# PROTECTING GYPSUM SHEATHING IN INSULATED STEEL-STUD WALLS

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# PROTECTING GYPSUM SHEATHING IN INSULATED STEEL-STUD WALLS

**Final Report**
**May 1997**

**Prepared for:**
**Canada Mortgage and Housing Corporation**

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# EXECUTIVE SUMMARY

A potential loss of strength and the growth of mould and mildew are two of the problems resulting from moisture accumulation in exterior gypsum sheathing. The purpose of this research was to examine methods of protecting various insulated steel stud and exterior gypsum wall systems when exposed to condensation conditions. To fulfil this purpose, eighteen different wall panels were exposed to laboratory-controlled, freezing and non-freezing temperatures and 100% relative humidity conditions at the exterior gypsum sheathing surface. The test panels varied according to the type of warm-side protection on the gypsum sheathing (unprotected, SBPO, or polyethylene) and according to six different assemblies of cold-side materials. Numerical analyses were carried out using a finite difference package to assist in determining the necessary test duration by finding the time required for the gypsum sheathing to approach a steady-state moisture condition.

The results from the test panels were compared on the basis of moisture content and percentage moisture distribution in each wall component. The final moisture content of the gypsum sheathing in each test showed that SBPO and polyethylene are very effective at reducing the amount of moisture absorbed by the gypsum sheathing. Polyethylene was the most effective at reducing the amount of moisture accumulating in the sheathing, as well as reducing the amount of moisture diffusing through the wall. Theoretical test panel results from numerical analyses compared favourably with the laboratory test results.

The use of protective barriers resulted in the accumulation of moisture in the warm-side batt insulation. Under freezing conditions, a layer of ice formed on the warm side of the gypsum. During non-freezing tests, most of the moisture was either absorbed by the sheathing (unprotected panels) or accumulated in the warm-side insulation. Thus, the use of protective layers in practice will require the development of designs which allow for the removal of this accumulated moisture.

The results of preliminary field trials[1] of two full-scale walls are also included in the report. Two wall samples, one unprotected and one SBPO protected, were exposed to actual weather conditions on their exterior face from November 1994 to February 1995 in Calgary, Alberta. Two-dimensional heat flow in a vertical cavity and gaps between the protective layer and gypsum sheathing may have affected the amount and location of moisture accumulation in the wall samples. Generally, results from the full-scale field tests were not as promising as the laboratory and theoretical studies. The moisture content in the SBPO protected gypsum sheathing was higher than expected, and occasionally approached the moisture content values of the unprotected gypsum sheathing.

It is clear that SBPO and polyethylene can be used to protect exterior gypsum sheathing from moisture. The use of protective layers can improve wall performance when condensation, due to either air leakage or diffusion, occurs at the exterior gypsum sheathing. However, further work is necessary to find ways to efficiently remove water which may accumulate in the stud cavity under severe exposure conditions.

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[1] "Investigation of the Performance of Gypsum Sheathing" Canada Mortgage and Housing Corporation. CMHC CR file 6585/HO66-2. September, 1993.

# Résumé

L'accumulation d'humidité dans le revêtement d'ossature en plaques de plâtre risque d'occasionner une perte de résistance et la prolifération de moisissure. La présente recherche avait pour objectif d'étudier les moyens de protéger différents murs extérieurs à ossature d'acier revêtue de plaques de plâtre, exposés à des conditions propices à la condensation. Dans la poursuite de cet objectif, la face extérieure du revêtement d'ossature en plaques de plâtre de dix-huit panneaux muraux a été exposée, dans des conditions contrôlées en laboratoire, à des températures de gel et de dégel et à un degré d'humidité relative de 100 % . Les panneaux d'essai variaient selon le type de protection assuré du côté chaud à l'égard du revêtement d'ossature en plaque de plâtre (aucune protection, polyoléfine filée-liée ou polyéthylène) et suivant six différents assemblages de matériaux du côté froid. Des analyses numériques ont été effectuées à l'aide d'un progiciel de différence finie dans le but d'aider à déterminer la durée des essais nécessaire en trouvant le temps requis pour que le revêtement d'ossature en plaque de plâtre atteigne un régime hygrométrique permanent.

Les résultats obtenus des panneaux d'essai ont été comparés en fonction de la teneur en humidité et de la répartition procentuelle d'humidité de chaque élément mural. La teneur en humidité finale du revêtement d'ossature en plaque de plâtre lors de chaque essai a montré que la polyoléfine filée-liée ou le polyéthylène parviennent avec beaucoup d'efficacité à réduire la quantité d'humidité qui s'accumule dans la masse du revêtement d'ossature et à réduire la quantité d'humidité se diffusant par le mur. Les résultats théoriques obtenus des panneaux d'essai à partir des analyses numériques se comparent favorablement aux résultats des essais en laboratoire.

L'utilisation de barrières protectrices a donné lieu à l'accumulation d'humidité dans l'isolant en matelas placé du côté chaud. Dans des conditions de gel, une couche de glace se formait du côté chaud des plaques de plâtre. Dans les autres conditions, la majorité de l'humidité était absorbée soit par le revêtement d'ossature (panneaux laissés sans protection) ou s'accumulait dans l'isolant disposé du côté chaud. Par conséquent, l'utilisation de barrières protectrices en pratique nécessitera l'élaboration de modèles qui permettront d'éliminer l'humidité accumulée.

Le rapport fait également état des résultats obtenus lors des premiers essais sur place1 de deux des murs pleines dimensions. La face extérieure de deux échantillons de mur, l'un laissé sans protection et l'autre protégé de polyoléfine liée-liée, a été exposée à des conditions climatiques réelles de novembre 1994 à février 1995 à Calgary, en Alberta. Le mouvement de chaleur bidimensionnel dans la cavité verticale et les interstices entre la couche protectrice et le revêtement d'ossature en plaque de plâtre ont pu influer sur la quantité et l'emplacement de l'humidité accumulée dans les échantillons muraux. En règle générale, les résultats obtenus des essais sur des murs pleines dimensions n'ont pas été aussi prometteurs que les essais en laboratoire et les études théoriques. La teneur en humidité du revêtement d'ossature en plaques de plâtre protégées par de la polyoléfine filée-liée était plus élevée que celle qui était escomptée et s'approchait occasionnellement de la teneur en humidité du revêtement d'ossature en plaques de plâtre laissées sans protection.

Il est évident que la polyoléfine filée-liée et le polyéthylène peuvent servir à protéger de l'humidité le revêtement d'ossature. L'utilisation de couches protectrices permet d'améliorer la performance des murs lorsque la condensation, qu'elle soit causée par des fuites d'air ou par diffusion, se forme à la surface du revêtement d'ossature en plaques de plâtre. Par contre, d'autres travaux devront être consacrés à trouver des moyens d'éliminer efficacement l'eau qui risque de s'accumuler dans les cavités entre les poteaux dans de sérieuses conditions d'exposition.

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1 «Étude des performances du revêtement de plâtre», Société canadienne d'hypothèques et de logement. Dossier SCHL 6585/H066-2, septembre 1993.

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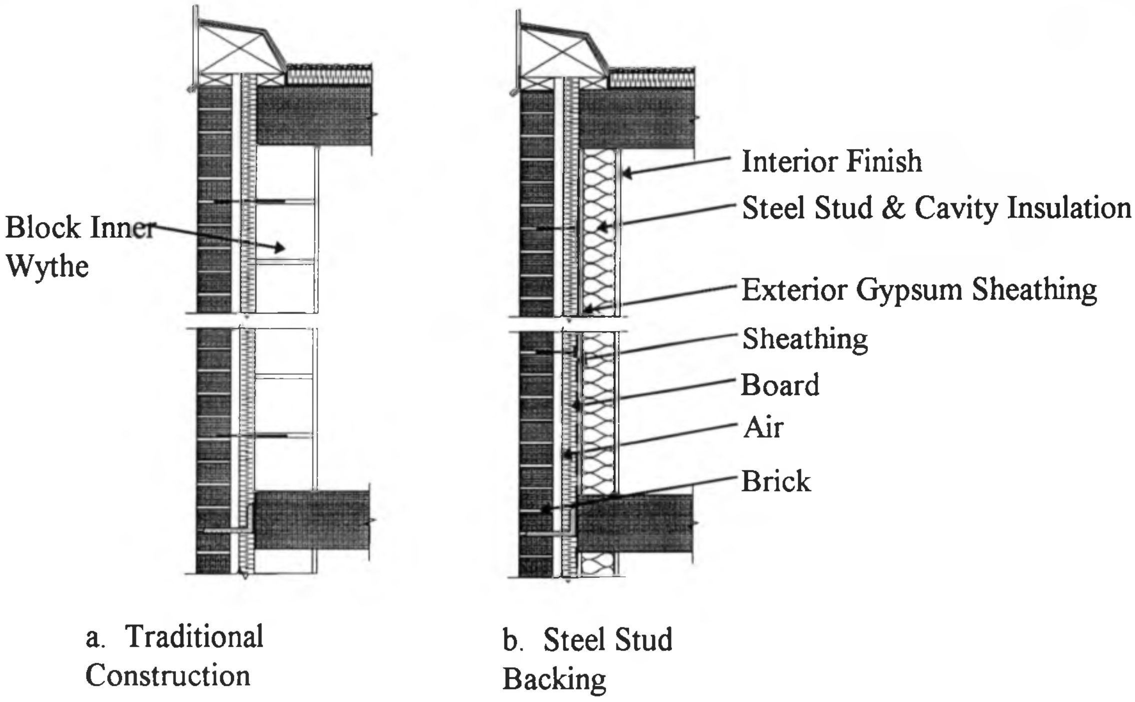
# 1. INTRODUCTION

Multi-storey buildings have traditionally been enclosed by masonry cavity walls, as shown in Figure 1-1a. These walls consist of an exterior wythe of masonry veneer, a vented air space, rigid insulation, an interior wythe of masonry block, and some type of interior finish. When the exterior walls are not required to carry vertical loads, the inner masonry wythe can be replaced with a less expensive steel stud frame as shown in Figure 1-1b. Not only is the steel stud frame less expensive than masonry backing, but the stud cavity can also be filled with low-cost batt insulation for additional thermal resistance.

To compensate for lateral stability losses incurred by replacing the masonry inner wythe with steel studs, a rigid sheathing board is attached to the exterior face of the frame. Exterior-grade gypsum sheathing is often used because it provides adequate rigidity against wind loading; it is fire resistant and it is inexpensive. A water-repellent, high permeability sheathing paper is installed on the exterior surface of the gypsum sheathing after the framework is erected. The purpose of the sheathing paper is to repel wind-driven rain and to act as an air barrier.



a. Traditional Construction

b. Steel Stud Backing

**Figure 1-1: Components of two insulated wall systems.**

Rigid insulating board is installed in the air space of both the traditional and the steel stud walls. Its purpose is to reduce thermal bridging and consequent loss in thermal efficiency in spandrel beams, columns, and slabs. The insulating board also reduces the chance of concealed and surface condensation occurring due to thermal bridging in the steel stud frame.

The insulated steel stud building envelope is used extensively in modern high-rise construction because it provides many benefits over traditional construction. Table 1-1 shows the advantages with respect to construction costs, assembly time, and thermal resistance.

**Table 1-1: Comparison of advantages in steel stud envelopes over double wythe envelopes.**

| | Double wythe, insulated cavity wall | Insulated, steel stud envelope | Savings or Improvement |
|---|---|---|---|
| Construction cost* ($\$/m^2$) | $\$336/m^2$ | $\$314/m^2$ | $\$22/m^2$ |
| Assembly time* ($hrs/ft^2$) | 0.38 | 0.26 | 32% |
| Thermal resistance | RSI = 2.336 $m^2$ °C/W | RSI = 4.405 $m^2$ °C/W | 1.9 |

* Obtained from MEANS data (1993a&b).

For a typical 12-storey building, the use of an insulated steel stud envelope rather than a double wythe, insulated cavity wall can result in a construction cost capital savings of close to $200,000 (CDN). The assembly time saved can result in earlier occupancy and, therefore, increased income for owners. The additional insulation provided in the stud cavity can almost double the thermal resistance of the building envelope. Approximately

$19,000 per year in lost energy can be saved in a typical 12-storey residential/commercial building in Toronto.[2]

Although there are several benefits to the insulated steel stud wall system, there are also potential problems. Moisture is constantly moving through the wall by means of vapour diffusion and, possibly, air leakage (Handegord, 1985). This moisture may condense at the locations shown in Figure 1-2 if the exterior gypsum sheathing drops below the dew point temperature of the inside air. During winter, this may occur despite the use of exterior insulation.

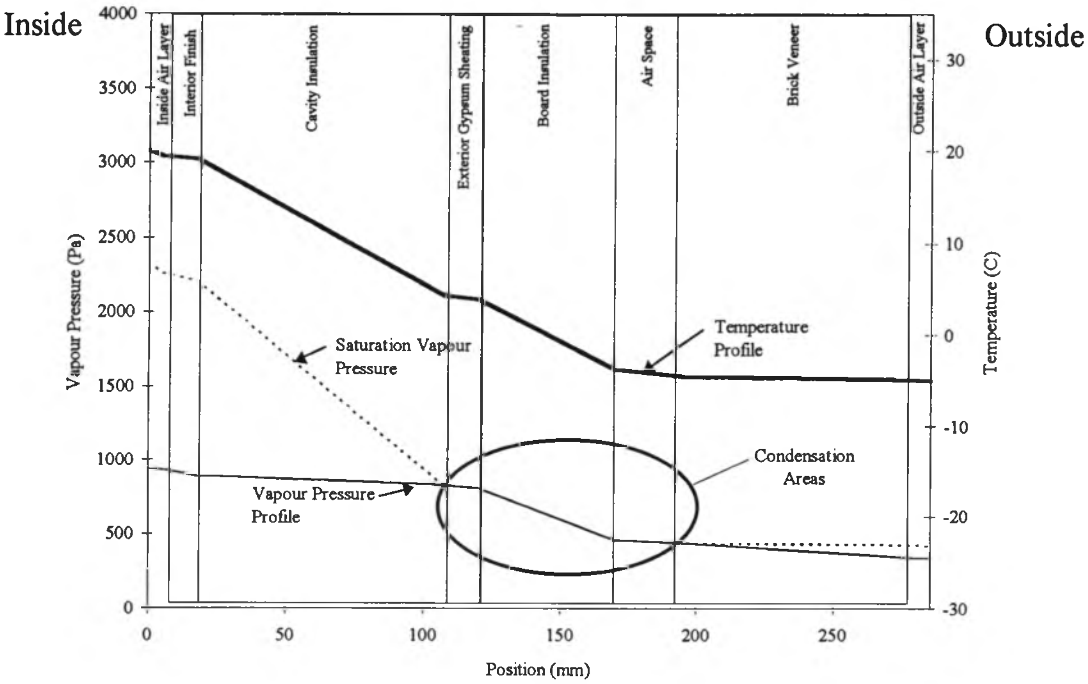


**Figure 1-2: Temperature and vapour pressure profile through an insulated steel stud wall system.**

The quantity of moisture that may accumulate in the exterior gypsum sheathing and adjacent materials is also dependent on the amount and type of insulation installed on the cold side of the sheathing.

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[2] Based on comparison of insulated steel stud wall and double wythe insulated cavity wall. Assumptions include electrical heating, 9322 $m^2$ envelope area, and equivalent air leakage for both walls.

Excessive concealed condensation can cause damage to a building envelope in a number of ways. Wetting of the exterior gypsum sheathing reduces its rigidity and, consequently, requires that other wall components provide lateral resistance (British Standards Institution, 1992). This can result in damage to the steel studs and interior finishes. Moisture accompanied by moderate temperatures at the gypsum sheathing surfaces can lead to the growth of mould and mildew, which may cause health concerns for occupants with respiratory problems. Finally, wicking of moisture back into the frame cavity can cause corrosion of the steel studs, a decrease in the thermal resistance of the insulation, and water staining of interior finishes.

Considering the high probability of occasional condensation within the wall during the heating season, insulated wall systems must be adequately designed to avoid the adverse consequences of moisture accumulation (Handegord, 1992). It may be possible to prevent condensation from occurring on gypsum sheathing when highly permeable board insulation is installed in the wall air space. The high permeability of the exterior insulation allows outward drying of the sheathing. Furthermore, the application of hydrophobic materials on the high pressure side of the wall may also restrict moisture flow sufficiently so that the moisture contents of downstream wall components are kept to safe levels. Laboratory investigations carried out under controlled conditions are, however, required to examine the effectiveness of such a design approach.

The purpose of this study is to examine the moisture performance of various insulated steel stud and gypsum wall systems when the exterior gypsum sheathing is exposed to condensation conditions. By assessing the performance of various walls when the exterior gypsum sheathing is exposed to condensation, it is possible to identify which wall systems are likely to be the best at managing moisture.

To fulfil this purpose, several gypsum wall test panels were exposed to two different laboratory-controlled winter conditions. Test panels were exposed to temperatures that resulted in the gypsum sheathing being either above or below freezing. Water vapour was supplied to the sheathing by means of vapour diffusion from a warm-side reservoir of conditioned air. Through careful temperature control, the warm side of the exterior gypsum sheathing became the first condensing surface. Test panels were exposed to condensation conditions until the gypsum sheathing approached a constant moisture content. It was reasoned that the maximum moisture content for a given test specimen would occur once the specimen had reached equilibrium conditions. The maximum moisture content in the gypsum sheathing for a given set of conditions was then used as the basis to compare the different types of test panels.

Numerical analyses were carried out to assist in determining the time required for the gypsum sheathing to reach a steady-state moisture condition. The main purpose of these analyses was to define the duration of the tests. The results of the numerical analyses were also used in comparing theoretical results with actual test results.

Finally, previous field tests were completed using both a full-scale protected and a full-scale unprotected gypsum wall. These test walls were exposed to actual climatic conditions in Calgary, Alberta during the 1994-95 winter season. Results from these tests were compared to the results from the laboratory tests.

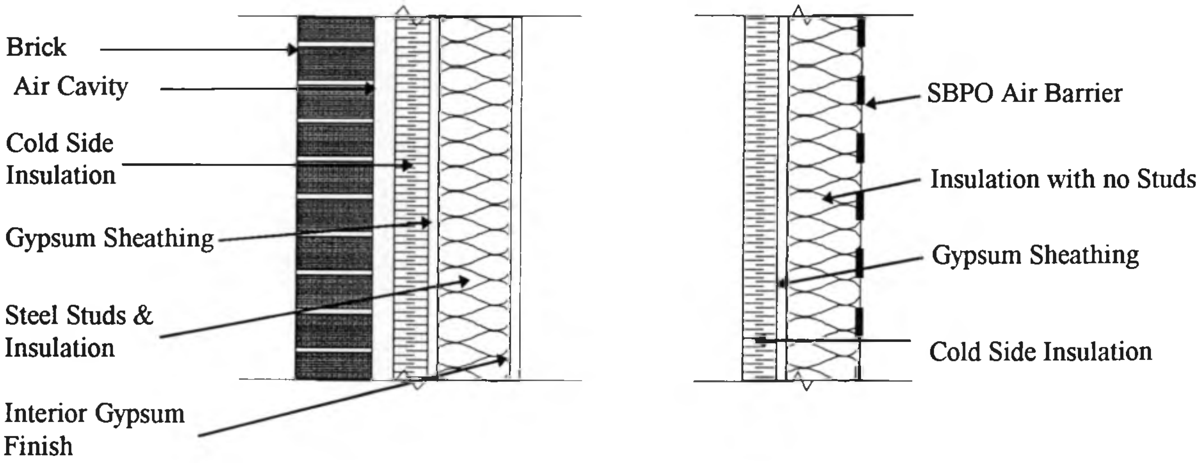
This work may help in identifying which wall system would perform best with respect to moisture control when subjected to heating season conditions. The results from all of the different tests revealed which combination of cold-side insulation and warm-side protection creates the best moisture managing system. It is hoped that knowledge obtained from this research will be used to assist in establishing guidelines for insulated steel stud wall systems that reduce the likelihood of moisture problems.

# 2. LABORATORY RESEARCH TECHNIQUE

## 2.1 METHOD

The experimental portion of this study examined the factors affecting the accumulation of moisture on the exterior gypsum sheathing in insulated steel stud envelopes. The experiment was designed to test which envelope designs could best manage this moisture. Small, modified wall sections of various composition were placed in a chamber in an environmental simulator until steady-state moisture conditions were achieved in the gypsum sheathing.

Figure 2-1 illustrates the differences between an actual insulated steel stud envelope and the modified wall sections tested. The test panels included what were considered to be the critical elements of the envelope cross-section. The effect of the brick veneer on moisture movement and accumulation was considered to be negligible, and therefore omitted from the test sections. For the purposes of this study, the vapour pressure in the vented cavity was assumed to be the outdoor vapour pressure. One dimensional heat flow was assumed and the effect of the steel studs was neglected. In some cases, the presence of steel studs will lead to two-dimensional heat flow, which may cause variations in moisture movement and moisture distribution in the wall. In order to reduce the number of variables, the thermal bridge effect of the steel studs was not considered.



a. Actual Building Envelope b. Modified Wall Section

**Figure 2-1: Cross-sections of an actual building envelope and a modified wall section.**

To ensure uniform exposure to water vapour, the interior gypsum finish found in an actual building envelope was replaced with a spun-bonded polyolifin (SBPO) air barrier for the test panels. The latter material was chosen because it has vapour permeability properties similar to gypsum. Furthermore, the vapour permeability of the SBPO air barrier was expected to remain constant during the course of testing.

Eighteen different wall panels were tested under two different simulated winter conditions. The test panels were divided into groups of six, where each group had one of the following conditions on the surface of the warm side of the exterior gypsum. The three variations of warm side protection were:

I. No protection;
II. A vapour-permeable but water-repellent membrane (SBPO air barrier);
III. A vapour barrier (2 mil polyethylene).

To study the effects of different types of exterior board insulation on the accumulation of moisture within the wall, six different systems on the cold side of the gypsum sheathing were examined for each of the above groups. The cold-side materials, in order of decreasing permeability, were:

1. 25 mm glass fibre insulating board;
2. SBPO barrier and 25 mm glass fibre insulating board;
3. Sheathing paper and 25 mm glass fibre insulating board;
4. Two coats of exterior gloss paint on the surface of the cold side of the sheathing and 25 mm glass fibre insulating board;
5. 25 mm polystyrene bead board insulation;
6. 25 mm extruded polystyrene insulation.

