INNOVATIONS IN VENTILATION TECHNOLOGY

21ST ANNUAL AIVC CONFERENCE
THE HAGUE, NETHERLANDS, 26-29 SEPTEMBER 2000

EXPERIMENTAL TESTING OF A VENTILATED ROOF COMPONENT FOR ENERGY SAVING IN COOLING

A. Dimoudi, A. Androutsopoulos, S. Lykoudis

Center for Renewable Energy Sources (CRES), 19th km Marathonos Av.,
190 09 Pikermi, Greece. e-mail : adimoudi@cres.gr

EXPERIMENTAL TESTING OF A VENTILATED ROOF COMPONENT FOR ENERGY SAVING IN COOLING

A. Dimoudi, A. Androutsopoulos, S. Lykoudis

Center for Renewable Energy Sources (CRES), 19th km Marathonos Av.,
190 09 Pikermi, Greece. e-mail : adimoudi@cres.gr

Synopsis

A Ventilated roof component was built and tested in the outdoor testing facilities (Test Cells) of CRES, Greece. A conventional Greek roof structure of the same area was also installed at the roof of the Test Cell allowing simultaneous measurements in order to perform a comparative study of the performance of the two parts. Different configurations in the Ventilated roof were investigated, like ventilation air gap height and application of a radiant barrier. The tests carried out under summer weather conditions will be discussed in this paper. The experimental results showed a better performance of the Ventilated roof compared to a conventional roof construction under summer climatic conditions.

1. Introduction

In regions with high levels of solar radiation, ventilated structures maintain the internal shell of double skinned buildings at a temperature closer to the ambient, reducing significantly the impact of incident radiation. For conventional constructions, in such regions, roof surface temperatures can easily reach 75 ^oC to 80 ^oC, depending on the time of the year. By effectively applying this technique over the entire building envelope, it is possible to considerably reduce envelope heat gains.

The aim of this paper is to present the experimental work carried out at a Ventilated roof component under summer climatic conditions. The Ventilated roof component was built according to the design specifications given by the Ventilated prefabricated building components' manufacturer PROKELYFOS S.A. and installed at the roof of the Outdoor Test Cell of CRES, in Greece. The performance of the Ventilated roof was compared to a conventional roof structure, by carrying out simultaneous measurements at a component of the same area installed at the roof of the Test Cell. Each of the roof components covered half of the roof area of the Test Cell and separated with an insulation layer. Additionally, the effect of different parameters, like ventilation air gap height and application of a radiant barrier, was also investigated.

2. Outdoor facilities

The Test cells are highly insulated boxes, with dimensions of 8.4 m x 3.8 m x 3.6 m, located in an outdoor environment, able to accommodate into a full scale building component, roof or wall, for testing under real climatic conditions [1]. The interior of a test cell is partitioned into two rooms: the Test Room with dimensions of 2.75 m x 2.75 m x 5.00 m, in which the test is taking place, and the Service Room which contains auxiliary equipment for the operation of the test procedures. The test cells are equipped with a sophisticated heating and cooling system controlled by a data acquisition and control unit for implementation of specially designed dynamic test sequences. Both indoor and outdoor climatic conditions are monitored using a standard set of sensors, including solar radiation (diffuse and global), long wave radiation, wind speed and direction, relative humidity, air and surface temperatures, and heating and cooling power. All these measurements are recorded at one minutely intervals by the central data acquisition system.

3. Description of the component

The total dimensions of the roof in the Test Cell are 2.715 m wide by 4.970 m long, which was divided into two equal areas: Half of it was constructed as a conventional roof (according to conventional guidelines for a roof construction in Greece) and the other half was constructed as a Ventilated roof component according to the design specifications of the Ventilated prefabricated building components' manufacturer PROKELYFOS S.A. [2]. The two components were separated with an insulation layer, in order to avoid heat flow between them, and tested under actual outdoor conditions.

