

Low Cost Green Roofs for Cooling

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ABSTRACT: Green roofs have many benefits over conventional roofs, they reduce storm water runoff, the heat island effect in cities, and energy requirements for cooling; all of this while sequestering some CO₂ from the atmosphere. But because of their expense, the building industry has yet to fully embrace their large scale implementation. Over the course of three summers several green roofs have been built and tested at the Lyle Center for Regenerative Studies in Cal Poly Pomona University to determine their cooling potential combined with night ventilation. Results indicate that the test cell with the uninsulated green roof consistently performs better than the test cell with the insulated green roof and the conventional white insulated roof. This indicates that in mild climates with warm summers, green roofs can be thermally coupled with the interior of the space to improve the performance of night cooling systems, reducing energy consumption and greenhouse gas emissions.

Keywords: night ventilation, passive cooling, green roofs, [times 9 italic, followed by 2 blank lines]

INTRODUCTION

A living or green roof is a roof that is substantially covered with vegetation. Such a strategy has been proven to have positive effects on buildings by reducing the stress on the roof surface, improving thermal comfort inside the building, reducing noise transmission into the building, reducing the urban heat island effect by reducing “hot” surfaces facing the sky, reducing storm water runoff, re-oxygenating the air and removing airborne toxins, recycling nutrients and providing habitat for living organisms, all of this while creating peaceful environments.

The positive thermal effects of green roofs are usually described by the the reduction of the external surface temperature due to effect of vegetation, and the reduction of the thermal transmittance of the assembly, mostly due to the effects of insulation, usually placed between the sustaining material and the interior space of the building. A green roof without this added insulation has a low thermal resistance. Apart from providing protection against overheating, a green roof can also provide some cooling through the evaporative process in the plants [1]. Their vegetative matter absorbs solar radiation through the biological processes of photosynthesis, respiration, transpiration, and evaporation. However, the solar radiation that bypasses these processes can seep into the building envelope [2].

Studies have demonstrated that a well planned and managed green roof –with insulation- acts as a high quality insulation device in the summer [3]. But little has been done to take advantage of the mass of the green roof

as a heat sink in temperate or hot climates. By reducing daily thermal fluctuations on the outer surface of the roof and increasing thermal capacity in contact with the indoors, green roofs can contribute to the cooling of spaces if the mass of the soil is cooled. There has been some research in this direction that indicates potential to reduce the cooling loads inside buildings [4] [5].

Nocturnal ventilative cooling occurs when an insulated high-mass building is ventilated with cool outdoor air so that its structural mass is cooled by convection from the inside, bypassing the thermal resistance of the envelope. During the daytime, if there is a sufficient amount of cooled mass and it is adequately insulated from the outdoors, it will act as a heat sink, absorbing the heat penetrating into and generated inside the building, reducing the rate of indoor temperature rise. This ventilation system can be either fan forced or natural through windows that are opened and closed at appropriate times. During overheated periods the ventilation system (windows or fans) must be closed to avoid heat gains by convection. Nocturnal ventilative cooling is a well known strategy that has been used for many years, mostly in warm and dry climates [6].

The main parameters that determine the efficiency of night-ventilation can be classified in three broad groups: climatic parameters, building parameters and technical parameters of the technique [7].

During the course of three summers several green roofs have been built and tested at the Lyle Center for Regenerative Studies in California State Polytechnic

University Pomona. This paper analyzes the cooling potential of green roofs combined with night ventilation by looking at the internal temperature of experimental test cells and in a full size residential building.

EXPERIMENTAL SYSTEM

Three test cells with a dimension of 1.2 x 1.2 x 1.2 meters were built using 2 by 4 inch stud wall construction with drywall on the inside, plywood on the outside and batt insulation in between for a U value of 0.12 W /m² K. Exterior is white and the three cells have 0.61 m by 0.61 m (2' x 2') single glazed windows facing south that were replaced by double glazed windows in 2007 the last series. All of the cells have 3.8 cm thick concrete pavers as the slab.

