Dairy Freestall Barn Design – A Northeast Perspective[1]

by
Curt Gooch, P.E.
Dairy Facilities and Waste Management Engineer
Biological and Environmental Engineering
Cornell University

Dairy producers are faced with many decisions when building new or renovating existing dairy housing facilities. The decisions made should be based on supporting a few key items regardless of where the farm is geographically located. These items include: maximizing cow comfort, milk quality, labor efficiency, expansion potential, manure handling, neighbor relations, and overall farm profitability.

Dairy farm growth and expansion in much of the Northeast (and similarly the upper Midwest) frequently takes place on existing farmsteads. New barns and milking centers are constructed on sites where existing facilities are present and in some cases there is multiple generation's worth of facilities. Existing facilities present pre-existing conditions that can, and many times do, limit the overall optimization of the new facilities. Unlike much of the central Midwest and West where dairy farming is comparatively new and thus facilities are constructed on green sites, this is seldom the case in the Northeast.

Overall, farmstead pre-existing conditions and site topography coupled with hot, humid conditions (compared to aired conditions in the non-traditional dairy states) and economics are the basis for thinking through the various options for providing housing for dairy cows.

The goal of this paper is to review these prevalent Northeast factors as they relate to barn design and cow comfort, keeping in mind there are no absolutes.

Barn Orientation

Freestall barn orientation is characterized by the direction the roof peak (ridge) is oriented; most often barn orientation is expressed as "North-South" or "East-West" although it can be any direction of the compass. Several factors need to be considered when determining the best barn orientation for a freestall barn in the Northeast. These include other existing and future farmstead buildings and feed storages, topography, prevailing summer wind direction, manure flow and handling, utilities, and cow grouping and flow.

From a natural ventilation perspective freestall barns, especially those with an aspect ration (length:width) of 2:1 or greater, are ideally oriented so the prevailing summer winds are perpendicular to the barn ridge. Barns oriented in this fashion will be better ventilated than a barn oriented otherwise (with all other factors the same) and are generally a "North-South" orientation in the Northeast but truly is site specific. "North-

[1]Written for presentation at the Ninth Annual Fall Dairy Conference. November 12 -13, 2008. Cornell University College of Veterinary Medicine and Cornell PRO-DAIRY Program

South" orientations result in issues with summer afternoon sunlight penetration in 3- and 6-row barns and 2- and 4-row barns with tail-to-tail configuration. Two- and 4-row barns with head-to-head stalls, 10' wide outside alleys and eaves that extend four or more feet horizontally from the barn sidewall significantly reduces the solar load on cows resting in the freestalls.

The chosen barn orientation for most Northeast dairies will be a compromise but should be based on maximizing the goals that are most important to the farm.

Ventilation

Determining the best dairy barn ventilation system to employ is one of the biggest facility related decisions to make. The options, that are familiar to most of us, are natural ventilation and mechanical ventilation. "Should I build a mechanically ventilated barn or a naturally ventilated barn with cooling fans" is a common question contemplated by many Northeast producers. The answer is based largely on the existing and planned future farmstead layout and other site specific conditions. No matter which ventilation system chosen, the goals are the same: to provide sufficient barn air exchange based on the cows' needs.

Basics of Ventilation

Proper barn ventilation consists of exchanging barn air with fresh outside air uniformly throughout the structure. Incoming air mixes with barn air contaminants (moisture, dust, pathogens, manure gases, and heat) and is discharged as shown in Figure 1. **Fans hanging over stalls or alleys, although important for cow cooling, do not provide air exchange and are not a substitute for open sidewalls and endwalls or well-designed mechanical ventilation systems.**

