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Experimental study of using PCM in brick constructive solutions for passive cooling

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ABSTRACT

This work presents the results of an experimental set-up to test phase change materials with two typical construction materials (conventional and alveolar brick) for Mediterranean construction in real conditions. Several cubicles were constructed and their thermal performance throughout the time was measured. For each construction material, macroencapsulated PCM is added in one cubicle (RT-27 and SP-25 A8). The cubicles have a domestic heat pump as a cooling system and the energy consumption is registered to determine the energy savings achieved. The free-floating experiments show that the PCM can reduce the peak temperatures up to 1 °C and smooth out the daily fluctuations. Moreover, in summer 2008 the electrical energy consumption was reduced in the PCM cubicles about 15%. These energy savings resulted in a reduction of the CO_2 emissions about 1–1.5 kg/year/m^2.

1. Introduction

Energy consumption for thermal comfort in buildings has grown a lot in few years because of increasing users demand for comfort conditions and the associated market penetration of more cooling systems. This increase of energy consumption and the increase of the fuel price and CO_2 emissions are promoting a new policy of more sustainable buildings.

Phase change materials (PCM) have been studied for thermal storage in buildings since before 1980 [1–5]. Those systems provide a higher thermal inertia to the building that, combined with thermal insulation can reduce the energy consumption of the building by absorbing the heat gains and reducing the heat flow. During daytime the PCM can absorb part of the heat through the melting process, and during night the heat is released by the solidification of the PCM, resulting in a lower heat flow from outdoors to indoors.

In first step, development and testing were conducted for prototypes of PCM wallboard and PCM concrete systems to enhance the thermal energy storage (TES) capacity of standard gypsum wallboard and concrete blocks, with particular interest in peak load shifting and solar energy utilization. Several researchers have investigated methods for impregnating gypsum wallboard, concrete and other architectural materials with phase change materials [6,14]. Different types of PCMs and their characteristics are described. The manufacturing techniques, thermal performance and applications of gypsum wallboards and concrete blocks which have been impregnated with phase change materials as well as concrete with microencapsulated PCM have been presented and discussed previously [7–12].

All those systems used microencapsulated PCM, presenting some important problems that reduced the chances to reach a commercial state. Such problems are the high investment cost and the degradation of the mechanical properties of the material. In this work the use of macroencapsulated PCM is considered, reducing the investment cost and overcoming the mechanical problems. Using macroencapsulated PCM avoids the over cost of the microencapsulation process and does not present any mechanical problem since the material is not integrated in the construction material. The encapsulation system is resistant by itself and does not reduce the strength of the wall.

Although many research has been done studying the incorporation of PCM in several construction materials, almost no work has been carried out on brick constructive solutions, widely used in Mediterranean countries. Alawadhi [13] studied numerically the introduction of PCM in bricks, obtaining good results and a theoretical reduction of the heat flux entering the indoor space in summer. However, the model used was not validated. No experimental work has been done up to the date and no real data is available for this kind of constructive solution. Therefore, this study can provide very useful data for demonstrating the concept and contributing to the integration of PCM in typical Mediterranean construction.

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Fig. 1. Demonstration cubicles in Puigverd de Lleida.

In this work macroencapsulated PCMs were tested with typical Mediterranean constructive solutions. A new experimental set-up consisting of several cubicles (using conventional brick and alveolar brick) was built. Macroencapsulated PCM is added in one conventional brick and in one alveolar brick cubicle (CSM panels, containing RT-27 and SP-25 A8, respectively) and the thermal behaviour of the cubicles is studied.

Moreover, all the previous works found in the literature were either theoretical or they did not measure the real energy savings achieved by the PCM. Only the temperature profile was analyzed, presenting estimations of the energy savings based on the temperature difference achieved by the PCM. However, these estimations did not consider the dynamic schedule and operation of the building and its HVAC system. In this work a step further is done and a heat pump is installed in the cubicles to measure the real energy consumption. These results will provide real data for the energy savings and to determine the reduction of CO_2 emissions considering the dynamics of the building.

