on the brick ties and the exterior surface of the exterior gypsum board sheathing. Experience has shown that condensation on the back face of the brick veneer may lead to back spalling of the brick units due to freeze/thaw action. In addition, condensation within the cavity can lead to corrosion and eventual failure of the brick ties. Therefore, the air leakage and the lack of adequate cavity venting at the test building, similar to many buildings already in existence, will likely result in a reduced service life of the BV/SS wall system. However, to date there is insufficient data available to predict more accurately what the service life expectancy will be given these unfavourable conditions. In addition, minor condensation regularly occurred on the interior surface of the exterior sheathing. This condition could also be detrimental to the long term performance of the wall system, by way of reduced thermal effectiveness of the insulation due to wetting, or deterioration of the exterior gypsum board and building paper such that water penetration problems develop.

3.2 Temperature

The thermal performance of the test wall was evaluated primarily by using data recorded during the period of January 16 to 29, 1993. Exterior air temperatures dropped to only about -20°C during this period, 10°C higher than the coldest temperatures typically experienced during the winter in the Ottawa-Hull area. However, -20°C was still sufficiently cold that to properly evaluate the thermal performance of the test wall.

Fig. 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.

In comparing the data presented in Figs. 7 and 8, it is noted that the temperature at the exterior surface of the sheathing is an average of 5°C warmer at the steel stud than at the insulation. Thermal bridging also causes the interior surface of the interior gypsum board to be typically about 2.5°C colder at the steel stud than at the insulation. Occasionally, the surface temperature of the interior drywall is up to 3.5°C colder at the stud than at the insulation. Thermal bridging of this magnitude can cause dusting of the drywall at the stud locations. As discussed in Section 4, severe dusting was, in fact, observed during the visual observations made in March 1994.

The thermal profiles presented in the June 1993 report, using January 1992 data, were very similar to those illustrated in Figs. 7 and 8. Furthermore, a detailed analysis of January 1992 and January 1993 data indicate that the thermal performance of the wall has not changed over the one-year period between data sets.

It was observed that the measured thermal profile of the backup wall often differed significantly from the theoretical thermal profile. In-situ conditions such as wind pressure, air leakage through the wall system, wet masonry and the sun shining on the brick veneer cause the test wall to behave differently from the manner assumed in a theoretical calculation of the temperature profile, which uses steady-state conditions. 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.

Fig. 9 illustrates the difference between the actual and theoretical temperatures at the exterior of the exterior sheathing (T8) and at the interior face of the brick veneer (T9). The surface temperature on the interior of the interior drywall at the insulation (T22) and the exterior air temperature (T14) are also plotted. To plot Fig. 9, the theoretical values of sheathing and brick temperatures (Th T8 and Th T9, respectively) were calculated as shown below:

$$t_x = t_i - (R_x/R_t)(t_i - t_o)$$

where:

t_x = the temperature at any point in the wall (in this case, Th T8 or Th T9)
t_i = indoor air temperature
t_o = outdoor air temperature
R_x = thermal resistance from exterior air to any point in the wall at which the temperature is to be determined
R_t = overall thermal resistance of the wall, from interior air to exterior air

The theoretical and actual values of T8 and T9 differ by as much as 14°C and 10°C, respectively. Such large differences are uncommon; the difference between actual and theoretical values of T8 and T9 is usually less than 7°C and 5°C, respectively.

In order to determine if the thermal performance of the wall is affected by wind forces, all readings for the pressure difference across the test wall, P1-P4, were plotted against the corresponding values of the "Temperature Index", T_i, of the backup wall. The actual Temperature Index of the backup wall was calculated for each hourly set of readings using the actual data and the formula T_i = (T31-T8)/(T31-T14), where T31 is the interior air temperature. P1-P4 readings ranged between about -3 Pa and -22 Pa while T_i ranged between about 0.55 and 1.05. While the plot indicated that there may be a relationship between P1-P4 and T_i, the plot did not provide sufficient evidence to draw such a conclusion (as such the plot is not included in this report). To evaluate the trends more closely, it was decided to plot the mean (and median) P1-P4 readings that resulted in various values of T_i, as shown in Fig. 10.

To provide a better understanding of what Fig. 10 represents, the steps involved in making this graph are outlined below:

1. The Temperature Index values were broken down into nine small groups of readings ranging from 0.55 - 0.60, 0.60 - 0.65, etc. up to 1.00 - 1.05.

2. Each set of P1-P4 and T_i data was then reviewed and sorted into one of the nine data groups according to the T_i reading. For example, all P1-P4 readings for wind events that produced a T_i reading of 0.55 to 0.60 were grouped together.

3. Next, the mean and median of all P1-P4 readings within a group were calculated for each of the nine data groups.

4. The mean and median values of P1-P4 for each data group was then plotted against the T_i readings, using the mid-point of each range as the X-axis value for the T_i readings. That is, $T_i = 0.575$ is the X-axis value for the 0.55 to 0.60 range. Therefore, the mean and median values for P1-P4 of about -18 Pa were plotted against the T_i value of 0.575 (shown as 0.58 on Fig. 10).

5. In order to test the statistical reliability of the above plot, the standard deviation of the P1-P4 readings was also evaluated to ensure that the relationship demonstrated in the graph was not a random occurrence.

An evaluation of the temperature data indicates that warm air exfiltration under high pressure differences across the test wall is the key reason that the actual and theoretical temperature profiles differ. This finding is also illustrated in Fig. 10 as this plot illustrates that, in general, as suction pressures increase due to high winds, the Temperature Index of the backup wall is reduced. Note that at lower pressure differences, i.e. P1-P4 $\approx$ -10 Pa, the actual Temperature Index of the backup wall is about 0.8 to 1.0, which is a range that straddles the theoretical value of the Temperature Index of about 0.9. It should be noted that the apparent deterioration of the thermal performance of the wall is not due to the brick veneer being "short-circuited" by wind blowing more air into the cavity. Air movement behind the cavity is usually minimal and, in fact, warm interior air that leaks into the cavity is often trapped in the cavity, causing the cavity air to be much warmer than the exterior air.

3.3 Air Pressure

For this monitoring program, the air pressures at the exterior, the air space, the stud space and at the interior are denoted P1, P2, P3 and P4, respectively. Given these notations, the upper floor test wall would be considered to be performing well if the data recorded meets the following criteria (assuming windows are closed such that wind does not blow directly into the building and the mechanical systems cause building pressurization):

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.

2. P2-P4 and P3-P4 should be virtually equal (i.e. P2-P3 ≈ 0) since the exterior sheathing should not act as an air barrier that causes a pressure difference across the sheathing. (Moisture exfiltration from the interior must be able to freely migrate past the exterior sheathing.)

3. P3-P4 should be significant (as should be P2-P4 if P2-P3 ≈ 0) as this indicates 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 effective pressure equalization between the cavity air and the exterior air and if the air barrier does not leak significantly. 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, the air barrier allows air leakage and/or that the cavity is not effectively vented or compartmented.

5. The thermal performance of the insulated stud wall should 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.

High pressure differences across the test wall were experienced most frequently during the first three monitoring periods but the January 16 - 29 pressure data best illustrates the typical trends that occur (Fig. 11 and Fig. 12). Therefore, this data set provided the most useful information regarding air pressure differences. Figs. 11 and 12 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. 11 illustrates the hourly average pressure differences while Fig. 12 illustrates the daily average pressure differences.

The hourly average of P1-P4 varied between about 6.0 and 21.5 Pa during the monitoring period while the daily average of P1-P4 varied between about 8.0 and 16.5 Pa. This data demonstrates that, as expected, the wall system is effective at isolating the exterior air from the interior air. Note that smaller values for P1-P4 are generally recorded when P1 increases due to the test wall being exposed to winds from the easterly direction. (eg. Day 7 of Figs. 11 and 12).

Note that the pressure difference is still negative (i.e. outwards, as viewed from a structural engineering application) during mild easterly winds, due to building pressurization and stack effect. However, strong easterly winds sometimes cause positive pressure differences. The positive pressure differences on Days 13 and 14 of Fig. 13 (March 4 and 5, 1993) are due to easterly winds in the 30 to 50 km/h range. Similarly, high values of P1-P4 occur when strong winds occur from a direction that causes high suction pressures at the test wall. For example, negative pressure differences greater than 30 Pa occurred in the early morning of March 14, 1993 (Day 23 of Fig. 13) during northerly winds of about 40 km/h.

An evaluation of the data indicates that Criteria 2 and 3 above are met by the test wall and, therefore, 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 difference 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.

The data of February 1991 to January 1992 indicates small values for P2-P3 but there is generally a distinct difference between P2-P4 and P3-P4. During that 1991/92 monitoring period, the exterior sheathing typically accounted for about 5% of the total pressure difference across the test wall. It is interesting to note that the 1992/93 data generally shows that P2-P3 $\approx$ 0, indicating no pressure difference across the exterior sheathing. This finding may indicate that, while the exterior sheathing never acted as an air barrier, air more easily moves past the exterior sheathing now than it did when the building was first completed. It is possible that the easier movement of air past the exterior sheathing is a result of additional minor gaps opening up between sheets of exterior sheathing. These additional gaps would likely be due to normal building movements.

As was found from the 1991/92 data, Figs. 11 and 13 illustrate that there is a simultaneous increase in pressure on the exterior and within the cavity, indicating that pressure equalization does occur to some degree. However, the graphs also illustrate that when wind speeds and wind directions change, there is a greater change in P1-P4 than in P2-P4. Since the changes in the pressure difference between the interior and exterior air tend to be greater than changes in the pressure difference between the cavity air and the interior air, pressure equalization is not fully effective. Therefore, this data also indicates that a certain portion of the wind load is carried by the brick veneer rather than solely by the steel stud backup wall.

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. The existence of air leakage through the air/vapour barrier system was discussed earlier in the report and is illustrated by Fig. 10, which shows that the thermal performance of the backup wall is reduced, due to air leakage, under high pressure differences across the test wall.

3.4 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, the effects of water vapour are best evaluated using data collected during colder weather. Liquid water from exterior sources is a concern only if its presence becomes detrimental to the brick veneer/steel stud wall. Such cases include rain water that penetrates the brick veneer, bridges the cavity and wets the backup wall. Also, water which penetrates the cavity but cannot escape due to poor venting will result in larger amounts of water vapour being trapped and increased condensation on building elements within the cavity. Therefore, the presence of liquid water within the cavity is best evaluated using spring and fall data, when wind driven rains are more frequent and when freezing or condensation of trapped moisture can occur as well. It is also useful to examine summer data related to moisture conditions to determine if other seasonal moisture accumulations are able to dissipate.

The wetness of the brick surface at monitoring points M1, M2, M3, M4, M5 and M6 is shown in Figs. 14, 15 and 16 for the first, fourth and sixth 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 observed when the brick becomes wetter. 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 reviewing the graphs.

This point is illustrated in Fig. 14 as the readings indicate very wet conditions at M2, M3 and M4 for the first six days until readings suddenly increase. These increased readings occurred simply because the weather became much colder on Day 7 and the moisture in the brick froze. An example of drastic changes in readings that does reflect wetness levels is shown in Fig. 16, where the brick became much wetter on Day 6 due to rainfall.

While the moisture sensor data indicates the wetness levels, the source of this wetness is determined by evaluating weather data as well as the data recorded that provides information regarding the occurrence of condensation with the test wall. Comparing wetness levels to weather data is straightforward since increases in wetness are simply correlated with the occurrence of precipitation, wind speeds and directions, or even sunny weather. To evaluate how condensation may be affecting wetness levels, the dew point temperature in the cavity and the stud space is plotted against surface temperatures of building elements in contact with the cavity or stud space air.

Fig. 17 is a plot of the dew point temperature of the cavity air (DPT2) versus the temperature of the interior surface of the brick veneer (T9). As shown in Fig. 17, cavity moisture was continuously condensing on the back face of the brick veneer during the period of January 16 - 29, 1993. Fig. 18 illustrates the dew point temperature within the backup wall as compared to the surface temperature on the exterior sheathing and on the exterior flange of the steel stud. The data plotted in Fig. 18 indicates that, on the interior of the exterior gypsum board, condensation does not occur at the steel stud but minor condensation may occasionally occur on the gypsum board. While "corrected" data was used for these plots, it is important to note that a properly calibrated RH sensor is only accurate to within 2% RH and, therefore, even the "corrected" data may not be precise. Therefore, plots of relative humidity or dew point temperature data must be compared to moisture sensor data to determine how frequently condensation is occurring at a given location.

