HEAT TRANSMISSION THROUGH
FARM BUILDING METAL ROOFS
UNDER SUMMER CONDITIONS

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ABSTRACT

HEAT TRANSMISSION THROUGH FARM BUILDING
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By

Ilse Vierma de Trujillo

The objective of this study was to evaluate the sol-air temperature equation of heat flow into open livestock buildings in hot climates. Roof, air and globe temperature measurements were made under Michigan conditions. Venezuelan climatic data were also used for calculations of possible radiation heat loads under tropical conditions.

Michigan tests were conducted in the Michigan State University Beef Cattle Research Center. A section of the East-West oriented wing of the cattle barn was used for the environmental measurements. The South side of this gable roofed structure was open and the North side had continuous mobil-type windows.

The sol-air temperature approach is a computation method designed to include the radiant heat load on an exposed surface and the resulting heat transfer through that exposed roof or side wall. The sol-air method was

evaluated in this study by measure roof surface temperatures, air temperatures, air velocities and black-globe temperatures. Heat flow calculations based upon these measurements were compared to sol-air computations.

Solar radiation intensity data were obtained from the Michigan State University meteorological station located about one mile from the test building. Environmental measurements were made during the higher temperature hours (10:00 a.m. to 4:00 p.m.) of a few days in September of 1970 and June of 1971.

One Black-globe thermometer was located outside of the cattle building and three inside at heights of 3, 6 and 10 feet.

An analysis was also made of the possible justification for insulation of metal roofs for minimizing the heat stress on the housed animals during hot weather. Tests were not made in this study to confirm any possible advantages.

Approved Merle L Esmay
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HEAT TRANSMISSION THROUGH FARM BUILDING METAL ROOFS UNDER SUMMER CONDITIONS

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A los amigos, a mis padres,

a Gustavo y Valentina.

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1. INTRODUCTION

An animal's environment as defined by Bond (5) is the total of all external conditions that affect its development, response and growth. It could include, for example, the type and slope of floor as part of the piglet's environment.

The external factors that affect the regulation and balance of animal heat are important. These climatic factors include air temperature, moisture, radiation, light and air velocity.

Climatic factors directly affect production and growth of livestock and birds. First of all domestic animals are homeothermic and thus attempt to maintain a constant body temperature. Animals, like human beings, can exist only within a limited range of body temperature; they must maintain a rather delicate balance between the heat produced within their body and the heat they lose to or gain from their environment.

The thermo environment surrounding the animal has a direct influence on the amount of heat exchanged. Physiological adjustments must be made by the animal to maintain a body heat balance. If the heat balance becomes unbalanced it can reflect directly on growth, production and health. Therefore, these environmental factors are of great importance in livestock and poultry production.

Cold weather is the dominant environmental problem in the northern areas of North America and Europe, while in tropical countries the critical problem is hot weather.

In cold weather the problem is to protect the animal from low temperatures, ventilate to remove water vapor and detrimental gases and provide enough oxygen.

In hot weather regions the problem is with high air temperature, high solar radiation and high humidity (depending upon the relative humidity on the season of the year) (11).

In some tropical areas, and that is the case in Venezuela exists two marked seasons; winter and summer. Winter season is considered the rainy season; high rainfall, lower ambient temperature, high humidity. Summer season is considered to be the dry season; little or no rainfall; higher air temperature and low humidity (12).

These climatic conditions of high solar radiation combined with high environmental wet and dry bulb temperatures affect animal productivity adversely. Domestic animals and chickens are affected to a greater extent than man, because man can sweat and livestock cannot (5).

The body temperature for dairy cattle, beef cattle, sheep and swine is about 102°F and for laying hen 106°F (14). When body temperature surpasses these levels, due to the environment, the animals are under "thermal stress." If body temperatures continue increasing the homeothermic mechanism fails and the animal will die (5).

An animal needs food to substain its metabolic life process. Part of the food is utilized by the body processes, part is lost in urine, feses and gases and part must be dissipated from the body as heat energy. The excess heat must be dissipated from the body or a heat balance does not exist.

Air temperatures above the animal's body temperature brings about some convective heat gain and tends to cause "thermal stress." Evaporation is then the only means of heat dissipation available to the animal, so it cuts down on feed intake and increases its rate of respiration (22). The resulting heat stress and reduced food consumption causes reductions in weight gain and other products such as milk or eggs.

The main problem then in tropical climates is for animals to dissipate excess metabolic heat without undesirable physiological reactions. This can be enhanced by means of environmental control.

Agricultural engineers have been working to improve environmental control. Any economic improvement of the thermal environment for livestock and birds may be considered to be functional environmental control (8).

A building is part of the animal's environment and roofing materials are part of that building. The objective of this study was to investigate the rate of heat flow through metal roofs of open livestock buildings. The sol-air temperature approach was used for analytical purposes. A second part of the study pertained to measurement of actual roof and black-bulb temperatures to check the sol-air method of analysis. The possible radiant heat load on animals was analyzed, roof insulation was considered and projected radiant heat loads under tropical conditions were made.

2. REVIEW OF LITERATURE

The attainment of hot weather comfort for animals is a problem in heat transfer. Animals may dissipate heat by conduction, convection radiation and evaporation. The three basic means of heat transfer depend on the temperature of the ambient air and surroundings (22). Evaporation depends on the vapor pressure differences between the ambient air and evaporative surfaces.

2.1 Heat Loss by Convection

Temperature differences and air velocity directly effect convective heat losses. Cooling can be done by air conditioning equipment, and velocity increased by using fans.

According to Bond (8) complete environmental control can be accomplished only with a well-designed air conditioning system. Air conditioning systems for livestock have not been economically practical; and there are dust filtration problems if the air is recirculated too much along with ammonia accumulation.

The idea of partial air conditioned system was tested by Hahn, *et al*. (19). Only the air inspired directly by dairy cows was cooled as an alternative to total air conditioning. An increase in feed intake and milk production resulted. They concluded, however, that cows will produce more and eat more while under less physiological stress due to the improved heat dissipation when breathing cooled air in a hot environment, but that only total environmental control would provide maximum production and relief from heat stress.

2.2 Heat Loss by Evaporation

Low humidity air is advantageous for evaporative cooling because it maximizes vapor pressure differences and the potential for absorbing moisture from the wetted surfaces of an animal. Evaporative heat loss can continue in hot weather when air temperatures are above body temperature so is beneficial in summer conditions (13).

Water sprays have been used to cool the animals. Kelly and Ittner (22) used sprays under aluminum shades to wet beef cattle. Cattle made little use of the shower until they were changed from a mist spray to a more wetting shower. The showers were modified to provide a coarse spray and the head of the shower was brought down to within 6 feet of the floor. The coarse spray soaked the cattle and caused a drop in respiration rates and body temperatures. Wetted animals quite often had body temperature reductions of 2 or 3 degrees, and respiration rate drops of 20 or more per minute within one half hour after wetting.

Water sprays have also been used on birds. The main benefit has been to reduce mortality from heat prostration. Little benefit to egg production or broiler growth was found by Wilson, *et al*. (33).

2.3 Heat Loss by Conduction

Heat dissipation from animals may also be by conduction. This necessitates body contact with a cool floor, walls or water. One of the practical cooling devices for swine has been the wallow. This combines conductive losses to a cool liquid with evaporative cooling from the wetted surfaces (20).

2.4 Heat Loss by Radiation

Radiation heat exchange is continuous between all objects. If they are of different temperature there is a net gain to the cooler object. Animals can dissipate heat by radiation to a cool surrounding. May be influenced by various structural and environmental control means (9).

2.5 Radiant Heat Load on an Animal

The greatest source of radiation is the sun. An animal in the sun receives radiant energy from four sources: (a) direct beam solar energy from the sun, (b) diffuse sky radiation that has been scattered, reflected, and diffused out of the original beam, (c) atmospheric radiation emitted by particles or gases in the atmosphere, and (d) emitted and reflected energy from surrounding terrestrial objects (7). The radiant heat load on an animal in the sun as measured by black globe thermometer by Kelly, et al. (23) was found to be 244 BTU per hour square feet (of animal surface). The total radiation was subdivided into 121 BTU per hour square feet, for radiation from the sun and sky, 16 BTU per hour square feet for radiation from the horizon and 107 BTU per hour square feet for radiation from the hot ground. A shaded animal does not receive the direct solar beam; but is exposed to indirect solar radiation as diffused sky radiation and reflected and reradiated from the ground, shade and surrounding objects (9).

2.6 The use of a shade for environmental control

The most economical means of environmental control for animals in tropical countries may be a shade. A simple shade can reduce the incoming radiation and consequently the radiant heat load on the animal. A reduction of from 30 to 50 percent of the total radiant heat load on an animal was found by Bond, et al. (7).

In other work Bond, et al. (2) found that the shade reduced the heat load from 244 BTU/hr (sq ft) of animal surface to 167 BTU/hr (sq ft). A shade reduces the direct radiant heat load from the sun and the sky and substitutes shaded area for part of the hot ground, but it adds a new source of energy; the shade material itself.

Kelly, et al. (23), measured thermal radiation from various sources surrounding a shaded animal they found in one example that 28 percent of the total radiant heat load came from the sky; 21 percent from the shade material; 18 percent from the sunny ground and 33 percent from shaded ground.

2.7 Orientation of Shade

Usually shades in the United States are quite often oriented with the long axis North and South. Thus the moving shadow allows direct sun drying of the ground under the shade sometime during each day. In tropical regions the shades are more often oriented with the long axis East and West (8).

Kelly, et al. (23) studied the orientation of shades as an important factor which accounts for the amount of radiant heat load on the animals. They found that a shade with its long axis oriented East to West will provide a cooler environment than one with a North-South orientation. Ground temperatures will be lower because the ground will be shaded for a greater part of the day. Another advantage of the East-West orientation is that a great portion of the shadow lies to the North of the shade, providing possible exposure to the colder North sky. Kelly, *et al*. (24) and Bond (8) have shown that the North area of a clear sky is generally cooler than other areas of the sky.

2.8 Shade Size

Kelly, *et al*. (23) studied the effect of shade size on the reduction of radiant heat load on animals. As the shade size increases there is more shaded ground as compared to hot ground, therefore the animal receives less radiation from the ground. However at the same time the portion clear sky for radiant cooling is smaller. In summary the radiant heat load on animals is affected little by shade size.

A later study by Kelly, *et al*. (26) pertained to the shade area requirement for beef feed lots. An increase in the average daily gain was observed when yearling steers were provided 48 square feet of shade per head as compared with 27 square feet per head.

2.9 Shade Height

Shade height was studied by Kelly, *et al*. (23), they found that the radiant heat load on animals under high shades was less than under low ones.

R. L. Givens (15) tested three different heights of artificial shades for cattle in the southeast (formerly

Tifton, Georgia). Three shades 12 by 24 feet were erected at heights of 6, 9 and 12 feet and each covered with galvanized metal. He concluded that radiant heat load on animals in the southeast was greater under high shades than under low ones. The 12 foot high shade gave a value of 189.7 BTU/hr (sq ft) for radiant heat load at 12:00 noon and the radiant heat load under the 6 feet high shade was 175.1 BTU/hr (sq ft) at the same time. There was evidently no thermal comfort for shades over six feet high.

Bond, *et al*. (7) studied the influence of shade height on the radiant heat load on the animal. They found that an animal receives more diffuse solar energy reflected from the shade material from a high shade than from a low one. An animal *under the center* of a low shade receives less total radiant energy from the surroundings than an animal under the center of a high shade, but the influence of shade height is reversed when an animal is at the *center of the shadow* of the shade.

2.10 Animal Location Under the Shade

Shade height has been shown to be related to the location of animals under the shade. Also the height of the animal above ground effects the radiant heat load. Hogs or chicken being closer to the cool shadow and away from the hot underside of the shade material will receive less amount of radiant energy per unit body surface than taller animals like cattle (7).

Kelly, *et al.* (23) further showed that radiant heat loads on chickens increased with height above the ground.

2.11 Shade Materials

Kelly, *et al.* (23) showed that 21 percent of the total radiant heat load on an animal may come from the shade material. This varies with the temperature of the roofing material; thus, the cooler the material the less the heat will be radiated to the animal. Many studies have been conducted to test shade materials. Kelly, *et al.* (22) used four different materials and tested effectiveness of reducing solar radiation. The four materials tested were: wood, hay, aluminum and galvanized iron. At 12:00 noon with an air temperature of 99°F, the energy measured under the hay shade was 181 BTU/hr (sq ft), 190 BTU/hr (sq ft) under the aluminum shade, 193 BTU/hr (sq ft) under the galvanized iron shade and 223 BTU/hr (sq ft) under the wood slat shade. At the same time the incoming solar radiation was 527 BTU per hour per square foot which means that the hay covered shade cut off 1.7 percent more the incoming solar energy than did the aluminum shade; 2.3 percent more than the galvanized iron and 8 percent more than the wood slat shade.

The use of paint for altering the radiation characteristics of shade materials was studied by Bond, *et al.*

(2). White paint has a high reflectivity value for short wave-length radiation (low absortivity) and high emissivity for long wave-length radiation. Black paint in contrast has a low reflectivity and high absortivity (30). Several paint combinations of black and white were tested. White top surface painted aluminum sheets were up to 15°F cooler than unpainted aluminum sheets. And white painted galvanized iron sheets were as much as 50°F cooler than unpainted ones. They concluded that the best paint characteristics were white on the top and black on the bottom.