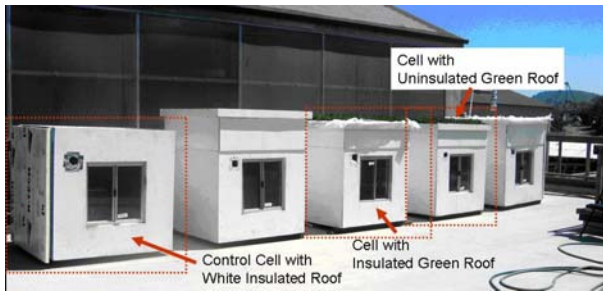


Fig. 1: The Test Cells

The roof is the only difference between the cells. The first cell has a code compliant insulated roof, with a U value of 0.055 W /m² K, painted white (Fig. 2), the second cell has an insulated green roof (Fig 3), and the third one an uninsulated green roof (Fig 4). The soil in the uninsulated green roof is thermally coupled with the interior via a metal plate, while in the the other green roof there are 10 cm of matt insulation between the space and the soil. Night ventilation is provided with a fan and all of the cells are equipped with dimmers and timers to adjust the ventilation rate and start/end times.

The green roofs were of the extensive type. Two types were built. The first one, in 2005, was covered with Saint Augustine grass above a layer of soil 7.5 cms thick with 2.5 cm of gravel and a plastic liner underneath. Drainage tubes are spread through the gravel with perforations that capture the excess water and drain it outside the building. The plastic liner is spread above a metal plate, supported by wooden joists. The metal plate assures thermal coupling between the mass and the space underneath (Fig 4). The second green roof was designed so that it could be built at a large scale with minimal technology, low cost materials, and little maintenance [8]. “Rice sack” tubular bags developed by the Cal Earth Institute, were cut and filled with a growth medium containing 50% native soil and 50% perlite. These bags were placed

above an impermeable layer of plastic, placed on top of the roof decking as a moisture barrier. Slits were cut into the topside of the bag where sedums and succulents were planted, which have little need for water, maintenance, or soil depth. The bags are photodegradable to sunlight, thus over time the surface of the bags disappear creating a soil strata evenly distributed over the roof. This same system was also used in an affordable low cost house prototype for Tijuana, Mexico.

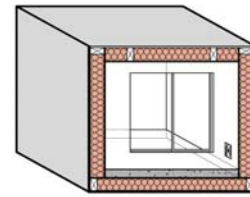


Fig. 2: Cell with insulated white roof

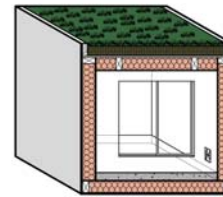


Fig. 3: Cell with the insulated green roof.

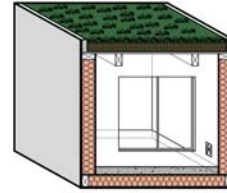


Fig. 4: Cell with the uninsulated green roof.

EXPERIMENTAL RESULTS

Many series were performed over the course of several years. Some of them are presented in this section.

Surface Temperature

Surface temperatures were higher than the ambient temperature and the surface temperature of the white painted roof was significantly higher than the surface temperature of the green roof. In a series recorded in 2008 with succulent plants, the surface temperature under the plants average 11.2 C less than the surface temperature in the white painted roof. If the roof was painted a darker cooler the temperature difference would be even more significant. Surface and ground temperatures in these cells are studied in more detail in another paper in this conference titled “Green Roofs: Beneficial in a Semi-Arid Climate” by M Figueroa.

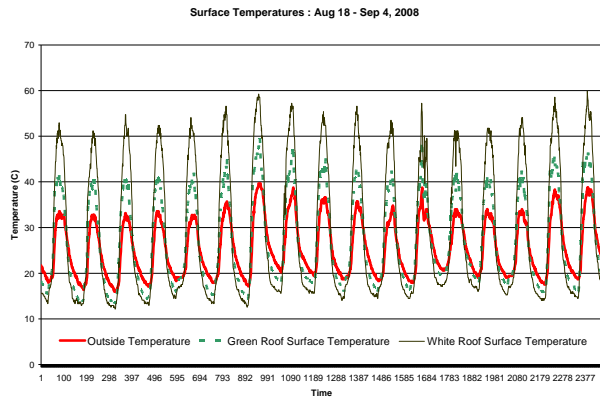


Fig. 5: Comparison of Surface Temperatures Fall 2008.

