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A SURVEY OF NATURALLY VENTILATED DAIRY BARNS IN MICHIGAN

presented by

Timothy Mark Harrigan

has been accepted towards fulfillment
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Major professor

William Bickert

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MOISTURE RELATED DETERIORATION OF THE WOOD TRUSS SYSTEM: A SURVEY OF NATURALLY VENTILATED DAIRY BARNS IN MICHIGAN

By

Timothy Mark Harrigan

A THESIS

Submitted to
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ABSTRACT

MOISTURE RELATED DETERIORATION OF THE WOOD TRUSS SYSTEM: A SURVEY OF NATURALLY VENTILATED DAIRY BARNS IN MICHIGAN

By

Timothy Mark Harrigan

Ten naturally ventilated dairy barns located in Michigan's lower peninsula were surveyed to determine the relationship between management and design factors and the occurrence of elevated wood moisture contents in the wood truss system at the area beneath the open ridge.

Wood moisture contents exceeding 20% dry basis were found to occur in exposed lumber subsequent to cold weather operations. Barns well ventilated throughout the year were more resistant to excessive moisture accumulation than less well ventilated barns. Neither the pick test nor culturing of increment cores were found to be acceptable methods for detection of wood decay when using multiple sample surveys.

DEDICATION

To my wife

Leslie

our children

Matthew and Lauren

and my parents

Bob and Roseanne Harrigan

ACKNOWLEDGEMENTS

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I. INTRODUCTION

1.1 Statement of the Problem

Naturally ventilated dairy barns represent a particularly harsh environment for the wood truss system. The wood and the metal fasteners are exposed to wide variations in temperature, relative humidity, and air contaminant levels, as well as intermittent wetting by rain and snow that enters through the open ridge. When design or management factors act alone or in combination to permit abnormally high wood moisture content levels, wood decay may result.

Thorough drying of wood truss components is not generally a problem during warm weather when all vents and doors are fully opened. However, during cold weather, air inlets are often closed in an effort to force interior temperatures above those that should be reasonably expected. Under these conditions, air movement through the open ridge is restricted and under the worst conditions may be completely stopped. When air movement is obstructed, drying is inhibited and wood moisture contents rise above acceptable upper limits.

The interaction of management and design and their relationship to the occurrence of wood truss decay are not well understood. When the interaction permits elevated wood moisture contents, dramatic strength losses due to wood decay, as well as accelerated corrosion of metal fasteners may compromise the safety and reliability of the

wood truss system. Future recommendations regarding design specifications, repair procedures, and management efforts must be based on an understanding of these complex factors and their relationship to the probability of wood and metal fastener deterioration.

1.2 Objectives

The overall objectives of this research are:

Objective 1: To measure changes in the moisture content of wood truss members in the area of the open ridge of naturally ventilated dairy barns during cold weather operations: December through March.

Objective 2: To delineate a convenient and reliable technique for detecting wood decay in wood trusses.

Objective 3: To assess the overall potential for deterioration of the wood truss system in naturally ventilated dairy barns in Michigan.

II. LITERATURE REVIEW

2.1 Wood Decay

Wood decay is caused by one or more of several species of fungi that penetrate the wood cells and utilize the wood constituents as a source of food. Wood decay fungi require four conditions for successful germination and continued growth (Scheffer and Verrall, 1973; Eslyn and Clark, 1979): (1) sufficient oxygen, (2) favorable temperature, (3) an adequate food supply, and (4) an adequate water supply. Prevention of wood decay requires elimination of at least one of these variables.

Wood decay fungi require very little oxygen. One situation where a lack of available oxygen will limit fungal growth is where the wood is submerged into water or buried deeply in the ground.

The optimal temperature range for growth of decay fungi is 24 to 29°C (75 to 85°F). Growth is severely limited above 32°C (90°F) and below 10°C (50°F). Temperatures well in excess of 38°C (100°F) are required for eradication of decay fungi (Scheffer and Verrall, 1973).

Sapwood and heartwood of all species can be used as a food source for wood decay fungi. The heartwood of many lumber species contains varying amounts of extractives, naturally occurring substances that are able to resist fungal growth (Scheffer and Cowling, 1966).

Decay fungi require an available source of free water within the lumen, or cavity of the wood cell. Decay fungi grow in wood with a moisture content above fiber saturation (about 30% moisture content, dry basis), but below total saturation (total saturation varies widely among species, usually about 60% moisture content, dry basis for most structural lumber). At moisture contents below fiber saturation, the water is bound within the cell wall, unavailable to the fungi. Maintaining wood moisture contents below fiber saturation is usually the easiest way to prevent wood decay in most structures.

The basidiomycetes, commonly referred to as white rotters and brown rotters, are the most destructive of the wood decay fungi. When significant wood decay damage is found, particularly in hidden areas where rapid drying is inhibited, white rot or brown rot fungi are usually responsible.

In advanced stages, distinctions between white rot and brown rot can be made by noting differences in color and texture of the decayed wood (Scheffer and Verrall, 1973; Eslyn and Clark, 1979).

Wood degraded by brown rot fungi is brittle, brownish in color, and develops cross-grain checks similar to charcoal on burned timber. Wood degraded by white rot fungi will typically be whitish in color with a soft, punky texture. Cross checking typical of brown rotted wood will not be present on white rotted wood.

The relationship between other wood colonizing organisms and wood decay is not clearly defined. Banerjee and Levy (1971) submit that a sequence of colonizing organisms invade vulnerable lumber. The sequence begins with bacteria and progresses to molds, staining and soft rot fungi and finally basidiomycetes. Bacteria, molds, and staining fungi are generally not considered to be serious strength reducing organisms in structural lumber. However, these organisms appear to have the ability to increase the permeability of wood, facilitating the ease of penetration and depth of saturation of water into exposed lumber (King and Eggins, 1973).

A typical wood cell consists of a relatively thin primary wall surrounding a much thicker secondary wall composed of an outer layer (S_1), a central layer (S_2), and an inner layer (S_3) surrounding the cavity or lumen of the cell. Wilcox (1968) has described the fundamental differences in the way that brown rot and white rot fungi attack wood at the cellular level.

Both brown rot and white rot fungi develop a straw-like hyphae that penetrate the wood, infecting it cell by cell. The hyphae of white rot fungi enter the wood cells through pit canals and bore holes. Cell degradation proceeds from the lumen outward by removal of cellulose from the S_3 layer until it disappears, progressing to the S_2 layer and finally the S_1 layer.

Concurrently, the pit canals and bore holes through which the hyphae have penetrated the cells are progressively enlarged. This manner of attack indicate that the cellulolytic enzymes of the white rot fungi are restricted to the cell wall surfaces of the lumen or other exposed cavities.

Wood degradation by brown rot fungi is noticeably different from that by the white rot fungi. Brown rot fungi first removes the cellulose from the S_2 layer until it is depleted, proceeds to the S_1 layer and finally the S_3 layer. The cellulolytic enzymes of the brown rot fungi are not limited to exposed cell wall surfaces, but are able to penetrate and act within the cell wall.

The order of attack of white rot fungi within the cell structure corresponds to the wood lignin content, with low lignin content structures attacked first. Softwoods, which are generally higher in lignin content are more resistant to white rot than hardwoods. Brown rot fungi are the primary decay fungi of the softwood species commonly used for structural purposes in Michigan.

2.2 Strength Loss Due to Wood Decay

An extensive review of wood strength loss due to wood decay has been published by Wilcox (1978). It is important to note that significant strength losses are experienced before visual detection of decay can be made. Brown rotted wood loses strength more rapidly than white rotted wood, although equivalent weight losses result in equivalent strength reductions. Specific strength loss varies among wood species, but toughness, or the ability to withstand shock loading is the strength property most rapidly degraded by wood decay. Potential strength reductions of brown rotted softwoods at 5-10% weight reduction are summarized in Table 2.1.

2.3 Detection of Wood Decay

Significant losses of wood strength can occur before wood decay can be detected visually (Wilcox, 1978). The long-term safety

Table 2.1. Strength reductions of brown rotted softwoods at 5-10% weight loss

Strength	Expected Strength Loss (% of sound wood strength)
Toughness	80+
Impact bending	80
Static bending (MOR & MOE)	70
Compression perpendicular	60
Tension parallel	60
Compression parallel	45
Shear	20
Hardness	20

Source: Wilcox, 1978, adapted from Meyer and Kellogg, 1980.

of any wood structure requires effective and accurate methods for detecting decay in its developmental stages. Repair procedures are costly and time consuming. Decisions regarding corrective action must be based on precise information regarding the location and extent of decay damage.

2.3.1 Pick Test

A simple test to indicate wood decay in relatively advanced stages is the pick test (Graham and Helsing, 1979). A sharp instrument such as a pick or screwdriver is used to lift a sliver of wood. A splintering break indicates sound wood. Abrupt failure or a brash break near the tool indicates wood decay. Although convenient, the results of this test are somewhat subjective and difficult to quantify. The pick test is of limited value for detection of early stages of decay.

2.3.2 Sonic Testing

A sonic testing device has been developed at Detroit Edison Company to aid in detecting decay in wood poles in power transmission lines (Graham and Helsing, 1979). Probes are placed on opposite sides of the pole and a trip hammer sends a pulse through the pole between the probes. Low wave velocities indicate decay or voids in the specimen tested. Results are variable among species. Satisfactory results have been obtained on Douglas-fir and western red cedar but not on southern pine. This instrument should be used by trained personnel and calibrated frequently.

The James Electronics V-Meter®[1] also measures sonic pulse transmission time (ASCE, 1982). This device has been used successfully on Douglas-fir and southern pine poles.

2.3.3 Electrical Resistance Meters

Resistance to a pulsed electrical current decreases as wood decays. An instrument developed by Shigo et al. (1977) measures electrical resistance with a probe inserted into a hole 24mm (3/32") in diameter. Changes in electrical resistance as the probe penetrates the wood indicate moisture gradients, decay, or other defects. This instrument should be used in wood with a moisture content above 27% moisture content dry basis. This generally limits its use to living trees or locations near ground line in structural timbers. This instrument can effectively detect decay, but can also give misleading readings on sound poles (Graham and Helsing, 1979).

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[1]James Electronics, Inc., 4050 North Rockwell Street, Chicago, Illinois 60618.

2.3.4 Penetrometers

A penetrometer type shock resistor that shoots a blunt pin into the wood surface using a known amount of energy has been investigated as a means of detecting wood decay (Hoffmeyer, 1978). The depth of penetration is read directly on a scale and the presence of decay inferred from the results. The Penetrometer is useful for detecting soft rot, but is insensitive to intermediate stages of decay (ASCE, 1982). This method is useful when estimating the depth of a shell of sound wood in utility poles. Depth of the wood shell is important when estimating the section modulus of remaining wood.

2.3.5 Resistance-Type Moisture Meters

Resistance-type moisture meters are not able to detect decay directly. However, they can be used to locate wood with moisture contents sufficient to support wood decay fungi (James, 1975). Insulated electrodes permit measurement of moisture gradients through the sample.

2.3.6 Increment Cores

All the techniques and instruments previously discussed are able to indicate an increased probability of wood decay. However, instrument readings vary among species and among wood samples within a species. Positive identification of wood decay fungi in its early stages can only be made by microscopic examination (Wilcox, 1968) or by culturing increment cores (Graham and Helsing, 1979).

Culturing wood for identification of wood decay fungi requires removal of increment cores from the wood being tested (Maeglin, 1979).

Increment corers are available in various diameters from 3.8mm (0.15in) to 12mm (0.47in) which can be used to extract wood cores. The cores can then be taken to the laboratory for culturing and identification of wood decay fungi.

2.4 Weathering of Wood

Wood in exterior use begins a slow degradation process commonly known as weathering (USDA, 1974; Feist, 1982). When wood is subjected to light, moisture, and heat the wood surface gradually wears away. Checks and large cracks eventually develop. The wood surface splinters and fragments break off. This natural process should not be confused with wood decay.

2.4.1 Exposure to Sunlight

The initial effect of prolonged exposure to sunlight is a color change from light yellow to a brownish color and finally a silver grey (Sherwood, 1983). Ultraviolet radiation is the primary degrading factor. Lignin, a phenolic adhesive bonding wood fibers together is degraded more rapidly than the cellulose and hemicullulose fraction (Kalnins, 1966). Surface water from rain and condensation act in conjunction with sunlight to speed up the weathering process (Feist, 1982). Surface water washes away wood fibers as the lignin is decomposed, exposing additional lignin to ultraviolet light and further degradation. Estimates of wood erosion rates range from 6.4mm per century (Browne, 1960) to as much as 13mm per century for western red cedar (Feist and Mraz, 1978).

2.4.2 Cyclic Variations in Moisture Content

Cyclic variations in wood moisture content contribute to the weathering process (USDA, 1974). Absorption of free water and adsorption of water vapor cause wood fiber cells to swell. Moisture gradients between the interior and exterior parts of the wood create stresses as the wood shrinks and swells. Warping, cupping, and face checking may result. Face checks expose interior portions of the wood to more rapid and thorough moisture penetration in subsequent wetting cycles.

Since weathering is primarily a surface phenomena, very little change in the mechanical and structural properties of wood can be expected, provided that the wood is free from decay (Borgin et al., 1975).

2.5 Wood Moisture Content

Wood moisture content is generally reported on a dry basis calculated as the weight of water in the wood divided by the ovendry weight (dry matter) of the wood. Most physical and mechanical properties of wood are dependent on moisture content (USDA, 1974).

Moisture content varies among wood species and within a single species varies among locations within the tree (USDA, 1974). Sapwood is generally of a higher moisture content than heartwood, particularly in softwoods. Moisture contents of freshly cut lumber range from near 30% for the heartwood of some softwoods to over 200% for the sapwood.

In freshly cut lumber, moisture is present within the wood cell as both free water and water vapor within the lumen of the cell and as bound water within the cell wall (Scheffer and Verrall, 1973; USDA, 1974). The fiber saturation point is the point at which no free water exists within the lumen of the cell, yet the cell walls are completely saturated. Fiber saturation is near 30% moisture content (dry basis) for most species (USDA, 1974).

2.5.1 Equilibrium Moisture Content

Structural lumber is generally kiln dried to about 15% moisture content before use. Wood in place continually responds to both seasonal and daily fluctuations in temperature and relative humidity in an effort to reach equilibrium with microclimatic conditions. The equilibrium moisture content (EMC) is the point at which the wood is neither gaining nor losing moisture when kept at a constant temperature and relative humidity (USDA, 1974). Typical equilibrium moisture contents for lumber in exterior use in Michigan range from 20% MC at -1°C (30°F) with 90% R.H., down to 10% MC at 28°C (80°F) with 40% R.H. Prolonged exposure to high relative humidities alone are not sufficient to raise the moisture content above the fiber saturation point (USDA, 1974).

2.5.2 Rate of Water Penetration

Truss members in the area beneath the open ridge in naturally ventilated barns are subject to intermittent wetting by rainfall, condensation, and melting snow. Design features exist beneath the open

ridge that may enhance the ability of decay causing fungi to successfully germinate and begin wood deterioration. Fastener holes, joint interfaces, and seasoning checks have a tendency to trap water (Scheffer and Verrall, 1973; Eslyn and Clark, 1979). Drying may be inhibited in localized areas due to severely restricted air flow and/or protection from solar insolation. Water that is able to penetrate fastener holes and other areas where end grain is exposed can quickly penetrate the wood. The rate of water penetration is highly dependent upon the location of the wood face exposed to wetting. Water moves along the wood grain much more quickly than across the grain. Permeability in the longitudinal direction is 50 to 100 times greater than in the transverse direction (Tarkow et al., 1970).

2.5.3 Affect of Moisture Content on Mechanical Properties

Moisture content is an important factor affecting the mechanical properties of wood. Below fiber saturation, most of the mechanical properties of wood increase as moisture content decreases (USDA, 1974).

Cyclic variations in wood moisture content may have a negative effect on the strength properties of wood. Cycling relative humidities have been shown to cause creep failure at loads well below the short-term breaking load (Hearmon and Patton, 1964). Small beams exposed to alternate twenty-four hour periods of 0 and 93% relative humidity broke under 3/8 maximum load after fourteen complete cycles. Deflection prior to failure was twenty-five times the initial deflection. An identical specimen held at a constant 93% relative humidity

did not break and deflection was limited to two times the initial value.

Shear strength was reduced by nearly 70% of the original value in a red pine sample after twenty-five wetting and drying samples (Keith, 1960 from Bodig, 1982).

2.6 Interaction of Moist Wood with Metal Fasteners

2.6.1 Corrosion of Metal Fasteners in Contact with Moist Wood

Corrosion of metal fasteners in contact with moist wood is a well known phenomena (Baker, 1974). The natural acidity of most wood is a contributing factor to metal corrosion. The average pH of wood is between 3.0 and 5.5 (Stamm, 1964). The rate of metal corrosion increases greatly when the pH falls below 4.0 and moisture is present (Thompson, 1982). Douglas Fir is a wood species with a pH value of 4.0 or less that is occasionally used for structural purposes in Michigan.

Single metal fastener corrosion in moist wood can be explained in terms of crevice corrosion (Baker, 1974). The exposed end of a steel fastener in wet wood rapidly shows evidence of hydroxyl ion (OH^-) formation. Baker compared the exposed head of the fastener to the cathode and the shank to the anode of a galvanic corrosion cell. The chemical reaction of the cathode can be written as:

$$O_2 + 2H_2O + 4e \rightarrow 4OH^- \qquad \text{(Baker, 1974)}$$

The reaction at the anode for an iron fastener can be written as:

$$Fe \rightarrow Fe^{++} + 2e \qquad \text{(Baker, 1974)}$$

Iron ions from the resulting rust act as catalysts that accelerate chemical reactions destructive to cellulose. The primary strength loss is a decline of the tensile strength of the wood (Thompson, 1982).

Dissimilar metals in contact with wet wood form a galvanic corrosion cell with accelerated corrosion of the less resistant metal and less corrosion of the more resistant metal (Baker, 1974).

