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ANALYSIS OF WALLBOARD CONTAINING A PHASE CHANGE MATERIAL†

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ANALYSIS OF WALLBOARD CONTAINING A PHASE CHANGE MATERIAL

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ABSTRACT

Phase change materials (PCMs) used on the interior of buildings hold the promise for improved thermal performance by reducing the energy requirements for space conditioning and by improving thermal comfort by reducing temperature swings inside the building. Efforts are underway to develop a gypsum wallboard containing a hydrocarbon PCM. With a phase change temperature in the room temperature range, the PCM wallboard adds substantially to the thermal mass of the building while serving the same architectural function as conventional wallboard.

To determine the thermal and economic performance of this PCM wallboard, the Transient Systems Simulation Program (TRNSYS) was modified to accommodate walls that are covered with PCM plasterboard, and to apportion the direct beam solar radiation to interior surfaces of a building. The modified code was used to simulate the performance of conventional and direct-gain passive solar residential-sized buildings with and without PCM wallboard. Space heating energy savings were determined as a function of PCM wallboard characteristics. Thermal comfort improvements in buildings containing the PCM were qualified in terms of energy savings. The report concludes with a present worth economic analysis of these energy savings and arrives at system costs and economic payback based on current costs of PCMs under study for the wallboard application.

1. INTRODUCTION

Thermal energy storage is an essential constituent for meeting a building heating load with an energy source that varies in time or strength such as solar energy or off-peak electricity. In passive solar energy systems, conventional thermal storage technologies include sensible heat storage in water or masonry and latent heat storage in chemical compounds termed PCMs. In general, these materials require either containment or a dedicated structure. This requirement becomes particularly problematic in the case of lightweight building construction. Consequently, thermal storage systems based on these technologies are often economically unattractive. Therefore it is interesting to consider how conventional architectural components such as walls, floor, or ceiling might be modified for increased thermal storage capacity.

As a first target for enhancing the thermal storage capacity of building components, ordinary gypsum wallboard is being studied as a vehicle for introducing latent heat storage into a building [1]. The latent heat storage is provided by a blend of paraffins carefully selected to melt and freeze (change phase) at room temperature. Several methods for incorporating the paraffin PCM into gypsum wallboard have been identified; the simplest method consists of soaking the wallboard in a bath of melted paraffin before hanging. Experiments have shown [2] that the soaking process results in paraffin uptake as high as 35% by weight of composite. Additional testing has shown that the paraffin is stably contained by the wallboard and that adhesion of paint and joint compound remains unaffected by the presence of the paraffin.

Based on the technical success of the PCM wallboard, it becomes important to address several questions:

1. What sort of building would best benefit from the technology?
2. What is the economic value of the PCM wallboard?
3. Based on current PCM costs, what payback periods can be expected?
4. How does the PCM wallboard affect thermal comfort conditions inside the building?

To answer these questions, a series of computer simulations of a typical building for a heating season were performed. This paper describes the results of these simulations.

2. THE BUILDING SIMULATION

An examination of available building simulation codes led to TRNSYS [3] which was modified to include subroutines for PCM wallboard and for tracking direct solar beam radiation into a building.

The structure modelled using TRNSYS was similar to one from an earlier study [4]: a single zone with a total load coefficient (TLC) equal to 14,100 Btu/°F · d. Other characteristics of the building are the following:

Building dimensions (in feet) = 50 x 36 x 8
Orientation: 50-foot dimension runs E-W
Total window area = 360 ft^2
Infiltration rate = 1/2 air change per hour
Wall insulation = R-18
Ceiling insulation = R-30
Windows (double glazed), $U = 0.56$ Btu/h· $ft^2 \cdot °F$
Interior wall convection coefficient = 0.47 Btu/h·$ft^2 \cdot °F$)
Maximum room temperature = 75°F
Floor = ASHRAE (5) No. 30 with $U = 0.107$ Btu/h· $ft^2 \cdot °F$
Location: Denver

All walls were considered to be stud walls with insulation between the studs and a layer of PCM wallboard on the inside surface. The outside insulating layer was assumed to have a thermal resistance equivalent to R-18 ($U = 0.056$ Btu/h·$ft^2 \cdot °F$). Several inside layer configurations were analyzed as shown in Table 1.