Control and Validation Series

Several series were performed in 2005 to validate their thermal performance. Figure 6 shows results of a series in 2008 comparing both green roof cells with the same level of insulation. Both curves are very close together and there is no need for a correction factor. The insulation was then taken off in one of the cells to compare the performance of insulated and uninsulated green roofs.

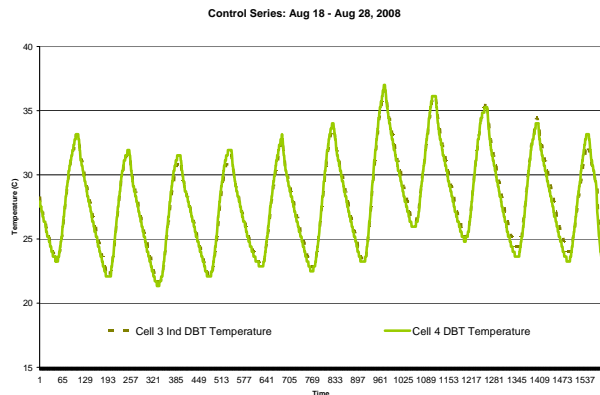


Fig. 5: Comparison of Insulated Green Roof Cells.

Indoor Temperature with Different Window Dimensions

The climatic parameters that determine the effectiveness of nocturnal ventilative cooling are the minimum air temperature, which determines the lowest temperature achievable inside the building; the daily temperature swing, which determines the potential for lowering the indoor maximum below the outdoor maximum; and the water vapor pressure level, which determines the upper temperature limit of indoor comfort with still air or with air movement [9]. During the measurement period, night temperatures and relative humidity were sufficiently low for nocturnal ventilative cooling and all three cells have a timer that sets the fan set to operate from 9 PM to 5 AM at 25 air changes per hour.

The main building parameters that affect the effectiveness of nocturnal ventilative cooling are the insulation level, thermal mass and glazing. Three series were performed in 2005 with the same amount of thermal mass and insulation. The window dimension was “modified” by adding insulation, to determine the effects of direct solar radiation inside the space. Three series were performed with different window dimensions: 0.37 m² window, 0.165 m² window, and no window.

Series 1: 100% window

In this series initiated September 7, 2005, the window is 0.37 m² in area or 25% of the floor area. Temperatures in all three cells are always higher than outdoor, especially during the daytime, due to the solar gain through the windows of the control cell. (Fig. 7). The values of the maximum temperature in the control cell are an average of 10.4 °C above the outdoor temperatures and in the insulated green roof they are 7.6 °C above the outdoor temperatures, in the uninsulated green roof they are 4.5 °C above the outdoor temperature.

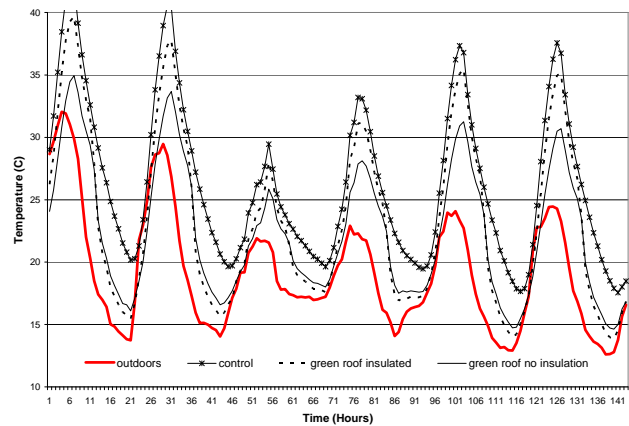


Fig. 7: Series 1: 100% window, glazing to floor ratio 25%

Series 2: 50% Window

In this series initiated September 7, 2005, the window is 0.185 m², or 12.5% of the floor area. During the day, the values of the maximum temperatures in the control cell are an average of 4.8 °C above the outdoor temperature, in the insulated green roof they are 3.2°C above the outdoor temperatures, in the uninsulated green roof they are 1.2 °C above the outdoor temperature. Because the glazing to floor ratio is smaller, the difference between the maximum temperatures inside all cells and the outdoor maximum temperature is less than in the previous series (Fig. 8).

