A Solar Wall and Roof Air Preheater for In situ Hay-Drying for the Province of Quebec

by

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Barn Solar Hay Dryer for Quebec

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ABSTRACT

A solar air preheating system was designed, built and tested for drying forage in a hay storage barn and two main research activities were defined.

In the first Phase, controlled experiments were undertaken to try and assess the advantages of using solar heat combined with forced convection drying. Three methods of forage drying were compared: field curing; forced convection with ambient air; and forced convection with solar heated air. The advantages of using solar heated forced air were better quality hay than field curing and less electrical energy used than forced convection with ambient air.

The second Phase was the evaluation of a full scale prototype dryer comprised of a bare plate roof collector and solar wall air preheater integrated into a conventional hay dryer. The average seasonal air temperature increase in the system was 2.4°C for airflow rates of 650 m^3/min. The average system solar efficiency was evaluated at 25.9% for the summer test period.

RESUMÉ

Un système solaire a été conçu et évalué pour préchauffer l'air de ventilation des séchoirs a foin. Deux principales phases ont été étudiées.

Au cours de la première phase, des experiences controllées ont permis d'évaluer les avantages d'utilisation de la chaleur provenant de l'énergie solaire avec un système de séchage a convection forcée. Trois types de séchage a fourrages ont été comparés: le séchage au champs; la ventilation sous l'air ambient et la ventilation avec de l'air préchauffé par l'énergie solaire. Les avantages de ce dernier était une meilleure qualité du foin comparé au séchage au champs et une diminution de la consommation d'éléctricité qu'avec la ventilation sous l'air ambient.

La deuxième phase du projet était l'évaluation d'un prototype de grandeur réel comprenant un capteur plan monté sur un toît avec un mûr solaire préchauffeur d'air integré a un séchoir a foin conventionnel. La moyenne saisonnière de l'augmentation de la temperature dans le système était de 2.4°C pour un débit d'air de 650 m^3/min. L'éfficacite moyenne du système était de 25.9% pendant la periode d'évaluation.

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a = constant

A = area (m^2)

b = constant

B = dry matter density (kg/m^3)

C = drying capacity (kg/m^3)

cp = specific heat (kJ/kg °C)

d.b. = dry basis

dm = mass dry matter (kg)

exp = Naperian exponent

E = east

EFF = efficiency (%)

f = mass transfer coefficient (kg/s m^2)

G = mass rate of airflow (kg dry air/m^2 s)

G_2 = mass velocity of air (kg dry air/h/kg dry matter

h = heat transfer coefficient (W/m^2 °C)

H = relative humidity (kg water/kg dry air)

H_θ = proportion of time required for exposed hay to reach half of its equilibrium moisture content (%)

I = solar radiation intensity (W/m^2)

k = constant

K = constant

l = length (m)

m = constant

$\dot{m}$ = mass flow rate (kg/s)

M = moisture content (kg water/kg matter)

M_c = critical moisture content (kg water/kg matter)

M_e = equilibrium moisture content (kg water/kg matter)

M_o = original moisture content (kg water/kg matter)

N = north

Nu = Nusselt number

$p^{\#}$ = constant

P = vapour pressure (Pa)

Pr = Prandtl number

q = constant

Q_{in} = heat inputs (kWhr)

Q_{out} = heat outputs (kWhr)

r = radius (m)

R = respiration rate (mg CO_2/g dry matter)

Re = Reynolds number

sp = static pressure (cm water)

S = cross sectional area (m^2)

T = temperature (^oC)

T_e = ambient medium temperature (^oC)

T_o = original temperature (^oC)

V = velocity (m/s)

V_o = superficial velocity (m/s)

w.b. = wet basis

W = west

∂ = differential segment

Δ = change or difference in

η = efficiency (%)

θ = time (s)

λ = latent heat of vaporization (kJ/kg)

ρ_b = dry bulk density (kg/m^3)

Φ = angle of incidence (degrees)

ψ = weight (kg)

% = percent

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CHAPTER 1: INTRODUCTION

1.1 Background

The Province of Quebec produced approximately 3.09 million tonnes of milk in 1982. This represents about 41% of Canada's entire dairy produce (Statistics Canada, 1982). One of the main feeds given to dairy cows is forage in the form of silage or dried hay. The primary difference between these two feeds is the moisture content at which they are harvested and later stored. Of the 4.7 million tonnes of forages cultivated in Quebec in 1982, an estimated 13% or 625,000 tonnes of forage was artificially dried (M.A.P.A.Q, 1983). As dairy cattle in Quebec are kept indoors for more than six months per year, the quality and quantity of the hay produced is of fundamental importance in the Province (Bouvry, 1983).

Forages are the most popular winter feed given to dairy cows in Quebec as they add both fiber and protein to the diet. Legumes such as alfalfa are often preferred forage crops as they are high in carotene and protein and capable of fixing nitrogen in the soil, which reduces the need for soil fertilizer application. Generally hay is considered to be an economical feed that can be easily stored over the winter months once it has been properly dried.