Typical roof part
Half part of the Test Cell roof was constructed according to conventional guidelines for a roof construction in Greece, henceforth, called "Typical roof". This Typical roof consisted of:

- a 12 cm thick reinforced concrete slab which is in direct contact with the interior of the room (the thickness of the concrete slab was limited by the maximum load withstand of the Test Cell),
- a 5 cm thick layer of extruded polystyrene placed on top of the concrete slab, and
- a 2.5 cm thick prefabricated reinforced concrete slab, exposed to the external environment.

The dimensions of the Typical roof part were 2.43 m x 2.71 m with a total roof thickness of 19.5 cm. The dimensions together with the different layers of the roof component are shown in Figure 1.

V*entilated roof part*
The Ventilated roof component consisted of :

- a 12 cm thick reinforced concrete slab which is in direct contact with the interior of the room,
- a 5 cm thick layer of extruded polystyrene placed on top of the concrete slab,
- a ventilation air gap, formed by lining bricks on top of the polystyrene layer. During the experiments, two different air gap heights were tested, namely 6 and 8 cm,
- a 2.5 cm thick prefabricated reinforced concrete slab, supported by the bricks, and exposed to the external environment.

In the centre of this roof part, a circular chimney of 35 cm height and 5 cm diameter, made of a metallic sheet and painted black externally, was positioned in order to facilitate the extraction of the hot air from the ventilated gap. The dimensions of the Ventilated roof part were 2.43 m x 2.71 m with a total thickness of 25.5 and 27.5 cm. The dimensions together with the different layers of the roof component are shown in Figure 1.

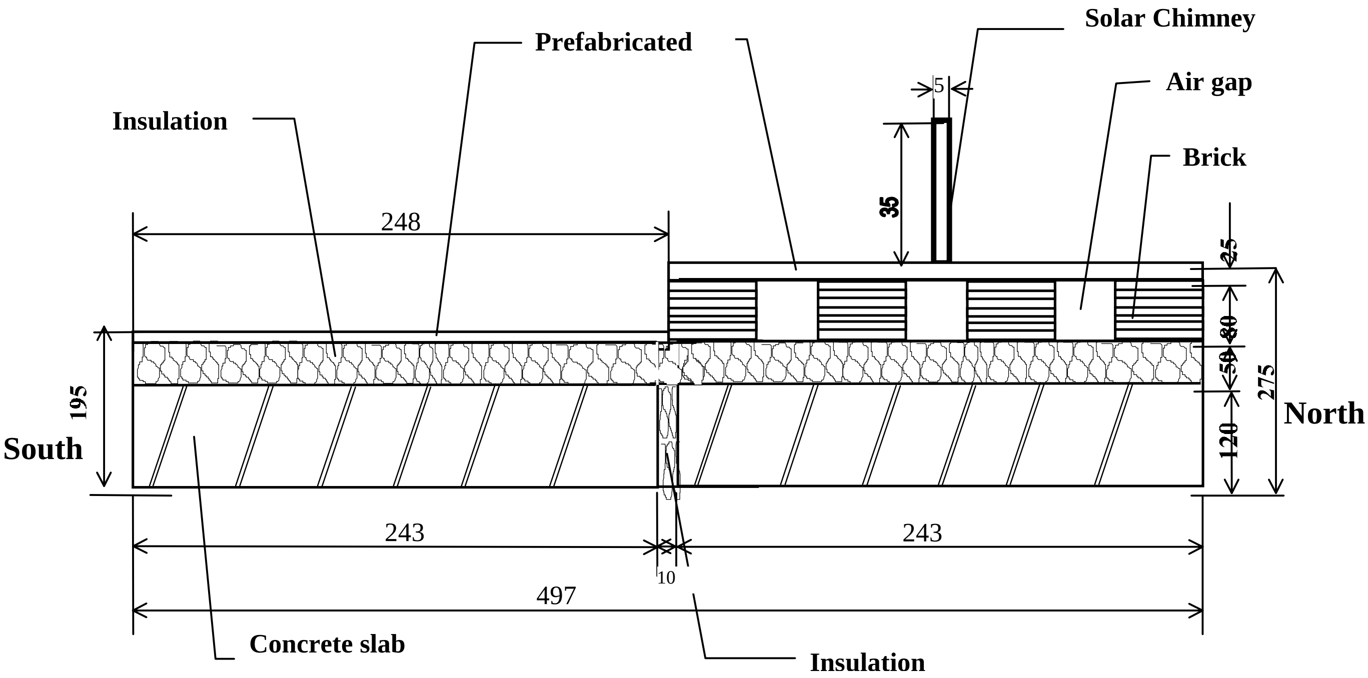

Figure 1. Cross-section of the roof components (not to scale).