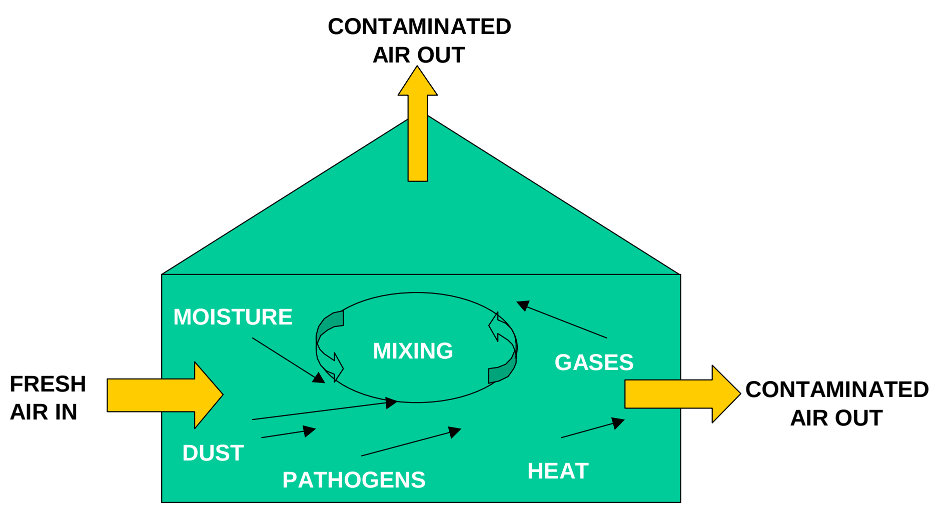

Figure 1. Basic principle of ventilation; fresh air mixes with shelter air contaminants and is discharged.

The required air exchange rate depends on a number of variables including the conditions of the outside air (temperature and moisture level) and animal population and density. The target air exchange rates for dairy cattle shown in Table 1 are used to design mechanical ventilation systems for dairy cow barns. A properly designed and managed system should result in barn air that is nearly equal in quality as the outside air on a year-round basis. The barn air concentrations of manure gases, dust, and pathogens should be low and the relative humidity should be about the same level as the outside air.

Table 1. Target barn ventilation rates for various ambient temperatures.

Animal Group	Weight (lbs.)	Air Exchange Rate cfm per head (No. room volumes/hr.)			
		Cold	Mild	Warm	Summer
Cows	1,250 – 1,800	100 (6)	300 (12)	500 (30)	1,000 (60)

Natural Ventilation with Cooling Fans

A natural ventilation system relies on natural air movement (summer and winter) and thermal buoyancy (mainly winter) to ventilate a barn. Theoretical wind speed needed to achieve adequate summer-time ventilation, using the 1,000 cfm per cow benchmark, based on barn configuration, curtain height, and stocking density is shown in Table 2. Table vales can be used in conjunction with knowledge of site specific summertime sustained air speeds to help determine if a natural ventilation system is an appropriate choice. Sites with leeward wind obstructions are not well-suited for a naturally ventilated barn if they are closer than four times their height. For example, a bunker silo that is 15 ft. high when filled will significantly obstruct ventilation of a downwind barn that is up to 60 feet away.

Table 2. Theoretical wind speed needed to meet summer ventilation needs and recommended number of cooling fans based on various barn configurations.

Barn Configuration	Sidewall Height (ft)	Curtain Opening	No. Stalls/ 100' Barn Length[1]	No. Cows[3]	Ambient Wind Speed (fpm) req'd for 1,000 cfm/cow	No. Cooling Fans[4]
2-row	12	10	50	58	49	12
3-row	12	10	80	92	78	16
3-row	14	12	80	92	65	16
4-row[2]	12	10	100	115	97	24
4-row[2]	14	12	100	115	81	24
6-row	14	12	160	184	130	32
6-row	16	14	160	184	111	32

[1]Based on a freestall width of 48" and one 12' wide cross over every 100' and crossovers at each end of the barn
[2]Head-to-head design
[3]Assumes 15% overstocking (not appropriate for all management levels)
[4]Based on a 36" fan spaced 30' apart with fan rows over each stall row and feed bunk

Some points that can be made based on the required wind speeds shown in the Table 2 are:

1. The theoretically required wind speeds range from 49 to 130 fpm. Wind speed should be considered as much from a sustainability basis as from a pure magnitude basis. In many locations, the winds will blow harder than this for part of the summer but a few days to weeks without can result in significant ventilation challenges and translate into lost milk, reduced conceptions and a whole host of other challenges that come from heat stress.

2. Incoming ventilation air speed is distributed evenly over the height of the sidewall and in environmentally challenging cases will not result in sufficient air exchange at cow level. Thus air velocities at cow level that are higher than stated in the table are generally required to ensure proper ventilation.

