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Armin Rudd

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A.F. Rudd

ABSTRACT

Two moisture-storage coating mixtures developed and tested between late 1990 and early 1991 could provide a low-cost, building-integrated method of managing indoor humidity in hot and humid climates. Approximate loading curves for the moisture-storage mixtures, the base materials alone, and regular gypsum wallboard were experimentally determined in an environmental chamber, using digital balances to monitor weight change as a function of relative humidity. Since there are large surface areas of interior gypsum wallboard in nearly all new houses, the effort centered around coatings that could be applied to those surfaces. Silica gel desiccant was mixed with base materials of flat latex paint and vinyl joint compound. Preliminary results showed that although both base materials reduced desiccant utilization somewhat, the coatings have significant potential for moisture storage. Calculations showed that if they were applied to the walls and ceilings of a house in Miami, there could be enough moisture storage (26.6 kg [58.7 lb]) between the equilibrium relative humidities of 40% and 60% to shift the on-peak latent air-conditioning load (13.6 kg [30 lb]) to off-peak periods.

BACKGROUND AND PURPOSE

In many parts of the country, electric power utilities are finding that they cannot meet the summer peak electrical demands of their customers. Florida utilities in particular are faced with high growth rates; nearly every new house has central air conditioning. For the largest power utility in Florida, the average peak summer day demand profile has nearly the same shape as the demand profile of a house's air conditioner for the same time period. Figure 1 shows the utility load shape (Taylor 1990) and the measured average load profile of 58 residential central air conditioners (Paxon and Hinchcliffe 1980) in percent of load. If some of the peak air-conditioning demand could be shifted to off-peak hours, there would be a tremendous savings in capital costs of electricity-generating equipment. The utility's savings could eventually translate into lower costs for customers.

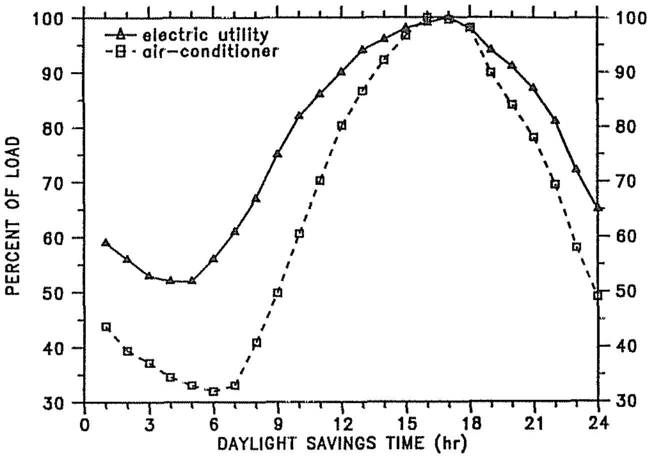

Figure 1 *Average peak summer day load shape for a Florida electric utility and the average load shape of 58 residential central air conditioners.*

Thermal storage concepts for off-peak cooling in residential buildings have been heavily researched but have rarely been put to use. The economies of scale, demand charges, and time-of-day rates have made ice-storage systems popular for load shifting in commercial buildings, but ice storage generally has not been cost-effective for residences. The equally important concept of moisture storage in buildings is only beginning to gain prominence in the research community.

What is needed is a low-cost way to integrate both thermal and moisture energy storage into the building itself (Fairey and Vieira 1984). Work by Shapiro et al. (1987) and Salyer and Sicar (1989) identified phase-change material (PCM) wallboard as a method to achieve thermal storage in buildings. Side-by-side room calorimeter tests were conducted with full-size sheets of PCM wallboard and showed that small-scale differential scanning calorimeter results could adequately predict results obtained from full-scale testing (Rudd 1993). PCM wallboard may have the potential to shift most of an electric utility's peak load coming from residential air conditioners to off-peak hours (Neeper 1990). However, in hot and humid climates, thermal storage alone will not provide comfort when implementing air-conditioning load shifting (Kamel et al. 1991). Thermal storage can keep the room's temperature

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lower but, with the same absolute amount of moisture in the air, a lower room temperature will make the room's relative humidity higher. Since environmental comfort is a function of both temperature and humidity (ASHRAE 1989), both thermal and moisture storage must be utilized.