2. Experimental set-up

Five different cubicles were built using different Mediterranean typical constructive solutions. To be able to compare the results obtained with the concrete cubicles studied previously [7], the internal dimensions of the new cubicles are the same as the old ones (2.4 m × 2.4 m × 2.4 m). The cubicles are located in Puigverd de Lleida (Fig. 1), which represents a typical Spanish continental climate, with cold winters and warm and relatively dry summers. The important temperature oscillations during day and night make it very suitable for the PCM operation since the material can be melted during the day and solidified during the night. The PCMs tested were designed for cooling applications.

2.1. Brick cubicles

The walls consist of perforated bricks (29 cm × 14 cm × 7.5 cm, Fig. 2) with an insulating material (depending on the cubicle) on the external side, an air chamber of 5 cm and hollow bricks. The roof was done using concrete precast beams and 5 cm of concrete slab. The insulating material is placed over the concrete, protected with a cement mortar roof with an inclination of 3% and a double asphalt membrane.

Three cubicles using different insulating solutions are compared:

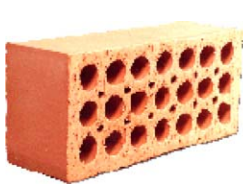

Fig. 2. Hollow brick.

Table 1
Physical properties of polyurethane.

Property	Polyurethane
Thermal conductivity (W/m K)	0.028
Density (kg/m^3)	35

1. Reference cubicle (Reference): This cubicle has no insulation.
2. Polyurethane cubicle (PU): The insulation material used is 5 cm of spray foam polyurethane (Table 1).
3. PCM cubicle (RT27 + PU): The insulation used is again 5 cm of spray foam polyurethane and an additional layer of PCM. CSM panels (Fig. 3) containing RT-27 paraffin (Table 2) are located between the perforated bricks and the polyurethane (in the southern and western walls and the roof).

Figs. 4–6 show the demonstration cubicles built with brick, polyurethane, and RT-27 PCM and polyurethane, respectively, during construction.

2.2. Alveolar brick cubicles

Two different cubicles were built with alveolar brick:

1. Reference cubicle (Alveolar): The alveolar brick (Fig. 7 and Table 3) has a special design which provides both thermal and

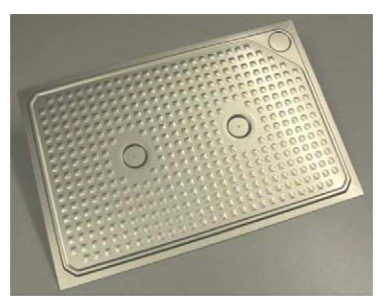

Fig. 3. CSM panel containing the PCM.

Table 2
Physical properties of PCM.

Property	RT-27	SP-25 A8
Melting point (°C)	28	26
Congealing point (°C)	26	25
Heat storage capacity (kJ/kg)	179	180
Density (kg/L)		
Solid	0.87	1.38
Liquid	0.75	
Specific heat capacity (kJ/kg K)		
Solid	1.8	2.5
Liquid	2.4	
Heat conductivity (W/m K)	0.2	0.6

Fig. 4. Brick cubicle.

Fig. 5. Brick cubicle with polyurethane.

Fig. 6. Brick cubicle with RT-27 and polyurethane.

Fig. 7. Alveolar brick.

Table 3
Physical properties of the alveolar brick.

Property	Alveolar brick
Heat transmittance (W/m^2 K)	0.66
Thickness (mm)	290

Fig. 8. Alveolar brick cubicles.

acoustic insulation. No additional insulation was used in this cubicle.

2. PCM cubicle (SP25 + Alveolar): Several CSM panels (Fig. 3) containing SP-25 A8 hydrate salt (Table 2) are located inside the cubicle, between the alveolar brick and the plaster plastering in order to increase the thermal inertia of the wall (in the southern and western walls and the roof).

Both cubicles have the same roof structure as the brick cubicles with polyurethane as insulation material. Fig. 8 shows one alveolar brick cubicle during construction.

Figs. 9 and 10 present a section of the two different constructive solutions used in the cubicles: brick and alveolar brick structure. Both sections represent the corresponding cubicle with PCM.

The specific heat as function of the temperature was measured for both PCM using DSC tests (Figs. 11 and 12). The results obtained showed some differences compared to the data provided by the manufacturer for SP-25. For the experimental analysis, the considered phase change range is the one measured with the DSC.

