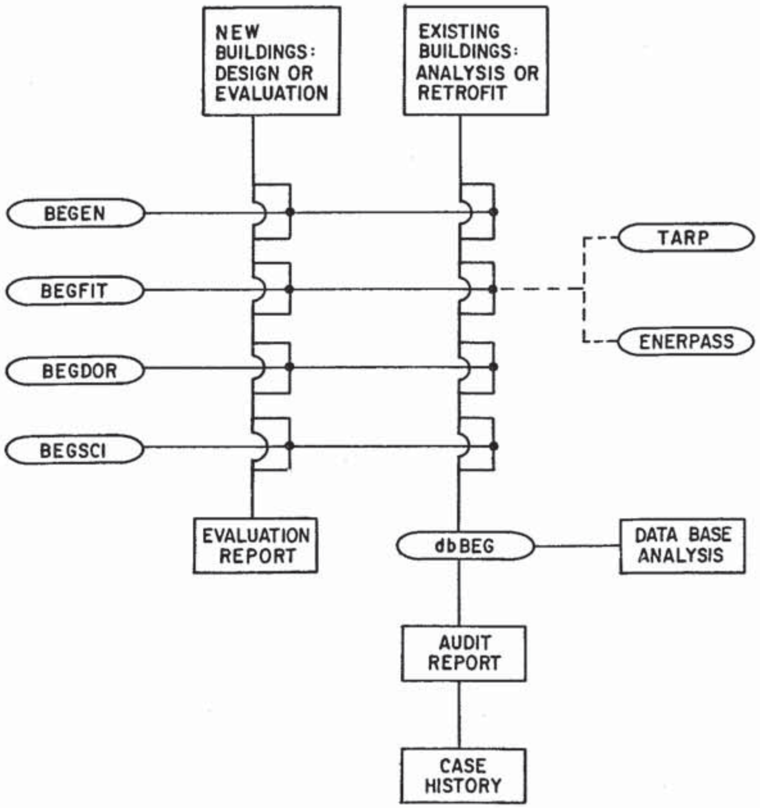

Fig. 1: ENERGY ANALYSIS PROCEDURES FOR WAREHOUSE AND LIGHT INDUSTRIAL BUILDINGS.

The Energy Performance of Buildings with Distributed Thermal Storage

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KEYWORDS

Building Energy Usage, Energy Conservation, Performance Analysis, Solar Energy, Storage Materials, and Thermal Storage.

ABSTRACT

The cost of comfort control in a building can be reduced by moderating its temperature swings with distributed thermal energy storage components. Various storage concepts involving either heat or cool storage have been evaluated and potentially cost effective designs for passive solar and energy efficient buildings have been identified. The analyses make use of finite difference methods to solve thermal network building models at short time intervals over a full year's simulation. Each thermal storage component concept is modeled parametrically so that a series of annual building simulations provides a basis for selecting an optimum storage component design. The focus is on new, solid-state, phase-change materials which, unlike previous phase-change materials, remain solid throughout the range of service temperatures. These materials are readily incorporated into concrete, gypsum board, wood products, etc. Results indicate that optimized, phase-change thermal storage components used in Trombe walls or as wall coverings in direct solar gain designs can provide greater energy savings than conventional masonry or wall-board. Low temperature phase-change components may be used to shift the demand for air conditioning power to off-peak periods, thereby reducing the cost of building cooling.