Building-integrated thermal and moisture storage could also make conditions more favorable for the use of advanced solar cooling and heating technologies. One such solar-cooling technology has been under research and development for several years (Swami et al. 1989). Figure 2 shows the basic operating modes of the desiccant-enhanced radiant cooling (DESRAD) concept.

For the adsorption mode, excess moisture and heat stored by the house during the day are rejected at night to a desiccant bed and the cooler night sky. The desorption mode begins the next day when the sun's heat is used to regenerate the desiccant bed. The cycle repeats itself every 24 hours, using electrical energy only for fans and an evaporative cooler pump. The system relies on solar regeneration heat, nocturnal cooling, and thermal and moisture energy storage for its operation. PCM wallboard could be used to provide thermal energy storage, while moisture storage could be provided by moisture-storage coatings, yielding a composite thermal and moisture- or enthalpy-storage wallboard.

This paper describes a preliminary research effort toward the development of moisture-storage coatings that could be applied to thermal storage wallboard to achieve enthalpy storage (thermal and moisture storage) in buildings. As moisture is adsorbed in the outer desiccant layer, the PCM layer provides a sink for the heat of adsorption. As moisture is later desorbed from the outer desiccant layer, the wallboard is cooled, removing energy from the PCM so that it may be heated again in the next cycle. This could work well with off-peak cooling since heat and moisture are simultaneously entering the building during on-peak periods and are simultaneously being removed from the building during off-peak cooling periods.

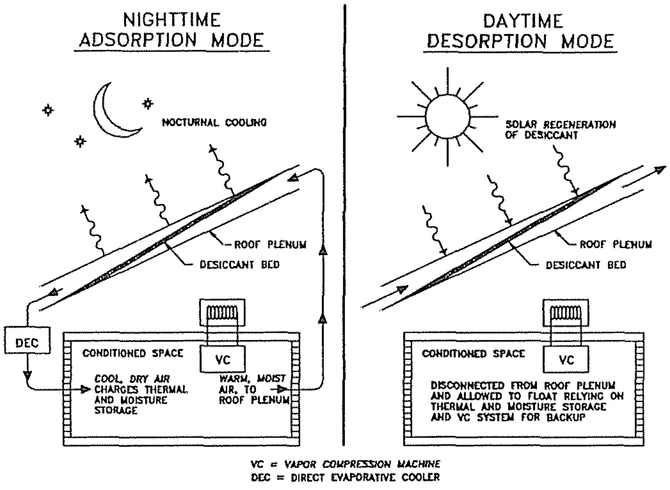

Figure 2 DESRAD operating modes.

It should be clear that moisture storage alone will not allow air conditioner load shifting. As moisture is sorbed, the heat of sorption must be captured by thermal energy storage in addition to the normal sensible cooling load for any load shifting to be possible.

TEST DESCRIPTION

Two moisture-storage coatings were developed and tested in an environmental chamber between late 1990 and early 1991. One coating consisted of grade 11 silica gel desiccant (GR11) mixed with flat latex paint (FLP) as the base material. The other coating was made from grade 40 silica gel (GR40) mixed with vinyl joint compound (VJC) as the base material. Approximate loading curves for the two moisture-storage coatings, the base materials alone, and gypsum wallboard (GWB) were experimentally determined. The tests were conducted in an environmental chamber. Digital balances were used to monitor the weight change of the samples as a function of relative humidity (RH). The manufacturer of the balances specifies reproducibility at 0.01 g. Table 1 describes the samples that were tested.

Equilibrium moisture-loading curves were measured at 26.7°C (80°F). The environmental chamber was controlled within ±1% RH. At each of the 15 equilibrium points, the chamber conditions were held constant until all sample weights were stable within ±0.5 grams or ±0.4%, whichever was less. All measurements were made every 15 seconds and averaged over six-minute data-logging intervals.

RESULTS

Dry weight was approximated for each sample by curve-fitting the equilibrium sample weights as a function of relative humidity and extrapolating to 0% relative humidity. The moisture content of each sample could then be calculated at each equilibrium point. These data were plotted versus relative humidity. The maximum moisture content, U_{max}, was determined from these plots by extrapolating to 100% relative humidity.