Kelly, et al. (25) continued studying different shade materials and tested fifty different materials that might be used for shades. These materials ranged progressively from hay through aluminum, galvanized steel, asbestos cement sheets, plywood, several types of plastic and finally snow fence. As in previous studies hay was found to be one of the best materials for shade construction, with respect to its thermal qualities. (In tropical conditions this material is not recommended because it is a wonderful shelter for all kinds of insects.) This was attributed mainly to its relatively high insulating value and its convective heat dissipation ability. Aluminum was found to be a good shade material and if painted white on the top and black on the bottom was improved considerably. Galvanized steel was found slightly less effective than aluminum. Painting the top white and the bottom black increased its effectiveness markedly. Snow fence was found to be the least effective of all materials tested.

Kelly, et al. (25) and Bond, et al. (6) tested the effectiveness of 50 materials and rated the effectiveness value "E" as a ratio of the reduction in radiant heat load to that of standard embossed corrugated aluminum. The standard aluminum was assigned an "E" value of 1:00. A material with an "E" value greater than 1 was more effective than aluminum in reducing the radiant heat load. A material with a lower value was less effective.

2.12 Types of Shade

Different roof types were tested by Neubauer, et al. (28). Temperatures measurements were made on several kinds of black and white roofs and panels exposed to the sun at various slopes and orientation. The effective cool sky exposure was to the North during the middle of the day but faced toward West or East in the morning and afternoon, respectively. The type of roof was not found to be as important as location and time of the day. A good shade should be well ventilated, sloped up and toward the North, be well insulated and colored white on top.

Hahn, et al. (18) studied the surface temperature differences that exist between metal roofs exposed to solar radiation and wind. They found an uneven distribution of temperatures over the surface of each plate and differences in surface temperatures were caused primarily by wind. The results of this study point out the importance of identifying the location of temperatures of metal roofs or metal sheets exposed to solar radiation and wind, in order for such temperatures to be meaningful.

2.13 Effect of Surrounding Objects on an Animal's Radiant Heat Load

Surrounding buildings and objects greatly effect the animal's environment. Radiant heat load on the animal can be reduced by a grass surround instead of bare ground, concrete or black-top (9). Ittner, *et al.* (21) made some measurements at Davis and found when air temperature was 31.8°C (89.2°F) the surface temperature of clover and the ground under it was near that of the air; while for bare ground the surface temperature was 60°C (140°F), for gravel 50.2°C (122.3°F), concrete 48.3°C (118.9°F) and black-top 49°C (120.2°F). Radiation from nearby buildings can add to the animal's radiant heat load, particularly if it is a reflective surface exposed to the sun.

Bond, *et al.* (4) found a radiation value of 844 Kcal/hr(m^2) [311.43 BTU/hr(ft^2)] from white painted galvanized steel building in the sun, and 499 Kcal/hr(m^2) [184.13 BTU/hr(ft^2)] from the shaded side of the building. Radiation from an unpainted galvanized steel building was

627 Kcal/hr(m^2) [231.36 BTU/hr(ft^2)] from the sunny side and 467 Kcal/hr(m^2) [172.12 BTU/hr(ft^2)] from the shaded side.

The radiant heat load on the animals can be reduced to make a better environment and improve productivity. Buildings, as part of the animal's environment have an important role in livestock enterprises. In tropical countries animal shelters, particularly those for cattle, are built essentially as shades consisting of a roof and possibly two side walls. More elaborate buildings are necessary in some cases. In temperate climates insulating materials are used to minimize heat losses to the outside during cold weather. Insulation has not been used in tropical countries to minimize heat gain through the roof from the outside. Some insulating materials have however been tested and recommended for summer conditions (16).

If the total amount of heat flow through the roof which may represent 21 percent of the total radiant heat load (23), can be reduced, a better environment for the farm animals will be provided for tropical conditions.

3. FACILITIES AND EQUIPMENT

3.1 The Building

The data were collected at the Beef Cattle Research Center at Michigan State University.

The building is a single story, clear span barn, consisting of two sections; the East and the West. The data were collected in the East section which has its long axis oriented exactly East to West. The building is open to the South and closed on the North by a mobil-type window. The North side of the building was kept completely open as it normally is in hot weather. The building has a gable roof of aluminum. Figure 1 shows the South side of the East section of the building and Figure 2 shows the type of roof. The East section of the building where the study was conducted is 111 feet long and 30 feet wide. A floor plan of the cattle pen with location of Black globe thermometers is shown in Figure 3.

3.2 Equipment

Roof surface temperatures were measured with Copper-Constantan Thermocouples installed at the center of the roof. Location of thermocouples are shown in Figure 4 and Table 1.

Figure 1. View from the south side of the east section building.

Figure 2. Lateral view of the building, showing the roof type.

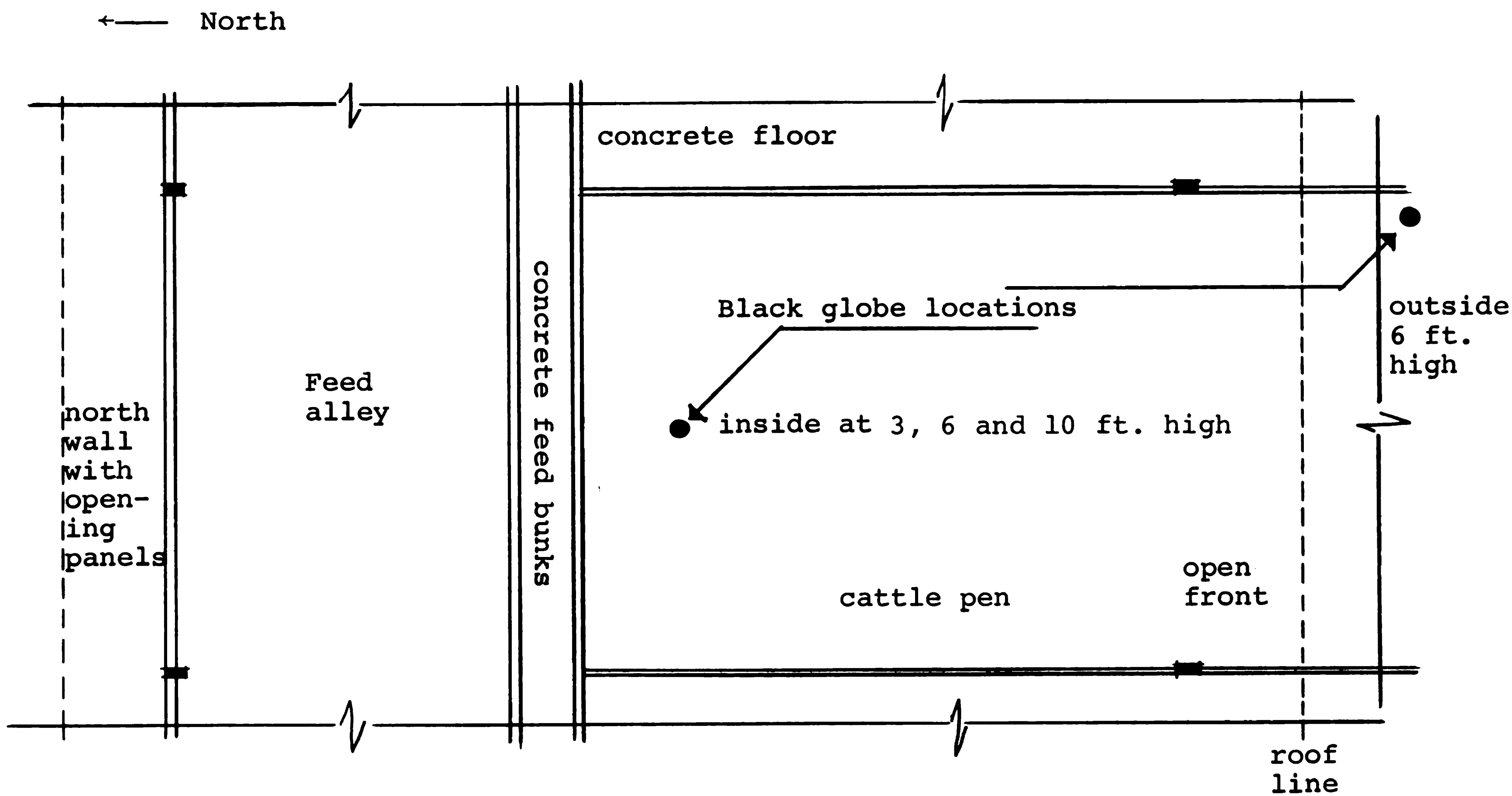


Figure 3. Floor plan of cattle pens where Black globe thermometers were located.

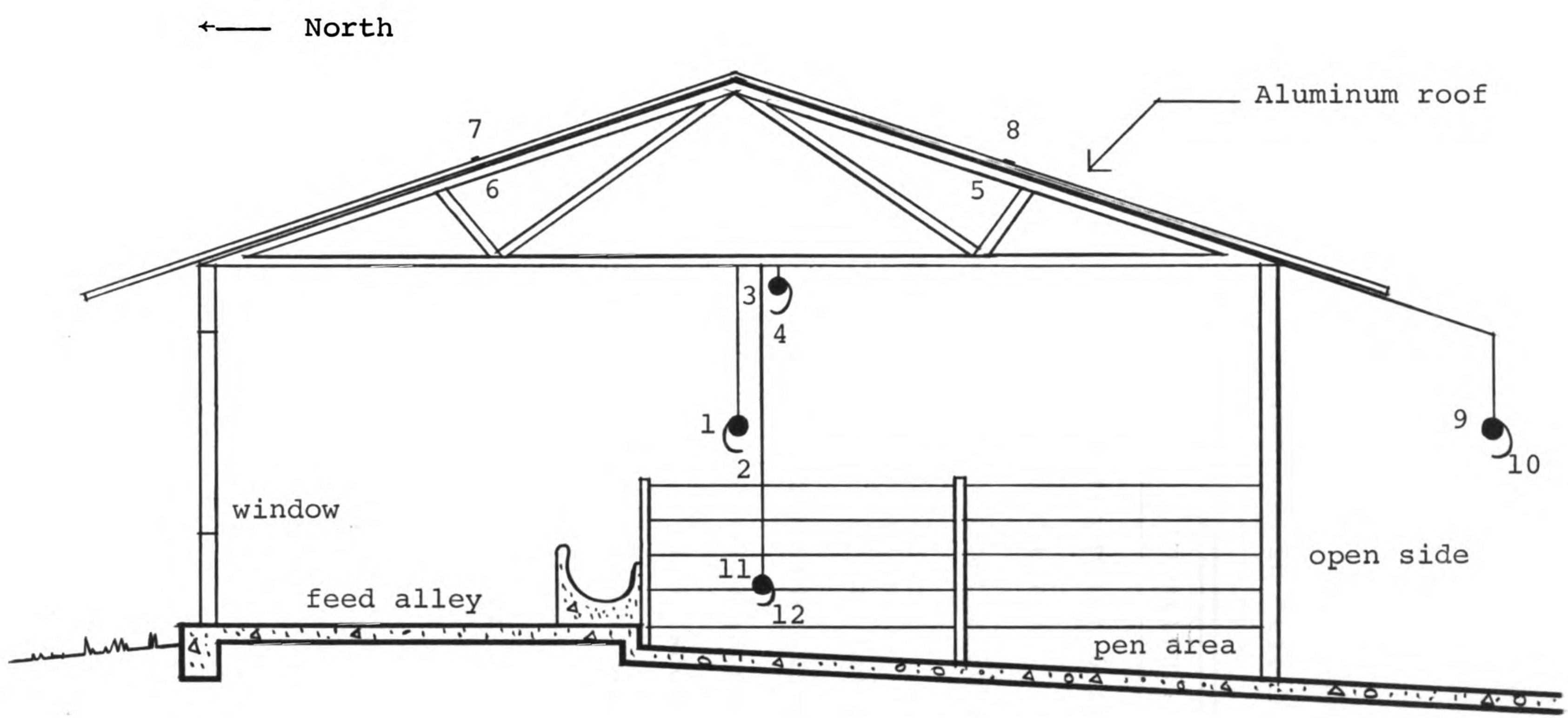


Figure 4. Cross section of East section with thermocouples and Black globe thermometers location.

Table 1. Thermocouple locations in test building.

Thermocouple	Location
1	Black-globe thermometer 6 feet high
2	Inside air temperature
3	Black-globe thermometer 10 feet high
4	Inside air temperature
5	Roof surface underside (south slope)
6	Roof surface underside (north slope)
7	Roof surface top side (north slope)
8	Roof surface top side (south slope)
9	Black-globe thermometer outside 6 feet high
10	Outside air temperature
11	Black-globe thermometer 3 feet high
12	Inside air temperature

Black globe thermometers were used to measure the radiant heat load. In the test conducted during the summer of 1970 two thermocouples were placed inside the building; at 6 feet and 10 feet high; one was placed outside the building under the sun at 6 feet high. In the second test conducted in the summer of 1971 another Black globe thermometer 3 feet high was placed inside the building.

Thermocouples were located two inches away from the Black globe to measure air temperature (3). Black globe thermometers were built from ping pong balls according to Pereira specifications (29). Figures 5 and 6 show Black globe thermometers and their location.