3. Table air speed values fall far short of the target goal of 500 to 600 fpm at cow level justifying the need for cooling fans located in strategic locations throughout the barn.

Also shown in Table 2 is the number of cooling fans, per 120 ft. of length, needed to ensure target air speeds of 500 to 600 fpm in strategic locations in the barn. These locations, also considered sites of productive activity for cows, are above cows when they are standing at the feed bunk and when cows are lying in freestalls. The number of fans for each barn configuration along with their total annual economic costs will be compared to that of a tunnel system later in this paper.

Mechanical Ventilation Combined with Cow Cooling

Tunnel ventilation (Figure 2) and cross ventilation (Figure 3) systems can be designed not only to provide barn air exchange but also meaningful air speed at cow lying level in the freestall.

Measurable air speed at cow lying level is key to minimizing the deviation from cow target resting times during warm and hot periods. Air speeds between 500 to 600 ft./min. have been reported to be beneficial in reducing heat stress (Shearer et al., 1991). Both tunnel-ventilated and cross-ventilated barns can be designed based on providing this target air speed at cow lying level by combining sufficient in-place fan capacity with barn attributes. Additionally, in-place tunnel fan capacity for tunnel-ventilated barns can be determined based on the goal to simply provide ventilation (1,000 cfm/head for the Northeast) and then cooling fans can be located over freestall rows to provide requisite air speed at cow level.

We also know that naturally ventilated barns with cooling fans placed over freestall rows and cows at the feed table, when properly positioned, can provide requisite air speeds.

From an economic perspective, the return on investment of a system that provides requisite air speed at cow level can be determined by calculating the annual ownership cost of the system and comparing this to sustained milk production as a result of the system. Grant (2008) has shown that each hour of cow resting time results in 2.5 to 3.8 lbs. of milk per cow per day.

Natural or Mechanical Ventilation?

The natural ventilation process relies on a combination of key freestall barn characteristics and their management coupled with natural air movement for air exchange to happen. As already discussed, barns need to be properly oriented to maximize natural ventilation--ideally with the sidewall perpendicular to prevailing summer winds. They need adequate sidewall, endwall, and ridge openings for air to enter and exit. Sufficient space must exist between a barn and any wind blocking objects so naturally moving air has the opportunity to properly enter the barn. The minimum distance between nearest sidewalls of adjacent shelters should be at least 80 feet—more is better with large structures.

Barns that have inadequate openings or are poorly sited with respect to prevailing winds are subject to inadequate air exchange. Incorrect siting includes locating barns too close together, orienting them incorrectly, or placing them immediately down wind from wind barriers that are seasonal such as corn or deciduous trees or permanent such as hills or bunker silos. Under all such situations, these barns are viable candidates for mechanical ventilation. Not all barns that are viable candidates to be mechanically ventilated are easy to mechanically ventilate.

For almost all freestall barns that are destine to be ventilated mechanically, the approach of choice is to employ a negative pressure ventilation system. Negative ventilation systems develop inside barn air pressures that are slightly less (0.05 to 0.125 inches of water column) than outside. Ventilation fans located primarily on a barn’s sidewall (cross ventilation), endwall (tunnel ventilation), or at the peak to blow barn air out to the ambient are all examples of negative pressure ventilation systems.

Observation has shown that the average annual period for operating the summertime mechanical ventilation system on Central New York diaries is 150 days. Contrast this to a naturally ventilated barn with cooling fans and in almost all cases there is less expense associated with naturally ventilated barns with cooling fans. So if all else were equal, there would be more profitability associated with this option. However, in some cases, the air quality experienced by cows would not be adequate without a mechanical ventilation system. Thus the bottom line questions are: 1) what system provides the best air quality at the lowest capital and operating cost and 2) what system provides the best effective air speed at cow lying level at the least cost?

Each of the three negative pressure ventilation schemes is briefly discussed below with additional resources listed in the References for more detailed information.