2.6.2 Corrosion of Metal Fasteners in Contact with Preservative Treated Wood

Accelerated corrosion of metal fasteners in contact with wood treated with salt-type preservatives has been a problem. Thompson (1982) cites work done by Ormstad (1973) reporting that preservatives that remain soluble in wood had caused serious corrosion of thirteen types of metal and alloy fasteners when the wood moisture content was in excess of 15% dry basis. Work by Bengelsdorf (1982) utilizing accelerated exposure methods indicated that fasteners in preservative treated wood corrode more rapidly at elevated wood moisture contents. Fastener corrosion was much lower at 19% moisture content than at elevated moisture conditions.

2.7 Natural Ventilation

Definitive work describing the behavior of thermally buoyant air in livestock structures has been done by J. M. Bruce (1973, 1975, 1977(a), 1977(b), 1978(a), 1978(b)). Well defined laws of fluid mechanics were used to describe the separate and combined forces of wind and thermal buoyancy.

2.7.1 Airflow Due to Thermal Buoyancy

Wind provides the primary motive force in naturally ventilated buildings. In the absence of wind, livestock heat production creates air exchange by thermal buoyancy in well designed buildings. Airflow due to thermal buoyancy alone may be estimated from the following equation (Bruce, 1978b):

$$Q = 60\ AC\sqrt{\frac{2gH\Delta T}{T}}$$

where

Q = Ventilation rate (M^3/sec)

A = Area of inlet or outlet opening (M^2)

C = Effectiveness of opening (approximately 0.6)

g = Acceleration due to gravity (9.8m/sec^2)

H = Height differential between inlets and outlets (M)

ΔT = Temperature difference between inside and outside (°C)

T = Absolute temperature outside (K = 273 + °C)

The area of the inlet and outlet openings has a direct influence on the ventilation rate. Control of airflow may best be accomplished by regulating the area of the inlet and outlet openings.

2.7.2 Airflow Due to Wind

The quantity of air forced through inlet openings by wind is estimated as (ASHRAE, 1977):

$Q = EAV$

where:

Q = Air flow, cubic feet per minute (0.4719474 liter per second)

A = Free area of inlet openings. Square feet (= 0.0929034 square meter)

V = Wind velocity, feet per minute (= 0.00508 meter per second)

E = Effectiveness of openings (E = 0.50 to 0.60 for perpendicular winds, and 0.25 to 0.35 for diagonal winds).

($Q = EAV \times 1000$ when the above SI units are used.)

2.7.3 Airflow due to Combined Wind and Thermal Buoyancy

The effect of the combined forces of wind and thermal buoyancy do not yield airflow rates equal to the sum of the separate forces. Estimates of the combined flow rate can be made in reference to figures provided by ASHRAE Handbook of Fundamentals (1977) by calculating the ratio of airflow due to thermal buoyancy to the sum of the air flow due to wind and air flow due to thermal buoyancy calculated separately. When the two flows are equal, actual flow is about 30% greater than the flow caused by either force alone.

2.7.4 Recommended Design Features

The development of functional relationships describing the interaction of design features and air movement have led to design recommendations for naturally ventilated dairy barns (Graves and Brugger, 1975; Bodman, 1980; MWPS, 1983).

2.7.4.1 Roof slope. Airflow through a building by thermal buoyancy can be achieved given a temperature differential, provided that two openings separated by a height differential exists. Height differential is a function of roof slope and building width. The upward velocity of airflow is increased as the roof slope is increased. A minimum 4:12 roof slope is recommended.

2.7.4.2 Ridge openings. Intake and exhaust openings are provided by openings at the eaves or sidewalls and an open ridge at the peak. Ridge openings should provide 5 cm (2") per 3.04m (10') of building width (12.16m (40'-0") building requires a 20.27cm (8") ridge opening). An equivalent opening is required at the eaves. Provide 2.54cm (1") of clear opening at each eave per 3.04m (10'-0") building width.

2.7.4.3 Livestock heat and moisture production. A 454kg (1,000 lb) dairy cow produces about 864W (2,950 BTU/Cow-hr) sensible heat, 234W (800 BTU/cow-hr) latent heat, and .35kg (0.77 lb/cow-hr) water when ambient conditions are near 0°C (32°F) (MWPS, 1983). The sensible heat produced by livestock provides the major source of heat to warm the air in a thermally buoyant system. In order to remove moisture at the rate at which it is produced, sufficient sensible heat must be provided. Animal density should be kept close to design capacity.

2.7.4.4 Building orientation. Air exchange rates in naturally ventilated buildings rarely depend solely on the buoyancy of warmed air. On all but the calmest days, ventilation rates in naturally ventilated buildings are the result of combined wind forces and thermal buoyancy. Attention must be given to the direction of prevailing winds and the presence of obstructions that may inhibit air movement such as trees, silos, or other buildings when planning barn location and orientation. Placement and orientation with respect to prevailing winds plays a critical role in the effort to realize the confluent action of wind and thermal buoyancy. As wind flows across the open ridge, a negative pressure is created at the barn interior. In response to the negative pressure, warm, moisture-laden air is actively drawn out through the ridge and replaced with an equal volume of colder, drier air entering at the eaves. Wind action is critical. Barns should be placed in an area exposed to the wind, unobstructed by trees, silos, etc. The long axis of the barn should be at right angles to prevailing winds.

2.7.4.5 Sidewall openings. Large, adjustable sidewall openings should be provided to maximize airflow through the barn during hot weather. An opening equivalent to a continuous row of panels 0.61m (2'-0") high for all buildings up to 12.16m (40'-0") in width should be provided. Buildings wider than 12.16m (40'-0") should have an equivalent of 15.2cm (6") panel height for each 3.04m (10'-0") building width (24.32m (80'-0") building width requires 1.22m (4'-0") panel height).

2.7.4.6 Raised ridge caps. The open ridge at the peak is often a cause for concern among farm managers. The main problem is

the ability of rain and snow to enter at the ridge and accumulate in feed alleys, free stalls, or on mechanical equipment. Ridge cap design factors have been investigated by Mitchell (1971, 1982). The performance of raised ridge caps is unpredictable and often unsatisfactory. Field experience indicates that ridge caps do not eliminate rain entry and may actually direct driven snow into the barn, rather than allowing it to pass over the open ridge.

Ridge caps are not generally recommended. However, design recommendations and specifications are available (Bodman, 1980).

III. EXPERIMENTAL

3.1 Facilities

Ten naturally ventilated dairy barns located in Michigan's lower peninsula were chosen for inspection. Two barns were located in Mason County on the western side of the state, seven barns were located in Huron County in Michigan's thumb region, and an additional barn was located in central mid-Michigan in Gratiot County. All barns were built between 1976 and 1980.

3.2 Equipment

9.7m (32') OSHA Class I extension ladder

2.43m (8') step ladder

Increment corer (0.64cm (¼")) #4334, Keuffel & Esser Co., Sweden

Resistance-type moisture meter (Model RC-1C, Delmhorst Instrument Co., Boonton, N.J.)

Sling Psychrometer (Bacharach Instruments, Pittsburgh, PA)

Plastic straws 0.79cm (5/16") diameter

Wood Chisel

Ratchet brace

Propane torch

95% ethyl alcohol

0.95cm (3/8") hardwood replacement dowels

3.3 Experimental Procedure

Wood cores 1.91cm (3/4") long were removed from two trusses in each barn with an increment boring bit in the following locations (Appendix B)

1. Top chord near the ridge gusset plate directly beneath the open ridge
2. Top chord 30.4-45.6cm (12-18") beyond the edge of the roofing at the open ridge
3. Web member adjacent to the ridge gusset plate directly below the ridge opening
4. Truss tail

All cores were transferred from the coring bit directly into plastic straws and labeled for later transfer onto petri plates.

Prior to removing each core, a thin (1.6mm) (1/16") layer of wood was chiseled from the wood surface to eliminate inclusion of mold, bacteria, or fungal spores from the weathered wood surface. The chiseled area was sterilized with a low propane flame to avoid including extraneous microorganisms with the sample.

After each wood core was removed from the increment corer, the bit was sterilized by immersion in 95% ethyl alcohol and flamed to eliminate the possibility of transferring fungal spores to subsequent samples.

Hardwood replacement dowels 0.95cm (3/8") in diameter were hammered into the core holes after the sample was removed.

At each location a pick test was performed to detect advanced decay.

Wood moisture contents were recorded at 0.64cm (1/4") increments to a depth of 1.91cm (3/4") at each core location.

Moisture meter readings were affected by the wood temperature. Temperature corrections were applied in reference to the temperature slide rule supplied with the moisture meter.

Due to the inability to identify all wood species involved, the species correction was not applied. Therefore, in most instances wood moisture content may have been underestimated 1 - 1.5%.

Dry bulb and wet bulb temperatures were recorded with a sling psychrometer at the following locations:

1. At the ridge peak
2. Outside the barn in the area of the sidewall opening

Relative humidities were calculated with reference to a psychrometric chart.

All wood cores were taken to the laboratory and embedded in a malt extract agar containing lactic acid and benlate according to recommendations reported by Graham and Helsing (1979). Plates were checked each day for the presence of decay fungi.

Identification of decay fungi was through consultation with the Center for Forest Mycology Research at the USDA Forest Products Lab in Madison, Wisconsin.

The moisture content of all core locations was checked a second time in mid-February and early March.

IV. RESULTS AND DISCUSSION

Design specifications for naturally ventilated dairy barns have been made under the assumption that the wood in service does not attain a moisture content significantly exceeding 19% dry basis (Goehring, 1985). This assumption is based on equilibirum moisture content values provided in the USDA Wood Handbook (1974). Information obtained during this study indicates that this assumption may be incorrect in the case of naturally ventilated dairy barns.

4.1 Field Estimates of Equilibrium Moisture Contents

Microclimatic conditions determine the wood moisture content at fixed locations in a barn. Variations in temperature and absolute humidity are found in all barns. In naturally ventilated buildings, these temperature and moisture gradients are primarily a function of height, as cooler, drier air enters at the sidewalls and rises toward the ridge outlet with the addition of animal heat and moisture. Temperature differentials of 3-6°C (5-10°F) between incoming and exhaust air are common during winter operations. The absolute himidity always increases, although the relative humidity will not necessarily increase due to the increased vapor carrying capacity of the warmer air.

Daily fluctuations in temperature and relative humidity occur much more rapidly than moisture can migrate through wood. Continuous internal moisture gradients are always present and short-term variations will not be dramatic. The equilibrium moisture content (EMC) is never attained under field conditions. When wood is not exposed to a source of free water, rough estimates of the expected wood moisture content for the given microclimatic conditions can be made by measuring wood moisture contents at protected areas.

Estimates of the wood moisture content at each barn were made by measuring the moisture gradient at 0.64cm (1/4") increments to a depth of 1.91cm (3/4") at two locations: (1) in the top chord near the open ridge beneath the protective roofing material (TCP position); and (2) at the eaves in the truss tail of the top chord (TT position). Table 4.1 lists the arithmetic mean moisture contents of all the barns in the study at each depth and at each location protected from wetting by rain and/or snow.

Estimates of wood moisture contents listed in Table 4.1 are consistent with predicted values provided by the USDA Wood Handbook (1974) for climatic conditions common in Michigan in early December and late February, 0-6°C (30-40°F) with 70-85% relative humidity. Warmer mean temperatures near the peak create a predictably lower wood moisture content at that area than at the cooler area near the truss tail.

The wood moisture content values listed in Table 4.1, along with individual average readings at each barn at the same locations, will be considered to be benchmark moisture contents. Moisture content readings significantly above these benchmark values were assumed

Table 4.1 Arithmetic mean moisture contents for all barns, percent dry basis, TCP and TT positions

Location	December to November				February to March			
	0.64cm (.25in)	1.27cm (.5in)	1.91cm (.75in)	Avg.	0.64cm (.25in)	1.27cm (.5in)	1.91cm (.75in)	Avg.
Truss tail	17.0	15.75	15.0	15.9	18.6	17.2	16.9	17.6
Top chord protected by roofing material	16.0	15.33	14.4	15.2	17.0	16.0	15.0	16.0

to result from contact with free water in the form of rain, snow, or condensation.

4.2 Categories of Deterioration Potential

The arithmetic mean ($\bar{X}$) moisture contents of two trusses in each barn were tabulated and categorized as follows:

1. $X < 20\%$ MC
2. $20\% \leq \bar{X} \leq 24.9\%$ MC
3. $25\% \leq \bar{X} \leq 29.9\%$ MC
4. $\bar{X} \geq 30\%$ MC

Wood moisture contents less than 20% were assumed detrimental to neither the wood nor the metal fasteners. Moisture contents in the 20-24.9% range were assumed to be potentially corrosive to metal fasteners. Moisture contents between 25% and 29.9% were assumed to be corrosive to metal fasteners and possibly conducive to wood decay. Wood moisture contents greater than 30% were considered capable of supporting wood decay fungi and conducive to metal fastener corrosion.

The set of histograms in Figure 4.1 indicate wood moisture contents relative to date taken and location within each barn. The following general classifications were used to compare and contrast design and management features of the ten barns surveyed:

1. No excessive (<20%) moisture accumulation
2. Excessive ($\geq$20%) moisture accumulation in web members
3. Excessive moisture accumulation in web members and in the exposed top chord (TCE position) at the open ridge
4. Moisture accumulations in excess of 30%

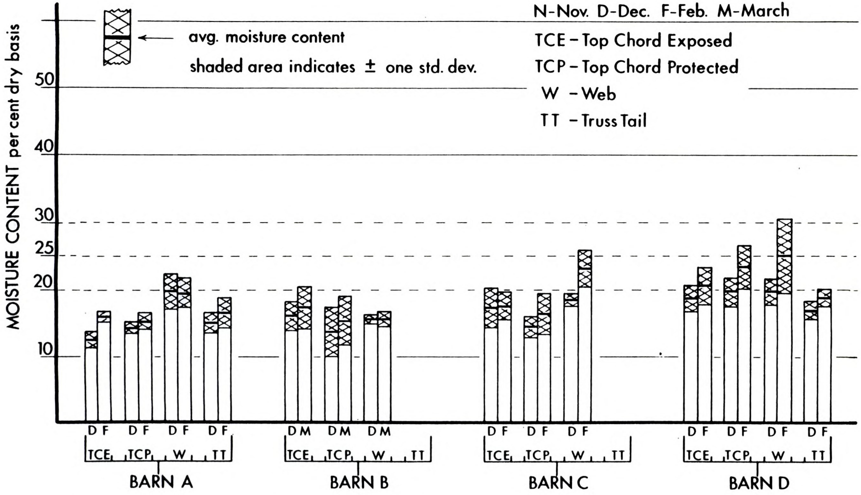

Figure 4.1. Arithmetic Mean Moisture Contents by Location and Date.

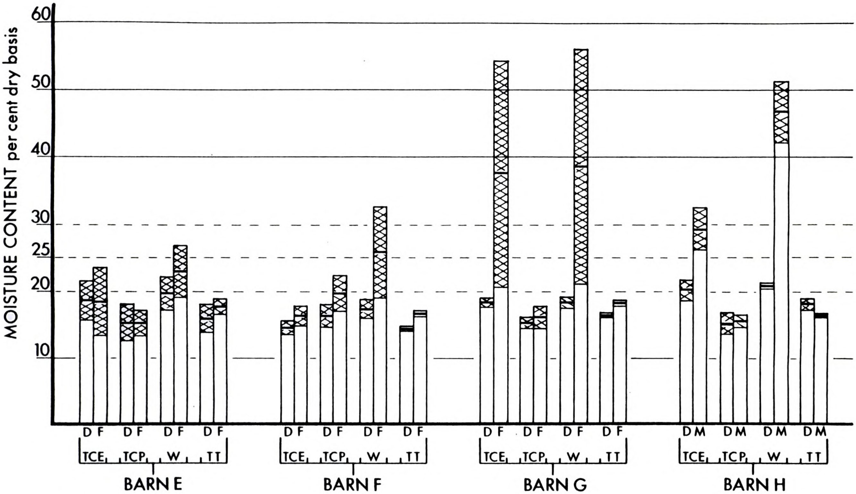

Figure 4.1. Continued.

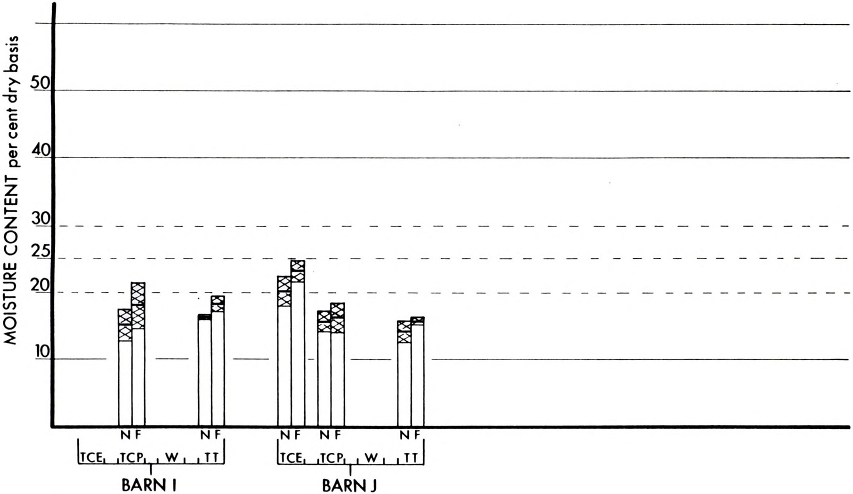

Figure 4.1. Continued.

Specific information regarding design details for all barns studied are contained in Appendix B.

4.3 Barn Comparisons Based on Moisture Accumulation Characteristics

4.3.1 No Excessive (<20%) Moisture Accumulation

Barns A (see Appendix B.1) and B (see Appendix B.2) had mean recorded moisture contents below 20% at all locations prior to and after winter operation.

Common major design features include a north/south orientation and properly sized ridge openings. (Note: The test area for Barn B was the new addition, 13.4m x 48.8m (44' x 154') at the south end of the existing structure.) Barn A had no exterior obstructions to wind movement. Barn B had no obstructions influencing air movement at the truss No. 2 location (see Figure B.2), but silos and mechanical equipment adversely affected air movement at the truss No. 1 location.