4. Experimental procedure and instrumentation

The experimental testing had the following objectives: a) to obtain information on the operational characteristics of the Ventilated roof component, so that specific aspects of its design and operation can be more fully understood and b) investigate the effect of different parameters on the performance of the Ventilated roof.

The Typical roof part was used as a reference. Since both roof parts are subject to the same ambient conditions, in order to investigate the performance of the two roof parts, a constant room temperature was applied in the interior of the test cell during the whole testing period. The test room temperature was set at 27 $^oC \pm 0.2$ ^oC and was controlled by a combination of heating and cooling modes.

Four different Ventilated roof layouts were investigated, namely:
Ventilation gap : 8 cm
Case 1. Without radiant barrier.
Case 2. With radiant barrier.
Ventilation gap : 6 cm
Case 3. With radiant barrier.
Case 4. Without radiant barrier.

The settings of each individual case and its duration can be found in Table 1.

Table 1. Settings and duration of each individual case.

Case Nr.	Air gap height (cm)	Duration (days)	Configuration
1	8	6	Ventilated roof
2	8	7	Ventilated roof equipped with reflective layer
3	6	4	Ventilated roof equipped with reflective layer
4	6	5	Ventilated roof

Apart from the standard instrumentation of the Test Cell, additional sensors were installed to measure the performance of the roof components:

- Prefabricated reinforced concrete slab (2.5 cm thick) : Three T-type thermocouples were positioned with two layers of tape, one of them insulating, on the external surface of the slab, two in the Ventilated roof part and one in the Typical roof part.
- Insulation layer : Two T-type thermocouples for the measurement of the upper surface temperature, one at the centre of each roof part.
- Concrete slab (12 cm thick) : Ten T-type thermocouples. Five thermocouples were placed at different heights inside the concrete slab, at the centre of each roof part.
- Roof component heat flux : Two heat flux meters installed, one in each roof part.
- Air gap : One T-type thermocouple for the measurement of the air temperature at air gap middle height.
- Chimney : Two T-type thermocouples and one air velocity sensor (hot wire) for the measurement of the temperature and velocity of the air extracted through the chimney.

The positions of the sensors on the test component can be seen in Figure 2. The data from all the sensors were collected by the Test Cells' central data acquisition system.