Appendix F contains a list of the permeance and thermal resistance values for each material and the composite panel.

The climate simulator in the Building Science Laboratory at the University of Toronto was used to create two different winter conditions: freezing and non-freezing temperatures at the gypsum sheathing. The cold-side air temperatures for the above and below freezing simulations were approximately 0°C and -12°C respectively. In both cases, the cold-side relative humidity was between 90% and 100%. During both the freezing and non-freezing tests, the temperature of the gypsum sheathing was maintained at the dew point temperatures of 7°C and -2°C respectively, so that the sheathing would become the first condensing surface. Air leakage was minimized by equalizing the air pressure between the warm side and the cold side of each test panel.

The tests proceeded until the gypsum sheathing reached a steady-state moisture content. The time to reach equilibrium was estimated using the MOIST computer simulation program (Burch & Thomas, 1993). MOIST is a finite difference analysis software package used for predicting heat and moisture transfer through building envelopes. According to the finite difference analyses, the test panels with no protection on the warm side required fifteen days of exposure to attain steady-state conditions while only five days of testing were required for the protected walls.

In all tests, the gypsum sheathing and cold-side insulation were weighed immediately before and after each test to determine the amount of water absorbed during testing. In order to calculate their moisture content after testing, both of these wall components were dried to 0% moisture content. Generally, the insulation dried very quickly, but a two-stage process was required for drying the gypsum sheathing.

The two-stage process used to find the dry weights of the gypsum sheathing samples involved the following steps. First, all pieces of gypsum sheathing were dried to an equivalent moisture content after testing. Next, representative samples were completely dried to 0% moisture content in a desiccating box using DRIERITE desiccant.[3] Desiccant drying of the wall components was used instead of oven drying to avoid the extraction of chemically combined water from the gypsum. The representative sample moisture contents after the first drying stage were then calculated using the following equation:

$$\gamma_1 = \frac{m_{w1} - m_d}{m_d} \qquad [2\text{-}1]$$

where

$\gamma_1$ = sheathing moisture content after the first drying stage;
$m_{w1}$ = mass of the sheathing after the first drying stage [g];
$m_d$ = dry mass of the sheathing [g].

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[3] DRIERITE is a desiccant composed of 97% $CaSO_4$, and has a relative humidity under 1% at room temperatures.

The moisture contents of all the sheathing samples after exposure to test conditions were calculated based on the average moisture content of the representative samples. The following equation was used to determine the overall moisture content for the sheathing samples:

$$\gamma_0 = \frac{m_{w0} - \dfrac{m_{w1}}{\gamma_1 + 1}}{\dfrac{m_{w1}}{\gamma_1 + 1}} \qquad [2\text{-}2]$$

where

$\gamma_0$ = sheathing moisture content after the test period;
$m_{w0}$ = mass of the sheathing after the test period [g].

It is also useful to know how much moisture is being held by each wall component. For the non-freezing tests, the amount of moisture that was retained by the warm-side insulation and the amount that diffused into the guardroom were not measured. Therefore, the moisture distributions for the non-freezing tests were determined by a combination of theoretical predictions and actual measurements. For the subsequent freezing tests, the warm-side insulation was weighed before and after testing.

To aid in determining the amount of moisture passing entirely through the test panel, the experimental procedure was refined and aluminum catch plates were installed on the cold side of the unprotected test panels during the freezing tests. Any moisture diffusing through the wall froze on the aluminum plates and was then measured at the end of the test period. The amount of moisture diffusing through the wall was estimated for the protected test panels during the freezing tests, since the catch plates were not available during earlier tests.

Finally, the two test panels that were judged to have performed best during the non-freezing tests were re-tested, again under non-freezing conditions, using the refined procedure. These panels were re-tested in order to compare moisture distributions in the wall components of non-freezing tests with distributions in freezing tests. Accordingly, by using the refined procedure, the amount of moisture entering each component was measured and a mass balance was carried out.

## 2.2APPARATUS DETAILS

### 2.2.1 Environmental Chamber

A chamber was built into the wall that separates the warm room and the guardroom in the environmental simulator. The purpose of the chamber was to support a precisely controlled environment on the warm side of the test panels. The guardroom was used to dampen temperature fluctuations in the cold room of the simulator. The air temperature on the cold side of the test panels in the guardroom was much colder than required for the experiments; hence, a heater was used to control and increase the guardroom temperature.

The test chamber, shown in Figure 2-2, consisted of a 0.59 x 0.59 x 0.59 m (2' x 2' x 2') hollow plywood box having one side open to the guardroom. Two sheets of 6 mil polyethylene lined the interior of the chamber. The chamber contained a light bulb to heat the chamber, a saturated salt solution reservoir to supply a specific humidity, a fan to circulate humidity, and a bottle of distilled water to keep the wet bulb saturated. The sides of the chambers facing the warm room were lined with 60 mm (2.5") of glass fibre insulation board and an air barrier to dampen the influence of any temperature fluctuations occurring in the warm room.

The environmental chamber was oriented so that its open side faced the guardroom, allowing installation of the test panels. Between the test panels and the open space inside the chamber was a SBPO air barrier and 110 mm (4.5") of insulation. The purpose of the insulation and the air barrier was to evenly distribute the vapour over the face of the wall panel. Air leakage was presented by sealing the air barrier to the interior of the chamber with weather stripping. As an additional precaution against air leakage through the test panels, the air pressures in the guardroom and the environmental chamber were equalized by means of a small diameter tube.

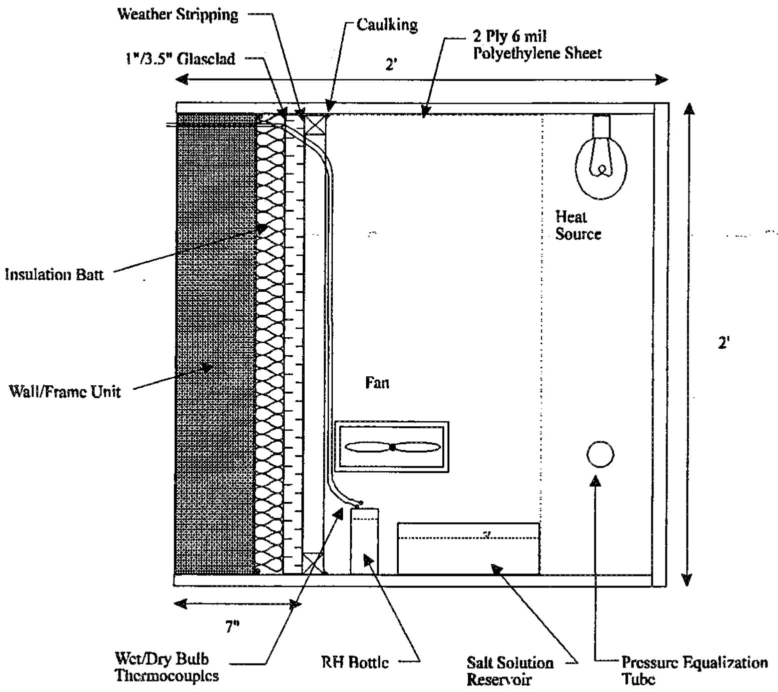


**Figure 2-2: Environmental chamber.**

### 2.2.2 Test Panels

Figure 2-3 is a diagram of a test panel with its surrounding frame. Each test panel was surrounded by a frame of 49 x 98 mm (2" x 4") strips of extruded polystyrene insulation wrapped in cellulose-based tape. The polystyrene was wrapped in cellulose-based tape to reduce moisture penetration by vapour diffusion and adsorption. The frame acted as an insulator and provided a tight fit between the environmental chamber and the test panel. The panels were connected to the frame by first inserting the sheathing board into grooves in the polystyrene and then taping the frame to the warm side of the sheathing to prevent the collection of water in the frame.

Troughs were cut into the frame to collect any condensate not absorbed on the warm or cold surfaces of the gypsum sheathing. These troughs directed condensate to containers located in the warm room, where it could be measured. Testing under non-freezing conditions revealed that almost all of the non-absorbed condensate appearing on the warm side of the sheathing was held by the batt insulation instead of flowing into the collection containers. Therefore, in subsequent tests under freezing conditions, the amount of moisture absorbed in the batt insulation was measured.

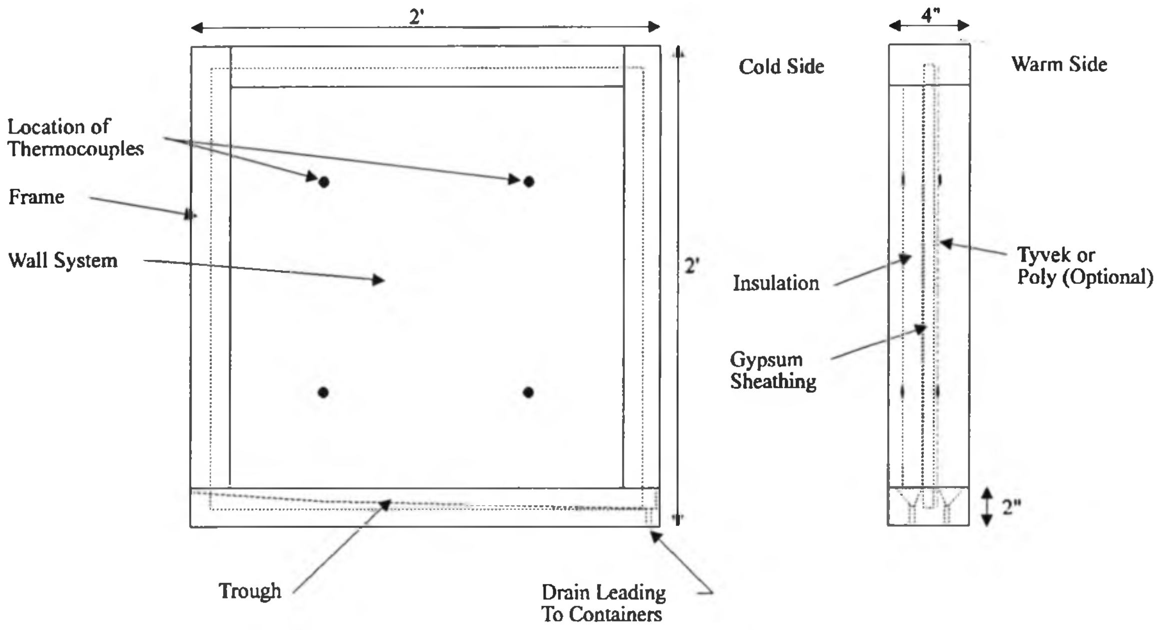


Figure 2-3: Wall frame with test panel in place.

### 2.2.3 Temperature and Vapour Pressure Controllers

The temperatures on the warm and cold sides of the gypsum sheathing were controlled by an HP and an IBM system. The IBM system controlled the temperature in the warm room, as well as in the guardroom. The HP system controlled the temperature inside the environmental chamber using the four thermocouples shown in Figure 2-3, The HP system also recorded the temperature for both the warm and cold surfaces of the test panels. The average chamber temperature for each panel is listed in Appendix D.

Relative humidity inside the environmental chamber was maintained with a saturated NaCl solution reservoir (Wexler and Hasegawa, 1954). The relative humidity was recorded by means of two J-type thermocouples, one of which was wrapped in a damp cloth (the wet bulb), and the other exposed to the air (the dry bulb). The wet bulb cloth was continuously fed by a bottle of distilled water placed inside the chamber. The thermocouples were situated in front of a fan, which was also used to distribute the humidity evenly around the chamber. The saturated salt solution produced a relative humidity of approximately 75% for a typical interior chamber temperature of 20°C. The relative humidity of the cold side of the wall did not need any type of control mechanism, as it rarely varied outside the desired 90% to 100% range.

A summary of the temperature and relative humidity levels attained at the various locations in the samples is listed in Table 2-1.

**Table 2-1: Summary of temperature and relative humidity levels.**

| | | Environmental Chamber | Gypsum Sheathing Surface | Guardroom | Cold Room |
|---|---|---|---|---|---|
| Temperature | non-freezing | 21 °C | 7 °C | 0 °C | -10 °C |
| | freezing | 20 °C | -2 °C | -12 °C | -25 °C |
| Relative Humidity | non-freezing | 75% | 100% | 90-100% | 100% |
| | freezing | 75% | 100% | 90-100% | 100% |

# 3. EXPERIMENTAL RESULTS

This chapter contains the results from laboratory tests of the wall panels described in Chapter 2. The gypsum test panels were exposed to steady-state non-freezing and freezing conditions until the exterior gypsum sheathing approached equilibrium moisture content. In this chapter, the net moisture gain of the wall components are examined because they are indicators of the relative performance of the wall systems. The moisture contents of the exterior gypsum sheathing are presented to indicate how well each envelope system managed moisture under unfavourable condensation conditions. The moisture content of the gypsum sheathing can also be used to identify which walls may be more susceptible to moisture or moisture-induced problems. These problems include the formation of mould and mildew, the corrosion of steel studs, and the deterioration of exterior brick.

At the end of this chapter, details on the preliminary field trials of two full-scale walls are also presented. The trials were performed in Calgary, Alberta, from November 1994 to February 1995. Unlike the laboratory test panels, the full-scale wall sections were exposed to fluctuating outdoor weather conditions. The preliminary field tests were carried out in order to explore possible differences in behaviour between field and the laboratory-tested walls.

## 3.1 MOISTURE SUPPLIED TO LABORATORY TEST PANELS

The amount of moisture supplied to each test panel is listed in Table 3-1. The moisture was supplied from a salt bath placed on the warm side of the test panel in the environmental chamber. This moisture was permitted to enter the test panels by vapour diffusion. In order to maintain a constant temperature at the warm side of the gypsum sheathing, the air temperature in the environmental chamber was controlled and allowed to fluctuate as required.

Differences in the average environmental chamber temperature for the tests resulted in slightly different vapour pressure gradients across the materials as shown in Table 3-2. For non-freezing tests, the vapour pressure difference between the environmental chamber and the warm side of the gypsum sheathing was, on average, 864 Pa.

## Table 3-1: Total amount of moisture supplied to each test panel.

### Non-Freezing Tests

| Wall Type | | Test Duration | Total Moisture Supplied (g) | Average Moisture Supplied (g) | Ratio to Unprotected |
|---|---|---|---|---|---|
| Warm Side | Cold Side | | | | |
| Unprotected | Fibreglass Board | 15 Days | 406 | 438 | 1.0 |
| | Fibreglass & SBPO | | 377 | | |
| | Fibreglass & Bldg. Paper | | 445 | | |
| | Paint & Fibreglass | | 518 | | |
| | Bead Board | | 549 | | |
| | Extruded Polystyrene | | 334 | | |
| SBPO Protected | Fibreglass Board | 5 days | 174 | 125 | 3.5 |
| | Fibreglass & SBPO | | 120 | | |
| | Fibreglass & Bldg. Paper | | 100 | | |
| | Paint & Fibreglass | | 102 | | |
| | Bead Board | | 163 | | |
| | Extruded Polystyrene | | 92 | | |
| Polyethylene Protected | Fibreglass Board | 5 days | 110 | 132 | 3.3 |
| | Fibreglass & SBPO | | 168 | | |
| | Fibreglass & Bldg. Paper | | 105 | | |
| | Paint & Fibreglass | | 100 | | |
| | Bead Board | | 172 | | |
| | Extruded Polystyrene | | 136 | | |

### Retested Panels (Non-Freezing)

| Wall Type | | Test Duration | Total Moisture Supplied (g) |
|---|---|---|---|
| Warm Side | Cold Side | | |
| SBPO | Fibreglass Board | 5 days | 265 |
| Polyethylene | Fibreglass Board | 5 days | 170 |

### Freezing Tests

| Wall Type | | Test Duration | Total Moisture Supplied (g) | Average Moisture Supplied (g) | Ratio to Unprotected |
|---|---|---|---|---|---|
| Warm Side | Cold Side | | | | |
| Unprotected | Fibreglass Board | 15 Days | 835 | 856 | 1.0 |
| | Fibreglass & SBPO | | 840 | | |
| | Fibreglass & Bldg. Paper | | 995 | | |
| | Paint & Fibreglass | | 1245* | | |
| | Bead Board | | 978 | | |
| | Extruded Polystyrene | | 630 | | |
| SBPO Protected | Fibreglass Board | 5 days | 165 | 199 | 4.3 |
| | Fibreglass & SBPO | | 180 | | |
| | Fibreglass & Bldg. Paper | | 163 | | |
| | Paint & Fibreglass | | 227 | | |
| | Bead Board | | 269 | | |
| | Extruded Polystyrene | | 187 | | |
| Polyethylene Protected | Fibreglass Board | 5 days | 206 | 213 | 4.0 |
| | Fibreglass & SBPO | | 203 | | |
| | Fibreglass & Bldg. Paper | | 179 | | |
| | Paint & Fibreglass | | 237 | | |
| | Bead Board | | 265 | | |
| | Extruded Polystyrene | | 185 | | |

* This value excluded from calculations.

**Table 3-2: Average vapour pressures and pressure differences in laboratory tests.**

| Test | Average Vapour Pressure (Pa) | | | | |
|---|---|---|---|---|---|
| | Environmental Chamber | Gypsum Sheathing | Difference Across Warm-side Insulation | Guardroom | Difference Across Panel |
| Non-Freezing | 1865 | 1001 | 864 | 611 | 1254 |
| Freezing | 1753 | 517 | 1236 | 217 | 1536 |
| Re-tests | 2116 | 1001 | 1115 | 541 | 1575 |

Generally, more moisture entered the test panels during freezing tests; this increase is due to larger vapour pressure differences across the warm-side insulation. Larger vapour pressure differences during the freezing tests were the result of lower gypsum sheathing temperatures, which were required to achieve freezing conditions. The vapour pressure difference across the warm-side insulation for the freezing tests was approximately 1236 Pa.

It is important to notice that more moisture was supplied to the unprotected test panels than to the protected panels. This difference is attributable, in part, to different test durations. The protected test panels were only exposed to condensation conditions for five days, while the unprotected test panels were exposed for fifteen days.

## 3.2 MOISTURE DISTRIBUTION IN LABORATORY WALL COMPONENTS

After the test panels had been exposed to condensation conditions long enough to reach equilibrium, wall components were disassembled and weighed. For comparison purposes, it is useful to examine the amount of moisture in each component in terms of the percentage of total moisture entering the test panel. The actual mass of moisture gained can be calculated for each component by multiplying the percentage gain in each component by the total mass of moisture supplied (Table 3-1).

Moisture leaving the environmental chamber enters the test panel and can end up in one of four locations:

1. Warm-side insulation: Moisture that remained on the warm side of the gypsum sheathing is referred to as warm-side accumulation in this study. The warm-side accumulation represents the moisture that would be gained in the stud space insulation in an actual building envelope.
2. Exterior gypsum sheathing.

3. Cold-side insulation: This is the moisture remaining in the insulation on the cold side of the sheathing. Cold-side insulation represents the insulating sheathing typically placed in the air space of building envelopes.
4. Guardroom: Moisture that passes entirely through the test panel is referred to as diffused moisture. This moisture may have arrived here by vapour diffusion, liquid water diffusion, or air leakage, and represents the water that would enter into the air space of a building envelope.

These four locations are illustrated in Figure 3-1.

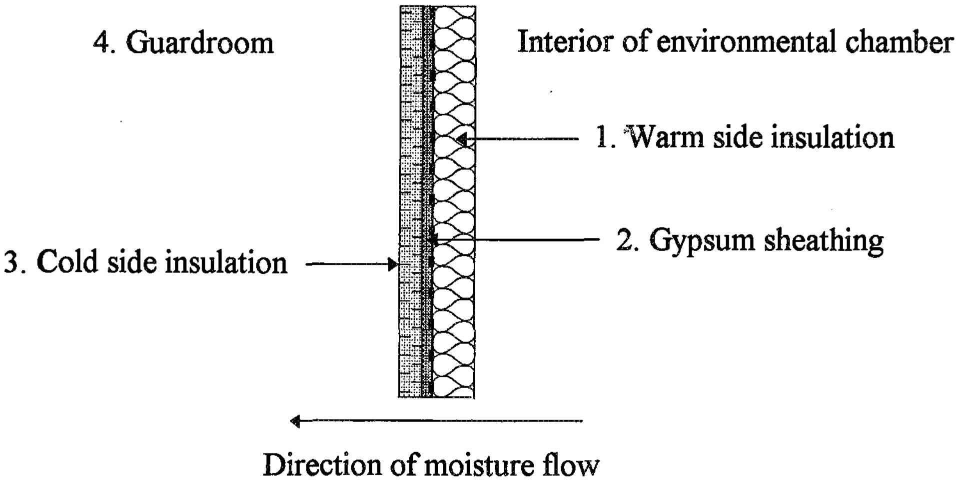


**Figure 3-1: Locations of possible moisture accumulation in a test panel.**

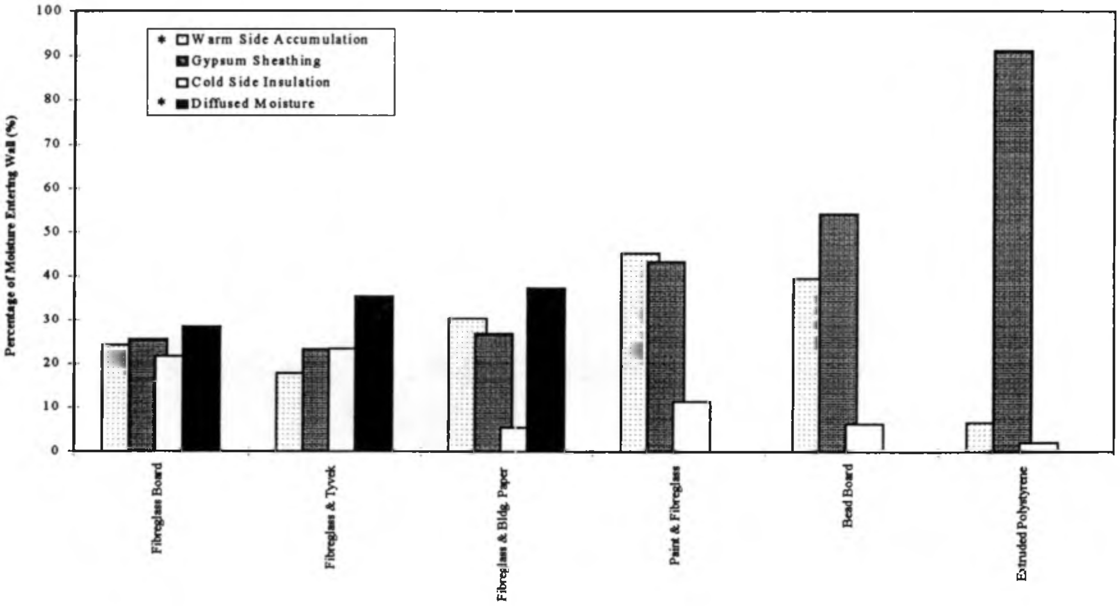
In the sections that follow, the amount of moisture in each wall component is presented in terms of the percentage of the total moisture entering the test panel for both non-freezing and freezing conditions.

