FULL SCALE THERMAL PERFORMANCE OF LATENT HEAT STORAGE IN PCM WALLBOARD

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ABSTRACT

FULL SCALE THERMAL PERFORMANCE OF LATENT HEAT STORAGE IN PCM WALLBOARD

Simona Gabriela Scalat

Incorporating Phase Change Materials (PCM's) into building materials to store energy is a practical approach to improve thermal comfort conditions and to improve the energy efficiency.

The intend of the present work is to address this need. To that purpose, PCM gypsum board was selected as ideal candidate for the full scale evaluation of its thermal capabilities.

Based on the previous laboratory work and on the Differential Scanning Calorimetry (DSC) tests, the PCM selected for this study was EMEREST 2326, a mixture of 50 % Butyl Stearate and 48 % Butyl Palmitate, due to its favourable phase change temperature range, very close to human comfort zone and, latent heat of transition.

At a loading of 20 % by weight, the DSC tests measured an average latent heat of 28±2.4 kJ/kg for PCM impregnated wallboard.

The PCM gypsum boards used in this study were made by immersing regular boards into liquid and heated PCM.

The experimental studies were conducted in a test facility consisting of two identical side-by-side rooms located at the Centre for Building Studies. Interior walls and ceiling of one of the rooms were lined with PCM wallboard while the other with regular gypsum boards. The test facility was equipped with a computer controlled data acquisition system.

The results showed a significant higher room air temperature due to the heat released by PCM gypsum boards as compared to room air temperature of regular boards, indicating the fact that the PCM boards have a high thermal inertia due to the heat released during the solidification process, giving a more stable air temperature.

Most important, it was determined that laboratory scale DSC can adequately predict the performance of PCM wallboard.

The results demonstrated that the concept of latent heat storage is workable at large scale and that PCM wallboard can function efficiently as a thermal storage medium.

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ABBREVIATION

PCM	phase change material
Q_s	sensible heat storage, kJ
Q_l	latent heat storage, kJ
λ	latent heat of change, kJ/kg
C_p	specific heat of the material, kJ/kg$\cdot{}^0$C
M	mass of the material, kg
T_f	final temperature, ^{0}C
T_i	initial temperature, ^{0}C
ΔT	temperature change of a material, ^{0}C
R_T	thermal resistance, $m^2\cdot{}^0C/W$
U	overall coefficient of heat transmission, $W/m^2\cdot{}^0C$

CHAPTER 1 INTRODUCTION

Investigation of organic phase change materials (PCM's) for energy storing, particulary in building materials, has been studied at the Centre for Building Studies, for the past 15 years.

The use of organic PCM's comprise a number of advantages over the traditional inorganic PCM's, so studies at the CBS have been focused in this direction. Within organic PCM's, fatty acids and particularly their esters, were considered as ideal candidates for building applications since they can be impregnated or directly incorporated into conventional building products at some stage of their manufacture.

PCM's have the potential to save energy for heating or cooling, improving thermal comfort for building occupants. The benefit comes from having a natural source of heat storage, without changing standard building construction. Another advantage would be the fact that PCM's could help avoid uncomfortable temperature swings, giving a more stable air temperature. The storage acts as a true thermal inertia slowing any rise or fall of room temperature.

Thermal storage with PCM allows heat to be stored and than released as required. How does it work? Building materials containing PCM's store energy for heating. PCM's absorb heat in changing from the solid to the liquid state and release it as they change in the opposite direction.

Energy storing materials need to be specifically designed for the particular climate to get maximum utilization during the dominant season.

This research was conducted in a full scale testing facility in order to evaluate the thermal storage characteristics of gypsum wallboard containing about 20 % PCM and to determine the performance advantage over regular wallboard. This was achieved by the construction of two identical side-by-side test rooms in a controlled environment at the Centre for Building Studies, Concordia University, Environmental Laboratory.

This work enhanced the thermal storage capacity of regular gypsum board impregnated with PCM, when used as interior lining. The gypsum board matrix makes an ideal supporting medium for phase change materials, since approximately 70 % of its volume is air voids.

The PCM used for this research was a mixture of 50 % Butyl Stearate and 48 % Butyl Palmitate. This is a mixture of fatty acids esters produced by Henkel Canada under the trade name Emerest 2326.

1.1 RATIONALE AND APPLICATIONS

This field of investigation is the development of an appropriate and economical means of thermal storage using the building mass. One aspect of this activity is the storage of energy in gypsum wallboard which has been impregnated with PCM's. Energy stored in this manner has the following applications:

(i) Peak Load Shifting

Thermal storage can be employed to transfer an energy load from one period to another. Energy load transfer can be achieved by storing energy at a given time for use at another. Heating loads can comprise a significant portion of total power demand at certain times. Through appropriate use of thermal storage, large portions of this load could be eliminated and shifted from periods of peak demand to periods of low demand.

Reduction of peak demand or shifting energy loads from high consumption periods to low consumption periods is of increasing interest to energy production that must cope with fluctuating energy demand.

(ii) Use of Waste Heat

Thermal storage enables the use of excess heat which would otherwise be wasted. This energy may derive from a variety of sources:

- heat generated by occupants;
- heat produced from lighting, cooking, appliances and heat emitting equipment;
- waste heat from industrial, commercial and utility cooling systems or processes which permit heat flow recuperation;
- solar heat.

1.2 MEANS OF THERMAL STORAGE

The principal building elements used for thermal storage are walls, ceilings and floors. There are two practical ways to store energy:

(1) By raising the material temperature without changing its physical state; the thermal energy is than stored as sensible heat;

(2) By changing the material physical state or phase; the thermal energy is than

stored as latent heat;

1.2.1 Sensible Heat Storage

Every material stores heat as its temperature rises and release this later as it cools. This is called sensible heat storage if no change of phase is accompanied. The amount of energy stored over a fixed temperature range depends on the mass of material and on its ability to store heat (specific heat). In an equation form:

$$Q_s = M \cdot C_p \cdot (T_f\text{-}T_i)$$

Where:

Q_s = the quantity of stored sensible heat, kJ

C_p = the specific heat of the material, kJ/kg·^{0}C

M = the mass of heat storage material, kg

T_f = final temperature, ^{0}C

T_i = initial temperature, ^{0}C

Building materials such as stone, brick and concrete have been used in this manner to achieve thermal storage At present, all thermal storage in existing building materials depends upon their sensible heat capacity. Using conventional building materials, in order to obtain an adequate sensible storage capacity a large temperature range or a large structure mass are required.

1.2.2 Latent Heat Storage

This occurs when a material changes its state or phase. For example, when a material changes from solid to liquid, the change of phase is accompanied by the absorption of heat. Conversely, in changing from liquid to solid, the stored latent heat is released. Materials used for their thermal storage capacity as latent heat are called phase change materials (PCM's). Energy storage is achieved by melting the PCM and energy recovery by freezing it. The amount of thermal energy stored as latent heat by a material depends upon the mass of the material used and its latent heat of phase change. In an equation form:

$$Q_l = M \cdot \lambda$$

Where:

Q_l = the quantity of stored latent heat, kJ

λ = latent heat of phase change, kJ/kg

M = the mass of the material, kg

1.3 ADVANTAGES OF USING LATENT HEAT STORAGE

Compared with sensible heat storage, latent heat storage has the following advantages for building applications:

(i) It stores large quantities of energy (referring to Table 1.1, based on laboratory determinations);

(ii) Thermal storage may occur in the comfort temperature range;

(iii) It stores energy within a small temperature swing and thus avoids the uncomfortable temperature variations;

(iv) It avoids the use of large structural mass.

Table 1.1. Comparison between Latent Heat and Specific Heat for Some Materials

MATERIAL	**TRANSITION TEMPERATURE**		**LATENT HEAT (kJ/kg)**	**SPECIFIC HEAT (kJ/kg·°C)**
	Melting Point (°C)	**Freezing Point (°C)**		
Granite	-	-	-	1.73
Portland Cement	-	-	-	0.29
Building Brick	-	-	-	0.69
Concrete	-	-	-	0.76
$KF \cdot 4H_2O$	18.5		231	2.39
$CaCl_2 \cdot 6H_2O$	29.7		171	1.45
$Na_2SO_4 \cdot 10H_2O$	32.4		254	1.93
EMEREST 2326	17.0-21.0	17.6-19.8	140	2.41
Paraffin	49.0-64.0	52.0-64.0	148	1.94
Octadecane	24.0-29.0	27.0-32.0	253	1.81
Commercial Wax	30.0-45.0	35.0-47.0	147	1.83
Stearic Acid	50.0-64.0	55.0-71.0	191	2.07
Gypsum Board loaded 20% with EMEREST 2326	17.0-21.0	17.0-19.9	28	1.34

CHAPTER 2 OBJECTIVES OF THE THESIS

The objectives of this research are:

(i) To test and to evaluate the thermal storage capabilities for the full scale PCM wallboard,

(ii) To compare these characteristics with those of regular gypsum board, and

(iii) To compare the small-scale Differential Scanning Calorimetry results with the full scale test results

Chapter 1 presents an introduction into the field of latent heat storage to provide the reader with an overview of the importance and applications of thermal storage, the means and the advantages of using latent heat storage.

A literature review is summarized in chapter 3 about the present status of the research work on phase change materials. The most relevant categories of PCM's including their selection criteria are described. Reasons for the selection of gypsum wallboard among other building materials, for latent heat storage, and the achievements of the incorporation of PCM's in gypsum wallboard are also presented.

Chapter 4 presents the experimental studies of the thermal performance of PCM gypsum board and the effects on the overall thermal performance on a full scale application. The experimental study was conducted in a full scale test facility consisting of two identical side-by-side rooms. Interior walls and ceiling of one of the rooms were finished with regular gypsum board while the interior walls and ceiling of the other room were finished with PCM gypsum board. The test rooms were equipped with a computer control data acquisition system and microprocessor based digital controllers. The measurements were performed under various control schemes and the resulting characteristics for each type of board were compared. Procedure for fabricating the PCM impregnated gypsum boards was also presented. The PCM used for this research was EMEREST 2326 at an average loading of 20 % by weight.

Chapter 5 presents the analysis of the comparative thermal performance of the regular gypsum board and the PCM gypsum board. The calculation of thermal storage in PCM wallboard was done using the data recorded in chapter 4. Latent heat values of PCM and of PCM wallboard were calculated and compared with those obtained by the small-scale DSC. The fire tests carried out for the evaluation of the flammability characteristics of PCM gypsum wallboard are also presented.

Finally, the conclusions on the benefits obtained from the use of PCM gypsum board are summarized in chapter 6. Some recommendation for future work are than presented.

CHAPTER 3 LITERATURE REVIEW

3.1 DEVELOPMENT OF LATENT HEAT STORAGE

Interest in PCM's can probably be traced back to earlier work on solar heat storage. The search for alternate approaches, more efficient than sensible heat storage in water containers and rock beds, led to the investigation of latent heat systems. Researchers in this field include M. Telkes. Already in 1940, her first reported application was in the field of testing of an active solar system with heat storage by fusion-solidification of Glauber's Salt ($Na_2SO_4 \cdot 10H_2O$). The system was operational for three years, however problems of corrosion and water loss developed and the experiment had to be interrupted.

Later on, a lot of work has been done to find the suitable PCM's which could be used as means of energy storing materials. Since late 1970 studies have been reported by many authors, such as Feldman, Shapiro (1983, Canada), Abhat (1982, Germany), Van Ghalen (1986, Netherland), Lane, Salyer (1983, 1985, USA), Shibasaki and Fukuda (1985, Japan), Hawes, Feldman and Banu (1989, Canada). In these studies, the PCM's usually considered were inorganic.

Of the inorganic PCM's, one of the most interesting groups are the salt hydrates, (in which the salt is bound by water of crystallization) such as Glauber's Salt and Calcium Chloride Hexahydrate ($CaCl_2 \cdot 6H_2O$) (Altman et al., 1972; Hariri and Ward, 1988).

Unfortunately these materials are corrosive and require special containers as well as space for containers. The extra cost of these facilities offsets the cost advantage of PCM's themselves (Feldman et al., 1985). But the major reasons why inorganic PCM's are not suitable for use in building materials are corrosion and their tendencies to supercool and to melt incongruently (Feldman et al., 1986).

The value of organic materials as heat storage media has been known for a long time, but it was only since 1970 that general interest has been shown in respect to their incorporation into building materials (Lane, 1983).

At the Centre for Building Studies (CBS) research in the field of organic PCM's has been ongoing for the past 15 years. This research has been largely concentrated on the incorporation of various PCM's into different building materials such as wallboard, bricks, tiles, concrete blocks (Feldman et al., 1986; Feldman et al., 1987; [illegible]wes et al., 1989). The PCM's studied and selected for incorporation comprise:

- fatty acids
- fatty esters
- fatty alcohols
- paraffins (alkanes)

These studies indicate that if properly selected and applied, various combinations of PCM's and building materials have a high potential for thermal storage (Feldman et al., 1986; Feldman et al., 1989; Paris et al., 1991; Feldman et al., 1995).

Other studies brought a significant accomplishment in introducing different organic PCM's into concrete blocks (Hawes et al., 1989).

One of the best candidate selected as a matrix for different PCM's was gypsum wallboard. A major advance was the direct incorporation of organic PCM in gypsum board (Feldman et al., 1987; Salyer and Kedl 1989; Ghanbary, 1990; Paris et al., 1991).

Whereas several means of incorporation can be used, direct incorporation, which can be realized at the production stage of gypsum wallboard, appears to be the most successful and economical procedure (Feldman, 1991).

Thermal energy storage in PCM's incorporated in building materials by encapsulation in laminated aluminium foil for water heating and space heating application was also done studied (Jotshi et al., 1995).

Other studies focused on the application of PCM's in building envelope components, (floors, walls) for the investigation of their thermal storage performance (Athienitis et al., 1992).

3.2 PHASE CHANGE MATERIALS

PCM'S are employed in building materials to provide thermal storage as latent heat. The selection of a PCM with an appropriate phase change temperature range and a sufficient high latent heat can result in the addition of latent heat values which can increase the total thermal storage capacity within the human thermal comfort zone (Feldman et al., 1991).

3.1.1 Inorganic PCM's

The salt hydrates shown in Table 3.1 are among the inorganic PCM's considered potentially useful for thermal storage (Feldman et al., 1993).

Table 3.1. Hydrated salt PCM's (typical values)

PCM	**Melting Point (°C)**	**Latent Heat (kJ/kg)**
$KF \cdot 4H_2O$ Potassium fluoride tetrahydrate	18.5	231
$CaCl_2 \cdot 6H_2O$ Calcium chloride hexahydrate	29.7	171
$Na_2SO_4 \cdot 10H_2O$ Sodium sulphate decahydrate	32.4	254
$Na_2HPO_4 \cdot 12H_2O$ Sodium orthophosphate dodecahydrate	35.0	281
$Zn(NO_3)_2 \cdot 6H_2O$ Zinc nitrate hexahydrate	36.4	147

These PCM's have some **attractive** properties such as:

(i) high latent heat value;

(ii) not flammable;

(iii) useful transition temperature range;

(iv) inexpensive and readily available.

Unfortunately, these materials have also some **unwanted** characteristics:

(i) they are corrosive, therefore, incompatible with many other materials used in buildings;

(ii) they need special containers which require support and space;

(iii) they have a tendency to supercool;

(iv) components do not melt congruently and segregation may occur;

(v) they may loose the hydration water after many freeze-thaw cycles, and consequently changing their thermal properties.

3.2.2 Organic PCM

In order to avoid some of the problems inherent in organic PCM's an interest was developed in the use of organic PCM's. They have a number of important **advantages**:

(i) there is a wide selection;

(ii) the components melt congruently and do not segregate;

(iii) they are chemically stable;

(iv) they can be incorporated in the building materials without containment;

(v) they are compatible and suitable for absorption in various building materials;

(vi) the installed cost is low;

(vii) they may be tailored for melting and freezing in the desired temperature range.

However, organic PCM's have also some **disadvantages**. These are:

(i) flammability and smoke generation;

(ii) some have strong odour;

(iii) some presents oily exudation;

(iv) a few have appreciable volume changes during phase change.

But appropriate selection can eliminate the undesirable characteristics of some of the organic PCM's. From many PCM's studied at the CBS those presented in Table 3.2 are among the best selected for thermal storage (Feldmanet al., 1993)

Table 3.2 Organic PCM (typical values)

PCM	**Melting point (^{0}C)**	**Latent Heat (kJ/kg)**
$CH_3(CH_2)_{16}COO(CH_2)_3CH_3$ butyl stearate	21	140
$CH_3(CH_2)_{11}OH$ 1-dodecanol	25	200
$CH_3(CH_2)_nCH_3$ paraffin	49-60	200
45% $CH_3(CH_2)_8COOH$ 55% $CH_3(CH_2)_{10}COOH$ 45/55 capric-lauric acid	21	143
$CH_3(CH_2)_{12}COOC_3H_7$ propyl palmitate	20	190

3.3 PCM'S SELECTION CRITERIA

The selection of an appropriate PCM must be carried out with respect to the relevant combinations of thermal, physical, chemical, kinetic and economical properties (Feldman et al., 1993).

3.3.1 Thermodynamic Consideration

(i) Latent Heat of Transition

The selected PCM should have the highest possible latent heat of transition, since the greater the latent heat, the less amount of PCM is required. A satisfactory range for the latent heat of fusion was established as 130-200 kJ/kg.

(ii) Heat Transfer Properties

The thermal performance of an energy storage system is dependent on the heat transfer properties of the PCM and the matrix. The efficiency with which the heat is transferred to and from a storage system depends strongly upon the thermal conductivities of the PCM and matrix. The higher the conductivities, the more efficient is the transfer. Salt hydrates generally have higher thermal conductivities.

Table 3.3. Thermal conductivity for some salt hydrates

Material	**Melting Point (^{0}C)**	**Latent Heat (kJ/kg)**	**Specific Heat (kJ/kg·^{0}C)**		**Thermal Conductivity (W/m·^{0}C)**	
			liquid	**solid**	**liquid**	**solid**
$KF \cdot 4H_2O$ Potassium fluoride tetrahydrate	18.5	231	2.39	1.84	0.510	0.678
$CaCl_2 \cdot 6H_2O$ Calcium chloride hexahydrate	29.7	171	2.10	1.42	0.540	1.088
$Na_2HPO_4 \cdot 12H_2O$ Sodium orthophosphate dodecahydrate	35.0	281	1.95	1.70	0.476	0.514

(iii) Transition Temperature

The phase transition temperature range must be appropriate and usually PCM's are selected so that heat would be released and absorbed in the comfort zone. The initial melting and freezing temperatures should be within 1 ^{0}C to prevent excursions outside the comfort zone and these characteristics should not change over the life of the material.

(iv) Phase Equilibrium

As the PCM changes from one phase to the other, it is desirable that equilibrium should be maintained in both phases. That is, the composition of PCM in liquid form should be identical with that in solid form, which does not happen in the case of inorganic PCM's. This implies that the melting of the components should be congruent and that they do not segregate during this process.

3.3.2 Physical Properties

(i) Appearance

The PCM must remain within the host material in both states and not cause changes in colour, oily exudation or crystalline formation.

(ii) Density

The density of a PCM is very important because it affects the storage efficiency per unit volume. It is usually desirable to select the material within the greatest density so that heat storage per unit volume will be maximum.

3.3.3 Chemical Properties

(i) Chemical Stability

The PCM's used must have a long life. This means that chemical reaction such as oxidation or thermal decomposition must not occur.

(ii) Compatibility

The PCM's must be inert in respect to the materials with which it will come into contact.

(iii) Toxicity

The PCM's used must be non-toxic; thereof must be such that injury cannot result from skin contact, ingestion or inspiration.

(iv) Flammability

The incorporation of an organic PCM into a building material must not constitute a fire or smoke hazard, so it should be within the acceptable limits imposed by fire codes.

(v) Nuisance

There are certain nuisance factors to be avoided when selecting a PCM such as any allergic reaction caused by unpleasant odour.

3.3.4 Kinetic Properties

(i) Avoidance of Supercooling

Some materials remain in the liquid state even when temperature drops bellow freezing point. In this case, the latent heat is not released at the desired temperature range.

(ii) Crystallization Rate

The process of crystallization begins with the formation of tiny crystallite nuclei on which the rest of the solid forms. For salt hydrates this process must be induced with additives to produce satisfactory results. More important is the rate of crystal growth, in order to effect solidification at a satisfactory rate. Therefore, these processes must proceed at a speed which will ensure the exchange of heat within an acceptable period of time.

3.3.5 Economic Factors

The PCM's selected should be readily available on the market and at a low cost.

• Conclusions

On the basis of the foregoing criteria, from the results of previous work done at CBS, the principal PCM candidates are presented in Table 3.4. As it can be seen from from this table, the PCM selected for the impregnation of gypsum wallboard for this research was a commercial mixture of 50 % butyl stearate, 48 % butyl palmitate and 2 % other fatty esters (EMEREST 2326). The cost is $0.55/lb.

Evaluation of the thermal characteristics of Emerest 2326 and gypsum wallboard impregnated with EMEREST 2326 was carried out by (DSC) tests. The results in each case are presented in Figures 3.1 to 3.4 on, which we may distinguish the heat storage and release, the melting and freezing points, at a scanning rate of 0.2 and 2 ^{0}C/min respectively.

Table 3.4. Final selection of PCM candidates (Feldman et al., 1993).