For all six monitoring periods, the moisture sensor readings were compared to the weather data and plots such as Figs. 17 and 18, and this review provided the following findings:

1. The exterior of the brick veneer at the floor slab level (M1) was generally fairly dry during November to May and M1 was generally very dry in summer, although frequent wetting occurs.

2. The exterior of the brick veneer at the roof level (M3) was very wet during November to May but M3 was generally dry in the summer.

3. The back face of the brick veneer at the floor slab level (M2) and at the roof level (M4) were very wet during November to May although M2 and M4 were dry in the summer, particularly M4.

4. The moisture sensor at the bottom of the cavity (M5) generally indicated somewhat damp conditions during November to April although wet conditions were experienced occasionally during this period. M5 was dry in the summer.

5. The moisture sensor within the backup wall (M6) generally indicated somewhat damp to dry conditions during November to March but M6 was dry during the spring and summer.

6. Water vapour levels within the cavity were very high in comparison to exterior water vapour levels, except during the summer. The high water vapour content not only caused condensation to occur regularly, but drying of the back face of the brick veneer could not occur until late spring.

7. The primary source of moisture in the cavity air is the leakage of moist interior air into the cavity.

8. At temperatures of approximately 5°C or lower, condensation occurred on the back face of the brick veneer, on the exterior surface of the exterior sheathing and on brick ties.

9. Condensation frequently occurred on the interior surface of the exterior drywall at temperatures of approximately 0°C or lower.

10. The brick veneer was usually wetted by precipitation to a significant degree if the wind direction was towards the test wall.

11. Throughout the monitoring program, precipitation was the main source of moisture on the exterior of the brick veneer (M1 and M3).

12. It appears that precipitation penetrating through the brick veneer and condensation of moist cavity air on the brick veneer both contribute to the moisture on the interior face of the brick veneer (M2 and M4). Condensation is not a factor during warm weather but condensation may be the primary factor during cold weather.

13. The only source of water within the backup wall was the condensation of exfiltrating interior air within the wall. There was no evidence of water penetration into the backup wall.

14. Since there was no water leakage into the wall and the back face of the brick veneer was significantly wetter than Sensor M5 at the bottom of the cavity, the brick veneer acts as an effective rain screen, even though pressure equalization is not fully effective.

The above findings indicate that serious building performance problems may occur over the long term. The regular occurrence of condensation on brick ties could lead to the premature corrosion and the eventual failure of the ties. The continuous wet conditions on the back face of the brick veneer during freezing conditions is a serious concern. The freeze/thaw action that occurs throughout the colder months could cause backspalling of the brick veneer, a condition which could lead to unexpected failure of the brick veneer even though the exterior face of the brick veneer may show little or no distress. Even if a failure does not occur, it is possible that expensive masonry repairs will be required long before the building reaches the end of its intended service life. Condensation within the steel stud backup wall is a concern due to the longterm potential for corrosion to the point where it is no longer structurally sound. In addition, frequent wetting of the exterior gypsum board may cause the sheathing to deteriorate such that it can no longer resist water penetration to the interior, especially since the building paper is also deteriorating prematurely. Another consequence of condensation within the backup wall is that the thermal resistance of the glass fibre insulation could be significantly reduced by wetting of the insulation.

4. INSPECTION OPENINGS

4.1 Description of Openings

On March 8, 1994, two inspection openings were made in the test wall. The primary purpose of making openings in the test wall was to replace the original RH sensors and the condensation sensor with ones that were properly calibrated. However, the need to make openings in the wall presented an opportunity to visually document the conditions across the test wall and to compare these conditions with the findings of the data analysis. The two inspection openings were made as follows:

1. The first opening in the interior drywall was three stud spaces (1.2 m) wide and was located in the middle of the test wall. The opening started 1.2 m from the floor and the opening was 0.6 m in height. The location of the opening was specifically selected to allow for replacement of the RH sensors and the condensation sensor. At this opening, a small opening was also made in the exterior gypsum board in order that the condition of the building paper and the brick veneer could be examined.

2. The second opening was made at the floor level in order that the condition of the bottom track could be documented. The opening was located in line with the centre of the first opening and it was 0.4 m high by 0.6 m wide.

Upon documenting wall conditions and replacing the sensors, the test wall was carefully repaired in order that opening the wall does not have detrimental effects on the condition of the wall.

4.2 Observations Made at Inspection Openings

On the day that the inspection openings were made, the exterior air temperature ranged from approximately -3°C overnight and early morning up to approximately 2°C during the late afternoon. Except for a small amount of snow (0.2 cm) that fell during the late morning, there was no precipitation.

Prior to making the inspection openings, it was observed that severe dusting was occurring on the interior surface of the drywall at the stud locations, due to thermal bridging through the studs. In fact, dusting at the stud locations was so severe that even the location of the drywall screws was evident.

Observations made at the inspection openings are as follows:

1. The brick veneer did not have frost on its inside surface and the masonry appeared to be fairly dry.

2. The building paper and exterior gypsum board were very wet. Mildew covered much of the interior surface of the exposed exterior gypsum board at the lower inspection opening. Mildew was generally minor at the upper opening, except that there was a significant amount of mildew at a joint between adjacent sheets of gypsum board.

3. The exterior surface of the glass fibre insulation was generally damp, with a small portion of insulation at the lower inspection opening being very wet. The exterior of the insulation was stuck to the exterior gypsum board at both openings.

4. A cut in the polyethylene vapour barrier was observed at the lower inspection opening. An attempt had been made during construction to repair the vapour barrier with another small piece of polyethylene crudely sealed around the cut using acoustical sealant. The repair attempt was unsuccessful as significant dusting (indicating air leakage) was observed on the insulation at the cut in the vapour barrier.

5. The copper sensor element of the condensation sensor had oxidized significantly due to frequent exposure to condensation, rendering the sensor ineffective. This observation explained the unreliable readings obtained from this sensor during 1992/93. Note that the head of the screw holding the sensor in place was corroded, further indicating the presence of moisture.

6. A gasket had been used on the electrical outlet beside the lower opening but significant dusting, due to air leakage through the outlet, was still observed on the cover plate.

7. Minor corrosion was observed on the tip of one exterior, corrosion-resistant drywall screw. Very minor corrosion was observed on the screws for the stud wall and brick ties as well as on the edge of the C-channel portion of the brick tie.

8. The steel studs, lateral bracing and bottom track were in good condition although the bottom track was suffering minor oxidation. (The top track was not observed). Metal shavings observed in the bottom track were corroded, indicating that moisture was present in the bottom track on various occasions.

4.3 Findings of Inspection Openings

Based on the observations made at the inspection openings, it appears that condensation frequently occurs within the insulated stud wall assembly, particularly at the exterior gypsum board. The visual observations confirmed the findings of the data analysis that minor air leakage was occurring through the air/vapour barrier. This air leakage occurs even though the air barrier (interior drywall) appeared to be in generally good condition, the vapour barrier was sealed at the bottom track and the electrical outlet is sealed to the vapour barrier, including the use of a gasket at the outlet. While evidence of air leakage through a defect in the vapour barrier was observed, dusting on the cover plate for the outlet was the only obvious sign of air leakage past the drywall.

While the use of galvanized products in the construction of the stud wall has so far kept the stud wall in good condition, the glass fibre insulation and exterior gypsum board are being wetted to an unacceptable degree. Since minor oxidation of the bottom track has occurred, it is possible that moisture formation within the stud wall will lead to deterioration of the bottom track over the long term.

No conclusive visual evidence was obtained to prove that condensation regularly occurs within the cavity, on the back face of the brick veneer or on the building paper. However, based on the condition of the building paper and the exterior gypsum board, it appears that condensation within the cavity is a significant contributing factor to the deterioration of these elements. Since visual observations indicate that condensation regularly occurs within the cavity on the exterior surface of the backup wall, then this finding implies that condensation also occurs regularly on the back face of the brick veneer, since the temperature of both cavity surfaces is typically similar and both surfaces are exposed to the same moisture conditions.

5. CONCLUSIONS

The findings outlined in the preceding sections indicate that the brick veneer/steel stud test wall is performing in an unsatisfactory manner since moisture and temperature conditions are not properly controlled. The key performance problems are air leakage through the air/vapour barrier system, a lack of exterior insulation, and poor venting of the cavity. Compartmentation of the cavity would have improved pressure equalization in the cavity. The performance problems that exist may cause significant building distress problems over the long term. The findings emphasize the need for improved standards since buildings constructed according to current standards generally do not perform in a satisfactory manner. As reported in the June 1993 report, the BV/SS wall system would have performed better if a tight air barrier, exterior insulation, a wider cavity and compartmentation were used.

6. RECOMMENDATIONS

Given the poor performance of this BV/SS wall system, it is recommended that this monitoring program be extended over several more years so that additional data may be obtained. Ideally, this program should be ongoing for many years so that the performance of the brick veneer/steel stud wall system may be evaluated over the long term. The information obtained through this monitoring program will be invaluable to designers, investigators and building owners as it clearly shows the potential vulnerability of the BV/SS wall system to workmanship defects, and thus, the potential for accelerated deterioration.

Since the deterioration primarily occurs within the wall system such that major distress problems could remain concealed until failure occurs, it is strongly recommended that periodic inspections of BV/SS wall systems, including inspection openings, be mandatory.

It is further recommended that the test wall be repaired to the extent possible to evaluate how well the wall performs when it is improved. As a minimum, the air barrier should be improved.

Finally, and as an extension of the above comments, it is recommended that performance monitoring work, similar to this program, be carried out on other buildings. Some buildings monitored should have typical BV/SS construction and other buildings should have BV/SS construction carried out in accordance with best practices. In this manner, further valuable knowledge will be gained about the in-situ performance of brick veneer/steel stud wall systems in different climatic regions.

References

(1) "Brick Veneer/Steel Stud Design and Construction Practices in Canada, Results of a 1986 Survey", Report submitted to and published by CMHC, Ottawa, 1987. The report was also part of a Canada-wide seminar series, entitled "Seminar on Brick Veneer Wall Systems", that occurred in 1989.

(2) "Field Investigation of Brick Veneer/Steel Stud Wall Systems", Report submitted to and published by CMHC, Ottawa, 1989. The report was also part of a Canada-wide seminar series, entitled "Seminar on Brick Veneer Wall Systems", that occurred in 1989.

(3) Various laboratory research projects for which reports were submitted to CMHC.

(4) "Exterior Wall Construction in High-Rise Buildings, Brick Veneer on Concrete Masonry or Steel Stud Wall Systems", Advisory Document submitted to CMHC in 1989 and published by CMHC in 1991. The Advisory Document was also part of a Canada-wide seminar series, entitled "Seminar on Brick Veneer Wall Systems", that occurred in 1989.

(5) "Performance Monitoring of a Brick Veneer/Steel Stud Wall System", Report submitted to CMHC, Ottawa, 1993.