The annual heating energy savings shown in Table 2 were substituted into Eq. 2 along with the appropriate UPWF and adjusted energy cost to determine the PVES for each combination of latent storage capacity and fuel type for the solar building simulated by TRNSYS. The results of these calculations are detailed in Table 4. This table can be used not only to evaluate the PVES for the lifetime of the system but also to determine the discounted payback for the PCM wallboard. For example, a PCM wallboard system with latent heat capacity of 26 Btu/ft^2 and a lifetime of 30 years has a present value of $3542 if the building is heated by an electrical heat pump. To provide a three-year payback, that same PCM wallboard system must have an installed cost no greater than $321.

Table 4. PVES ($) of PCM addition to walls of 1800 ft^2 home in Denver; 200 ft^2 of S. glazing; no window insulation

	Backup Fuel		
N(years)	Natural gas	Electricity	Fuel oil
Wallboard latent heat = 14 Btu/ft^2			
1	64	114	73
3	185	332	212
5	297	533	342
30	297	538	342
Wallboard latent heat = 26 Btu/ft^2			
1	97	172	111
3	280	503	322
5	450	815	517
30	1807	3542	2078
Wallboard latent heat = 35 Btu/ft^2			
1	112	200	129
3	324	582	372
5	521	944	599
30	2091	4100	2405
Wallboard latent heat = 65 Btu/ft^2			
1	128	229	148
3	372	667	428
5	599	1084	663
30	2403	4711	2763

As a first case (and the one that would most favor the economics of PCM wallboard), electricity was assumed as the backup fuel and selected data from Table 4 were plotted as shown in Figure 3 (ignore for the moment the straight lines).

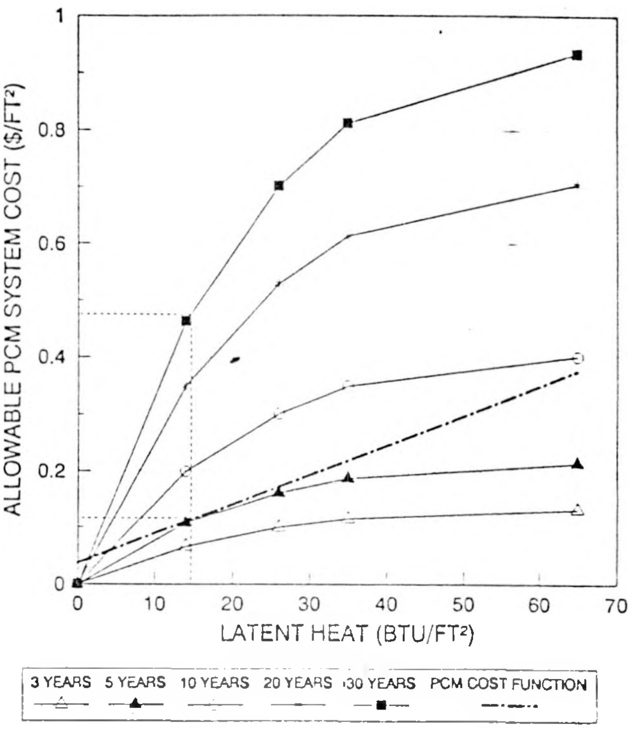

Figure 3. PCM system allowable cost with electricity backup as function of period and areal latent heat capacity.

For simplicity, the term PWEC was changed to 'allowable cost' for the PCM system. It should be noted that, since the baseline storage system was conventional gypsum wallboard with no PCM, the costs shown represent the maximum allowable cost of the PCM itself including the cost of incorporating the PCM into the wallboard.

Clearly for an economic winner, the cost of the PCM installed in the wallboard must be less than the allowable.

PCM Wallboard cost

The cost of PCM wallboard depends on the amount (weight) of PCM, the unit cost of PCM, and the cost required to incorporate the PCM into the gypsum board. It was assumed that installation costs of PCM wallboard and conventional wallboard into a building would be equal since the same building trades (drywall hangers and finishers) would be needed in either case. As mentioned before, TRNSYS was used to simulate the performance of an 1800-ft^2 solar house in Denver. The house was characterized by 200-ft^2 of south-facing glazing, no window insulation and 5040-ft^2 of interior walls and ceiling made of ½-inch PCM wallboard. The weight of wallboard and PCM used in the simulations are given in Table 5 shown below.