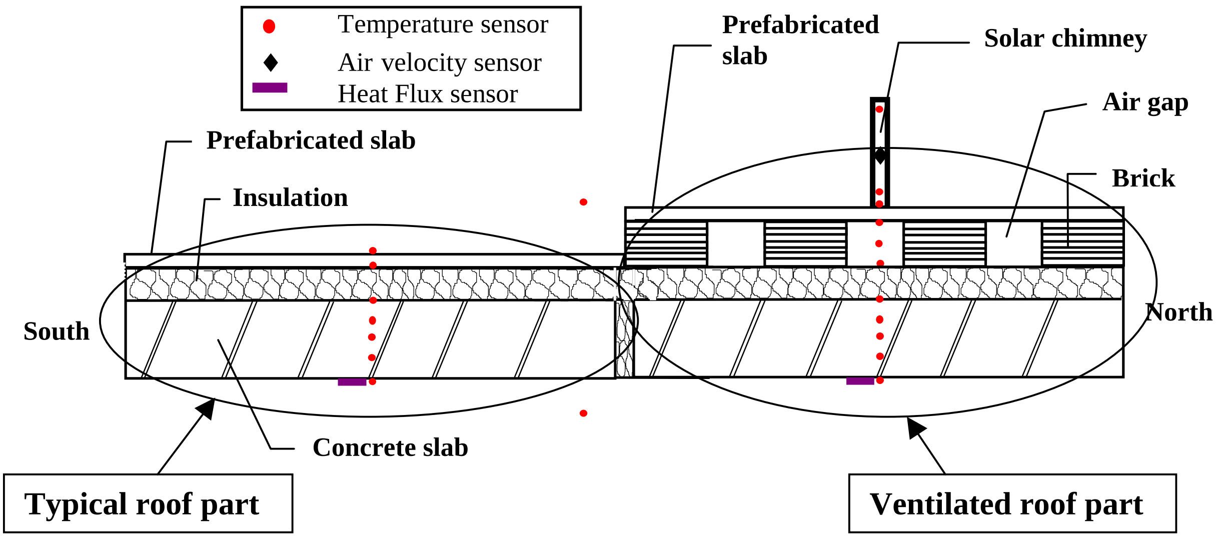

Figure 2. Sensor positions on the roof component.

5. Experimental results

The differentiation of the two roof components performance was investigated by examining the temperatures developed at the upper prefabricated slab and the upper surface of the insulation layer in each roof component. Since the outdoor conditions are variable and the number of days for each experimental case is rather limited, in order to allow meaningful statistical results, selected day and night time periods, not necessarily continuous, were selected and studied.

The analysis of the experimental data was performed in two parts [3] :

- a qualitative assessment of the performance of each Ventilated roof layout separately, using the respective performance of the Typical roof as a base for the comparison, and
- a quantitative assessment of the relative performance of the various Ventilated roof layouts in terms of changing air gap height and presence or not of the radiant barrier, comparing one to the other and to the Typical roof as well.

Comparison of Ventilated and Typical roof performance (Qualitative asessment)

For the first part of the analysis, days with meteorological conditions unfavorable for the performance of a building component were selected (worst case scenarios) in order to assess the relative performance of the two roof components. Since the worst day and night periods encountered in the different experimental cases may differ significantly from one to the other, direct comparison between the different layouts could not be made and thus, qualitative results can be derived. The selected day time periods for all Cases were sunny with solar irradiance exceeding 800 $W.m^{-2}$, maximum ambient air temperature over 30 °C for Cases 1 and 2 and over 25 °C for Cases 3 and 4 and wind speed ranging between 2 to 4 $m.s^{-1}$. The nighttime periods were selected to have small temperature drop, indicating the possibility of a cloudy sky. This inference was also supported by the fact that all selected nights were either followed or preceded by a cloudy daytime period. The temperature drop during the selected nighttime periods ranged from 5 to 10 K. The lowest wind speed, less than 1.5 $m.s^{-1}$, was observed during Case 1.

During daytime, when the radiant barrier was installed (Cases 1 and 2), the two upper prefabricated slabs reached almost the same temperature, the Ventilated upper prefabricated slab being slightly warmer (less than 0.5 K). On the other hand, when there is no radiant barrier, the Typical roof upper slab temperature is 1 to 3 K higher than the Ventilated upper prefabricated slab. During nighttime, the upper prefabricated slab without radiant barrier is slightly warmer than the Typical roof upper slab but the situation reverses with the presence of the radiant barrier. The observed temperature differences in all cases are less than 0.5 K.

The insulation temperature in the Ventilated and Typical roof components present significant differences during daytime, ranging from 8 K, without a radiant barrier, to 14 K with a radiant barrier (Figure 3). The Typical roof insulation begins the day a few centigrade cooler than the Ventilated one, but soon after 8:00, the situation is reversed and the Typical roof insulation becomes hotter than the Ventilated until sunset.