APPENDIX A: 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

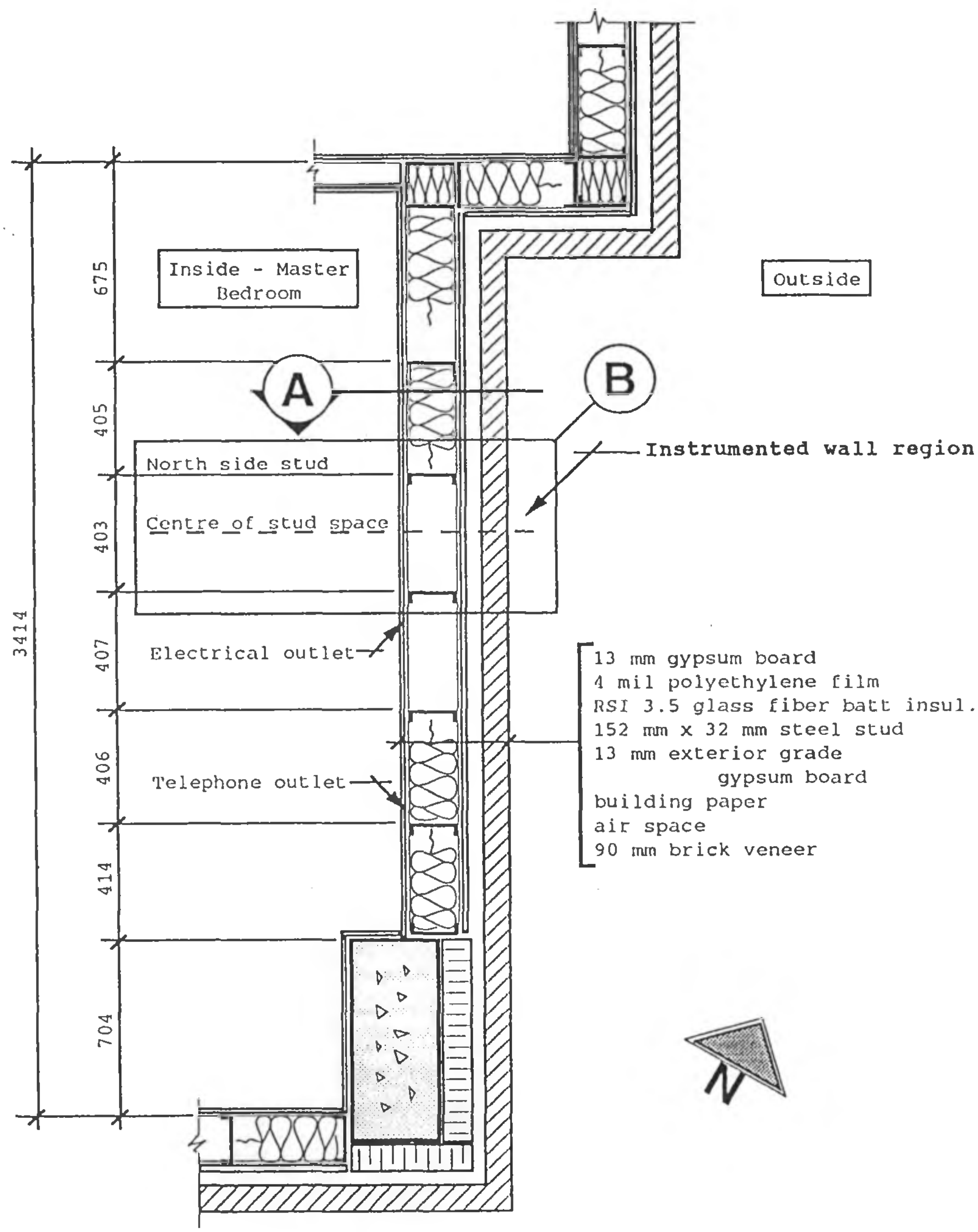


Fig. 1 Plan View of Test Wall

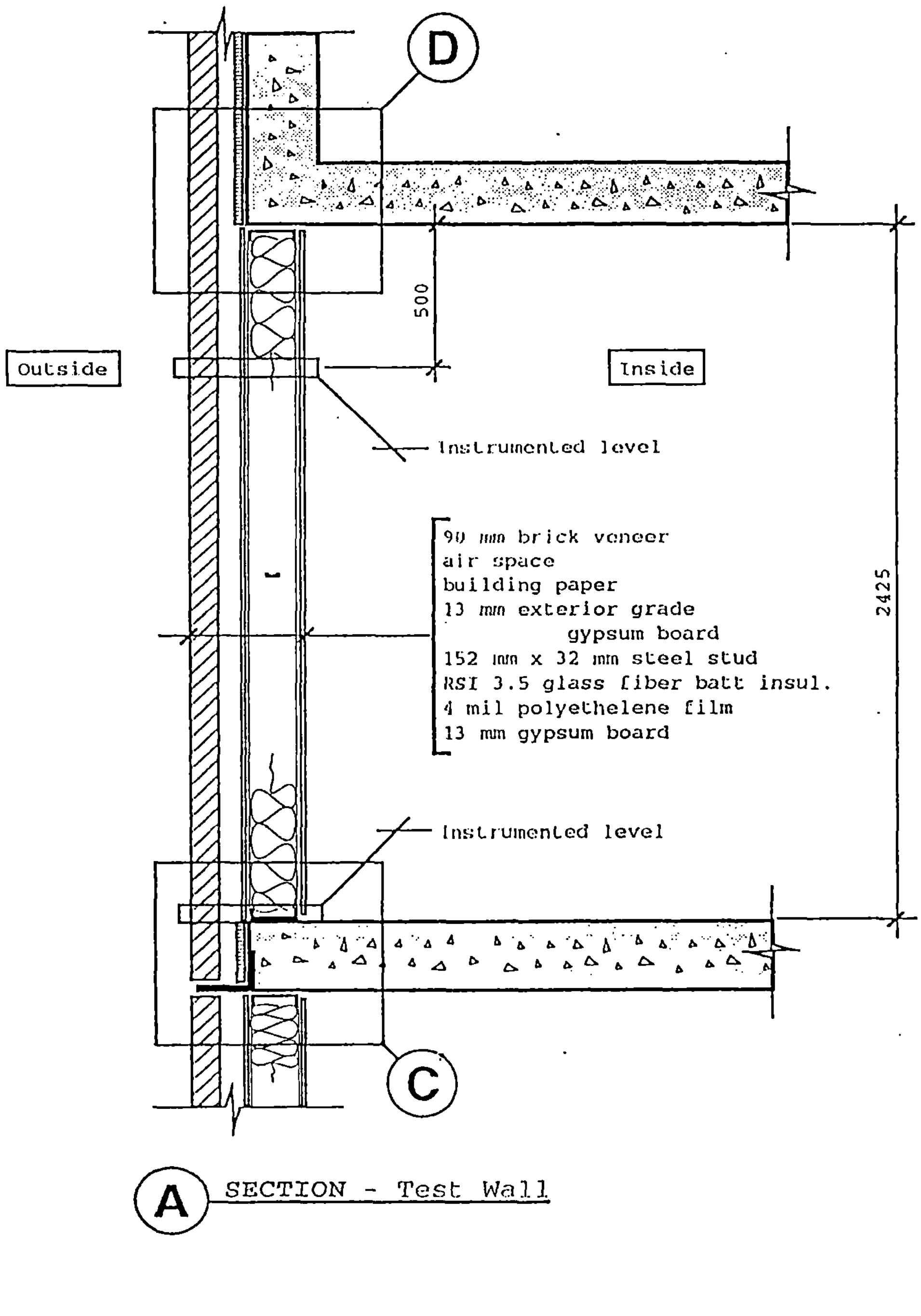
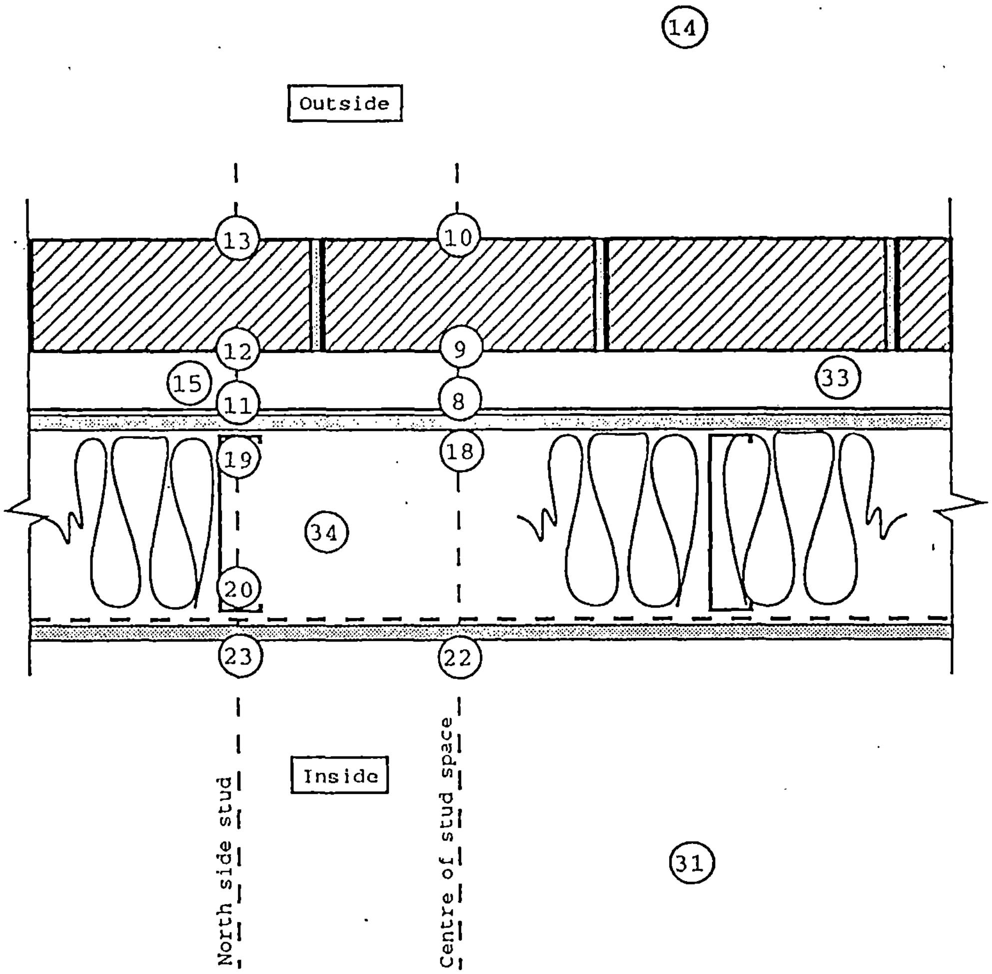


Fig. 2 Cross-section Through Test Wall



B TEST WALL DETAIL

○ 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

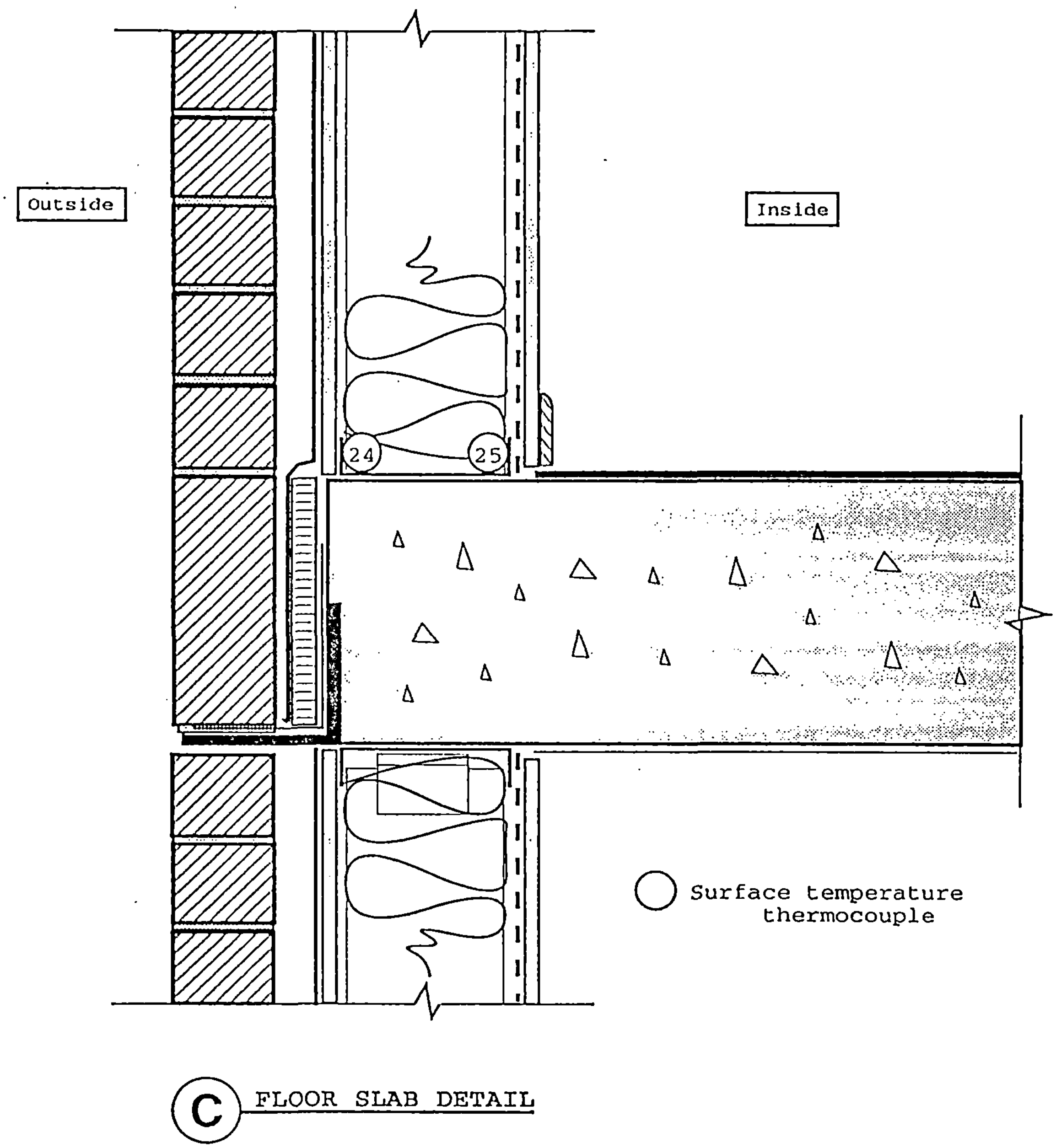
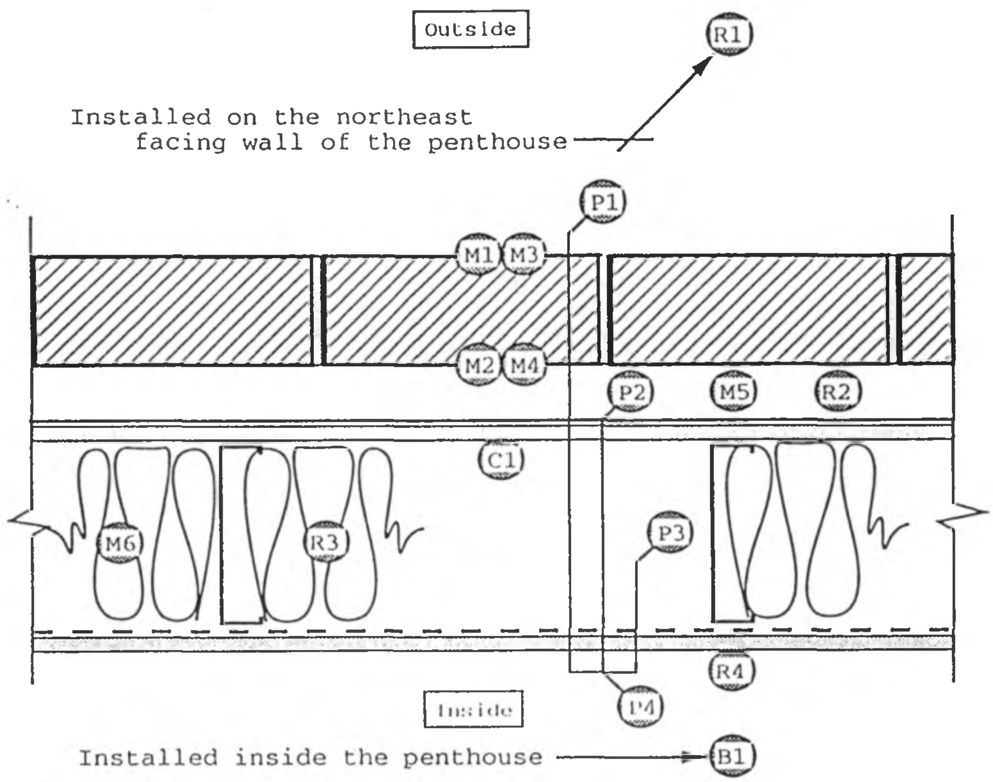