Air velocity was measured with a hot wire anemometer in feet per minute.

Radiation values were obtained from the Michigan State University Meteorlogical Station at South Farm, East Lansing, approximately one mile away from the building.

A 12 point Brown-Honeywell recording potentiometer was used to record thermocouple output for the test period.

Tests were conducted during September 1, 2, 4, 5, 9, 1970 and June 27, 28 and 30, 1971.

Temperatures were measured during each day from 10:00 a.m. to 4:00 p.m. Data for 3 days of 1970 and 2 for 1971 were analyzed; the days chosen were the most representative of all; clear days with higher radiation measurements.

Figure 5. Location of black globe thermometers.

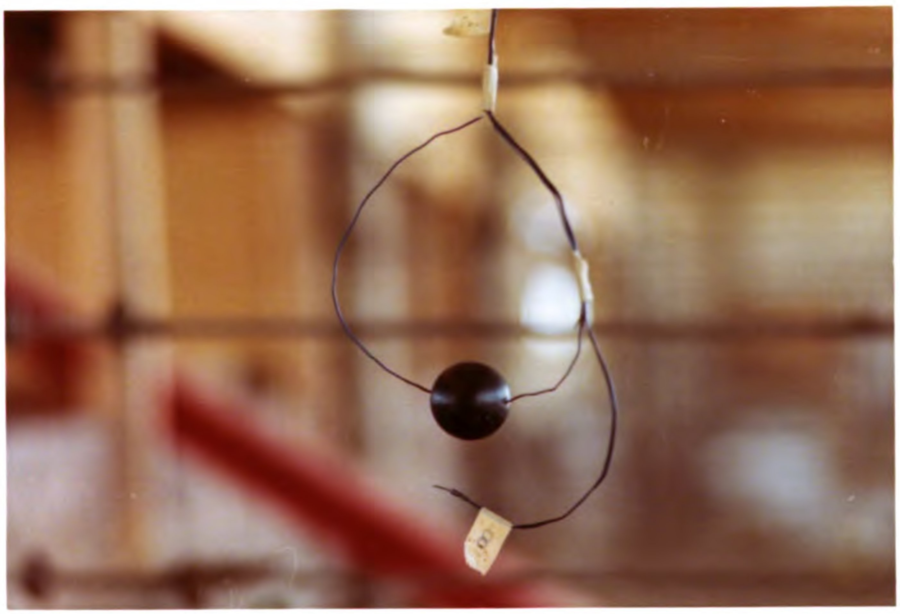


Figure 6. Black globe thermometers made from ping pong balls.

4. THEORETICAL ANALYSIS

Heat flow through the roof was computed using two methods: one was the sol-air temperature approach and the second was based upon measured roof surface temperatures.

4.1 Sol-Air Temperature

The sol-air temperature "t_e" is an equivalent outdoor air temperature which in the absence of all radiation exchanges gives the same rate of roof heat transfer that exists with the actual combination of incident solar radiation, radiant energy exchange with the sky and the outdoor surroundings and convective heat exchange with the outdoor air (1).

The sol-air temperature as developed by Mackey and Wright (27) is:

$$t_e = t_o + (\alpha \cdot \frac{I}{f_{co}}) \qquad (4.1)$$

where:

t_e = sol-air temperature °F

t_o = outside air temperature °F

α = solar absortivity of the outside surface

I = the intensity of solar radiation incident upon the outdoor surface in BTU per hour per square foot of surface

f_{co} = convective film coefficient on the outside surface. It is the time rate of heat exchange by radiation, conduction and convection of a unit area of a surface with the surroundings, including air and other fluids BTU/hr (sq ft) (°F) (1)

4.2 Intensity of Solar Radiation "I"

The intensity "I" of solar radiation incident upon the outdoor surface is (1):

$$I = I_{dn} \times K \tag{4.2}$$

where:

I_{dn} = total incident radiation on a plane normal to the sun's ray or direct normal radiation [BTU/hr (sq ft)]

K = cosine of the angle of incidence Θ

4.3 Angle of Incidence Θ

Angle of incidence Θ is the angle between the rays of the sun and a line perpendicular to the surface being considered (14).

When the roof surface is horizontal the angle of incidence is:

$$\Theta = 90 - \beta$$

where:

β = solar altitude

When the roof is sloped, the value of the angle of incidence Θ is a function of the roof slope. For gable type roofs the angle of incidence will have two values; one for each slope and as affected by the orientation of the buildings (Figure 7).

In this study, the building has its long axis oriented East and West thus the angle of incidence Θ is:

For the South facing slope:

$$\Theta = 90° - r° - \beta \qquad (4.3)$$

For the North facing slope:

$$\Theta = 90 + r - \beta \qquad (4.3a)$$

where:

r = angle of roof's slope (see Figure 8)

β = solar altitude

4.4 Solar Altitude β

The altitude angle β is the angle in a vertical plane between the sun's rays and the projection of the sun's rays on the horizontal plane (30).

Solar altitude β can be computed for any location in the northern hemisphere from the equation (30):

$$\sin \beta = \cos L \times \cos \delta \times \cos H + \sin L \times \sin \delta$$

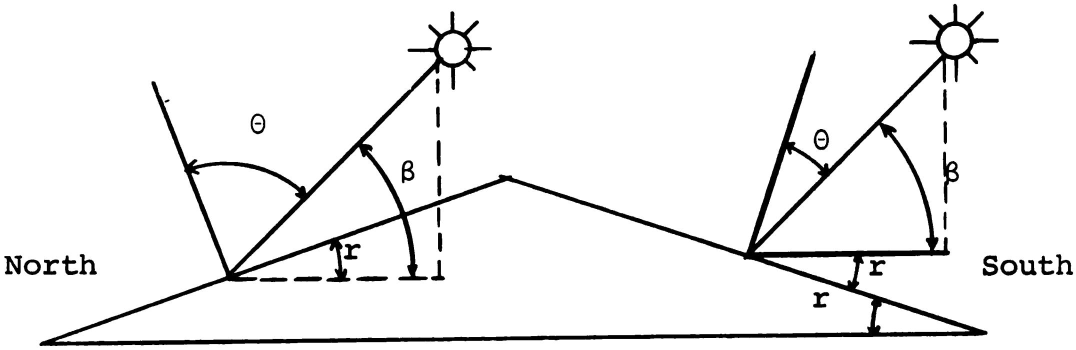
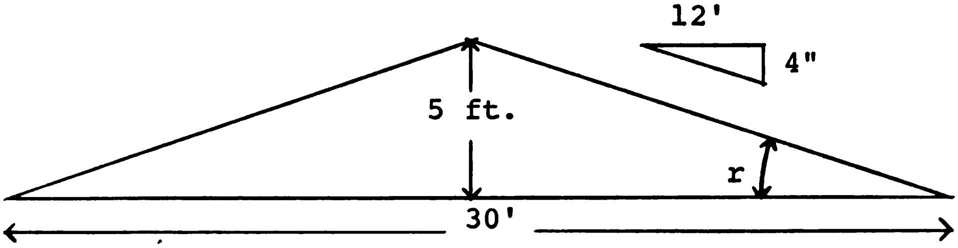


Figure 7. Sun angles on the roof planes of a gable-type building oriented East-West (Esmay, 1969).



$$\text{Tan } r = \frac{5}{30} = \frac{1}{3} = 0.333$$

if Tan $r = 0.333$, $r = 18° \; 26'$

Figure 8. Angle of the roof "r" with the horizontal.

where:

L = North latitude of location (degrees)

δ = seasonal declination of sun (degrees)

H = hour angle (equal 15° times number of hours from solar noon; positive from 12 noon to 12 midnight) (degrees)

The seasonal declination of sun "δ" is independent of location and is a function of time of the year (season) (30).

4.5 Direct Normal Radiation "I_{dn}"

The direct normal radiation is the total incident radiation on a plane normal to the sun's ray [BTU/hr (sq ft)] and is:

$$I_{dn} = \frac{I_h}{\sin\beta} \qquad (4.5)$$

where:

I_h = incident solar radiation on a horizontal surface [BTU/hr (sq ft)]

β = solar altitude (degrees)

4.6 Heat Flow Through the Roof Q

Once the sol-air temperature has been computed the rate of heat flow through the roof can be computed from the equation (14):

$$Q = U\,(t_e - t_i)$$

where:

Q = heat flow through the roof [BTU/hr (sq ft)]

U = overall coefficient of heat transmission or thermal transmittance [BTU/hr (sq ft) (°F)]

t_e = sol-air temperature °F

t_i = inside air temperature °F

4.7 Rate of Heat Flow to the Inside "q_i"

If inside surface's roof temperature is known the rate of heat transfer q_i to the inside is:

$$q_i = f_{ci}\ (t_{si} - t_i)$$

where:

q_i = rate of heat flow to the inside building from the roof [BTU/hr (sq ft)]

f_{ci} = inside film or surface conductance. It is the time rate of heat exchange by radiation, conduction and convection of a unit area of a surface with the surroundings, including air and other fluids BTU/hr (sq ft)(°F)

t_{si} = temperature of the inside surface

t_i = inside air temperature

4.8 Mean Radiant Temperature

The mean radiant temperature MRT of an environment is the temperature of a uniform black enclosure with which an object would exchange the same amount of energy as in the actual environment (3).

In the case of a mean radiant temperature determination with the globe thermometer, the globe is the object and the MRT so determined will be true only for the globe (3).

4.9 Radiant Heat Load: "RHL"

The radiant heat load "RHL" (3) is the total radiation received by an object from all of the surrounding space. It is the spherical, or whole-space, irradiation of the object; it includes only the incoming radiation at the object.

The black globe thermometer has been made from copper spheres and used successfully to indicate the thermal radiant heat load at a point represented by the globe (3). Black-globe thermometers made from a ping pong ball can also be used (Pereira, *et al.*, 1967) (29).

The radiant heat load calculation for the ping pong ball globe can be determined from equations:

$$RHL = 0.232\ \sqrt{v}\ (t_g - t_a) + \delta\ T_g^{\ 4} \text{ English units}$$

$$RHL = 1.85 \times 10^{-4}\ \sqrt{v}\ (t_g - t_a) + \delta\ T^4 \text{ Metric units}$$

where:

RHL = BTU/hr (sq ft) or watts/ sq cm

t_g = temperature of globe, °F or °C

t_a = temperature of air, °F or °C

v = air velocity, fpm or cm per second

δ = Stefan-Boltzman constant

0.173×10^{-8} BTU/hr (sq ft) (°R) or

5.67×10^{-12} watts/sq. cm. (°K)

T = t + 460 degrees R or t + 273 degrees K

5. RESULTS

Numerous variables must be quantified in order to compute sol-air temperature. The variables are: "β" solar altitude, "I_{dn}" direct normal radiation and "I," the incident solar radiation upon the surface.

5.1 Solar Altitude "β" Computation

Solar altitude was computed from the equation:

$$\sin \beta = \text{cox } L \times \cos \delta \times \cos H + \sin L \times \sin \delta \quad (4.4)$$

where:

β = solar altitude (see Appendix)

L = 42° 47' (latitude North)

δ = seasonal declination of sun (see Appendix)

H = hour angle (see Appendix)

5.2 Computations of Direct Normal Radiation

Direct normal radiation was computed from the equation:

$$I_{dn} = \frac{I_h}{\sin\beta} \quad (4.5)$$

where:

I_h = incident solar radiation on a horizontal surface for September 1, 4 and 5 and for June 27 and 28 (Tables 2, 3, 4, 5 and 6)

"β" = solar altitude is shown in the Appendix

Computed values of "I_{dn}" are shown in Table 7.

5.3 Computations of the angle of incidence Θ

The angle of incidence was computed from the equations:

$$\Theta = 90 - R - \beta \text{ (south side slope)} \quad (4.3)$$

$$\Theta = 90 + R - \beta \text{ (north side slope)} \quad (4.3a)$$

where:

β = solar altitude

R = angle of roof slope = 18° 26'

The value of R was computed by the equation:

$$\text{Tan } R = \frac{l}{h}$$

L and h value are indicated in Figure 8; values of the angle of incidence Θ for the south facing slope and K (cosine Θ) are shown in Table 35 in the appendix.

Values of the angle of incidence Θ for the north facing slope and K (cosine Θ) are shown in the Appendix.

Table 2. Incident solar radiation on a horizontal surface "I_h" for September 1, 1970.

Hour	Grcal/cm^{2}hr.	Kcal/m^{2}hr.	BTU/ft^{2}hr.
10:00	61.8	618	228.04
11:00	70.5	705	260.14
12:00	79.3	793	292.61
1:00	80.5	805	297.04
2:00	74.9	749	276.38
3:00	62.9	629	232.10
4:00	47.1	471	173.79

Table 3. Incident solar radiation on a horizontal surface "I_h" for September 4, 1970.

Hour	Grcal/cm^{2}hr.	Kcal/m^{2}hr.	BTU/ft^{2}hr.
10:00	54.7	547	201.84
11:00	71.4	714	263.46
12:00	73.0	730	269.37
1:00	73.6	736	271.58
2:00	65.9	659	243.17
3:00	49.6	496	183.02
4:00	30.4	304	112.17

Table 4. Incident solar radiation on a horizontal surface "I_h" for September 5, 1970.

