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Thermal Storage Mass in Radiative Cooling Systems*

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An experiment was conducted to determine the role of the thermal storage mass and its location in a cooling system based on longwave nocturnal radiation. This parameter was found to be significant both for the amount of cooling power obtainable and for the internal temperatures of the cooled space.

BACKGROUND

NOCTURNAL radiative cooling of buildings has been studied extensively, particularly in the years following the energy crisis of the 1970s, when issues of energy conservation in buildings received considerable attention. The theoretical aspects of the subject were covered thoroughly by, among others, Clark and Berdahl [1]. Gordon and Zarmi [2] described the transient behavior of an unutilized radiator, expressing the relationship between the stagnation temperature, the relaxation time and the effective temperature of the surroundings. Givoni [3] reviewed the basic physics describing the phenomenon and evaluated a number of strategies proposed to utilize its potential. In fact a number of workable systems were developed and implemented on experimental buildings. The biggest success in the field was claimed by Hay [4, 5], developer of the "Skytherm" system. A number of versions of this design were constructed, in Las Cruces (N.M.), Phoenix (Ariz.) and Atascadero (Ca.). These buildings were monitored, and their interiors remained comfortable even under extreme ambient conditions. However, no data is given on the contribution of radiative cooling alone to the total thermal performance of the houses.

The effectiveness of all radiative cooling systems may in fact be quite limited. This is because nocturnal longwave radiation from materials commonly found on the earth's surface is rarely more than 100 W m^{-2}, under ideal meteorological conditions. By comparison, noon-time solar radiation levels in excess of 1000 W m^{-2} are common in many countries, and even solar heating systems installed in high-latitude countries can rely on solar radiation levels of several hundred watt/square metre for at least part of the day.

Since the potential for radiative cooling of buildings is inherently limited, any system designed to make use of this phenomenon must be very efficient.

One approach taken by researchers to increase the efficiency of radiative cooling systems was to improve the emissivity of the radiator, thus increasing its heat exchange with the sky. Michell and Biggs [6] compared the performance of a galvanized steel radiator painted with white titanium dioxide paint with that of a similar radiator covered with 12 μm thick sheets of "Tedlar". Both were covered with polythene windscreens, which had a transmissivity in the infra-red region of about 85%. They concluded that there was no significant difference between the two cooling systems, which produced 29 W m^{-2} of cooling by circulating air against the lower surface of the radiator. Granqvist and Hjortsberg [7] used selectively emitting coatings to achieve low temperatures in small test radiators with a three-layer polyethylene windscreen. A temperature depression of up to 14°C below ambient air was achieved on a clear night. However, they also reported that for temperature depressions of up to 10°C below ambient, ordinary paint with an emissivity of 0.9 (simulating a black body radiator) achieved a greater cooling rate under the same conditions. The highest cooling rate recorded for the selectively coated radiator was 61 W m^{-2}, with the radiator at ambient temperature.

Givoni [3] identified two types of problems involved in the design of radiative cooling systems. The first is maximizing the net heat flux from the radiating surface, taking into account such problems as convective heat gain from the ambient air and the effects of dust and dew on the radiator. The second is the utilization of the "cold" produced by the nocturnal radiation—the transfer of this cold to the building and the way in which it is utilized to provide comfort conditions.

Givoni [3] turned his efforts to the design of better heat transfer mechanisms with the fabric of the building. The basic issue involved is the following: since radiative cooling is effective only at night, a thermal storage mass must be incorporated in the building to carry over the benefits of nocturnal cooling to the warmer daytime hours when it is most needed. This in turn involves making a choice between two basic approaches. In the first

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option the thermal storage mass of the building (in this case, generally a horizontal roof) is cooled directly, and sealed and insulated during the day to avoid unwanted heat gains. The "Skytherm" system mentioned briefly above operates on this principle, as does the "Living Systems" roof pond constructed by Hammond on a house in Davis, Calif. The second option involves the use of a fluid, such as air or water, as a heat transfer medium between a radiator constructed outside the thermally insulated envelope of the building, generally on the roof. The "Roof Radiation Trap" designed by Givoni [8] and the system proposed by Juchau [9] operate on this principle.

