ENVIRONMENTAL TEMPERATURES IN FLORIDA DAIRY HOUSING

R. A. Bucklin, D. R. Bray, J. G. Martin, L. Carlos, V. Carvalho

ABSTRACT. *Environmental conditions in an air-conditioned barn and in evaporatively cooled sprinkler and fan and tunnel-ventilated barns are compared and recommendations for dairy barn design for hot, humid climates are given. Temperature Humidity Indexes (THI) observed in the air-conditioned barn were always below 72. Average THIs in the evaporatively cooled barns during afternoon hours were seldom less than 75.*

The environmental conditions observed in these studies are typical for many areas adjacent to the Gulf Coast of the United States and for tropical regions throughout the world. Providing comfortable environmental conditions for cows housed in area with hot, humid climates is difficult using only evaporative cooling and ventilation. Air-conditioning dairy housing is a possible alternative method, particularly for high value cows.

Keywords. *Air-conditioning, Dairy, Tunnel ventilation, Heat stress.*

Over the last 20 years, the dairy industry in Florida has moved from grazing systems with limited use of shade structures to widespread use of feed barns and freestall housing. Much of the initial move to wider use of structures was caused by state requirements mandating the adoption of best management practices for handling manure. Hot, humid weather has always caused drops in feed intake, milk production and fertility during the summer in Florida, but with the move to housing of cows in structures, the use of cooling systems became essential. Besides satisfying state environmental regulatory requirements for capturing and storing manure nutrients, barns equipped with cooling systems provide improved thermal comfort for cows compared to cows without access to shade. Several studies at the University of Florida (Strickland et al., 1989, Bucklin et al., 1991; Bucklin et al., 1992; Bray et al., 1992; Means et al., 1992; Montoya et al., 1995) demonstrated the feasibility and advantages of sprinkler and fan cooling systems for cooling dairy cows. Work has continued with sprinkler and fan systems as well as with high pressure fog systems, cooling ponds, air-conditioning systems, and most recently with evaporative cooling systems in tunnel-ventilated barns (Bray and Bucklin, 1994; Bray et al., 1994, Bray et al., 1997; Bray et al., 2003). This report updates results of projects conducted during the summers of 2001, 2002, and 2004 (Bray et al., 2003; Bray and Bucklin, 2004; Bucklin and Bray, 2005, Bray and Bucklin, 2005) which dealt with evaluating the feasibility of using air-conditioned housing and of tunnel-ventilated housing to cool cows on commercial dairies in a hot, humid climate.

STUDY 1. AIR-CONDITIONING COMPARED TO FAN AND SPRINKLER COOLING (2001)

Results of air-conditioning studies on dairy cattle housing conducted in the 1960's and 1970's (Wiersma and Stott, 1966; Johnson et al., 1966; Hahn and Osburn, 1969; Thatcher, 1974; Thatcher et al., 1974) indicated that mechanical refrigeration or air-conditioning had the potential to effectively cool cows. However, it was judged that air-conditioning dairy housing was too expensive to run and maintain to be practical.

As refrigeration technology has improved, air-conditioners have become more efficient and in addition, design and insulation of buildings have improved. The management practices on many large dairies have also changed. The care of the transition cow, the late dry period through the early fresh period, has been become more highly managed than in the past. In the southeastern United States, cows calving in the summer give less milk than cows calving in the cooler times of the year (2000 Florida DHIA Annual Report). Death losses for cows are also higher in the summer.

Many managers wish to keep heavier cows on a pack of sand or sawdust to reduce feet and leg problems and improve overall cow comfort. The traditional fan and sprinkler systems cannot be used with a pack because they wet the pack. Air-conditioning may be a good option to cool this type of housing

Internal barn temperatures and relative humidities of an air-conditioned barn (Barn B) were compared with values observed in a feed barn (Barn A) equipped with a sprinkler cooling system and with external conditions. The feed barn

Submitted for review in June 2008 as manuscript number SE 7533; approved for publication by the Structures & Environment Division of ASABE in July 2009.

The authors are **Ray A. Bucklin, ASABE Fellow,** Professor, Agricultural and Biological Engineering Department, University of Florida, Gainesville, Florida; **David R. Bray, ASABE Member,** Extension Agent IV, Animal Science Department, University of Florida, Gainesville, Florida; **Jake Martin, ASABE Member,** Joseph G. Martin Dairy Design, Gainesville, Florida; **Luiz Carlos,** Student, Rural Engineering Department, University of São Paulo, Piracicaba, SP, Brazil; and **Victor Carvalho,** Post-Doctoral, Collaborator Professor, Agricultural Engineering Department, State University of Campinas (UNICAMP),Campinas, SP-Brazil. **Corresponding author:** Ray A. Bucklin, Agricultural and Biological Engineering Department, University of Florida, Gainesville, FL; phone: 352-392-1864 ext.169; fax: 352-392-4092; e-mail: bucklin@ufl.edu.

  ISSN 0883-8542

was an open-sided barn 50 m (160 ft) in length, 20 m (65 ft) wide, and 4.5 m (15 ft) high at the eaves with a 2:12 roof slope with a ridge cap and a galvanized steel roof. The low pressure sprinkler system (138 kPa, 20 psi) was activated when the barn temperature reached 23.9°C (75.0°F). There were no fans in the barn. Figure 1 shows the sprinkler-cooled feed barn.

The air-conditioned barn (B) was 70 m (230) in length and 25 m (80 ft) wide with eave and ceiling heights of 4.5 m (15 ft). The walls and ceiling were insulated with R16 insulation. The floor was bedded with sand, with an open floor plan. The barn was equipped with five 25-ton (88-kW) air-conditioning units. The units were controlled by thermostats and were activated at a temperature of 21.1°C (70.0°F). Utility bills during the summer of 2001 averaged $5,400 monthly for about 90,000 kWh. Figures 2 and 3 show the air-conditioned barn.