Adequate cold weather ventilation was assured at Barn A by continuous, nonadjustable openings at the eaves. (See detail A, Figure A.1.) Winter air inlets at Barn B were located low on the sidewall. (See detail B, Figure A.1.) Closure of this type opening is often the cause of inadequate ventilation either by snow blockage or planking installed by the manager. However, such closures were not observed at this barn during the time of the study.

Despite the lack of design similarities, indications were that both barns were well ventilated throughout the year. Both barns were clean along the inner surface of the roof from the eaves to the open ridge. There was no indication of mold, mildew, or cobweb formation in either barn. The implication was that air movement was adequate at all times of the year, including the warm months when cobweb formation and various microbial activities proceed at a rapid rate.

Moisture contents throughout Barn A were fairly uniform. Moisture accumulation beneath the molded flashing (TCE position) was lower than the wood moisture content at the truss tail or the truss ridge. As expected, the February readings were slightly higher than the December readings due to much lower temperatures and elevated relative humidities in February. Molded flashing protected the wood from contact with rain and snow. Solar insolation may warm the wood, creating moisture content values below the estimated values at the ridge or truss tail locations.

Moisture contents of web members were slightly below the 20% MC cutoff limit in Barn A. A small number of readings, primarily at the 0.64cm (1/4") level, were greater than 20% MC. The relatively steep moisture content gradients indicated that the wetting was of short duration and drying was imminent; e.g., 20% at 0.64cm (1/4") to 16% at 1.91cm (3/4").

The most conspicuous aspect of the data collected at Barn B was the large variation between recorded values at equivalent positions in each truss. The widely varying values resulted from differences in air movement between truss locations.

Truss No. 1 (see Figure B.1) in Barn B was located near the north end of the new addition. Silos adjacent to the building on the east side of the barn obstruct air movement at this location by interfering with prevailing northwest winds. Overhead feeding equipment at this end of the barn interfered with air movement toward the open ridge. Truss No. 1 was located further from air inlets than truss No. 2. The combination of increased distance from air inlet to outlet with mechanical equipment along the inner roof surface created a tortuous pathway offering excessive resistance to airflow at this location. Reduced air movement resulted in elevated moisture contents relative to Truss No. 2.

Truss No. 2 in Barn B was located 6.1m (20') from the south end. Air movement at this location was much less affected by exterior obstructions to air movement than Truss No. 1. The lack of dust, mold, and mildew along the rafters and the inner roof surface indicates optimal air exhange rates throughout the year. Air movement at this location was a major factor influencing wood moisture content in Barn B.

The important similarity between Barn A and Barn B was not one or more specific design features, but the overall adequacy of the ventilation system as evidenced by limited moisture accumulation in susceptible truss members and the clean condition of the building components along the inner roof surface.

4.3.2 Excessive Moisture Accumulation in Web Members

Barns C, E, and F (see Appendices B.3, B.5, and B.6) indicated a tendency to accumulate excessive moisture in the web members.

Barns E and F were adjacent to each other and shared a large number of structural similarities. The most important differences between Barns E and F were that Barn E was partially insulated with 2.54cm (1") rigid foam beneath the roofing material, Barn F was not; Barn E had flashing over the truss, Barn F had molded ridge caps. Winter air inlets in both barns were provided by continuous openings at the eaves. Neither barn had large adjustable sidewall panels for summer ventilation.

The molded ridge caps in Barn F effectively protected the truss. Moisture contents beneath the molded caps were lower than moisture contents in the adjacent position under the metal roofing. The range of moisture contents recorded at the TCE position in Barn E were much greater than the range of moisture contents recorded at the position in Barn F. Molded ridge caps performed more effectively and consistently than flashing over the truss as measured by moisture accumulation in the affected area.

The TCP location in Barn F did not accurately reflect the protected wood moisture content at that location. Excessive moisture contents in the surface 0.64cm (1/4") and the presence of a steep moisture gradient to the depth of 1.91cm (3/4") indicate short-term surface wetting. The location for this reading should have been further under the roofing, inaccessible to surface water.

Both Barn E and Barn F were well ventilated relative to winter demands. However, summer ventilation demands were not being met. This was predictable given the lack of large sidewall panels for summer ventilation. Both barns had marked accumulations of dust, mold, and mildew on the purlins and truss members. The elevated moisture contents in the kingpost web in each barn could be due to increased permeability caused by microbial activity during warm weather.

Wood in the kingpost web below the metal gusset plates may have been exposed to greater quantities of water than the top chord adjacent to the metal plates as water from rain and melted snow ran down the metal plate onto the wood below.

Although condensation at the surface of the metal plates was not observed, condensation may have been an additional source of free water at the kingpost web.

Barn C had moisture contents in the web members in excess of 20% MC, also. Barn C was well ventilated throughout the year. All purlins and truss members were clean. There was no indication of cobwebs, mold, or mildew formation.

Two design features in Barn C may have contributed to greater water contact and delayed drying at the junction of the web members at the ridge gusset. The truss design configuration was a double W. Web members were at an angle that provided greater surface area perpendicular to the open ridge than the kingpost truss design. In addition to the increased contact surface area, the decreased web angle relative to the 90° angle of the kingpost design may have reduced the rate at which water was shed from the truss surface. Greater water contact time would allow increased penetration and, ultimately, higher moisture contents.

The raised ridge cap at Barn C was partially effective in preventing rain and snow entry. However, truss wetting did occur from blowing snow and driven rain. Subsequent to truss wetting, the raised ridge cap may have delayed drying by blocking the warming and drying action of the sun.

Based on observations of Barns C, E, and F, excessive moisture accumulation in exposed web members may be enhanced by: (1) greater permeability of the wood caused by wood surface microbial activity; (2) truss web configurations that increase the water contact area and delay water runoff; (3) raised ridge caps that limit the warming, drying action of the sun.

4.3.3 Excessive Moisture Accumulation in Web Members and the Exposed Top Chord at the Open Ridge

Moisture content levels above 20% occurred in Barns D (see Appendix B.4) and Barn J (see Appendix B.10) in both the web members and in the top chord beneath the open ridge (TCE).

Barn J was not well ventilated at many times throughout the year. The primary limiting factor was the east-west building orientation complicated by exterior obstructions (bunker silo, older barn) directly west of the building. Furthermore, winter air inlets were located low on the sidewalls and closed with planking from December through February.

The purlins and truss members had cobweb, mildew, and mold formations along the inner surface of the roof.

Examination of the data collected at location 6, Truss No. 2, Barn J (see Table B.10) indicated that short-term surface wetting had occurred. That location was no considered indicative of the protected wood moisture content at that location. The readings should have been taken further under the roofing material, well protected from water penetration.

Barn J provided an example of metal fastener corrosion and the concurrent degradation of wood in contact with rusting iron (see Figure 4.2).

During January and February of 1985, a heavy, unevenly distributed snow load accumulated on the roof at Barn J. A failure occurred at the ridge gusset where the kingpost web was connected by the metal plate fastener. Under tension, the kingpost web was pulled down as much as 4cm (+1½") at some locations. Surface wood was stripped away by the plate teeth in all cases. Corrosion weakened plate teeth were pulled from the plate and, in some instances, could be recovered from the wood below.

Barn D was built according to most of the recommended design specifications regarding inlet and outlet openings, roof slope, etc. However, directly west of the barn were many large trees, a house, and the original old barn converted to heifer housing. Air movement was obstructed at all times of the year, but particularly during warm weather. However, there were no indications of mold, mildew, or cobweb formations.

Figure 4.2. Failure at the Wood-Metal Fastener Connection, Barn J.

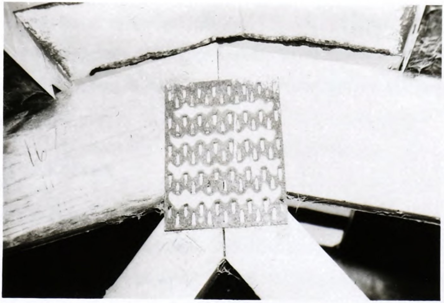

Figure 4.3. Metal Fastener Corrosion, Barn G.

Both TCP locations in Barn D were indicative of short-term surface wetting and were not considered as reliable indicators of the protected wood moisture content.

Both visits to Barn D were near the end of the day when temperatures were dropping rapidly. Potential errors may have occurred under those conditions. If the wood had been significantly warmer than the air temperature recorded for corrective purposes, the corrected moisture content would have been artificially high.

Barn D had molded ridge caps over the exposed truss area. High wood surface moisture contents and the steep moisture content gradient indicated short-term surface wetting. In contrast to the conditions found at Barns A and F, condensation may have occurred beneath the molded ridge cap at this barn.

Moisture contents in the web members of Barn D indicated considerable surface wetting. However, there were no water stains or obvious corrosion of the metal plates.

The most important smilarity between Barns D and J was the east-west building orientation which created insufficient air movement throughout the year.

4.3.4 Moisture Contents Exceeding 30%

Barns G (see Appendix B.6) and H (see Appendix B.7) had moisture contents in excess of 30%. Moisture contents at this level are conducive to corrosion of metal fasteners and capable of supporting wood decay fungi.

Both barns were difficult to ventilate throughout the year. Barn G was built with an east-west orientation. The west end was blocked by silos and a feed center. To the south 4.6m (15') was the milking center and calf raising facilities. Large sidewall panels for summer ventilation were not provided.

Barn H was built with a north-south orientation. However, the milking center and silos erected at the west side of the building prevent air movement due to wind action. Winter air inlets built low on the sidewalls were closed from December through March.

Both barns G and H have had mechanical fans added to improve warm weather conditions. Both had double W truss design configurations. Both had noticeable accumulations of mold, mildew, and cobwebs along the inner roof line.

The exceptionally high moisture contents at Location 1, Barn G (see Table B.7) during February were caused by melting frost dripping from the flashing above directly onto the truss below. Had the barn been well ventilated, drying would probably have occurred before such deep water penetration could have occurred.

Excessively high moisture contents at Location 2, Barn G (see Table B.7) indicated that surface wetting had occurred and that this location could not be considered indicative of the protected wood moisture content. Readings at this location should have been taken further under the edge of the roofing material.

Metal fastener corrosion at the ridge gussets in Barn G were occurring at a much more rapid rate than at any of the barns tested (see Figure 4.3).

Several factors appeared to be interacting at Barns G and H to permit elevated moisture contents subsequent to cold weather operations. The critical limiting factor was the overall poor ventilation due primarily to exterior obstructions inhibiting air movement. Cobweb, mold, and mildew formation were evident in both barns. Microbial activity at the wood surface in both barns may have increased the permeability of the wood permitting rapid moisture accumulation. Inadequate air movement delayed rapid drying after wetting had occurred. The W type truss design configuration maximized exposed surface area and minimized runoff rates from the web members. The ridge cap at Barn H further delayed drying by preventing the warming action of the sun at the ridge.

4.3.5 Observations at Barn I

Problems experienced at Barn I (see Appendix B.9) provided the rationale for this study. During the summer, 1984, the operator and his builder observed what they perceived as wood decay at the ridge gussets and at the junction of the kingpost web with the lower chord. All kingpost webs were removed and replaced with new lumber. Metal truss plates were removed and replaced with oversized, 1.27cm (1/2") preservative treated plywood gussets. Unfortunately, all lumber removed had been destroyed before diagnostic tests would be performed to assess its adequacy as a structural member. The oversized gussets prevented inspection of the lumber adjacent to that removed.

Barn I was built with a north-south orientation. However, prevailing winds from the northwest were obstructed by the milking

center, upright silos, a bunker silo, and other buildings and trees. Winter air inlets located low on the sidewall were frequently obstructed by drifting snow or planking placed in the inlet opening. Bird netting had been installed over the open ridge which caused frequent blockage by snow and frost accumulation. Mold, mildew, and cobweb formations were clearly evident along the inner surface of the roof. Ventilation at Barn I was inadequate at all times of the year.

Neither the accuracy of the operator's observations nor the appropriateness of the repairs made at Barn I can be verified at this time. Given the difficulty associated with maintaining adequate ventilation throughout the year, metal truss plate corrosion and/or wood decay may have occurred.

4.4 Results of the Pick Test

Table 4.2 indicates the arithmetic mean occurrence of a brash break at each general location of the barns tested. The pick test was performed during the November-December visits. Pick test results for individual locations are included in Tables B.1 to B.10.

Table 4.2. Pick test, percent brash break

Barns Included	TCE	TCP	WEB	TRUSS TAIL
All barns	50	40	75	0
Barns A, B	0	0	50	0
Barns G, H	50	75	100	0
Poor Summer Ventilation	70	58	100	0
Well Ventilated Summer	25	12	33	0

Based on the observations made during this study and on examination of the data, the use of the pick test as an indicator of early decay is questionable. Examination of the individual data indicates that a brash break is not indicative of abnormally high moisture contents. Similarly, a clean break does not necessarily indicate drier wood. However, examination of the grouped data indicates that areas subject to intermittent wetting may be more likely to yield a brash break, indicating wood decay. Surface phenomena, such as weathering and/or wood colonizing organisms other than wood decay fungi, may interact to weaken the wood surface, causing a brash break on otherwise sound wood.

Interpretation of the pick test is complicated by problems related to uniformly repeating the test in each location. Independent of the condition of the wood being tested, the results obtained by the pick test are a function of size and shape of the tool used, the angle of penetration, and the depth of penetration. Blunt tools have a tendency to rupture adjacent wood fibers, particularly when shallow (= 0.47cm (3/16")) tests are taken. Often, wood that breaks abruptly upon tool penetration of 0.32cm (1/8") will break cleanly when the tool is driven deeper into the wood. Low tool angles relative to the plane of the wood tend to rupture more adjacent wood fibers during penetration than the same tool driven into the wood at a much sharper angle. As greater amounts of wood fibers are ruptured upon insertion of the tool, sound wood will display greater frequencies of brash breaks.

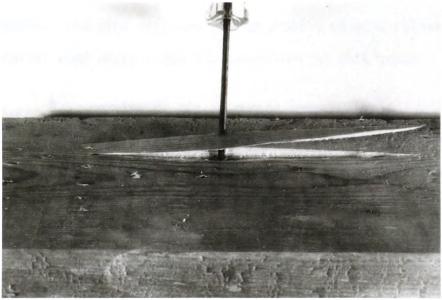

Figure 4.4. Pick test. Clean break indicates wood free of decay.

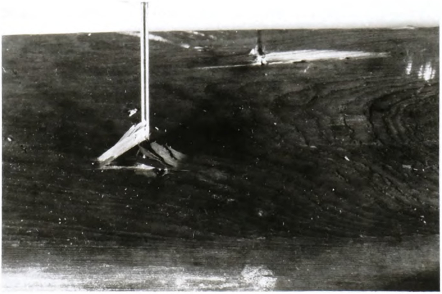

Figure 4.5. Pick test. Brash break indicates presence of decay.

Uniform application of the pick test is difficult to achieve in all situations. The results are somewhat subjective and difficult to quantify. The pick test was not considered to be a reliable indicator of wood decay under the conditions of this study.

4.5 Results of the Increment Core Analysis

Increment cores were taken at each location, along with moisture content readings in an attempt to establish the relationship between seasonal fluctuations in moisture content and the presence of wood decay fungi. Based on the problems encountered in this study, sampling large numbers of locations for positive identification of wood decay is not recommended.

Three separate batches of a malt extract agar containing Benlate (10 parts per million) for suppression of nondecay fungi and lactic acid to prevent bacterial growth were prepared. Both the nutrient agar recipe and the core plating technique used in the survey were those outlined by Graham and Helsing (1979).

By January 3, 1985, significant bacterial and fungal growth were evident on the cores plated December 3, 1984. All plates displaying growth were grouped according to gross morphological similarities such as color, presence of fruiting bodies, texture, etc. Preliminary identification of possible decay causing fungi was made with the assistance of Dr. Jerry Adams of the Department of Plant Pathology at Michigan State University. A pure culture was made of suspect samples and sent to the Center for Forest Mycology Research at the Forest Products Laboratory in Madison, Wisconsin, in care of Dr. Harold Burdsall for possible identification.

Figure 4.6. Increment core culture plate.

Results of the core cultures were variable between nutrient agar batches. The agar prepared in early December did not inhibit growth of nondecay fungi or bacteria. Rapid growth of these substances obscured the possible identification of the slower growing decay fungi. In an attempt to salvage these cores, additional plates were prepared with the Benlate concentration increased from the original 10 parts per million (ppm) to 20 ppm. The cores were removed from the original plates, soaked in a 10% solution of Clorox for 4-5 minutes, dried, and placed on the new plates.

No growth was observed on any of the plates prepared December 14, 1984. Given the problems encountered with the previous nutrient agar, it is not known if the lack of growth on this nutrient agar was due to the absence of decay fungi or additional problems with the nutrient agar.

The replated cores were quickly invaded by bacteria and nondecay fungi. At this point the decision was made that reliable results could not be obtained from this portion of the survey and the increment cores were abandoned.

Collecting increment cores may be a reliable and convenient field test for the detection of decay fungi. However, the following factors should be considered.

Nutrient agar mixing and pouring should be done by those experienced with preparing this type nutrient agar. Nutrient agar should be tested by culturing wood known to contain decay fungi prior to culturing research related cores.

Positive identification of wood decay fungi is a time-consuming process that involves a great deal of expertise. Very few people have the time or ability to rapidly identify a large number of samples. For this reason, surveys involving the analysis of a large number of increment cores may be impractical. Recommended procedure would be to identify areas with sufficiently high moisture contents to support decay fungi. Cores should be taken only at those locations.

V. SUMMARY AND CONCLUSIONS

5.1 Assessment of the Potential for Deterioration of the Wood Truss System

Wood moisture contents well in excess of equilibrium moisture contents predicted for enclosed lumber have been recorded in the area of the open ridge in naturally ventilated dairy barns. In locations where design details and management efforts allow optimal air exchange rates, moisture content rise will be minimized.

Increases in moisture content are roughly proportional to the degree of difficulty related to sustaining adequate air movement through the barn. Year round ventilation capabilities must be considered in the assessment of the potential for excessive moisture accumulation. Summer ventilation capabilities may affect not only animal health and comfort during warm weather, but also the tendency for wood colonizing organims to successfully attack the wood surface. If these organisms can significantly increase the permeability of the wood exposed to wetting from rain, condensation, and melting snow, the rate and extent of water penetration during cold weather operation will increase. Barns that are well ventilated throughout the year will be more resistant to excessive moisture penetration than poorly ventilated barns.