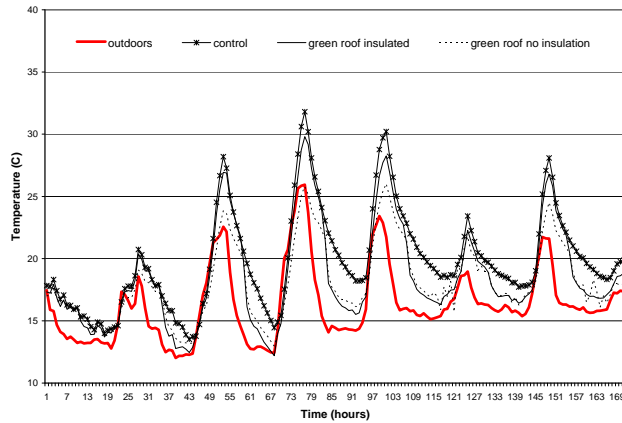


Fig. 8: Series 2: 50% window, glazing to floor ratio 12.5%

Series 3: No window

In this series initiated September 7, 2005, there is no window. During the day, the values of the maximum temperatures in the insulated control cell are an average of 0.7 °C below the outdoor temperature, in the insulated green roof they are 2.6 °C below the outdoor temperature, in the uninsulated green roof they are 3.6 °C below the outdoor maximum temperature.

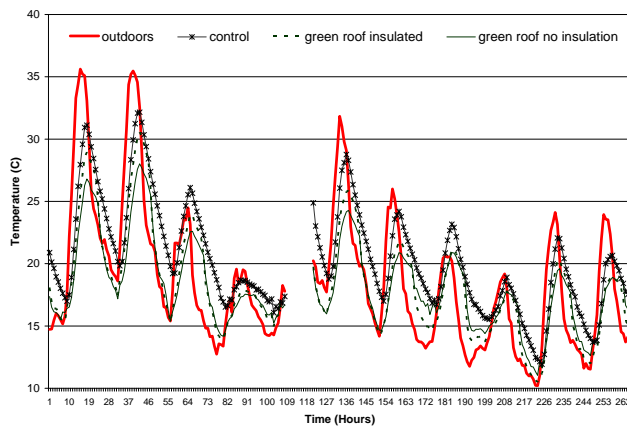


Fig. 9: Series 3, No window.

Tests with different plants, shading and windows.

In 2008 the single glazed window was substituted by a double glazed window, which was shaded with a 60 cm overhang that provided complete shading during the summer noon hours and partial shading during the morning and afternoon hours. The Saint Augustine grass was substituted by succulent species that needed little water. Results of tests in 2008 are consistent with previous series and also indicate that the green roof with no insulation performs better than the insulated green roof and the insulated white roof (Fig 9).

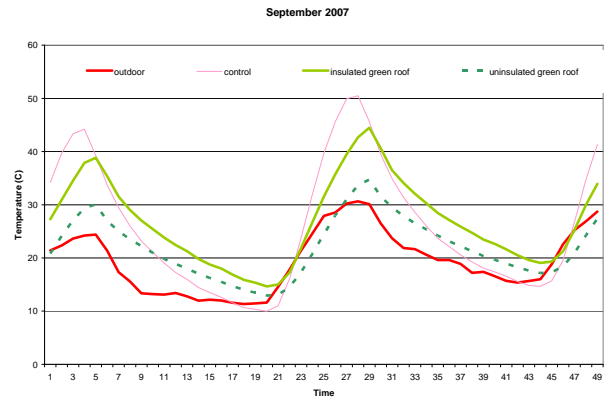


Fig. 10: Two days in the 2008 series.

Temperature Difference Ratio

The three series performed in 2005 are compared with each other using the Temperature Difference Ratio, TDR. This concept was proposed by Givoni and used with good results to compare passive cooling systems with different configurations [11] TDR is calculated using the following equation:

$$TDR = (T_{maxout} - T_{maxin}) / (T_{maxout} - T_{minout}) \quad (1)$$

Where:

TDR: Temperature Difference Ratio
 T_{maxout} : Maximum temperature outside
 T_{maxin} : Maximum temperature inside
 T_{minout} : Minimum temperature inside

In a well ventilated building the TDR can't be higher than 1.0 and the resulting fraction can be expressed as a percentage. The higher the value (closer to one) of the TDR, the better the performance. A higher value indicates that there is a larger temperature difference between outdoors and indoors and more cooling. A negative value indicates that the average maximum temperature inside is higher than outdoors. The TDR concept normalises the capacity to reduce the indoor maximum temperature, as a function of the outdoor swing, permitting comparison of the different series. TDR is calculated for the three series and averaged for all the days in each one. The best TDR is in series 3, which performs much better than the other cells (Fig 10).