Several points are evident from Figures 1 and 2 and summary Table 2.

Table 2. Total Heating Energy Use Summary

PCM %	Areal latent heat Btu/ft^2	Supplemental energy use (mBtu)	
		Non solar house	Solar house
0	0	73.7	50.0
10	14	70.5	49.0
15	25	70.2	43.5
20	35	70.0	41.0
30	55	69.9	38.2

First, energy can be saved by locating windows to face south—a zero cost item if incorporated into the original building design. Second, in the non-solar house there is virtually no improvement in energy savings as the PCM concentration in the wallboard is increased. However, in the case of the solar house there is clear evidence that as the PCM concentration increases, the energy savings grow. The obvious task at this point is to determine the present worth of these energy savings and, based on estimates of PCM wallboard system cost, to determine the economics of the concept and how these economics depend on PCM content in the wallboard.

4. PCM WALLBOARD ECONOMICS

An economic analysis of PCM wallboard was performed for the solar building to determine the economic benefit of the latent heat storage system and to determine how estimates of the cost of the PCM system affect this benefit. The economic analysis was based on the energy savings by using the PCM wallboard rather than conventional wallboard on the interior of the building. It was assumed that these energy savings (derived from the last column of Table 2) would be constant from year to year for the lifetime of the PCM system. From the annual energy savings, annual cost savings were determined based on the price of the displaced fuel: either natural gas, home heating oil, or electricity. The present value of these energy savings (PVES) was determined by multiplying the annual cost savings by a uniform present worth factor (UPWF) defined as follows:

$$UPWF = \left[\frac{1+e}{d-e}\right]\left[1-\left(\frac{1+e}{1+d}\right)^{N}\right] \quad , \qquad (1)$$

where
e = energy price escalation rate
d = discount rate
N = number of years for analysis.

Therefore,

$$PVES = (\text{annual energy savings})(\text{energy cost})(UPWF). \qquad (2)$$

Since the PVES is the economic benefit provided by the PCM, it may be thought of as the "allowable cost" of the PCM system. In other words, the initial installed cost of the PCM must not exceed the allowable cost (which is the present worth of the energy saved for the given period).

Economic Assumptions

The effective discount rate, d, is a measure of the anticipated return of capital and depends upon the distribution of debt and equity as well as the tax rate. The effective discount rate was determined through the relation,

$$d = r_e f_e + r_d f_d (1 - m), \qquad (3)$$

where

r_e = the return on equity (e.g., from savings)
r_d = the return to debt (mortgage interest rate)
m = the tax rate (tax bracket)
f_e = fraction financed by equity
f_d = fraction financed by debt.

For the PCM wallboard system installed in a home, debt capital is raised through a first or second mortgage and is provided by a lender at an interest rate, r_D. This interest rate was assumed to be 10%, reflecting what is currently available through fixed rate mortgages. The return on equity (e.g., interest earned in a long-term savings account) was assumed to be 7% and the tax rate taken to be 33% according to the recent Tax Reform Act. It was further assumed that the PCM wallboard system was financed along with the house with a 20% down payment provided by equity. Therefore, Eq. 3 yields a real discount rate,

$$d = (.07)(.20) + (.10)(.80)(.67) = 6.76\%. \qquad (4)$$

From Eq. 2, the economic attractiveness of PCM wallboard as measured by the PVES depends on the cost of the energy displaced and the energy cost escalation rate, e. For this analysis, three supplemental heating systems were considered as shown in Table 3.

Table 3. Supplemental Heating System Data

Heating system	Fuel cost[A]	Efficiency	Adjusted fuel cost[B]	e[C]
Gas furnace	$4.96/mBtu	0.80	$6.20/mBtu	3.0%
Oil furnace	$5.70/mBtu	0.80	$7.13/mBtu	3.0%
Heat pump	7.50c/kWh	SPF = 2.0	$10.98/mBtu	3.8%

[A] Average prices of fuel for residential sector during 1988 as taken from the Monthly Energy Review, DOE/EIA-0035(88/12), December 1988.
[B] Fuel costs adjusted for system efficiencies shown.
[C] Fuel escalation rates estimated for a nominal base case provided by the EIA Short-Term Energy Outlook, DOE/EIA-0202(89/3Q), July 1989. Escalation rates for outyears were projected to remain unchanged from the DOE short-term estimates.