Hour	Grcal/cm^{2}hr.	Kcal/m^{2}hr.	BTU/ft^{2}hr.
10:00	56.2	562	207.37
11:00	71.9	719	265.31
12:00	71.4	714	263.46
1:00	77.9	779	287.45
2:00	66.6	666	245.75
3:00	52.7	527	194.46
4:00	34.0	340	125.46

Table 5. Incident solar radiation on a horizontal surface "I_h" for June 27, 1971.

Hour	Grcal/cm^{2}hr.	Kcal/m^{2}hr.	BTU/ft^{2}hr.
10:00	66.7	667	246.12
11:00	75.3	753	277.85
12:00	78.7	787	290.40
1:00	78.0	780	287.82
2:00	79.5	795	293.35
3:00	71.5	715	263.83
4:00	58.3	583	215.12

Table 6. Incident solar radiation on a horizontal surface "I_h" for June 28, 1971.

Hour	Grcal/cm^{2}hr.	Kcal/m^{2}hr.	BTU/ft^{2}hr.
10:00	65.9	659	243.17
11:00	73.6	736	271.58
12:00	79.8	798	294.46
1:00	81.0	810	298.89
2:00	78.2	782	288.55
3:00	71.3	713	263.09
4:00	58.0	580	214.02

Table 7. Direct solar radiation on a plane normal to the sun's ray (BTU/ft^{2}hr.) I_{dn}.

	1970			1971	
Hour	Sept. 1	Sept. 4	Sept. 5	June 27	June 28
10:00	316.1	284.42	293.82	289.58	286.33
11:00	327.61	336.68	340.72	302.85	296.21
12:00	357.36	333.66	327.88	308.77	313.29
1:00	373.62	347.06	369.15	313.72	326.00
2:00	383.12	342.66	348.20	345.15	339.77
3:00	383.12	308.22	329.68	355.33	354.69
4:00	381.78	253.32	285.96	357.05	355.73

5.4 Computation of the Intensity of Solar Radiation "I"

The intensity of solar radiation incident upon the outdoor surface "I" was computed from the equation:

$$I = I_{dn} \times K \tag{4.2}$$

where:

I_{dn} = direct normal radiation [BTU/hr (sq ft)] (values are shown in Table 7)

K = cosine Θ (degrees) (see Appendix)

There are two values of the intensity of solar radiation "I," one for the south facing roof shown in Table 8 and another for the north facing roof shown in Table 9.

5.5 Computation of the Sol-Air Temperature "t_e"

The sol-air temperature was computed from the equation:

$$t_e = t_o + \left(\frac{I}{f_{co}}\right) \tag{4.1}$$

where:

t_e = sol-air temperature

t_o = outside air temperature °F (measured values are shown in Table 10)

α = 0.32 (value for aluminum (14).

I = values for South and North side roof are shown in Tables 8 and 9

f_{co} = 4 BTU/hr (sq ft)(°F)

Table 8. Intensity of solar radiation "I" incident upon the outdoor surface (direct, diffuse and reflected) BTU/hr ft^2 south slope.

	1970			1971	
Hour	Sept. 1	Sept. 4	Sept. 5	June 27	June 28
10:00	285.54	164.15	262.52	281.73	278.49
11:00	309.76	316.24	319.38	301.71	295.03
12:00	342.46	317.80	311.65	308.67	313.17
1:00	353.26	325.98	346.03	312.54	324.70
2:00	337.50	306.92	311.11	335.79	330.47
3:00	316.55	252.01	268.67	325.57	324.81
4:00	272.30	178.23	200.31	294.19	292.87

Table 9. Intensity of solar radiation "I" incident upon the outdoor surface (direct, diffuse and reflected) BTU/hr ft^2 north slope.

	1970			1971	
Hour	Sept. 1	Sept. 4	Sept. 5	June 27	June 28
10:00	147.10	128.09	130.87	185.23	182.89
11:00	183.82	183.69	184.07	225.65	220.24
12:00	212.73	193.28	188.21	242.31	245.52
1:00	209.64	189.35	199.42	233.74	242.39
2:00	178.28	154.32	155.09	220.77	217.03
3:00	123.78	95.15	100.32	175.06	174.38
4:00	57.30	34.59	37.82	113.98	113.16

Table 10. Outside air temperature "t_o" (degrees F).

	1970			1971	
Hour	Sept. 1	Sept. 7	Sept. 7	June 27	June 28
10:00	74	78	78	89	91
11:00	79	85	87	93	95
12:00	84	93	88	94	96
1:00	80	91	88	95	96
2:00	80	93	87	95	97
3:00	78	93	88	97	96
4:00	75	93	90	96	98

Sol-air temperature values were computed for the following days: September 1, 4 and 5; and for June 27 and 28 for every hour from 10:00 a.m. to 4:00 p.m. Values are shown in Tables 11 and 12 for South and North slopes,

5.6 Computation of the Heat Flow Through the Roof "Q"

The rate of heat flow through the roof was computed for both sides of the roof from the equation:

$$Q = U\ (t_e - t_i) \tag{4.6}$$

Table 11. Sol-air temperature "t_e" degrees F, for the south slope.

	1970			1971	
Hour	Sept. 1	Sept. 4	Sept. 5	June 27	June 28
10:00	96.84	91.13	99.00	111.53	113.27
11:00	103.78	110.29	112.55	117.13	118.60
12:00	111.39	118.42	112.93	118.69	121.05
1:00	108.26	117.07	115.68	120.00	121.97
2:00	107.00	117.55	111.88	121.86	123.43
3:00	103.32	113.16	109.49	123.04	121.98
4:00	96.87	107.25	106.02	119.53	121.90

Table 12. Sol-air temperature "t_e" degrees F, for the north slope.

	1970			1971	
Hour	Sept. 1	Sept. 4	Sept. 5	June 27	June 28
10:00	85.76	88.24	88.46	103.81	105.63
11:00	93.70	99.69	101.72	111.05	112.61
12:00	101.01	108.46	103.05	112.38	115.64
1:00	96.77	106.14	103.95	113.69	115.39
2:00	94.26	105.34	99.46	112.66	114.36
3:00	89.90	100.61	96.02	111.00	109.95
4:00	79.58	95.76	93.02	105.11	107.05

where:

Q = heat flow through the roof [BTU/hr (sq ft)]

U = 0.923 BTU/hr (sq ft)(°F)

t_e = sol-air temperature (°F) values are shown in Tables 11 and 12

t_i = inside air temperature (°F) (measured values are shown in Table 13)

Values for "Q" the rate of heat flow through the roof was computed for both sides, south and north and for the following days of September: 1, 4 and 5 and June 27 and 28 for every hour from 10:00 a.m. to 4:00 p.m. Values are shown in Tables 14 and 15.

Table 13. Inside air temperature "t_i" (degrees F).

	1970			1971	
Hour	Sept. 1	Sept. 4	Sept. 5	June 27	June 28
10:00	69	74	76	87	89
11:00	74	85	82	91	92
12:00	79	89	83	91	93
1:00	77	90	83	93	94
2:00	78	90	84	93	95
3:00	77	90	85	95	96
4:00	74	89	88	95	96

Table 14. Rate of heat flow through the south roof "Q" (BTU/hr ft^2)

	1970			1971	
Hour	Sept. 1	Sept. 4	Sept. 5	June 27	June 28
10:00	25.69	15.81	22.22	22.64	22.40
11:00	27.48	23.34	28.19	24.11	24.55
12:00	29.89	27.15	27.62	25.55	25.89
1:00	28.85	24.98	30.16	24.92	25.81
2:00	26.76	25.42	25.73	26.63	26.24
3:00	24.29	21.37	22.60	25.88	23.97
4:00	21.08	16.84	16.63	22.64	23.90

Table 15. Rate of heat flow through the north side roof "Q" (BTU/hr ft^2)

	1970			1971	
Hour	Sept. 1	Sept. 4	Sept. 5	June 27	June 28
10:00	15.46	13.60		15.51	16.63
11:00	18.18	13.65	18.20	18.50	19.02
12:00	22.01	17.96	18.50	19.73	20.89
1:00	18.24	14.89	19.33	19.09	19.74
2:00	15.00	14.15	14.25	18.14	17.86
3:00	11.90	9.79	10.17	14.76	12.87
4:00	5.15	6.23	4.63	9.33	10.19

5.7 Rate of Heat Flow to the Inside q_i

The rate of heat flow to the inside through the roof can also be computed by the equation:

$$q_i = f_{ci} \ (t_{si} - t_i) \qquad (4.7)$$

if the surface temperature of the underside of the roof is known.

where:

q_i = rate of heat flow [BTU/hr (sq ft)]

f_{ci} = 1.2 BTU/hr (sq ft)(°F)

t_{si} = temperature of the inside roof's surface °F (measured values are shown in Tables 16 and 17)

t_i = inside air temperature °F (values are shown in Table 13)

Values for "q_i" were computed for south and north facing roofs and for the following days of September: 1, 4 and 5 and June 27 and 28; for every hour from 10:00 a.m. to 4:00 p.m. Values are shown in Tables 18 and 19.

5.8 Computation of the Radiant Heat Load "RHL"

The radiant heat load was computed from black-blobe thermometers readings, under the sun and inside the building from the equation:

$$RHL = 0.232 \sqrt{v} \ (t_g - t_a) + T_g^{\,4} \cdot \sigma \qquad (4.9)$$

Table 16. Temperature of the inside roof's surface °F (south).

	1970			1971	
Hour	Sept. 1	Sept. 4	Sept. 5	June 27	June 28
10:00	90	87	94	106	108
11:00	96	104	105	111	115
12:00	104	112	106	112	116
1:00	101	111	108	114	116
2:00	100	110	106	115	120
3:00	97	108	104	116	118
4:00	92	103	101	112	114

Table 17. Temperature of the inside roof's surface °F (north).

	1970			1971	
Hour	Sept. 1	Sept. 4	Sept. 5	June 27	June 28
10:00	82	85	86	102	102
11:00	89	96	97	107	108
12:00	96	104	98	108	112
1:00	92	103	99	110	111
2:00	91	102	96	109	110
3:00	87	98	93	108	108
4:00	78	94	91	105	105

Table 18. Rate of heat flow to the inside "q_i" BTU/hr ft^2 (south).

	1970			1971	
Hour	Sept. 1	Sept. 4	Sept. 5	June 27	June 28
10:00	25.2	15.6	21.6	22.80	22.80
11:00	26.4	22.8	27.6	24.00	27.60
12:00	30.0	27.6	27.8	25.20	27.60
1:00	28.8	25.2	30.0	25.20	26.40
2:00	26.4	24.0	26.4	26.40	30.00
3:00	24.0	21.6	22.8	25.20	26.40
4:00	21.6	16.8	15.6	20.40	21.60

Table 19. Rate of heat flow to the inside "q_i" BTU/hr ft^2 (north).

	1970			1971	
Hour	Sept. 1	Sept. 4	Sept. 5	June 27	June 28
10:00	15.6	13.2	12.0	18.00	15.60
11:00	18.0	13.4	18.0	19.20	19.20
12:00	20.4	18.0	18.2	20.40	22.80
1:00	18.0	15.6	19.2	20.40	20.40
2:00	15.6	14.4	14.4	19.20	18.00
3:00	12.0	9.6	9.6	15.60	14.40
4:00	4.8	6.0	3.6	12.00	10.80

where:

RHL = radiant heat load [BTU/hr (sq ft)]

t_g = temperature of globe °F (values are shown in Tables 20 and 21)

t_a = air temperature °F (inside and outside air temperatures are shown in Tables 10 and 13)

v = air velocity (ftpm) (see Appendix)

σ = 0.173×10^{-8} [BTU/hr (sq ft)](°R)

T_g = inside or outside black globe temperature in degrees R; (t_g + 460°) (see Appendix)

Radiant heat load was computed for the following days in September: 1, 4 and 5 and June 27 and 28; for 12:00 noon and for outside and inside the building. The computed values for June 27 and 28 of 1971 includes RHL for a black-globe thermometer at 3 feet high. Computed values are shown in Table 22.

Table 20. Outside black globe temperature measurement °F.

	1970			1971	
Hour	Sept. 1	Sept. 4	Sept. 5	June 27	June 28
10:00	81	82	85	97	103
11:00	85	92	94	98	105
12:00	98	98	99	102	106
1:00	89	97	96	105	103
2:00	90	101	96	101	105
3:00	86	102	97	107	104
4:00	82	104	97	102	104

Table 21. Inside black globe temperature measurement °F.

	1970			1971			
	Sept. 1	Sept. 4	Sept. 5	June 27		June 28	
Hour	6 ft.	6 ft.	6 ft.	3 ft.	6 ft.	3 ft.	6 ft.
10:00	70	74	77	88	87	93	90
11:00	75	81	83	92	92	97	93
12:00	81	91	85	93	92	98	95
1:00	80	91	84	96	95	97	95
2:00	79	91	84	95	95	99	98
3:00	78	92	86	97	96	99	97
4:00	75	92	88	96	95	98	96

Table 22. Radiant heat load at 12:00 noon BTU/hr (sq ft)

Day	Inside		Outside
	3 feet high	6 feet high	6 feet high
Sept. 1	-	155.01	228.44
Sept. 4	-	166.42	185.11
Sept. 5	-	159.95	209.26
June 27	168.34	164.28	201.92
June 28	179.31	170.70	210.34

Note: Values for the black-globe thermometer at 10 feet high are the same as the values for 6 feet high.