Les Performances Énergetiques des Constructions à Accumulation Thermique Répartie

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MOTS-CLES

Analyse des Performances, Économies d'Énergie, Energie Solaire, Matériaux de Stockage, Stockage Thermique, et Utilisation de l'Énergie des Batiments

RESUME

Le coût de la climatisation des constructions peut être rèduit en modèrant l'amplitude des changements de tempèrature à l'aide de composants à accumlation d'ènergie thermique. Divers concepts portant sur l'accumulation de chaleur ou de froid ont ètè èvaluès et des conceptions de constructions solaires passives, à bon rendement ènergètique et susceptibles de rèduire les frais, ont ètè identifièes. Les analyses utilisent des mèthodes de diffèrences finies pour rèsoudre les modèles de construction à rèseau thermique à intervalles courts, sur une annèe entière de simulation. Chaque concept de composant d'accumulation thermique est ètudiè paramètriquement de sorte qu'une sèrie de simulations de constructions annuelle offre une base de sèlection de conception de composant d'accumulation optimale. L'accent est mis sur des matèriaux à accumulation solides et d'un tupe nouveau, lesquels, contrairement aux anciens matèriaux, demeurent solides sur toute la gamme des tempèratures de service. Ces matèriaux s'incorporent facilement au bèton, au plâtre, au placoplâtre, aux produits à base de bois, etc. Les rèsultats indiquent que les composants à accumulation thermique optimisès, utilisès dans les murs Trombe ou en guise de tenture dans des conceptions à gain thermique solaire direct, peuvent permettre de plus grandes ècomonies d'ènergie que la maconnerie ou la plaque mixte traditionnelles. Les composants à accumulation à basse tempèrature peuvent servir à dèplacer la demande de puissance de climatisation hors heures de pointe, ce qui rèduit les frais de refroidissement des constructions.

INTRODUCTION

The heat flow into and out of a building is cyclic with a large diurnal component driven by changing solar intensities and outdoor air temperatures. Thermal energy storage within a building is most effective when it attenuates the amplitude of the temperature cycles and shifts the phase of this heat flow into and out of the occupied space to better match the comfort needs of the occupants, i.e., delaying delivery of daytime solar heat into the nighttime or absorbing unwanted heat during the day so that is may be rejected at night.

New materials now being studied at several laboratories[1-4] may provide a convenient and economical way to distribute large amounts of heat storage throughout a building in the form of modified finish materials such as wall board, ceiling tiles, floor slabs, or floor tiles. These composite building materials will reversibly absorb large amounts of heat over a narrow temperature range. The active temperature can be selected by the design of the composite to optimize its operation in different kinds of buildings or in different parts of a building.

Computer models have been used to estimate the energy conservation and economic benefits of such thermal storage materials in three kinds of applications: a Trombe wall, a direct solar gain space and a "cool" storage application. The composite thermal energy storage materials under study have a range of active temperatures, heat storage capacities and other thermal properties; so the computer simulations have been performed parametrically over a range of these properties.

The thermal energy storage materials under study are described briefly in the next section. The computer simulation models and modeling results are described in the following sections.

PHASE CHANGE MATERIAL (PCM) COMPOSITES

Two classes of PCM are being evaluated for use in composite interior finish materials: solid-liquid PCMs and solid-solid PCMs. Representative of the solid-liquid PCMs are the paraffins and representative of the solid-solid PCMs are the polyhydric, crystalline alcohols. Table 1 lists some typical properties of such materials.

1. D. K. Benson, et. al., "Materials Research for Passive Solar Systems: Solid-State Phase-Change Materials", Solar Energy Research Institute Report TR-255-1828, March, 1985 (available NTIS).

2. Dr. Chandra, et. al., "Adjustment of Solid-Solid Phase Transition Temperatures of Polyalcohols by the Use of Dopants", to be published in Advances in X-ray Analysis, Vol. 29, Plenum Press, NY, NY, 1986.

3. I. O. Salyer, et. al., "Advanced Phase-Change Materials for Passive Solar Storage Applications", Proceedings of the 20th IECEC Meeting, Miami, FL, August, 1985.

4. M. C. P. deLima and C. d. Maycock, "Low Temperature Thermal Energy Storage Using Solid-State Phase-Change Materials", Proceedings of the European Congress on Economics and Management of Energy in Industry, Albufeira, Portugal, April 1983, Pergamon Press, 1983.