2.3. Experimental methodology

Walls temperatures, inside temperature and inside humidity of the cubicles were registered as well as the heat flux entering

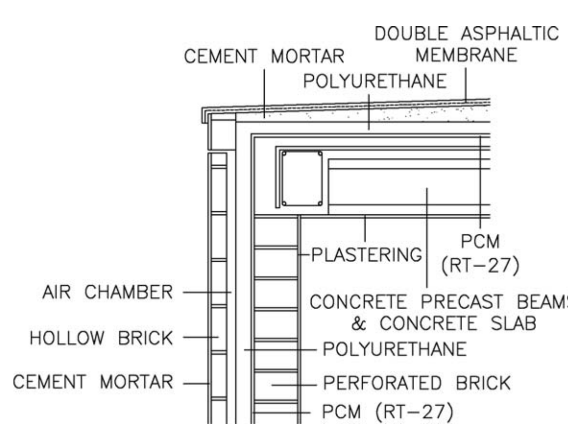

Fig. 9. Section of the constructive solution for the brick cubicles.

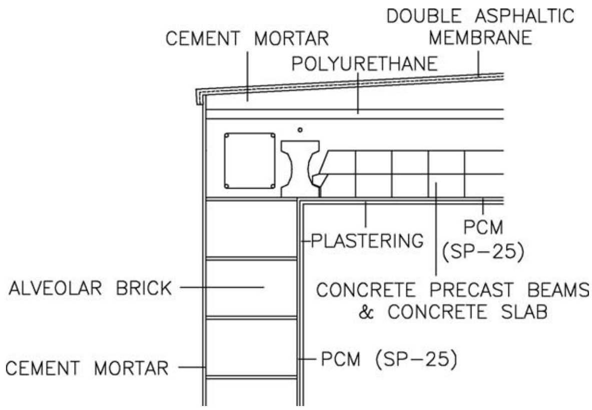

Fig. 10. Section of the constructive solution for the alveolar brick cubicles.

through the south wall and the electrical energy consumption of the heat pump. Also the weather conditions were measured.

Two different experiments were preformed in the experimental set-up.

- Free-floating temperature, where no cooling system is used. The temperature conditions inside the cubicles are compared. The ones with PCM are expected to have a better behaviour.
- Controlled temperature, where a heat pump is used to set a constant ambient temperature inside the cubicle. The energy consumption of the cubicles is compared. The cubicles using PCM are expected to have lower energy consumptions.

3. Results and discussion

Figs. 13–16 present the results for free-floating experiments in a week of August for conventional and alveolar brick.

The results show lower peak temperatures (up to 1 °C) and more constant conditions inside the cubicles with PCM. The PCM effect is clearly visible in both constructive typologies, but especially in the alveolar brick cubicle, since the thermal resistance of the wall is lower. In both cubicles the PCMs (RT-27 and SP-25 A8) are within their melting ranges almost during all the experiment. However, some problems were observed with the solidification of the PCM during night, since no ventilation system for the PCM is installed.

For the conventional brick cubicles the Reference cubicle presents high temperature fluctuations because of the lack of insulation. In the PU cubicle those fluctuations are significantly reduced, but are still present. Finally, the inside temperature of the cubicle with PCM remains cooler (up to 1 °C) during all the experiment and the temperature fluctuations are further reduced. Moreover, for some days when the phase change effect is maximized the temperature fluctuations are completely prevented.

Considering the alveolar brick cubicles, when the weather is getting warmer the PCM is melting and the maximum peak temperatures are reduced in the SP25 + Alveolar cubicle. After some extremely warm days (outside temperatures of 36 °C), when the weather is getting cooler during the day (outside temperature of 30 °C), the cubicles with PCM present a better temperature stability, reducing the minimum peak temperatures.