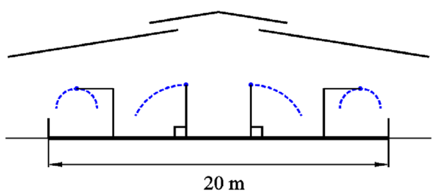

Figure 1. Feed barn (Barn A) with sprinkler evaporative cooling system.

Figure 2. End of Barn B with air-conditioning equipment.

Figure 3. Interior of Barn B with air-conditioning system.

Results and Discussion

Data collected included dry bulb temperature, relative humidity, and dew point temperature. Based on these data, Temperature Humidity Index (THI) values were calculated using the expression given by Hahn (1999):

$$THI = 0.8T_{DB} + (RH/100)(T_{DB} - 14.4) + 46.4 \qquad (1)$$

where

T_{DB} = dry bulb temperature, °F.

RH = relative humidity expressed as %

Values of climatic variables were recorded at hourly intervals on a 24-h basis in both barns and outside 20 m (65 ft) from Barn B and 30 m (100 ft) from Barn A. Data from 64 days were grouped by time and then statistically evaluated using a randomized block experimental design. Averages were compared using SAS® (SAS Institute Inc., Cary, N.C.) to conduct Tukey's Test at 5% significance level. Statistically significant differences were found between both temperatures and humidities in the barns. The average temperatures in Barn A, Barn B, and outside for 64 days for the hours between 11 AM and 4 PM were 27.4°C (81.3°F), 22.0°C (71.6°F), and 27.7°C (81.9°F). Relative humidities were 71%, 85%, and 70%, and THIs were 77.6, 70.5, and 77.9.

THI values were not significantly different between external conditions and inside Sprinkler Barn A. However, highly significant differences were observed between external conditions and conditions inside air-conditioned Barn B. THI values above the 72 are stressful for high production cows (Igono et al., 1992). During the day, animals in Sprinkler Barn A and the external environment were subjected to heat stressing conditions as shown in figure 4. However, cows in Air-conditioned Barn B were always exposed to THI values of 72 or below. Based on the observed environmental conditions, the air-conditioned barn provided the best conditions for cows.

Study 2: Tunnel Barns vs. Open Barn (2001 and 2002)

The use of tunnel-ventilated barns is common in the poultry industry in the southeastern United States. Recently,

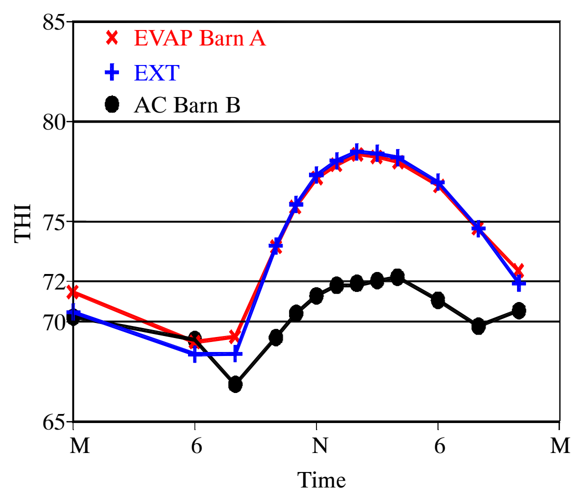

Figure 4. Average values of Temperature and Humidity Index (THI) for 64 days. EVAP - sprinkler cooling; AC - air conditioned; EXT - external.

tunnel barns are also being constructed for dairy housing (Brouk et al., 2003; Gooch and Stowell, 2003) and several tunnel barns have been constructed in Florida to house dairy cows since 2000. The first tunnel barn (Barn C) observed was 120 m (400 ft) long × 30 m (100) wide, with an eave height of 4.6 m (15.0 ft). Roof slope was 4:12 (33%). The underside of the metal roof was sprayed with insulating foam. The barn had canvas curtains on the sidewalls and had an open intake endwall. It was a 4-row tail to tail freestall barn with a drive through feed alley (fig. 5).

Evaporative cooling was provided by low-pressure sprinklers mounted above the feed face. Ventilation was provided by 30 belt-driven exhaust fans 1.3 m (48 in.) in diameter with 0.75-kW (1-hp) motors mounted in one endwall of the building. The fans were activated when the temperature exceeded 22.2°C (72.0°F). At 23.9°C (75.0°F), all the fans were activated. The sprinklers were also activated at 22.2°C (72.0°F) and ran for 1.5 min out of every 5 min.

Environmental conditions were measured and recorded hourly next to the exhaust fans (east), in the center of freestalls and at the intake end (west) as shown in figure 5. Ambient dry bulb temperature and relative humidity were recorded and equation 1 was used to calculate THI as a comfort index.

Environmental conditions observed in the tunnel-ventilated barn were compared to conditions in another freestall barn (Barn D) 150 m (500 ft) away. Dimensions of both barns were the same. Barn D was open on all sides with a continuously open roof ridge vent 0.9 m (3 ft) wide. Roof slope was 4:12 (33%), the same as the first barn, but the metal roof was not insulated. Open-sided Barn D did not have exhaust fans. Instead, air was circulated with forty 0.9-m (3-ft) diameter, 0.38-kW (0.5-hp) fans located over the freestalls. These fans were located 5 m (16 ft) apart, 3 m (10 m) above the floor. Three 7-m (23-ft) diameter 10-blade high volume, low speed (HVLS) ceiling fans driven by 0.56-kW (0.75-hp) motors provided additional air circulation. The HVLS fans were mounted in the middle of the barn over the feed alley (fig. 6). The sprinklers in Barn D were identical to those in Barn C and used the same timing and temperature set points.