Fig. 4 Location of Thermocouples at Floor Slab Level



B TEST WALL DETAIL

(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 B: Data Tables and Sample Graphs

Table 2 Range of Readings at Key Locations, November 28 to December 26, 1992

Reading Type	Minimum Hourly Average	Maximum Hourly Average	Absolute Minimum	Absolute Maximum
Surface Temperatures:				
· exterior of brick (10)	-14.4°C	7.0°C	-14.4°C	7.3°C
· interior of brick (9)	-12.0°C	7.1°C	-12.0°C	7.2°C
· ext. of ext. drywall at insulation (8)	-7.2°C	8.5°C	-7.3°C	8.5°C
· ext. of ext. drywall at stud (11)	-0.6°C	11.4°C	-0.7°C	11.4°C
· int. of ext. drywall at insulation (18)	-6.6°C	8.7°C	-6.7°C	8.7°C
· exterior flange of stud (19)	4.1°C	13.3°C	4.1°C	13.3°C
· int. of int. drywall at insulation (22)	20.1°C	23.6°C	19.7°C	23.9°C
· int. of int. drywall at stud (23)	17.6°C	21.4°C	17.3°C	21.7°C
Air Temperatures:				
· exterior (14)[1]	-17.0°C	8.5°C	17.6°C	9.0°C
· air space (DBT2 or 33[2])	-9.0°C	8.0°C	-9.3°C	8.1°C
· stud space (DBT3 or 34[2])	7.7°C	15.4°C	7.6°C	15.4°C
· interior (31)	19.7°C	23.6°C	19.3°C	24.0°C
Relative Humidities:				
· exterior (RH1)	10%	89%	10%	96%
· air space (RH2)	81%	94%	70%	103%
· stud space (RH3)	40%	70%	40%	70%
· interior (RH4)	27%	57%	27%	66%
Condensation Sensor (C1)[3]	0 .8 Volts	1.5 Volts	0 .7 Volts	1.5 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 were listed under the headings of DBT2 and DBT3, respectively, by NRCC/IRC when the raw data was transferred to spreadsheet 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. Note that the condensation sensor was not functioning properly during the 1992/93 monitoring program.

Table 3 Range of Readings at Key Locations, January 16 to 29, 1993

Reading Type	Minimum Hourly Average	Maximum Hourly Average	Absolute Minimum	Absolute Maximum
Surface Temperatures:				
· exterior of brick (10)	-16.2°C	5.0°C	-16.3°C	5.2°C
· interior of brick (9)	-13.2°C	5.5°C	-13.5°C	5.6°C
· ext. of ext. drywall at insulation (8)	-7.5°C	7.1°C	-7.6°C	7.1°C
· ext. of ext. drywall at stud (11)	-0.7°C	10.2°C	-0.8°C	10.3°C
· int. of ext. drywall at insulation (18)	-6.8°C	7.3°C	-6.9°C	7.3°C
· exterior flange of stud (19)	3.6°C	12.4°C	3.5°C	12.4°C
· int. of int. drywall at insulation (22)	18.5°C	23.4°C	18.5°C	23.5°C
· int. of int. drywall at stud (23)	15.9°C	20.8°C	15.8°C	21.1°C
Air Temperatures:				
· exterior (14)[1]	-19.7°C	4.7°C	-20.0°C	6.4°C
· air space (DBT2 or 33[2])	-10.0°C	6.5°C	-10.2°C	6.6°C
· stud space (DBT3 or 34[2])	7.0°C	14.4°C	6.9°C	14.4°C
· interior (31)	18.2°C	23.0°C	18.1°C	23.4°C
Relative Humidities:				
· exterior (RH1)	16%	87%	16%	88%
· air space (RH2)	79%	92%	69%	99%
· stud space (RH3)	41%	68%	41%	68%
· interior (RH4)	27%	58%	27%	62%
Condensation Sensor (C1)[3]	1.1 Volts	1.5 Volts	1.0 Volts	1.5 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 were listed under the headings of DBT2 and DBT3, respectively, by NRCC/IRC when the raw data was transferred to spreadsheet 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. Note that the condensation sensor was not functioning properly during the 1992/93 monitoring program.

Table 4 Range of Readings at Key Locations, February 20 to March 19, 1993

Reading Type	Minimum Hourly Average	Maximum Hourly Average	Absolute Minimum	Absolute Maximum
Surface Temperatures:				
· exterior of brick (10)	-19.3°C	8.2°C	-19.5°C	8.6°C
· interior of brick (9)	-16.3°C	8.7°C	-16.4°C	8.8°C
· ext. of ext. drywall at insulation (8)	-9.3°C	10.3°C	-9.5°C	10.3°C
· ext. of ext. drywall at stud (11)	-2.0°C	13.0°C	-2.1°C	13.0°C
· int. of ext. drywall at insulation (18)	-8.7°C	10.5°C	-8.8°C	10.5°C
· exterior flange of stud (19)	3.5°C	14.7°C	3.4°C	14.7°C
· int. of int. drywall at insulation (22)	18.6°C	24.2°C	18.4°C	24.5°C
· int. of int. drywall at stud (23)	16.3°C	20.9°C	16.1°C	21.1°C
Air Temperatures:				
· exterior (14)[1]	-23.1°C	5.6°C	-23.4°C	8.1°C
· air space (DBT2 or 33[2])	-13.1°C	9.3°C	-13.2°C	9.3°C
· stud space (DBT3 or 34[2])	7.2°C	16.1°C	7.1°C	16.2°C
· interior (31)	18.2°C	24.2°C	17.9°C	24.7°C
Relative Humidities:				
· exterior (RH1)	31%	95%	30%	100%
· air space (RH2)	73%	97%	72%	101%
· stud space (RH3)	36%	72%	36%	72%
· interior (RH4)	19%	54%	19%	65%
Condensation Sensor (C1)[3]	1.1 Volts	1.4 Volts	1.0 Volts	1.4 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 were listed under the headings of DBT2 and DBT3, respectively, by NRCC/IRC when the raw data was transferred to spreadsheet 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. Note that the condensation sensor was not functioning properly during the 1992/93 monitoring program.

Table 5 Range of Readings at Key Locations, April 3 to 19, 1993

Reading Type	Minimum Hourly Average	Maximum Hourly Average	Absolute Minimum	Absolute Maximum
Surface Temperatures:				
· exterior of brick (10)	0.1°C	20.2°C	0.1°C	20.7°C
· interior of brick (9)	1.4°C	18.0°C	1.3°C	18.2°C
· ext. of ext. drywall at insulation (8)	3.9°C	18.4°C	3.9°C	18.5°C
· ext. of ext. drywall at stud (11)	8.0°C	19.6°C	8.0°C	19.6°C
· int. of ext. drywall at insulation (18)	4.3°C	18.6°C	4.3°C	18.6°C
· exterior flange of stud (19)	10.6°C	20.0°C	10.6°C	20.0°C
· int. of int. drywall at insulation (22)	19.8°C	23.8°C	19.8°C	24.1°C
· int. of int. drywall at stud (23)	17.9°C	22.6°C	17.9°C	22.9°C
Air Temperatures:				
· exterior (14)[1]	-1.3°C	17.9°C	-1.7°C	18.6°C
· air space (DBT2 or 33[2])	3.1°C	17.7°C	3.0°C	17.8°C
· stud space (DBT3 or 34[2])	12.8°C	20.4°C	12.8°C	20.4°C
· interior (31)	20.2°C	23.4°C	20.1°C	23.8°C
Relative Humidities:				
· exterior (RH1)	19%	95%	18%	100%
· air space (RH2)	81%	93%	72%	101%
· stud space (RH3)	59%	87%	59%	87%
· interior (RH4)	28%	58%	27%	62%
Condensation Sensor (C1)[3]	1.1 Volts	1.3 Volts	1.0 Volts	1.4 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 were listed under the headings of DBT2 and DBT3, respectively, by NRCC/IRC when the raw data was transferred to spreadsheet 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. Note that the condensation sensor was not functioning properly during the 1992/93 monitoring program.

Table 6 Range of Readings at Key Locations, May 1 to 14, 1993

Reading Type	Minimum Hourly Average	Maximum Hourly Average	Absolute Minimum	Absolute Maximum
Surface Temperatures:				
· exterior of brick (10)	5.4°C	36.1°C	5.4°C	36.5°C
· interior of brick (9)	6.6°C	32.8°C	6.6°C	33.0°C
· ext. of ext. drywall at insulation (8)	9.0°C	30.9°C	8.8°C	31.1°C
· ext. of ext. drywall at stud (11)	12.4°C	30.8°C	12.3°C	30.8°C
· int. of ext. drywall at insulation (18)	9.2°C	30.8°C	9.1°C	32.6°C
· exterior flange of stud (19)	14.5°C	29.9°C	14.4°C	29.9°C
· int. of int. drywall at insulation (22)	21.3°C	27.7°C	21.3°C	27.8°C
· int. of int. drywall at stud (23)	20.1°C	27.8°C	20.0°C	27.9°C
Air Temperatures:				
· exterior (14)[1]	3.8°C	32.4°C	3.1°C	33.5°C
· air space (DBT2 or 33[2])	7.6°C	31.8°C	7.5°C	32.2°C
· stud space (DBT3 or 34[2])	16.4°C	29.2°C	16.3°C	29.2°C
· interior (31)	21.6°C	27.2°C	21.4°C	27.5°C
Relative Humidities:				
· exterior (RH1)	14%	94%	13%	100%
· air space (RH2)	62%	99%	60%	101%
· stud space (RH3)	54%	100%	54%	100%
· interior (RH4)	20%	53%	19%	59%
Condensation Sensor (C1)[3]	0.2 Volts	1.4 Volts	0 Volts	1.4 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 were listed under the headings of DBT2 and DBT3, respectively, by NRCC/IRC when the raw data was transferred to spreadsheet 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. Note that the condensation sensor was not functioning properly during the 1992/93 monitoring program.