When all recommended design and management directives are observed, air movement is optimal and wood moisture content rise is

minimized. However, many modifications made during planning and construction adversely affect the building's ventilation capabilities. In many cases, management efforts obstruct air movement through otherwise well designed barns.

The importance of proper building location with respect to prevailing winds and avoidance of exterior obstructions are often misunderstood or overlooked. Recommended barn placement is with the long axis of the barn perpendicular to prevailing winds, unobstructed by other barns, silos, trees, etc. Building placement is one of the single most important variables affecting the overall performance of naturally ventilated buildings. Well designed and managed buildings have experienced substantial problems related to air movement when unwise decisions were made regarding building placement.

Wood moisture contents in excess of 30% dry basis have been measured in some barns after 2-3 months of cold weather operation. At this moisture content level, both wood decay and corrosion of metal fasteners are possible. However, the seriousness of the problem created by elevated moisture contents during cold weather is difficult to assess. It is important to note that the rate of deterioration caused by wood decay and metal fastener corrosion are greatly influenced by temperature, as well as moisture. During the time period November through March, low temperatures are rate limiting. The growth of wood decay fungi is greatly restricted below 10°C (50°F). A general rule of thumb used to predict the rate of chemical reactions is that the rate doubles for each 10°C (18°F) rise in

temperature (Brady and Humiston, 1975). Low temperatures will limit the progression of chemical reactions typical of corroding metal. At 0-6°C (30-40°F), even in the presence of adequate moisture, both fungal growth and fastener corrosion will proceed slowly, if at all.

The potential hazard is related to the persistence of elevated moisture contents as temperatures warm above the 10-15°C (50-60°F) range. In most cases, the affected areas may dry rapidly to moisture contents below harmful levels. High moisture contents may persist in poorly ventilated barns. Further research is needed to quantify the time-temperature-moisture relationship involved.

Reliable estimates of the serviceability of the wood truss system suspected of experiencing some deterioration will be difficult to make. Detection of incipient decay is difficult and time consuming. Since extensive strength losses occur before visual detection of wood decay can be made, estimates of residual strength properties may contain a wide margin of error. Similarly, observation of conditions at the wood-wood fastener interface will not be easily accomplished. Further research will be needed to identify which component or combination of components will limit the structural integrity of the system.

5.2 Conclusions

Based on experience and data obtained during this study, the following conclusions are drawn.

1. Wood moisture contents exceeding 19% dry basis are common in the area of the open ridge of naturally ventilated dairy barns subsequent to winter operations.

2. Summer ventilation capabilities affect cool weather moisture uptake by wood truss members. Poorly ventilated barns are more susceptible to excessive moisture accumulation than well ventilated barns.
3. Molded ridge caps perform more effectively and consistently than flashing over the truss.
4. The pick test is not a reliable indicator of wood decay.
5. Problems associated with culturing and interpreting results of increment core cultures limit the use of increment coring in large-scale surveys.

VI. RECOMMENDATIONS

The following recommendations are made with respect to the need for future research.

1. Additional measurements of wood moisture contents should be made in order to delineate the extent and duration of moisture contents exceeding 19% dry basis as temperatures increase in barns.
2. Specific design features such as raised ridge caps and the truss web configuration may influence moisture accumulation in the wood truss members. These interactions must be better defined.
3. The interaction of the physical, chemical, biological, climatic, and microclimatic variables that influence metal fastener corrosion in the area of the open ridge must be defined.
4. Changes in material properties caused by continuous exposure to weathering, moisture, and chemical degradation must be quantified. The most probable limiting components of the structural system must be known before reliable corrective measures can be recommended.
5. Methods for detecting wood decay and estimating strength losses due to wood decay must be improved.

APPENDICES

APPENDIX A

SIDEWALL AND OPEN RIDGE CONSTRUCTION DETAILS

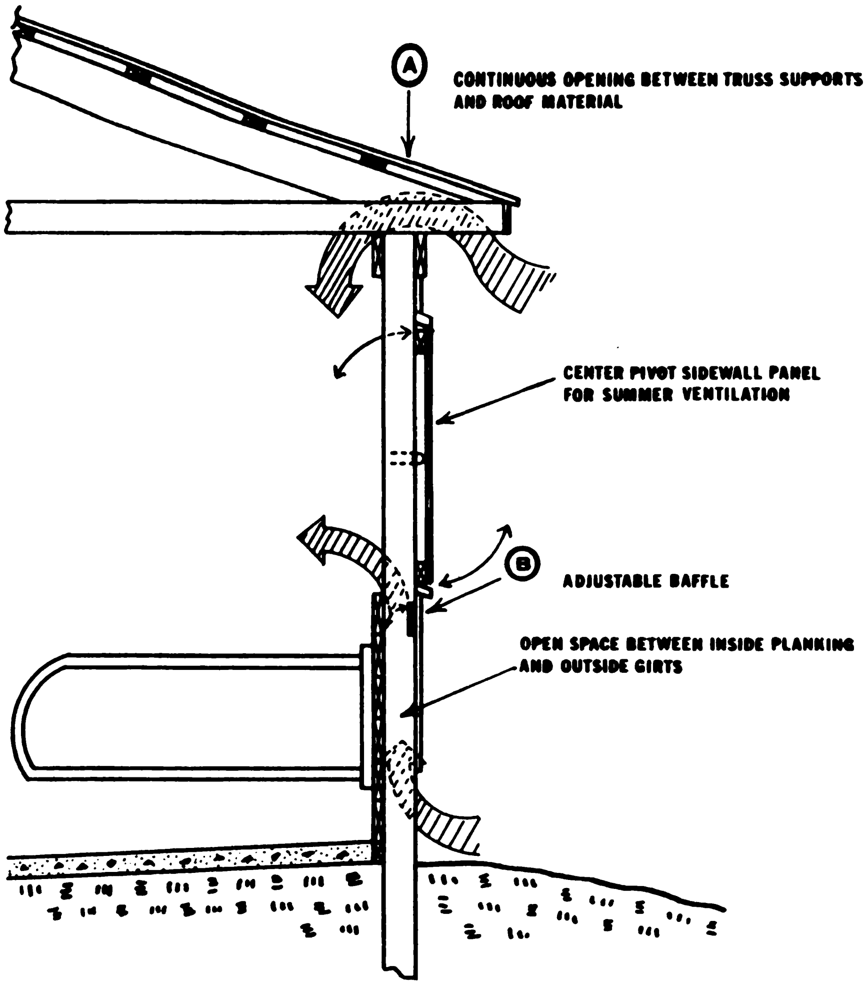

Figure A.1. Alternative sidewall construction details.

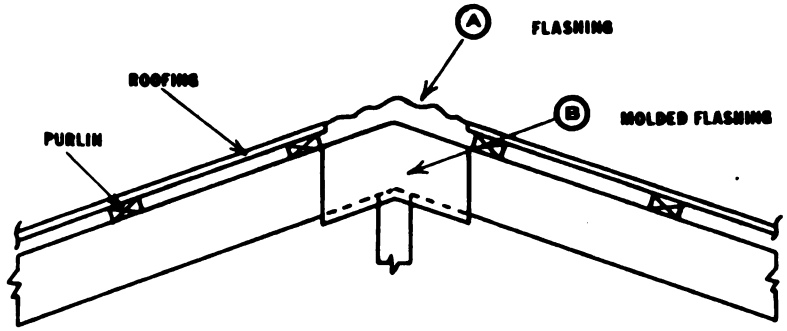

Figure A.2. Alternative details of flashing over truss peaks with an open ridge.

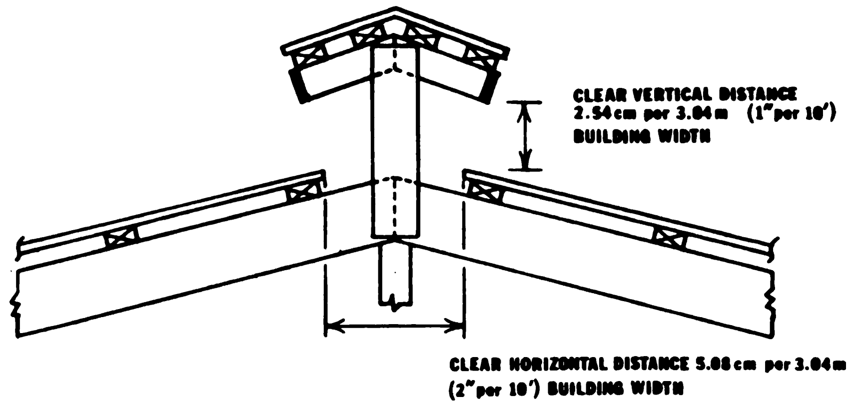

Figure A.3 Open ridge and raised ridge cap details with recommended dimensions.

Figure A.4 Flashing at the open ridge--Barn I

Figure A.5 Molded flashing at the open ridge--Barn A

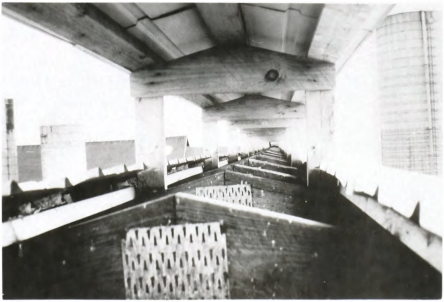

Figure A.6 Raised ridge cap--Barn C.

APPENDIX B

BARN DESIGN SPECIFICATIONS AND RECORDED MOISTURE CONTENTS

APPENDIX B.1: Barn A

Location: Perrington, MI
County: Gratiot
Year built: 1980
Dimensions: 31.5m x 51.1m (104' x 168')
Building design: 6-row drivethrough
Design capacity: 200 free stalls with 200 cows

Building material/color: red sheet metal siding
white sheet metal roofing

Sidewall height: 3.04m (10'-0")

Sidewall openings: Summer air inlets--1.1m x 2.28m (3'-6" x 7'-6") pivot type doors in each bay

Endwall openings: 4--3.65m x 3.04m (12'-0" x 10'-0") doors at each end 1--3.65m x 3.65m (12'-0" x 12'-0") at each end of the feed alley

Eave openings: 30.4 cm (12") continuous vertical opening

Manure handling: daily tractor scraping to injection pump at the center alley

Roof slope: 4:12

Insulation: None

Ridge opening: 40.4cm (16") continuous

Truss ridge weather protection: molded sheet metal ridge caps

Wood species: Top chord--S. Pine No. 1

Truss spacing: 1.22m (4'-0") o.c.

Purlin spacing: 0.61m (2'-0") o.c.

Truss design: Modified queen post

Top chord: 3.8cm x 18.4cm (1½" x 7¼")

Bottom chord: 3.8cm x 14.0cm (1½" x 5½")

Web members: 3.8cm x 8.9cm (1½" x 3½")

Ridge gusset: metal press plates 30.4cm x 17.7cm x 0.95cm (12" x 7" x 3/8")

Building orientation: North/South

Surrounding terrain: No obstructions

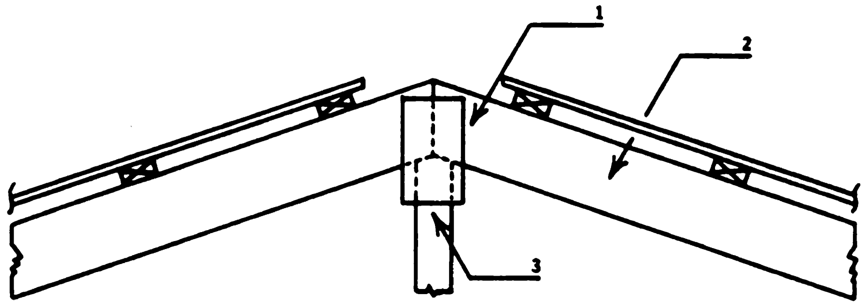

Figure B.1 Location of test sites, Barn A. Truss No. 1, 6.1m (20') from north end. South elevation. Molded flashing not shown.

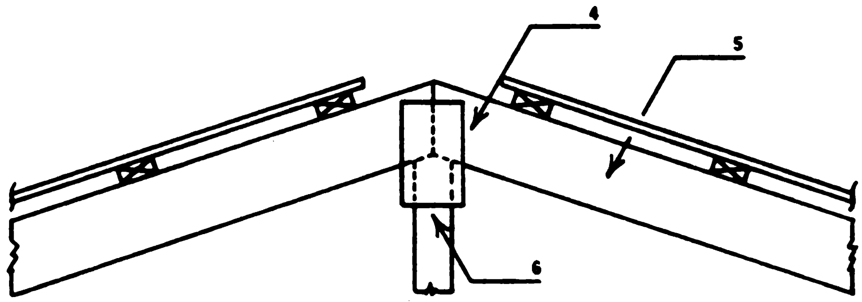

Figure B.2 Location of test sites, Barn A. Truss No. 2, 21.9m (72') from north end. South elevation. Molded flashing not shown.

Table B.1. Results of pick test and recorded moisture contents, Barn A

Location	Pick Test	Moisture Content % Dry Basis December 17, 1984			Moisture Content % Dry Basis February 26, 1985		
		0.64cm (0.25in)	1.27cm (0.50in)	1.19cm (0.75in)	0.64cm (0.25in)	1.27cm (0.50in)	1.91cm (0.75in)
1	Clean	12.0	12.75	13.0	17.25	16.50	16.0
2	Clean	16.50	16.0	15.0	16.25	16.50	16.25
3	Clean	21.0	18.25	16.0	20.50	17.50	16.25
4	Clean	10.25	13.25	14.0	15.0	15.50	15.50
5	Clean	14.0	11.5	13.25	14.0	14.25	14.25
6	Clean	24.0	20.0	19.0	22.0	20.75	20.0
Truss Tail	Clean	16.75	14.75	13.75	19.0	15.75	14.75

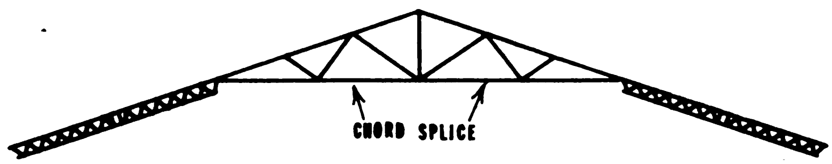

Figure B.3. Truss schematic, Barn A.

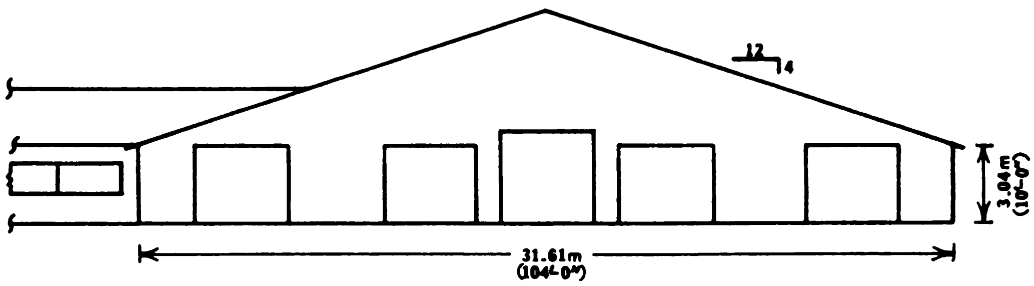

Figure B.4. North elevation, Barn A.

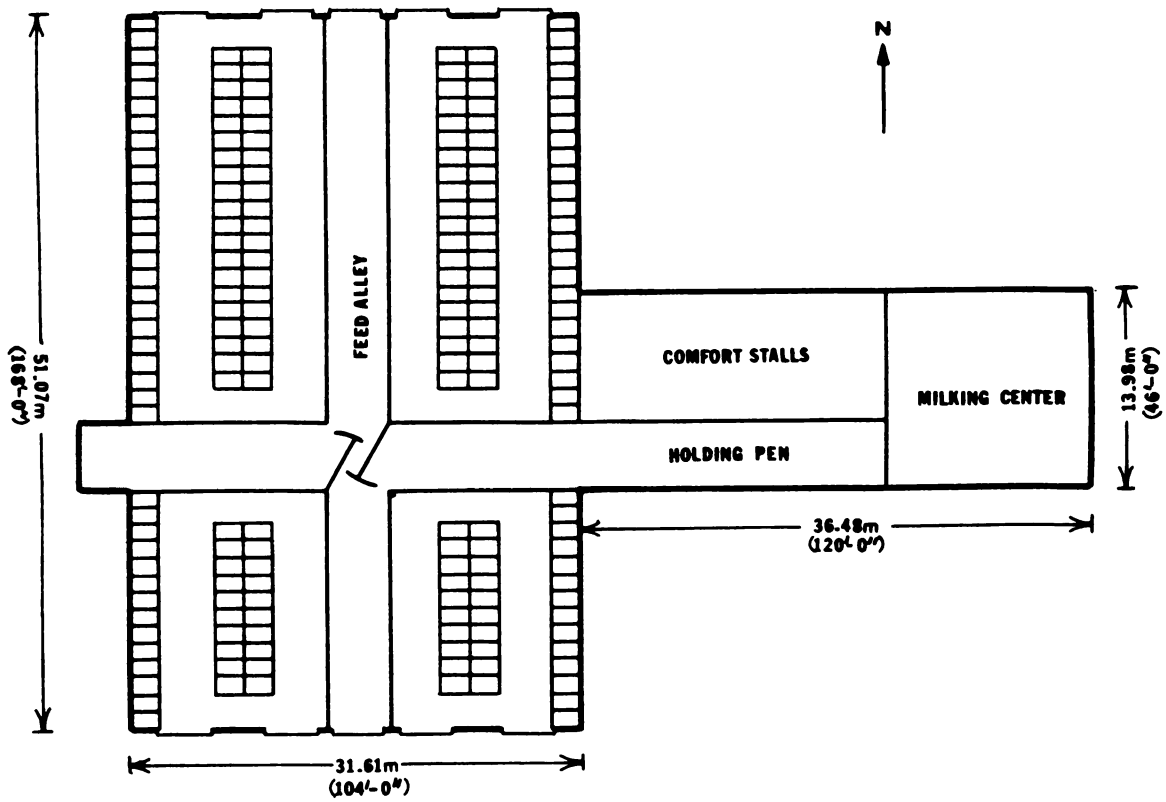

Figure B.5. Plan view, Barn A.