### 3.2.1 Moisture Distribution: Non-Freezing Tests

The first series of tests were done at above freezing temperatures. During testing, the batt insulation, which was placed on the warm side of the gypsum sheathing to control the surface temperature of the gypsum, was found to absorb and retain some of the water that condensed at the gypsum surface. Unfortunately, the quantity of water retained by the batt insulation was not measured in this first series of tests. However, the total amount of water entering the wall, the amount of water retained in the gypsum sheathing, and the amount of water retained in the cold-side insulation were measured. In order to estimate the percentage of moisture retained on the warm side (warm-side accumulation), and the percentage of moisture diffusing to the cold side (diffused moisture), it was necessary to use theoretical values as determined by the finite difference program, MOIST.

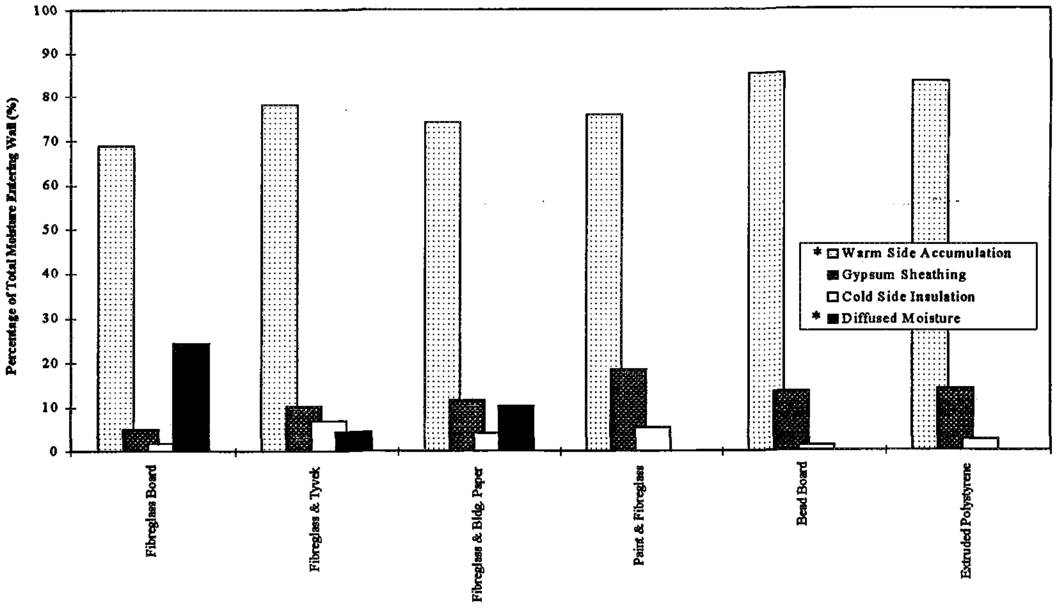
Following completion of the non-freezing tests, the experimental method was modified as described in Chapter 2. The warm-side batt insulation was weighed following each test, and aluminum catch plates were added to the cold side of each test panel. In this way, the "warm-side accumulation" moisture and the "diffused" moisture could be measured directly. To support the validity of the previous model estimates, two of the most promising wall sections were tested again under non-freezing conditions using the modified test method.

Figures 3-2 through 3-4 show the results of the tests carried out under non-freezing conditions. These figures show the results of the estimated moisture distribution in unprotected, SBPO protected, and polyethylene protected walls respectively.



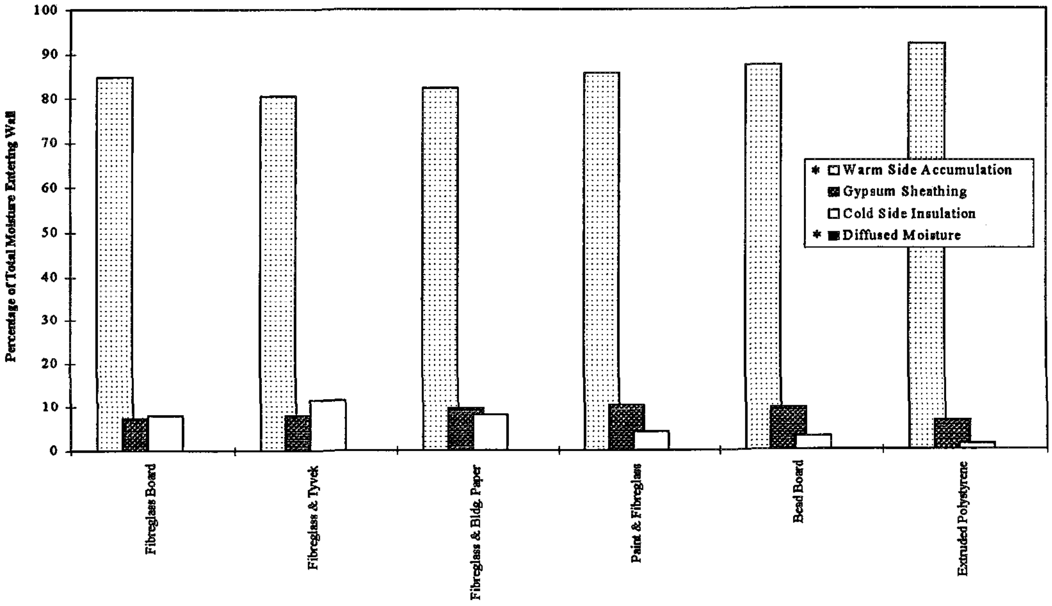
* Note: These values are not observed values, but are percent values based on theoretical model estimates of warm-side accumulation and diffused moisture.

**Figure 3-2: Moisture distribution in unprotected test panels under non-freezing conditions.**



* Note: These values are not observed values, but are percent values based on theoretical model estimates of warm-side accumulation and diffused moisture.

Figure 3-3: Moisture distribution in SBPO protected test panels under non-freezing conditions.

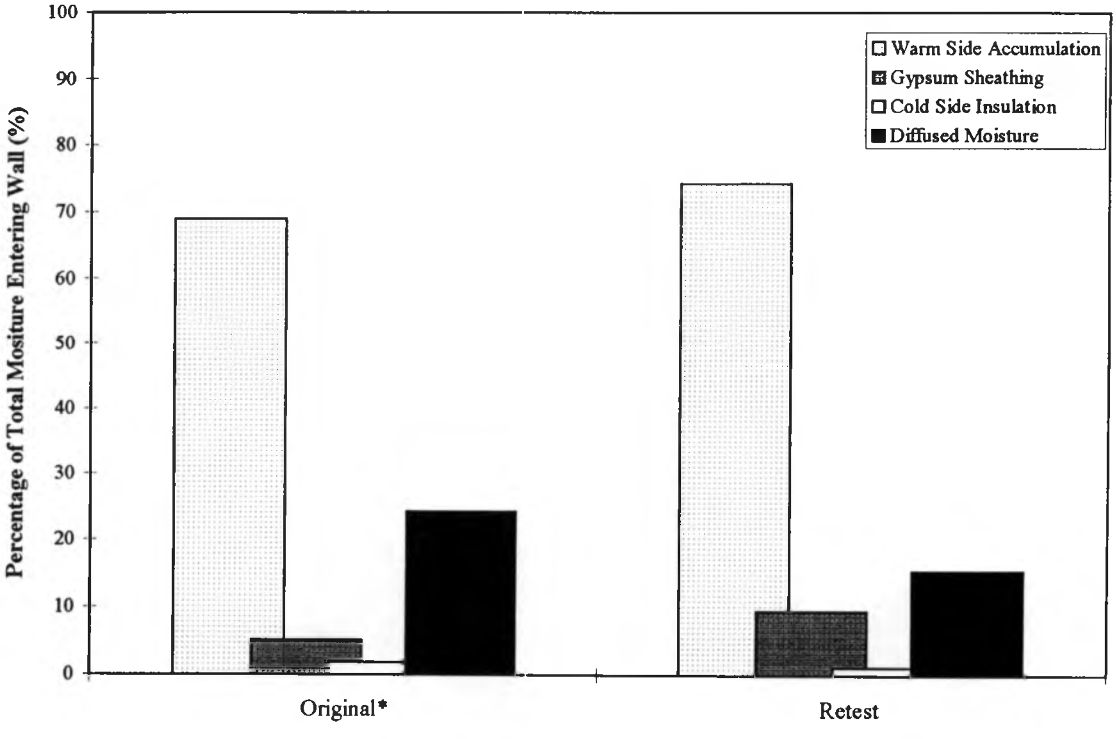


* Note: These values are not observed values, but are percent values based on theoretical model estimates of warm-side accumulation and diffused moisture.

Figure 3-4: Moisture distribution in polyethylene protected test panels under non-freezing conditions.

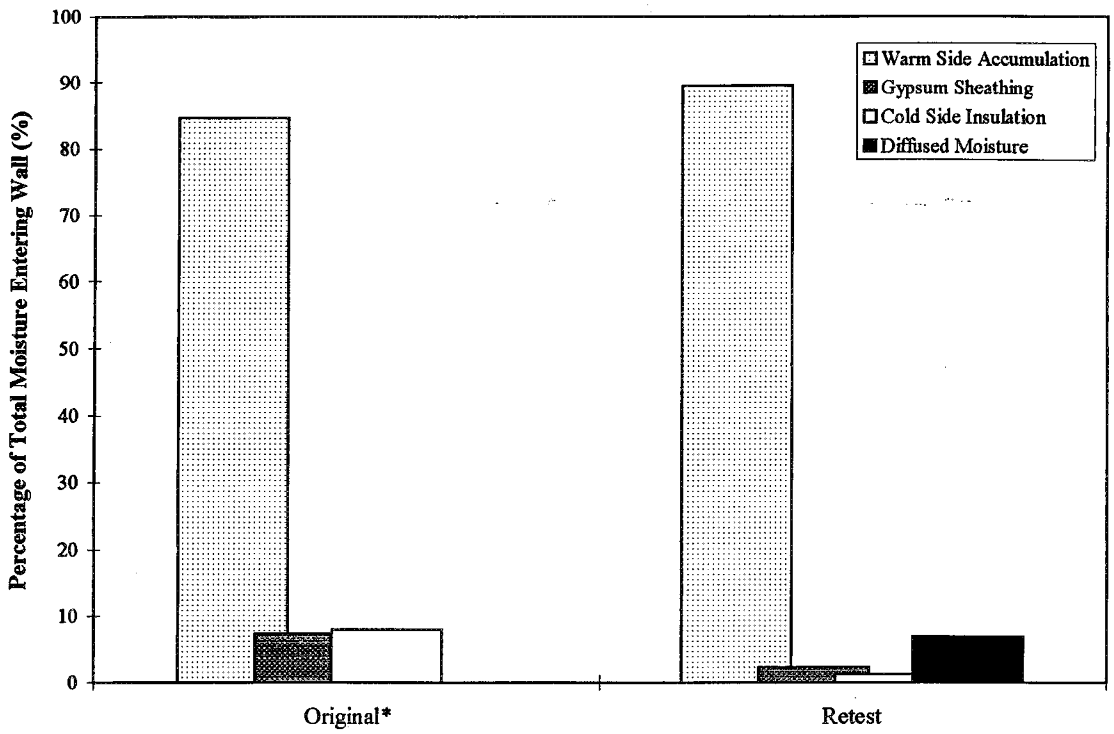
When all of the unprotected test panels were removed from the environmental chamber following testing, the lower portion of the gypsum sheathing was found to be damp and to have lost strength. Gypsum sheathing loses rigidity at higher moisture contents. As well, the warm-side batt insulation was found to contain large quantities of moisture, particularly in the protected test panels. This water, which did not drain as expected, was measured in the later tests when the experimental procedure was refined.

Two of the protected wall panels which were chosen on the basis of performance, were re-tested under non-freezing conditions using the modified test method. The two walls selected were protected with the SBPO and polyethylene and contained fibreglass insulation on the cold side of the sheathing. These two wall systems had both shown a relatively low moisture content in the gypsum sheathing under earlier non-freezing testing. The results of these tests are shown in Figures 3-5 and 3-6, together with the corresponding original test results presented previously in Figures 3-3 and 3-4.



* Note that warm-side accumulation and diffused moisture are theoretical quantities for this test panel.

**Figure 3-5: Moisture distribution in re-tested and original test panels with SBPO protection and fibreglass insulation.**



* Note that warm-side accumulation and diffused moisture are theoretical quantities for this test panel.

**Figure 3-6: Moisture distribution in re-tested and original test panels with polyethylene protection and fibreglass insulation.**

During the first eighteen hours of the re-testing, computer control of the guardroom temperature was lost and the temperature dropped to -10°C. To maintain a temperature of 7°C on the warm side of the gypsum sheathing, the environmental chamber rose to approximately 32°C. Because of this eighteen hour period, the average vapour pressure difference across the sample was 1575 Pa, far greater than the usual 1254 Pa for the non-freezing tests. Thus, the results derived from the modified tests, shown in Figures 3-5 and 3-6, may reflect the slight difference in exposure conditions from the original non-freezing test conditions.

It is evident from Table 3-1 that more moisture diffused through the wall during the re-tests than in the earlier non-freezing tests. It is also evident that the total diffused moisture is greater than expected. The presence of moisture is due in part to the brief period in which temperature control was lost and the vapour pressure on the warm side increased. However, this does not account for the significant differences in diffused moisture that appear in Figures

3-5 and 3-6. It is likely that, despite precautions, some moisture-laden air leaked past the wall assembly and onto the aluminum catch plate.

### 3.2.2 Moisture Distribution: Freezing Tests

Following the non-freezing tests, freezing tests were carried out on the test panels using the refined test procedure. Unlike the earlier non-freezing tests, in these freezing tests, the moisture that accumulated in the warm-side batt insulation was measured. Figures 3-7 through 3-9 show the actual percentage moisture distribution in the unprotected, SBPO protected, and polyethylene protected walls, respectively. Appendix E presents a table of the total amount of moisture retained by each component. During testing of the unprotected wall panels, the experimental procedure was further refined by the addition of aluminum catch plates on the cold side of the test apparatus. By using this apparatus, which has been described in Chapter 2, the amount of diffused moisture could be measured directly.

In all freezing cases, the majority of the moisture entering the panels remained at the interface between the gypsum sheathing and the warm-side insulation in the form of ice. In the case of the SBPO protected walls, this moisture appeared as a sheet of ice fused to both the SBPO barrier and the warm-side batt insulation. Similarly, in the polyethylene protected walls, this ice appeared between the polyethylene and the warm-side batt insulation.

The percentage of the total moisture remaining at this interface ranges between 50% and 72% for the unprotected walls. The permeance of the test panel does not appear to affect the percentage of moisture retained in the warm-side insulation. Walls protected with SBPO have noticeably higher moisture percentages in the warm-side batt insulation than the unprotected panels. Percentage values of warm-side accumulation range from 80% to 92% for the various walls. Again, there does not appear to be a relationship between the permeance of the walls and percentage of moisture in the warm-side insulation. Similarly, walls protected with polyethylene have noticeably higher moisture percentages in the warm-side batt insulation, ranging from 77% to 94%, than the unprotected panels. In the case of all the other walls, warm-side accumulation does not appear to be related to the permeance of the wall systems.

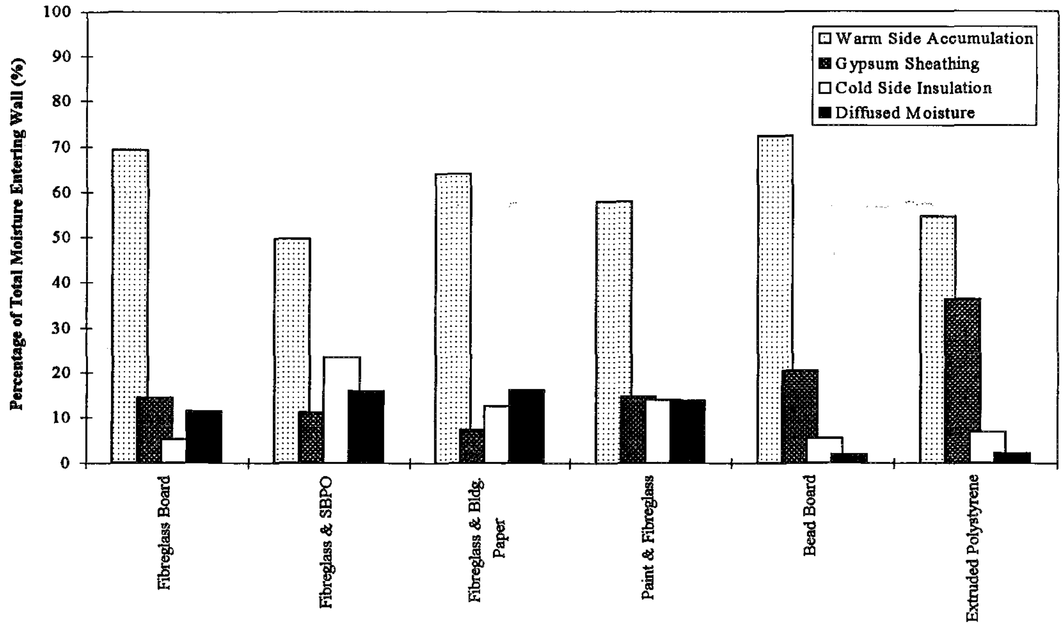
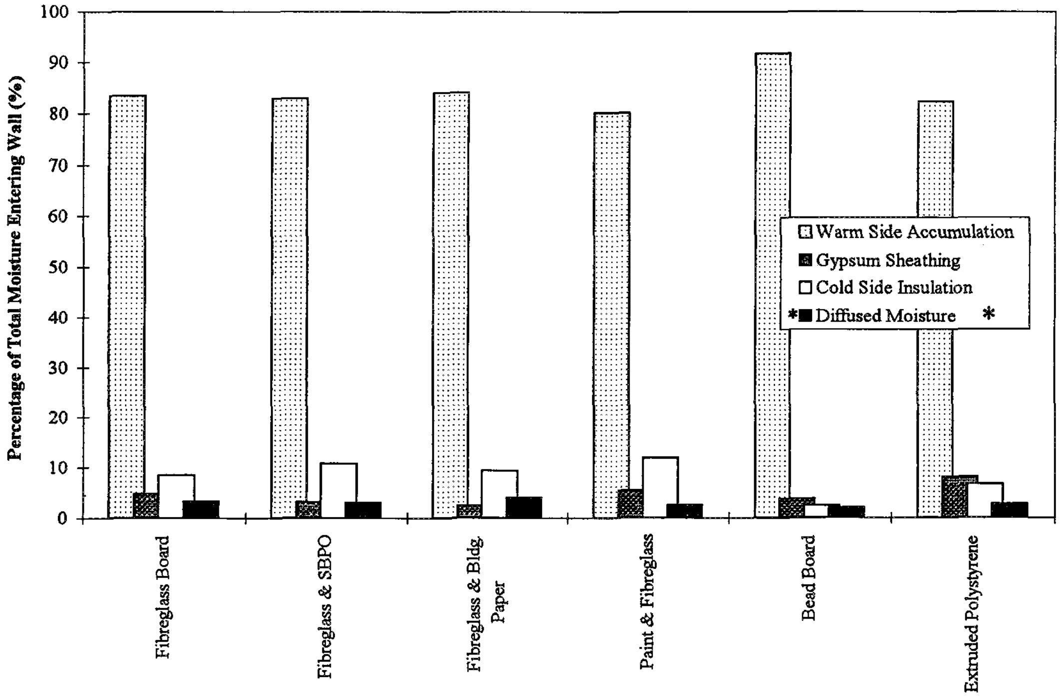
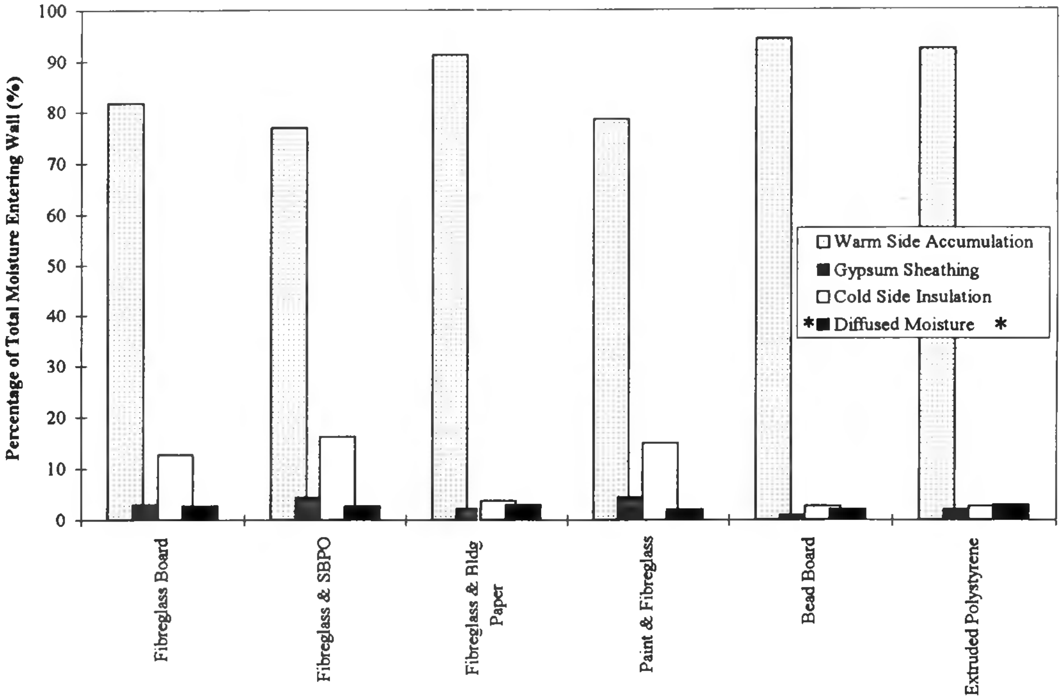


Figure 3-7: Moisture distribution in unprotected test panels under freezing conditions.