TABLE 1
Descriptions of Samples Weighed on Digital Balances

Sample	Description of Samples
VJC	Aluminum sheet coated on both sides with *vinyl joint compound*,
VJC/GR40	Aluminum sheet coated on both sides with a *mixture of vinyl joint compound and grade 40 silica gel* desiccant,
FLP	Aluminum sheet coated on both sides with several layers of *flat latex paint*,
FLP/GR11	Aluminum sheet coated on both sides with a *mixture of flat latex paint and grade 11 silica gel*,
GWB	*Regular gypsum wallboard*; sealed from moisture on the back and edges.

Figures 3, 4, 5, and 6 show preliminary results for experimentally determined loading curves. Moisture-loading curves for the base materials, FLP and VJC, are shown in Figure 3. Figure 4 shows the manufacturer's isotherms for grade 11 (GR11) and grade 40 (GR40) silica gel (DC n.d.). Figure 5 gives the loading curves for the two moisture-storage coating mixtures—FLP/GR11 and VJC/GR40. Figure 6 shows the loading curve for gypsum wallboard.

Brunauer (1945) published a classification of five types of adsorption isotherms. According to Gregg and Sing (1982), most isotherms resulting from physical adsorption may be grouped into one of the Brunauer types. To get a simple label for the differences in the loading curve shapes, the samples tested in the environmental chamber were identified by visual inspection only as one of the five Brunauer types. Both the paint and the joint compound alone have a type III shape. When these materials are mixed with silica gel, which is a type II desiccant, the resulting mixtures have a type IV shape. The type IV shape is good for moisture-storage applications, where a sharp positive slope is required in the middle RH ranges, as in building applications. Gypsum wallboard has a type II shape.

Ideally, in order to verify all the results, the entire test procedure would have been repeated several times with several identical samples. However, the single-test method took nearly four months to complete and more environmental chamber time was not available. Since the results presented here are from only one test, they should be taken in the context of preliminary research. Also, these results do not provide information concerning the measured shape of partial loading curves when materials are cycled back and forth through intermediate humidities. That information would be quite useful when making applications to real building situations and should be considered in future work.

A fundamental question that arises from mixing base materials with desiccant is, How much does the base

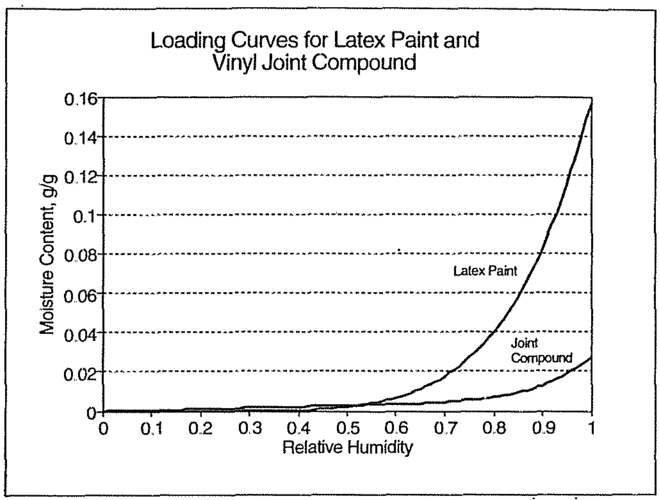

Figure 3 *Loading curves for flat latex paint and vinyl joint compound at 26.7°C (80°F) in grams of water per gram of dry material.*

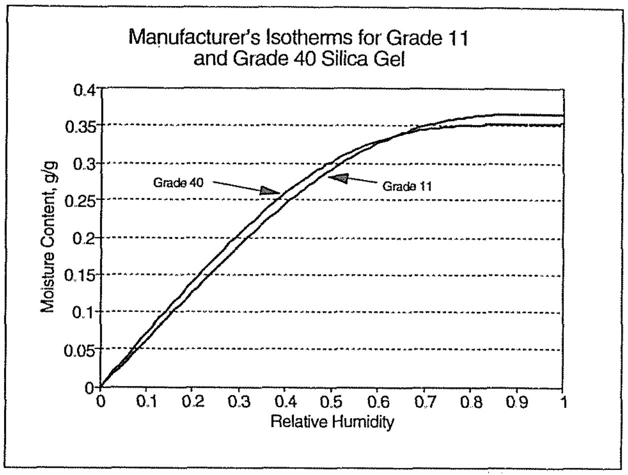

Figure 4 *Manufacturer's isotherms for grade 11 and grade 40 silica gel desiccant in grams of water per gram of dry desiccant.*

