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SIMULATION AND EVALUATION OF VENTILATION MANAGEMENT PRACTICES IN A COLD CONFINEMENT NATURALLY VENTILATED DAIRY FREESTALL BARN

by

Richard James Tillotson

A DISSERTATION

Submitted to
Michigan State University
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ABSTRACT

SIMULATION AND EVALUATION OF VENTILATION MANAGEMENT PRACTICES IN A COLD CONFINEMENT NATURALLY VENTILATED DAIRY FREESTALL BARN

by

Richard James Tillotson

During winter, cold confinement naturally ventilated dairy freestall housing is designed to maintain the inside temperature no more than a few degrees warmer than the outside temperature. However, to keep the building warmer for the benefit of man or machines, ventilation may be reduced or the building over-stocked. This may result in an unhealthy animal environment. Evidence of this potentially unhealthy condition is less obvious when the roof is insulated. Condensation or frost will not occur as rapidly and a "close or "barny" odor may then become the management tool used to identify underventilation.

To study the effect of different wintertime ventilation rates and roof insulation levels on a naturally ventilated cold confinement dairy freestall barn environment, a simulation model was developed that predicted the steady state nighttime ventilation rate, air temperature, relative humidity, air exchange, roof condensation or frost formation, and carbon dioxide concentration. When soffit openings were less than minimum design area, a roof insulation thickness of 12.7 mm reduced the probability of roof condensation to less than 100%. Doubling the roof

insulation thickness to 25.4 mm caused relatively insignificant reductions in potential roof condensation. However, even with roof insulation the potential for roof condensation still existed. Closing the barn ventilation to less than minimum design area reduced the air exchange, maintained inside relative humidity at an unhealthy level, and prolonged a damp, virulent, condensing environment that was detrimental to the structure and animal health. Conversely, unobstructed soffits, ridge, and open end doors caused the lowest CO_2 concentration and relative humidity as well as the greatest air exchange and should be considered as a minimum ventilation recommendation for an uninsulated cold confinement dairy barn during winter.

To my wife, Becky,

and my four adult children

Jim, Amber, Sarah, and Carrie

My greatest supporters.

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How can I thank a wife and children who were willing to leave a stable home as a high school senior, a college freshman, a wheelchair confined teenager, a college junior, or a part time nurse; to move to a new high school, new college, new people, different living conditions, and a full time nursing job? Maybe the best way is to say IT'S DONE. Through this, and much more, I can say that I know I am loved; and I think we can all say that it was a great experience. Finally, I would like to thank my Lord and savior Jesus Christ. You have led us through this effort and what a blessing it has been.

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LIST OF SYMBOLS

Symbol	
A	Area, m^2
C	Concentration, ppm
Cd	Discharge coefficient
Cp	Pressure coefficient
D	Days pregnant
E	Wind effectiveness factor
F	Heat transfer rate, W/mK
f	Air film or surface conductance, W/m^2K
g	Acceleration due to gravity, 9.8 m/s^2
h	Convective heat transfer coefficient, W/m^2K
h	Height above a datum, m
h_p	Neutral pressure plane height, m
k	Thermal conductivity, W/mK
L	Latent
L	Length, m
m	Mass, kg
p	Perimeter distance, m
P	Pressure, Pa
Q	Heat production, Watts
Q_L	Latent heat production, Watts/kg
q	Heat flow, Watts or Joules/sec.

Symbol

R	Resistance, m^2K/W
T	Temperature, °C
t	Temperature, °K
U	Unit area conductance, W/m^2K
V	Volume, m^3/s or ppm
v	Velocity, m/s
W	Width, m
W	Watts
x	Homogeneous material
Y	Milk production, kg/day
α	$2g(\Delta\rho/\rho_n)$
Δ	Change in an item
ΔP	Pressure difference, Pa
ϵ	Emissivity
ρ	Density, kg/m^3
σ	Stefan-Boltzmann Constant, W/m^2K^4
Φ	$v^2_w(Cp_{o,n}-Cp_i)$
Ω	$h_p+\Phi_n/\alpha_n$

Subscripts

a	Number of items in a group or series
C	Conductive
f	Floor
g	gauge pressure
i	Inside or internal
iaf	Inside air film

Subscripts (continued)

Symbol	
L	Latent
ls	Lower surface
m	One horizontal opening in a group or series
n	One non-horizontal opening in a group or series
o	Outside or external
p	Production, m^3/s
r	Roof
rt	Reference temperature, °C
s	Sensible
T	Total
t	Thermally induced
us	Upper surface
w	Wind
x	A specific homogeneous material
y	An item in a group or series

I. INTRODUCTION

1.1 Statement of the Problem

Ideally, the purpose of livestock housing ventilation is to provide warm weather temperature moderation and cold weather moisture and air quality control so as to promote animal productivity and maximum economic gain. Often this goal is compromised by placing the needs of people and equipment ahead of the needs of animals (Bickert, 1994). Cold confinement naturally ventilated freestall dairy housing is designed to maintain the inside temperature no more than a few degrees warmer than the outside temperature during winter. However, to keep the building warmer for the benefit of man or machines, ventilation may be reduced or the building may be over-stocked. This may result in an unhealthy environment for the animals.

Evidence of this potentially unhealthy condition is less obvious when roof components of the cold confinement dairy housing are insulated. Condensation and frost formation will not occur as rapidly and a "close" or "barny" odor may then become the "early warning" management tool that may be used to identify potential underventilation. Absence of roof insulation would cause visible condensation

to occur at warmer temperatures and provide a more sensitive management tool to signal potential underventilation.

1.2 Objective

1.2.1 Simulation Model Development

To develop a simulation model that would predict the steady state, nighttime, ventilation rate, air temperature, relative humidity, air exchange, roof condensation or frost formation, and carbon dioxide concentration, in modern insulated and uninsulated freestall dairy barns during winter.

1.2.2 Environmental Evaluation

To evaluate the influence of the environmental conditions mentioned in Section 1.2.1 upon potential wintertime ventilation management practices.

II. LITERATURE REVIEW

2.1 Reduced Ventilation and Wintertime Animal Health

Cattle health is influenced by air quality which, in turn, is related to ventilation. This fact was mentioned as early as 1925 when F. E. Fogle wrote in the Michigan Quarterly Bulletin, "Ventilation is necessary for the health and comfort of animals. It will preserve the building and contents from mold and rot, due to excessive moisture, and will aid in the prevention and control of disease. ... With the advent of tight buildings, comes the necessity for ventilation. For best results we must admit fresh air, remove stale air, and control temperature and humidity." (Fogle, 1925). More recently, Curtis (1983) stated that closed houses - and in particular the gases, particles, odorous vapors, and ions in the air - are sometimes blamed for poor animal health and performance. Also, Hartung (1994) states that increased herd size and close contact between confined animals favors a quick passage of pathogens, leading to increased virulence and infection pressure.

Although the exact relationship between these factors is not fully understood, empirical observations and field trials suggest that the aerosol spread of pathogens between cattle and the influence of air pollutants on pulmonary

defense mechanisms are important, especially to respiratory health (Bickert and Herdt, 1985). Noble (1969) notes that a number of reports can be found of infection attributed to direct airborne transfer in hospital wards and army barracks. This transfer is by way of droplet or dust particle vectors in the air and is affected by the size and number of these dust particles.

A microbe's ability to withstand aerial transport is an important determinant of its distribution pattern and contagiousness. This ability is mainly a function of the microorganism's resistance to temperature change, desiccation, and ultraviolet radiation. Other factors include air-movement patterns, ventilation rate, and animal density (Curtis, 1983). Songer (1966) found that a temperature of 10 °C and 90% relative humidity favored maximum survival of viruses in a dynamic system. Wright et al. (1969) also found that *Mycoplasma pneumonia* survival was best at relative humidities below 25% or greater than 90% and at lower temperatures. Certain pathogens may actually multiply in dust when the atmospheric humidity approaches the saturation point (Lidwell and Lowbury, 1949). Typical results of experiments with pneumococcus at three different relative humidities are presented in Figure 2.1. Illustrated is the capacity of microorganisms to survive for long periods at both very low and very high relative humidities, but not at intermediate values (Dunklin and Puck, 1947).

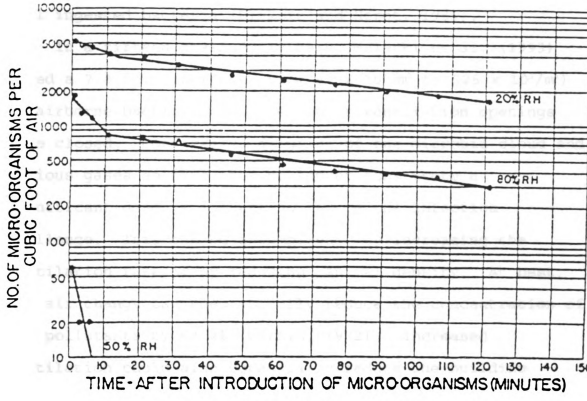


Figure 2.1 Logarithmic Plot of the Survival of Pneumococci Sprayed From Broth Culture Into Atmospheres of Various Relative Humidities, at 22.2°C.

Lipid-containing viruses seem to survive better at low humidities, whereas viruses composed only of proteins and nucleic acids survive better at higher vapor pressures. Also, airborne bacteria survive better at relative humidities either higher or lower than the most lethal 50 to 80 percent range. For both airborne bacteria and viruses, the higher the air temperature, the quicker they die (Curtis, 1983).

The interaction of air quality with pulmonary defense mechanisms might play a substantial role in bovine

respiratory disease as well. Noxious gases apparently suppress the ability of pulmonary alveolar macrophage to kill ingested bacteria (Bickert and Herdt, 1985).

In a fifteen stall dairy barn, Malecki et al. (1993) noted a 7.8 fold increase (from 67 x $10^3/m^3$ to 525 x $10^3/m^3$) in airborne bacteria when the outlet ventilation openings were closed. Conversely, dilution of the microbic cloud and noxious gases so that they no longer constitute a significant dose is one way to reduce the infection challenge. This can be accomplished by increasing the ventilation rate or by reducing animal density. At best, one air change can theoretically reduce the concentration of air pollutants by 63.2% (Curtis, 1972). Increased ventilation could also potentially reduce the building relative humidity and thereby speed the wintertime microbial death rate.

Lapedes (1978) defines health as a state of dynamic equilibrium between an organism and its environment in which all functions of mind and body are normal. Hartung (1994) goes on to state that, when health is a balance between internal and external factors, environmental conditions can decisively tip the balance out of level. Many diseases in modern animal farming are thought to have a direct link to the environment.

2.2 Reduced Ventilation and Building Deterioration

As previously cited, early concern about adequate ventilation in Michigan barns was mentioned by F. E. Fogle in a 1925 bulletin. Regarding building deterioration, he wrote that "it (ventilation) will preserve the building and contents from mold and rot, due to excessive moisture" (Fogle, 1925). Similarly, in an investigation of condensation in uninsulated livestock buildings, Andersen (1987) stated that during the winter period, condensation can be so serious that the lifetime of the building materials is greatly reduced.

In winter, typical Michigan equilibrium moisture contents for lumber in exterior use would be near 20% (dry basis) at -1°C (30°F) and 90% relative humidity (Harrigan, 1985). Fiber saturation point however is near 30% (dry basis) for most species. Prolonged exposure to high relative humidities alone is not sufficient to raise the moisture content above the fiber saturation point (USDA, 1974). However, free water exposure (possible during condensation, melting frost, or exposure to rain or snow) at joint interfaces, fastener holes, and seasoning checks could raise the moisture content to the saturation level. If this happened, wood decay, loss of mechanical strength, and metal fastener corrosion could occur. Moisture contents above 20% were considered suitable for metal fastener corrosion and, above 25% moisture, wood decay was imminent (Harrigan, 1985).

In a survey of ten naturally ventilated Michigan dairy barns, Harrigan (1985) found a positive relationship between signs of underventilation and wood moisture contents in excess of 20%. Barns with wood moisture contents in excess of 30% typically exhibited obstructions to natural ventilation that delayed drying after wetting had occurred. Cobwebs, mold, and mildew formations were evidence of the underventilation that occurred in those buildings. Similarly, it was not uncommon to find steel that had rusted through at the contact surfaces between the insulation and the steel in Michigan dairy barns having insulated roofs and signs of underventilation. Bird damage, insulation shrinkage, mechanical damage, or poor construction practices compromised the vapor barrier provided by most rigid insulation roof boards. Moisture laden air moved through the insulation voids, contacted the roof steel, condensed, and wetted the steel. This poorly ventilated cavity then stayed wet long after exposed structural members had dried, thus promoting accelerated metal corrosion.

2.3 Confined Cattle Air Quality Recommendations

Early systems for environmental control in livestock buildings used a safe carbon dioxide concentration as the criterion for defining minimum ventilation rates (Brannigan and McQuitty 1971). An example of this mindset was the King system of ventilation (devised by F. H. King of the University of Wisconsin in the 1890's). Popular in the early 1900's, this confinement ventilation system admitted air near the ceiling and removed it near the floor to remove the heavier-than-air carbon dioxide (Fogle, 1925). However, in most confinement ventilation systems today, carbon dioxide concentration is not used as a ventilation system design parameter. Curtis (1983) states that if animal housing is ventilated to maintain heat and moisture balances, the ventilation rate will be sufficient to provide adequate oxygen and keep carbon dioxide levels low enough. Brannigan and McQuitty (1971) would qualify Curtis's statement by adding that the minimum ventilation rate criterion based on moisture removal may not be valid in all cases. Other contaminants such as dust, bacteria, and noxious gases may set the lower limit on building ventilation.

Two common noxious gases found in dairy barns are ammonia and hydrogen sulfide. Under normal wintertime conditions, neither of these two gases appears to be of environmental concern (Bruce, 1987; Clark and McQuitty 1987). Clark and McQuitty (1987) point out, however, that definitive data on the effects of long-term exposure to low concentrations of ammonia on dairy cows is not available.

Bruce (1987) stated that carbon dioxide is enjoying a resurgence as a general indicator of air quality and as a criterion for ventilation design in livestock buildings. Clark and McQuitty (1987), in an Alberta study of air quality in six freestall dairy barns, also found that average ventilation rates can be estimated by measuring building carbon dioxide concentrations.

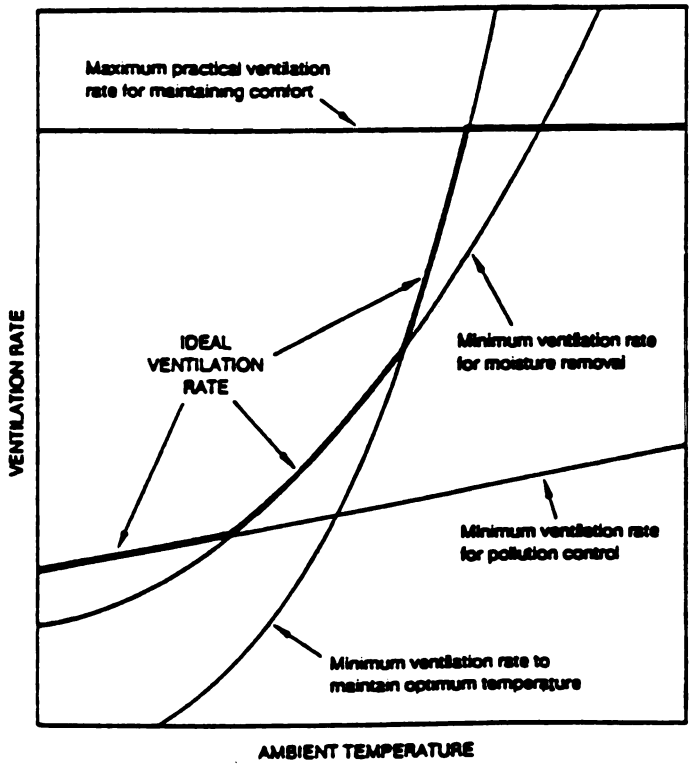


Figure 2.2 Ideal Ventilation Rate

A graphical representation of an ideal ventilation rate that would control temperature, moisture, and pollutants is seen in Figure 2.2 (ASHRAE, 1989). The thicker line represents the ideal ventilation rate under varying environmental conditions. The shape of the curve would vary, however, depending upon the choice of maximum allowable

values for temperature, moisture, and pathogen control. Temperature control ventilation in Figure 2.2 is intended to reduce heat stress and, therefore, is usually not a wintertime problem. The wintertime recommendation to maintain inside temperature a few degrees (3 to 6 degrees Celsius) higher than outside temperature (Bickert and Stowell, 1990; Albright, 1990) is used as a guide to keep moisture and pathogens at a safe level.

If moisture content, not temperature, is used as the guide to minimum ventilation requirements, less agreement is found between sources. A major reason for the difference in recommendations is that warm confinement is assumed. Several sources that were specifically dealing with cold confinement (the last three recommendations in Table 2.1) recommend lower maximum relative humidities.

Table 2.1 Recommended Winter Relative Humidity

% Relative Humidity	Source
50 - 95	CIGR, 1984
85 max.	DeShazer and Overhults, 1982
70 - 80	Scott et al., 1983
70 - 80	MWPS-1, 1987
55 - 75	Bickert and Herdt, 1985
65 - 70	ASAE Standards, 1990
50 - 70	MWPS-33, 1989

Although the effects on dairy cattle of long-term exposure to low concentrations of noxious gases are apparently not available (Clark and McQuitty, 1987), and acceptable upper limits of noxious gas concentrations in

animal housing have yet to be firmly established, sufficient data are available to conclude that the potential for noxious gas related health problems exists in total confinement dairy housing (Curtis and Drummond, 1982). Most recommendations for maximum concentration levels are based on exposure limits for a time weighted average concentration of a normal 8 hour day per 40 hour week for adult humans. However, as can be seen in Table 2.2, there is still a divergence of agreement as to what is the maximum acceptable level of several gases prevalent in livestock barns. Some authors cite only industrial standards while others modify an industrial standard with judgements deemed appropriate to livestock buildings. The last two rows of concentrations in Table 2.2 are examples of such modifications. Definitive statements of tolerable levels of aerial contaminants for livestock buildings are needed (Wathes, 1994).

Table 2.2 Maximum Recommended Concentration of Noxious Gases.

CO_2	NH_3	H_2S	Source
	ppm		
10000	25	10	DeShazer and Overhults, 1982
5000	25	10	Am Conf of Govt Ind Hygn, 1990
5000	50	10	MWPS-33, 1989
3000	20	0.5	CIGR, 1992
2000	-	-	Bartussek, 1989

2.4 Weather Conditions Typical For This Model

Approximately 84.5% of Michigan's farms that sell milk are in the area of the state below the 44th parallel (Michigan DHIA, 1991). Temperatures in this section of the state are similar to those in dairy areas from New York (South and West of the Adirondacks) to Illinois. For example, Table 2.3 lists several cities in the aforementioned region and their hours of temperatures less than -17.7 °C (0 °F). Albany is the only city listed with more than two days (48 hours) of the year with temperatures less than -17.7 °C (0 °F). At the extreme, these cities have a 99% design temperature that is within 5.5 °C of each other.

Table 2.3 Hourly Temperature Occurrences per Year, 99% Winter Design Dry Bulb Temperature, and Mean Winter Wind Speed at Select Cities. (From ASHRAE, 1989; *, From U.S. Dept. of Commerce, 1956)

Location	Frequency ≤17.7 °C/yr hrs./yr	99% Winter Design Temp °C (°F)	Mean Winter 10 m Wind Speed m/s (mph)
Albany, NY	51	-20.0 (-4)	4.1 (9.2)
Syracuse, NY	32	-19.4 (-3)	3.6 (8.1)
Buffalo,NY	26	-16.7 (2)	5.2 (11.5)
Cleveland, OH	13	-17.2 (1)	6.2 (13.8)
Columbus, OH	16	-17.7 (0)	4.1 (9.2)
Flint, MI	16*	-20.0 (-4)	4.1 (9.2)
Lansing, MI	33*	-19.4 (-3)	6.2 (13.8)
Grand Rapids, MI	12	-17.2 (1)	4.1 (9.2)
Ft. Wayne, IN	26	-20.0 (-4)	5.2 (11.5)
Indianapolis, IN	18	-18.9 (-2)	5.2 (11.5)
Chicago, IL	40	-22.2 (-8)	4.6 (10.4)

The average wind speed of the cities represented in Table 2.3 is 4.8 m/s. Esmay and Dixon (1986) point out that

wind velocity does not fall below one half of its average for more than a few hours a month. Also, knowing that wind forces begin to dominate natural ventilation between two and three meters per second (Bruce 1988), and that all of the average wind velocities represented in Table 2.3 are above three meters per second, wintertime wind driven natural ventilation in this region should be more than adequate.

With the exception of a few geographic anomalies, Lansing's relative humidity is also very similar to the other areas listed in Table 2.3 (Visher, 1966). For example, during the months of December and January relative humidities between 80% and 90% occur most frequently (U.S. Department of Commerce, 1956). Consequently, the geographic areas identified in this section should see similar cold confinement freestall dairy barn environments when those barns are stocked and ventilated in the manner discussed in this research.

2.5 Historical Developments in Natural Ventilation

Natural ventilation is the movement of air through designed and undesigned building openings by the natural forces of wind pressure and thermal buoyancy. Consequently, natural ventilation could be said to be the oldest form of building ventilation since housing has been provided for animals.

2.5.1 Comparison of Warm and Cold Confinement Barns

A barn can be classified according to its interior wintertime ambient temperature. A cold confinement barn has an indoor winter temperature that is maintained within a few degrees of outdoor temperature. These barns are often uninsulated, naturally ventilated, and designed to be operated under freezing weather conditions. Absence of ceilings, large ridge and soffit vent openings, and removable or operable sidewalls are typical. Reduced initial construction cost, lower annual energy expense, and possibly better livestock health could be suggested as advantages of cold confinement dairy housing.

A warm confinement barn is usually kept at or above about 5 °C (40 °F) by the use of wall and ceiling insulation. Heating is provided by the livestock, supplemental heating equipment, or both. This type of barn is usually mechanically ventilated. Construction costs and annual operating costs are greater in this type of barn than in a cold confinement dairy barn.

Warm confinement dairy buildings primarily benefit the operators and equipment. Dairy animals don't require a warm building. For example, calves have been successfully raised in cold outdoor hutches; and producing dairy cattle have a lower critical temperature well below 5 °C. Comfortable working conditions, reduced problems from frozen water or manure, severe and prolonged winter weather, and less mechanical problems with feeding and manure handling equipment would be several reasons given to justify the added expenses resulting from investments and recurring costs of warm confinement dairy housing.

2.5.2 Resurgence of Interest in Cold Confinement

Due to the potential for reduced electrical expense, improved animal health and productivity, and lower construction costs, an increased interest in cold confinement naturally ventilated dairy housing has occurred. The adoption of the open freestall housing design by many dairy farmers in the 1960's spread the use of natural ventilation. However, these freestall barns (patterned after the more open loose housing barns of the 1940's and 1950's) were more enclosed than would be recommended today (Bickert and Stowell, 1990).

2.5.3 Cold Confinement Ventilation Opening Recommendations

Winter ventilation openings are often continuous soffit inlets along both sides of the barn and a continuous open ridge vent at the peak. Figure 2.3 illustrates four common ridge configurations. Open and baffled ridge designs are

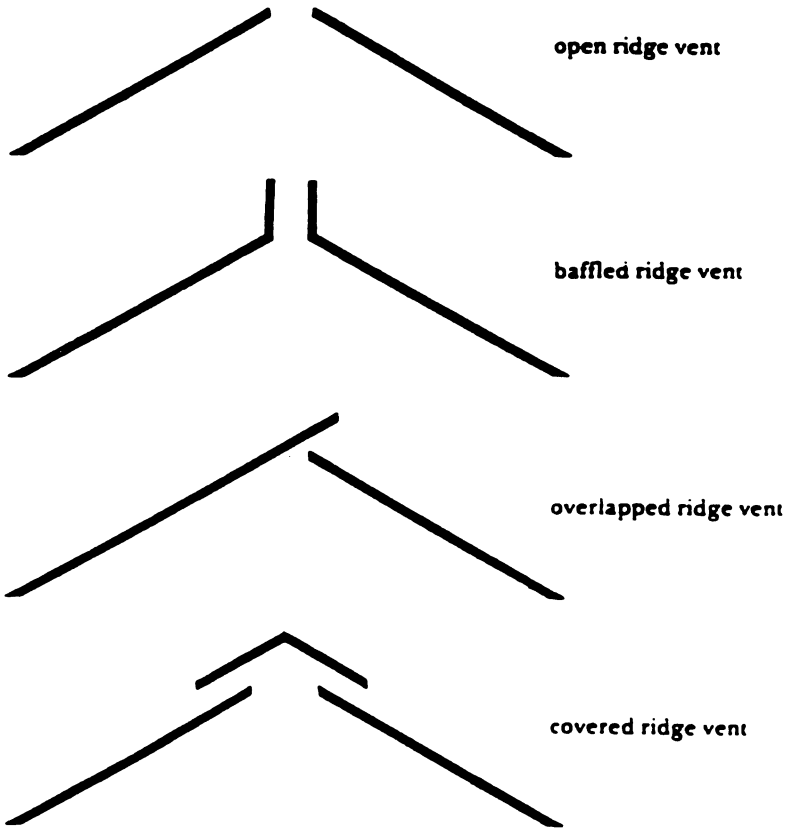


Figure 2.3 Basic Ridge Vent Designs for Naturally Ventilated Barns

used in many naturally ventilated barns in Michigan.

Hellickson (1983) recommends a continuous ridge opening of 2.5 cm for each 2 m of building width (2 in per 13 ft) or 1-1.5% of the floor area. The sidewall openings should be the same total area as the ridge opening. Albright (1990) recommends a ridge vent approximately 0.15 m (6 in) wide for buildings up to 12 m (40 ft) wide and an additional 0.05 m (2 in) for each additional 3 m (10 ft) of building width. He also recommends that the sidewall openings be equally divided on both sides of the building and sum to the area of the ridge vent opening. Bickert and Stowell (1993) and

Midwest Plan Service (MWPS-33, 1989) recommends a ridge opening of 5 cm per 3 m (2 in per 10 ft) of building width, with an equivalent inlet area divided between the two eaves.

2.5.4 Existing Natural Ventilation Models

Natural ventilation has been studied experimentally and theoretically. Emswiler (1926) formulated the concept of a neutral pressure plane to calculate natural ventilation due to thermal buoyancy. He defined the neutral pressure plane as the height above some datum or plane (typically the floor) where thermally-induced pressure differences are zero (see Figure 2.5). He further established that, in still air, the pressure difference across an opening is proportional to the vertical distance of that opening from the neutral pressure plane.

Using field measurements, linear regression was used to determine appropriate parameter values to predict infiltration for residences and animal buildings. Such models have been shown to be effective for predicting long-term averages for air infiltration (Brockett, 1986). However, linear regression equations inherently yield inaccurate results due to the complex interaction between thermal and wind induced ventilation (Sinden, 1978).

Tamura (1979) and Sherman (1980) calculated thermal buoyancy and wind ventilation separately in natural ventilation models that were not site-specific. Tamura (1979) determined the combined ventilation rate experimentally using the equation:

$$V=V_{large}(1+0.24(V_{small}/V_{large})^{3.3}) \qquad (2.1)$$

where:

V = combined ventilation rate, m^3/s

V_{small} = the smaller of $V_{thermal}$ and V_{wind}

V_{large} = the larger of $V_{thermal}$ and V_{wind}.

Sherman (1980) combined the separate ventilation rates by quadrature to determine total ventilation.

Both Tamura and Sherman excluded wind direction factors from their models under the general assumption that wind direction was not a vital factor when determining average heat loss due to infiltration. This assumption was acceptable, as their models were applied to residential homes. However, for long narrow buildings common to agricultural design, wind direction could be critically important in predicting natural ventilation or infiltration (Brockett, 1986). The principles of airflow are the same for both natural ventilation and air infiltration.

The most comprehensive work in natural ventilation of animal housing has been done by James Bruce of the Scottish Farm Building Investigation Unit in Aberdeen, Scotland (Brockett, 1986). Using the neutral pressure plane concept developed earlier by Emswiler, Bruce (1978) defined the pressure difference across an opening caused by thermal buoyancy as:

$$\Delta P_t = g(\rho_o - \rho_i)(h_p - h) \qquad (2.2)$$

where:

ΔP_t = thermally-induced pressure difference, Pa

g = acceleration due to gravity, 9.8 m/s²

ρ_o = density of outside air, kg/m³

ρ_i = density of inside air, kg/m³

h_p = neutral pressure plane above some datum plane (typically the floor), m

h = height above the datum plane where P_t was calculated, m.

Applying Bernoulli's theorem to calculate velocity of air-flow through an opening, integrating over the area of the opening, and assuming flow continuity, the neutral pressure plane was determined by numerical iteration. Once determined, the neutral pressure plane value was then used to determine the thermally-induced ventilation rate.

Bruce (1975) also developed a theory of natural ventilation due to wind. The wind-induced pressure difference across an opening was calculated by:

$$\Delta P_w = (Cp_o - Cp_i)^{0.5} v_w^2 \qquad (2.3)$$

where:

ΔP_w = wind induced pressure difference, Pa

Cp_o = estimated external pressure coefficient

Cp_i = internal pressure coefficient

v_w = wind velocity, m/s.

Similar to thermally induced ventilation, Bruce used Bernoulli's equation to calculate the velocity of airflow through an opening and then, by iteration, determined the internal pressure coefficient and ventilation rate due to wind.

Other experiments have been done and models have been developed to determine the intensity of natural ventilation. Timmons and Baughman (1981) experimentally determined airflow rate through unrestricted open ridge buildings, but did not consider possible ventilation occurring through sidewall openings. Janni and Bussmann (1983, 1984) developed a model using heat, mass, momentum, and mechanical energy. The model included both wind and thermal ventilation components, but whether sidewall openings were inlets or outlets was not derived. Down et al. (1985), after a review of existing equations and extensive experiments, concluded that the models developed by Bruce (1975, 1977) were acceptable for independent theoretical study of wind or thermal buoyancy ventilation.

Much of the investigation work on natural ventilation used simple building designs. One inlet and one outlet was used in research done by Bruce, 1977; Fabian and Albright, 1982; and Janni and Bussmann, 1984. One outlet and inlets on opposite sides of the building at equal heights and/or size were calculated by Bruce, 1978, Timmons and Baughman,

1981, Shrestha and Cramer, 1984, Timmons et al., 1984, and Down et al. 1985. For more complex designs, Hellickson (1983) provided a chart to make adjustments in stack ventilation flow rate when inlet and outlet areas were not equal. Likewise, Timmons et al. (1984) provided nomographs to determine a dimensionless ventilation rate as a portion of his stack ventilation equation.

Table 2.4 compares the solution for thermal buoyancy ventilation of one barn solved by five different formulas. The formulas were either empirically based (EB) or derived from basic mathematical and physical principles (BP). The solution derived from the equations by Timmons used equations derived from work originally done by Bruce (as are the BP solutions of Albright and Zhang) but Timmons incorporated nomographs as aids in arriving at a final answer.

Table 2.4 Comparison of Stack Ventilation Calculated by Five Different Methods.

Ventilation Rate m^3/s	Equation Type	Source
16.9	EB	Albright, 1990
25.3	EB	Helickson, 1983
23.8	BP	Timmons, 1984
17.5	BP	Albright, 1990
17.6	BP	Zhang, 1989

In a comparison of empirical and basic principle equations for wind induced ventilation, there was very close agreement. The empirical formula presented by Albright, (1990), Hellickson, (1983), and Esmay and Dixon, (1986):

$$V=EAv_w \qquad (2.4)$$

where:

V = airflow, m^3/s

E = wind effectiveness factor

A = opening area, m^2

v_w = wind speed, m/s,

when compared with a BP formula by Bruce, (described in Section 2.6.1) resulted in ventilation rates of 85.6 m^3/s EB and 87.4 m^3/s BP.

Natural ventilation models and field experience have shown that thermal and wind induced ventilation rates approximately add through quadrature (Albright, 1990). However, addition by quadrature can be in error by as much as 25% when ventilation by wind and stack effects are approximately equal or when the neutral pressure plane falls within a vent opening and acts as both an inlet and an outlet (Albright, 1990) (see Figure 2.4). Since airflow through each opening is essentially caused by the inside and outside pressure difference, the total pressure difference can be obtained by adding the pressure differences due to thermal and wind effects (Brockett and Albright, 1987). Bernoulli's equation can then be used to describe the relationship between the potential energy in the pressure difference across each opening and then integrated with the airflows across the areas of all openings (Brocket and Albright, 1987) (see Section 2.6.3).

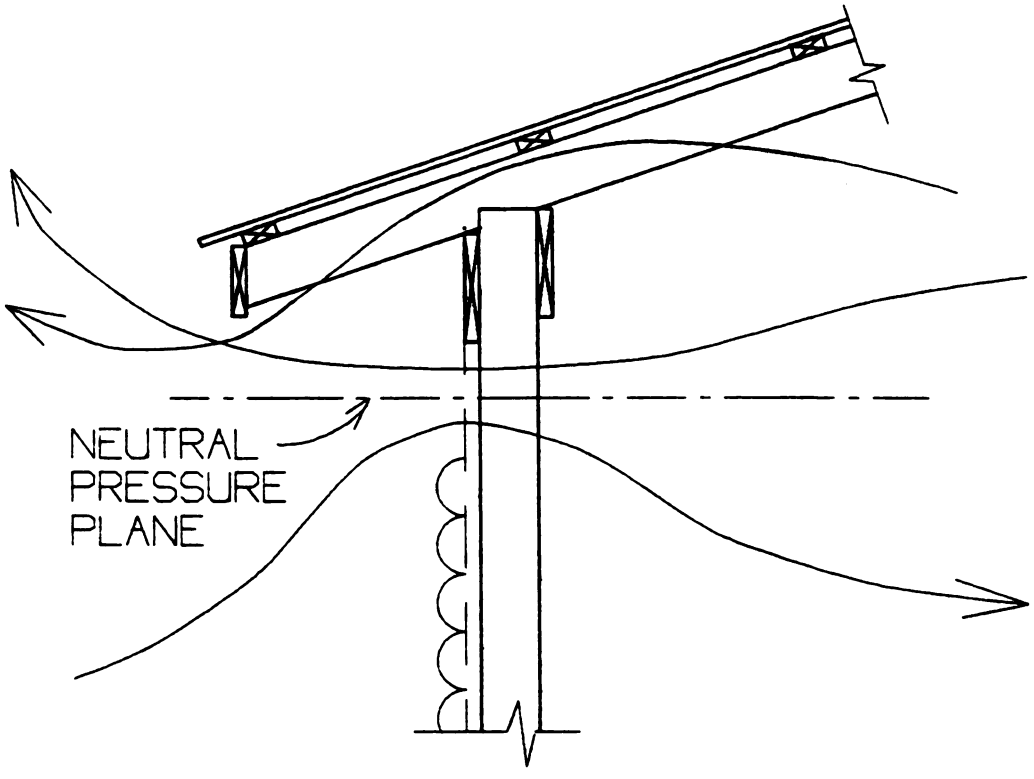


Figure 2.4 Ventilation Airflow When the Neutral Pressure Plane (NPP) is Located Within a Ventilation Opening.

2.6 Natural Ventilation Equation Development

2.6.1 Thermal Buoyancy Ventilation

If there were only one inlet and only one outlet available for ventilation in a building, a rather straight forward empirical equation could be used to calculate ventilation due to thermal buoyancy (Albright, 1990):

$$V=0.65A\left[\frac{g\Delta h(t_i-t_o)}{t_i}\right]^{1/2}. \qquad (2.5)$$

This equation could also be used with inlets at several locations if the inlets were at the same elevation and each had the same coefficient of discharge (air velocity is assumed to be uniform across each of the openings). An example of a thermal buoyancy ventilation calculation incorporating this equation is seen in Appendix A.

Since many naturally ventilated barns use end doors to increase or decrease the ventilation rate, a simpler two opening stack ventilation equation is often inadequate. To model a natural ventilation system that has inlets at several heights and which vary in area, a neutral pressure plane concept can be incorporated into the equations. As mentioned in Section 2.5.4, Bruce (1977) calculated the airflow through an opening due to hydrostatic pressure using a neutral pressure plane as the reference point (Equation 2.2).

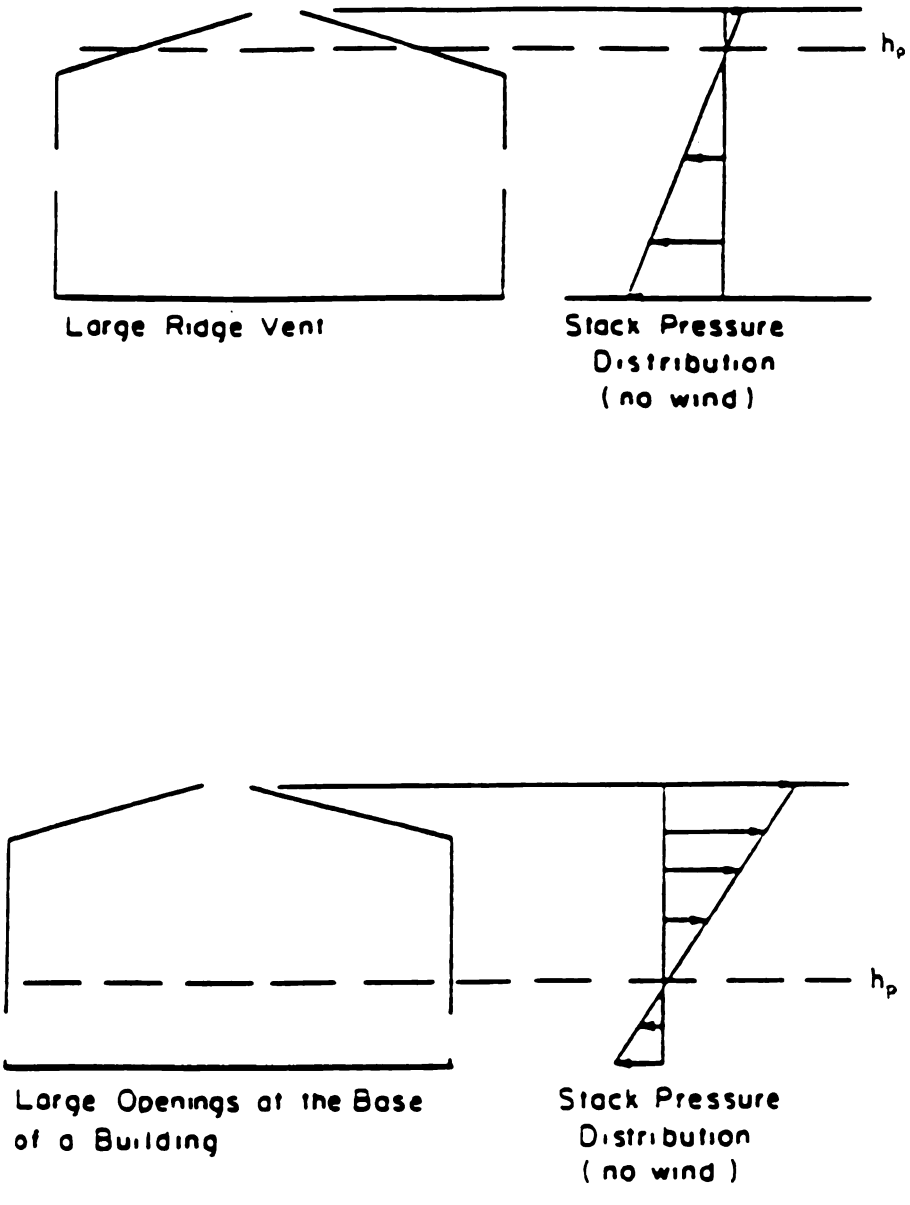


Figure 2.5 Location of the Neutral Pressure Level

The neutral pressure plane is the height above some datum (usually the floor) where the pressure difference due to thermal buoyancy is zero. As can be seen in Figure 2.5, the size of the inlet or outlet opening affects the height of the neutral pressure plane. For example, if the building had a large ridge vent, the neutral pressure plane would be located closer to the top of the enclosure. If the building had larger inlet areas, the neutral pressure plane would be located closer to the inlets.

The pressure difference across a vent opening is potential energy. Assuming that air is incompressible, this potential energy is converted into kinetic energy, and Bernoulli's equation applies (Brockett, 1986):

$$v=\sqrt{\frac{2P_t}{\rho}} \qquad (2.6)$$

where:

v = air velocity, m/s

P_t = thermally induced stack pressure (negative above the neutral pressure plane), Pa

ρ = air density, kg/m^3.

Equations 2.5 and 2.6 can be combined to determine the velocity through an opening (Albright, 1990):

$$v=\frac{|2g(\Delta\rho/\rho)\,(h_p-h)|^{3/2}}{2g(\Delta\rho/\rho)\,(h_p-h)}. \qquad (2.7)$$

This equation was arranged so that if h_p is greater than h, v is positive. If h_p is less than h, v is negative and air flow is out of the building at that ventilation opening. The value chosen for ρ in Equation 2.7 depends upon the direction of air flow. If air is entering the building, ρ_o (density outside) is used, whereas ρ_i (density inside) is used if air flow is out of the building.

For a non-horizontal opening (e.g., sidewall vents), air velocity is not uniform across the opening; therefore, volumetric air flow rate is the integral of velocity over area:

$$V=Cd\int_{area} v dA \qquad (2.8)$$

where:

Cd = discharge coefficient of an opening

A = opening area, m^2

V = volumetric air flow, m^3/s.

For horizontal openings (e.g., ridge vents), the equation for volumetric flow is:

$$V=CdvA. \tag{2.9}$$

To maintain continuity of flow, the airflows in and out of the building should sum to zero:

$$\sum_{n} Cd_n\rho_n\int_{area_n}\frac{|2g(\Delta\rho/\rho)\,(h_p-h|^{3/2}}{2g(\Delta\rho/\rho)\,(h_p-h)}dA+$$

$$\sum_{m} Cd_m\rho_m\frac{|2g(\Delta\rho/\rho)\,(h_p-h)\,|^{3/2}}{2g(\Delta\rho/\rho)\,(h_p-h)}W_mL_m=0 \tag{2.10}$$

where:

n = non horizontal opening number

m = horizontal opening number

W = opening width, m

L = opening length, m.

If one lets:

$$\alpha=2g(\Delta\rho/\rho) \tag{2.11}$$

each integral in Equation 2.10 can be rewritten as:

$$\int\frac{|\alpha\,(h_p-h)|^{3/2}}{\alpha\,(h_p-h)}dA. \tag{2.12}$$

Also, the equation for rectangular, non-horizontal vent openings can be rearranged as:

$$dA = LdW. \tag{2.13}$$

Now the terms of the continuity equation for non-horizontal opening becomes:

$$\sum Cd_n\rho_n L_n(\alpha_n)^{1/2}\int_{bottom}^{top}\frac{|(h_p-h)|^{3/2}}{(h_p-h)}dW. \tag{2.14}$$

Finally, converting the integral portion of the equation to an analytical solution and rewriting the continuity equation produces (Albright, 1990):

$$(-2/3)\sum_n Cd_n\rho_n L_n(\alpha_n)^{1/2}|(h_p-h)|^{5/2}(h_p-h)^{-1}|_{bottom}^{top}+$$

$$\sum_m Cd_m\rho_m L_m W_m(\alpha_m)^{1/2}|(h_p-h)_m|^{3/2}(h_p-h)^{-1}=0. \tag{2.15}$$

The single unknown in Equation 2.15 is h_p. Once determined, air velocity through each vent and building ventilation can be calculated. However, because of the interplay between ventilation rate and indoor temperature, both inside temperature and ventilation rate need to be

determined together. This leads to an iterative calculation method.

First, an indoor air temperature and air density are assumed and Equation 2.15 is solved for h_p. The neutral pressure height would be found when the air flow into the building matched the air flow out of the building. This ventilation rate would then be used to solve a sensible energy balance for the airspace. Then, a new estimate of indoor air temperature and density would be determined. These steps are repeated until a stable solution is obtained.

2.6.2 Wind Induced Ventilation

Bruce (1975) also developed the following equation to calculate natural ventilation due to wind pressure at each vent opening.

$$\Delta P_n = (1/2(\rho_o v_w^2))(Cp_o - Cp_i) \qquad (2.16)$$

where:

ΔP_{wind} = inside-outside pressure difference due to wind force at opening n, Pa

ρ_o = density of outside air, kg/m³

v_w = eave height wind velocity, m/s

Cp_o = external pressure coefficient at opening n

Cp_i = internal pressure coefficient at opening n.

In this equation, outdoor air density is a constant as only wind induced ventilation is considered (no heat was added to the building). Also, C_p and v_w are defined using eave height winds (see Section 2.8).

At each vent,

$$\Delta P_n = (Cp_{o_n} - Cp_i)\,(1/2\,(\rho_o v_w^2)), \tag{2.17}$$

based on the definitions of pressure coefficients (see Section 2.8), and

$$\Delta P_n = 1/2\,(\rho_o v_n^2), \tag{2.18}$$

based upon the Bernoulli equation, where v_n is the velocity of air moving through the inlet. Thus (Albright, 1990):

$$v_n = v_w \frac{(Cp_{o_n} - Cp_i)}{\sqrt{|(Cp_{o_n} - Cp_i)|}}. \tag{2.19}$$

2.6.3 Combined Thermal and Wind Induced Ventilation

ASHRAE Handbook of Fundamentals (1989) recommends combining the effects of thermal and wind induced ventilation by quadrature:

$$V_{total} = \sqrt{(V_{wind}^2 + V_{thermal}^2)} \tag{2.20}$$

where:

V = volumetric flow rate, m^3/s.

Addition by quadrature is in error by as much as 25% when wind and thermal contributions to ventilation are almost equal, or when the neutral pressure plane falls within an opening and the opening acts as both an inlet and an outlet (Albright, 1990) (see Figure 2.4). Albright (1990) suggests adding the pressure differences due to wind and thermal buoyancy at each ventilation opening, describing the resulting air velocity by using the Bernoulli equation, and integrating the airflows over the areas of the building openings:

$$\Delta P_{total} = \Delta P_{wind} + \Delta P_{thermal} \qquad (2.21)$$

where:

ΔP_{total} = total effective pressure difference, Pa.

Rewriting the equation with the pressure terms previously described yields:

$$\Delta P_{total} = (1/2\,(\rho_o v_w^2)\,(Cp_o - Cp_i)) + g(\rho_o - \rho_i)\,(h_p - h)\,. \qquad (2.22)$$

Solving for air velocity, v, at vent opening, n, and elevation h_p :

$$v_n=\frac{\left|2g(\Delta\rho/\rho_n)\,(h_p-h_n)+v_w^2(Cp_{o_n}-Cp_i)\right|^{3/2}}{2g(\Delta\rho/\rho)\,(h_p-h_n)+v_w^2(Cp_{o_n}-Cp_i)}. \qquad (2.23)$$

As in Equation 2.10, combined air flows in and out of the building must sum to zero to maintain continuity of flow:

$$\sum_n\left[(Cd)_n\rho_n\int_{area}\frac{\left|2g(\Delta\rho/\rho_n)\,(h_p-h_n)+v_w^2(Cp_{o_n}-Cp_i)\right|^{3/2}}{2g(\Delta\rho/\rho_n)\,(h_p-h_n)+v_w^2(Cp_{o_n}-Cp_i)}dA_n\right]+$$

$$\sum_m\left[(Cd)_m\rho_m\frac{2g(\Delta\rho/\rho_m)\,(h_p-h_m)+v_w^2(Cp_{o_m}-Cp_i)^{3/2}}{2g(\Delta\rho/\rho_m)\,(h_p-h_m)+v_w^2(Cp_{o_m}-Cp_i)}W_mL_m\right]=0. \qquad (2.24)$$

Each integral of Equation 2.24 is:

$$\int_{area}\frac{\left|\alpha_n(h_p-h_n)+\Phi_n\right|^{3/2}}{\left[\alpha_n(h_p-h_n)+\Phi_n\right]}dA_n \qquad (2.25)$$

Where grouped terms are:

$$\alpha_n=2g(\Delta\rho/\rho_n)\,; \qquad (2.26)$$

$$\Phi_n = v_w^2 (Cp_{o_n} - Cp_i) ; \qquad (2.27)$$

and

$$\Omega_n = h_p + \Phi_n / \alpha_n . \qquad (2.28)$$

Like Equation 2.15, converting the integral portion of the equation to an analytical solution and rewriting the continuity equation results in (Albright, 1990):

$$(-2/3) \sum_n (Cd)_n \rho_n L_n (\alpha_n)^{1/2} |(\Omega_n - h_n)|^{5/2} (\Omega_n - h_n)^{-1} \Big|_{bottom}^{top} +$$

$$\sum_m (Cd)_m \rho_m L_m W_m (\alpha_m)^{1/2} |\Omega_m - h_m|^{3/2} (\Omega_m - h_m)^{-1} = 0 . \qquad (2.29)$$

2.7 Livestock Heat Production and its Partitioning

Important components of a stack ventilation equation are the rate and total amount of heat production in the structure. In cold confinement dairy housing, heat input from motors, lights, and heaters is usually very small and typically neglected. Solar gain, though possibly significant, is also usually not considered as a heat source when doing a heat balance equation on a freestall dairy barn (Albright, 1990). The only heat source of any significance

that remains is the dairy cattle. Therefore, it is important to determine a reasonably accurate estimate of cattle heat production if a usable model is to be developed. The following paragraphs discuss several of those estimates.

Total heat loss within a livestock confinement building is partitioned into sensible heat and latent heat. In cold confinement structures, the sensible heat component is primarily derived from the energy emitted by the livestock. The latent heat component, however, comes from livestock respiration and water vapor evaporated from livestock manure and other sources within the structure.

Under naturally ventilated cold confinement conditions, sensible and latent heat, as well as the percent of total heat that each comprises are important. The amount of sensible heat greatly influences ventilation rate under calm or mild wind conditions. Latent heat, on the other hand, affects the moisture concentration within the barn. Both values need to be determined under current commercial livestock housing conditions to be of use in accurately modeling the environment within modern freestall dairy facilities.

Results of calorimeter studies are available that calculated the sensible and latent heat production of large, high producing dairy cows (Flatt et al. 1965, Leahey et al. 1972, Moe 1981). These studies have primarily focused on input energy needed for the production of milk and meat or for body maintenance. Calorimeter studies typically do not include a net sensible heat component, as conversion of

sensible to latent heat is usually not of interest. Also, calorimetric data alone, applied to a barn, does not adequately estimate the amount of sensible and latent heat actually added to the airspace. As well, differences in genetic makeup, production level, or livestock environment make calorimetric data less useful when modeling commercial operations.

For livestock building studies, the amount of building heat load that is sensible and latent will be affected by the method of handling waste and water within the barn. The evaporation of water in the structure will reduce the sensible heat in the air and increase the latent heat load of the facility. Therefore, to accurately model these structures, environmental data need to be collected under, as near as possible, current confinement housing conditions.

Various resources provide data on animal heat and moisture production, including ASAE Standards (1995), Esmay and Dixon (1986), Scott et al. (1983), Albright (1990), and Midwest Plan Service (1987). Interestingly, all these sources reference their heat loss data to either a ten year summary report done by Yeck and Stewart (1959) or a University of Missouri research bulletin that Yeck and Stewart (1959) referenced. Though considered barn studies, in each case data were collected under animal husbandry conditions very different from today's commercial dairy operations. For example, Smith et al. (1980) found moisture loads significantly higher and total heat slightly lower in two freestall barns with scraped passageways when compared

with two tie-stall barns more representative of facilities used by Yeck and Stewart (1959). On the other hand, Strom and Feenstra (1980), in an extensive literature review, considered not only barn temperature in their latent and sensible heat prediction equations but included rate of milk production and stage of pregnancy. A prerequisite for their selection of usable data was that it be from research done under near-production conditions. This stringent screening of data coincidentally resulted in all acceptable data being from facilities where no bedding was used.

Because Strom and Feenstra's (1980) heat loss equations were highly correlated with production, a higher or lower milk yield will affect the calculated heat loss considerably. For example, in a comparison using a 550 kg cow housed at 20 °C and producing 20 kg of milk per day, their calculations yielded a total heat loss ratio of 1.12 to 1 when compared with ASAE data. In other words, Strom and Feenstra's calculations resulted in a 12% higher total heat production than the University of Missouri's research found (the source of ASAE data).

A limited wintertime study by Quille et al. (1986) compared the forty-eight hour total and latent heat production from three solid floor and three slatted floor freestall dairy barns with Yeck and Stewart (1959) and Strom and Feenstra (1980) data. This study calculated predicted average total heat production values of 3.5% less for Yeck and Stewart (1959) and 3.4% less for Strom and Feenstra (1980) than Quille's measurements. Also, average measured

latent heat values were 27.6% and 68.8% higher than Yeck and Stewart (1959) and Strom and Feenstra (1980) predictions, respectively.

Summarized statistically, at the five percent significance level, both comparisons showed no significant difference for total heat production and a significant difference for latent heat production. In other words, though the calculated total heat production of Yeck and Stewart (1959) and Strom and Feenstra (1980) compared favorably with Quille et al. (1986) measurements, the partitioning of sensible and latent heat did not.

Quille et al. (1986) suggested that the Strom and Feenstra (1980) values may differ because of the use of physiological data in the derivation of the Strom equations. He further stated that, though Yeck and Stewart (1959) accounted for evaporation, it was in a different context than that of freestall housing. In this regard, Quille et al. (1986) reported an overall average evaporative latent heat load of 54.2% vs. Yeck and Stewart (1959) suggesting that, up to 10°C (50 °F), 40 to 45% of the total moisture load was attributable to evaporation from wet surfaces. Of note is the fact that the Quille et al. (1986) data were for barns with up to a 19.7°C (68 °F) difference between inside and outside ambient air temperatures. On the other hand, Yeck and Stewart (1959) data were based on a Thompson (1957) study where the incoming air was pre-conditioned to maintain a desired test chamber relative humidity. Also of note is the fact that the temperatures at animal level in the

different barns studied by Quille et al. (1986) varied from 4.0 °C (39 °F) to 13.6 °C (56 °F).

Sällvik (1981), reporting for the International Commission of Agricultural Engineering (CIGR) Section II Working Group For Climatization, presented guidelines for the development of computer applicable formulas for total heat and partitioning of sensible and latent heat from dairy cattle. Their efforts led to a published recommendation in 1984. This report, Climatization of Animal Houses (1984), considered formulas derived from research by J. Bruce (Scotland), J. Landis (Switzerland), S Eriksson (Sweden), and J. Strom (Denmark). The group chose heat loss equations for maintenance and milk production essentially equal to those developed by J. Bruce of Scotland (a noted developer of equations for the prediction of natural ventilation in livestock housing) while maintaining the pregnancy heat loss, temperature corrected total heat loss, and sensible heat partitioning formulas presented by Strom in 1980. Using the same data in a comparison of sensible and latent heat output per herd, this author found that the CIGR (1984) equations yielded 11.6% more sensible heat and 1.7% more latent heat than Yeck and Stewart (1959) values.

Other methods have also been used to determine "housing condition" sensible and latent heat production. Diesch (1987) used regression equations of section D270.4 design graphs in Agricultural Engineering Standards to this end. Ehrlemark and Sällvik (1990) developed a model that predicted sensible heat based on animal surface area and

thermal conductance. They used CIGR (1984) equations to determine total heat production while asserting that sensible heat was a function of thermal conductance and not the total heat production of an animal.

2.8 Pressure Coefficients

2.8.1 External Pressure Coefficient

The external pressure coefficient is defined as the ratio of the difference between the static pressure at a given location on the building envelope and the freestream pressure to the dynamic pressure at the reference height (Shrestha et al., 1990). This definition could be restated also as the ratio between the over or under pressure created at a point on a building's surface, divided by the stagnation pressure of the free wind (Albright, 1990). Written in equation form, the external wind pressure coefficient is:

$$Cp_o = P_g / (\rho v_w^2 / 2) \qquad (2.30)$$

where:

Cp_o = External wind pressure coefficient

P_g = Gauge pressure on the building surface, Pa

ρ = Air density, kg/m^3

v_w = Wind velocity, m/s.

Each external pressure coefficient value on a building depends on the following: the location on the building where the measurement was taken, wind direction, ventilation

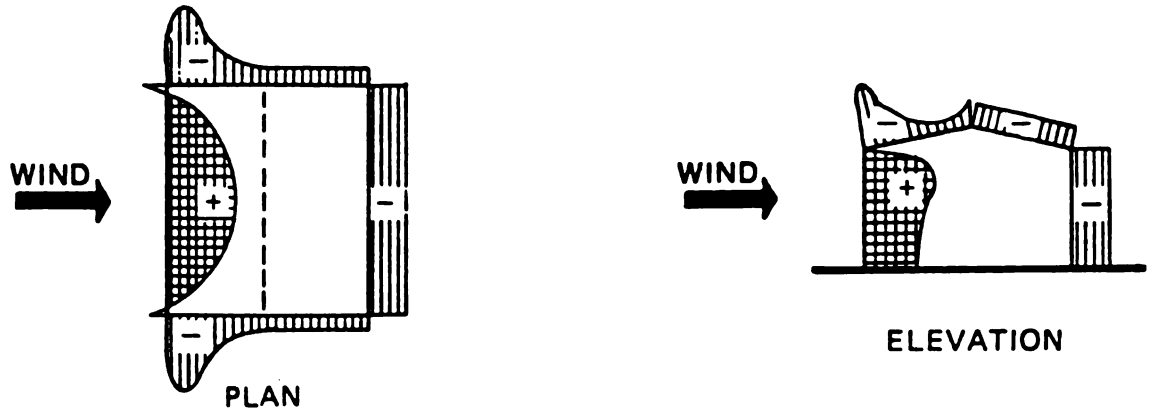


Figure 2.6 Airflow Due to Difference in Pressures on Internal and External Building Surfaces Caused by Wind.

opening size, leakage opening area, building shape, local obstructions to wind flow, and building size (see Figure 2.6). Because of these many variables and the constant changing nature of the wind, external pressure coefficient values at a given building location were based on steady and constant wind pressures when the wind was approaching from a right angle to the ridge of an unobstructed low profile gable roof building. Table 2.5 lists external pressure coefficients found by several sources for winds approaching from a right angle to the ridge and at different locations on the building. Varying results in Table 2.5 were caused by such differences as size of the scale model tested, location of the pressure sensors, and whether or not the model had a ridge vent (Shrestha et al.,1990).

Table 2.5 Pressure Coefficients (Shrestha et al., 1990)

Windward Wall		Leeward Wall	Ridge	Source
At Eave	Mid-wall	Mid-wall		
0.55	*	*	*	Bottcher (1986)
0.62	0.72	*	-0.42c	Shrestha (1990)
0.5	0.7	-0.7avg.	-1.0a	Sachs (1978)
*	0.7	-0.3	-0.7b	Newberry (1974)
*	0.5	-0.3	-0.6b	Bruce (1974)
0.5	0.7	-0.25	-1.2a	MacDonald (1975)
0.8	0.8	-0.4	*	ASHRAE (1981)
0.8	0.8	-0.3	*	MBMA (1986)
*	0.4d	-0.3d	-0.8b,d	Brockett (1987)
*	0.5c	-0.2c	-0.7b,c	Brockett (1987)
*	*	*	-0.7a	Hoxey (1984)

a = no ridge opening, b = with ridge opening, c = mid-section value, d = end-section value, * = no data reported

Using a 1/25 scale model poultry building with mid-wall ventilation openings, Bottcher et al. (1986) found upwind pressure coefficients ranging from 0.54 to 0.3 and downwind pressure coefficients ranging from -0.55 to -0.43 as the ventilation inlet area increased from 0 to 80 percent of the wall area. Zhang et al. (1989), using averaged data derived from Down et al. (1985), derived very different pressure coefficient values of 0.443 upwind, -0.05 downwind, and -1.261 at the peak.

2.8.2 Internal Pressure Coefficient

The internal pressure coefficient is defined similarly to the external pressure coefficient. It is the ratio between the existing indoor gauge pressure and the wind stagnation pressure (Albright, 1990). The internal pressure coefficient differs from free stream atmospheric pressure and is affected by the external pressure coefficients and

the sizes of the ventilation openings. The value for the internal pressure coefficient is bounded by the range of the highest and lowest external pressure coefficients.

2.9 Discharge Coefficients

As air approaches an opening, streamlines converge. That convergence acts to reduce the effective area of flow. Turbulence effects and the resulting energy loss also act to reduce flow through an opening. The loss of effective area and reduced flow due to turbulence are combined and expressed as a coefficient of discharge. The discharge coefficient, when multiplied by the inlet area and the ideal air velocity, yields the actual ventilation rate.

Values used for discharge coefficients must be determined empirically; with the standard value for a sharp-edged orifices being 0.6 (Albright 1990). Many inlets which are used to ventilate agricultural buildings have a discharge coefficient equal to or greater than 0.6. Poly-tubes, for example, have a discharge coefficient between 0.61 and 0.64 (Albright, 1990). Albright (1978), in studies of air flow through baffled, slotted inlets, found coefficients as low as 0.2; whereas, Shepherd (1965) reported a coefficient of 0.98 for well designed nozzles (Timmons and Baughman, 1981). While modeling the natural ventilation of an instrumented swine barn, Zhang et al. (1989) found that a discharge coefficient of 0.61 gave the best estimation of the actual inside temperature. Based on results of work done by Bottcher et al. (1986), Timmons

(1990) suggests that a discharge coefficient of 0.65 was appropriate for winds normal to the building. Bruce (1977) also concluded from a simulation experiment of thermal buoyancy, that a discharge coefficient of 0.6 was perhaps pessimistic and that a value of between 0.7 and 0.8 would be more appropriate. Curtis (1983) used a rule of thumb of 0.67 (two thirds) as the discharge coefficient in his text example of stack ventilation.

2.10 Building Infiltration

To account for undesigned building ventilation, an allowance for air leakage into the structure was necessary. The ASAE Standards (1995) give infiltration rates for dairy facilities with tight or very tight construction. To use those equations, the pressure difference between inside and outside must be known or estimated. The ASHRAE Handbook of Fundamentals (1989) also gives detailed methods to determine infiltration around windows and doors. However, Albright (1990) notes that the ASAE data are based on negative pressure mechanically ventilated dairy stable studies done over 30 years ago and that the ASHRAE method of infiltration determination has not been proven to apply accurately to agricultural buildings.

Choiniere et al. (1990) used ASHRAE and industry data to arrive at infiltration rates for livestock buildings. He estimated that warm, fully insulated barns had an average air change per hour (ac/h) of 1.1 ac/h (0.75 minimum to 1.5 maximum ac/h), modified environment barns had an average air exchange of 1.5 ac/h (1.0 minimum to 2.0 maximum ac/h), and cold confinement barns had an average air exchange of 2.2 ac/h (1.5 minimum to 3.0 maximum ac/h).

2.11 Roof Temperature Calculation

The calculation method universally used to determine a building surface temperature is to convert convection and radiation heat transfer values into a combined resistance coefficient (also called a surface coefficient or film

coefficient) value (Albright, 1990; ASHRAE Handbook of Fundamentals, 1989). The building resistance coefficients found in most heat transfer texts, building heat loss calculation examples, and reference books are referenced to empirical research done by Jürges (1924) regarding flow parallel to a vertical plate. The work done by Jürges was cited by McAdams (1954) in his book *Heat Transmission*; since that time McAdams has been ascribed as the source of the data (Iqbal and Khatry, 1977).

Research done by Fujita and Nara (1993), related to the effect of roofing materials on the heat balance in livestock buildings, found that Jürges's work, regarding the coefficient of convective heat transfer at different wind speeds, to be in good agreement with their results. Strictly speaking, these empirical film coefficient values are accurate only under conditions similar to those under which the original data were obtained -- a surface-air temperature difference of 5.5 °C (10 °F) and a surface temperature of 21 °C (70 °F). At those conditions, several options of emissivity, building surface orientation, direction of heat flow, and wind velocity were published (see Appendix F). Again, if an emissivity, surface orientation, wind velocity, or surface roughness did not match that of the original research, the values derived from using those film coefficients would only be approximations. Also, for moving air, surface orientation and heat flow direction were not required to select a film coefficient. The three wind conditions for which film coefficients were

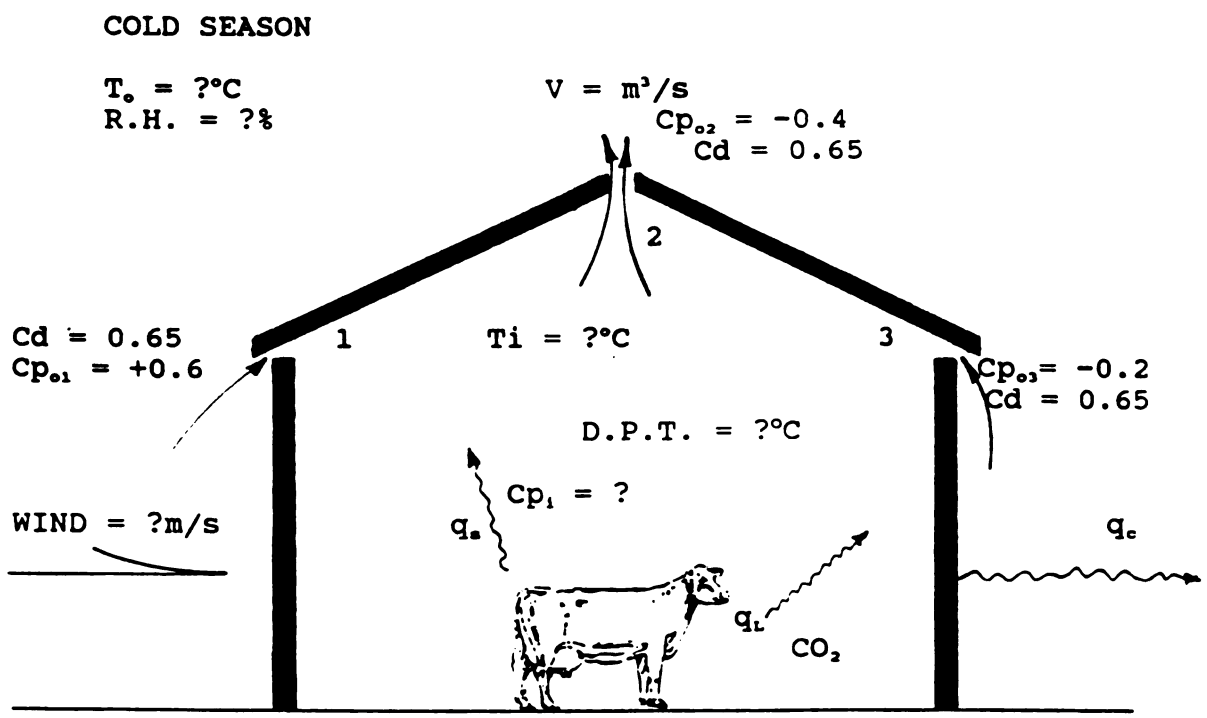
published were calm, 3.4 m/s (7.5 mph), and 6.7 m/s (15 mph). The film coefficient corresponding to a 3.4 m/s wind speed was frequently published as the summer film coefficient value. The resistance coefficient that corresponded to a 6.7 m/s wind was often stated as the winter film coefficient. Another important fact regarding the resistance coefficients was that, in a strict sense each applies only when the air temperature involved in the heat exchange was the same temperature as the mean radiation temperature of the surroundings of the surface in question (Albright, 1990). For example, the inside surface of a glass window pane in a well insulated and heated building during winter would represent a poor application of these data as the window pane was not the same temperature as the adjacent inside air. Fortunately, a cold confinement building has outside wall and roof temperatures that are relatively close to that of the surrounding air. Also, the surface-air temperature difference is often close to the 5.5 °C condition under which the original data were obtained. Therefore, the major difference between the conditions under which the original resistance coefficient data were obtained and the condition under which the freestall barn roof being modeled was being evaluated was that the modeled roof surface temperature was considerably colder.