Tunnel Ventilation

Tunnel ventilation is a special and simple summer-time ventilation system that historically had the combined goal to provide **air movement** and **air exchange** concurrently in a barn. Fans (called tunnel fans) are placed in one endwall of a building. They are operated to create a negative pressure in the barn causing air to be drawn into the opposite gable endwall opening (Figure 2). Once in the barn, the fresh inlet air travels longitudinally through the structure and is exhausted by the tunnel fans. For tunnel ventilation to function at its maximum potential, essentially all sidewall, ceiling, and floor openings must be closed to form the "tunnel."

Tunnel ventilation is suited for freestall barns: 1) that would be otherwise poorly ventilated in the summer by natural means, 2) with low ceilings that aid in keeping air speed at cow level or, 3) that do not have ceilings but have cooling fans placed over freestall rows.

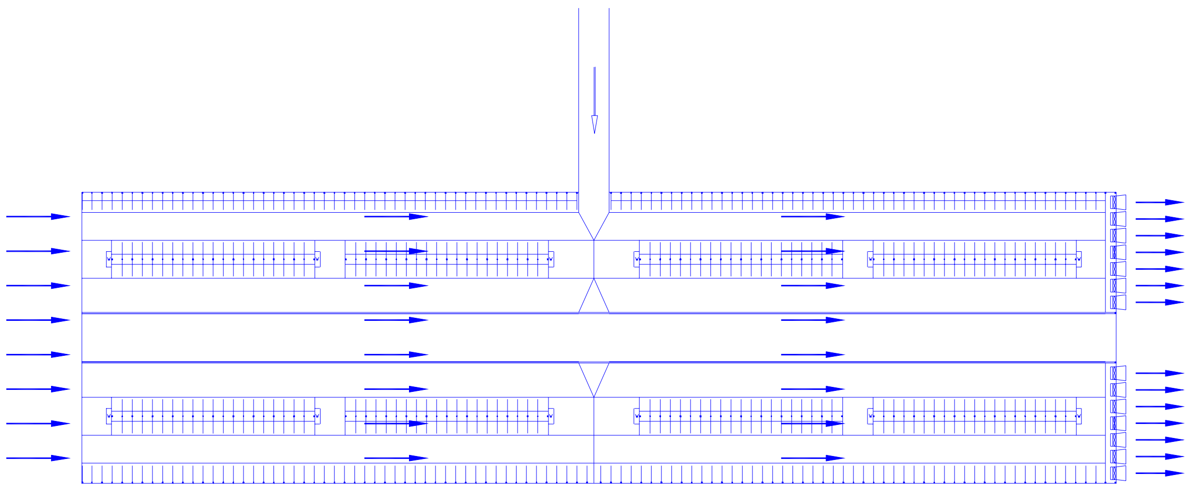

Figure 2. Plan view of a typical tunnel-ventilated freestall barn.

The break-even barn size (number of cows) when the governing design criteria switches from air speed (600 fpm) to air exchange (1,000 cfm/cow) is shown in Table 3. The break even numbers for each barn configuration means that barns targeted to house more cows than shown by the break even numbers need to be designed based on the air exchange criteria and not on average air speed criteria to ensure adequate barn air quality.

Table 3. Target air exchange rate, break even No. of cows, and No. of tunnel ventilation fans required for each barn configuration.

Barn Configuration	Sidewall Height (ft) x Barn Width (ft)	In-place Fan Capacity[1] (cfm)	Break Even No. of Cows	No. Fans Required[2]
2-row	12 x 51	367,200	367	13
3-row	12 x 62	446,400	446	16
3-row	14 x 62	520.800	521	18
4-row	12 x 96	691,200	691	24
4-row	14 x 96	806,400	806	28
6-row	14 x 116	974,400	974	34
6-row	16 x 116	1,113,600	1,114	39

[1]Based on providing an average air velocity of 600 fpm
[2]Based on a fan capacity of 28,200 cfm per fan

Cross Ventilation

The concept of cross-ventilating a dairy barn is essentially the same as tunnel-ventilation except the ventilation fans are located on one sidewall and the opposite is open as the air inlet; therefore, ventilation air travels in a transverse direction in cross-ventilated barns.

