EVALUATION OF A DIRECT EVAPORATIVE
ROOF-SPRAY COOLING SYSTEM

Carrasco, A., Pittard, R., Kondepudi, S. N., and Somasundaram, S.

Mechanical Engineering Department,

Texas A&M University, College Station.

ABSTRACT

Roof-Spray cooling systems are being extensively used to reduce the air-conditioning usage in industrial and commercial buildings. In buildings without air-conditioning, evaporative roof spray cooling systems help to reduce the interior temperatures. The spray cooling systems also have been found to increase roof life and decrease maintenance.

The present work involved designing and installing a roof-spray cooling system on a storage building in the Research Annex of Texas A&M University. The roof spray cooling system and the associated hardware were donated and set up on the roof by a commercial vendor. Tests were done during the summer of 1986 to compare the sprayed and unsprayed conditions on the roof surface temperatures, heat transfer through the roof, and the interior temperatures. The results showed that there was an 60 percent reduction in the heat transfer through the roof and also a reduction in inside temperatures.

A numerical simulation was also developed to be able to predict the temperatures and the various heat transfer rates based on a simple energy conservation model. The model underpredicted the temperatures and the heat transfer through the roof when the roof was dry. But the results were closer to the experimental values when the heat loss due to evaporation was also included in the sprayed case.

INTRODUCTION

Direct evaporative roof spray cooling systems are being widely used as a means to decrease air-conditioning costs in both industrial and commercial buildings. Their use is not a new idea, studies have been done dating back to as early as 1939. Because of the "energy crisis", roof spray cooling methods have recently become acceptable and desirable.

The process of roof spray cooling is a simple and fundamental one; the basic concept is to wet the hot surface and cool it down with sprayed water. The main purpose is to keep the heat out before it gets in and reduce cooling costs in residential, commercial, and industrial buildings.

This study was carried out on one of the small buildings at Texas A&M University. The experiment was designed to quantify the amount of heat transferred through the roof. Simultaneously, the effort was made to estimate the impact of the spray system in the hot and humid weather conditions of central Texas. The building tested was number 7500 at the Texas A&M Research Annex in Bryan. It had a flat roof of 1000 square feet, and no air circulation.

LITERATURE REVIEW

The concepts of Roof Spray or Pond methods to cool roofs in hot climates, thereby providing cooling to the inside of the building, have been studied by Houghten, F.C., et al. [1], and recently by Yellot [2] in 1965. Houghten showed, in tests done at the ASHVE Testing Facility in Pittsburgh, Pa., that the method of an open roof pond and a water spray reduces the heat flux through all types of roofs. Yellot studied the use of intermittent water sprays on poorly insulated roofs. Yellot's work also demonstrated the usefulness of the water spray in reducing discomfort levels in cases where the costs of conventional air-conditioning could be prohibitive. Yellot provided a highly simplified energy balance to determine the roof surface temperatures. However, Yellot ignored any relative humidity effects in his model.

Jain and Rao [3] have obtained experimental results on the effect of roof-cooling by evaporation on non-conditioned and conditioned buildings. Their experimental set-up was elaborate, and the study looked at the effects of roof pond, roof spray, and wetted gunny bags on the temperatures and heat flux at the ceiling surface of thick roofs. They concluded that, in the tropics, for the effect of reduced indoor temperatures to be more effective, the roofs needed to be treated. They further confirmed the reduction of indoor discomfort as a result of the use of various evaporative cooling methods. The gunny bag appeared to be the best alternative followed by the roof spray and roof pond, in that order of effectiveness.

Tiwari, et al. [4] considered the transient heat transfer mechanism of the two cases of a roof pond and spray cooling. In their analytical study, they determined the water surface temperature as a function of the environmental conditions. They presented a simple heat-mass transfer analysis to determine the evaporative heat loss as a function of pressures, velocities, and relative humidity using actual weather data in the form of a Fourier series for the city of New Delhi, India. They also expressed the saturation water vapor pressure as a linear function of temperature range of 20 degrees C to 45 degrees C. Their conclusions were extremely supportive of the experimental results of other investigators. More specifically, they reported that the reduction in the heat flux through the roof is greater for lower relative humidities and that wind velocity does not play a major role in the heat transfer mechanism. They also concluded that varying roof thickness does significantly affect the heat flux rates.