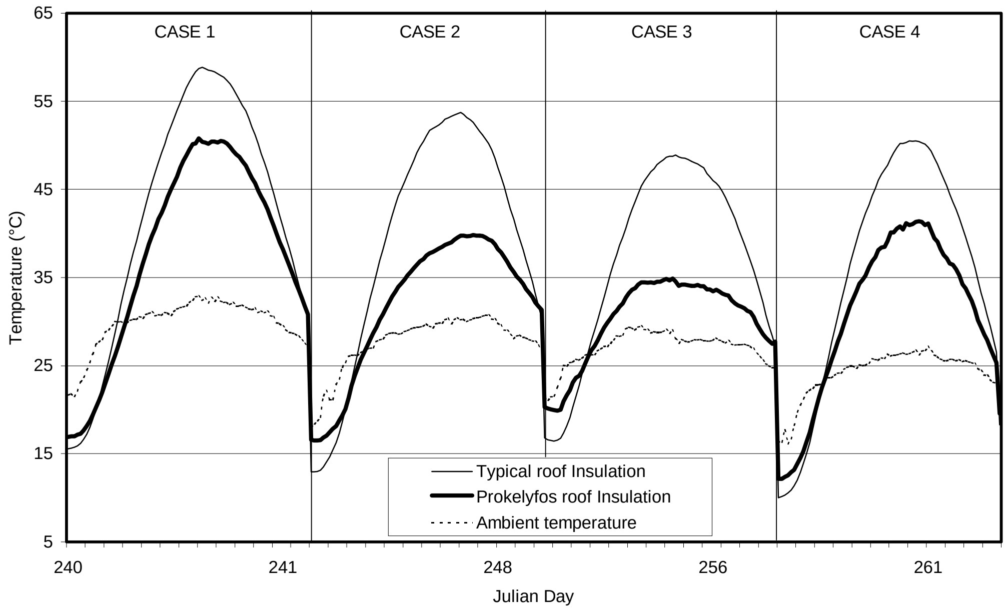

Figure 3. Daytime, temperature distribution of the Typical and Ventilated roofs insulation upper surface.

During nighttime, the temperature of the Ventilated roof insulation is always higher than that of the Typical roof insulation by 1 to 2 K when there is no radiant barrier and up to 4 K with the radiant barrier installed (Figure 4).

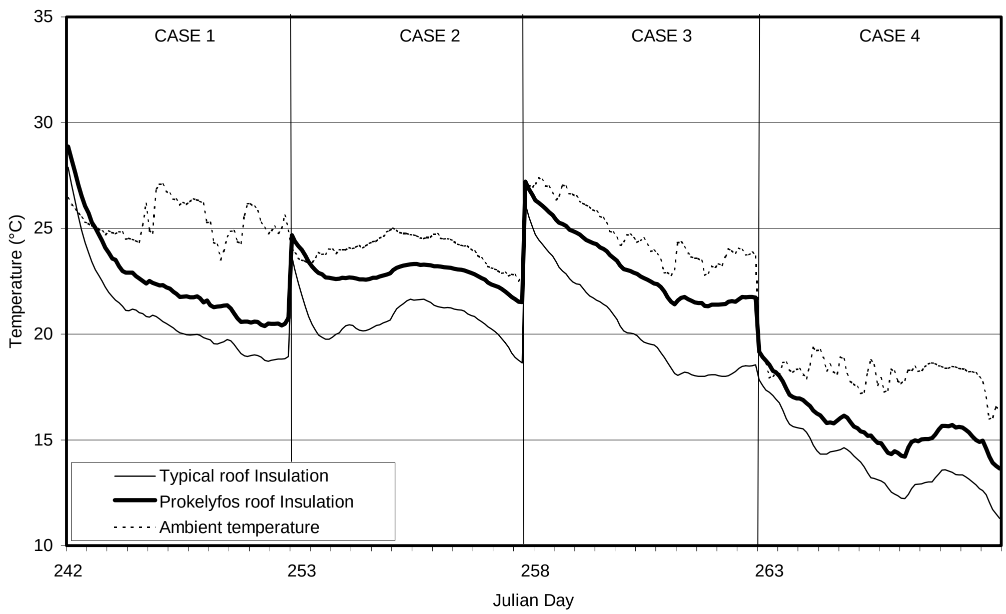

Figure 4. Nighttime temperature distribution of the Typical and Ventilated roofs insulation upper surface.