Candidate	**Freezing Point (°C)**	**Latent Heat (kJ/kg)**	**Disposition**	**Reason for Rejection**
Carbowax 600	20	130	Rejected	Melting range too large
Dodecanol	25	200	Rejected	Too flammable
Hexadecane	19	230	Rejected	Too expensive
Mixture of Capric Acid (67%) Lauric Acid (33%)	20	137	Rejected	Oily exudation
Mixture of Capric Acid (45%) Lauric Acid (55%)	21	143	Rejected	Can not be directly introduced into gypsum paste
Mixture of Capric Acid (85%) Palmitic Acid (15%)	21	150	Rejected	Quite strong odour
Coconut Fatty Acid (Emery 626)	19	120	Rejected	Melting range too large
Propyl Palmitate	20	190	Rejected	Not on the market for the moment
Mixture of Butyl Stearate (50%) Butyl Palmitate (48%) (Emerest 2326)	17	140	**Accepted**	

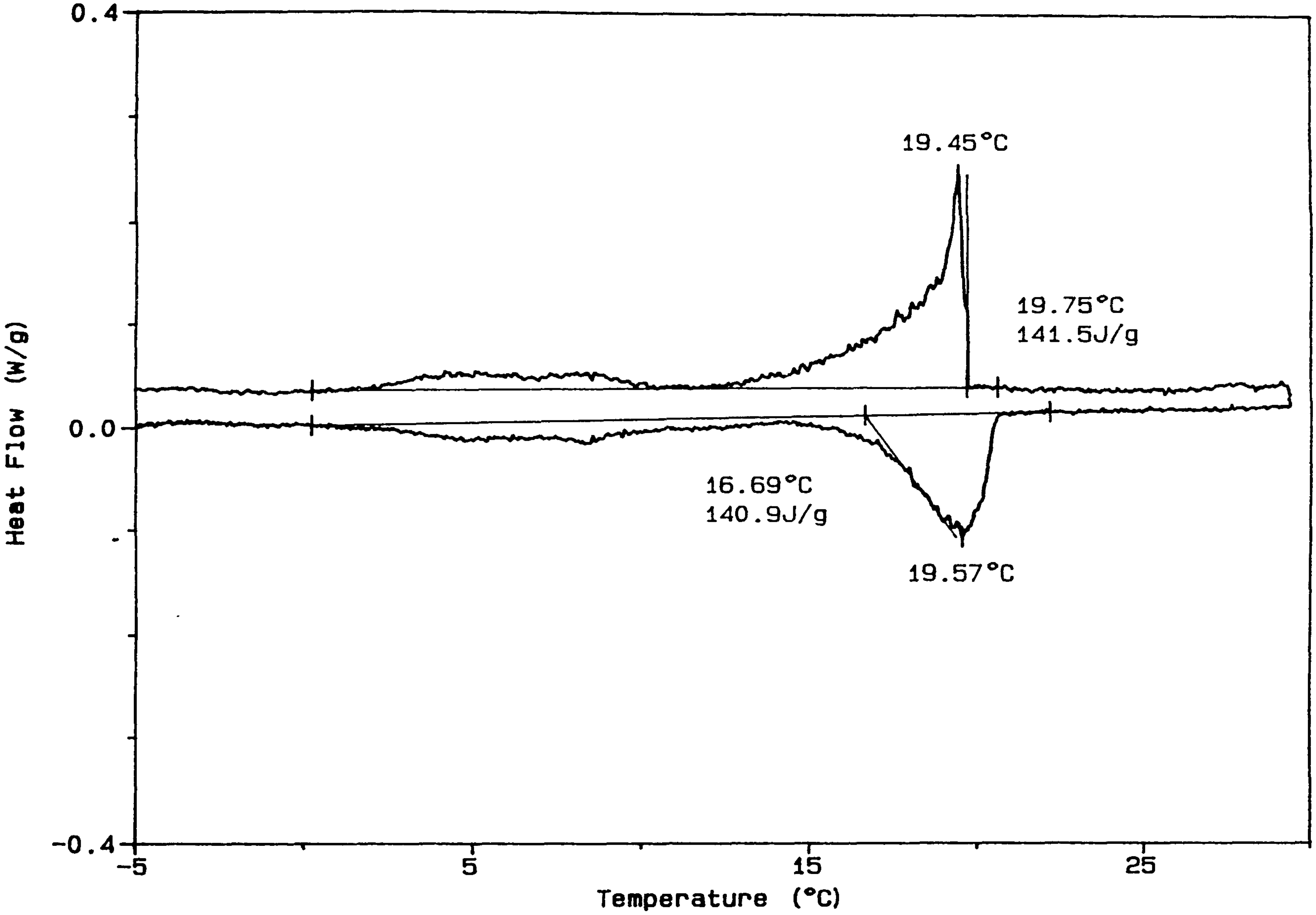


Figure 3.1 DSC test result of Emerest 2326, with testing rate 0.2 °C/min

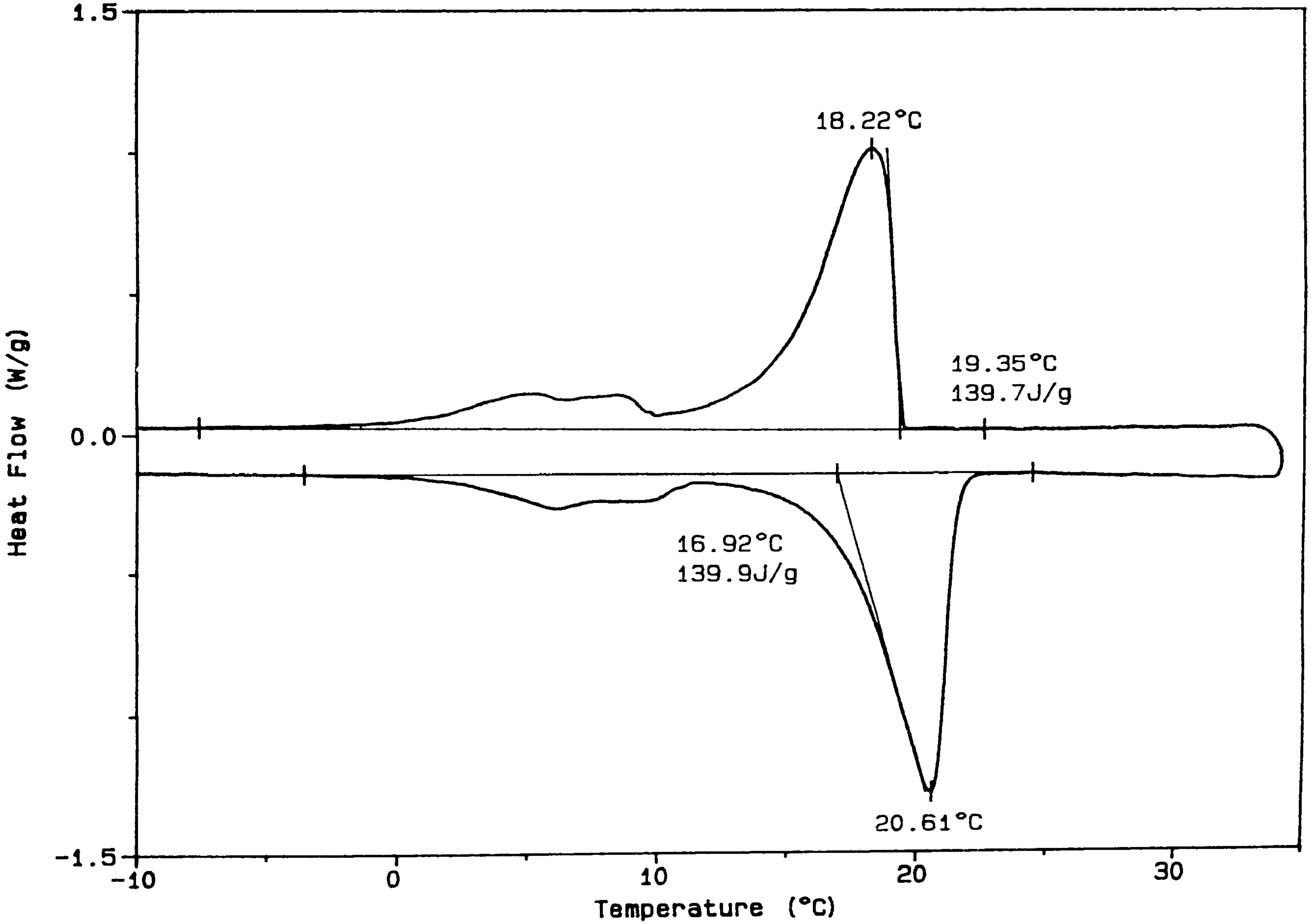


Figure 3.2 DSC test result of Emerest 2326, with testing rate 2 °C/min

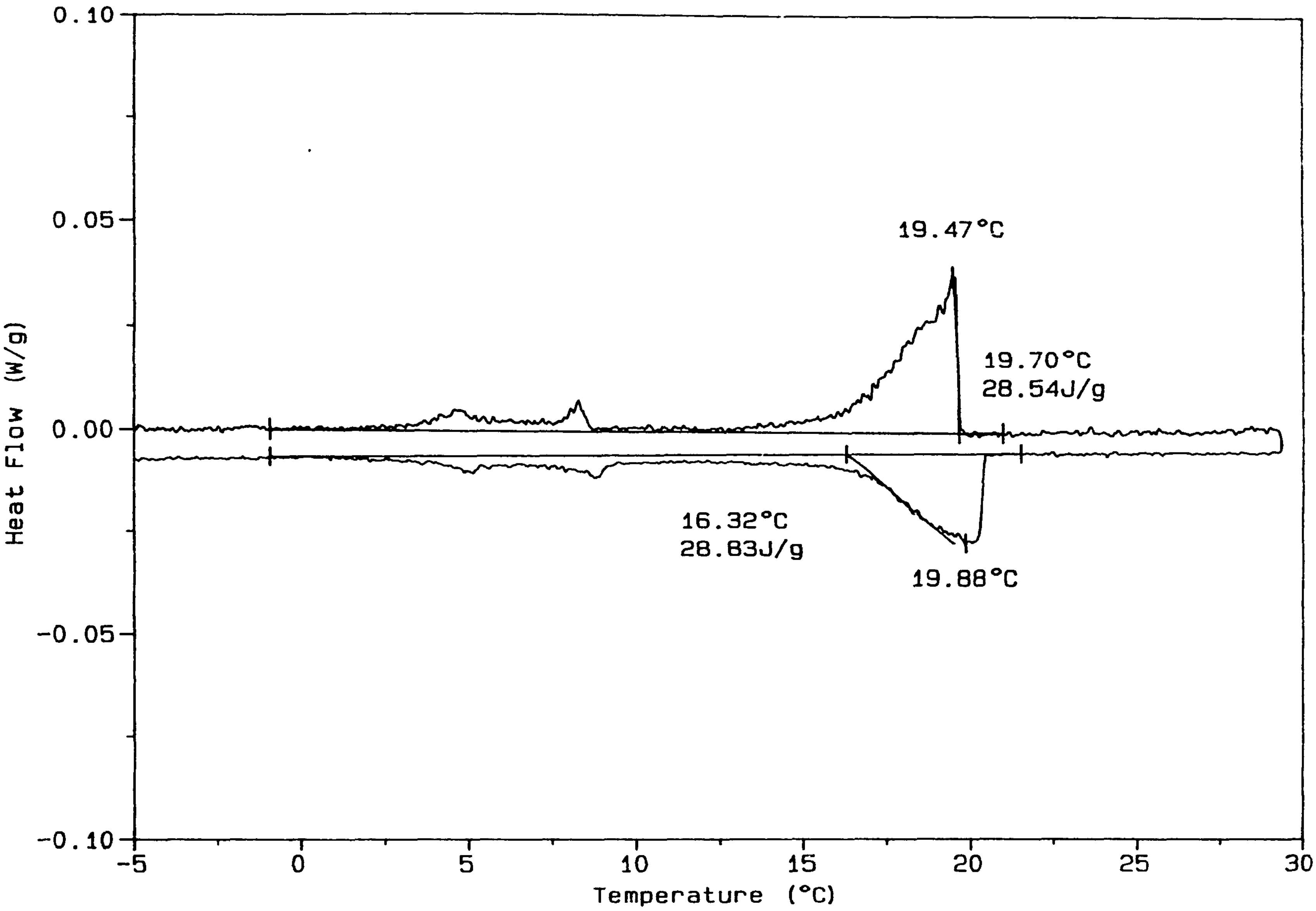


Figure 3.3 DSC test results of EMEREST 2326 gypsum board, loaded 20 % with testing rate 0.2 °C/min

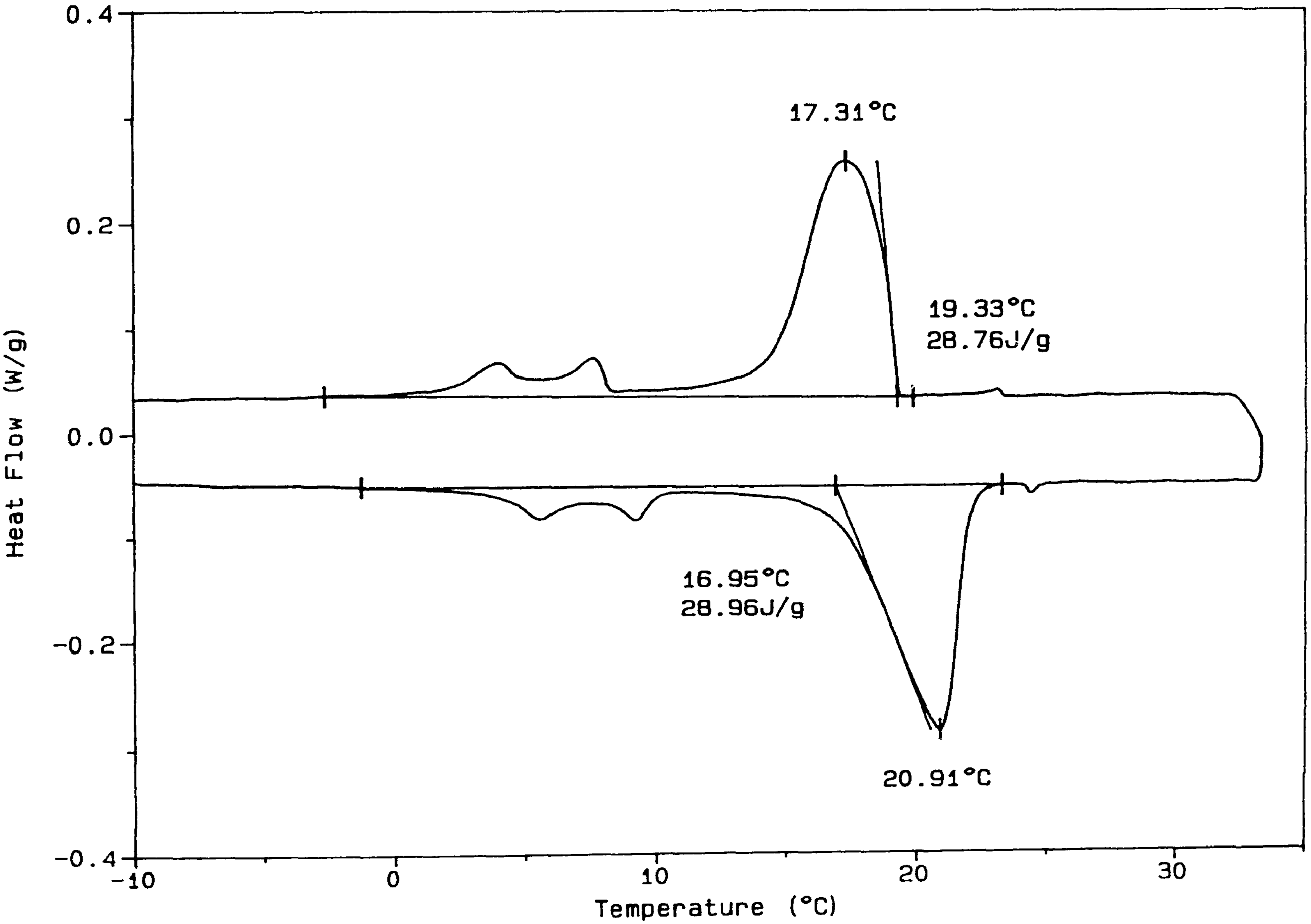


Figure 3.4 DSC test results of EMEREST 2326 gypsum board,

loaded 20 % with testing rate 2 °C/min

3.3 PCM GYPSUM BOARD

3.3.1 Reasons for Selection

PCM gypsum wallboard is made by the incorporation of PCM into standard gypsum wallboard. There are a number of reasons for choosing the incorporation of PCM in gypsum wallboard as a best building material.

(i) The use of wallboard is widespread and is found in every type of building in Canada and North America;

(ii) The surface area is very large for heat exchange to be effective;

(iii) By its geometry, structure and location PCM-wallboard is able to combine the functions of heat reservoir, heat exchanger and building element;

(iv) Its porous structure is such that even in liquid state the PCM will be retained by the virtue of surface tension;

(v) Addition of PCM to the wallboard can be easily achieved in two ways:

    (1) **immersion** of the wallboard for a short time into a bath of liquid PCM.

    (2) **direct incorporation** of PCM in the gypsum paste which can be obtained at small and large scale production.

The PCM gypsum wallboard developed for this work contains about 20 % by weight proportion of EMEREST 2326. Some results of the calorimetric tests are presented in Table 3.5.

Table 3.5. Results of DSC laboratory tests for various EMEREST 2326 loadings

Gypsum Board Loaded with EMEREST 2326 (wt %)	**Freezing Point (°C)**	**Latent Heat (kJ/kg)**
22.4	19.9	31.2
21.5	19.9	29.9
21.0	19.8	29.4
20.5	19.6	29.0
20.0	19.5	28.8

Tests results represents an average of 3 scans

Table 3.6. presents some physical and thermal characteristics of Emerest 2326 and of gypsum board loaded with 20 % EMEREST 2326.

Table 3.6. Thermal characteristics of EMEREST 2326 and gypsum board loaded with 20 % EMEREST 2326

Material	**Density (kg/m^3)**	**Specific Heat (kJ/kg·°C)**	**Thermal Conductivity (W/m·°C)**	**Phase Change Range (°C)**	**Latent Heat (J/g)**
EMEREST 2326	855	2.41	0.200	17-21	141.0
Regular gypsum board	720	1.08	0.187	-	-
Gypsum board loaded with 20% Emerest 2326	900	1.34	0.214	17-21	28.8

Laboratory tests undertaken at the CBS in order to evaluate the PCM wallboard in comparison with regular wallboard have shown that:

- flexural strengths are comparable;
- durability after more than 300 freeze-thaw cycling is complete satisfactory;
- compatibility with fasteners and representative paints and wall covers is very good;
- moisture absorption is about one third lower than that of ordinary wallboard.

3.3.2 Means of PCM Incorporation

There are three principal means of incorporating PCM's into building materials. They are (Feldman et al., 1993):

(i) **Direct incorporation**, at time of mixing, incorporating the PCM with other components which make up the building material (gypsum, concrete, etc.);

(ii) **Immersion**, incorporating the PCM by immersing dried and heated boards into liquid PCM for a certain amount of time;

(iii) **Encapsulation**, comprising the addition of small plastic containers of PCM when blending the components of the building material (gypsum, concrete, etc.).

The incorporation of PCM's into building materials has been a subject of research in the past years at the CBS. The immersion method can be conveniently used for experiments. For this research PCM was incorporated into gypsum wallboard by immersion.

CHAPTER 4 EXPERIMENTAL STUDIES FOR PCM WALLBOARD

4.1 TEST FACILITY

The experimental studies were conducted in a full scale test facility located at the Centre for Building Studies, Environmental Laboratory. The test facility, with its schematic shown in Figure 4.1, and detail structure shown in Figure 4.2, consisting of two identical insulated side-by-side rooms. The rooms are 2.29 m by 2.27 m by 2.45 m high and were constructed in a similar manner. A common insulated wall separates the two rooms. Interior walls and ceiling of one of the rooms were finished with ordinary gypsum board while the interior walls and ceiling of the other room were finished with PCM impregnated gypsum board. The interior covering of each wall consist of two panels of 1.15 x 2.29 m gypsum board. The frames were made of 38 x 63 mm (1.5 x 2.5") studs. The exterior surfaces of the walls were covered with 12.5 mm (1/2") thick sheets of plywood and wall cavities were filled with fibreglass thermal insulation.

Two air conditioners and two heaters were installed on the top of each room. Each unit was equipped with a microprocessor based digital controller so that programming features could be accessed and controlled through digital communication ports. In each room, a ceiling fan was operated continuously to keep the room air well mixed.

In order to obtain lower temperature in and to control the environment surrounding the testing structure, this was isolated from the rest of the laboratory by constructing a separation wall. Environmental temperature as low as 12 ^{0}C were obtained by using an additional air conditioning unit.

The testing structure was also provided with a computer controlled data acquisition system of which a total of 68 data channels were used to collect data. Temperatures were measured at 66 locations which included the front and the back surface temperatures of the wallboards, as shown in Figure 4.3, and room air temperatures. The room air temperature was measured at four equal heights on a stud installed in the middle of each room with the purpose to obtain measurements regarding the uniformity of room air temperature. In addition to the measurements taken in the test rooms, environmental temperature were also recorded using 2 channels.

The computer program was designed to record temperature measurements and energy consumption for heating. The measured data were recorded every 5 seconds and an average value was given every 5 minutes.