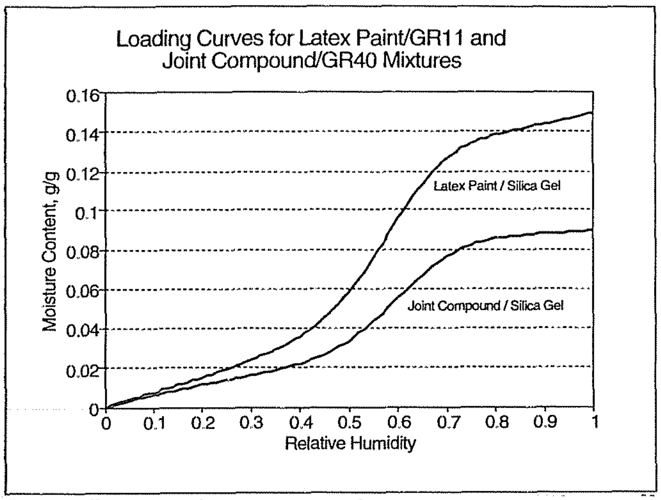

Figure 5 *Loading curves for two moisture-storage coatings, FLP/GR11 and VJC/GR40, at 26.7°C (80°F) in grams of water per gram of dry mixture.*

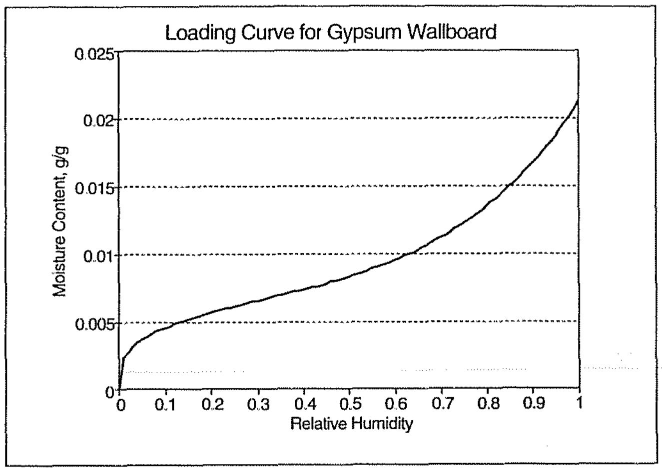

Figure 6 *Loading curve for gypsum wallboard at 26.7°C (80°F) in grams of water per gram of dry wallboard.*

material limit the moisture capacity of the desiccant? To determine this, the following analysis was performed:

$$M_{mix} = M_{base} + M_{des} \tag{1}$$

where

M_{base} = mass of base material, FLP or VJC;
M_{des} = mass of desiccant, GR11 or GR40; and
M_{mix} = mass of mixture, FLP/GR11 or VJC/GR40;

and

$$U_{des} = \frac{(U_{mix} \cdot M_{mix} - U_{base} \cdot M_{base})}{M_{des}} \tag{2}$$

where

U_{base} = moisture content of base material, g_{water}/g_{base};
U_{des} = moisture content of desiccant, g_{water}/g_{des}; and
U_{mix} = moisture content of mixture, g_{water}/g_{mix}.

Tables 2 and 3 list the values of the calculated moisture content of the desiccant, U_{des}, as it functions within the respective mixture. U_{des} was calculated for relative humidities between 40% and 60% using Equation 2. The columns with headings U_{GR11} and U_{GR40} list the corresponding values of desiccant moisture content published by the manufacturer. The last column was obtained by dividing the calculated desiccant moisture content by the manufacturer's desiccant moisture content, at the same relative humidity, to give a utilization factor for the desiccant in the mixture. The utilization factor then indicates how much the base material interferes with the sorption capacity of the desiccant.