Table 7 Range of Readings at Key Locations, July 24 to August 6, 1993

Reading Type	Minimum Hourly Average	Maximum Hourly Average	Absolute Minimum	Absolute Maximum
Surface Temperatures:				
· exterior of brick (10)	15.4°C	41.0°C	15.2°C	41.7°C
· interior of brick (9)	17.0°C	37.3°C	16.8°C	37.5°C
· ext. of ext. drywall at insulation (8)	18.6°C	36.4°C	18.4°C	36.4°C
· ext. of ext. drywall at stud (11)	20.5°C	34.8°C	20.2°C	34.9°C
· int. of ext. drywall at insulation (18)	18.8°C	36.2°C	18.6°C	36.2°C
· exterior flange of stud (19)	21.4°C	33.6°C	21.3°C	33.6°C
· int. of int. drywall at insulation (22)	23.5°C	28.7°C	23.4°C	28.8°C
· int. of int. drywall at stud (23)	23.3°C	29.5°C	23.1°C	29.6°C
Air Temperatures:				
· exterior (14)[1]	13.5°C	33.6°C	13.0°C	36.5°C
· air space (DBT2 or 33[2])	17.3°C	36.1°C	17.2°C	36.2°C
· stud space (DBT3 or 34[2])	21.8°C	32.4°C	21.7°C	32.4°C
· interior (31)	24.0°C	28.3°C	23.7°C	28.6°C
Relative Humidities:				
· exterior (RH1)	28%	92%	23%	101%
· air space (RH2)	35%	59%	35%	60%
· stud space (RH3)	36%	74%	36%	74%
· interior (RH4)	31%	64%	30%	68%
Condensation Sensor (C1)[3]	0 Volts	1.2 Volts	2.3 Volts	1.2 Volts

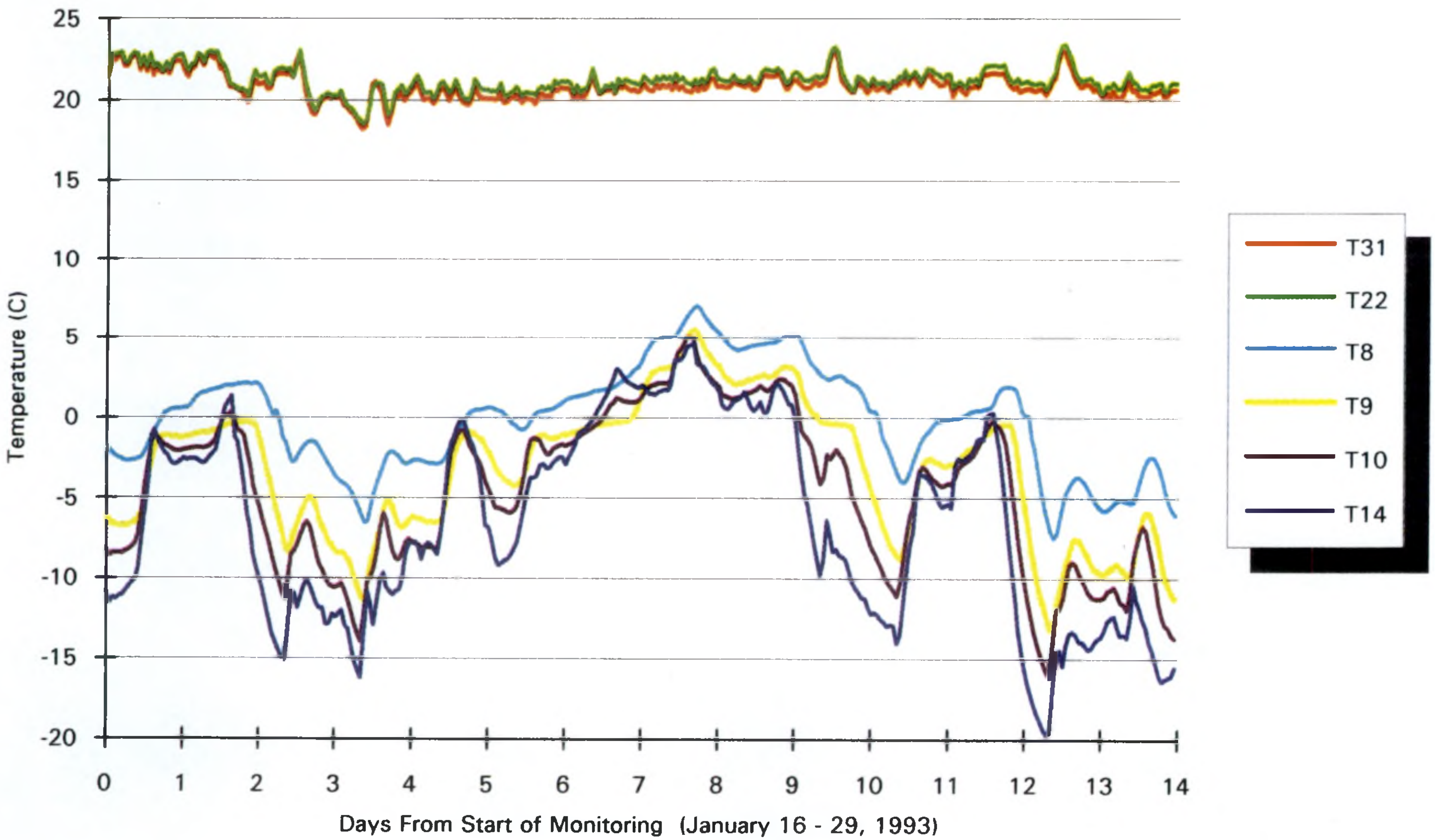
Notes:

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 were listed under the headings of DBT2 and DBT3, respectively, by NRCC/IRC when the raw data was transferred to spreadsheet files.

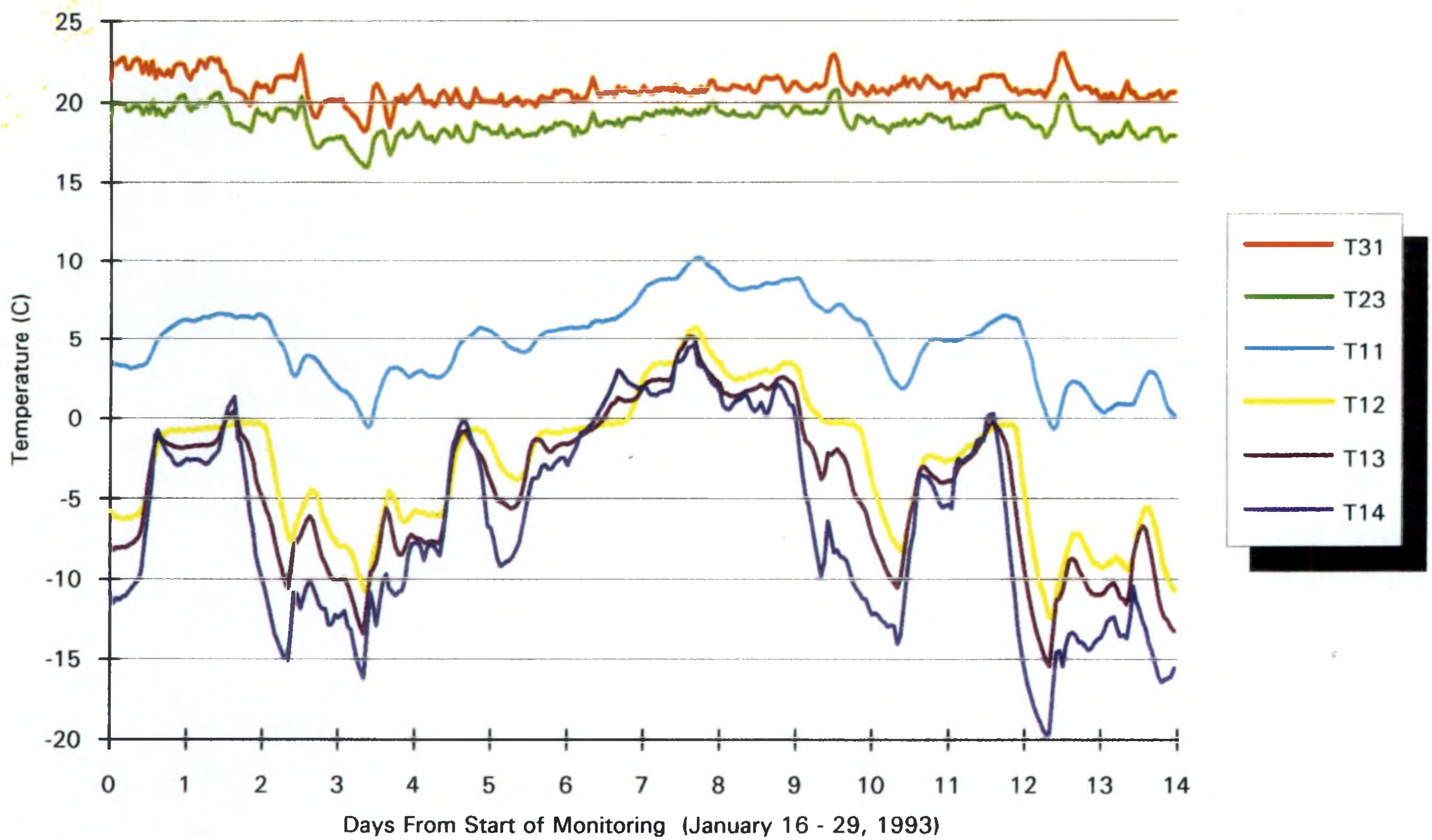
3. Readings of, or close to, 0 Volts represent dry conditions while readings of, or close to, 2.5 Volts represent wet conditions, indicating that condensation has occurred. Note that the condensation sensor was not functioning properly during the 1992/93 monitoring program.

Fig. 7 Temperature Profile Across Test Wall at Insulation



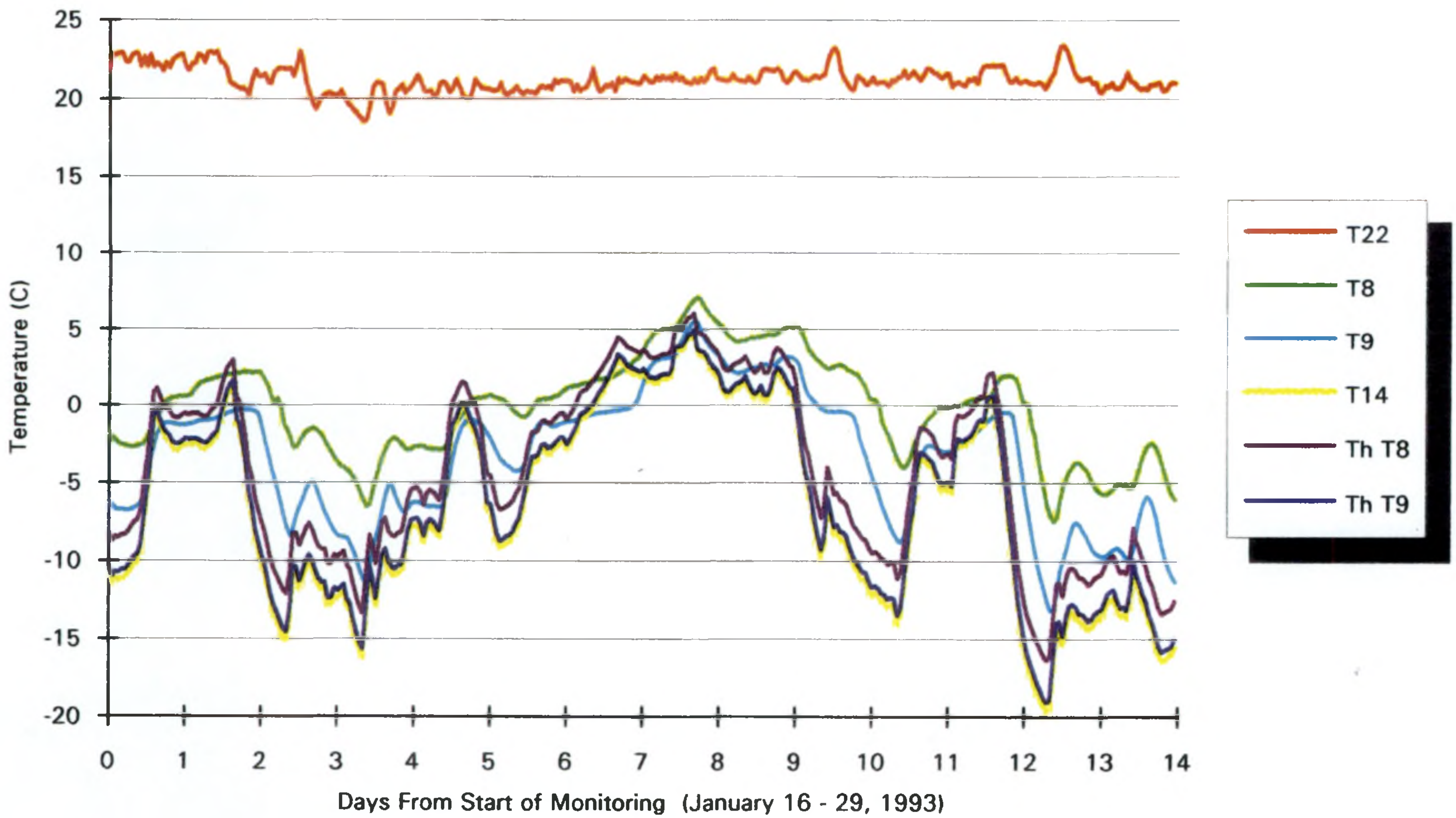
T31: interior air	T9: interior of brick veneer, at insulation
T22: interior of interior drywall, at insulation	T10: exterior of brick veneer, at insulation
T8: exterior of exterior drywall, at insulation	T14: exterior air