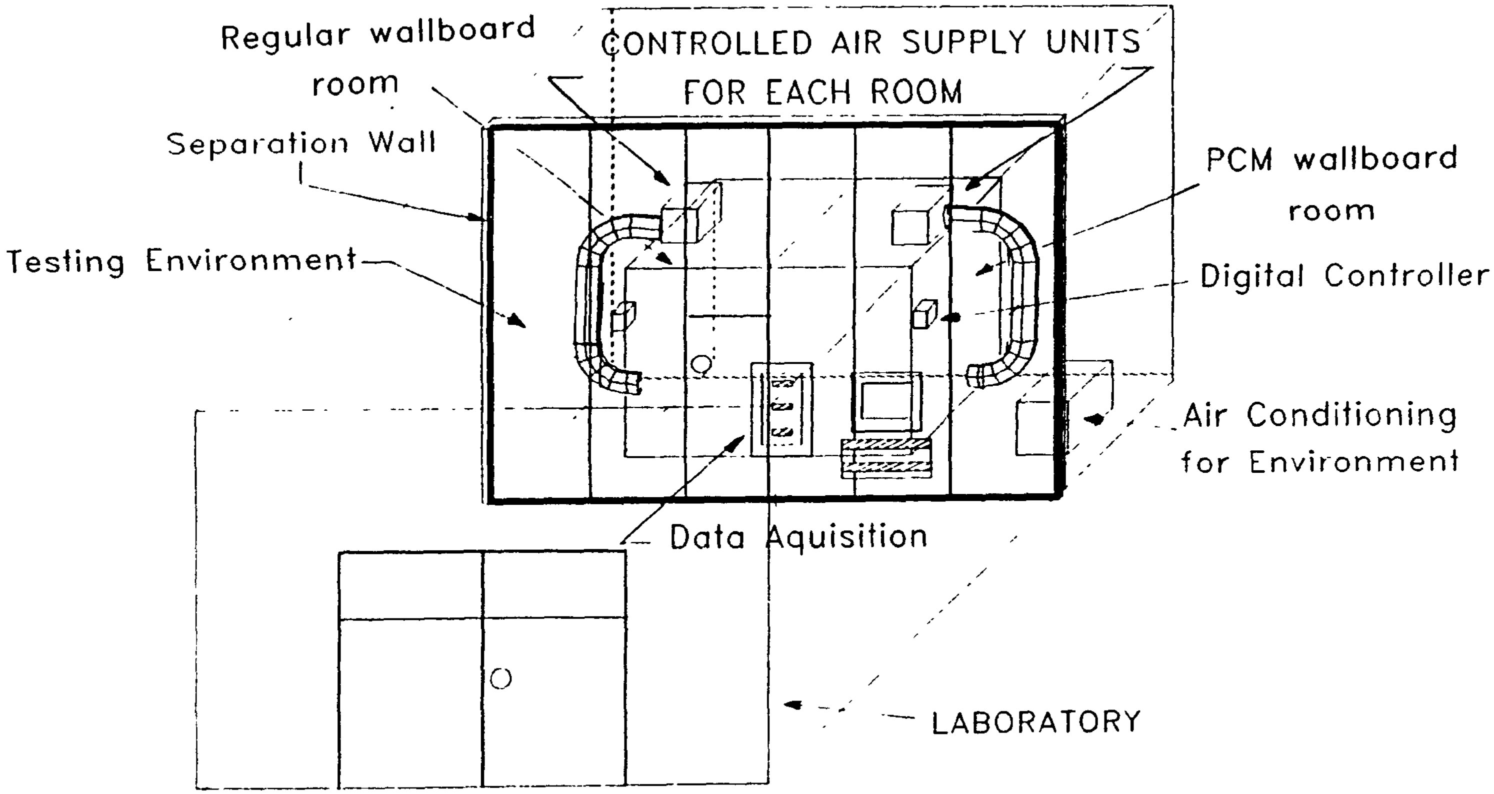
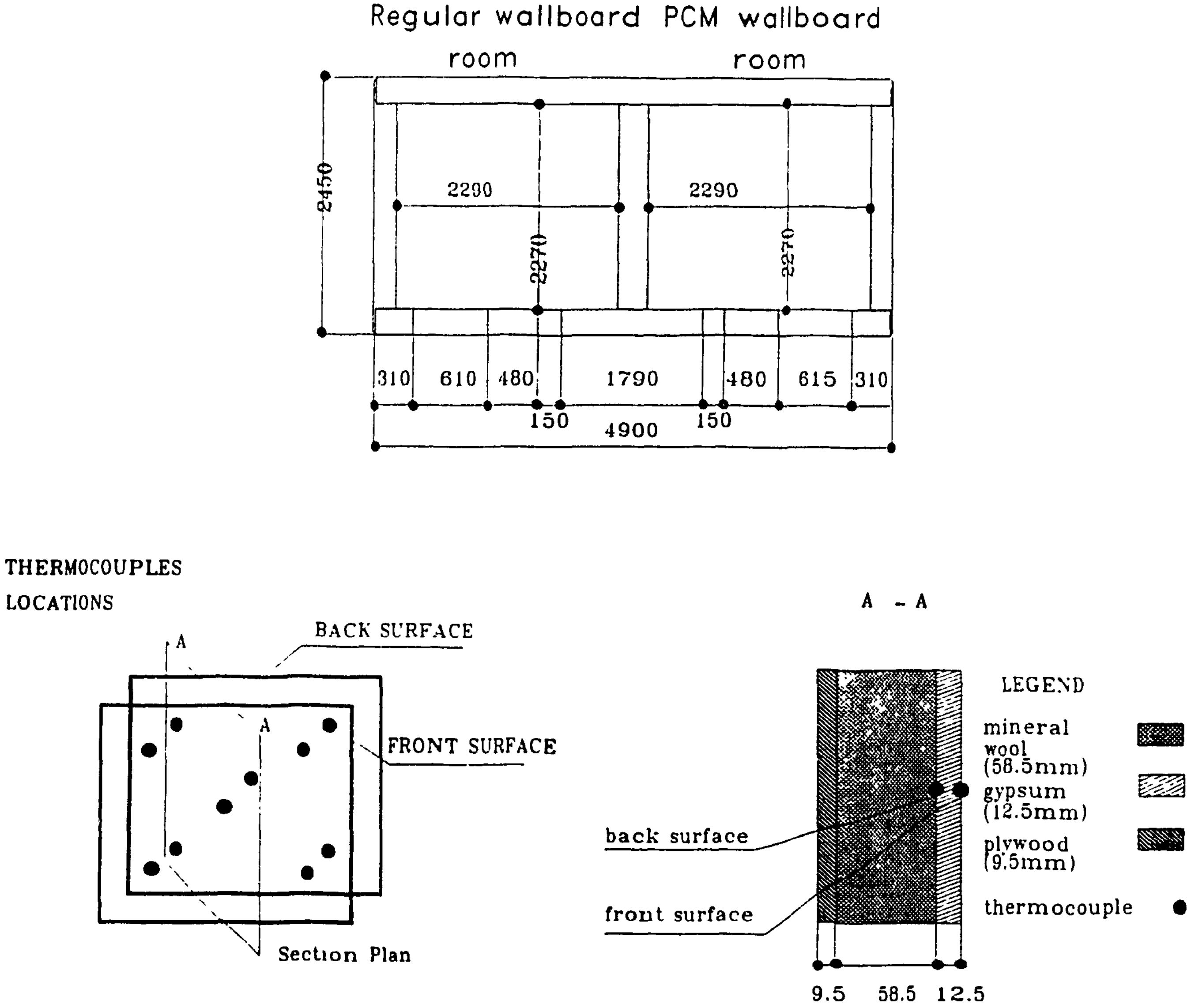
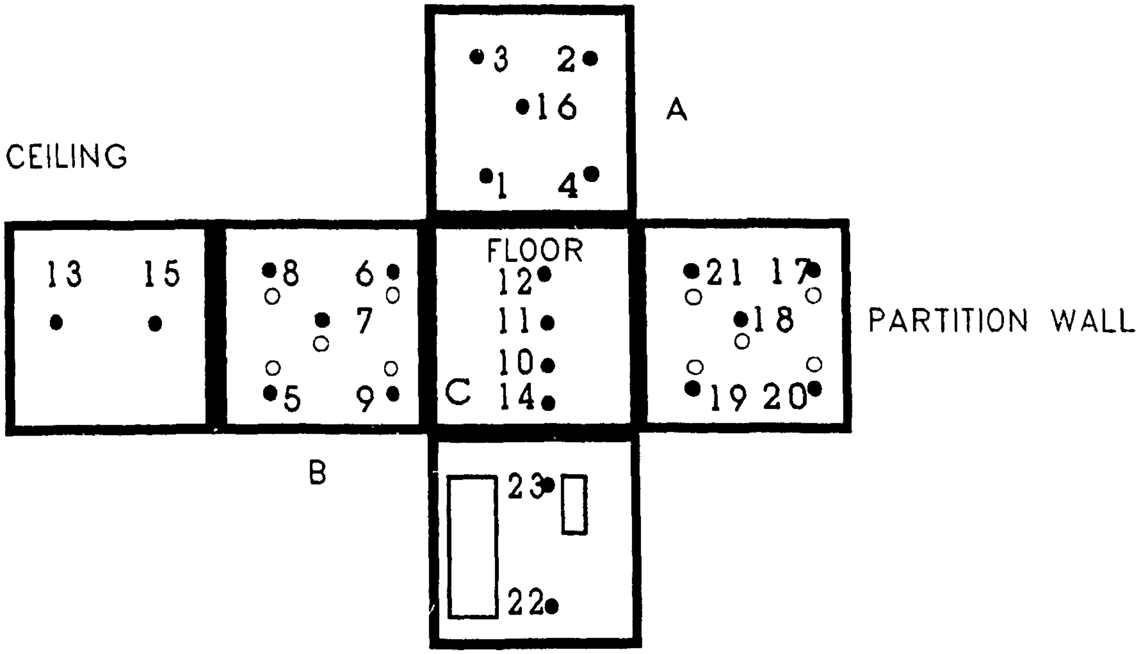


Figure 4.1 Schematic of the Two Rooms Testing Structure



- Both rooms are 2450 mm high
- All dimensions are in mm

***Figure 4.2** Plan of the Two Rooms Testing Structure and Wall Thermocouples Locations (plan and cross-section)*



● Front Surface Thermocouples

○ Back Surface Thermocouples

4.3 Schematic of Room Thermocouples Locations

4.2 PROCEDURE FOR FABRICATING PCM WALLBOARD

Impregnation of wallboard with PCM was achieved by immersing ordinary wallboard in a 2.5 x 1.2 x 0.1 m bath which was filled with PCM while the temperature of PCM was maintained at 50 ± 5 ^{0}C. Prior to immersion, the wallboard was kept at 50 ± 5 ^{0}C for about four hours. The immersion time varied between 1.5 to 4 min. All boards were weighted before and after immersion to establish the percentage of absorbed PCM. The PCM concentration are shown in Table 4.1.

At this point it is of interest to note that since PCM wallboard can be produced with comparatively little modification to existing production facilities and since it can be installed with the same techniques and equipment used for conventional building wallboard, minimal changes will be required for production and construction facilities.

Table 4.1. PCM concentration in wallboard prepared for PCM room

Wallboard No.	Dry Weight at 53^{0}C (kg)	Impregnated Weight (kg)	PCM in Wallboard	
			(kg)	(%)
1	20.9	25.7	4.8	18.7
2	21.0	26.1	5.1	19.5
3	21.0	26.5	5.5	20.8
4	21.0	25.0	4.0	16.0
5	21.0	26.8	5.8	21.6
6	21.9	27.7	5.8	20.9
7	21.0	26.8	5.8	21.6
8	20.7	25.9	5.2	20.1
9	21.3	27.4	6.1	22.3
10	0.3	0.4	0.1	25.0
11	0.8	1.0	0.2	20.0
12	5.3	6.5	1.2	18.5
13	3.6	4.5	0.9	20.0
TOTAL	*199.8*	*250.3*	*50.5*	*20.2*

4.3 EXPERIMENTAL METHODOLOGY

The experiments were performed mainly from January to May 1995, and November 1995 to February 1996. Three types of tests were performed. The first in the test facility cooling mode, the second in the heating mode. Those tests were conducted to determine air and wallboard temperatures in both rooms and hence to evaluate the comparative thermal storage and release performances of regular and PCM wallboards.

The third type of test was conducted to obtain direct measurement of the energy stored in the PCM wallboard relative to the regular one.

Test temperatures ranged between 10 and 26 ^{0}C. Tests were conducted at various conditions and the resulting characteristics for each type of wallboard were compared.

4.3.1 Natural Cooling Mode

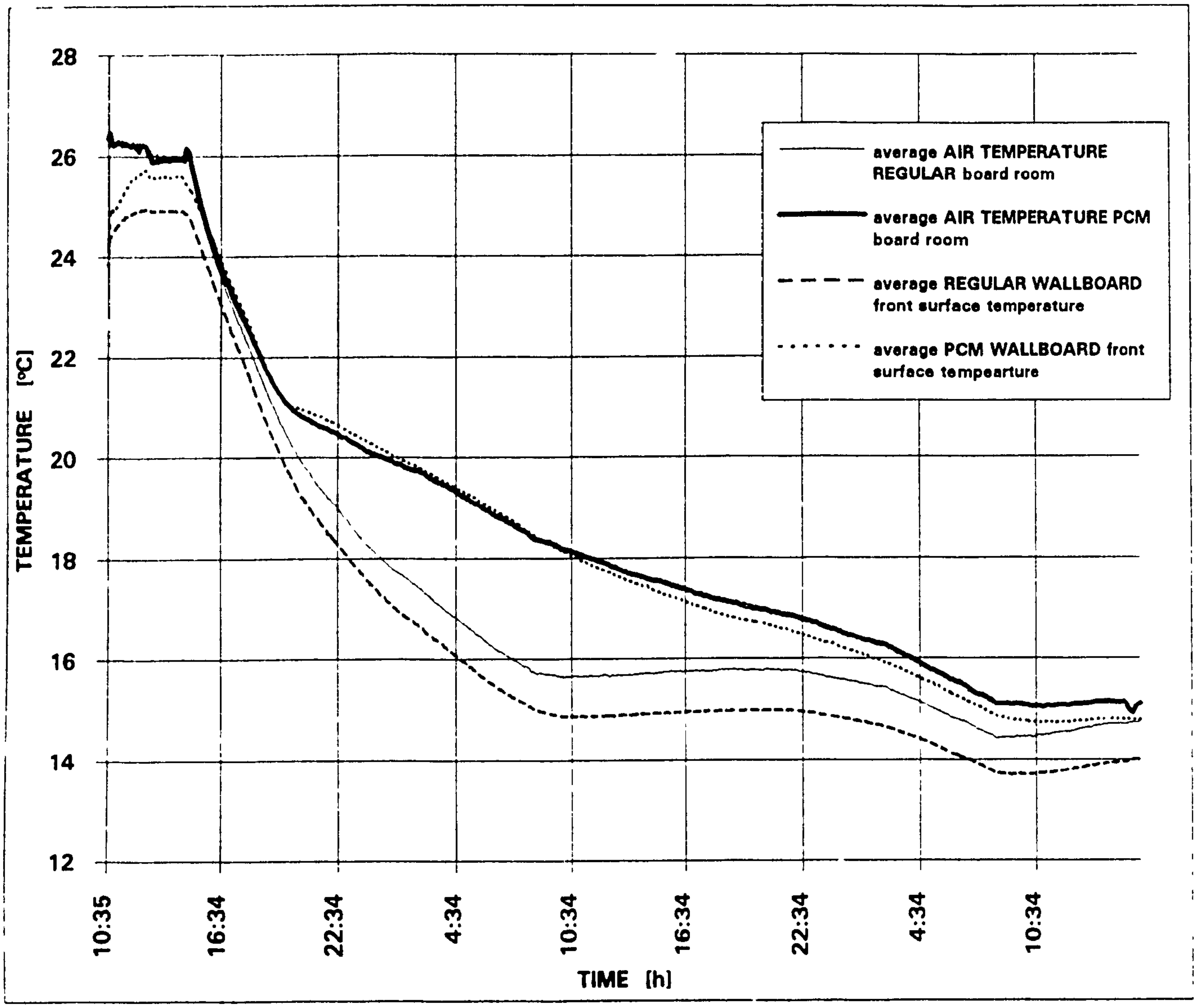
Figures 4.4 to 4.11 present the temperature profiles for PCM and regular boards as well as for room air temperature in the natural cooling mode (the release of stored heat). These experiments were conducted while maintaining the environmental air temperature surrounding test rooms around 13 ^{0}C. The room air temperature of both rooms was brought to a high set point of 26 ^{0}C or 24 ^{0}C for 24 hours. Then the heating system was turned off, and temperature drops were captured for 48 hours.

When the heat supply is stopped, under the effect of cooler environmental air, the room air temperature slowly drops. As the room air temperature dropped bellow the PCM transition temperature, the PCM began to crystallise and latent heat was released in the PCM wallboard room and continued until the phase change process was completed.

The temperature profiles of PCM wallboard clearly show the beginning of the crystallization (latent heat release) stage at about 21 ^{0}C, as expected from DSC test results.

By comparison, after the heating system was turned off, the temperature profiles of the room equipped with ordinary wallboard exhibited a much more rapid decline which is characteristic of wallboard having only sensible heat storage.

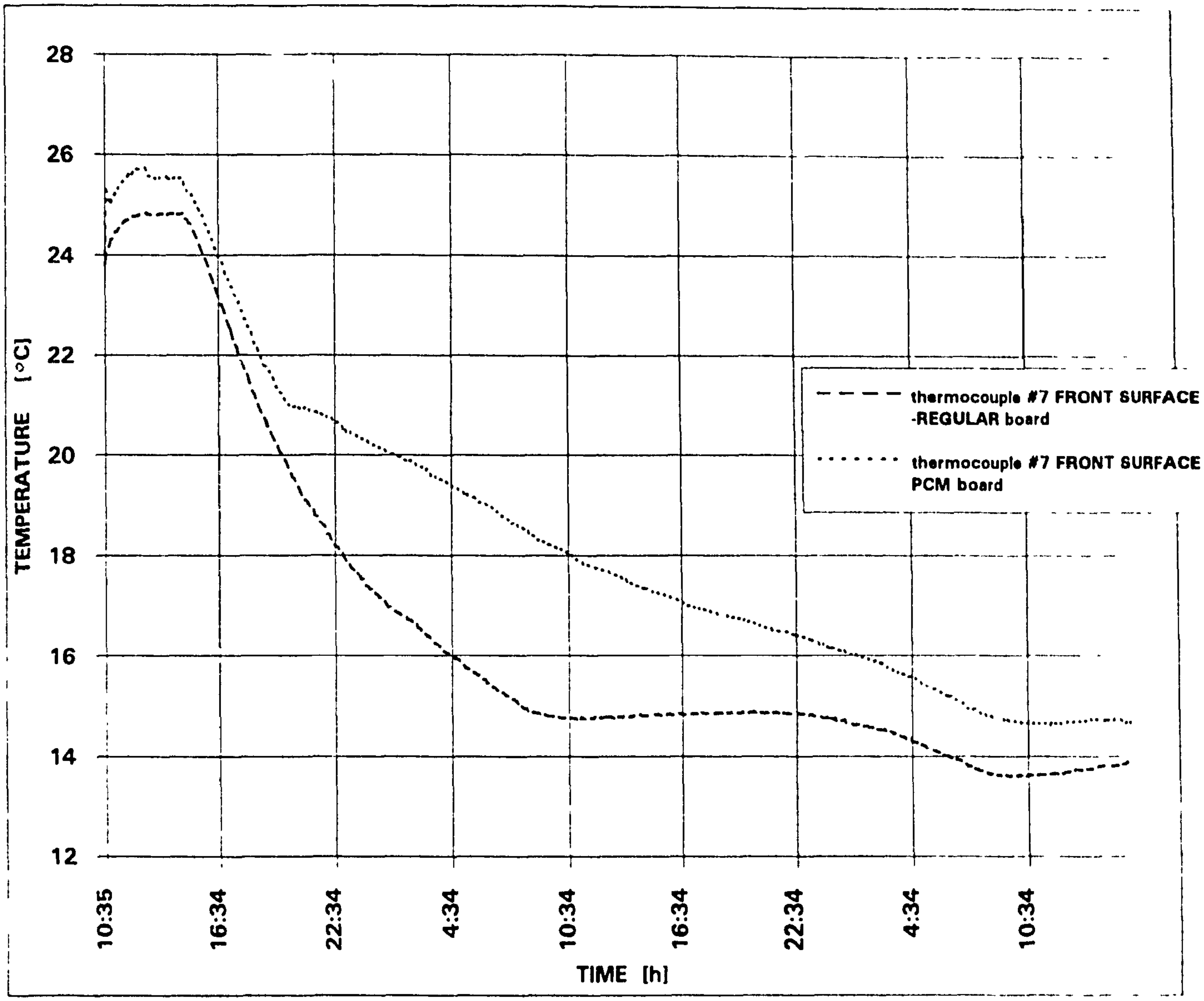
The fact that the rate of decrease of air and wallboard temperatures was significantly slower for the room with PCM boards than with regular boards, indicated that PCM wallboard has a high thermal inertia and gives a more stable air temperature.