The paraffins, which are byproducts of petroleum refining, are lower in cost. However, the paraffins become liquid when they absorb heat and may be more difficult to contain than the crystalline alcohols. The solid-solid PCMs absorb heat by changes in their solid crystal structure. Both kinds of PCMs are hydrocarbons and are combustible. Consequently, fire safety must be a concern in designing appropriate composite structures.

The simplest and most economical means of incorporating either kind of PCM into a building material is by infusion. The porous building material (wood, gypsum board, concrete aggregate, etc.) is merely dipped into the hot melted PCM which is readily absorbed into its pore volumes. When the composite cools, the PCM is trapped. Figure 1 shows that heat storage capacities of representative composites are much greater than conventional building materials.

In general, the composite PCM materials could be handled, installed, and finished with the same tools and labor skills that are used now for conventional non-PCM construction materials. However, for both classes of PCM composites, a surface coating of somekind would be required to prevent liquid or vapor loss over long periods.

COMPUTER SIMULATIONS

Modeling

The building energy performance models use finite difference methods to calculate heat flows in thermal networks over successive short intervals for a full year. The thermal networks represent entire buildings or representative portions of buildings with heat flows that are driven by typical hourly weather changes and occupancy demands for heating or cooling. For each choice of parameters, a full year's performance is simulated and the total annual purchased energy requirement is calculated.

Table 2 summarizes the modeling conditions for each of the three cases described below.

Solar Heat Storage Wall (Trombe wall)

The modeling compared the annual purchased heating energy requirements for a small residential building with and without a 200 ft^2 south facing Trombe wall. The effectiveness of the Trombe wall was expressed as the fraction of annual heating energy requirement which it meets (the so-called Solar Saving Fraction). Figure 2, for example, shows results of sixteen separate annual simulations in which several different thicknesses of Trombe wall were simulated and concrete was compared to a phase change material (PCM) as the heat storage medium. Two different thermal coductivities were used to characterize the PCMs.

Notice the different thickness scales for the concrete and PCM. The PCMs are predicted to provide heat storage performances which are comparable or superior to concrete four times as thick. These results also indicate that an increased thermal conductivity would improve the performance of the PCM Trombe wall.

The advantages of the PCM are that it would be much less massive (as little as 1/10 the mass of equivalent concrete) and it may provide a somewhat larger fraction of the heating requirements than any thickness of concrete could.

Directly Illuminated Interior Walls

Figure 3 shows the solar saving fraction predicted to be achievable in a small house with directly illuminated internal walls providing the solar heat storage. Three different materials were modeled: conventional gypsum wall board, a four inch thick concrete wall, and a very effective PCM. The surface areas of illuminated wall, A_s, are larger than the window areas, A_w, and were based on interior surface areas typically available for the different types of storage materials. When small window areas are used (small solar saving fractions), the solar gains are small compared to heating loads for most of the heating season and are therefore well-utilized. When larger window areas are used (larger solar saving fractions), the added solar heat is less well utilized and the energy savings per unit window area decline. With PCMs, the delivery of absorbed solar heat is delayed and prolonged so that the heat is well utilized even at high solar saving fractions.

Cool Storage

In the core space of many commercial buildings, cooling is the most expensive component of the occupant comfort system. Low temperature PCMs distributed in the core space could absorb heat generated during the day and then reject it at night when the building is ventillated or mechanically cooled. In many locations, nighttime forced ventilation could provide most of the cooling requirements. Where chillers would be required, they would be smaller and would operate more efficiently in the colder nighttime temperatures. Depending on the local utility rate structure, the savings in demand charges could also be substantial.

In the base case simulation, the amount of PCM was selected to allow all of the daytime cooling load to be shifted to the night. The transition temperature was selected, along with the other PCM parameters, so as to allow the daytime heat to be fully absorbed. Figure 4A shows results for PCM thicknesses up to the base case thickness. Note that while the total annual cooling energy has not been significantly affected, all of the daytime cooling demand has been shifted to the night at the base case PCM thickness. Figure 4B shows how increasing the area of the PCM (and shifting the transition temperature and thickness accordingly) permits reduction of total cooling energy requirements as well as complete ellimination of daytime chiller demand. A PCM with area twice the floor area and with transition temperature of 23C (73.5°F) and thickness of 8.5 mm (0.33 in) would reduce total cooling energy requirements by about 20% and completely elliminate daytime cooling demands.