Temperature and relative humidity were measured manually each hour from 11 AM to 4 PM. Data were collected at three locations inside the barns and the average of the three values was used with equation 1 to calculate THI values. SAS (SAS Institute Inc., Cary, N.C.) was used to analyze results using a randomized block design and Tukey's Test at 5% probability.

Figure 5. Exhaust fans on tunnel-ventilated barn (Barn C) with sprinkler evaporative cooling system.

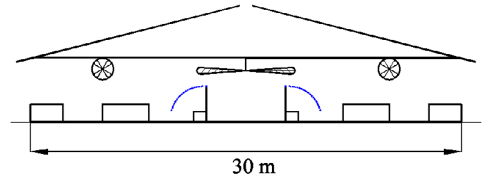

Figure 6. Sprinkler lines, vertical fans and ceiling fan in Barn D.

As shown in figure 7, environmental conditions in both tunnel-ventilated Barn C and in open-sided Barn D were more comfortable for cows, than conditions observed outside. For the hours between 11 AM and 4 PM, dry bulb temperatures for tunnel-ventilated Barn C, open-sided Barn D, and external conditions were 29.0°C (84.2°F), 29.7°C (85.4°F), and 33.9°C (93.0°F), respectively. Relative humidities were 56.0%, 55%, and 50% and THIs were 77.8, 78.6, and 83.8.

Environmental conditions inside the two barns were not statistically different. THI values above 72 are considered to produce heat stress for producing cows (Igono et al., 1992). The average THI value was 84 for the external environment, and about 78 for the two barns. Cows in both barns were exposed to similar environmental conditions that were more comfortable than outside conditions, but conditions in both barns were above the desired THI of 72. It was concluded that the choice between the two cooling systems should be based on initial costs and on water and energy consumption.

2002

In 2002, cow body temperatures were compared in three different barns at the commercial dairy located near Bell, Florida. Data were collected from 29 July to 6 August. Cows were housed in the tunnel barn and the open freestall barn (tunnel-ventilated Barn C and open-sided Barn D) observed in 2001 and in an additional tunnel-ventilated barn (Barn E). Barn E, shown in figure 8, was a converted naturally-ventilated freestall barn. It was 30 m (100 ft) wide × 180 m (600 ft) long, 3.8 m (12.5 ft) at the eaves, and had a 1:12 (8%) roof slope. This barn had a sprinkler system identical to those in Barns C and D, but was also equipped with thirty-eight, 1.3-m (50-in.) belt-driven, 0.75-kW (1-hp) fans mounted

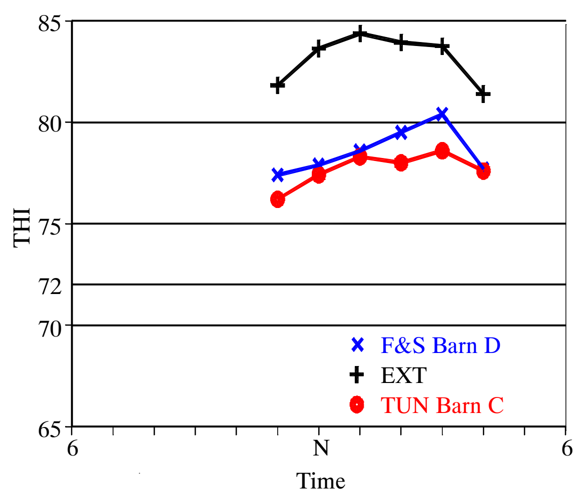

Figure 7. Average values of THI for each treatment (2001). TUN - sprinkler cooling with tunnel ventilation; F&S - fan and sprinkler cooling; EXT - external.

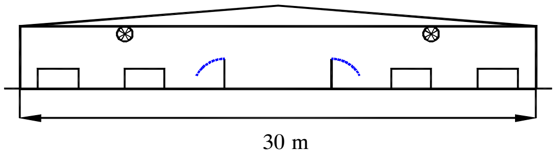

Figure 8. Tunnel-ventilated Barn E with sprinkler evaporative cooling system.

on one endwall. These barns are designed for one air change per minute. This longer barn had 28,300 m^3/min (1,000,000 ft^3/min) total fan capacity.

Barn Data

Temperatures and relative humidity were recorded every 15 min, from the open end, middle, and fan end of the barn, and outside of the barns. There were no differences in the temperature or relative humidity by location inside the barns. Average temperatures from noon to 6 PM were 28.8°C (83.8°F), 28.9°C (84.0°F), 29.0°C (84.2°F), and 28.7°C (83.7°F) for Barn C, Barn D, Barn E, and outside, respectively. Average relative humidities from noon to 6 PM were 74%, 77%, 75%, and 73%. Average THIs were 80.1, 80.7, 80.6, and 79.8. Average THIs for the barns and at an outside pole located near the barns are shown in figure 9.

Cow Tympanic Temperatures

Cow body temperatures were recorded every 15 min by sensors placed in the cows' ears. There was basically no difference in body temperature of the cows in the three barns (fig. 10). The method of cooling the cows in all barns was wetting the cows' backs with water and using airflow to evaporate the water and cool the cows. In the tunnel barns, fans were located at one end of the barn and in the open freestall barn, many small fans were located down the length of the barn, but air velocities over cows were about the same in all barns.

The only data collected on the large ceiling fans operating independently of the other fans in open-sided Barn D was one day when all the small horizontal airflow fans were shut off and only the three large ceiling fans were used to evaporate the water from the cows' backs. The result of this study was that the HVLS fans did not generate sufficient air movement to evaporate the water from the cows' backs. When cows exhibited open mouth breathing, the horizontal airflow fans were turned back on. Worley and Bernard (2006) evaluated HVLS fans in dairy housing in a hot, humid climate and also found them to be of limited benefit.