Experimental result for February, 20, 1995

High set point = 26 ^{0}C
Environmental temperature = 13 ^{0}C
A 48 hour test from 10:35 to 10:34

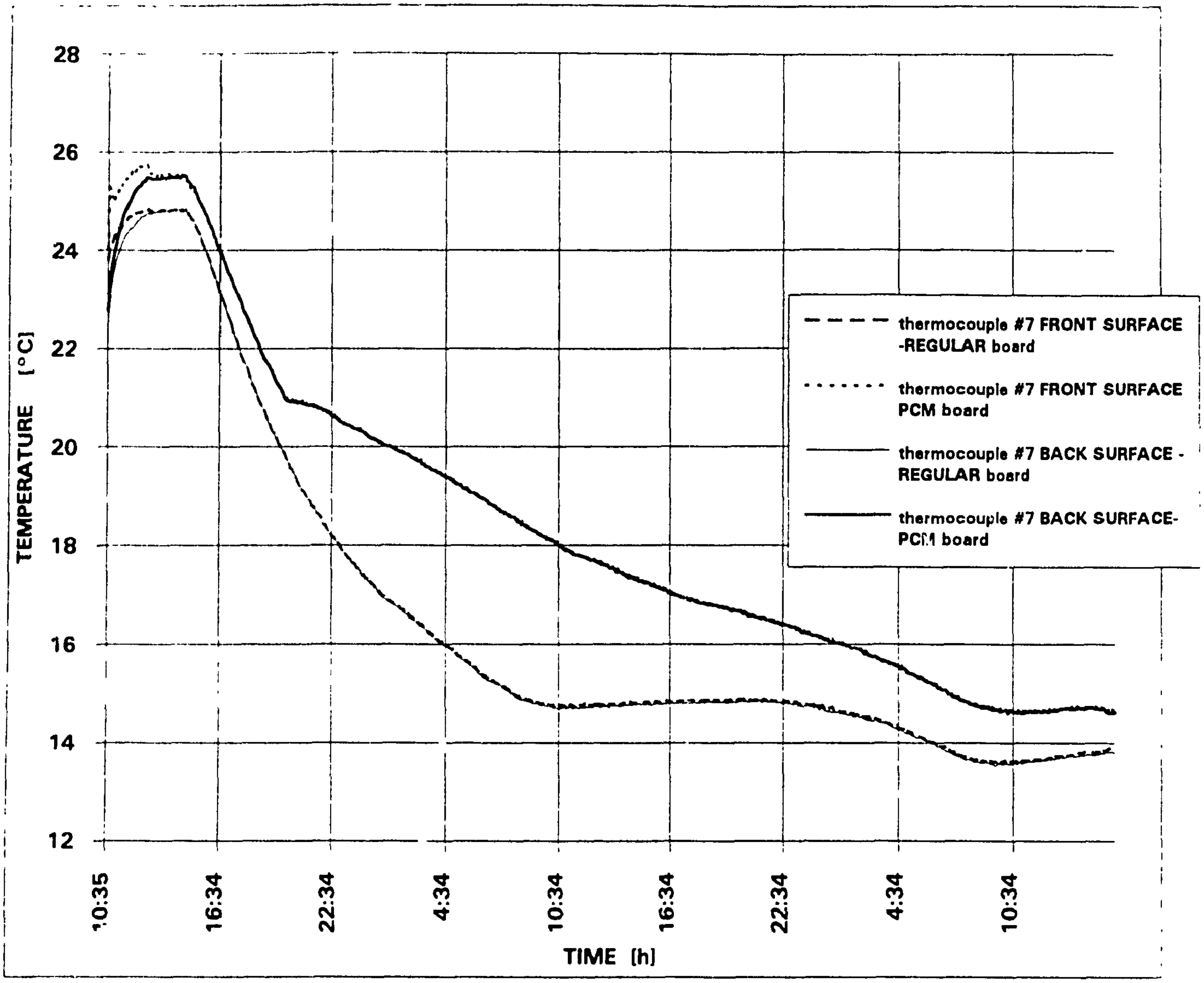
Figure 4.4 Comparison of thermal response of the PCM and regular wallboards (wallboard B, average temperature profiles)



Experimental result for February, 20, 1995

High set point = 26 °C
Environmental temperature = 13 °C
A 48 hour test from 10:35 to 10:34

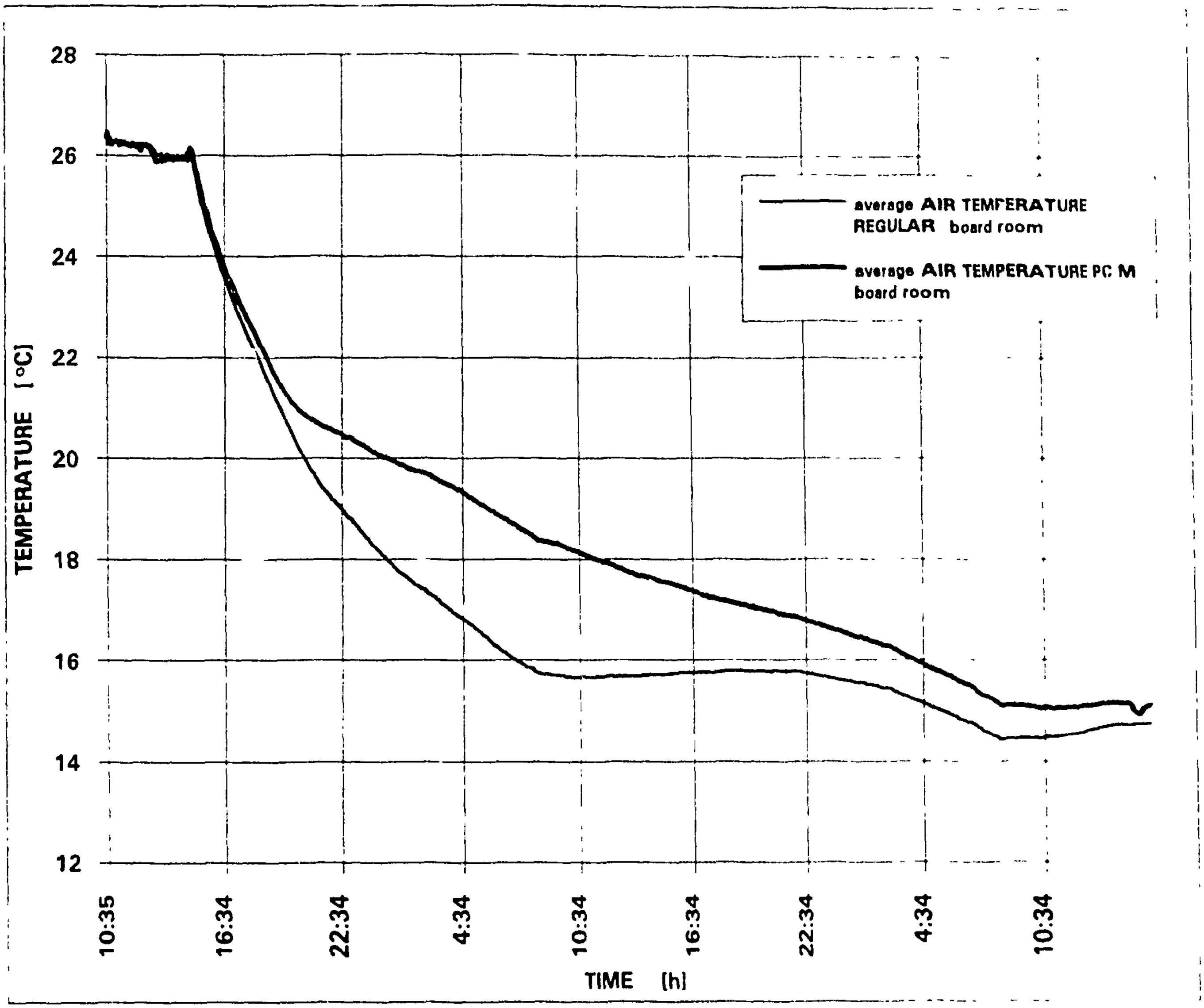
Figure 4.5 Comparison of thermal response of the PCM and regular wallboards (wallboard B, front surface temperature profiles)



Experimental result for February, 20, 1995

High set point = 26 °C
Environmental temperature = 13 °C
A 48 hour test from 10:35 to 10:34

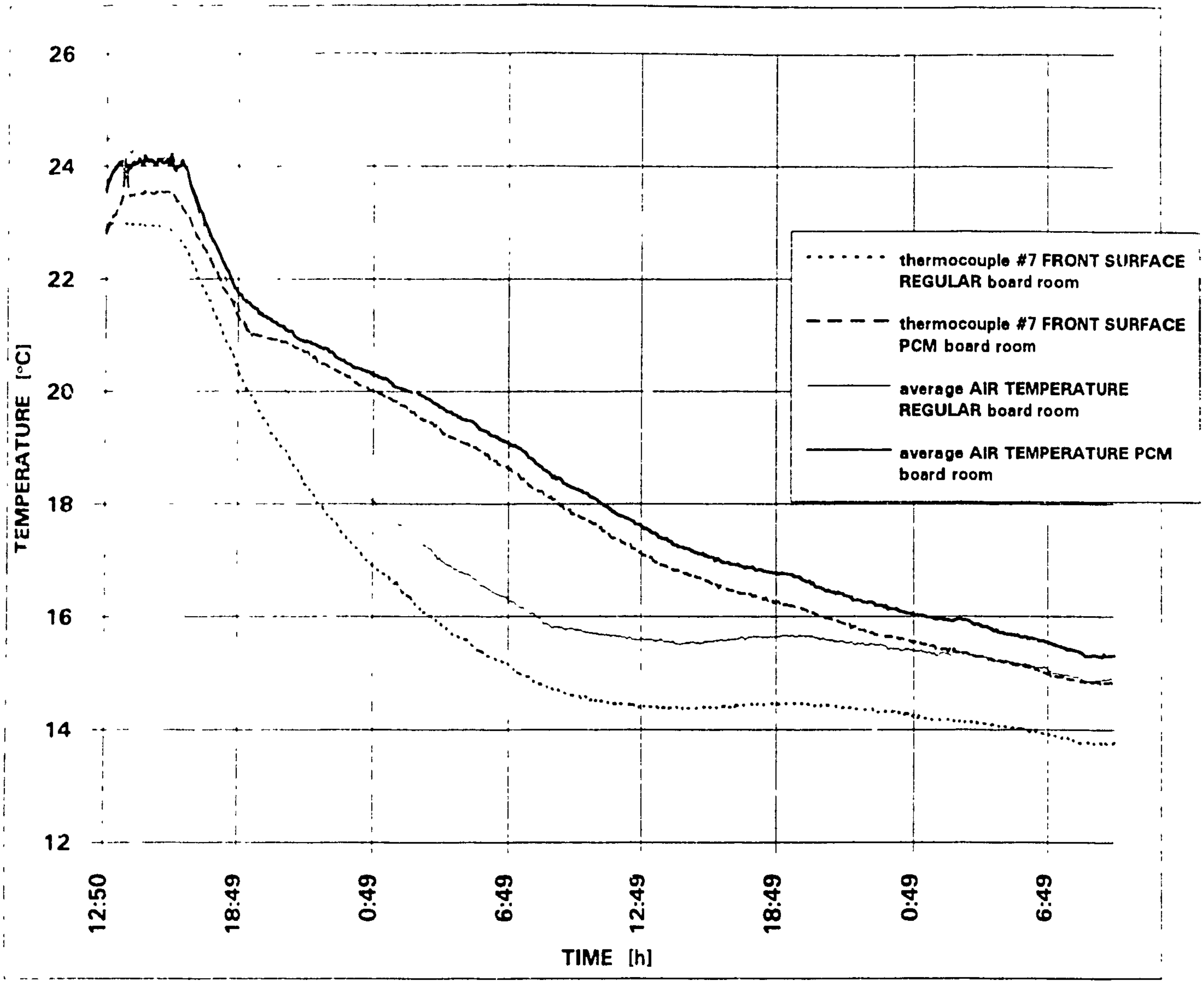
Figure 4.6 Comparison of thermal response of the PCM and regular wallboards (wallboard B, front and back surface temperature profiles)



Experimental result for February, 20, 1995

High set point = 26 °C
Environmental temperature = 13 °C
A 48 hour test from 10:35 to 10:34

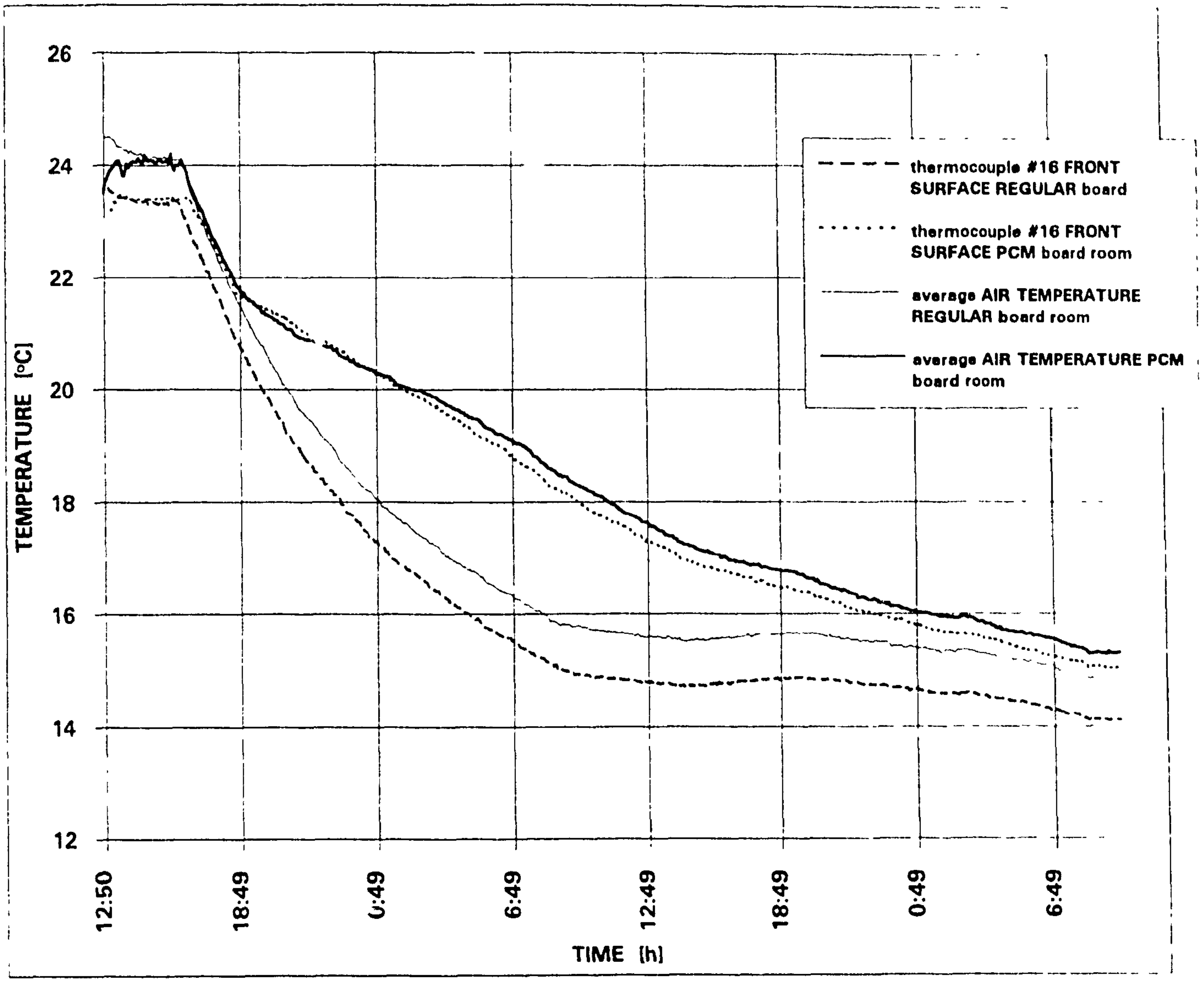
Figure 4.7 Comparison of thermal response of the PCM and regular wallboards (average air temperature profiles)



Experimental result for March, 24, 1995

High set point = 24 °C
Environmental temperature = 13 °C
A 48 hour test from 12:50 to 6:49

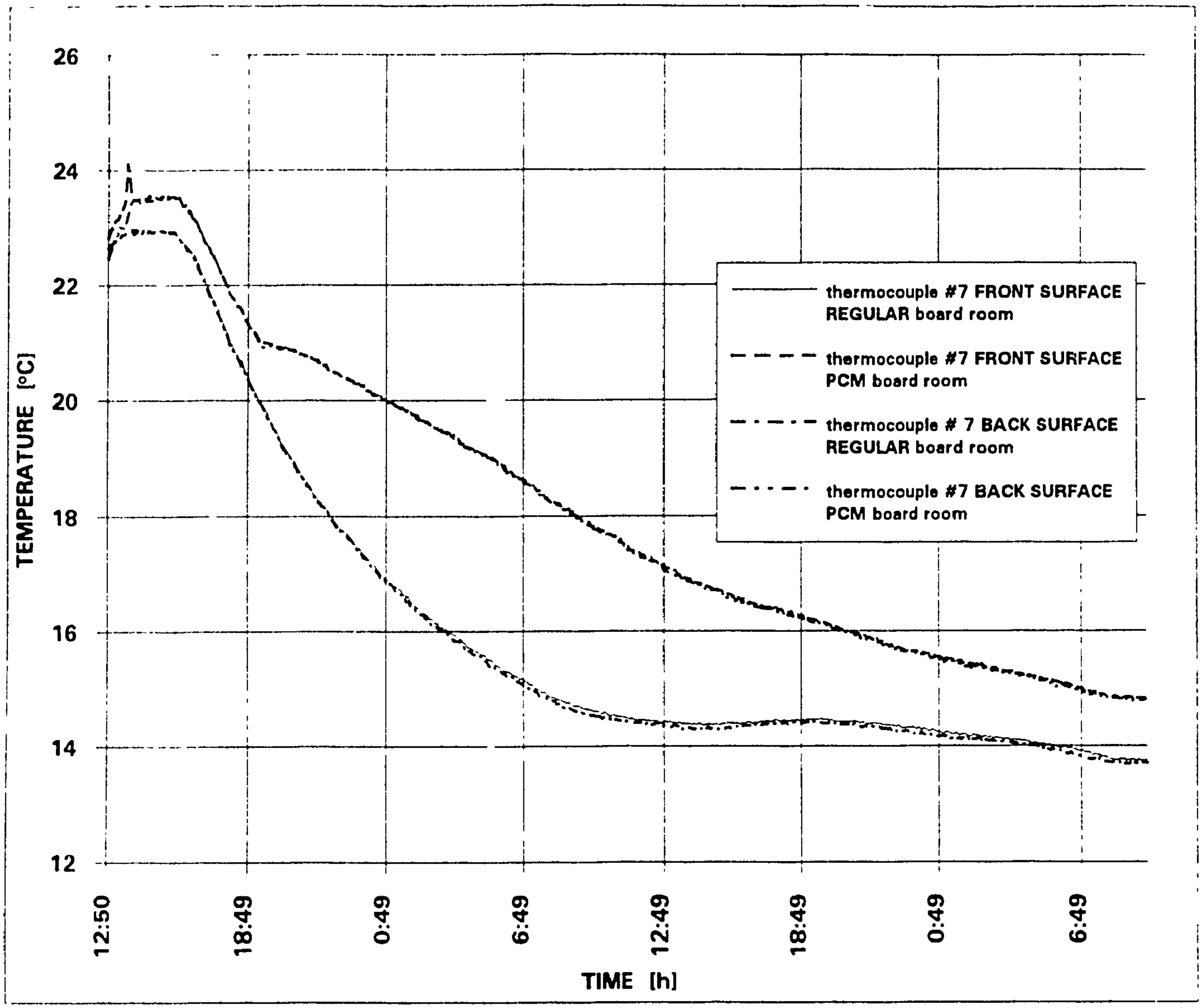
Figure 4.8 Comparison of thermal response of the PCM and regular wallboards (wallboard B, front surface and average air temperature profiles)



Experimental result for March, 24, 1995

High set point = 24 °C
Environmental temperature = 13 °C
A 48 hour test from 12:50 to 6:49

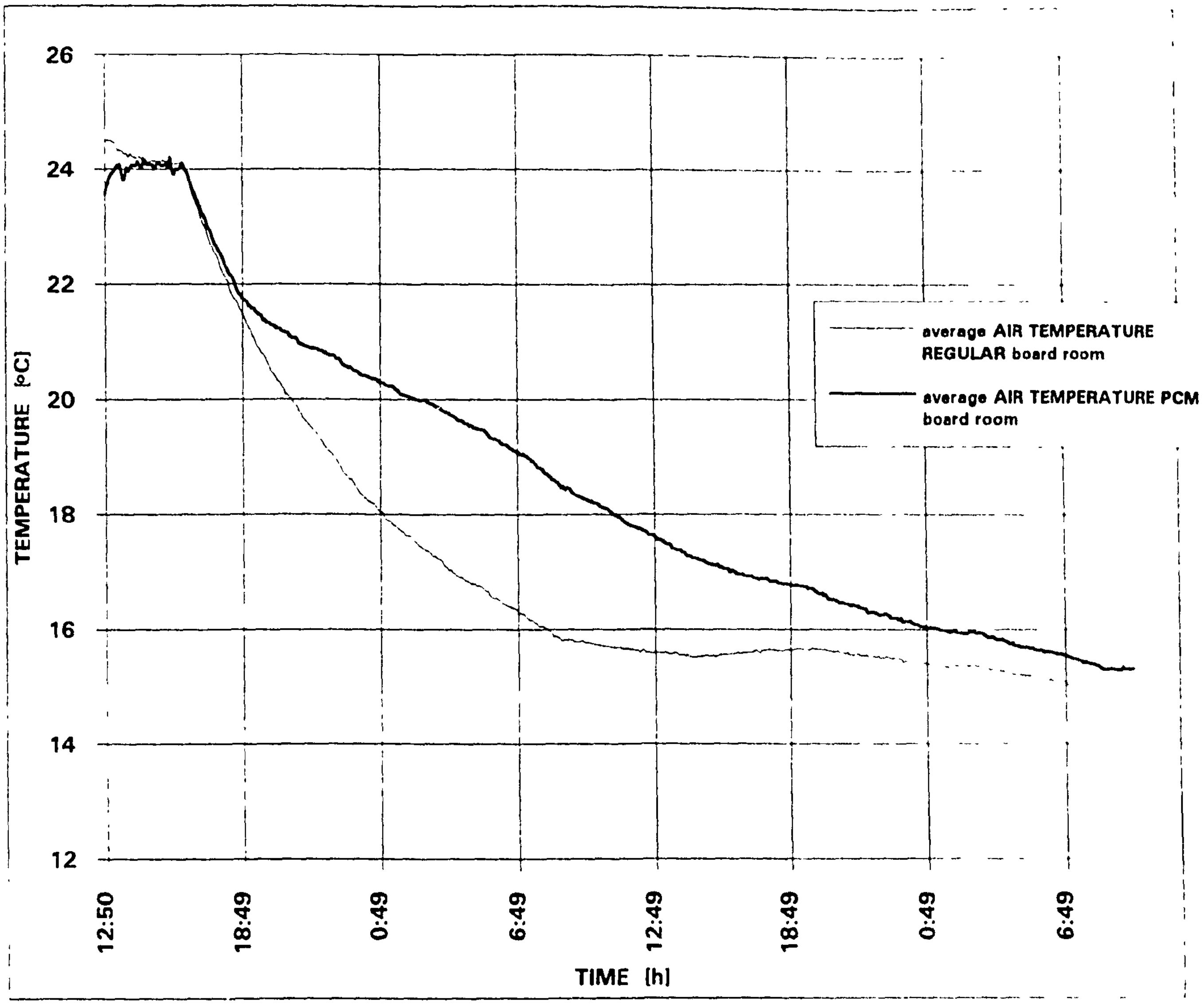
Figure 4.9 Comparison of thermal response of the PCM and regular wallboards (wallboard A, front surface and average air temperature profiles)