6. USE OF INSULATION

The term insulation refers to materials which have a high resistance to heat flow (10). Some building materials, such as wood, have good insulating properties, while others like concrete are poor insulators.

Insulation materials as well as other building materials are rated according to their ability either to conduct or to resist the flow of heat (10). This rating can be used to compare the effectiveness of the materials and determine the amount of insulation needed.

The property that expresses the ability of a material to conduct heat is termed the thermal conductivity, "k" (30). This "k" value gives the amount of heat (BTU/hr) that will pass through a piece of material one inch thick and one square foot in area, when the temperature difference between the two surfaces is one degree Fahrenheit (30).

The second method of rating materials is based on their ability to resist the flow of heat. Therefore, the thermal resistivity "R" of a material is a measure of that material's ability to resist the flow of heat (14). Numerically this is the reciprocal of the heat transmission value.

Both the thermal conductivity and the thermal resistivity of a given material are related properties; and if one is known the other can be found by using the following equation:

$$k = \frac{1}{R} \; ; \; R = \frac{1}{k} \text{ and } U = \frac{1}{R}$$

Insulating materials are therefore used to prevent loss of heat in farm buildings during the cold season. In this study the idea of using insulation to prevent the heat flow from the outside to the inside during hot weather is considered.

For the computation of the decrease in heat flow through the roof, the following "R" values were chosen:

R = 2, 4, 6, 8, 10 [inch/BTU/hr(sq.ft.)(°F)]

6.1 Computation of Decrease in the Rate of Heat Transfer Through the Roof by Using Insulating Materials

Decrease in the rate of heat transfer was computed by the general heat transfer equation:

$$Q_t = U \times \Delta t \qquad (6.1)$$

where:

Q_t = overall heat flow

U = overall coefficient of heat transmission

Δt = temperature difference

The overall coefficient of heat transmission U is:

$$U = \frac{1}{R}$$

where:

R = the overall resistance to heat transmission or insulation.

The following values for R were used in the computations:

R = 2, 4, 6, 8 and 10.

If we substitute in equation (6.1) U by $\frac{1}{R}$ equation (6.1) is:

$$Q_t = \frac{\Delta t}{R} \tag{6.1a}$$

Values of the rate of heat transfer were computed by using equation (6.1a) and for values of R = 2, 4, 6, 8 and 10. To compare the decrease in the rate of heat flow, the highest values already computed were taken from Table 14, one value for every day (the highest) from September 1, 4 and 5 and June 27 and 28.

Decrease in the rate of heat flow is expressed in percentage. Table 23 shows values of Q already computed and values for Q_t for the same days and for different values of R.

Table 23. Rate of heat flow "Q"; BTU/hr ft^2; "Q_t" BTU/hr ft^2 for different "R" values and decrease of heat flow in percentage.

Days	"Q" BTU/hr ft^2	"Q_t" BTU/hr ft^2 and decrease of heat flow in percentage for "R" values									
		R=2	D %	R=4	D %	R=6	D %	R=8	D %	R=10	D %
Sept. 1	29.89	16.19	45.84	8.09	72.94	5.37	82.04	4.04	86.49	3.23	89.20
Sept. 4	27.15	14.71	45.82	7.35	72.93	4.88	82.03	3.67	86.48	2.94	89.19
Sept. 5	30.16	16.34	45.83	8.17	72.92	5.42	82.02	4.08	86.47	3.26	89.18
June 27	26.63	14.42	45.84	7.21	72.93	4.80	81.98	3.60	86.49	2.88	89.19
June 28	26.24	14.21	45.85	7.10	72.95	4.73	81.98	3.55	86.48	2.84	89.18

7. DISCUSSION OF THE RESULTS AND CONCLUSIONS

7.1 Heat Flow Through the Roof "Q" and Rate of Heat Flow to the Inside "q_i"

The rate of heat flow through the roof "Q" was computed by using the sol-air temperature approach. The rate of heat flow to the inside was computed by using the surface temperature measurements for the purpose of checking the sol-air method. Both results have shown similar values (see Figures 9, 10, 11, 12 and 13). It means that the sol-air temperature approach can be used for analytical purposes of computing the rate of heat flow through the roof for open livestock buildings, under summer conditions.

The highest computed value for the rate of heat flow was 30.16 BTU/hr (sq ft) obtained at 1:00 p.m. on September 5 when air temperature was 83°F and through the south facing slope.

The lowest computed value for the rate of heat flow was 4.63 BTU/hr (sq ft) obtained at 4:00 p.m. on September 5 and through the north facing slope.

7.2 Black-Globe Thermometer Readings

The globe-thermometer measurements were not significantly different for one at 6 feet high and the other

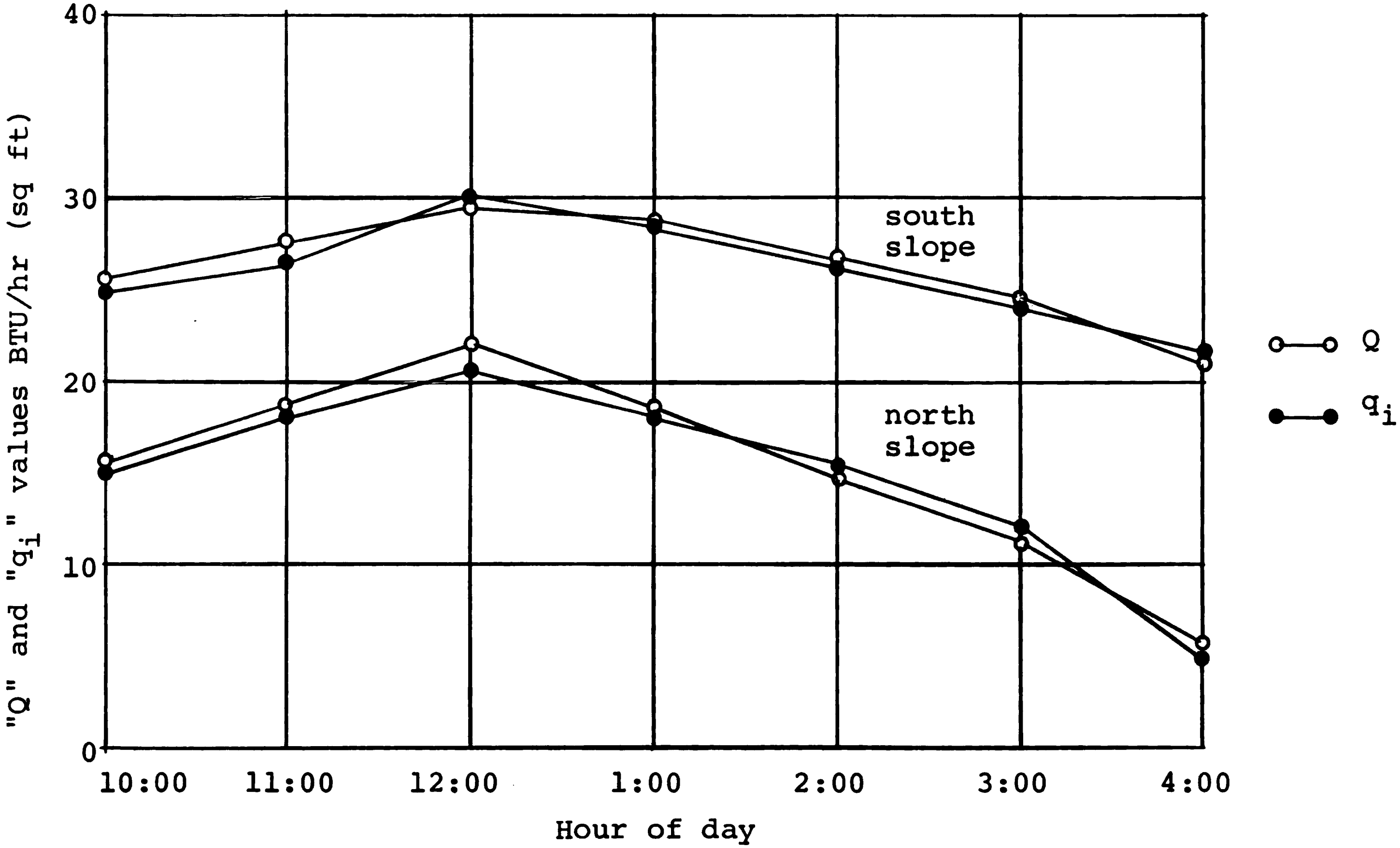


Figure 9. Rate of heat flow through the roof "Q" and rate of heat flow to the inside q_i BTU/hr (sq ft) for September 1, 1970.

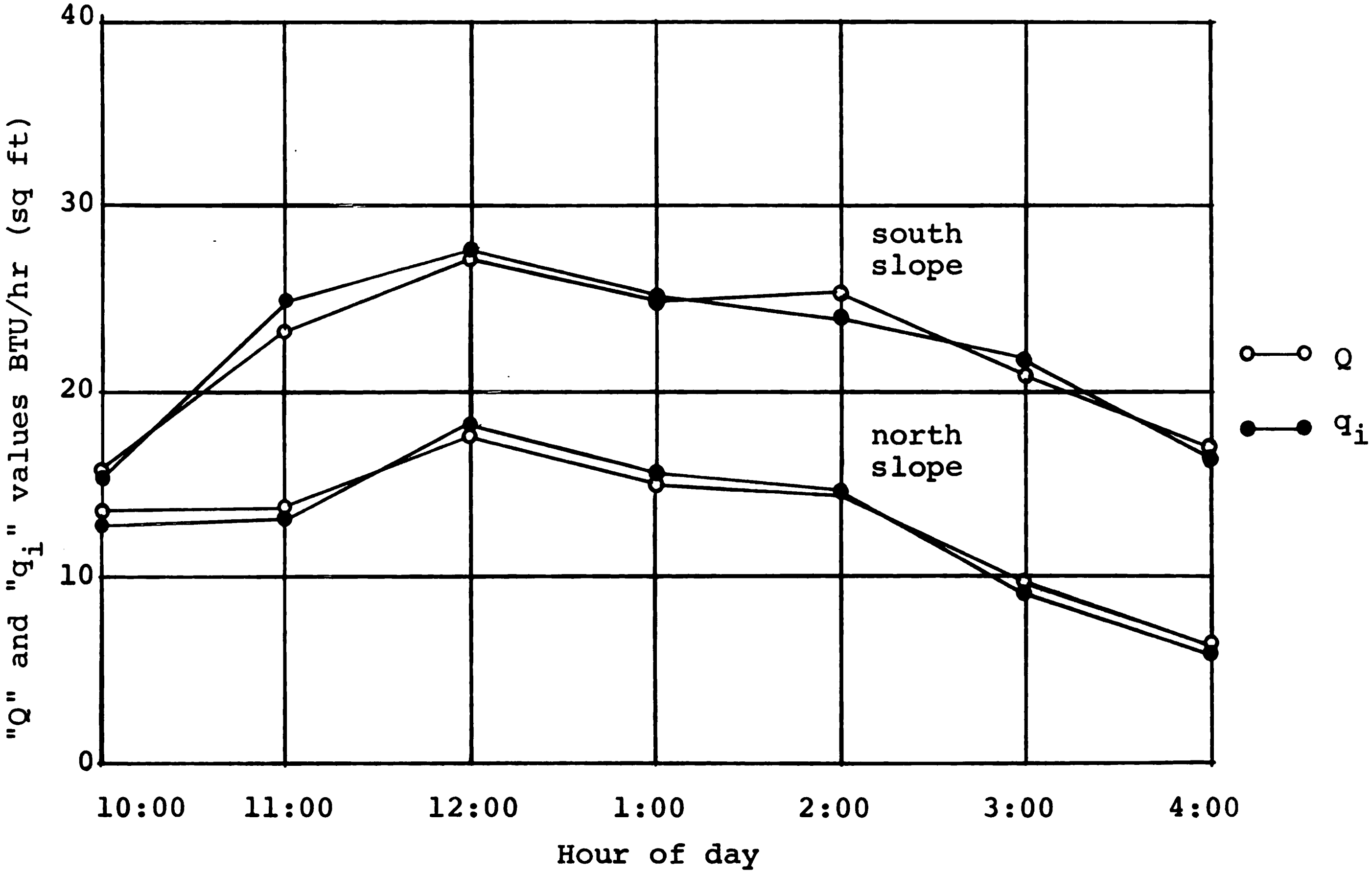


Figure 10. Rate of heat flow through the roof "Q" and rate of heat flow to the inside q_i BTU/hr (sq ft) for September 4, 1970.