Study 3. Temperatures in Tunnel Barns Equipped with High Pressure Fog Systems (2004)

Environmental conditions and cow body temperatures were compared in two new barns located on a commercial dairy located near Live Oak, Florida. Cow body temperatures were compared in two identical 4-row tunnel barns (Barn F and Barn G) 210 m (690 ft) in length and 31 m (102 ft) wide with fans on the south end of the barns and fully open on the north end. Each barn contained 584 freestalls. Sidewall height was 3.5 m (11.7 ft) and peak height was 4.1 m (13.3 ft) with a 1:12 (8%) roof slope (fig. 11). Sidewall curtains were closed during the experiment. Only barn F was equipped with a high-pressure (10,000 kPa, 1,500psi) fogging system that operated when barn temperature exceeded 27°C (80°F) from 9:30 AM to 9:00 PM. Low-pressure feed face sprinklers were available in both barns and operated when barn temperature exceeded 22°C (72°F). Cycle time was 1.6 min on and 4.8 min off. Six cows in each barn were fitted with vaginal temperature recorders and body temperatures were recorded from 27 May to 1 June 2004.

Figure 12 shows the combined body temperatures of the cows in Barns F and Barn G and one cow in an outside lot to show the variation. The high spikes of all cows usually occurred at milking time. There were no overhead sprinklers in the holding area of this dairy at the time of this trial. Cows in this fog and sprinkler barn (Barn F) had the high pressure foggers in the daytime and feed face sprinklers at night. Body

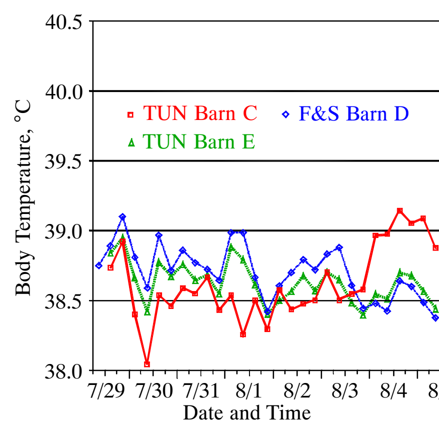

Figure 10. Average body temperatures of cows (2002). TUN - sprinkler cooling with tunnel ventilation; F&S - fan and sprinkler cooling.

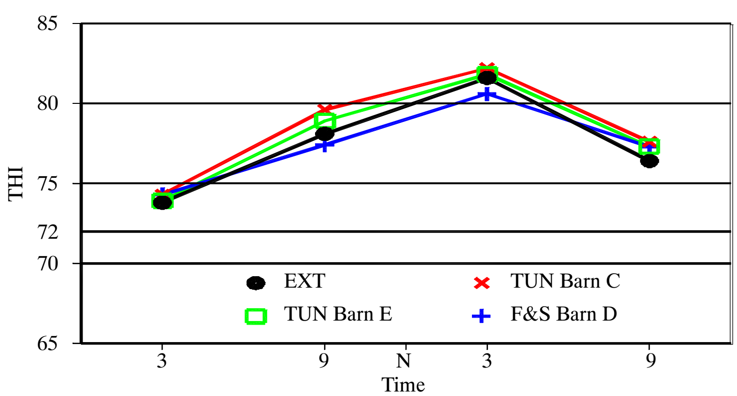

Figure 9. Average THI values in barns (2002). TUN - sprinkler cooling with tunnel ventilation; F&S - fan and sprinkler cooling; EXT - external.

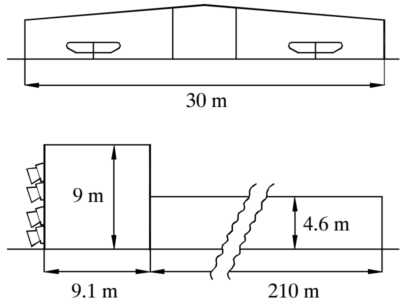

Figure 11. Tunnel-ventilated Barns F and G observed in 2004.

temperatures of cows in the sprinkler-only barn (Barn G) had higher body temperatures but body temperatures in both barns varied greatly. The sprinkler cows in Barn G had feed face sprinklers 24 h a day.

Figure 13 shows THIs for both barns and outside conditions. This is not the same week as the body temperatures were taken but the results were similar throughout the test. In the sprinkler Barn G, the temperature in the barn is the same as the outside temperature. Weather was stormy and cloudy during this study and ambient temperatures throughout the study were lower than during a typical Florida summer.

Average daily temperatures for Barn F, Barn G, and external conditions from 10 AM to 4 PM for Barn F, Barn G, and external conditions were 25.7 (78.2), 27.8 (82.1), and 27.5 (81.8), respectively. Relative humidities were 99%, 89%, and 84%, respectively, and THIs were 78.1, 80.6, and 79.4, respectively.THIs in Barn F were consistently lower than in Barn G; however, THIs in both barns were consistently above 72. Brouk et al. (2005) reported similar results for observations collected in the same two barns during the same time period.