III. MATERIALS AND METHODS

The objective of this research was to formulate and validate a mathematical model that predicted the inside, nighttime, environmental parameters of ventilation rate, relative humidity, absolute humidity, air temperature, air exchange, and dew point temperature for a modern freestall dairy barn in wintertime climates similar to the lower peninsula of Michigan. As well, from those findings and a calculation of roof inside surface temperature, an analysis of the effect of different ventilation rates and roof insulation levels on potential roof condensation (or frost formation) and carbon dioxide concentration was to be done at outside temperatures between -20.6 °C (-5 °F) and 4.4 °C (40 °F). After analyzing these results, a judgement could be made as to the potential harmful effects upon cattle and buildings of reduced rates of building ventilation.

As seen in Figure 3.1, the simulation model input data variables included outside weather conditions, barn physical features, ventilation-related building variables, and livestock variables. Figure 3.2 also describes the model variables in flow chart form. The outside weather condition input variables (see Tables 4.7 and 4.8) were derived from three years of sorted and averaged data from six modern,

NATURAL VENTILATION



Cp_o = Ratio between existing outdoor gauge pressure and wind stagnation pressure at site 1, 2, or 3.

Cp_i = Ratio between existing indoor gauge pressure and wind stagnation pressure.

Cd = Coefficient of discharge of vent 1, 2, or 3.

CO_2 = Carbon dioxide concentration, ppm.

D.P.T. = Dew Point Temperature, °C.

q_c = Conductive heat loss, Watts.

q_L = Latent heat loss, Watts.

q_s = Sensible heat loss, Watts.

R.H. = Relative Humidity, %.

T = Temperature, °C.

V = Ventilation rate, m³/s.

Figure 3.1 Variables Affecting Dairy Barn Natural Ventilation

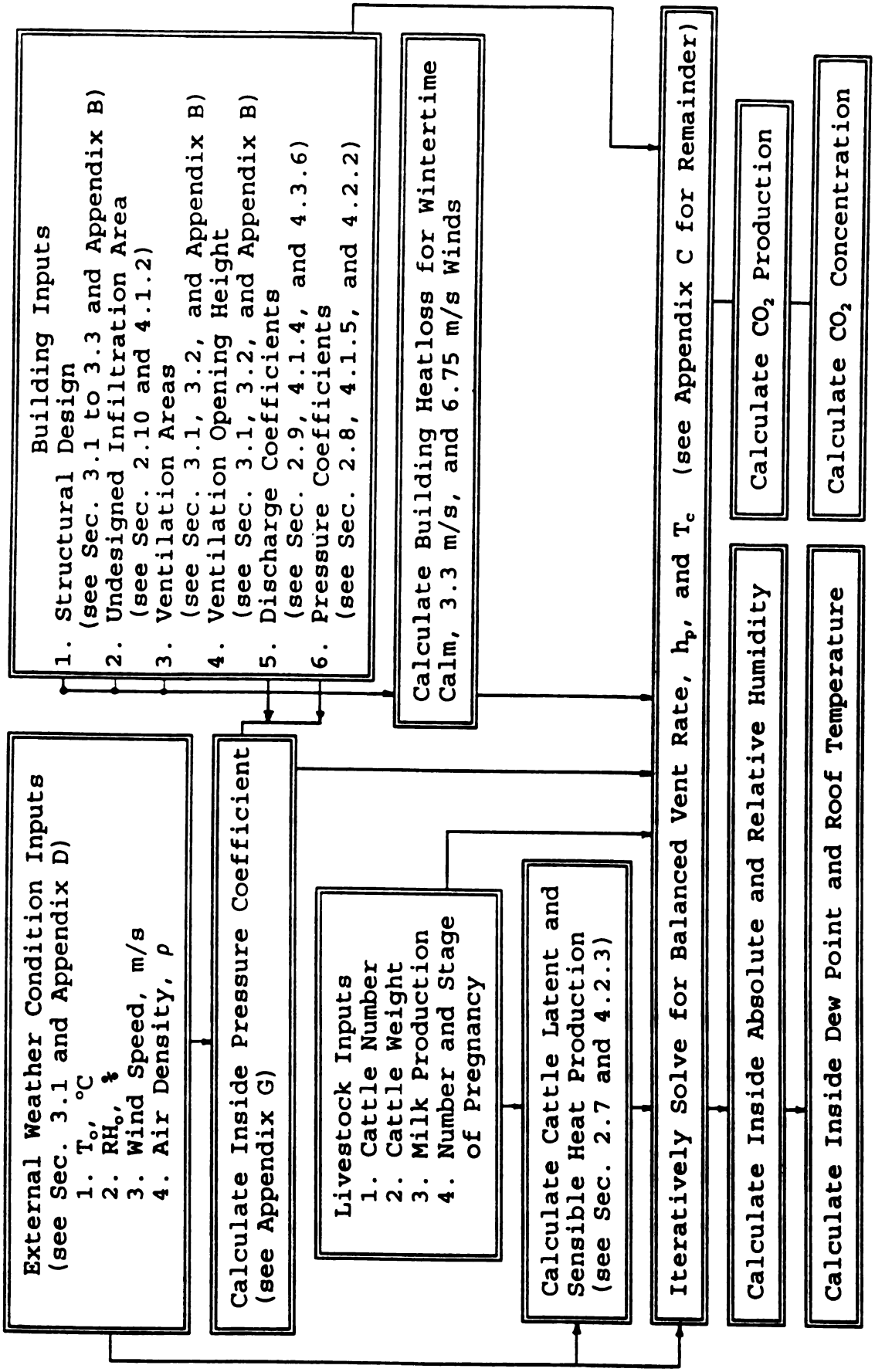


Figure 3.2 Flow Chart of Barn Environment Variables and Equations

instrumented, cold confinement, freestall dairy barns located in the Lower Peninsula of Michigan. The barn design modeled was a modern cold confinement freestall barn typical for the region (Bickert, 1992).

3.1 Validation Barn Data

The validation barn (located near St. Johns, Michigan) was one of fourteen cold confinement freestall barns in the lower peninsula of Michigan included in a three year monitoring program of inside and outside environmental parameters. The barn (illustrated in Figures 3.3 and 3.4) measured 26.2 meters (86 feet) wide, 51.2 meters (168 feet) long, and averaged 3.05 meters (10 feet) high at the eaves. Ventilation openings included continuous soffit vents 0.16 meters (6 inches) high and a continuous ridge vent 0.46 meters (18 inches) wide. The ridge vent was baffled (see Figure 2.3) with approximately 0.6 meter (2 foot) high sides. During the winter months, the feed alley and cattle alley doors were used as ventilation openings also. The doors (located at each gable end) included two cattle alley doors 2.92 meters (9 feet 7 inches) wide by 2.44 meters (8 feet) high, two cattle alley doors 3.15 meters (10 feet 4 inches) wide by 2.44 meters (8 feet) high, and two feed alley doors 4.27 meters (14 feet) wide by 3.96 meters (13 feet) high. The overall building height averaged 8.08 meters (26 feet 6 inches).

The validation barn was oriented long axis east to west and was unobstructed to the east, south, and west. Other

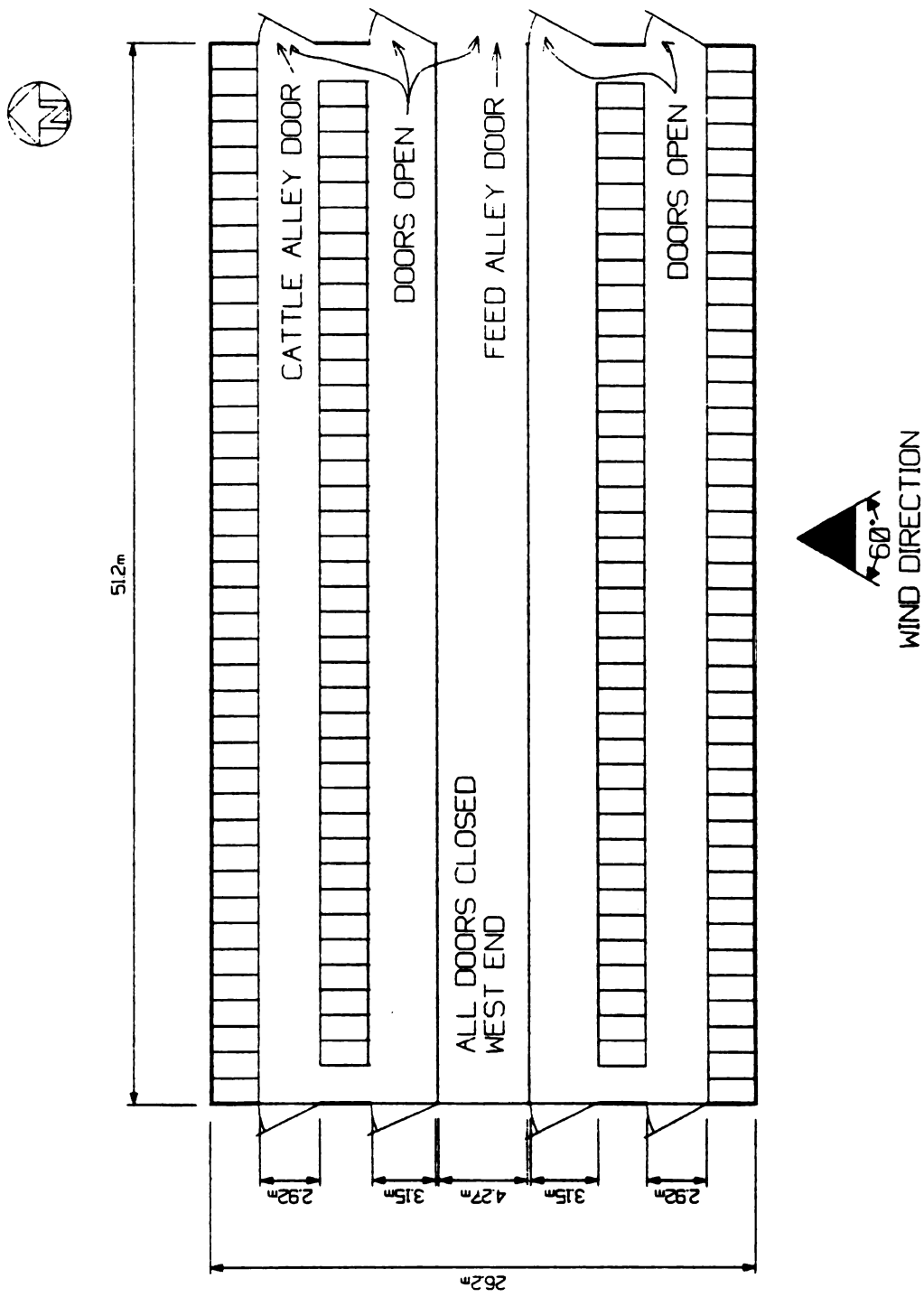


Figure 3.3 Validation Barn Floor Plan and Wind Angle Used When Sorting Weather Data.

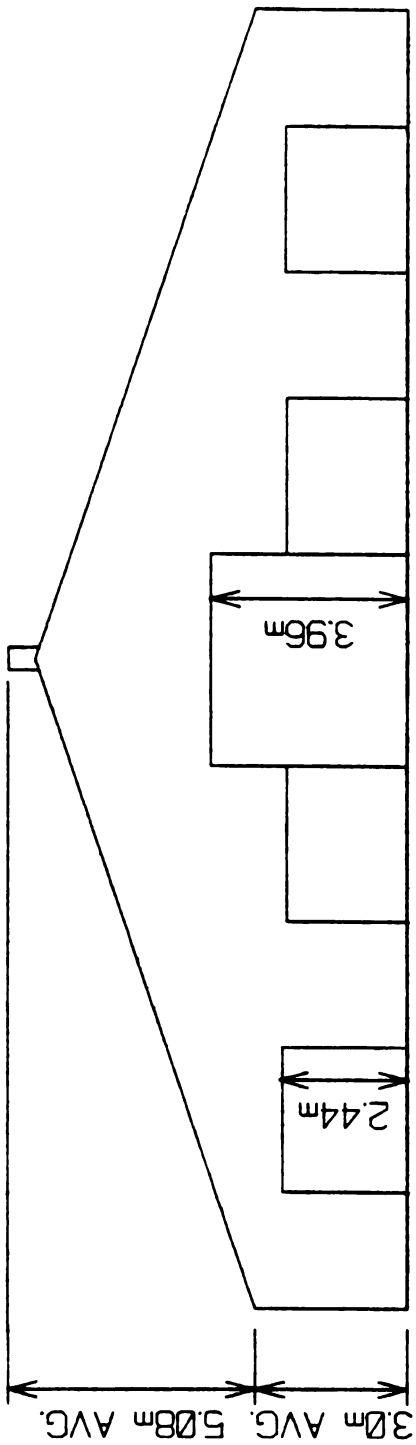


Figure 3.4 Validation Barn East or West Elevation.

buildings partially obstructed winds from the north. The building was constructed with square posts, had curtain sidewalls and an uninsulated metal roof. The gable end truss areas were metal clad and the west wall area was covered with a curtain. The area between the east end doors below the trusses was plywood covered.

During winter, the cattle alley doors on the east end remained open while the west end doors remained closed. Also, the feed alley door on the west end was closed during cold or windy weather and usually each night. However, the east end feed alley door usually remained open unless there was an easterly wind blowing rain or snow inside. Because the milking crew moved cows out of or past the east end of the validation barn day and night, and pushed feed up to the bunk twice nightly, the east feed alley door opening was often adjusted several times a night.

Other features of note in the validation barn included a sloping floor (that caused a 2.7 meter (9 foot)sidewall height on the west end and a 3.35 meter (11 foot) sidewall height on the east end), an upstand along the ridge opening (also called a chimney - see Figure 2.3), lack of doors for the east end cattle alley door openings, and a herd average of 43 kilograms (95 lbs) of milk per day.

Inside temperatures in this barn were measured with six copper-constantan thermocouples (error of ± 1 °C (Campbell Scientific, 1989)) positioned approximately one meter above the freestall floor. Four of these thermocouples were attached to posts on each side of the feed alley

approximately one sixth of the way in from each gable end. The two remaining temperature sensors were similarly located half way through the barn. Other inside sensors included a single thermocouple located midway through the barn at the peak and a thermistor and relative humidity sensor also located mid-building and approximately two and a half meters above the freestall floor. Outside temperature and relative humidity were measured with a shaded thermistor positioned approximately two meters above grade. For the 1990-91 and 1991-92 winters, this barn also had a weather station that recorded three meter high wind speed, wind direction, solar insolation, and outside temperature and relative humidity. Data acquisition was done each minute and averaged hourly for storage in a Campbell Scientific, CR10, Measurement and Control Module.

Weather data for the months of December, January, and February from the winters of 1989-90 to 1991-92 were used for validation calculations. As the weather station was not installed the winter of 1989-90, that season's wind direction data were obtained from weather station data at a similarly monitored barn approximately seventeen kilometers away.

The data were first sorted by wind direction, with any wind angle within thirty degrees of south being included (illustrated as the wind direction arrow on Figure 3.3). The decision on the degrees of wind angle to include was based on work done by Zhang et al. (1989). Their natural ventilation model calculated that a thirty degree deviation

for winds normal to the long axis of the barn resulted in a ventilation rate change of 0.04 m^3/s and an inside temperature change of 0.19 °C.

All data that fell within the acceptable wind direction range were ranked in ascending order by outside temperature. These data were then further sorted by outside temperature into 2.8 °C (5 °F) increments, with any temperature reading within one degree Fahrenheit of an even five degree increment being included (see Appendix D). To include outside temperatures below -17.8 °C (0 °F) (that met both the wind direction and five degree Fahrenheit incrementing conditions) only the data from the winter of 1989-90 were used for validation purposes as the outside weather data values. Also, to remove the effects of solar gain, data collected during hours during which solar gain was recorded were sorted out. Finally, to eliminate any hours that did not represent a fully stocked barn environment, a final data sorting was done to eliminate any hours that the cows would be out of the barn for milking.

Next, mean values of hourly weather data within each 2.8 °C group were calculated. These averages included outside and inside relative humidity, wind speed, outside and inside temperature, and were used as the basis for comparison between validation barn calculated environmental values and measured environmental values. Table 4.7 lists the average weather data and number of hours used to calculate those averages after all sorting criteria had been met.

3.2 Simulation Model Data

The simulation barn was representative of a modern cold confinement freestall dairy barn. It measured 27.4 meters (90 feet) wide, 53.6 meters (176 feet) long, and 3 meters (10 feet) high to the eaves. It typically would be called a four row drive through freestall barn and would be designed to house approximately 160 cows (see Figures 3.5 and 3.6).

The building had 2.44 meter (8 foot) high by 3.05 meter (10 foot) wide cow alley doors at each end of the four cow alleys and a 4.3 meter (14 foot) wide by 3.7 meter (12 foot) high feed alley door located at each end of the drive-through feed alley. The side walls had full curtains, the gable ends were metal sided, and the roof was metal clad. Continuous soffit vents were 0.15 meters (6 inches) high and the continuous ridge opening measured 0.46 meters (18 inches) wide (see Figure 3.7). Appendix B lists building features and heat loss calculations.

Inside environmental conditions were calculated at 2.8 °C (5 °F) outside temperature increments from -20.6 °C to 4.4 °C (-5 °F to 40 °F). This set of inside environment calculations (at each of the 2.8 °C outside temperatures) was repeated for four different ventilation opening conditions (see Figures 3.7 to 3.10). To represent a very closed building, ventilation at an inlet area equal to 10 percent of full soffit opening was calculated (inlet and infiltration areas equaled 5.5 m^2 (59 ft^2)). Partially blocked inlet ventilation was represented by calculations of ventilation at 50 percent of full soffit area (inlet and

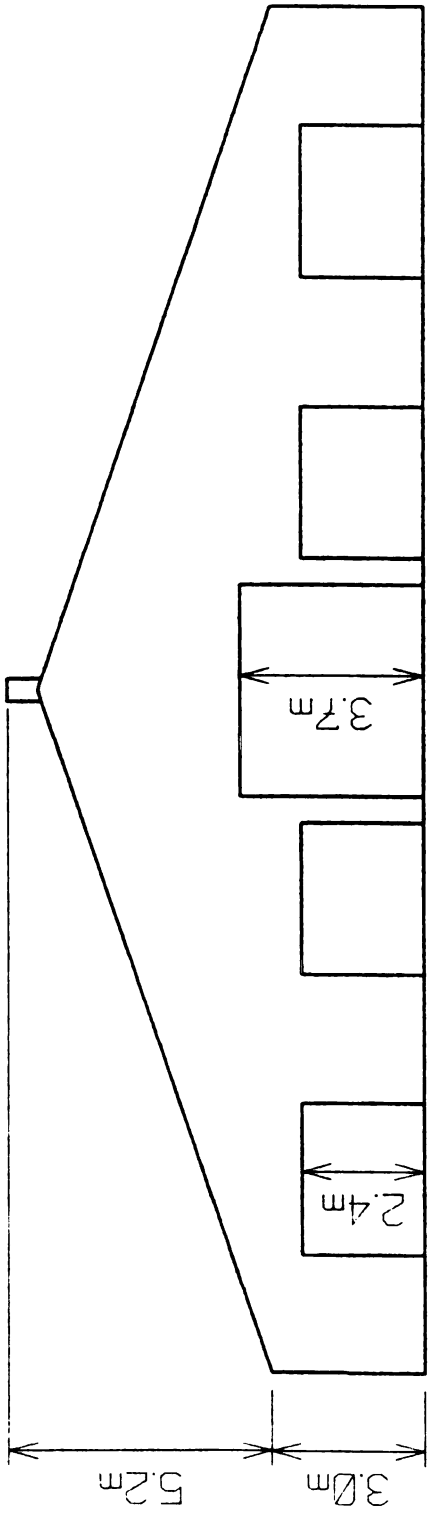


Figure 3.5 Model Barn Gable End Elevation.

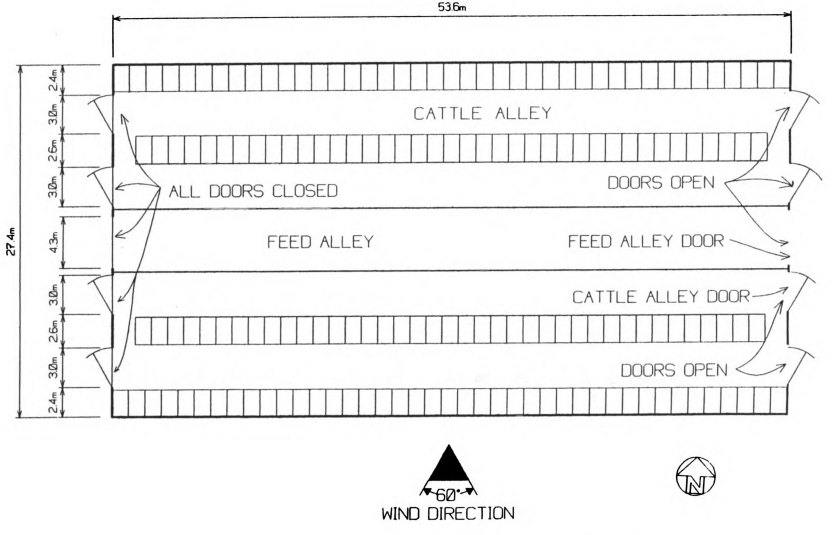


Figure 3.6 Model Barn Floor Plan and Wind Directions Included in Weather Data Summary

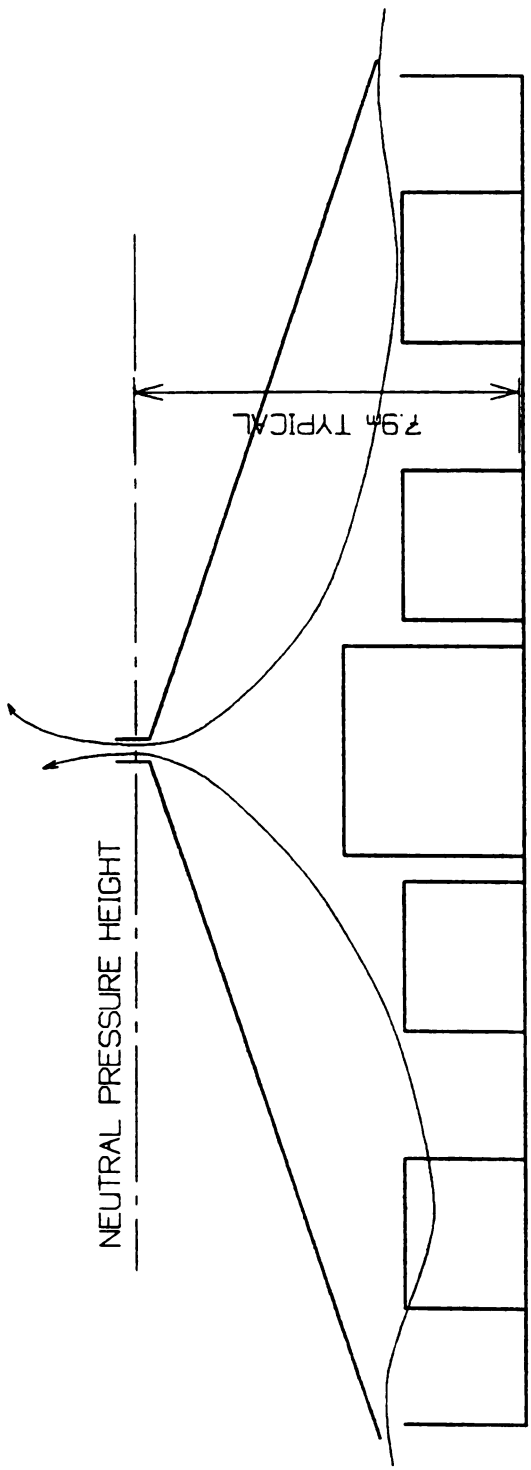


Figure 3.7 Typical Model Barn Ventilation With 10% of Soffit Vents Open.

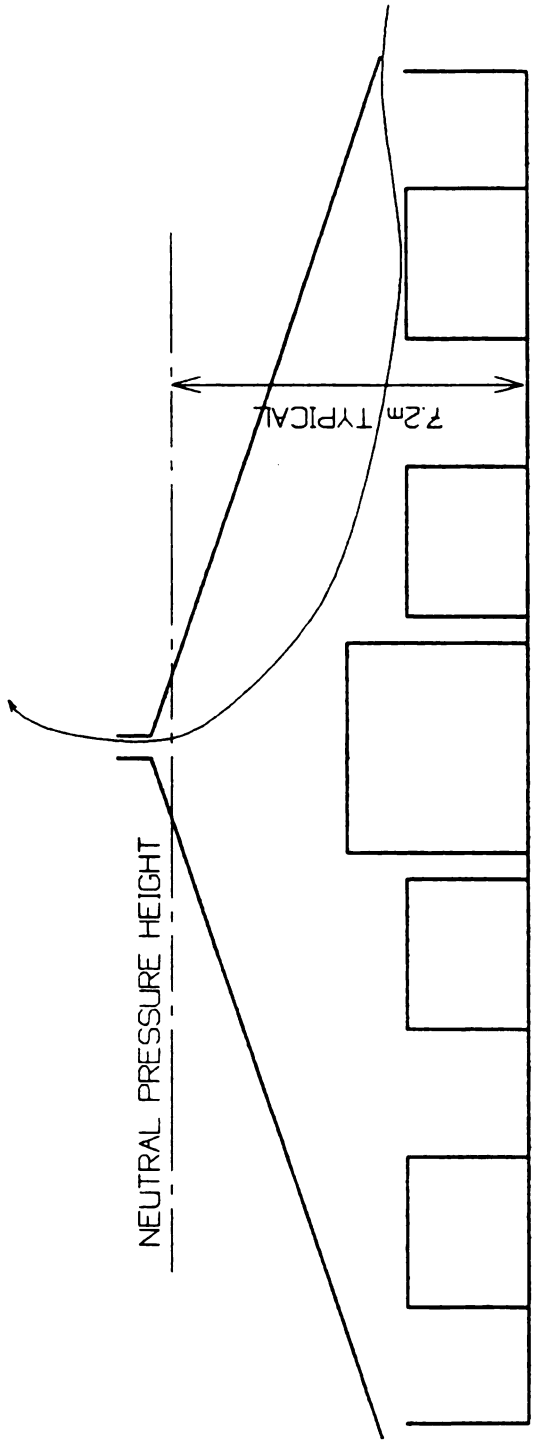


Figure 3.8 Typical Model Barn Ventilation With Upwind Soffit Blocked.

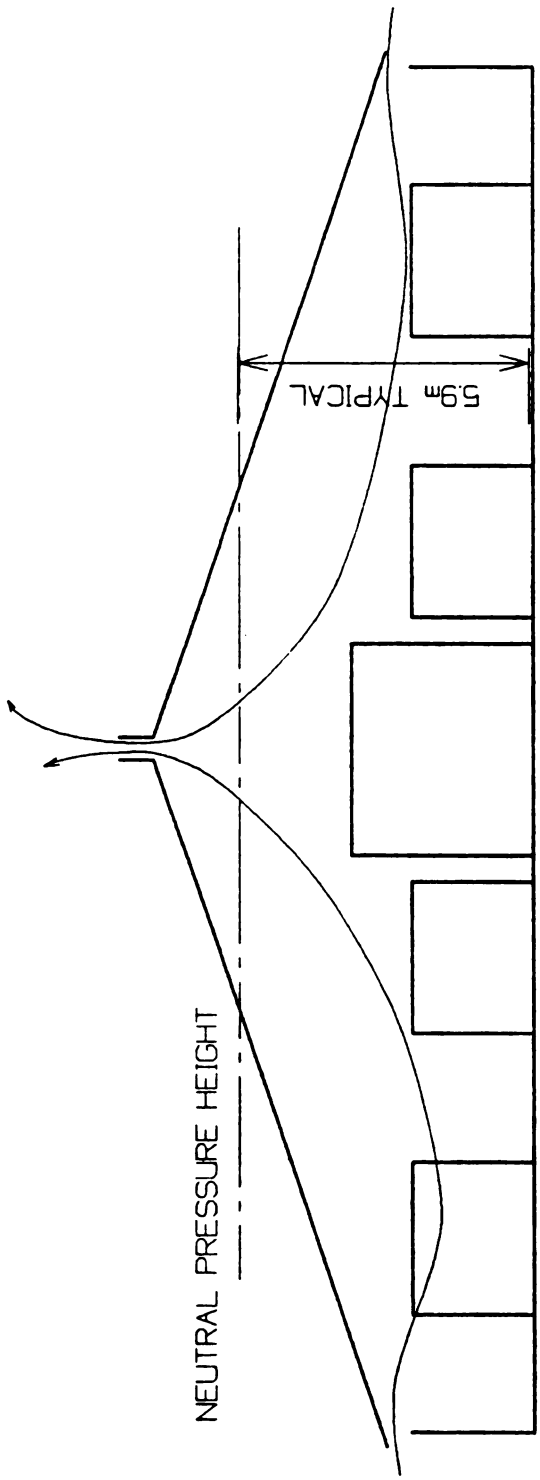


Figure 3.9 Typical Model Barn Ventilation With 100% Open Soffits.

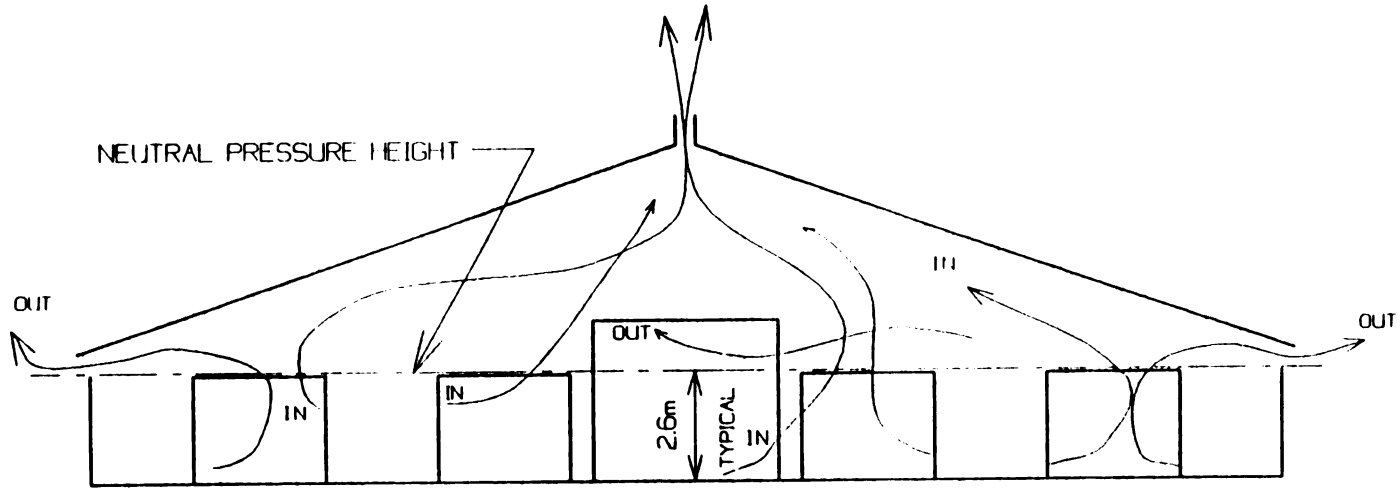


Figure 3.10 Typical Model Barn Ventilation with Soffits and East End Cattle and Feed Alley Doors Open (called 343% of full soffit ventilation openings).

infiltration areas equaled 11.3 m^2 (122 ft^2)). The upwind soffit was considered closed and the downwind soffit was considered open for all 50 percent vent opening calculations (see Figure 3.8). This blocking scheme was chosen on the assumption that if a person were going to partially close the soffits he would close the openings on the windy side first. Due to upwind and downwind pressure coefficient differences, the effect of this closing arrangement was a lower calculated ventilation rate than would have resulted had the conditions been reversed (i.e., downwind soffit vent openings blocked and upwind openings left open).

Calculations at 100 percent and 343 percent soffit area (343 percent being equivalent to unblocked soffits and opening one feed alley and four cow alley doors) (see Figures 3.9 and 3.10) were also done to compare a closed barn and a barn with manual ventilation control through door openings (the sum of inlet and infiltration areas for each opening condition equaled 18.7 m^2 (201 ft^2) and 64 m^2 (688 ft^2) respectively).

The building was assumed to be stocked with 160 mature milk cows weighing 610 kilograms (1345 pounds) each and averaging 10,000 kilograms (22,050 pounds) of milk per 305 days. A sample set of calculations to determine inside environmental conditions is presented in Appendix C.

The simulation barn environmental calculations used inputs of outside wind speed and relative humidity obtained from six monitored barns in the Lower Peninsula of Michigan. Section 3.1 describes the data retrieval and data averaging

procedure for one of the six, the validation barn. The other five monitored barns had identical instrumentation and data retrieval systems. The outside weather data and inside environmental data were collected each minute and averaged each hour. These hourly data, from each of the six barns, for the months of December, January, and February, over three years, were used for the simulation barn calculations. As described in Section 3.1, all data were first sorted to eliminate any data that did not fall within a wind direction of within ±30 degrees normal to the long axis of the barn. The data were then further sorted into temperature groups. All data that fell within 0.6 °C (1 °F) of each 2.8 °C (5 °F) temperature group were selected. The temperature groups began at -20.6 °C (-5 °F) and ended at 4.4 °C (40 °F). The resulting data from each barn were then averaged and used with the other five barn's averages to calculate the mean wind speed and relative humidity used in the simulation calculations (see Section 4.3.1 and Table 4.8).

3.3 Calibration Barn Data

The calibration barn measured 36.6 meters (120 feet) long by 31.7 meters (104 feet) wide at the gable ends. It had 3 meter (10 foot) sidewalls and a 0.9 meter (3 foot) high by .43 meter (17 inch) wide chimney. Wintertime ventilation openings included soffits, ridge, chimney, and a 4.26 meter (14 foot) high by 4.26 meter wide feed alley door. This barn was instrumented for collection of inside and outside temperature and relative humidity. It also

included a weather station that recorded wind speed, wind direction and solar insolation. As with the validation barn, sorted data for the months of December, January, and February of 1989-90 were used to compare with calculated inside temperature and relative humidity.

3.4 Roof Surface Temperature Measurement

To provide a set of field measurements that would allow for a comparison between calculated and measured lower roof surface temperature, three sets of barn roof data were collected on the validation barn. The measured values for the validation barn were taken from approximately midnight to 4 A.M., when none of the groups of cows in the barn were out for milking. The sets of readings were taken on December 21, 1992, and January 7 and 9, 1993. The night of December 20 to December 21, 1992 had an outside temperature of approximately 8 °C (17 °F) with calm to mild winds and a very clear sky. There was approximately 1.5 millimeters (1/16 inch) of frost on both upper and lower roof surfaces of both north and south roof slopes. Because of the slippery roof conditions, the roof surface measurements were taken approximately 1.8 meters (6 feet) uproof from the fascia. This put the measurement on the underside of the roof approximately 0.6 meters (2 feet) in from the headers (near the incoming ventilation air). Wind was entering from both soffits.

The second set of data were taken on the night of January 6 to 7 1993, with an overcast sky and mild winds.

There was patchy ice on the roof's upper surface, a film of frost on the roof's lower north surface, and light condensation on the roof's lower south surface. The ambient temperature was approximately -3.3 °C (26 °F). Wind was blowing in from both soffits.

The third set of data were taken the night of January 8 to 9 1993. The sky was lightly overcast (stars and a full moon could be seen) and winds were in the 3.4 to 5.4 m/s (7.4 to 12 mph) range. The validation barn and two other identical barns located approximately 30 meters (100 feet) apart all had approximately 25 mm (1 in) of snow on the north upper roof surface and bare south upper roof surfaces. Also, they all had light frost on the north lower roof surface beginning about 0.3 m (1 ft) from the soffit vent and ending about 1 m (3 ft) from the ridge opening. The south lower roof surface of the validation barn was dry and the same slope of the other two barns appeared dry from floor observations. Winds were from the north and the outside temperature was approximately -6 °C (21 °F).

Identically positioned upper and lower roof surface temperatures were taken with a Model 110 Everest Interscience pistol grip infrared thermometer positioned approximately 75 mm (3 in) from the roof surface. The site, located mid-building, was scraped free of frost when necessary and cleared of snow or ice within approximately a 3.3 meter (4 ft) diameter. The measurement locations for data sets two and three were at exactly the same site; and all sites were mid-way between roof purlins and roof

trusses. Wind speed was measured by a Solomat Model MPM500E. The hot wire anemometer probe of this unit was held approximately 25 mm (1 in) from the test site. Air temperature was taken as the average of three VRW Scientific model 61016-208 mercury in glass thermometers whose sensing bulbs were approximately 0.3 meters (1 ft) from the surface in question.

The sequence of sampling was to take an outside set of readings and an inside set of readings for each roof slope. This sequence was repeated two additional times. One set of readings (one outside set then one inside set for the same spot) took about 45 minutes. Consequently, there were some minor changes in inside and outside temperature and wind speed as the night progressed and as the measuring process moved from a sheltered side to a windy side or vice versa. Also, the first set of data (12/21/92) was comprised of only two sets of readings for the north and south roof slopes as, after that time, the infrared thermometer failed to function in the cold weather. This problem was corrected for the following sets of measurements by keeping the instrument at near room temperature (inside the author's coat) between tests. Several wind velocity readings on January 7th and one reading on January 9th were not taken due to breakdowns in the hot wire anemometer. Also, one set of data on the south side of the barn roof on January 9th was discarded due to readings that were obviously incorrect due to measurement or recording errors.

3.5 Carbon Dioxide Measurement Data

Carbon dioxide concentration validation was done using a barn in the monitoring program located approximately forty eight kilometers from the validation barn. The building was a 61 meter (200 foot) by 13.3 meter (43.75 foot) by 3 meters (10 foot) high curtain sided freestall pole barn with 38 millimeters (1.5 inches) of roof insulation. A row of stalls faced each side wall and a middle row was at the ends of a central feed bunk. It had a 15.2 centimeter (6 inch) continuous ridge vent. Sidewall soffit ventilation was accomplished between rafters whose tails had been cut flush with the side of the barn and a canvas flap installed. A higher air pressure exerted against the flap from the inside allowed exhaust air to escape but little ventilation air to enter. The building housed 75 cows each weighing an average of 610 kilograms and producing 5489 kilograms (12100 pounds) of milk per 305 days.

To study the effect of inadequate ventilation on air quality, the building doors were tightly closed, soffit flaps nailed shut, and any holes in the closed curtain sides were covered with plastic. The ridge vent was left open. The only inlet ventilation air provided was infiltration through cracks around the barn doors, sidewall curtain edges, joints between gable end wall metal siding, and permeability through the sidewall curtain material. With all cows present, the closed building's environment was allowed to stabilize for several hours. Air samples were then taken at half hour intervals from 12 M. to 4 P.M.,



using a Matheson Gas Products model AP-1 Kitagawa Aspirating Pump and 126SC carbon dioxide gas detector tubes. Gas concentration was determined by matching the CO_2 parts per million etched on the detector tube with the leading edge of a reagent color change two minutes after an air sample had been drawn through the reagent. The detectable limit was reported to be 30 ppm (Matheson, 1990). In this author's opinion, the subjective nature of determining exactly where the reagent color began to change made readings of less than 100 ppm increments difficult to defend.

Each half hour a mid-barn sample was taken in the center of both alleys at approximately a 1.4 meter (4.5 foot) height. Those readings were averaged to yield the CO_2 concentration for that half hour interval.

IV. RESULTS AND DISCUSSION

4.1 Simulation Model Development

Once the preliminary input data were established, equations were solved for variables that led to a determination of roof condensation potential and inside air quality. The following paragraphs sequentially describe the steps involved in that determination process. Figure 3.2, also, illustrates the process in flow chart form.

4.1.1 Building Heat Loss

Thermal conduction is the process of diffusing thermal energy through a continuous medium. The rate of conduction is dependent upon the physical properties of the medium. Under steady-state conditions, conductive heat flow can be stated as the following:

$$q=-kA(\Delta t/\Delta x) \qquad (4.1)$$

where:

q = Heat flow in one direction, Watts or Joules/sec

k = Thermal conductivity, W/m·K

A = Cross-sectional area, m^2

$\Delta t/\Delta x$ = Temperature gradient, K/m.

Heat flow through roofs, walls, windows, and doors can be calculated for each component using the following equation:

$$q = UA(t_i - t_o) \tag{4.2}$$

where:

U = Unit area thermal conductance, $W/m^2 \cdot K$

A = Area normal to the direction of heat flow, m^2

t_i = Inside air temperature, C

t_o = Outside air temperature, C.

Unit area thermal conductance can be calculated using the equation:

$$U = \left[(1/f_i) + \sum_{x=1}^{a} ((L_x/k_x) + (1/f_o)) \right]^{-1} \tag{4.3}$$

where:

f_i = Inside film or surface conductance, $W/m^2 \cdot K$

f_o = Outside film or surface conductance, $W/m^2 \cdot K$

L_x = Length of homogeneous material heat flow path, m

k_x = Coefficient of conduction of a homogeneous material, $W/m \cdot K$

a = Number of layers of homogeneous material

x = A specific homogeneous material.

A typical example of a calculation solving for the wintertime U value of an uninsulated barn roof is shown in Table 4.1.

Table 4.1 Typical Wintertime U Value Calculation

Homogeneous Material	R(SI)	R
outside air film	0.03	0.17
26 ga. steel roofing	0.00001	0.00
inside air film	0.11	0.62
	0.14001 $m^2 \cdot K/W$	0.79 $hr \cdot ft^2 \cdot F/BTU$

$U = 1/R = 1.3\ W/m^2 \cdot K = 0.23\ BTU/hr \cdot ft^2 \cdot F$

Using the equality R(SI) = R * 0.176 as a check on calculation accuracy, 0.79 * 0.176 = 0.14.

Albright (1990) states that heat transfer through an unheated floor on grade has been found to lose heat primarily from its perimeter, rather than from the interior part of the building. Consequently, in terms of heat conduction, the outer two meters of the perimeter become the only parts of the floor which are important. This conduction loss is in proportion to the length of the perimeter and the temperature difference between air inside and outside the building. Under steady-state conditions, heat loss from the perimeter was estimated by the equation:

$$q_f = fp(t_i - t_o) \qquad (4.4)$$

where:

q_f = Floor conductive heat loss, W

p = Building perimeter linear distance, m

f = Average value of building perimeter linear heat transfer, 1.5 W/m·K.

For this research, steel siding or roofing and curtain sidewall material were assumed to have negligible resistance to heat flow. For building components consisting of only those materials, resistance to heat flow was comprised of inside and outside boundary layers (resistance to heat flow due to the insulating properties of air films adjacent to each side of the building material) only. For calculations of wintertime conductive heat loss during calm conditions (0 to 1.35 m/s (0 to 3 mph)), the inside boundary layer value was also used as the outside boundary layer value. For winds between 1.35 and 3.38 m/s (3 to 7.5 mph) an R(SI) value of 0.044 (R = 0.25) was used to represent the outside boundary layer heat flow resistance. Beyond 3.38 m/s an R(SI) value of 0.030 (R = 0.17) was used. This was done to determine a more accurate estimation of interior roof surface dew point temperature. Appendix F lists the surface conductances and resistances for three wind speeds and three surface emittances. The heat flow direction, wind speed and film coefficients of interest are in bold type.

The building heat loss was found by totaling the heat loss for each homogeneous structural material, using Equation 4.2, and adding to that the building perimeter heat loss, calculated using Equation 4.4

4.1.2 Building Infiltration

To evaluate the appropriateness of a cold confinement infiltration rate between 1.5 and 3.0 ac/h (discussed in Section 2.10), the ASAE calculations (appropriate for closed confinement mechanically ventilated barns) were used to determine the infiltration rate of the validation barn. First, the validation barn neutral pressure height was calculated under no wind (stack ventilation) conditions. Using the equation:

$$\Delta P = \Delta \rho g (h_p - h) \qquad (4.5)$$

the inside/outside pressure difference was then determined. This value was used in the equation:

$$V = 0.017 (\Delta P)^{0.67} \qquad (4.6)$$

where:

V = Ventilation rate per dairy cow unit, m^3/s

to determine the infiltration rate per 500 kg cow in a "tight construction" building (Albright, 1990). Upon conversion to a 610 kg cow weight and multiplied by the 160

head, an infiltration rate of 2.5 m^3/s or 1.4 ac/h resulted. When considering that the result was calculated for a windless condition and that cold confinement is not a "tight construction" type of housing, the minimum value of 1.5 ac/h suggested by Choiniere et al. (1990) seemed acceptable. Hellickson (1983) notes also that weathered, double layer plastic film covered greenhouses had an air exchange between 1 and 2 ac/h and "old construction" glass greenhouses had an air exchange between 2 and 4 ac/h.

From the above evaluation, the minimum infiltration rate of 1.5 ac/h suggested by Choiniere et al. (1990) would reasonably represent the tightest construction for cold confinement dairy housing. Therefore, the average value of 2.2 ac/h seemed acceptable as a recommended average infiltration rate for cold confinement dairy housing and was chosen as the infiltration value for this research.

To make the value more useful, a conversion from air exchange to square meters of open infiltration area was needed. For the validation barn, a minimum infiltration rate of 2.2 ac/h resulted in a ventilation rate of 4.3 m^3/s. Through an iterative process, the building inlet area for stack effect (no wind) ventilation calculations was adjusted until a ventilation rate of 4.3 m^3/s was achieved. This resulted in an inlet area for infiltration of 3 m^2 at -17.8 °C. Due to the reduced stack effect at warmer temperatures, an area of 3.6 m^2 was needed at -1.1 °C to achieve an infiltration rate of 4.3 m^3/s. Because of the difficulty in reconstructing the equations with a different

inlet area each time the ventilation system was evaluated at a different outside temperature, the infiltration area of 3 m^2 was chosen as the infiltration area for all validation barn calculations. To evaluate this decision, a comparison of 3 m^2 versus 3.6 m^2 infiltration area at -1.1 °C was made. This comparison resulted in a calculated inside temperature of 4.278 °C at 3 m^2 and 4.272 °C at 3.6 m^2 infiltration area. The air changes per hour were identical for both infiltration areas. Obviously, from this analysis either choice would have been acceptable. As winds increased, the larger opening would show a more dramatic change in air exchange and inside temperature reduction so the 3 m^2 was left as the infiltration rate for the validation barn calculations.

4.1.3 Building Heat Gain

The only heat gain assumed in this model was that produced by the livestock. However, after an in-depth search of the literature on livestock heat production (see Section 2.7), no single acceptable resource was found in the winter time temperature range being studied (-21 °C to 4 °C (-5 °F to 40 °F)). Either the predicted lower critical temperature was too high (Strom and Feenstra, 1980) or too low (Ehrlemark and Sällvik, 1990) resulting in unrealistically high or low sensible heat values, the data were not based on studies in a production environment, or the temperature range of the resource was not all inclusive.

Because of this, a composite solution for sensible and latent heat production was chosen. Uncorrected total heat production (at some average weight per head) was determined by using the CIGR (1984) recommendations for maintenance, milk production, and reproductive heat output. Maintenance total heat production was found using the equation:

$$Q_{maintenance}=5.6*m^{0.75} \tag{4.7}$$

where:

Q = Heat production, Watts

m = Mass, kg.

Total body heat production due to milk production was represented by the equation:

$$Q_{milk}=22*Y \tag{4.8}$$

where:

Y = Milk production, kg/day.

Heat production resulting from stage of pregnancy was determined by the equation:

$$Q_{pregnancy}=1.6*10^{-5}*D^{3} \tag{4.9}$$

where:

D = Days pregnant.

The assumption was made that, at any one time, seventy five out of each 100 cows were bred; and a uniformly spaced breeding interval occurred.

CIGR (1984) equations were chosen because, to this author's knowledge, these equations were the only current, peer reviewed formulas that allowed for tailoring heat output to changes in milk production and stage of pregnancy and that readily lent themselves to computer modeling. Through these equations, total heat production of modern high producing herds and herds of lower milk production could be compared as to their effects upon a barn environment.

Maintenance, milk production, and reproductive heat production, when summed, equals total animal heat production. That value, multiplied by the number of head and then divided by the total herd weight, yielded total heat production per kilogram of body weight. As suggested by Webster (1973), ten percent of the total heat production was used as the latent heat portion of the total heat production at the animals lower critical temperature (the lower critical temperature being defined as -40 °C (-40 °F) for a high producing dairy cow) (Webster, 1973).

Next, latent heat production for a 500 kg cow was calculated from a regression equation. The data points used to form the regression equation (see Table 4.2) were calculated from various sources believed to be reliable in meeting the criteria of being values taken from a producing herd environment. Due to the manner in which the limited amount of available data in the temperature range being studied was presented, all data points chosen were derived from unit conversions, body weight conversions,

interpolations, conversions from heat output per area to heat output per mass, conversions from averaged data, or a combination of these methods. Each of the final data points was then subjectively chosen from a very extensive plot of the available data, based on their approximation to a least squares regression curve between the end data points of 0.2 W/kg at -40 °C and 0.77 W/kg at 4.3 °C. The end points were chosen based on their presumed reliability. The averaged value or 0.20 W/kg at -40 °C resulted from the citing by several authors (see Table 4.2) of very similar values for cattle heat output at the cold end of the thermoneutral zone (see Figure 4.1). The value of 0.77 W/kg at 4.3 °C was chosen because it was from a recent barn study specifically researching the validity of the various references available on latent and sensible heat production and it's partitioning in housed dairy cattle.

Table 4.2 Latent Heat Values for 500 kg Dairy Cattle at Various Outside Temperatures Used as Reference or Base Values for Linear Regression Calculations.

T_o °C	Latent Heat W/kg	Reference/Calculation Method
-40.0	0.20	Webster (1973) and Bruce (1992) (averaged value)
-30.0	0.24	Interpolated value
-20.0	0.29	Interpolated value
-13.9	0.32	Thompson and Stewart (1952)
-13.3	0.34	Thompson and Stewart (1952)
-10.3	0.39	Thompson (1957)
0.0	0.58	Thompson and Stewart (1952)
4.3	0.77	Quille et al. (1986)

The initial data points were from work done by Quille et al. (1986), Bruce (1992), selected summaries of Holstein

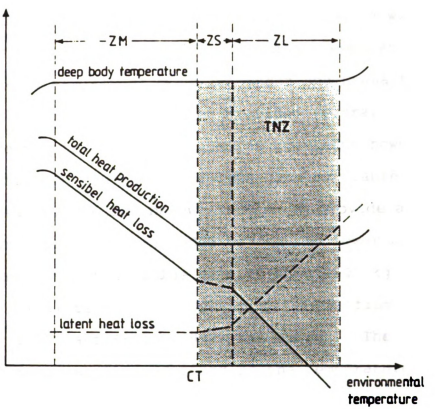


Figure 4.1 Animal Heat Production TNZ = Thermoneutral Zone, CT = Critical Temperature, ZL = Latent Heat Dominating Zone, ZS = Sensible Heat Dominating Zone, ZM = Metabolic Heat Dominating Zone (Ehrlemark and Sällvik, 1990)

dairy cow heat production done at the energetics laboratory in Missouri, and research done by Webster (1973). As the temperature range of interest was approximately between 4 °C (40 °F) and -21 °C (-5 °F), no data points were used above 5 °C. As mentioned previously, the Quille et al. (1986) data were used because their values were obtained from modern

dairy facilities specifically studying sensible and latent heat production. However, because their Alberta, Canada study was done under warm confinement conditions, only data points at the high end of the temperature zone of interest were available. The University of Missouri energetics laboratory did several "barn study" experiments with Holstein dairy cows that included indoor temperatures down to approximately -15 °C (5°F) (Thompson and Stewart 1952, Thompson 1957). Those studies provided several intermediate reference points. To this author's knowledge however, there were no housing condition research data available on dairy cattle heat production below -15 °C. To provide a regression curve that extended beyond the lower temperature of interest, the mean value of 0.20 W/kg (500 kg cow) at the lower critical temperature of -40 °C (-40°F) from data by Webster (1973) and Bruce (1992) was chosen. The lower critical temperature is defined as the temperature below which the animals total heat production shows a significant rise to maintain homeostasis (see Figure 4.1).

Since the latent heat regression equation was based on a 500 kg cow, the latent heat production of any herd (at some average weight per head) first needed to be converted to latent heat production on a 500 kg cow basis through the equation:

$$(Q_L)_{old_{rt}} = (Q_L)_{new_{rt}} (m_{old}/m_{new})^{0.734} \qquad (4.10)$$

where:

Q_L = Latent heat production, W/kg

new = Value at herd average weight, kg

old = Value at 500 kg

m = Mass, kg

rt = Reference temperature , °C.

The difference between the answer to Equation 4.10 and the lower critical temperature latent heat value of 0.20 W/kg was added to each of the reference latent heat values (column 2 Table 4.2, column 2 Table 4.3) for the other temperatures listed in column 1 of Tables 4.2 or 4.3. For example, in Table 4.3 the difference between the reference latent heat value of 0.20 W/kg and the validation herd latent heat value of 0.243 W/kg was 0.043 W/kg. That value, added to the remaining values in column 2, yielded the numbers in column 3 of Table 4.3. That sum represented the latent heat value for a 500 kg cow at current production rates. Each of those numbers was then converted to latent heat production (W/kg) at the average weight of the herd being modeled, by the equation:

$$Q_L)_{new_{rt}} = (Q_L)_{old_{rt}} (m_{new}/m_{old})^{0.734}, \qquad (4.11)$$

and are recorded for the validation herd in the fourth column of Table 4.3. The resulting values were used to derive a third-order polynomial regression equation for herd latent heat production, valid for any outside temperature

between -40 °C to 4 °C (-40 °F to 40 °F). Total heat production (W/kg) of the herd minus herd latent heat production yielded the sensible heat production (W/kg) for each reference value. Those sensible heat values were then used to create a second third-order polynomial regression equation for cattle sensible heat production. Table 4.3 lists validation barn cattle heat production values for a herd consisting of 160 cows weighing an average of 610 kg each and having a milk production average of 13,281 kg per cow per 305 days.

Table 4.3 Validation Herd Calculated Latent and Sensible Heat Production Values.

T_o °C	Reference Latent Heat W/kg	Latent Heat @ 500 kg W/kg	Latent Heat @ 610 kg W/kg	Total Heat W/kg	Sensible Heat @ 601 kg W/kg
-40.0	0.20	0.243	0.278	2.78	2.50
-30.0	0.24	0.283	0.324	2.78	2.46
-20.0	0.29	0.333	0.381	2.78	2.40
-13.9	0.32	0.363	0.415	2.78	2.37
-13.3	0.34	0.383	0.438	2.78	2.34
-10.3	0.39	0.433	0.496	2.78	2.28
0.0	0.58	0.623	0.713	2.78	2.07
4.3	0.77	0.813	0.931	2.78	1.85

4.1.4 Discharge Coefficient Selection

As there was no strong consensus about which discharge coefficient to use in various inlet and outlet opening situations and because the apparent trend by researchers of natural ventilation was to use discharge coefficients higher than 0.6 (see Section 2.9), a discharge coefficient of 0.65 was used for all openings in this research.

4.1.5 Pressure Coefficients Selection

4.1.5.1 External Pressure Coefficients

As a comparison of the effect of the various external pressure coefficients upon a building's air exchange, several sets of values in Table 2.5 were used to calculate wind ventilation at 4.5 m/s (10 mph) for the same barn. The calculations assumed that the building had two soffit inlets of 6.84 m^2 each at a 0.65 discharge coefficient and one ridge outlet of 15.28 m^2 at a 0.70 discharge coefficient (see discharge coefficient in Section 2.9). The results, shown in Table 4.4, would indicate that limited changes or the correct combination of pressure coefficient changes yielded similar air exchange rates.

Table 4.4 Effect of External Pressure Coefficients On Air Exchange (Shrestha et al., 1990).

Source	Pressure Coefficients			Building AC/h
	Upwind	Downwind	Peak	
Newberry (1974)	0.7	-0.25	-0.8	10.39
Bruce (1974)	0.5	-0.3	-0.6	9.11
Brockett (1987)	0.4	-0.3	-0.8	10.55
Brockett (1987)	0.5	-0.2	-0.7	10.55

AC/h = air change per hour

After determining the air exchange rate from many combinations of external pressure coefficients, coefficients of 0.5 upwind, -0.7 peak, -0.2 downwind, and -0.1 gable ends were chosen. These values were selected because they yielded an air exchange rate midway between the extreme possibilities and because of the frequency of each value being mentioned in reference literature. However, when the

inside temperature and relative humidity were calculated for the barn used to validate the equations, errors appeared. There was close agreement only when soffit and ridge ventilation was allowed. When the ventilation area was increased to include end doors, the iterative solution approach could not yield an answer, irregardless of the number of iterations. Consequently, the pressure coefficients were adjusted until valid results were obtained for all possible ventilation opening options. The final pressure coefficients chosen were: 0.6 upwind, -0.4 peak, -0.2 downwind, and -0.2 gable ends.

4.1.5.2 Internal Pressure Coefficient

After building heat gains, building heat losses, orifice discharge coefficient, and external pressure coefficients had been determined, the inside pressure coefficient was found by solving for a net ventilation rate of zero between all inlets and outlets. First, the velocity of ventilation air entering or leaving each ventilation opening was calculated using the equation:

$$v_y = v_w \frac{(Cp_{o_y} - Cp_i)}{\sqrt{|(Cp_{o_y} - Cp_i)|}} \qquad (4.12)$$

where:

v_y = Air velocity at opening y, m/s

v_w = Wind velocity, m/s

Cp_o = External pressure coefficient at opening y

Cp_i = Internal pressure coefficient.

An initial estimate of Cp_i was used to arrive at a value for the air velocity at each ventilation opening. The ventilation rate was then solved for iteratively. The process involved adjusting the inside pressure coefficient in Equation 4.12 until the net ventilation rate summed to zero in equation:

$$V=\sum Cd_y A_y v_y \qquad (4.13)$$

where:

V = Volumetric ventilation rate, m^3/s

Cd_y = Discharge coefficient at opening y

A_y = Ventilation opening area at opening y, m^2.

An example of the calculation process to solve for the internal pressure coefficient is given in Appendix G.

4.1.6 Neutral Pressure Plane

Once the internal pressure coefficient was known, the elevation of the neutral pressure plane was solved for. Since the neutral pressure plane is dependent upon inside air density and inside air density is dependent upon inside building temperature, an iterative approach was again used. An initial estimate of inside temperature was chosen and then, using Equation 2.29, the neutral pressure plane value was adjusted until mass flow continuity was established. Once the net ventilation rate into and out of the building reached zero (with the adjustment of the neutral pressure

plane value), the building ventilation rate and inside temperature were solved.

4.1.7 Carbon Dioxide Concentration

As seen in the flow chart of Figure 3.2, the barn air quality, as it relates to carbon dioxide concentration, could be determined after the inside temperature and ventilation rate were known. The carbon dioxide concentration was based on an estimate of the ambient carbon dioxide level, building ventilation rate, and a livestock production rate of one liter of CO_2 per 24.6 kJ of total heat (as compared to latent or sensible heat) added to the environment by the animal (Albright, 1990). The equation to calculate the building concentration of carbon dioxide was:

$$V_i = V_o + V_p \tag{4.14}$$

where:

V_i = Volume of CO_2 inside, m^3/s or ppm

V_o = Volume of CO_2 outside, m^3/s

V_p = Volume of CO_2 produced, m^3/s.

V_p was determined by the equation:

$$V_p = \left(\frac{Q_T}{1000} * \frac{1}{24.6}\right) 1000 \tag{4.15}$$

where:

Q_T = Cattle total heat production, W.

V_o was determined by the equation:

$$V_o = \frac{C_{CO_2}}{1000000} * V_{air} \qquad (4.16)$$

where:

C_{co2} = Concentration of carbon dioxide, ppm

V_{air} = Volume of ventilation air, m^3/s.

4.1.8 Psychometric Calculations

With outside environmental conditions provided and building heat loss, livestock heat production, ventilation rate, and inside temperature calculated, standard psychometric conversions were used to calculate inside absolute humidity, relative humidity, and dew point temperature. Appendix C presents, in spreadsheet format, a sample problem that includes each of the psychometric calculations first as cell values and then as cell formulas.

4.1.9 Roof Inside Surface Temperature

Next, roof inside surface temperature was calculated for different wind speeds and insulation levels. Two different calculation methods were used to determine the roof lower surface temperature. One calculation method, called the "short method", used the equation:

$$T_{ls} = T_i - (R_i/R_T)(T_i - T_o) \qquad (4.17)$$

where:

T_{ls} = Roof lower surface temperature, °C

T_i = Inside air temperature, °C

R_i = Inside air film resistance, m^2K/W

R_T = Total roof resistance, m^2K/W

T_o = Outside air temperature, °C.

The second equation set, called the "long method", included exterior surface emittance and the Swinbank Model (Swinbank, 1963) for sky temperature approximation in the calculation process. The solution was comprised of six equations (Albright 1990). First, an approximation of sky temperature was calculated using the Swinbank model equation:

$$t_{sky}=0.0552\,t_{air}^{1.5} \tag{4.18}$$

where:

t_{sky} = Sky temperature, °K

t_{air} = Ambient air temperature, °K.

In a situation where there was no solar gain (at night), heat losses were calculated next. Convective heat loss was estimated by the equation:

$$q_{convective}=h\Delta t \tag{4.19}$$

where:

h = Convective heat transfer coefficient for air, W/m^2K

Δt = Roof upper surface temperature minus outside air temperature, °K.

The value chosen for h is dependent upon the wind velocity present. For example, h = 48 W/m^2K for a wind velocity of 4 m/s (9 mph) (Iqbal and Khatry, 1977).

Then conductive heat loss was calculated using the equation:

$$q_{conductive}=\Delta t/R_{r+iaf} \qquad (4.20)$$

where:

R_{r+iaf} = Resistance from the roof material and inside air film, m^2K/W.

Radiation heat loss from the barn roof to the sky can be considered a situation of a relatively small object in large surroundings. Thus, thermal radiation loss to the sky was derived next from the equation:

$$q_{radiation}=\epsilon_{us}\sigma(t_{us}^4-t_{sky}^4) \qquad (4.21)$$

where:

ϵ_{us} = Roof upper surface emissivity

σ = Stefan-Boltzmann Constant, W/m^2K^4

t_{us} = Roof upper surface temperature, °K.

Those equations were then combined to solve iteratively for the upper roof surface temperature. The rearrangement could take the form of:

$$T_{us}=h(t_{us}-t_{air,o})+(t_{us}-t_{air,i}/R_T)+\epsilon_{us}\sigma(t_{us}^4-t_{sky}^4) \qquad (4.22)$$

Finally the roof lower surface temperature was solved for using the equation:

$$t_{ls} = t_{us} + (R_r / R_{r+iaf})(t_i - t_{us}) \qquad (4.23)$$

where:

t_{ls} = Roof lower surface temperature, °K

R_r = Resistance from roof material, m^2K/W.

4.2 Model Calibration

4.2.1 Differences Between the Calibration and Validation Barns

The significant differences between the calibration barn and the validation barn were herd milk production, amount of ventilation openings, and animal density. The calibration barn herd average was 29.3 kilograms per day (64.6 pounds per day) where the validation barn had a 43.5 kilogram per day (95.9 pounds per day) production rate. The calibration barn used soffits, ridge, and one feed alley door for ventilation openings where the validation barn also had four cattle doors continuously open. Also, the validation barn had frequent adjustments to the feed alley door opening and, under warmer weather conditions, had the opposite feed alley door opened as well. The calibration barn opposite feed alley door was not routinely left open until weather warmed in the spring. Also, the validation barn had 18.5 m^3 (654.7 ft^3) of building volume per cow while the calibration barn had 25.7 m^3 (906.9 ft^3) per cow

4.2.2 External Pressure Coefficients

To determine the effect of different external pressure coefficients upon the results of the mathematical model, the original coefficient selection (discussed in Section 2.8.1) of 0.6 for the upwind soffit, -0.4 for the ridge, -0.2 for the downwind soffit, and -0.2 for the gable ends, and numerous other realistic coefficient combinations, were used to calculate calibration barn inside temperature and

relative humidity. Upon completion of the calculation process, the original selection of 0.6, -0.4, -0.2, and -0.2 was as acceptable a match to measured average data as any other combination studied. The average variation between calibration barn calculated and measured temperature was -0.1 °C and calculated vs. measured relative humidity was +4%. Only four other combinations gave calculated temperatures and/or humidities closer to measured values than the original selection. In each of the four cases either an adjustment to the ratio between sensible and latent heat had to be made or temperature and relative humidity were not both closer to measured values than those achieved by using the originally selected coefficients.

When the selection of 0.6,-0.4,-0.2,and -0.2 was used to calculate inside temperature and relative humidity for the validation barn, values comparable to measured averages were not as close as those found for the calibration barn. Inside temperature averaged 0.2 °C higher than measured averages and relative humidity averaged 7.5% lower than measured averages. Other pressure coefficient combinations didn't provide values closer to both measured temperature and relative humidity.

4.2.3 Partitioning of Sensible and Latent Heat

As discussed in Section 4.1.3, due to lack of research data in the temperature range of interest, the partitioning of latent and sensible heat was based on values compiled from several sources. Third order polynomial regression

equations of those values were then derived for calculation of sensible and latent heat. Those regression equations were accurate to the extent that calibration and validation barn measured vs. calculated temperature and relative humidity were -0.1 °C and +4%, and +0.2 °C and -7.5% respectively. Though the average measured and calculated values, particularly for the calibration barn, were quite close, the individual values were not. As can be seen in Figures 4.2 and 4.3 adjusting the percent of total heat credited to sensible and latent heat was particularly beneficial in bringing the calculated relative humidities closer to measured values. As shown in Figures 4.4 and 4.5, had only inside temperature been of primary interest, adjustments to the partitioning of latent and sensible heat would have yielded results possibly no different than could have occurred from variability within the model.