Like with tunnel-ventilated barns, in-place fan capacity for cross-ventilated barns can be determined based on providing sufficient air exchange to meet summer ventilation needs and to provide target air speed at cow lying level. Since the air exchange needs of a cow are the same whether the barn is ventilated by natural, tunnel, or crossways, the number of fans to provide requisite ventilation is the same.

Again like tunnel-ventilated barns, additional ventilation fan capacity can be added in cross-ventilated barns with the goal of increasing air speed at cow level. Wide-body barns (barns with more than 6-rows of freestalls) that are cross-ventilated include air flow baffles located within barn to help increase air speed at cow lying level as shown in Figure 3. In this case, the number of fans needed is based on the size of the opening under the baffle (usually 6’ to 7’), the presence or lack of an evaporative cooling pad located on the air inlet sidewall, and the specifics of the fan chosen.

Many of the recently constructed cross-ventilated wide-body barns are mechanically ventilated year-round. Several fans are grouped together and controlled in stages based on the barn ventilation needs. As the temperature increases, additional fans in each group are turned on. Careful consideration is needed by the ventilation system designer to ensure all in-barn static pressure drops are accounted for and used when selecting an appropriate ventilation fan. At least one Midwest cross-ventilated wide-body barn recently visited had one out of every six fans turned off reportedly due to poor overall fan performance when all fans were operating.

Operational experience and data are needed to fully understand the performance of wide-body cross-ventilated barns located in the Northeast during non-summer months. Fall, winter, and spring air exchange rates (Table 1) are significantly less than summer rates and thus concern exists due to the width of the barn and the distance the air must travel from air inlet to air outlet. The maximum distance suggested between air inlet and fan discharge in order to maintain acceptable air quality is 75' (MWPS-32) for non-summer mechanical ventilation system. The distance from an air inlet to fan discharge in an 8-row wide-body barn can exceed the recommended maximum distance by almost a factor of three.

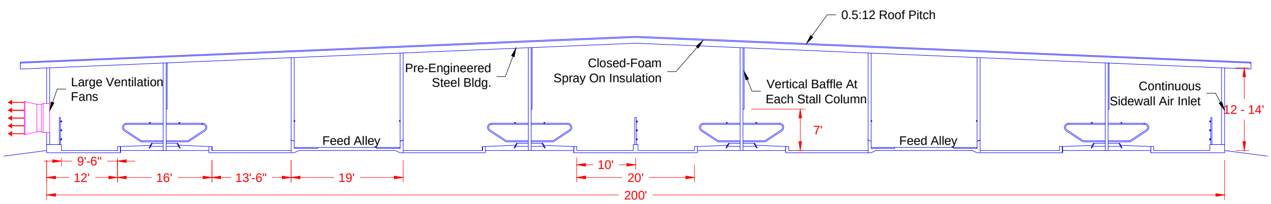

Figure 3. Cross-sectional view of a wide-body cross-ventilated freestall barn.

<u>Mechanical Ventilation with Peak-Mounted Fans</u>
This ventilation scheme is well-suited for freestall barns when: 1) they are operated as a warm barn, 2) mechanically ventilated year-round, and/or 3) the barn is tunnel-ventilated in the summer but not well-suited for natural ventilation the rest of the year.

Ventilation fans can be located in vertically oriented ductwork that discharges at (as shown in Figure 4) or near the roof peak. It is most advantageous to locate the fan low in the air duct so fan maintenance can more easily be facilitated. In-place fan capacity is based on providing the air exchange rates shown in Table 1.

Fan spacing depends on the barn size, ventilation needs, and the in-place fan capacity with a spacing of about 20 feet acceptable. In the late fall, winter, and early spring, some of the fans are turned off. Those fans not operating need to have either automatic louvers or a temporary means of blocking unwanted airflow through the fan. It is advantageous to provide variable frequency drives on those fans (or even on all to reduce the electrical demand during starting) designated to run during cool and cold weather to increase barn air quality management flexibility.

A cupola can be used to reduce or even eliminate rainwater from entering the duct and possibly adversely affecting the ventilation fan. Cupolas need to be designed so ventilation air passes through them with minimal restriction to flow; allow at least 2.5 ft^2 of net opening for every 1,000 cfm of fan capacity and select the fan based on its performance when operating against 0.10 inches of water column static pressure.