The range of relative humidity between 40% and 60% covers the range normally found in conditioned living spaces where the desiccant coatings may be useful for moisture storage. In that range, the moisture capacity of the paint and joint compound alone and the regular gypsum wallboard was negligible. However, the moisture capacities of the desiccant mixtures were large enough to warrant further study.

A comparison of Tables 2 and 3 shows that both of the base materials reduce desiccant utilization somewhat. Latex paint reduces desiccant utilization less than the vinyl joint

TABLE 2
Comparison of Moisture Content Values for FLP/GR11 Mixture and Individual Components

RH	<------ Moisture Content (g/g) ------> FLP/GR11 Mixture	Paint	U_{DES}	Manuf. U_{GR11}	Utilization Factor
0.40	0.0359	0.0006	0.111	0.245	0.451
0.42	0.0392	0.0008	0.121	0.256	0.473
0.44	0.0431	0.0010	0.132	0.265	0.499
0.46	0.0475	0.0013	0.145	0.275	0.530
0.48	0.0526	0.0017	0.160	0.283	0.566
0.50	0.0584	0.0022	0.178	0.292	0.608
0.52	0.0649	0.0028	0.197	0.300	0.656
0.54	0.0722	0.0036	0.218	0.307	0.709
0.56	0.0800	0.0045	0.240	0.314	0.765
0.58	0.0880	0.0056	0.263	0.321	0.820
0.60	0.0960	0.0068	0.285	0.327	0.873

TABLE 3
Comparison of Moisture Content Values for VJC/GR40 Mixture and Individual Components

RH	<------ Moisture Content (g/g) ------> VJC/GR40 Mixture	VJC	U_{DES}	Manuf. U_{GR40}	Utilization Factor
0.40	0.0219	0.0022	0.059	0.260	0.226
0.42	0.0235	0.0023	0.063	0.269	0.235
0.44	0.0255	0.0024	0.069	0.278	0.246
0.46	0.0277	0.0025	0.075	0.287	0.261
0.48	0.0305	0.0026	0.082	0.294	0.280
0.50	0.0336	0.0027	0.091	0.302	0.303
0.52	0.0373	0.0029	0.102	0.308	0.330
0.54	0.0414	0.0030	0.113	0.314	0.360
0.56	0.0458	0.0031	0.126	0.320	0.393
0.58	0.0505	0.0032	0.139	0.325	0.427
0.60	0.0553	0.0034	0.152	0.330	0.462

compound. Between 40% and 60% RH, desiccant utilization for the FLP/GR11 mixture ranged from 0.45 to 0.87. As relative humidity reached 65%, the paint reduced desiccant utilization by less than 2%. Desiccant utilization for the VJC/GR40 mixture ranged from 0.23 to 0.46 between 40% and 60% RH.

Both moisture-storage coatings showed excellent moisture capacity compared to the base material alone. As shown in Table 4, between 40% and 60% RH, the FLP/GR11 mixture had 10 times the change in moisture content as the paint alone and 29 times that of gypsum wallboard. The VJC/GR40 mixture had 28 times the change in moisture content as the joint compound alone and 16 times that of gypsum wallboard.

The moisture-storage coatings were successfully applied to wallboard surfaces to create both fine- and coarse-textured finishes. When dry, both coatings were resistant to damage under normal handling. Other determinations of acceptability need to be made, including but not limited to resistance to general household cleaning and desiccant contamination by airborne particles from tobacco smoke.

POTENTIAL APPLICATION OF RESULTS

One practical use of the moisture-storage coatings might be in a house where the FLP/GR11 mixture could be applied to the interior walls as a fine-textured finish and the VJC/GR40 mixture could be applied to the ceilings as a coarse-textured finish. Table 5 shows the calculation of the mass of moisture that could be stored in an average 139-m^2 (1,500-ft^2) house with only gypsum wallboard and with the moisture-storage coatings applied.

The FLP/GR11 desiccant mixture was made by a volume proportion of one part paint to one part desiccant. Dry weight (as a function of out-of-the-container volume) for the FLP, VJC, and desiccant was determined by weighing a measured volume of material before and after it was completely dried in an oven. By dry weight, the desiccant was 32% of the total FLP/GR11 mixture; thus, from Table 5, the 266 kg of FLP/GR11 mixture for the walls contained 85 kg of desiccant. The VJC/GR40 desiccant mixture was made by a volume proportion of four parts joint compound to six parts desiccant. By dry weight, the desiccant was 35% of the mixture; thus, the 319 kg of VJC/GR40 for the ceilings contained 112 kg of desiccant. Therefore, the total amount of desiccant needed for the house example was 197 kg (434 lb).