CONCLUSIONS

Composite building materials which contain hydrocarbon PCMs can be easily and economically manufactured. So far, these composite PCMs remain subjects for laboratory research but computer simulation studies indicate that the use of PCM composites on interior surfaces of a building may:

- allow the use of greater passive solar heating (a larger solar saving fraction) without causing overheating, and without requiring massive structures; and
- shift cooling demands from periods of peak power usage to off-peak periods when cooling can be provided more efficiently and more economically.
- enhance occupant comfort by moderating temperature variations and by providing a more suitable radiant temperature;

ACKNOWLEDGEMENTS

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Table 1

TYPICAL PROPERTIES OF PCMS FOR USE IN COMPOSITE BUILDING MATERIALS

NAME (Formula)	TRANSITION Temp (°C)	TRANSITION Enthalpy (kJ/kg)	MELT TEMP. (°C)	SPECIFIC HEAT (kJ/kgK)	DENSITY (kg m^{-3})	THERMAL CONDUCTIVITY (W/mK)	COST ($/kg)
A. SOLID-SOLID PCMS							
Neopentyl-Glycol[1] NPG ($C_5H_{12}O_2$)	43	131	126	2.76	1046	0.25	1.30[a]
Trimethylolethane[1] TME ($C_5H_{12}O_3$)	81	193	198	2.75	1193	0.36	(1.21)[b]
Pentaerythritol[1] PE ($C_5H_{12}O_4$)	188	323	260	2.84	1333	1.0	1.65[a]
NPG(60%) + TME(40%)[1]	26	76	140	2.64	1071	0.23	(1.26)[b]
B. SOLID-LIQUID PCMS							
Mixed paraffins:							
WITCO 45-A[3]	29	170	29				(44-55)[8]
SHELL WAX X-100[3]	48	209	48				0.55[7]
Commodity	53-54		53-54				0.64[a]
Pure paraffins:							
N-Eicosane[5] ($C_{20}H_{42}$)	36.7	247	36.7	2.21	856	0.15	149[c]
N-Octadecane[5] ($C_{18}H_{38}$)	28.0	243	28.0	2.16	814	0.15	100[c]

a-commodity prices, truckload lots, FOB plant[6].
b-estimated (from verbal quotations of TME producer)
c-typical reagent grade, in small quantities.

5. D. V. Hale, et. al., "Phase-Change Materials Handbook", NASA Technical Report MFS-22064, p. 5-43 through 5-46, 1972, (available NTIS).

6. Chemical Marketing Reporter, Vol. 229, No. 7, Feb. 17, 1986, p. 37-38, Schnell Publishing Co., New York, NY.

7. Private communication, Shell Chemical Co., Houston, TX, Feb. 28, 1986.

8. Private communication, WITCO Chemical Co., Kendall/Amalie Div., Bradford, PA, Feb. 28, 1986 (this is an estimated cost of an upgraded byproducts stream).

Table 2

PARAMETERS AND ASSUMPTIONS OF SIMULATION STUDIES

A. TROMBE WALL SIMULATION

- Building*
  - Location - Denver, CO, USA
  - Floor area - 100 m^2 (1080 ft^2)
  - Internal Gains - 6.47 kW (5.3 x 10^6 Btu/day)
  - Infiltration - 0.5 air change/h
  - Insulation
    - Ceilings - 0.16 W/m^{2}K (R 36°F h ft^2/Btu)
    - Walls - 0.52 W/m^{2}K (R 11)
    - Crawl space walls - 0.3 W/m^{2}K (R 19)
  - HVAC Set Temperatures
    - Heat 15.6C (60°F)
    - Vent 24.4C (76°F)
    - Cool 25.6C (78°F)
  - Simulation Code: SERIRES[9]