During daytime the air gap in the Ventilated roof acts as an extra insulating layer, keeping the insulation layer of the Ventilated roof at lower temperature than that of the Typical roof, even though the air flow velocity in the gap is considerable lower than the ambient wind speed. The temperature of the air inside the gap is equal to that of the insulation, about 15 K higher than the ambient air. In the Ventilated roof, part of the daytime solar heat gains through the upper prefabricated slab are transferred to the air in the gap and warm it instead of the insulation layer as it is the case of the Typical roof, thus, keeping the temperature of the insulation lower. During nighttime, both, the ambient and the ventilation gap, air flows decrease but the temperature of the air inside the gap, though lower than that of the ambient air, is higher than that of the upper slab. So, the air gap in the Ventilated roof acts as a heat source between the upper slab and the insulation layer thus, limiting the cooling of both components.

The radiant barrier placed immediately under the upper prefabricated slab blocks the thermal radiation of the hot - up to 60 °C - upper prefabricated slab thus keeping the Ventilated insulation up to 14 K cooler than that of the Typical roof, during daytime. During nighttime the radiant barrier blocks the heat radiated from the insulation layer, thus, limiting its cooling by about 2 K.

Assessment of the different layouts (Quantitative assessment)

For the second part of the analysis, days with similar meteorological conditions but still representative of the of the summer period were selected, to gain knowledge on the relative effect of the air gap size and the radiant barrier on the Ventilated roof performance. The Typical roof temperatures are used as a reference for the comparison of the various Ventilated roof layouts. For all selected cases, the daytime period was clear and sunny with average global horizontal irradiance ranging between 480 to 520 $W.m^{-2}$. The maximum ambient temperature ranged from 26 to 31 °C while the average wind speed was 1.7 up to 3.5 $m.s^{-1}$. The nighttime periods were also characterized by clear skies, with the ambient temperature ranging between 16 and 27 °C and the average wind speed smaller than 1 $m.s^{-1}$.

A decrease of the air gap improves the performance of the system under summer conditions for both layouts, with and without the radiant barrier. Without the barrier, during daytime, both the upper prefabricated slab and the insulation layer were kept at a lower temperature with the small air gap, by 1 to 2 K with respect to the corresponding Typical roof temperatures. The same is true for nighttime conditions, but the observed temperature differences are much lower, 0.5 K for the upper prefabricated slab and 1 K for the insulation layer.

The addition of the barrier weakens the effect of the reduced air gap and the above mentioned temperature differences are retained only for the upper prefabricated slab during daytime.

Regardless the size of the air gap, the addition of the radiant barrier was shown to be an improvement on the system's performance under daytime summer conditions. As an example, the temperature differences of the upper slab and insulation layers for the layouts with 8 cm air gap, cases 1 (without a radiant barrier) and 2 (with a radiant barrier) can be seen in Figure 5. On the other hand, the layout without the radiant barrier seems preferable under summer nighttime conditions, based on the higher temperature difference between the

Ventilated and the Typical insulation layer, observed with the radiant barrier installed, as shown in Figure 6.