After the percent of total heat credited to calibration and validation barn sensible and latent heat was adjusted, the average difference between measured and calculated inside temperature and relative humidity was -0.3 °C and +1.1% for the calibration barn, and -0.2 °C and 0.3% for the validation barn. The calculated inside temperatures were slightly farther from measured values than those not adjusted but the relative humidity figures were much closer. Table 4.5 lists the percent of original latent heat values for both the calibration and validation barns. The percent credited or discounted from the herd latent heat load was

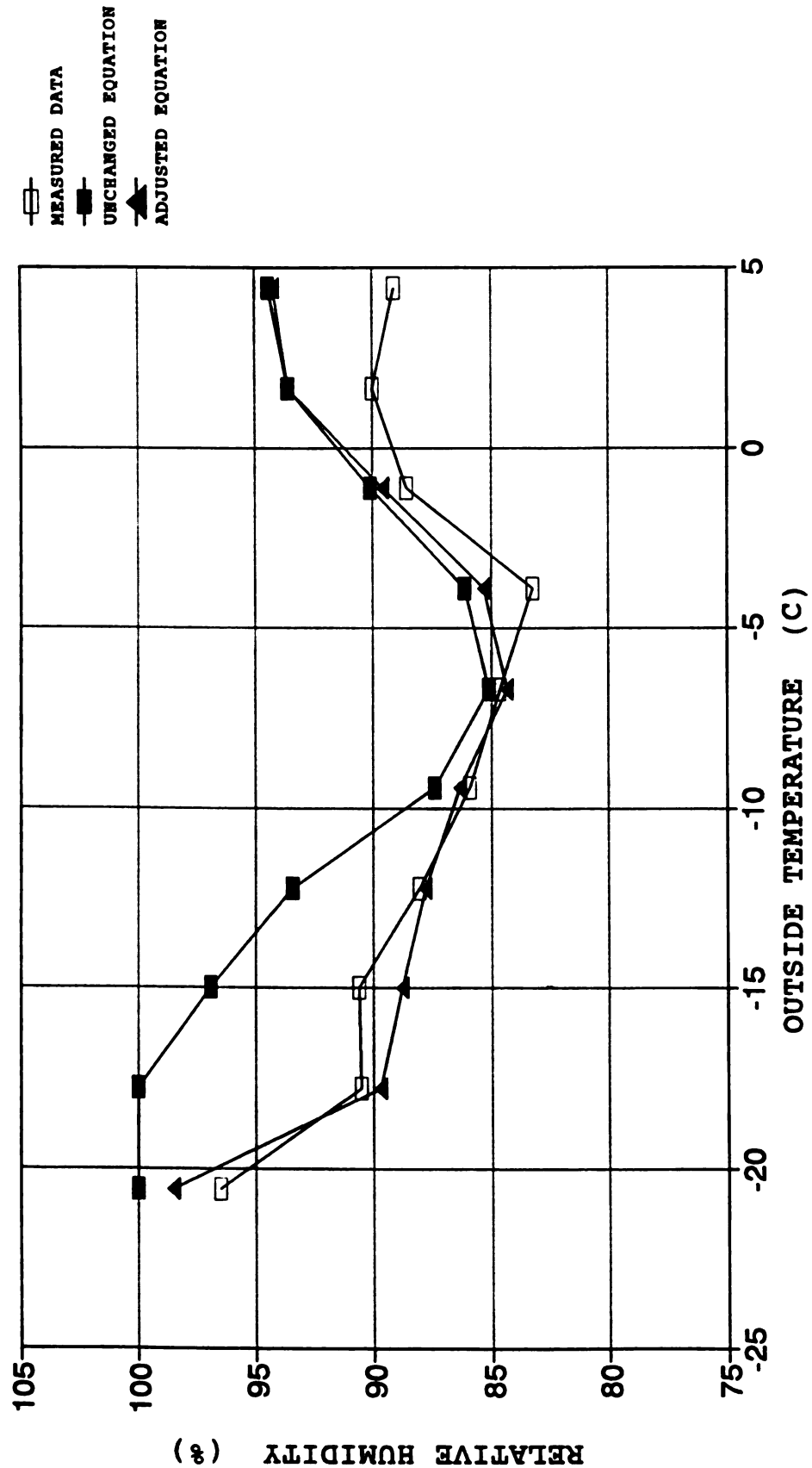


Figure 4.2 Calibration Barn Inside Relative Humidity From Measured Data, Calculated Total Heat Partitioning, and Calculated and Adjusted Total Heat Partitioning (Markers Indicate 5 °F Temperature Increments Studied.

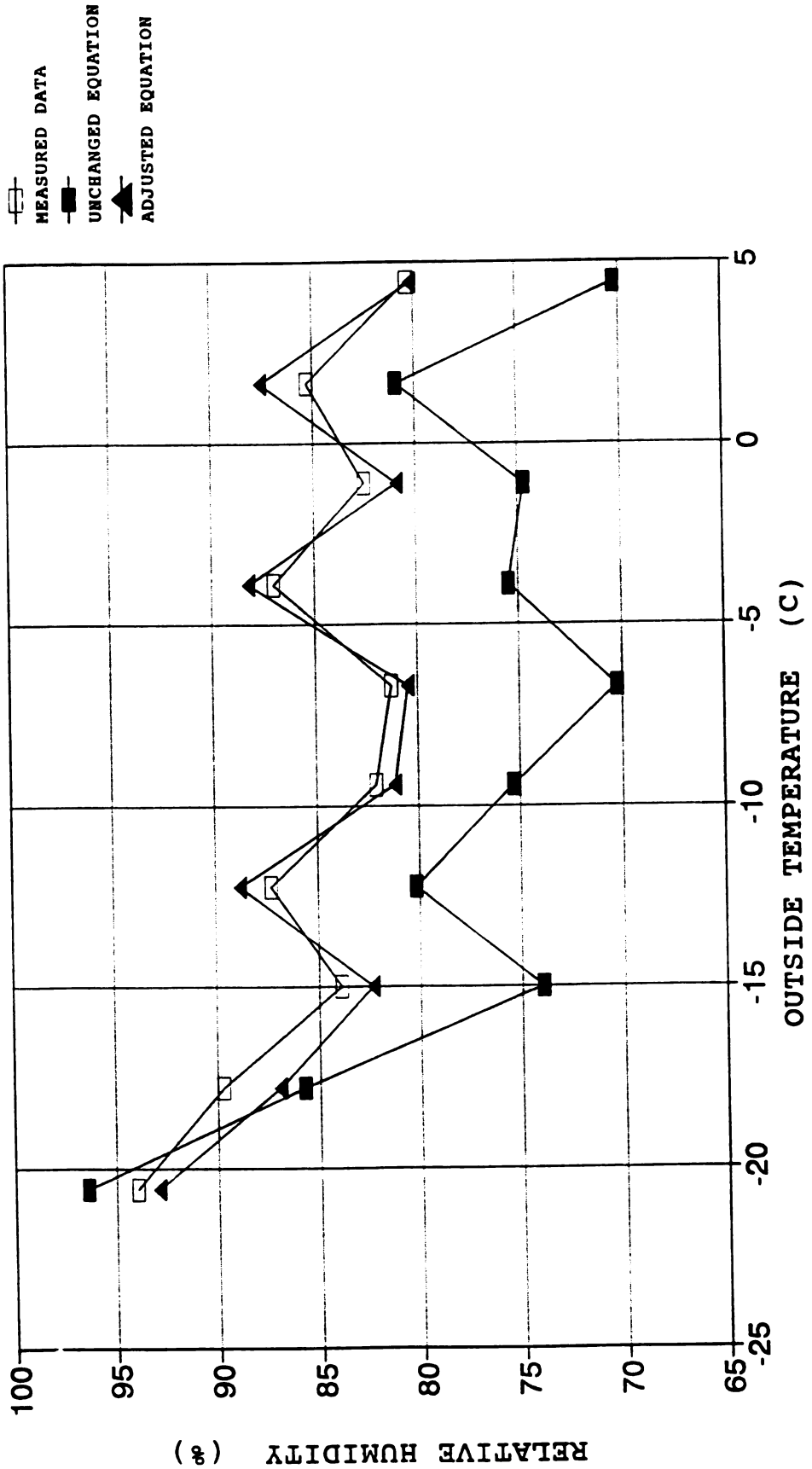


Figure 4.3 Validation Barn Inside Relative Humidity From Measured Data, Calculated Total Heat Partitioning, and Calculated and Adjusted Total Heat Partitioning (Markers Indicate 5 °F Temperature Increments Studied).

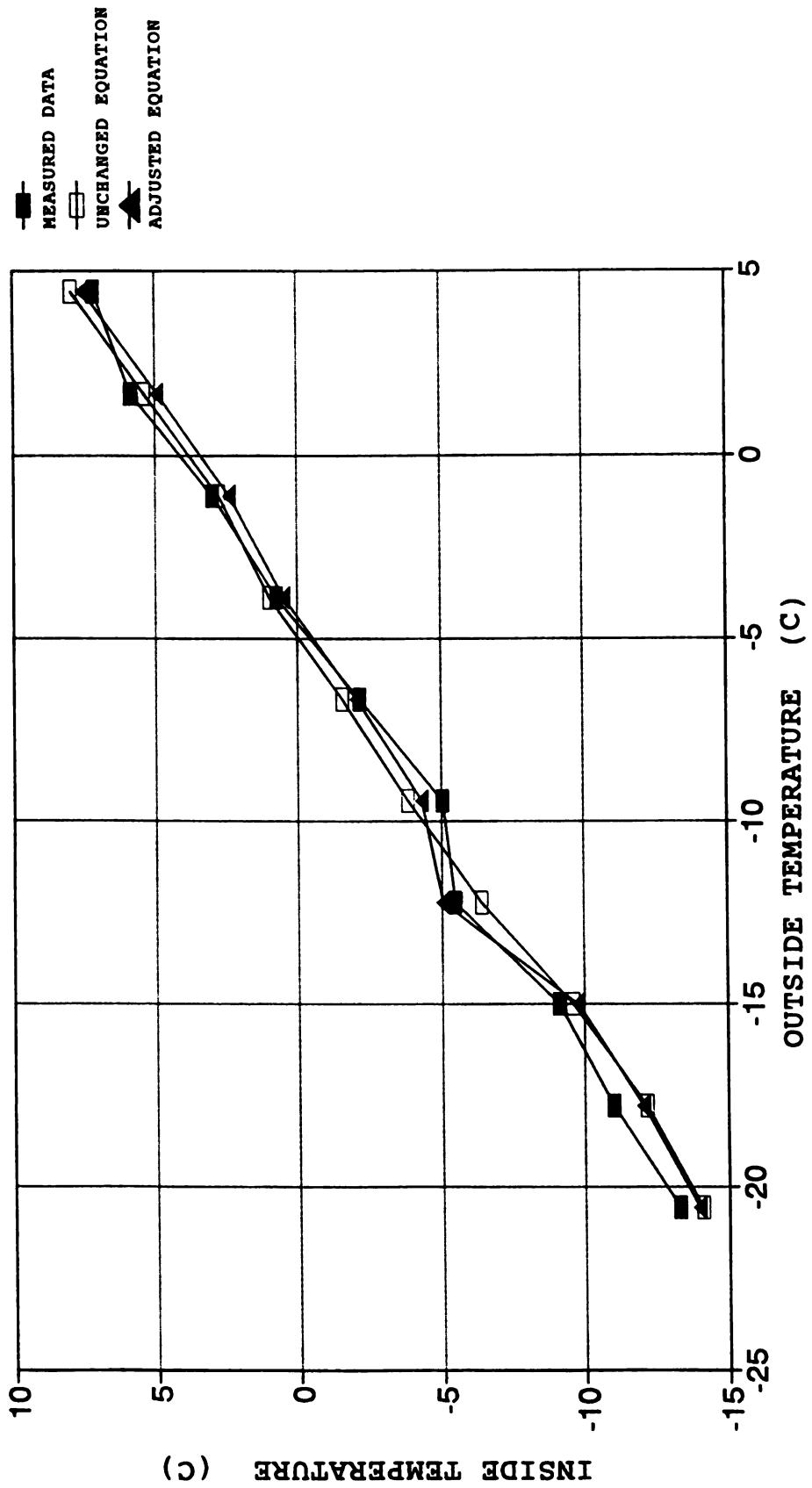


Figure 4.4 Calibration Barn Inside Temperature From Measured Data, Calculated Total Heat Partitioning, and Calculated and Adjusted Total Heat Partitioning (Marker Indicate 5 °F Temperature Increments Studied).

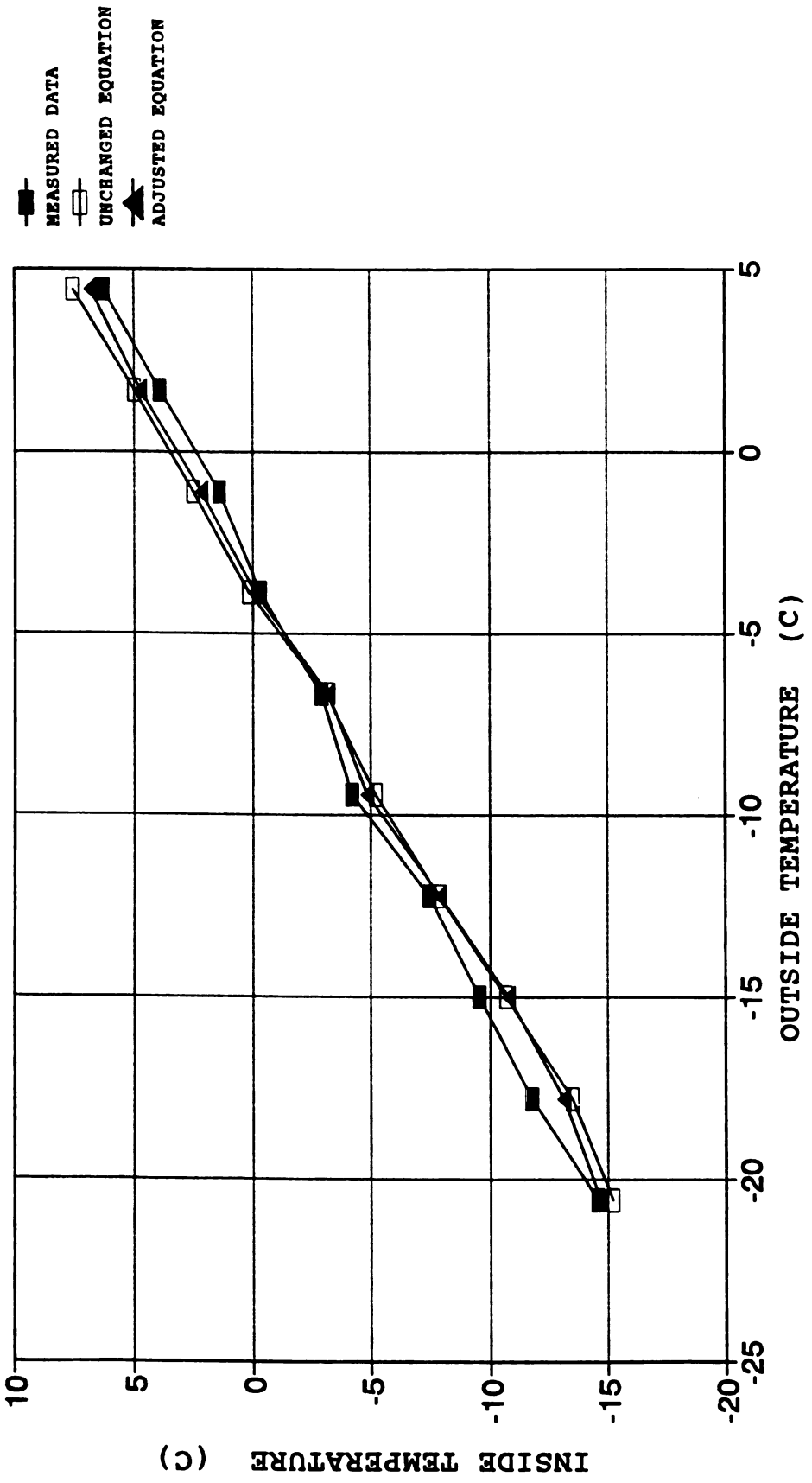


Figure 4.5 Validation Barn Inside Temperature From Measured Data, Calculated Total Heat Partitioning, and Calculated and Adjusted Total Heat Partitioning (Markers Indicate 5 °F Temperature Increments Studied).

consequently discounted or credited to the remaining sensible heat portion of the calculated livestock total heat production. The listing represents the percent adjustment necessary between latent and sensible heat to calculate a temperature and relative humidity closest to measured values, within the framework of a five percent rate of adjustment. The calibration adjustment was considered accomplished when an adjustment to latent heat caused both the calculated temperature and relative humidity values to go farther away from the measured values.

Table 4.5 Percent of Original Value in the Partitioning of Sensible and Latent Heat to Reduce Variability Between Measured and Calculated Inside Temperature and Relative Humidity for the Calibration and Validation Barns

Outside Temperature °C	°F	Calibration Barn % Latent Heat	Validation Barn % Latent Heat
-21.6	-5	85	90
-17.8	0	85	95
-15.0	5	90	105
-12.2	10	90	105
-9.4	15	95	100
-6.7	20	95	110
-3.9	25	95	110
-1.1	30	95	110
1.7	35	95	100
4.4	40	95	115

The trend in Table 4.5 would indicate that the amount of total heat credited to sensible heat, especially at colder temperatures, was somewhat undervalued. Also, the heat of milk production (the major difference between the two facilities) could to be a factor in how latent and sensible heat should be partitioned. In other words, a

greater proportion of the total heat of the higher producing herd should be credited to latent heat as outside temperatures within the range of interest warmed. Obviously, the facts that the calibration barn has approximately seventy five percent of the building volume per cow, compared to the validation barn, and that the validation barn had a more open ventilation scheme, also played a part in the ratios between latent and sensible heat.

The uniformity of change in latent heat adjustment, seen in the calibration barn but not in the validation barn data, is possibly due to variability in the field data. For example, at -9.4 °C (15 °F), a two degree difference in measured average temperature would have caused a change in the selected latent heat adjustment.

To further analyze the effects of using adjusted latent and sensible heat calculations, the validation barn inside temperature and relative humidity were calculated for sixty randomly sampled, sorted, validation barn weather data sets, using unadjusted and adjusted calculation methods. The choice of percentage adjustment to each 5 °F temperature group was based on observations from Table 4.5. That is, higher milk production caused a higher latent heat demand at warmer temperatures and the lack of uniformity in change of adjustment in the validation barn was due to field data variability. The decision as to the rate of adjustment was based on the assumption that the original error in the

polynomial regression curve would be uniform. That is to say, any adjustment should change the slope of the curve but not cause it to become sinusoidal in shape. Using those considerations, the final adjustment chosen for the validation barn calculations was somewhat comparable to the calibration barn adjustment in rate of change and to the first validation barn calibration (seen in Table 4.5) in intensity. The final percentage adjustments to the model latent heat values are listed in Table 4.6.

Table 4.6 Final Percentage Adjustment in Validation Barn Calculated Latent Heat.

Outside Temperature °C	°F	Latent Heat Adjustment %
-20.6	-5	90
-17.8	0	95
-15.0	5	105
-12.2	10	105
-9.4	15	105
-6.7	20	110
-3.9	25	110
-1.1	30	110
1.7	35	110
4.4	40	110

The results of calculating relative humidity are seen in Figures 4.6 to 4.11. They are grouped into pairs, with each pair comparing measured and calculated relative humidity for a different wind speed range. Each figure has a mark for each measured and calculated relative humidity condition, a regression line for the data marks, a line of perfect correlation between measured and calculated values, and regression statistics.

Comparing Figures 4.6 and 4.7, it is obvious that there

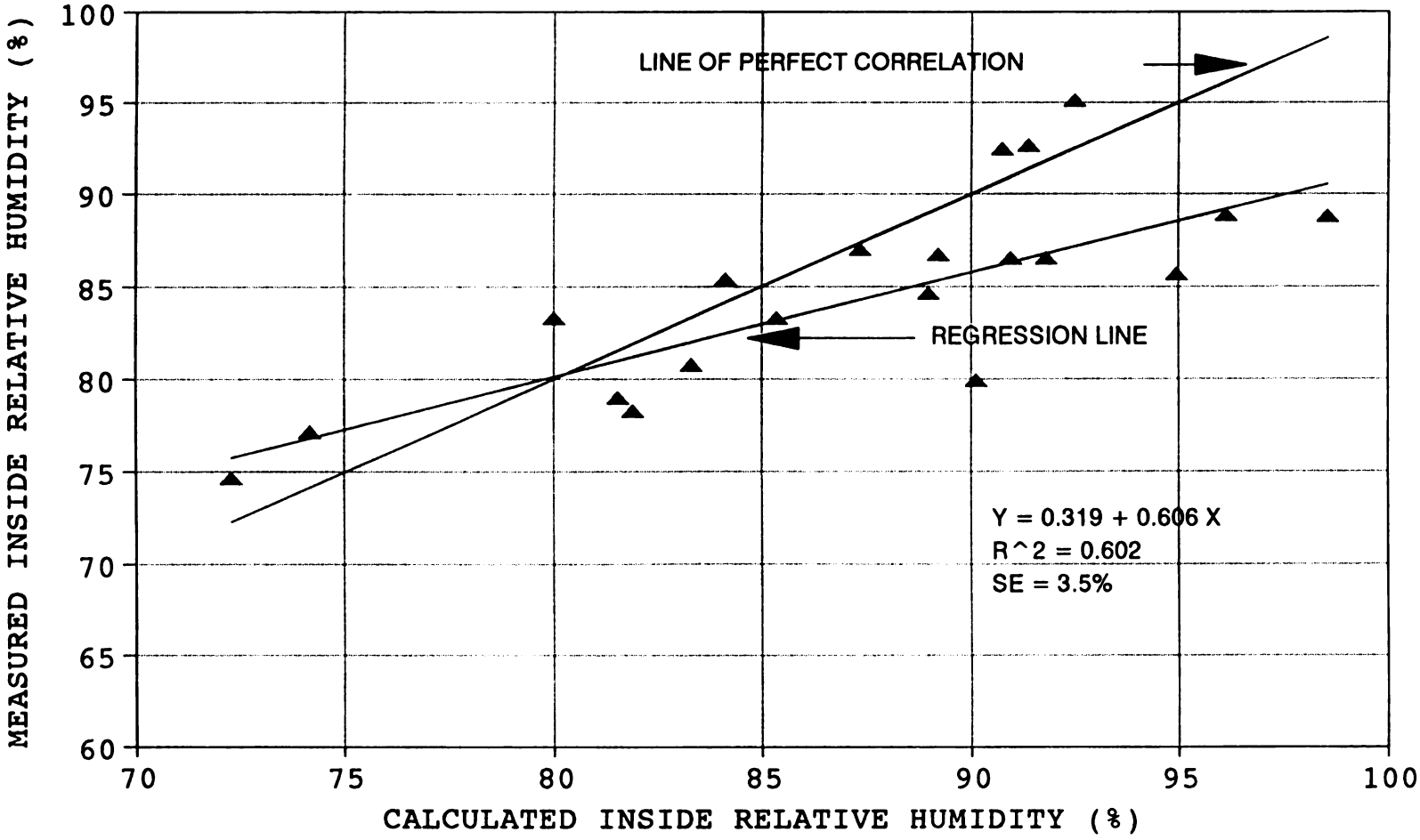


Figure 4.6 Validation Barn Relative Humidity for Wind Between 0 and 2.25 m/s (0 and 5 mph), Calculated From an Adjusted Ratio Between Latent and Sensible Heat.

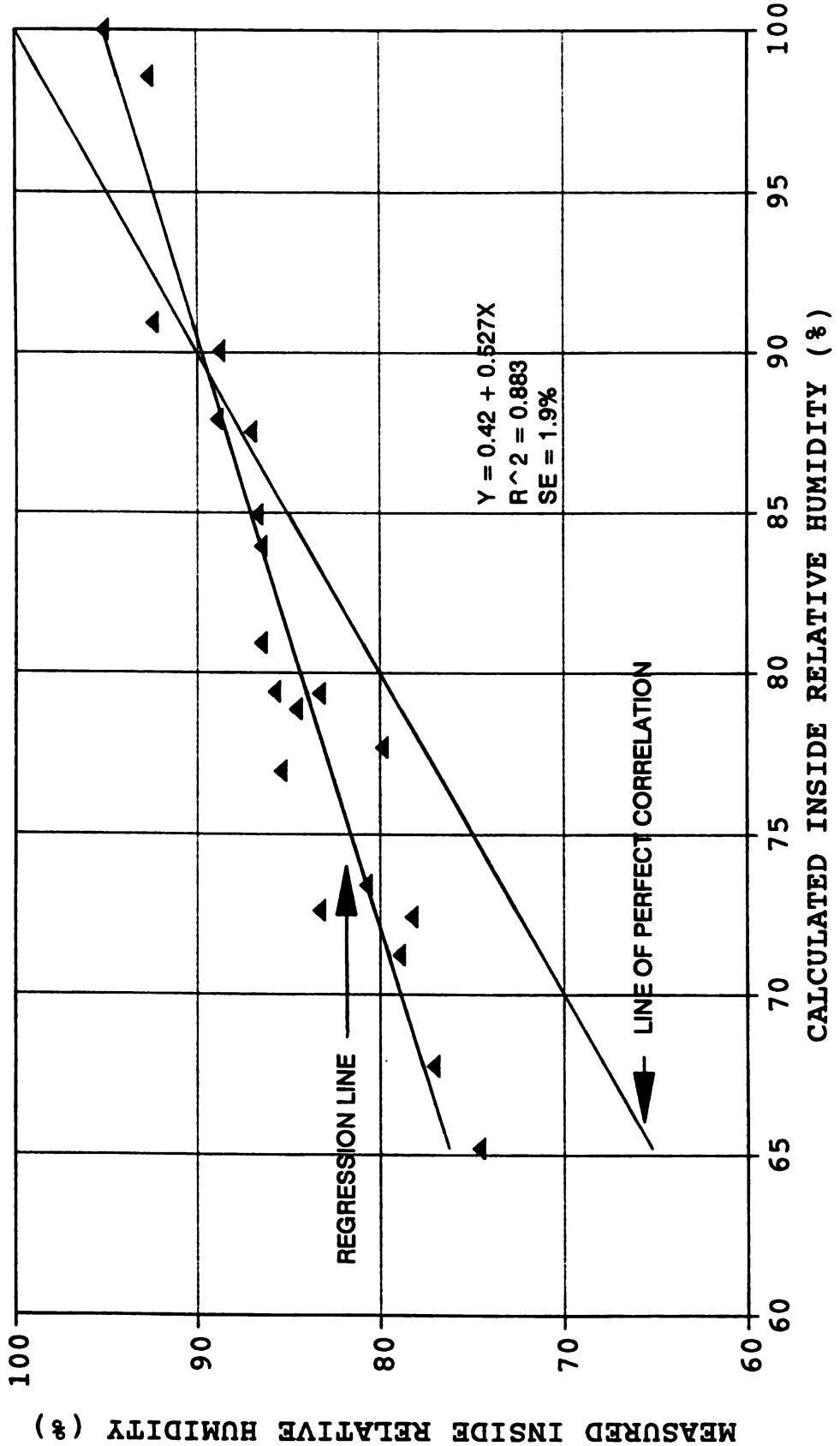


Figure 4.7 Validation Barn Relative Humidity for Winds Between 0 and 2.25 m/s (0 and 5 mph), Calculated From an Unadjusted Ratio Between Latent and Sensible Heat.

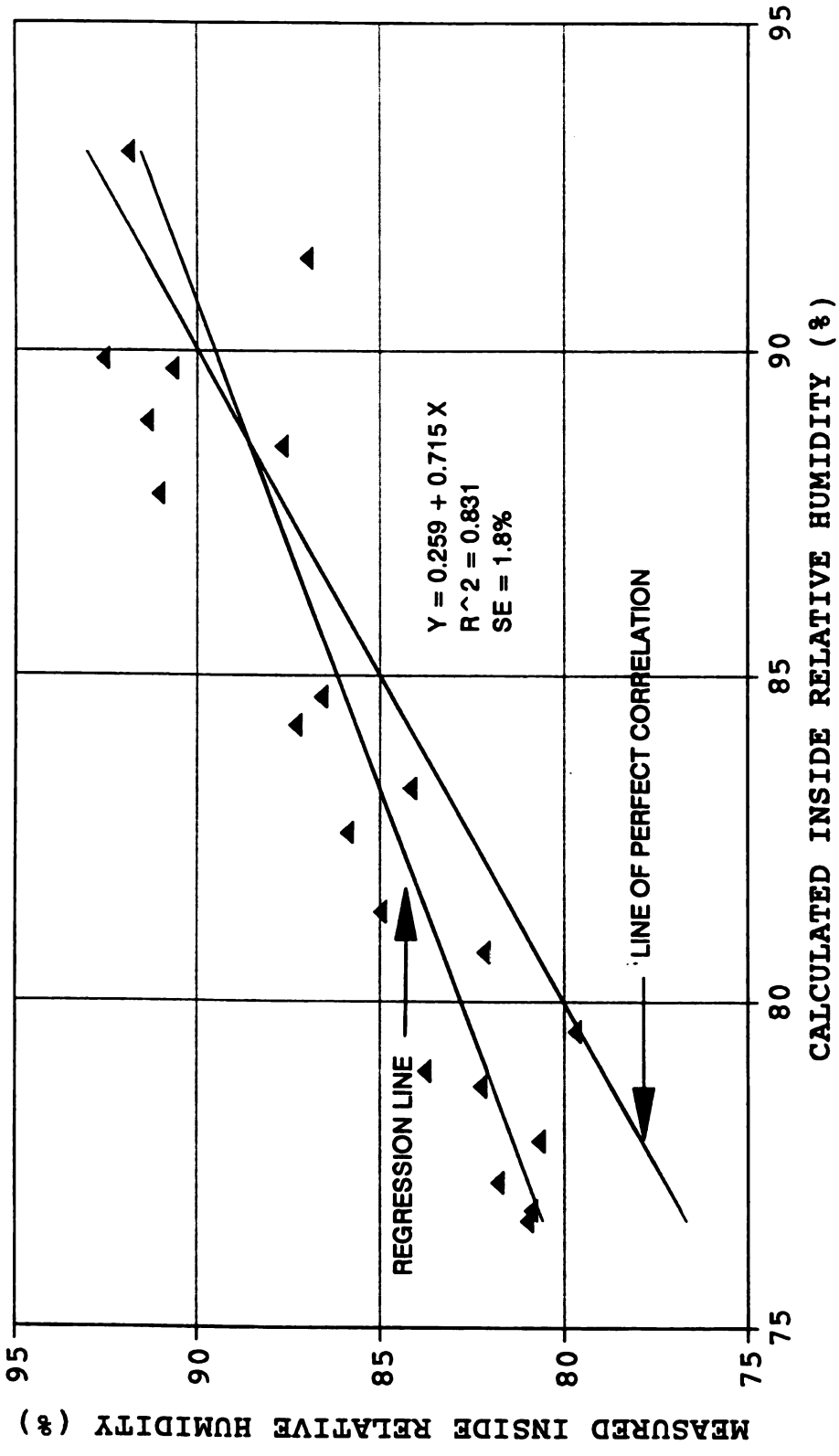


Figure 4.8 Validation Barn Relative Humidity for Winds Between 2.25 and 4.5 m/s (5 and 10 mph), Calculated From an Adjusted Ratio Between Latent and Sensible Heat.

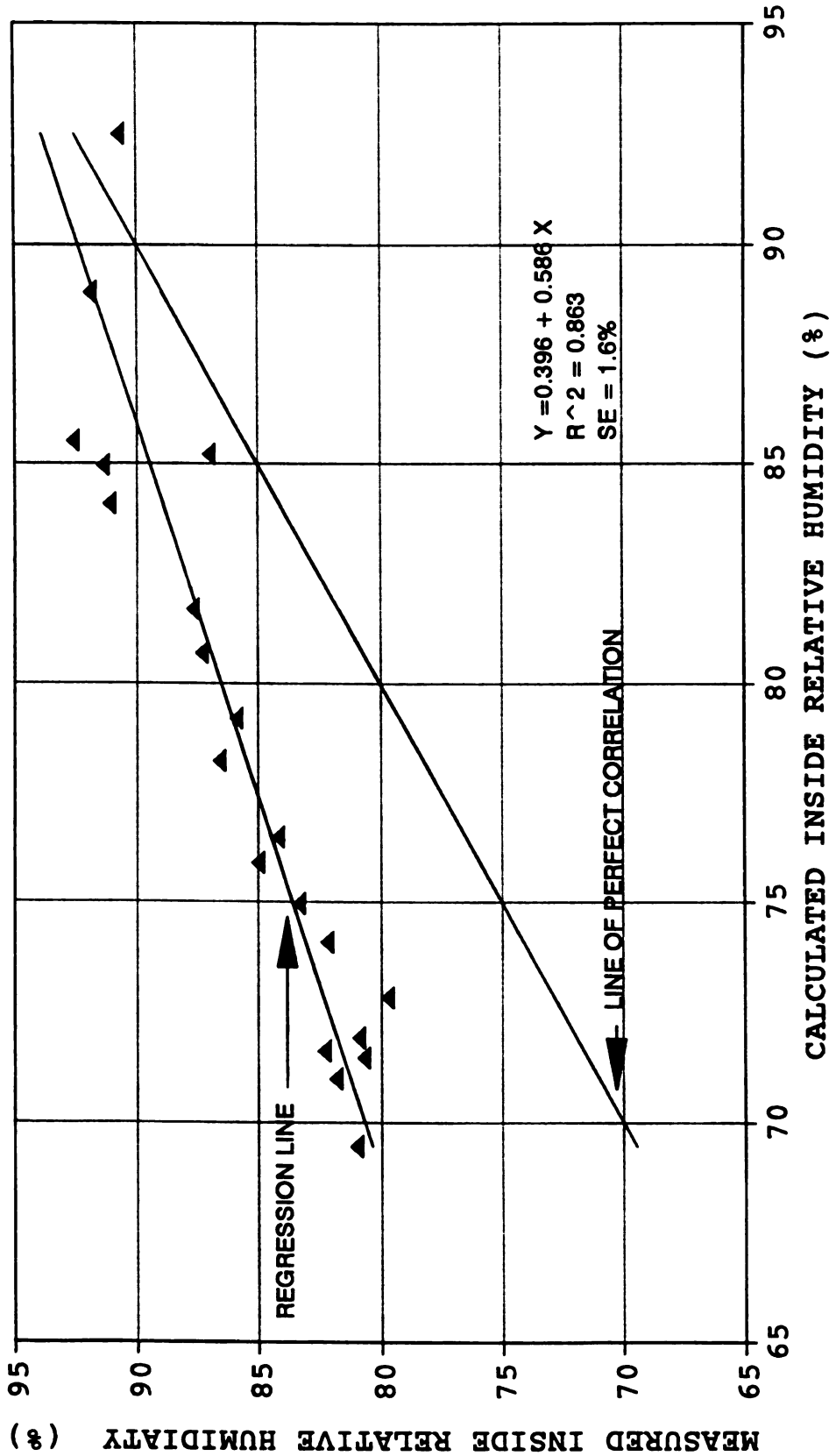


Figure 4.9 Validation Barn Relative Humidity for Winds Between 2.25 and 4.5 m/s (5 and 10 mph), Calculated From an Unadjusted Ratio Between Latent and Sensible Heat.

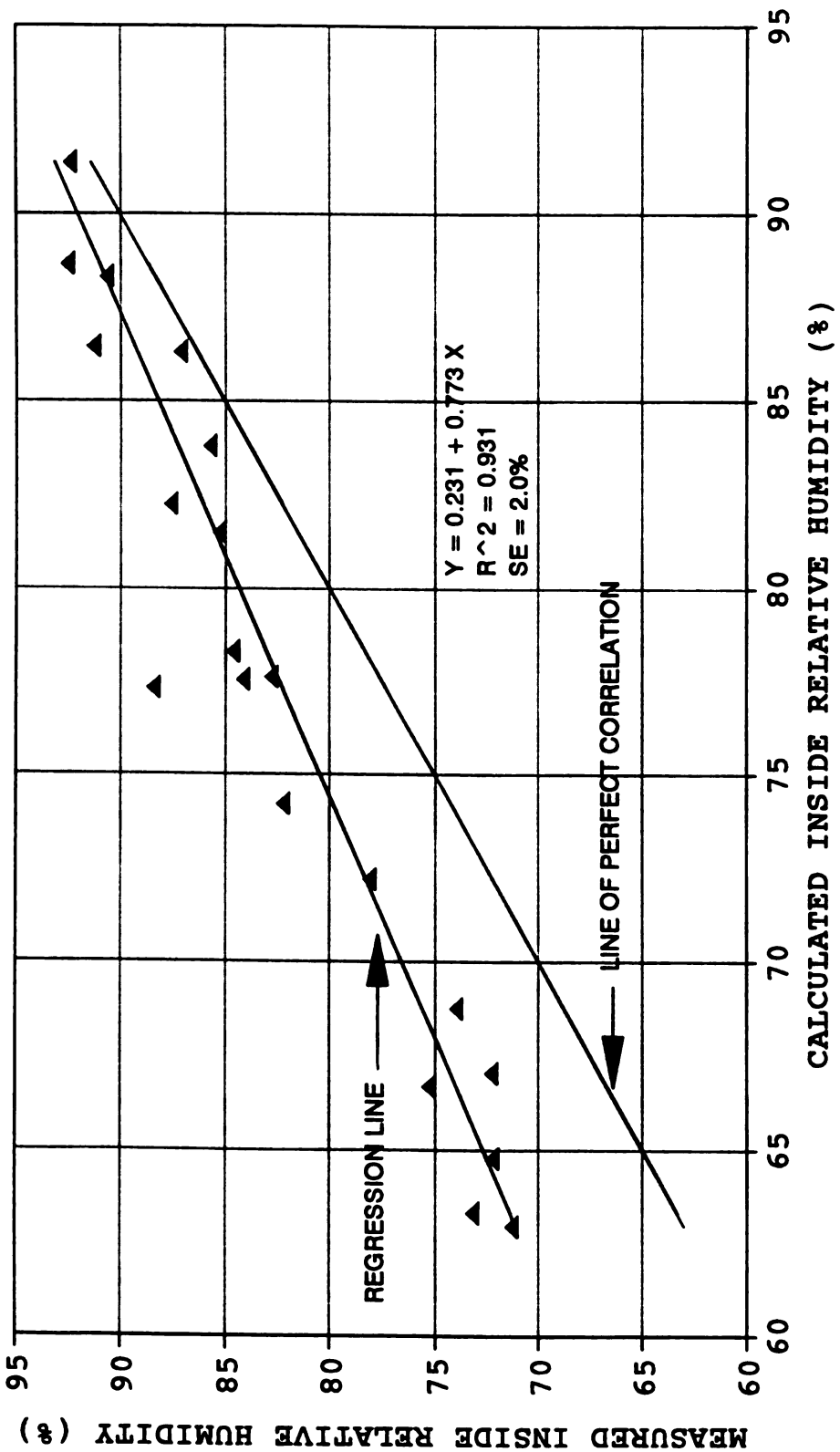


Figure 4.10 Validation Barn Relative Humidity for Winds Between 4.5 and 6.75 m/s (10 and 15 mph), Calculated From an Adjusted Ratio Between Latent and Sensible Heat.

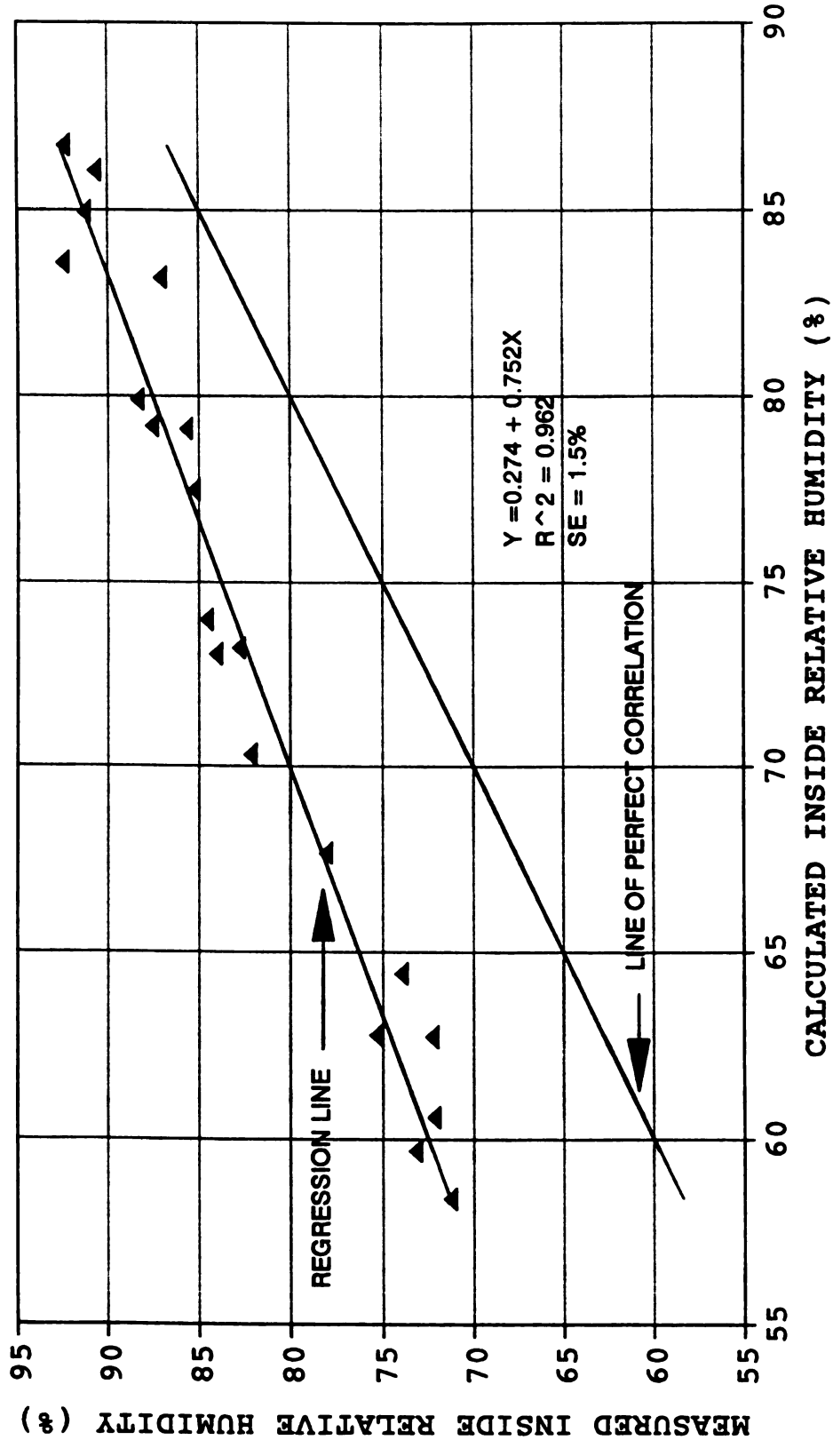


Figure 4.11 Validation Barn Relative Humidity for Winds Between 4.5 and 6.75 m/s (10 and 15 mph), Calculated From an Unadjusted Ratio Between Latent and Sensible Heat.

is more scatter in the data marks using the adjusted calculation method. The standard error is approximately 1.5 percent greater. However, in each of the three wind speed comparisons, the calculations with adjusted latent and sensible heat produced marks that more closely followed the line of perfect correlation. In other words, though the adjusted calculations showed more scatter about the regression line, they clustered closer to a line of perfect correlation than did the values calculated without adjustment. The somewhat subjective choice of adjustment percentages would be a reasonable explanation for the increased scatter in the calculated results, as that was the only change in the calculations.

Other factors of note were that the adjusted results tended to overestimate relative humidity under low wind conditions, clustered around the line of perfect correlation at moderate winds, and tended to underestimate relative humidity under higher wind conditions. The unadjusted calculations tended to underestimate relative humidity under all three wind groupings. The extent of the underestimation increased with wind speed. For example, at the 4.5 to 6.75 m/s (10 to 15 mph) wind speed, the approximate difference between the regression line and the line of perfect correlation was between seven and twelve percent relative humidity. The adjusted calculations however yielded approximately a two to nine percent difference.

In summary, the adjusted calculations had more scatter,

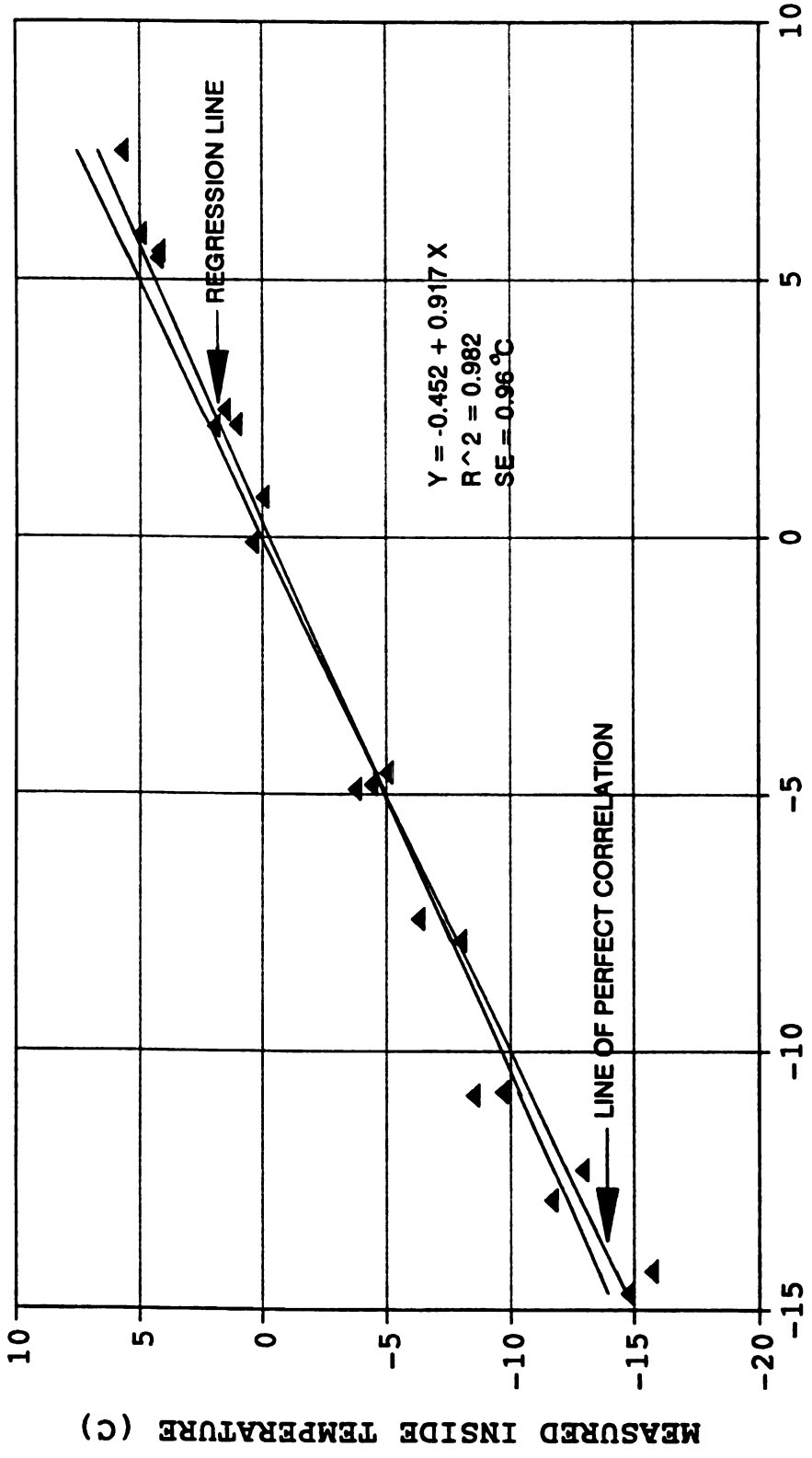


Figure 4.12 Validation Barn Temperature for Winds Between 0 and 2.25 m/s (0 and 5 mph), Calculated From an Adjusted Ratio Between Latent and Sensible Heat.

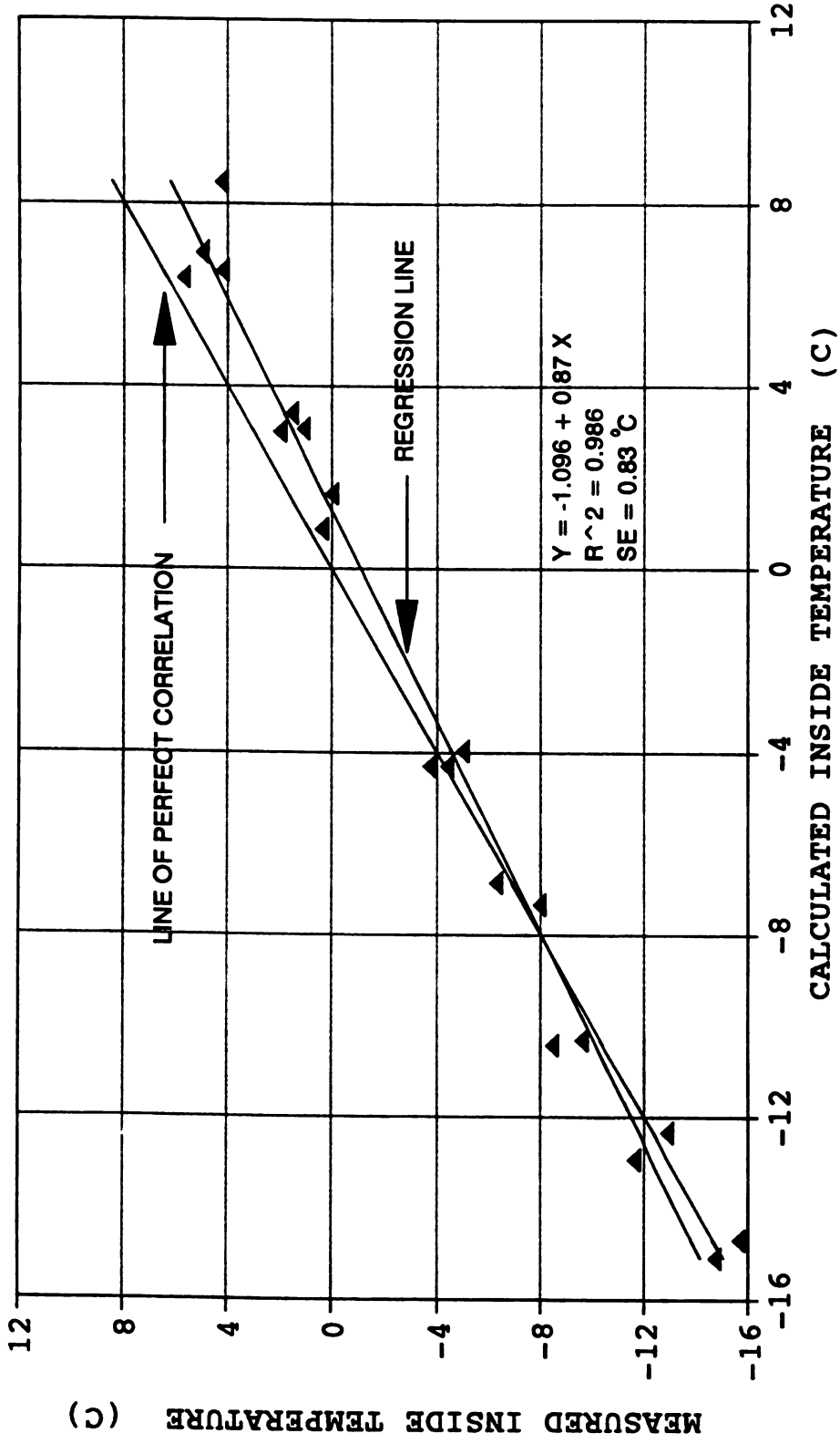


Figure 4.13 Validation Barn Temperature for Winds Between 0 and 2.25 m/s (0 and 5 mph), Calculated From an Unadjusted Ratio Between Latent and Sensible Heat.

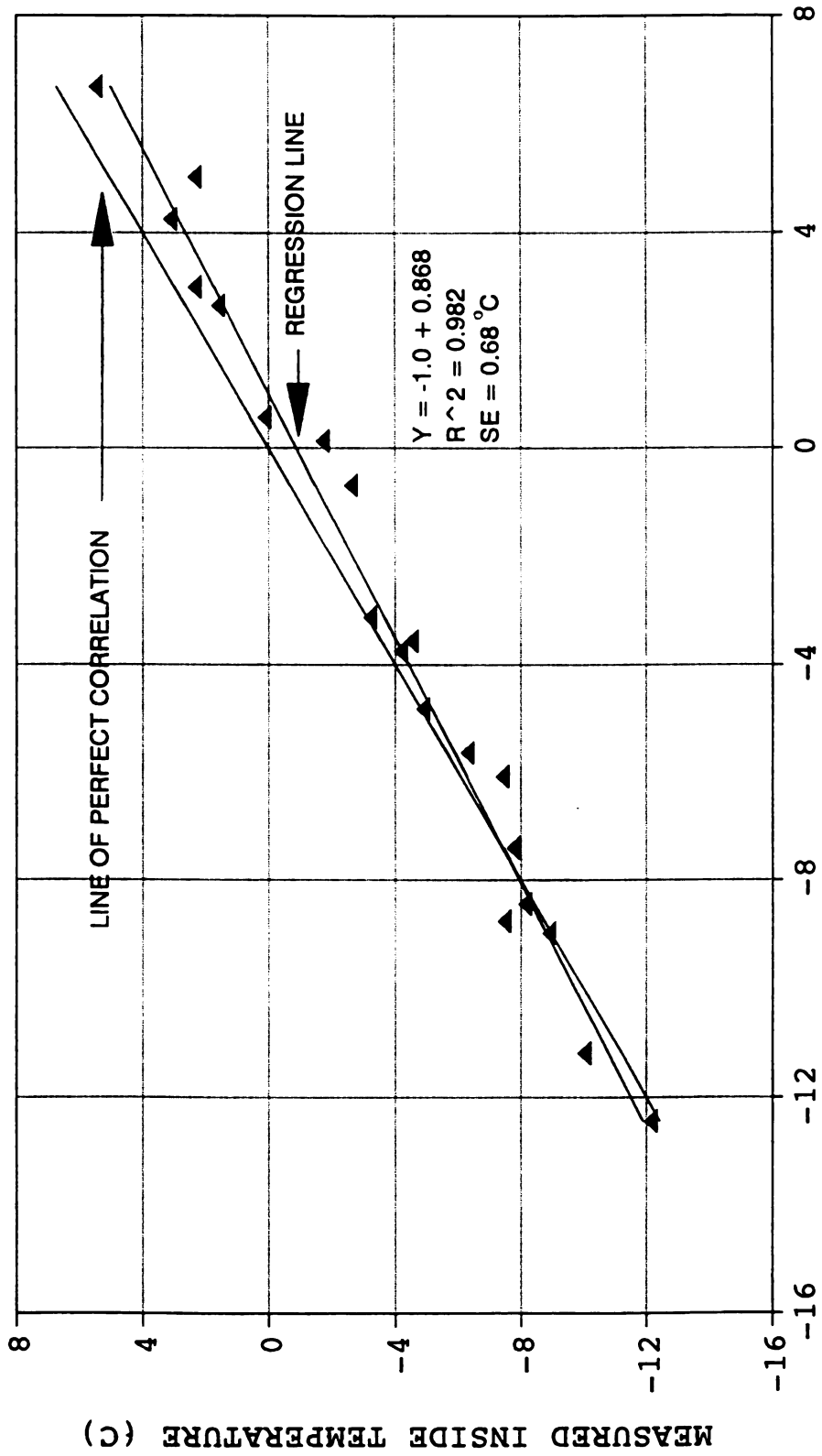


Figure 4.14 Validation Barn Temperature for Winds Between 2.25 and 4.5 m/s (5 and 10 mph), Calculated From an Adjusted Ratio Between Latent and Sensible Heat.

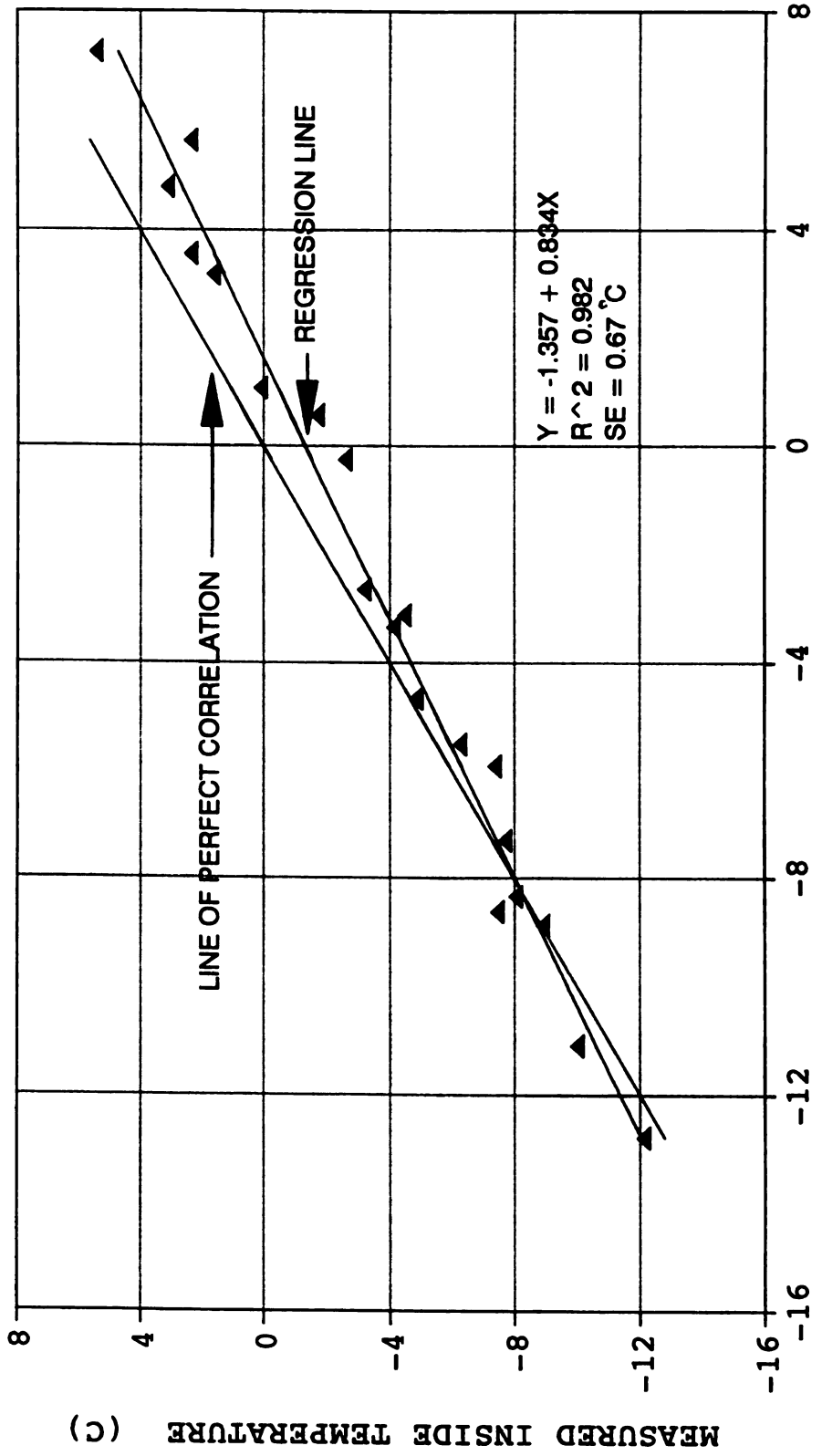


Figure 4.15 Validation Barn Temperature for Winds Between 2.25 and 4.5 m/s (5 and 10 mph), Calculated From an Unadjusted Ratio Between Latent and Sensible Heat.

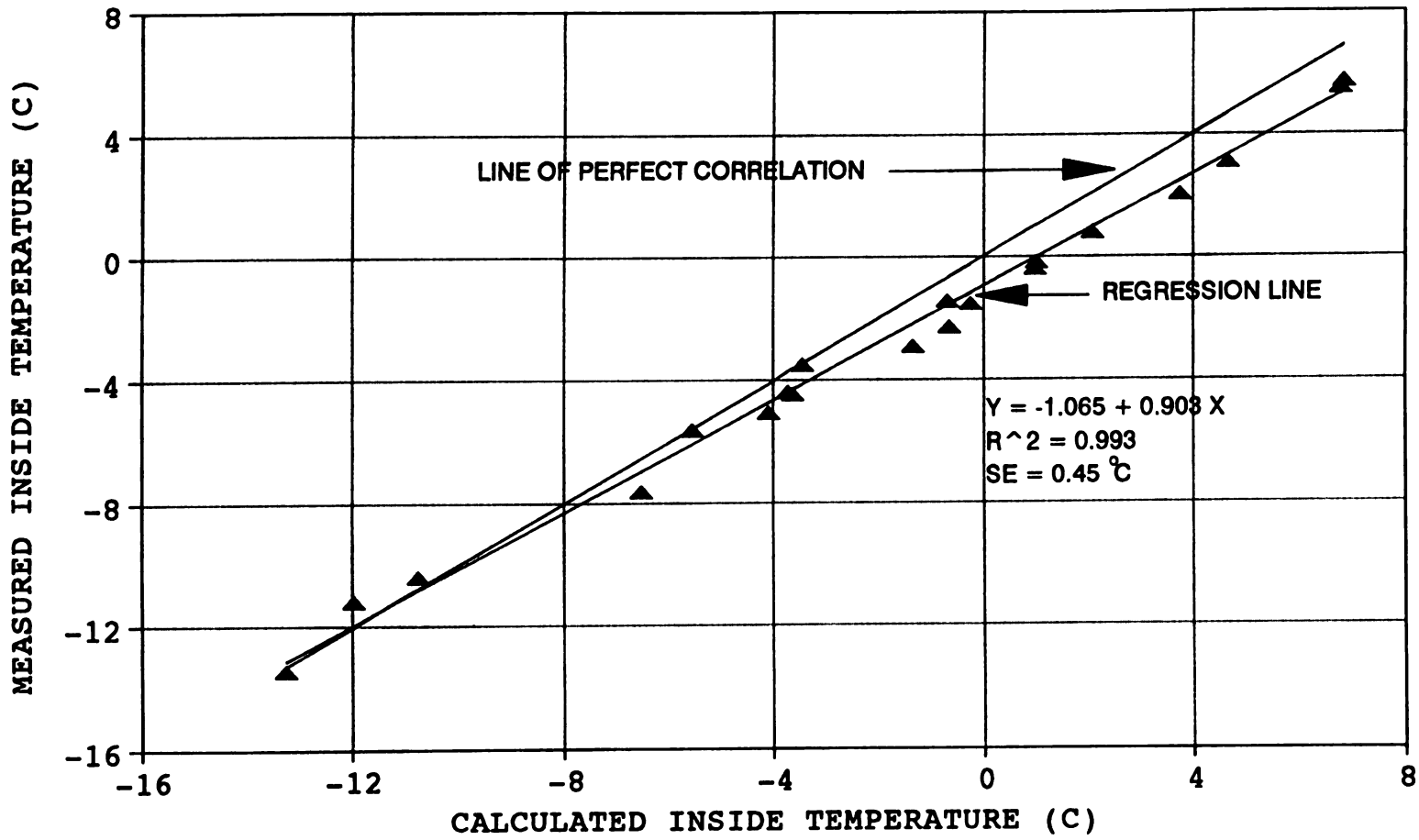


Figure 4.16 Validation Barn Temperature for Winds Between 4.5 and 6.75 m/s (10 and 15 mph), Calculated From an Adjusted Ratio Between Latent and Sensible Heat.

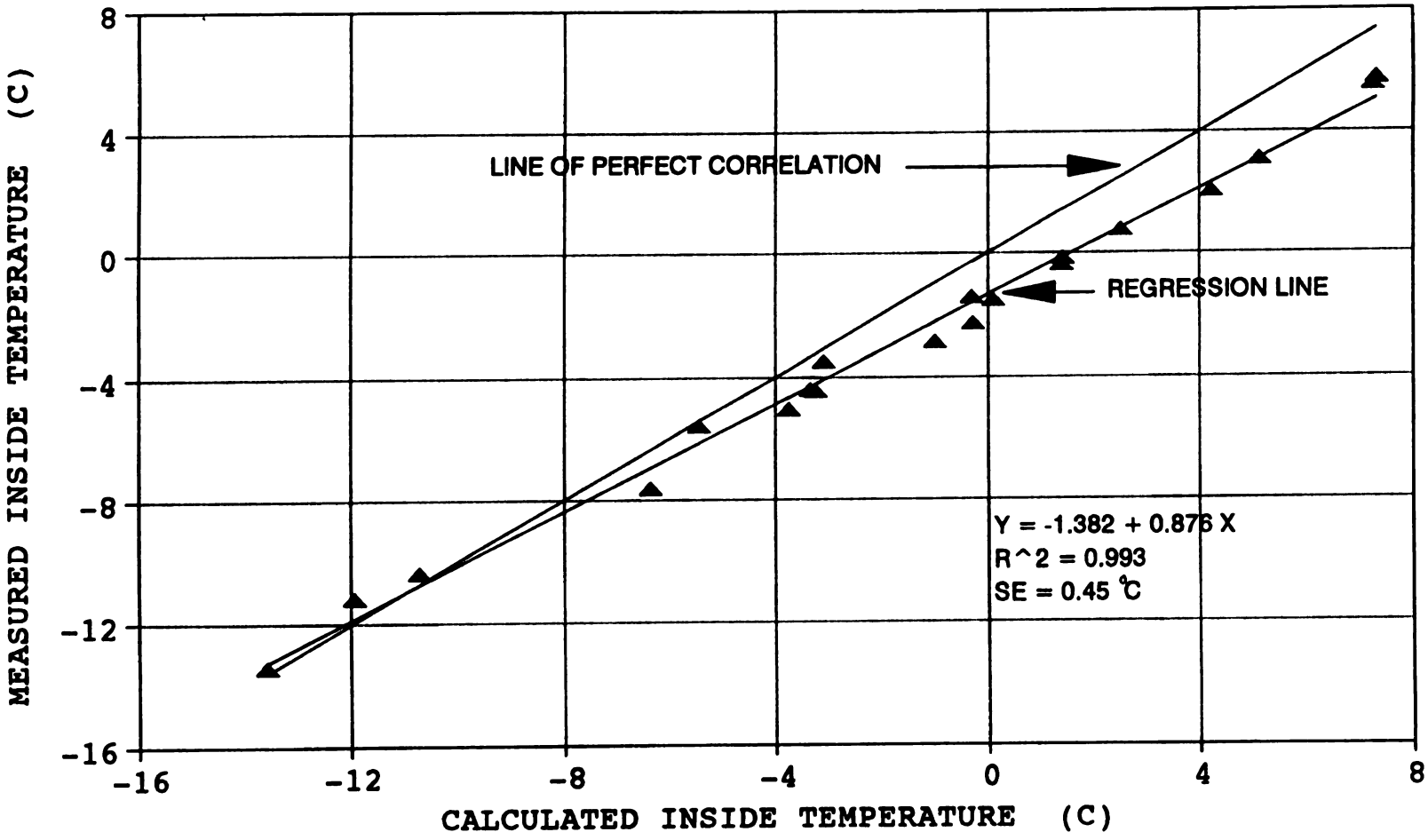


Figure 4.17 Validation Barn Temperature for Winds Between 4.5 and 6.75 m/s (10 and 15 mph), Calculated From an Unadjusted Ratio Between Latent and Sensible Heat.

as evidenced by the higher standard errors, but tended to cluster closer to the line of perfect correlation. The unadjusted calculations had less scatter, and therefore lower standard errors, but tended to underestimate measured relative humidity and be farther removed from the line of perfect correlation. On average the adjusted calculations should yield values closer to measured values than unadjusted calculations would.

As seen in Figures 4.12 to 4.17, results of similar calculations performed to determine building temperature showed less variability than did relative humidity calculations. There were measurable but relatively insignificant differences between the standard errors of the adjusted and unadjusted calculations. Also, like the relative humidity calculations, at higher winds the unadjusted temperature calculations yielded data points farther from the line of perfect correlation than did adjusted values.