Discussion

Evaporative cooling methods generally provided conditions more comfortable in the barns observed than conditions outside; however, during the day cows in barns were exposed to heat stressing conditions (THI above 72), except for those housed in the air-conditioned barn. THIs also exceeded 72 during nights in all but one of the evaporatively cooled barns. The Relative humidity approaches 100% after Midnight on most summer nights in areas bordering the Gulf Coast and other locations with hot, humid climates. At 100% Relative humidity the dry bulb temperature, dew point temperature and wet bulb temperature are equal and the THI is equal to the dry bulb temperature in Fahrenheit. Nighttime low temperatures greater than 22.2°C (72.0°F) have a great potential for heat stress in hot, humid climates. Mean minimum temperatures in Central Florida equal or exceed 21.1°C (70°F) from 24 June to 16 September and equal

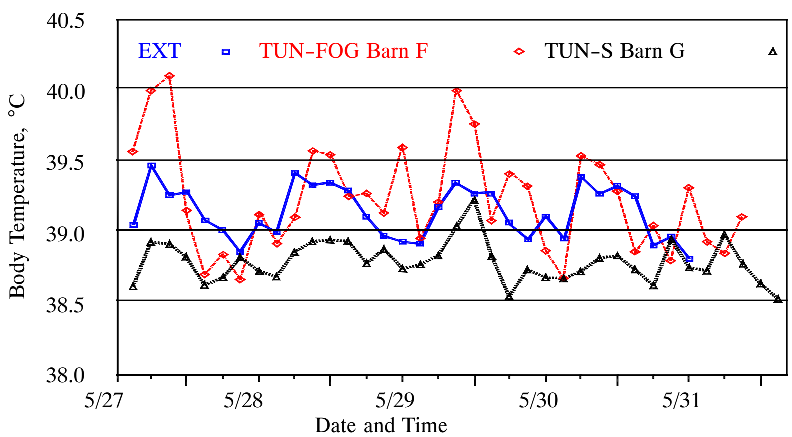

Figure 12. Average body temperatures for cows (2004) in a TUN-FOG - tunnel barn (Barn F) with fog and sprinklers, TUN-S - tunnel barn (Barn G) with sprinklers, and EXT - outside.

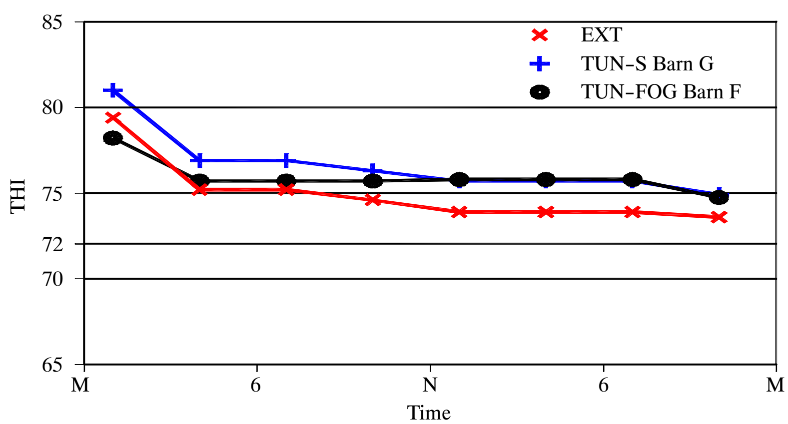

Figure 13. Average THIs (2004) in tunnel barn with fog and sprinklers (FOG) and in tunnel barn with fans and sprinklers (F&S) compared to outside ambient (EXT) THI.

or exceed 22.2°C (72°F) from 22 July to 5 August (DOD, 2003). The 99% confidence limits for the upper limit of nighttime lows for this region exceed 23.2°C (73.8°F) for each day of the months of June through September. Tables 1 and 2 summarize the THIs calculated from observed conditions in afternoons and from midnight to dawn. Average THIs in both tunnel-ventilated and in open-sided housing were usually lower than outside conditions, but were never below 77 during afternoon hours. Because of high nighttime humidities, average THIs in both tunnel-ventilated and in open-sided housing for the time between midnight and dawn also exceeded 72 for all but open-sided Barn A and outside temperatures were cooler than normal during the period Barn A was observed. Conditions in air-conditioned Barn B were consistently below 72 for both afternoon and nights. The THI values above 72 in the evaporatively cooled barns indicate that heat stress conditions occurred. THI is an accepted method of evaluating environmental conditions for heat stress based on dry bulb temperature and humidity; however, it does not evaluate the effects of air velocity and does not take into account the effects of sprinkled water evaporating from the hair coat.

In a tunnel barn, the air is cooled by evaporative cooling, and then fans are used to raise air velocity which increases convective heat losses beyond the heat losses that would take place if the cow only lost heat by respiration and conduction to the air. In a sprinkler and fan barn, if the cow's hair coat is kept wet, then evaporative cooling takes place at the skin surface if air velocity is sufficient to keep the air adjacent to the cow from saturating. The THI given by equation 1 correctly describes cow comfort in the air-conditioned barn and outside conditions, but does not fully predict heat stress if convective and/or evaporative cooling are increased and if solar radiation is reduced under shades. Improved indexes of thermal comfort that include the effects of air velocities are being developed for feedlot cattle (Brown-Brandl et al., 2005; Eigenberg et al., 2005; Mader et al., 2004, Mader et al., 2006; Gaughan et al., 2007). Evaluation of these expressions or development of new expressions for the conditions of high humidity and high air velocity typical of dairy housing in hot, humid climates is needed.

Cows in an air-conditioned barn should never suffer any of the effects of heat stress. This is especially important for the "Transition Cow," who must go through the most stressful period in her life, giving birth. Thus, this type of barn may be affordable to build and maintain because of all the health problems dairy cows suffer in the summer in these hot and humid conditions. All the other barns observed relied on evaporative cooling methods to reduce heat stress. In previous studies at the University of Florida, it was found that cows in non air-conditioned barns can have normal body temperature 38.6°C (101.5°F) and normal respiration rates, below 75 even though barn THI was above 72. But these barns cannot provide constant cooling for cows. Cows must lie down in an area away from the water and at night the water is often turned off because of high humidities. While the meaning of this is uncertain as far as cow health is concerned, it should be noted that elevated cow death losses occur in the summer in hot, humid climates both in sprinkler and fan evaporatively open-sided cooled barns and in closed-sided

Table 1. Average environmental conditions during middle of day sorted by THI.