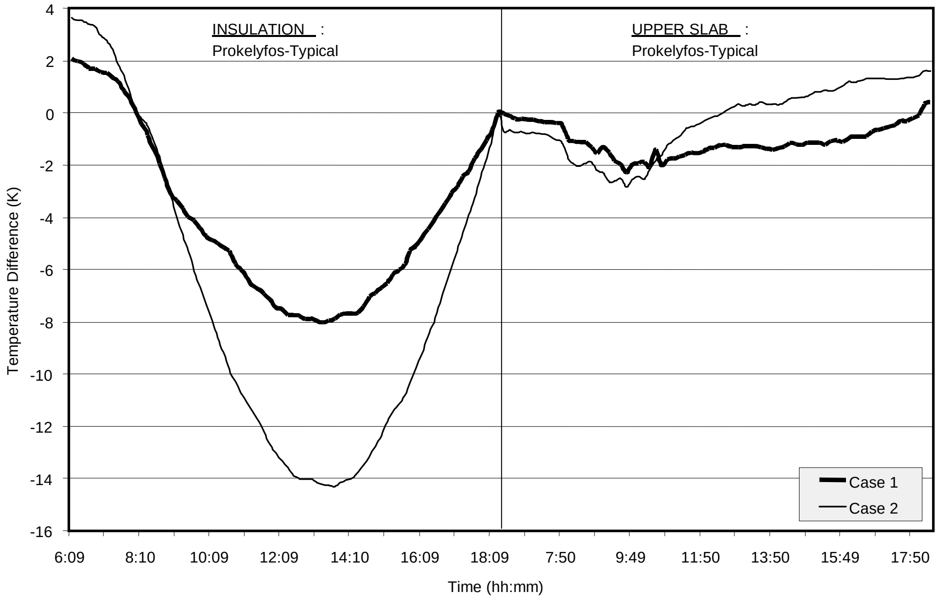

Figure 5. Daily temperature differences between the Ventilated and Typical roof components.

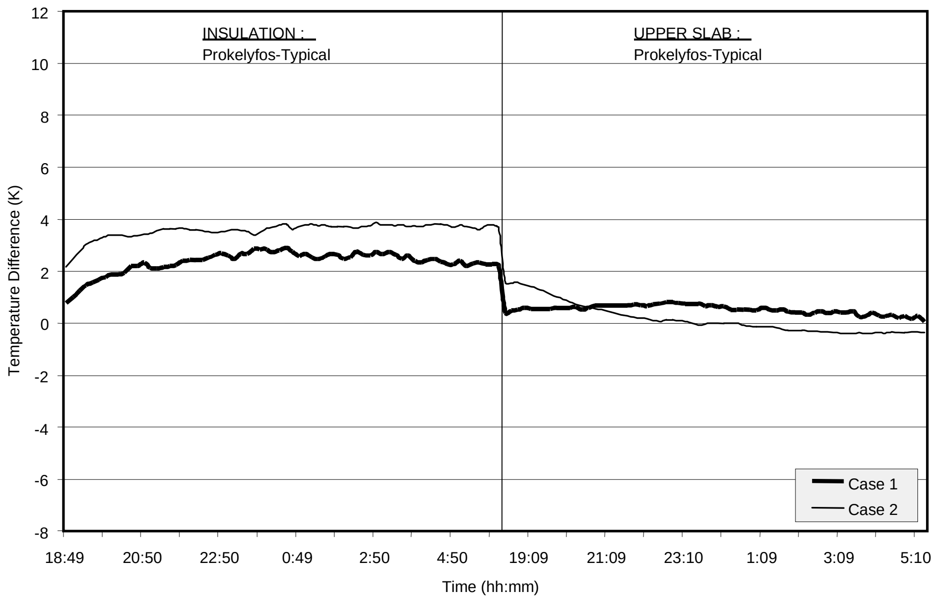

Figure 6. Nighttime temperature differences between the Ventilated and Typical components.

The analysis of the experimental results indicates that the reduction of the air gap from 8 cm to 6 cm is expected to yield a temperature decrease of 1 to 2 K for the Ventilated insulation layer surface, during daytime. During nighttime, the reduced air gap keeps the insulation layer temperature closer to that of the Typical roof. A very significant profit – up to 14 K relatively to the Typical roof – was observed during daytime from the installation of the radiant barrier. During nighttime, though, the barrier keeps the insulation layer up to 1 -2 K warmer with both gap heights.

Results Summary

In order to have a quantitative assessment of the overall performance of the various Ventilated roof layouts and the Typical roof, the heat flux through them was calculated. Only the lower part of the roof, consisting of the insulation and the lower concrete slab, that is common in both the Ventilated and the Typical roof was considered in order to enable a direct comparison with the Typical roof and reduce the ambient induced variation.