Experimental result for March, 24, 1995

High set point = 24 °C
Environmental temperature = 13 °C
A 48 hour test from 12:50 to 6:49

Figure 4.10 Comparison of thermal response of the PCM and regular wallboards (wallboard B, front and back surface temperature profiles)



Experimental result for March, 24, 1995

High set point = 24 °C
Environmental temperature = 13 °C
A 48 hour test from 12:50 to 6:49

Figure 4.11 Comparison of thermal response of the PCM and regular wallboards (average air temperature profiles)

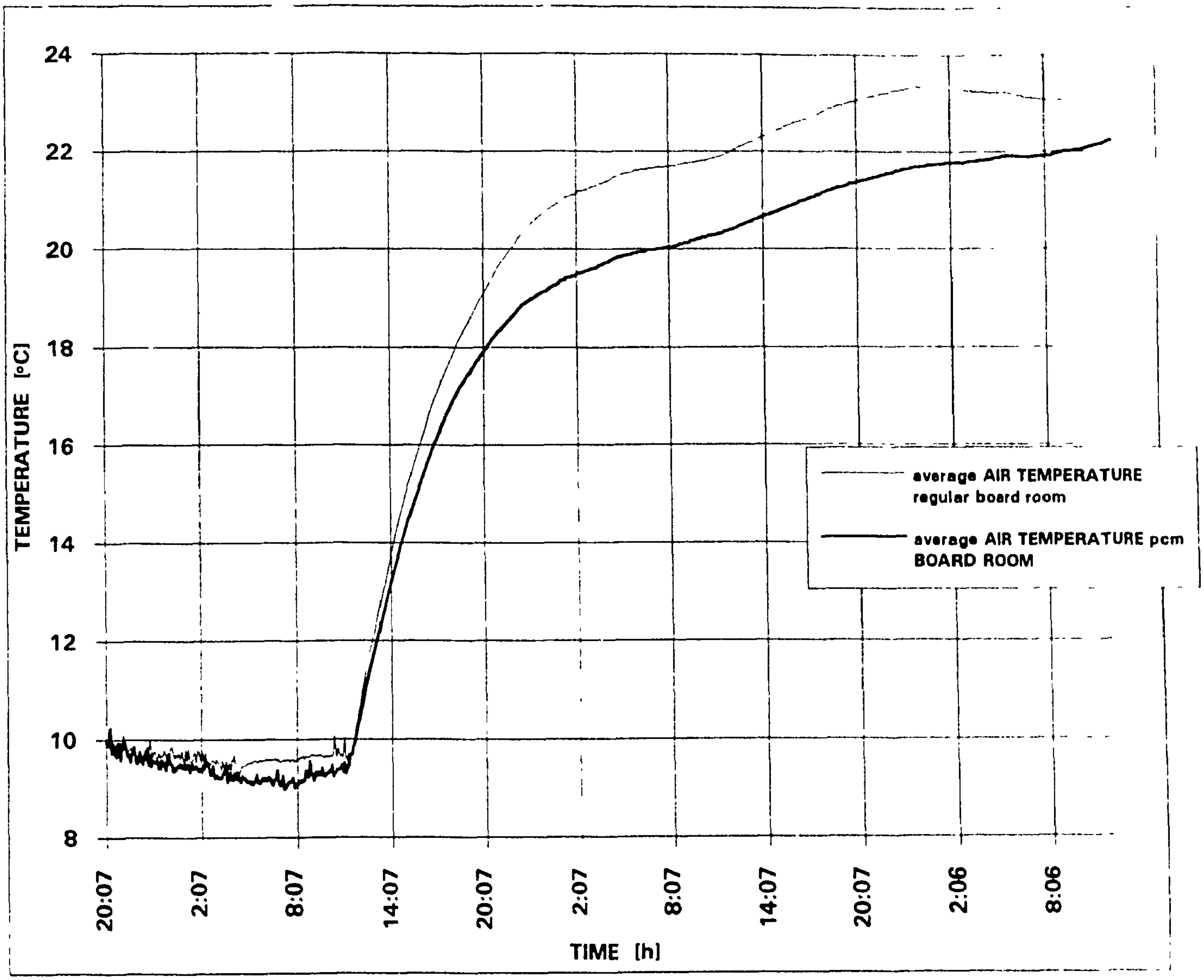
4.3.2 Natural Heating Mode

Figures 4.12 to 4.16 present the temperature profiles for both PCM and regular wallboards as well as for room air temperatures during the natural heating mode (the absorption of heat in the room by thermal storage). These experiments were conducted while maintaining the environmental temperature at about 23 ^{0}C, Figures 4.12 to 4.14, and at about 24 ^{0}C, Figures 4.15 and 4.16. The room air temperature was set to a low point of 9 ^{0}C. After 24 hours, the air conditioners were turned off and temperature rises were captured.

Under the effect of warmer environmental air, the room temperatures rise. As it rises through the solid-liquid phase change range (17 ^{0} - 21 ^{0}C), the PCM melts by absorbing heat and latent heat is thus stored. In this manner the thermal storage wallboard acts as a cooling medium.

On the other hand, in the room equipped with ordinary wallboard, the temperature rose more quickly; the heat storage capacity being limited only to the sensible heat storage.

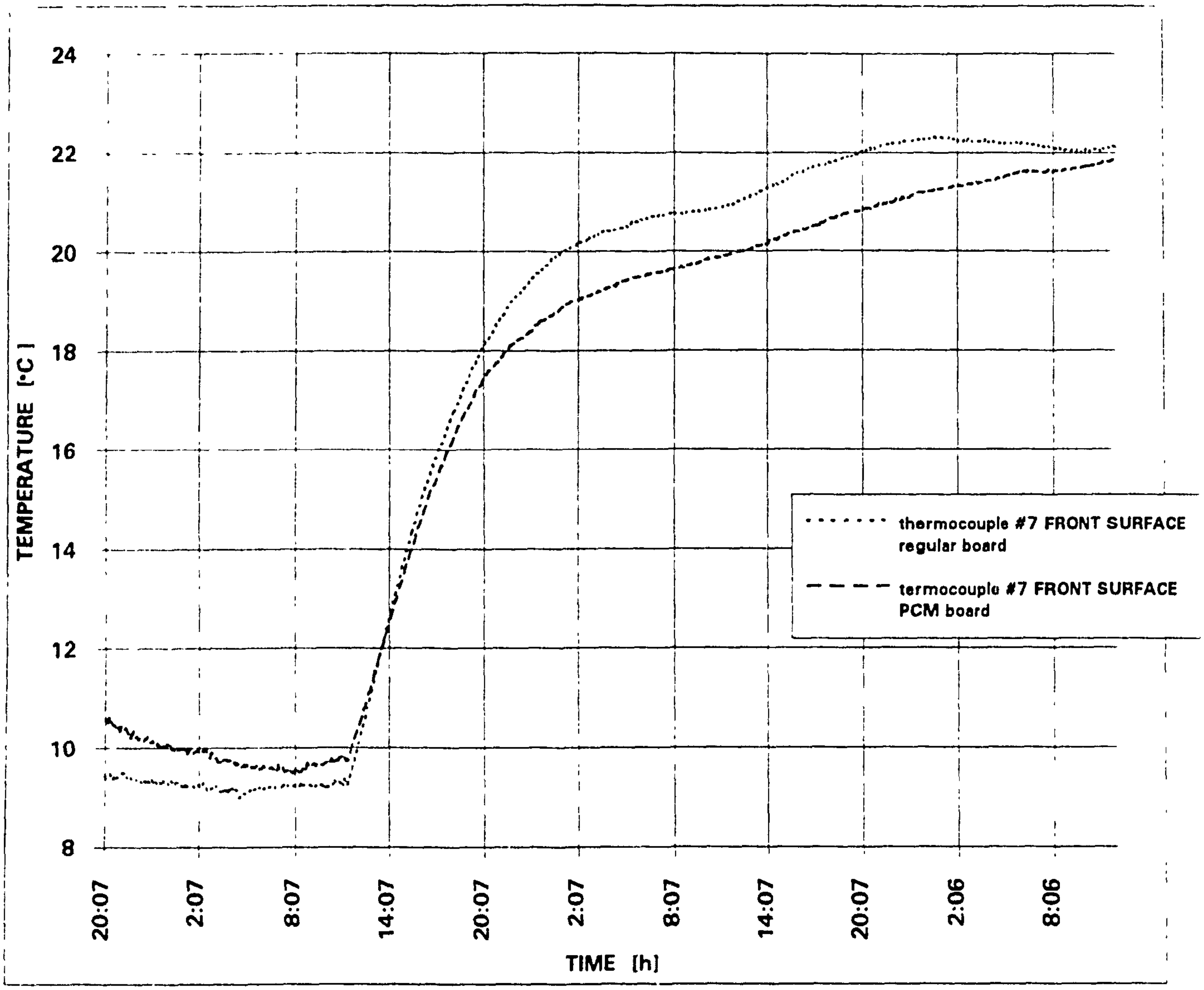
As can be seen from Figure 4.15, when the PCM wallboard temperature increases as high as 17 ^{0}C, the melting of PCM starts to affect the air temperature. At this time, the room air temperature has as low increase as compared to room air temperature in regular gypsum board room, because a large amount of heat was absorbed by the PCM's melting process. The lowered PCM wallboard surface temperature contributes to the reduction of overheating, functioning as a cooling surface.



Experimental result for February, 27, 1995

Low set point = 9 °C
Environmental temperature = 24 °C
A 60 hour test from 20:07 to 8:06

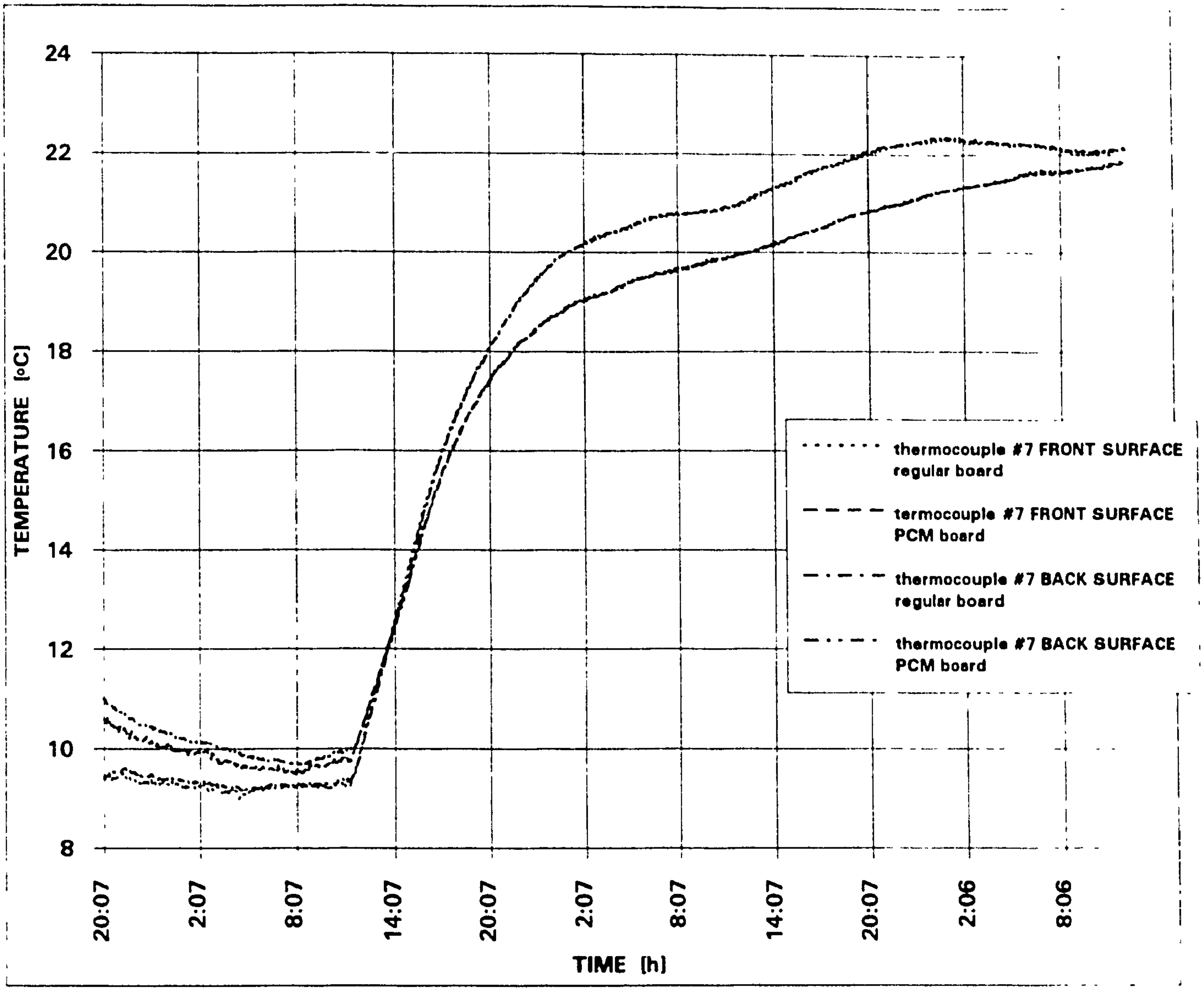
Figure 4.12 Comparison of thermal response of the PCM and regular wallboards (average air temperature profiles)



Experimental result for February, 27, 1995

Low set point = 9 °C
Environmental temperature = 24 °C
A 60 hour test from 20:07 to 8:06

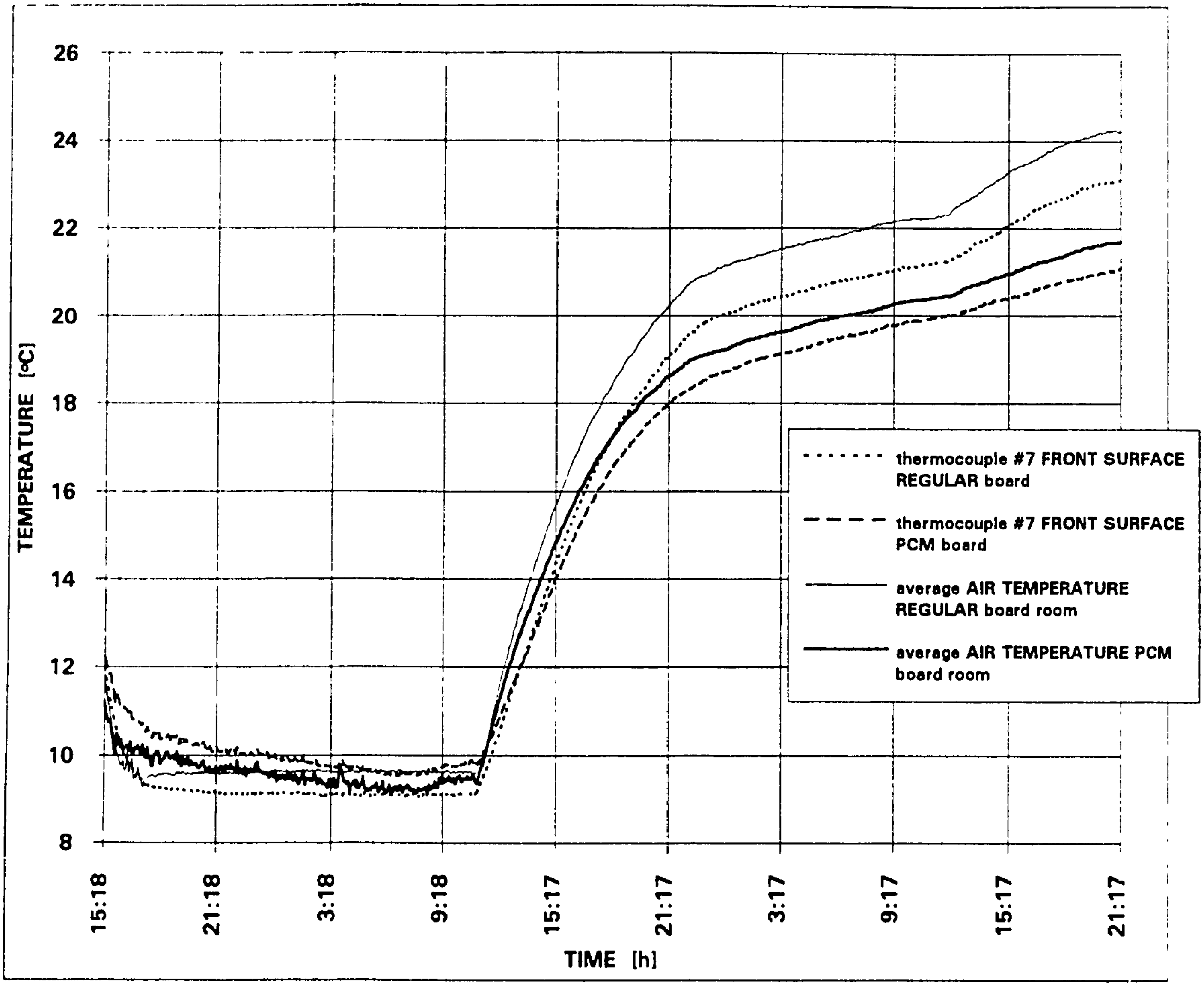
Figure 4.13 Comparison of thermal response of the PCM and regular wallboards (front surface temperature profiles)



Experimental result for February, 27, 1995

Low set point = 9 °C
Environmental temperature = 24 °C
A 60 hour test from 20:07 to 8:06

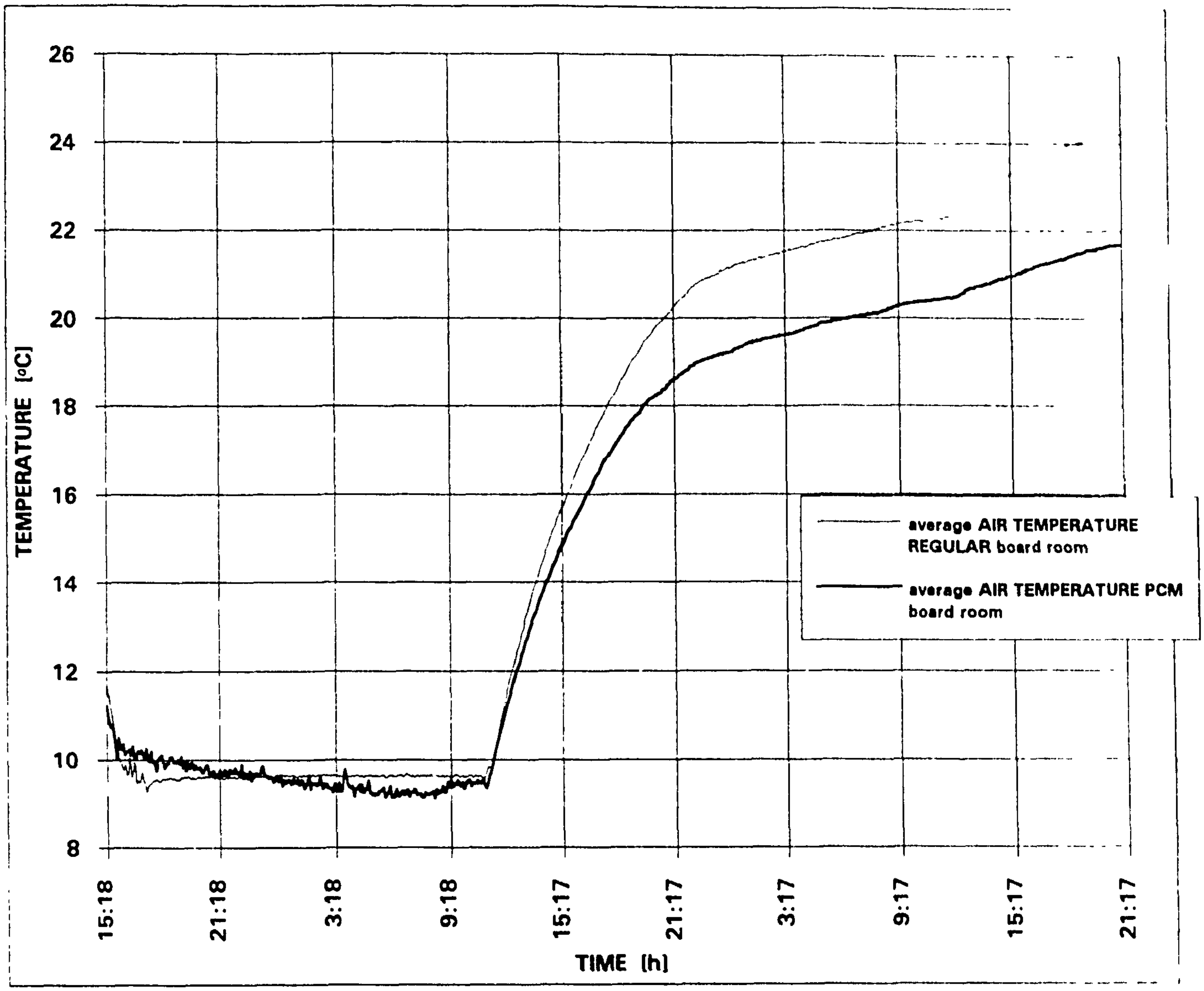
Figure 4.14 Comparison of thermal response of the PCM and regular wallboards (front and back surface temperature profiles)



Experimental result for March, 27, 1995

Low set point = 9 ^{0}C
Environmental temperature = 24 ^{0}C
A 54 hour test from 15:18 to 21:17

Figure 4.15 Comparison of thermal response of the PCM and regular wallboards (front surface and average air temperature profiles)



Experimental result for March, 27, 1995

Low set point = 9 °C
Environmental temperature = 24 °C
A 54 hour test from 15:18 to 21:17

Figure 4.16 ***Comparison of thermal response of the PCM and regular wallboards (front surface temperature profiles)***