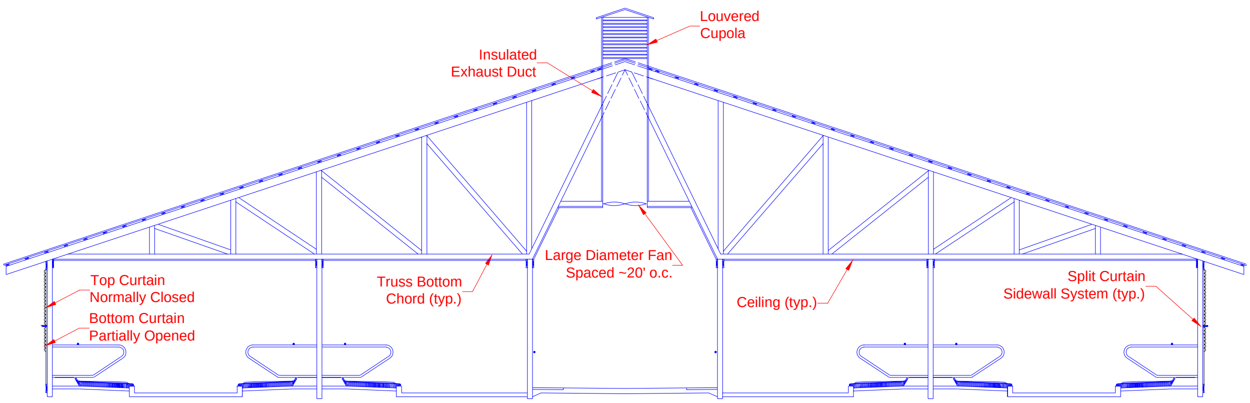

Figure 4. Freestall barn with ventilation fans located at the roof peak.

System Comparisons

There are several comparisons that can be made between the ventilation/cooling systems discussed above.

Mechanical Ventilation System Application Comparisons

Each of the three mechanical ventilation/cooling systems discussed above has benefits, drawbacks, and shortcomings. Comparing each system's attributes to the others can be helpful in making a decision which is best for a specific barn and/or overall farmstead. Table 4 provides an application comparison for each of the three systems when applied to freestall barns.

Table 4. Application comparison of three freestall barn mechanical ventilation/cow cooling schemes.

Consideration	Peak Ventilated	Tunnel Vent. & Cross Vent.	Tunnel Vent. w/ air speed	Tunnel Vent. w/ cooling fans	Cross Vent. w/ air speed
New Const.	√	√	√	√	√
Retrofit	√	√	√	√	√
Initial Cost	More	Low	Moderate	High	High
O & M Cost	More	Low	More	High	High
Ceiling Req'd	No	No	Yes	No	Yes (low roof)
Baffles Req'd	No	No	No	No	Yes - Vertical
Use w/ Evap. Cooling	√	√	√	√	√
Air Speed at Cow Resting Level	Little	Little	More	Most	More
Barn Size Limitations	None	Length ~ 1,000' for TV	Length ~ 1,000'	Length ~ 1,000'	?
Use Year-round	√	Barn Size Dependent	Barn Size Dependent	Barn Size Dependent	Barn Size Dependent
Emissions Mitigation Potential	Not Practical	Possible	Less Possible	Possibly	Less Possible

<u>Tunnel Ventilation vs. Natural Ventilation with Cooling Fans: Performance Comparison</u>
Given that both systems are selected based on individual farm-specific considerations, both can work very well.

The overwhelming advantage of a natural ventilation system with cooling fans is better assurance of target air speed at cow level. Cooling fans placed in the strategic locations, as outlined above, will encourage cows to perform productive activities (lying in stalls and eating feed) since cows will naturally position themselves to take advantage of the air speed during environmentally stressful conditions. The major disadvantage of this system is the poor air quality conditions (higher barn temperatures, humidity, and manure gases than ambient air) that will exist when air exchange is compromised during low or nonexistent wind conditions.