Based on computer simulation (Swami et al. 1988), the average peak-day moisture (latent) load for a 139-m^2 (1,500-ft^2) house in Miami, Florida, is about 70.6 MJ for the entire day and about 30.9 MJ for the utility's on-peak hours of noon to 9 p.m. To find the mass of moisture storage needed to eliminate the on-peak latent load, 30.9 MJ was divided by the enthalpy of vaporization for water (2,257 kJ/kg at 20°C), yielding 13.6 kg of moisture to be stored. Table 5 showed that between the equilibrium moisture contents of 40% and 60% RH, only 7.6 kg of moisture could be stored in the gypsum wallboard, but 26.6 kg of moisture could be stored in the moisture-storage coatings. Thus, for a house in Miami with the coatings applied to the walls and ceilings, there could be enough moisture-storage capacity between the equilibrium relative humidities of 40% and 60% to eliminate the on-peak latent air-conditioning load (13.6 kg). The heat of adsorption, as well as the normal sensible cooling load, would have to be eliminated by thermal storage in order to shift air conditioner use from peak to off-peak periods.

Figure 7 shows the time response of moisture adsorbed per unit area to a step change in relative humidity (from 47% to 64% RH) for the samples of gypsum wallboard, FLP/GR11 mixture, and VJC/GR40 mixture. Since the electric utility's on-peak time is nine hours (between 12 and 9 p.m.) and our aim is to shift air-conditioning loads away from those hours, it is important to determine how much of the moisture-storage material will be utilized during that on-peak time. Figure 7 shows a vertical line from the nine-hour mark and the percentage of the total change in moisture content at that point for each of the samples. The FLP/GR11 mixture was 99.7% through its total weight change after nine hours. That compares to 90.6% for the VJC/GR40 mixture and 97.6% for the gypsum wallboard sample. Thus, all of the materials were almost fully utilized

TABLE 4
Change in Moisture Content for Test Samples Between 40% and 60% Relative Humidity

	Moisture Content (g/g)		Change in Moisture Content
	40% RH	60% RH	(g/g)
Vinyl Joint Compound (VJC)	0.0022	0.0034	0.0012
Flat Latex Paint (FLP)	0.0006	0.0068	0.0062
Grade 40 Silica Gel (GR40)	0.2600	0.3300	0.0700
Grade 11 Silica Gel (GR11)	0.2450	0.3270	0.0820
VJC/GR40 mixture	0.0219	0.0553	0.0334
FLP/GR11 mixture	0.0359	0.0960	0.0601
Gypsum Wallboard	0.0074	0.0095	0.0021

TABLE 5
Moisture Storage Potential of Gypsum Wallboard and Desiccant Textured Finishes Applied to Walls and Ceilings of a House, Between Equilibrium Conditions of 40% and 60% RH

	Area m^2	Mass Per Area kg/m^2	Mass kg	ΔU g/g	Mass of Moisture Stored kg	Mass of Moisture Stored Per Area g/m^2
GWB alone on walls and ceilings	443.0	8.353	3700.0	0.0021	7.771	17.5
FLP/GR11 mixture on walls	304.0	0.874	265.8	0.0601	15.980	52.6
VJC/GR40 mixture on ceilings	139.0	2.294	318.9	0.0334	10.650	76.6
Total moisture storage potential in wall and ceiling moisture storage coatings between equilibrium conditions of 40% and 60% relative humidity					26.630	60.1