* Note: Percentage values of diffused moisture are based on estimated diffused moisture quantities, not direct measurements.

Figure 3-8: Moisture distribution in SBPO protected test panels under freezing conditions.



* Note: Percentage values of diffused moisture are based on estimated diffused moisture quantities, not direct measurements.

**Figure 3-9: Moisture distribution in polyethylene protected test panels under freezing conditions.**

## 3.3 MOISTURE CONTENT OF THE TEST PANEL COMPONENTS

The distribution of moisture in the test panel components is a useful means of evaluating wall performance. The moisture content of the wall components is another important indicator of how each test panel performs. In the laboratory tests, the gypsum sheathing was allowed to reach equilibrium moisture content when exposed to adverse condensation conditions. The equilibrium moisture content of the gypsum sheathing was determined for each test panel for both non-freezing and freezing tests. The corresponding moisture content of the cold-side insulation was also found. It must be remembered that the moisture content values for the cold-side insulation are not necessarily equilibrium moisture content values.

Figure 3-10 shows the moisture contents of the gypsum sheathing for the panels exposed to non-freezing conditions. The unprotected sheathing samples have moisture contents which vary between 4.2% and 14% for the various walls. In comparison, the protected walls have sheathing moisture contents with a narrower range between 1.0% and 1.7%.

Figure 3-11 shows the moisture contents of the gypsum sheathing for the panels exposed to freezing conditions. Like the non-freezing tests, the freezing tests show that unprotected walls have significantly higher sheathing moisture contents than the protected walls. The moisture content of the gypsum sheathing in these unprotected walls ranges between 3% and 8.6%, while all protected walls have sheathing moisture contents of approximately 1.0%.

Figure 3-12 shows the moisture contents of the cold-side insulation for the panels that were exposed to non-freezing conditions. The cold-side materials in the SBPO and polyethylene protected walls consistently have moisture contents lower than the unprotected walls.

Figure 3-13 shows the moisture content of the cold-side insulation for the panels that were exposed to freezing conditions. While the results vary more than the results of the non-freezing tests, once again it is clear that the protected panels have lower cold-side insulation moisture contents than the unprotected panels.

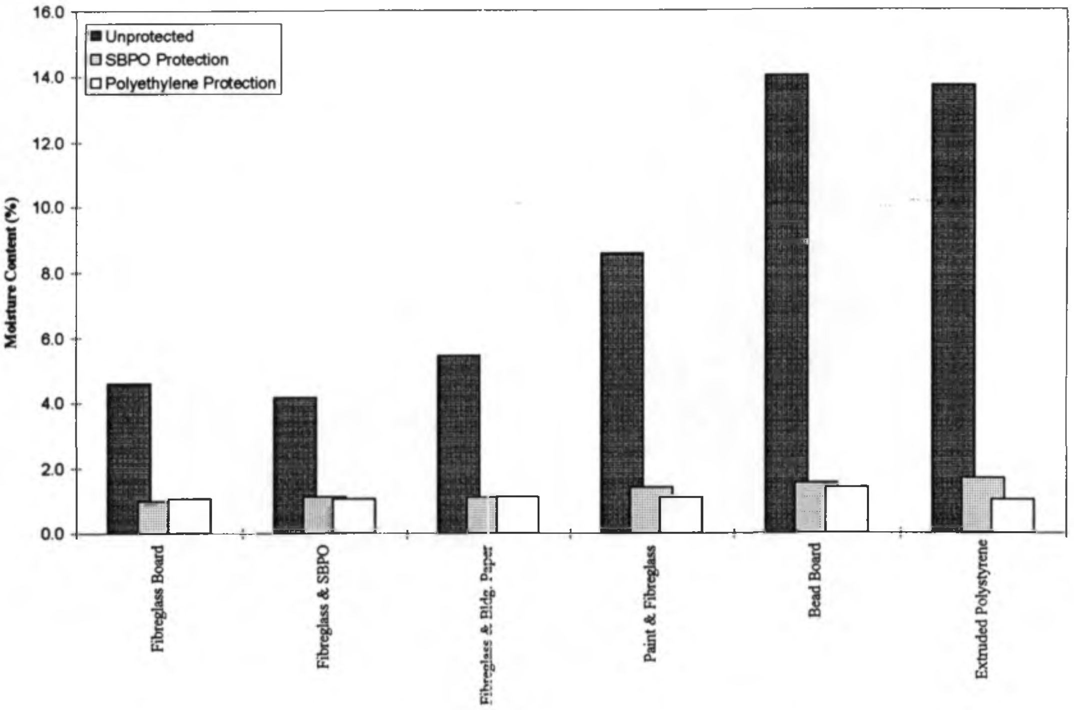


Figure 3-10: Gypsum sheathing moisture contents - non-freezing conditions.

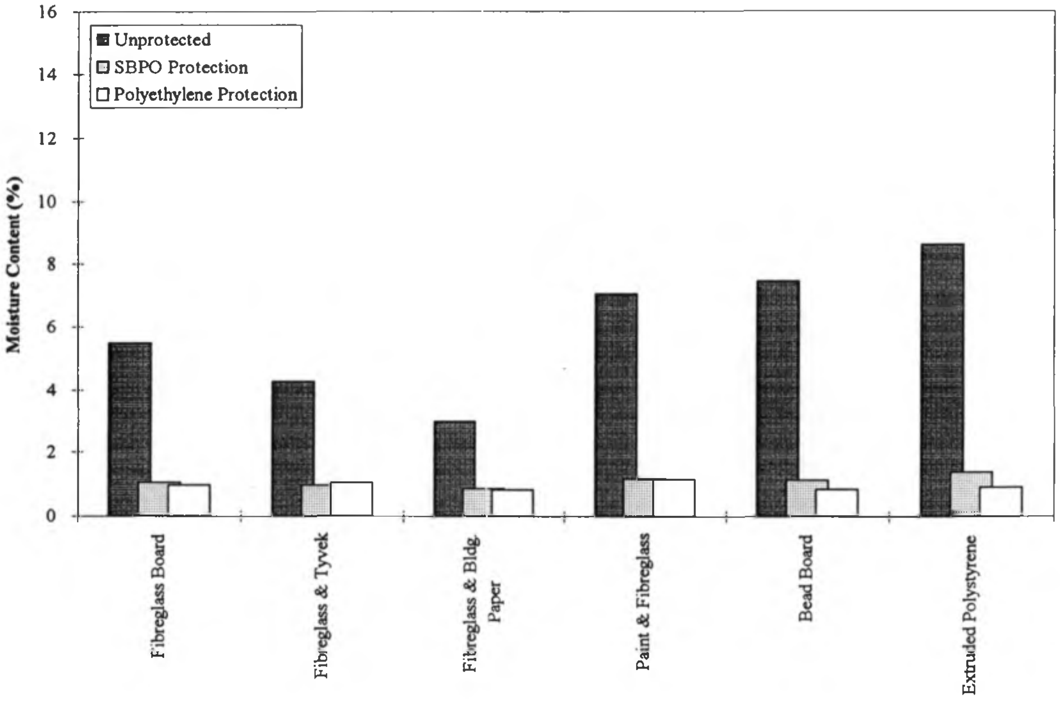


Figure 3-11: Gypsum sheathing moisture contents - freezing conditions.

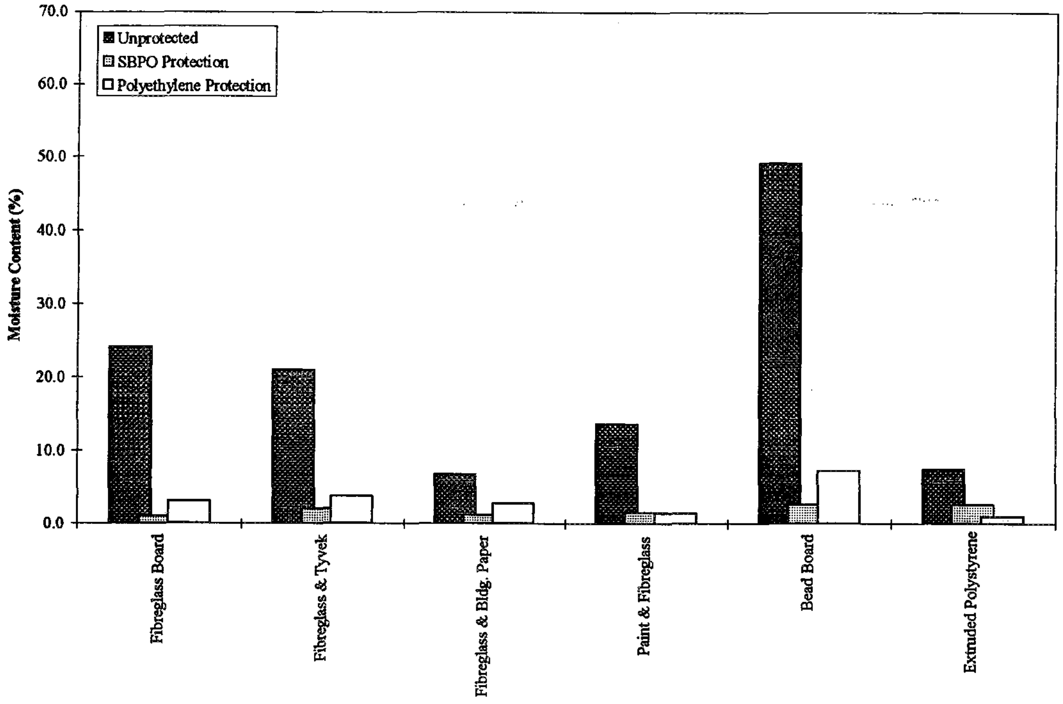


Figure 3-12: Cold-side insulation moisture content - non-freezing conditions.

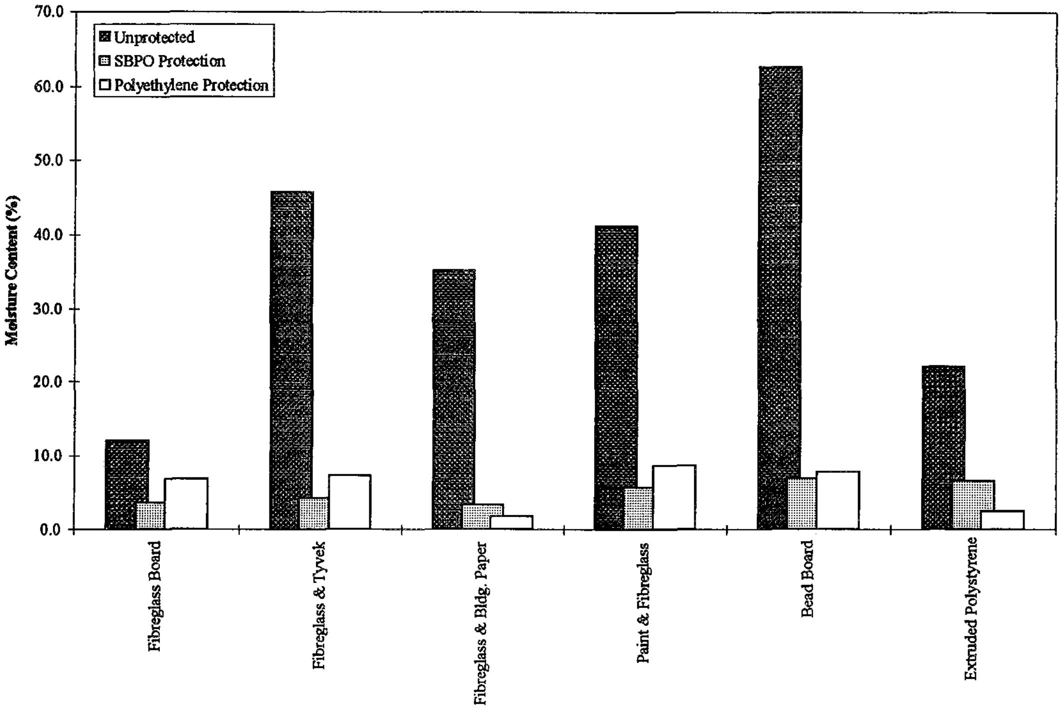


Figure 3-13: Cold-side insulation moisture content - freezing conditions.

### 3.4 SOURCES OF EXPERIMENTAL ERROR

There are a few possible sources of error that can lead to small inconsistencies in laboratory test results. Through prudent experimental design and careful operation and control, laboratory tests can yield reliable and enlightening results. However, there are always some errors that creep into experimental results despite a researcher's best efforts. During the research carried out here, there were several different sources of error that have affected the experimental results. In this section, sources of error will be identified and quantified where possible.

One source of error is related to the attempts that were made to keep the temperature of the gypsum sheathing constant. The temperature of the environmental chamber, which supplied moisture to the test panel by diffusion, was varied in order to keep the temperature of the warm side of the sheathing constant. The warm side temperature had to be increased because the thermal resistance of wall components decreased as the materials gained moisture. These variations caused different vapour pressure gradients for each test. Consequently, different amounts of moisture were supplied to each test panel.

Different amounts of moisture were also supplied to individual test panels because the thermal resistance of the section varied from panel to panel. By design, the surface of gypsum sheathing was held constant for all panels. Thus, test panels which had less outboard insulation required higher warm side conditions, and therefore, these panels were exposed to slightly higher vapour pressure gradients.

It was also found that small amounts of moisture could not be accounted for when a mass balance was carried out on the tests that used an aluminum catch plate. Typically, less than 30 grams of the total moisture supplied to the test panels were not found in any of the wall components or recorded as diffused moisture. This moisture could have ended up on the interior lining of the box, been absorbed by the test frame, or escaped from the chamber by air leakage through small cracks.

Air leakage may also account for the higher-than-expected values of moisture found in the cold-side insulation after some tests. The test apparatus was carefully air-sealed and a pressure equalization tube was used to equalize the pressure between the warm and cold sides of the panel. However, it is possible that some small openings existed and that pressure equalization was not rapid enough to counter the pressure changes induced by the refrigeration system.

Moisture contents of the cold-side insulation may have also been influenced by moisture from the guardroom wall. During non-freezing testing, liquid water was observed dripping into the test area. It is possible that some of this moisture may have been absorbed by the cold-side insulation. This potential problem was eliminated by the installation of a small flashing to direct moisture away from the test panels.

Finally, during the freezing tests, the presence of ice made it difficult to separate panel components. As a result, the gypsum moisture content measurements may have been affected. In unprotected tests, ice fused the gypsum sheathing and the warm-side insulation together. The two components were separated with a putty knife, leaving as much of the moisture with the batt insulation as possible. Frequently, some of the moisture could not be separated from the gypsum without damaging the sheathing. Leaving this additional moisture on the warm side of the sheathing would increase the moisture content of the gypsum sheathing slightly, while reducing the amount of moisture retained by the warm-side batt insulation.

## 3.5 PRELIMINARY FIELD TRIALS

In addition to the laboratory study, a preliminary field test of two full-scale walls was carried out. The field test wall assembly and results are presented below.

### 3.5.1 Field Sample Wall Assembly

Two full-scale wall samples were constructed to simulate the critical elements from insulated steel stud envelopes. Similar in design to the experimental test panels, the full-size wall samples were assembled as shown in Figure 3-14. The wall samples measured 380 mm by 2100 mm (15" x 83") in width and height. A 25 mm (1") layer of permeable insulation (air filter media) covered the warm side of the gypsum sheathing. The cold side of the sheathing was covered with a SBPO barrier. The final wall component, a plywood panel, was placed on the cold side to create a sealed air cavity next to the SBPO layer. The two samples were the same, except that the interior face of the gypsum sheathing of one sample was protected with a SBPO barrier, while the other wall sample was left unprotected.

The wall samples were situated so that the cold side was subjected to the outdoor winter season climatic conditions. The warm-side conditions were controlled by means of a heater, humidifier, and fan. The warm side was heated and humidified to the point where condensation occurred on the warm face of the gypsum sheathing.

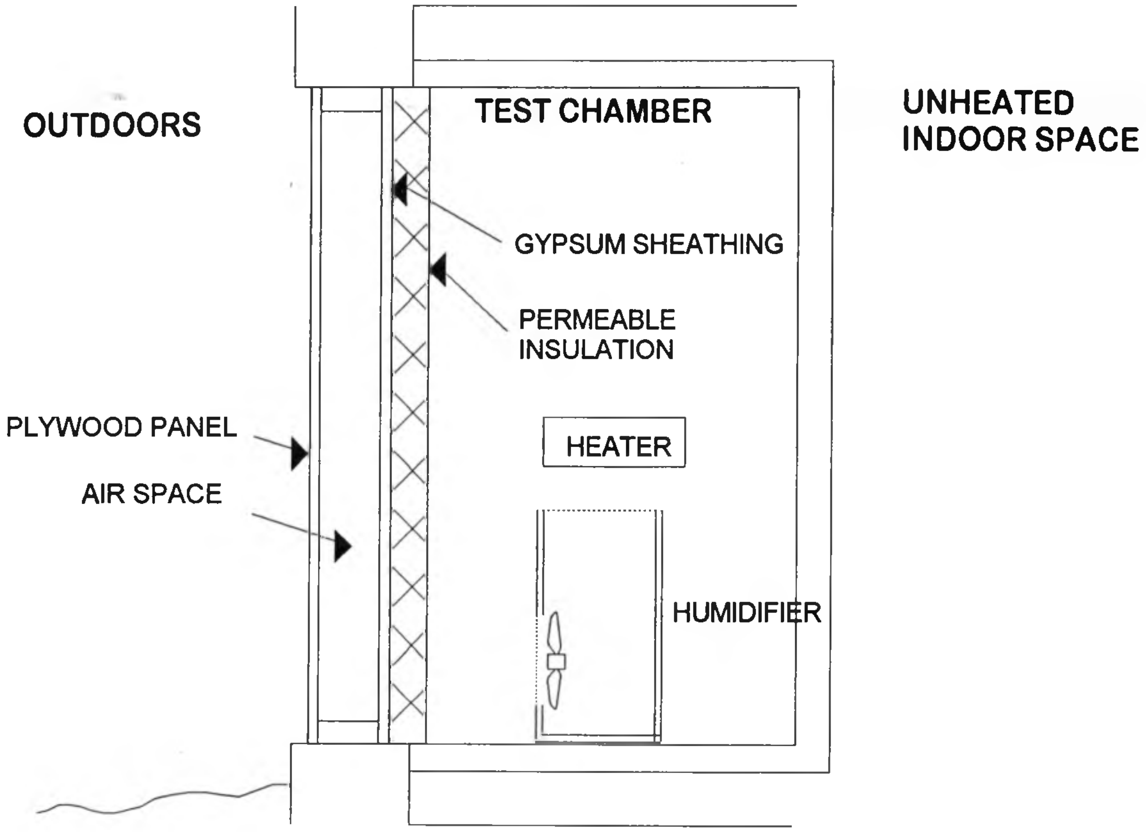


**Figure 3-14: Test arrangement and apparatus for field trials.**

### 3.5.2 Field Trial Results

The field trials were performed in Calgary, Alberta over the period from November 1994 to February 1995. During a 68-day period, the temperature and weight gain of each wall sample was recorded periodically. The temperature of the indoor chamber, the gypsum sheathing, and the outdoor plywood siding was measured daily.

The periodic temperature and weight gain measurements are shown in Figure 3-15. The increase in the moisture content of the sheathing in the unprotected wall sample was greater than the moisture content increase in the wall sample protected on the warm face with a SBPO barrier. The rate of increase in the moisture content varied throughout the test period and varied between the two wall samples. At various times throughout the test period, the weight gain of the two wall samples approached similar levels. Toward the end of the 68-day test period, the moisture content of the SBPO protected panel again approached that of the unprotected panel.

During two of the coldest periods, days 24 to 28 and days 47 to 60, freezing of the humidifier may have caused a reduction in moisture supply; however, this reduction does not appear to be reflected in the moisture content measurements. The rapid drop in moisture content of the unprotected panel from day 38 to day 46 may have been due to experimental measurement error.

Visual examinations for signs of condensation were made periodically. Condensation was visually detected only over the lower quarter of each wall sample. Condensation as liquid or frost was evident on the inner face of the SBPO barrier on the protected wall, as well as on the inner face of the unprotected gypsum. Condensation was also observed on the inner face of the outermost layer of SBPO, and on the inner face of the exterior plywood siding.

The gypsum sheathing panels were removed on day 69 and cut horizontally into seven 305 mm (1') sections. The sections were weighed and allowed to dry for several weeks in an indoor environment of approximately 27°C and 25% relative humidity. The measured moisture loss due to drying the sections under these conditions has been listed as a percentage for each section in Table 3-3. These values are an indication of how the moisture was distributed within the sheathing by the end of the test period. Generally, most of the moisture accumulated in the lower 600 mm of the wall, while the upper 600 mm of the wall remained dry in both protected and unprotected walls.

While the methods of drying and weighing the samples may have introduced some error into the measurements, the final moisture content of the undivided gypsum panel agreed fairly well with the average moisture content determined from the seven sections. The moisture content of the unprotected, undivided gypsum sample was 9.8%, while the average moisture content of the seven sections was found to be 9.1%. Similarly, the undivided, protected gypsum sample had a moisture content of 7.7%, while the seven sections produced an average moisture content of 7.9%.