Tiwari, et al. [4] considered the heat transfer only through the roof and not the entire building envelope. How-

94

ever, Chandra, et al. [5] performed an analytical study of the problem and determined the overall thermal response of the building and the inside air due to evaporative cooling. They used a periodic heat transfer analysis similar to the familiar Transfer Function method to determine the various heat transfer mechanisms. They also concluded that more cooling was achieved by the method of roof spray rather than by the method of a roof pond.

Rao and Kaushika [6] studied the possibility of using non-convective roof spray ponds with a salt-gradient. They concluded, however, that the effects of convection were beneficial, but that the use of these ponds was not recommended.

The present study involves a two part investigation, experimental and theoretical, of a non-air-conditioned building. This is to quantify both the direct and indirect effects of a roof spray cooling system.

EXPERIMENTAL DESIGN

The building tested, as already mentioned, contained a flat roof construction which consisted of a wooden deck with a thin layer of tar and gravel on top. There was no ceiling added to the inside of the roof, and the walls of the building were also made of wood. Thick black plastic sheets were placed over all the windows to block out solar radiation. There was no air circulation inside the building and it remained empty throughout the test.

The initial set up of the spray system involved several steps. PVC tubing, with special spray orifices, was mounted on wooden blocks. Solenoid valves were connected to the PVC tubing and then to the controller which activated them. The controller was also connected to a 95 degree F thermostat that was located on the roof. The sophistication of the controller was such that the spray time, the interval between sprays, the length of the daily cycle, and the sections to be sprayed could all be manipulated. To measure the amount of water used by the system, a flow meter was installed between the main water line and the controlling valve of the system.

The monitoring of the roof required the construction and installation of eighteen thermocouples to measure the temperature on the outside roof surface and also the temperature differences across the heat flux meters. Ten of the thermocouples were placed directly on the outer roof surface by drilling a hole in the ceiling and encasing the thermocouples in copper tubing. The remainder of the thermocouples were used with thermal flux meters to measure the heat flux through the roof. Four thermal flux meters were built by placing a piece of plexiglass ($k = 0.1125$ $Btu/h\ ft\ F$) with a thermocouple on each side between two aluminum plates and sealing it with epoxy (figure 1). Once the thermal flux meters were built, three were placed flush against the inside of the roof and one was placed flush against the wall. All the thermocouples were the wired to a data logger which converted the signals into usable temperature readings. A psychrometer was built to measure the wet and dry bulb temperatures of the air to calculate the relative humidity. Finally, six standard mercury thermometers were strung down from the roof to give the temperature in the building.

Three basic types of tests were conducted (refer to figure 2):

1. One Section Spraying- The roof was divided into two sections and the spray system was activated on one half of the roof while maintaining the other half of the roof completely dry. This was done in order to evaluate and compare wet and dry roof surfaces under identical weather conditions.

2. Complete Coverage Spraying- Activating the system to spray the entire roof. This test enables temperature profiles inside the building to be monitored. However, to evaluate the cooling benefit, this test needs to be compared to a "Dry Test" conducted on a climatically similar day.

3. Dry Test- The system remains idle. This test is done in conjuction with a "Complete Coverage Spray Testing" to provide reference data.

An analysis was completed on the data collected over the summer and typical days were chosen. A typical day consisted of hot, sunny days which could be assumed climatically similar.
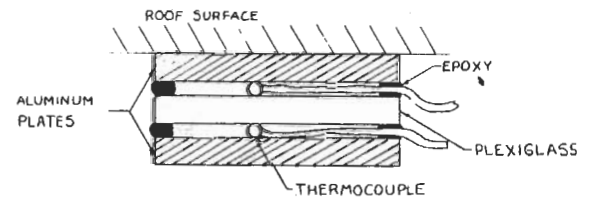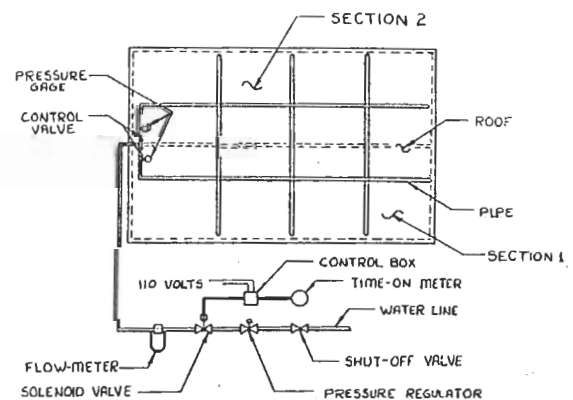

Figure 1. Flux Meter Design

Figure 2. Roof-Top Layout

95

THEORETICAL MODEL

A simple computer program was developed to solve a one dimensional quasi-steady energy balance on an ordinary roof. The main reason behind assuming a quasi-steady state model is the lack of sudden weather changes through the day. Twelve hours of sunny conditions bring a slow change in boundary conditions. Therefore, one may assume constant ambient temperature and solar radiation profiles at predetermined time intervals, and which vary during the day. The computer program periodically solves a steady state energy equation with boundary conditions that are constantly changing during the day.