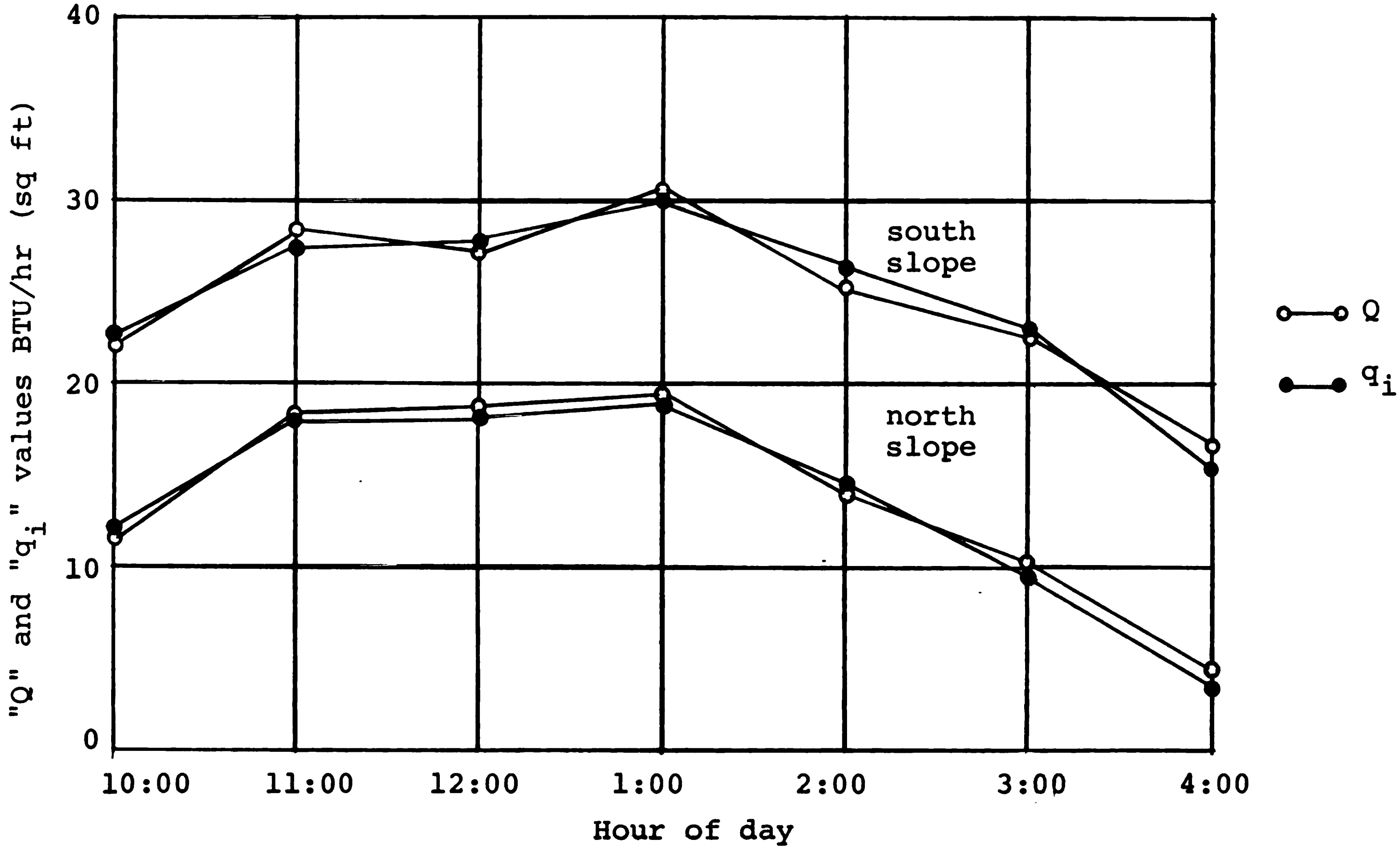


Figure 11. Rate of heat flow through the roof "Q" and rate of heat flow to the inside q_i BTU/hr (sq ft) for September 5, 1970.

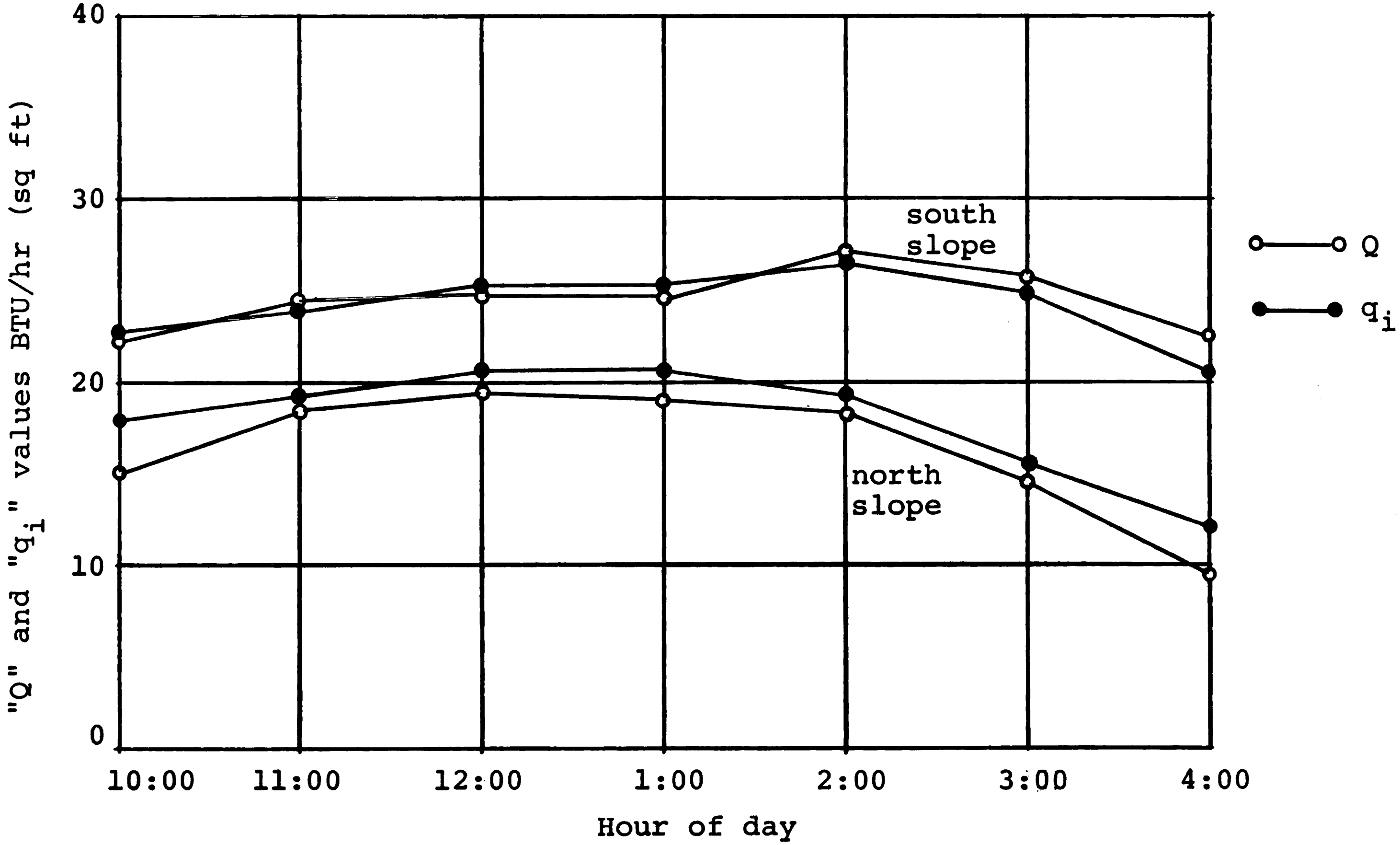


Figure 12. Rate of heat flow through the roof "Q" and rate of heat flow to the inside q_i BTU/hr (sq ft) for June 27, 1971.

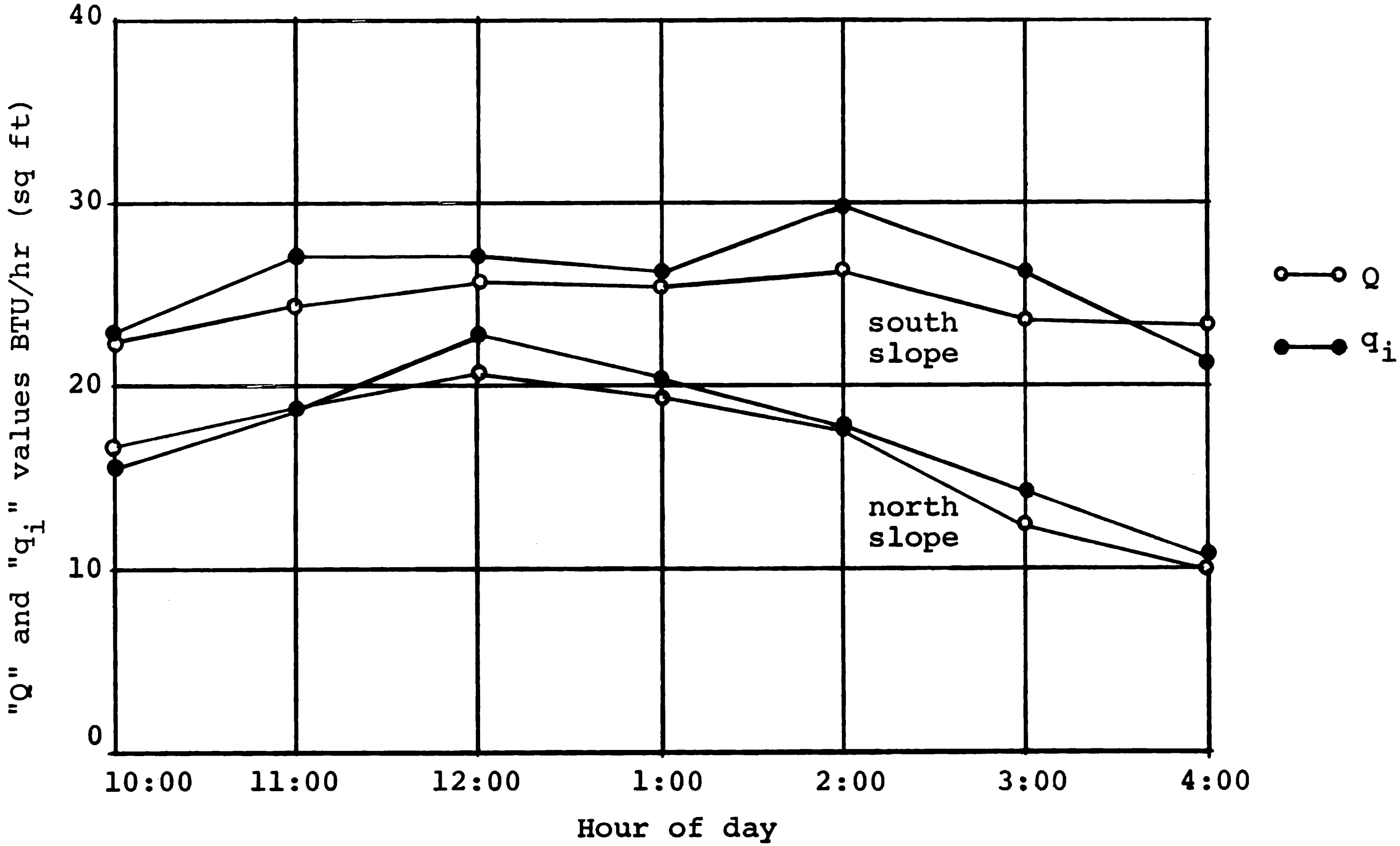


Figure 13. Rate of heat flow through the roof "Q" and rate of heat flow to the inside q_i BTU/hr (sq ft) for June 28, 1971.

at 10 feet high. The black-globe thermometer at 3 feet high showed higher temperature readings than the globes at 6 and 10 feet high. Differences in temperature readings were of one to five degrees. There were differences between the black-globe thermometer readings under the sun and inside as it was expected. Also the black-globe thermometers inside the building at 6 and 10 feet high did show temperature differences from one to three degrees in some cases from that of the air. The black-globe at 3 feet high showed temperature differences up to five degrees from that of the air. It means that the cooling effect of the wind influence more the black-globe at 6 and 10 feet than the black-globe at 3 feet high.

7.3 Radiant Heat Load

The radiant heat load computed from black-globe thermometer readings at 12:00 noon outside and inside the building are shown in Figure 14.

The highest value computed for radiant heat load was 228.44 BTU/hr (sq ft) for September 1 under the sun when wind velocity was 350 feet per minute. The lowest RHL value under the sun was 185.11 BTU/hr (sq ft) for September 4 when wind velocity was 225 feet per minute. Direct normal radiation value at 12:00 noon for both days was: 357.36 BTU/hr (sq ft) for September 1 and 333.66 BTU/hr (sq ft) for September 4.