**Table 3-3: Moisture loss (percentage) in gypsum sections after drying to uniform conditions.**

| | Height of section above base of wall sample. (mm) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 0-305 | 305-610 | 610-915 | 915-1220 | 1220-1525 | 1525-1830 | 1830-2130 |
| Unprotected | 37% | 20% | 4% | 2% | 1% | 0% | 0% |
| Protected | 35% | 14% | 4% | 1% | 1.5% | 0% | 0% |

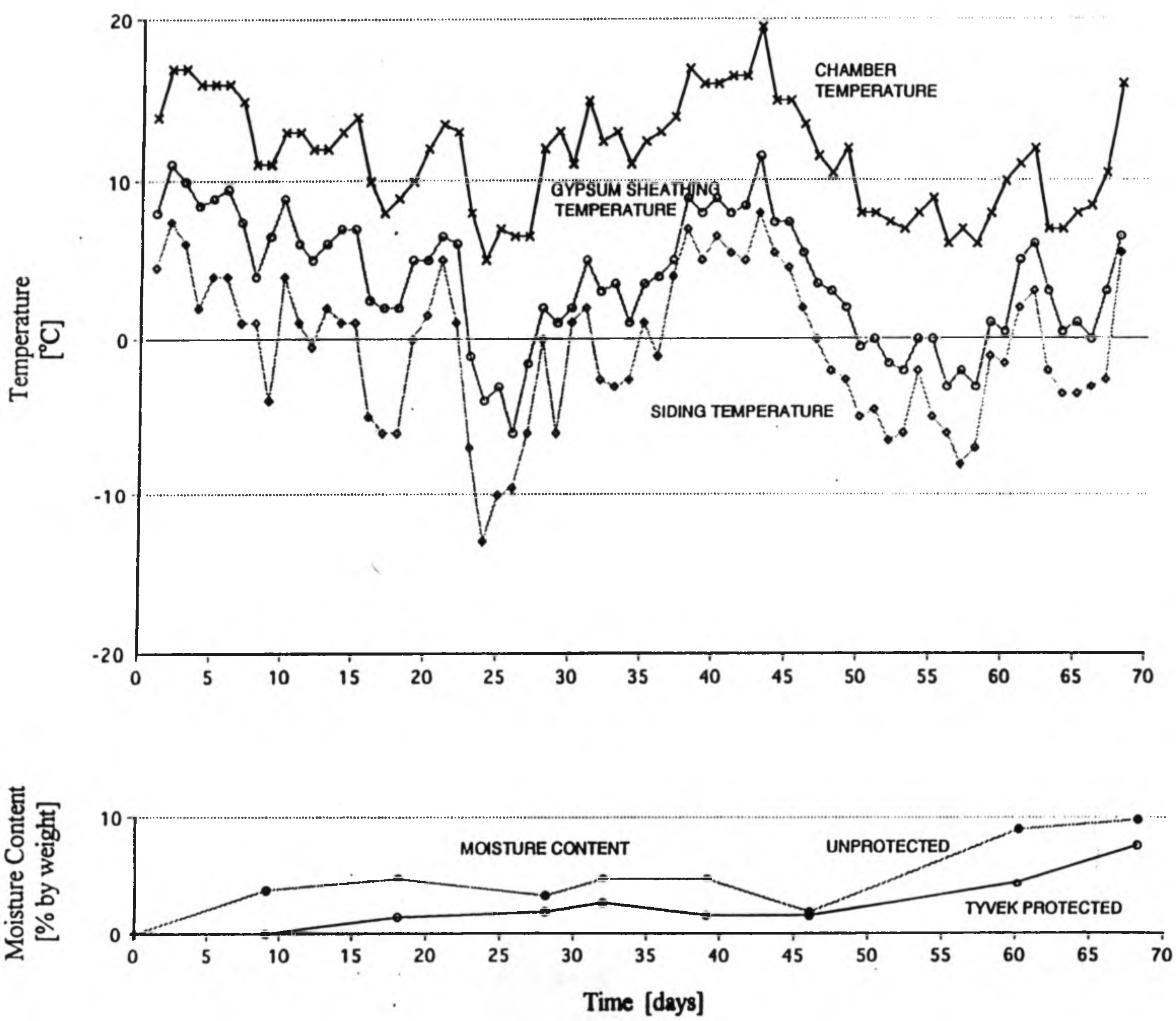


Figure 3-15: Temperature and Moisture Content Measurements from full-scal field trials.

# 4. DISCUSSION

The occurrence of condensation inside insulated steel stud backing envelopes can cause many problems. Liquid moisture in the stud space can significantly decrease the thermal resistance of the warm-side insulation and corrode the steel studs. If sufficient quantities of moisture accumulate in the lower track, then even the interior finishes may be damaged. However, condensation causes the most damaging problems to the building envelope when it occurs at the exterior gypsum sheathing. Gypsum sheathing moisture contents in excess of 1.4% are high enough to support mould and mildew growth (Burch and TenWolde, 1993); such growths may raise health concerns for occupants. Furthermore, high moisture contents in the gypsum sheathing reduce its rigidity, requiring other wall components to provide lateral resistance. Moisture problems in the gypsum sheathing are compounded by the fact that they are occurring in a concealed space where detection is difficult and access is limited.

To determine which insulated wall systems perform best when exposed to condensation conditions, eighteen different test panels were exposed to vapour diffusion. Both non-freezing, as well as freezing conditions, were tested for each panel. Wall performance was evaluated by determining the distribution of moisture in the wall components and the moisture content of both the gypsum sheathing and the cold-side insulation. Condensation conditions were maintained until the gypsum approached an equilibrium moisture content.

In order to maintain condensation conditions, there existed a continuous supply of moisture in the warm-side environmental chamber. To facilitate comparisons, attempts were made to supply moisture by diffusion to the test panels at a more or less constant rate. As shown in Table 3-1, this approach resulted in variations in the quantity of moisture supplied to each test panel. Such variations can be explained by examining the factors which gave rise to these variations.

One factor that influenced the quantity of moisture supplied to a test panel was the duration of the test. In Table 3-1, the ratio of the average moisture supplied to non-freezing, unprotected panels to the average moisture supplied to non-freezing, SBPO protected panels is shown to be 3.5. Since the unprotected tests ran three times longer than the protected tests, ratios around 3 are expected. A similar ratio was found for the non-freezing, polyethylene protected panels. Although the values are higher, similar ratios were found for the freezing tests.

The amount of moisture supplied by the reservoir in the environmental chamber is not only a function of time, but it is also a function of the vapour pressure gradient across the warm-side insulation. Figures 5-1 and 5-2 show the relationship between the amount of water supplied by the reservoir and the average vapour pressure difference across the warm-side insulation for each of the fifteen and five day tests respectively.

It is apparent from these figures that the amount of water supplied by the reservoir is a function of the vapour pressure difference across the warm-side insulation and innermost SBPO layer. The warm-side environmental chamber temperature was varied in order to maintain a constant temperature at the gypsum surface. It is the warm-side temperature of the environmental chamber which determines the vapour pressure difference. A higher environmental chamber temperature must be maintained when lower thermal resistance materials, such as bead board, are tested. This higher temperature results in a larger vapour pressure difference across the warm-side insulation. Consequently, test panels that had a lower thermal resistance received more moisture.

Moisture moves from the reservoir, through the innermost SBPO layer and the warm-side insulation, to the gypsum sheathing almost exclusively by diffusion. According to Fick's Law of diffusion, the amount of moisture leaving the reservoir should be a function of: the permeance of the outer SBPO covering and the warm-side insulation; the area of the sample; the duration of the test; and, the vapour pressure difference across the SBPO and warm-side insulation. The slopes of the linear regression lines in Figures 5-1 and 5-2 reveal this functional relationship. As expected, the slope of the line for the fifteen-day tests is approximately three times the slope of the line for the five-day tests.

In Figures 5-1 and 5-2, the data do not all lie along these straight lines. In the case of the five-day tests, departures from these lines may be due to changes in permeance during the course of the each test. Accumulating moisture may lead to a change in the permeance of the warm-side insulation. During the five-day tests involving the SBPO and

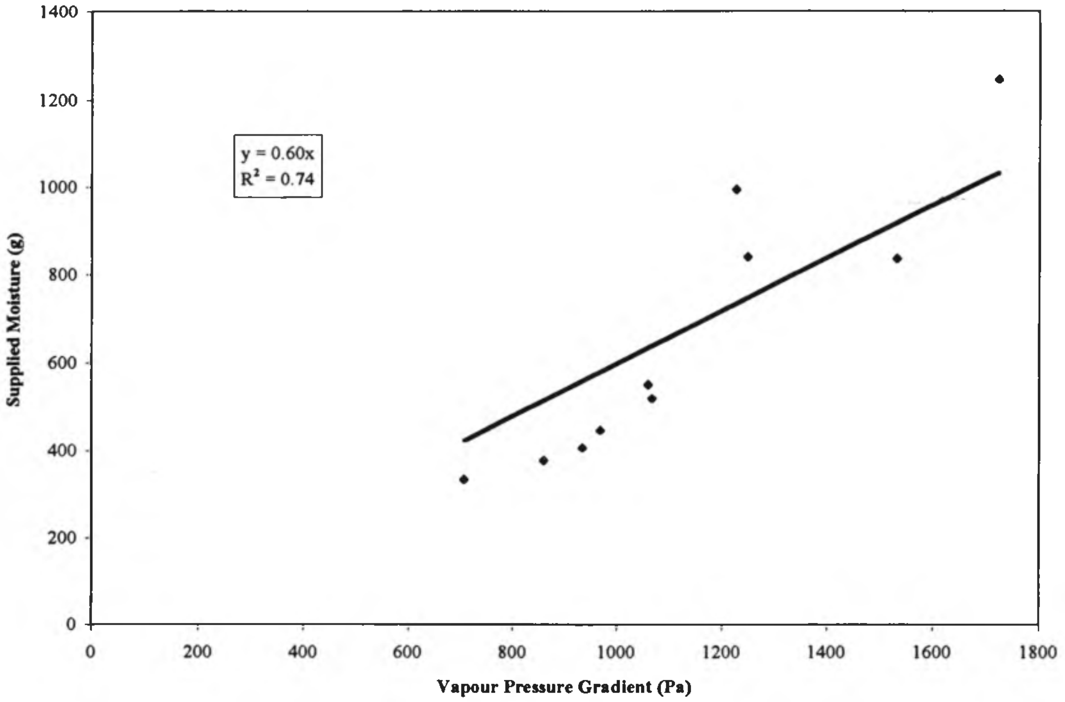


Figure 5-1: Vapour pressure gradient versus supplied moisture for fifteen-day tests.

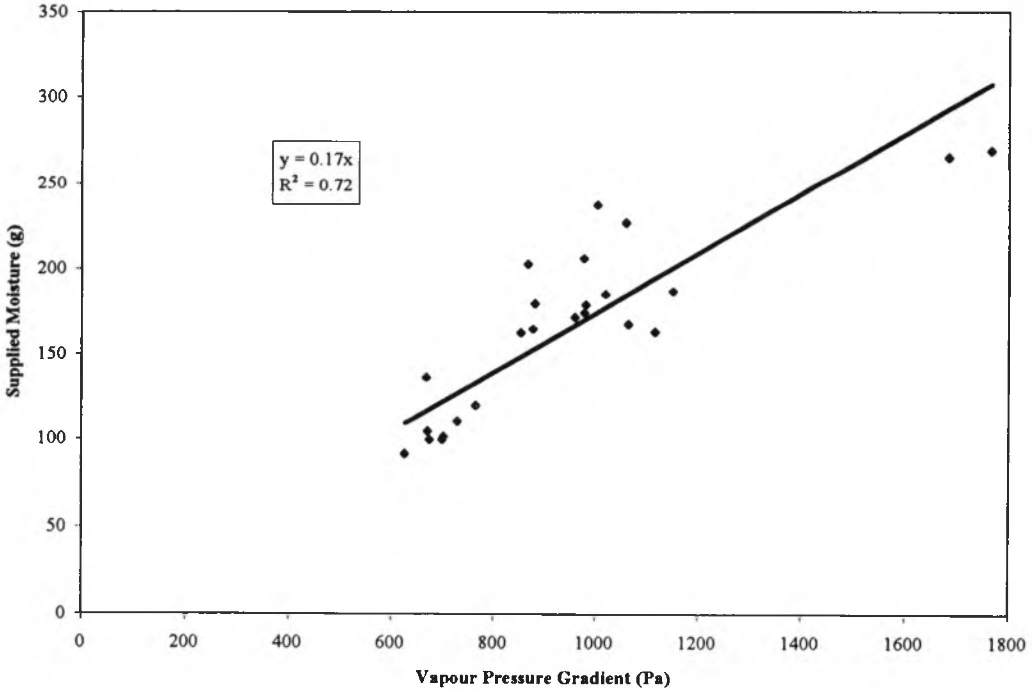


Figure 5-2: Vapour pressure gradient versus supplied moisture for five-day tests.

polyethylene-protected gypsum walls, condensation on these protective surfaces was observed to wet adjacent areas of the batt insulation, particularly, the lower areas. The presence of this water may have increased the permeance of the warm-side insulation, and consequently, the amount of moisture supplied by the reservoir.

Under ideal conditions, constant moisture supply rates are preferred. However, in choosing to maintain both the temperature at the warm face of the gypsum and the vapour pressure difference across the gypsum and cold-side materials, then the environmental chamber temperature had to be varied. This resulted in different moisture supply rates for each sample. However, the vapour pressure gradient across the gypsum and the cold-side materials remained the same for all freezing samples and for all non-freezing samples. Problems associated with different supply rates could have been avoided by fixing the environmental chamber temperature and the gypsum sheathing temperature, and then allowing the cold-side temperature to vary. Yet, this approach would have caused the vapour pressure gradient across the different samples to vary slightly.

Different supply rates have most likely affected the moisture contents of the unprotected gypsum panels. In protected tests, most of the supplied moisture either condensed and drained to the warm-side collection container, or was absorbed by the warm-side batt insulation. In the unprotected tests, most of the supplied moisture was absorbed by the gypsum sheathing. Consequently, given comparable drying conditions for all tests, it is likely that the unprotected gypsum panels have slightly higher equilibrium moisture contents. These slightly higher equilibrium moisture contents resulted from slightly higher supply rates.

Test panels with unprotected gypsum sheathing under both non-freezing and freezing conditions revealed that the permeance of the cold-side insulation had a strong influence on the moisture content of the unprotected gypsum sheathing boards. As shown in Figures 3-10 and 3-11, the fibreglass board (high-permeance) insulated walls had lower sheathing moisture contents than the polystyrene (low-permeance) insulated walls. Similarly, the moisture content of the painted sheathing fell between the values found for the polystyrene insulated walls and the other fibreglass insulated walls. This observed phenomenon is likely due to the ability of moisture to continue to pass through the sheathing and penetrate the high-permeance insulation. Other than the existence of some inconsistencies in the fibreglass insulated walls under freezing conditions, the moisture content of the sheathing in the unprotected test panels increased as the permeance of the material on the cold side decreased.

Moisture contents of the SBPO protected sheathing, shown in Figures 3-10 and 3-11, also illustrate that lower permeance insulation caused the sheathing moisture content to increase slightly. However, because of the moisture-retarding effect of the SBPO barrier, the variance in sheathing moisture content was not as pronounced as in the unprotected test panels. Under non-freezing conditions, the moisture content increased from 1.0% for the fibreglass insulated wall to 1.7% for the extruded polystyrene insulated wall. Under freezing conditions, the SBPO protected walls had gypsum moisture contents which ranged between 0.9% and 1.4%. The gypsum moisture content increased slightly as the permeance of the cold-side material decreased.

Unlike the unprotected and SBPO protected walls, the permeance of the cold-side materials had no effect on the moisture content of the polyethylene protected sheathing. This is because the polyethylene barrier, due to its high vapour resistance, reduced the total amount of moisture reaching the sheathing to insignificant amounts. Since the sheathing moisture content was low, the ability of the cold-side insulation to allow drying became inconsequential. The sheathing moisture contents for polyethylene protected walls varied between 1.0% and 1.4% for the non-freezing walls and 0.8% and 1.1% for the freezing walls.

Generally, the influence of the permeance of the cold-side insulation on the sheathing moisture content is most apparent in the unprotected test panels. In these cases, low permeance polystyrene insulation caused a higher moisture content in the gypsum sheathing than in the fibreglass insulation. When protection was provided on the warm side of the wall, the permeance of the cold-side insulation had less of an impact on sheathing moisture content. In fact, all of the polyethylene protected test panels had similar sheathing moisture contents, regardless of the type of material on their cold side.

Differences in the equilibrium moisture content of the unprotected gypsum during freezing and non-freezing tests were likely due to differences in moisture transport mechanisms. During non-freezing testing, most of the moisture entering the unprotected sheathing condensed on the warm face and was then absorbed by the gypsum. Once absorbed, this moisture could be transported into the relatively dry gypsum by a combination of vapour diffusion, surface diffusion, and capillary transport. However, under freezing conditions, the same wall could only move moisture by vapour diffusion and by surface diffusion along frozen ice crystals. Since the freezing tests had fewer active mechanisms of moisture transport, the unprotected gypsum under freezing conditions remained drier than the gypsum under non-freezing conditions. Furthermore, the outward drying potential of a wall becomes more important as the moisture content of the gypsum sheathing rises. Thus, during non-freezing conditions, the influence of the permeance of the cold-side insulation becomes more pronounced.

When the gypsum is protected by either SBPO or polyethylene, differences due to non-freezing and freezing conditions are very small. The differences are small because the method of transport from the protective surface in both non-freezing as well as freezing cases is predominantly by vapour diffusion.

Although the gypsum sheathing moisture contents were lower in the freezing tests than in the non-freezing tests, freezing conditions on the warm side of the sheathing may represent the worst condition. Ice that has accumulated during freezing periods will eventually melt, resulting in large amounts of concealed liquid moisture. These large amounts of moisture may significantly reduce the strength of the sheathing in unprotected walls, or damage interior finishes, or cause ponding inside the envelope of protected walls.

Given these circumstances, it would be wise to incorporate some type of draining mechanism inside the wall. Moisture distribution graphs (Figures 3-7, 3-8, and 3-9) show that the majority of the condensation forming in any wall system was retained in the warm-side insulation. This could present a problem if there is no method available for draining the insulation. To prevent the corrosion of steel studs, the formation of mould and mildew, or the reduction of thermal resistance in warm-side insulation, the condensation must be directed out of the envelope. This could be accomplished by installing a flashing inside the sheathing and providing a draining material between the sheathing and the stud-space insulation. In addition, holes could be incorporated into the lower track to provide drainage. These design modifications would allow unobstructed liquid moisture flow out of the envelope and, consequently, avoid many of the associated moisture-induced problems.

During the first series of tests on the non-freezing walls, moisture that accumulated in the warm-side batt insulation was not recorded. To compensate for this oversight, computer modelling using the program MOIST was carried out. Figures 3-5 and 3-6 compare the results from the two re-tested panels with the results of the computer modelling. Generally, the moisture distribution values measured for the re-tested walls were similar to the predicted theoretical values. More diffused moisture was found in the laboratory-tested, polyethylene-protected panels than predicted by the computer model. It is possible that small quantities of moisture came into contact with the cold-side insulation because of air leakage between the warm and cold sides of the test panel. Such air leakage, if it occurred, could explain the observed differences.

However, the relatively close agreement of the experimental readings with the values predicted by the model supports the validity of the use of the computer model to supplement the non-freezing experimental results. Furthermore, given this close agreement, the use of the program MOIST to estimate the time to reach equilibrium moisture content in the gypsum is a reasonable and supportable approach.

To examine the behaviour of full-scale wall samples exposed to actual winter conditions, a preliminary field test was carried out. The degree of protection afforded by the SBPO layer was less than expected. Laboratory tests showed that SBPO kept the gypsum relatively dry. However, field conditions were different from the controlled laboratory experiments. Although an outward acting temperature gradient was maintained in both cases, varying temperatures were experienced in the field tests, with sheathing temperatures fluctuating above and below freezing. Outward drying was limited by the vapour pressure of saturation at the plywood siding temperature, while the laboratory tests involved exposure to guardroom conditions of 90-100% relative humidity.

In the full-scale tests, gaps existed between the SBPO layers and the sheathing. These gaps could cause temperature differences to be experienced within the space. Condensation could occur and drip to the base of the wall.

Air convection currents were set up on both sides of the gypsum sheathing. These were likely due to the existence of the outer air cavity, the high porosity of the warm side insulation, and the gaps between the insulation and the sheathing. Natural convection currents likely caused a substantial vertical temperature gradient. The temperatures recorded in Figure 5-2 were measured at the mid-height of the wall assembly and are considerably warmer than those occurring at its lower portions. Below freezing conditions tended to occur more frequently at the lower levels of the wall than are indicated in Figure 5-2. This was confirmed by the observation of frost at the base of the wall even when the temperatures at mid-height were above freezing. Thus, this vertical temperature gradient, together with gravity drainage, are likely the prime causes of higher than expected gypsum moisture contents. Based on the results from these preliminary field tests, and considering the favourable experimental and theoretical results, the next logical research step is to explore the behaviour of full-scale walls in a controlled laboratory and field exposure setting.

# 5. CONCLUSIONS AND RECOMMENDATIONS

A protective moisture barrier placed on the warm side of exterior gypsum sheathing can be very effective at reducing the moisture content of the gypsum. The protective barrier limits the moisture content of the gypsum sheathing to a level where mould and mildew growth or loss of sheathing strength is not a concern. Polyethylene proved to be the most effective barrier at reducing the amount of moisture transported into gypsum sheathing. The SBPO protected panels had higher, but acceptable, moisture contents when exposed to winter condensation conditions.

A high permeance insulation placed on the cold side of the gypsum can also assist in maintaining a low moisture content in the sheathing. The placement of insulation on the cold side of the exterior gypsum raises the gypsum temperature, which, in turn, reduces the likelihood of condensation forming on the gypsum. As well, high permeance insulation increases the outward drying potential of a panel by allowing absorbed moisture to continue through to the exterior of the wall. Fibreglass insulation, with a permeance of 5108 ng/Pa·s·m$^2$, was shown in the laboratory tests to have the best outward drying potential of all the wall assemblies tested.

Low permeance insulation, such as extruded polystyrene (50 ng/Pa·s·m$^2$), also reduces the likelihood of condensation on the gypsum. However, the use of low permeance insulation on the cold side reduces the outward drying potential of the wall. During winter conditions, this may result in higher gypsum moisture contents. Even though this study only examined winter-like conditions, it must be remembered that in the summer, when the direction of moisture movement is reversed, the use of such low permeance sheathings can be expected to keep the gypsum sheathing drier. Furthermore, the use of any type of cold-side insulation reduces the thermal bridge effect of steel studs in actual assemblies.

In general, the laboratory tests produced results similar to those of the theoretical computer analyses. The use of materials, such as SBPO and polyethylene, on the warm side of the wall reduced the amount of moisture entering the sheathing. When such materials are used, condensed moisture can only be transported to the gypsum by vapour diffusion. In contrast, low permeance materials on the cold side of the wall increased the sheathing moisture content.

Protective barriers on test panels resulted in lower gypsum sheathing moisture contents than in the unprotected panels because the primary mechanism of wetting was by vapour diffusion. Even in the case of the freezing panels, surface diffusion from the protective layer was unlikely. Upon disassembly, very little ice crystal growth through the hydrophobic protective layer was observed. Consequently, it can be concluded that vapour diffusion was the only mechanism of moisture transport through the protective layers.