The basic heat transfer mechanisms can be represented by energy balances at the outside roof surface and the inside roof surface.
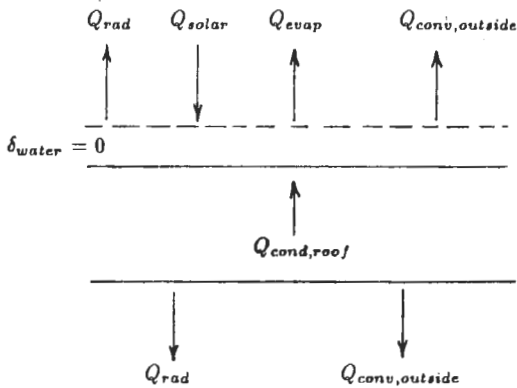
Energy equation on the outside roof surface

$$Q_{cond} = -Q_{rad} - Q_{evap} - Q_{conv,outside} + Q_{solar} \quad Btu/h \ ft^2 \tag{1}$$

Energy equation on the inside roof surface

$$Q_{cond} = Q_{rad} + Q_{conv,inside} \quad Btu/h \ ft^2 \tag{2}$$

An important assumption is considering the water thickness to be negligible since it evaporates on contact with the roof. The water sprayed on the roof adds a constant evaporative heat flux to the energy balance outside the roof and does not affect the convective heat transfer from the roof.

All heat transfer equations may be found in most undergraduate heat transfer books. The equations in this paper are referenced in [7]. It should be noted that there are no capacitance effects being considered due to the thermal mass of the water film or the roof.

The heat conducted through the roof is calculated as follows

$$Q_{cond} = \frac{T_r - T_\infty}{R_r} \quad Btu/h \ ft^2 \tag{3}$$

where

R_r = thermal resistance of roof $F \ h/Btu$
T_r = roof temperature F
T_∞ = ambient temperature F

Both radiation terms (inside and outside) are computed from

$$Q_{rad} = \epsilon\sigma(T_r^4 - T_\infty^4) \quad Btu/h \ ft^2 \tag{4}$$

ϵ (emissivity of roof)= 0.85
σ (Stefan-Boltzmann constant)= $0.1714 \ x10^{-8}$
$\qquad\qquad\qquad\qquad\qquad Btu/h \ ft^2 \ R^4$

It should be noted that wind effects are considered with the outside convection heat transfer term as

$$Q_{conv,outside} = h_o(T_r - T_\infty) \quad Btu/h \ ft^2 \tag{5}$$

where

$h_o = (Nu)K/L \quad Btu/h \ ft^2 \ F$
Nu (Nusselt Number)= $0.037(Re^{0.8} Pr^{0.333})$
Re (Reynolds Number)= $\frac{VL}{\nu}$
V = wind velocity ft/h
ν = kinematic viscosity ft^2/h
Pr (Prandtl Number)= $\frac{\nu}{\alpha}$
α = thermal diffusivity ft^2/h
K = thermal conductivity of roof $Btu/h \ ft \ F$
L = reference length of the roof ft

The inside convection heat transfer is assumed to be a free convection term and it is calculated as

$$Q_{conv,inside} = h_i(T_{r,i} - T_\infty) \quad Btu/h \ ft^2 \tag{6}$$

where

$h_i = Nu_i(K/L) \quad Btu/h \ ft^2 \ F$
$Nu_i = 0.58[4.905(T_{r,i}^2 - T_\infty^2)(L^3 Pr/\nu^2)]^{0.2}$
$T_{r,i}$ = inside roof surface temperature F

The evaporative heat flux equation is given by Tiwari,et al.[4],

$$Q_{evap} = 0.013h_e(P_w - \gamma P_a) \quad W/m^2 \tag{7}$$

where

γ = relative humidity
h_e (convective heat transfer coefficient from water surface to ambient)= $5.678 \ W/m^2 \ C$ [4]
P_a = partial pressure of air Pa
P_w = partial pressure of water vapor Pa

The above equation takes into account the relative humidity effect, which becomes an important factor when implementing the Texas weather. A high relative humidity will decrease the rate at which water will evaporate from the top of the roof.