These results confirm the previously observed tendencies when studying the integration of PCM in building envelopes using other

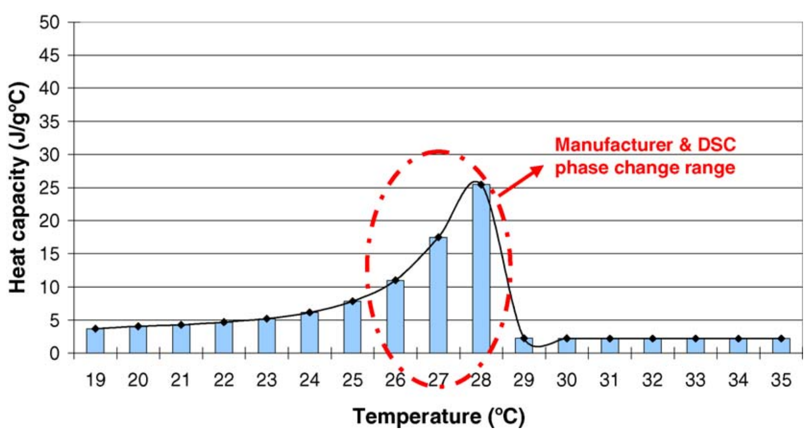

Fig. 11. Specific heat of RT-27. DSC test results.

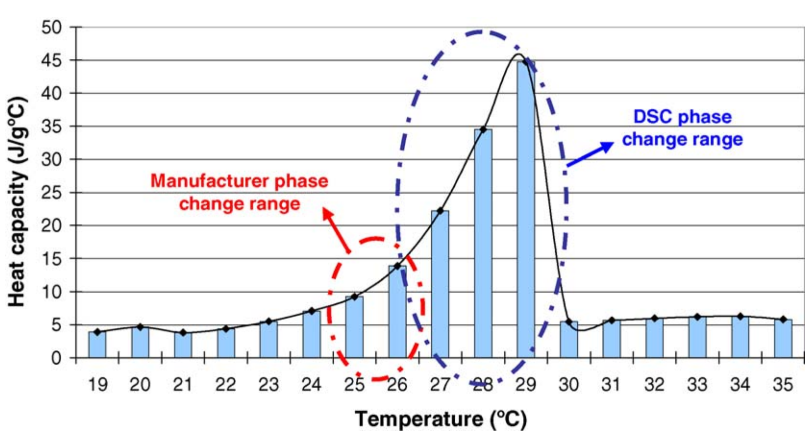

Fig. 12. Specific heat of SP-25 A8. DSC test results.

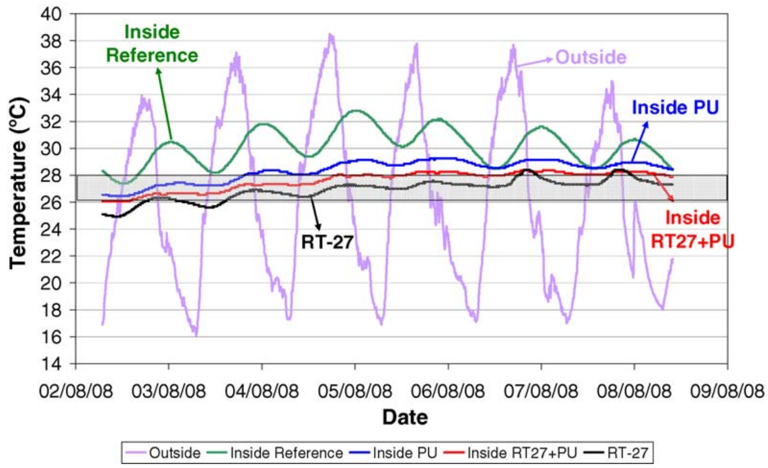

Fig. 13. Conventional brick cubicles. Outside, Inside Reference, PU and RT27 + PU, and RT-27 temperatures.

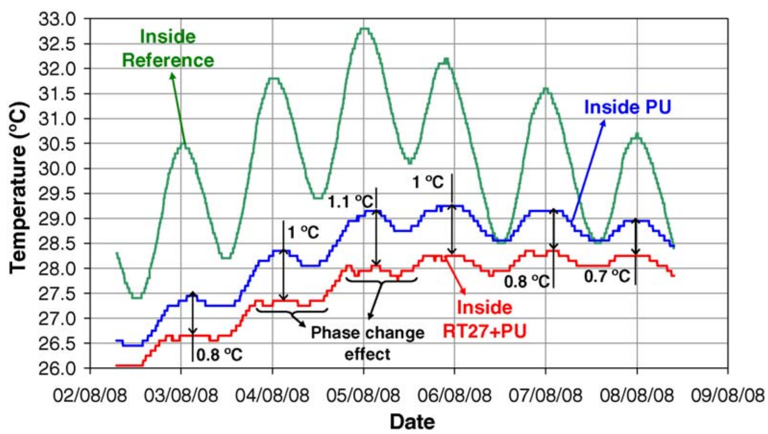

Fig. 14. Conventional brick cubicles. Inside Reference, PU and RT27 + PU temperatures.