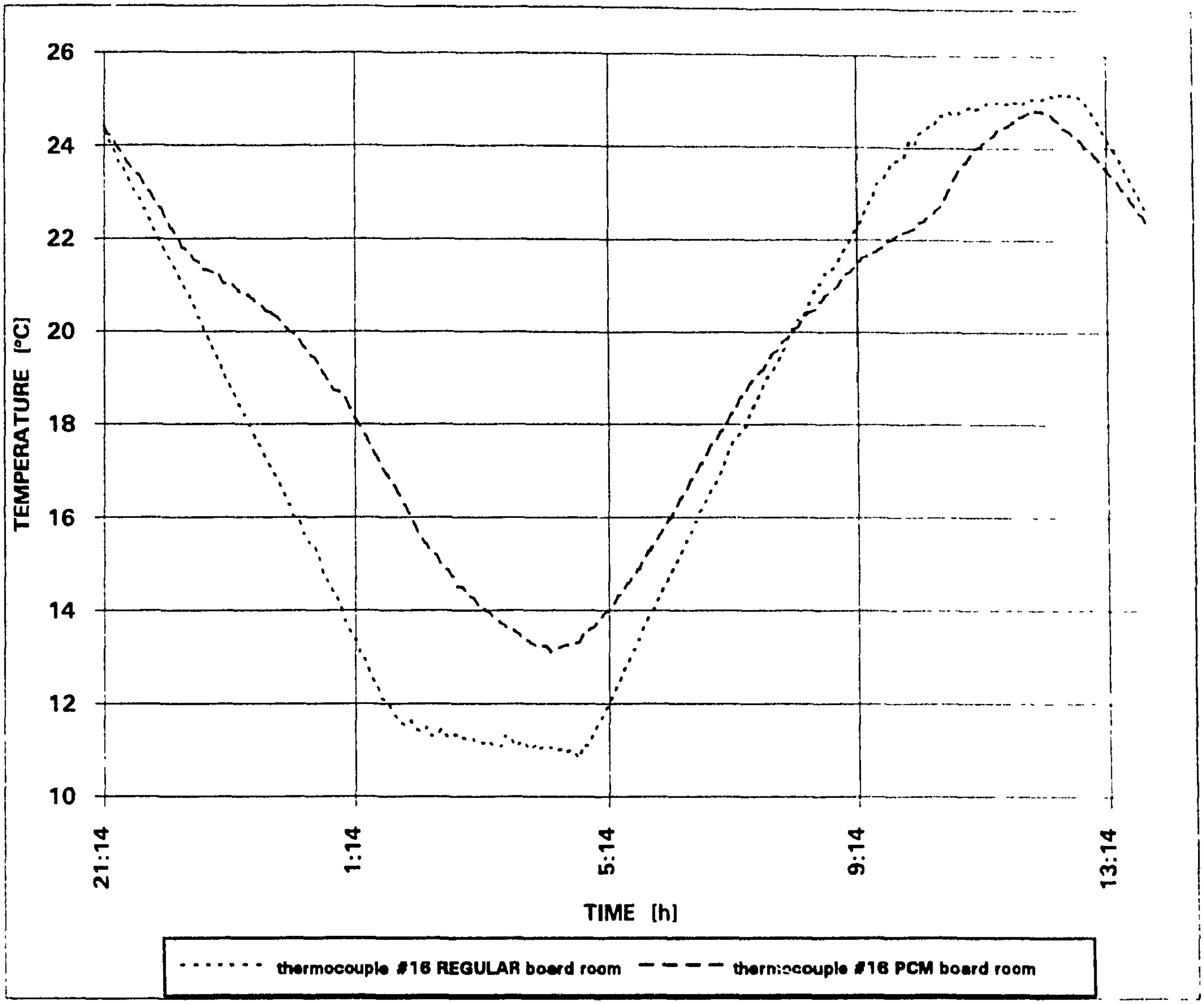
4.3.3 Temperature Cycling Test

Figures 4.17 to 4.24 present the temperature profiles for regular and PCM wallboards as well as for heating energy consumption. The controllers were programmed so that the temperature in both rooms would cycle between 11 ^{0}C - 26 ^{0}C with various heating and cooling rates.

For example, Figure 4.22 presents a 24 hour test. The air temperature in both rooms was cycled between 11 ^{0}C and 26 ^{0}C. The heating and cooling rate were of 0.03 ^{0}C/min and environmental temperature was maintained at about 14 ^{0}C.

Because the same temperature conditions were maintained in each room, the difference in the measurement of electrical energy used to heat each room should directly provide the amount of additional energy that went into storage in the PCM wallboard. However this would only be true if we assume all other loads to be identical (infiltration loads, conduction loads). The temperature range of 11 ^{0}C to 26 ^{0}C is outside the region of indoor comfort conditions. However, these temperatures were used to compare the DSC results to full scale results.

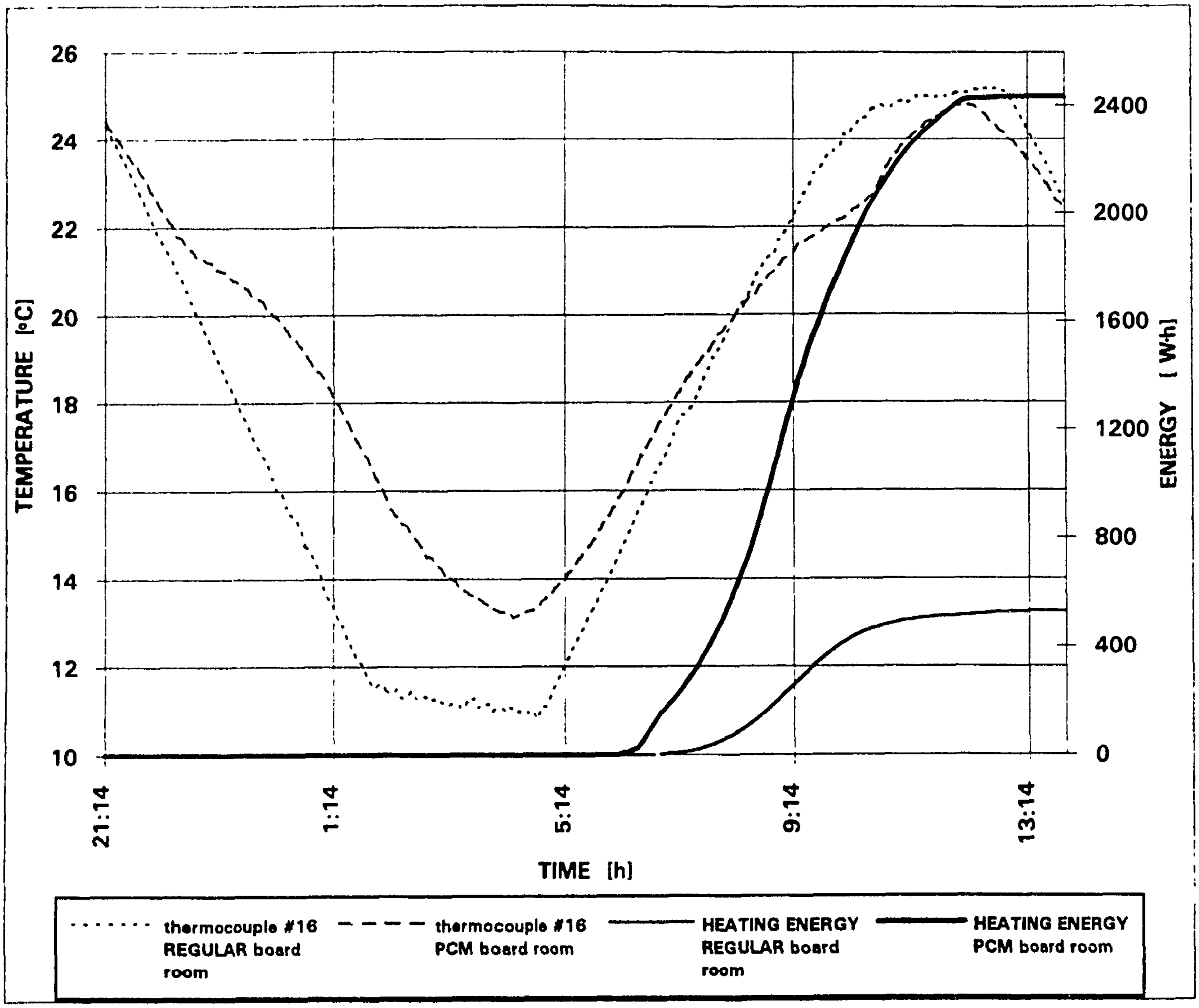
Data analysis presented in chapter 5 entailed the calculation of latent heat values for PCM and PCM impregnated wallboard.



Experimental result for November, 22, 1995

High set point = 26 °C, Low set point = 9 °C
Heating rate = 0.04 °C/min, Cooling rate = 0.04 °C/min
Dwell time = 4 hours
Environmental temperature = 23 °C
A 16 hour test from 21:14 to 13:14

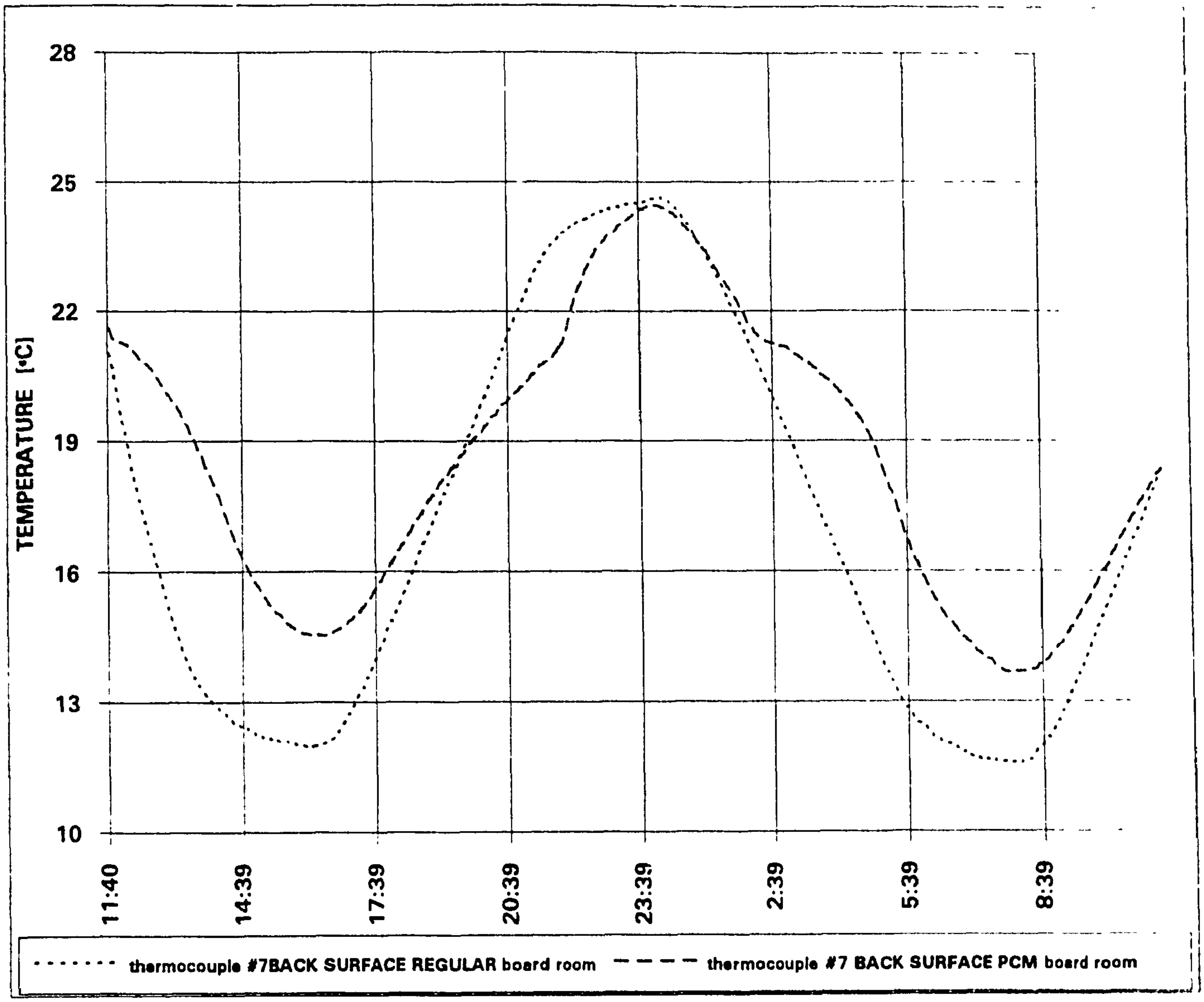
Figure 4.17 Comparison of thermal response of the PCM and regular wallboards (front surface temperature profiles)



Experimental result for November, 22, 1995

High set point = 26 °C, Low set point = 9 °C
Heating rate = 0.04 °C/min, Cooling rate = 0.04 °C/min
Dwell time = 4 hours
Environmental temperature = 23 °C
Heating energy consumption regular board room = 528 W·h
Heating energy consumption PCM board room = 2443 W·h
A 16 hour test from 21:14 to 13:14

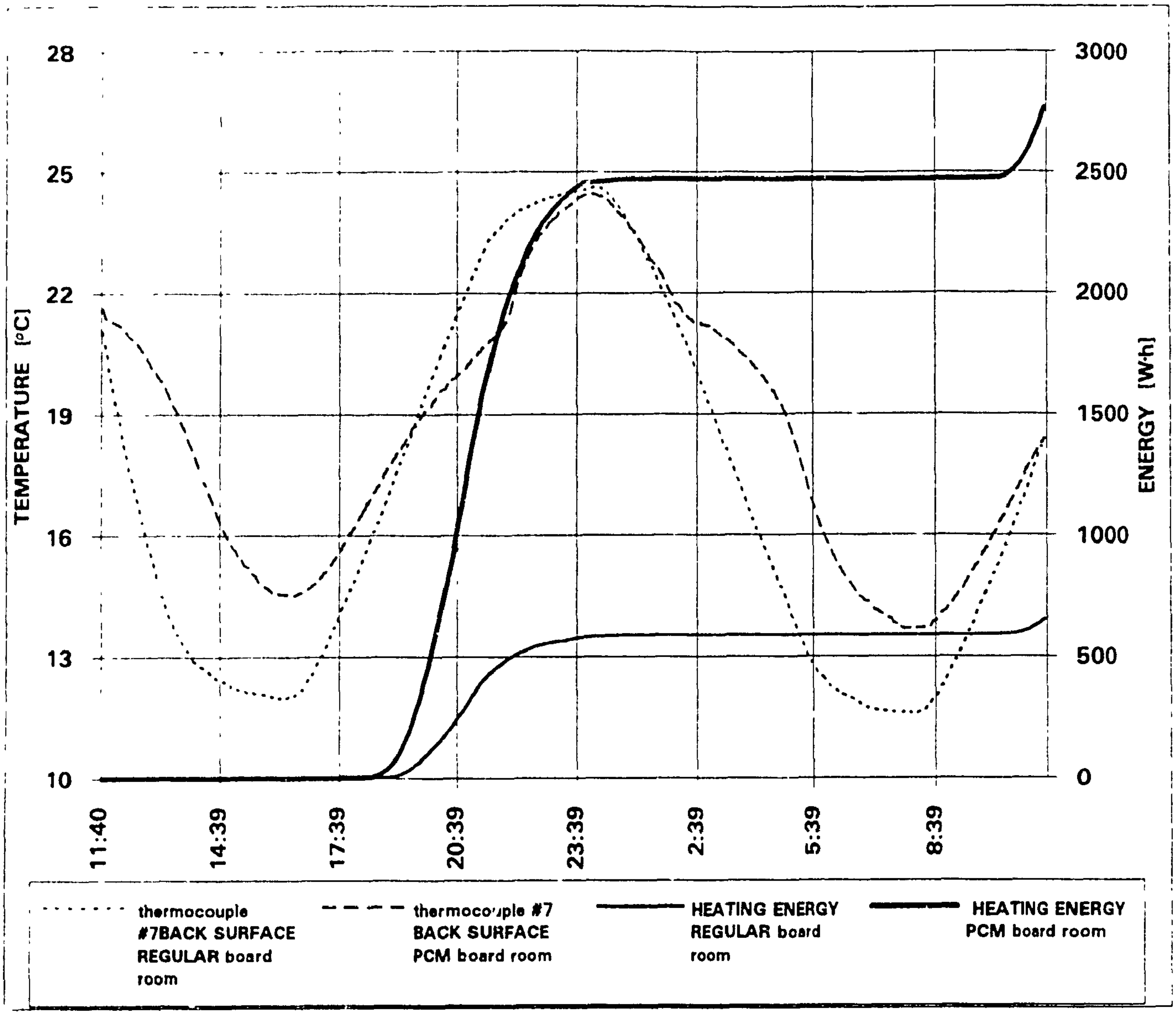
Figure 4.18 Comparison of thermal response of the PCM and regular wallboards (heating energy consumption)



Experimental result for November, 28, 1995

High set point = 25 °C, Low set point = 12 °C
Heating rate = 0.03 °C/min, Cooling rate = 0.03 °C/min
Dwell time = 4 hours
Environmental temperature = 23 °C
A 24 hour test from 11:40 to 11:39

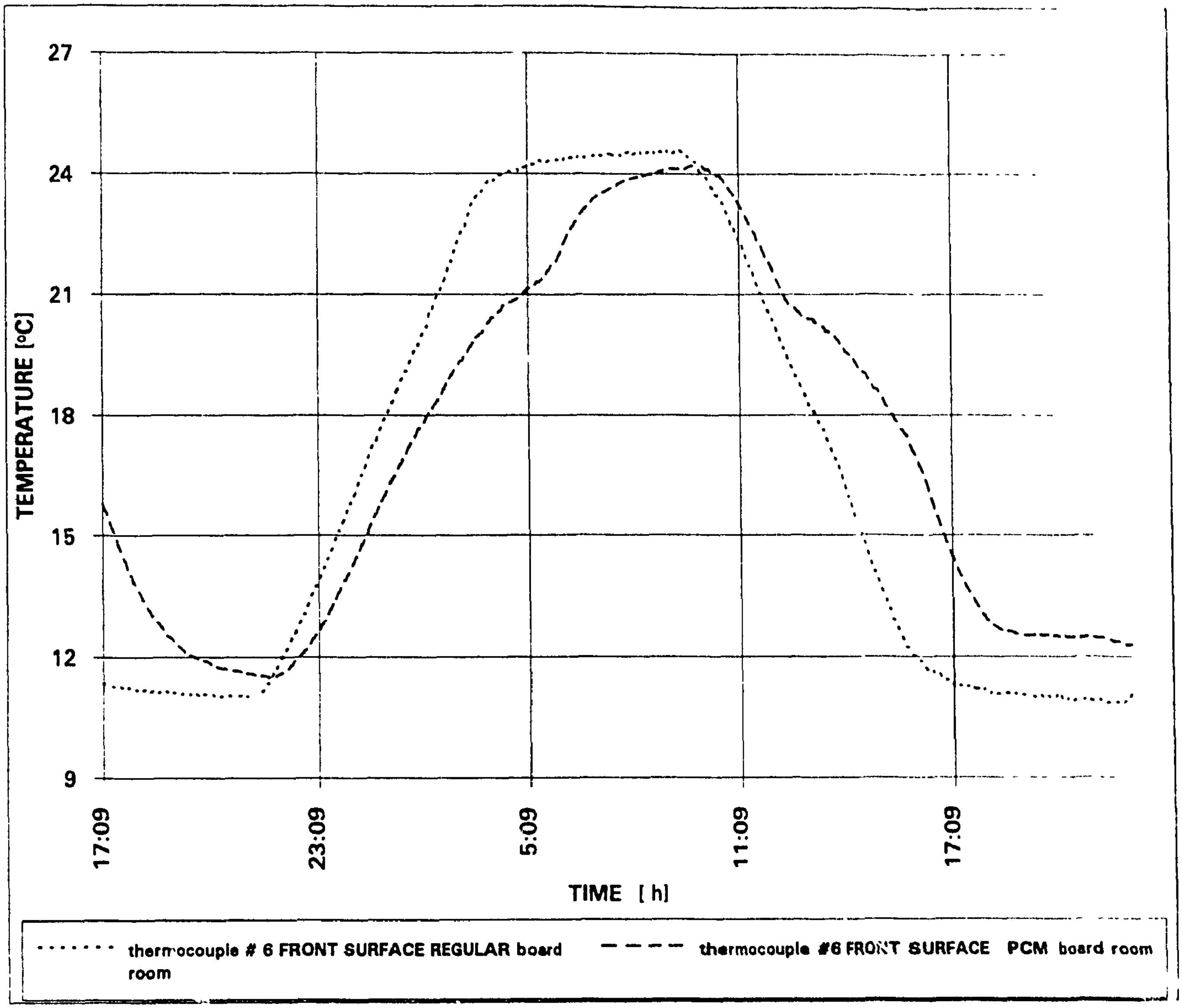
Figure 4.19 Comparison of thermal response of the PCM and regular wallboards (front surface temperature profiles)



Experimental result for November, 28, 1995

High set point = 26 ^{0}C, Low set point = 12 ^{0}C
Heating rate = 0.03 ^{0}C/min, Cooling rate = 0.03 ^{0}C/min
Dwell time = 4 hours
Environmental temperature = 23 ^{0}C
Heating energy consumption regular board room = 543 W·h
Heating energy consumption PCM board room = 2490 W·h
A 24 hour test from 11:40 to 11:39