The computer program developed then iteratively solves for the inside roof temperatures until a balance is obtained

96

for both energy equations (1) and (2). An inside roof surface temperature is assumed and an outside roof surface temperature is computed from the inside energy balance equation (2). Then, using the outside energy balance equation (1) , an inside roof surface temperature is calculated and compared to the originally assumed inside roof surface temperature. The program increases the value of the inside roof surface temperature by small increments until it satisfies both equations.

The model initially requires four input values:

1. Solar radiation data for the day.
2. Ambient temperature for the day.
3. Relative humidity and wind velocity (*miles/hour*).
4. Roof resistance.

A typical output of the program includes:

1. Heat flux through the roof for both wet and dry conditions.
2. Inside roof surface temperature - wet and dry.
3. Outside roof surface temperature - wet and dry.
4. Percent difference between wet and dry conditions.

RESULTS AND DISCUSSION

Based on the experimental results, roof spray cooling provides a substantial reduction in both the roof temperatures and the heat flux through the roof. Percent differences in heat flux ranged from a 20 percent to a 75 percent difference favoring the use of roof spray cooling. Temperatures differed by as much as 25 degrees F on the top of the roof and they corresponded to a 4 to 6 degree F difference in the inside air temperature.

Figure 3 shows the variation of the heat flux through the roof on July 29, 1986. A close observation of the figure indicates that the roof spray system was turned on at about 1:00 PM. The cooling down of the roof led to a heat flux difference of 25 $Btu/hr\ ft^2\ F$ at about 2:15 PM. At later periods of the day, the heat flux in the sprayed side even becomes negative which implies a removal of heat from the inside of the building because of its negative sign. These results were repeatedly observed during the rest of the days and were consistent with results of other investigators [4].

Figure 4 provides the temperatures on the outside surface of the roof as measured on July 29. As in the case of the heat flux through the roof, the temperature differences are very small early in the afternoon, but become extremely large (about 18 degrees F) in the later hours. The roof spray system effectively lowered the temperature on the sprayed side of the roof reducing the heat flux through it.

The temperature of the air inside of the building deserves a more thorough observation. While spraying the roof with water decreases the outside roof surface temperature considerably (about 20 degrees F), the inside roof surface temperature does not undergo a drastic temperature decrease. The dry-roof heat flux is considerably larger than the wet-roof heat flux, therefore the dry-roof temperature difference between the inside surface and the outside surface is larger than

the wet-roof temperature difference between the inside and the outside roof surfaces. This leads a 4 to 6 degree F temperature drop in the inside roof surface temperature. In other words, most of the heat flux differences between the wet and dry conditions occur because of the large outside roof surface temperature differences.

The computer model predictions were consistently good when compared with the experimental data. Figures 3,4,5, 6, 7, and 8 present the predictions and the experimental data for the days of July 29, July 8, and July 24. July 8 was analyzed for the purpose of this paper since it was a typically hot summer day.

A good starting point in the validation of the model is to consider the predicted roof-top temperatures. The temperatures derived from the model for a dry roof seem extremely high when compared to the experimental data. Three basic reasons can be given as to the differences in temperature: the first involves the value of the absorptivity of the roof used in the calculations in the program; the second questions the edge effects generated from the small size of the roof; and the third refers to the formulation of the program without the heat capacitance effects due to the thermal mass of the roof.

1. The value of the absorptivity used was 0.54 [4]. A reduction of this number would mean a reduction in the solar radiation absorbed by the roof. There was difficulty in arriving at this number because of the configuration of the roof-top surface which is made up of gravel and tar.

2. The small size of the roof may affect the computation of the temperatures on the roof by adding a convective term through the sides of the roof and making this more of a two dimensional energy balance. This means that the roof may have experimentaly cooled down faster because of its smaller area than has actually been predicted.

3. The program does not consider the effects of the thermal mass of the roof material or of water. The ability of the roof to absorb heat is limited by its thickness, and it could lead to a lower roof-top temperature and inside temperature.

Roof-top surface temperature predictions for a wet roof were quite accurate compared to the experimental data. The largest difference was about 5 degrees F, and the trends of the temperature profiles agreed with each other. The roof surface temperature was easily controlled with the water sprayed on it, leading to an environment partially independent of solar radiation and ambient temperature.