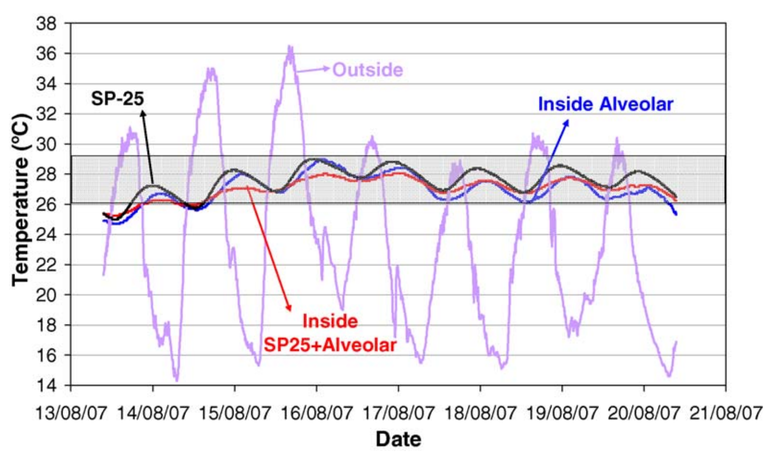

Fig. 15. Alveolar brick cubicles. Outside, Inside Alveolar and SP25 + Alveolar, and SP-25 temperatures.

construction materials and encapsulation systems [12,7]. The use of insulation in these cubicles reduces the effect of the PCM compared to previous experiments where no insulation was used.

Additionally, in this work, one step further was done. The cubicles were equipped with a heat pump as a cooling system to simulate the real conditions of a house. The energy consumption of the heat pump was measured to determine the real energy savings achieved when the cubicles remain within the comfort range.

Fig. 17 presents the results of the controlled temperature experiments using a set point of 24 °C. The accumulated energy consumption of the Reference cubicle is higher than that of all the other cubicles. The RT27 + PU cubicle is the one with the lowest energy consumption while the SP25 + Alveolar cubicle is the second one, consuming even less energy than the PU cubicle. Finally, the Alveolar cubicle is the one that more energy consumes after the Reference cubicle.

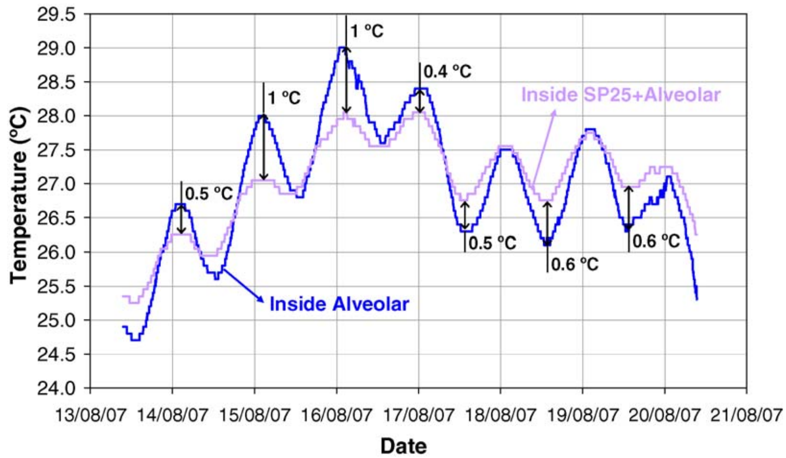

Fig. 16. Alveolar brick cubicles. Inside Alveolar and SP25 + Alveolar temperatures.