The experimental results show that exterior gypsum sheathing wall systems can be protected by using either a vapour barrier or a hydrophobic air barrier when exposed to condensation conditions. Under such conditions, the protected sheathing maintains a low moisture content. This occurs even in cases where a low permeance material is placed on the cold side of the sheathing. Exposed to similar conditions, unprotected gypsum sheathing will have significantly higher moisture contents.

The most promising wall systems tested are those with either polyethylene sheathing or an air barrier material, such as SBPO, on the warm side of the sheathing. The protective layer can be coupled with a high permeance insulation, such as fibreglass board insulation, on the cold side of the wall in order to reduce the likelihood and duration of condensation on the warm side of the gypsum.

In order to maintain similar condensation conditions at the sheathing surface, the temperature in the environmental chamber was allowed to fluctuate. A rise in chamber temperature increases the vapour pressure difference across the warm-side insulation, which results in a greater amount of moisture being supplied to the panel. Since the environmental chamber temperature fluctuated slightly between each test, different amounts of moisture were supplied to the warm side of the gypsum sheathing throughout the laboratory testing.

The two full-scale tests provided insight into how insulated gypsum wall systems perform in the field. The full-scale wall samples showed two-dimensional moisture flow in the gypsum sheathing. Natural convection within the full-scale cavity likely resulted in more moisture accumulating in the lower, and cooler, areas of the wall sample. In addition, moisture condensing on the surface of the gypsum may have accumulated in the lower areas of the wall sample because of gravity.

In the field tests, the SBPO protected sample had a higher moisture content than expected. Based on theoretical and laboratory tests, the SBPO protected gypsum sheathing should have had moisture contents much lower than the unprotected sheathing. The higher than expected moisture contents may have been caused by the existence of an air space between the SBPO layer and the gypsum. Such an air space would result in sheathing temperatures which are below the temperature of the SBPO layer. Under such circumstances, condensation may occur and be absorbed at the gypsum surface instead of solely at the surface of the SBPO layer.

Differences in mechanisms of moisture transport can be used to explain differences in gypsum moisture contents in freezing and non-freezing tests. Unprotected gypsum sheathing under freezing conditions had lower moisture contents because it is likely that the moisture could only move into the gypsum by vapour diffusion and surface diffusion. Unprotected sheathing under non-freezing conditions had higher moisture contents because liquid water could be readily absorbed at the surface and transported by capillary movement, surface diffusion, and vapour diffusion.

In the design of a protected exterior gypsum sheathing wall system with an insulated stud space, it is important that some type of drainage be provided on the warm side of the sheathing. Condensation testing has revealed that a wall with moisture protection on the warm side of the sheathing will retain the majority of moisture entering the wall in the insulation filling the stud space.

While conducting this research, it became evident that there is a need for more research on the movement of moisture through building envelopes when freezing conditions exist. The movement of ice through a material such as SBPO has not, to the knowledge of the authors, been examined. Furthermore, in practice, walls are subjected to cyclic freezing and non-freezing conditions. The formation of ice in a wall may not necessarily be deleterious, so long as it can be removed later by drainage or evaporation.

Thus, cyclic above and below freezing tests should be carried out to determine the behaviour of actual walls.

More research is required into the behaviour of an actual steel stud and exterior gypsum sheathing wall. The existence of metal studs introduces a complicated two-dimensional heat flow effect which no doubt influences the behaviour of moisture distribution in the wall. Full-scale wall sections should be fabricated and tested using the most promising wall panel configurations from this study. Such full-scale tests would necessarily incorporate the study of two- and three-dimensional heat and moisture flow effects.

Finally, further tests should be carried out for longer periods of time. Longer-term tests may provide a better indication of the rates of water accumulation in warm-side insulation and the rates of diffused moisture. This information would help determine the feasibility of relying on the outward drying potential of a wall system to reduce the sheathing moisture content. The results of such tests could also determine the requirements of internal drainage. The results could lead to the development of new products which not only protect the exterior gypsum sheathing, but also provide an efficient means of removing accumulated moisture from the wall.

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# APPENDIX A

## COMPUTER ANALYSIS

## A.1 PURPOSE OF COMPUTER ANALYSIS

A computer analysis was completed for this study for two reasons:

1. To determine the required duration for the test to reach equilibrium;
2. To allow comparison of the experimental results with theoretically predicted values.

The analysis was completed with a mass and heat transfer program called MOIST (Burch and Thomas, 1993), which uses finite difference methods.

For effective comparison of the results among the various tests, it was important that the gypsum sheathing in all of the test panels approach a steady-state moisture condition as closely as possible. The time required to approach a steady-state condition can be determined in two ways:

1. By periodically weighing the gypsum sheathing until the changes in mass are negligible;
2. By completing a numerical analysis that evaluates moisture content of the sheathing as time progresses.

The first method may lead to errors because during weighing the moisture flow through the wall will be disrupted. Moreover, the exposure conditions are difficult to control while weighing the sheathing. Therefore, to avoid such problems, numerical methods can be used to estimate the time required for the gypsum sheathing to approach an equilibrium moisture content.

The accuracy of a moisture flow model depends upon the incorporation of valid moisture transport models. The numerical model chosen should consider all the intricacies of moisture transport, including vapour diffusion, capillary flow, and liquid diffusion. The finite difference program, MOIST, predicts heat and moisture flow through building envelopes by applying currently accepted transport models.

## A.2 MODELLING DETAILS

The two varying features of the wall systems analyzed with MOIST were the permeability of the cold-side insulation and the permeability of the protective barrier on the warm side of the gypsum sheathing. A schematic of the walls modelled by MOIST is shown in Figure A-1. As in the experimental tests, the walls had either polyethylene protection, or SBPO protection, or no protection on the warm side of the sheathing. Unlike the experiments, only fibreglass board and extruded polystyrene insulation were used to model the insulation on the cold side of the gypsum sheathing. Insulation composed of fibreglass board or extruded polystyrene was selected because each represents an extreme case in insulation permeability; the permeability of fibreglass is high, while the permeability of extruded polystyrene is low. Given the condition of condensation at the warm face of the sheathing, the computer model can be used to show the extreme values in gypsum moisture content and define the limiting times required to approach steady-state conditions. All material parameters are listed in Appendix B.

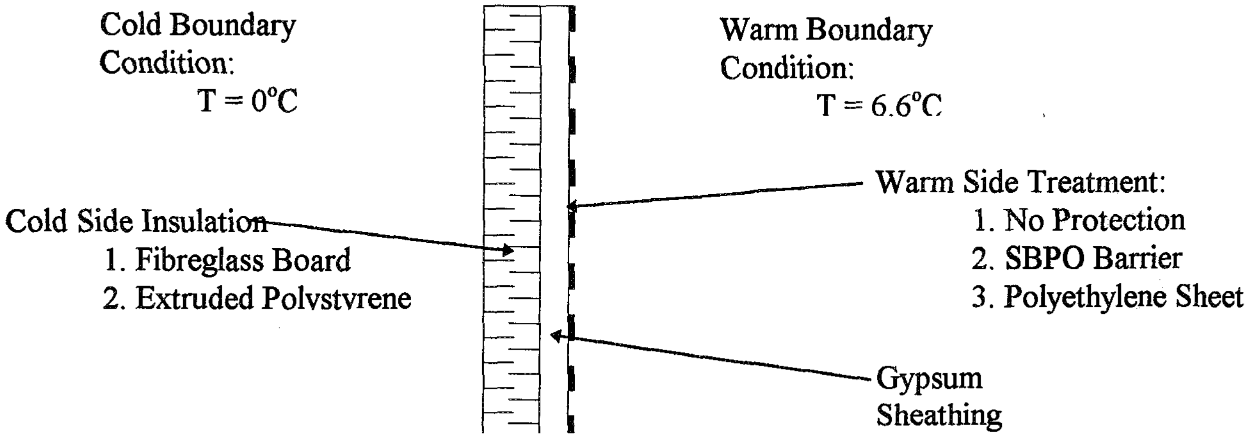

**Figure A-1: Schematic of wall modelled by MOIST.**

The accuracy of finite difference simulations is dependent upon proper specifications for the model. The more important details include:

1. A proper model of the warm-side barrier;
2. A sufficient number of nodes for each wall component;
3. Realistic initial moisture conditions;
4. Realistic boundary conditions;
5. The use of an acceptable convergence factor;
6. A sufficient number of iterations.

The choices made in specifying the above details are explained in the following paragraphs.

The polyethylene and SBPO barriers were modelled as a paint layer with a permeance of 8 and 2600 ng/s $m^2$ Pa, respectively. The warm-side barriers were modelled this way for two reasons: MOIST does not allow a non-storage component as a boundary layer; and preliminary simulations where the barrier was modelled as a storage component produced unacceptable results.

The number of nodes assigned to each wall element was chosen arbitrarily in the initial analysis. The results obtained with the first node assignments were then compared to a second analysis having an increased number of nodes. If the difference between the moisture contents of the two analyses was negligible, then it was assumed that the number of nodes in the original analysis was sufficient; otherwise, a greater number of nodes was required. In general, more nodes were used if a large temperature or moisture gradient was expected across a particular material. For all analyses, twenty nodes for the gypsum sheathing and forty nodes for the insulation were sufficient.

It was necessary to specify an initial moisture content and temperature for each material used in the wall model. Sorption isotherms were used to find initial moisture contents for each layer under typical conditions in the laboratory (approximately 45% relative humidity). The initial moisture contents of the wall components are given in Table A-1. The initial wall temperature of each component was estimated to be 2°C, because the components started off between the lab work area temperature of approximately 20°C and the guardroom temperature of 0°C. In the opinion of the authors, accuracy of the initial temperatures of the wall materials is not critical to the model because the temperature change of each component is rapid when compared to the rate of change of its moisture content.

**Table A-1: Initial moisture contents of the wall materials for the computer analysis.**

| Material | Moisture Content (%) |
|---|---|
| Gypsum | 0.47 |
| Fibreglass Board Insulation | 0.14 |
| Bead Board Insulation | 3.62 |
| Extruded Polystyrene | 3.62 |

To model the conditions in the laboratory experiments as closely as possible, preliminary experimental temperature data were used in MOIST. The temperatures for the cold and warm-side boundaries started at approximately 0°C. The warm-side temperature was then increased to 8°C, and finally stabilized at 6.6°C. The cold-side temperature was maintained at 0°C, so that all computer modelling was for non-freezing conditions. The change in relative humidity at the warm face of the wall was assumed to be linear between 75% and 100%. over the first two days. After two days, the relative humidity remained constant at 100%. Condensation after two days of testing was confirmed in the laboratory.

A convergence factor of 1.0E-6 and 500 iterations were selected for all finite difference analyses. Smaller convergence factors produced no difference in moisture content results; therefore, the chosen convergence factor was adequate. A high humidity model, such as the wall systems included in this study, typically requires 500 iterations (Burch and Thomas, 1993).

## A.3 RESULTS OF FINITE DIFFERENCE ANALYSES

### A.3.1 Required Experimental Test Duration

The first reason for completing a computer analysis was to determine how long the experimental tests should run. This duration was based on the time required for the gypsum sheathing to approach a steady-state moisture condition. Table A-2 shows the output from MOIST that relates sheathing moisture content and time for the test panels exposed to non-freezing conditions. The gypsum sheathing in the unprotected walls approaches a constant moisture content at the end of fifteen days. The moisture content of the gypsum sheathing in the SBPO and polyethylene protected walls approaches a steady-state condition at a much more rapid rate than the unprotected walls. For the most part, the moisture content in the gypsum sheathing in the protected wall systems does not change significantly after five days. The graphs of moisture content versus time for each of the cases shown in Table A-2 are included in Appendix C.

**Table A-2: Theoretical time required to approach steady-state moisture content in gypsum sheathing under non-freezing conditions.**

| Cold-side Insulation | Warm-side Protection | | |
|---|---|---|---|
| | Unprotected | SBPO | Polyethylene |
| Fibreglass | 15 days | 4 days | 2 days |
| Extruded Polystyrene | 12 days | 5 days | 3 days |

Based on these MOIST analyses, it was concluded that steady-state gypsum sheathing moisture contents would be approached within five and fifteen days for the protected and unprotected wall models respectively. Since the walls modelled with MOIST used the two cold-side insulation types that had the minimum and maximum limits of permeability for the test series in this research, it was assumed that the other experimental wall systems would also reach steady-state conditions within the time periods determined for the extreme cases. Therefore, all protected walls were tested for five days and all unprotected walls were tested for fifteen days when exposed to non-freezing temperatures. It was also assumed that all freezing tests should be tested for the same period of time to reach steady-state moisture conditions.

### A.3.2 Gypsum Moisture Content

The final gypsum sheathing moisture contents from the computer analyses are shown in Figure A-2. The wall modelled with no warm-side protection and polystyrene insulation was found to have the highest moisture content at 6.5%. The second-highest sheathing moisture content was found to occur when there was no protection on the warm side of the sheathing and fibreglass insulation was placed on the cold side of the wall. Similar effects of insulation type on the sheathing moisture content were found for the SBPO protected walls.

The finite difference analyses also show that providing some type of protection on the warm side of the wall reduces the sheathing moisture content significantly. Both the SBPO and polyethylene protected walls have significantly reduced sheathing moisture contents compared to the unprotected walls. Polyethylene is so effective at protecting the sheathing that changing the type of cold-side insulation had no effect on the sheathing moisture content. Both the fibreglass and polystyrene insulated walls protected with polyethylene have sheathing moisture contents of approximately 0.5%, which is almost the same as the starting moisture content.

Further investigation of the results reveals that changing the protective layer on the warm side had a greater effect on sheathing moisture content than changing the type of insulation on the cold side of the wall. For example, adding a SBPO protective barrier to a polystyrene insulated wall caused a greater drop in sheathing moisture content than replacing the polystyrene insulation with fibreglass board. Changing the SBPO protection to the higher-resistance polyethylene barrier was also more effective at reducing the gypsum moisture content than was changing the insulation from extruded polystyrene to the lower-resistance fibreglass board.

### A.3.3 Moisture Distribution in the Wall Components

The finite difference analyses were also used to predict the amount of moisture in each wall component after the complete test period. Figure A-3 shows the theoretical percentages of the total supplied moisture that remained in the various wall components. Each simulation assumed that 1.75 $kg/m^2$ (650 g for the test panels) of liquid water was supplied to the warm side of the sheathing over the test period. This amount of moisture was chosen because it is approximately equal to the mass flux of the wall with the highest overall permeability (no protection, fibreglass insulation). For this reason, the results of the numerical analysis should be compared on a relative basis only.

As the permeability of the protective barrier on the warm side of the gypsum decreases, the amount of moisture remaining on the warm side of the wall increases (see Figure A-3). Furthermore, the polystyrene insulated walls have larger moisture quantities remaining on the warm side than the fibreglass insulated walls. The effect of cold-side insulation type on warm-side moisture accumulation varies according to the type of protective barrier used. For example, unprotected walls that use polystyrene rather than fibreglass insulation have an increase in warm-side moisture accumulation of almost 45%; when the walls are protected with polyethylene, however, the type of insulation used on the cold side has little effect on the accumulation of moisture on the warm side.

As shown in Figure A-3, the percentages of the total moisture retained by the gypsum sheathing in the various wall systems follow a similar trend to the sheathing moisture contents shown in Figure A-2. Unprotected walls with polystyrene insulation retained the largest percentage of water in the gypsum sheathing at 22.0%, while the sheathing in polyethylene protected walls absorbed virtually no moisture.

Figure A-3 illustrates that polystyrene insulation retains more moisture than fibreglass insulation in these wall systems. The amount of moisture held by the cold-side insulation is dependant upon the type of warm-side protection provided. As the permeability of the warm-side barrier decreases, the amount of moisture in the cold-side insulation decreases.

Finally, Figure A-3 shows that walls with higher overall permeabilities allowed more moisture to escape through to the cold side of the wall systems. The unprotected fibreglass insulated wall (the wall with the highest overall permeability) allowed 78.2% of the total moisture entering the wall to diffuse through. The SBPO protected fibreglass insulated wall allowed the second-largest percentage of moisture to diffuse through the wall (33.1%). Both polyethylene protected walls had no amount of moisture diffusing all the way through the wall.

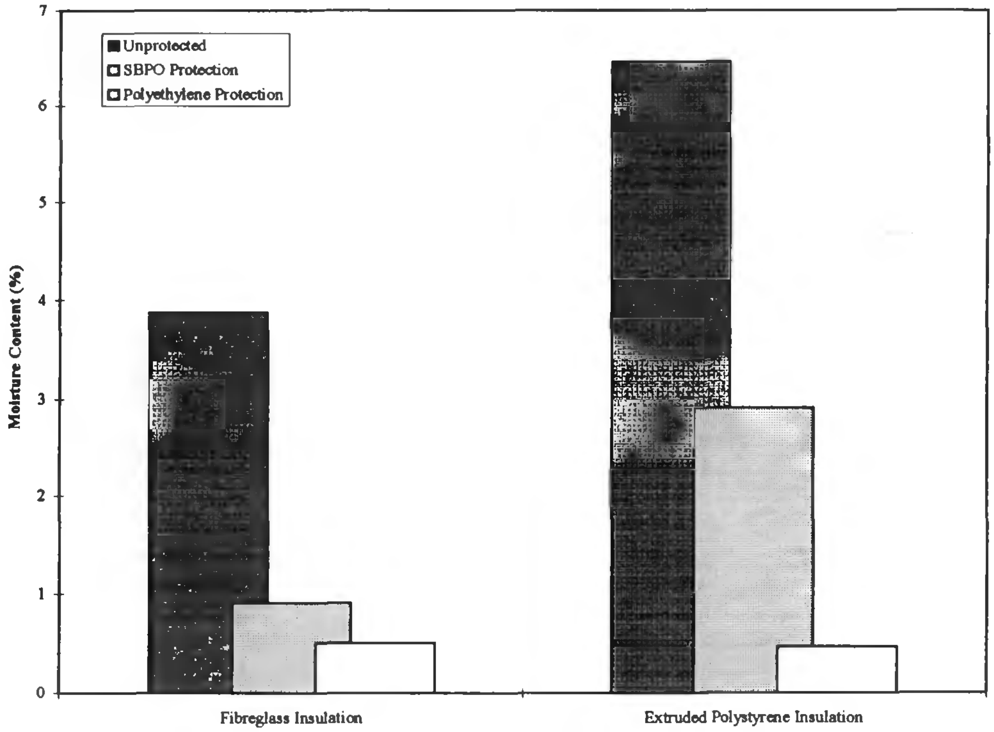

Figure A-2: Theoretical final moisture contents of gypsum sheathing.

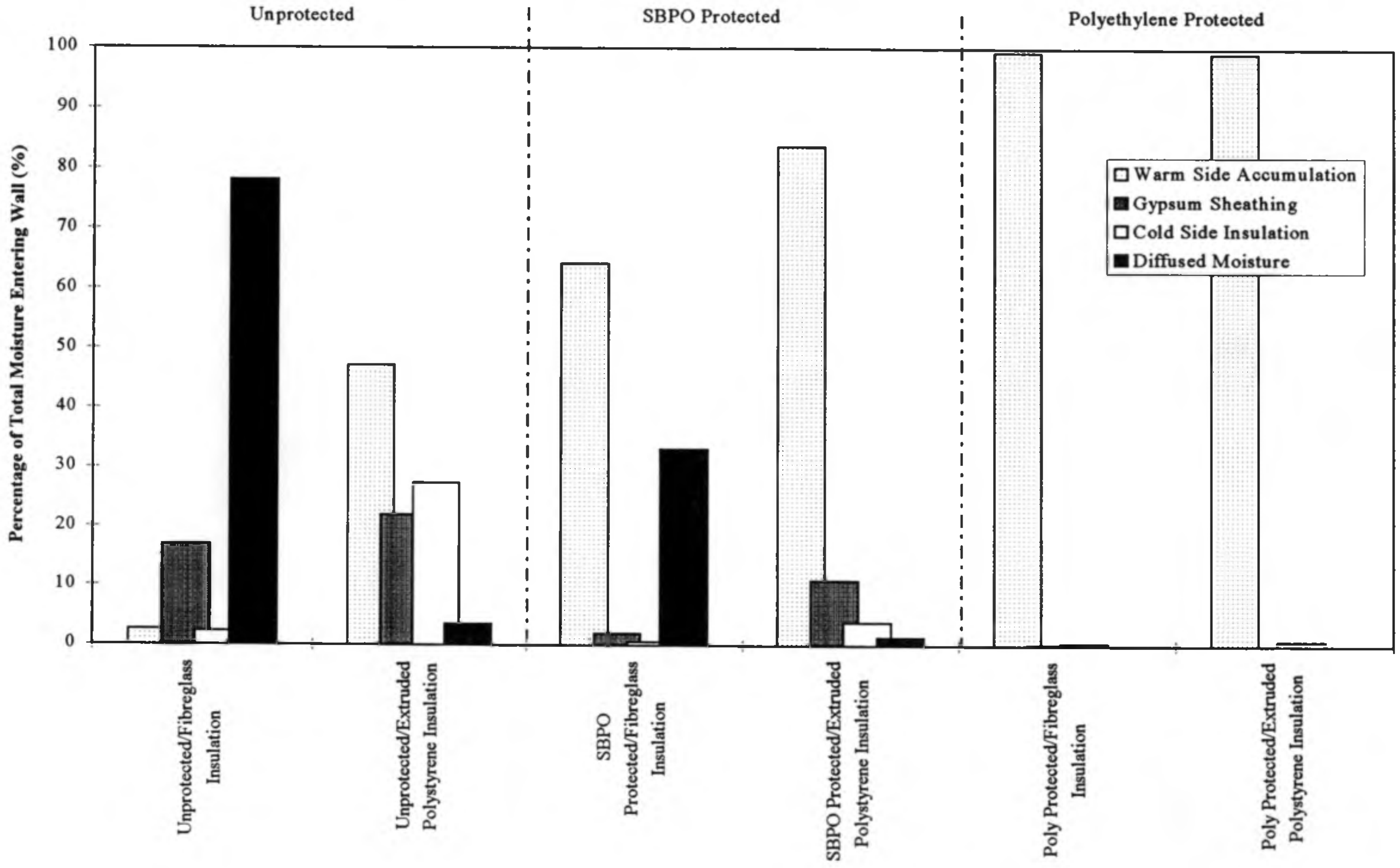

**Figure A-3: Theoretical moisture distribution in wall components, in percentages of the total supplied moisture.**

# APPENDIX B

Material parameters used in MOIST computer analyses

# MOIST Material Parameters

### GYPSUM BOARD

| | |
|---|---|
| SORPTION COEFFICIENTS | |
| A1 | .3360E-02 |
| A2 | .1000E-07 |
| A3 | .9010E+00 |
| CAPILLARY COEFFICIENTS | |
| LIQUID PERMEABILITY | .1115E-13 |
| DRY POROSITY | .5000E+00 |
| HEAT TRANSFER PROPERTIES | |
| DRY DENSITY | .6285E+03 |
| SPECIFIC HEAT | .1090E+04 |
| DRY THERMAL CONDUCTIVITY | .1590E+00 |
| PERMEABILITY PROPERTIES | |
| 1ST FIT COEFFICIENT | -.2348E+02 |
| 2ND FIT COEFFICIENT | .0000E+00 |
| 3RD FIT COEFFICIENT | .0000E+00 |