- Trombe Wall
  - Orientation - vertical, south facing
  - Area - 18.6 m^2 (200 ft^2)
  - Overhang - 0.7m, 0.3m above glazing (2.25, 1.0 ft)
  - Vent area - 3%

Wall material - Concrete	PCM
density - 2243 kg/m^3 (140 lb/ft^3)	1067 (66.6)
specific heat - 0.84 kJ/kgK (0.2 Btu/lb °F)	2.5 (0.6)
latent heat -	120 kJ/kg (52 Btu/lb)
thermal conductivity - 1.3W/mK (0.76 Btu/hftF)	0.2 (.116)
thermal nodes used 1/12 mm (2/in)	6

B. DIRECT GAIN SIMULATION

- Building*
  - Location - Albuquerque, NM, USA
  - Heat loss coefficient - 159 W/K (7200 Btu/°F-day)
  - Floor area - 111 m^2 (1200 ft^2)
  - HVAC Set Temperatures
    - Heat 18.3C (65°F)
    - Vent 23.9C (75°F)
    - Cool 23.9C (75°F)
  - Simulation Code: SERIRES[9]

- Direct Gain Window
  - Orientation - vertical, south facing
  - Area - was varied to achieve the solar savings fraction shown
  - Thermal Storage

Concrete	Gypsum	PCM
density 2243 kg/m^3 (140 lb/ft^3)	801 (50)	1067 (66.6)
thickness 10.16 cm (4 in)	12.7mm (0.5 in)	**
specific heat 0.84 kJ/kgK (0.2 Btu/lb°F)	0.84 (0.2)	2.5 (0.6)
latent heat		120 kJ/kg (52 Btu/lb)
Thermal conductivity 1.3 W/mK (.76 Btu/hftF)	0.16 (.093)	0.2 (.116)

** PCM thickness was varied to provide 156 kJ (1562 Btu) of thermal storage per m^2 (ft^2) of direct gain window area.

C. COOL STORAGE SIMULATION

- Building*
  - Location - Denver, CP, USA
  - Floor area - a parameter
  - Ventillation (daytime) - 0.15 air change/h
  - Internal gains - 43 W/m^2 (13.7 Btu/hft^2)
  - HVAC
    - chiller capacity - 43.8 W/m^2 (13.9 Btu/ft^{2}h)
    - (per unit floor area)
    - chiller COP - 2.4
    - venting capacity - 2.36 air change/h
    - fan power - 0.783 W/CFM
  - HVAC Set Temperatures
    - Heat - 20C (68°F) daytime
    - Vent - 25C (77°F)
    - Cool - 25.6C (78°F)

Walls/Ceiling	Gypsum	PCM
Heat transfer coefficients		
ceiling		
daytime		9.44 W/m^{2}K (1.63 Btu/hft^{2}F)
nightime		6.25 (1.08)
walls	8.46 W/m^2 (1.46 Btu/hft^{2}F)	
floors	Concrete (15.2cm thick (6 in.))	
daytime	6.25 W/m^{2}K (1.08 Btu/hft^{2}F)	
nightime	9.44 (1.63)	
Area/Floor area	1	1
Thickness	12.7 mm (9.5 in)	16.8 mm (0.66 in)
Density	801 kg/m^3 (50 lb/ft^3)	1072 kg/m^3 (66.9)
Latent Heat		75 kJ/kg (32.7 Btu/lb)
Transition Temperature (Base case)		20.55C (69°F)

Simulation Code: SERIRES[9]

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*All modeled as single thermal zones. All windows are double glazed.

[9] L. Palmiter and T. Wheeling, "SERIRES Version 1.0 User's Manual", available NTIS.