Year	Barn and Cooling System Type	T (°C)	T (°F)	RH (%)	THI
2001	B: Closed feed barn/air-conditioned	22.0	71.6	85	70.5
2001	A: Open-sided feed barn/sprinklers only	27.4	81.3	71	77.6
2001	C: Tunnel freestall barn/sprinklers & fans	29.0	84.2	56	77.8
2001	A & B: External conditions	27.7	81.9	70	77.9
2004	F: Tunnel freestall barn/fog & fans	25.7	78.2	99	78.1
2001	D: Open-sided freestall barn/sprinklers & fans	29.7	85.4	55	78.6
2004	F & G: External conditions	27.5	81.8	84	79.4
2002	C: D & E: External conditions	28.7	83.7	73	79.8
2002	C: Tunnel freestall barn/sprinklers & fans	28.8	83.8	74	80.1
2002	E: Tunnel freestall barn/sprinklers & fans	29.0	84.2	75	80.6
2004	G: Tunnel freestall barn/sprinklers & fans	27.8	82.1	89	80.6
2002	D: Open-sided freestall barn/sprinklers & fans	28.9	84.0	77	80.7
2001	C & D: External conditions	33.9	93.0	50	83.3

Table 2. Environmental conditions from midnight to dawn (barns in same order as in table 1).

Year	Barn and Cooling System Type	T (°C)	T (°F)	RH (%)	THI
2001	B: Closed feed barn/air-conditioned	21.5	70.7	87	69.8
2001	A: Open-sided feed barn/sprinklers only	21.5	70.7	93	70.2
2001	A & B: External conditions	21.0	69.8	96	69.5
2004	F: Tunnel freestall barn/fog & fans	23.7	74.7	97	74.4
2004	F & G: External conditions	22.3	72.1	99	72.1
2002	C, D & E: External conditions	23.3	73.9	98	73.8
2002	C: Tunnel freestall barn/sprinklers & fans	23.8	74.8	94	74.3
2002	E: Tunnel freestall barn/sprinklers & fans	23.5	74.3	96	73.9
2004	G: Tunnel freestall barn/sprinklers & fans	23.3	73.9	100	73.9
2002	D: Open-sided freestall barn/sprinklers & fans	23.6	74.5	99	74.4

tunnel barns no matter what type of cooling was provided during the day or night. In its one year of use, no deaths occurred in the air-conditioned barn. The barn was used for pre-calving, calving, and for about 30 days after calving. This is usually the time of the highest death losses in dairy cattle in Florida.

In all the non air-conditioned barns, open or tunnel, cows produce more milk than they would otherwise, which means they are eating, but this seems to diminish as the summer drags on. Reproduction does not seem to be helped much in evaporatively cooled barns. The exact cause of poor reproduction is unknown, but it is generally attributed to the combined negative effects of heat stress and concrete floors. Death losses occur in the summer even in the fog tunnel barns, often due to mastitis, but other cows die due to unknown causes. The only truly comfortable cows observed in Florida's summers were in the air-conditioned barn. All the non air-conditioned barns were damp and dark. Cows had wet feet, wet hides, and constantly breathed high humidity air. The high initial and operating costs combined with the high management requirements of air-conditioned barns limits the practical application of this type of housing, but air-conditioned housing should be considered as an option for high value cows in hot, humid climates.

Recommendations

Feed barns consisting only of a roof over a feed lane and concrete to stand on are not recommended for lactating cattle on dairies in hot, humid climates. Feed barns without ventilation and cooling systems do not provide more comfort than is available if cows are outside with access to shade and ponds. Cows in hot, humid climates must be housed in well-ventilated housing equipped with cooling systems (Bray and Bucklin, 1996, Bray, 2006).

Fan and Sprinkler

As can be seen in figures 9 and 13, cows housed in open barns located in hot, humid climates often are exposed to THIs over 72 at night. No matter what type of barn, for hot, humid conditions, sprinklers should be run all night, and thermostats controlling fans should be set to 21°C to 22°C (70°F to 72°F). There is limited potential for cooling by evaporative cooling at night, but this applies to both sprinklers and cows' natural mechanism of evaporative cooling by respiration. The limited evaporative cooling provided by the evaporation of sprinkler water, combined by the sensible cooling provided by sprinkler water provides useful cooling. It is essential to operate fans to generate air movement over cows to utilize the potential for latent cooling that does exist and to provide sensible cooling by convection.

One of the problems with fan and sprinkler systems is keeping the fans clean. In open barn systems, natural air movement is present even if the fans are shut off or dirty. This air movement evaporates some water from cows and aids in the cooling process in warm weather. During cooler weather conditions, this natural air movement and an open ridge vent remove heat, moisture, and gasses from the barns. In tunnel barns, air velocities from 2.2-3.6 m/s (5-8 mile/h) are needed where cows are located (laying and eating). If fans are not cleaned within six months, air movement will drop to 1.3 m/s (3 mile/h) or less. This leads to hot cows and high ammonia levels.

Tunnel barns are less effective when doors are left open. Care must be taken during feed cleanout, feed delivery, bedding maintenance, and when scraping manure (if done). If not monitored, the back door is often left open and no cooling takes place. Rear door technology needs to be improved. It takes a good roll-up or sectional garage-type door to withstand the pressure difference required to provide 28,300 m^3/min (1,000,000 ft^3/min) airflow capacity. Some facilities have resorted to fabricating and installing "barn-type" hinged doors with manual or automatic operation to reduce the installed cost of these doors and to simplify repairs and maintenance. Thoughts of an enclosed turn around in the fan bay area might be in order.