4.3 Model Sensitivity Analysis

4.3.1 Weather Data

An area that directly impacts a models equation results is the input data. Due to the nature of this modeling research, the weather conditions used as inputs to the model equations have a dramatic impact upon the simulation process results. Section 3.1 describes the process used to arrive at the input weather data for the validation and calibration barns. Upon completion of the input weather data sorting from the six different barn sites in Michigan it was found that only the winter of 1989-90 had any outside temperatures below -17.8 °C (0 °F) that met both the wind direction and five degree Fahrenheit incrementing conditions. Consequently, that season's data were used for validation and calibration purposes i.e., as the outside weather data values. Table 4.7 lists the outside temperature, wind speed, and relative humidity as well as the average inside temperature, wind speed, and relative humidity that occurred at each of the 5 °F outside temperatures being researched. Also,the number of data sets remaining within each 5 °F group after all the sorting criteria had been met is listed under the "n" column. Due to the lack of long periods of colder weather during the winters studied there were only four hours that remained in the -20 °C to -17.7 °C groups after the sorting process was completed.

Table 4.7 Validation Barn Mean Outside and Inside Temperature, Wind Speed, and Relative Humidity at 2.8 °C (5 °F) Increments for the Months of December, January, and February 1989-90.

Temperature			Wind Speed		Relative Humidity		n
Outside		Inside			Outside	Inside	
°C	°F	°C	m/s	mph	%	%	
-20.6	-5	-14.6	0.9	2.0	89	94	4
-17.7	0	-11.8	2.9	6.4	82	90	4
-15.0	5	-9.6	2.9	6.5	71	84	9
-12.2	10	-7.4	2.5	5.5	85	87	8
-9.4	15	-4.3	2.1	4.7	81	82	13
-6.7	20	-3.1	3.9	8.6	76	81	14
-3.9	25	-0.3	2.7	5.9	86	87	25
-1.1	30	1.6	3.6	8.1	76	83	36
1.7	35	3.9	3.8	8.5	83	85	25
4.4	40	5.7	4.9	10.8	73	80	17

n = weather data remaining (hours) that met sorting criteria

For simulation purposes, only a representative value for outside relative humidity and wind speed was needed at a given outside temperature. Consequently, all three years winter data from six different geographic locations were used in the sorting process (see Section 3.2).

Table 4.8 Average Outside Wind Speed and Relative Humidity From Six Monitored Freestall Dairy Barns in the Lower Peninsula of Michigan for the Months of December, January, and February, During the Years of 1989-90, 1990-91, and 1991-92.

Outside Temp (C)		Wind Speed (m/s)	Relative Humidity (%)
-20.6	(-5°F)	2.0 (4.5 mph)	90
-17.8	(0°F)	2.4 (5.4 mph)	88
-15.0	(5°F)	2.6 (5.7 mph)	84
-12.2	(10°F)	3.0 (6.7 mph)	84
-9.4	(15°F)	3.5 (7.7 mph)	82
-6.7	(20°F)	3.5 (7.8 mph)	81
-3.9	(25°F)	3.4 (7.5 mph)	84
-1.1	(30°F)	3.5 (7.7 mph)	87
1.7	(35°F)	3.3 (7.4 mph)	88
4.4	(40°F)	3.7 (8.2 mph)	84

4.3.2 Rate of Milk Production

One area of comparison for sensitivity analysis was to observe the effect of variations in milk production on inside environmental parameters (see Table 4.9). The calculations for this comparison were first made on a barn with 25 mm of roof insulation, open soffits, open ridge, one open feed alley door, and four open cattle alley doors (343% of fully open soffit ventilation rate). The herd was comprised of 160 cows averaging 610 kg each. The outside temperature was 4.4 °C (40 °F) and the wind speed was 1.4 m/s (3.1 mph). The lowest herd average milk production rate of 18 kg/day (40 lbs/day, 12,200 lbs/305 days) was 42 percent of the highest milk herd average production rate of 43.5 kg/day (96 lbs/day, 29,280 lbs/305 days). This milk production difference resulted in a lowest to highest sensible heat production difference of 1:1.76. At 32.8 kg/day herd average (72.3 lbs/day, 22,050 lbs/305 days), the sensible heat production ratio (compared to 43.5 kg/day) was 1:1.18

Table 4.9 Sensible Heat Production and Inside Environment Conditions as Affected by Milk Production in a Barn With an Insulated Roof. (ac/h= air changes per hour)

Input Data		Calculated Output			
Milk Prod. kg/day	Sensible Heat Watts	Inside Temp. °C	ac/h	R.H. %	CO^2 Conc. ppm
18.0	90,015	7.4	10.3	87	785
32.8	134,480	8.4	11.5	82	737
43.5	158,450	8.9	12.1	79	720

A large change in sensible heat production (a 76% increase) between the highest and lowest milk production rates resulted in a relatively small change in building temperature (1.5 °C). Similar results were seen with changes in carbon dioxide concentration (65 ppm). Of note however were the changes in relative humidity and air exchange. The building temperature increase of 1.5 °C was enough to cause stack effect ventilation to increase the air exchange by 1.8 exchanges per hour and reduce the relative humidity by 8%. This air exchange increase would improve the air quality; and the reduction in relative humidity would reduce the potential for condensation related problems.

Table 4.10 shows an identical comparison for a barn with an uninsulated roof. It can be seen that, although the inside temperatures were lower than the insulated barn (0.4 °C), the <u>difference</u> between inside temperatures was unchanged. The colder building also caused the cattle sensible heat production to be slightly higher. The colder barn also had reduced stack effect ventilation and, consequently, the air exchanges were slightly lower and the relative humidities and carbon dioxide concentrations were slightly higher than the barn with an insulated roof. The <u>differences</u> between values for each of the other environmental parameters also stayed essentially the same as those for the insulated barn.

It could be concluded that variation in milk production and its effect upon inside environmental conditions was not

altered to any significant degree by the barn roof insulation level (at the ambient temperature and wind speed used for this comparison). In other words, the change in building temperature due to insulation levels did not significantly change the difference between a highest and lowest environmental value, only the magnitude of that value. The variable that did have a measurable impact on the barn environment was the difference in cattle heat production due to milk production, i.e., for the insulated barn, a 1.5 °C increase in building temperature, an increase in air exchange of 1.8 times, and an 8% drop in building relative humidity.

Table 4.10 Sensible Heat Production and Inside Environmental Conditions as Affected by Milk Production in an Uninsulated Barn. (ac/h= air changes per hour)

Input		Output			
Milk Prod. kg/day	Sensible Heat Watts	Inside Temp. °C	ac/h	R.H. %	CO^2 Conc. ppm
18.0	91,630	7.0	9.9	89	800
32.8	136,885	8.0	11.1	85	754
43.5	161,075	8.5	11.6	82	735

A question that could also be asked would be whether the same changes in magnitude occurred at lower temperatures. To test this, a comparison between the 32.8 kg and 43.5 kg milk production rates was done at -17.8 °C (0 °F), 88% outside relative humidity, and a 2.4 m/s (5.4 mph) wind speed. As seen in Table 4.11, the changes in magnitude were very comparable for inside temperature but somewhat less repetition was seen for several of the other variables.

For example, for the uninsulated barn at 4.4 °C, the air exchange difference between 32.8 kg/day and 43.5 kg/day milk production was 0.5 ac/h, the relative humidity difference was 3%, and the carbon dioxide concentration difference was 19 ppm. For the same milk production difference at -17.8 °C and an uninsulated barn, the air exchange difference was 0.2 ac/h, the relative humidity difference was 1%, and the carbon dioxide concentration difference was 33 ppm. The insulated barn at -17.8 °C compared more closely to differences at 4.4 °C.

Table 4.11 Difference Between Calculated Environmental Values for Milk Production Rates of 32.8 kg/day and 43.5 kg/day at -17.8 °C. (ac/h= air changes per hour)

Model Barn	Inside Temp. °C	ac/h	R.H. %	CO^2 Conc. ppm
Insulated	0.5 °C	0.5	2.1	10
uninsulated	0.6 °C	0.2	1.0	33

In summary, large variations in milk production produced large changes in sensible heat production and relatively small changes in inside temperature. Changes in other parameters such as air exchange, carbon dioxide concentration, and relative humidity did occur but were not large. Roof condensation and air quality could potentially show a noticeable improvement with small changes in those variables.

4.3.3 Outside Relative Humidity Level

The outside relative humidity was an input parameter to the barn inside environment equations. The calibration and

validation barn outside relative humidity value used at any five degree Fahrenheit calculation increment was based on the hourly averaged humidity for the months of December, January, and February during 1989 to 1990 for the respective building. The simulation barn used a three year average for the same months from six monitored barns (see Sec. 4.3.1).

A comparison was made at -17.8 °C (0 °F) and 4.4 °C (40 °F) for a very closed uninsulated barn (10% of fully open soffit ventilation area available) and an open uninsulated barn (343% of fully open soffit ventilation area available). Wind speed was 3.1 m/s (6.9 mph). For the closed barn at -17.8 °C, the outside relative humidity had to fall below 30% before any change in inside relative humidity or dew point temperature occurred. The building was so underventilated that only very dry outside air would hold enough moisture to be an influencing factor. At 4.4 °C however, an outside relative humidity of 60% or less did have an impact upon the inside relative humidity and dew point temperature. From 60% down to 20% outside relative humidity, the inside relative humidity dropped 30% and the dew point temperature dropped 3.8 °C.

At the 343% ventilation rate, the choice of outside relative humidity also directly impacted the inside relative humidity and dew point temperature. When the outside temperature was 4.4 °C, for each 10% drop in outside relative humidity, there was approximately an 8% drop in inside relative humidity and about a 1.5 °C drop in dew point temperature. At -17.8 °C similar changes occurred.

The inside relative humidity dropped approximately 7% and the dew point declined an average of 1.1 °C for each 10% reduction in outside relative humidity.

Consequently, the relative humidity value chosen as an input to the calculations would have a definite impact on the calculated results of dew point temperature and anticipated roof frost/condensation conditions. Only a very closed barn operating under colder temperatures in the -17.8 °C range would not show changes resulting from adjustments in outside relative humidity.

4.3.4 Wind Speed

Wind speed begins to have a dominant effect upon natural ventilation between 1 m/s and 3 m/s (2.2 mph and 6.7 mph) (Bruce, 1988, Jardineer, 1980). The amount of impact is affected by the ventilation area open to the wind. Table 4.12 lists the results of a 10% and 343% ventilation rate. All environmental changes in both of the ventilation areas listed were the result of modifying only wind speed.

Table 4.12 Barn Environment as Affected by Wind Speed at 10% and 343% Ventilation Openings. (Uninsulated Barn at 80% Relative Humidity and -17.8 °C Outside Temperature)

Ventilation Openings Equal 10% of Full Soffit Area						
Wind Speed m/s	T_i Roof °C	T_i °C	AC/H	R.H. %	D.P.T. °C	CO^2 Conc ppm
1	-13.2	-8.6	3.3	100	-8.6	1718
2	-13.5	-9.2	3.8	100	-9.1	1521
3	-15.5	-9.9	4.6	100	-9.8	1326
4	-16.2	-10.6	5.5	100	-10.5	1168
5	-16.4	-11.2	6.5	100	-11.1	1043
6	-16.5	-11.8	7.5	100	-11.7	948
7	-16.6	-12.3	8.6	100	-12.2	874

Table 4.12 Continued:

Ventilation Openings Equal 343% of Full Soffit Area

Wind Speed m/s	T_i Roof °C	T_i °C	AC/H	R.H. %	D.P.T. °C	CO^2 Conc ppm
1	-15.6	-13.3	11.7	93	-14.0	733
2	-15.8	-13.8	13.4	91	-14.7	682
3	-16.7	-14.2	15.3	89	-15.3	640
4	-16.8	-14.5	17.4	88	-15.8	605
5	-17.1	-14.8	19.5	87	-16.2	576
6	-17.2	-15.1	21.7	86	-16.6	553
7	-17.2	-15.3	24.0	85	-16.9	534

T_i= Inside Temperature, AC/H= Air Changes Per Hour,
D.P.T.= Dew Point Temperature

At the 10% ventilation rate a 7 m/s wind caused only 8.6 air exchanges in an hour, while at the 343% ventilation rate, a 1 m/s wind caused 11.7 air changes per hour. This was an increase of 3.1 air exchanges per hour with approximately 14% of the wind speed. Also, as the wind speed increased in the 10% vented barn, the air exchange almost tripled and the carbon dioxide level was more than cut in half. This showed that increases in wind velocity had dramatic effects on improving the environmental quality in a closed barn.

Since the ventilation rate was greater and air quality better in the open barn, the effect of increased wind speed was less dramatic. Table 4.12 shows that, for a 7 m\s wind speed increase, the building air exchange was somewhat greater than double and the carbon dioxide levels were reduced to near normal ambient quantities.

As a whole the model was very sensitive to wind speed. Small wind speed changes produced noticeable differences in the barn environment.

4.3.5 Building Heat Loss

As will be discussed in Section 4.5.2, reducing heat loss (through the addition of roof insulation) did produce noticeable changes in the barn environment. For each ventilation opening area studied, applying roof insulation reduced building heat loss, increased inside air temperature and air exchange, reduced relative humidity and carbon dioxide concentration, and raised the roof temperature. Also, reducing heat loss by increasing insulation thickness beyond the initial 12.7 mm (0.5 in) thickness studied showed few significant changes in the barn environment. At 10% ventilation openings and -20.6 °C (-5 °F), increasing from no insulation to 25.4 mm (1.0 in) of R(SI) = 1.27 (R = 7.3) insulation caused the inside temperature to rise 3.4 °C while at 343% ventilation and 4.4 °C (40 °F), similar insulation changes caused a 0.4 °C increase in building temperature. The insulated barn heat loss was approximately a third of the uninsulated value. Appendix E lists the heat loss data.

It can be seen that it took a large numerical reduction in heat loss to produce a small increase in building temperature. For example, to achieve the 3.2 °C temperature rise previously mentioned, it required the building heat loss to drop from 11,636 W/K to 3976 W/K. This would roughly equate to a 1000 W/K heat loss reduction for each degree Celsius temperature rise in the structure.

It should also be repeated that, as described in Section 4.3.2, a temperature increase of 1.5 °C allowed the

relative humidity to drop 8% and the air exchange to increase by 1.8 air changes per hour. Consequently, although changes in building temperature may have been relatively small when heat loss reductions were relatively large, the effect of those small temperature increases on air exchange and building moisture content could cause a noticeable improvement in building air quality.

4.3.6 Discharge Coefficients

To determine the effect of the choice of 0.65 as the discharge coefficient for all ventilation openings in this research (discussed in Section 2.9), a sensitivity analysis was done on a barn with 11.2 m^2 (120.5 ft^2) of soffit and 15.3 m^2 (164.6 ft^2) of ridge opening at -17.8 °C (0 °F). The results, written in Table 4.13, indicate that combined thermal buoyancy and wind ventilation calculations of inside temperature could be in error by approximately 0.3 °C (0.5 °F), if a discharge coefficient of 0.65 was used, and in fact, 0.7 or 0.6 was the correct discharge coefficient.

Table 4.13 Comparison of Discharge Coefficients on Inside Temperature at -17.8 °C (0 °F) Ambient Temperature and a 4.5 m/s (10 mph) Wind Speed.

C_d		Stack Vent.		Wind Vent.	Combined Vent.		
Peak	Eaves	T_i	m^3/s	m^3/s	T_i	R.H.	DPT
0.7	0.65	-10.2	11.6	23.9	-13.1	84.0	-14.9
0.7	0.7	-10.3	12.1	25.1	-13.3	83.7	-15.1
0.65	**0.65**	-10.1	11.4	23.3	**-13.0**	84.3	-14.8
0.6	0.6	-9.8	10.7	21.5	-12.7	85.0	-14.4

C_d = Discharge coefficient T_i = Inside temperature, °C
R.H. = Relative humidity, % DPT = Dew point temperature, °C

4.4 Model Validation and Validity

4.4.1 Model Validation

4.4.1.1 Validation Barn Building Temperature

A numerical comparison between calculated and measured validation barn inside temperature at each of the 2.8 °C (5 °F) temperature groups was done. The mean outside relative humidity, wind speed, and temperature from each temperature group was used as input data for the calculations. The calculations included the adjusted ratio between latent and sensible heat discussed in Section 4.2.3.

Figure 4.18 shows that the inside temperature values were in good agreement at -6.7 °C (20 °F) while calculated values deviated a maximum of approximately one degree Celsius below field measurements at colder temperatures and one degree Celsius above field measurements at warmer temperatures.

In addition to errors in equation variables, a factor that most likely affected the relationship between calculated and measured inside temperature was the actual building ventilation rate. As mentioned in Section 4.2.3, because this barn was so closely monitored, (with three milkings per day, employees were frequently going through or past this barn) doors and curtains had probably been left increasingly closed or open as ambient temperatures declined or rose. The trend of undercalculating inside temperature during colder weather and overcalculating building temperature during warmer weather would tend to support this

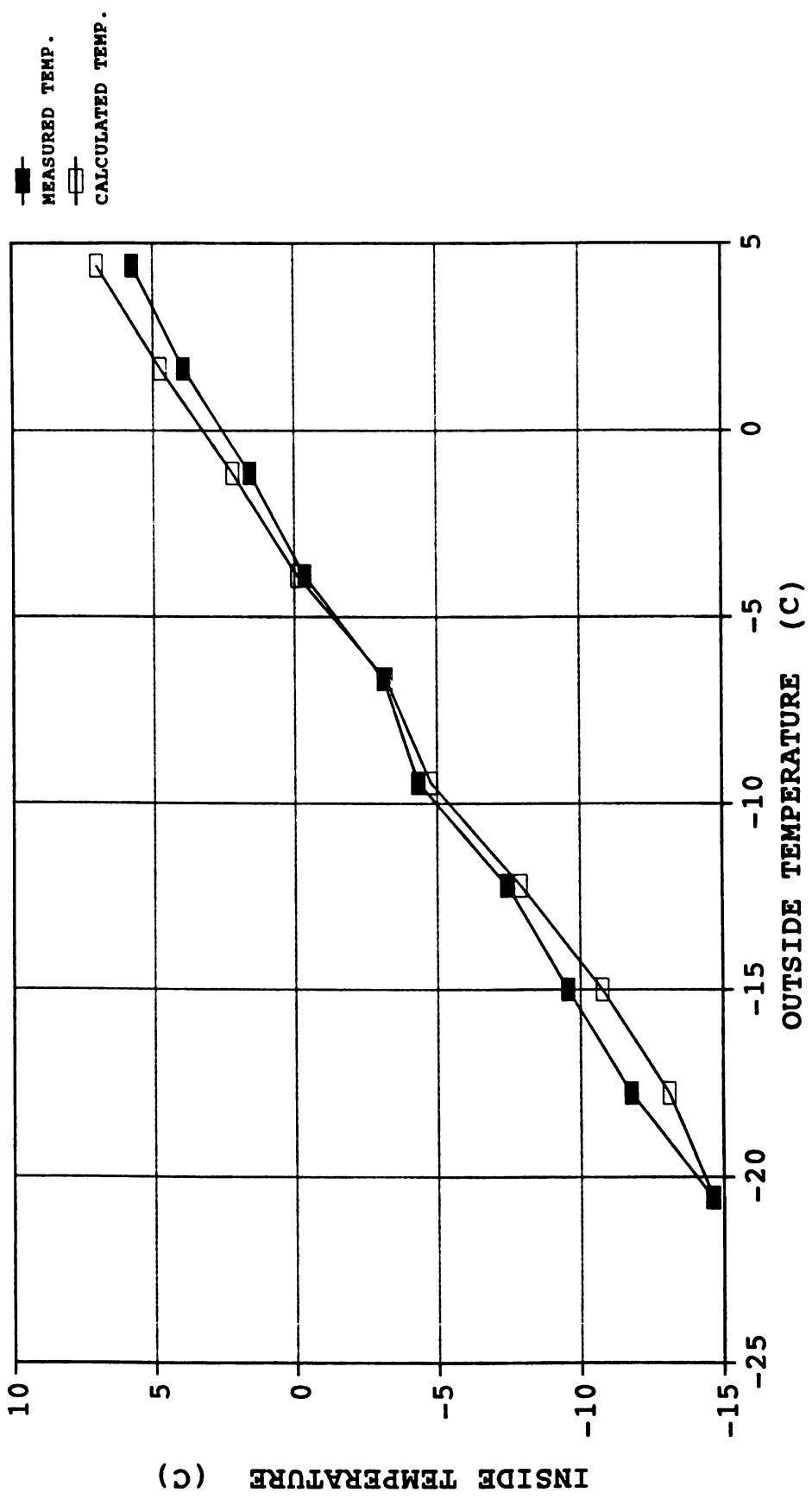


Figure 4.18 Measured and Calculated Inside Barn Temperature -- Uninsulated Validation Barn (markers at 5 °F (2.8 °C) increments from -5 to 40 °F (-20.8 to 4.4 °C)).

assumption. The calculations assume a constant ventilation opening area. However, as no daily log was kept of ventilation opening modification during winter, this is not a verifiable assumption.

Other factors possibly contributing to variability were the reliability of the field data and/or the "n" or sample size of the sorted data averaged. Beyond the possibility of calibration errors, the thermocouple temperature measurements could only be considered accurate to within one degree Celsius of the actual value (Campbell Scientific, 1989). Also, the multiple sortings of a very large weather data set produced sample sizes quite small in several temperature groups, i.e. n = 4 at -20.6 °C and n = 4 at -17.8 °C.

In this model, temperature is a relatively stable value. It takes large changes in other variables to produce a significant change in building temperature. As a whole, there is very good agreement between measured and calculated inside building temperatures.

4.4.1.2 Validation Barn Relative Humidity

A numerical comparison similar to the temperature comparison was done for relative humidity. The resulting calculated and measured validation barn relative humidity values can be seen in Figure 4.19. Unlike Figure 4.18, there was no discernible pattern in the difference between measured and calculated values. On average, the calculated relative humidities were 0.3 percent below measured relative

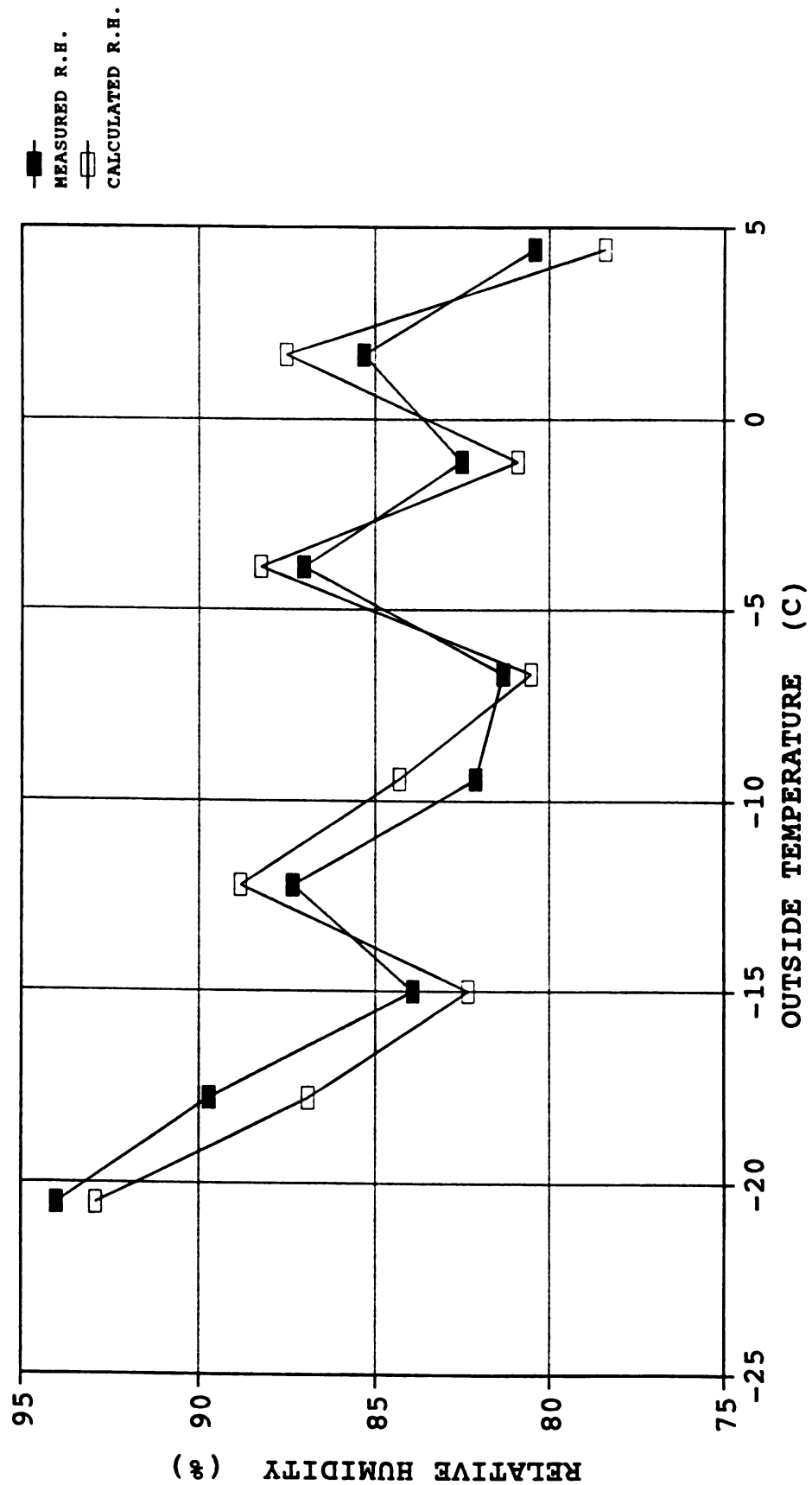


Figure 4.19 Measured vs. Calculated Relative Humidity -- Uninsulated Validation Barn (markers at 5 °F (2.8 °C) increments from -5 to 40 °F (-20.6 to 4.4 °C).

humidities. The extremes ranged from approximately two percent above measured relative humidity to three percent below measured values. Considering that the maximum error on the humidity sensor is ± 4%, there is good agreement between the measured and calculated values.

4.4.1.3 Carbon Dioxide Concentration Validation

Figure 4.20 shows the results of a comparison between nine measured carbon dioxide readings and a calculation of each carbon dioxide level. There was close agreement between measured and calculated values for six of the nine samples. Because of the number of draw tubes available at the time of the gas analysis, it was not possible to redo the obviously inconsistently low CO_2 concentrations during two time periods. It is this author's contention that the tubes were defective or that the vacuum pump was malfunctioning so that an incomplete gas sample was drawn into the reagent during those two periods.

Of the six close comparisons, the calculated CO_2 levels averaged 64 ppm below measured values. For all readings the CO_2 levels averaged 29 ppm above measured values. For comparisons of desirable and undesirable carbon dioxide levels, the calculations are adequate.

4.4.1.4 Validation Barn Roof Temperature

To evaluate the accuracy of the resistance coefficient method of determining lower roof surface temperature, three sets of barn roof data were collected on the validation

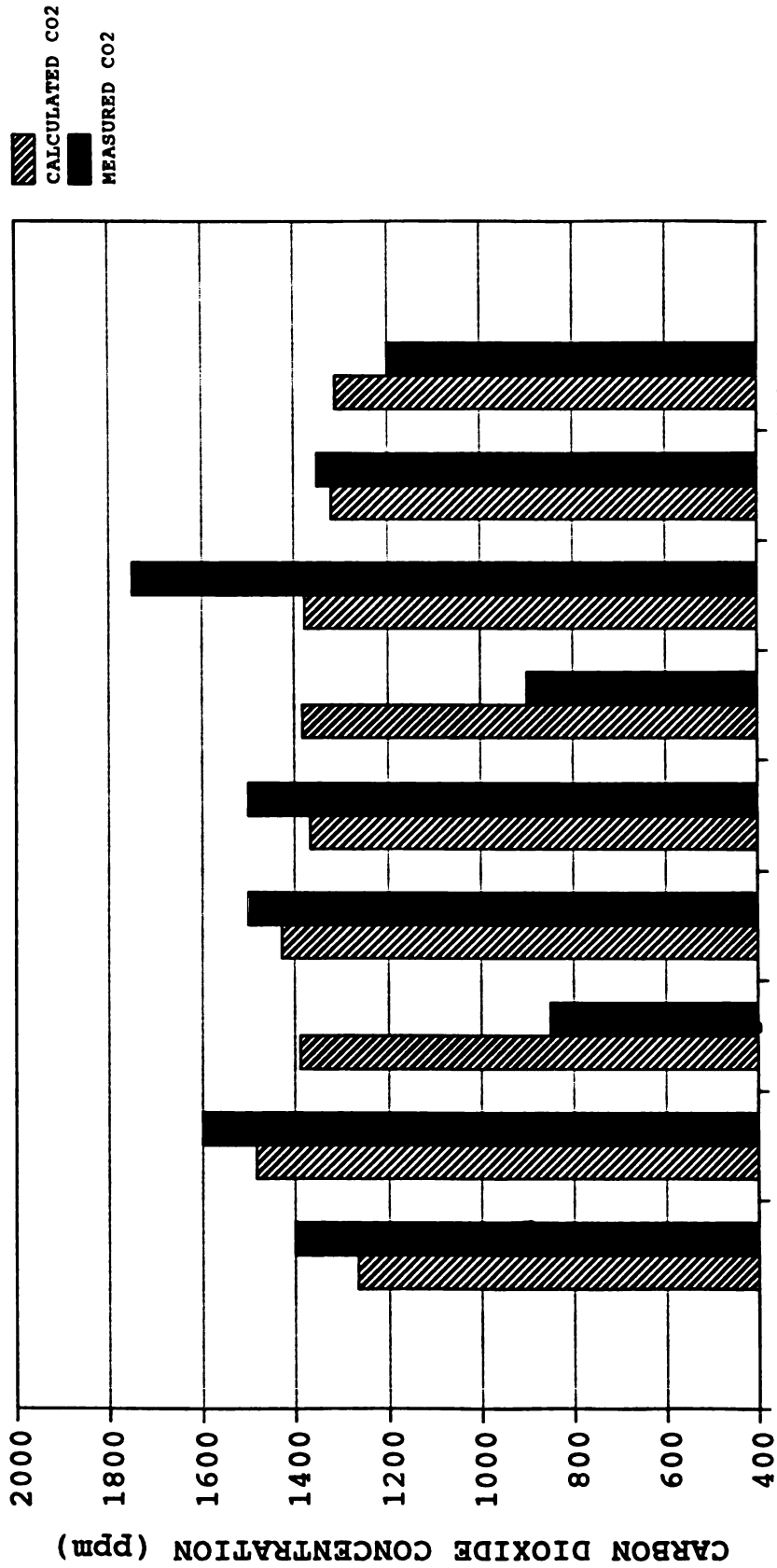


Figure 4.20 Measured vs. Calculated Carbon Dioxide Concentration in a 61 Meter by 13.3 Meter Freestall Barn.

barn. The measured values for the validation barn were taken from approximately midnight to 4 A.M., when none of the groups of cows in the barn was out for milking. Table 4.14 lists the data values for three nights of roof temperature and wind speed measurements. The averaged results are highlighted with bold type.

Table 4.15 lists the results of the calculated lower surface roof temperature using averaged data from each of the three sets of measurements (see Section 4.1.9). As noted in Section 4.1.9 the "calculation method" column listing of long or short refers to the two surface temperature calculation methods used. The selection of upper and lower roof surface film coefficients was based on the measured wind speed. For winds less than 1.4 m/s (3 mph) a resistance coefficient of 0.11 $m^2 \cdot K/W$ was used. Between wind speeds of 1.4 m/s and 3.4 m/s (3 mph and 7.5 mph) a resistance coefficient of 0.044 $m^2 \cdot K/W$ was used. Beyond 3.4 m/s a value of 0.030 $m^2 \cdot K/W$ was used as the resistance coefficient. Appendix F lists each of these values as found for example in the ASHRAE Handbook of Fundamentals.

Table 4.15 shows that the data for a clear night (December 21, 1992) resulted in calculated roof lower surface temperatures being between approximately one and one half to three degrees celsius warmer than the measured values. On an overcast night (January 7, 1993) the calculated values were about equal to three quarters of a

Table 4.14 Validation Barn Roof Surface, Temperature Measurements.

Date	Side	Upper Surface Measurements						Lower Surface Measurements					
		Temperatures				Wind Speed		Temperatures				Wind Speed	
		Roof		Air				Roof		Air			
		°C	°F	°C	°F	m/s	mph	°C	°F	°C	°F	m/s	mph
12/21	N	-7.4	18.7	-6.0	21.2	1.2	2.6	-8.3	17.1	-3.0	26.6	0.5	1.0
	N	-6.9	19.6	-6.0	21.2	1.0	2.3	-7.7	18.1	-3.0	26.6	0.5	1.2
Avg.	N	-7.2		-6.0		1.1		-8.0		-3.0		0.5	
	S	-7.6	18.3	-6.0	21.2	2.5	5.5	-7.9	17.8	-5.0	23.0	3.0	6.7
	S	-7.9	17.8	-6.5	20.3	4.5	10.1	-7.9	17.8	-5.5	22.1	3.4	7.5
Avg.	S	-7.8		-6.3		3.5		-7.9		-5.3		3.2	
Avg.		-7.5	18.5	-6.1	21.0	2.3	5.1	-8.0	17.6	-4.1	24.6	1.9	4.1
1/7	N	-3.5	25.7	-3.8	25.2	1.7	3.7	-2.3	27.9	0.5	32.9	0.3	0.7
	N	-3.0	26.6	-4.5	23.9	1.6	3.5	-2.1	28.2	0.0	32.0	0.3	0.7
	N	-3.2	26.2	-4.0	24.8	1.5	3.3	-2.2	28.0	0.0	32.0	0.5	1.0
Avg.	N	-3.2		-4.1		1.5		-2.2		0.2		0.4	
	S	-3.6	25.5	-3.5	25.7	1.7	3.8	-2.0	28.4	-0.5	31.0	---	---
	S	-3.5	25.7	-4.0	24.8	---	---	-2.1	28.2	0.0	32.0	---	---
	S	-3.4	25.9	-4.0	24.8	---	---	-2.5	27.5	0.0	32.0	---	---
Avg.	S	-3.5		-3.8		1.7		-2.2		-0.2		---	
Avg.		-3.4	25.9	-4.0	24.8	1.6	3.6	-2.2	28.0	0.0	32.0	0.4	0.8
1/9	N	-12.7	9.1	-9.0	15.8	5.5	12.2	-9.8	14.4	-6.5	20.3	1.0	2.2
	N	-12.4	9.7	-9.0	15.8	5.4	12.0	-10.0	14.0	-6.8	19.9	0.5	1.2
	N	-12.9	8.8	-9.0	15.8	4.2	9.3	-9.9	14.2	-7.0	19.4	---	---
Avg.	N	-12.7		-9.0		5.0		-9.9		-6.8		0.8	
	S	-13.3	8.1	-8.5	16.7	1.4	3.1	-10.0	14.0	-5.0	23.0	0.6	1.4
	S	-13.5	7.7	-9.0	15.8	1.5	3.3	-10.6	12.9	-6.0	21.2	0.7	1.5
Avg.	S	-13.4		-8.8		1.5		-10.3		-5.5		0.6	
Avg.		-13.1	8.4	-8.9	16.0	3.3	7.4	-10.1	13.8	-6.2	20.8	0.7	1.6

--- = Hot wire anemometer failure

Table 4.15 Calculation of Roof Lower Surface Temperature From Averaged Data.

Measurement Date	Roof Slope Averaged	Calculation Method	Coefficients Used URS	Coefficients Used LRS	Average Measured RLST	Calculated RLST
12/21	North	Short	0.044	0.11	-8.0	-5.1
	North	Long	0.044	0.11	-8.0	-5.1
	South	Short	0.030	0.044	-7.9	-5.9
	South	Long	0.030	0.044	-7.9	-6.3
	All Data	Short	0.044	0.044	-8.0	-5.1
	All Data	Long	0.044	0.044	-8.0	-5.4
1/7	North	Short	0.11	0.044	-2.2	-2.9
	North	Long	0.11	0.044	-2.2	-2.4
	South	Short	0.11	0.044	-2.2	-2.8
	South	Long	0.11	0.044	-2.2	-2.5
	All Data	Short	0.11	0.044	-2.2	-2.9
	All Data	Long	0.11	0.044	-2.2	-2.5
1/9	North	Short	0.11	0.030	-9.9	-8.5
	North	Long	0.11	0.030	-9.9	-8.7
	South	Short	0.11	0.030	-10.3	-8.1
	South	Long	0.11	0.030	-10.3	-7.8
	All Data	Short	0.11	0.030	-10.1	-8.3
	All Data	Long	0.11	0.030	-10.1	-8.3

URS = Upper roof surface
LRS = Lower roof surface
RLST = Roof lower surface temperature

degree celsius colder than measured values. On a partly overcast night (January 9, 1993) the calculated roof lower surface temperatures were about one to two and one half degrees celsius warmer than the measured values.

This set of data does not represent a rigorous study of actual roof temperatures. For example, the first set of data was partly compromised by the site of data collection being in close proximity to the ventilation inlets (causing roof lower surface temperatures to be lower than average for the entire roof). Also, though calibrated, the data collection equipment was all hand held and therefore subject to errors in positioning, wind obstruction etc. As well, the number of samples was not of a large enough magnitude to effectively average out isolated environmental anomalies. In other words, it would appear from the calculated and measured comparisons and the previous discussion regarding the conditions under which the resistance coefficients were determined, that the exact calculated surface temperature is not a reliable criteria for determining roof lower surface temperature and that likewise, the measurements taken were not of sufficient number to totally discredit the calculated values. For these reasons, less credibility was placed on the extremes of the differences between calculated and measured roof lower surface temperature and more on the trends.

One trend was that clearer sky conditions tended to produce lower roof surface temperatures that were colder

than a calculated value would predict by approximately one to two degrees celsius (for reasons previously mentioned, this temperature range obviously somewhat discredits the extremes of the results of the December 21, 1992 measurements i.e., the measured vs. calculated difference of 2.9 °C). Another possible trend would be that, under overcast sky conditions, the roof lower surface temperature may be about one degree celsius warmer than a calculation would predict.

A Danish study by Andersen (1987), comparing the calculated and measured temperature of the uninsulated metal roof of an experimental building, found that the measured roof surface temperature was one to two degrees celsius higher than his calculated value. He also noted that cloud cover had an impact upon the amount of roof condensation. Clear sky condensation was 1.5 to 3 times greater than cloudy sky condensation when the temperature difference between inside and outside was greater than 5 °C. This research supports the findings that clear sky radiation as well as air temperature plays a part in determining roof lower surface temperature.

Because of the uncertainty as to the accuracy of the calculated roof lower surface temperature, a range around the calculated value was chosen to represent the actual roof lower surface temperature. The trend for measured data vs. calculated data was two degrees celsius below the calculated value to one degree above the calculated value. Andersen's

(1987) findings would suggest measured values up to two degrees above calculated values. Therefore, for this research a range of two degrees about the calculated value was chosen as the zone of possible roof lower surface temperatures.

4.4.2 Model Validity

Calculated inside temperatures for both the calibration barn and the validation barn deviated approximately one degree celsius above field measurements at warmer temperatures and one degree below field measurements at colder temperatures (see Figures 4.4 and 4.5). The average difference was 0.3 °C below measured values for the calibration barn and 0.2 °C below field measurements for the validation barn. The average validation barn standard error for determination of inside temperature was 0.7 °C.

Calibration barn relative humidities followed measured values very closely except for temperatures just above freezing (see Figure 4.2). At those temperatures, the humidity values were approximately four to five percent below field values. Validation barn relative humidity calculations also followed measured values very closely (see Figure 4.3), with extremes ranging approximately two percent above to three percent below measured values. The average calibration barn calculated relative humidity was 1.1% lower than measured values while the validation barn relative humidity calculations averaged 0.3% less than field

measurements. The average validation barn standard error was 2.4%.

Carbon dioxide concentration calculations were compared with a set of draw tube tests done on another barn in the monitoring program (see Section 4.4.1.3). That comparison showed calculated CO_2 values to average 29 ppm greater than the measured values.

Lower roof surface temperature calculations were compared with three nights of roof temperature measurements taken on the validation barn. The measured values coincidentally included the range of variability in sky radiation, namely, a clear night, a partly overcast night, and an overcast night. Due to actual versus calculated heat radiation to the sky, estimated versus actual upper roof surface film coefficient, and other variables mentioned in Section 4.4.1.4, the calculated roof lower surface temperatures ranged from two and one half degrees celsius above measured values to three quarters of a degree celsius below measured roof temperatures.

4.5 Wintertime Simulation Model Analysis of Typical Freestall Dairy Barns

4.5.1 Four Row Uninsulated Barn Simulation From -20.6 °C to 4.4 °C

Like the validation barn, the inside environmental conditions were calculated at 2.8 °C (5 °F) outside temperature increments from -20.6 °C to 4.4 °C (-5 °F to 40 °F). This set of inside environment calculations (at each of the 2.8 °C (5 °F) outside temperatures) was repeated for four different ventilation opening conditions. In other words, the inside temperature, relative humidity, inside roof temperature etc. were calculated ten times (once for each five degree fahrenheit increment from -5 to 40 °F) for a barn with the ventilation soffit openings blocked to 10% capacity and then calculated again for three other ventilation opening scenarios.

To represent a very closed building, ventilation at an inlet area equal to 10 percent of full soffit openings was calculated. Partially blocked inlet ventilation was represented by calculations of ventilation at 50 percent of full soffit area with the upwind soffit considered closed and the downwind soffit considered open. Calculations at 100 percent soffit area (fully open soffits) and 343 percent soffit area (an area equivalent to unblocked soffits and opening one feed alley and four cow alley doors) completed the ventilation openings studied.

4.5.1.1 Roof Frost/Condensation Conditions

Figures 4.21 through 4.23 illustrate the calculated potential for nighttime roof frost formation (onset of dew point conditions) at outside temperatures of 4.4 °C, -6.7 °C, and -17.8 °C, respectively. The rectangles used as legend symbols in these figures are positioned at the four ventilation opening conditions discussed previously (10% (5.5 m^2), 50% (11.3 m^2), 100% (18.7 m^2), and 343% (64 m^2) of full soffit opening area). Frost or condensation (a condition of saturation) would be expected to occur on the underside of the roof when the line representing barn roof temperature was below the line representing dew point temperature. In other words, when the inside roof temperature line was below the dew point line the roof was colder than the dew point and consequently any air touching that surface would have been below its saturation temperature and condensation or frost would have occurred.

As discussed in Section 4.4.1.4, an exact calculation of roof temperature is impacted by equation derivation and local environmental parameters. Thus, roof temperature is not an independently reliable value. Therefore, a temperature range extending plus or minus two degrees Celsius around the calculated inside roof temperature (represented by two dashed lines) was a more realistic estimate of actual roof temperature.

If the assumption was made that a dew point temperature two degree Celsius below calculated roof temperature

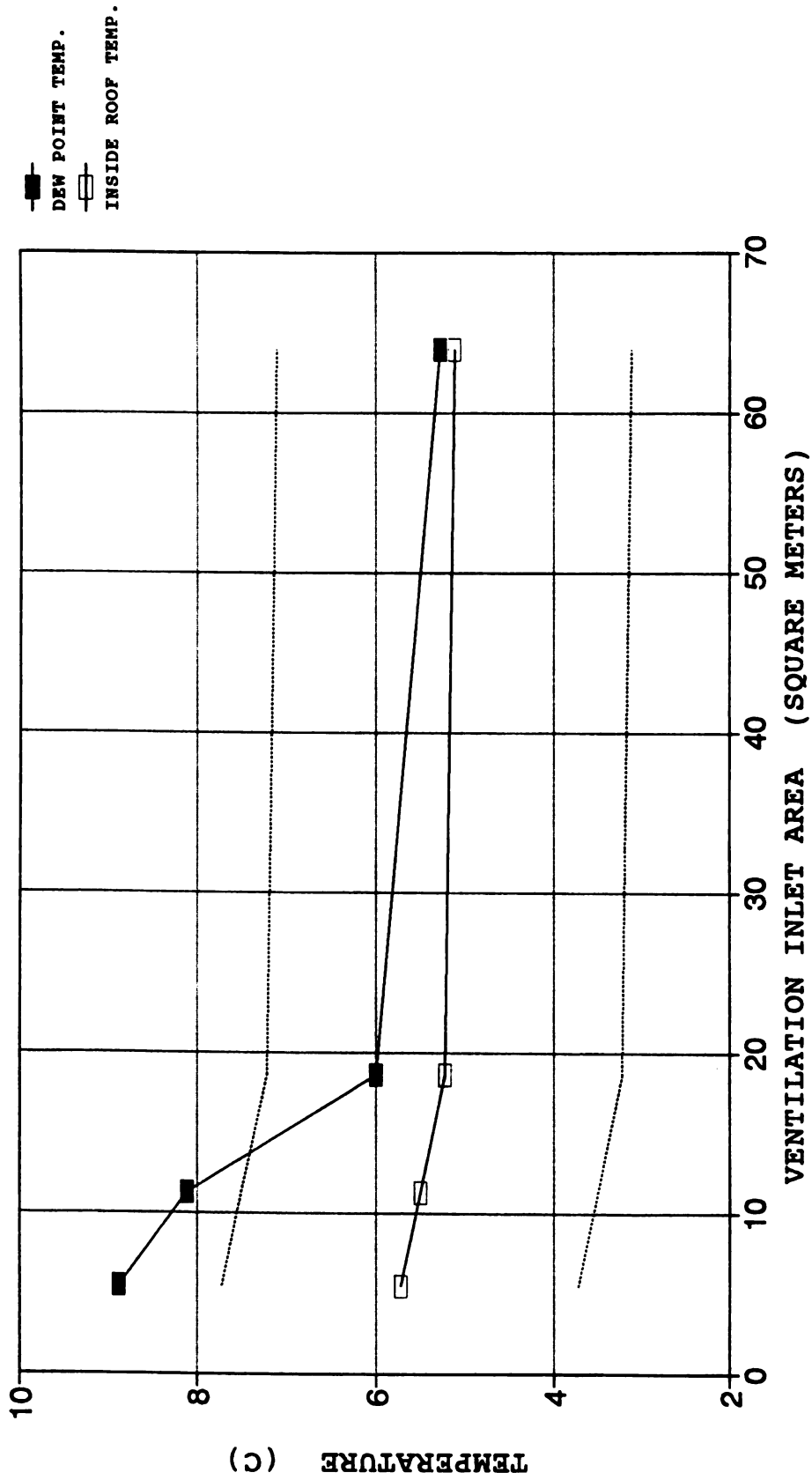


Figure 4.21 Comparison of Calculated Dew Point and Inside Roof Temperature at Four Ventilation Opening Sizes (Vent Openings at 10% (5.5 m^2), 50% (11.3 m^2), 100% (18.7 m^2), & 343% (64 m^2) of Fully Open Soffits) for an Uninsulated Barn at 4.4 °C (40 °F) Outside Temperature. Dashed Lines Border The Zone of Potential Roof Temperature.

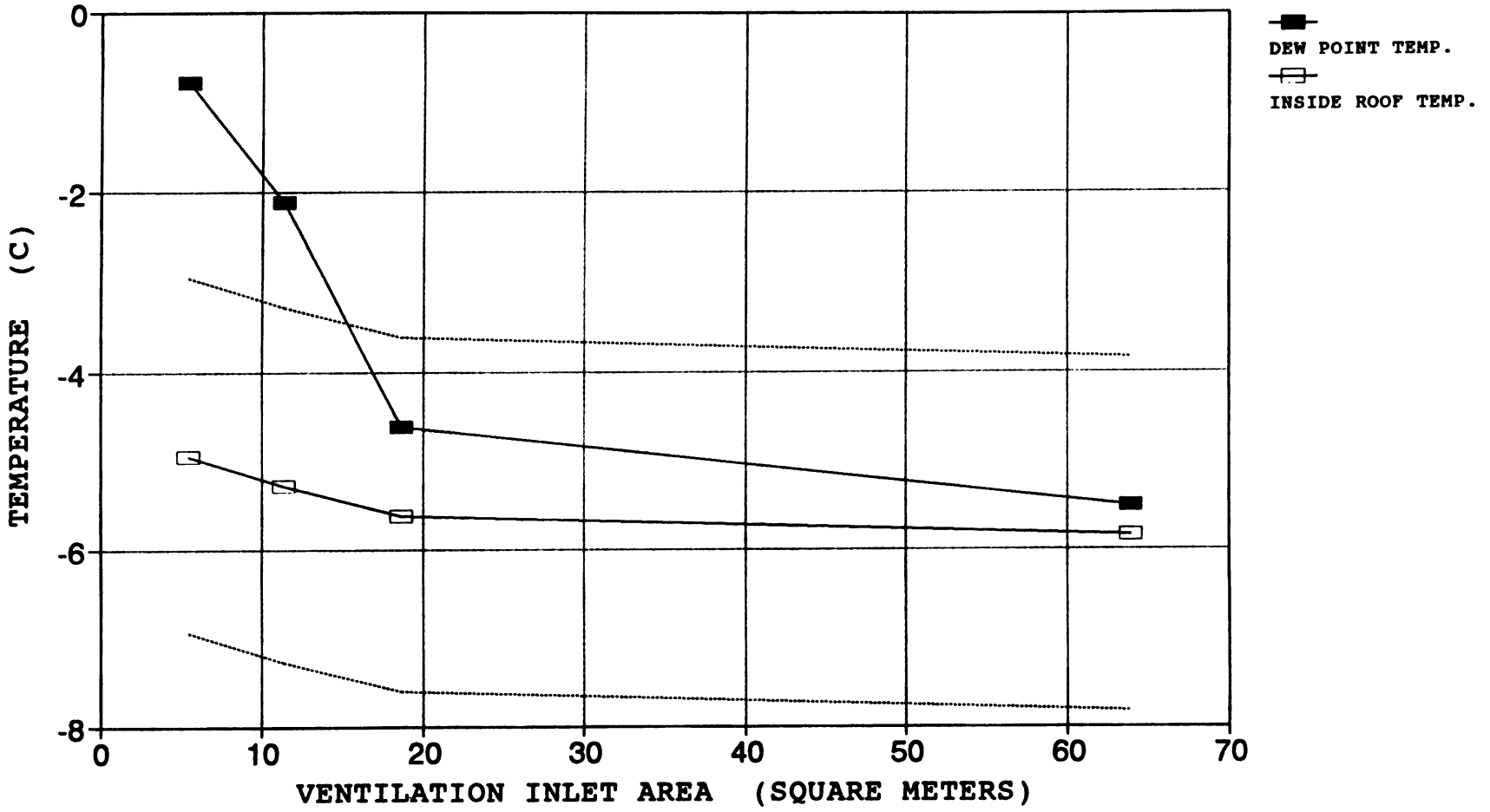


Figure 4.22 Comparison of Calculated Dew Point and Inside Roof Temperature at Four Ventilation Opening Sizes (Vent Openings at 10% (5.5 m^2), 50% (11.3 m^2), 100% (18.7 m^2), & 343% (64 m^2) of Fully Open Soffits) for an Uninsulated Barn at -6.7 °C (20 °F) Outside Temperature. Dashed Lines Border The Zone of Potential Roof Temperature.

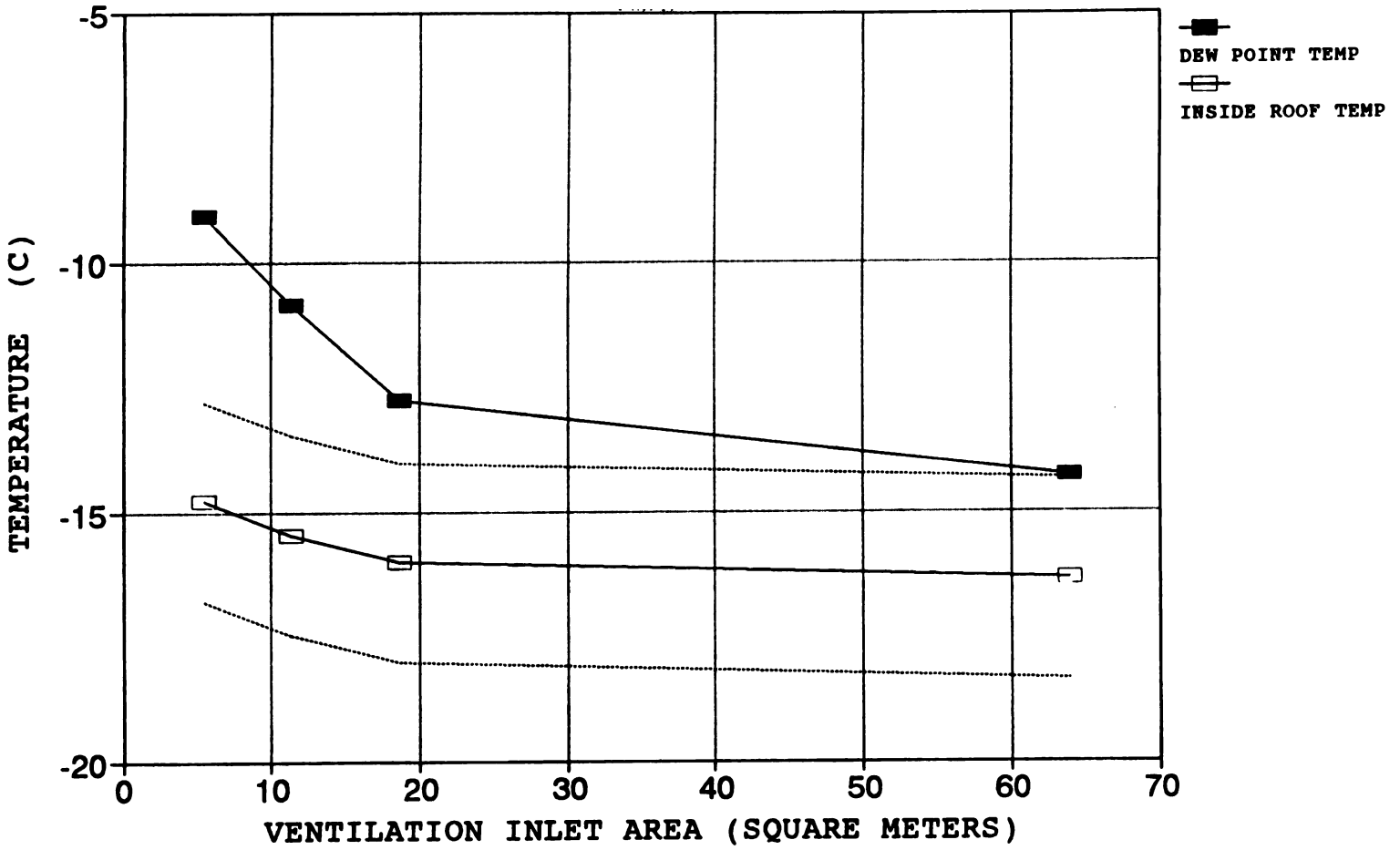


Figure 4.23 Comparison of Calculated Dew Point and Inside Roof Temperature at Four Ventilation Opening Sizes (Vent Openings at 10% (5.5 m²), 50% (11.3 m²), 100% (18.7 m²), & 343% (64 m²) of Fully Open Soffits) for an Uninsulated Barn at -17.8 °C (0 °F) Outside Temperature. Dashed Lines Border The Zone of Potential Roof Temperature.

represents a 0% chance of condensation and two degree Celsius above the calculated roof temperature represented a 100% chance of condensation, Figure 4.21 shows that, at 4.4 °C, a 343% ventilation rate had approximately a 50% chance of causing roof condensation. At 100% of full soffit ventilation, there would have been approximately a 70% chance of condensation. Ventilation openings of 50% or 10% of full soffit area, however, produced the potential for condensation to occur every night.

Figure 4.22 shows that as outside temperature dropped to -6.7 °C (20 °F) conditions of frost formation increased an insignificant amount. As can be seen in Figure 4.23 however, at -17.8 °C (0 °F) or lower, frost accumulation would be anticipated every night for all ventilation openings studied.

4.5.1.2 Absolute Humidity and Relative Humidity

As would be expected, the lowest absolute humidity occurred at the greatest ventilation opening for each outside temperature studied. This fact is illustrated in Figure 4.24. Also,the ability of warmer air to hold more moisture is depicted in this graph. For example, at 4.4 °C the absolute humidity was approximately four times greater at the 10% ventilation level and five and a half times greater at the 343% ventilation level respectively than was found at -20.6 °C.

Reducing the ventilation area approximately two and one half times (from soffits and five end doors open to soffits

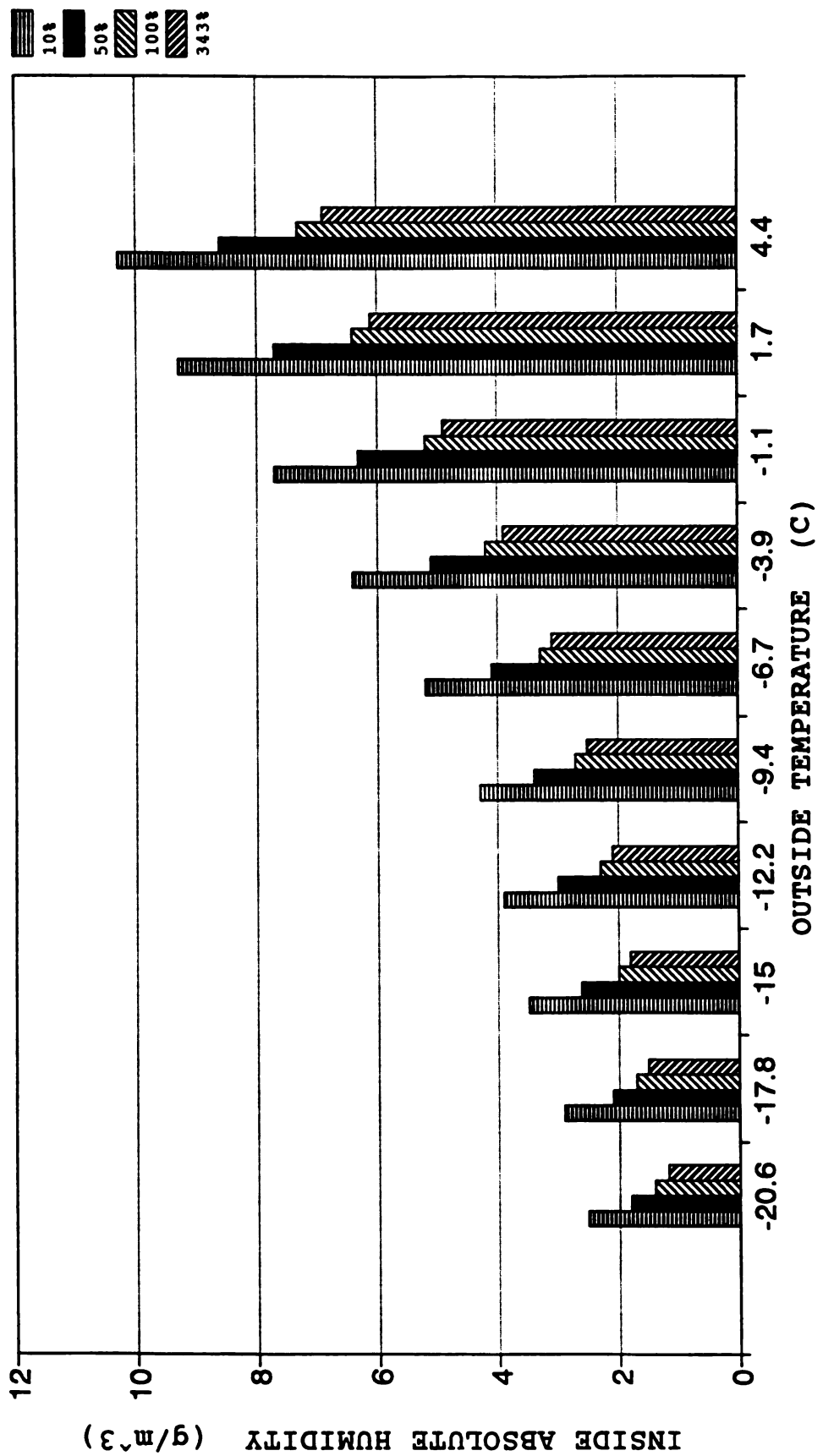


Figure 4.24 Uninsulated Simulation Barn Absolute Humidity at Four Ventilation Opening Sizes (Vent Openings at 10%, 50%, 100%, & 343% of Fully Open Soffits) at Different Outside Temperatures.

only open) showed only a relatively small change in absolute humidity. At -20.6 °C the difference was 0.2 g/m³. At 4.4 °C the difference was 0.3 g/m³. When the ventilation area was reduced from fully open soffits to 10% open soffits however, the increase in absolute humidity was much more dramatic. At -20.6 °C, the change was 1.1 g/m³ and at 4.4 °C the change was 3 g/m³.

The amount of moisture held in the barn was almost doubled by closing the doors and blocking the soffit inlets down to 10% when the outside temperature was down to -20.6 °C. Had the doors been closed and the soffits blocked to only 50%, there would have been approximately a 50% increase in the absolute humidity within the barn. As mentioned earlier, when the weather warmed up to 4.4 °C the amount of total moisture in the barn increased. The barn with 10% ventilation openings had approximately a third greater moisture content than did the barn with open soffits and open doors.

The relative humidity calculations complement the absolute humidity data. While the absolute humidity values show the quantity of moisture in the barn, the relative humidity values show how saturated the air is at a given temperature. Looking at Figure 4.25 it can be seen that the barn with unblocked soffits and open end doors had the lowest inside relative humidities. Had the end doors been closed, the outside temperature would have had to rise to approximately -17.8 °C (0 °F) before the inside relative

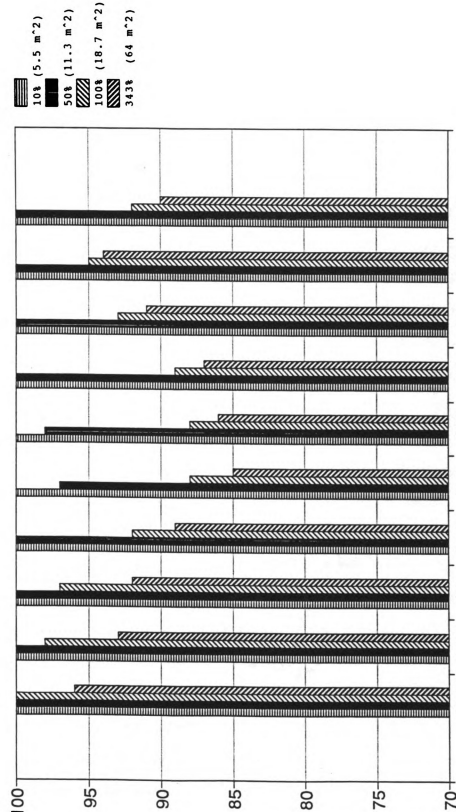


Figure 4.25 Uninsulated Simulation Barn Relative Humidity Under Four Ventilation Opening Sizes (Vent Openings at 10%, 50%, 100%, & 343% of Fully Open Soffits) at Different Outside Temperatures.

humidity would have dropped below 100%. Also of interest in this graph is that, had the vent openings been blocked to the 10% level and the ambient temperature stayed at or below 4.4 °C, under steady state conditions, every night of the study period from December to March the relative humidity would have been at the saturation point. Conversely, had the ventilation been at the 343% level, building relative humidity would have averaged approximately 90%.

Another observation on the graph in Figure 4.25 is the dip in relative humidity and then rise again as the outside temperature warmed up. Two possible explanations for this shift could be: 1) the similar pattern in outside relative humidity (an input parameter to the equations) as outside temperatures rose (see Table 4.8), and 2) the increase in cattle latent heat production with warmer building temperatures. The higher inside relative humidity at warming temperatures could be stated as very representative of the conditions often found in underventilated barns in the spring. As outside temperatures rise, cattle latent heat production increases, ambient relative humidity is often high, and the barn hasn't been opened up yet. This could be the scenario seen graphed on the warmer temperature side of Figure 4.25. Only the barn with unblocked soffits or unblocked soffits and open end doors was able to produce an inside nighttime relative humidity below ninety percent.

4.5.1.3 Dew Point Temperature

The change in building moisture content, as outside temperature and ventilation area changed, can also be shown by graphing building dew point temperatures. As the building was closed from 343% to 10% the dew point temperature rose 3.6 °C at 4.4 °C and 5.4 °C at -20.6 °C. (see Figure 4.26). On average, moisture striking a cold surface would condense at 4.5 degrees celsius higher when the building was closed than when it was open. The effects of this surface temperature vs. dew point temperature relationship has been previously discussed in Section 4.5.1.1

4.5.1.4 Inside Temperature

As seen in Figure 4.27, the calculated inside building temperature was warmest for the nearly completely closed barn at each outside temperature studied. The temperature rise difference between the barn with blocked soffits and the barn with open doors was greatest at the coldest outside temperatures and decreased as outside temperature rose. At -20.6 °C, the temperature rise was 9.6 °C (17.2 °F) at a 10% ventilation rate and 4.6 °C (8.2 °F) at a 343% ventilation rate. This was a difference of 5 °C (9 °F). At 4.4 °C and a 10% ventilation rate, however, the temperature rose 4.6 °C (8.2 °F) while a 343% ventilation rate produced a 2.5 °C (4.5 °F) rise. This temperature rise difference of 2.1 °C (3.8 °F) was less than half the rise at -20.6 °C. A logical explanation for this change would be that the wind speed

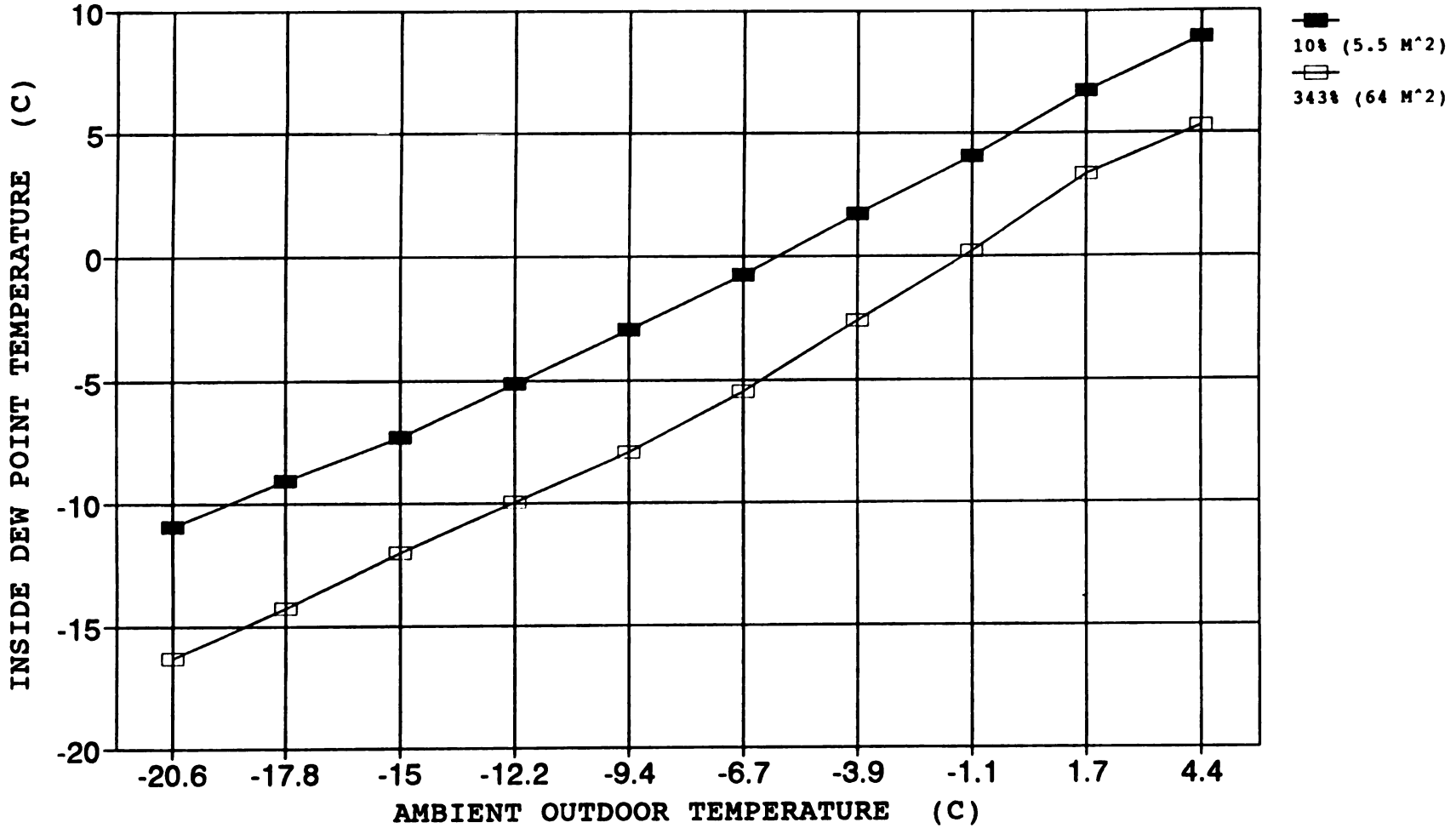


Figure 4.26 Uninsulated Simulation Barn Roof Dew Point Temperature Under Two Ventilation Conditions (Vent Openings at 10% & 343% of Fully Open Soffits).