APPENDIX B.2: Barn B

Location: Bad Axe, MI
County: Huron
Year built: 1977 (New addition)
Dimensions: 46.8m x 13.4m (154' x 44') (New addition)

Building design: 3-row with mechanical feeding system

Design capacity: 85 free stalls with 84 cows

Building material/colors: red sheet metal siding, white sheet metal roof

Sidewall height: 3.34m (11'-0")

Sidewall openings: Summer air inlets--0.61m x 2.28m (2'-0" x 7'6") pivot type panels in every other bay. Winter air inlets--openings between inside planking and outside girts located 0.46m (1'-6") above grade on the outside, 1.06m (3'-6") above the stall floor on the inside. Openings are continuous, 13.9m x 2.28m (5' x 7'-6") between columns spaced 2.43m (8--0") o.c.

Endwall openings: 2-3.04m x 3.04m (10'-0" x 10'-0") doors on rollers at the south end

Eave openings: None

Manure handling: Daily scraping

Roof slope: 3:12

Insulation: 2.54cm (1") rigid plastic foam

Ridge opening: 20.4cm (8") continuous

Truss ridge weather protection: 20.4cm (8") sheet metal flashing

Wood species: Top chord--S. Pine No. 1
Web members--S. Pine No. 3

Truss spacing: 1.22m (4'-0") o.c.

Purlin spacing: 0.61m (2'-0") o.c.

Truss design: Modified queen post

Top chord: 3.8cm x 18.4cm (1½" x 7 1/4")

Bottom chord: 3.8cm x 10.0 cm (1½" x 5½")

Web members: 3.8cm x 8.9cm (1'" x 3½")

Ridge gussets: Metal plate plates 20.4cm x 25.4cm x 0.95cm (8" x 10" x 3/8")

Building orientation: North/South

Surrounding terrain: Feed center on the east side of the building, original building is on the north end of the new addition.

NOTES: Bird netting over the ridge.

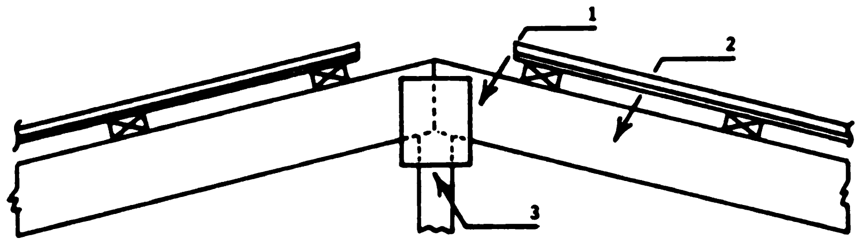

Figure B.6. Location of test sites, Barn B. Truss No. 1, 40.7m (134') from south end. North elevation. Flashing, bird netting not shown.

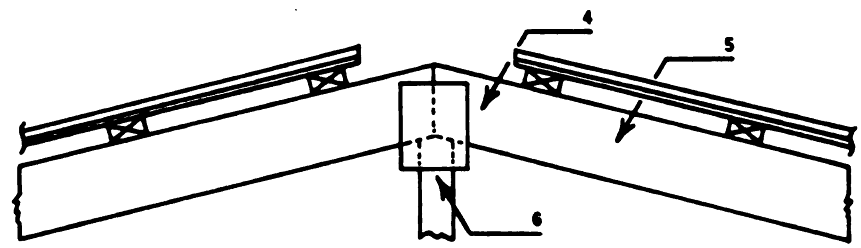

Figure B.7. Location of test sites, Barn B. Truss No. 2, 6.1m (20') from south end. North elevation. Flashing, bird netting not shown.

Table B.2 Results of pick test and recorded moisture contents, Barn B

Location	Pick Test	Moisture Content % Dry Basis December 13, 1984			Moisture Content % Dry Basis March 13, 1985		
		0.64cm (0.25in)	1.27cm (0.50in)	1.91cm (0.75in)	0.64cm (0.25in)	1.27cm (0.50in)	1.91cm (0.75in)
1	Clean	18.75	18.0	17.0	20.25	19.75	19.75
2	Clean	17.50	17.0	16.50	18.75	18.25	18.0
3	Brash	16.0	14.50	15.0	16.0	14.75	15.0
4	Clean	15.0	13.25	14.25	16.75	14.25	12.75
5	Clean	10.5	10.4	10.0	14.25	11.5	10.75
6	Brash	16.5	15.75	15.25	17.5	16.0	14.0
Truss Tail							

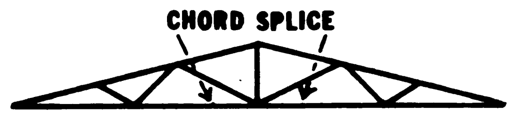

Figure B.8. Truss schematic, Barn B.

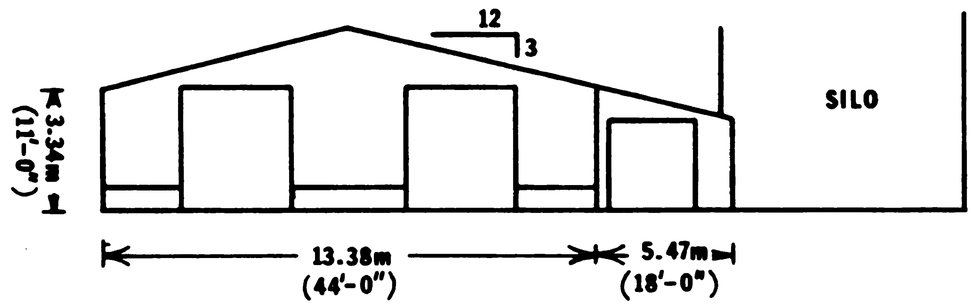

Figure B.9. South elevation, Barn B.

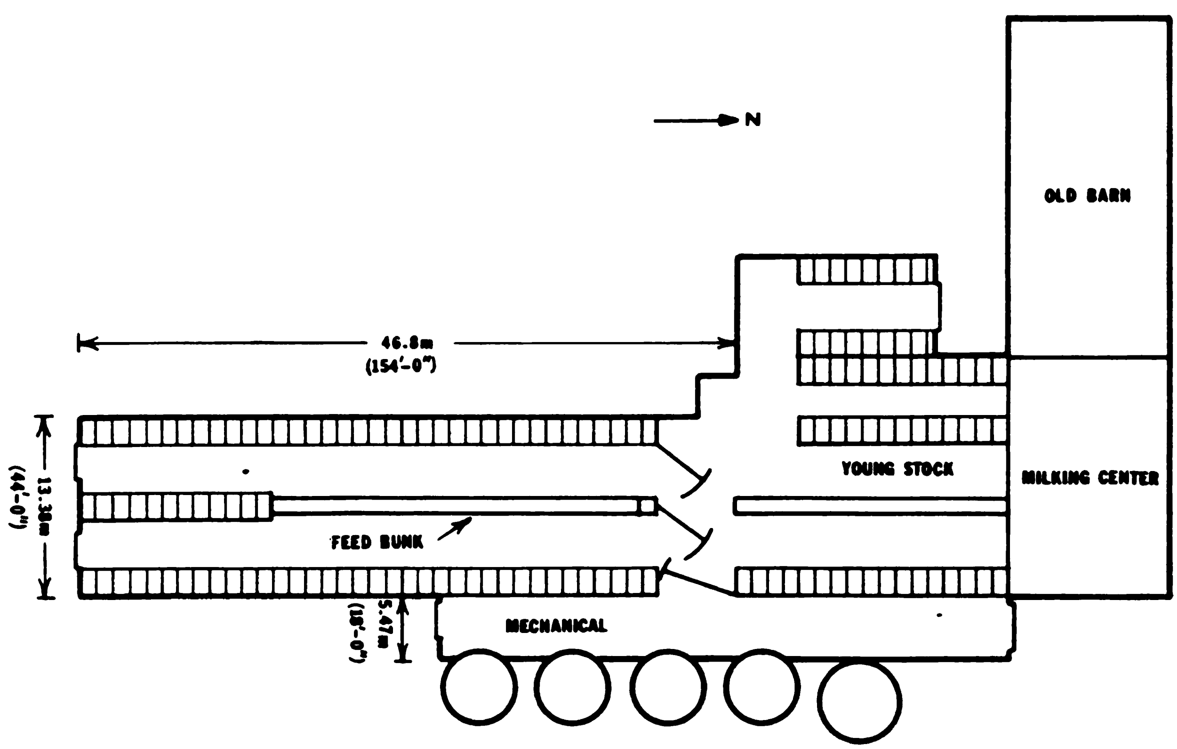

Figure B.10. Plan view, Barn B.

APPENDIX B.4: Barn C

Location: Harbor Beach, MI
County: Huron
Year built: 1978
Dimensions: 46.8m x 32.2m (154' x 106')
Type: 6-row drivethrough
Desing capacity: 200 free stalls with 185 cows

Building material/color: red sheet metal siding
white sheet metal roof

Sidewall height: 3.34m (11'-0")

Sidewall openings: summer air inlets--2.28m x 1.22m (7'-6" x 4'-0") pivot type openings in each bay.

Endwall openings: 2--3.04m x 3.04m (10'-0" x 10'-0") doors at each end
4--4.26m x 4.26m (14'-0" x 14'-0") doors at each end

Eave openings: 30.4cm (12") vertical opening continuous

Manure handling: daily scraping to injection pump at center cross alley

Roof slope: 3:12

Insulation: 2.54cm (1") rigid plastic foam

Ridge opening: 53.2cm (19") continuous

Truss ridge weather protection: raised ridge cap

Wood species: All truss members, S. Pine No. 1 Dense

Truss spacing: 0.81m (32") o.c.

Purlin spacing: 0.61m (2'-0") o.c.

Truss design: Triple W

Top chord: 3.8cm x 18.4cm (1½" x 7¼")

Bottom chord: 3.8cm x 18.4cm (1½" x 7¼")

Web members: 3.8cm x 8.9cm (1½" x 3½")

Ridge gussets: Metal press plates 26.6xm x 16.5cm x 0.95cm (6½" x 10½" x 3/8")

Building orientation: East/West

Surrounding terrain: Heifer barn and feed center 22.8m (75') to the east

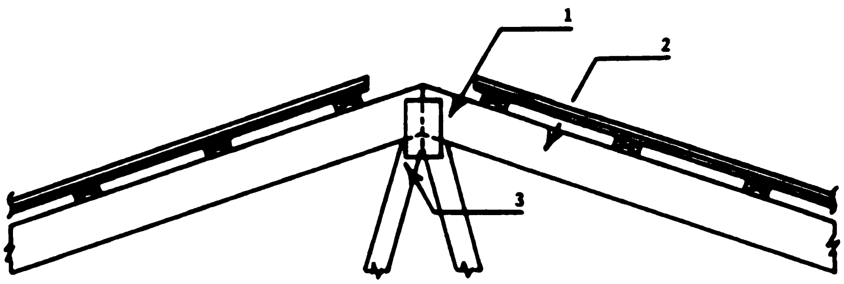

Figure B.11 Location of test sites, Barn C. Truss No. 1, 15.4m (50'8") from east end. West elevation. Raised ridge cap not shown

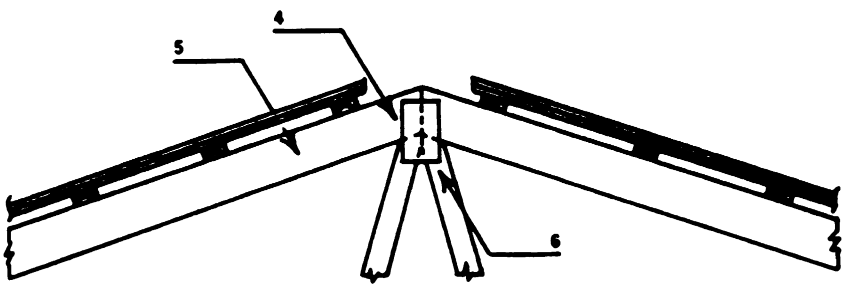

Figure B.12 Location of test sites, Barn C. Truss No. 2, 30.8m (101'-4") from East End. West elevation. Raised ridge cap not shown.

Table B.3 Results of pick test and recorded moisture contents, Barn C

Location	Pick Test	Moisture Content % Dry Basis December 14, 1984			Moisture Content % Dry Basis February 28, 1985		
		0.64cm (0.25in)	1.27cm (0.50in)	1.91cm (0.75in)	0.64cm (0.25in)	1.27cm (0.50in)	1.91cm (0.75in)
1	Clean	18.50	19.75	21.25	20.50	19.25	17.50
2	Clean	17.25	15.0	14.0	20.75	18.75	15.25
3	Clean	18.50	17.25	17.0	21.50	20.50	19.75
4	Clean	15.0	14.5	14.25	16.25	15.25	15.50
5	Clean	13.25	13.25	13.25	14.0	14.50	14.50
6 Truss Tail	Clean	19.25	19.0	18.75	25.50	25.50	25.0

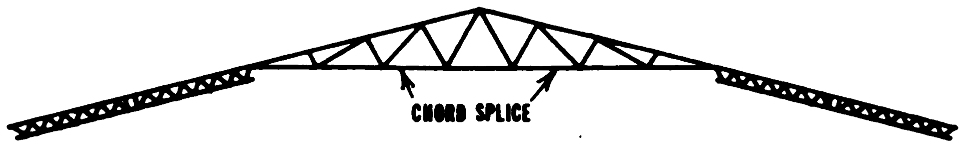

Figure B.13. Truss schematic, Barn C.

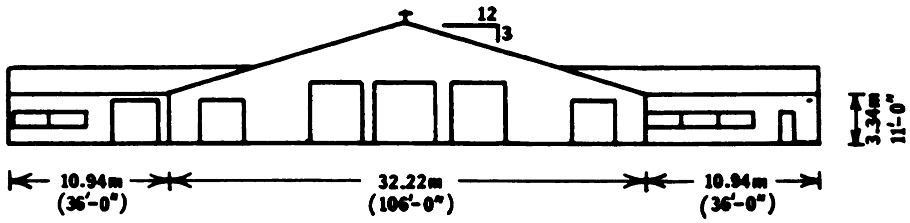

Figure B.14. East elevation, Barn C.

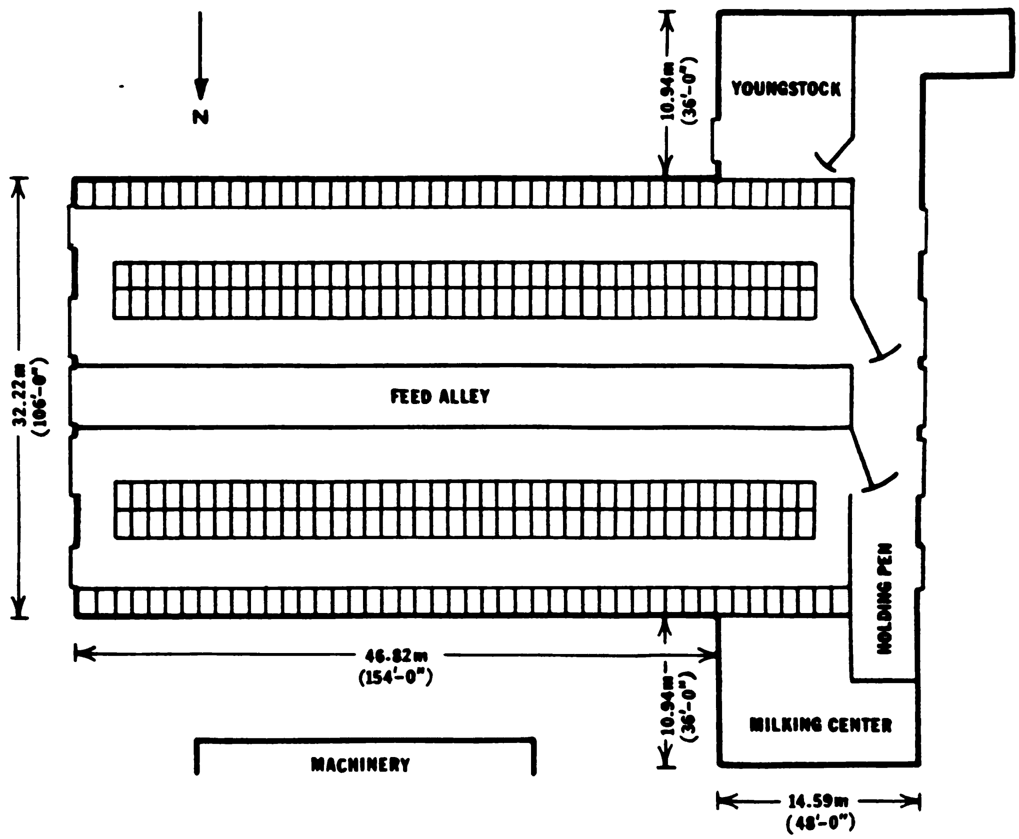

Figure B.15. Plan view, Barn C.

APPENDIX B.5: Barn D

Location: Port Austin, MI
County: Huron
Year built: 1978
Dimensions: 68.1m x 27.36m (224' x 90")

Building design: 6-row drivethrough

Design capacity: 153 free stalls

Building material/color: red sheet metal sidewalls
white sheet metal roof

Sidewall height: 2.74m (9'-0")

Sidewall openings: Summer air inlets--tilt up panels in each bay, each panel 2.28m x .76m (7'6" x 2'6"), 1.22m (4'-0") above stall floor. Winter air inlets--openings between inside planking and outside girts located 0.46m (1'-6") above grade on the outside, 1.06m (3'-6") above stall floor on the inside. Openings are continuous, 0.14m x 2.23m (5½" x 7'6") between columns spaced 2.43m (8'-0") o.c.

Endwall openings: 2--3.04m x 3.04m (10'-0" x 10'-0") doors on rollers at each end. 1--3.65m x 3.65m (12'-0" x 12'-0") roll up door at each and of feed alley

Eave openings: None

Manure handling: Liquid storage, daily tractor scraping to injection pump in center cross alley.