THE SIGNIFICANCE OF THE EXPERIMENT

The thermal storage mass is an integral component of every long-wave nocturnal radiation system. The thermal performance of this mass determines, to a very large extent, the total efficiency of the whole radiative cooling system. The role of the thermal storage mass in radiative cooling systems is two fold:

1. To function as a heat sink, absorbing day-time heat gains, thus enabling effective day-long cooling resulting from nocturnal long wave radiation which occurs for only about 10 out of every 24 hours.
2. To maintain the radiator temperature no lower than the design temperature in the cooled space. The cooling obtained by the system is a function of the temperature difference between the radiator and the sky: a warmer radiator will increase the rate at which heat is dissipated from the building to the sky. One of the biggest difficulties with low-mass radiative cooling systems is that once the cooling starts, the radiator cools down very rapidly, diminishing the temperature difference between it and the sky. As a result, the cooling rate also quickly diminishes. In addition, the radiator reaches temperatures which are below the dew-point temperature, and this causes water to condense on its external surface and the cooling rate is further reduced.

EXPERIMENTAL SET-UP

The experiment was conducted in Sede-Boqer, Israel (30.8°N, elev. 480 m) in the summer of 1988. A number of small test boxes were built. Various combinations of radiator and storage mass were tested, each of them in a different test box.

This paper describes and discusses the performance of four of the test boxes that were used in the experiment. All four boxes were identical, except for the presence and location of some thermal storage mass in three of them, the fourth serving as a low-mass control (Fig. 1). The thermal storage mass consisted of a concrete slab, which had an identical mass and surface area, but was positioned in a different manner in each of the boxes.

The walls of all four boxes were made of panels of 5 cm polystyrene sandwiched between two layers of plywood. The roof (and floor) area of each box was approximately 1.85 m^2. The roof of the box served as a radiator, and its net radiating area was 1.35 m^2. The radiator was painted white, having an emissivity value (ε_{rad}) of approximately 0.9. The other external surfaces of the boxes were also painted white, to reduce daytime solar radiation gain. All boxes were exposed equally to the sun throughout the day, and had a clear unobstructed view of the sky during the night. During the day the radiator was sealed from the outside by a removable panel made of 10 cm polystyrene sandwiched between two layers of plywood. This technique, though difficult to apply on a full-size building, was simple and effective on this scale. In each box temperatures were measured at a number of points, including air temperature at the bottom, middle and top of the box and the temperature of the internal radiator surface. Other temperatures were measured where necessary in accordance with the type and purpose of the box.

Box 1 had a 0.5 mm sheet-metal roof. This box served as a control box, and did not have a concrete thermal storage mass.

Box 2 had a 10 cm concrete slab roof. In this box the radiator was combined with the thermal storage in one concrete slab. In this case the external surface temperature of the radiator was also recorded.

Box 3 had a 0.5 mm sheet-metal roof and a concrete slab inside the box, fixed to the interior surface of the insulated panel which formed the north wall.

Box 4 had a 0.5 mm sheet-metal roof and a concrete slab inside the box, placed above the insulated floor panel.

The data acquisition system was based on a Data Trapper model 1806 manufactured by Z.L. & Co. Electronic Industries Ltd., Israel. Temperature measurements were made with PT-100 sensors. Relative humidity was measured using a Rotronic Hygromer model L-200. Wind velocity was monitored with a Lambrecht Transmitter for Wind Velocity model 1469, which was installed near the test boxes at a height of 1.2 m above the ground (the height of the radiator surface). All data were recorded at 3 minute intervals, from which 15 minute averages were calculated.