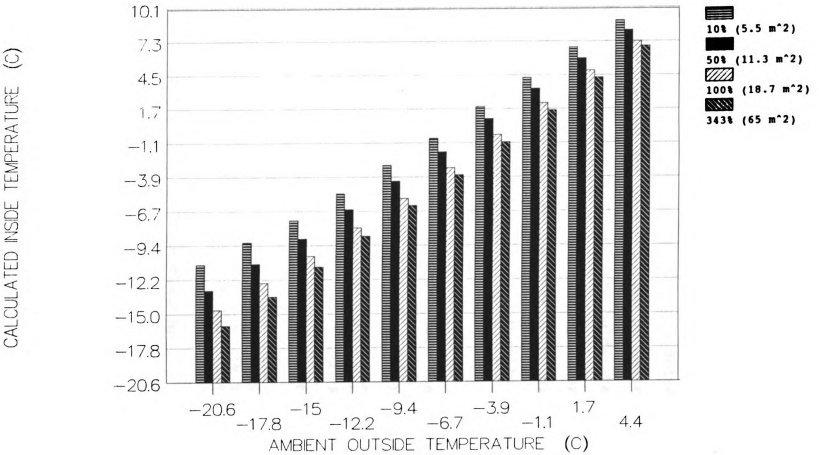


Figure 4.27 Uninsulated Simulation Barn Inside Temperature at Four Ventilation Opening Sizes (Vent Openings at 10%, 50%, 100%, & 343% of Fully Open Soffits).

increased from 2.0 m/s (4.5 mph) at -20.6 °C to 3.7 m/s (8.2 mph) at 4.4 °C (see Table 4.8). The increased ventilation would drive the inside temperature closer to a common value.

Table 4.16 lists the effect upon inside temperature of closing up the simulation barn. As mentioned earlier, the inside-outside temperature difference decreased as the outside temperature rose. It can be noticed that, at other times as well but particularly at colder temperatures, the closed building had a significantly greater temperature rise than the "few degrees" recommendation by Bickert and Stowell (1993) and Albright (1990) for a naturally ventilated building.

Table 4.16 Uninsulated Simulation Barn Inside-Outside Temperature Difference at Four Ventilation Opening Sizes and Three Outside Temperatures. (100% = Fully Open Soffits)

Vent Area	Outside Temperature (°C)					
	-20.6	(-5°F)	-6.7	(20°F)	4.4	(40°F)
	Inside-Outside Temperature Difference					
10%	9.6	(17.2)	6.0	(10.8)	4.6	(8.2)
50%	7.5	(13.5)	5.9	(8.8)	3.8	(6.8)
100%	5.9	(10.5)	3.6	(6.5)	2.9	(5.1)
343%	4.6	(8.2)	3.0	(5.4)	2.5	(4.5)

4.5.1.5 Carbon Dioxide Concentration

Carbon dioxide concentration in the model barn was the result of ambient air carbon dioxide level, livestock CO_2 production rate, and CO_2 removal rate through ventilation. Since carbon dioxide production is calculated on the basis of livestock total heat production, the output should be constant for a given herd. Normally, ambient carbon dioxide

concentration is also a constant. Ventilation rate then becomes the only driving force affecting building carbon dioxide levels. As can be seen in Figure 4.28, the carbon dioxide concentration at a 10% soffit opening was almost double that of 100% soffit ventilation and more than double that of 343% soffit ventilation. Thus, the less the ventilation openings were blocked the greater was the air exchange and the lower the carbon dioxide level. Both the 100% and 343% ventilation rates kept CO_2 concentrations at near ambient levels.

Remembering that there was no constant wind speed or relative humidity used throughout the calculations (see Table 4.8), observing the tops of the 10% carbon dioxide concentration bars could, to a large extent, be described as watching a fluctuating ventilation rate (or wind speed). The exceptions to this comment would be at warmer temperatures. For example, at -9.4 °C (15 °F) and -1.1 °C (30 °F) the wind speed was 3.5 m/s (7.7 mph) but the carbon dioxide level was slightly higher at -1.1 °C (a difference of 31 ppm). Air density was included in the calculation process and would be the likely reason for the increased carbon dioxide level. In other words, the stack effect would not be as aggressive at warmer temperatures resulting in slightly lower building ventilation and a slightly higher carbon dioxide concentration.

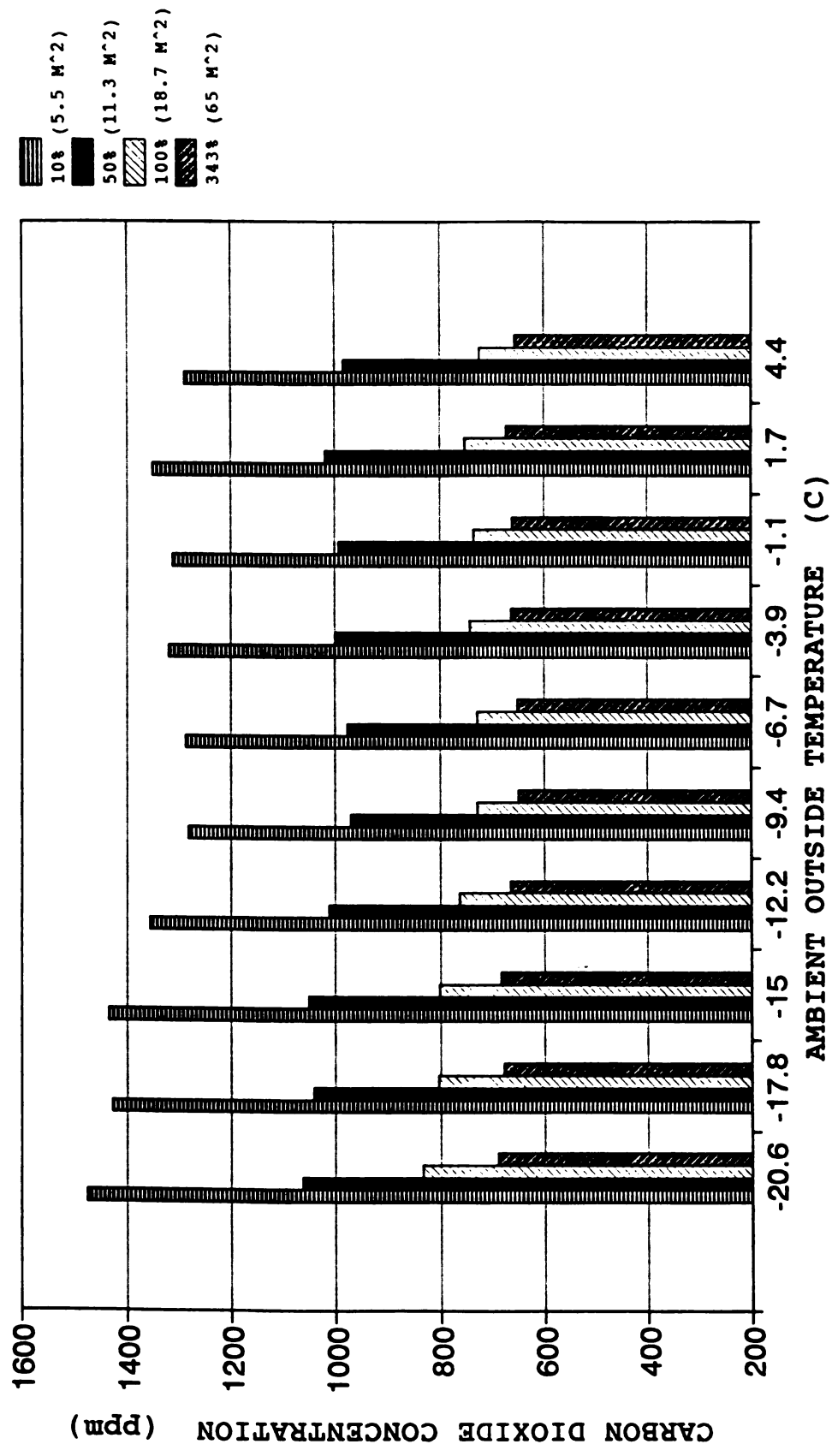


Figure 4.28 Uninsulated Simulation Barn Carbon Dioxide Concentration at Four Ventilation Opening Sizes (Vent Openings at 10%, 50%, 100%, & 343% of Fully Open Soffits).

4.5.1.6 Air Exchange Rate

Air exchange rate, like carbon dioxide concentration, was a function of ventilation rate. Like carbon dioxide, the results of wind and stack effect ventilation are seen here also, except in reverse (see Figure 4.29). As ventilation decreased so did air exchange. Notice that when the building ventilation openings were closed it took approximately twelve to fifteen minutes to make one air exchange in the barn. In contrast, full soffit openings produced the same result in approximately five to seven minutes; and at a 343% ventilation opening it took only approximately four to five minutes. In other words, the rate of ventilation for the closed barn was approximately one third of the ventilation rate produced by the barn with open soffits and open doors. Consequently, the dilution rate for air born pathogens would be three times greater for the open barn than it would be for the closed building.

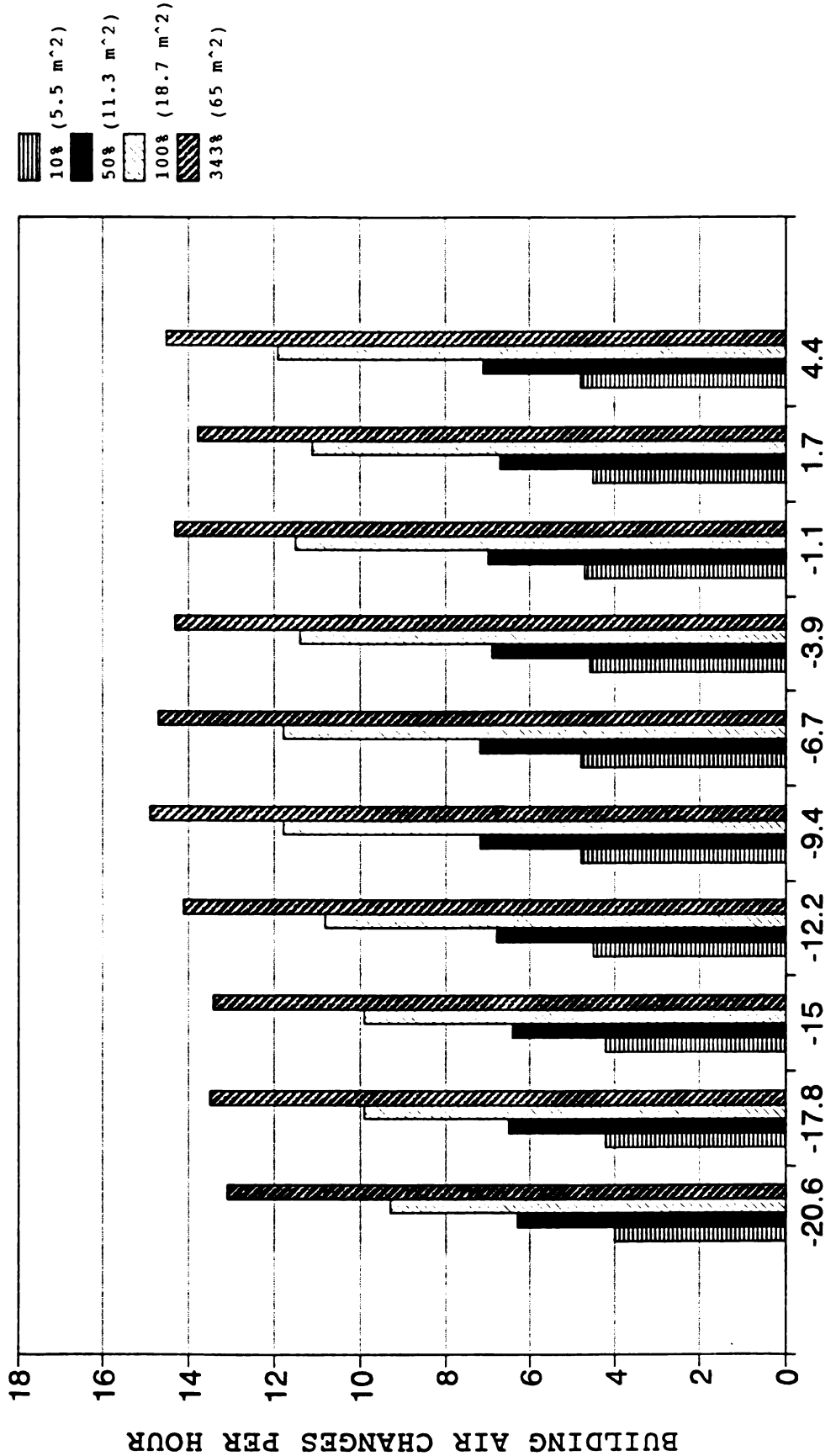


Figure 4.29 Uninsulated Simulation Barn Air Exchange at Four Ventilation Opening Sizes (Vent Openings at 10%, 50%, 100%, & 343% of Fully Open Soffits).

4.5.2 Four Row Insulated Barn Simulation at -20.6 °C to 4.4 °C

To study the effect of roof insulation on the simulation barn environment, 12.7 mm (1/2 inch) or 25.4 mm (1 inch) of roof insulation (RSI value of 1.27 per 25.4 mm (R value of 7.2 per inch)) was included in the simulation barn calculations. With that one structural modification (see Figure 4.30), the same environmental parameters discussed in section 4.5.1 were again studied.

4.5.2.1 Roof Frost/Condensation Conditions

Figures 4.31 through 4.36 illustrate the effect of roof insulation on the potential formation of nighttime roof frost at outside temperatures of -17.7 °C, -6.7 °C, and 4.4 °C. When scanning all six graphs it becomes apparent that there was only a marginal reduction in frost formation potential as the insulation level was increased from 12.7 mm to 25.4 mm. Similarly, at each of the outside temperatures graphed, there was, almost without exception, less than one degree Celsius difference in roof temperature between the two insulation levels. At the 343 percent ventilation rate, there was essentially no difference. Had the temperature been -17.7°C, Figures 4.31 and 4.32 show that there was a 30% to 40% chance of frost even at the 343% ventilation level. At the 50% ventilation rate, the chances increased to about 50% and, when the barn was closed up, the probability was approximately 75% for 25.4 mm of roof insulation and 90% for 12.7 mm of roof insulation. Of note

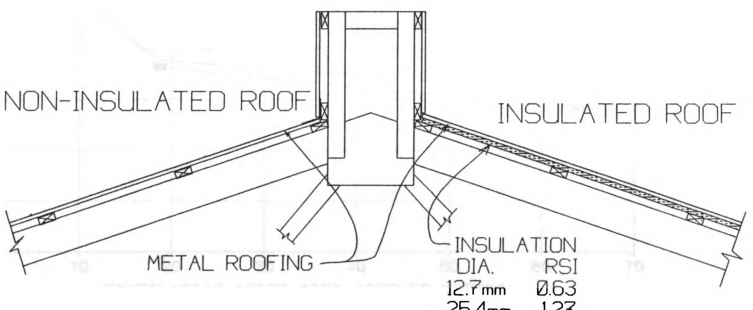


Figure 4.30 Typical Freestall Barn Insulated and Non-insulated Roof Section.

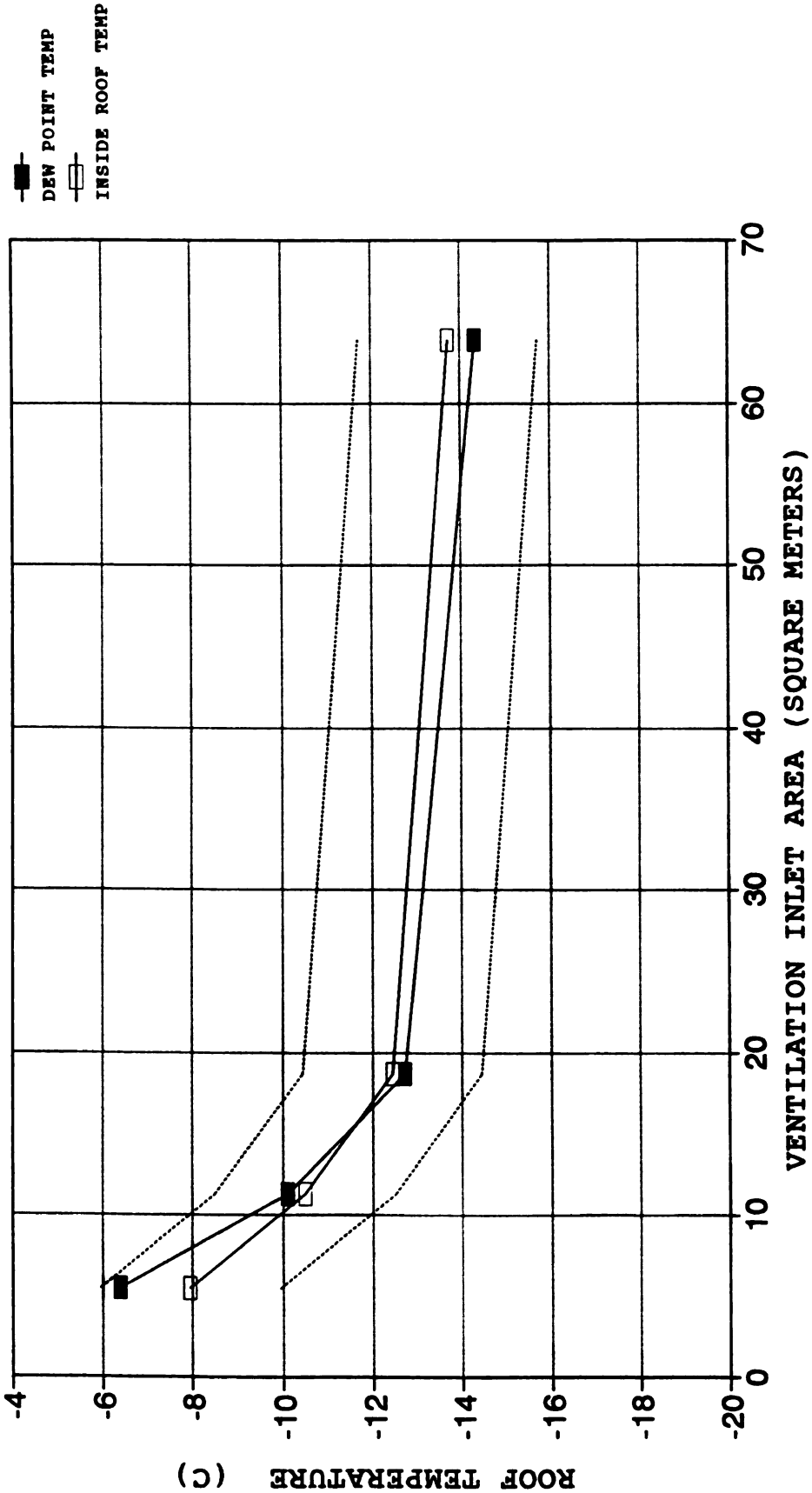


Figure 4.31 Dew Point and Roof Temperature at -17.7 °C Outside Temperature and 12.7 mm Roof Insulation (Markers Indicate Inlet Areas Studied). Dashed lines boarder the zone of potential roof temperature.

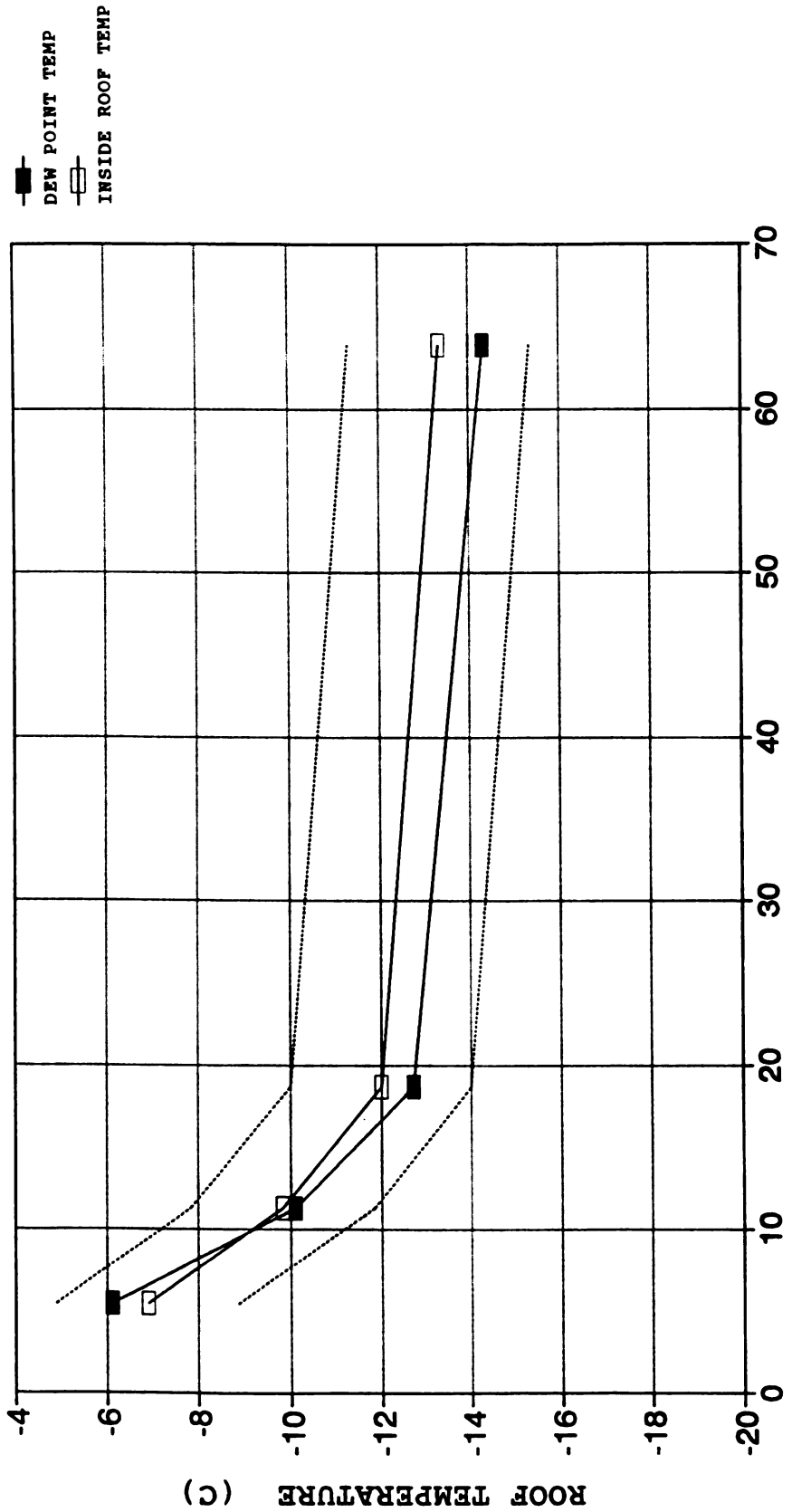


Figure 4.32 Dew Point and Roof Temperature at -17.7°C Outside Temperature and 25.4 mm Roof Insulation (Markers Indicate Inlet Areas Studied). Dashed lines boarder the zone of potential roof temperature.

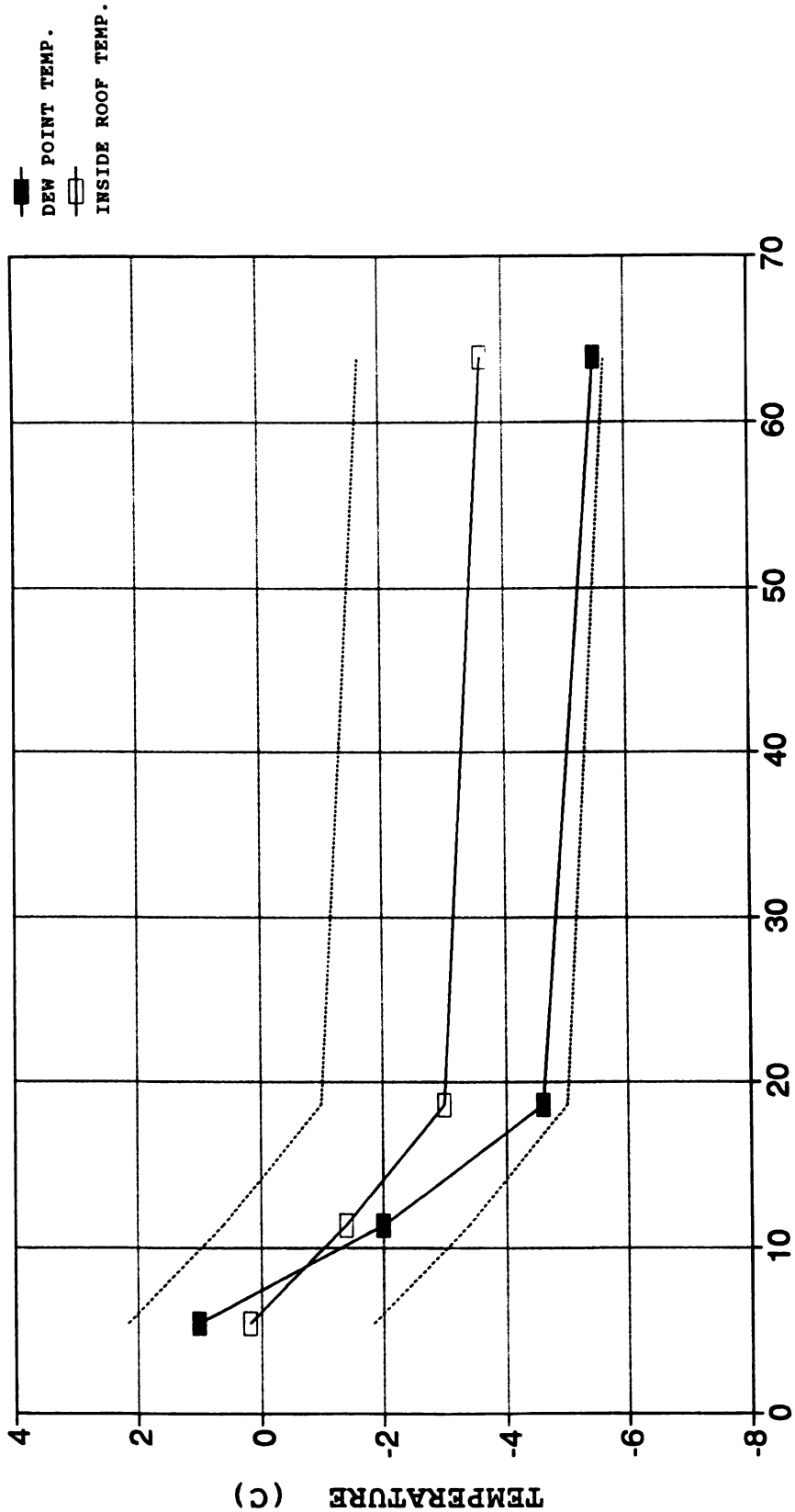


Figure 4.33 Dew Point and Roof Temperature at -6.7 °C Outside Temperature and 12.7 mm Roof Insulation (Markers Indicate Inlet Areas Studied). Dashed lines boarder the zone of potential roof temperature.

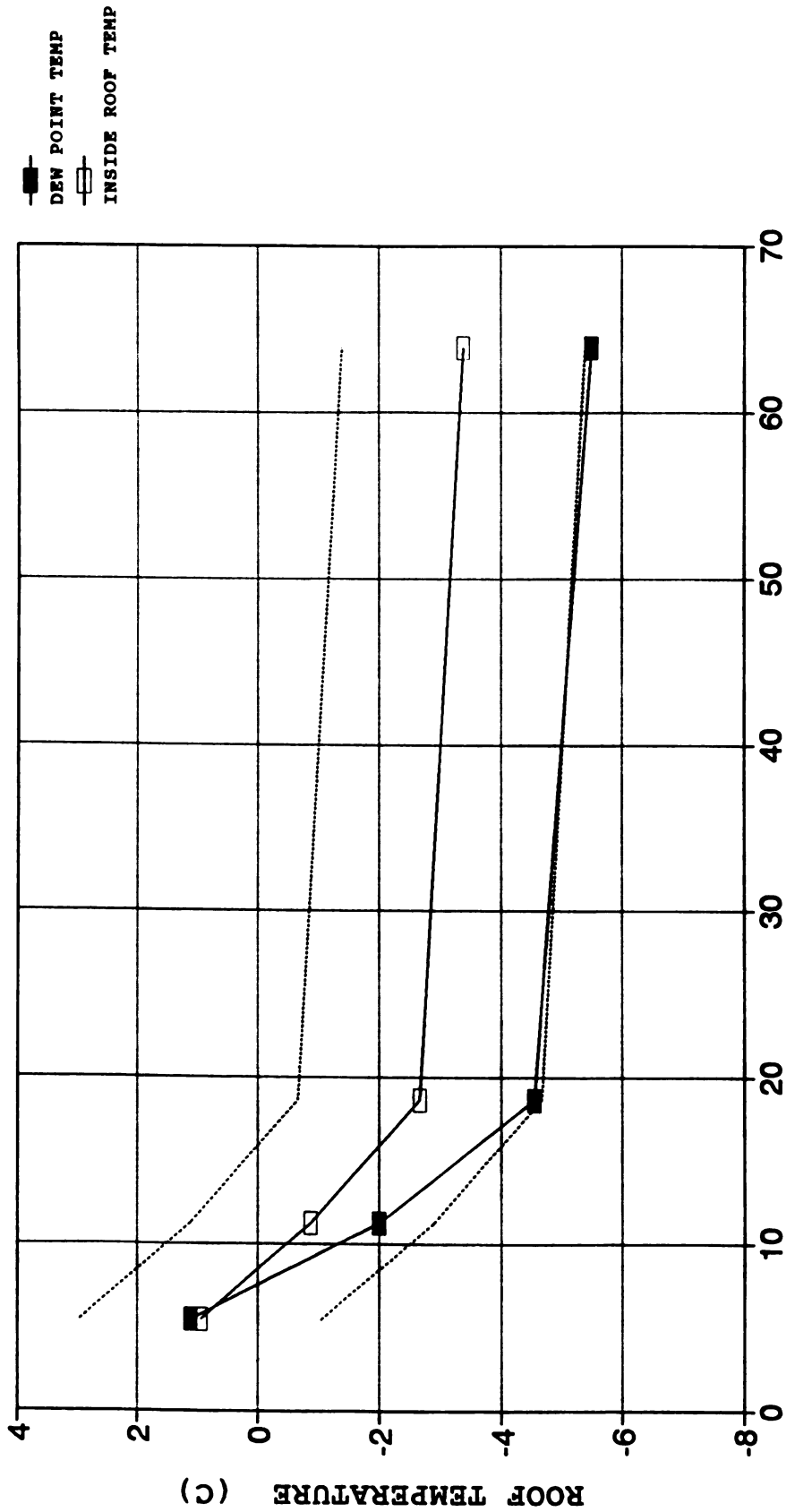


Figure 4.34 Dew Point and Roof Temperature at -6.7°C Outside Temperature and 25.4 mm Roof Insulation (Markers Indicate Inlet Areas Studied). Dashed lines boarder the zone of potential roof temperature.

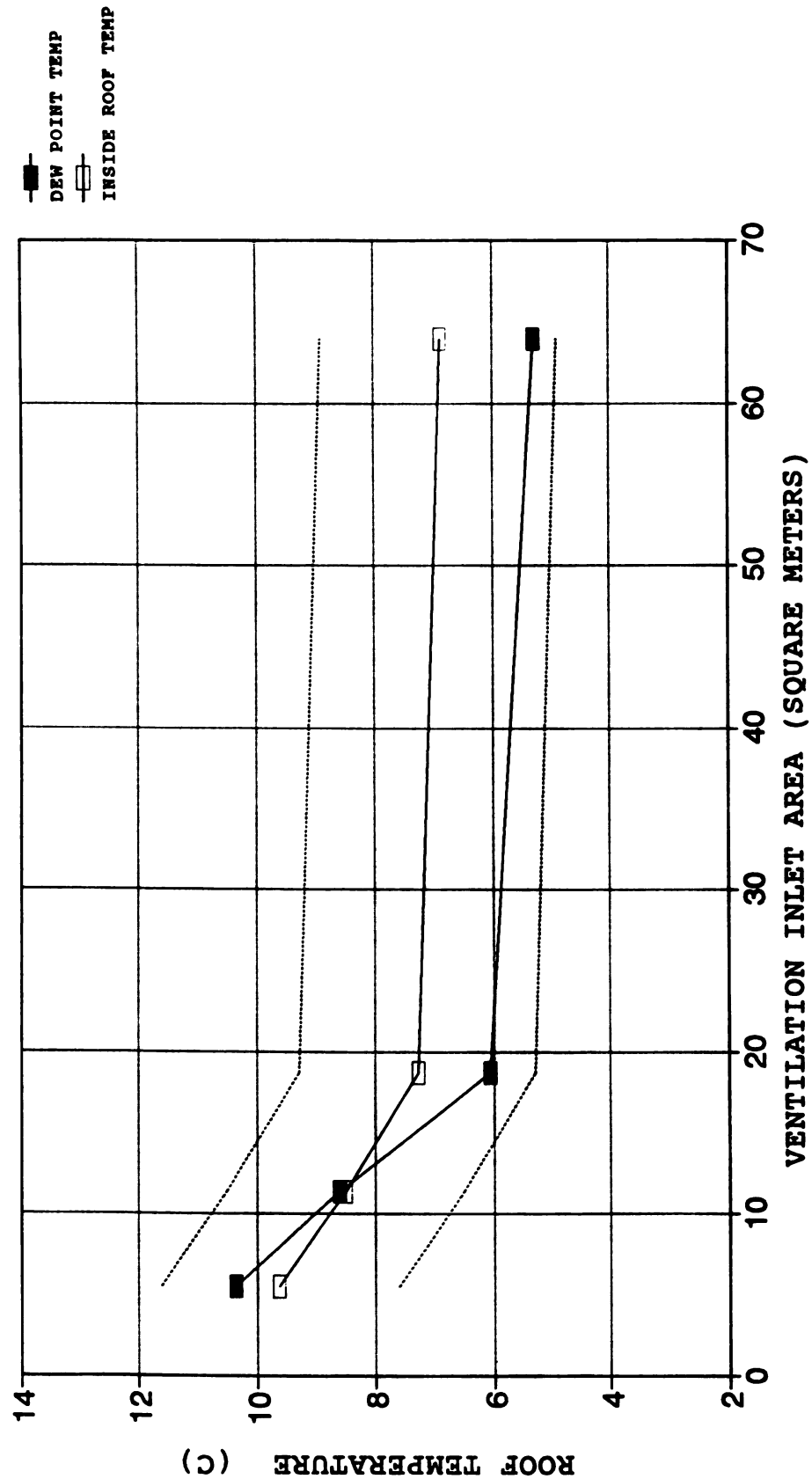


Figure 4.35 Dew Point and Roof Temperature at 4.4 °C Outside Temperature and 12.7 mm Roof Insulation (Markers Indicate Inlet Areas Studied). Dashed lines boarder the zone of potential roof temperature.

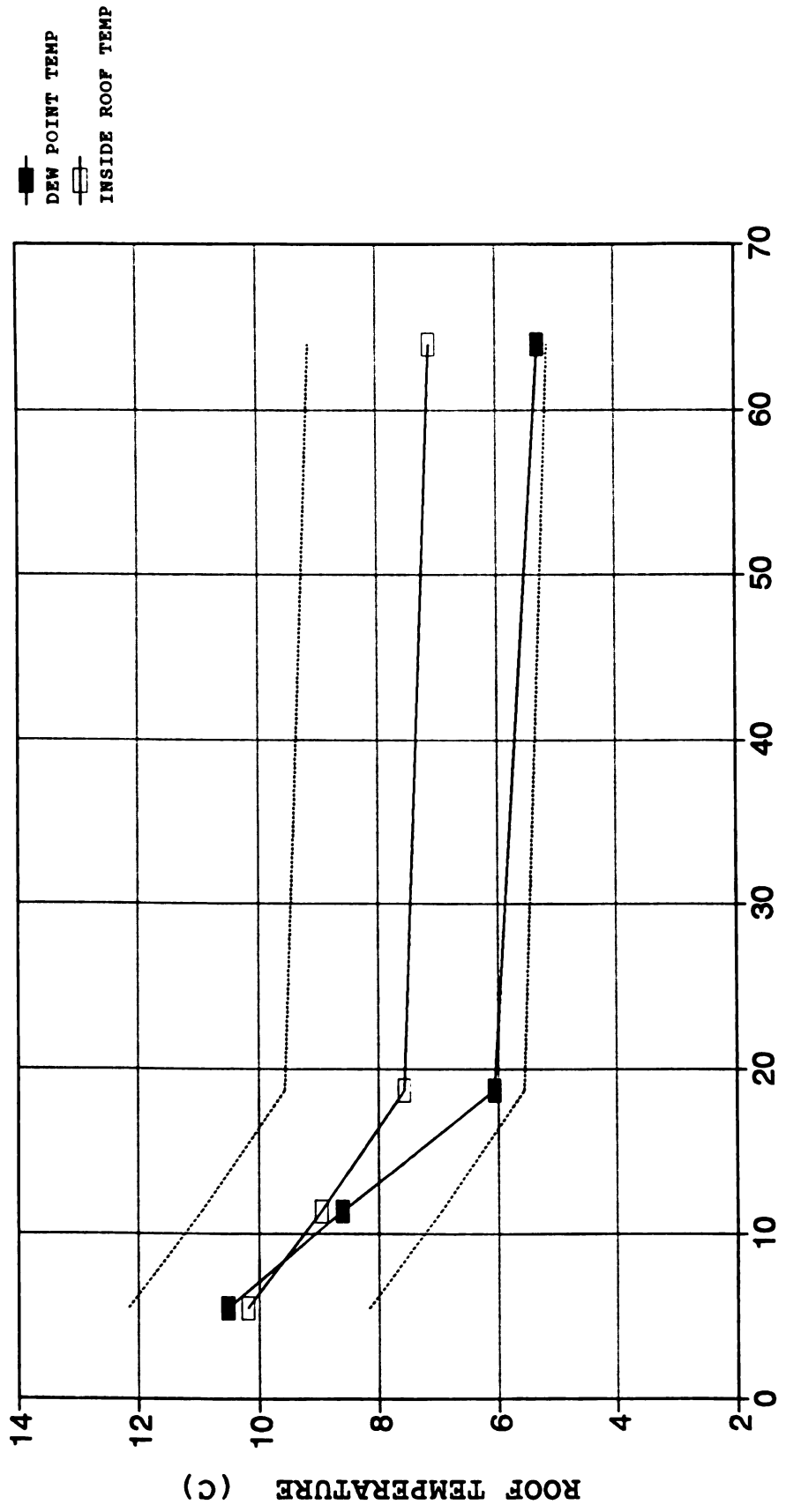


Figure 4.36 Dew Point and Roof Temperature at 4.4 °C Outside Temperature and 25.4 mm Roof Insulation (Markers Indicate Inlet Areas Studied). Dashed lines boarder the zone of potential roof temperature.

however, was the fact that, even at the 10 percent ventilation rate and a 12.7 mm insulation value, there could have been nights when roof frost may not have occurred (the upper limit of potential roof temperature was still warmer than the dew point temperature).

Figures 4.33 to 4.36 show that, at warmer temperatures, only 50% soffit ventilation or less had roof temperatures that hovered around the dew point temperature. At -6.7 °C and above, half blocked soffits had roof frost potential between approximately 25% and 50%, while ventilation rates equal or greater than full soffit levels had essentially a 20% or less chance for roof frost. At the 10% ventilation level and -6.7 °C or above, the frost potential ranged from approximately 55% to 75%.

4.5.2.2 Absolute Humidity and Relative Humidity

As could be expected, the absolute humidity values were essentially unchanged when roof insulation was added. For example, at -20.6 °C and 10 percent ventilation, the uninsulated barn had an absolute humidity that, when combined with the building ventilation rate, removed 1311 grams per minute (0.35 gallons per minute) of moisture. At the same ventilation opening amount, but with the roof insulated to 25.4 mm, there was 1516 grams per minute (0.4 gallons per minute) of moisture removed. At 4.4 °C the value for the uninsulated roof was 6452 grams per minute (1.7 gallons per minute) and 6848 grams per minute (1.8 gallons per minute) for the insulated roof. The fact that

the insulated roof allowed the building to maintain a slightly warmer temperature, and thus increase the water holding capacity of the air, could logically be assumed as the reason for the slight absolute humidity increase at a given ambient temperature. As discussed in Section 4.5.1.2 and shown in Figure 4.24, the uninsulated roof, like the insulated roof, also showed the reduction or dilution of building moisture as building ventilation increased.

Figures 4.37 and 4.38 show building relative humidity levels at the four ventilation options and two roof insulation levels. The only variable that was changed in the calculation of building relative humidity was the reduced building heat loss due to added roof insulation. As can be seen by the appearance of graphs 4.25, 4.37, and 4.38, roof insulation had a measurable impact upon building relative humidity.

Under very closed ventilation conditions, both insulation levels allowed the relative humidity to drop below 100 percent when the outside temperature was -9.4 °C (15 °F). This was primarily the result of a lower ambient relative humidity at that outside temperature. At a 25.4 mm (1 inch) level of roof insulation, humidities less than 100 percent also occurred at -20.6, -17.8, and -6.7 °C outside temperatures. As compared to no roof insulation (seen in Figure 4.25), The 50% ventilation level had inside relative humidities less than 100% at all temperatures studied. Also,the spread between building relative humidity at 100%

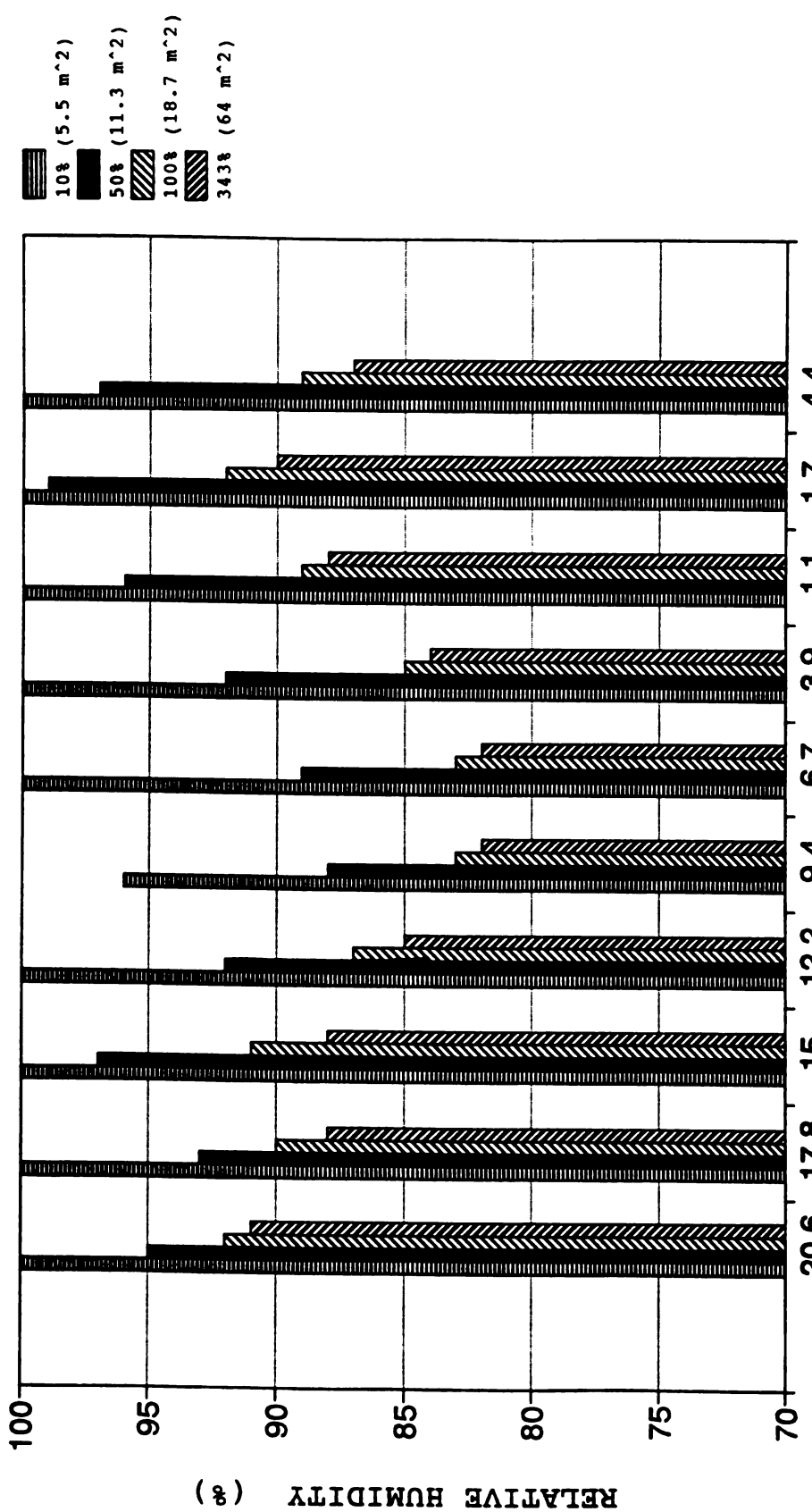


Figure 4.37 Relative Humidity at Four Ventilation Rates (10%, 50%, 100%, and 343% of fully open soffits) and 12.7 mm Roof Insulation.

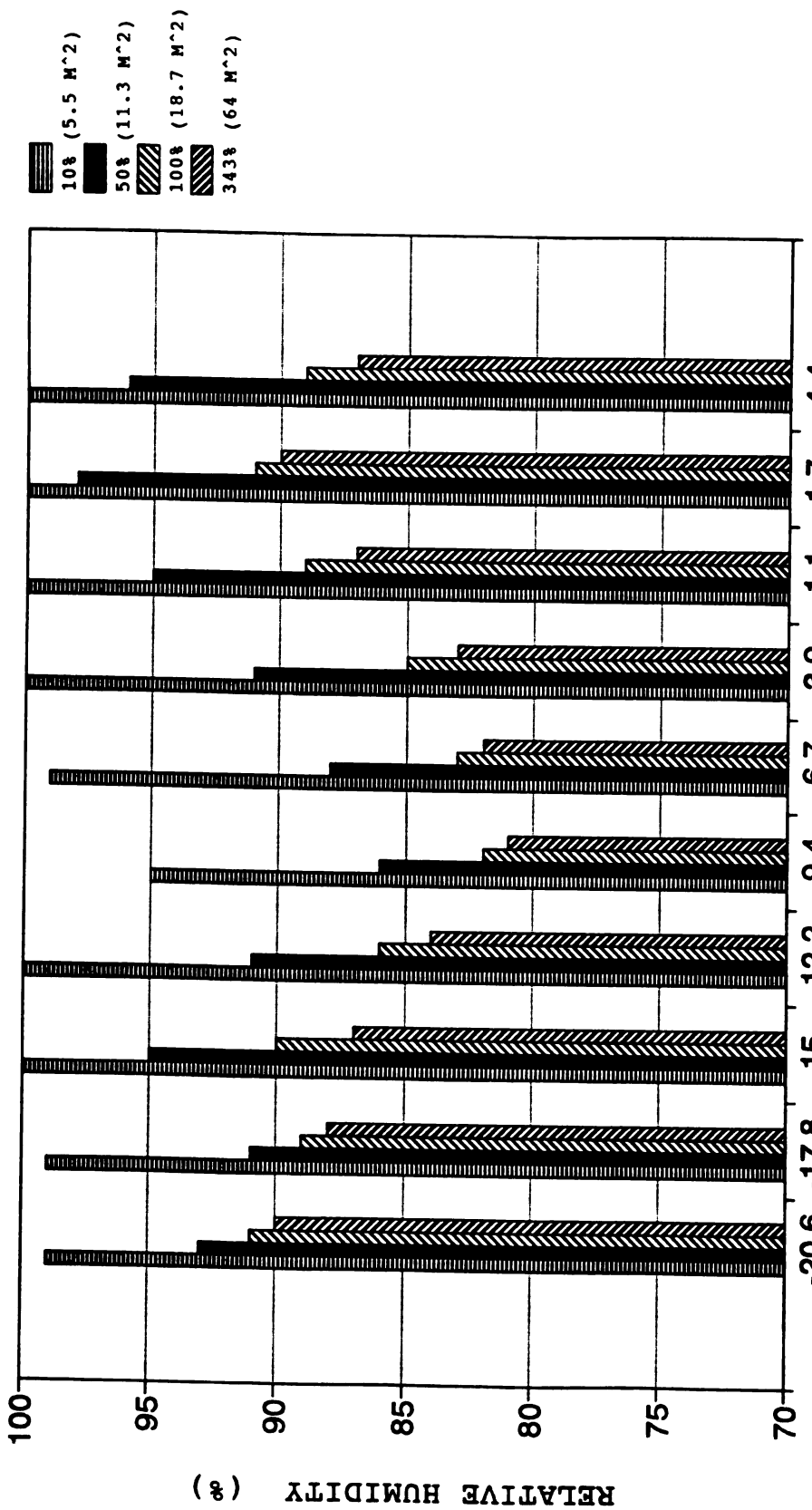


Figure 4.38 Relative Humidity at Four Ventilation Rates (10%, 50%, 100%, and 343% of fully open soffits) and 25.4 mm Roof Insulation.

and 343% vent levels, for a roof with no insulation versus an insulated roof, was noticeably less. The spread was less noticeable when the thickness of roof insulation was changed.

The primary influencing factor causing the amplitude shift in the bar graphs as temperature rose was the change in ambient relative humidity (see Table 4.8). However, another influencing factor was the changing relationship between latent and sensible heat as ambient temperature changed (see Table 4.3). For example, at -15 °C, the outside relative humidity dropped 4% and the wind speed increased 0.2 m/s (both factors that should cause building relativity humidity to drop) but Figures 4.37 and 4.38 show that the inside relative humidity at 50% and 100% ventilation levels rose. This temperature coincided with an increase in latent heat adjustment from 0.95% at -17.8 °C to 1.05% at -15 °C. A similar situation is seen between -9.4 °C and -6.7 °C where latent heat adjustment changed from 1.05% to 1.1%. Though these changes in relative humidity were relatively minor, it does show how the rate of latent heat production (i.e., quantity of animal moisture entering the air supply) impacted the building environment.

When graphing only the two extremes of ventilation conditions studied, Figure 4.39 shows the impact of ventilation opening on relative humidity. For example, at the 25.4 mm insulation level, opening up the barn caused an average decrease in building relative humidity of

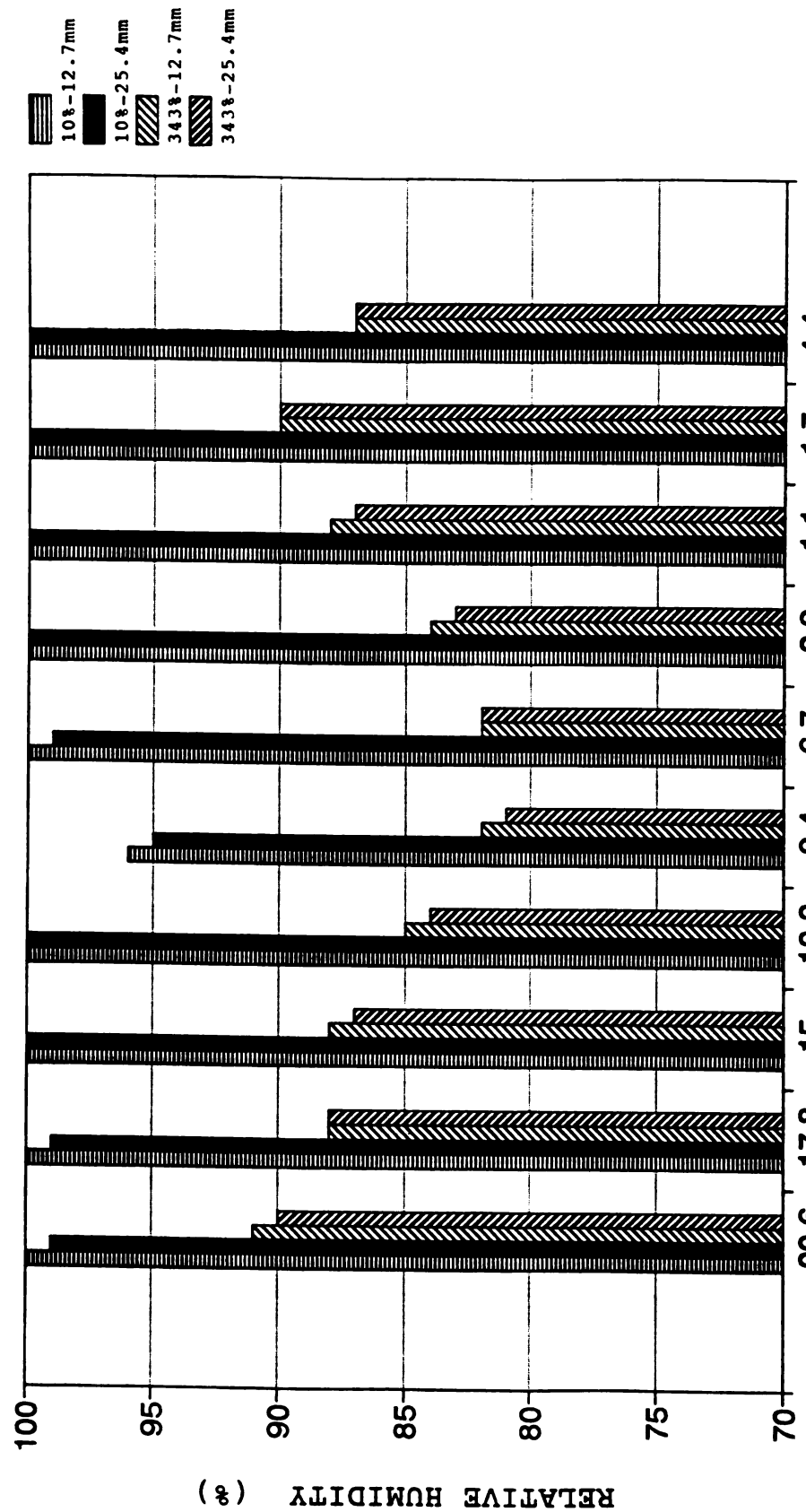


Figure 4.39 Relative Humidity at Two Ventilation and Two Insulation Levels (10% and 34% Ventilation Openings and 12.7 mm and 25.4 mm Levels of Roof Insulation).

approximately 15 percent. Also, increasing the insulation level from 12.7 mm to 25.4 mm had a minimal impact upon building relative humidity. For all practical purposes, the benefit of thicker roof insulation beyond 12.7 mm (for the purpose of reducing building relative humidity) was essentially nonexistent.

4.5.2.3 Dew Point Temperature

Scanning Figure 4.40, it can be observed that, when the ventilation rate was low, the barn with an insulated roof had noticeably higher dew point temperatures than the uninsulated barn. Between -20.6 °C and -9.4 °C the insulated barn averaged about three degrees Celsius (five degrees Fahrenheit) warmer than the uninsulated barn (see Figure 4.43). This would allow the air to hold more moisture and thus increase the dew point temperature slightly. When the barn was open, Figure 4.41 shows that there was essentially no difference in dew point temperature as the roof became insulated. Also, Figures 4.40 to 4.42 repeat the results stated earlier in this section; i.e., that increasing the roof insulation thickness from 12.7 mm to 25.4 mm produced no appreciable change, in this case, in building dew point temperature. Figure 4.42, also, illustrates that closing the barn allowed the dew point temperature to rise between approximately five and nine degrees Celsius. This was, on average, 2.4 °C higher than the uninsulated barn under the same conditions (see Section 4.5.1.3).

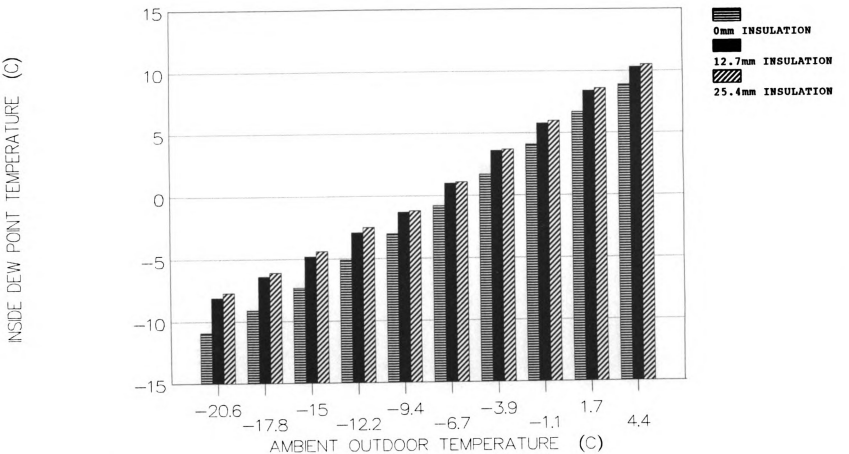


Figure 4.40 Effect of Insulation On Dew Point Temperature at the 10% Ventilation Rate and 0 mm, 12.7 mm and 25.4 mm Roof Insulation Levels.

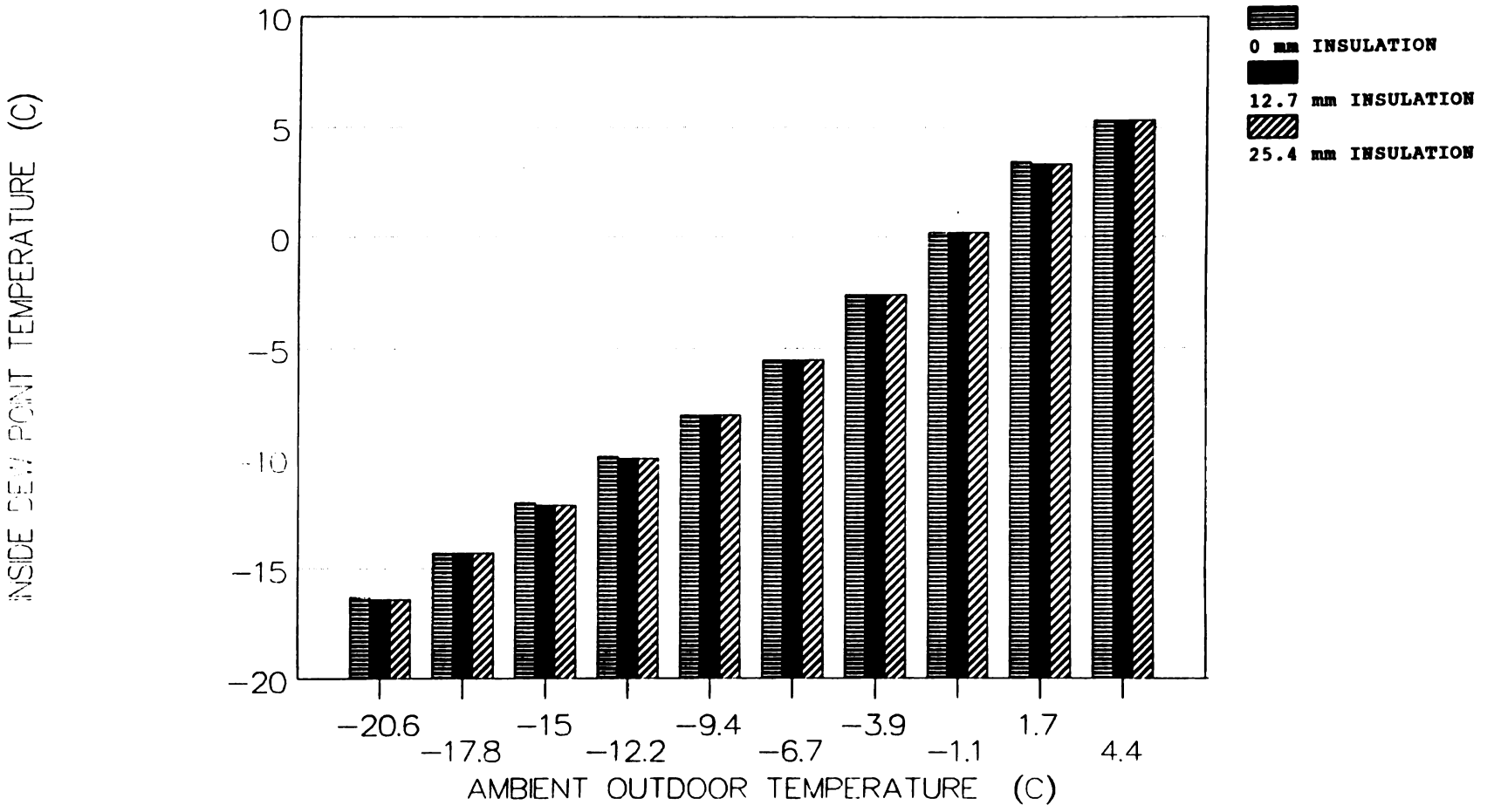


Figure 4.41 Effect of Insulation on Dew Point Temperature at the 343% Ventilation Rate and 0 mm, 12.7 mm, and 25.4 mm Roof Insulation Levels.

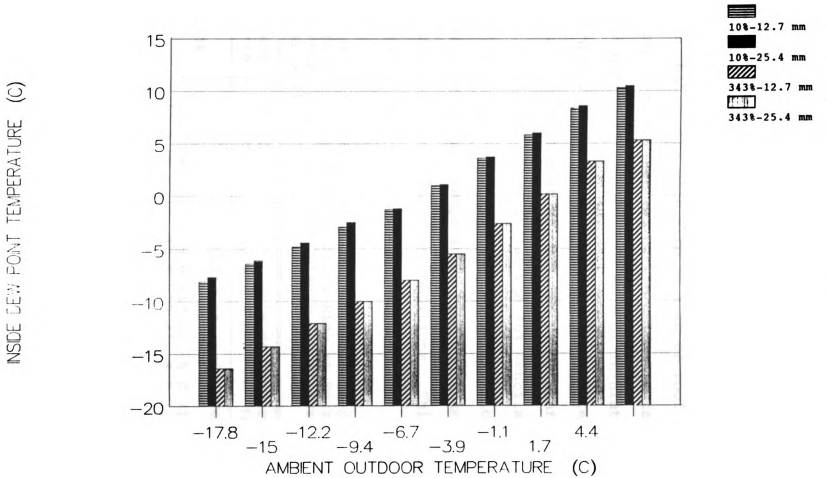


Figure 4.42 Ventilation Area and Insulation Level vs. Dew Point Temperature (10% and 343% Ventilation Rates and 12.7 mm and 25.4 mm Insulation Levels).

4.5.2.4 Inside Temperature

As seen in Figure 4.43, at the 10 percent ventilation rate, there was between 1.5 and 2.5 degrees Celsius difference between the uninsulated roof inside temperature and that of the barn with 25.4 mm of roof insulation. The largest difference was at the coldest outside temperatures. Going from 12.7 mm to 25.4 mm roof insulation, at the 10% ventilation rate, there was one half degree Celsius or less temperature rise at any outside temperature studied. Also, as noted in Table 4.17, at the 10% ventilation rate and at colder temperatures for the 50% ventilation rate there was a very significant temperature rise above ambient temperatures under all roof insulation conditions. This rise was greatest when the roof was insulated.