Roof slope: 4:12

Insulation: None

Ridge opening: 30.4cm (12")

Truss ridge weather protection: Molded sheet metal truss caps

Wood species: Not available

Truss spacing: 1.22m (4'-0") o.c.

Purlin spacing: 0.61m (1'-0:) o.c.

Truss design: Modified queen post

Top chord: 3.8cm x 18.4cm (1½" x 7¼")

Bottom chord: 3.8cm x 14.0cm (1½" x 5½")

Web members: 3.8cm x 8.9cm (1½" x 3½")

Gusset plates: Metal press plates 18.4cm x 22.8cm x 0.95cm (7¼" x 9" x 3/8")

Building orientation: East/West

Surrounding terrain: Air movement is obstructed by an old heifer barn 30m (100') to the northwest, large trees to the west.

NOTES: Barn is generally well ventilated throughout the winter, winter air inlets are not closed and large summer air inlets are opened a few inches, except during severe weather.

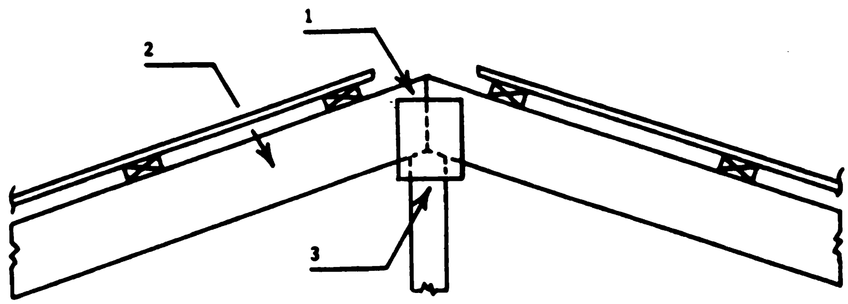

Figure B.16 Location of test sites, Barn D. Truss No. 1, 7.3m (24') from west end. East elevation. Molded flashing not shown

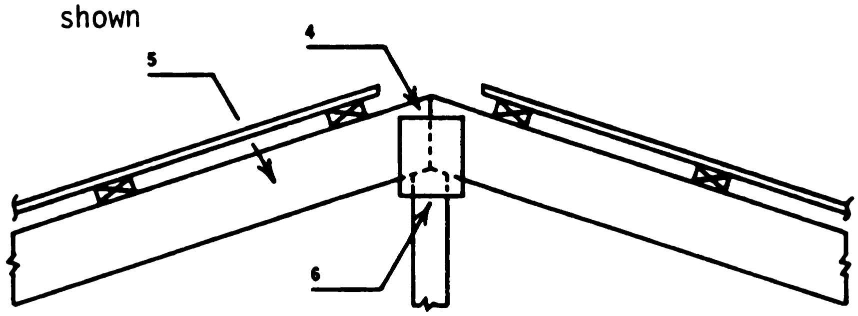

Figure B.17 Location of test sites, Barn D. Truss No. 2, 31.6m (104') from west end. East elevation. Molded flashing not shown

Table B.4 Results of pick test and recorded moisture contents, Barn D

Location	Pick Test	Moisture Content % Dry Basis December 11, 1984			Moisture Content % Dry Basis February 28, 1985		
		0.64cm (0.25in)	1.27cm (0.50in)	1.91cm (0.75in)	0.64in (0.25in)	1.27cm (0.50in)	1.91cm (0.75in)
1	Brash	21.0	19.75	16.0	25.50	20.75	18.0
2	Brash	22.50	20.25	17.25	27.0	23.50	18.25
3	Brash	22.0	20.50	17.0	35.0	25.0	18.50
4	Clean	19.75	18.25	16.25	20.50	20.0	17.75
5	Clean	21.0	19.0	17.0	26.50	23.0	21.0
6	Brash	21.0	18.50	18.50	24.50	23.50	23.0
Truss Tail	Clean	18.25	16.50	15.75	19.75	18.25	18.0

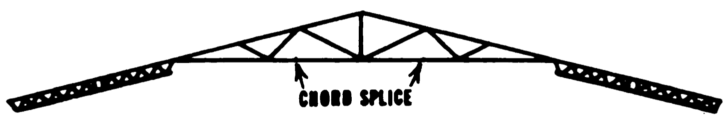

Figure B.18. Truss schematic, Barn D.

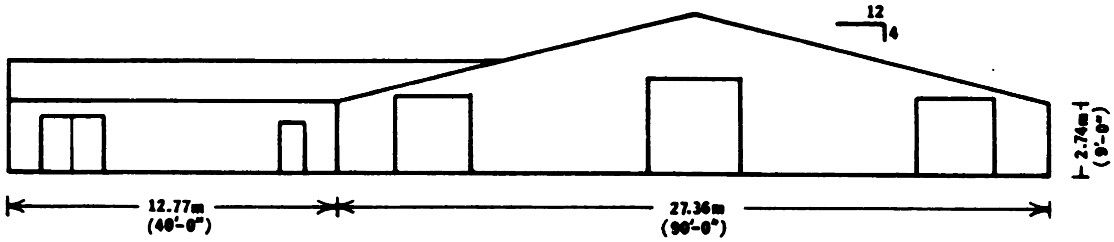

Figure B.19. East elevation, Barn D.

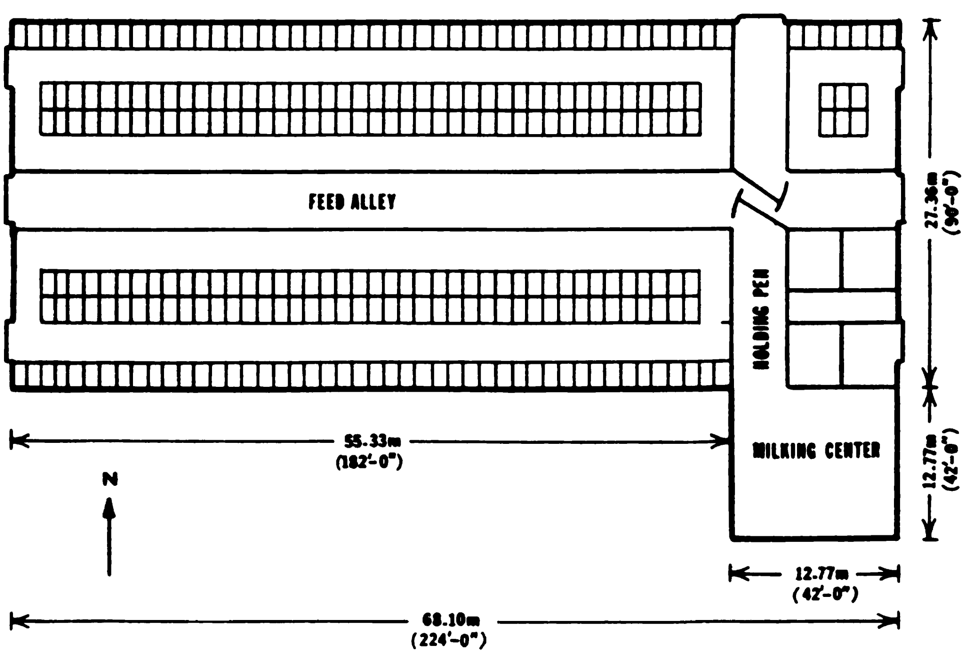

Figure B.20. Plan view, Barn D.

APPENDIX B.6: Barn E

Location: Port Hope, MI
County: Huron
Year built: 1977
Dimensions: 58.37m x 30.4m (192' x 100')

Building design: 6-row drivethrough

Design capacity: 200 free stalls with 200 cows

Building material/color: blue sheet metal sidewalls
white sheet metal roof

Sidewall height: 3.04m (10'-0")

Sidewall openings: None

Endwall openings: 4-3.04m x 3.65m (10'-0" x 12'-0") doors on rollers at the north end. 1-3.65m x 3.65m (12'-0" x 12'-0") roll up door at the north end of the feed alley.

Eave openings: continuous 30.4cm (12") opening

Manure handling: daily tractor scraping

Roof slope: 3:12

Insulation: 2.54cm (1") rigid plastic foam

Ridge opening: 45.6cm (1'-6")

Truss ridge weather protection: 20.4cm (8") sheet metal strip

Wood species: S. Pine No. 1

Truss spacing: 1.22m (4'-0") o.c.

Purlin spacing: 0.61m (2'-0") o.c.

Truss design: Pratt truss

Top chord: 3.8cm x 18.4cm (1½" x 7¼")

Bottom chord: 3.8cm x 14.0cm (1½" x 5½")

Web members: 3.8cm x 8.9cm (1½" x 3½")

Ridge gussets: Metal press plates 26.6cm x 16.5cm x 0.95cm (10½" x 6½" x 3/8")

Building orientation: North/South

Surrounding terrain: open to the west, 200 free stall barn 9.12m (30') to the east

NOTES: Bird netting covering the open ridge.

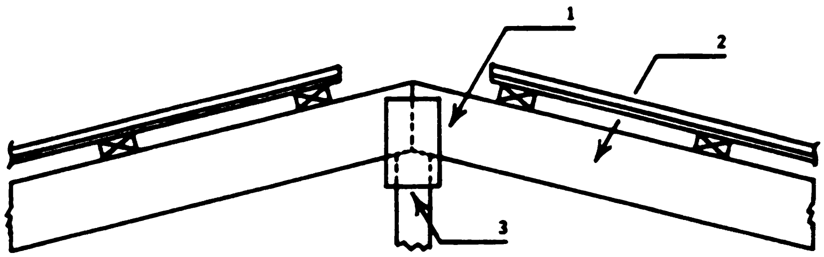

Figure B.21. Location of test sites, Barn E. Truss No. 1, 8.5m (28') from north end. North elevation. Flashing, bird netting not shown.

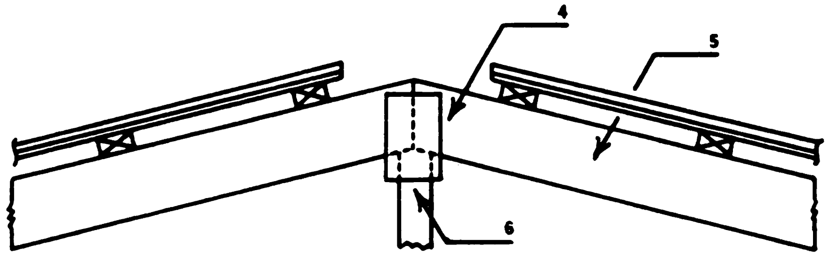

Figure B.22. Location of test sites, Barn E. Truss No. 2, 29.2m (104') from north end. North elevation. Flashing, bird netting not shown.

Table B.5 Results of pick test and recorded moisture contents, Barn E.

Location	Pick Test	Moisture Content % Dry Basis December 12, 1984			Moisture Content % Dry Basis February 28, 1985		
		0.64cm (0.25in)	1.27cm (0.50in)	1.91cm (0.75in)	0.64cm (0.25in)	1.27cm (0.50in)	1.91cm (0.75in)
1	Brash	22.25	21.0	20.0	25.75	22.0	21.0
2	Clean	20.0	16.75	14.0	18.75	16.0	15.25
3	Brash	19.25	17.25	16.75	20.25	19.75	18.75
4	Brash	19.0	16.0	14.75	15.0	14.0	14.0
5	Clean	16.0	12.75	12.75	13.75	14.0	14.0
6	Brash	22.0	22.0	21.75	27.0	25.0	27.0
Truss Tail	Clean	18.25	15.75	14.0	18.5	18.0	16.75

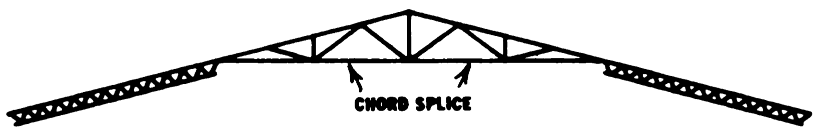

Figure B.23. Truss schematic, Barn E.

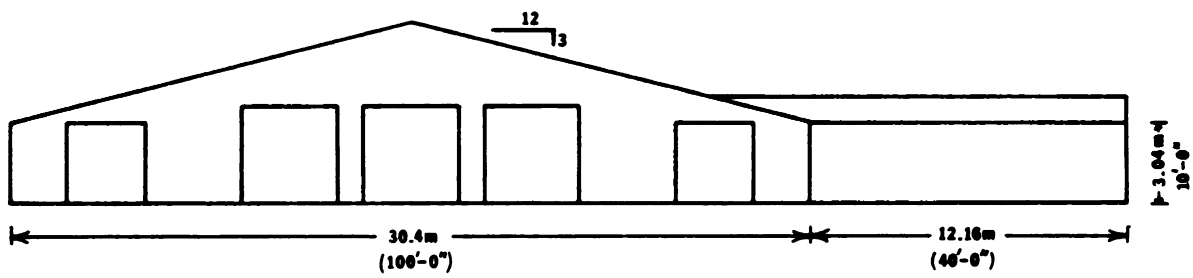

Figure B.24. North elevation, Barn E.

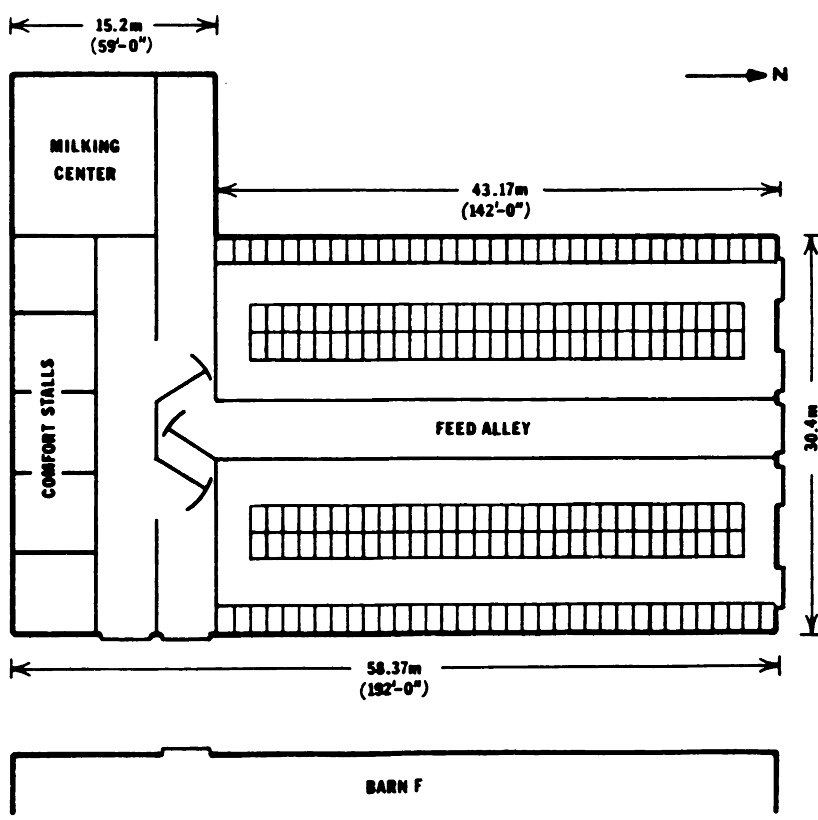

Figure B.25. Plan view, Barn E.

APPENDIX B.7: Barn F

Location: Port Hope, MI
County: Huron
Year built: 1977
Dimensions: 58.37m x 30.4m (192' x 100')
Building design: 6-row drivethrough

Design capacity: 200 free stalls with 140 cows plus calf housing

Building material/color: blue sheet metal sidewalls
white sheet metal roof

Sidewall height: 3.04m (10'-0")

Sidewall openings: None

Endwall openings: 4-3.04m x 3.65m (10'-0" x 12'-0") doors on rollers at each end. 1--3.65m x 3.65m (12'-0" x 12'-0") roll up door at each end of the feed alley

Eave openings: continuous 30.4 cm (12") opening

Manure handling: daily tractor scraping

Roof slope: 3:12

Insulation: None

Ridge opening: 45.6cm (1'-6") continuous

Truss ridge weather protection: Molded sheet metal ridge cap

Wood species: S. Pine No. 1

Truss spacing: 1.22m (4'-0") o.c.

Purlin spacing: 0.61m (2'-0") o.c.

Truss design: Modified queen post

Top chord: 3.8cm x 18.4cm (1'" x 7¼")

Bottom chord: 3.8cm x 10.0cm (1½" x 5½")

Web members: 3.8cm x 8.9cm (1½" x 3½")

Ridge gussets: metal press plates 22.8cm x 25.3cm x 0.95cm (9" x 10" x 3/8")

Building orientation: North/South

Surrounding terrain: 200 free stall barn 9.12m (30') to the west

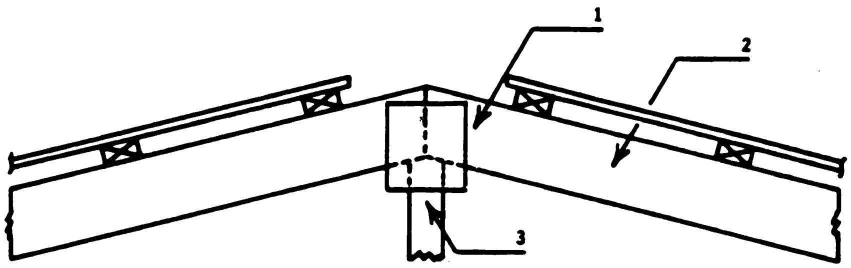

Figure B.26. Location of test sites, Barn F. Truss No. 1, 7.3m (24') from north end. North elevation. Molded flashing not shown.

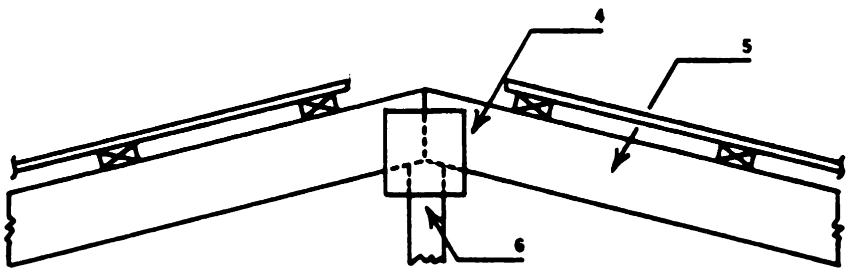

Figure B.27. Location of test sites, Barn F. Truss No. 2, 29.2m (104') from north end. North elevation. Molded flashing not shown.