In analyzing the predicted heat flux through the roof, one could almost parallel conclusions with those for the temperature. The controlled environment originating from the roof spray system allowed for an accurate prediction of results because of the dominant evaporative heat flux. The experimental heat flux, though not smoothly, decreased rapidly from its starting point until it became almost zero. The calculated data similarly contained itself within a range of 3 $Btu/hr\ ft^2\ F$

97

The dry roof case, on the other hand, did not yield good results. Because of the wrong temperature predictions, the heat flux through the roof was not consistent with experimental results either. The predicted inside roof temperatures were higher in comparison to the experimental results. The total effect of this calculation is a decrease in the difference between the inside surface temperature and the outside surface temperature. Hence, a smaller value of heat flux is computed when this difference is multiplied by the resistance of the roof. The largest heat flux difference of predicted values from experimental values was about 7 $Btu/hr\ ft^2\ F$, and the profile of their curves was consistently similar.

CONCLUSION

The results obtained from the model agree well with the experimental results. Although predictions for dry conditions are not accurate, the model produces very close results when the heat loss due to evaporation is included. The results showed that evaporative cooling has a positive effect on the reduction of cooling loads for a building. There was a 60 percent reduction in heat transfer and a 20 percent reduction in the roof-top surface temperatures.

REFERENCES

1. Houghten, F.C., et al, "Summer Cooling Load as Affected by Heat Gain Through Dry, Sprinkled and Water Convered Roofs", ASHVE Trans., Vol. 46, pp. 231-42, (1940).

2. Yellott, J.I., "Roof Cooling with Intermittent Sprays", ASHRAE 73rd Annual Meeting, June 1966.

3. Jain and Rao, "Experimental Study on the Effect on Roof Spray Cooling on Unconditioned and Conditioned Buildings", Building Science, Vol. 9, pp. 9-16, (1974).

4. Tiwari, G.N., Kumar, A., and Sodha, M.S., "A Review-Cooling by Water Evaporation Over Roof", Energy Conversion and Management, Vol. 22, pp. 143-53, (1982).

5. Chandra et al, "Thermal Performance of a Non-Air-Conditioned Building for Passive Solar Air-Conditioning: Evaluation of Roof Cooling Systems", Energy and Buildings, Vol. 8, pp. 51-69, (1985).

6. Rao and Kaushika, "Winter Temperature Control in a Non-Air-Conditioned Building with a Non-Convective Roof Pond", Energy Conversion and Management, Vol. 24, pp. 5-14, (1984).

7. Incropera, Frank P., De Witt, David, Fundamentals of Heat and Mass Transfer, New York, John Wiley & Sons, Inc., (1985).

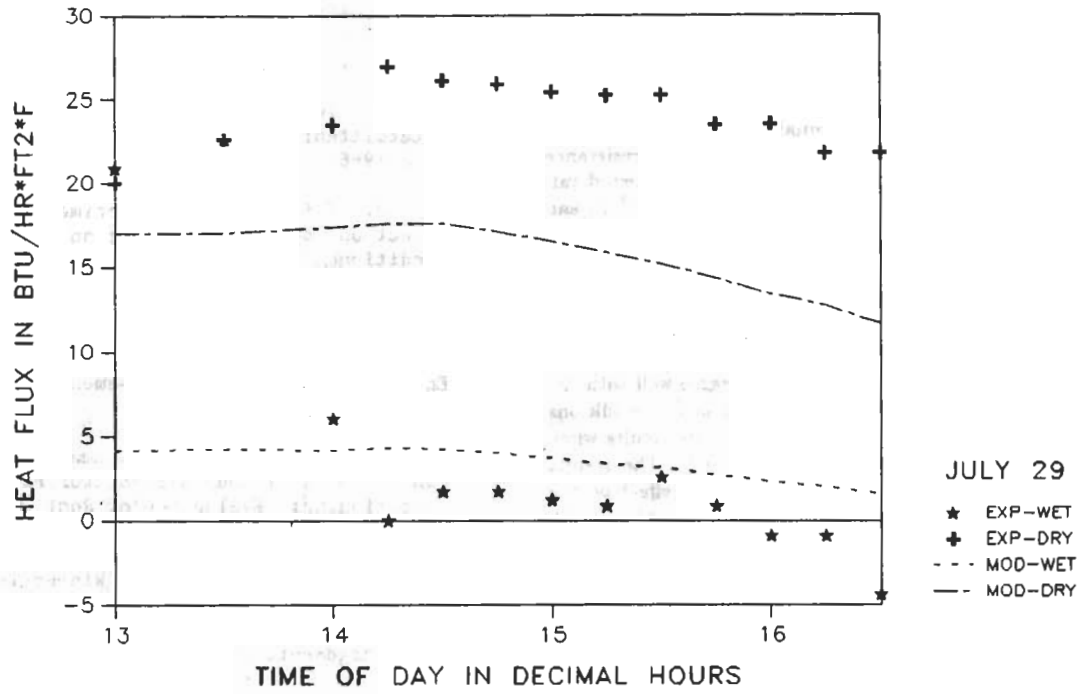8. Kondepudi, S.N., "A Simple Analysis of Evaporative Cooling of Roofs", Project Report, (1986).