Analysis

Using the discount rate shown in Eq. 4 and the fuel escalation rates from Table 3, the UPWF was calculated for periods up to 30 years. As expected, for all years the UPWF for electricity is marginally higher than that for natural gas and fuel oil due to the higher initial cost and the higher escalation rate for electricity.

Table 5. PCM wallboard characteristics in an 1800-ft² house with an interior wall area equal to 5040 ft². PCM latent storage capacity measured to be 83 Btu/lb.

Total wallboard weight (lb)	% PCM	PCM weight (lb)	Areal latent heat capacity (Btu/ft²)
13105	30	3932	55
10500	20	2100	35
9975	15	1500	25
9450	10	945	14

The PCM wallboard cost was separated into the two components: one that indicates costs attributable to the PCM and the second is a term that collects all other costs such as manufacturing costs (incorporation of the PCM into the wallboard), overhead, and profit. Thus the following terms were defined:

h_m = the latent heat of the PCM (Btu/lb)
LH = the areal latent heat of the PCM wallboard ($\mathrm{Btu/ft^2}_{\mathrm{wallboard}}$)
C_{PCM} = the unit cost of the PCM ($/lb)
C_{other} = other costs associated with incorporation of the PCM into drywall ($\$/\mathrm{ft^2}_{\mathrm{wallboard}}$)
C_{total} = the total cost of the PCM wallboard.

Therefore, the total cost of the PCM wallboard can be written as

$$C_{total} = \left(\frac{C_{PCM}}{h_m}\right) (LH) + C_{other} \tag{5}$$

This is the equation of a straight line of slope $(C_{PCM})/(h_m)$ and intercept C_{other}. This cost function can be superimposed on Figure 3 to determine the payback and optimal PCM content in the wallboard.

As an example of this technique for estimating the economic attractiveness of the PCM wallboard, data from ongoing PCM wallboard experiments at Oak Ridge National Laboratory were used. The paraffin wax obtained for wallboard experiments (a mixture of C-18 and near neighbor carbon atoms) was developed by Witco Chemical and purchased for $0.50/lb in barrels. The latent heat was measured to be 83 Btu/lb. These data were substituted into Eq. 5 and the resulting equation superimposed as a straight line on the allowable cost curves as shown in Figure 3. For this example, it was assumed that C_{other} = $.03/ft². This PCM cost function intersects all allowable cost curves above N = 5 years and does not intersect any cost curve below N = 5 years. In other words, the allowable cost curve that is tangent to the PCM cost function defines the earliest time at which the PCM system cost equals the allowable cost and is the discounted payback under the assumptions given. Note also from Figure 3 that (1) the installed PCM wallboard cost will be $.12/ft², (2) the optimal latent heat content of the wallboard will be approximately 15 Btu/ft², and (3) if the lifetime of the PCM wallboard system is 30 years, the present worth of the PCM system will be $.48/ft². If C_{other} is larger than $.03/ft², a 5-year payback requires identification of a PCM that is either lower in cost or has a higher latent heat capacity so that the slope of the cost function line remains tangent to the N = 5 line. It is also apparent that for N = 5 years, C_{other} cannot be much above $.20/ft² regardless of the price of the PCM.

5. COMFORT CONSIDERATIONS

It is interesting to consider whether the isothermal nature of the PCM wallboard materially affects the thermal comfort of the building by extending the time over which the interior building temperature is in a comfort range. Based on a heuristic assumption that thermal comfort is a combination of the magnitude temperature excursions away from a "desired" room temperature and the duration of these excursions (i.e., rooms that seldom overheat or often slightly overheat are generally more comfortable than ones that often overheat), a "comfort index," CI, was defined as follows:

$$\begin{aligned} CI = &\ |75° - T_D|(\text{No. of hours room is at } 75°) \\ &+ |74° - T_D|(\text{No. of hours room is at } 74°) \\ &+ \cdots + |60° - T_D|(\text{No. of hours room is at } 60°) \end{aligned}$$

where T_D = the desired room temperature. The term CI is simply the product of temperature excursions away from T_D and the duration of these excursions and has units of °F·h. The higher the CI, the less comfortable the room.