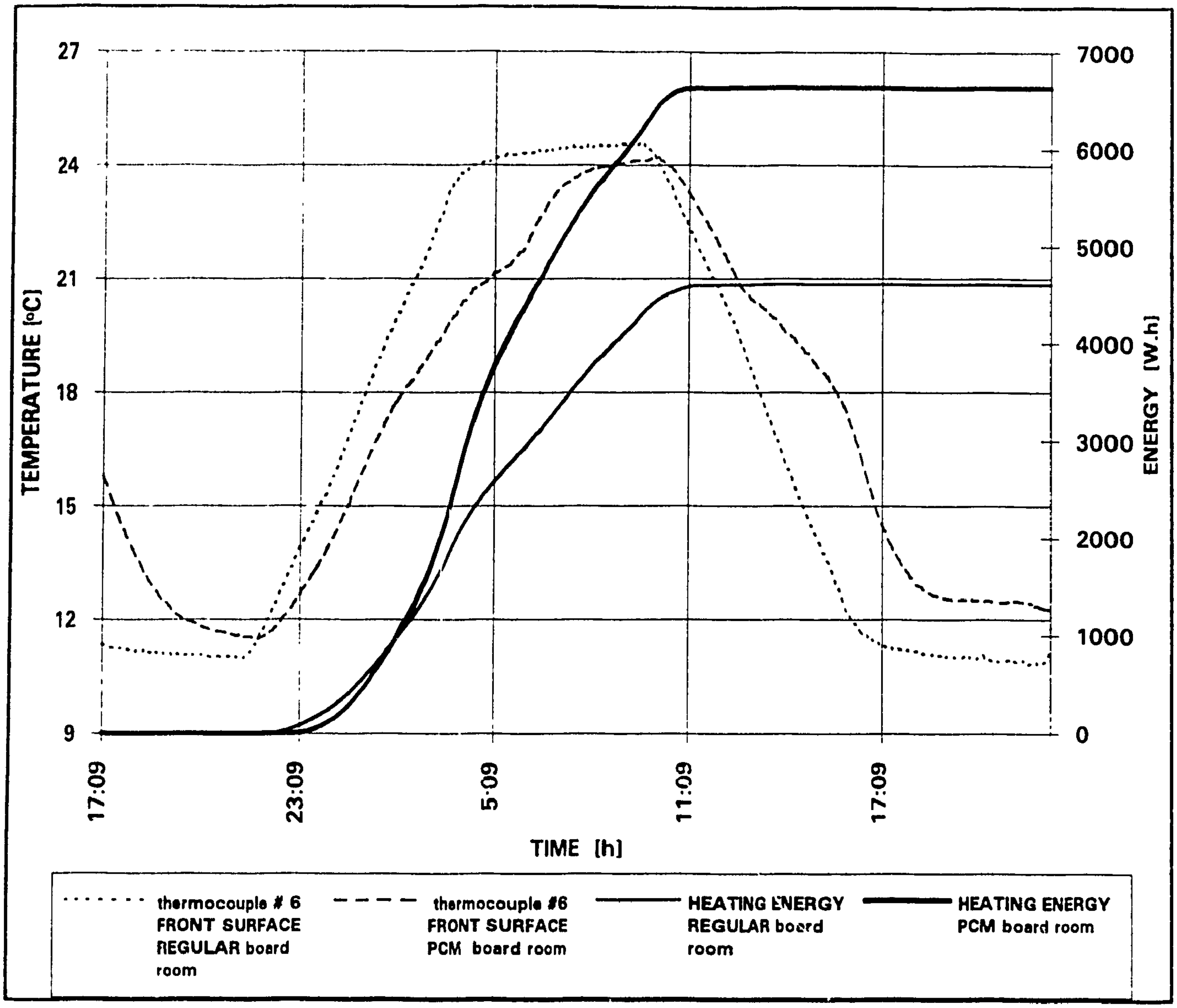
Figure 4.20 Comparison of thermal response of the PCM and regular wallboards (heating energy consumption)



Experimental result for January, 22,1996

High set point = 26 °C, Low set point = 11 °C
Heating rate = 0.03 °C/min, Cooling rate = 0.03 °C/min
Dwell time = 6 hours
Environmental temperature = 14 °C
A 30 hour test from 17:09 to 23:09

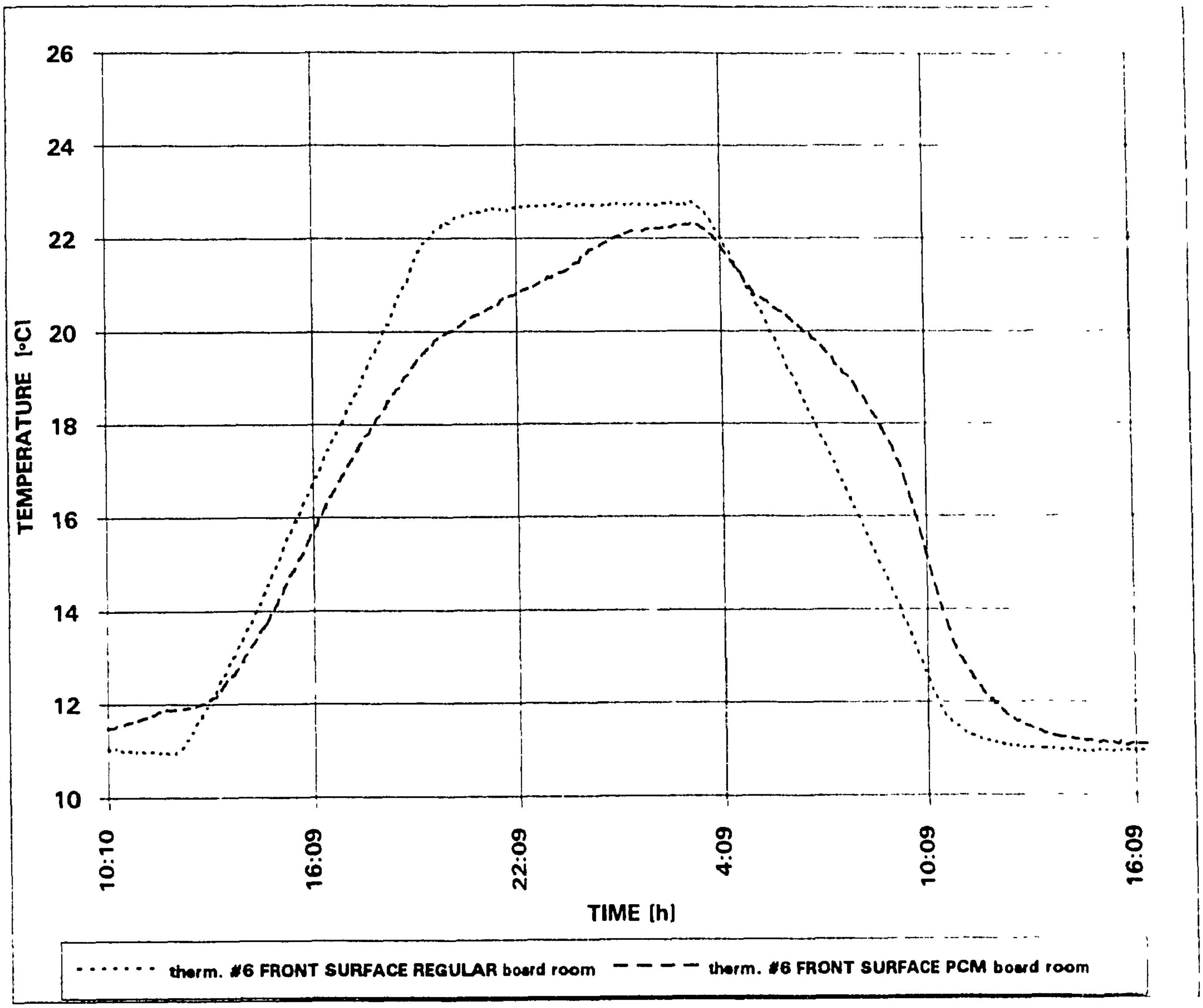
Figure 4.21 Comparison of thermal response of the PCM and regular wallboards (front surface temperature profiles)



Experimental result for January, 22, 1996

High set point = 26 °C, Low set point = 11 °C
Heating rate = 0.03 °C/min, Cooling rate = 0.03 °C/min
Dwell time = 6 hours
Environmental temperature = 14 °C
Heating energy consumption regular board room = 4618 W·h
Heating energy consumption PCM board room = 6622 W·h
A 30 hour test from 17:09 to 23:09

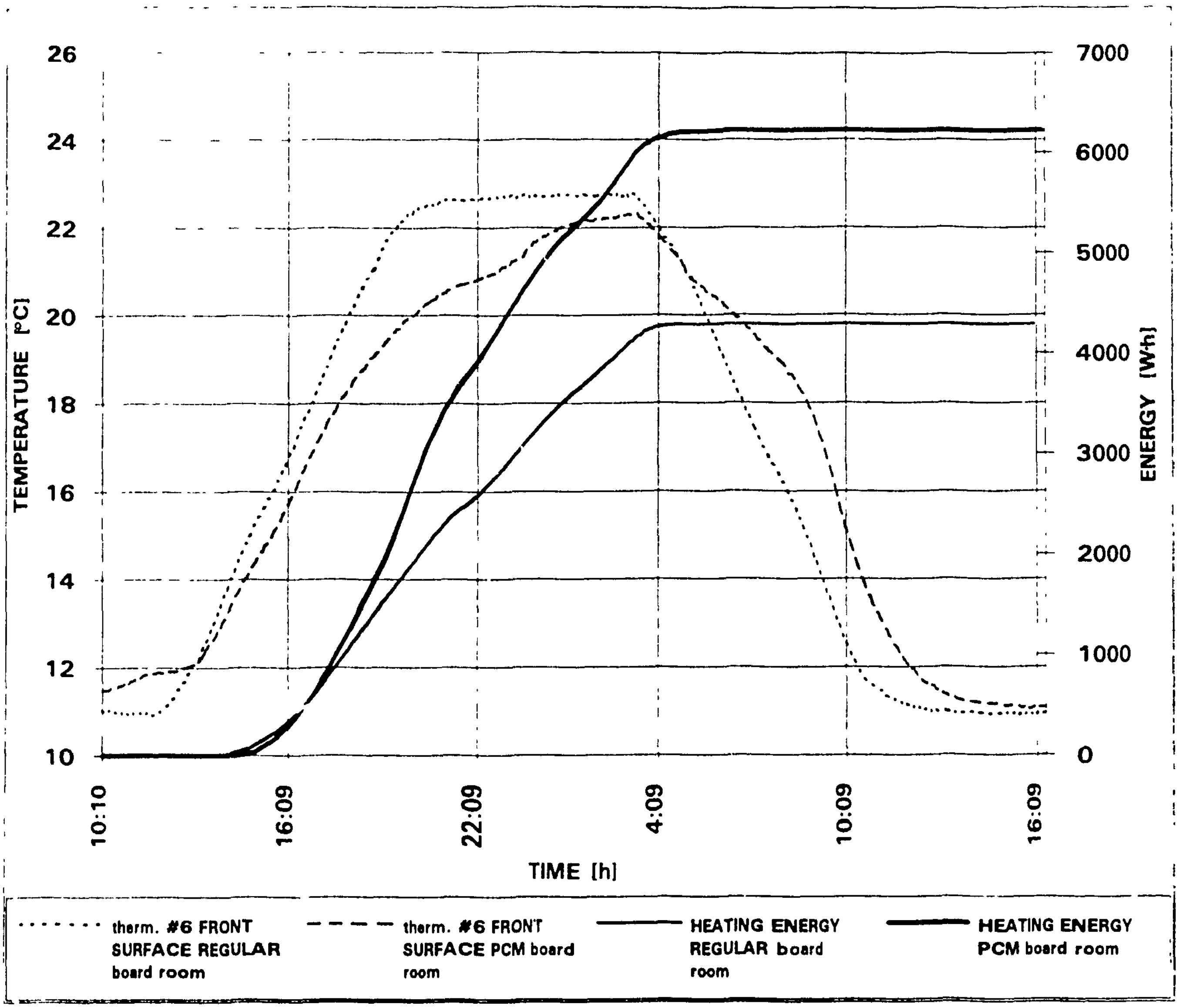
Figure 4.22 Comparison of thermal response of the PCM and regular wallboards (heating energy consumption)



Experimental result for January, 31,1996

High set point = 24 °C, Low set point = 11 °C
Heating rate = 0.03 °C/min, Cooling rate = 0.03 °C/min
Dwell time = 8 hours
Environmental temperature = 14 °C
A 30 hour test from 10:10 to 16:09

Figure 4.23 Comparison of thermal response of the PCM and regular wallboards (front surface temperature profiles)



Experimental result for January, 31, 1996

High set point = 24 °C, Low set point = 11 °C
Heating rate = 0.03 °C/min, Cooling rate = 0.03 °C/min
Dwell time = 8 hours
Environmental temperature = 14 °C
Heating energy consumption regular board room = 4272 W·h
Heating energy consumption PCM board room = 6222 W·h
A 30 hour test from 10:10 to 16:09

Figure 4.24 Comparison of thermal response of the PCM and regular wallboards (heating energy consumption)

CHAPTER 5 ANALYSIS OF COMPARATIVE THERMAL PERFORMANCE

5.1 THERMAL RESPONSE OF PCM GYPSUM WALLBOARD

The thermal response of PCM gypsum wallboard compared to regular wallboard was investigated by analyzing the experimental results obtained from various test conditions (i.e. temperature-time curves for PCM wallboard and room air in both rooms).

5.1.1 Changes at the Freezing Point

Figure 4.5 shows the differences in the manner of heat release between ordinary wallboard and PCM wallboard. As the room temperature drops to 21 ^{0}C, the form of heat released from regular wallboard and PCM wallboard is sensible. Bellow 21 ^{0}C, which represents the freezing point for the PCM used, heat released from regular wallboard remains entirely sensible in form, while that from impregnated wallboard comprises sensible heat but mostly latent heat from the PCM crystallization. This effect is clearly shown in the curves showing temperature variations of the PCM wallboard and the air in that room, changing from a steep drop to a gradual diminution because of the latent heat release which began at the freezing point and continues until all the latent heat has been expended.

5.1.2 Cooling Mode Performance

Figures 4.5 shows the thermal storage performance of PCM wallboard as compared to that of regular wallboard when it was operated in a cooling mode in a full scale test facility.

The rate of wallboard temperature decrease during the heat release period was found to be significantly slower in the PCM wallboard than in the regular wallboard. If we consider 17 ^{0}C to be the lower limit to comfort zone at night, it will be seen from Figure 4.11 that the time for the air temperature to fall from 22 ^{0}C to 17 ^{0}C in the room lined with regular wallboard is of 9 hours.

On the other hand, in the case of the room equipped with PCM wallboard, it can be seen that the latent heat released **will allow to maintain a comfortable temperature (i.e. above 17 ^{0}C) for 24 hours.**

The use of PCM gypsum boards improves significantly the air temperature which is about 2.5 ^{0}C higher than the air temperature of regular wallboards after a period of time of about 20 hours as shown in Figure 4.11.

As it can be seen from Figure 4.5, the surface temperature of PCM wallboards after a period of time of 20 hours is about 3.8 ^{0}C higher than the surface temperature of regular boards. This is due to the latent heat released stored in PCM wallboard, while in the regular wallboard heat is stored only as sensible.

As a conclusion, the above results show that during the PCM solidification process, the surface temperature of PCM wallboard is always higher than the surface temperature of regular wallboard, restricting the air temperature drop. The surface temperature of PCM wallboard was even maintained equal or very close to PCM temperature during the solidification process, as showed in Figure 4.4.

5.1.3 Heating Mode Performance

Figures 4.12 and 4.16 shows the comparative effect when the two rooms are operated in the natural heating mode. In this case the rooms were cooled and than allowed to absorb heat and thus maintaining a comfortable air temperature as long as possible. In practise for winter conditions, the charged heat for subsequent release could be obtained from solar, waste or off-peak energy sources.

In Figure 4.13 the front surface temperature of PCM wallboard was 2 ^{0}C lower than front surface temperature of regular board room. This indicates that the use of PCM gypsum board can effectively reduce space overheating, functioning as a cooling surface.

For summer conditions, cooling the wallboard would be achieved by using cool night air or off-peak power for air conditioners.

From Figure 4.12 it can be seen that, under the stated conditions the air temperature in the room equipped with regular wallboard roses much faster from 17 ^{0}C to 22 ^{0}C, in about 20 hours, while in the PCM wallboard room, the temperature was maintained bellow 22 ^{0}C for 36 hours.

As showed in the these Figures, the heat storage capacity of regular boards is much more limited as compared to PCM wallboards.

This is due to the storage of heat as latent heat in the PCM wallboard, while in the regular wallboard the heat is stored only as sensible, resulting in an increase of surface temperature.

5.1.4 Improvement of the Thermal Comfort

The experimental results demonstrated that the changes of the room air temperature in the PCM wallboard room are much more restricted. Its smooth surface temperature variations helps provide a slower temperature rise or fall, giving a more stable air temperature.

5.2 CALCULATION OF THERMAL STORAGE IN PCM WALLBOARD

Data recorded from temperature cycling tests for heating energy consumption were used for the calculation of thermal storage in PCM wallboard. The calculation was done taking in account the following assumptions:

(i) First, the difference in electrical heat generation required to keep both rooms at the same temperature should directly give the amount of energy that went into storage in the PCM.

(ii) Second, we consider the infiltration loads and the conduction loads through the walls, ceiling and floor to be identical for the two rooms. This because the rooms were constructed alike and they are subjected to the same environmental conditions during the tests. The values ror thermal conductivity for regular wallboard and PCM wallboard are very closed, as it can be seen from the tables bellow.

Table 5.1. Thermal resistance of regular wallboard

Material	**Thickness (mm)**	**Thermal Conductivity (W/m·°C)**	**Thermal Resistance (m²·°C/W)**
Plywood	9.5	0.115	0.082
Mineral wool	58	0.046	1.260
Regular gypsum board	12.5	0.186	0.067
			R_T=1.409

Total thermal resistance of the wall $R_T = 1.409\ \mathrm{m^2 \cdot {}^oC/W}$

Overall coefficient of heat transmission $U = 1/R_T = 0.7097\ \mathrm{W/m^2 \cdot {}^oC}$

Table 5.2. Thermal resistance of PCM wallboard

Material	Thickness (mm)	Thermal Conductivity (W/m·°C)	Thermal Resistance (m²·°C/W)
Plywood	9.5	0.115	0.082
Mineral wool	58	0.046	1.260
Gypsum board with 20% Emerest	12.5	0.212	0.060
			R_T=1.402

Total thermal resistance of the wall $R_T = 1.402\ \mathrm{m^2 \cdot {}^oC/W}$

Overall coefficient of heat transmission $U = 1/R_T = 0.7132\ \mathrm{W/m^2 \cdot {}^oC}$

Because the two values obtained for the overall coefficient of heat transmission are very close, we can consider the conduction loads through walls and ceiling to be identical for the two rooms.

The difference between the electrical heat generation to keep both room at the same temperature will be equal to the difference between the heat absorbed by wallboard surfaces. To determine the heat absorbed by wallboard surfaces , the energy balance terms were summed.

The steady-state room energy balance in equation form:

$$Q_{gen} = Q_{inf} + Q_{wind} + Q_{door} + Q_{wb} \quad [kJ]$$

where:

Q_{gen} = electrical heat generation

Q_{inf} = infiltration load

Q_{wind} = window conduction load

Q_{door} = door conduction load

Q_{wb} = heat absorbed by wallboard surfaces

The difference between the heat absorbed on one side and heat conducted to the other was equated to energy storage in the wallboard:

$$Q_{wbstor} = Q_{wb} - Q_{cond}$$

where:

Q_{wbstor} = thermal storage in wallboard

Q_{cond} = wallboard conduction load

And consequently, the difference in wallboard storage between PCM wallboard room and regular wallboard room was equated to the energy stored in PCM:

$$Q_{PCM\ stor} = Q_{PCM\ wbstor} - Q_{R\ wbstor}$$

Where:

$Q_{PCM\ stor}$ = thermal storage in phase change material

$Q_{PCM\ wbstor}$ = thermal storage, PCM wallboard room

$Q_{R\ wbstor}$ = thermal storage, regular wallboard room

Data from four temperature cycling tests were analyzed in the table 5.3 below. The difference in electrical heat generation (which is the electrical energy used for heating converted in kJ) is equal to the difference in thermal storage between PCM wallboard and regular wallboard.

Table 5.3. Difference in electrical energy used for heating

Temperature		**Heating Rate**	**Difference in Electrical Energy Use for Heating (W·h)**	**Difference in Electrical Heat Generation (kJ)**
Environmental (°C)	**Range (°C)**	**(°C/min)**		
23	26-09	0.04	2443 - 528 = 1915	6894
23	25-12	0.03	2490 - 543 = 1947	7009
14	26-11	0.03	6622 - 4618 = 2004	7214
14	24-11	0.03	6222 - 4272 = 1950	7020

When the difference in thermal storage between PCM wallboard room and regular wallboard room, which is the storage due to PCM only, is divided by the total weight of PCM, then the latent heat of PCM is obtained.

(i.e.)

Total weight of PCM = 50.5 kg

$$\boxed{\lambda_{PCM} = \frac{(6222-4272)*3.6}{50.5} = \frac{7020}{50.5} \quad 139kJ/kg}$$

When the difference in thermal storage between PCM wallboard room and regular wallboard room is divided by the total weight of PCM wallboard, then the latent heat of PCM wallboard is obtained.

(i.e.)

Total weight of PCM wallboard = 250.3 kg

$$\boxed{\lambda_{PCMwb} = \frac{(6222-4272)*3.6}{250.3} = \frac{7020}{250.3} \quad 28kJ/kg}$$

Table 5.4. Latent heat values for PCM and PCM wallboard obtained by room-scale tests

Difference in Electrical Heat Generation (kJ)	Latent Heat PCM Wallboard (kJ/kg)	Latent Heat PCM (kJ/kg)
6894	27.5	136.5
7009	28.0	138.8
7214	28.8	142.8
7020	28.0	139.0

The experimental average latent heat value for PCM λ_{PCM} = **139.3 kJ/kg**

The experimental average latent heat value for PCM wallboard $\lambda_{PCM\ wb}$ = **28 kJ/kg**

Table 5.5. Latent heat values for PCM and PCM wallboard obtained by DSC laboratory tests

Latent Heat PCM (kJ/kg)	Latent Heat at 20% PCM in wb (kJ/kg)
141	28.8

The latent heat values for PCM wallboard and PCM thus obtained agreed very close with the values obtained by DSC. This indicates that small-scale DSC can adequately predict the performance of PCM wallboard when installed in full-scale applications.