DETERMINATION OF OBTAINABLE COOLING

The procedure that was used to determine the *net radiative cooling* followed the one published by Givoni [3]. According to this procedure, the net radiative cooling is expressed by

$$R_{\text{net}} = \sigma \times \varepsilon_{rad}(T_{rad}^4 - \varepsilon_{sky} \times T_{air}^4) \quad (1)$$

where

R_{net}—the net radiative cooling (W/m^2)
σ—the Stephen-Boltzman constant ($5.67 * 10^{-8}$ W/m^2/°K^4)
ε_{rad}—the emissivity of the radiator
T_{rad}—the absolute temperature of the radiator (°K)
ε_{sky}—the sky emissivity
T_{air}—the absolute temperature of the ambient air (°K)

Sky emissivity was calculated using the expression developed by Clark and Berdahl [1980]

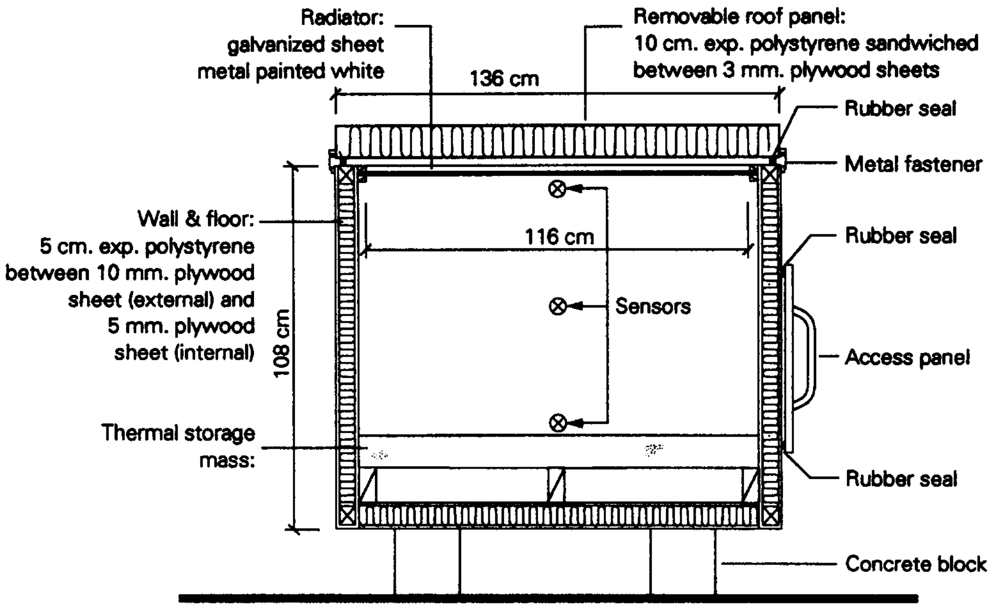

Fig. 1. Section through test box (with lightweight radiator).

$$\varepsilon_{sky} = 0.74 \times 0.006 T_{dp} \quad (2)$$

where

T_{dp}—dew point temperature

The dew point temperature (°C) was computed as a function of the ambient air temperature (T_{air}) and the relative humidity (RH), using the expression by Murray [10] (Citing Tetens):

$$T_{dp} = 237.3 \times \frac{\ln RH + a \times b}{(a - \ln RH) + a \times b} \quad (3)$$

where

$$a = 17.2693882$$

$$0 \leqslant RH \leqslant 1$$

and

$$b = \frac{T_{air}}{T_{air} + 237.3}$$

The *effective cooling* is the combined effect of the net radiative cooling, *and* the convective heat exchange between the radiator and the air. The general expression for the convective heat exchange at the surface of the radiator (Q_c) is:

$$Q_c = h_c \times (T_{rad} - T_{air}) \quad (4)$$

Q_c—convective heat exchange (W m^{-2})
h_c—convective coefficient (W m^{-2}*°C^{-1})
T_{rad}, T_{air}—the radiator and air temperatures (°C)

The convective heat exchange is dependent on the temperature of the air and its velocity, which is expressed in the convection coefficient. Clark and Berdahl [1] developed an expression for evaluating the convective coefficient of the boundary layer and Givoni [3] simplified it. According to Givoni, the convective coefficient when the radiator is cooler than the ambient air is

$$h_c = 1 + 6V^{0.75} \quad (5)$$

where

V—wind speed (m/s^{-1})

This expression provides a reasonable representation of the convective coefficient over the wind speed range experienced in practice, when the radiator temperature is below the ambient air. In this experiment measurements showed that all radiators were cooler than the ambient air within one hour after the insulating cover was removed, shortly before sunset.