The heat flux (positive for gains, negative for losses) for a given period, t, through the lower part of the Ventilated roof is:

$$Q_P = \sum_t U_P \cdot \left(T_{insulation} - T_{room}\right)\Big|_P = U_P \cdot \sum_t \left(T_{insulation} - T_{room}\right)\Big|_P$$

Similarly for the Typical roof:

$$Q_T = \sum_t U_T \cdot \left(T_{insulation} - T_{room}\right)\Big|_T = U_T \cdot \sum_t \left(T_{insulation} - T_{room}\right)\Big|_T$$

A performance indicator was selected in order to examine the relative difference of the heat flow in the different layouts, represented by the ratio (since for this part, the thermal transmittances are $U_P = U_T$) :

$$A = (Q_p - Q_T)/\left|Q_T\right|$$

When the Ventilated roof presents higher heat losses or lower heat gains than the Typical, then *A* is negative. Correspondingly, a positive *A* value represents lower heat losses or higher heat gains from the Ventilated than the Typical roof. According to the above, negative *A* values mean that the Ventilated outperforms the Typical roof, while positive *A* values mean that the Typical is better.

The heat fluxes and *A* values calculated for the day, night and 24 hrs periods for each experimental case are presented in Table 2.

Table 2. Heat flows on the roof components.

	Day			Night			24 hrs		
	Q_T ($W.m^{-2}$)	Q_P ($W.m^{-2}$)	•	Q_T ($W.m^{-2}$)	Q_P ($W.m^{-2}$)	•	Q_T ($W.m^{-2}$)	Q_P ($W.m^{-2}$)	•
Case 1	651	356	-45%	-921	-759	18%	-270	-403	-49%
Case 2	896	373	-58%	-645	-399	38%	251	-26	-110%
Case 3	755	241	-68%	-648	-434	33%	107	-193	-281%
Case 4	608	269	-56%	-957	-830	13%	-348	-561	-61%

According to the above Table:

- the Ventilated roof outperforms the Typical during daytime, while the opposite is observed for nighttime. On a 24hrs basis, the Ventilated is much better than the Typical roof,
- the radiant barrier (Cases 2 and 3) enhances the performance of the Ventilated roof significantly during daytime and on a 24 hrs basis, while the opposite is observed for nighttime.
- both, with and without the radiant barrier, the small air gap (Cases 3 and 4) performs better during daytime, and marginally better, during nighttime. On a 24hrs basis the smaller gap is also better.

6. Conclusions

A series of tests on advanced Ventilated roof components had been carried out by the use of the outdoor testing facilities of CRES. The components were built in full scale dimensions and tested under actual weather conditions.

The tested Ventilated roof component showed a good performance in terms of cooling demand and it can significantly contribute to a building's energy conservation during summer periods. Ventilated roof components can be a promising solution for the Mediterranean countries, concerning summer performance where their intermediate air gap layer interacts actively with the ambient conditions. Air circulation inside the air gap enhances the heat removal and contributes to reduced heat gains through the roof and thus, a smaller cooling load. Especially during the summer daytime, an application of a radiant barrier was found to ameliorate the cooling performance of the component. During the nighttime however, the use of the radiant barrier is not favorable since it actually obstructs the heat removal through the component but the overall daily performance is positive. Different air inlet and outlet openings dimensions, and alternative use of mechanical ventilation system to guide the airflow through the ventilation gap should be investigated in order to determine its optimum performance.

Acknowledgments
This work was carried out in the frame of the EC Craft-Joule project called AIRinSTRUCT (JOE3-CT97-7003), which was co-funded by the European Commission (DG XII) and the General Secretariat of Research and Technology of the Greek Ministry of Development. The constructive contribution of Mr. Iosifides, General Director of PROKELYFOS S.A. in the course of this work should be acknowlegmented.

References

[1] P. WOUTERS, VANDAELE L. (eds)
"The PASSYS Services – Summary report of the PASSYS project"
EC, DG XII for Science, Research & Development. EUR 15113 EN, 1994.

[2] M. IOSIFIDES
"Introduction on the technology of the totally ventilated Prokelyfos building component" • echnika Chronika Journal, July-August 1996, pp. 47-71. [in Greek]

[3] A. ANDROUTSOPOULOS, LYKOUDIS S. and DIMOUDI A.
"Testing of Prokelyfos Ventilated Wall Component at CRES Test Site"
AIRinSTRUCT Final Technical Report, EC-DGXII (JOE3-CT97-7003), 2000.