To obtain the total amount of thermal storage in PCM wallboard, the thermal storage due to sensible heat of gypsum must be added to the latent heat storage of the PCM. The storage by sensible heat is given by:

$$\mathbf{Q_s = M * C_p * \Delta T = 199.8\ kg * 1.08\ kJ/kg{\cdot}{}^0C * (21\text{-}17)\ {}^0C = 865\ kJ}$$

The total storage capacity for a 4 ^{0}C temperature rise, corresponding to PCM phase change range, is given by

$$\boxed{Total\text{-}storage_{PCMwb} = \frac{7020+865}{250.3} = \frac{7885}{250.3} = 31.5\,kJ/kg}$$

The ratio of PCM wallboard thermal storage to regular wallboard was determined to be an average of:

$$\boxed{\frac{31.5}{4.3} = 7.3}$$

As a conclusion, the total thermal storage capacity of PCM wallboard is 7 times higher than the thermal storage capacity of regular wallboard, this calculated for a 4 °C temperature difference.

5.3 FIRE TESTS

The flammability of all materials used in buildings is an important consideration, particularly in respect to safety and structural integrity. For this reason fire tests of PCM impregnated gypsum wallboard have been conducted. The fire tests were carried out by ORTECH corporation which is accredited by Standards Council of Canada and it is ISO 9002 registered and they were:

(1) "Standard Method of Test for Surface Burning Characteristics of Building Materials" - CAN/ULC S-102 which is designated to determine the relative surface burning characteristics under specific tests conditions. Results are expressed in terms of Flame Spread Classification (FSC) and Smoke Development (SD).

(2) "Standard Test Method for Heat and Visible Smoke Release rates for Materials Using an Oxygen Consumption Calorimeter" - ASTM E 1534 which is designed to determine mass loss rate, time of ignition, peak rate of heat released, total heat released and smoke obscuration at aspecified radiant heat flux.

5.3.1 Surface Burning Characteristics (CAN-ULC-S 102)

- **Summary of Test Procedure**

The samples were mounted in a Steinner Tunnel. Upon ignition of gas burners, the flame spread distance was recorded and than plotted versus time.

Smoke development was determined by comparing the area under the obscuration curve for the test sample to that of inorganic reinforced cement board and red oak, arbitrary established as 0 and 100, respectively.

Two resulting plots are illustrated in Figures 5.1 and 5.2 In this figures the results obtained for both tests are compared with those for red oak which represents a control specimen whose FSC value is set to 100 and whose SD value is also set to 100.

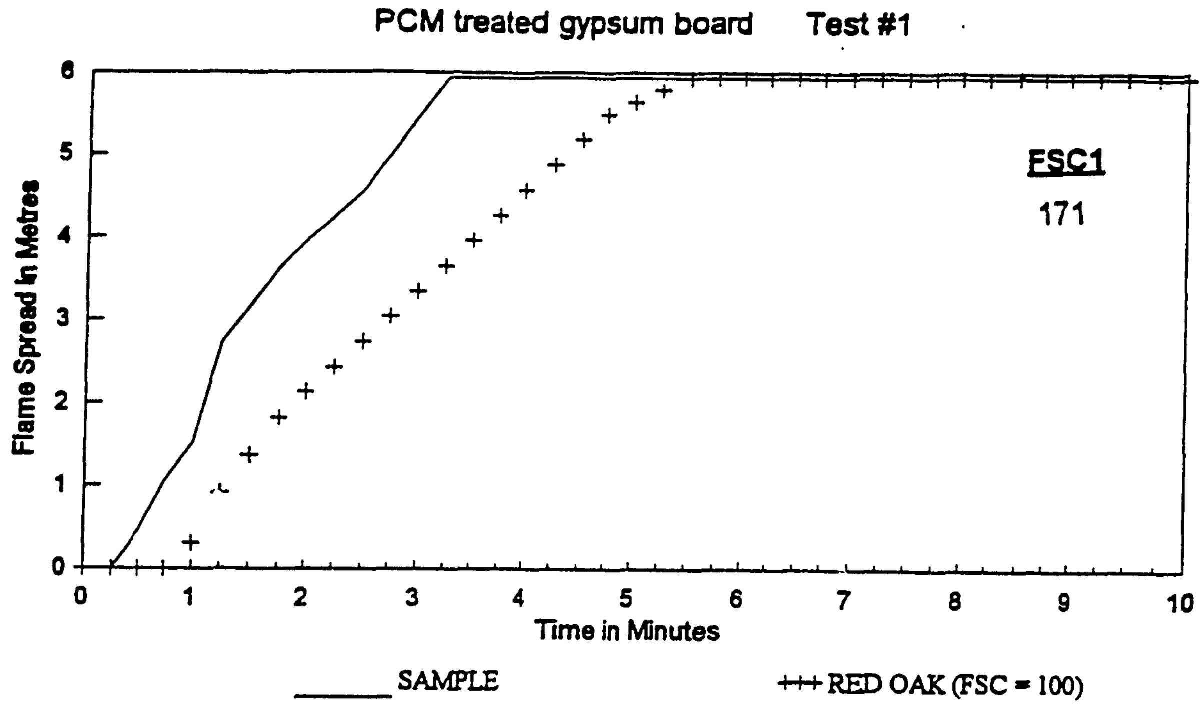
- **Test Results**

The test results obtained are presented in Table 5.6 below:

Table 5.6. Flame Spread Classification and Smoke Development values

Test No.	Average PCM Loading (%)	FSC	SD
1	21.0	171	43
2	20.0	158	39
3	19.6	162	< 5
4	18.8	160	< 5

FLAME SPREAD CLASSIFICATION



SMOKE DEVELOPED

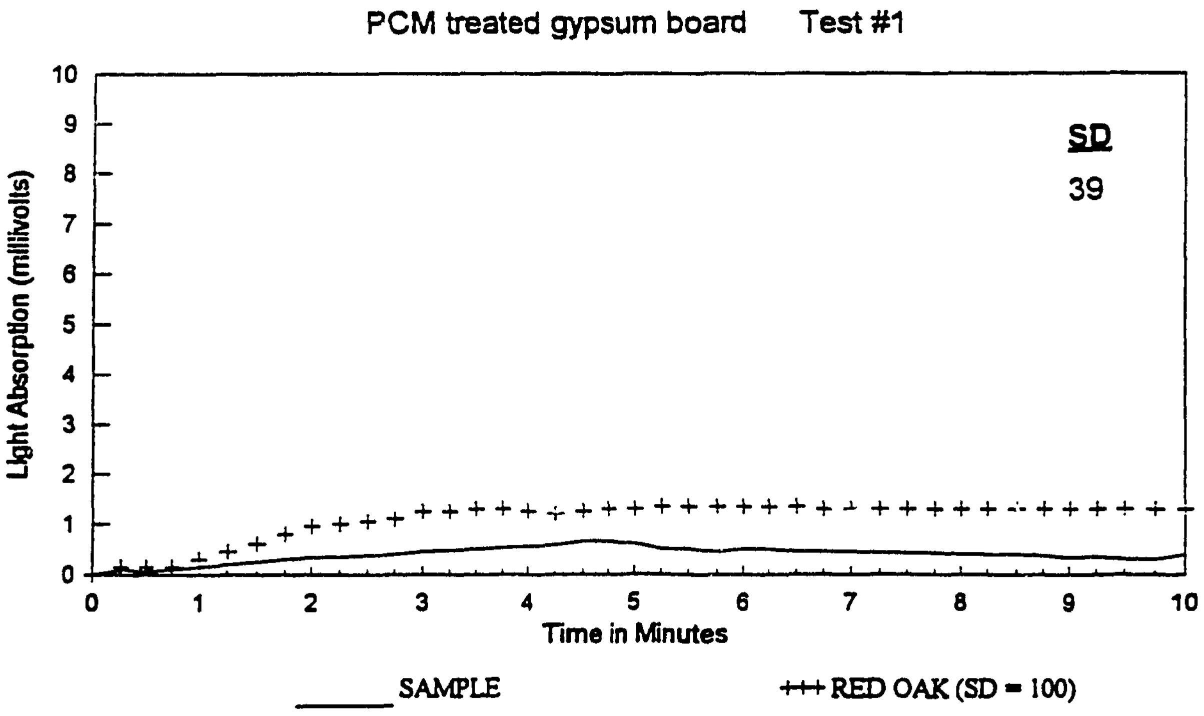
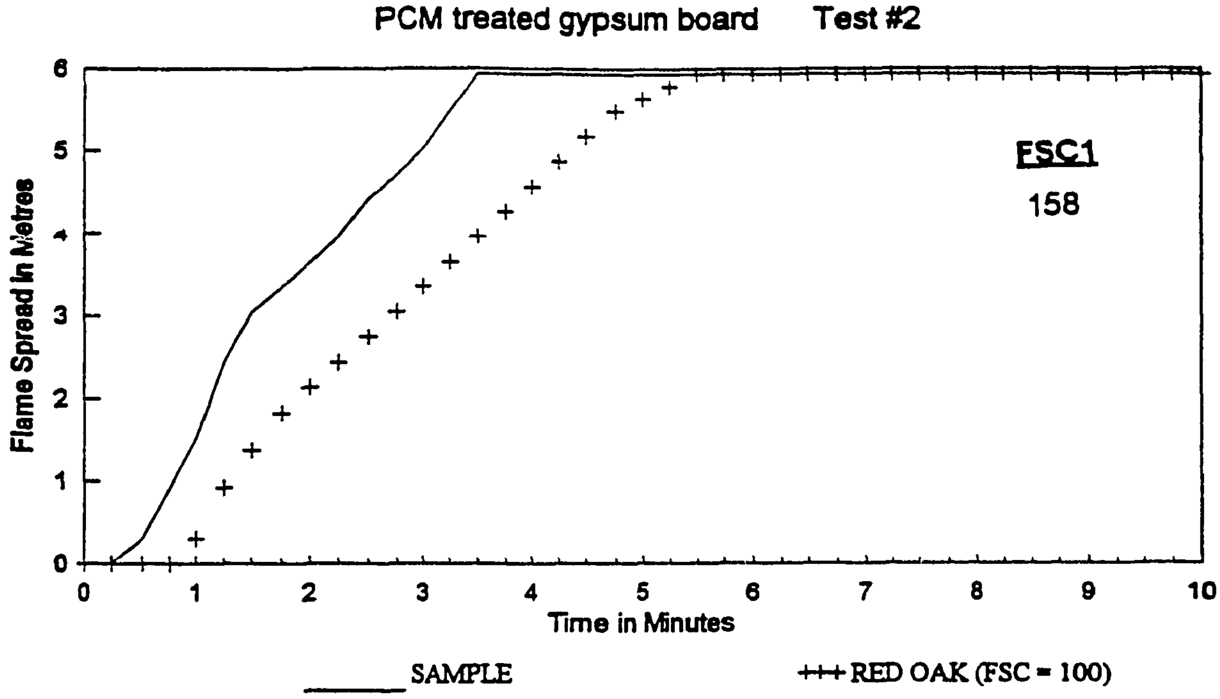


Figure 5.1 Surface burning characteristics for PCM impregnated gypsum wallboard (test # 1)

FLAME SPREAD CLASSIFICATION



SMOKE DEVELOPED

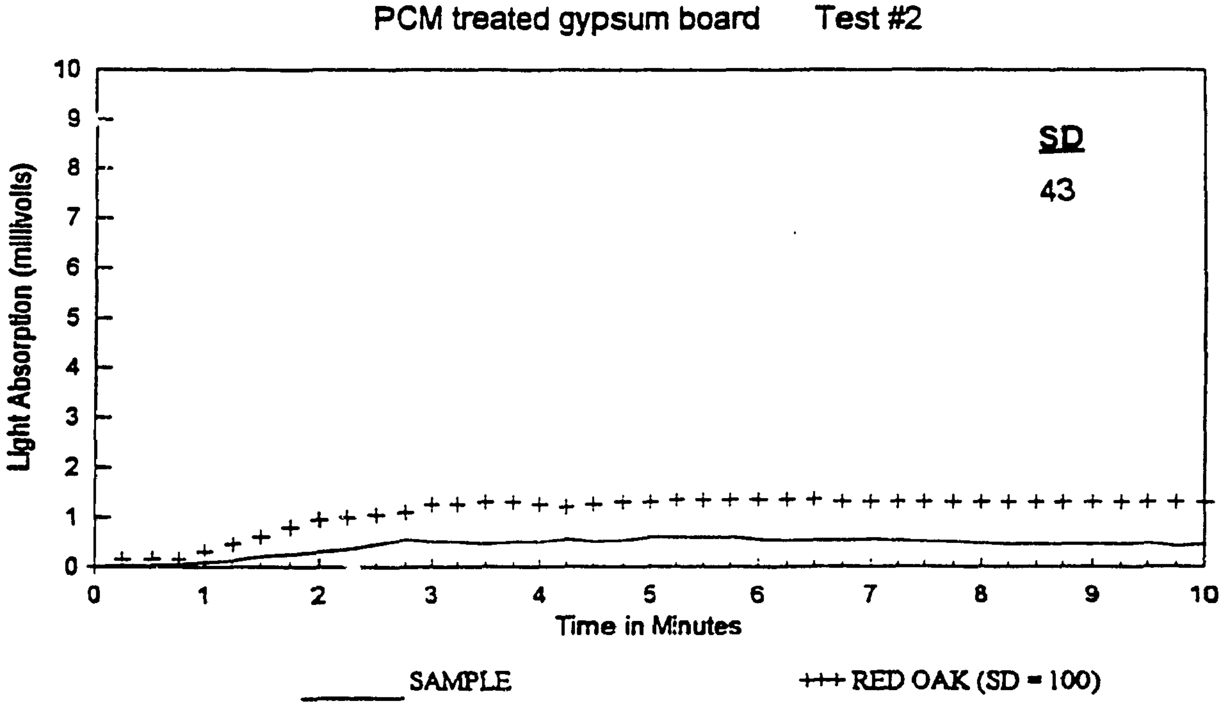


Figure 5.2 Surface burning characteristics for PCM impregnated gypsum wallboard (test # 2)

- **Conclusions**

As expected, the test results show a strong correlation between the PCM loading and the values of FSC and SD. For comparison, Table 5.7 shows some of the assigned FSC and SD values for different combination of building materials as presented in the Supplement of National Building Code of Canada (NBCC) 1990 (Table 3.1. A). The upper number of each entry relates to flame spread and the lower number to smoke development limits.

The FSC value (160) for PCM wallboard is higher than for ordinary wallboard (25) because of the organic nature of PCM. It approaches the values for plywood (150) and particleboard (150).

According to NBCC requirements, walls in rooms are permitted to have an FSC of 150, walls in corridors to have an FSC of 75 and walls in exits to have an FSC of only 25.

The average SD classification results falls within the classification for gypsum wallboard as shown in Table 5.7.

Table 5.7. Assigned Flame-Spread Ratings and Smoke Development Classification for Combinations of Wall and Ceiling Finish Materials and Surface Coatings

Materials	Minimum Thickness (mm)	Unfinished FSC/SD	Paint or Varnish not more than 1.3mm Thick, Cellulosic Wallpaper not more than One Layer FSC/SD
Asbestos cement board Brick concrete tile	None None	0/0	25/25
Gypsum wallboard	9.5	25/50	25/50
Douglas Fir plywood Poplar plywood Plywood with Spruce face veneer	11	150/100	150/300
Douglas Fir plywood	6	150/100	150/100
Fibreboard low density	11	X/100	150/100
Hardboard	9	150/X	
Type 1	6	150/300	150/300
Standard			
Particle board	12.7	150/300	

5.3.2 Heat and Visible Smoke Release Rates (ASTM E 1354)

- **Summary of Test Procedure**

The ASTM E 1354 is a standard test method for determining the rate of heat released from materials and products using the cone calorimeter. The calorimeter is a fire test instrument based on the principle of oxygen consumption. This principle is based on the observation that, generally, the net heat of combustion of any material is directly related to the oxygen-required for combustion.

Four PCM gypsum wallboard specimens were prepared in the CBS laboratory with the PCM loading as shown in Table 5.8. A fifth specimen (#3) of regular wallboard of same size was also prepared.

Table 5.8. PCM gypsum wallboard specimens loading

Specimen #	Average PCM Loading
1	18.8
2	18.8
3	-
4	18.0
5	18.0

- **Tests results**

The following tests results were obtained and they are presented in Table 5.9.

Table 5.9. Results of cone calorimeter tests

Specimen	#1	#2	#3	#4	#5
Mass Loss (kg/m^2)	3.84	3.87	0.47	3.78	3.80
Time to Ignition (s)	60.00	57.00	152.00	34.00	32.00
Peak Rate of Heat Release (kW/m^2)	142.00	151.40	24.80	179.70	161.80
Total Heat Released (MJ/m^2)	73.01	67.03	0.26	74.50	79.99
Total Heat Released @15min (MJ/m^2)	-	-	-	62.61	65.57
Average Extinction Area(m^2/kg)	28.70	26.90	1.10	61.10	87.20

Taking into account that the method of testing is new, limit values for various type of products are not provided. However, in order to establish a rating of materials in a full scale fire hazard, two parameters have been taken into consideration:

- **Flashover propensity** , which is indicated by the ratio of the Peak Rate of Heat Released to Time of Ignition ;
- **Total Heat Released (THR)** which is an indication of the degree of combustibility of a material.

As a function of the magnitude of these two data and considering the results obtained in similar conditions, i.e. at an level of irradiance (heat flux) of 50 kW/m^2, the materials can be rated as follows (Petrella, 1994).

Flashover Propensity	**Total Heat Released**
0.1 to 1 = Low	0.1 to 1.0 = Very low
1.0 to 10 = Intermediate	1.0 to 10 = Low
10 to 100 = High	10 to 100 = Intermediate
	100 to 1000 = High

For the specimens #4 and #5, which were tested at the same heat flux of 50 kW/m^2, the average value of Total Heat Released is 77 MJ/m^2 and the average value of Flashover Propensity is 5.2 kW/m^2.s.

Based on these data, PCM wallboard can be rated as having an intermediate fire hazard.

Based on published data, Both values for Peak Rate of Heat Released and Total Heat Released as determined in PCM wallboard are fairly lower than those determined for plywood which are 188 kW/m^2 and 65 MJ/m^2 but higher than those obtained for flame retardant treated plywood which are 118 kW/m^2 and 40 MJ/m^2 respectively (Richardson, 1991).

- **Conclusions**

Presence of a fire retardant in PCM wallboard would have similar effects as in plywood. Because ignition of such treated PCM wallboard would be delayed and the rate of burning reduced, the total amount of heat released would be decreased.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATION

6.1 SUMMARY

In this study, full-scale tests were conducted for a PCM impregnated gypsum board to enhance the thermal energy storage capacity as compared to regular gypsum board. Two identical side-by-side rooms were used for the experimental study. Interior walls and ceiling of one of the rooms were finished with regular gypsum board while the interior walls and ceiling of the other room were finished with PCM impregnated gypsum board. The test rooms were equipped with a computerized data acquisition system and a controlled system for temperatures and energy measurements.

Based on the DSC tests, a mixture of 50 % Butyl Stearate and 48 % Butyl Palmitate (EMEREST 2326) was selected for the full-scale PCM wallboard tests due to its favourable melting and freezing temperature range and latent heat storage capacity.

For this research, the PCM was incorporated into regular gypsum boards by dipping dry boards into a heated and melted PCM for a certain amount of time.

Initial small-scale tests using a DSC showed a an average latent of 28±2.4 kJ/kg at an average PCM loading of 20 % by weight. The average PCM melting point was 20.4 ^{0}C and the average freezing point was 19.5 ^{0}C. Full-scale test showed that PCM wallboard had an average latent heat of 28 kJ/kg. This indicates that small-scale DSC can adequately predict the performance of PCM wallboard when installed in full-scale applications.

6.2 CONCLUSIONS

(i) The experimental results showed that PCM gypsum board is able to act as a thermal storage device when it is used as building interior lining.

(ii) The utilization of PCM gypsum board can reduce room air temperature rise by 2 ^{0}C, thus restricting the overheating of the space. The room air temperature is reduced due to the thermal storage of PCM in the gypsum board and the thermal comfort could be significantly improved.

(iii) The recovery of the stored latent heat in the PCM gypsum board can be realized when the space temperature decreases.

(iv) The room-scale tests showed a significant higher room air temperature, almost 2.5 ^{0}C, due to the heat released by PCM gypsum boards as compared to room air temperature of the room standard gypsum boards.

(v) The surface temperature of PCM wallboard is about 3.8 ^{0}C higher than the surface temperature of regular wallboard due to the latent heat released during the solidification process.

(vi) The rate of decrease of boards temperature during natural cooling is significantly slower in PCM wallboard than in regular wallboard, indicating the fact that the PCM board has a higher thermal inertia due to the heat released during the PCM solidification process, thus giving a more stable air temperature.

(vii) The PCM wallboard can shift most of the power loading from peak to off-peak periods of time.

(viii) The experimental results obtained at large scale show that the transition process of PCM wallboard takes place in the expected temperature range and the values obtained for latent heat are very close to those determined by DSC. This indicates that the small-scale DSC can adequately predict the performance of PCM wallboard when installed in full-scale application.

(ix) The organic PCM wallboard study has shown that the concept of latent heat storage is workable on large scale and that PCM's can be successfully integrated within a building with a significant thermal storage effect.

(x) In summary, the utilization of PCM wallboard has shown a promising improvement of thermal comfort for both space heating and cooling.

6.3 RECOMMENDATIONS FOR FUTURE WORK

6.3.1 Reducing the Flammability of PCM wallboard

The search for an ideal PCM candidate has been ongoing for several years and it seems that fatty acid esters posses the most desirable properties of a PCM, as previous research as well as the results of the present project demonstrated.

However, their flammability is an important concern and the efforts should be concentrated towards reducing the flammability of PCM wallboard to meet flammability standards imposed by NBCC requirements.

One of the most appropriate way to reduce flammability, without compromising performance properties, will be the incorporation of an efficient flame retardant.

The laboratory scale search for an efficient flame retardant alone or in combination with conventional flame retardant additives should comprise most of laboratory tests. The use of X type reinforced with glass fibre wallboard might also be examined.

6.3.2 Finding New PCM's or Mixtures of PCM's

Further research in respect to the development of other types of PCM's with high latent heat and melting points in the comfort range of temperatures suitable for this application might be done.

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