RESULTS AND DISCUSSION

The following analysis of the test results examines three parameters of performance: air temperatures in the boxes, radiator surface temperature and cooling power obtained in each of them. The results that are described here are of two days (6 and 7 July, 1988), typical of a measurement period of three months.

Air temperatures

Air temperatures recorded by all three separate sensors in each of the test boxes were averaged for the period of 48 hours beginning on 0600 h of the first day, to yield the average internal temperature of the box.

The "damping effect" of the thermal storage mass is evident from the comparison between the temperatures measured in Box 1 (the control box, no mass) and the temperatures measured in the other three boxes. Even though the average temperature in Box 1 was only slightly higher than the average temperatures in the other boxes, its standard deviation was much greater (5.9°C compared to 2.9–3.4°C), reflecting a much higher average maximum (35.8°C) than the maximum of the other boxes (29.5–30.6°C) as well as a lower average minimum (16.2°C

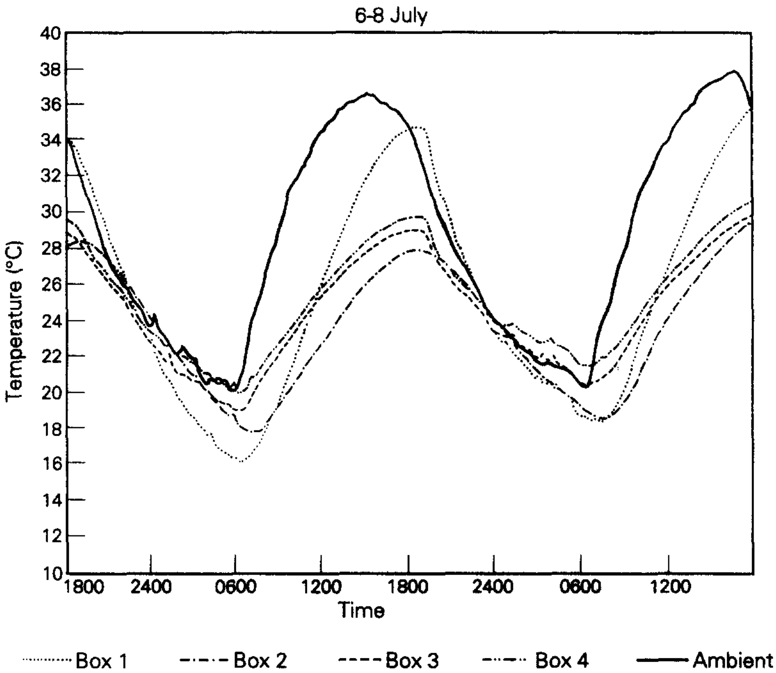

Fig. 2. Test box internal air temperatures.

Table 1. Average internal air temperatures in the test boxes for the two day period examined

Box	Avg. Temp (°C)	Avg. Max (°C)	Avg. Min (°C)	σ (°C)
1	25.4	35.8	16.2	5.9
2	23.7	29.5	17.8	3.4
3	24.5	29.8	19.0	3.1
4	25.2	30.6	20.1	2.9

compared to 17.8–20.1°C), resulting in a larger swing of temperatures during the daily cycle (Fig. 2).

The internal air temperatures measured in Box 2, in which the radiator and the thermal storage were combined in the roof of the box, were the lowest of all boxes (daily average, minimum and maximum). Of the three high-mass boxes, the highest overall temperatures were measured in Box 4 (mass in floor), whereas temperatures in Box 3 (mass in the wall) were between those of Box 2 and those of Box 4. The pattern of air temperature swing, though, was reversed: Box 2 had the biggest standard deviation of temperature (3.4°C) and Box 4 had the smallest (2.9°C). Again, Box 3 presented values between the two other boxes.