Table 4.17 Effect of Roof Insulation on Simulation Barn Outside to Inside Temperature Rise at Four Ventilation Opening Sizes and Three Outside Temperatures. (100% = Fully Open Soffits)

Vent Area	Insulation Level	Outside Temperature (°C) -20.6 (-5°F)	-6.7 (20°F)	4.4 (40°F)
		Outside to Inside Temperature Rise		
10%				
	0 mm	9.6 (17.2)	6.0 (10.8)	4.6 (8.2)
	12.7 mm	12.5 (22.4)	8.0 (14.4)	6.0 (10.8)
	25.4 mm	13.0 (23.2)	8.3 (14.9)	6.3 (11.2)
50%				
	0 mm	6.8 (13.5)	4.9 (8.9)	3.8 (6.8)
	12.7 mm	9.1 (16.4)	6.1 (11.0)	4.8 (8.5)
	25.4 mm	9.4 (16.8)	6.3 (11.3)	4.9 (8.8)
100%				
	0 mm	6.0 (10.5)	3.6 (6.5)	2.9 (5.1)
	12.7 mm	7.0 (12.3)	4.3 (7.6)	3.4 (6.0)
	25.4 mm	7.1 (12.5)	4.3 (7.8)	3.4 (6.1)
343%				
	0 mm	4.6 (8.2)	3.0 (5.4)	2.5 (4.5)
	12.7 mm	5.1 (9.2)	3.5 (6.3)	2.9 (5.1)
	25.4 mm	5.2 (9.3)	3.6 (6.4)	2.9 (5.2)

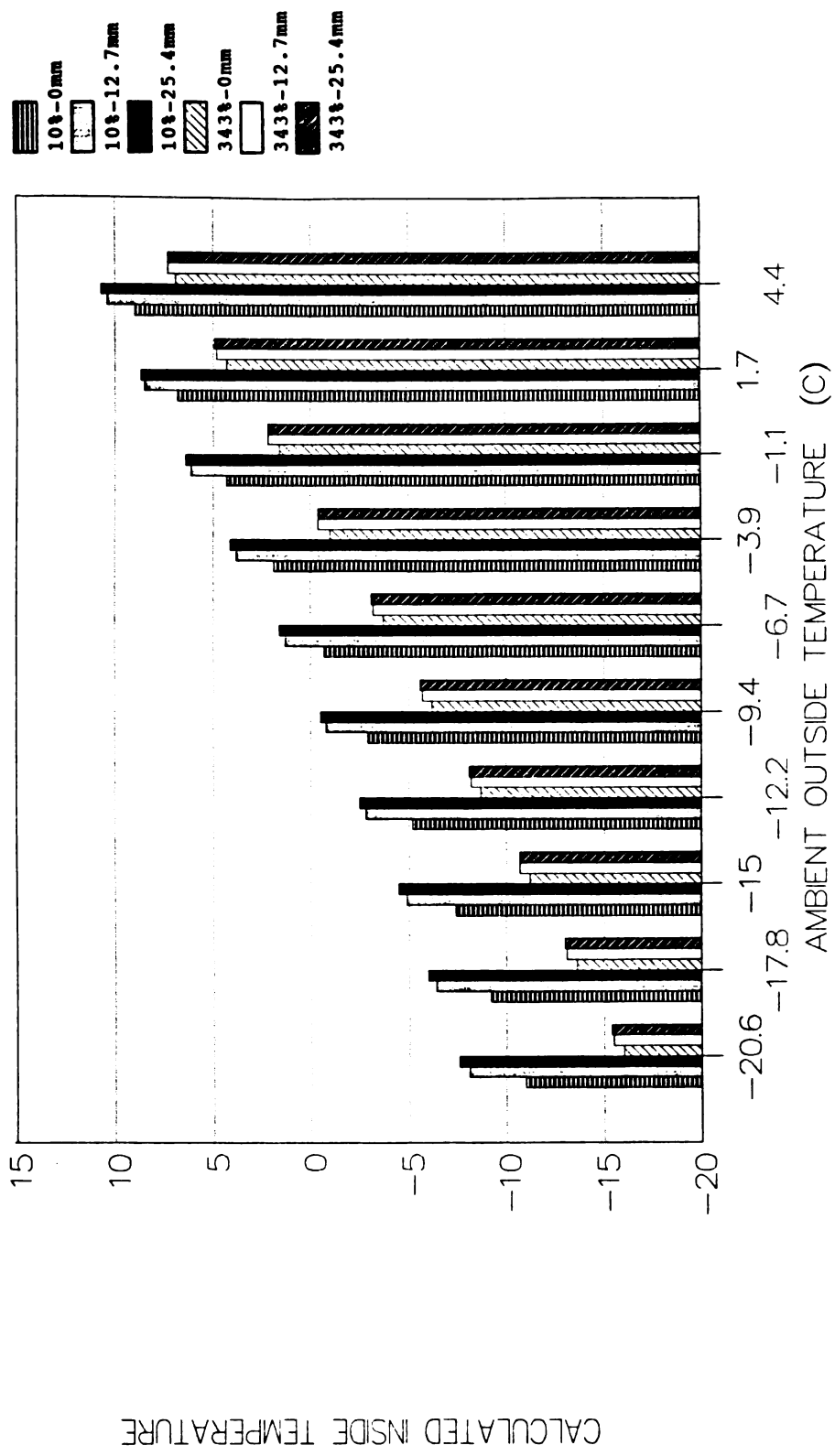


Figure 4.43 Inside Building Temperature at 10% and 343% Ventilation Rates and 0 mm, 12.7 mm, and 25.4 mm Roof Insulation Levels.

Opening up the barn to a ventilation rate of 343 percent obviously cooled the building down. The outside to inside temperature rise was considerably less and there was only a negligible increase in inside temperature when the roof insulation level was increased from 12.7 mm to 25.4 mm.

4.5.2.5 Carbon Dioxide Concentration

Similar results are seen with the insulated barn roof as were seen in the uninsulated building. As discussed in section 4.5.1.5, the carbon dioxide concentration was directly affected by the ventilation rate. Looking at Figure 4.44, the rise in building temperature caused by roof insulation allowed for an increase in stack effect ventilation and consequently a decline in carbon dioxide concentration. At the 10 percent ventilation rate, under colder temperatures, the increased ventilation resulting from added roof insulation amounted to a decrease in CO_2 concentrations of approximately 100 ppm. As the ambient temperature increased, the influence of stack effect ventilation decreased and consequently the effect of roof insulation on building CO_2 also declined to approximately a 30 ppm difference between no insulation and 25.4 mm.

When building ventilation was very open, there was even less difference in building temperature caused by adding roof insulation, and consequently only insignificant declines in building CO_2 concentration resulted as roof insulation was added. Similarly, doubling the thickness of roof insulation showed barely visible declines in the barn

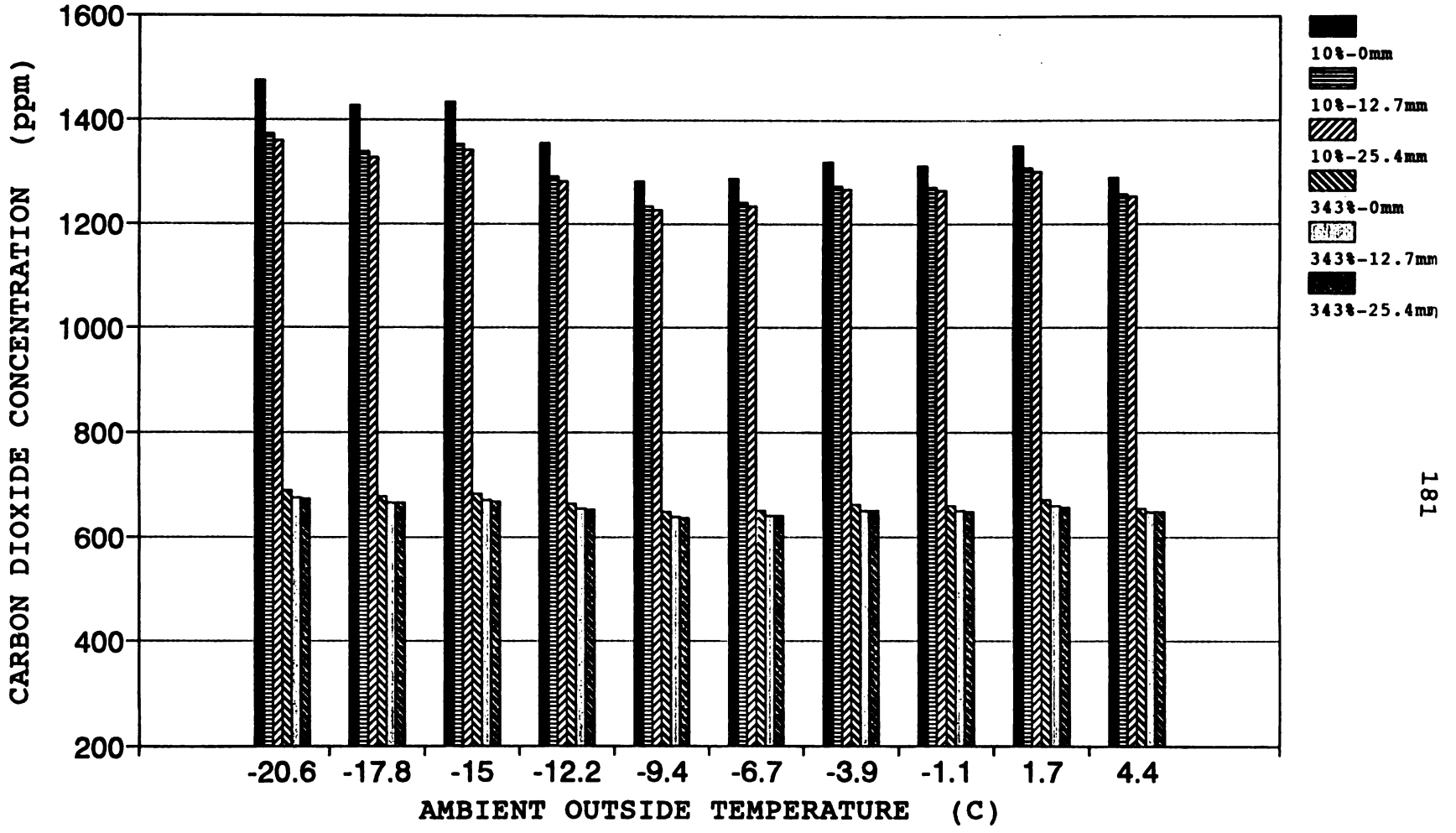


Figure 4.44 Carbon Dioxide Concentration at 10% and 100% Ventilation Rates and 0 mm, 12.7 mm, and 25.4 mm of Roof Insulation.

CO_2 concentration.

4.5.2.6 Air Exchange Rate

The air exchange in the barn with an insulated roof was very similar to the air exchange rate of the uninsulated building. Figure 4.45 illustrates this. As in other examples, the increase in roof insulation thickness was of little effect in modifying the air exchange rate. Also, a very noticeable observation from Figure 4.45 was the large difference in air exchange rate as the ventilation opening area went from 10 percent to 343 percent. The air exchange rate was slightly higher for the insulated barn because of the increased stack effect ventilation; but the approximately three fold increase in air exchange rate as the ventilation area was increased was very consistent regardless of roof insulation considerations. Also, as would be expected, the fluctuation in air exchange copied the fluctuation in outside wind speed. As the wind speed increased the air exchange increased and as the wind speed decreased so did the air exchange. At warmer temperatures this effect was somewhat dampened. For example, the wind at -9.4 °C and -1.1 °C were the same (3.4 m/s (7.7 mph)) but the air exchange was slightly less at -1.1 °C. Also, the highest wind value in this study (3.7 m/s (8.2 mph)) was at 4.4 °C but the air exchange rates at -9.4 °C and -6.7 °C were greater. The reduced livestock sensible heat production as building temperature rose, and subsequent reduction in stack effect ventilation, would explain this condition.

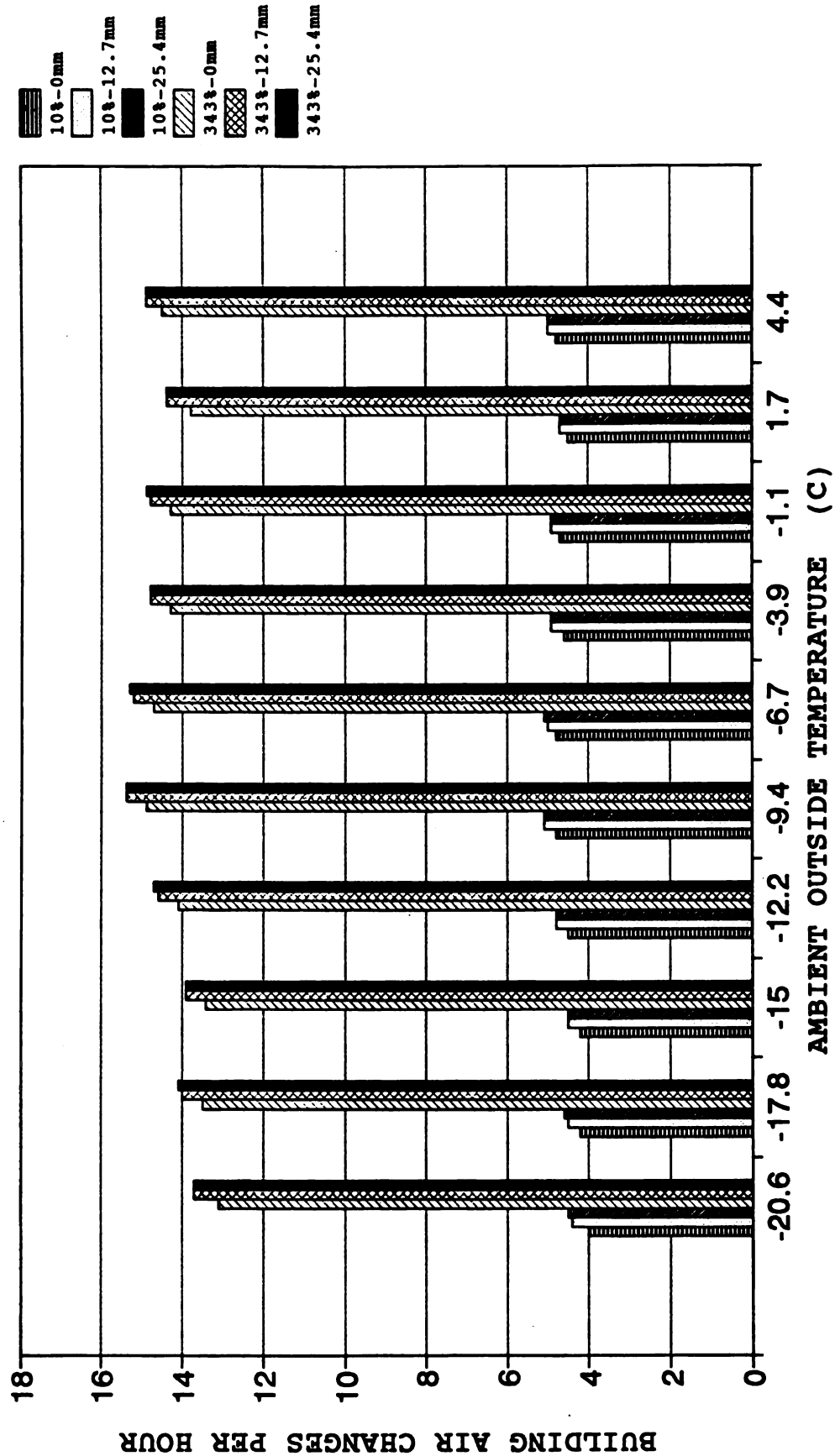


Figure 4.45 Building Air Exchange at 10% and 343% Ventilation Rates and 0 mm, 12.7 mm, and 25.4 mm of Roof Insulation.

4.6 Simulation Model Applications

As illustrated in Figure 3.1, many variables affect the existing environment within a naturally ventilated cold confinement freestall dairy barn at any one moment in time. Because of those dynamics, it is difficult to accurately model a changing environment within a barn. Consequently, for this research steady state modeling under "average" conditions was used. However, average environmental conditions do not represent actual environmental conditions within a given cold confinement freestall dairy barn. Therefore, in portions of the sections to follow, extremes, as opposed to averages, are used to better describe the range of real life environments within a confinement cattle facility.

4.6.1 Effect of Inlet Area Restrictions Upon Condensation Potential

Under the weather conditions of this research, with an uninsulated roof and ambient temperature of -17.7 °C, roof frost would have been a certainty at all ventilation areas studied (see Figure 4.23). Closing vents less than 343% of full soffit area, even at 4.4 °C, created a potential condensation problem for the uninsulated barn. In fact, at 4.4 °C or lower, ventilation openings of approximately 70% or less of full soffit area would have caused frost to occur every winter night this research included (see Figures 4.21 to 4.23).

Insulating the roof reduced the potential for

condensation or frost conditions exhibited by the uninsulated roof (see Figures 4.31 to 4.36). However, even with 24.5 mm of roof insulation, there was approximately a 25% to 75% chance of frost accumulation in the model barn when the outside temperature was at or below -17.6 °C. The possibility became even more pronounced as the ventilation rate was reduced. As the ambient temperature increased, roof insulation caused the potential for roof condensation to decrease. Still, at ventilation rates less than fully open soffits and doors, roof insulation did not eliminate the potential for roof frost formation, even at 4.4 °C

Another barn environmental condition of interest often occurs during the springtime snowmelt period when thawing conditions promote high relative humidities. Figures 4.46 and 4.47 illustrate such weather conditions at 4.4 °C. It can be seen from Figure 4.46 that, at 95% ambient relative humidity and calm winds, roof dripping would have been expected each night in the uninsulated barn having full soffit ventilation or less. Even with the end doors open, there was about a 75% chance of roof condensation under such high humidity and low wind conditions. Insulating the roof to 25.4 mm did reduce the condensation probability at each ventilation level but the likelihood of not having condensation problems was still best at the 343% ventilation rate. If, on the other hand, had the weather been dryer and windy (70% ambient relative humidity and 6.8 m/s wind speed), as shown in Figures 4.48 and 4.49, either an

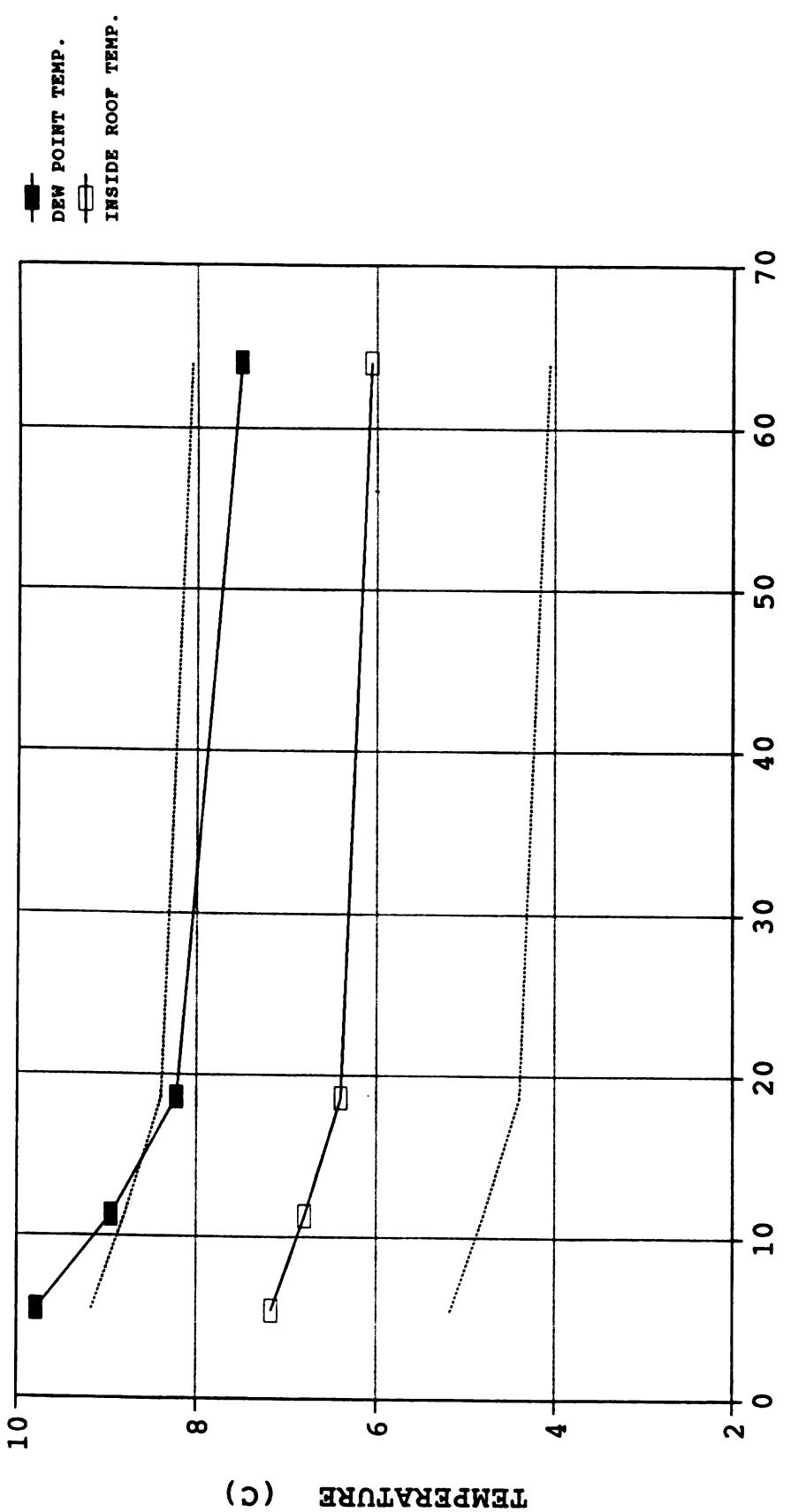


Figure 4.46 Uninsulated Barn Roof Temperature and Dew Point Temperature at Outside Conditions of: 4.4°C, 1.4 m/s Wind Speed, and 95% Relative Humidity.

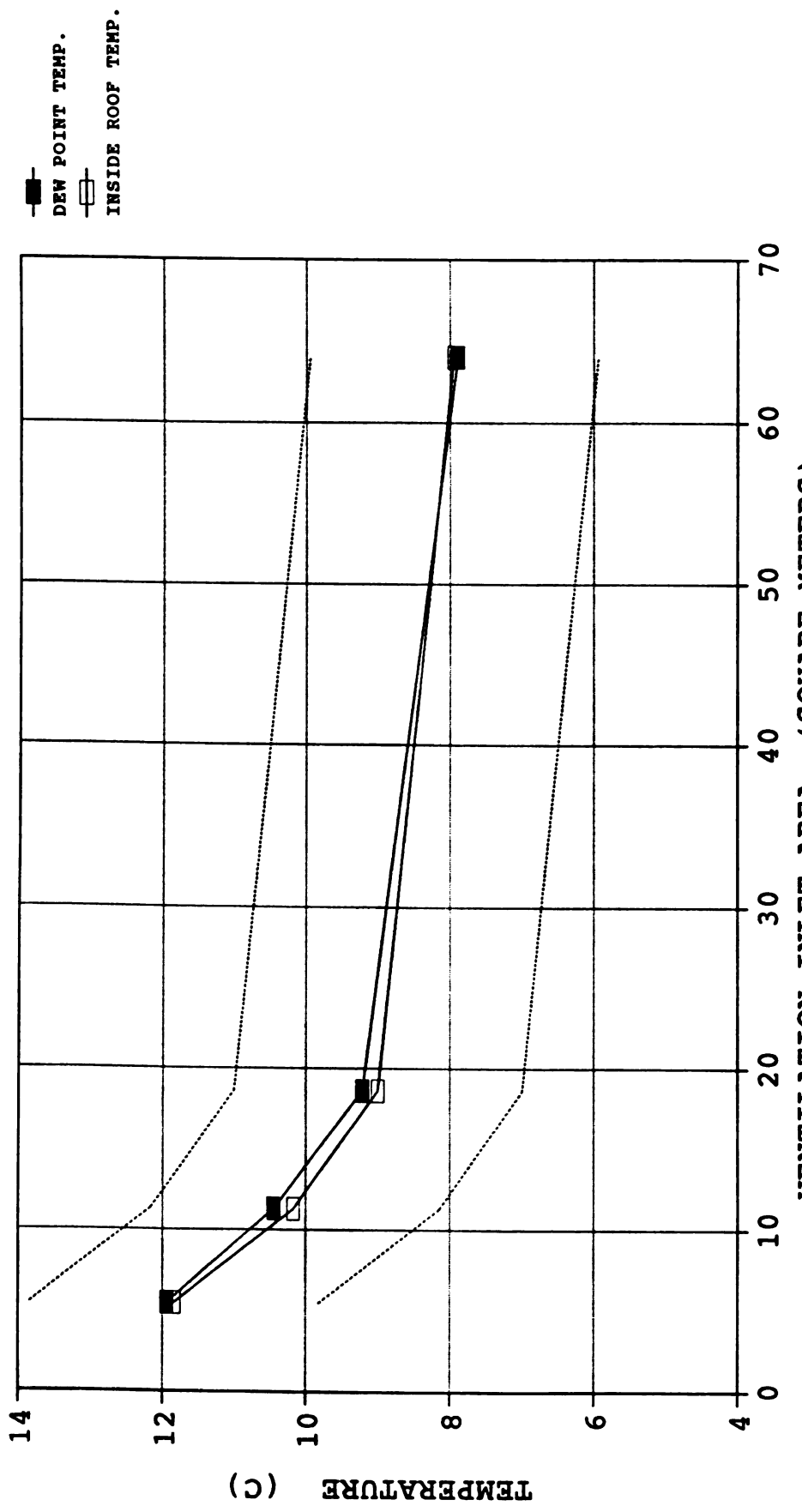


Figure 4.47 Insulated Barn Roof Temperature and Dew Point Temperature at Outside Conditions of: 4.4°C, 1.4 m/s Wind Speed, and 95% Relative Humidity.

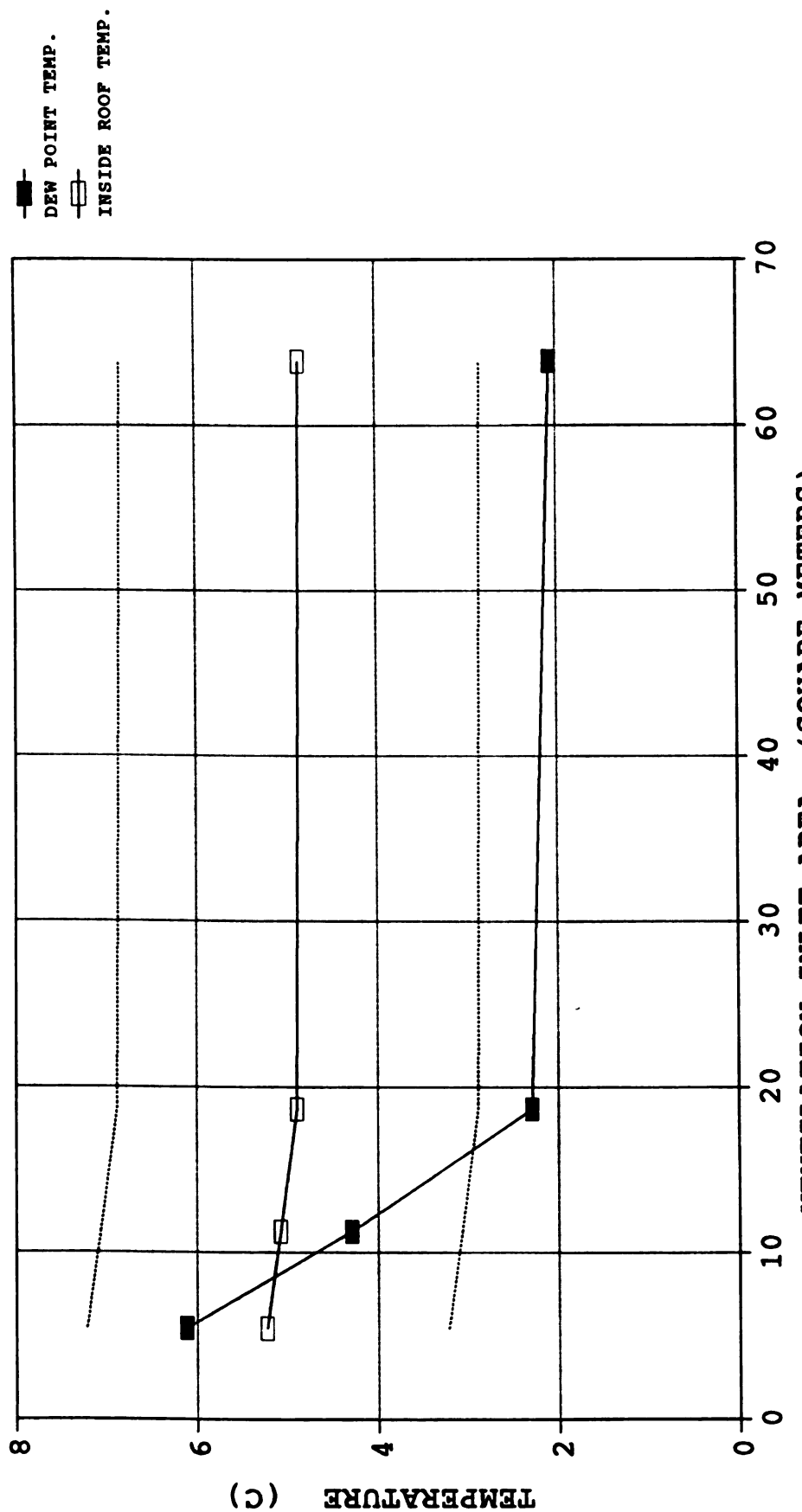


Figure 4.48 Uninsulated Barn Roof Temperature and Dew Point Temperature at Outside Conditions of: 4.4 °C, 6.8 m/s Wind Speed, and 70% Relative Humidity.

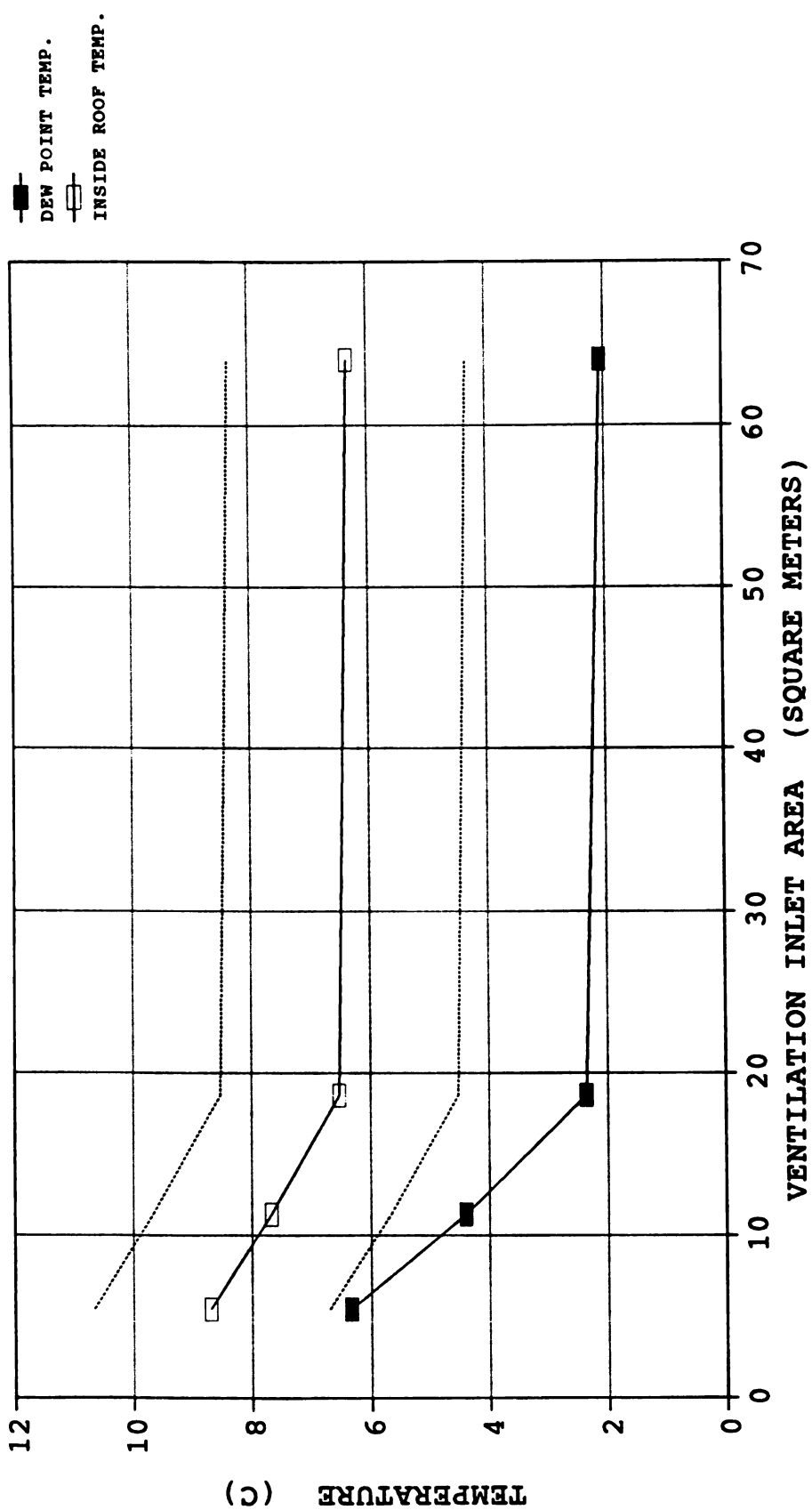


Figure 4.49 Insulated Barn Roof Temperature and Dew Point Temperature at Outside Conditions of: 4.4 °C, 6.8 m/s Wind Speed, and 70% Relative Humidity.

insulated or uninsulated barn would have been condensation free down to full soffit ventilation rates (100% ventilation). Though the insulated barn would have remained condensation free even at a 10% ventilation area, at ventilation rates more restricted than 100%, the uninsulated barn would have had potential condensation problems since dew point temperatures were within the 2 °C envelope of the roof temperature.

In summary, under the weather conditions (see Tables 4.7 and 4.8), milk production, and stocking density studied in this research, reducing the ventilation openings to less than full soffit area imposed a high risk for roof condensation, even at roof insulation levels of 24.5 mm. The least risk occurred at the largest ventilation opening. The variables that changed roof temperature would have an impact upon exactly when roof condensation occurred.

4.6.2 Effect of Inlet Area Restrictions Upon Air Quality

Looking at the effect of ventilation area restriction upon relative humidity, Figure 4.25 illustrates that, for an uninsulated building at 10% open soffits, the relative humidity never dropped below saturation, and at 50% open soffits, the relative humidity never dropped below 97%. The insulated building showed similar conditions when the ventilation rate was restricted to 10% of full soffit area (see Figure 4.38).

As discussed in Section 2.1, airborne bacteria survive best at relative humidities above 90% and may multiply in

building dust when humidities approach saturation. The ventilation opening that caused the relative humidity to least exceeded that 90% threshold (and theoretically provided the poorest pathogen environment) was the 343% ventilation rate. Also, at that ventilation rate, the difference in building relative humidity between an insulated and noninsulated barn roof was only approximately 3%. The roof insulation had an increasing impact, however, on reducing building relative humidity as the ventilation rate was reduced. Also, the only situation where relative humidity didn't reach 100%, at any of the outside temperatures studied, was when the ventilation rate was at 343%.

Another ventilation parameter affected by inlet area that has an impact on barn pathogen levels was air exchange. Concentration dilution reduces the potential for airborne pathogen related health problems. Curtis (1972) states that, at best, one air exchange could theoretically reduce the concentration of air pollutants by 63.2%. If outside air is assumed to be the most diluted and contain the lowest pathogen concentration, the ventilation scheme that produces the greatest air exchange possible, while not producing excessive drafts, would seem to be the most logical choice. At 10% soffit openings, one air exchange took approximately twelve to fifteen minutes. This time was reduced to five to seven minutes at 100% soffit ventilation and to four to five minutes at the 343% ventilation rate. This would mean that

the open barn would have about three air exchanges for every air exchange of the 10% ventilation building. As the relationship between minimum acceptable air exchange and pathogen concentration is not well defined, if all other things are held constant, it would seem that the best choice of ventilation scheme would be one that created the greatest pathogen dilution. This assumption could be used as one component in a decision making process regarding building ventilation design. The assumption would promote an open ventilation scheme.

Noxious gas concentration is another variable affected by ventilation area. Depending on author, Table 2.2 suggests a maximum acceptable carbon dioxide concentration between 2000 ppm and 3000 ppm. Under the conditions of this study, a CO_2 concentration of slightly under 1500 ppm was the maximum value obtained. This was arrived at for the uninsulated barn with 10% ventilation, -20.6 °C ambient temperature, and a 2.0 m/s wind speed. Had there been no wind, the concentration would have been at 1780 ppm. While still using 10% of fully open soffit area ventilation, but using 4.4 °C ambient temperature and no wind, the carbon dioxide level for the uninsulated barn would have been 1971 ppm. The condition that produced the lowest carbon dioxide concentrations was at the greatest ventilation rate.

From those calculations it is evident that, in most cases, carbon dioxide toxicity is not an issue for even a very poorly ventilated barn. A word of caution, however,

might be the statement by Clark and McQuitty (1987) that the long term effects of low concentrations of noxious gases on dairy cattle have not yet been determined.

Summarizing the extremes of the values discussed, reducing the ventilation openings from 343% to 10% increased the carbon dioxide concentration 2.8 times, kept building relative humidity above ninety five percent, and reduced the air exchange to less than a third of the 343% value.

4.6.3 Management Decisions Affected by Adding Roof Insulation

For a cold confinement freestall dairy barn in the planning stages, an initial decision may be whether or not to install roof insulation and, if so, what resistance value should be chosen. The choice to include roof insulation may be based on a desire to reduce roof condensation and dripping or to raise building temperature as an aid in manure management, equipment operation, or human or livestock comfort. The decision may result from observing other dairy barns, from advice of others, or simply a personal choice. Whatever the reason, if roof insulation is added, there will be an environmental impact within the building that must be understood.

Insulation allows the building to be operated at lower ventilation rates without having roof dripping occurring. But at lower ventilation rates, the air exchange will be less, carbon dioxide and other noxious gas concentrations will increase, and building moisture load will increase.

The building will have a higher inside temperature than had it not been insulated. Stack effect ventilation and air exchange will increase and relative humidity will decrease somewhat. If ventilation openings were compromised at warmer temperatures, prolonged underventilation conditions with high relative humidities and trapped free water may extend pathogen life, increase pathogen multiplication, and promote building deterioration.

If the purpose of roof insulation is to reduce roof dripping (when the ventilation rate was decreased) so that the barn could be operated at warmer temperatures, a new set of management decisions is created. Management decisions of importance may now include: When does the barn moisture level become excessive? What are the levels of noxious gasses? Is building decay occurring? Is air exchange sufficient for pathogen control?

If the purpose of roof insulation is to reduce roof dripping (when the ventilation rate was decreased) so that the barn could be closed for inclement weather, still another set of management decisions is created. In this context the insulation has allowed a degree of management flexibility. A wider range of inside temperatures and relative humidities could be tolerated with little roof dripping. Along with this flexibility comes the responsibility of understanding the effects of pathogen concentrations, noxious gas concentrations, and moisture levels upon buildings and livestock, and the need to improve

the ventilation conditions as weather conditions improve.

4.6.4 Ventilation Management Recommendations

Given the range of potential weather conditions, total elimination of the risk of roof condensation would be very difficult and probably unnecessary. Also, condensation can be as useful a tool as a low fuel warning light when used as a visual aid in ventilation management. Roof insulation would tend to compromise the effective use of that management tool.

To include the offsetting effect of daytime drying, a concept of managed roof condensation needs to be developed. If condensation or frost occured at night, the building ventilation openings should be increased during the daylight hours so that typically warmer temperatures can promote structural drying and reduced building humidity and pathogen content. If ventilation openings were reduced due to inclement weather or for livestock control, confinement, or security reasons, the onset of dripping or frost accumulation on an uninsulated roof would be a signal that it is time to increase building ventilation openings. In this management scheme, fully open soffits and ridge should be considered a minimum rate of ventilation. Other wall openings should be increased as condensation or frost became obvious. The maximum ventilation opening would be when the health or cleanliness of the cattle was being compromised by excessive drafts or dust (blown silage, ground feed, soil, dry manure, etc.), rain, snow, or other gas (diesel fumes,

methane gas, anhydrus ammonia gas, etc.) or particle contaminents. The livestock structure is a form of animal shelter and confinement. The more open the confinement structure, while still providing necessary environmental protection, the better will be the quality of ventilation air and consequently the quality of the livestock environment. A building design should also allow for convenient adjustment to the ventilation area. Feed alley and cattle alley overhead doors with motor driven openers and side wall, end wall, and gable curtains or panels that are cable operated would be examples of equipment that would allow for convenience in management of cold confinement dairy barn ventilation.

V. SUMMARY AND CONCLUSIONS

5.1 Summary

In this research, a mathematical model that predicted the nighttime environmental parameters of ventilation rate, air changes per hour, relative humidity, absolute humidity, interior air temperature, dew point temperature, and carbon dioxide concentration for a modern freestall dairy barn, in wintertime climates similar to the lower peninsula of Michigan, was formulated and validated. Based on this information and calculated roof inside surface temperature, the effects of different ventilation rates and roof insulation levels were analyzed for outside temperatures between -20.6 °C and 4.4 °C. From this analysis it was determined that uninsulated barns, similar to the simulation barn, required at least the largest ventilation area studied in this research to minimize the potential of roof condensation or frost. Likewise, the lowest building relative humidity was achieved at the largest ventilation area and, at best, a 50% ventilation rate allowed inside relative humidity to drop to only 97% (a 10% ventilation rate kept relative humidity at saturation). Also, as ventilation openings were reduced from 343% to 10%, carbon dioxide concentration more than doubled, air exchange was

reduced by two thirds, and at -20.6 °C ambient temperature, building temperature rise went from 4.6 °C (8.2 °F) to 9.6 °C (17.2 °F).

A similar building with roof insulation thickness of 25.4 mm (RSI of 1.27 $m^2 \cdot K/W$) and ventilated with fully open soffits and closed end doors would have had a high probability of maintaining a condensation free roof down to approximately -6.7 °C. Below that temperature, the barn ventilation area would need to be increased to minimize roof condensation.

Humid and calm ambient conditions necessitated an open ventilation approach at all roof insulation levels to reduce roof condensation. During dry and windy conditions, closing the ventilation openings down to 10% of fully open soffits did not produce a condensation problem for the 25.4 mm (1.27 $m^2 \cdot W/K$) insulated roof. The uninsulated roof, however, needed fully open soffits or greater to reduce the probability of roof frost under equal weather conditions.

Closing the ventilation openings to 10% of fully open soffits in an insulated barn similar to the model barn, as compared to having soffits, ridge, one downwind feed alley door and four downwind cattle alley doors open, cut the air exchange by two thirds, kept inside relative humidity above 95% (often at 100%), and caused carbon dioxide concentrations to more than double. For the temperature range studied, the average inside temperature rise went from 3.9 °C (7.0 °F) at 343% ventilation to 9.2 °C (16.4 °F) at

10% ventilation (at -20.6 °C the rise was 13 °C (23.2 °F)). Increasing the roof insulation from 12.7 mm (R(SI) 0.63 $m^2 \cdot K/W$) to 25.4 mm (RSI 1.27 $m^2 \cdot K/W$) caused minimal improvement in any of the environmental parameters studied.

5.2 Conclusions

1. A model was developed to calculate nighttime environmental conditions during winter in a cold confinement freestall dairy barn. The model had an average standard error for determining inside relative humidity of 2.4% and an average standard error for determining inside temperature of 0.7 °C. Carbon dioxide concentration calculations averaged 29 ppm above measured values and roof temperature calculations yielded answers two and one half degrees celsius above to three quarters of a degree celsius below measured values (depending upon sky condition measurements used for comparison).

2. Roof insulation thickness of 12.7 mm (R(SI) = 0.63 $m^2 \cdot K/W$ ($R = 3.6\ °F \cdot ft^2 \cdot h$)) reduced the probability of roof condensation to less than 100% when ventilation openings of less than fully open soffits were the only ventilation openings allowed. Doubling the insulation thickness caused relatively insignificant reductions in the potential formation of condensation or frost on the roof. Also, roof insulation did not eliminate the potential for roof condensation, but did provide the ability to reduce building ventilation without developing roof condensation. When the ventilation restriction was not extreme, the increased

building temperature (resulting from added insulation) increased stack ventilation and reduced building relative humidity.

3. Open soffits, ridge, and end doors (343% ventilation level) provided the lowest potential risk for roof condensation in an uninsulated barn. This amount of ventilation openings should be considered as a minimum recommendation for freestall dairy barns with uninsulated roofs.

4. Closing the barn ventilation to less than full soffit area excessively reduced the air exchange, maintained inside relative humidities at unhealthy levels, and prolonged a damp, virulent, condensing environment that was potentially detrimental to the structure, animal productivity, and maximum economic gain. Conversely, the ventilation rate that provided the lowest carbon dioxide concentration, lowest relative humidity, and the greatest air exchange was the open (343%) ventilation scheme.

5. Considering the range of potential weather conditions, managed roof condensation should be the plan in an uninsulated cold confinement barn. The building's ventilation openings should be increased when roof dripping or frost accumulation occurs and during favorable daytime weather conditions. Maximum vs. minimum ventilation should be the emphasis. Conveniently operated ventilation openings

should be a design consideration for uninsulated cold confinement dairy barns.

VI. AREAS FOR FURTHER RESEARCH

The following is a list of areas for further study as identified through this research project:

1. Empirical data need to be gathered to allow conclusive validation of mathematical models predicting inside roof surface temperature. These research data should include the measurement of onset and quantity of frost and/or condensation. A list of necessary field data might include: instrumentation and/or observation of hourly nighttime roof inside surface temperature, time of onset and duration of frost or condensation and amount of condensate, inside relative humidity near the roof at locations low, mid, and upper roof, and at several sites along the building, cloud cover, outside roof surface conditions (snow depth, ice depth, wet,... etc.), inside and outside surface wind speeds and near-roof air temperatures.

2. Conditions appropriate for frost/condensation have been demonstrated by this research and building deterioration conditions have been identified in research done by Harrigan (1985). Further research needs to be done to develop a rate of decay model; i.e., during what conditions and duration does roof condensation change from a nuisance to a structural degradation issue. Within this study, the effects of favorable daytime drying conditions

that offset the nighttime condensation formation problem needs to be studied to develop the concept of managed roof condensation. Work by Fujita and Nara (1993), regarding the heat balance of barn roofing materials, may be useful in accomplishing these first two research areas.

3. A quantifiable value needs to be developed that expresses the impact of inadequate ventilation on cattle productivity. Productivity might be defined as a balance sheet of income from milk, extended productive life and offspring versus losses from cattle health maintenance expenses, reduced productive life, and offspring related losses. Once a value is given to adequate ventilation, a break even cost could be given to various forms of ventilation controls and structural designs that impact adequate ventilation. Modeling work done by Turner et al. (1993) regarding the economic impact of respiratory diseases on swine and a computer model by Jalvingh (1992) regarding decision making in dairy cattle production, may be useful for this purpose.

4. Empirical research needs to be done to provide a more inclusive list of pressure coefficients for low profile structures with various size wall and roof openings and length to width ratios.

5. To better understand the interaction between a barn and the livestock occupying the structure, accurate values need to be determined for the amount of latent and sensible heat production of moderate and high producing dairy cattle

under cold housing conditions during wintertime. The temperature range should include values to -34.4 °C (-30 °F).

APPENDICES

APPENDIX A

Sample Thermal Buoyancy Calculation Results

APPENDIX A

Sample Thermal Buoyancy Calculation Results

RIDGE OPENING % MAX	COEFFICNT OF DSCHRG AT PEAK	OPEN AREA AT PEAK M^2	COEFFICNT OF DSCHRG AT PEAK	OPEN AREA AT EAVE M^2	INITIAL EXHAUST VEL m/s	OUT AIR DENSITY Po kg/m^3	OUTSIDE TEMP To (K)	OUTSIDE TEMP To (F)	OUTSIDE TEMP (C)	ACCEL OF GRAVTY g m/s
100%	0.65	22.97	0.65	19.30	1.00	1.34	255.37	0.00	-17.78	9.80
100%	0.65	22.97	0.65	19.30	1.19	1.34	255.37	0.00	-17.78	9.80
100%	0.65	22.97	0.65	19.30	1.10	1.34	255.37	0.00	-17.78	9.80
100%	0.65	22.97	0.65	19.30	1.12	1.34	255.37	0.00	-17.78	9.80
100%	0.65	22.97	0.65	19.30	1.12	1.34	255.37	0.00	-17.78	9.80

IN/OUTLET HT DIFF delta h m	CATTLE WEIGHT Kg	NUMBER OF HEAD	SENSIBLE HEAT PRODUCED W	BLDG HEAT LOSS W/m^2-K	SPECIFIC HEAT AIR CP J/kgK	QUADRADIC VALUES a	b	c	IN AIR DENSITY Pi kg/m^3	INSIDE TEMP T2 (K)
5.11	610.00	160.00	207406.70	4602.00	1006.00	1.06	101.16	-134.21	1.31	261.45
5.11	610.00	160.00	200971.43	4602.00	1006.00	1.49	101.56	-134.21	1.30	263.88
5.11	610.00	160.00	197132.90	4602.00	1006.00	1.27	101.36	-134.21	1.30	262.65
5.11	610.00	160.00	199183.45	4602.00	1006.00	1.32	101.40	-134.21	1.30	262.94
5.11	610.00	160.00	198717.03	4602.00	1006.00	1.31	101.40	-134.21	1.30	262.91

INSIDE TEMP T2 (C)	ERROR FLAG SENSIBLE HT LOSS	INSIDE TEMP T4 (F)	V2 NUMERATOR	V2 DENOM A	V2 DENOM B	FINAL VELOCITY V2 m/s	FINAL AIR VOLUME m^3/s
-11.70	-11.70	10.94	20773025.6	2.38	24261.06	1.19	17.71
-9.27	-9.27	15.31	20128494.4	2.37	27703.85	1.10	16.36
-10.50	-10.50	13.10	19744043.2	2.38	26039.66	1.12	16.69
-10.21	-10.21	13.62	19949417.8	2.38	26448.06	1.12	16.65
-10.24	-10.24	13.56	19902702.7	2.38	26401.00	1.11	16.64

APPENDIX B

Simulation Barn Specifications

APPENDIX B

Simulation Barn Specifications

Dimensions: 27.4m X 53.6m (90' X 176')

Building Design: four row, drive-through, freestall

Building Capacity: 160 freestalls with 160 cows

Sidewall Height: 3.03m (10')

Winter Ventilation Openings:

1. Soffits: 48m X 0.15m (net area) continuous per side (157.7' X 0.5')
2. Ridge: 51.9m X 0.46m (net area) (170.4' x 1.5')
3. Doors:
    1. Feed alley: two at 4.3m x 3.7m (14' x 12')
    2. Cattle alley: eight at 2.4m x 3.1m (8' x 10')

Overall Height: 8.2m (27')

Area Comparisons:

1. Soffits represent five percent of wall area
2. One alley door: 15.6 m^2 (168 ft^2)
3. One cattle alley door: 7.4 m^2 (80 ft^2)
4. 20% of end wall area: 15.6 m^2

Building Material: Non-breathing curtain sidewalls, sheet metal siding on gable ends, fiberglass doors

Heat Loss Calculations:

	wind speed					
	calm		3.3m/s		6.75m/s	
ROOF:(uninsulated)	RSI	(R)	RSI	(R)	RSI	(R)
Outside air film	0.11	0.62	0.04	0.25	0.03	0.17
Steel	0.00	0.00	0.00	0.00	0.00	0.00
Inside air film	0.11	0.62	0.11	0.62	0.11	0.62
RSI (R) Total	0.22	1.24	0.15	0.87	0.14	0.79
U Total (W/K)	4.55		6.49		7.14	

	wind speed					
	calm		3.3m/s		6.75m/s	
ROOF:(insulated)	RSI	(R)	RSI	(R)	RSI	(R)
Outside air film	0.11	0.62	0.04	0.25	0.03	0.17
Steel	0.00	0.00	0.00	0.00	0.00	0.00
Insulation (13mm)	0.63	3.6	0.63	3.6	0.63	3.6
(25mm)	1.27	7.2	1.27	7.2	1.27	7.2
Inside air film	0.11	0.62	0.11	0.62	0.11	0.62
RSI (R) Total (13mm)	0.85	4.84	0.78	4.48	0.77	4.39
RSI (R) Total (25mm)	1.49	8.44	1.42	8.07	1.41	7.99
U Total (13mm)(W/K)	1.18		1.26		1.30	
U Total (25mm)(W/K)	0.67		0.70		0.71	

APPENDIX B (Continued)

	wind speed					
	calm		3.3m/s		6.75m/s	
SIDEWALLS:	RSI	(R)	RSI	(R)	RSI	(R)
Outside air film	0.12	0.68	0.04	0.25	0.03	0.17
Curtain sidewall	0.00	0.00	0.00	0.00	0.00	0.00
Inside air film	0.12	0.68	0.12	0.68	0.12	0.68
RSI (R) Total	0.24	1.36	0.16	0.93	0.15	0.85
U Total (W/K)	4.17		6.10		6.67	

	wind speed					
	calm		3.3m/s		6.75m/s	
WALL FRAMING:	RSI	(R)	RSI	(R)	RSI	(R)
Outside air film	0.12	0.68	0.04	0.25	0.03	0.17
38mm pine	0.33	1.85	0.33	1.85	0.33	1.85
Inside air film	0.12	0.68	0.12	0.68	0.12	0.68
RSI (R) Total	0.57	3.21	0.49	2.78	0.48	2.70
U Total (W/K)	1.77		2.05		2.11	

Building Heat Loss (W/K):

	calm	3.3m/s	6.75m/s
Roof: uninsulated	6,931	9,903	10,892
13mm insul.	1,795	1,946	1,981
25mm insul.	1,023	1,074	1,081
Gables:	523	765	836
Side walls:			
curtain area	726	1,061	1,161
framed area	271	323	313
End walls:			
metal area	182	266	291
framed area	59	68	70
door area	380	555	607
Perimeter:	243	243	243

Total Heat Loss:

All doors closed:			
Uninsulated	9,315	13,184	14,413
13mm insul.	4,174	5,227	5,502
25mm insul.	3,407	4,355	4,602
Four cattle and one feed alley doors open			
Uninsulated	9,126	12,909	14,109
13mm insul.	3,990	4,952	5,198
25mm insul.	3,218	4,080	4,298

APPENDIX C

Sample Combined Thermal Buoyancy and Wind Ventilation Calculation Results and Cell Values

APPENDIX C

Sample Combined Thermal Buoyancy and Wind Ventilation Calculation Results and Cell Values

CHANGABLE VALUES:	MPH WIND	Cpi	To	AIR DNSIT	HT LOSS	RH OUT
	15	-0.22488	40	1.23	4360	0.7

CALCULATION STEPS:
1)CHANGE VALUES ABOVE
2) GO TO COLUMN "AM" AND ITERATE TILL NEUTRAL PRESSURE HEIGHT IS FOUND
(COLUMN "AL" IS <= 0.005)

NOTE: THIS RUN--100% SOFFET AREA IS OPEN

A WIND VELOCITY mph	B WIND VELOCITY m/s	C WIND PRS COEF INSIDE Cpi	D WIND PRS COEF UPWIND Cpo	E WIND PRS COEF DOWNWIND Cpo	F WIND PRS COEF PEAK Cpo	G WIND PRS COEF GABLE END Cpo	H OUTSIDE TEMP To (F)	I OUTSIDE TEMP To (C)	J OUTSIDE TEMP To (K)
15	6.7	-0.22488	0.6	-0.2	-0.4	-0.2	40	4.44	277.59
15	6.7	-0.22488	0.6	-0.2	-0.4	-0.2	40	4.44	277.59
15	6.7	-0.22488	0.6	-0.2	-0.4	-0.2	40	4.44	277.59
15	6.7	-0.22488	0.6	-0.2	-0.4	-0.2	40	4.44	277.59
15	6.7	-0.22488	0.6	-0.2	-0.4	-0.2	40	4.44	277.59
15	6.7	-0.22488	0.6	-0.2	-0.4	-0.2	40	4.44	277.59
15	6.7	-0.22488	0.6	-0.2	-0.4	-0.2	40	4.44	277.59
15	6.7	-0.22488	0.6	-0.2	-0.4	-0.2	40	4.44	277.59

APPENDIX C (Continued)

K COEF DISC EAVE	L COEF DISC PEAK	M COEF DISC DOORS	N AIR DENSITY OUTSIDE Kg/m^3	O AIR DENSITY INSIDE Kg/m^3	P ACCEL OF GRAVITY	Q EAVE OPENING LENGTH m	R BOTM EAVE OPENING HEIGHT m	S TOP EAVE OPENING HEIGHT
0.65	0.65	0.65	1.23	1.30	9.8	48	3.01	3.2
0.65	0.65	0.65	1.23	1.22	9.8	48	3.01	3.2
0.65	0.65	0.65	1.23	1.22	9.8	48	3.01	3.2
0.65	0.65	0.65	1.23	1.22	9.8	48	3.01	3.2
0.65	0.65	0.65	1.23	1.22	9.8	48	3.01	3.2
0.65	0.65	0.65	1.23	1.22	9.8	48	3.01	3.2
0.65	0.65	0.65	1.23	1.22	9.8	48	3.01	3.2
0.65	0.65	0.65	1.23	1.22	9.8	48	3.01	3.2

T *****UPWIND ALPHA-N	U SOFFET Cd*pn*Ln *ALPHA-n ^.5	V CALCS***** BETA-N ß	W ß-H TOP MINUS ß-H BOTM	X SUM UPWIND VALUE kg/s	Y ***DOWNWIND ALPHA-N	Z SOFFET Cd*pn*Ln *ALPHA-n ^.5	AA CALCS**** BETA-N ß	AB ß-H TOP MINUS ß-H BOTM	AC SUM DOWNWIND VALUE kg/s
1.11826	40.57627	34.1683	-1.58843	42.97	1.11826	40.57627	4.000421	-0.26956	7.29
0.129719	13.81984	292.0112	-4.84421	44.63	0.129719	13.81984	14.70425	-0.97064	8.94
0.174686	16.03724	218.4084	-4.18187	44.71	0.174686	16.03724	12.48424	-0.87282	9.33
0.170102	15.82541	224.1307	-4.23708	44.70	0.170102	15.82541	12.65684	-0.88082	9.29
0.170575	15.8474	223.5259	-4.23128	44.70	0.170575	15.8474	12.6386	-0.87998	9.30
0.170526	15.84514	223.5881	-4.23187	44.70	0.170526	15.84514	12.64047	-0.88006	9.30
0.170531	15.84537	223.5817	-4.23181	44.70	0.170531	15.84537	12.64028	-0.88005	9.30
0.170531	15.84535	223.5824	-4.23182	44.70	0.170531	15.84535	12.6403	-0.88006	9.30

APPENDIX C (Continued)

AD RIDGE OPENING LENGTH m	AE RIDGE OPENING WIDTH m	AF OUTLET HEIGHT FROM FLOR m	AG *****RIDGE ALPHA-N	AH CALCULATIONS**** Cd*pn*Ln *ALPHA-n	AI BETA-N β	AJ BETA-H	AK SUM RIDGE OUTLET kg/s	AL NET VALUE (MASS BALANCE)	AM NUTRL PRESR HEIGHT m
51.93	0.457	8.23	1.057902	20.62595	-6.4433	-3.83057	-79.01	-28.7488	6.08
51.93	0.457	8.23	0.130584	6.810113	-54.2207	-7.90258	-53.82	-0.24362	6.08
51.93	0.457	8.23	0.176257	7.893671	-38.595	-6.84288	-54.02	0.027025	6.08
51.93	0.457	8.23	0.171591	7.790325	-39.8099	-6.93108	-54.00	9.73E-05	6.08
51.93	0.457	8.23	0.172072	7.801055	-39.6815	-6.92181	-54.00	0.002883	6.08
51.93	0.457	8.23	0.172023	7.79995	-39.6947	-6.92277	-54.00	0.002596	6.08
51.93	0.457	8.23	0.172028	7.800064	-39.6933	-6.92267	-54.00	0.002625	6.08
51.93	0.457	8.23	0.172027	7.800052	-39.6935	-6.92268	-54.00	0.002622	6.08

AN EXHAUST VENLATON RATE m^3/s	AO INLET VENLATON RATE m^3/s	AP CATTLE WEIGHT Kg	AQ NUMBER OF HEAD	AR SENSIBLE HEAT PRODUCED W	AS BUILDING HEAT LOSS W/m^2-K	AT SPECIFIC HEAT AIR CP J/kgK	AU INSIDE AIR TEMP (C)	AV INSIDE AIR TEMP (K)	AW INSIDE AIR TEMP (F)
-60.776	40.868	610	160	155064	4360	1006	6.29	279.44	43.33
-44.052	43.562	610	160	146036	4360	1006	6.94	280.09	44.49
-44.316	43.943	610	160	142654	4360	1006	6.87	280.02	44.37
-44.289	43.905	610	160	143005	4360	1006	6.88	280.03	44.39
-44.292	43.909	610	160	142969	4360	1006	6.88	280.03	44.39
-44.291	43.908	610	160	142972	4360	1006	6.88	280.03	44.39
-44.292	43.908	610	160	142972	4360	1006	6.88	280.03	44.39
-44.292	43.908	610	160	142972	4360	1006	6.88	280.03	44.39

APPENDIX C (Continued)

AX AIR CHANGE PER HR	AY COMBINED VENLASON RATE m^3/s	AZ OUTSIDE TEMP (F)	BA OUTSIDE TEMP (C)	BB OUTSIDE TEMP (K)	BC INSIDE TEMP (F)	BD INSIDE TEMP (C)	BE INSIDE TEMP (K)	********** BF WATR VAPR SATURASON PART PRES -100 TO 0C	BG WATR VAPR SATURASON PART PRES 0-200C
27.87	60.78	40	4.44	277.59	5.00	-15.00	258.15	165.30	191.43
20.20	44.05	40	4.44	277.59	43.27	6.26	279.41	1011.50	952.22
20.32	44.32	40	4.44	277.59	44.50	6.94	280.09	1067.14	998.03
20.31	44.29	40	4.44	277.59	44.38	6.88	280.03	1061.50	993.40
20.31	44.29	40	4.44	277.59	44.39	6.88	280.03	1062.04	993.84
20.31	44.29	40	4.44	277.59	44.39	6.88	280.03	1061.99	993.80
20.31	44.29	40	4.44	277.59	44.39	6.88	280.03	1061.99	993.80
20.31	44.29	40	4.44	277.59	44.39	6.88	280.03	1061.99	993.80

**********INSIDE AIR CONDITIONS**********

BH RELATIV HUMIDTY	BI PART PRES AT GIVEN R.H. KPa	BJ ATMOS PRESURE KPa	BK HUMIDTY RATIO kg/kg	BL GAS CONSTANT	BM SPECIFIC VOL OF MOIST AIR m^3/Kg	BN INSIDE AIR DENSITY Kg/m^3	BO COW WEIGHT kgs	BP NUMBER OF COWS	BQ SENSIBLE COW HEAT PER HERD W
0.800	0.13224	98.264	0.000838	287.055	0.755	1.325	610	160	155064
1.000	0.952222	98.264	0.006086	287.055	0.819	1.221	610	160	146036
0.741	0.7398	98.264	0.004718	287.055	0.821	1.219	610	160	142654
0.712	0.706931	98.264	0.004507	287.055	0.820	1.219	610	160	143005
0.715	0.710228	98.264	0.004528	287.055	0.820	1.219	610	160	142969
0.714	0.709906	98.264	0.004526	287.055	0.820	1.219	610	160	142972
0.714	0.709939	98.264	0.004526	287.055	0.820	1.219	610	160	142972
0.714	0.709936	98.264	0.004526	287.055	0.820	1.219	610	160	142972

					**********	**********	**********	OUTSIDE
BR	BS	BT	BU	BV	BW	BX	BY	BZ
BUILDING HEAT LOSS	SPECIFIC HEAT AIR	INSIDE TEMP DUE TO WIND	INSIDE TEMP DUE TO WIND	AIR COND <<IN OUT>	WATR VAPR SATURASON PART PRES	WATR VAPR SATURASON PART PRES	RELATIV HUMIDTY	PART PRES AT GIVEN R.H.
W	J/Kg-K	C	F	<<IN OUT>-100 TO 0C		0-200C		KPa
4360	1006	6.26	43.27	<<IN OUT>	876.04	839.25	0.7	0.587
4360	1006	6.94	44.50	<<IN OUT>	876.04	839.25	0.7	0.587
4360	1006	6.88	44.38	<<IN OUT>	876.04	839.25	0.7	0.587
4360	1006	6.88	44.39	<<IN OUT>	876.04	839.25	0.7	0.587
4360	1006	6.88	44.39	<<IN OUT>	876.04	839.25	0.7	0.587
4360	1006	6.88	44.39	<<IN OUT>	876.04	839.25	0.7	0.587
4360	1006	6.88	44.39	<<IN OUT>	876.04	839.25	0.7	0.587
4360	1006	6.88	44.39	<<IN OUT>	876.04	839.25	0.7	0.587

AIR CONDITIONS**********						**********	**********	REL ATIVE	
CA	CB	CC	CD	CE	CF	CG	CH	CI	CJ
ATMOS PRESURE	HUMIDTY RATIO	GAS CONSTANT	SPECIFIC VOLUME OF MOIST AIR	OUTSIDE AIR DENSITY	RH IN>>>	OUTSIDE AIR MOISTURE	MOISTURE PRODUCSON PER HERD	COW MOIST @ GIVEN VENT RATE	TOTAL INSIDE MOISTURE
KPa	kg/kg		m^3/Kg	Kg/m^3	RH IN>>>	kg/m^3	kg/s	kg/m^3	kg/m^3
98.264	0.003741	287.055	0.813	1.230	RH IN>>>	0.004958	0.015619	0.000257	0.0052151
98.264	0.003741	287.055	0.813	1.230	RH IN>>>	0.004566	0.039977	0.000908	0.0054739
98.264	0.003741	287.055	0.813	1.230	RH IN>>>	0.004559	0.041455	0.000935	0.0054944
98.264	0.003741	287.055	0.813	1.230	RH IN>>>	0.004561	0.041306	0.000933	0.0054933
98.264	0.003741	287.055	0.813	1.230	RH IN>>>	0.00456	0.041321	0.000933	0.0054934
98.264	0.003741	287.055	0.813	1.230	RH IN>>>	0.004561	0.041319	0.000933	0.0054934
98.264	0.003741	287.055	0.813	1.230	RH IN>>>	0.004561	0.041319	0.000933	0.0054934
98.264	0.003741	287.055	0.813	1.230	RH IN>>>	0.004561	0.041319	0.000933	0.0054934

HUMIDITY CONDITIONS**********

CK INDOOR DRY AIR DENSITY Kg/m^3	CL NEW INSID HUMID RAS W\ COWS kg/kg	CM REVISED PARSL PRSR Pwvi Pa	CN INSIDE RELATIVE HUMIDITY %	CO DEW PT -60≤0 C @RH≤100% (C)	CP DEW PT 0≤70 C @RH≤100% (C)	CQ EXT SURFS DEW PT TMP @RH≤100% (C)	CR EXT SURFS DEW PT TM @RH≤100% (F)
1.33	0.003933	621.306	324.6%	-14.88	-13.52	-13.52	7.66
1.23	0.004468	705.846	74.1%	1.60	2.05	2.05	35.69
1.22	0.004495	710.225	71.2%	1.67	2.14	2.14	35.84
1.22	0.004493	709.909	71.5%	1.66	2.13	2.13	35.83
1.22	0.004494	709.939	71.4%	1.67	2.13	2.13	35.83
1.22	0.004494	709.936	71.4%	1.67	2.13	2.13	35.83
1.22	0.004494	709.936	71.4%	1.67	2.13	2.13	35.83
1.22	0.004494	709.936	71.4%	1.67	2.13	2.13	35.83

UNINSULATED BUILDING** CS ROF INSID SRFS TMP NO WIND (F)	CT ROF INSID SURFS TMP 7½MPH WND (F)	CU ROF INSID SURFS TMP 15MPH WND (F)	### ½" ROOF INSULATION ### CV ROF INSID SRFS TMP NO WIND (F)	CW ROF INSID SURFS TMP 7½MPH WND (F)	CX ROF INSID SURFS TMP 15MPH WND (F)	%%%% 1"ROOF INSULATION%%%%% CY ROF INSID SRFS TMP NO WIND (F)	CZ ROF INSID SURFS TMP 7½MPH WND (F)	DA ROF INSID SURFS TMP 15MPH WND (F)
41.63	40.94	40.70	42.85	42.82	42.81	43.03	43.02	43.01
42.25	41.29	40.97	43.92	43.87	43.86	44.17	44.15	44.15
42.19	41.26	40.94	43.81	43.77	43.76	44.05	44.04	44.04
42.19	41.26	40.94	43.82	43.78	43.77	44.06	44.05	44.05
42.19	41.26	40.94	43.82	43.78	43.77	44.06	44.05	44.05
42.19	41.26	40.94	43.82	43.78	43.77	44.06	44.05	44.05
42.19	41.26	40.94	43.82	43.78	43.77	44.06	44.05	44.05
42.19	41.26	40.94	43.82	43.78	43.77	44.06	44.05	44.05

APPENDIX C (Continued)