Table B.6. Results of pick test and recorded moisture contents, Barn F

Location	Pick Test	Moisture Content % Dry Basis December 12, 1984			Moisture Content % Dry Basis February 28, 1985		
		0.64cm (0.25in)	1.27cm (0.50in)	1.91cm (0.75in)	0.64cm (0.25in)	1.27cm (0.50in)	1.91cm (0.75in)
1	Brash	16.0	14.0	13.50	18.25	16.25	16.25
2	Clean	18.0	16.0	14.75	23.50	18.0	17.0
3	Brash	18.5	18.25	17.0	28.0	22.0	17.75
4	Brash	16.0	14.75	14.0	18.0	15.0	14.75
5	Brash	18.5	15.75	14.75	22.25	20.5	17.25
6	Brash	18.5	17.25	15.0	35.5	31.0	21.0
Truss Tail	Clean	15.0	14.25	14.25	17.50	16.50	16.50

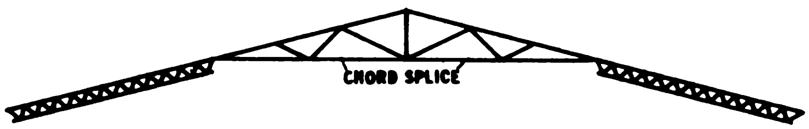

Figure B.28. Truss schematic, Barn F.

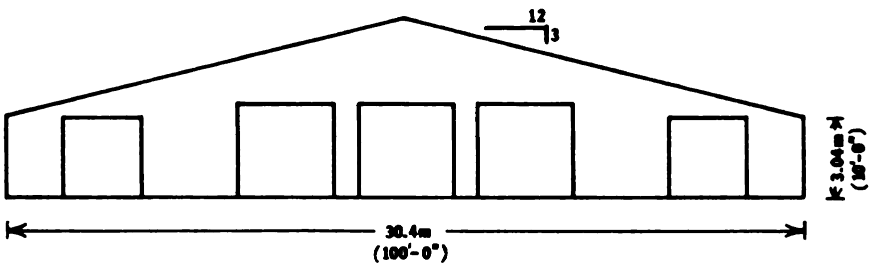

Figure 29. North elevation, Barn F.

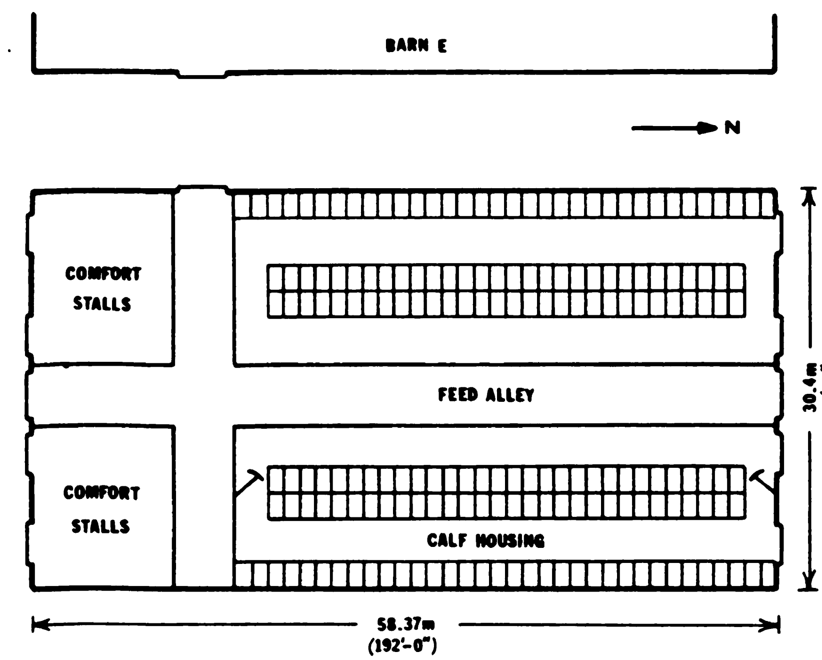

Figure B.30. Plan view, Barn F.

APPENDIX B.7: Barn G

Location: Bad Axe, MI
County: Huron
Year built: 1977
Dimensions: 31m x 45.6m (102' x 150')
Building design: 6-row drivethrough

Design capacity: 154 free stalls with 160 cows

Building material/color: Brown sheet metal siding, white sheet metal roof.

Sidewall height: 2.74m (9' - 0")

Sidewall openings: Summer air inlets--not provided. Winter air inlets --openings between inside planking and outside girts located 0.46m (1'-6") above grade on the outside, 1.06m (3'-6') above the stall floor on the inside. Openings are continuous 13.9cm x 2.28m (5½" x 7'6") between columns spaced 2.43m (8' - 0") O.C.

Endwall openings: 4 - 3.04m x 3.04m (10'.0" x 10'.0") doors on rollers at each end. 1 -- 3.65m x 3.65m (12'.0" x 12'.0") roll up door at each end of feed alley.

Eave openings: None

Manure handling: liquid storage, daily tractor scraping to injection pump at center cross alley

Roof slope: 3:12

Insulation: 2.54cm (1") rigid plastic foam

Ridge opening: 45.6cm (1'-6") continuous

Truss ridge weather protection: 20.3cm (8") sheet metal strips

Wood species: Not available

Truss spacing: 1.22m (4'-0") o.c.

Purlin spacing: 0.61m (2'-0") o.c.

Truss design: Double W

Top chord: 3.8cm x 18.4 cm (1½" x 7¼")

Bottom chord: 3.8 cm x 18.4 cm (1½" x 7¼")

Web members: 3.8 cm x 8.9 cm (1½" x 3½")

Ridge gussets: Metal press plates 19 cm x 14.6 cm x 1.58 cm (7½" x 5 3/4 " x 5/8")

Building orientation: East/West

Surrounding terrain: Feed center 22.8 m (75') to the west, calf barn and milking center 4.56m (15') to the south.

NOTES: Metal ridge gusset plates and flashing at the ridge indicate extensive corrosion. Four 0.91m (36") intake, fans have been installed to improve summer ventilation, two fans in each endwall.

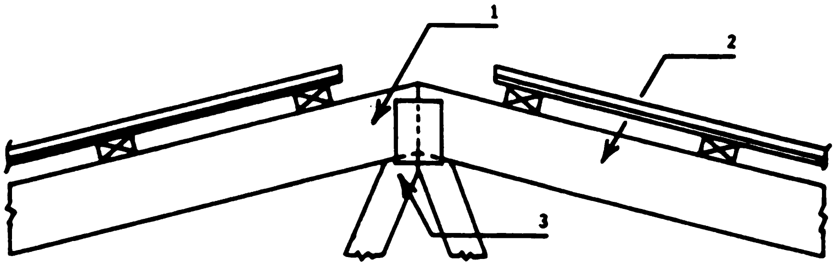

Figure B.31. Location of test sites, Barn G. Truss No. 1, 13.4m (44') from east end. East elevation. Flashing not shown.

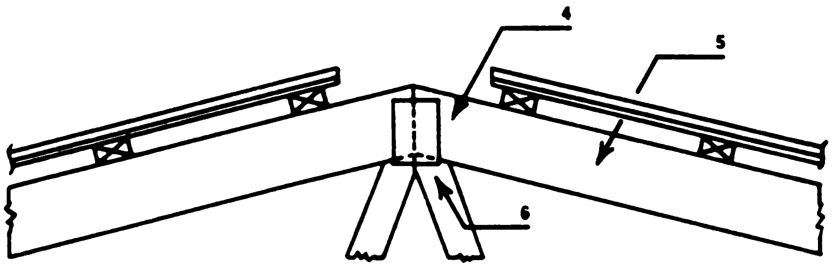

Figure B.32. Location of test sites, Barn G. Truss No. 2, 29.2m (104') from east end. East elevation. Flashing not shown.

Table B.7. Results of pick test and recorded moisture contents, Barn G.

Location	Pick Test	Moisture Content % Dry Basis December 13, 1984			Moisture Content % Dry Basis February 28, 1985		
		0.64cm (0.25in)	1.27cm (0.50in)	1.91cm (0.75in)	0.64cm (0.25in)	1.27cm (0.50in)	1.91cm (0.75in)
1	Clean	19.0	18.75	18.75	54.0	55.0	50.0
2	Brash	18.5	17.25	17.0	24.0	23.50	23.0
3	Brash	19.0	17.0	18.25	35.0	56.0	62.0
4	Clean	18.5	17.75	17.25	21.75	22.25	22.75
5	Clean	16.25	15.0	14.75	17.25	16.75	14.25
6	Brash	19.0	18.0	18.75	24.25	27.50	27.0
Truss Tail	Clean	16.75	16.25	16.25	18.5	18.25	17.75

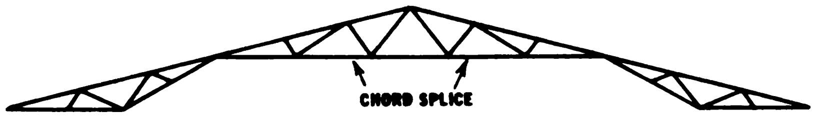

Figure B.33. Truss schematic, Barn G.

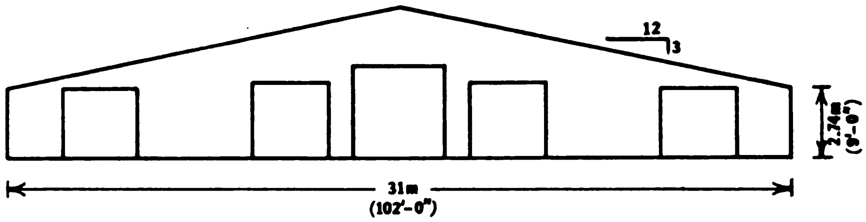

Figure B.34. West elevation, Barn G.

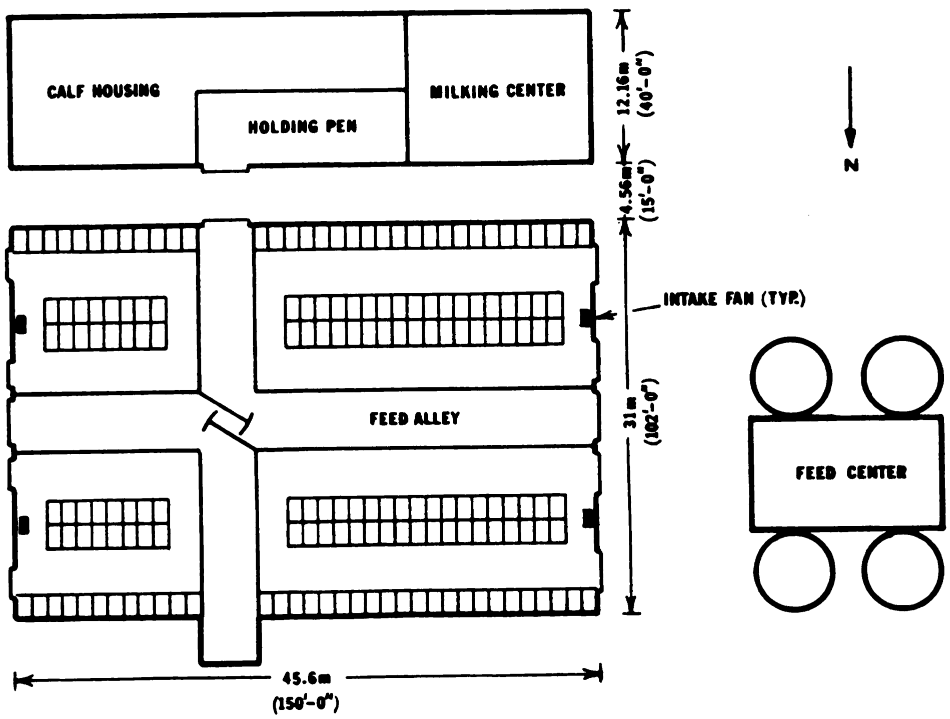

Figure B.35. Plan view, Barn G.

APPENDIX B.8: Barn H

Location: Elkton, MI
County: Huron
Year Built: 1976

Dimensions: 41.34m x 25.54m (136' x 84')

Building design: Free stalls with mechanical feeding and mechanical alley scrapers.

Design capacity: 122 free stalls with 135 cows

Building material/color: Red sheet metal sidewalls, white sheet metal roof

Sidewall height: 3.65m(12' - 0")

Sidewall openings: Summer air inlets--tilt up panels in every other bay, each panel 0.61m x 2.28m (7'-6" x 2'-0"), 1.06m (3'-6") above stall floor. Winter air inlets--openings between inside planking and outside girts located 46cm (1'-6") above grade on the outside, 1.06m (3'-9") above stall floor on the inside. Openings are continuous, 14cm x 2.2cm (5'½" x 7'-6") between columns spaced 2.43m (8'-0") o.c.

Endwall openings: 4-3.65m x 3.65m (12'-0" x 12'-0") doors on rollers at each end.

Eave openings: None

Manure handling: Mechanical alley scrapers

Roof slope: 3:12

Insulation: 2.54cm (1") rigid plastic foam

Ridge opening: 30.4cm (12")

Truss ridge weather protection: raised ridge cap

Wood species: Top-bottom chords--not available. Webs--S. Pine No. 3

Truss spacing: 1.22m (4'-0") o.c.

Purlin spacing: 0.61m (2'-0") o.c.

Truss design: Double W

Top chord: 3.8cm x 14.0cm (1½" x 5½")

Bottom chord: 3.8cm x 14.0cm (1½" x 5½")

Web members: 3.8cm x 8.9cm (1½" x 3½")

Ridge gussets: Metal press plates 15.2cm x 15.2cm x 0.95cm (6" x 6" x 3/8")

Building orientation: North/South

Surrounding terrain: All sides are clear except the west side. Silos and milking center obstruct air movement from the west.

NOTES: Ventilation is generally inadequate. Note six .91m (36") intake fans retrofit to improve summer ventilation. Bird netting over the open ridge.

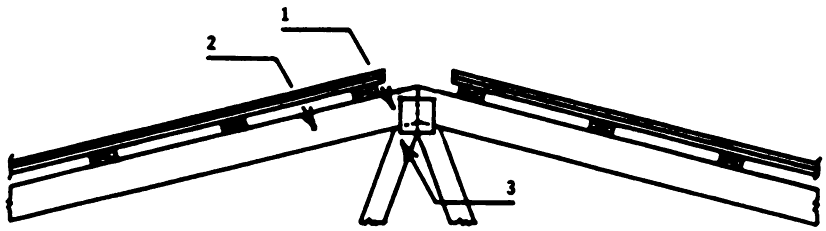

Figure B.36. Location of test sites, Barn H. Truss No. 1, 4.9m (16') from north end. South elevation. Raised ridge cap, bird netting not shown.

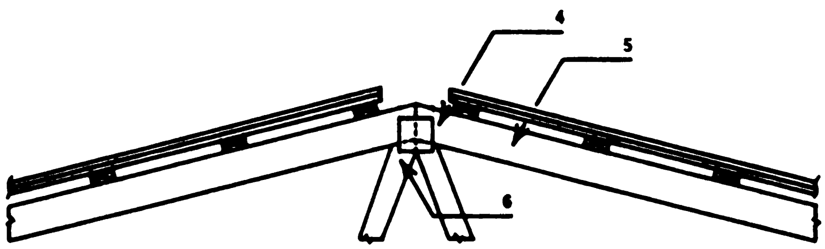

Figure B.37. Location of test sites, Barn H. Truss No. 2, 18.2m (60') from north end. South elevation. Raised ridge cap, bird netting not shown.

Table B.8. Results of pick test and recorded moisture contents, Barn H.

Location	Pick Test	Moisture Content % Dry Basis December 11, 1984			Moisture Content % Dry Basis March 13, 1985		
		0.64cm (0.25in)	1.27cm (0.50in)	1.91cm (0.75in)	0.64cm (0.25in)	1.27cm (0.50in)	1.91cm (0.75in)
1	Brash	22.75	20.25	20.25	25.50	26.50	27.50
2	Brash	19.25	18.50	16.25	22.25	19.0	19.0
3	Brash	20.75	20.25	20.50	46.0	51.0	54.0
4	Brash	21.0	18.25	19.0	33.0	32.0	31.5
5	Brash	17.0	15.25	13.75	16.50	16.0	14.25
6	Brash	21.50	21.50	20.75	44.0	43.0	43.0
Truss Tail	Clean	18.75	18.25	17.0	16.75	16.25	16.25

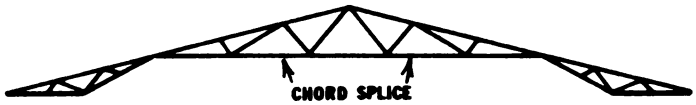

Figure B.38. Truss schematic, Barn H.

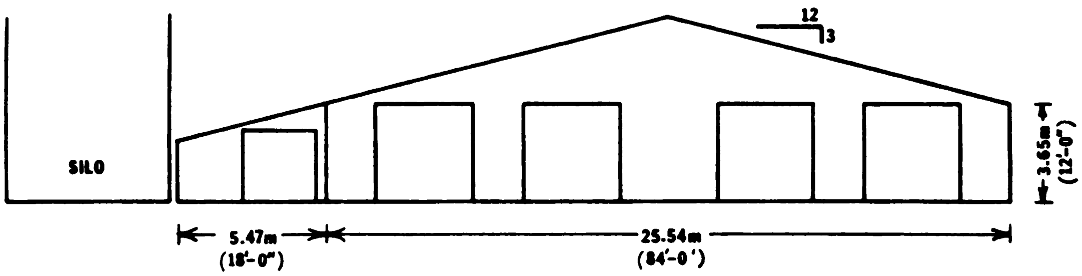

Figure B.39. South elevation, Barn H.