Fig. 8 Temperature Profile Across Test Wall at Steel Stud



T31: interior air	T12: interior of brick veneer, at steel stud
T23: interior of interior drywall, at steel stud	T13: exterior of brick veneer, at steel stud
T11: exterior of exterior drywall, at steel stud	T14: exterior air

Fig. 9 Comparison of Actual and Theoretical Surface Temperatures in Cavity



T22:	interior of interior drywall, at insulation	T14:	exterior air
T8:	exterior of exterior drywall, at insulation	Th T8:	Theoretical T8, given actual T22 and T14
T9:	interior of brick veneer, at insulation	Th T9:	Theoretical T9, given actial T22 and T14

Fig. 10 Relation Between the Pressure Difference Across the Test Wall and the "Temperature Index" of the Backup Wall

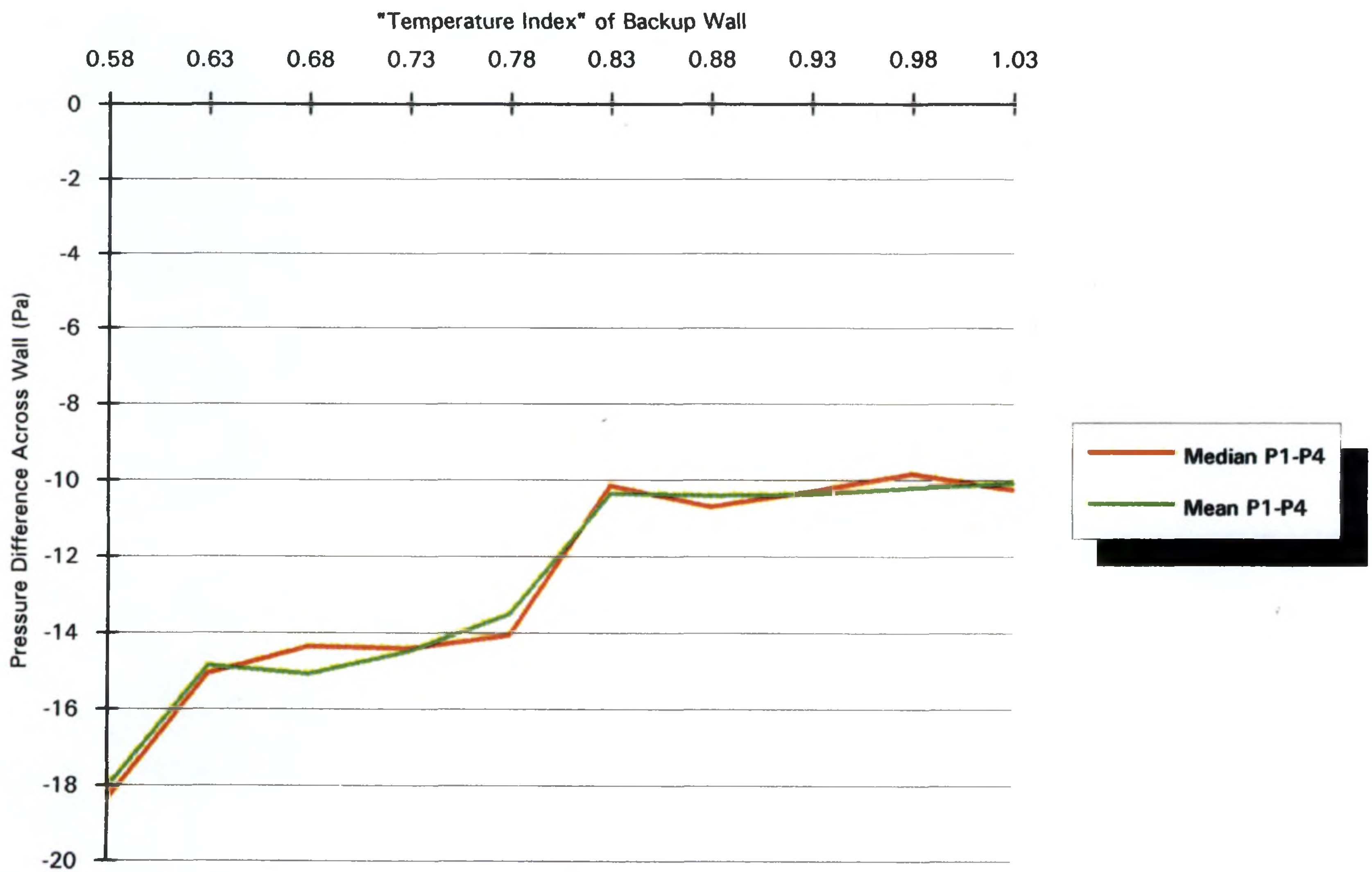


Fig. 11 Hourly Average Pressure Differences Across Test Wall

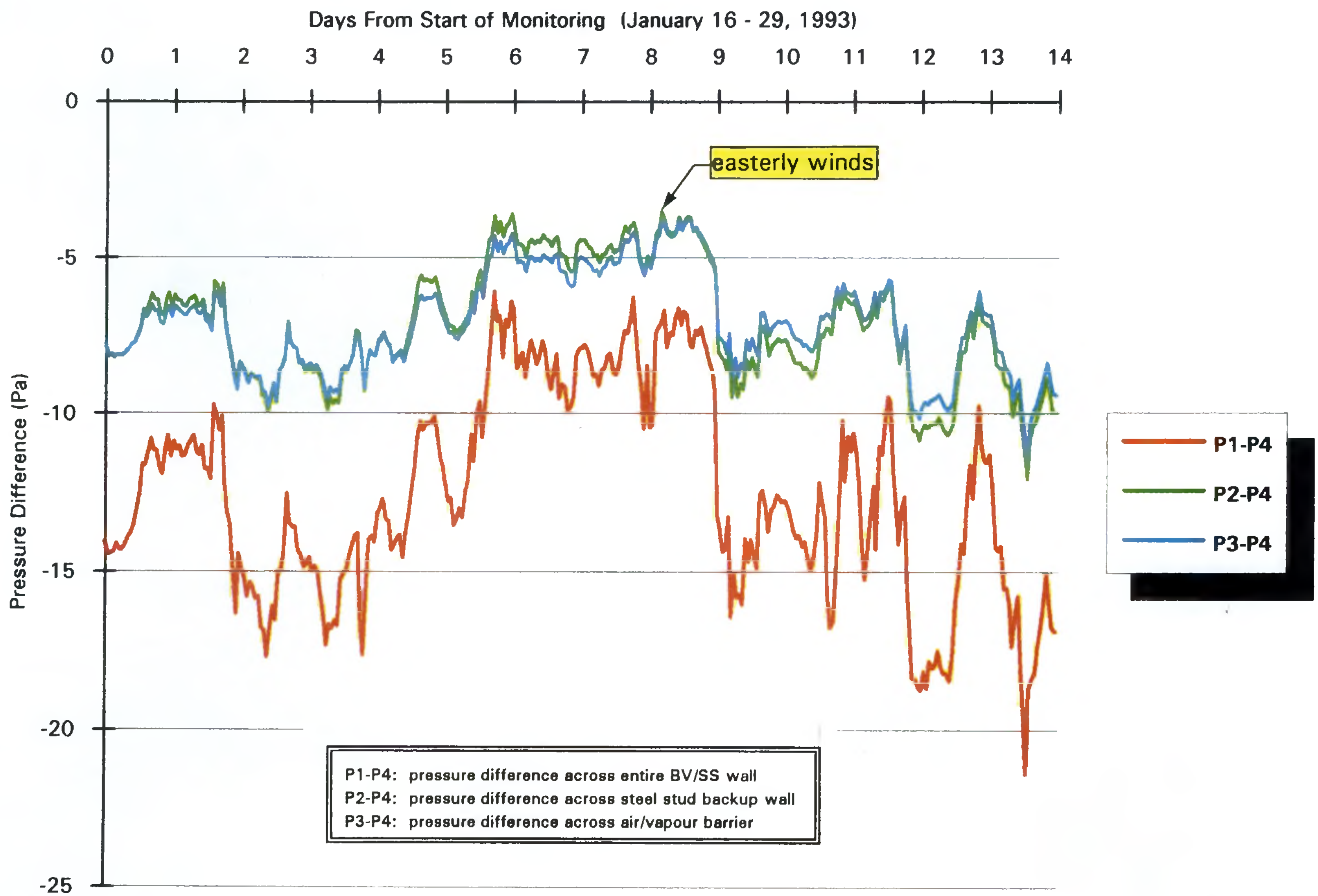


Fig. 12 Daily Average Pressure Differences Across Test Wall

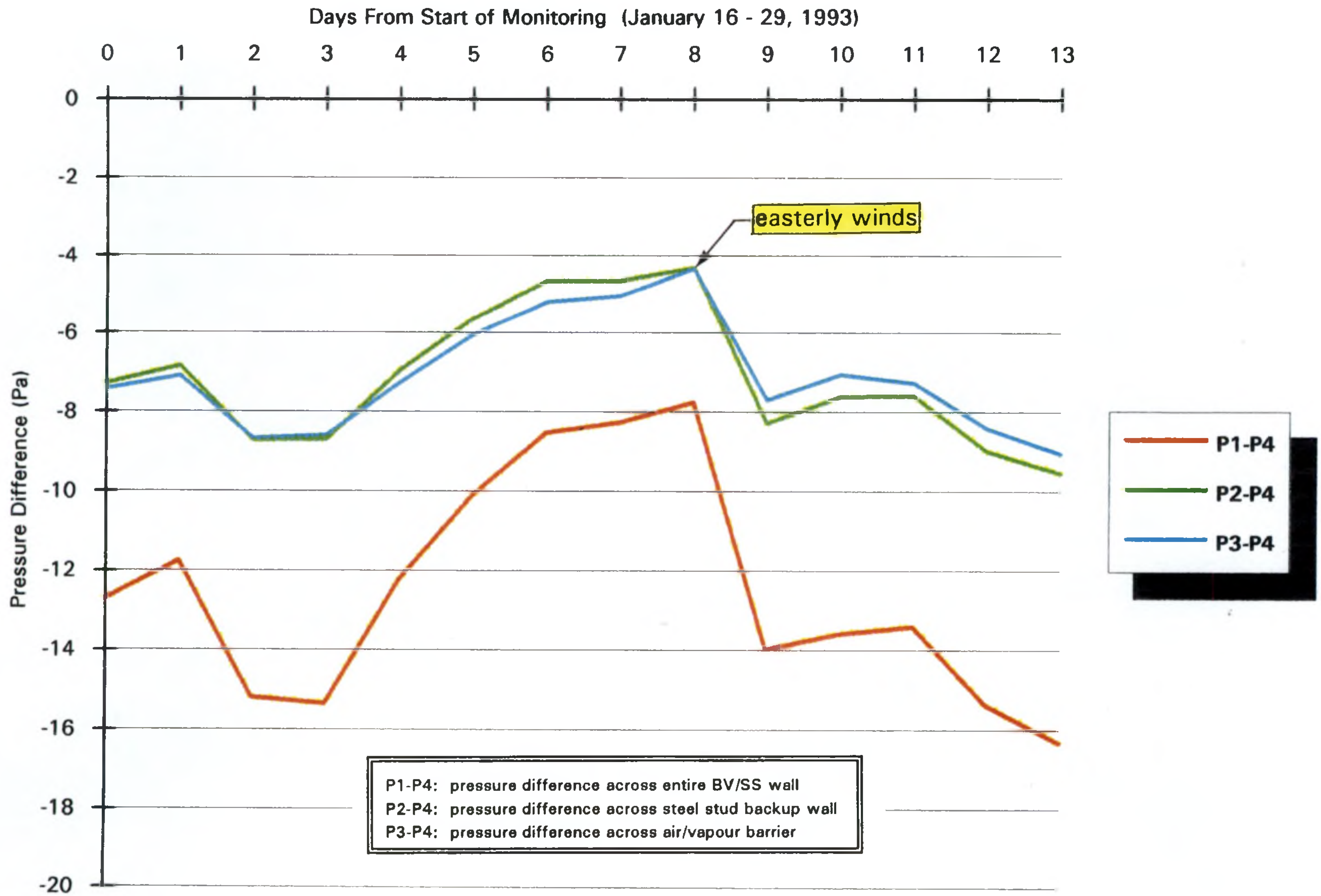
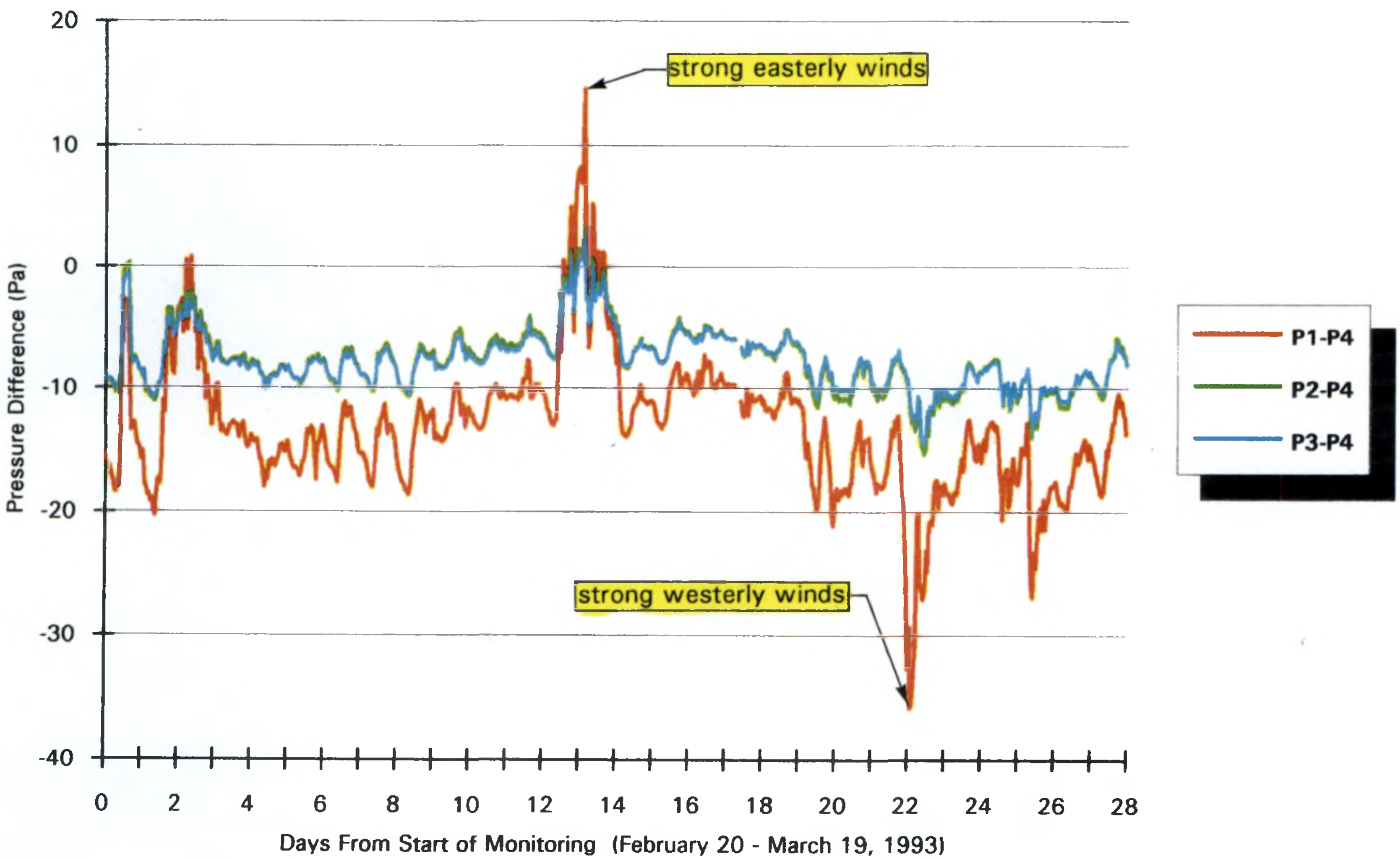


Fig. 13 Hourly Average Pressure Differences Across Test Wall



P1-P4: pressure difference across entire BV/SS wall
P2-P4: pressure difference across steel stud backup wall
P3-P4: pressure difference across air/vapour barrier