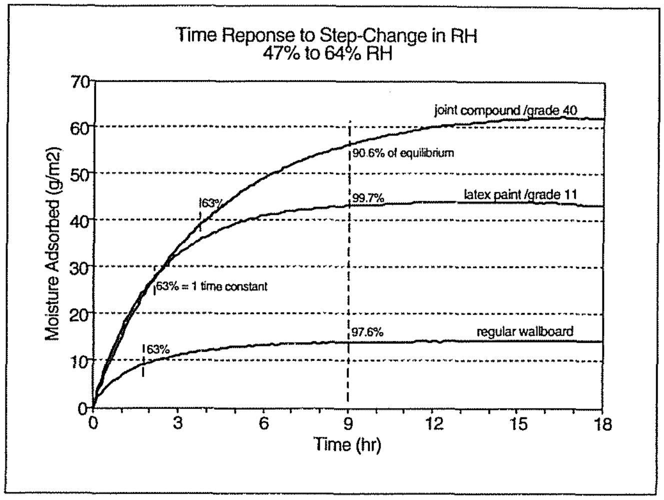

Figure 7 *Time response of moisture adsorbed per unit area to step change in relative humidity, 47% to 64% RH, for FLP/GR11 and VJC/GR40 and gypsum wallboard.*

within the on-peak time period. The time constants (time to reach 63.2% of total change) were 1.7 hours for gypsum wallboard, 2.1 hours for the FLP/GR11 mixture, and 3.9 hours for the VJC/GR40 mixture. These values are marked in Figure 7.

A relatively energy-efficient house conditioned by a conventional vapor compression refrigeration system typically has an average space relative humidity between 50% and 55% (Cummings 1990; Henderson et al. 1991). Therefore, achieving 40% RH in practice would require enhanced air conditioners with high latent removal fractions. Also, the samples tested in the environmental chamber were exposed to a step function in relative humidity and the example application calculations were based on that. In an actual house, the change in relative humidity would be an up-down ramping. This would have the effect of lowering the moisture-storage potential within the nine-hour electric utility peak period. However, the step change shows that almost twice the storage needed is possible, so it may not be a problem. Given more time and effort, this dynamic could be modeled.

It is important to note that to achieve comfort in a building that is mechanically conditioned only during utility off-peak hours, both moisture and thermal storage systems must be utilized; moisture storage or thermal storage alone would not be sufficient.

CONCLUSION

Two moisture-storage coatings were developed and tested. Approximate loading curves for the two moisture-storage coatings, the base material components, and gypsum wallboard were experimentally determined in an environmental chamber using digital balances to measure weight change as a function of relative humidity. The aim of this preliminary research effort was to make a first cut toward the development of a low-cost, building-integrated method of managing indoor humidity in hot and humid climates, especially as it relates to shifting on-peak air-conditioning loads to off-peak hours (both thermal and moisture storage required). Two basic conclusions can be drawn.

1. The moisture-storage coatings developed show potential for moisture-storage applications in buildings.
2. The moisture-storage coatings can be almost fully utilized within a nine-hour period, making them potentially useful for eliminating the latent portion of on-peak air-conditioning loads. To allow any electric air-conditioner load shifting, thermal storage must also be available to store the heat of sorption and the normal sensible cooling load.

The particular application of moisture-storage coatings on walls and ceilings is based on the preliminary results presented here and may be only one of many possible applications for such coatings.

FUTURE WORK

Continued research is anticipated to test these moisture-storage coatings after applying them to thermal storage wallboard to create an enthalpy storage wallboard for use in buildings. Other work may yield a two-layer wallboard product—the back layer of gypsum infused with phase-change material and the front layer consisting of gypsum with desiccant for moisture storage—to provide a composite enthalpy storage wallboard. This arrangement may help to reduce the flammability of the phase-change material layer (Chandra 1990).

More research needs to be conducted to experimentally determine and analytically predict the dynamics of building-integrated moisture and thermal storage when the conditioned space is cycled on a diurnal basis between specific setpoints.

ACKNOWLEDGMENTS

Appreciation is conveyed to the U.S. Department of Energy and the Florida Power and Light Company for funding this research and development as part of a solar cooling project. The author gratefully acknowledges Dr. Arthur Shavit, Dr. Kirk Collier, Philip Fairey, Dr. Muthusami Swami, and Dr. Subrato Chandra for their helpful review of this work. Special thanks go to Philip Read for his work in preparing the test samples and to David Beal for his help with the environmental chamber.

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DISCUSSION

Edgar Galson, Vice Chairman, Board of Directors, Galson Corporation, East Syracuse, NY: This is a very clever concept and it was well done.

A.F. Rudd:

About this Report

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