	DB	DC	DD	DE	DF	DG
CO2	IN >>>	C.I.G.R.	CO2	AMBIENT	INCOMING	BUILDING
CO2	IN >>>	TOTL HEAT	PRODUCSN	CO2	CO2	CO2
CO2	IN >>>	PRODUCED	PER HERD	LEVEL	CONCTRASN	CONCTRASN
CO2	IN >>>	W	m^3/s	ppm	m^3/s	ppm
CO2	IN >>>	242668	0.009865	345	0.020968	507.3
CO2	IN >>>	242668	0.009865	345	0.015198	568.9
CO2	IN >>>	242668	0.009865	345	0.015289	567.6
CO2	IN >>>	242668	0.009865	345	0.015280	567.7
CO2	IN >>>	242668	0.009865	345	0.015281	567.7
CO2	IN >>>	242668	0.009865	345	0.015281	567.7
CO2	IN >>>	242668	0.009865	345	0.015281	567.7
CO2	IN >>>	242668	0.009865	345	0.015281	567.7

Cell Values (last row of results)

A24: [W9] +$C$2
B24: [W9] +A24*0.44704
C24: [W9] +$D$2
D24: [W9] 0.6
E24: [W9] -0.2
F24: [W9] -0.4
G24: [W9] -0.2
H24: [W9] +$E$2
I24: [W9] (H24-32)/1.8
J24: [W9] +I24+273.15
K24: [W9] 0.65

APPENDIX C (cell values continued)

```
L24: [W9] 0.65
M24: [W9] 0.65
N24: [W9] +$F$2
O24: [W9] (N24*J24)/AV23
P24: [W9] 9.8
Q24: [W9] 48
R24: [W9] 3.01
S24: [W9] 3.2
T24: [W9] 2*P24*(@ABS(N24-O24)/N24)
U24: [W9] +K24*N24*Q24*T24^0.5
V24: [W9] +AM23+(B24^2*(D24-C24))/T24
W24: [W9] (@ABS(V24-S24)^2.5*@ABS(V24-S24)^-1)-(@ABS(V24-R24)^2.5*(V24-R24)^-1)
X24: [W9] -0.66667*U24*W24
Y24: [W9] 2*P24*(@ABS(N24-O24)/N24)
Z24: [W9] +K24*N24*Q24*Y24^0.5
AA24: [W9] +AM23+(B24^2*(E24-C24))/Y24
AB24: [W9] (@ABS(AA24-S24)^2.5*(AA24-S24)^-1)-(@ABS(AA24-R24)^2.5*(AA24-R24)^-1)
AC24: [W9] -0.66667*Z24*AB24
AD24: [W9] 51.93
AE24: [W9] 0.457
AF24: [W9] 8.23
AG24: [W9] 2*P24*(@ABS(N24-O24)/O24)
AH24: [W9] +L24*O24*AD24*AE24*AG24^0.5
AI24: [W9] +AM23+(B24^2*(F24-C24))/AG24
AJ24: [W9] @ABS(AI24-AF24)^1.5*(AI24-AF24)^-1
AK24: [W9] +AH24*AJ24
AL24: [W9] +X24+AC24+AK24
AM24: U [W9] 6.0801
AN24: [W9] +AK24/O24
AO24: [W9] (X24+AC24)/N24
AP24: [W9] 610
AQ24: [W9] 160
AR24: U [W9] ((1.77402+(-0.0361864)*AU23+(-0.00117393)*AU23^2+(-1.40191E-05)*AU23^3)*AP24*AQ24)
AS24: [W9] +$G$2
```

APPENDIX C (cell values continued)

```
AT24: [W9] 1006
AU24: [W9] +I24+AR24/(AS24+(AT24*O24*@ABS(AN24)))
AV24: [W9] +AU24+273.15
AW24: [W9] (1.8*AU24)+32
AX24: [W9] (@ABS(AN24)*3600)/7850
AY24: [W9] @ABS(AN24)
AZ24: [W9] +H24
BA24: [W9] (AZ24-32)/1.8
BB24: [W9] +BA24+273.15
BC24: [W9] +BU23
BD24: [W9] (BC24-32)/1.8
BE24: [W9] +BD24+273.15
BF24: [W9] @EXP(-5674.5359/BE24+6.3925247+(-0.009677843*BE24)+(6.22157E-07*BE24^2)+(2.0747825E-09*BE24^3)+(-9.484024E-13*BE24^4)+4.1635019*@LN(BE24))
BG24: [W9] @EXP(-5800.2206/BE24+1.3914993+(-0.048640239*BE24)+(4.1764768E-05*BE24^2)+(-1.4452093E-08*BE24^3)+6.5459673*@LN(BE24))
BH24: [W9] @IF(CN23<1,CN23,1)
BI24: [W9] @IF(BD24<=0,BF24,BG24)*BH24/1000
BJ24: [W9] 98.264
BK24: [W9] 0.62198*(BI24)/(BJ24-BI24)
BL24: [W9] 287.055
BM24: [W9] ((1/(BJ24*1000))*BL24*BE24*(1+(1.6078*BK24)))/(1+BK24)
BN24: [W9] 1/BM24
BO24: [W9] +AP24
BP24: [W9] +AQ24
BQ24: [W9] +AR24
BR24: [W9] +AS24
BS24: [W9] 1006
BT24: [W9] +BA24+(BQ24/(BR24+(BS24*BN24*AY24)))
BU24: [W9] (BT24*1.8)+32
BV24: [W9] ^<<IN OUT>>
BW24: [W9] @EXP(-5674.5359/BB24+6.3925247+(-0.009677843*BB24)+(6.22157E-07*BB24^2)+(2.0747825E-09*BB24^3)+(-9.484024E-13*BB24^4)+4.1635019*@LN(BB24))
BX24: [W9] @EXP(-5800.2206/BB24+1.3914993+(-0.048640239*BB24)+(4.1764768E-05*BB24^2)+(-1.4452093E-08*BB24^3)+6.5459673*@LN(BB24))
```

APPENDIX C (cell values continued)

```
BY24: [W9] +$H$2
BZ24: [W9] @IF(BA24<=0,BW24,BX24)*BY24/1000
CA24: [W9] 98.264
CB24: [W9] 0.62198*(BZ24)/(CA24-BZ24)
CC24: [W9] 287.055
CD24: [W9] ((1/(CA24*1000))*CC24*BB24*(1+(1.6078*CB24)))/(1+CB24)
CE24: [W9] 1/CD24
CF24: [W9] ^RH IN>>>
CG24: [W9] +CB24*BN24
CH24: U [W9] (((0.711982+0.0361864*BD24+0.00117393*BD24^2+1.40191E-05*BD24^3)*BO24*BP24)/(670*3600))
CI24: [W9] +CH24/AY24
CJ24: [W9] +CG24+CI24
CK24: [W9] 3.4838*(BJ24/BE24)
CL24: [W9] +CJ24/CK24
CM24: [W9] +CJ24*461.5*BE24
CN24: [W9] +CM24/@IF(BT24<0,BF24,BG24)
CO24: [W9] -60.45+7.0322*@LN(@IF(CM24>BF24,BF24,CM24))+0.37*(@LN(@IF(CM24>BF24,BF24,CM24)))^2
CP24: [W9] -35.957-1.8726*@LN(@IF(CM24>BG24,BG24,CM24))+1.1689*@LN(@IF(CM24>BG24,BG24,CM24))^2
CQ24: [W11] @IF(BA24<=0,CO24,CP24)
CR24: [W9] (1.8*CQ24)+32
CS24: [W11] +BU24-((0.62/1.24)*(BU24-AZ24))
CT24: [W9] +BU24-((0.62/0.87)*(BU24-AZ24))
CU24: [W11] +BU24-((0.62/0.79)*(BU24-AZ24))
CV24: [W9] +BU24-((0.62/4.84)*(BU24-AZ24))
CW24: [W9] +BU24-((0.62/4.47)*(BU24-AZ24))
CX24: [W9] +BU24-((0.62/4.39)*(BU24-AZ24))
CY24: [W9] +BU24-((0.62/8.44)*(BU24-AZ24))
CZ24: [W11] +BU24-((0.62/8.07)*(BU24-AZ24))
DA24: [W11] +BU24-((0.62/7.99)*(BU24-AZ24))
DB24: [W11] ^CO2 IN >>>
DC24: [W9] 242668
DD24: [W11] ((DC24/1000)*1/24.6)/1000
DE24: [W9] 345
DF24: [W11] +DE24/1000000*AY24
DG24: [W11] ((DD24+DF24)/AY24)*1000000
```

APPENDIX D

Sorted and Averaged Validation Barn Weather Data

APPENDIX D

(150-210 DEGREE WINDS INCLUDED) (MILK 3:30-6:30 & 15:30-18:30)
(STEADY STATE HOURS ARE 24:00-3:30, 6:30-15:30 & 18:30-24:00)
NOTE: ****WINTER 1989-90 WEATHER DATA****

-6 TO -4 F OUTSIDE

Yr	Mo	Day	Hour	Outside Temp. (F)	Inside Temp. (F)	Outside R.H. (%)	Inside R.H. (%)	Wind Speed (mph)	Wind Direct. (deg N)	********** Thermocouple Temperatures (F) ********** #1 SE	#2 NE	#3 Mid-S	#4 Mid-N	#5 SW	#6 NW	#7 Peak	AVG T1TOT6 (F)	PEAK-TCPL AV (F)	Tpk-To (F)	TCPL AVG MINUS To (F)
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
89	12	15	7	-4.0	5.1	89.6	92.7	2.6	190.1	2.7	1.2	3.9	2.9	7.0	5.1	6.3	3.8	2.5	10.3	7.8
89	12	15	8	-3.9	5.0	89.4	93.6	1.9	165.8	3.7	0.8	5.9	2.9	8.3	5.6	6.2	4.5	1.6	10.0	8.4
89	12	23	2	-6.4	7.0	87.8	95.1	1.6	174.8	3.1	3.6	4.7	5.2	7.7	8.1	8.6	5.4	3.2	14.9	11.8
89	12	23	9	-5.1	5.9	88.0	94.5	1.8	187.9	3.8	3.3	7.4	4.7	8.5	5.4	6.5	5.5	0.9	11.5	10.6
AVERAGES>>>				-4.8	5.7	88.7	94.0	2.0									4.8	2.1	11.7	9.6
				"F"-"E"=	10.6	"H"-"G"=	5.3										AVG "U" MINUS AVG "T" =			-2.1

-1 TO +1 F OUTSIDE

Yr	Mo	Day	Hour	Outside Temp. (F)	Inside Temp. (F)	Outside R.H. (%)	Inside R.H. (%)	Wind Speed (mph)	Wind Direct. (deg N)	********** Thermocouple Temperatures (F) ********** #1 SE	#2 NE	#3 Mid-S	#4 Mid-N	#5 SW	#6 NW	#7 Peak	AVG T1TOT6 (F)	PEAK-TCPL AV (F)	Tpk-To (F)	TCPL AVG MINUS To (F)
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
89	12	15	2	0.8	10.0	87.2	92.5	4.3	194.3	7.2	8.4	9.2	8.3	9.8	9.8	9.9	8.8	1.1	9.1	8.0
89	12	15	1	1.0	11.0	86.0	90.7	5.8	199.5	8.1	9.7	10.4	10.2	11.3	11.7	11.2	10.2	0.9	10.1	9.2
89	12	24	3	1.4	9.7	72.6	88.4	11.9	207.7	7.3	7.5	7.8	9.2	7.0	8.1	8.9	7.8	1.0	7.5	6.4
90	2	26	3	-0.5	12.7	79.1	87.0	3.6	168.8	10.7	8.8	10.8	9.8	13.4	13.2	13.4	11.1	2.3	13.9	11.6
AVERAGES>>>				0.7	10.8	81.2	89.7	6.4									9.5	1.3	10.1	8.8
				"F"-"E"=	10.2	"H"-"G"=	8.4										AVG "U" MINUS AVG "T" =			-1.3

APPENDIX D (continued)

Yr	Mo	Day	Hour	4 TO 6 F OUTSIDE Outside Temp. (F)	Inside Temp. (F)	Outside R.H. (%)	Inside R.H. (%)	Wind Speed (mph)	Wind Direct. (deg N)	********** Thermocouple Temperatures (F) ********** #1 SE	#2 NE	#3 Mid-S	#4 Mid-N	#5 SW	#6 NW	#7 Peak	AVG T1TOT6 (F)	PEAK-TCPL AV (F)	Tpk-To (F)	TCPL AVG MINUS To (F)
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
89	12	17	22	6.2	14.6	81.1	87.1	10.3	201.8	13.0	13.1	12.2	14.3	12.6	14.8	13.4	13.3	0.1	7.2	7.1
89	12	23	24	4.2	12.7	74.1	87.6	11.1	204.2	11.2	11.2	12.1	11.7	12.1	13.2	12.1	11.9	0.2	7.9	7.7
89	12	23	23	6.2	14.6	74.2	87.7	10.1	195.9	13.9	13.1	13.1	14.3	13.6	15.6	13.2	13.9	-0.7	6.9	7.7
90	2	20	8	6.3	16.4	82.4	85.4	1.1	210.1	15.0	12.4	15.6	14.2	17.8	15.4	14.1	15.1	-0.9	7.8	8.8
90	2	25	23	3.8	14.1	59.3	80.9	5.2	188.8	13.2	11.8	14.2	13.8	15.9	15.0	13.4	14.0	-0.5	9.6	10.1
90	2	28	7	4.0	16.4	89.8	88.8	3.1	195.1	12.9	12.8	15.3	13.8	18.3	15.4	15.5	14.7	0.7	11.5	10.8
90	2	25	20	4.2	15.5	51.3	74.7	4.1	155.3	16.8	15.7	17.7	15.3	18.1	17.4	15.6	16.8	-1.3	11.4	12.7
90	2	26	8	4.5	13.0	77.5	91.0	9.1	189.2	9.8	11.8	10.2	12.5	11.4	12.2	10.8	11.3	-0.6	6.2	6.8
90	2	25	19	4.8	16.0	47.3	71.5	5.0	154.0	16.8	14.3	18.8	15.9	20.9	18.6	17.3	17.5	-0.2	12.5	12.8
AVERAGES>>>				4.9	14.8	70.8	83.9	6.5									14.3	-0.4	9.0	9.4
				"F"-"E"=	9.9	"H"-"G"=	13.1										AVG "U"	MINUS AVG	"T" =	0.4

APPENDIX D (continued)

9 TO 11 F OUTSIDE

Yr	Mo	Day	Hour	Outside Temp. (F)	Inside Temp. (F)	Outside R.H. (%)	Inside R.H. (%)	Wind Speed (mph)	Wind Direct. (deg N)	********** Thermocouple Temperatures (F) ********** #1 SE	#2 NE	#3 Mid-S	#4 Mid-N	#5 SW	#6 NW	#7 Peak	AVG T1TO T6 (F)	PEAK-TCPL AV (F)	Tpk-To (F)	TCPL AVG MINUS To (F)
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
89	12	17	10	8.9	17.4	84.6	91.1	8.6	206.6	16.2	16.0	15.6	17.1	14.9	15.9	16.3	16.0	0.3	7.3	7.0
89	12	16	24	9.5	18.6	91.5	91.9	7.0	209.0	16.7	16.8	18.1	17.3	18.2	17.6	18.0	17.4	0.5	8.5	8.0
89	12	12	21	9.8	19.6	92.6	88.9	2.2	170.7	18.8	18.5	20.5	20.9	22.5	23.0	20.2	20.7	-0.5	10.4	10.9
89	12	18	24	10.3	20.3	92.3	92.0	2.3	169.1	18.1	17.7	19.5	18.6	20.8	20.0	20.5	19.1	1.4	10.3	8.8
89	12	17	11	10.8	19.3	84.1	89.5	9.6	202.6	16.9	17.5	16.4	18.5	15.8	18.3	17.7	17.2	0.5	6.9	6.5
89	12	26	22	9.5	17.9	75.3	85.4	3.6	177.6	16.7	16.4	18.4	16.6	19.3	18.5	18.1	17.6	0.4	8.6	8.2
89	12	23	21	9.5	19.4	80.3	87.3	9.0	204.0	19.2	16.5	18.4	19.8	18.0	19.9	17.6	18.6	-1.0	8.1	9.1
89	12	27	1	10.9	19.4	87.1	92.6	5.7	169.3	16.3	16.5	18.6	18.1	19.4	19.5	19.1	18.1	1.0	8.2	7.2
90	2	18	1	10.2	17.3	79.0	80.4	4.9	149.6	15.7	13.5	15.4	16.9	17.6	18.3	17.1	16.2	0.9	6.9	6.0
90	2	18	2	11.2	16.1	79.3	80.2	9.3	157.0	15.4	12.9	15.2	16.2	17.8	18.0	15.9	15.9	0.0	4.7	4.7
90	2	25	14	10.2	16.9	37.3	72.5	3.7	209.7	14.0	14.7	15.7	16.1	17.2	17.6	18.7	15.9	2.9	8.5	5.7
AVERAGES>>>				10.1	18.4	80.3	86.5	6.0									17.5	0.6	8.0	7.5
				"F"-"E"=	8.3	"H"-"G"=	6.2										AVG "U" MINUS AVG "T" =			-0.6

APPENDIX D (continued)

14 TO 16 F OUTSIDE

Yr	Mo	Day	Hour	Outside Temp. (F)	Inside Temp. (F)	Outside R.H. (%)	Inside R.H. (%)	Wind Speed (mph)	Wind Direct. (deg N)	********** Thermocouple Temperatures (F) ********** #1 SE	#2 NE	#3 Mid-S	#4 Mid-N	#5 SW	#6 NW	#7 Peak	AVG T1TOT6 (F)	PEAK-TCPL AV (F)	Tpk-To (F)	TCPL AVG MINUS To (F)
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
89	12	8	23	14.8	22.6	76.9	80.8	1.8	160.6	22.9	19.1	23.4	22.0	25.5	22.9	21.4	22.6	-1.2	6.6	7.8
89	12	8	22	15.1	23.0	74.8	78.6	3.7	182.5	22.7	19.9	23.2	22.6	25.2	24.7	21.6	23.0	-1.4	6.6	8.0
89	12	4	2	16.1	23.9	75.3	83.8	6.9	168.5	22.3	21.8	23.3	23.4	24.5	23.7	22.6	23.2	-0.6	6.4	7.0
89	12	17	15	14.5	20.9	81.2	85.9	9.5	208.6	18.0	18.5	18.2	19.1	17.6	20.6	19.6	18.7	0.9	5.0	4.1
89	12	11	21	15.3	21.7	90.3	86.5	2.8	167.6	20.9	20.0	22.6	23.1	26.2	25.1	22.7	23.0	-0.3	7.3	7.7
89	12	27	9	13.9	21.9	85.5	90.8	6.5	192.1	19.0	19.3	18.9	21.4	19.2	20.9	19.9	19.8	0.1	6.0	5.9
89	12	27	10	14.8	22.9	89.1	91.4	7.5	177.2	20.1	20.6	19.6	22.1	19.8	21.9	21.2	20.7	0.5	6.4	5.9
89	12	25	10	15.1	20.4	88.1	91.3	14.8	204.4	17.6	18.4	17.6	19.5	17.0	19.8	19.0	18.3	0.7	4.0	3.3
89	12	27	11	15.8	23.7	89.9	90.7	10.4	159.9	21.0	21.5	20.7	23.4	21.4	23.1	22.4	21.8	0.6	6.6	6.0
90	2	4	23	16.1	26.6	100.0	92.0	3.9	189.3	27.1	25.1	27.4	27.2	27.4	26.6	25.2	26.8	-1.6	9.1	10.7
90	2	18	8	14.9	18.9	97.1	92.0	11.6	154.8	17.4	15.5	19.3	18.4	19.5	19.3	17.2	18.2	-1.0	2.3	3.3
90	2	27	24	14.6	25.4	69.2	79.9	2.5	176.1	24.3	23.0	25.8	23.9	28.3	26.2	25.6	25.3	0.4	11.1	10.7
90	2	23	22	14.7	26.9	82.6	76.8	3.9	161.2	27.1	24.4	28.1	25.8	28.7	25.7	25.1	26.6	-1.5	10.4	11.9
90	2	23	23	15.2	25.8	84.8	79.1	3.8	173.7	26.0	23.1	26.9	25.2	27.7	26.4	24.4	25.9	-1.5	9.2	10.7
90	2	23	21	15.3	27.7	78.0	72.0	4.3	177.5	29.6	25.9	30.1	29.0	30.7	28.5	26.8	29.0	-2.1	11.6	13.7
90	2	28	23	15.4	24.9	65.8	77.2	4.5	190.8	24.8	23.2	24.7	23.7	24.5	23.7	22.3	24.1	-1.8	6.9	8.7
90	2	28	24	15.4	24.8	68.7	78.1	5.4	201.3	22.9	22.0	23.8	23.4	23.5	23.1	22.0	23.1	-1.1	6.6	7.7
90	2	26	11	16.0	22.5	61.5	82.5	14.4	186.2	19.5	22.2	18.6	21.0	18.6	19.5	20.1	19.9	0.2	4.1	3.9
AVERAGES>>>				15.2	23.6	81.0	83.9	6.6									22.8	-0.6	7.0	7.6
				"F"-"E"=	8.4	"H"-"G"=	2.8										AVG "U" MINUS AVG "T" =			0.6

APPENDIX D (continued)

19 TO 21 F OUTSIDE

Yr	Mo	Day	Hour	Outside Temp. (F)	Inside Temp. (F)	Outside R.H. (%)	Inside R.H. (%)	Wind Speed (mph)	Wind Direct. (deg N)	Thermocouple Temperatures (F) #1 SE	#2 NE	#3 Mid-S	#4 Mid-N	#5 SW	#6 NW	#7 Peak	AVG T1TOT6 (F)	PEAK-TCPL AV (F)	Tpk-To (F)	TCPL AVG MINUS To (F)
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
89	12	9	10	19.7	23.0	78.3	84.3	8.1	155.5	23.7	22.1	23.3	24.0	25.9	24.9	22.9	24.0	-1.1	3.2	4.3
89	12	4	7	20.4	24.1	79.5	85.5	12.3	171.7	23.0	21.7	22.6	24.3	24.1	24.8	22.2	23.4	-1.2	1.8	3.0
89	12	27	14	19.2	26.3	86.2	87.7	7.9	204.0	24.1	23.9	23.6	24.7	22.6	24.6	24.8	23.9	0.9	5.6	4.7
90	1	13	22	20.8	28.2	83.6	86.5	7.3	194.1	27.7	25.9	27.9	27.9	27.9	27.8	26.3	27.5	-1.3	5.4	6.7
90	1	13	23	21.4	27.6	85.3	87.1	6.1	179.9	27.9	24.4	28.5	26.9	28.7	28.6	26.9	27.5	-0.6	5.5	6.1
90	2	4	21	19.5	27.9	96.0	87.0	4.0	200.9	31.3	29.4	29.3	29.2	28.8	25.9	26.7	29.0	-2.3	7.2	9.5
90	2	2	22	20.5	24.4	86.9	86.1	5.9	158.4	21.5	21.9	23.0	24.4	25.3	25.1	23.9	23.5	0.4	3.4	3.0
90	2	21	3	18.9	26.0	71.8	80.7	8.1	189.5	24.4	23.9	24.5	26.1	23.8	24.3	23.0	24.5	-1.5	4.1	5.6
90	2	20	11	19.5	27.7	68.4	81.0	6.0	195.2	26.4	27.1	25.9	26.0	25.9	26.0	25.8	26.2	-0.5	6.3	6.7
90	2	18	9	19.7	23.4	92.6	92.4	14.2	184.0	21.9	24.7	23.2	22.6	21.8	22.9	21.2	22.9	-1.7	1.4	3.1
90	2	20	24	21.3	28.6	89.0	74.3	7.8	193.0	27.0	26.5	27.4	27.1	26.5	26.3	25.8	26.8	-1.0	4.5	5.5
90	2	26	13	19.2	26.0	88.0	75.2	17.1	207.9	23.0	25.0	22.0	25.1	22.1	24.8	24.4	23.7	0.7	5.2	4.5
90	2	26	23	20.0	26.7	67.5	78.1	12.0	191.5	23.1	25.6	22.5	26.2	22.4	24.8	23.7	24.1	-0.4	3.7	4.1
90	2	26	14	20.2	27.8	82.0	71.7	17.9	185.6	24.6	26.3	23.8	26.4	23.4	25.4	25.4	25.0	0.4	5.2	4.8
90	2	26	22	20.3	25.9	69.0	74.0	12.5	191.7	23.2	23.7	22.7	25.9	22.7	25.5	23.6	23.9	-0.4	3.3	3.7
90	2	26	21	20.6	26.9	61.2	72.3	12.4	170.0	24.9	25.8	24.5	27.6	23.9	27.2	24.7	25.7	-0.9	4.2	5.1
90	2	26	20	21.4	26.9	83.0	70.2	12.3	169.1	25.9	25.8	24.8	27.8	24.7	27.6	25.4	26.1	-0.6	4.1	4.7
AVERAGES>>>				20.1	26.3	80.5	80.8	10.1									25.2	-0.6	4.4	5.0
				"F"-"E"=	6.2	"H"-"G"=	0.3										AVG "U" MINUS AVG "T" =			0.6

APPENDIX D (continued)

24 TO 26 F OUTSIDE

Yr	Mo	Day	Hour	Outside Temp. (F)	Inside Temp. (F)	Outside R.H. (%)	Inside R.H. (%)	Wind Speed (mph)	Wind Direct. (deg N)	********** Thermocouple Temperatures (F) **********							AVG T1TOT6 (F)	PEAK-TCPL AV (F)	Tpk-To (F)	TCPL AVG MINUS To (F)
										#1 SE	#2 NE	#3 Mid-S	#4 Mid-N	#5 SW	#6 NW	#7 Peak				
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
89	12	9	12	24.3	26.4	75.5	84.1	11.9	168.5	27.4	25.6	26.7	26.1	28.1	26.8	26.5	26.8	-0.2	2.2	2.5
89	12	4	12	25.2	27.9	55.8	71.3	10.0	179.4	28.7	27.1	28.2	27.8	27.7	28.0	27.5	27.9	-0.4	2.3	2.7
89	12	4	13	25.5	29.2	59.2	72.2	11.4	159.7	29.6	28.7	29.1	29.6	29.3	30.0	29.0	29.4	-0.4	3.5	3.9
89	12	28	11	24.2	31.0	83.6	87.9	5.6	187.3	30.5	30.2	30.5	30.9	29.7	27.9	30.3	30.0	0.3	6.1	5.7
89	12	25	19	25.4	29.7	99.6	93.8	8.2	197.4	27.3	28.4	28.5	28.9	27.2	28.9	27.9	28.2	-0.3	2.5	2.8
89	12	28	12	25.8	29.2	82.0	86.6	6.8	196.1	29.6	29.4	29.1	29.1	29.2	27.0	29.5	28.9	0.6	3.8	3.1
90	1	6	24	24.9	30.8	88.4	92.0	9.2	208.4	29.4	28.6	29.7	30.1	29.6	30.6	28.3	29.7	-1.4	3.4	4.8
90	1	6	22	25.0	30.3	84.5	87.8	5.0	201.1	30.8	29.7	29.6	29.9	30.1	30.4	28.4	30.1	-1.6	3.4	5.1
90	1	3	2	25.5	33.0	82.4	89.9	5.6	168.7	31.1	31.1	31.1	32.6	30.3	31.0	30.7	31.2	-0.5	5.3	5.7
90	1	7	1	26.0	31.0	89.4	92.5	10.4	200.7	29.0	28.3	29.4	30.1	28.8	29.9	28.2	29.3	-1.1	2.2	3.2
90	1	3	3	26.1	33.2	85.2	91.6	7.9	166.0	31.1	31.2	31.4	32.8	30.4	31.4	30.8	31.4	-0.6	4.7	5.3
90	1	14	3	24.0	30.7	81.9	88.2	5.7	163.8	28.6	27.6	30.1	30.2	29.7	29.9	29.1	29.3	-0.2	5.1	5.3
90	1	19	9	24.1	29.9	79.8	90.3	6.8	169.5	28.6	27.3	29.3	28.9	28.6	27.7	27.1	28.4	-1.4	2.9	4.3
90	1	19	10	25.8	31.4	77.7	89.3	8.2	184.0	29.8	29.8	29.9	30.4	29.7	29.2	28.6	29.8	-1.2	2.8	4.0
90	1	29	24	23.8	32.8	92.1	82.6	3.3	169.1	31.7	29.9	32.9	32.6	34.3	33.6	31.5	32.5	-1.0	7.7	8.8
90	1	30	1	23.8	31.8	84.9	81.8	3.1	195.7	30.3	29.3	31.2	31.5	31.9	32.4	29.9	31.1	-1.2	6.1	7.3
90	1	30	3	24.3	31.0	77.4	82.3	5.3	191.3	29.2	28.4	30.1	30.8	30.8	31.0	28.4	30.0	-1.6	4.1	5.8
90	1	23	8	24.9	30.2	100.0	99.8	5.4	186.9	29.8	28.2	29.7	29.1	30.2	30.1	28.6	29.5	-0.9	3.7	4.6
90	1	29	22	25.2	33.0	90.6	79.9	2.3	163.6	32.6	31.3	33.3	32.8	34.4	33.7	31.4	33.0	-1.6	6.2	7.9
90	1	29	21	26.1	35.3	81.7	76.5	2.1	157.1	34.6	33.2	36.1	35.5	36.1	36.7	34.2	35.4	-1.2	8.1	9.3
90	1	23	9	26.3	32.1	100.0	100.0	4.7	189.3	31.1	29.4	30.9	31.1	31.2	31.4	30.4	30.9	-0.5	4.1	4.6
90	1	26	19	26.3	33.2	78.9	84.2	5.8	167.6	32.6	31.1	32.2	32.5	32.1	32.5	30.8	32.2	-1.4	4.4	5.8
90	2	4	19	24.0	33.1	85.2	83.3	2.2	193.3	34.5	32.8	33.3	33.0	32.7	29.7	30.9	32.7	-1.7	6.9	8.7
90	2	5	7	26.1	30.6	100.0	95.1	10.4	180.7	28.2	27.7	28.3	29.2	28.0	29.3	29.2	28.4	0.8	3.1	2.3
90	2	21	8	23.9	28.0	67.4	78.5	8.2	204.2	26.3	25.9	26.3	26.5	25.1	25.9	25.5	26.0	-0.5	1.6	2.1
90	2	18	10	24.7	27.9	83.7	89.7	15.9	194.8	26.7	27.6	25.9	26.3	25.4	27.0	25.4	26.5	-1.1	0.6	1.7
90	2	20	13	24.9	31.4	48.5	70.3	9.6	202.5	30.9	30.0	30.6	29.5	29.7	28.8	30.6	29.9	0.6	5.7	5.0
90	2	20	19	25.6	31.6	52.0	63.4	6.2	195.5	33.1	32.5	31.5	30.9	30.9	28.2	29.2	31.2	-1.9	3.7	5.6
90	2	12	9	26.1	33.2	87.1	86.5	3.6	160.3	31.7	31.2	32.8	31.7	32.1	32.3	32.0	32.0	0.1	6.0	5.9

APPENDIX D (continued)

24 TO 26 F OUTSIDE (Continued)

Yr	Mo	Day	Hour	Outside Temp. (F)	Inside Temp. (F)	Outside R.H. (%)	Inside R.H. (%)	Wind Speed (mph)	Wind Direct. (deg N)	Thermocouple Temperatures (F) #1 SE	#2 NE	#3 Mid-S	#4 Mid-N	#5 SW	#6 NW	#7 Peak	AVG T1TOT6 (F)	PEAK-TCPL AV (F)	Tpk-To (F)	TCPL AVG MINUS To (F)
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
90	2	21	9	26.1	29.1	64.0	75.2	9.9	200.1	30.1	36.5	28.5	28.9	27.6	27.1	27.4	29.8	-2.4	1.3	3.6
90	2	27	2	24.4	29.2	72.4	81.8	7.4	207.5	27.2	27.0	26.8	27.9	27.2	27.4	27.0	27.3	-0.3	2.6	2.9
90	2	27	3	25.8	29.5	73.5	82.3	4.6	197.4	27.6	28.0	27.8	28.6	28.4	28.8	28.1	28.2	-0.2	2.3	2.4
AVERAGES>>>				25.1	30.8	80.1	84.7	7.0									29.9	-0.8	4.0	4.8
				"F"-"E"=	5.7	"H"-"G"=	4.6										AVG "U" MINUS AVG "T" =			0.8

29 TO 31 F OUTSIDE

Yr	Mo	Day	Hour	Outside Temp. (F)	Inside Temp. (F)	Outside R.H. (%)	Inside R.H. (%)	Wind Speed (mph)	Wind Direct. (deg N)	Thermocouple Temperatures (F) #1 SE	#2 NE	#3 Mid-S	#4 Mid-N	#5 SW	#6 NW	#7 Peak	AVG T1TOT6 (F)	PEAK-TCPL AV (F)	Tpk-To (F)	TCPL AVG MINUS To (F)
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
89	12	9	23	28.8	34.3	52.9	70.8	10.5	190.6	32.2	31.5	31.8	33.2	31.6	34.0	31.9	32.4	-0.5	3.1	3.6
89	12	9	19	28.8	32.5	51.5	67.5	12.5	175.7	32.5	31.0	31.5	32.9	32.5	33.0	31.2	32.2	-1.0	2.4	3.4
89	12	6	2	30.6	39.0	100.0	92.0	6.2	199.2	36.8	36.7	37.5	39.1	37.5	38.0	36.6	37.6	-1.0	6.0	7.0
89	12	6	5	30.4	37.4	100.0	94.4	3.3	207.5	35.0	35.4	37.8	37.4	37.0	37.7	36.9	36.7	0.1	6.4	6.3
89	12	6	3	30.4	38.6	100.0	93.1	4.5	193.1	36.3	36.4	37.3	38.3	37.1	37.7	36.3	37.2	-0.9	5.9	6.8
89	12	1	2	30.3	36.4	86.4	87.1	4.3	171.5	33.9	33.9	34.6	36.1	36.5	36.6	35.6	35.3	0.3	5.4	5.0
89	12	10	1	30.1	34.4	54.5	71.5	9.8	203.4	32.8	31.7	32.7	32.7	32.4	33.1	32.5	32.6	-0.1	2.5	2.5
89	12	1	1	29.8	35.6	87.3	85.3	4.4	170.0	33.5	32.6	32.9	34.3	34.7	35.0	35.7	33.8	1.9	6.0	4.1
89	12	9	24	29.4	34.4	54.2	71.6	10.4	200.9	32.8	31.8	32.2	33.2	32.1	33.3	32.1	32.6	-0.4	2.8	3.2
89	12	9	16	29.1	32.3	55.7	71.3	12.3	168.3	32.0	30.3	32.1	32.1	32.6	33.1	31.6	32.0	-0.5	2.5	3.0
89	12	9	15	29.0	31.9	57.9	73.2	13.2	174.4	31.3	30.2	30.8	31.4	31.7	32.6	31.1	31.3	-0.2	2.1	2.4

APPENDIX D (continued)

29 TO 31 F OUTSIDE (continued)

Yr	Mo	Day	Hour	Outside Temp. (F)	Inside Temp. (F)	Outside R.H. (%)	Inside R.H. (%)	Wind Speed (mph)	Wind Direct. (deg N)	********** Thermocouple Temperatures (F) ********** #1 SE	#2 NE	#3 Mid-S	#4 Mid-N	#5 SW	#6 NW	#7 Peak	AVG T1TOT6 (F)	PEAK-TCPL AV (F)	Tpk-To (F)	TCPL AVG MINUS To (F)
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
89	12	9	18	28.9	32.3	54.3	68.9	11.5	192.4	32.1	31.9	32.1	33.0	33.5	33.8	31.6	32.7	-1.1	2.8	3.8
89	12	9	14	28.9	31.8	61.6	75.3	12.3	161.2	32.2	30.5	31.7	31.4	32.0	32.3	31.2	31.7	-0.5	2.3	2.8
89	12	9	17	28.9	32.9	55.5	71.5	12.3	177.9	32.4	31.6	32.3	32.5	32.2	32.8	31.6	32.3	-0.7	2.7	3.5
90	1	30	9	31.2	35.2	70.0	79.1	11.6	180.3	33.5	33.9	33.4	34.9	33.0	33.9	33.5	33.8	-0.3	2.4	2.6
90	1	10	24	31.0	35.5	90.9	93.9	17.8	184.0	33.5	33.2	33.0	34.3	32.9	34.2	33.1	33.5	-0.4	2.2	2.5
90	1	10	22	31.2	35.2	93.0	94.5	14.4	177.2	33.5	33.5	32.8	34.6	32.6	34.4	33.4	33.6	-0.2	2.2	2.4
90	1	10	23	31.2	35.5	91.9	94.3	15.2	186.5	33.8	33.5	33.2	34.7	33.0	34.6	33.5	33.8	-0.3	2.3	2.6
90	1	11	1	31.3	35.5	90.3	93.6	17.9	194.3	33.6	32.9	33.3	34.4	33.0	34.6	33.3	33.6	-0.3	2.0	2.3
90	1	5	18	30.9	35.6	73.9	82.6	8.2	208.0	35.7	36.5	35.1	35.8	34.8	33.1	33.6	35.2	-1.6	2.6	4.2
90	1	28	19	30.9	37.2	54.7	63.7	6.2	197.4	38.0	36.0	37.2	37.3	37.1	35.8	35.1	36.9	-1.8	4.2	6.0
90	1	14	12	30.9	32.5	69.4	81.2	11.2	156.8	33.3	31.1	33.0	32.1	32.9	32.5	31.9	32.5	-0.6	1.1	1.6
90	1	6	17	30.8	37.8	70.2	82.3	5.3	195.4	36.9	35.4	36.4	36.7	36.3	35.5	35.8	36.2	-0.4	5.0	5.4
90	1	7	22	30.8	34.7	92.1	93.1	5.3	199.9	35.5	34.9	34.9	35.0	34.5	32.2	32.5	34.5	-2.0	1.7	3.7
90	1	26	24	30.7	35.3	81.4	85.7	11.3	175.1	33.4	32.2	33.2	34.3	33.1	34.3	33.0	33.4	-0.4	2.3	2.7
90	1	15	8	30.5	35.9	86.3	88.4	4.1	188.0	35.5	34.1	35.1	34.4	35.0	34.9	33.8	34.8	-1.0	3.3	4.3
90	1	15	9	30.5	35.5	90.6	90.6	4.1	194.1	36.3	35.7	35.6	35.1	34.5	33.2	33.9	35.1	-1.2	3.4	4.6
90	1	2	24	30.4	34.5	74.2	87.1	6.2	194.4	32.8	32.6	33.3	33.1	32.4	33.3	32.9	32.9	-0.0	2.5	2.5
90	1	14	21	30.4	34.0	72.3	79.7	6.2	151.1	34.9	33.0	34.6	34.5	36.9	35.6	33.3	34.9	-1.6	2.9	4.5
90	1	2	22	30.2	33.9	74.1	85.5	9.4	191.3	32.3	32.4	31.3	33.2	30.9	32.5	31.8	32.1	-0.3	1.6	1.9
90	1	26	23	30.1	34.8	77.9	84.5	10.8	193.5	32.5	31.9	32.5	33.8	32.4	34.0	32.4	32.8	-0.4	2.3	2.7
90	1	28	20	30.0	34.0	57.8	67.4	7.7	188.6	35.8	34.7	35.8	35.2	35.0	34.0	33.2	35.1	-1.9	3.1	5.1
90	1	2	21	29.9	33.6	73.1	84.6	9.3	190.0	33.4	33.2	32.6	33.7	32.0	33.5	31.9	33.1	-1.2	2.0	3.1
90	1	14	20	29.9	34.0	71.7	78.4	5.6	158.8	35.8	33.6	34.7	34.6	37.4	35.3	33.5	35.3	-1.7	3.6	5.3
90	1	30	8	29.7	34.4	72.1	81.4	9.3	188.7	32.2	31.7	32.3	33.2	32.1	32.8	32.5	32.4	0.1	2.8	2.7
90	1	14	11	29.6	32.4	71.4	82.4	10.2	165.6	32.6	30.3	32.5	32.4	32.8	33.0	31.2	32.3	-1.1	1.5	2.6
90	1	19	20	29.5	33.4	73.2	78.3	4.0	156.4	35.9	32.8	35.7	34.1	36.1	34.4	34.0	34.8	-0.8	4.5	5.3
90	1	31	12	29.5	30.5	72.6	76.8	7.0	158.4	31.4	29.6	30.7	30.7	30.8	31.1	30.6	30.7	-0.1	1.1	1.2
90	1	28	21	29.4	34.7	58.3	68.6	8.0	189.3	34.8	34.0	35.1	35.4	34.6	34.0	32.9	34.7	-1.8	3.5	5.3

APPENDIX D (continued)

29 TO 31 F OUTSIDE (continued)

Yr	Mo	Day	Hour	Outside Temp. (F)	Inside Temp. (F)	Outside R.H. (%)	Inside R.H. (%)	Wind Speed (mph)	Wind Direct. (deg N)	********** Thermocouple Temperatures (F) ********** #1 SE	#2 NE	#3 Mid-S	#4 Mid-N	#5 SW	#6 NW	#7 Peak	AVG T1TOT6 (F)	PEAK-TCPL AV (F)	Tpk-To (F)	TCPL AVG MINUS To (F)
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
90	1	19	12	29.3	31.2	68.6	84.1	10.9	193.1	32.1	31.9	31.8	31.0	31.8	29.7	30.5	31.4	-0.9	1.2	2.1
90	1	28	23	29.2	34.2	59.1	70.5	9.0	191.1	32.1	31.6	32.1	34.3	32.5	34.1	31.2	32.8	-1.6	2.0	3.6
90	1	28	22	29.2	34.0	58.9	69.4	8.8	170.0	31.6	31.7	31.9	33.8	32.0	33.4	30.8	32.4	-1.6	1.6	3.2
90	1	19	21	29.2	32.5	74.0	79.0	4.9	161.2	34.2	30.9	35.1	33.1	36.3	34.4	32.7	34.0	-1.3	3.5	4.8
90	1	6	18	29.1	36.5	72.1	83.3	5.0	202.0	36.8	35.8	36.4	35.8	35.5	32.9	34.4	35.6	-1.1	5.3	6.4
90	1	3	4	29.1	33.0	84.9	92.2	8.3	170.4	32.2	31.3	32.6	32.5	31.8	32.0	31.5	32.1	-0.6	2.4	3.0
90	1	26	22	29.1	33.8	76.8	84.4	8.3	171.1	31.1	31.4	31.4	33.2	31.4	33.0	31.3	31.9	-0.6	2.3	2.8
90	1	28	11	29.0	31.1	63.6	75.2	10.0	202.2	32.7	32.7	31.9	31.1	31.7	29.4	29.4	31.6	-2.2	0.4	2.6
90	1	20	2	28.8	33.9	79.6	85.9	7.5	161.5	32.3	31.0	33.1	33.8	34.7	34.8	32.6	33.3	-0.7	3.8	4.5
90	2	18	12	31.1	33.6	70.9	81.9	17.5	203.6	33.3	32.0	32.3	31.3	31.5	31.6	32.1	32.0	0.1	1.0	0.9
90	2	23	17	31.0	40.5	54.2	68.0	4.2	202.2	38.8	38.4	38.9	39.1	35.3	38.8	37.6	38.2	-0.6	6.6	7.2
90	2	23	16	30.5	40.2	65.0	68.0	2.1	207.9	39.9	38.7	39.3	38.7	35.8	39.5	37.6	38.6	-1.0	7.1	8.1
90	2	5	10	30.4	33.7	99.8	94.7	13.8	192.4	32.3	33.5	31.7	34.0	31.4	31.7	31.8	32.4	-0.6	1.4	2.0
90	2	12	12	30.3	33.5	81.0	82.9	8.3	200.3	34.1	32.5	33.8	33.5	33.7	32.7	33.3	33.4	-0.1	2.9	3.0
90	2	16	11	30.1	34.7	100.0	100.0	7.3	208.6	32.8	31.8	32.7	33.3	33.7	32.8	32.7	32.9	-0.2	2.6	2.8
90	2	23	18	29.1	39.5	51.3	67.3	4.0	203.1	36.9	36.6	36.6	37.9	36.0	41.9	35.6	37.7	-2.1	6.5	8.6
90	2	20	16	28.8	34.8	46.7	64.8	10.3	201.6	33.9	32.9	34.7	33.5	34.0	32.4	32.9	33.6	-0.7	4.1	4.8
AVERAGES>>>				29.9	34.6	72.9	80.8	8.8									33.8	-0.7	3.1	3.8
				"F"-"E"	4.7	"H"-"G"=	7.9										AVG "U" MINUS AVG "T" =			0.7

34 TO 36 F OUTSIDE

Yr	Mo	Day	Hour	Outside Temp. (F)	Inside Temp. (F)	Outside R.H. (%)	Inside R.H. (%)	Wind Speed (mph)	Wind Direct. (deg N)	********** Thermocouple Temperatures (F) ********** #1 SE	#2 NE	#3 Mid-S	#4 Mid-N	#5 SW	#6 NW	#7 Peak	AVG T1TOT6 (F)	PEAK-TCPL AV (F)	Tpk-To (F)	TCPL AVG MINUS To (F)
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
89	12	2	4	36.1	39.0	78.6	85.3	13.9	206.0	38.3	36.3	37.6	38.2	37.3	38.0	36.8	37.6	-0.8	0.8	1.6
89	12	2	3	35.7	39.0	80.8	87.1	12.7	182.7	37.5	36.9	37.4	38.5	36.9	38.0	36.4	37.5	-1.1	0.7	1.8
89	12	1	13	35.2	36.3	73.2	82.2	6.8	156.9	36.9	35.6	35.9	36.3	36.1	36.4	34.6	36.2	-1.6	-0.6	1.0
89	12	5	23	34.3	39.7	89.3	88.9	7.5	210.1	37.9	37.9	38.0	38.6	37.4	38.3	37.9	38.0	-0.1	3.7	3.8
89	12	5	22	34.2	39.2	88.3	87.0	8.8	197.4	37.5	38.0	37.4	38.1	36.6	38.0	37.6	37.6	-0.0	3.3	3.4
89	12	5	20	34.2	38.7	85.7	86.4	5.4	209.5	38.5	38.2	39.9	38.3	38.1	38.0	37.9	38.5	-0.6	3.7	4.3
89	12	5	21	33.9	40.2	87.5	86.8	7.4	190.2	38.5	38.9	40.2	39.7	39.4	40.0	39.0	39.5	-0.5	5.1	5.5
90	1	14	16	36.1	40.0	56.7	74.2	9.2	200.0	38.5	37.5	38.0	39.0	38.0	37.5	37.6	38.1	-0.5	1.5	2.0
90	1	14	15	36.1	39.4	56.3	74.3	11.0	181.6	37.9	36.9	37.1	37.9	37.1	36.8	37.1	37.3	-0.2	1.0	1.2
90	1	16	9	36.2	41.8	100.0	100.0	3.1	186.7	40.8	40.1	41.8	40.5	41.8	41.2	41.9	41.0	0.9	5.7	4.8
90	2	31	22	33.8	36.9	71.5	74.5	12.2	161.0	35.1	34.4	35.4	36.8	35.9	36.9	34.5	35.8	-1.3	0.7	2.0
90	1	15	21	36.1	39.5	72.7	80.8	3.8	195.7	42.7	41.3	42.1	40.5	41.3	38.2	39.2	41.0	-1.8	3.1	4.9
90	1	27	7	35.6	37.5	66.8	82.0	12.2	187.1	35.8	34.9	35.4	36.1	35.2	36.2	35.1	35.6	-0.5	-0.5	0.0
90	1	25	16	36.3	38.9	77.2	82.8	25.1	195.4	39.5	40.3	38.6	39.4	38.1	36.8	36.6	38.8	-2.2	0.3	2.5
90	1	30	19	36.3	39.4	51.4	60.6	9.2	204.5	40.8	40.2	40.4	40.1	39.4	37.6	38.7	39.8	-1.0	2.4	3.5
90	1	14	14	35.5	38.8	59.6	77.6	12.3	194.8	38.2	36.0	37.5	37.4	38.0	37.1	37.0	37.4	-0.4	1.5	1.9
90	1	15	22	35.5	39.2	80.5	84.6	4.1	194.6	41.6	40.4	40.6	39.1	39.2	37.0	38.1	39.6	-1.5	2.7	4.2
90	1	31	24	35.3	40.4	80.6	80.5	11.1	165.2	37.5	37.1	37.7	39.5	37.4	38.3	37.3	37.9	-0.6	2.0	2.6
90	1	28	14	35.2	37.1	50.6	64.2	12.1	200.3	38.1	37.2	37.5	36.4	37.2	35.8	36.0	37.0	-1.0	0.8	1.8
90	1	14	17	35.1	39.7	58.9	73.6	8.8	185.3	38.5	36.9	38.8	39.0	38.8	39.5	37.9	38.6	-0.7	2.8	3.5
90	1	30	11	34.9	37.1	57.7	72.0	13.4	195.9	35.8	36.9	35.5	36.6	35.7	35.3	35.3	36.0	-0.7	0.3	1.0
90	1	28	18	34.8	39.4	40.7	56.5	8.3	192.2	39.7	38.9	38.5	38.8	38.4	39.0	37.0	38.9	-1.9	2.2	4.1
90	1	31	20	34.7	36.8	63.8	68.2	10.2	170.0	38.5	36.1	39.1	37.4	38.7	37.7	36.7	37.9	-1.2	2.0	3.2
90	1	31	21	34.7	37.0	65.3	70.6	11.7	170.0	37.6	35.3	37.7	37.5	38.0	38.2	36.1	37.4	-1.3	1.4	2.7
90	1	3	10	34.7	37.7	78.3	88.2	13.0	193.1	37.6	38.6	36.9	37.8	36.3	36.6	37.1	37.3	-0.2	2.4	2.6
90	1	11	4	36.2	38.6	77.4	89.0	16.1	204.6	37.3	36.4	37.8	37.6	36.6	37.4	36.5	37.2	-0.7	0.3	1.0
90	1	27	6	34.5	37.6	70.7	83.7	10.8	192.0	36.2	35.3	35.8	36.5	35.6	36.6	34.8	36.0	-1.2	0.3	1.5
90	1	31	23	34.4	38.5	77.5	78.9	11.6	175.1	36.2	35.3	36.0	38.0	36.2	37.8	35.5	36.6	-1.1	1.1	2.2
90	1	5	15	34.3	36.3	66.8	80.3	8.7	196.8	36.9	36.3	36.3	36.1	36.5	34.8	34.5	36.2	-1.6	0.3	1.9

APPENDIX D (continued)

34 TO 36 F OUTSIDE (continued)

Yr	Mo	Day	Hour	Outside Temp. (F)	Inside Temp. (F)	Outside R.H. (%)	Inside R.H. (%)	Wind Speed (mph)	Wind Direct. (deg N)	********** Thermocouple Temperatures (F) ********** #1 SE	#2 NE	#3 Mid-S	#4 Mid-N	#5 SW	#6 NW	#7 Peak	AVG T1TOT6 (F)	PEAK-TCPL AV (F)	Tpk-To (F)	TCPL AVG MINUS To (F)
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
90	1	19	16	34.2	38.0	52.6	73.8	8.1	176.2	38.4	37.4	38.4	36.5	38.2	36.1	36.8	37.5	-0.7	2.6	3.3
90	1	3	6	34.1	37.3	79.4	91.0	9.5	201.4	35.9	34.7	36.1	36.0	35.9	36.3	35.4	35.8	-0.4	1.3	1.7
90	1	14	24	34.0	38.5	68.0	80.5	8.8	186.4	37.1	35.9	36.8	37.2	37.6	37.7	36.2	37.1	-0.8	2.2	3.0
90	1	27	4	34.0	36.6	74.3	84.6	12.1	178.4	35.6	34.8	35.5	36.0	35.7	36.5	34.6	35.7	-1.0	0.6	1.6
90	1	2	17	33.9	39.0	61.3	78.4	9.1	209.0	37.5	37.5	38.3	38.1	37.5	36.2	36.6	37.5	-0.9	2.8	3.6
90	2	8	8	35.8	40.5	100.0	98.4	7.9	163.4	39.0	38.8	38.7	39.4	38.4	37.5	38.1	38.6	-0.5	2.3	2.8
90	2	1	4	36.3	41.0	89.6	85.5	6.6	168.3	39.8	39.0	40.4	40.5	39.9	38.4	39.3	39.7	-0.4	3.0	3.4
90	2	7	4	35.7	40.9	94.7	88.9	3.9	199.9	40.4	40.4	40.5	40.3	40.3	37.7	40.4	39.9	0.5	4.7	4.3
90	2	12	15	35.6	39.2	70.6	78.1	10.9	167.6	37.5	38.3	36.7	38.2	36.3	36.3	38.5	37.2	1.3	2.9	1.6
90	2	18	14	35.6	40.3	59.6	73.2	17.2	200.5	37.9	36.8	37.7	37.7	37.3	38.0	37.9	37.6	0.3	2.3	2.0
90	2	5	12	35.6	36.3	80.3	88.5	16.5	208.6	36.9	36.6	36.6	35.6	36.0	35.1	35.1	36.1	-1.0	-0.5	0.6
90	2	1	2	35.5	40.9	86.8	85.7	6.3	154.6	38.5	38.3	38.5	40.0	38.4	37.7	38.0	38.6	-0.5	2.5	3.0
90	2	1	1	35.5	40.2	84.1	83.0	11.3	189.3	38.1	37.8	38.0	39.5	37.7	37.2	37.7	38.1	-0.3	2.3	2.6
90	2	1	3	35.4	42.5	89.0	86.7	4.8	155.1	39.4	38.9	40.0	41.1	39.8	38.9	39.5	39.7	-0.2	4.0	4.3
90	2	9	20	35.4	39.2	83.2	84.6	5.4	207.7	43.0	41.7	40.3	40.5	41.0	37.9	39.2	40.7	-1.5	3.8	5.3
90	2	8	7	35.3	39.7	100.0	96.5	8.0	175.0	38.6	38.6	38.0	38.5	37.6	36.6	37.8	38.0	-0.2	2.4	2.6
90	2	7	19	35.3	38.1	100.0	96.5	7.9	207.1	40.5	39.5	39.5	39.0	38.7	36.3	37.4	38.9	-1.5	2.1	3.6
90	2	7	6	35.0	39.4	97.4	91.9	4.1	202.7	40.7	39.9	38.5	39.2	39.6	36.6	38.7	39.1	-0.4	3.7	4.1
90	2	8	6	34.5	40.7	100.0	94.7	8.6	171.1	40.1	38.4	39.0	39.8	39.5	37.4	38.2	39.0	-0.9	3.7	4.5
90	2	8	5	34.3	40.4	100.0	94.4	8.5	188.4	39.7	39.1	39.5	40.5	39.3	38.5	38.3	39.4	-1.2	4.0	5.2
AVERAGES>>>				35.1	38.9	76.2	82.4	9.7									38.0	-0.7	2.1	2.8
				"F"-"E"	3.8	"N"-"G"=	6.1										AVG "U" MINUS AVG "T" =			0.7

APPENDIX D (continued)

39 TO 41 F OUTSIDE

Yr	Mo	Day	Hour	Outside Temp. (F)	Inside Temp. (F)	Outside R.H. (%)	Inside R.H. (%)	Wind Speed (mph)	Wind Direct. (deg N)	********** Thermocouple Temperatures (F) ********** #1 SE	#2 NE	#3 Mid-S	#4 Mid-N	#5 SW	#6 NW	#7 Peak	AVG T1TOT6 (F)	PEAK-TCPL AV (F)	Tpk-To (F)	TCPL AVG MINUS To (F)
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
90	1	4	2	38.8	43.4	87.9	93.2	6.1	193.7	42.3	42.2	41.8	43.0	42.1	40.4	41.6	42.0	-0.4	2.8	3.2
90	1	16	19	40.7	43.1	100.0	100.0	4.1	152.0	43.2	42.3	43.3	42.9	44.8	43.2	43.8	43.3	0.5	3.1	2.6
90	1	30	15	40.3	41.6	34.9	50.6	14.0	199.0	40.8	41.5	39.9	40.9	39.7	40.0	40.0	40.5	-0.5	-0.3	0.2
90	1	27	10	40.3	41.3	53.5	72.0	17.4	187.6	40.9	43.3	40.0	40.8	39.8	40.4	39.0	40.9	-1.9	-1.3	0.6
90	1	3	14	40.1	42.4	69.5	82.2	13.6	201.6	42.5	42.7	42.0	41.6	42.1	40.5	41.3	41.9	-0.6	1.2	1.8
90	1	3	17	39.9	42.8	72.6	82.8	11.9	194.1	42.4	43.7	42.4	42.6	42.2	40.7	41.1	42.3	-1.2	1.3	2.5
90	1	8	14	39.8	42.1	74.8	87.4	11.4	198.5	41.3	41.0	41.1	40.6	40.5	39.7	41.1	40.7	0.4	1.2	0.9
90	1	8	19	39.7	41.6	56.7	73.8	7.3	192.6	42.8	42.7	42.2	41.8	41.9	40.2	40.2	41.9	-1.7	0.5	2.2
90	1	16	12	39.7	43.5	100.0	100.0	4.5	188.9	43.3	42.1	42.8	42.6	43.0	41.6	43.1	42.6	0.5	3.4	2.9
90	1	3	13	39.5	40.9	70.7	84.3	13.3	204.9	41.7	41.2	41.6	40.4	41.5	39.6	40.4	41.0	-0.6	0.9	1.4
90	1	9	14	39.5	43.6	80.6	85.7	4.9	183.6	42.9	42.5	42.5	42.6	42.4	40.8	42.5	42.3	0.2	2.9	2.8
90	1	23	23	39.4	41.1	95.4	98.0	17.2	156.0	40.6	39.6	40.6	40.8	40.9	41.8	39.6	40.7	-1.1	0.2	1.3
90	1	9	13	39.4	43.4	80.6	86.3	6.8	166.0	42.9	42.4	42.8	43.0	43.4	42.0	42.2	42.7	-0.5	2.8	3.3
90	1	9	12	39.4	42.2	81.0	87.0	6.8	173.1	42.3	41.4	41.8	41.9	42.2	40.7	41.1	41.7	-0.6	1.8	2.4
90	1	30	14	39.3	40.5	37.8	53.4	17.1	200.5	39.9	40.8	39.2	39.7	39.0	39.0	39.1	39.6	-0.5	-0.1	0.3
90	1	3	18	39.2	41.8	75.9	85.0	9.9	207.7	42.5	43.2	41.4	42.1	41.1	40.3	40.7	41.8	-1.1	1.5	2.5
90	1	3	21	39.2	40.9	85.5	91.9	10.4	209.3	42.4	41.9	41.8	41.1	41.4	39.9	40.1	41.4	-1.3	0.9	2.2
90	1	8	13	39.2	40.6	80.6	92.4	9.7	192.1	41.1	40.5	41.5	39.6	40.6	38.9	40.1	40.4	-0.3	0.9	1.2
90	1	31	17	39.1	42.6	50.1	63.1	9.6	165.6	41.6	39.8	42.1	41.5	42.1	43.9	41.1	41.8	-0.8	2.0	2.7
90	1	31	16	39.1	41.1	50.9	62.7	9.9	161.5	41.1	38.8	40.9	40.7	41.9	41.6	40.4	40.8	-0.5	1.3	1.8
90	1	3	22	38.9	40.8	91.1	94.8	9.1	206.6	41.1	41.7	40.5	41.0	39.7	39.1	39.5	40.5	-1.0	0.6	1.6
90	1	8	20	38.9	40.4	60.3	76.7	8.3	194.4	41.7	41.3	41.2	40.8	41.4	39.4	39.5	41.0	-1.5	0.7	2.1
90	2	1	5	38.7	41.6	83.9	85.0	8.2	181.9	41.8	40.1	41.2	42.0	40.7	40.2	40.4	41.0	-0.6	1.7	2.3
90	2	1	7	41.1	43.2	78.3	81.8	10.1	187.6	41.9	41.9	41.1	42.6	41.0	41.1	41.4	41.6	-0.2	0.3	0.5
90	2	8	10	41.2	43.1	91.1	93.5	12.8	201.4	43.1	45.0	42.1	43.2	41.4	42.3	42.4	42.8	-0.4	1.2	1.6
90	2	1	8	41.3	43.8	86.0	86.1	9.9	202.2	42.4	42.5	41.9	43.6	41.9	41.6	42.2	42.3	-0.1	0.9	1.0
90	2	12	20	38.7	39.7	65.1	73.8	15.1	158.1	40.1	39.4	40.1	39.7	39.7	39.6	38.8	39.8	-1.0	0.1	1.1
90	2	22	5	40.7	44.1	64.2	71.9	4.8	184.0	43.2	42.6	43.8	44.0	42.2	43.3	42.4	43.2	-0.8	1.7	2.5

APPENDIX D (continued)

39 TO 41 F OUTSIDE (continued)

Yr	Mo	Day	Hour	Outside Temp. (F)	Inside Temp. (F)	Outside R.H. (%)	Inside R.H. (%)	Wind Speed (mph)	Wind Direct. (deg N)	********** Thermocouple Temperatures (F) ********** #1 SE	#2 NE	#3 Mid-S	#4 Mid-N	#5 SW	#6 NW	#7 Peak	AVG T1TOT6 (F)	PEAK-TCPL AV (F)	Tpk-To (F)	TCPL AVG MINUS To (F)
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
90	2	22	2	40.5	44.5	60.9	70.7	9.7	191.7	42.7	41.9	42.1	43.2	41.5	42.3	42.0	42.3	-0.3	1.5	1.8
90	2	22	1	40.4	44.0	60.9	71.0	9.9	199.6	42.5	41.7	42.6	42.6	41.3	42.3	41.7	42.2	-0.5	1.3	1.7
90	2	5	19	40.1	41.2	62.0	73.6	11.6	210.1	42.7	41.8	41.7	41.2	41.2	40.1	38.8	41.4	-2.6	-1.3	1.3
90	2	12	21	39.9	41.9	66.2	74.4	18.0	178.8	40.9	41.3	41.2	41.6	40.7	41.4	40.3	41.2	-0.9	0.5	1.3
90	2	12	22	41.3	43.4	67.0	75.3	17.5	185.1	41.6	41.8	41.1	42.2	40.7	41.7	41.0	41.5	-0.5	-0.3	0.2
90	2	22	3	39.8	44.8	62.8	71.1	10.1	204.2	42.9	42.3	42.1	43.7	41.7	42.5	42.2	42.6	-0.4	2.4	2.8
90	2	21	24	39.6	43.6	59.8	68.9	11.2	190.0	42.1	40.8	42.0	42.4	40.8	41.9	40.6	41.7	-1.1	1.0	2.0
90	2	1	6	39.6	43.1	79.7	82.7	9.0	203.8	41.8	41.4	41.6	42.6	41.3	40.5	41.0	41.5	-0.5	1.4	1.9
90	2	21	23	39.2	42.8	58.8	67.2	14.1	193.3	41.0	40.6	40.3	41.8	39.7	40.9	39.9	40.7	-0.8	0.7	1.5
90	2	21	21	39.2	42.5	52.2	61.0	11.0	179.9	42.8	40.7	42.0	42.7	41.9	42.2	40.7	42.0	-1.4	1.5	2.8
90	2	22	4	39.0	43.4	65.8	71.6	9.3	208.2	42.6	42.0	42.1	42.9	41.3	41.9	41.7	42.1	-0.4	2.7	3.2
AVERAGES>>>				39.7	42.4	70.6	79.0	10.6									41.6	-0.7	1.2	1.8
				"F"-"E"	2.6	"H"-"G"=	8.4										AVG "U" MINUS AVG "T" =			0.7

AVG T1TOT6 = Average temperature for thermocouples one through six
PEAK - TCPL AV = Peak temperature minus thermocouple average temperature
Tpk-To = Temperature at the peak minus outside temperature
TCPL AVG MINUS To = Average thermocouple temperature minus outside temperature

APPENDIX E

Simulation Barn Environment at Different Ventilation Opening Areas and Latent Heat Adjustments

APPENDIX E

Simulation Barn Environment at Different Ventilation Opening Areas and Latent Heat Adjustments

10% SOFFETS OPEN THIS RUN

LATENT HEAT CHANGE	OUTSIDE TEMP F	BLDG HEAT LOSS W/K	VENT RATE m^3/s	INSIDE TEMP C	INSIDE TEMP F	AIR CHANGE PER HOUR	R.H. INSIDE %	DEW PT TEMP C	DEW PT TEMP F	ROOF TEMP F	ABSOLUTE HUMIDITY kg/m^3	CO2 LEVEL ppm	NEUTRAL PRES HT m	R.H. OUTSIDE %	WIND OUTSIDE mph	INSIDE PRESSURE COEFFICIENT
*	-5	11636	8.5	-11.8	10.8	3.9	100.0%	-11.6	11.0	-0.4	0.002757	1504	7.939	90%	4.5	-0.37393
LH*.90	-5	11636	8.7	-11.0	12.2	4.0	100.0%	-10.9	12.3	1.4	0.002549	1474	7.939	90%	4.5	-0.37393
*	-5	4808	9.3	-9.0	15.8	4.3	100.0%	-8.9	16.0	13.0	0.002765	1401	7.939	90%	4.5	-0.37393
LH*.90	-5	4808	9.6	-8.1	17.4	4.4	100.0%	-8.1	17.5	14.4	0.002572	1373	7.939	90%	4.5	-0.37393
*	-5	3976	9.5	-8.5	16.6	4.3	100.0%	-8.5	16.8	15.0	0.002772	1387	7.939	90%	4.5	-0.37393
LH*.90	-5	3976	9.7	-7.6	18.2	4.5	99.1%	-7.7	18.1	16.4	0.002581	1360	7.939	90%	4.5	-0.37393
*	0	12100	9.0	-9.5	14.9	4.1	100.0%	-9.4	15.0	4.3	0.002994	1438	7.93	88%	5.4	-0.37393
LH*.95	0	12101	9.1	-9.2	15.5	4.2	100.0%	-9.1	15.7	5.4	0.002893	1426	7.93	88%	5.4	-0.37393
*	0	4906	9.8	-6.8	19.7	4.5	100.0%	-6.8	19.8	17.0	0.003040	1351	7.93	88%	5.4	-0.37393
LH*.95	0	4906	9.9	-6.4	20.4	4.5	100.0%	-6.4	20.5	17.7	0.002945	1340	7.93	88%	5.4	-0.37393
*	0	4090	9.9	-6.4	20.4	4.5	100.0%	-6.4	20.5	18.9	0.003051	1340	7.93	88%	5.4	-0.37393
LH*.95	0	4090	10.0	-6.0	21.2	4.6	98.9%	-6.1	21.0	19.6	0.002957	1329	7.93	88%	5.4	-0.37393
*	5	12255	9.2	-7.0	19.4	4.2	100.0%	-7.0	19.5	9.1	0.003386	1420	7.926	84%	5.7	-0.37393
LH*1.05	5	12255	9.1	-7.4	18.8	4.2	100.0%	-7.3	18.9	9.7	0.003495	1433	7.927	84%	5.7	-0.37393
*	5	4975	9.9	-4.4	24.0	4.5	100.0%	-4.4	24.0	21.4	0.003463	1341	7.927	84%	5.7	-0.37393
LH*1.05	5	4975	9.8	-4.9	23.3	4.5	100.0%	-4.8	23.3	20.8	0.003566	1353	7.927	84%	5.7	-0.37393
*	5	4127	10.0	-4.0	24.7	4.6	99.0%	-4.1	24.5	23.2	0.003479	1330	7.927	84%	5.7	-0.37393
LH*1.05	5	4127	9.9	-4.5	24.0	4.5	100.0%	-4.4	24.0	22.6	0.003581	1342	7.927	84%	5.7	-0.37393
*	10	12771	9.9	-4.8	23.3	4.5	100.0%	-4.8	23.3	13.8	0.003755	1345	7.915	84%	6.7	-0.37393
LH*1.05	10	12771	9.8	-5.1	22.7	4.5	100.0%	-5.1	22.8	14.0	0.003861	1355	7.916	84%	6.7	-0.37393
*	10	5115	10.5	-2.4	27.6	4.8	96.5%	-2.9	26.8	25.5	0.003861	1283	7.9165	84%	6.7	-0.37393
LH*1.05	10	5115	10.4	-2.8	27.0	4.8	100.0%	-2.8	26.9	24.6	0.003961	1292	7.916	84%	6.7	-0.37393
*	10	4254	10.6	-2.1	28.3	4.9	94.2%	-2.8	27.0	26.9	0.003880	1275	7.9165	84%	6.7	-0.37393
LH*1.05	10	4254	10.5	-2.4	27.6	4.8	99.7%	-2.5	27.5	26.2	0.003980	1283	7.916	84%	6.7	-0.37393