Freestall Barns

Four-row freestall barns provide shade, feed and water, and manure management in one area. This type barn is becoming the most common type of housing in hot, humid climates. Many good examples of this type of barn exist to evaluate for design concepts. Six-row freestall barns will work with excellent management but, by design, have overcrowded feed faces.

Tunnel freestall barns are ideal for six row barns, or transition cows if barns are equipped with fogger cooling. When equipped with sprinkler cooling, tunnel barns do not have a big advantage over open-sided housing. They are expensive to build and maintain, and no fresh air enters unless it comes in by a fan. They require regular maintenance and a high degree of management.

A transition cow barn may be the best barn value you can build, especially in the summer. Freestalls for semi-close ups, pack for calving, recovery and sick cows, sure beat calving outside in the mud and the sun.

If tunnel barns are to be used only as fan and sprinkler barns, before building one, compare the price between a tunnel barn and an open freestall barn equipped with fans and sprinklers. Open barns are usually much less expensive.

Air-Conditioned Barns

The air-conditioned barn observed was in use for a one year period, until the dairy ceased operations for reasons related to milk prices and the owner's decision to redirect his investments away from dairying. The owner was satisfied with the operation of the air-conditioned barn. Cow health and milk production were at much higher levels than typical of evaporatively cooled dairy housing in hot, humid climates. The most significant problem seen in the barn was air quality related to ammonia levels. The air-conditioning system was designed with 25% make up air similar to the rate used in many commercial buildings. This rate of make up air was adequate when sand bedding was freshly changed, but ammonia levels increased to objectionable levels with time. The owner operated the barn at 21.1°C (70.0°F) to attempt to suppress biological activity in the bedding. Additives to suppress odor were tried without success. He did not attempt to increase make up air rate and was reluctant to increase the frequency of bedding rotation. Ammonia scrubbing technology was investigated, but no system was implemented. Humidity levels were high but acceptable in the barn. No condensation was observed on wall or ceiling surfaces.

The barn provided comfortable housing for cows during its use. Management and equipment changes could be implemented to improve air quality and potentially reduce energy costs. Barns of this type should be considered as an option for dairy operations that can afford the initial investment, have a high value herd and are willing to commit to the higher levels of management required in exchange for improved cow health, fertility and milk production.

Conclusions

Each cooling system and type of barn construction has both advantages and disadvantages. The best advice is to study all available information, make an informed choice that suits personal preferences and size and type of operation, and then maintain the cooling system. Visit, as many operations as possible before building a new barn.

The environmental conditions observed in these studies are typical for many areas adjacent to the Gulf Coast of the United States and for tropical regions throughout the world. When relative humidities approach 100% at night, the effectiveness of evaporative cooling is greatly reduced. Air dry bulb temperatures are low when relative humidities approach 100% and fans continue to provide sensible cooling. Sprinkling systems can also continue to provide sensible cooling; however, providing comfortable environmental conditions for cows housed in area with hot, humid climates is difficult using only evaporative cooling and ventilation. Air-conditioning dairy housing is a possible alternative method, particularly for high value cows.

Acknowledgements

Appreciation is expressed to Don Bennink, North Florida Holsteins, Bell, Florida; Sammy Wright, Wisteria Dairy, Green Cove Springs, Florida; and Ed Henderson of Shenandoah Dairy, Live Oak, Florida, for their cooperation and the use of their facilities for this study.

References

Bray, D. R., D. K. Beede, R. A. Bucklin, and G. L. Hahn. 1992. Cooling, shade and sprinkling. In *Large Dairy Herd Management,* eds. H. H. Van Horn and C. J. Wilcox, 655-663. Champaign, Ill.: American Dairy Science Association.

Bray, D. R., and R. A. Bucklin. 1994. Cooling methods for dairy housing in the Southeastern United States. ASAE Paper 944501. St. Joseph, Mich.: ASAE.

Bray, D. R., R. A. Bucklin, R. Montoya, and R. Giesy. 1994. Means to reduce environmental stress on dairy cows in hot, humid climates. In *Dairy Systems for the 21st Century; Proc. of the 3rd Intl. Dairy Housing Conf.,* ed. R. A. Bucklin. St. Joseph, Mich.: ASAE.

Bray, D. R., and R. A. Bucklin. 1996. Recommendations for Cooling Systems for Dairy Cattle. IFAS Fact Sheet DS-29. Gainesville, Fla.: University of Florida..

Bray, D. R., R. A. Bucklin, J. K. Shearer, R. Montoya, and R. Giesy. 1997. Reduction of environmental stress in adult and young dairy cattle in hot, humid climates. In *Livestock Environment V,* 672-679. St. Joseph, Mich.: ASAE.

Bray, D. R., R. A. Bucklin, L. Carlos, and V. Carvalho. 2003. Environmental temperatures in a tunnel ventilated barn and in an air conditioned barn in Florida. In *Proc. of the 5th Intl. Dairy Housing Conf.,* ed. K. Janni. St. Joseph, Mich.: ASAE.

Bray, D. R., and R. A. Bucklin. 2004. Latest on tunnel barns for cow comfort. In *Proc. of the 41st Annual Florida Dairy Production Conf.* Gainesville, Fla.: Univ. of Florida, IFAS. Available at: dairy.ifas.ufl.edu/dpc/index.shtml#2004.

Bray, D. R., and R. A. Bucklin. 2005. Update: Barn cooling, tunnel and otherwise. In *Proc. of the 42nd Annual Florida Dairy Production Conference.* Gainesville, Fla.: Univ. of Florida, IFAS. Available at: dairy.ifas.ufl.edu/dpc/index.shtml#2005.

Bray, D. R. 2006. The "Gold Standard" or "Fools Gold?" *Dairy Update* 6(4): 1-2. Available at: dairy.ifas.ufl.edu/dairyupdate/index.shtml#2006. Gainesville, Fla.: Animal Science Department, University of Florida.