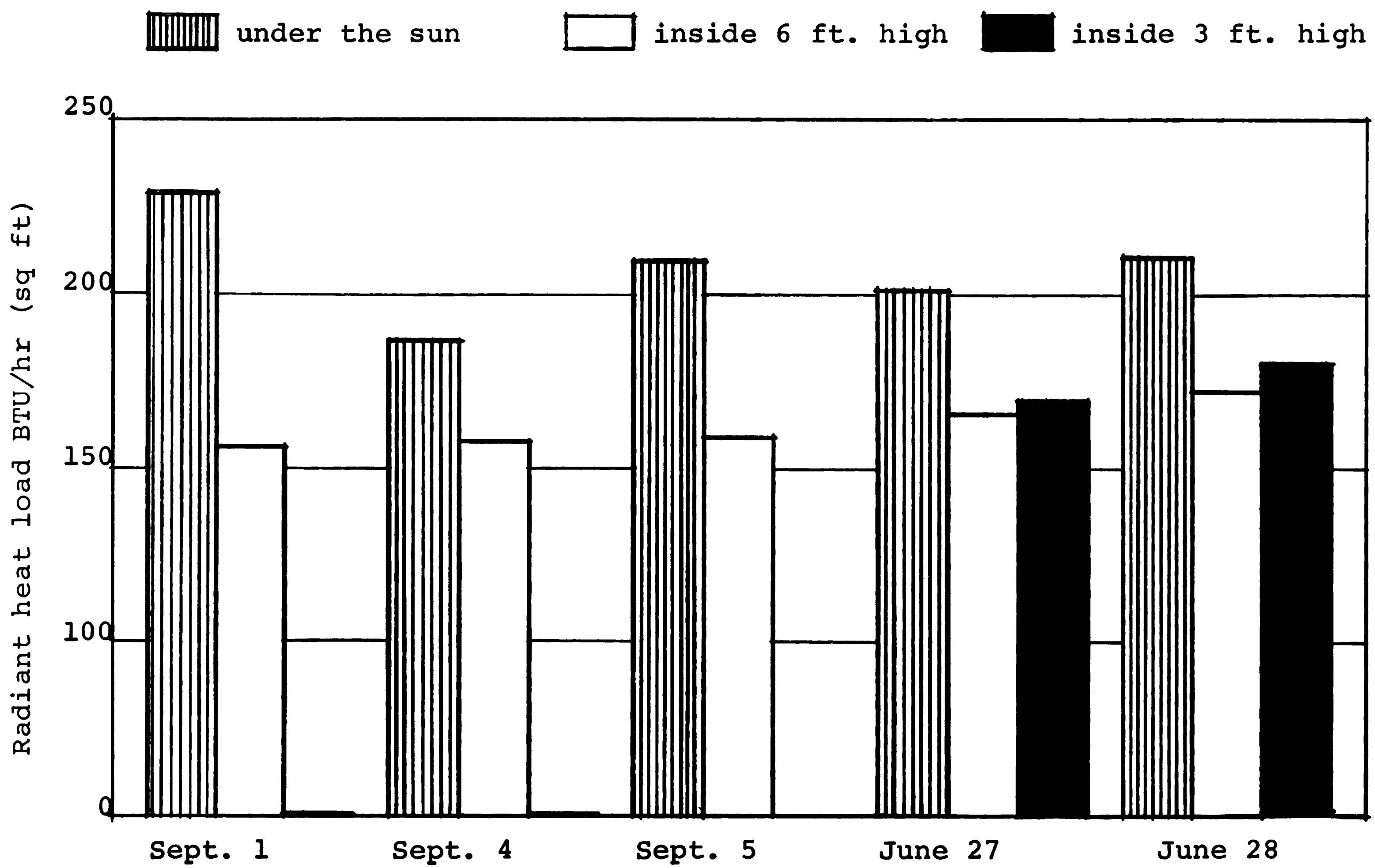


Figure 14. Radiant heat load BTU/hr (sq ft) at 12:00 noon for black-globe thermometers under the sun and inside the building at 3 and 6 feet high.

The highest computed radiant heat load value for globes inside the building was 179.31 BTU/hr (sq ft) for the black-globe at 3 feet high and for June 28. The computed RHL value for the globe at 6 feet high was 170.70 BTU/hr (sq ft) for the same day at the same hour, 12:00 noon. It gives a difference of 8.61 BTU/hr (sq ft) between the two black-globes. This difference shows that the RHL value in a point at 3 feet high (represented by the black-globe thermometer) is higher than one at 6 or 10 feet high. It was explained early that the globe-thermometer at 3 feet high is getting less cooling effect from the wind. The wind velocity for June 28 was 200 feet per minute at 6 feet high and 100 feet per minute at 3 feet high (both values were obtained near the globe). Also radiation from the shaded floor could account for the higher RHL value at 3 feet as compared at 6 feet high. Kelly, et al. (23) showed that 33 percent of the RHL on an animal came from the shaded ground.

A reduction from 30 to 50 percent of the total radiant heat load on the animal is possible with a well designed shade (7). In the case of this study reductions of 10 percent to 32 percent in the RHL were found inside the building as compared under the sun.

7.4 Use of Insulation

By using insulating materials with resistivity values from 2 to 10 (2, 4, 6, 8 and 10), decreases the rate of heat flow through the roof up to 89 percent.

A decrease of 45 percent was found if an insulating material with a resistivity value of two is used. The higher the resistivity value of the material the lower the rate of heat flow through the roof.

For example, if wood-fiber one inch thick is used (which has a resistivity value of R = 4 or U = 0.25 BTU/hr (sq ft)(°F)) the reduction in the heat flow is 72 percent.

In theory it would seem that insulating materials can be a solution for reduction of radiant energy through the roof for farm buildings. However more research in this field is needed before recommends its use.

7.5 Roof Surface Temperature

Roof surface temperature for the buildings were measured and the highest value was 120°F at 2:00 p.m. on June 28. Figure 15 shows measured surface temperature for June 28 as compared with air temperature. The highest surface temperature value was obtained on the South facing roof.

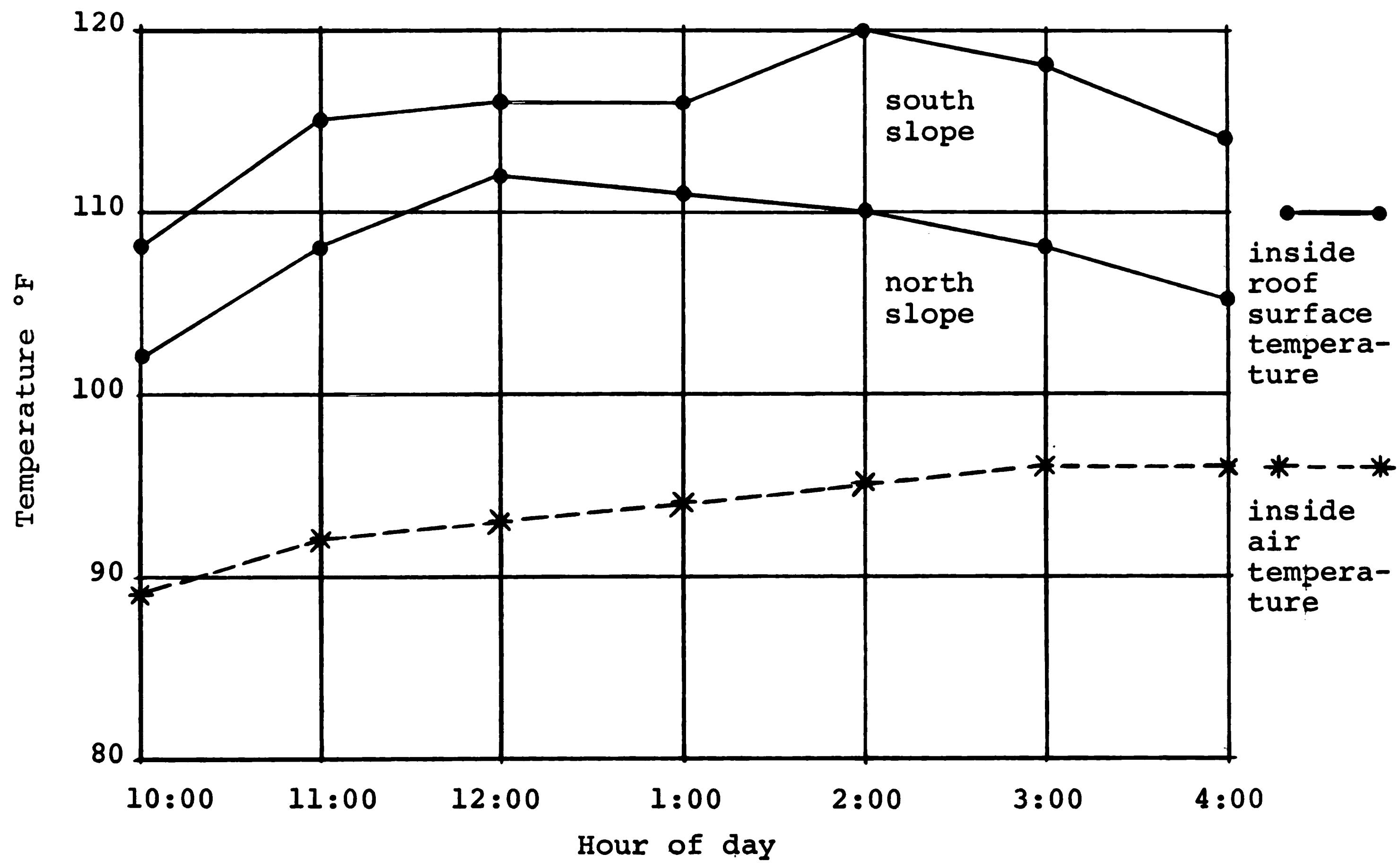


Figure 15. Inside surface and air temperature (degrees F) for June 28 in Michigan.

7.5 Conclusions

The following conclusions may be made based upon this research:

1. The sol-air temperature approach can provide reliable data on the additional heat load caused by solar radiation on exposed building roofs and sidewalls.
2. The similarity of results of the sol-air method and the calculation of heat transfer with measured roof surface temperature are highly dependent on the estimation of the surface film coefficient which varies considerably with air velocity.
3. Both methods of solar radiation heat load calculation accounted for the effect of the angle of the roof surface as related to the direct sun's rays. This varies with roof slope and orientation and the sun angle as effected by season, hour of day and location on the earth.
4. A reduction in the radiant heat load up to 32 percent was found inside of the open cattle barn as compared to outside in the direct sun. This was under Michigan conditions. A greater reduction would be expected under more intense radiation heat loads.

5. A practical amount of roof insulation showed a calculated reduction of heat transfer by 89 percent. The economic justification of this must be evaluated in specific locations based upon the actual reduction of heat stress on animals.

8. COMPUTATION OF SOL-AIR TEMPERATURE AND HEAT FLOW THROUGH METAL ROOFS FOR OPEN FARM BUILDINGS IN TROPICAL CONDITIONS (VENEZUELA)

Venezuela lies on the northern coast of South America, between the Tropic of Cancer and the Equator. It is bounded by latitudes 0° 45' and 12° 12' North, and longitudes 59° 45' and 73° 09' (32).

Air temperature and solar radiation data were measured in Maracay, Aragua State, during the year of 1962. Maracay is located in a central region of the country at 9° latitude North.

8.1 Solar Altitude Computation

Solar altitude was computed for 9° latitude North at 12:00 noon for one day each month corresponding with the seasonal declination days of Table 24 (14)
Solar altitude was computed from the equation:

$$\beta = 90° - (L - \delta) \tag{7.1}$$

where:

β = solar altitude (Table 24)

Table 24. Seasonal declination of sun "δ" and solar altitude "β" degrees for 12:00 noon and 9° latitude North.

Month	Day	"δ" Degrees	"β" Degrees
January	21	-20.2	60.8
February	20	-11.2	69.8
March	21	0.0	81.0
April	20	+11.2	92.2
May	21	+20.2	101.2
June	22	+23.45	104.4
July	23	+20.2	101.2
August	24	+11.2	92.2
September	23	0.0	81.0
October	23	-11.2	69.8
November	23	-20.2	60.8
December	22	+23.45	104.4

$L = 9°$ latitude North

δ = seasonal declination of sun (Table 24)

8.2 Computation of the Angle of Incidence Θ

The angle of incidence Θ for a 1/6 pitch gable-type roof with its long axis oriented east to west was computed from equations 4.3 and 4.3a. Values for the angle of incidence Θ and its cosine are shown in Table 25.

8.3 Computation of the Intensity of Solar Radiation "I"

The intensity of solar radiation "I" incident upon the outdoor surface was computed from equation 4.2 and is:

$$I = I_{dn} \times K$$

where:

I = intensity of solar radiation BTU/hr (sq ft)

I_{dn} = direct normal radiation (values are shown in Table 26) BTU/hr (sq ft)

K = cosine Θ, cosine of the angle of incidence (values are shown in Table 25)

Computed values of "I" are for 12:00 noon and for one day every month, are shown in Table 27 (31).

Table 25. Angle of incidence of sun Θ for the South and North slope and (cosine Θ) "K" values at 12:00 noon.

	South		North	
Month	Θ	K	Θ	K
January	10.77	0.98240	47.63	0.67387
February	1.77	0.99952	38.63	0.78116
March	-9.43	0.98648	27.43	0.88755
April	-20.63	0.93585	16.23	0.96021
May	-29.63	0.86921	7.23	0.99208
June	-32.88	0.83978	3.98	0.99758
July	-29.63	0.86921	7.23	0.99208
August	-20.63	0.93585	16.23	0.96021
September	-9.43	0.98648	27.43	0.88755
October	1.77	0.99952	38.63	0.78116
November	10.77	0.98240	47.63	0.67387
December	-32.88	0.83978	3.93	0.99758

Table 26. Direct solar radiation I_{dn} at 12:00 noon.