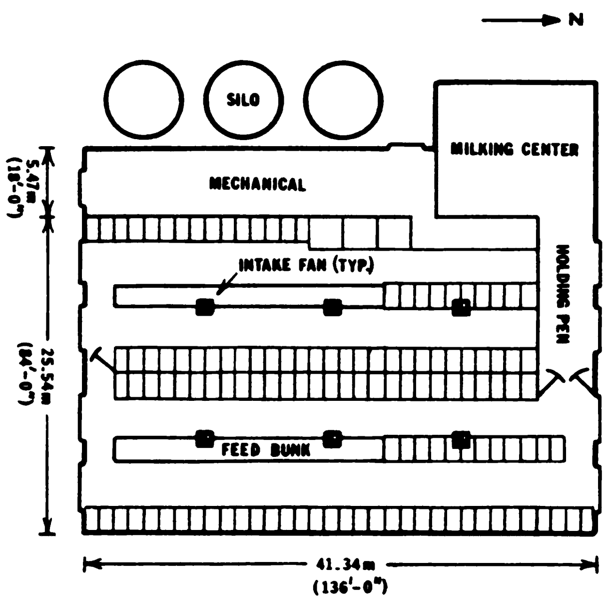

Figure B.40. Plan view, Barn H.

APPENDIX B.9: Barn I

Location: Scottville, MI
County: Mason
Year built: 1976

Dimensions: 31m x 59.58m (102' x 196')

Building design: 6-row drivethrough

Design capacity: 184 free stalls

Building material/color: Yellow sheet metal sidewalls
White sheet metal roof

Sidewall height: 3.04m (10'-0")

Sidewall openings: Summer air inlets--rolling panel doors 0.46m x 4.66m (1.6" x 15'-4"), 1.22m (4'-0") above stall floor. Winter air inlets--openings between inside planking and outside girts located 0.46m (1'-6") above grade on the outside, 1.22m (4'-0") above stall floor on the inside. Openings are continuous 0.14m x 2.28m (5½" x 7'-6") between columns spaced 2.43m (8'-0") o.c.

Endwall openings: 4-3.04m x 3.04m (10'-0" x 10'-0") doors on rollers at each end. 1-3.65m x 3.65m (12'-0" x 12'-0") roll up door at each end of feed alley.

Eave openings: None

Manure handling: liquid storage, daily tractor scraping to injection pump at center feed alley

Roof slope: 3:12

Insulation: 2.54cm (1") rigid plastic foam

Ridge opening: 48cm (1'-7") continuous

Truss ridge weather protection: 25.4cm (10") sheet metal strip above each truss

Wood species: Top-bottom chord--S. Pine No. 1 dense

Truss spacing: 1.22m (4'-0") o.c.

Purlin spacing: 0.61m (2'-0") o.c.

Truss design: Modified queen post

Top chord: 3.8cm x 18.4cm (1½" x 7¼")

Bottom chord: 3.8cm x 18.37cm (1½" x 7¼")

Web members: 3.8cm x 8.9cm (1½" x 3½")

Ridge gussets: Originally metal press plates throughout. Ridge gussets and gussets at the base of all kingposts were replaced with 1.26cm (½") preservative treated plywood, glued, and nailed in 1984.

Building orientation: North/South

Surrounding terrain: Level building site; Obstructions with 30.4m (100') include to the west, two upright silos, bunker silo, milking center, calf barn, machine shed.

NOTES: Extensive truss repair in 1984. Bird netting that previously covered the open ridge was removed. Molded sheet metal ridge caps were replaced with 25.4cm (10") sheet metal strips. All sidewall openings are closed from December through March.

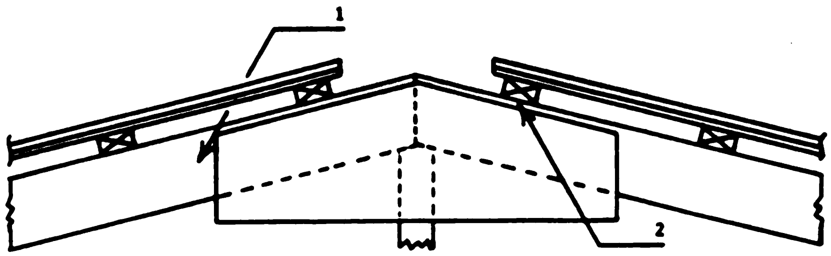

Figure B.41 Location of test sites, Barn I. Truss No. 1, 9.7m (32') from north end. South elevation. Flashing not shown

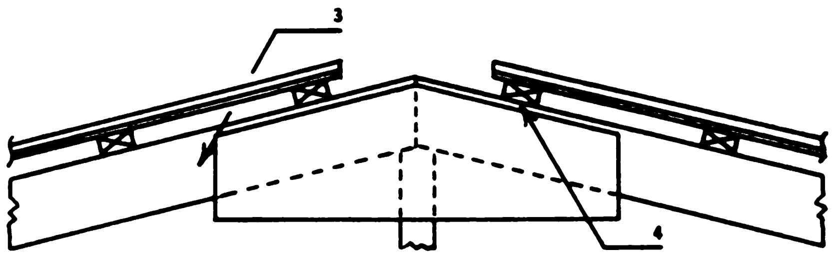

Figure B.42 Location of test sites, Barn I. Truss No. 2, 31.6m (104') from north end. South elevation. Flashing not shown

Table B.9 Results of pick test and recorded moisture contents, Barn I

Location	Pick Test	Moisture Content % Dry Basis November 29, 1984			Moisture Content % Dry Basis February 26, 1985		
		0.64cm (0.25in)	1.27cm (0.50in)	1.91cm (0.75in)	0.64cm (0.25in)	1.27cm (0.50in)	1.91cm (0.75in)
1	Brash	14.5	12.75	12.75	17.75	15.0	13.25
2	Brash	17.0	14.75	13.8	20.0	17.25	15.25
3	Brash	18.0	17.5	15.8	22.25	21.0	19.50
4	Clean	11.75	10.75	10.75	14.50	12.75	13.25
Truss Tail	Clean	16.75	16.25	16.25	19.75	17.75	17.75

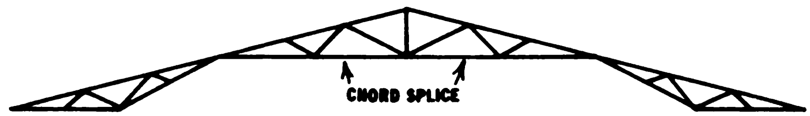

Figure B.43. Truss schematic, Barn I.

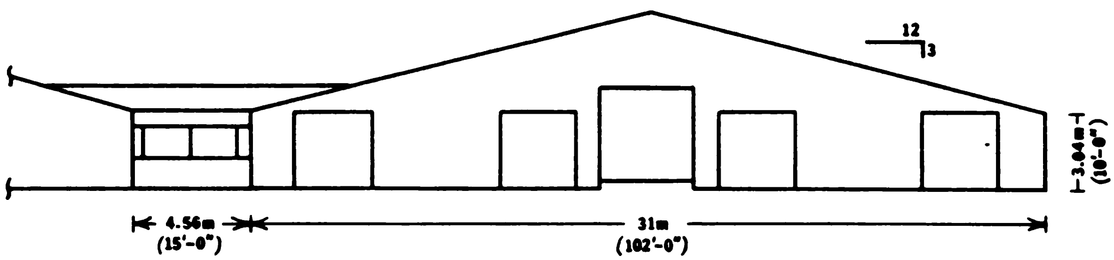

Figure B.44. South elevation, Barn I.

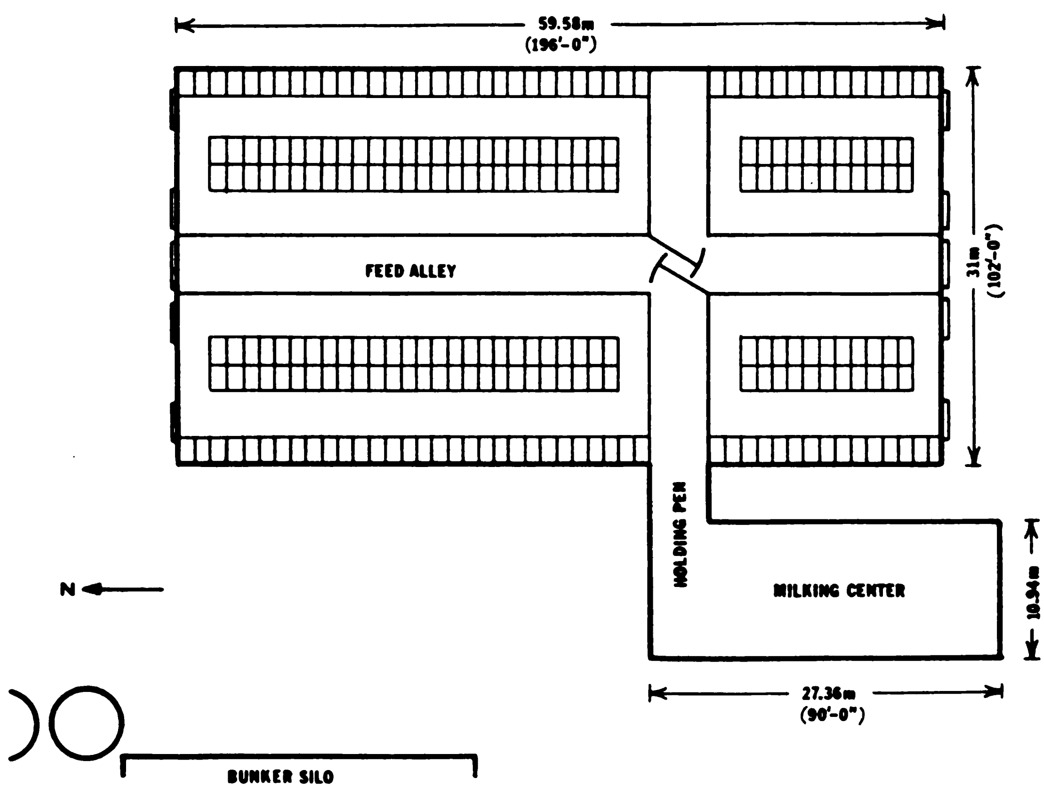

Figure B.45. Plan view, Barn I.

APPENDIX B.10: Barn J

Location: Custer, MI
County: Mason
Year built: 1976

Dimensions: 31m x 59.58m (102' x 196')

Building design: 6-row drivethrough

Design capacity: 184 free stalls

Building material/color: Yellow sheet metal sidewalls
White sheet metal roof

Sidewall height: 3.04m (10'-0")

Sidewall openings: Summer air inlets--rolling panel doors 0.46m x 4.66cm (1'6" x 15'4"). 1.22m (4'-0") above stall floor every other bay. Winter air inlets--openings between inside planking and outside girts, located 0.46m (1'-6") above grade on the outside, 1.22m (4'-0") above stall floor on the inside. Openings are continuous 0.14m x 2.28m (5½" x 7'6") between columns spaced 2.43m (8'-0") on center.

Eave openings: None

Manure handling: Daily tractor scraping

Roof slope: 3:12

Insulation: 2.54cm (1") ridge plastic foam

Ridge opening: 48cm (1'-7") continuous

Truss ridge weather protection: 25.4cm (10") sheet metal strip above each truss

Wood species: Top-Bottom chord--S. Pine No. 1 Dense

Truss spacing: 1.22m (4'-0") o.c.

Purlin spacing: 0.61m (2'-0") o.c.

Truss design: Double Howe

Top chord: 3.8cm x 18.4cm (1'½" x 7¼")

Bottom chord: 3.8cm x 18.4cm (1½" x 7¼")

Web members: 3.8cm x 8.9cm (1½" x 3½")

Ridge gussets: Metal press plates 30.4cm x 20.3cm x 0.95 cm (12" x 8" x 3/8")

Building orientation: East/West

Surrounding terrain: Open to the north and west, bunker silo within 15.2m (50') of the barn on the east end.

NOTES: All sidewall openings are generally closed from December through March.

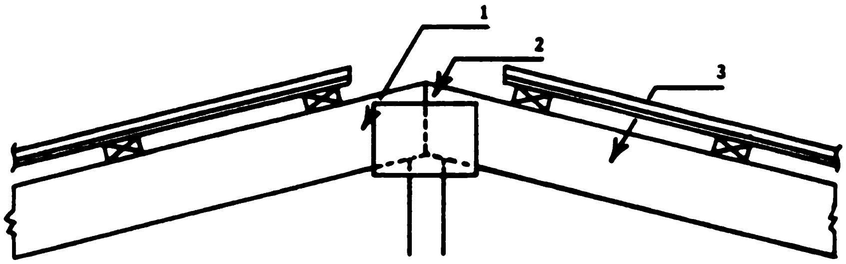

Figure B.46 Location of test sites, Barn J. Truss No. 1. 6.1m (20') from east end. West elevation. Flashing not shown

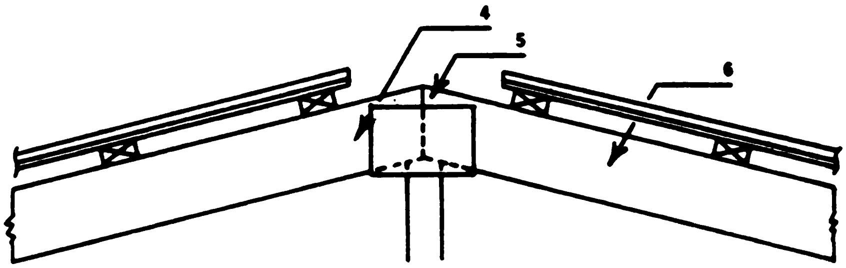

Figure B.47 Location of test sites, Barn J. Truss No. 2, 31.6m (104') from east end. West elevation. Flashing not shown

Table B.10 Results of pick test and recorded moisture contents, Barn J

Location	Pick Test	Moisture Content % Dry Basis November 29, 1964			Moisture Content % Dry Basis February 26, 1985		
		0.64cm (0.25in)	1.27cm (0.80in)	1.91cm (0.75in)	0.64cm (0.25in)	1.27cm (0.50in)	1.91cm (0.75in)
1	Brash	24.0	18.75	17.25	24.0	22.0	19.0
2	Brash	21.50	21.50	20.75	24.25	24.25	23.50
3	Clean	17.25	16.0	14.0	18.50	16.25	14.0
4	Brash	19.75	18.25	16.50	22.0	23.50	24.0
5	Brash	22.75	20.75	20.75	23.50	24.50	24.0
6	Clean	24.0	22.0	17.50	19.0	17.25	16.25
Truss Tail	Clean	16.0	14.0	12.75	16.25	15.75	15.50

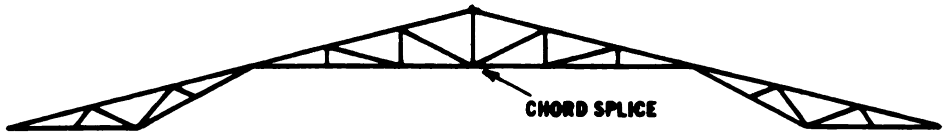

Figure B.48. Truss schematic, Barn J.

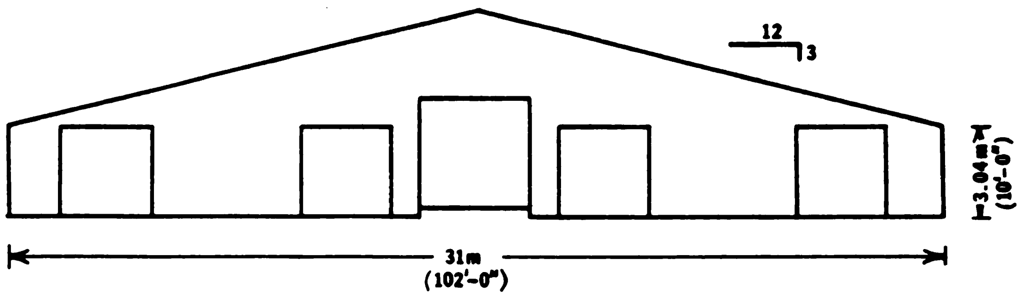

Figure B.49. East elevation, Barn J.

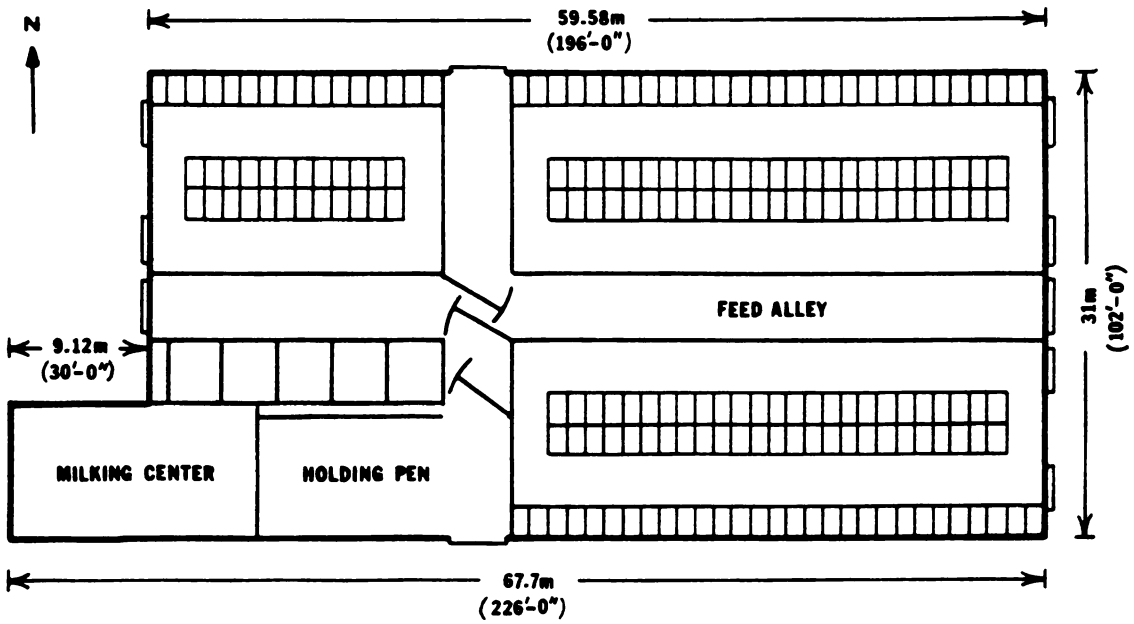

Figure B.50. Plan view, Barn J.

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