Radiator surface temperature

Radiator surface temperatures exhibited a wide amplitude, even greater than that of the ambient temperature (Fig. 3). In Box 1, which had little thermal mass, the amplitude of the radiator surface temperature was the biggest: $\sigma = 7.2$°C on the radiator, compared to 5.7°C of the ambient. In this case, the radiator heated during the day almost to the maximum ambient temperature (in spite of the insulated cover), but cooled down during the night well below the ambient due to radiative cooling (minimum temperature of the radiator 12.5°C compared to 20.1°C of the ambient). As a result of this swing, the average temperature of the radiator was also lower than the ambient average: 23.7°C for the radiator compared to 28.6°C of the ambient.

The presence of the thermal mass changed significantly the amplitude of the surface temperatures of the radiators. Here too, the location of the mass was very important. The amplitude of the surface temperature of the radiator in the boxes with the concrete storage mass was reduced compared to the radiator with the box that had no mass (3.1–6.2°C compared to 7.2°C). Box 2, in which the mass was integrated with the radiator, had the most noticeable reduction in the standard deviation of its radiator surface temperature, which was only 3.1°C. Box 4, where the storage mass was in the floor, had the biggest standard deviation.

The average surface temperature of the radiator of the low-mass Box 1 and those of the boxes with the storage mass in the floor and in the wall was similar. The average temperature of the mass-radiator combination of Box 2 was somewhat lower.

Table 2. Average temperatures of radiator surfaces 6–8 July

Box	Avg. Temp (°C)	Avg. Max (°C)	Avg. Min (°C)	σ (°C)
1	23.7	35.8	12.5	7.2
2	21.8	29.0	15.7	3.1
3	23.5	32.6	13.7	6.2
4*	23.4	32.7	13.8	6.1

* Comparison of the interior air temperatures of Boxes 3 and 4 (which had metal radiators and a poorly coupled thermal storage mass), indicates that the *radiator* temperatures recorded for Box 4 are possibly up to 0.5°C too high. The data for the internal air temperature of Box 4, reflecting the average of *three* sensors, suggest that the actual nocturnal cooling was slightly less than the calculated rate (see also Table 3). The calculated cooling rate is based on data from just *one* sensor per radiator.

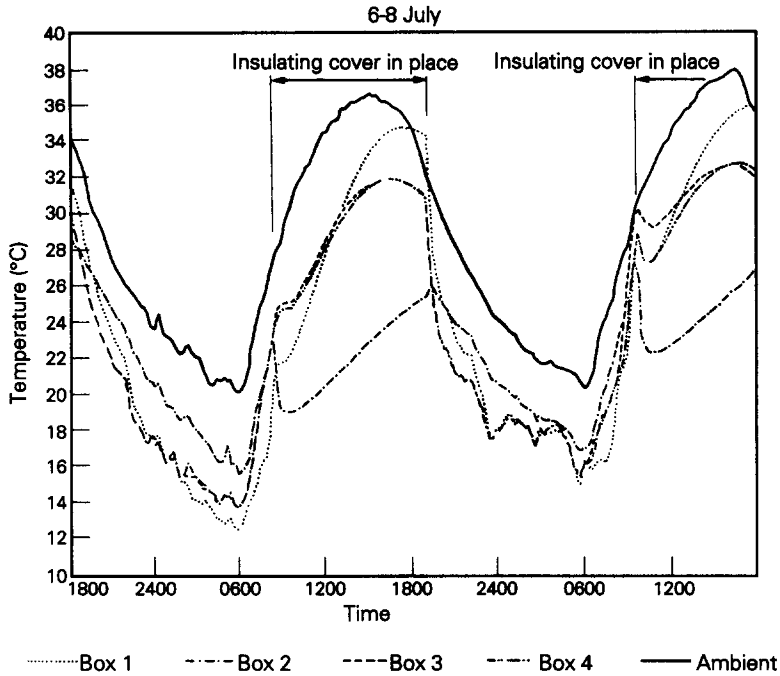

Fig. 3. Test box radiator temperatures.