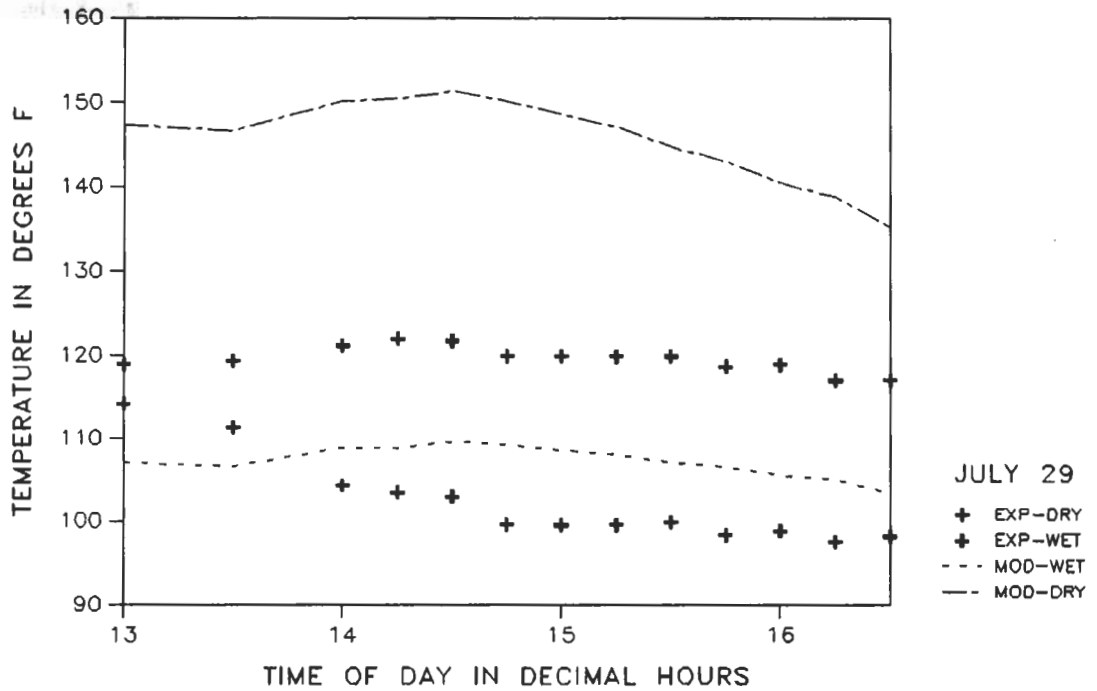Figure 3. Heat Flux Through the Roof – July 29