### GLASS FIBRE INSULATION

| | |
|---|---|
| SORPTION COEFFICIENTS | |
| A1 | .1703E-02 |
| A2 | .1000E-07 |
| A3 | .9630E+00 |
| CAPILLARY COEFFICIENTS | |
| LIQUID PERMEABILITY | .9290E-13 |
| DRY POROSITY | .9960E+00 |
| HEAT TRANSFER PROPERTIES | |
| DRY DENSITY | .5400E+02 |
| SPECIFIC HEAT | .9600E+03 |
| DRY THERMAL CONDUCTIVITY | .3600E-01 |
| PERMEABILITY PROPERTIES | |
| 1ST FIT COEFFICIENT | -.2176E+02 |
| 2ND FIT COEFFICIENT | -.3574E+00 |
| 3RD FIT COEFFICIENT | -.7139E+00 |

### EXTRUDED POLYSTYRENE

| | |
|---|---|
| SORPTION COEFFICIENTS | |
| A1 | .4194E+00 |
| A2 | .1293E+02 |
| A3 | .5247E+00 |
| CAPILLARY COEFFICIENTS | |
| LIQUID PERMEABILITY | .2787E-19 |
| DRY POROSITY | .9000E+00 |
| HEAT TRANSFER PROPERTIES | |
| DRY DENSITY | .4245E+02 |
| SPECIFIC HEAT | .1214E+04 |
| DRY THERMAL CONDUCTIVITY | .2890E-01 |
| PERMEABILITY PROPERTIES | |
| 1ST FIT COEFFICIENT | -.2707E+02 |
| 2ND FIT COEFFICIENT | .0000E+00 |
| 3RD FIT COEFFICIENT | .0000E+00 |

## Unprotected Walls

### INPUT PARAMETERS

```
 1  TYPE SOLUTION? (ISOTHERMAL=1 NONISOTHERMAL=2)   2
 2  CONVECTION COEF AT INSIDE SURFACE            3.600
 3  CONVECTION COEF AT OUTSIDE SURFACE            5.000
 4  CONVERGENCE CRITERIA FOR MOISTURE SOLUTION   .1000E-06
 5  MAXIMUM ITERATIONS IN MOISTURE LOOP           500
 6  SOLAR ABSORPTANCE OF EXTERIOR SURFACE          .300
 7  SURFACE TILT (DEGREES)                  90.
 8  SURFACE ORIENTATION (DEGREES)                 0.
 9  INDOOR TEMPERATURE                     6.600
10  INDOOR RELATIVE HUMIDITY, PERCENT          100.000
11  FILE TYPE (WYEC=1, SPECIAL=2)             2
12  BOUNDARY FILE NAME                     NFREEZE.TXT
13  INSIDE SURF PAINT PERMEANCE                 **********
14  OUTSIDE SURF PAINT PERMEANCE                 **********
```

### ANALYSIS INTERVALS

```
COMPUTER ANALYSIS
1  FIRST DAY.......................................  1
2  LAST DAY........................................ 15
PRINTING AND PLOTTING
3  FIRST DAY.......................................  1
4  LAST DAY........................................ 15
5  INTERVAL (HOURS)................................   1
```

### WALL CONSTRUCTION

### UNPROTECTED WALL/FIBREGLASS ISULATION

```
LAY   DES   L   T    MC    NX   R     M     VEI    VEO  SIDE
 1    GYPSUM  1.250  6.6  .5   20
 2    FIBREGLASS BOARD  2.500  6.6  .1   40
```

### UNPROTECTED WALL/EXTRUDED POLYSTYRENE

```
LAY   DES   L   T    MC    NX   R     M     VEI    VEO  SIDE
 1    GYPSUM  1.250  6.6  .5   20
 2    EXTRUDED POLYSTYRENE  2.500  6.6  3.6   40
```

## Polyethylene Protected Walls

### INPUT PARAMETERS

```
 1  TYPE SOLUTION? (ISOTHERMAL=1 NONISOTHERMAL=2)   2
 2  CONVECTION COEF AT INSIDE SURFACE              3.600
 3  CONVECTION COEF AT OUTSIDE SURFACE             5.000
 4  CONVERGENCE CRITERIA FOR MOISTURE SOLUTION   .1000E-06
 5  MAXIMUM ITERATIONS IN MOISTURE LOOP            500
 6  SOLAR ABSORPTANCE OF EXTERIOR SURFACE           .300
 7  SURFACE TILT (DEGREES)                   90.
 8  SURFACE ORIENTATION (DEGREES)                 0.
 9  INDOOR TEMPERATURE                      6.600
10  INDOOR RELATIVE HUMIDITY, PERCENT           100.000
11  FILE TYPE (WYEC=1, SPECIAL=2)                2
12  BOUNDARY FILE NAME                     nfreeze.txt
13  INSIDE SURF PAINT PERMEANCE                  8.000
14  OUTSIDE SURF PAINT PERMEANCE               **********
```

### ANALYSIS INTERVALS

```
COMPUTER ANALYSIS
1  FIRST DAY.......................................   1
2  LAST DAY........................................  15
PRINTING AND PLOTTING
3  FIRST DAY.......................................   1
4  LAST DAY........................................  15
5  INTERVAL (HOURS)................................   1
```

### WALL CONSTRUCTION

### POLYETHYLENE PROTECTED WALL/FIBREGLASS ISULATION

```
LAY   DES   L    T    MC     NX   R     M    VEI    VEO   SIDE
 1    GYPSUM  1.250  6.6   .5   20
 2   FIBREGLASS BOARD  2.500  6.6   .1   40
```

### UNPROTECTED WALL/EXTRUDED POLYSTYRENE

```
LAY   DES   L    T    MC     NX   R     M    VEI    VEO   SIDE
 1    GYPSUM  1.250  6.6   .5   20
 2   EXTRUDED POLYSTYRENE  2.500  6.6  3.6   40
```

## SBPO Protected Walls

### INPUT PARAMETERS

```
 1 TYPE SOLUTION? (ISOTHERMAL=1 NONISOTHERMAL=2)   2
 2 CONVECTION COEF AT INSIDE SURFACE            3.600
 3 CONVECTION COEF AT OUTSIDE SURFACE            5.000
 4 CONVERGENCE CRITERIA FOR MOISTURE SOLUTION   .1000E-06
 5 MAXIMUM ITERATIONS IN MOISTURE LOOP           500
 6 SOLAR ABSORPTANCE OF EXTERIOR SURFACE         .300
 7 SURFACE TILT (DEGREES)              90.
 8 SURFACE ORIENTATION (DEGREES)               0.
 9 INDOOR TEMPERATURE                 6.600
10 INDOOR RELATIVE HUMIDITY, PERCENT           100.000
11 FILE TYPE (WYEC=1, SPECIAL=2)             2
12 BOUNDARY FILE NAME                  NFREEZE.TXT
13 INSIDE SURF PAINT PERMEANCE               2600.000
14 OUTSIDE SURF PAINT PERMEANCE               **********
```

### ANALYSIS INTERVALS

```
COMPUTER ANALYSIS
1 FIRST DAY.......................................  1
2 LAST DAY........................................ 15
PRINTING AND PLOTTING
3 FIRST DAY.......................................  1
4 LAST DAY........................................ 15
5 INTERVAL (HOURS)................................  1
```

### WALL CONSTRUCTION

### SBPO PROTECTED WALL/FIBREGLASS ISULATION

```
LAY   DES   L   T    MC    NX   R     M    VEI   VEO  SIDE
  1    GYPSUM  1.250  6.6  .5  20
  2   FIBREGLASS BOARD  2.500  6.6  .1  40
```

### SBPO WALL/EXTRUDED POLYSTYRENE

```
LAY   DES   L   T    MC    NX   R     M    VEI   VEO  SIDE
 1    GYPSUM  1.250  6.6  .5  20
 2   EXTRUDED POLYSTYRENE  2.500  6.6  3.6  40
```

# APPENDIX C

Graphs of moisture content versus time for
test panels analysed in MOIST

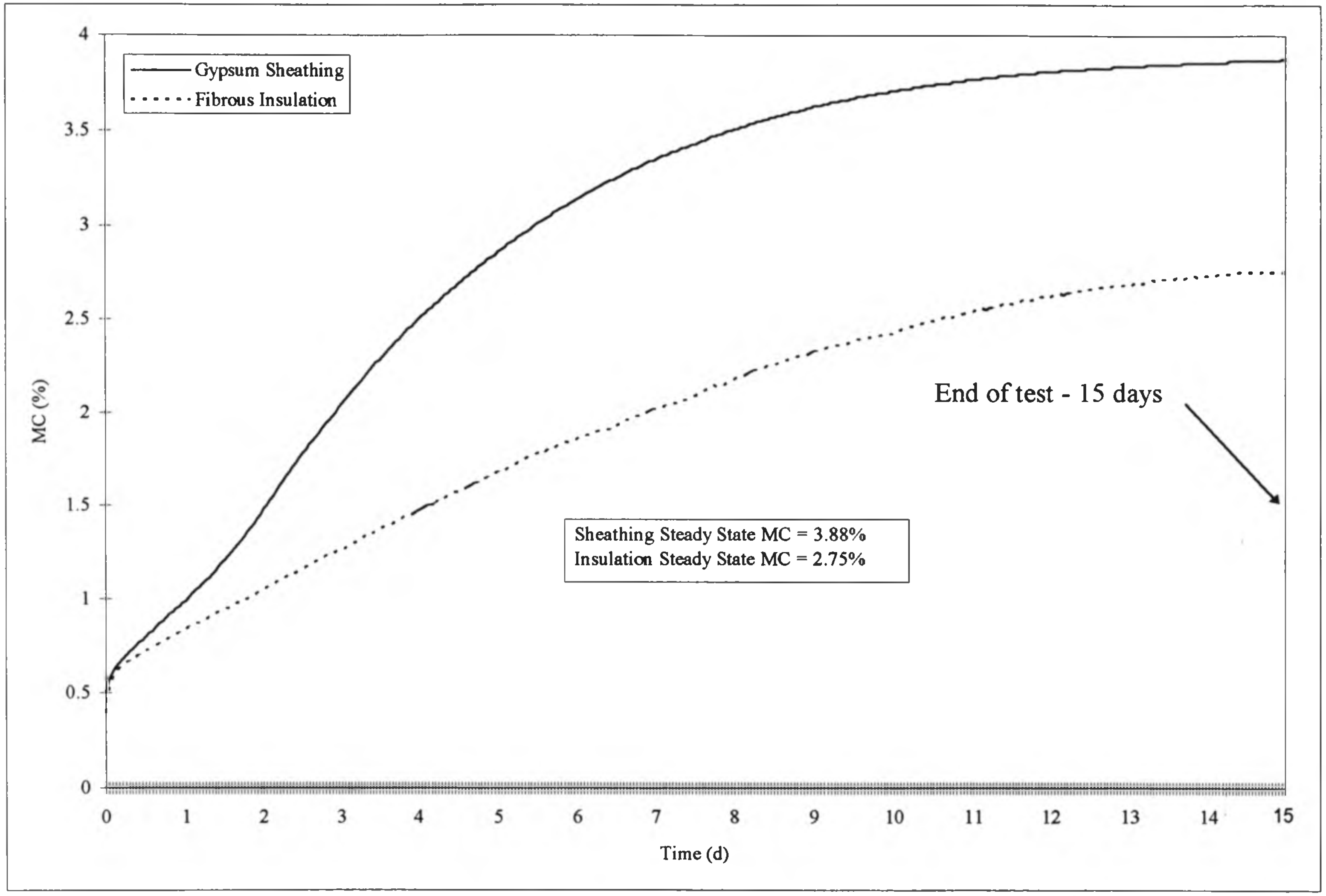

Figure C-1: No protection and fibreglass insulation - moisture content vs. time.

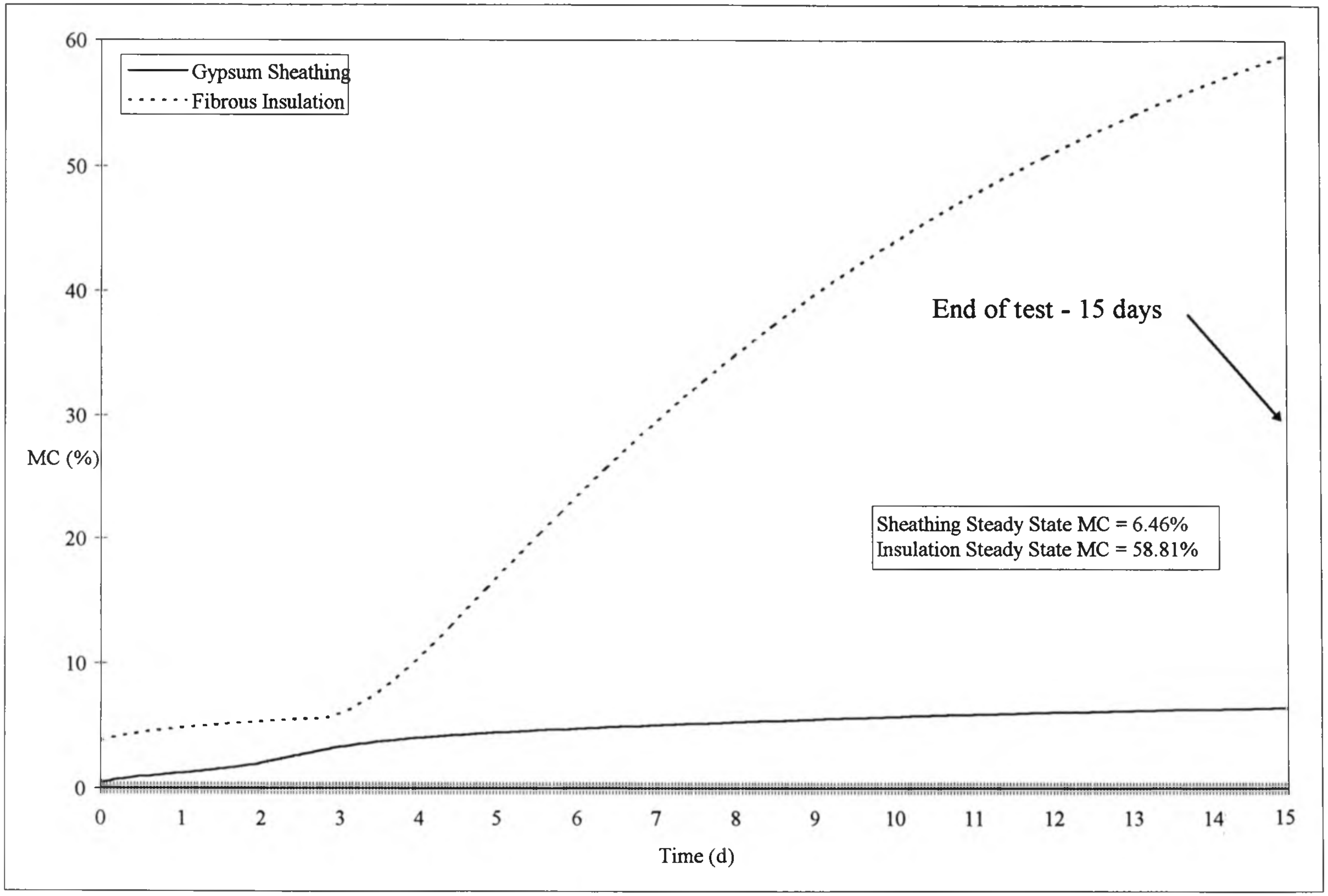

**Figure C-2: No protection and polystyrene insulation - moisture content vs. time.**

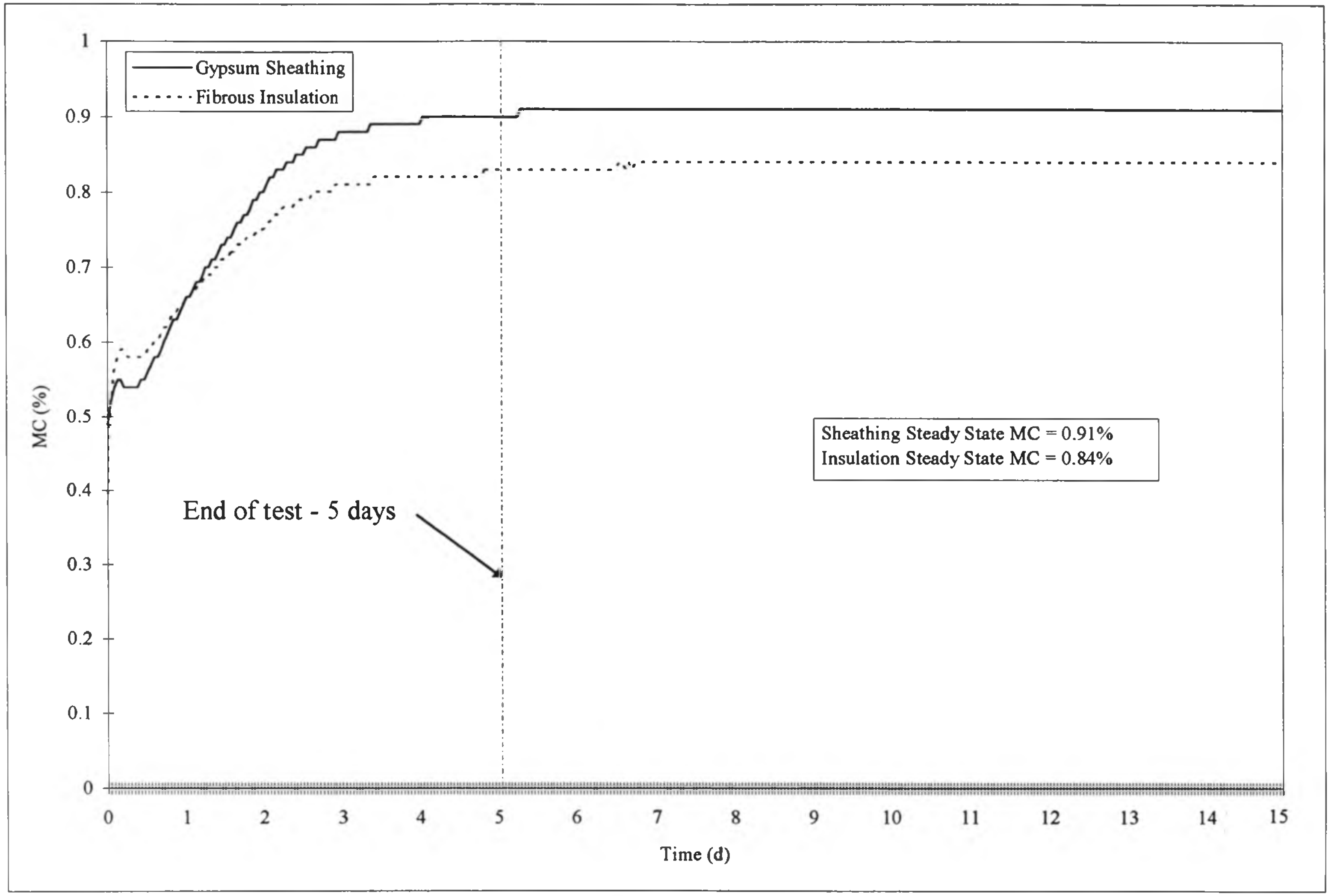

Figure C-3: SBPO protection and fibreglass insulation - moisture content vs. time.