Cooling power

The comparison of the cooling power obtained was done based on data from the two nights, each between the hours 2000 of one day and 0600 of the next day (10 h in each night). Figure 4 shows the average cooling power obtained during the two nights described here.

Box 2, in which the radiator and the thermal mass were combined in the roof of the box, had a nightly average net cooling rate higher than that of all other boxes, both with and without thermal storage. The average net radiative cooling power of Box 2, in which the thermal storage mass and the radiator were combined in the concrete roof, was 77.2 W m^{-2} compared to approximately 56 W m^{-2} in Boxes 3 and 4, where the thermal storage mass and the radiator were separate. Box 2 also demonstrated a significantly higher average effective cooling rate compared to the other boxes with thermal mass (62.2 W m^{-2} compared to 21.8 W m^{-2}) as well as the control box that did not have any mass (28.9 W m^{-2}).

The reason for this significant difference in performance was the fact that the temperature of the radiator-mass combination of Box 2 did not decrease as fast and as much as did the temperature of the low-mass sheet metal radiators of the other two boxes, in which the coupling of the radiating surface and the thermal storage mass was much weaker. While the coupling mechanism of the thermal mass and the radiating surface of Box 2 was conduction within the concrete slab, the coupling of the mass and the radiating surface of the other boxes was based on convection in the air locked inside the box, and by radiation between the internal surfaces of the radiators and the storage mass.

CONCLUSION

Comparison of the four test boxes indicates primarily that the very *existence* of the thermal storage mass as part of the cooling system is important, but its *location* and the *coupling* between it and the radiating surface are even more important. Thermal mass which is not closely

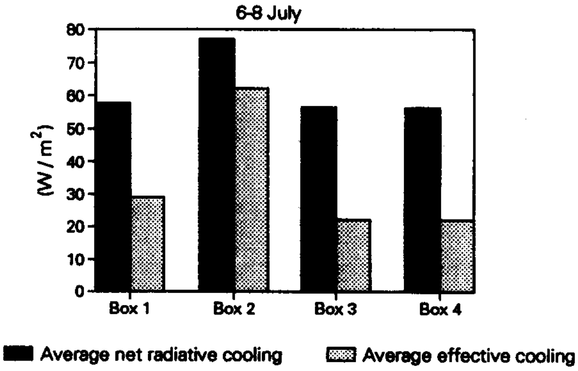

Fig. 4. Test box average cooling power.

Table 3. Two nights cooling data for test boxes

Box	Net radiative cooling rate (W/m^{-2})		Average effective cooling rate (W/m^{-2})	
	Avg.	Peak	Avg.	Peak
1	57.9	128.6	28.9	149.1
2	77.2	93.4	62.2	88.3
3	56.2	102.2	21.8	81.7
4*	56.1	105.0	21.8	88.8

* See note in Table 2 regarding possible inaccuracy of data regarding the temperature and calculated cooling rates of this radiator.

coupled to the radiator has little effect on average internal air temperatures—witness the small differences in this respect between Box 1 (no storage mass) and Boxes 3 and 4.

By integrating the radiating surface and the storage mass and achieving the most effective *coupling* between them, the obtainable net and effective radiative cooling reached maximum values. These values were significantly higher than the values obtainable in all other cases (by as much as 35%). The integrated configuration thus resulted in the lowest daily average temperature inside the box: 23.7°C compared to 24.5 and 25.2°C in the other boxes that also had thermal storage mass.

The damping effect of the mass on the internal temperature seems to be inversely related to the *location* and the *coupling* of the storage mass and the radiator. The greatest standard deviation of the internal temperatures was recorded in the case of the integrated radiator-storage box (coupling by conduction in the concrete), the smallest was recorded in the case of the poorest coupling (coupling by convection through the internal air and radiation).

In general, the data confirms the usual pattern of heavy vs. lightweight structures: as soon as the thermal storage mass is introduced, the standard deviation of the temperatures inside the box drops—in this case from 5.9°C in the box with no storage to 2.9–3.4°C in the cases with the storage mass.

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