APPENDIX E (continued)

10% SOFFETS OPEN THIS RUN

LATENT HEAT CHANGE	OUTSIDE TEMP F	BLDG HEAT LOSS W/K	VENT RATE m^3/s	INSIDE TEMP C	INSIDE TEMP F	AIR CHANGE PER HOUR	R.H. INSIDE %	DEW PT TEMP C	DEW PT TEMP F	ROOF TEMP F	ABSOLUTE HUMIDITY kg/m^3	CO2 LEVEL ppm	NEUTRAL PRES HT m	R.H. OUTSIDE %	WIND OUTSIDE mph	INSIDE PRESSURE COEFFICIENT
*	15	13184	10.6	-2.6	27.3	4.9	100.0%	-2.7	27.2	18.5	0.004174	1274	7.904	82%	7.7	-0.37393
LH*1.05	15	13184	10.5	-2.9	26.7	4.8	100.0%	-3.0	26.7	18.4	0.004279	1281	7.904	82%	7.7	-0.37393
*	15	5227	11.2	-0.4	31.2	5.1	91.6%	-1.5	29.2	29.0	0.004300	1226	7.9055	82%	7.7	-0.37393
LH*1.05	15	5227	11.1	-0.8	30.6	5.1	96.4%	-1.3	29.7	28.5	0.004401	1233	7.904	82%	7.7	-0.37393
*	15	4335	11.3	-0.1	31.8	5.2	89.7%	-1.5	29.4	30.6	0.004321	1220	7.9055	82%	7.7	-0.37393
LH*1.05	15	4335	11.2	-0.5	31.2	5.1	94.5%	-1.2	29.8	30.0	0.004425	1227	7.9055	82%	7.7	-0.37393
*	20	13184	10.6	-0.1	31.8	4.9	100.0%	-0.2	31.6	23.4	0.004934	1274	7.903	81%	7.8	-0.37393
LH*1.1	20	13184	10.5	-0.7	30.8	4.8	100.0%	-0.8	30.6	23.1	0.005165	1286	7.902	81%	7.8	-0.37393
*	20	5227	11.2	2.0	35.5	5.1	91.5%	0.5	32.9	33.4	0.005078	1228	7.904	81%	7.8	-0.37393
LH*1.1	20	5227	11.0	1.3	34.4	5.0	100.0%	1.0	33.8	32.3	0.005306	1241	7.903	81%	7.8	-0.37393
*	20	4335	11.2	2.3	36.1	5.2	90.0%	0.6	33.1	34.9	0.005102	1222	7.904	81%	7.8	-0.37393
LH*1.1	20	4335	11.1	1.6	34.9	5.1	98.5%	1.1	33.9	33.7	0.005330	1235	7.903	81%	7.8	-0.37393
*	25	13184	10.3	2.4	36.4	4.7	100.0%	2.2	36.0	28.3	0.006102	1307	7.905	84%	7.5	-0.37393
LH*1.1	25	13184	10.1	1.9	35.4	4.6	100.0%	1.7	35.1	28.0	0.006380	1320	7.905	84%	7.5	-0.37393
*	25	5227	10.8	4.5	40.0	4.9	95.5%	3.1	37.6	37.9	0.006265	1259	7.907	84%	7.5	-0.37393
LH*1.1	25	5227	10.6	3.8	38.9	4.9	100.0%	3.6	38.5	37.0	0.006541	1273	7.906	84%	7.5	-0.37393
*	25	4335	10.9	4.8	40.6	5.0	94.0%	3.2	37.8	39.4	0.006292	1253	7.907	84%	7.5	-0.37393
LH*1.1	25	4335	10.7	4.1	39.4	4.9	100.0%	3.7	38.6	38.3	0.006568	1266	7.906	84%	7.5	-0.37393
*	30	13184	10.3	4.8	40.6	4.7	100.0%	4.5	40.2	33.1	0.007372	1300	7.902	87%	7.7	-0.37393
LH*1.1	30	13184	10.2	4.3	39.8	4.7	100.0%	4.1	39.3	32.8	0.007685	1312	7.902	87%	7.7	-0.37393
*	30	5227	10.8	6.6	43.9	5.0	99.3%	5.5	41.8	42.1	0.007547	1258	7.904	87%	7.7	-0.37393
LH*1.1	30	5227	10.7	6.1	43.0	4.9	100.0%	5.8	42.4	41.2	0.007857	1270	7.903	87%	7.7	-0.37393
*	30	4335	10.9	6.9	44.4	5.0	97.9%	5.5	42.0	43.4	0.007575	1252	7.904	87%	7.7	-0.37393
LH*1.1	30	4335	10.7	6.3	43.4	4.9	100.0%	6.0	42.8	42.4	0.007885	1264	7.903	87%	7.7	-0.37393
*	35	13184	9.9	7.2	45.0	4.6	100.0%	7.1	44.9	37.9	0.008938	1338	7.905	88%	7.4	-0.37393
LH*1.1	35	13184	9.8	6.8	44.2	4.5	100.0%	6.7	44.1	37.6	0.009319	1351	7.905	88%	7.4	-0.37393
*	35	5227	10.4	9.0	48.2	4.8	100.0%	8.9	48.0	46.4	0.009115	1294	7.907	88%	7.4	-0.37393

APPENDIX E (continued)

10% SOFFETS OPEN THIS RUN

LATENT HEAT CHANGE	OUTSIDE TEMP F	BLDG HEAT LOSS W/K	VENT RATE m^3/s	INSIDE TEMP C	INSIDE TEMP F	AIR CHANGE PER HOUR	R.H. INSIDE %	DEW PT TEMP C	DEW PT TEMP F	ROOF TEMP F	ABSOLUTE HUMIDITY kg/m^3	CO2 LEVEL ppm	NEUTRAL PRES HT m	R.H. OUTSIDE %	WIND OUTSIDE mph	INSIDE PRESSURE COEFFICIENT
LH*1.1	35	5227	10.3	8.5	47.3	4.7	100.0%	8.4	47.1	45.6	0.009500	1307	7.907	88%	7.4	-0.37393
*	35	4335	10.5	9.3	48.7	4.8	100.0%	9.1	48.4	47.6	0.009143	1288	7.907	88%	7.4	-0.37393
LH*1.1	35	4335	10.3	8.7	47.7	4.7	100.0%	8.6	47.5	46.7	0.009529	1300	7.907	88%	7.4	-0.37393
*	40	13299	10.5	9.4	48.9	4.8	100.0%	9.3	48.7	41.9	0.009898	1281	7.895	84%	8.2	-0.37393
LH*1.1	40	13299	10.4	9.0	48.2	4.8	100.0%	8.9	48.0	42.3	0.010299	1290	7.894	84%	8.2	-0.37393
*	40	5253	10.9	10.9	51.6	5.0	100.0%	10.8	51.4	50.0	0.010071	1247	7.897	84%	8.2	-0.37393
LH*1.1	40	5253	10.8	10.4	50.8	5.0	100.0%	10.3	50.6	49.3	0.010480	1257	7.897	84%	8.2	-0.37393
*	40	4360	11.0	11.1	52.0	5.0	100.0%	11.0	51.8	51.1	0.010098	1243	7.897	84%	8.2	-0.37393
LH*1.1	40	4360	10.9	10.7	51.2	5.0	100.0%	10.5	50.9	50.3	0.010508	1253	7.897	84%	8.2	-0.37393

NOTES:

1. Wind and Outside Relative Humidity Data are the Average of 6 Instrumented Barn Sites From December to March of 1989 to 1992 For Winds 30 Degrees Plus or Minus 270 Degrees
2. * = Data Calculated From The Initial Partitioning Between Latent and Sensible Heat.
3. LH*x.xx Represents the Adjustment to the Original Calculation of Latent and Sensible Heat Partitioning at a Given Temperature

APPENDIX E (continued)

50% SOFFETS OPEN THIS RUN

LATENT HEAT CHANGE	OUTSIDE TEMP F	BLDG HEAT LOSS W/K	VENT RATE m^2/s	INSIDE TEMP C	INSIDE TEMP F	AIR CHANGE PER HOUR	R.H. INSIDE %	DEW PT TEMP C	DEW PT TEMP F	ROOF TEMP F	ABSOLUTE HUMIDITY kg/m^3	CO2 LEVEL ppm	NEUTRAL PRES HT m	R.H. OUTSIDE %	WIND SPEED mph	INSIDE PRESSURE COEFFICIENT
*	-5	11636	13.4	-13.6	7.5	6.14	100.0%	-13.5	7.7	-1.4	0.001949	1082	7.235	90%	4.5	-0.34615
LH*.9	-5	11636	13.8	-13.1	8.5	6.31	100.0%	-13.0	8.7	0.0	0.001814	1062	7.234	90%	4.5	-0.34615
*	-5	4808	14.4	-12.1	10.2	6.61	100.0%	-12.0	10.4	8.1	0.001914	1029	7.2325	90%	4.5	-0.34615
LH*.9	-5	4808	14.8	-11.5	11.4	6.79	94.7%	-12.0	10.5	9.1	0.001788	1011	7.233	90%	4.5	-0.34615
*	-5	3976	14.6	-11.9	10.6	6.68	100.0%	-11.8	10.8	9.4	0.001911	1023	7.2325	90%	4.5	-0.34615
LH*.9	-5	3976	15.0	-11.2	11.8	6.86	92.6%	-12.0	10.5	10.5	0.001785	1005	7.232	90%	4.5	-0.34615
*	0	12100	14.0	-11.2	11.8	6.42	100.0%	-11.1	12.0	3.4	0.002184	1050	7.22	88%	5.4	-0.34615
LH*.95	0	12101	14.2	-10.9	12.3	6.50	100.0%	-10.8	12.5	4.2	0.002117	1041	7.22	88%	5.4	-0.34615
*	0	4906	15.0	-9.7	14.6	6.86	98.5%	-9.8	14.4	12.5	0.002164	1004	7.219	88%	5.4	-0.34615
LH*.95	0	4906	15.2	-9.4	15.1	6.95	93.1%	-10.1	13.8	13.1	0.002100	996	7.219	88%	5.4	-0.34615
*	0	4090	15.1	-9.5	14.9	6.92	96.6%	-9.8	14.4	13.8	0.002163	998	7.219	88%	5.4	-0.34615
LH*.95	0	4090	15.3	-9.2	15.5	7.01	91.4%	-10.1	13.8	14.3	0.002099	990	7.219	88%	5.4	-0.34615
*	5	12255	14.1	-8.6	16.5	6.49	100.0%	-8.5	16.6	8.3	0.002506	1042	7.217	84%	5.7	-0.34615
LH*1.05	5	12255	14.0	-8.9	16.0	6.41	100.0%	-8.8	16.2	8.8	0.002579	1051	7.217	84%	5.7	-0.34615
*	5	4975	15.1	-7.1	19.2	6.92	91.5%	-8.1	17.5	17.2	0.002496	999	7.215	84%	5.7	-0.34615
LH*1.05	5	4975	14.9	-7.4	18.6	6.83	96.5%	-7.8	18.0	16.8	0.002566	1007	7.215	84%	5.7	-0.34615
*	5	4127	15.2	-6.9	19.6	6.98	89.9%	-8.1	17.5	18.5	0.002496	993	7.215	84%	5.7	-0.34615
LH*1.05	5	4127	15.0	-7.2	19.0	6.89	94.8%	-7.8	18.0	18.0	0.002565	1002	7.215	84%	5.7	-0.34615
*	10	12771	15.0	-6.3	20.7	6.87	98.4%	-6.4	20.5	13.1	0.002880	1004	7.204	84%	6.7	-0.34615
LH*1.05	10	12771	14.8	-6.5	20.3	6.80	100.0%	-6.5	20.4	12.1	0.002952	1011	7.205	84%	6.7	-0.34615
*	10	5115	15.8	-4.8	23.3	7.26	87.6%	-6.3	20.6	21.5	0.002884	968	7.2	84%	6.7	-0.34615
LH*1.05	10	5115	15.7	-5.1	22.8	7.18	91.9%	-6.1	21.1	21.0	0.002954	975	7.202	84%	6.7	-0.34615
*	10	4254	16.0	-4.6	23.6	7.32	86.3%	-6.3	20.6	22.6	0.002885	963	7.2	84%	6.7	-0.34615
LH*1.05	10	4252	15.8	-4.9	23.1	7.24	90.5%	-6.1	21.1	22.1	0.002955	970	7.202	84%	6.7	-0.34615
*	15	13184	15.9	-3.9	24.9	7.30	93.0%	-4.8	23.4	17.9	0.003297	965	7.192	82%	7.7	-0.34615
LH*1.05	15	13184	15.8	-4.2	24.5	7.23	96.8%	-4.5	23.9	17.7	0.003370	970	7.193	82%	7.7	-0.34615
*	15	5227	16.7	-2.6	27.4	7.65	83.9%	-4.6	23.6	25.7	0.003313	936	7.189	82%	7.7	-0.34615
LH*1.05	15	5227	16.5	-2.9	26.9	7.58	87.6%	-4.4	24.1	25.2	0.003386	942	7.19	82%	7.7	-0.34615
*	15	4335	16.8	-2.4	27.7	7.70	82.7%	-4.6	23.7	26.7	0.003316	933	7.188	82%	7.7	-0.34615

APPENDIX E (continued)

50% SOFFETS OPEN THIS RUN

LATENT HEAT CHANGE	OUTSIDE TEMP F	BLDG HEAT LOSS W/K	VENT RATE m^2/s	INSIDE TEMP C	INSIDE TEMP F	AIR CHANGE PER HOUR	R.H. INSIDE %	DEW PT TEMP C	DEW PT TEMP F	ROOF TEMP F	ABSOLUTE HUMIDITY kg/m^3	CO2 LEVEL ppm	NEUTRAL PRES HT m	R.H. OUTSIDE %	WIND SPEED mph	INSIDE PRESSURE COEFFICIENT
LH*1.05	15	4335	16.6	-2.7	27.2	7.63	86.4%	-4.4	24.1	26.3	0.003388	938	7.188	82%	7.7	-0.34615
*	20	13184	15.9	-1.3	29.6	7.29	90.4%	-2.6	27.4	22.8	0.003946	966	7.194	81%	7.8	-0.34615
LH*1.1	20	13184	15.6	-1.8	28.8	7.17	97.6%	-2.1	28.2	22.5	0.004107	976	7.195	81%	7.8	-0.34615
*	20	5227	16.6	-0.0	31.9	7.63	82.1%	-2.5	27.6	30.3	0.003968	938	7.188	81%	7.8	-0.34615
LH*1.1	20	5227	16.3	-0.6	31.0	7.49	89.0%	-2.0	28.4	29.5	0.004128	949	7.19	81%	7.8	-0.34615
*	20	4335	16.7	0.1	32.2	7.67	81.1%	-2.4	27.6	31.3	0.003972	935	7.188	81%	7.8	-0.34615
LH*1.1	20	4335	16.4	-0.4	31.3	7.54	87.9%	-2.0	28.4	30.4	0.004132	945	7.19	81%	7.8	-0.34615
*	25	13184	15.4	1.3	34.3	7.06	93.1%	0.2	32.3	27.7	0.004934	986	7.197	84%	7.5	-0.34615
LH*1.1	25	13184	15.1	0.9	33.6	6.94	99.6%	0.6	33.1	27.5	0.005127	997	7.2	84%	7.5	-0.34615
*	25	5227	16.1	2.6	36.6	7.39	85.9%	0.3	32.5	35.0	0.004959	957	7.193	84%	7.5	-0.34615
LH*1.1	25	5227	15.8	2.1	35.7	7.26	92.2%	0.7	33.2	34.2	0.005150	968	7.193	84%	7.5	-0.34615
*	25	4335	16.2	2.7	36.9	7.44	84.9%	0.3	32.5	36.0	0.004964	953	7.193	84%	7.5	-0.34615
LH*1.1	25	4335	15.9	2.2	36.0	7.31	91.2%	0.7	33.3	35.2	0.005154	964	7.193	84%	7.5	-0.34615
*	30	13184	15.4	3.8	38.8	7.08	96.9%	2.7	36.9	32.5	0.006073	984	7.198	87%	7.7	-0.34615
LH*1.1	30	13184	15.2	3.4	38.1	6.97	100.0%	3.1	37.6	32.3	0.006292	994	7.2	87%	7.7	-0.34615
*	30	5227	16.1	5.0	40.9	7.39	90.0%	2.8	37.1	39.4	0.006101	957	7.191	87%	7.7	-0.34615
LH*1.1	30	5227	15.9	4.5	40.1	7.27	96.1%	3.2	37.8	38.7	0.006319	967	7.192	87%	7.7	-0.34615
*	30	5227	16.1	5.0	40.9	7.39	90.0%	2.8	37.1	40.1	0.006101	957	7.191	87%	7.7	-0.34615
LH*1.1	30	4335	15.9	4.6	40.4	7.31	95.2%	3.3	37.9	39.6	0.006324	964	7.192	87%	7.7	-0.34615
*	35	13184	14.9	6.3	43.4	6.82	100.0%	6.2	43.2	37.4	0.007410	1008	7.202	88%	7.4	-0.34615
LH*1.1	35	13185	14.6	5.9	42.7	6.72	100.0%	5.9	42.6	37.2	0.007673	1019	7.205	88%	7.4	-0.34615
*	35	5227	15.5	7.4	45.4	7.13	93.2%	6.3	43.4	44.0	0.007436	980	7.196	88%	7.4	-0.34615
LH*1.1	35	5227	15.3	7.0	44.6	7.01	99.2%	6.8	44.3	43.3	0.007695	990	7.197	88%	7.4	-0.34615
*	35	4335	15.6	7.6	45.7	7.17	92.3%	6.4	43.5	44.9	0.007440	976	7.196	88%	7.4	-0.34615
LH*1.1	35	4335	15.4	7.2	44.9	7.05	98.3%	6.8	44.3	44.1	0.007699	986	7.197	88%	7.4	-0.34615
*	40	13299	15.6	8.6	47.4	7.16	97.1%	8.0	46.5	42.1	0.008335	977	7.198	84%	8.2	-0.34615
LH*1.1	40	13299	15.4	8.2	46.8	7.07	100.0%	8.1	46.6	41.9	0.008613	985	7.2	84%	8.2	-0.34615
*	40	5253	16.2	9.6	49.2	7.42	91.5%	8.1	46.7	47.9	0.008366	955	7.19	84%	8.2	-0.34615
LH*1.1	40	5253	16.0	9.2	48.5	7.32	96.9%	8.6	47.5	47.3	0.008646	963	7.193	84%	8.2	-0.34615

APPENDIX E (continued)

50% SOFFETS OPEN THIS RUN

LATENT HEAT CHANGE	OUTSIDE TEMP F	BLDG HEAT LOSS W/K	VENT RATE m^2/s	INSIDE TEMP C	INSIDE TEMP F	AIR CHANGE PER HOUR	R.H. INSIDE %	DEW PT TEMP C	DEW PT TEMP F	ROOF TEMP F	ABSOLUTE HUMIDITY kg/m^3	CO2 LEVEL ppm	NEUTRAL PRES HT m	R.H. OUTSIDE %	WIND SPEED mph	INSIDE PRESSURE COEFFICIENT
*	40	4360	16.3	9.7	49.5	7.45	90.7%	8.2	46.7	48.7	0.008372	952	7.19	84%	8.2	-0.34615
LH*1.1	40	4360	16.0	9.3	48.8	7.35	96.1%	8.6	47.5	48.1	0.008651	960	7.193	84%	8.2	-0.34615

NOTES:
1. Wind and Outside Relative Humidity Data are the Average of 6 Instrumented Barn Sites From December to March of 1989 to 1992 For Winds 30 Degrees Plus or Minus 270 Degrees
2. * = Data Calculated From the Initial Partitioning Between Latent and Sensible Heat.
3. LH*x.xx Represents the Adjustment to the Original Calculation of Latent and Sensible Heat Partitioning at a Given Temperature.

100% SOFFITS OPEN THIS RUN

	OUTSIDE TEMP F	BLDG HEAT LOSS W/K	VENT RATE m^3/s	INSIDE TEMP C	INSIDE TEMP F	AIR CHANGE PER HOUR	R.H. INSIDE %	DEW PT TEMP C	DEW PT TEMP F	ROOF TEMP F	ABSOLUTE HUMIDITY kg/m^3	CO2 LEVEL ppm	NEUTRAL PRES HT m	R.H. OUTSIDE %	WIND SPEED mph	INSIDE PRESSURE COEFFICIENT
	-5	11636	-19.8	-15.2	4.7	9.06	100.0%	-15.0	4.9	-2.2	0.001527	844	6.005	90%	4.5	-0.22488
LH*.9	-5	11636	-20.2	-14.7	5.5	9.26	100.0%	-14.6	5.7	-1.3	0.00144	834	6.013	90%	4.5	-0.22488
	-5	4808	-20.7	-14.2	6.4	9.47	100.0%	-14.1	6.6	4.8	0.00151	823	6.021	90%	4.5	-0.22488
LH*.9	-5	4808	-21.1	-13.7	7.3	9.68	91.9%	-14.5	5.8	5.6	0.001426	812	6.028	90%	4.5	-0.22488
	-5	3976	-20.8	-14.1	6.6	9.53	100.0%	-14.0	6.8	5.7	0.001508	820	6.023	90%	4.5	-0.22488
LH*.9	-5	3976	-21.2	-13.6	7.5	9.74	90.7%	-14.5	5.8	6.6	0.001424	809	6.03	90%	4.5	-0.22488
	0	12100	-21.3	-12.8	9.0	9.77	100.0%	-12.6	9.3	2.6	0.001718	808	5.93	88%	5.4	-0.22488
LH*.95	0	12101	-21.5	-12.5	9.4	9.86	97.4%	-12.7	9.1	3.2	0.001676	804	5.934	88%	5.4	-0.22488
	0	4906	-22.1	-11.9	10.6	10.15	93.6%	-12.5	9.5	9.2	0.001708	791	5.945	88%	5.4	-0.22488
LH*.95	0	4906	-22.3	-11.6	11.1	10.24	89.5%	-12.7	9.1	9.6	0.001667	787	5.95	88%	5.4	-0.22488

APPENDIX E (continued)

100% SOFFITS OPEN THIS RUN

	OUTSIDE TEMP F	BLDG HEAT LOSS W/K	VENT RATE m^3/s	INSIDE TEMP C	INSIDE TEMP F	AIR CHANGE PER HOUR	R.H. INSIDE %	DEW PT TEMP C	DEW PT TEMP F	ROOF TEMP F	ABSOLUTE HUMIDITY kg/m^3	CO2 LEVEL ppm	NEUTRAL PRES HT m	R.H. OUTSIDE %	WIND SPEED mph	INSIDE PRESSURE COEFFICIENT
	0	4090	-22.2	-11.8	10.8	10.19	92.6%	-12.5	9.5	10.0	0.001707	789	5.947	88%	5.4	-0.22488
LH*.95	0	4090	-22.4	-11.5	11.3	10.29	88.5%	-12.7	9.1	10.4	0.001666	784	5.95	88%	5.4	-0.22488
	5	12255	-21.8	-10.1	13.8	10.00	93.6%	-10.8	12.6	7.5	0.001982	798	5.905	84%	5.7	-0.22488
LH*1.05	5	12255	-21.6	-10.3	13.4	9.90	97.4%	-10.5	13.0	7.8	0.002027	802	5.9	84%	5.7	-0.22488
	5	4975	-22.6	-9.3	15.3	10.35	86.8%	-10.8	12.6	13.9	0.001976	782	5.92	84%	5.7	-0.22488
LH*1.05	5	4975	-22.4	-9.5	14.9	10.25	90.5%	-10.5	13.0	13.5	0.00202	786	5.915	84%	5.7	-0.22488
	5	4090	-22.7	-9.2	15.5	10.40	85.9%	-10.8	12.6	14.7	0.001976	780	5.9215	84%	5.7	-0.22488
LH*1.05	5	4127	-22.5	-9.4	15.1	10.30	89.6%	-10.5	13.0	14.3	0.002019	784	5.916	84%	5.7	-0.22488
	10	12771	-23.8	-7.8	18.0	10.90	89.2%	-9.0	15.8	12.3	0.002305	760	5.837	84%	6.7	-0.22488
LH*1.05	10	12771	-23.6	-8.0	17.7	10.82	92.4%	-8.8	16.2	11.7	0.002348	763	5.835	84%	6.7	-0.22488
	10	5115	-24.4	-7.0	19.4	11.21	83.5%	-9.0	15.9	18.1	0.002305	749	5.848	84%	6.7	-0.22488
LH*1.05	10	5115	-24.3	-7.2	19.1	11.12	86.6%	-8.8	16.2	17.8	0.002347	752	5.845	84%	6.7	-0.22488
	10	4254	-24.5	-6.9	19.6	11.25	82.8%	-8.9	15.9	18.9	0.002305	747	5.849	84%	6.7	-0.22488
LH*1.05	10	4252	-24.3	-7.1	19.2	11.16	85.9%	-8.8	16.2	18.5	0.002347	750	5.845	84%	6.7	-0.22488
	15	13185	-25.9	-5.4	22.3	11.87	84.9%	-7.2	19.0	17.1	0.002672	726	5.79	82%	7.7	-0.22488
LH*1.05	15	13184	-25.7	-5.6	22.0	11.79	87.5%	-7.0	19.3	17.0	0.002715	729	5.79	82%	7.7	-0.22488
	15	5227	-26.5	-4.7	23.6	12.13	80.2%	-7.2	19.1	22.4	0.002676	718	5.793	82%	7.7	-0.22488
LH*1.05	15	5227	-26.3	-4.9	23.2	12.06	82.8%	-7.0	19.4	22.1	0.002718	720	5.79	82%	7.7	-0.22488
	15	4335	-26.5	-4.6	23.8	12.17	79.6%	-7.2	19.1	23.1	0.002677	717	5.793	82%	7.7	-0.22488
LH*1.05	15	4335	-26.4	-4.8	23.4	12.09	82.2%	-7.0	19.4	22.8	0.002719	719	5.79	82%	7.7	-0.22488
	20	13184	-26.0	-2.7	27.1	11.91	82.8%	-4.9	23.1	22.0	0.003231	725	5.787	81%	7.8	-0.22488
LH*1.1	20	13184	-25.7	-3.1	26.5	11.78	87.6%	-4.6	23.7	21.9	0.003324	729	5.79	81%	7.8	-0.22488
	20	5227	-26.5	-2.0	28.3	12.17	78.5%	-4.9	23.2	27.2	0.003237	717	5.787	81%	7.8	-0.22488
LH*1.1	20	5227	-26.2	-2.4	27.6	12.03	83.4%	-4.6	23.7	26.6	0.00333	721	5.786	81%	7.8	-0.22488
	20	4335	-26.6	-2.0	28.5	12.20	77.9%	-4.9	23.2	27.8	0.003238	716	5.787	81%	7.8	-0.22488
LH*1.1	20	4335	-26.3	-2.3	27.8	12.06	82.8%	-4.6	23.8	27.2	0.003331	720	5.786	81%	7.8	-0.22488
	25	13184	-25.1	-0.0	32.0	11.52	84.6%	-2.1	28.2	27.0	0.004093	738	5.797	84%	7.5	-0.22488

100% SOFFITS OPEN THIS RUN

LATENT HEAT CHANGE	OUTSIDE TEMP F	BLDG HEAT LOSS W/K	VENT RATE m^3/s	INSIDE TEMP C	INSIDE TEMP F	AIR CHANGE PER HOUR	R.H. INSIDE %	DEW PT TEMP C	DEW PT TEMP F	ROOF TEMP F	ABSOLUTE HUMIDITY kg/m^3	CO2 LEVEL ppm	NEUTRAL PRES HT m	R.H. OUTSIDE %	WIND SPEED mph	INSIDE PRESSURE COEFFICIENT
LH*1.1	25	13184	-24.8	-0.4	31.3	11.39	89.2%	-1.8	28.8	26.8	0.004205	742	5.8	84%	7.5	-0.22488
	25	5227	-25.7	0.7	33.2	11.78	80.8%	-2.0	28.3	32.1	0.004101	729	5.799	84%	7.5	-0.22488
LH*1.1	25	5227	-25.4	0.3	32.5	11.64	85.2%	-1.7	28.9	31.5	0.004212	734	5.8	84%	7.5	-0.22488
	25	4335	-25.8	0.8	33.4	11.82	80.3%	-2.0	28.3	32.7	0.004102	728	5.799	84%	7.5	-0.22488
LH*1.1	25	4335	-25.4	0.4	32.7	11.67	84.7%	-1.7	28.9	32.1	0.004213	733	5.8	84%	7.5	-0.22488
	30	13184	-25.4	2.5	36.6	11.66	88.7%	0.6	33.1	31.9	0.005113	733	5.79	87%	7.7	-0.22488
LH*1.1	30	13184	-25.1	2.2	36.0	11.53	92.8%	0.9	33.6	31.7	0.005238	737	5.795	87%	7.7	-0.22488
	30	5227	-25.9	3.2	37.7	11.90	85.1%	0.7	33.2	36.6	0.005122	725	5.79	87%	7.7	-0.22488
LH*1.1	30	5227	-25.6	2.8	37.1	11.76	89.3%	0.9	33.7	36.1	0.005247	730	5.79	87%	7.7	-0.22488
	30	4335	-26.0	3.3	37.9	11.93	84.6%	0.7	33.2	37.3	0.005123	724	5.79	87%	7.7	-0.22488
LH*1.1	30	4335	-25.7	2.9	37.2	11.79	88.8%	1.0	33.7	36.7	0.005248	729	5.79	87%	7.7	-0.22488
	35	13184	-24.5	5.2	41.3	11.23	91.4%	3.9	39.0	36.8	0.006277	748	5.8	88%	7.4	-0.22488
LH*1.1	35	13185	-24.2	4.9	40.8	11.12	95.4%	4.2	39.5	36.7	0.006426	752	5.805	88%	7.4	-0.22488
	35	5227	-25.0	5.8	42.4	11.47	87.8%	3.9	39.0	41.4	0.006285	739	5.8	88%	7.4	-0.22488
LH*1.1	35	5227	-24.7	5.5	41.8	11.35	91.9%	4.2	39.6	40.9	0.006434	744	5.8	88%	7.4	-0.22488
	35	4335	-25.1	5.9	42.6	11.51	87.3%	3.9	39.1	42.0	0.006286	738	5.8	88%	7.4	-0.22488
LH*1.1	35	4335	-24.8	5.5	42.0	11.38	91.4%	4.2	39.6	41.4	0.006436	743	5.8	88%	7.4	-0.22488
	40	13299	-26.2	7.5	45.5	12.01	88.5%	5.7	42.2	41.2	0.007095	722	5.79	84%	8.2	-0.22488
LH*1.1	40	13299	-26.0	7.3	45.1	11.91	92.0%	6.0	42.8	41.4	0.007252	725	5.8	84%	8.2	-0.22488
	40	5253	-26.6	8.1	46.5	12.21	85.6%	5.7	42.3	45.6	0.007104	716	5.78	84%	8.2	-0.22488
LH*1.1	40	5253	-26.4	7.8	46.0	12.10	89.2%	6.0	42.9	45.1	0.007263	719	5.785	84%	8.2	-0.22488
	40	4360	-26.7	8.1	46.6	12.23	85.2%	5.7	42.3	46.1	0.007106	715	5.78	84%	8.2	-0.22488
LH*1.1	40	4360	-26.4	7.8	46.1	12.12	88.8%	6.0	42.9	45.6	0.007264	718	5.785	84%	8.2	-0.22488

NOTES:

1. Wind and Outside Relative Humidity Data are the Average of 6 Instrumented Barn Sites From December to March of 1989 to 1992 For Winds 30 Degrees Plus or Minus 270 Degrees
2. * = Data Calculated From the Initial Partitioning Between Latent and Sensible Heat.
3. LH*x.xx Represents the Adjustment to the Original Calculation of Latent and Sensible Heat Partitioning at a Given Temperature.

APPENDIX E (continued)

VENTS = SOFFETS, 1 ALLEY DOOR, 4 PEN DOORS, & RIDGE (343% OF OPEN SOFFITS)

LATENT HEAT CHANGE	OUTSIDE TEMP F	BLDG HEAT LOSS W/K	VENT RATE m^3/s	INSIDE TEMP C	INSIDE TEMP F	AIR CHANGE PER HOUR	R.H. INSIDE %	DEW PT TEMP C	DEW PT TEMP F	ROOF TEMP F	ABSOLUTE HUMIDITY kg/m^3	CO2 LEVEL ppm	NEWTRAL PRES HT m	R.H. OUTSIDE %	WIND SPEED mph	INSIDE PRESSURE COEFFICIENT
*	-5	11636	29.5	-16.5	2.3	13.52	103.5%	-16.4	2.5	-2.9	0.001254	680	2.7585	90%	4.5	-0.20306
LH*.9	-5	11396	28.6	-16.0	3.2	13.12	96.2%	-16.3	2.7	-2.0	0.001222	690	2.181	90%	4.5	-0.20306
*	-5	4808	30.6	-16.1	3.1	14.03	98.1%	-16.1	3.0	2.0	0.001239	667	2.767	90%	4.5	-0.20306
LH*.9	-5	4567	29.8	-15.5	4.2	13.65	90.6%	-16.4	2.5	2.9	0.001208	676	2.203	90%	4.5	-0.20306
*	-5	3976	30.7	-16.0	3.2	14.10	97.4%	-16.1	2.9	2.6	0.001238	666	2.7685	90%	4.5	-0.20306
LH*.9	-5	3735	29.9	-15.4	4.3	13.72	89.9%	-16.4	2.5	3.6	0.001206	675	2.206	90%	4.5	-0.20306
*	0	12100	30.9	-13.9	6.9	14.19	95.8%	-14.3	6.3	2.0	0.001459	664	2.7185	88%	5.4	-0.20306
LH*.95	0	11850	29.5	-13.6	7.5	13.54	93.0%	-14.3	6.3	2.6	0.001461	679	2.075	88%	5.4	-0.20306
*	0	4906	32.0	-13.5	7.7	14.70	91.3%	-14.4	6.1	6.7	0.001446	653	2.728	88%	5.4	-0.20306
LH*.95	0	4683	30.6	-13.1	8.5	14.05	88.1%	-14.3	6.2	7.3	0.001448	667	2.099	88%	5.4	-0.20306
*	0	4090	32.2	-13.4	7.8	14.75	90.7%	-14.4	6.1	7.2	0.001445	652	2.7296	88%	5.4	-0.20306
LH*.95	0	3839	30.8	-13.0	8.6	14.11	87.5%	-14.3	6.2	8.0	0.001447	666	2.101	88%	5.4	-0.20306
*	5	12255	31.3	-11.2	11.8	14.36	88.9%	-12.4	9.6	6.9	0.001710	660	2.7047	84%	5.7	-0.20306
LH*1.05	5	12001	29.2	-11.2	11.8	13.37	92.4%	-12.0	10.4	7.4	0.001782	683	2.029	84%	5.7	-0.20306
*	5	4975	32.4	-10.8	12.6	14.86	84.9%	-12.5	9.5	11.5	0.001697	649	2.715	84%	5.7	-0.20306
LH*1.05	5	4721	30.2	-10.7	12.7	13.86	87.9%	-12.1	10.3	11.6	0.001768	671	2.052	84%	5.7	-0.20306
*	5	4127	32.6	-10.7	12.7	14.93	84.4%	-12.5	9.5	12.1	0.001696	648	2.7162	84%	5.7	-0.20306
LH*1.05	5	3873	30.4	-10.7	12.8	13.92	87.3%	-12.1	10.3	12.2	0.001766	670	2.054	84%	5.7	-0.20306
*	10	12771	33.0	-8.7	16.3	15.13	85.9%	-10.3	13.4	11.8	0.002052	644	2.6615	84%	6.7	-0.20306
LH*1.05	10	12505	30.8	-8.7	16.4	14.14	88.8%	-9.9	14.1	11.9	0.002125	665	1.95	84%	6.7	-0.20306
*	10	5115	34.1	-8.3	17.1	15.62	82.4%	-10.4	13.3	16.1	0.002041	635	2.6735	84%	6.7	-0.20306
LH*1.05	10	4849	31.8	-8.2	17.2	14.60	84.9%	-10.0	14.0	16.2	0.002113	655	1.97	84%	6.7	-0.20306
*	10	4254	34.2	-8.2	17.2	15.68	82.0%	-10.4	13.3	16.7	0.002040	634	2.675	84%	6.7	-0.20306
LH*1.05	10	3988	32.0	-8.1	17.3	14.66	84.4%	-10.0	14.0	16.8	0.002112	654	1.971	84%	6.7	-0.20306
*	15	13184	34.7	-6.2	20.9	15.92	82.5%	-8.3	17.1	16.7	0.002437	629	2.6163	82%	7.7	-0.20306
LH*1.05	15	12941	32.5	-6.2	20.9	14.91	85.2%	-8.0	17.7	16.7	0.002511	648	1.893	82%	7.7	-0.20306
*	15	5227	35.7	-5.7	21.7	16.39	79.4%	-8.3	17.0	20.7	0.002428	621	2.631	82%	7.7	-0.20306

APPENDIX E (continued)

VENTS = SOFFETS, 1 ALLEY DOOR, 4 PEN DOORS, & RIDGE (343% OF OPEN SOFFITS)

LATENT HEAT CHANGE	OUTSIDE TEMP F	BLDG HEAT LOSS W/K	VENT RATE m^3/s	INSIDE TEMP C	INSIDE TEMP F	AIR CHANGE PER HOUR	R.H. INSIDE %	DEW PT TEMP C	DEW PT TEMP F	ROOF TEMP F	ABSOLUTE HUMIDITY kg/m^3	CO2 LEVEL ppm	NEWTRAL PRES HT m	R.H. OUTSIDE %	WIND SPEED mph	INSIDE PRESSURE COEFFICIENT
LH*1.05	15	4958	33.5	-5.7	21.7	15.38	81.6%	-8.0	17.6	20.8	0.002502	639	1.907	82%	7.7	-0.20306
*	15	4335	35.9	-5.7	21.8	16.45	79.1%	-8.3	17.0	21.2	0.002427	620	2.6325	82%	7.7	-0.20306
LH*1.05	15	4086	33.6	-5.6	21.8	15.43	81.2%	-8.0	17.6	21.3	0.002501	638	1.909	82%	7.7	-0.20306
*	20	13184	34.7	-3.5	25.8	15.89	80.7%	-5.9	21.3	21.7	0.002970	630	2.6075	81%	7.8	-0.20306
LH*1.1	20	12957	32.1	-3.7	25.4	14.71	85.6%	-5.5	22.1	21.5	0.003094	652	1.882	81%	7.8	-0.20306
*	20	5227	35.7	-3.1	26.5	16.35	77.9%	-6.0	21.3	25.6	0.002960	622	2.623	81%	7.8	-0.20306
LH*1.1	20	4962	33.2	-3.2	26.3	15.22	81.9%	-5.5	22.1	25.4	0.003082	642	1.896	81%	7.8	-0.20306
*	20	4335	35.8	-3.0	26.6	16.41	77.5%	-6.0	21.3	26.1	0.002959	621	2.6245	81%	7.8	-0.20306
LH*1.1	20	4089	33.3	-3.1	26.4	15.27	81.5%	-5.5	22.1	25.9	0.003081	641	1.897	81%	7.8	-0.20306
*	25	13184	33.7	-0.7	30.7	15.46	82.6%	-3.0	26.5	26.6	0.003780	638	2.6155	84%	7.5	-0.20306
LH*1.1	25	12909	31.1	-1.0	30.3	14.28	87.4%	-2.6	27.3	26.5	0.003928	662	1.89	84%	7.5	-0.20306
*	25	5227	34.7	-0.3	31.4	15.92	79.8%	-3.1	26.5	30.5	0.003768	629	2.6305	84%	7.5	-0.20306
LH*1.1	25	4952	32.3	-0.4	31.2	14.80	83.6%	-2.6	27.3	30.3	0.003913	651	1.905	84%	7.5	-0.20306
*	25	4335	34.8	-0.3	31.5	15.98	79.4%	-3.1	26.5	31.0	0.003767	628	2.6322	84%	7.5	-0.20306
LH*1.1	25	4080	32.4	-0.4	31.3	14.85	83.2%	-2.6	27.3	30.8	0.003912	650	1.907	84%	7.5	-0.20306
*	30	13184	33.7	1.9	35.4	15.46	86.5%	-0.2	31.6	31.6	0.004773	638	2.5995	87%	7.7	-0.20306
LH*1.1	30	12941	31.2	1.6	35.0	14.31	91.0%	0.2	32.3	31.4	0.004939	661	1.879	87%	7.7	-0.20306
*	30	5227	34.7	2.3	36.1	15.91	84.0%	-0.2	31.6	35.3	0.004759	629	2.616	87%	7.7	-0.20306
LH*1.1	30	4958	32.3	2.2	35.9	14.82	87.6%	0.2	32.3	35.1	0.004924	650	1.891	87%	7.7	-0.20306
*	30	4335	34.8	2.3	36.2	15.97	83.7%	-0.2	31.6	35.7	0.004758	628	2.6178	87%	7.7	-0.20306
LH*1.1	30	4086	32.4	2.2	36.0	14.87	87.2%	0.2	32.3	35.5	0.004922	649	1.893	87%	7.7	-0.20306
*	35	13184	32.6	4.6	40.2	14.96	88.9%	2.9	37.2	36.5	0.005868	647	2.605	88%	7.4	-0.20306
LH*1.1	35	12880	30.1	4.3	39.8	13.82	93.5%	3.4	38.0	36.4	0.006068	672	1.884	88%	7.4	-0.20306
*	35	5227	33.6	4.9	40.9	15.41	86.4%	2.9	37.2	40.1	0.005851	639	2.6215	88%	7.4	-0.20306
LH*1.1	35	4939	31.3	4.8	40.7	14.35	90.0%	3.3	38.0	39.9	0.006046	660	1.897	88%	7.4	-0.20306
*	35	4335	33.7	5.0	41.0	15.47	86.1%	2.9	37.2	40.5	0.005849	637	2.623	88%	7.4	-0.20306

APPENDIX E (continued)

VENTS = SOFFETS, 1 ALLEY DOOR, 4 PEN DOORS, & RIDGE (343% OF OPEN SOFFITS)

LATENT HEAT CHANGE	OUTSIDE TEMP F	BLDG HEAT LOSS W/K	VENT RATE m^3/s	INSIDE TEMP C	INSIDE TEMP F	AIR CHANGE PER HOUR	R.H. INSIDE %	DEW PT TEMP C	DEW PT TEMP F	ROOF TEMP F	ABSOLUTE HUMIDITY kg/m^3	CO2 LEVEL ppm	NEWTRAL PRES HT m	R.H. OUTSIDE %	WIND SPEED mph	INSIDE PRESSURE COEFFICIENT
LH*1.1	35	4069	31.4	4.9	40.8	14.40	89.6%	3.3	38.0	40.3	0.006044	659	1.9	88%	7.4	-0.20306
*	40	13299	33.7	7.0	44.7	15.46	86.3%	4.9	40.8	41.0	0.006709	638	2.553	84%	8.2	-0.20306
LH*1.1	40	13021	31.7	6.9	44.5	14.54	89.6%	5.3	41.5	41.2	0.006911	656	1.865	84%	8.2	-0.20306
*	40	5253	34.6	7.4	45.3	15.88	84.2%	4.9	40.7	44.6	0.006692	630	2.5735	84%	8.2	-0.20306
LH*1.1	40	4975	32.5	7.3	45.1	14.90	87.4%	5.3	41.5	44.4	0.006897	649	1.868	84%	8.2	-0.20306
*	40	4360	34.7	7.4	45.4	15.93	83.9%	4.9	40.7	45.0	0.006690	629	2.5755	84%	8.2	-0.20306
LH*1.1	40	4100	32.6	7.3	45.2	14.94	87.1%	5.3	41.5	44.8	0.006895	648	1.868	84%	8.2	-0.20306

NOTES:

1. Wind and Outside Relative Humidity Data are the Average of 6 Instrumented Barn Sites From December to March of 1989 to 1992 For Winds 30 Degrees Plus or Minus 270 Degrees
2. * = Data Calculated From The Initial Partitioning Between Latent and Sensible Heat.
3. LH*x.xx Represents the Adjustment to the Original Calculation of Latent and Sensible Heat Partitioning at a Given Temperature

APPENDIX F

Surface Conductance and Resistance For Air

APPENDIX F

SURFACE CONDUCTANCE (f) AND RESISTANCE (R) FOR AIR
f in W/m²K; R in m²K/W

A. Standard data for still air, as inside a building:

Orientation of Surface	Heat Flow Direction	Surface Emittance 0.90 f	0.90 R	0.20 f	0.20 R	0.05 f	0.05 R
Vertical	Horizontal	8.29	0.12	4.20	0.24	3.35	0.30
Horizontal	Upward	9.26	0.11	5.17	0.19	4.32	0.23
	Downward	6.13	0.16	2.10	0.48	1.25	0.80
45 Degree Slope	Upward	9.09	0.11	5.00	0.20	4.15	0.24
	Downward	7.50	0.13	3.41	0.29	2.56	0.39

B: Moving air, as outside a building, surface in any orientation:

Wind Velocity, m/s	f	R	
6.7	34.08	0.030	(for winter)
3.4	22.72	0.044	(for summer)

NOTES: 1. Assumes air temperature and mean radiant temperature of the surroundings are identical.

2. Values are based on smooth surfaces.

3. Values are based on a surface-air temperature difference of 5.5 K, and a surface temperature of 21°C.

APPENDIX G

Sample Internal Pressure Coefficient Calculation Results and Cell Values

APPENDIX G

Sample Internal Pressure Coefficient Calculation Results and Cell Values

THIS EQUATION CONTAINS SOFFET AND RIDGE VENTILATION OPENINGS ONLY (INFILTRATION AREA OF 4m^2 INCLUDED BY ADDING 2m^2 TO EACH SOFFET INLET AREA)

INTERNAL PRESSURE COEF	WIND SPEED @ EAVE m/s	WIND SPEED @ EAVE mph	EXT PRES COEF UPWIND	EXT PRSR COEF RIDGE	EXT PRSR COEF DOWNWIND	EXT PRSR COEF GABLES	AIR VELOCITY UPWIND m/s	AIR VELOCITY RIDGE m/s	AIR VELOCITY DOWNWIND m/s	OPENING DISCHARGE COEF VENT 1&3	OPENING DISCHARGE COEF VENT 2	UPWIND SOFFIT AREA m^2	RIDGE AREA m^2	DOWNWIND SOFFIT AREA m^2	VENT RATE UPWIND SOFFIT m^3/s	VENT RATE RIDGE OUTLET m^3/s
-0.2249	13.4	30	0.6	-0.4	-0.2	-0.2	12.17	-5.61	2.11	0.65	0.65	9.32	23.74	9.32	73.73	-86.53
-0.2249	11.2	25	0.6	-0.4	-0.2	-0.2	10.15	-4.68	1.76	0.65	0.65	9.32	23.74	9.32	61.49	-72.17
-0.2249	8.9	20	0.6	-0.4	-0.2	-0.2	8.12	-3.74	1.41	0.65	0.65	9.32	23.74	9.32	49.19	-57.73
-0.2249	6.7	15	0.6	-0.4	-0.2	-0.2	6.09	-2.81	1.06	0.65	0.65	9.32	23.74	9.32	36.89	-43.30
-0.2249	4.5	10	0.6	-0.4	-0.2	-0.2	4.06	-1.87	0.71	0.65	0.65	9.32	23.74	9.32	24.60	-28.87
-0.2249	3.4	7.5	0.6	-0.4	-0.2	-0.2	3.05	-1.40	0.53	0.65	0.65	9.32	23.74	9.32	18.45	-21.65
-0.2249	2.2	5	0.6	-0.4	-0.2	-0.2	2.03	-0.94	0.35	0.65	0.65	9.32	23.74	9.32	12.30	-14.43
-0.2249	1.3	3	0.6	-0.4	-0.2	-0.2	1.22	-0.56	0.21	0.65	0.65	9.32	23.74	9.32	7.38	-8.66
-0.2249	0.9	2	0.6	-0.4	-0.2	-0.2	0.81	-0.37	0.14	0.65	0.65	9.32	23.74	9.32	4.92	-5.77
-0.2249	0.4	1	0.6	-0.4	-0.2	-0.2	0.41	-0.19	0.07	0.65	0.65	9.32	23.74	9.32	2.46	-2.89

VENT RATE DOWNWIND SOFFIT m^3/s	VENT RATE SUMMARY m^3/s	AIR CHANGES PER HR
12.80	0.00188	39.68
10.68	0.00157	33.10
8.54	0.00126	26.48
6.41	0.00094	19.86
4.27	0.00063	13.24
3.20	0.00047	9.93
2.14	0.00031	6.62
1.28	0.00019	3.97
0.85	0.00013	2.65
0.43	6.3E-05	1.32

NOTE:

1. SPLIT SCREEN AND ITERATE INTERNAL PRESSURE COEFFICIENT UNTIL VENT RATE SUMS TO ZERO

Appendix G (continued)

First row cell values

```
A15: [W8] -0.22488
B15: (F1) [W8] 13.4
C15: [W6] 30
D15: [W9] 0.6
E15: [W9] -0.4
F15: [W9] -0.2
G15: [W9] -0.2
H15: (F2) [W9] +B15*(D15-A15)/@SQRT(@ABS(D15-A15))
I15: (F2) [W9] +B15*(E15-A15)/@SQRT(@ABS(E15-A15))
J15: (F2) [W9] +B15*(F15-A15)/@SQRT(@ABS(F15-A15))
K15: [W9] 0.65
L15: [W11] 0.65
M15: [W7] 9.32
N15: [W7] 23.74
O15: [W9] 9.32
P15: (F2) [W9] +K15*M15*H15
Q15: (F2) [W11] +L15*N15*I15
R15: (F2) [W9] +K15*O15*J15
S15: [W8] +P15+Q15+R15
T15: (F2) [W7] (@ABS(Q15)/7850)*3600
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LIST OF REFERENCES

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Albright, Louis D. 1978. Airflow Through Baffled, Center-Ceiling Slotted Inlets. Transactions of the ASAE. ASAE. St. Joseph, MI. 21(5): 944-952.

Albright, Louis D. 1990. Environmental Control for Animals and Plants. ASAE Technical Publication. American Society of Agricultural Engineers. St. Joseph, MI.

American Conference of Governmental Industrial Hygienists. 1990. Threshold Limit Values for Chemical Substances in the Work Environment. Adopted by ACGIH for 1990. Cincinnati, Ohio: ACGIH.

Andersen, Karl T. 1987. Investigation of Condensation in Uninsulated Livestock Buildings. In: Latest Developments in Livestock Housing. ASAE, St. Joseph, MI.

ASAE Standards. 1995. Design of Ventilation Systems For Poultry and Livestock Shelters. ASAE EP-270.5, American Society of Agricultural Engineers. 42nd ed. ASAE, St. Joseph, MI.

ASAE Standards. 1990. Standards, Engineering Practices and Data Adopted by the American Society of Agricultural Engineers. 37th ed. ASAE, St. Joseph, MI.

ASHRAE. 1989. Handbook of Fundamentals. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, Georgia.

ASHRAE. 1981. Handbook of Fundamentals. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, Georgia.

Bartussek, H. 1989. Natural Ventilation by Thermal Buoyancy and by Outside Convection: Practical Application of Natural Ventilation Systems With Chimneys and Breathing Ceilings. In: Agricultural Engineering: Vol. 2 Agricultural Buildings. Dodd, V. A., and P. M. Grace (eds.). Commission Internationale du Génie Rural, Balkema, Rotterdam. 2: 1299-1304.

Bickert, W. G. 1994. Designing Dairy Facilities to Assist in Management and to Enhance Animal Environment. Dairy Systems for the 21st Century. Proceedings of the Third International Dairy Housing Conference, Orlando, February 2-5, ASAE, St. Joseph, MI.

Bickert, W. G. and R. R. Stowell. 1993. Design and Operation of Natural Ventilation Systems in Dairy Free Stall Barns. Livestock Environment IV. Proceedings of the Fourth International Livestock Environment Symposium, Coventry, July 6-9, ASAE, St. Joseph, MI.

Bickert, W. G. Extension Agricultural Engineer, Michigan State University. 1992. Interview by author. 29 October, Michigan State University, Michigan.

Bickert, W. G. and R. R. Stowell. 1990. Experiences With Natural Ventilation in Michigan and Elsewhere. Paper No. 904553. American Society of Agricultural Engineers, St. Joseph, MI.

Bickert, W. G. and T. H. Herdt. 1985. Environmental Aspects of Dairy Calf Housing. Continuing Education Article. Michigan State University. 7(5): S309-S316.

Bottcher, R. W., D. H. Willits, and G. R. Baughman. 1986. Experimental Analysis of Wind Ventilation of Poultry Buildings. ASAE. St. Joseph, MI. 29(2): 571-578.

Brannigan, P. G. and J. B. McQuitty. 1971. The Influence of Ventilation on Distribution and Dispersal of Atmospheric Gaseous Contaminants. Canadian Agricultural Engineering. 13(2): 69-75.

Brockett, Betty L. 1986. A Control Model for Natural Ventilation Systems in Agricultural Buildings. Masters Thesis. Cornell University.

Brockett, B. L. and L. D. Albright. 1987. Natural Ventilation in Single Airspace Buildings. Journal of Agricultural Engineering Research. 37: 141-154.

Bruce, J. M. 1974. Wind Tunnel Study: Suckler Cow Building. Farm Building Progress. October, 38: 15-17.

Bruce, J. M. 1975. A Computer Program for the Calculation of Natural Ventilation Due to Wind. Farm Building Research and Development Studies. November, 1975.

Bruce, J. M. 1977. Thermal Buoyancy: A Comparison of Theory and Experiment. Farm Building Progress. 47(1): 23-25.

Bruce, J. M. 1978. Natural Convection Through Openings and Its Application to Cattle Building Ventilation. Journal of Agricultural Engineering Research. 23: 151-167.

Bruce, J. M. 1987. The Environmental Requirements of Livestock. Agricultural Engineer. 42(4) pp 137-140.

Bruce, J. M. 1988. The Theory and Application of Natural Ventilation to Livestock Housing. Third International Conference on Housing and Environment for Livestock. Pig Research Institute, Taiwan.

Bruce, J.M. 1992. Letter From J.M. Bruce to Richard Tillotson, 10 January. Original in the Hand of Richard Tillotson, RR2, Crookston, MN.

Campbell Scientific. 1989. CR10 Measurement and Control Module Operator's Manual. Campbell Scientific, Logan, Utah.

Choiniére, Y., J. A. Munroe, and A. S. Tremblay. 1990. Control Strategy For Sidewall Openings of Cold, Modified and Warm Environment Dairy Housing. Paper No. 90-4557. American Society of Agricultural Engineers. St. Joseph, MI.

CIGR. 1984. Report of Working Group on Climatization of Animal Houses. Commission Internationale du Génie Rural, Published by the Scottish Farm Building Investigation Unit, Craibstone, Bucksburn, Aberdeen.

CIGR. 1992. Climatization of Animal Houses. Second Edition. Center for Climatization of Animal Houses - Advisory Services, Faculty of Agricultural Sciences, State University of Ghent, Ghent, Belgium.

Clark, P. C. and J. B. McQuitty. 1987. Air Quality in Six Alberta Commercial Free-Stall Dairy Barns. Canadian Agricultural Engineering. 29(1): 77-80.

Curtis, Stanley E. 1983. Environmental Management in Animal Agriculture. Iowa State University Press, Ames, IA.

Curtis, S. E. and J. G. Drummond. 1982. Air Environment and Animal Performance. In: Handbook of Agricultural Productivity. M. Recheigl (ed.). C.R.C. Press Inc., Boca Raton, FL. 2: 107-118.

Curtis, Stanley E. 1972. Air Environment and Animal Performance. In: Journal of Animal Science. 35(3): 628-634. American Society of Animal Science, Champaign, IL.

DeShazer, J. A. and D. G. Overhults. 1982. Energy Demand in Livestock Production. Livestock Environment II. American Society of Agricultural Engineers, St. Joseph, MI. pp 17-27.

Diesch, Mark A. and D. P. Froehlick. 1987. Production and Environmental Simulations in Livestock Housing. ASAE, St. Joseph, MI. Paper No. 87-4514.

Down, M. J., T. A. McMahon and G. J. Redding. 1985. The Design of Livestock Buildings For Natural Ventilation: The Theoretical Basis and a Rational Design Method. Agricultural Engineering Report No. 73/85. University of Melbourne. Parkville, Australia.

Dunklin, Edward W. and T. T. Puck. 1947. The Lethal Effect of Relative Humidity on Air-borne Bacteria. In: Journal of Experimental Medicine. 87: 87-101. Rockefeller Institute for Medical Research, Baltimore.

Ehrlemark, A. and K. Sällvik. 1990. Calculation of the Heat and Moisture Dissipation From Cattle. ASAE Paper No. 90-4068. St. Joseph, MI.

Emswiler, J. E. 1926. The Neutral Zone in Ventilation. American Society of Heating and Ventilation Engineers. 32:59-63.

Esmay, Merle L. and John E. Dixon. 1986. Environmental Control for Agricultural Buildings. AVI, Westport, CN.

Fabian, E. E. and L. D. Albright. 1982. Natural Ventilation of Livestock Buildings Using Solar Chimneys. ASAE Paper No. 82-4041. St. Joseph, MI.

Flatt, W. P., L.A. Moore, N. W. Hoozen, and R. D. Plowman. 1965. Energy Metabolism Studies With a High Producing Lactating Cow. Journal of Dairy Science. 48: 797.

Fogle, F. F. 1925. Why Ventilate Farm Barns and How. Michigan Quarterly Bulletin. 8(1): 20-26.

Fujita, Sekai. and M. Nara. 1993. The Heat Balance Characteristics of Roof Materials in Livestock Building. Livestock Environment IV. Proceedings of the Fourth International Livestock Environment Symposium. American Society of Agricultural Engineers, St. Joseph, MI.

Harrigan, Timothy M. 1985. Moisture Related Deterioration of the Wood Truss System: A Survey of Naturally Ventilated Dairy Barns in Michigan. Masters Thesis. Agricultural Engineering Department, Michigan State University.

Hartung, J. 1994. Environment and Animal Health. In: Livestock Housing, Ch. 2. C. M. Wathes and D. R. Charles (eds.). Wellingford: CAB International.

Hellickson, Mylo A. and J. N. Walker. 1983. Ventilation of Agricultural Structures. American Society of Agricultural Engineers. St. Joseph, MI.

Hoxey, R. P. 1984. Design Wind Loads for Closed Farm Buildings. Journal of Agricultural Engineering Research, 29: 305-311.

Iqbal, M. and A.K. Khatry 1977. Wind-Induced Heat Transfer Coefficients from Glasshouses. Transactions of ASAE. St. Joseph, MI. 1977: 157-160.

Jalvingh, A. W. 1992. The Possible Role of Existing Models in On-farm Decision Support in Dairy Cattle and Swine Production. Livestock Production Science, 31: 351-365.

Janni, K. A. and K. M. Bussmann. 1983. Development of Transport Phenomena Equations Describing Summer Natural Ventilation in Livestock Buildings. Scientific Journal Series of Minnesota Agricultural Experiment Station on Research Paper No. 13,206. St. Paul, MN.

Janni, K. A. and K. M. Bussmann. 1984. Transport Phenomena Equations for Describing Natural Ventilation in Livestock Buildings. ASAE Paper No. 84-4530. St. Joseph, MI.

Lapedes, D. N., ed. 1978. McGraw-Hill Dictionary of Science and Technical Terms. McGraw-Hill Book Company, New York, London.

Leahey, G.M., J. B. Holter, and W. E. Urban Jr. 1972. Energy and Protein Utilization and Forages Fed to Dry Cows. Journal of Dairy Science. 56: 587-591.

Lidwell, O. M. and E. J. Lowbury. 1949. The Survival of Bacteria in Dust. II. The Effect of Atmospheric Humidity on the Survival of Bacteria in Dust. In: Journal of Hygiene. 48(6): 21-27. Cambridge University Press, New York, NY.

Macdonald, Angus J. 1975. Wind Loading of Buildings. Table 3.6. Pressure Coefficients for Pitch Roofs of Rectangular Clad Buildings. John Wiley and Sons. New York.

Malecki, J., S. Gorski, C. Tupaj, M. Lazoryszczak. 1993. Effect of Gravity Ventilation Facilities Control on the Microclimate Condition in Home Stockfarm Buildings. Proceedings of the Fourth International Livestock Environment Symposium, Coventry, ASAE. St. Joseph, MI.

Matheson Gas Products. 1990. Kitagawa Gas Detector Tube System Handbook, Chicago.

MBMA. 1986. Low Rise Building Systems Manual. Metal Building Manufacturers Association, Inc. 1230 Keith Building, Cleveland, Ohio.

Michigan Dairy Herd Improvement Association, 1991. Annual Summary of Production Records. Michigan DHIA, Lansing, MI.

Moe, P. W. 1981. Energy Metabolism of Dairy Cattle. Journal of Dairy Science. 64: 1120.

MWPS-1. 1987. Structures and Environment Handbook. Midwest Plan Service. Iowa State University, Ames, IA.

MWPS-33. 1989. Natural Ventilating Systems for Livestock Housing. Midwest Plan Service. Iowa State University, Ames, IA.

Newberry, C. W. 1974. Wind Loading Handbook. Department of the Environment. Building Research Establishment. London.

Noble, W. C. 1969. The Evidence for Airborne Infection. In: Aerobiology--Proceedings of the Third International Symposium. I. H. Silver (ed.). Academic Press, New York, NY.

Quille, T. J., J. B. McQuitty, and P.C. Clark. 1986. Influence of Manure-Handling Systems on Heat and Moisture Loads in Free-Stall Dairy Housing. Canadian Agricultural Engineering. 28(2): 175-181.

Sachs, Peter. 1978. Wind Forces in Engineering. Pergamon Press Inc., New York.

Sällvik, K. G. 1981. The CIGR Work for Climatization in Animal Houses. ASAE. St. Joseph, MI. Paper No. 81-4059.

Scott, N. R., J. A. DeShazer, and W. L. Roller. 1983. Effects of the Thermal and Gaseous Environment on Livestock. In: Ventilation of Agricultural Structures. Mylo Hellickson and John Walker (eds.). Monograph No. 7, ASAE, St. Joseph, MI, 49085-9656.

Shepherd, D. G. 1965. Elements of Fluid Mechanics. Harcourt, Brace, and World. New York.

Sherman, M. H. 1980. Air Infiltration in Buildings. Ph.D. Dissertation. University of California at Berkley.

Shrestha, G. L. and C. O. Cramer. 1984. Simulation of Ventilation by Thermal Buoyancy in an Enclosed Building. ASAE Paper No. 84-4026. St. Joseph, MI.

Shrestha, Ganesh, C Cramer, and B. J. Holmes. 1990. Wind Induced Natural Ventilation of an Enclosed Building. Paper Number 904001. American Society of Agricultural Engineers, St. Joseph, MI.

Sinden, F. W. 1978. Wind, Temperature, and Natural Ventilation -- Theoretical Considerations. Energy and Buildings. No. 3 pp. 275-280.

Smith, R. A., J. B. McQuitty, and J. J. R. Feddes. 1980. Heat and Moisture Loads in Dairy Barns. CSAE, Ottawa, ON.

Songer, Joseph R. 1966. Influence of Relative Humidity on the Survival of Some Airborne Viruses. In: Applied Microbiology. 14(1): 35-42. American Society for Microbiology, Baltimore, MD.

Strom, J. S. and Anne Feenstra. 1980. Heat Loss From Cattle, Swine, and Poultry. ASAE. St. Joseph, MI. Paper No. 80-4021.

Swinbank, W. C. 1963. Long Wave Radiation from Clear Skies. Royal Meteorological Society Quarterly Journal. 89(381): 339-348.

Tamura, G. T. 1979. The Calculation of House Infiltration Rates. ASHRAE Transactions. 85: 58-71.

Thompson, H. J. 1957. Influence of Humidity and Wind on Heat Loads Within Dairy Barns. University of Missouri Agricultural Experiment Station Research Bulletin 618. Columbia, MO.

Thompson, H. J. and R. E. Stewart. 1952. Heat and Moisture Exchange in Dairy Barns. Agricultural Engineering. 33(4): 201-206.

Timmons, M. B. and G. R. Baughman. 1981. Similitude Analysis of Ventilation by the Stack Effect From an Open Ridge Livestock Structure. ASAE. St. Joseph, MI. 24(4): 1030-1034.

Timmons, M. B., R. W. Bottcher and G.R. Baughman. 1984. Nomographs for Predicting Ventilation by Thermal Buoyancy. Transactions of the ASAE. 27(6): 1891-1893.

Timmons, M. B. 1990. How Does Natural Ventilation Work and Why. ASAE. St. Joseph, MI. Paper No. 904551.

Turner, L. W., C. M. Wathes, and E. Audsley. 1993. Dynamic Probabilistic Modelling of Respiratory Disease in Swine, Including Production and Economic Effects. Livestock Environment IV. Proceedings of the Fourth International Livestock Environment Symposium. American Society of Agricultural Engineers, St. Joseph, MI.

U.S. Department of Commerce, 1956. Summary of Hourly Observations: Lansing, Michigan. U.S. Government Printing Office, Washington, DC.

USDA, 1974. Wood Handbook: Wood as an Engineering Material. Forest Products Laboratory, USDA Forest Service. Agriculture Handbook No. 72.

Wathes, C. M. and D. R. Charles., ed. 1994. Livestock Housing. Ch. 6, Air and Surface Hygiene, by C. M. Wathes. Wellingford: CAB International.

Webster, A. J. F. 1973. Heat Loss From Cattle With Particular Emphasis on the Effects of Cold. in: Heat Loss From Animals and Man...Assessment and Control. J. L. Monteith and L. E. Mount (eds.). Proceeding of the 20th Easter School in Agricultural Science, University of Nottingham, London, Butterworths.

Wright, D. N., G. D. Bailey, and L. J. Goldberg. 1969. Effect of Temperature on Survival of Airborne *Mycoplasma Pneumonia*. In: Journal of Bacteriology. 99(2): 491-495. American Society for Microbiology, Baltimore, MD.

Visher, Stephen Sargent. 1966. Climates of the United States. Harvard University Press, Cambridge, MS.

Yeck, R. G. and R. E. Stewart. 1959. A Ten-Year Summary of the Psychroenergetic Laboratory Dairy Cattle Research at the University of Missouri. Transactions of the ASAE. 2: 71-77.

Zhang, J. S., K. A. Janni, and L. D. Jacobson. 1989. Modeling Natural Ventilation Induced by Combined Thermal Buoyancy and Wind. ASAE. St. Joseph, MI. 32(6): 2165-2174.

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