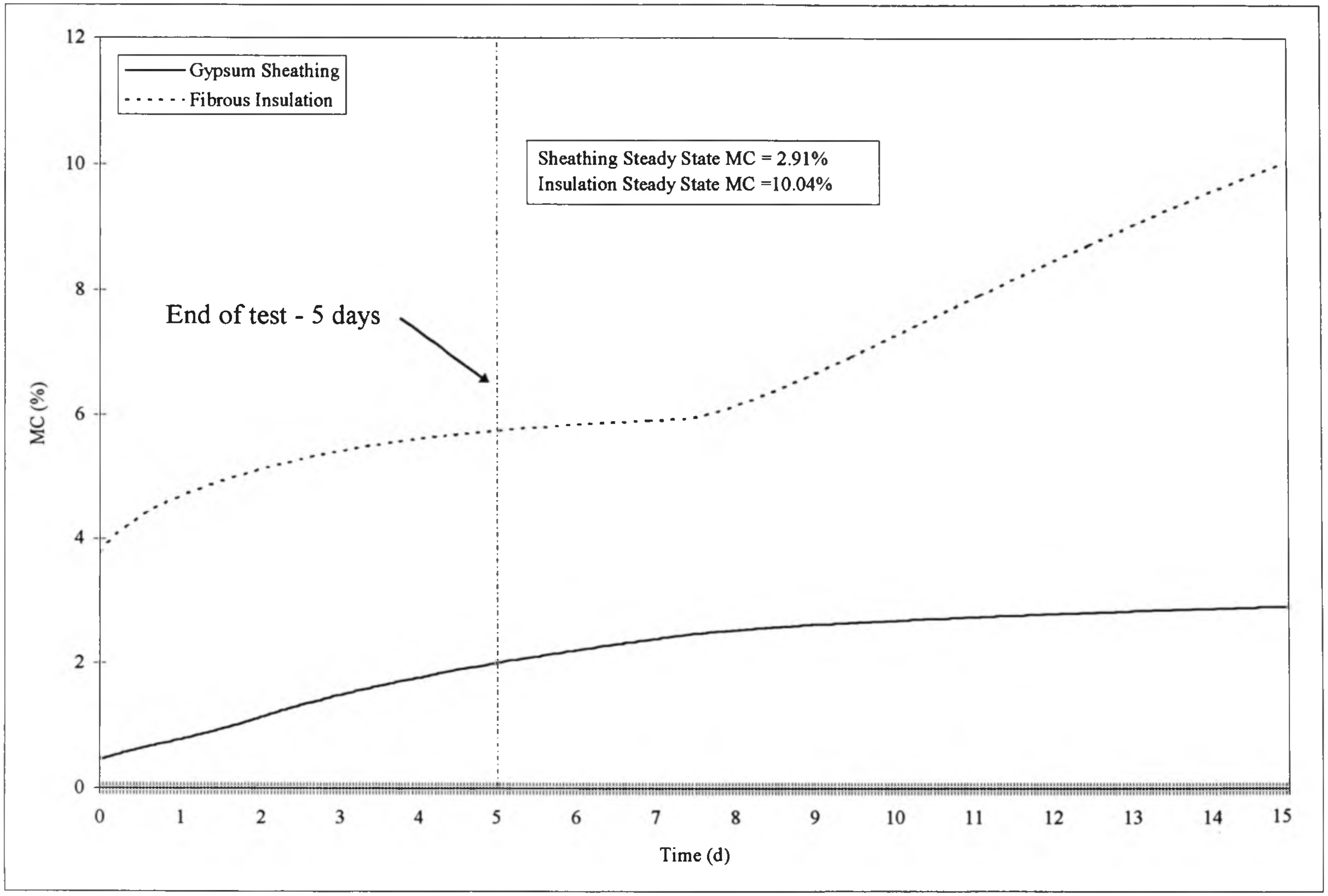

**Figure C-4: SBPO protection and polystyrene insulation - moisture content vs. time.**

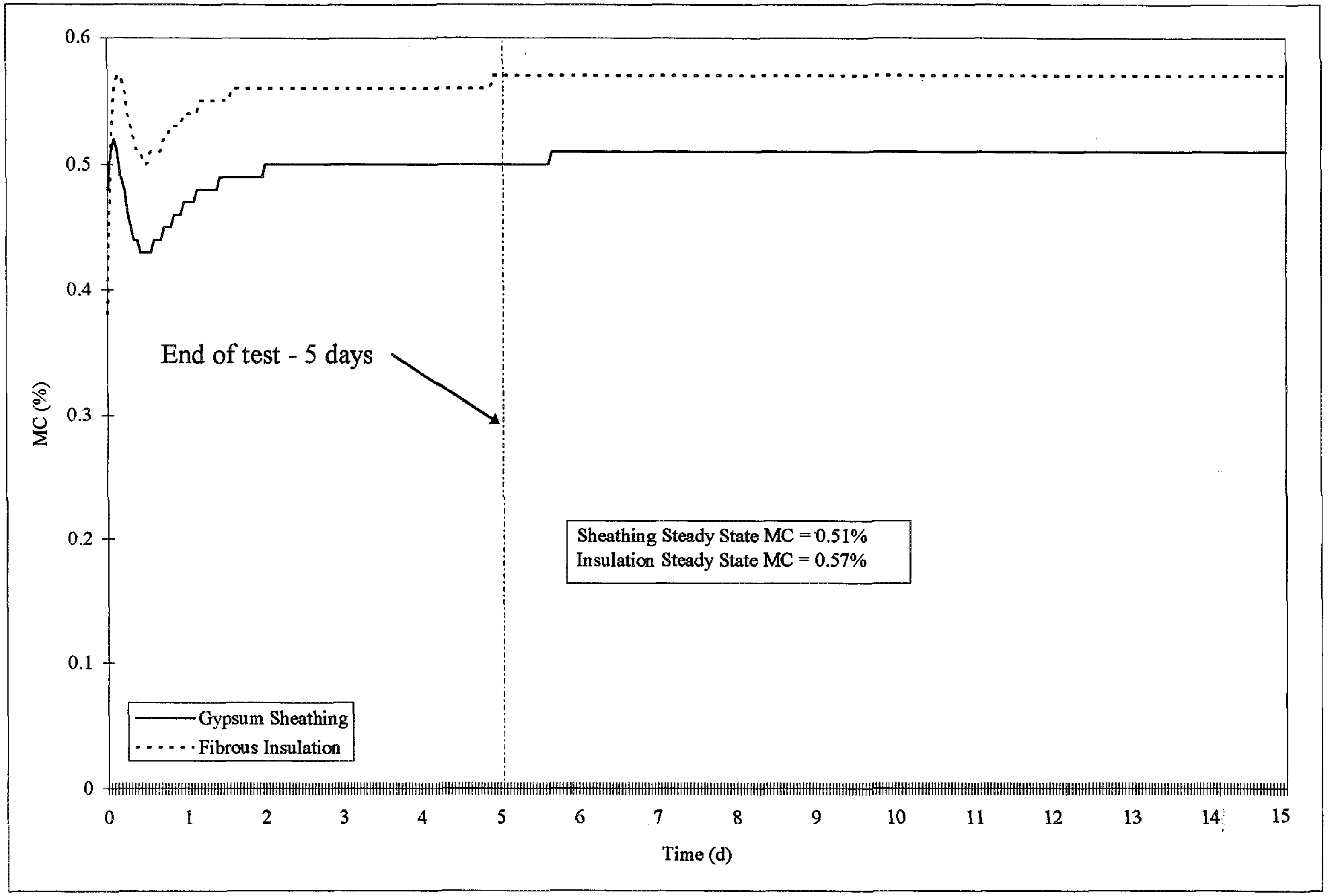

**Figure C-5: Polyethylene protection and fibreglass insulation - moisture content vs. time.**

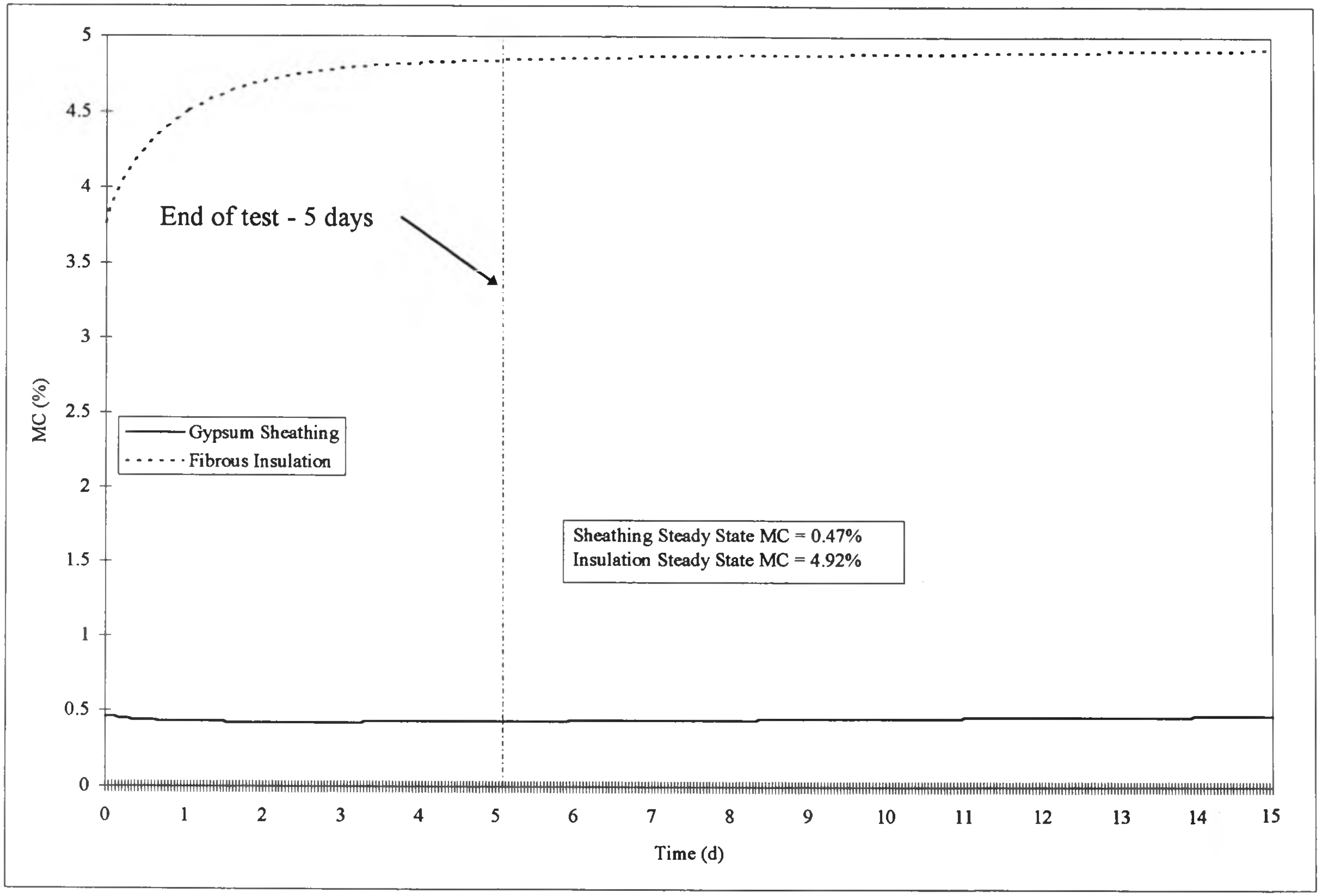

**Figure C-6: Polyethylene protection and polystyrene insulation - moisture content vs. time.**

# APPENDIX D

Average temperatures for cold room, warm room, and environmental chamber during non-freezing and freezing tests.

**Table D-1: Average temperature data for non-freezing tests.**

(All temperatures are in °C)

| Warm Side | Cold Side | Guardroom Avg. | Gypsum Avg. | Environmental Chamber Avg. |
|---|---|---|---|---|
| No Protection | Fibreglass Board | 1.24 ±0.09 | 6.72 ±0.05 | 21.44 ±0.18 |
| | Fibreglass & SBPO | 1.05 ±0.10 | 6.64 ±0.05 | 20.75 ±0.15 |
| | Fibreglass & Bld. Paper | -0.52 ±0.03 | 6.64 ±0.05 | 21.69 ±0.12 |
| | Paint & Fibreglass | -0.17 ±0.04 | 6.59 ±0.04 | 22.47 ±0.14 |
| | Bead Board | -0.05 ±0.03 | 7.38 ±0.04 | 22.85 ±0.12 |
| | Extruded Polystyrene | -0.01 ±0.03 | 7.38 ±0.05 | 19.82 ±0.07 |
| | Average | 0.26 | 6.89 | 21.50 |
| SBPO Protection | Fibreglass Board | 0.39 ±0.04 | 6.83 ±0.18 | 21.88 ±0.46 |
| | Fibreglass & SBPO | 0.21 ±0.04 | 6.81 ±0.14 | 20.01 ±0.26 |
| | Fibreglass & Bld. Paper | -0.07 ±0.09 | 6.74 ±0.19 | 19.34 ±0.26 |
| | Paint & Fibreglass | -0.46 ±0.07 | 6.53 ±0.21 | 19.23 ±0.42 |
| | Bead Board | 0.59 ±0.06 | 6.64 ±0.09 | 22.89 ±0.27 |
| | Extruded Polystyrene | 0.56 ±0.07 | 7.26 ±0.18 | 18.98 ±0.20 |
| | Average | 0.20 | 6.80 | 20.39 |
| Polyethylene Protection | Fibreglass Board | 0.94 ±0.06 | 7.44 ±0.03 | 20.08 ±0.08 |
| | Fibreglass & SBPO | 0.76 ±0.08 | 8.64 ±0.12 | 23.6 ±0.23 |
| | Fibreglass & Bld. Paper | -0.14 ±0.02 | 7.58 ±0.18 | 19.63 ±0.44 |
| | Paint & Fibreglass | 0.22 ±0.03 | 6.86 ±0.15 | 19.18 ±0.26 |
| | Bead Board | 0.91 ±0.15 | 6.97 ±0.17 | 21.8 ±0.15 |
| | Extruded Polystyrene | 0.77 ±0.18 | 7.95 ±0.22 | 19.85 ±0.16 |
| | Average | 0.58 | 7.57 | 20.69 |
| | Desired | 0.00 | 6.60 | --- |
| | Average | 0.35 ±0.24 | 7.09 ±0.25 | 20.86 ±0.67 |
| | Maximum | 1.24 | 8.64 | 23.60 |
| | Minimum | -0.52 | 6.53 | 18.98 |
| | Confidence Interval | ±0.24 | ±0.25 | ±0.67 |

Note: Intervals represent 95% confidence.

## Table D-2: Average temperature data for retested panels - non-freezing conditions.

(All temperatures are in °C)

| Warm Side | Cold Side | Guardroom Avg. | Gyspum Avg. | Environmental Chamber Avg. |
|---|---|---|---|---|
| SBPO | Fibreglass Board | -0.45 ±0.04 | 7.00 ±0.10 | 21.04 ±0.33 |
| Polyethylene | Fibreglass Board | -2.37 ±0.11 | 6.88 ±0.06 | 26.00 ±0.56 |
|  | Desired | 0.00 | 6.60 | -- |
|  | Average | -1.41 | 6.94 | 23.52 |
|  | Maximum | -0.45 | 7.00 | 26.00 |
|  | Minimum | -2.37 | 6.88 | 21.04 |
|  | Confidence Interval | 0.44 | 0.03 | 1.15 |

Note: Intervals represent 95% confidence.

## Table D-3: Average temperature data for freezing tests.

(All temperatures are in °C)

| Warm Side | Cold Side | Cold Side Avg. | Gypsum (warm-face) Avg. | Chamber Avg. |
|---|---|---|---|---|
| No Protection | Fibreglass Board | -13.78 ±0.13 | -1.73 ±0.05 | 22.71 ±0.35 |
| | Fibreglass & SBPO | -11.25 ±0.10 | -1.86 ±0.03 | 20.26 ±0.23 |
| | Fibreglass & Bld. Paper | -11.38 ±0.07 | -1.64 ±0.04 | 20.14 ±0.31 |
| | Paint & Fibreglass | -12.66 ±0.10 | -1.75 ±0.02 | 24.17 ±0.39 |
| | Bead Board | --- | --- | --- |
| | Extruded Polystyrene | --- | --- | --- |
| | **Average** | **-12.27** | **-1.75** | **21.82** |
| SBPO Protection | Fibreglass Board | -9.67 ±0.17 | -1.01 ±0.07 | 16.91 ±0.34 |
| | Fibreglass & SBPO | -10.56 ±0.17 | -1.89 ±0.10 | 16.56 ±0.43 |
| | Fibreglass & Bld. Paper | -11.36 ±0.12 | -0.77 ±0.07 | 16.76 ±0.22 |
| | Paint & Fibreglass | -11.5 ±0.12 | -1.99 ±0.04 | 18.4 ±0.37 |
| | Bead Board | -11.38 ±0.07 | -1.71 ±0.15 | 24.5 ±0.60 |
| | Extruded Polystyrene | -12.78 ±0.08 | -1.53 ±0.18 | 19.47 ±0.40 |
| | **Average** | **-11.21** | **-1.48** | **18.77** |
| Polyethylene Protection | Fibreglass Board | -12.23 ±0.11 | -1.57 ±0.22 | 17.73 ±0.35 |
| | Fibreglass & SBPO | -11.73 ±0.15 | -1.6 ±0.27 | 16.54 ±0.23 |
| | Fibreglass & Bld. Paper | -13.6 ±0.23 | -1.38 ±0.15 | 17.84 ±0.45 |
| | Paint & Fibreglass | -11.65 ±0.20 | -1.84 ±0.13 | 17.88 ±0.46 |
| | Bead Board | -11.75 ±0.38 | -1.64 ±0.15 | 23.91 ±0.88 |
| | Extruded Polystyrene | -11.19 ±0.26 | -1.54 ±0.13 | 18.18 ±0.47 |
| | **Average** | **-12.03** | **-1.60** | **18.68** |
| | Desired | -12.50 | -2.00 | --- |
| | Average | -12.27 | -1.59 | 19.50 |
| | Maximum | -12.27 | -0.77 | 24.50 |
| | Minimum | -12.27 | -1.99 | 16.54 |
| | Confidence Interval | ±0.47 | ±0.14 | ±1.27 |

Note: Intervals represent 95% confidence.

# APPENDIX E

Measured quantities of moisture in each wall component and supplied to each test panel in the laboratory tests.

## Table E-1: Measured data from non-freezing tests.

| Wall Type | | Total Moisture Supplied to Wall (g) | Moisture Distribution in Wall Components (g) | | | | |
|---|---|---|---|---|---|---|---|
| Warm Side | Cold Side | | Warm Side Accumulation | Gypsum | Cold Side Insulation | Diffused Moisture | Total of Wall Components |
| Unprotected | Fibreglass Board | 406 | * | 117 | 86 | * | - |
| | Fibreglass & SBPO | 377 | * | 104 | 89 | * | - |
| | Fibreglass & Bldg. Paper | 445 | * | 130 | 25 | * | - |
| | Paint & Fibreglass | 518 | * | 215 | 53 | * | - |
| | Bead Board | 549 | * | 344 | 41 | * | - |
| | Extruded Polystyrene | 334 | * | 341 | 14 | * | - |
| SBPO Protection | Fibreglass Board | 174 | * | 25 | 3 | * | - |
| | Fibreglass & SBPO | 120 | * | 29 | 9 | * | - |
| | Fibreglass & Bldg. Paper | 100 | * | 28 | 4 | * | - |
| | Paint & Fibreglass | 102 | * | 36 | 6 | * | - |
| | Bead Board | 163 | * | 39 | 2 | * | - |
| | Extruded Polystyrene | 92 | * | 43 | 5 | * | - |
| Polyethylene Protection | Fibreglass Board | 110 | * | 27 | 11 | * | - |
| | Fibreglass & SBPO | 168 | * | 27 | 16 | * | - |
| | Fibreglass & Bldg. Paper | 105 | * | 28 | 11 | * | - |
| | Paint & Fibreglass | 100 | * | 28 | 5 | * | - |
| | Bead Board | 172 | * | 35 | 6 | * | - |
| | Extruded Polystyrene | 136 | * | 26 | 2 | * | - |

* Not a measured quantity.

**Table E-2: Measured data from retests under non-freezing conditions.**

| **Wall Type** | | **Total Moisture Supplied to Wall (g)** | **Moisture Distribution in Wall Components (g)** | | | | |
|---|---|---|---|---|---|---|---|
| Warm Side | Cold Side | | Warm Side Accumulation | Gypsum | Cold Side Insulation | Diffused Moisture | Total of Wall Components |
| SBPO | Fibreglass Board | 265 | 182 | 23 | 3 | 38 | 245 |
| Polyethylene | Fibreglass Board | 170 | 139 | 4 | 2 | 11 | 156 |

**Table E-3: Measured data from freezing tests.**

| **Wall Type** | | **Total Moisture Supplied to Wall (g)** | **Moisture Distribution in Wall Components (g)** | | | | |
|---|---|---|---|---|---|---|---|
| Warm Side | Cold Side | | Warm Side Accumulation | Gypsum | Cold Side Insulation | Diffused Moisture | Total of Wall Components |
| Unprotected | Fibreglass Board | 835 | 572 | 119 | 43 | 93 | 826 |
| | Fibreglass & SBPO | 840 | 409 | 92 | 193 | 131 | 825 |
| | Fibreglass & Bldg. Paper | 995 | 628 | 72 | 123 | 159 | 983 |
| | Paint & Fibreglass | 1245 | 712 | 180 | 170 | 170 | 1232 |
| | Bead Board | 978 | 685 | 194 | 51 | 18 | 947 |
| | Extruded Polystyrene | 630 | 330 | 220 | 41 | 13 | 604 |
| SBPO Protection | Fibreglass Board | 161 | 126 | 7 | 13 | 19* | - |
| | Fibreglass & SBPO | 180 | 136 | 5 | 18 | 20* | - |
| | Fibreglass & Bldg. Paper | 163 | 105 | 3 | 12 | 43* | - |
| | Paint & Fibreglass | 227 | 160 | 11 | 24 | 32* | - |
| | Bead Board | 269 | 218 | 9 | 6 | 36* | - |
| | Extruded Polystyrene | 188 | 148 | 15 | 12 | 12* | - |
| Polyethylene Protection | Fibreglass Board | 206 | 157 | 6 | 24 | 19* | - |
| | Fibreglass & SBPO | 203 | 146 | 8 | 31 | 18* | - |
| | Fibreglass & Bldg. Paper | 179 | 157 | 4 | 6 | 12* | - |
| | Paint & Fibreglass | 237 | 188 | 10 | 36 | 3* | - |
| | Bead Board | 265 | 225 | 2 | 6 | 31* | - |
| | Extruded Polystyrene | 185 | 161 | 4 | 5 | 16* | - |

* A calculated quantity.

# APPENDIX F

Values of permeance and thermal resistance for materials
and composite test panels.

**Table F-1: Thermal resistance and permeance values for various materials.**

| Material | Thermal Resistance $m^2 \cdot {}^\circ C/W$ | Permeance $ng/Pa \cdot s \cdot m^2$ |
|---|---|---|
| SBPO | negl. | 2600 |
| polyethylene (2 mil) | negl. | 8 |
| warm-side insulation | 4.44 | negl. |
| gypsum (12.5 mm) | 0.08 | 2174 |
| fibreglass board (25 mm) | 0.77 | 5108 |
| fibreglass board (25 mm) with SBPO | 0.77 | 1723 |
| sheathing paper | 0.011 | 2400 |
| two coats of laytex paint | negl. | 600 |
| bead board (25 mm) | 0.65 | 300 |
| extruded polystyrene (25 mm) | 0.87 | 50 |

**Table F-2: Thermal resistance and permeance values for each test panel.**

| Test Panel | RSI value | Permeance of Unprotected Panels | Permeance of SBPO Protected Panels | Permeance of Polyethylene Protected Panels |
|---|---|---|---|---|
| fibreglass | 5.29 | 961.5 | 704.5 | 7.9 |
| SBPO & fibreglass | 5.29 | 704.2 | 555.5 | 7.9 |
| bldg. paper & fibreglass | 5.30 | 684.9 | 543.5 | 7.9 |
| paint & fibreglass | 5.29 | 365.0 | 320.5 | 7.8 |
| bead board | 5.17 | 241.5 | 221.2 | 7.7 |
| extruded polystyrene | 5.39 | 48.0 | 47.1 | 6.9 |