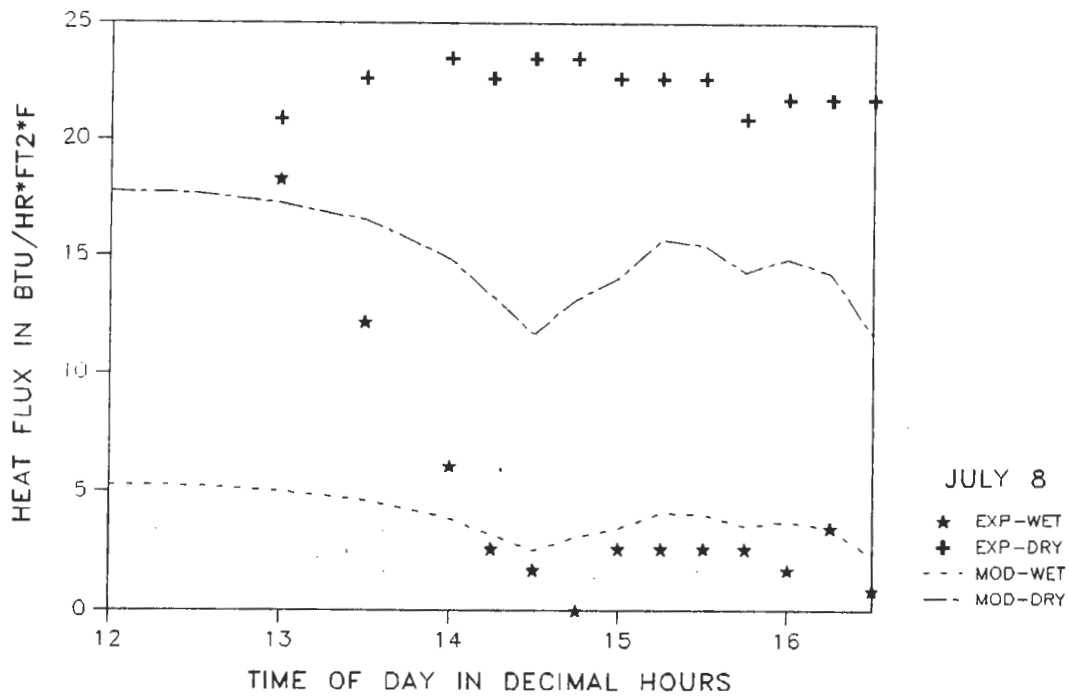Figure 4. Roof-Top Temperatures – July 29

Figure 5.   Heat Flux Through the Roof - July 8
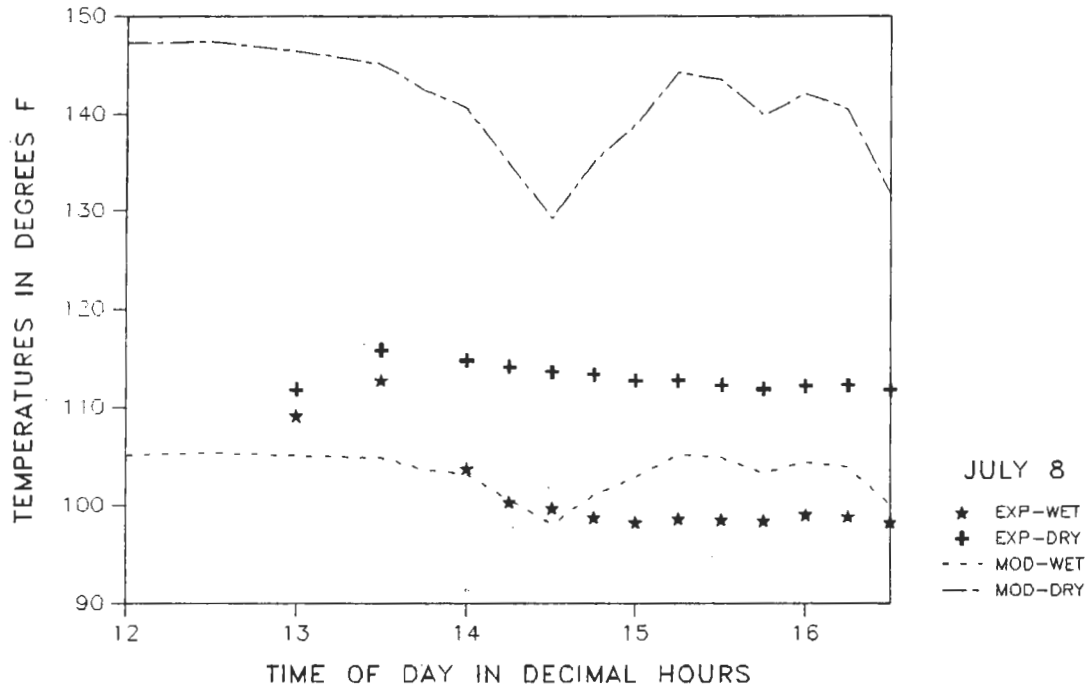