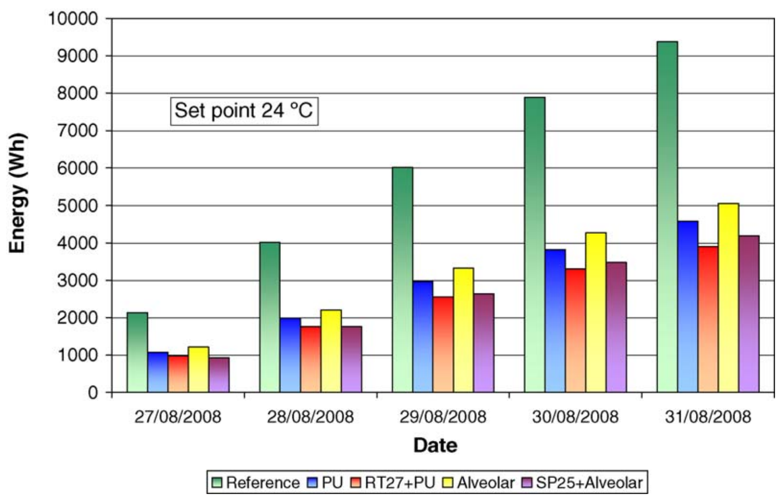

Fig. 17. Accumulated energy consumption. Set point 24 °C.

A moderate set point (like 24 °C) favours the PCM working conditions, since the inside temperature is close to the phase change range. Both PCM cubicles reduced the energy consumption compared with the same cubicle without PCM. The RT27 + PU cubicle achieved a reduction of 15% compared to the PU cubicle, while the SP25 + Alveolar cubicle reached a 17% of energy savings compared to the Alveolar one (Table 4). Moreover, the SP25 + Alveolar cubicle presents lower energy consumptions than the PU cubicle.

From the energy consumption of each cubicle, the CO_2 emissions to the atmosphere can be estimated. Considering the Spanish electricity production share a CO_2 emission rate of 572.9 g/kWh is determined. Table 5 presents the CO_2 emissions and savings for each cubicle.

Table 4
Accumulated energy consumption and savings for the different cubicles.

	Energy consumption[a] (Wh)	Energy savings[b] (Wh)	Energy savings[b] (%)	Improvement[c] (%)
Reference	9376	0	0	–
PU	4583	4793	51.12	0
RT27 + PU	3907	5469	58.33	14.75
Alveolar	5053	4323	46.11	0
SP25 + Alveolar	4188	5188	55.33	17.12

[a] Set point of 24 °C during 5 days.
[b] Referred to the Reference cubicle.
[c] Referred to the cubicle with analogue constructive solution and without PCM.

Table 5
CO_2 emissions to the atmosphere due to the energy consumption of the cubicle.

	Energy consumption[a] (kWh/year/m^2)	CO_2 emissions (kg/year/m^2)	CO_2 savings[b] (kg/year/m^2)	CO_2 improvement[c] (kg/year/m^2)
Reference	29.3	16.8	0.0	
PU	14.3	8.2	8.6	0.0
RT27 + PU	12.2	7.0	9.8	1.2
Alveolar	15.8	9.1	7.7	0.0
SP25 + Alveolar	13.1	7.5	9.3	1.6

[a] Set point of 24 °C during 90 days per year (cooling demand).
[b] Referred to the Reference cubicle.
[c] Referred to the cubicle with analogue constructive solution and without PCM.

4. Conclusions

In this work the benefits of using PCM in conventional and alveolar brick construction are studied experimentally.

Experiments under free-floating conditions showed lower peak temperatures (up to 1 °C) and more constant conditions in the cubicles with PCM, smoothing out the daily temperature fluctuations. These results present similar tendencies than those observed in previous works done with microencapsulated PCM in concrete and gypsum. However, some problems with the solidification of the PCM during the night were observed. Therefore, a cooling strategy (either natural or mechanical) must be defined to improve the performance of the PCM under free-floating conditions.

Additional experiments using a heat pump to set and control the inside temperature of the cubicles were performed. The experiments demonstrated that the energy consumption of the cubicles containing PCM was reduced about 15% compared to the cubicles without PCM. This demonstrates the significant contribution and potential of the use of PCM in building envelopes for energy savings and thermal comfort in a real house-shaped cubicle.

The new results demonstrate the good behaviour, energy savings and technical viability of using macroencapsulated PCM in typical Mediterranean constructive solutions.

Moreover, about 1–1.5 kg/year/m^2 of CO_2 emissions were saved in the PCM cubicles due to the reduction of the energy consumption. This reduction can help to mitigate the climate change and the global warming by means of a more efficient and sustainable use of energy.

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