Figure 4 shows the relation between CI and T_D for the 68°F PCM at two concentration levels in the wallboard. It can be observed that room comfort is improved by about 30% as the PCM content is raised from 14 to 35 Btu/ft².

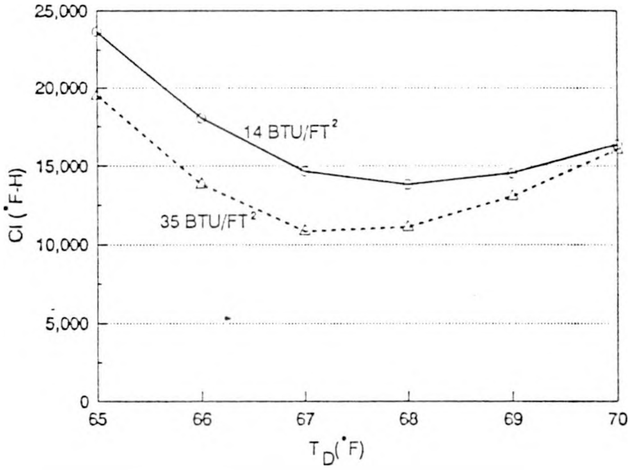

Figure 4. Comfort index for solar building as function of desired temperature, T_D, with a 68°F PCM.

Further, the least discomfort is achieved if T_D is near the PCM melt temperature of 68°F. Therefore, it appears that the melt temperature of the PCM should be near the desired room temperature, T_D, for greatest comfort. Further the thermostat setting, T_{set} should be such that $T_{set} = T_D - 1/2$ DB.

An analysis was conducted to quantify the comfort provided by the PCM wallboard in terms of energy savings. We anticipated that comfort equivalent to that provided by the PCM wallboard could be achieved without the PCM simply by raising the thermostat setpoint. To examine this issue, a series of simulations were conducted on the solar building with conventional (non-PCM) wallboard with T_{set} varied from 63° to 69°F. For each simulation, CI was calculated and plotted as a function of T_{set} as shown in Figure 5. Also plotted are the CI values found with PCM wallboard and T_{set} = 65°F. As can be seen, there was no way to adjust the setpoint of the non-PCM building to achieve CI value equivalent to that of the PCM wallboard. Raising or lowering T_{set} simply made the room, on average, either too warm or too cool.

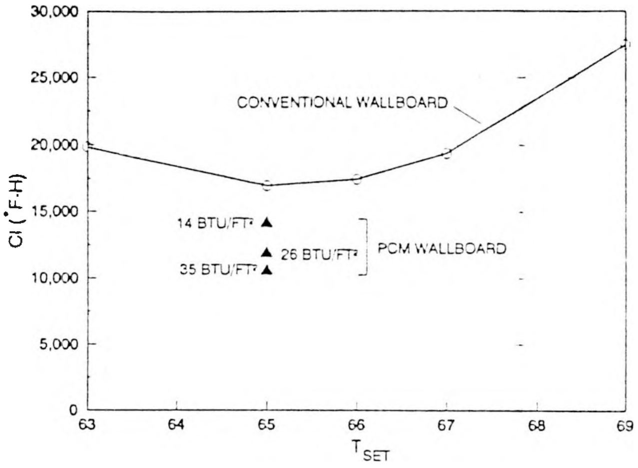

Figure 5. Comfort comparison of PCM wallboard with conventional wallboard in solar house.

6. CONCLUSIONS

Work is underway to enhance the heat capacity of conventional building components through the use of PCMs. Experiments conducted with gypsum plasterboard have shown that a paraffin mixture selected to freeze and melt in the room temperature range can be retained in the pore spaces of the wallboard up to 35% by weight of composite. To determine the value of the PCM wallboard, a series of simulations of a small building have been conducted and studied. From these simulations, performed for solar and non-solar buildings, it appears that the value of the PCM wallboard in reducing the supplemental energy requirements of the building is small for a non-solar building. In the case of a passive solar building that is reasonable in size and aperture, the presence of the PCM in the wallboard is a significant factor in reducing supplemental energy requirements. Simulations performed for a Denver climate showed that the energy savings were directly related to the quantity of PCM in the wallboard. An economic analysis showed that the discounted payback for the concept will be probably less than five years. Further, the analysis showed that the optimal PCM required is approximately 15% by weight of composite.

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