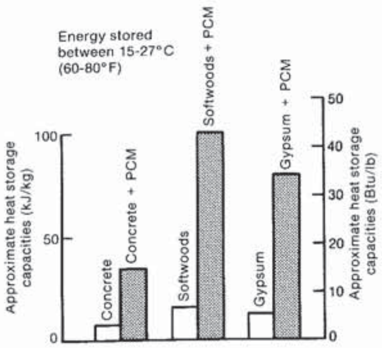

Figure 1. A Comparison of the Heat Storage Capacity of Conventional Building Materials and Similar Materials in which Pore Volume has been Filled with the PCM Neopentyl Glygol

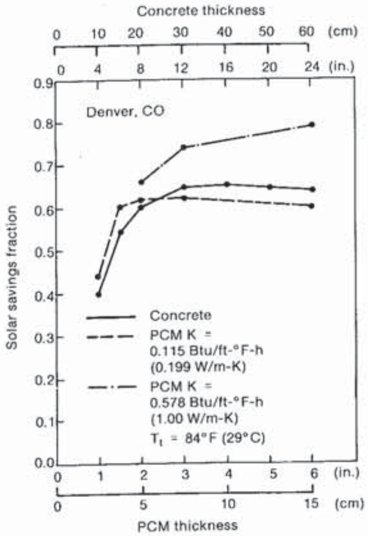

Figure 2. Solar Savings Fraction as a Function of Trombe Wall Thickness for PCMs and Concrete

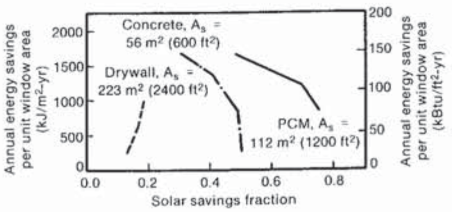

Figure 3. The Net Energy Savings per Unit Window Area for Different Heat Storage Materials in a Direct Gain Passive Solar Heated Building

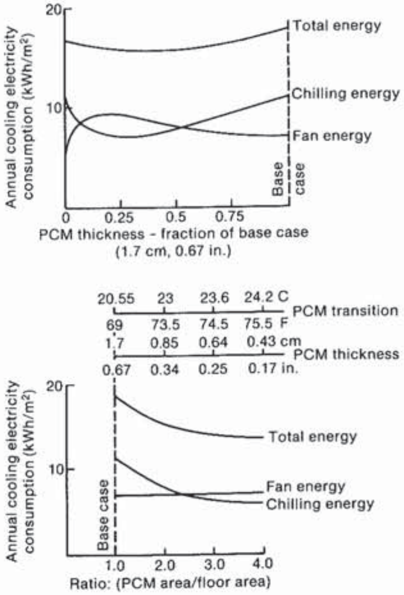

Figure 4. Cooling Energy Requirements: A, as a Function of PCM Thickness; B, as a Function of PCM Surface Area/Floor Area Ratio

Role of Orientation in Thermal Environmental Control of Buildings

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KEYWORDS

Orientation, Thermal Comfort, Quantification, Simulation

ABSTRACT

For years together, architects and planners have been guided by the assumption that, for better thermal performance, buildings should be oriented towards south as far as possible. It is believed that windows not facing south contribute to the higher indoor temperatures and add to increased thermal discomfort during summer months. Normal practice has been to orient buildings towards south and position windows on their south face to capture low winter sun and to curtail high summer sun. As a result, rows and rows of south facing building blocks, parallel to each other may be seen, often neglecting important parameters of design like, quality of resultant spaces and character of building sites.

Recently, research studies have been conducted on quantification of contribution of thermal discomfort in building envelopes with respect to several factors of building design including orientation. These studies have shown that role of orientation (with respect to pattern of solar radiation) in the thermal performance of building envelopes becomes insignificant, if other factors like quality of surfaces of building envelope and shading of openings are minutely considered.

Methodology of computer simulation has been adopted and internationally accepted program for simulation of thermal performance of building envelopes, have been used for these studies. The results are graphically presented.