Brouk, M. J., J. F. Smith, and J. P. Harner III. 2003. Effect of utilizing evaporative cooling in tiestall dairy barns equipped with tunnel ventilation on respiration rates and body temperature of lactating dairy cows. In *Proc. of the 5th Intl. Dairy Housing Conf.*, ed. K. Janni. ASAE Paper No. 701P0203. St. Joseph, Mich.: ASAE.

Brouk, M., D. Armstrong, J. Smith, M. VanBaale, D. Bray, and J. Harner III. 2005. Evaluating and selecting cooling systems for different climates. In *Proc. of the 7th Western Dairy Mgmt.* Conf.Reno, NV. Available at. http://www.wdmc.org/2005/4brouk.pdf.

Brown-Brandl, T. M., D. D. Jones, and W. E. Wold. 2005. Evaluating modeling techniques for cattle heat stress prediction. *Biosystems Eng*. 91(4): 513-524.

Bucklin, R. A., L. W. Turner, D. K. Beede, D. R. Bray, and R. W. Hemken. 1991. Methods to relieve heat stress for dairy cows in hot, humid climates. *Applied Eng. in Agric.* 7(2): 241-247.

Bucklin, R. A., G. L. Hahn, D. K. Beede, and D. R. Bray. 1992. Warm climate systems. In *Large Dairy Herd Management,* eds. H. H. Van Horn and C. J. Wilcox, 609-618. Champaign, Ill.: American Dairy Science Association.

Bucklin, R. A., and D. R. Bray. 2005. Dairy cooling systems in Florida. ASABE Paper No. 05-4113. St. Joseph, Mich.: ASABE.

DOD. 2003. Design: Engineering Weather Data. Unified Facilities Criteria. UFC 3-400-02. Available at: www.wbdg.org/ccb/DOD/UFC/ufc_3_400_02.pdf. Washington, D.C.: Department of Defense.

Eigenberg, R. A., T. M. Brown-Brandl, J. A. Nienaber, and G. L. Hahn. 2005. Dynamic response indicators of heat stress in shaded and non-shaded feedlot cattle: Part 2. Predictive relationships. *Biosystems Eng.* 91(1): 111-118.

Gaughan, J. B., T. L. Mader, S. M. Holt, and A. Lisle. 2007. A new heat load index for feedlot cattle. *J. Animal Sci.* 86(1): 226-234

Gooch, C. A., and R. R. Stowell. 2003. Tunnel ventilation for freestall facilities: Design, environmental conditions, cow behavior and economics. In *Proc. of the 5th Intl. Dairy Housing Conf.*, ed. K. Janni. ASAE Paper No. 701P0203. St. Joseph, Mich.: ASAE.

Hahn, G. L., and D. D. Osburn. 1969. Feasibility of summer environmental control for dairy cattle based on expected production losses. *Trans. ASAE* 12(4): 448-451.

Hahn, G. L. 1999. Dynamic responses of cattle to thermal heat loads. *J. Animal Science* 77(2): 10-20.

Igono, M. O., G. Bjotvedt, and H. T. Sanford-Crane. 1992. Environmental profile and critical temperature effects on milk production of Holstein cows in desert climate. *Intl. J. Biometerology* 36(2): 77-87.

Johnson, J. E., E. J. Stone, and J. B. Frye, Jr. 1966. Effect of hot weather in the productive function of dairy cows. Louisiana State University Agricultural Experiment Station Bulletin No. 608. Baton Rogue, La.: Louisiana State Univ.

Mader, T., S. Davis, J. Gaughan, and T. M. Brown Brandl. 2004. Wind speed and solar radiation adjustments for the temperature-humidity index. Meeting Abstract. *16th Conf. on B iometeorology and Aerobiology.* Vancouver, British Columbia, Canada. B.3. CDROM.

Mader, T. L., M. S. Davis, and T. M. Brown-Brandl. 2006. Environmental factors influencing heat stress in feedlot cattle. *J. Animal Sci.* 84(3): 712-719.

Means, S. L., R. A. Bucklin, R. A. Nordstedt, D. K. Beede, D. R. Bray, C. J. Wilcox, and W. K. Sanchez. 1992. Water application rates for a sprinkler and fan dairy cooling system in hot, humid climates. *Applied Eng. in Agric.* 8(3): 375-379.

Montoya, R. E., R. A. Bucklin, R. A. Nordstedt, H. H. Van Horn, and D. R. Bray. 1995. Factors affecting water usage in fan and sprinkler coolings for dairy cattle. *Applied Eng. in Agric.* 11(1): 125-130.

Strickland, J. T., R. A. Bucklin, R. A. Nordstedt, D. K. Beede and D. R. Bray. 1989. Sprinkler and Fan Evaporative Cooling for Dairy Cows in Hot, Humid Climates. *Applied Eng. in Agric.* 5(2):231-236.

Thatcher, W. W. 1974. Effects of season, climate and temperature on reproduction and lactation. *J. Dairy Sci.* 57(3).

Thatcher, W. W., F. C. Gwazdauskas, C. J. Wilcox, J. Toms, H. H. Head, D. E. Buffington, and W. B. Fredrickson. 1974. Milking performance and reproductive efficiency of dairy cows in an environmentally controlled structure. *J. Dairy Sci.* 57(3): 304-307.

Wiersma, F., and G. H. Stott. 1966. Microclimate modification for hot weather stress relief of dairy cattle. *Trans. ASAE* 9(3): 309-313.

Worley, J. W., and J. K. Bernard. 2006. Comparison of High Volume Low Speed (HVLS) vs. conventional fans in a free stall dairy in a hot humid climate. ASABE Paper No 064033. St Joseph, Mich.: ASABE.