Tunnel ventilation, on the other hand, provides predictable air exchange rates all summer as long as the system is maintained and electrical power is available. Early tunnel ventilation systems installed revealed that ventilation air does not move through the barn at the same air speed, rather air speed is lower at cow level and adjacent to curtain sidewalls and higher in the drive through feed alley and adjacent to the ceiling. This preferential air flow will affect cow behavior; cows will stand in stalls and at the feed bunk to expose their bodies to faster moving air, especially during the more environmentally challenging conditions. Iterations in tunnel ventilation system design and subsequent implementation by producers have shown that increasing the design average air speed has somewhat helped improve air speed at cow level while combining a tunnel ventilation system designed to provide the requisite air exchange rate of 1,000 cfm per cow combined with cooling fans over the stall rows largely meets barn ventilation and cow cooling needs.

Tunnel Ventilation vs. Natural Ventilation with Cooling Fans: Economic Comparison

Understanding the economics of any large investment, including the purchase, installation, operation, and maintenance of tunnel ventilation and cow cooling fans is also important. Unfortunately, the most meaningful economic indicator, return on investment, calculated based on the cow response to the system, is not quantified at this time due to the lack of data. However, some meaningful economic and also physical comparisons can be made between each system by calculating the total annual cost for each system.

The 36-in. cooling fan used to develop some of the information shown in Table 2 has a retail cost of $575 while the 51-in. tunnel ventilation fan used in Table 3 has a retail cost of $1,715. Since no one pays retail, these prices are reduced by 25 percent to $430 and $1,286 for this analysis. The installation cost used was $600 each for tunnel fans and $250 each for cooling fans. Therefore, total in-place cost per fan used was $1,886 and $680 per tunnel and cooling fan, respectively. The only difference in barn cost for each option is the presence of a ceiling material in the tunnel-ventilated barns.

The total annual cost (TAC) analysis results for each of the two systems for various barn configurations are shown in Table 5. The results are based on operating the fans 150 days per year, a seven year useful system life, salvage values equal to five percent of the initial investments, $0.10 per kWh electrical cost, and five percent lost opportunity cost. The analysis assumes no cost for borrowed money and therefore may not represent the true annual cost paid for the system.

Table 5. Total annual cost (TAC) values for a tunnel-ventilated barn and a naturally ventilated barn with cooling fans for each barn configuration shown.

Barn Configuration	Tunnel, $ (*A*)	Natural with Cooling[1], ($) (*B*)	$\frac{(A)}{(B)}$
2-row	11,564	3,929	2.94
3-row	14,230	5,234	2.72
3-row	16,007	5,234	3.06
4-row	21,337	7,845	2.72
4-row	24,891	7,845	3.17
6-row	30,222	10,455	2.89
6-row	34,664	10,455	3.32

[1]Per 120 ft of barn length

The ratio of the tunnel system TAC/natural ventilation system TAC ranges between 2.72 and 3.32. This means that a naturally ventilated barn with cooling fans that is 120 times this ratio in length results in the same TAC. Producers can use the appropriate ratio for their given situation to assist in choosing a system.

References

Gooch, C.A. 2007. “Wide-Body Dairy Barns”. *Hoard’s Dairman.* January 25, 2007.

Gooch, C.A. and M.B. Timmons. 2000. Tunnel Ventilation of Freestall Barns. Proceedings from Dairy Housing and Equipment Systems Conference. NRAES-129. Northeast Regional Agricultural Engineering Service. Cornell University, Ithaca, New York.

Gooch, C.A., M.B. Timmons., and J. Karszes. 2000. Economics of Tunnel Ventilation for Freestall Barns. Presented at the 2000 ASAE Annual International Meeting, July 9-12, 2000. Milwaukee, Wisconsin. Paper No. 00-4101. ASAE 2950 Niles Road, St. Joseph, MI 49085-9659

Grant, R. 2008. Proceedings from the Northeast Dairy Producers Association bi-annual conference. Liverpool, New York. pages 83-92

MWPS-32. 1990. Mechanical Ventilation Systems for Livestock Housing. MidWest Plan Service, Iowa State University, Ames, Iowa.

Shearer, J.K., D.K. Beede, R.A. Bucklin, and D.R. Bray. 1991. Environmental Modifications to Reduce Heat Stress in Dairy Cattle. *Agri-Practice*, Volume 12, No. 4, July/August, 1991.