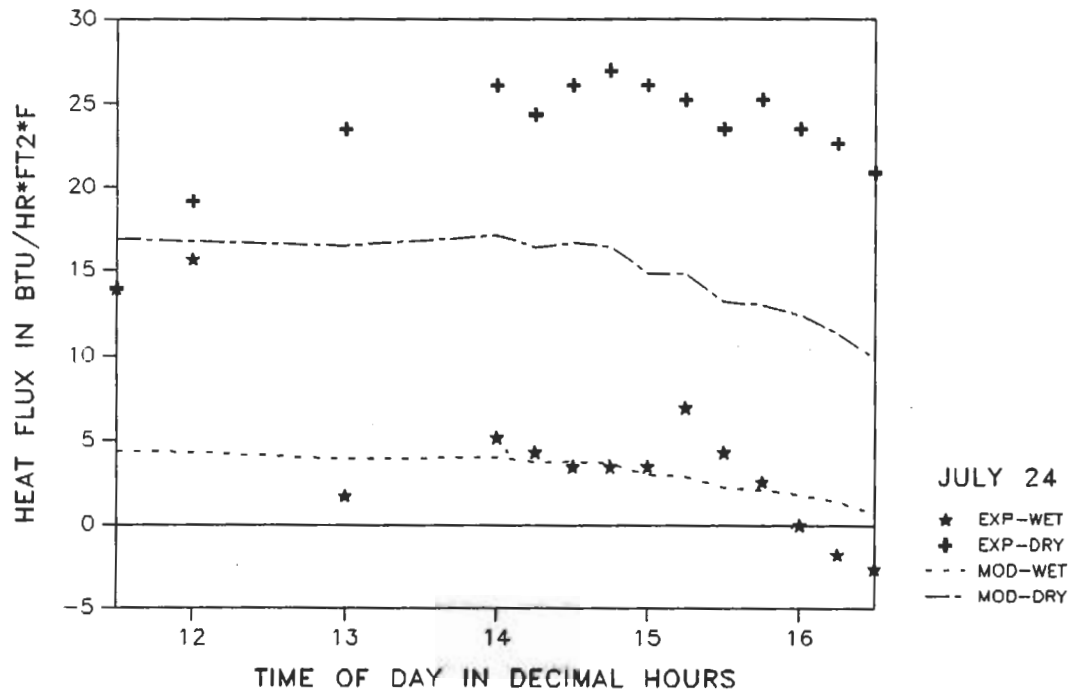Figure 6.   Roof-Top Temperatures - July 8
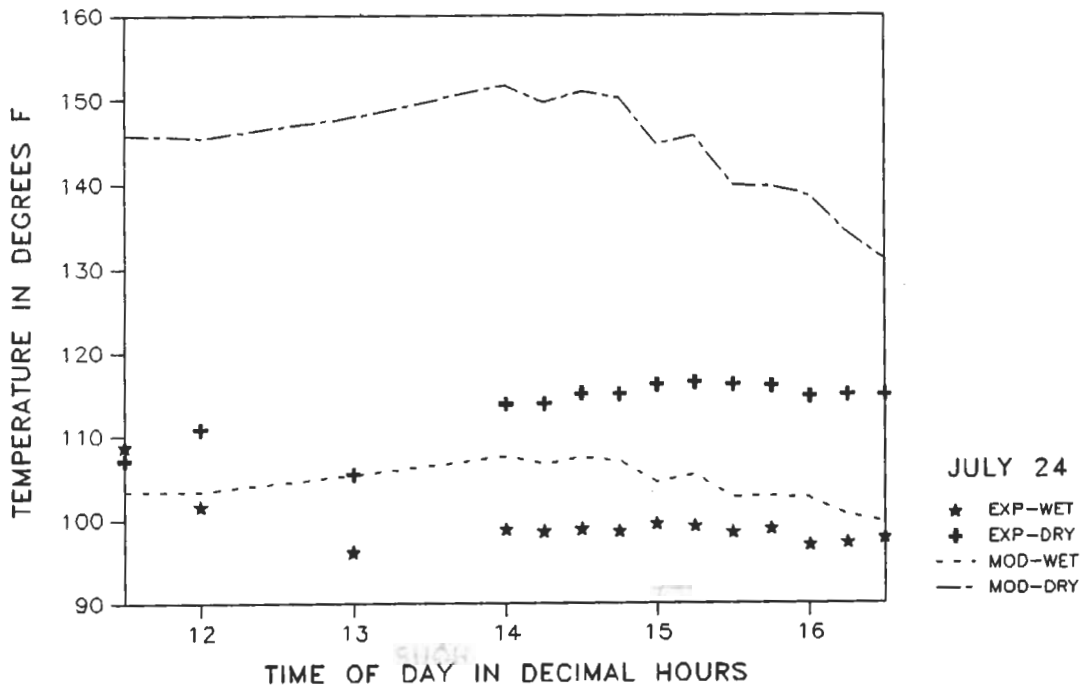
Figure 7. Heat Flux Through the Roof - July 24

Figure 8. Roof-Top Temperatures - July 24

101