Fig.14 Moisture Sensor Readings - During Late Autumn/Early Winter

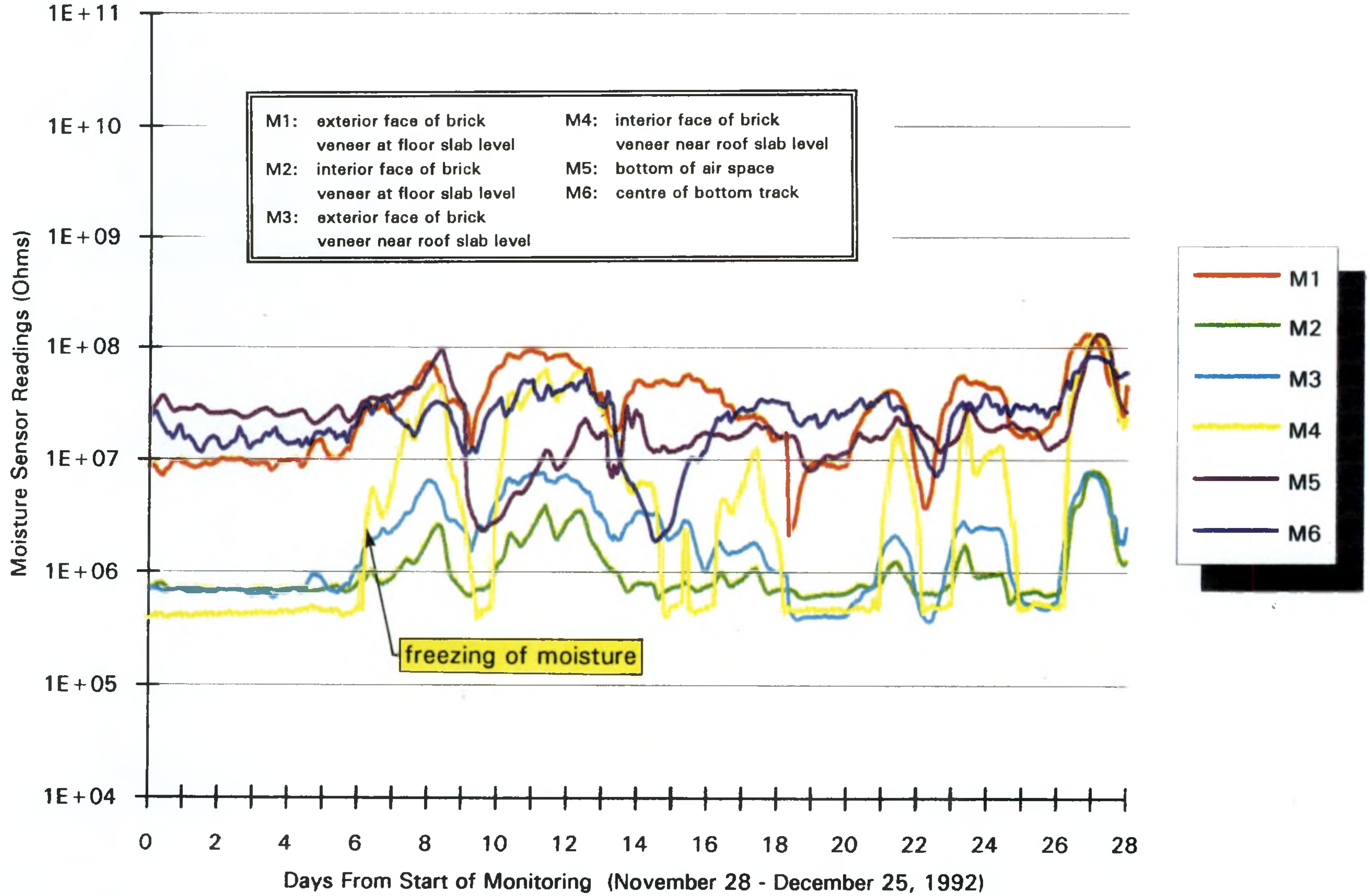


Fig.15 Moisture Sensor Readings - During Spring

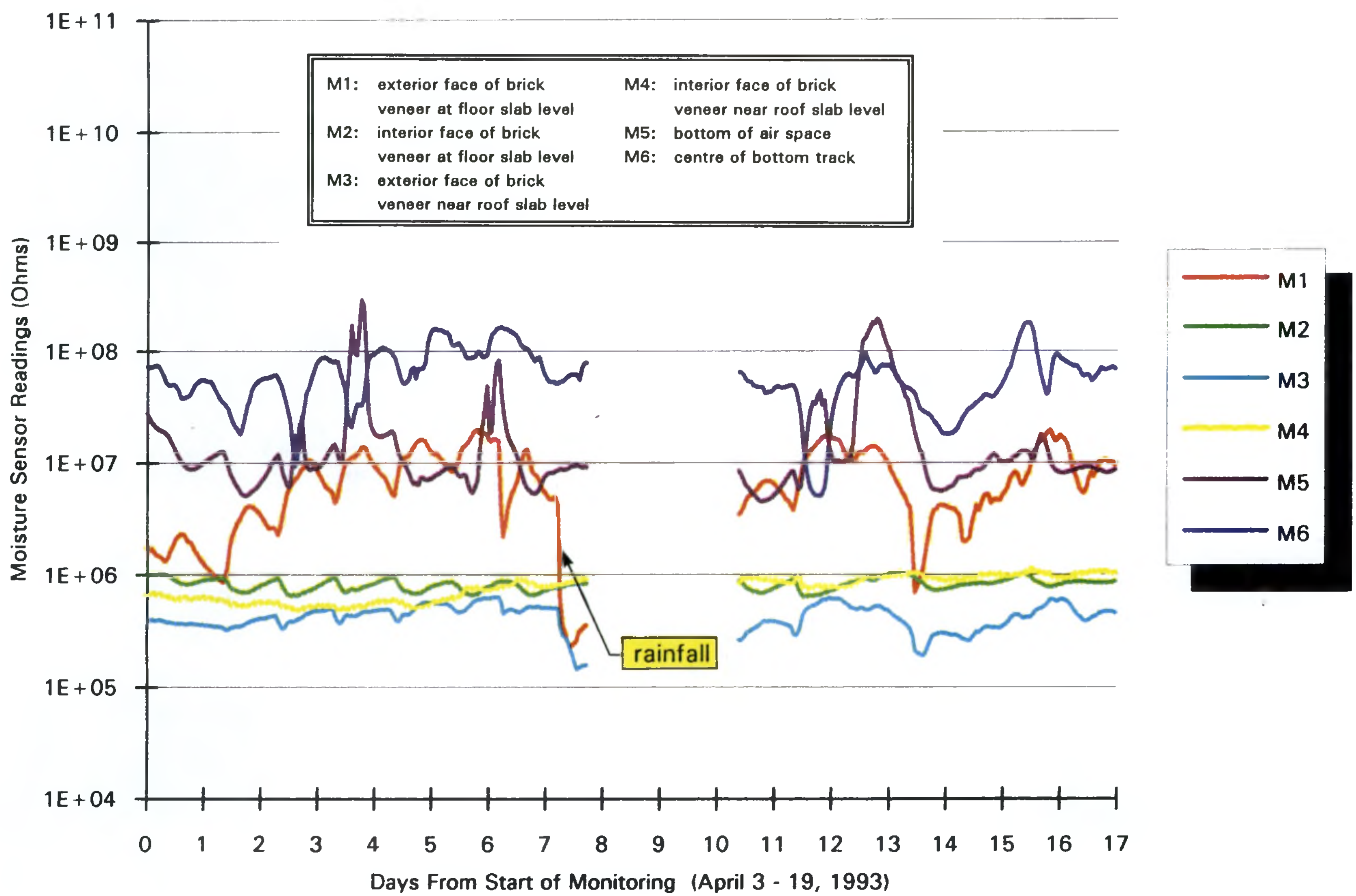


Fig.16 Moisture Sensor Readings - During Summer

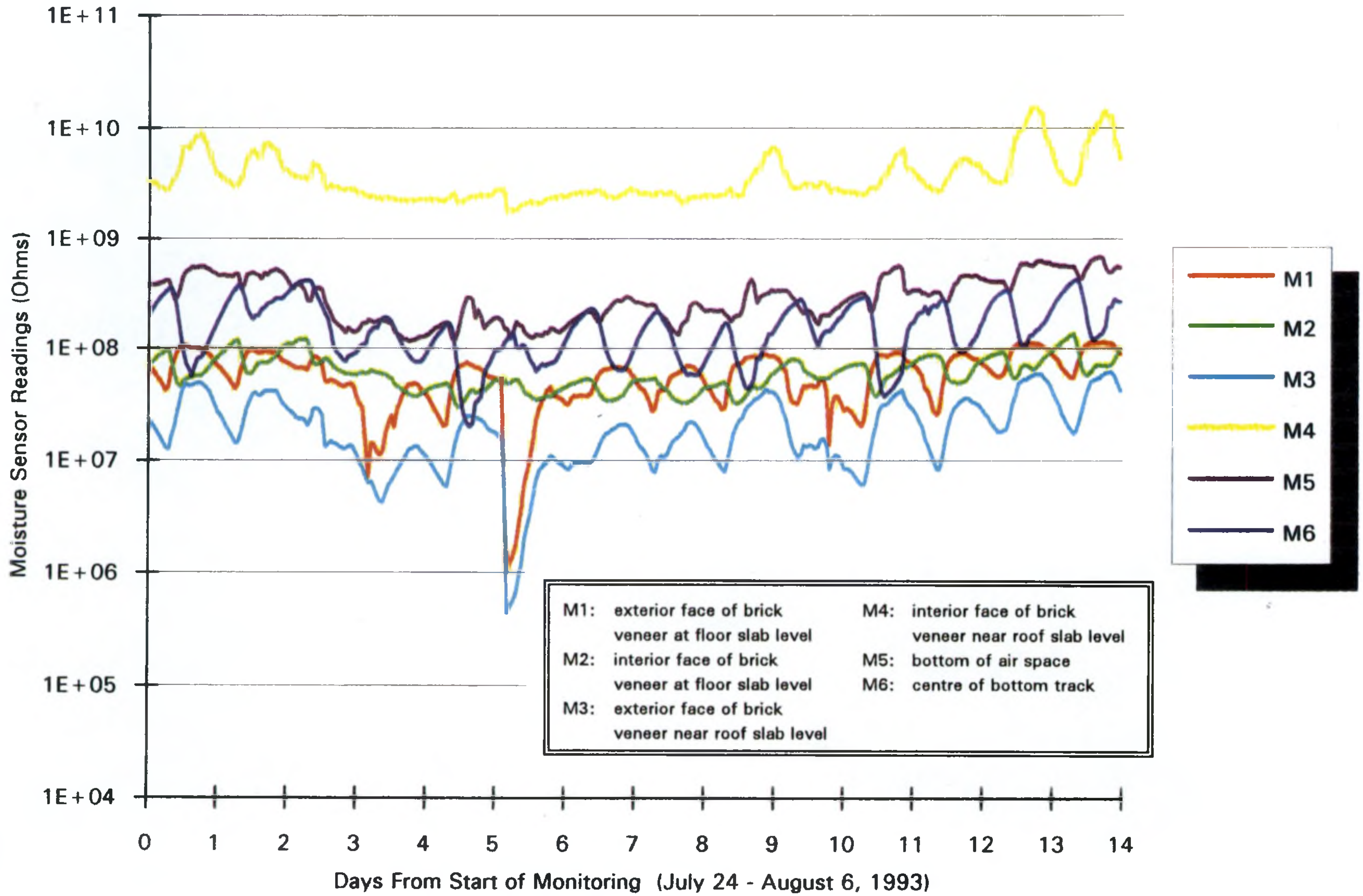
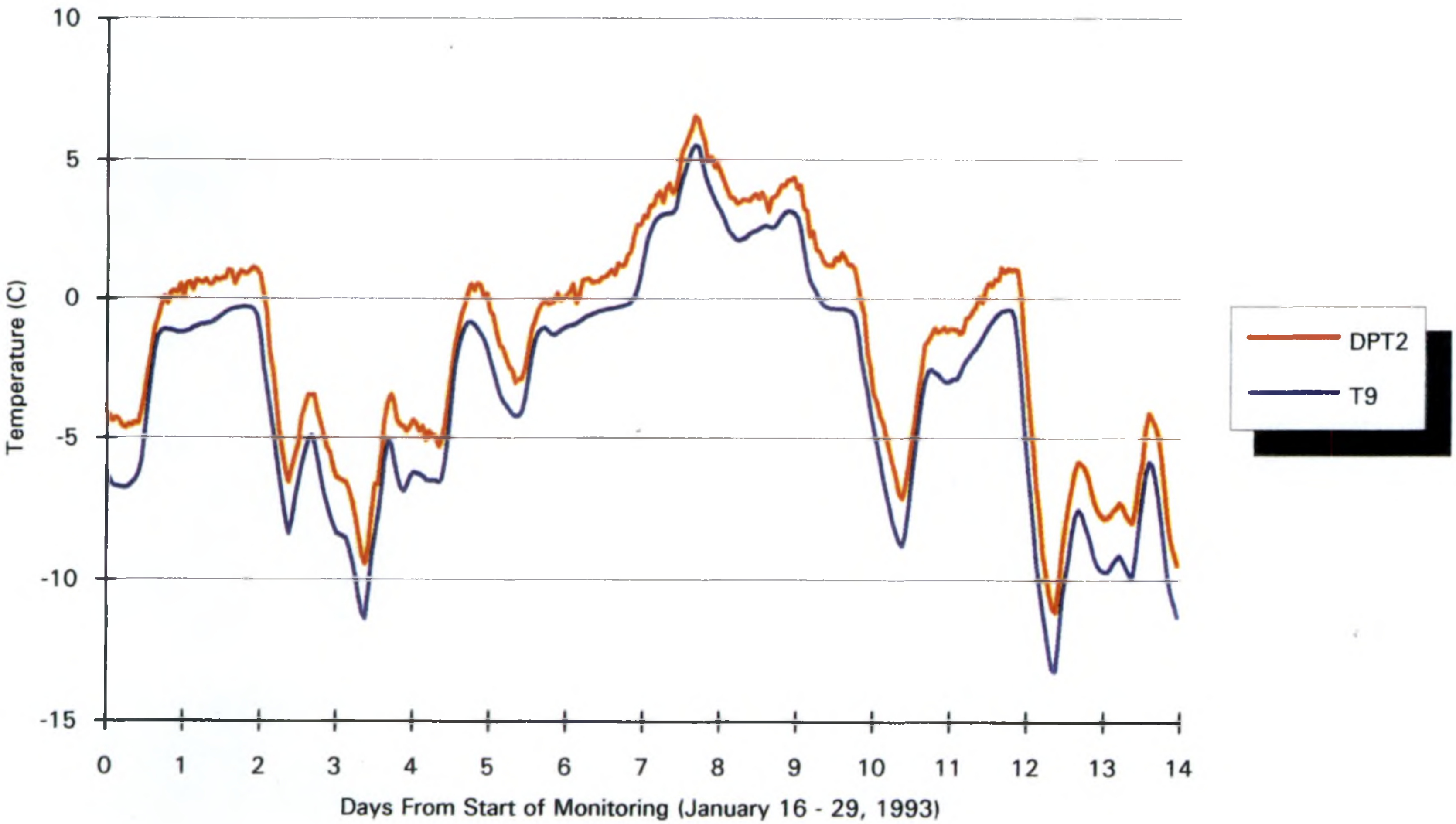
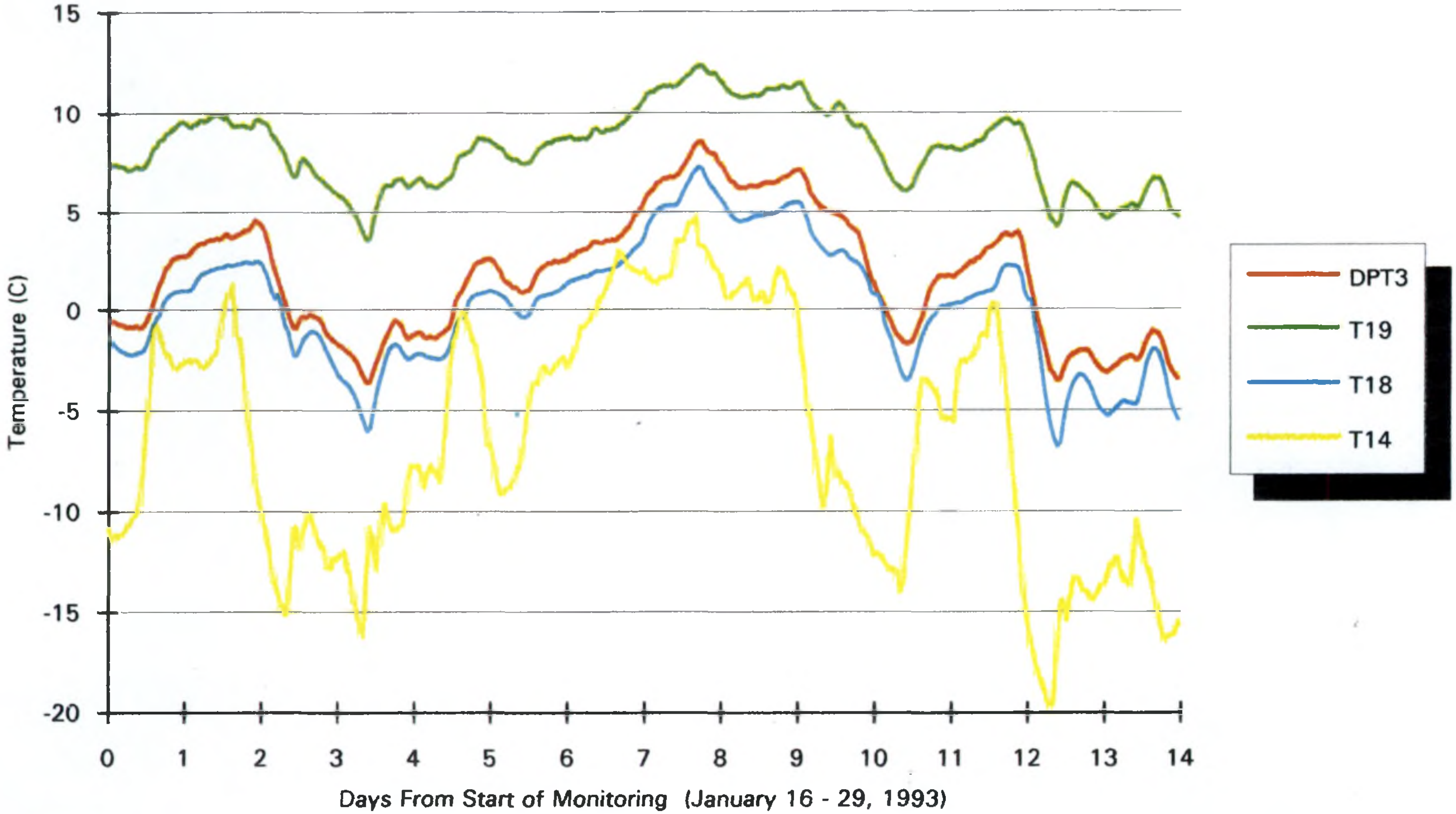


Fig. 17 Comparison of the Surface Temperature on the Interior Face of the Brick Veneer to the Dew Point Temperature of the Cavity Air



DPT2: Dew Point Temperature of air in cavity	T9: interior of brick veneer, at insulation

Fig. 18 Comparison of Surface Temperatures at the Exterior Gypsum Board to the Dew Point Temperature of the Air in the Stud Space



DPT3:	Dew Point Temperature of air in stud space	T18:	interior of exterior drywall, at insulation
T19:	exterior flange of stud	T14:	exterior air