Month	$Kcal/m^2hr$	$Grcal/cm^2hr$	BTU/ft^2hr
January	1.280	128	472.3
February	1.390	139	513.0
March	1.380	138	510.6
April	1.450	145	536.5
May	1.180	118	436.6
June	1.200	120	444.0
July	1.240	124	458.8
August	1.340	134	495.8
September	1.450	145	536.5
October	1.300	130	481.0
November	1.220	122	451.4
December	1.290	129	477.3

Table 27. Intensity of solar radiation "I" incident upon the outdoor surface at 12:00 noon in BTU/hr (sq ft)

Month	"I" South Slope	"I" North Slope
January	463.79	318.33
February	512.48	401.16
March	503.96	452.90
April	501.62	515.04
May	379.4	433.10
June	372.96	442.66
July	398.69	455.12
August	464.06	475.96
September	529.52	475.87
October	480.51	376.14
November	443.27	304.24
December	400.93	475.86

8.4 Computation of the Sol-Air Temperature "te"

The sol-air temperature was computed from equation 4.1 for aluminum roof, at 12:00 noon and for one day of every month, for both North and South slopes. Values are shown in Table 28 (Trujillo, 1970).

8.5 Computation of the Heat Flow Through the Roof "Q"

The heat flow through the roof "Q" was computed from equation 4.6, using the following values.

U = 0.923 [BTU/hr (sq ft)(°F)]

t_e = sol-air temperature (Table 28)

t_i = inside air temperature (Table 29) (monthly average)

Values of the rate of heat flow through the roof "Q" are shown in Table 30, for 12:00 noon and for both South and North slopes.

8.6 Computation of the Inside Roof Surface Temperature

Knowing the rate of heat flow and comparing equations (4.6) and (4.7) assuming $Q = q_i$ equations (4.6) and (4.7) can be equal, then giving:

$$Q = U\ (t_e - t_i) \tag{4.6}$$

$$q_i = f_{ci}\ (t_{si} - t_i) \tag{4.7}$$

Table 28. Sol-air temperature "t_e" at 12:00 noon °F.

Month	"t_e" South Slope	"t_e" North Slope
January	121	109
February	124	115
March	125	121
April	125	126
May	113	118
June	111	117
July	114	118
August	118	119
September	125	121
October	121	113
November	119	108
December	115	121

Table 29. Inside air temperature "t_i" °F and °C at 12:00 noon.

Month	"t_i" °F	"t_i" °C
January	84	29
February	83	28
March	85	29
April	85	29
May	83	28
June	82	28
July	82	28
August	82	27
September	83	28
October	83	28
November	84	29
December	83	28

Note: temperatures are average monthly during the day.

Table 30. Heat flow through the roof "Q" BTU/hr (sq ft) at 12:00 noon.

Month	"Q" South Slope	"Q" North Slope
January	34.59	23.74
February	38.22	29.92
March	37.58	33.78
April	37.41	38.41
May	28.29	32.30
June	27.81	33.01
July	29.73	33.94
August	34.61	35.50
September	39.49	35.49
October	35.83	28.05
November	33.06	22.69
December	29.90	35.49

$$U\ (t_e - t_i) = f_{ci}\ (t_{si} - t_i)$$

then

$$t_{si} = \frac{Ux\ t_e + t_i\ (f_{ci} - U)}{f_{ci}} \qquad (8.6)$$

if the following values are known:

$U = 0.923$

$f_{ci} = 1.2$

equation (8.6) converts to:

$$t_{si} = \frac{0.923\ t_e + t_i\ 0.27}{1.2} \qquad (8.6a)$$

then if the sol-air temperature and the inside temperature are known, the inside surface temperature could be known. Computed values of the inside surface temperature are shown in Table 31.

8.7 Discussion of the Results

The heat flow through metal roofs for Venezuela was higher than for Michigan as the radiation intensity was greater. Rate of heat flow values of 39.49 BTU/hr (sq ft) were computed for September on the South slope and 38.41 BTU/hr (sq ft) for April on the North slope.

Heat transfer through both slopes had not big differences as the values obtained for Michigan. It can be explained; first of all because of the location of both

Table 31. Inside surface temperature "t_{si}" °F at 12:00 noon.

Month	"t_{si}" South Slope	"t_{si}" North Slope
January	112	103
February	115	108
March	116	113
April	116	117
May	107	110
June	105	109
July	107	110
August	110	111
September	116	113
October	113	106
November	111	102
December	108	113

tests; one at 9° latitude North and the other at 42° 47' latitude North. At lower latitude sun's rays are more perpendicular than at higher latitudes. Seasonal declination is another factor that influences in the sun ray's incidence.

The highest projected roof surface temperature value was 116°F at 12:00 for April. This value is 4 degrees lower than that for roof surface temperature in Michigan (120° in one case). It is understandable because computation for Venezuela were made based upon average radiation values and average air temperature values. Figure 16 shows roof surface temperature for a year in Venezuela as compared with air temperature.

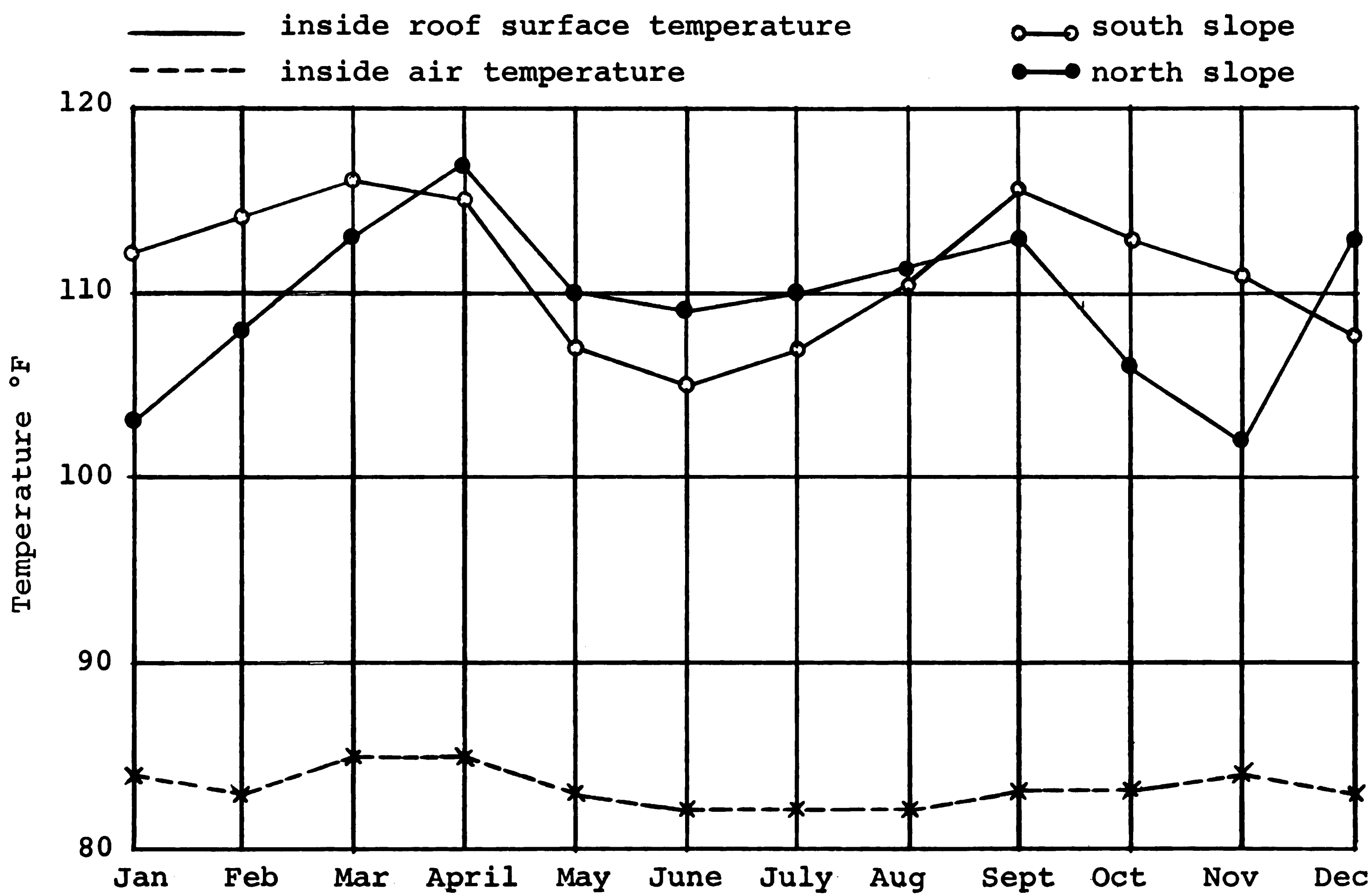


Figure 16. Inside surface temperature of the roof and inside air temperature at 12:00 noon for an average day of a month in tropical conditions (Venezuela).

9. RECOMMENDATIONS

Some recommendations for the roof construction of livestock open sided buildings in Venezuela can be suggested:

Use roofing material with high reflectivity and low absortivity value. One of the most suitable materials for livestock buildings in Venezuela is aluminum.

Air velocity has shown to be of a great importance in the amount of radiant heat load on the animal; therefore, building should be constructed in unobstructed wind path or on a hill.

General recommendations based upon experimental findings of many authors can be suggested:

Use of showers to wet the animals (22)

Lower temperature of surroundings by using trees, grass, etc. (9)

Paint the roof white on top and black on bottom (6) and buildings white (4)

Shades should be high (7) and its long axis oriented east to west (23).

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APPENDIX

Table 32. Seasonal declination of sun "δ" (degrees).

Month	Day	Declination Degree
September	1	7° 45'
September	4	6° 37'
September	5	6° 15'
June	27	22° 55'
June	28	22° 49'

Table 33. Hour angle "H" degrees.

Hour	Angle Degrees
10:00	150°
11:00	165°
12:00	0°
1:00	15°
2:00	30°
3:00	45°
4:00	60°

Table 34. Solar altitude "β" (degrees) for 42° 47' latitude North.

	1970			1971	
Hour	Sept. 1	Sept. 4	Sept. 5	June 27	June 28
10:00	46° 10'	45° 12'	44° 53'	58° 12'	58° 08'
11:00	52° 34'	51° 30'	51° 08'	66° 36'	66° 28'
12:00	54° 58'	53° 50'	53° 28'	70° 08'	70° 02'
1:00	52° 34'	51° 30'	51° 08'	66° 36'	66° 28'
2:00	46° 10'	45° 12'	44° 53'	58° 12'	58° 12'
3:00	37° 17'	36° 25'	36° 09'	47° 57'	47° 53'
4:00	27° 04'	26° 17'	26° 02'	37° 03'	36° 59'

Table 35. Angle of incidence of sun's ray Θ for the South facing slope.

	September 1		September 2		September 4		September 5		September 9	
Hour	Θ	K	Θ	K	Θ	K	Θ	K	Θ	K
10:00	25° 24'	0.90334	25° 43'	0.90095	26° 24'	0.89571	26° 41'	0.89350	27° 58'	0.88322
11:00	19° 00'	0.94552	19° 22'	0.94342	20° 04'	0.93929	20° 26'	0.93738	21° 52'	0.92805
12:00	16° 36'	0.95832	16° 59'	0.95639	17° 44'	0.95248	18° 06'	0.95052	19° 36'	0.94205
1:00	19° 00'	0.94552	19° 22'	0.94342	20° 04'	0.93929	20° 26'	0.93738	21° 52'	0.92805
2:00	25° 24'	0.90334	25° 43'	0.90095	26° 24'	0.89571	26° 41'	0.89350	27° 58'	0.88322
3:00	34° 17'	0.82626	34° 35'	0.82330	35° 09'	0.81765	35° 25'	0.81496	36° 35'	0.80299
4:00	44° 30'	0.71325	44° 45'	0.71019	45° 17'	0.70360	45° 32'	0.70049	46° 37'	0.74760

Table 36. Angle of incidence of sun's ray Θ for the North facing slope.

	September 1		September 2		September 4		September 5		September 9	
Hour	Θ	K	Θ	K	Θ	K	Θ	K	Θ	K
10:00	62° 16'	0.46536	62° 35'	0.46046	63° 14'	0.45036	63° 33'	0.44542	64° 50'	0.42525
11:00	55° 25'	0.56112	56° 14'	0.55581	56° 56'	0.54561	57° 18'	0.54024	58° 44'	0.51902
12:00	53° 28'	0.59529	53° 51'	0.58990	54° 36'	0.57928	54° 58'	0.57405	56° 28'	0.55242
1:00	55° 25'	0.56112	56° 14'	0.55581	56° 56'	0.54561	57° 18'	0.54024	58° 44'	0.51902
2:00	62° 16'	0.46536	62° 35'	0.46046	63° 14'	0.45036	63° 33'	0.44542	64° 50'	0.42525
3:00	71° 09'	0.32309	71° 27'	0.31813	72° 01'	0.30874	72° 17'	0.30431	73° 27'	0.28485
4:00	81° 22'	0.15011	81° 37'	0.14580	82° 09'	0.13658	82° 24'	0.13226	83° 59'	0.10481

Table 37. Air velocity feet per minute at 12:00 noon.

	Inside			Outside
Day	3 ft. high	6 ft. high	10 ft. high	6 ft. high
Sept. 1	-	350	350	350
Sept. 4	-	225	225	225
Sept. 5	-	250	250	250
June 27	200	250	250	250
June 28	100	200	200	200

Table 38. Black globe temperature measurements at 12:00 noon degrees R.

	Inside		Outside
Day	3 ft. high	6 ft. high	6 ft. high
Sept. 1	-	541	558
Sept. 4	-	551	558
Sept. 5	-	545	559
June 27	553	552	562
June 28	558	555	566