The equations that predict TDR as a function of the floor to window ratio (FWR) are:

For the control cell:
 $TDR = -4.352 * FWR + 0.0361 \quad (2)$
 In equation (2) $R^2 = 0.99$

For the green roof with insulation:
 $TDR = -3.9325 * FWR + 0.194 \quad (3)$
 In equation (3) $R^2 = 0.98$

For the green roof without insulation:

$$TDR = 3.0588 * FWR + 0.2955 \quad (4)$$

In equation (4) $R^2 = 0.98$

After TDR is calculated for a building using equations (2), (3), and (4) it is possible to predict the indoor maximum temperature using equation (1) and solving for T_{maxin}

$$T_{maxin} = T_{maxout} - [TDR * (T_{maxout} - T_{minout})]$$

Where outdoor maximum and minimum temperatures, or daily temperature swing, must be known. These equations would be valid in buildings with slab on grade concrete floors with a thickness of 1.5”.

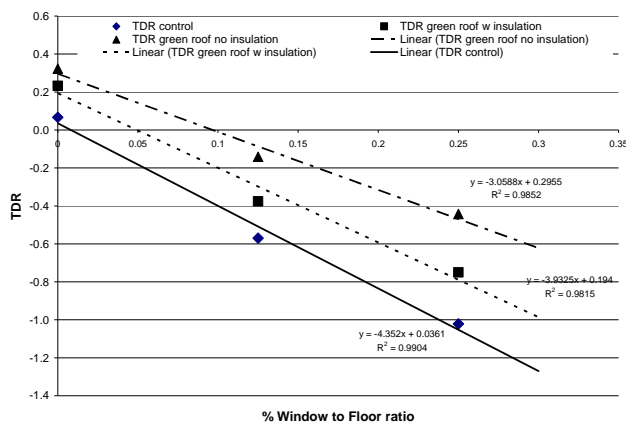


Fig. 10: TDR as a function of the window to floor ratio

Tests in a real building

The green roof was tested in a real size building: the Tijuana low cost housing prototype built at the Lyle Center for Regenerative Studies in Cal Poly Pomona [11]. This house explores the development and integration of low cost sustainable technologies in very low cost housing for Tijuana. The walls are made of papercrete a mixture of cement and paper, the floor slab is concrete and the windows are single pane glass [12].

A low cost green roof similar to the second one built in the test cells has been implemented on the larger west-facing roof. The green roof was built with an impermeable layer directly on top of the roof deck with the perimeter of the roof boxed in to contain the growth medium. The roof is supported by a series of trusses built from reclaimed pallet wood. The same “Cal Earth” bag system that is used in the test cells is used here, but the growth medium, a mixture of native soil and vermiculite to reduce weight. The bags are placed on the roof in rows perpendicular with the downward edge of the roof. The bags are cut in two foot sections that are easy to transport onto the roof. They also provide structure around the soil while the roots establish themselves.



Fig. 11: Green Roof of the Tijuana House

Three series were performed in this building, in the late summer of 2008: continuous ventilation, night ventilation and minimal ventilation with all the windows closed. Results for the series with night ventilation, the same strategy used in the test cells are presented in figure 12. The maximum temperature inside the house is an average of 6.1 C below the maximum average temperature outdoors. The daily temperature swing averages about 21.3 C and the reduction in maximum temperature is about 29% of the average swing.

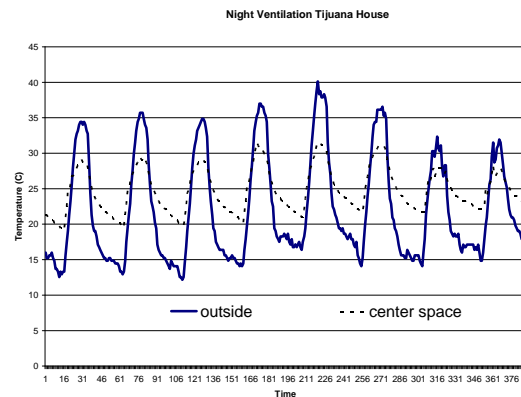


Fig. 12: Green Roof of the Tijuana House

Equation (4) for uninsulated green roofs with concrete slabs was tested. Maximum and minimum outdoor values were used. The south window to floor glazing ratio of the main living space where the main data logger sensor that is placed is 5%. Predicted values using equations (1) and (4) are compared with measured values. A good correlation is observed between the predicted values and measured values on cloudy days (table 1 & Fig 13). Because the house was not built to test these equations there are several variables that could account for the difference in performance between cloudy and sunny days. In the building there are additional windows that did not exist in the test cells, including east facing clerestory windows, the volume to envelope ratio of the space is much larger, and the U value and thermal lag of the walls is much different.

Table 1: Indoor Predicted and Measured Temperatures

| | SUNNY | CLOUDY | CLOUDY | CLOUDY | SUNNY | SUNNY |
|----------------------|-------|--------|--------|--------|-------|-------|
| Predicted Tmaxin= | 34.8 | 28.5 | 25.7 | 25.1 | 30.7 | 35.9 |
| Measured Tmaxin= | 28.3 | 27.9 | 26.3 | 25.2 | 27.1 | 28.1 |
| numerical difference | 6.5 | 0.6 | -0.6 | -0.1 | 3.6 | 7.8 |
| difference ratio | 22.9% | 2.2% | -2.2% | -0.2% | 13.4% | 27.9% |

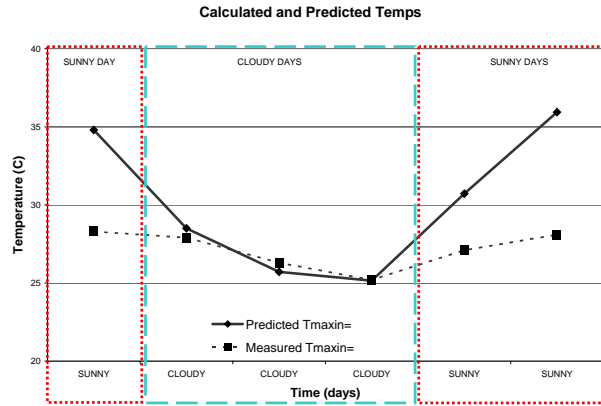


Fig. 13: Green Roof of the Tijuana House

CONCLUSION

A green roof can help cool a space in two ways: the canopy layer reduces the effect of solar gains by reducing the sol-air temperature, and the growth medium acts as a heat sink.

Results of tests over several years with different types of plants, windows, and shading systems, consistently indicate that in this climate, the uninsulated green roof performs better than the insulated green roof or the insulated white roof. This indicates that in a green roof with a soil layer with a density similar to that of earth, and in a warm or mild climate with cool nights it is possible use night ventilation and have the soil layer coupled with the interior of the building. The vegetation in the canopy layer blocks solar gains improving the performance of the thermal mass.

Simple equations are derived from the experimental work that permit to calculate internal maximum temperatures as a function of outdoor maximum temperature, daily swing, and glazing to floor ratios. One of these equations is tested in a real size building with acceptable results on cloudy days. More series should be performed under different climates and with different types of buildings to determine the effect of volume, thermal lag, thermal capacity and other skin variables. Until these series are performed it can be assumed that the applicability range should be similar to that indicated in Givoni and Milne's chart (Fig 14).

Green roofs, when combined with night ventilation can lead to more comfortable conditions inside buildings, with increased energy efficiency. This should give added value to green roofs increasing their applicability.

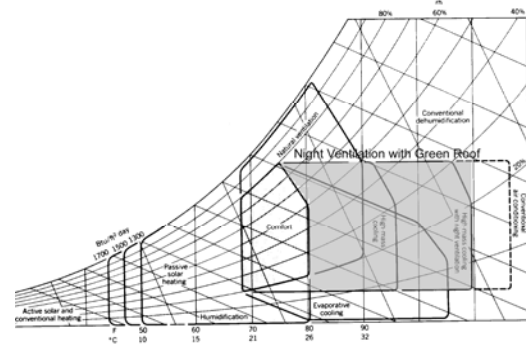


Fig. 14: Applicability of night ventilation with green roofs.

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