Up until the 1940's, the majority of all forage crops were field dried. The crop was cut and allowed to dry in the sun either stacked in bundles or in windrows. When the hay had reached a stabilized moisture content that would permit adequate safe storage, it was brought into the barn. Forages that are stored too wet may get moldy or may ferment and the gases produced may spontaneously combust which constitutes a real fire hazard on the farm.

There are several reasons why a farmer would want to dry his hay using forced ventilation. Field drying of hay usually involves much higher dry matter losses than artificially dried forage. Up to one quarter of the leaves can be lost when field cured hay is baled at 20% moisture content (dry basis) as the dried leaves shatter when mechanically handled. Fan dried hay can be collected at 40% moisture content (dry basis) and leaf losses are generally below 10% (Hall, 1980). The leaves contain most of the protein of the plant and hence leaf content affects milk yield. Farmers must increase the supplement given to the cow's diet with costly concentrates when the feed contains insufficient levels of protein. In addition to this, field curing in direct sunlight reduces carotene (vitamin A) and xanthrophyll (an important pigment) content due to ultra violet radiation deterioration (Hansen and Grenard, 1981).

The probability of rainfall during the haying season is quite high in Quebec. In Lennoxville for example, it has been statistically documented that 1 day out of every 2.3 days from mid-June to mid-July will be rainy (C.P.V.Q., 1980). As conventional haying can be spread over a three day period (cutting in the afternoon of day 1 and baling at noon on day 3), this suggests that there is a high risk that the hay will be rained upon, once it is cut. Cut hay which has been rained on loses much of its value. Another aspect which should be looked at is the optimum time at which hay should be harvested. To obtain the highest dry matter digestibility and protein content, the forage should be collected at the heading stage of the plant's development. This occurs before the blooming of the first flowers (Hanson, 1972). A forced ventilation system permits the farmer to harvest the hay at a higher moisture content, hence in much shorter time (cut and brought into the barn in 24 hours). The farmer can therefore select the optimum harvest timing to maximize the quality of the forage. In addition, the reduced harvesting time will permit the farmer to make better use of his own time or labour when suitable haying weather is forecasted. As a result of these many advantages related to better quality forage and labour management, many farmers have adopted artificial hay drying.

A preliminary study was undertaken in order to assess the importance of artificial forage drying in the Province of Quebec. An enquiry was conducted and members of the Quebec Ministry of Agriculture, agricultural consultants from Hydro-Quebec, hay-drying equipment manufacturers and local Agronomes were asked to estimate the number of dryers sold in Quebec during the past 25 years. The numbers quoted are estimates but they have correlated quite closely from one source to another. Each source contacted had records pertaining to their particular field of action (i.e.subsidies given, consultations offered or fans sold). Although forced ventilation hay drying equipment has been available in the province since the early 1960's, this technology has had relatively little popularity among farmers.

In Quebec, one of the primary advocates of artificial hay drying was the electric utility (Hydro-Quebec), maintaining a consulting service for farmers who installed these systems. A guide was published in 1967, which summarized the basic design elements of in-barn hay drying. By that year there were about 525 units installed in the province. In the six years that followed the number of installations increased significantly averaging approximately 600 units sold per year. This rate slowed down between 1974 and 1977, possibly due to the increase in the number of silage systems being constructed, or the increased cost of electricity. In 1978, the Provincial Government initiated a subsidy programme that contributed up to 75% of the material costs for farmers wanting to buy in-barn hay drying equipment. During the three year programme an estimated 4025 hay drying systems were purchased. The accelerated rate persisted, however when the government stopped offering subsidies and finally slowed down in 1982 when 450 units were sold. The estimated total number of artificial hay drying fans sold in the province to date is over 10,000 units. This figure, however, does not reflect the number of farms using two fans (in large barn applications), the fans that have been replaced on certain farms, or the dryers that are no longer in use. There are five major hay dryer fan suppliers in Quebec, but one company has sold more than 70 percent of all existing fans in the province. The regions which have the highest concentration of hay drying systems are those where inclement weather has hampered conventional field curing. These regions include the Eastern Townships, the Lower St.Lawrence, the Gaspe and the region around Quebec City.

These findings have established that artificial hay drying in Quebec has been increasing steadily in the past two decades. Dried forage generally involves a lower capital investment for the farmer than establishing a silage system. Recently high interest rates have caused a reduction in the number of silos being built each year. This has lead to a steady increase in the number of hay drying systems being installed. Government subsidies for hay dryers have been re-instated until 1985 and this should continue to influence the implantation of this technology in the Province.

A more recent improvement to this method of drying was the introduction of supplemental heat generated from solar energy into the system. Additional heat reduces the drying time even further and can actually improve hay quality over that of forced ventilation drying using ambient air. The main advantage to the farmer of using solar energy is a saving of the amount of conventional energy utilized to dry his hay. Savings of 30% of the electrical energy used by the fans has been noted by several researchers (Morrison and Shove, 1980; Ferguson and Bailey, 1981) working with solar air preheaters integrated to artificial hay drying systems. A simple solar collector which would involve slight modifications to an existing forced ventilation system could save the farmer substantial energy expenditures in the long term. Another advantage is that hay which is dried more rapidly should contain more vitamins and nutrients due to less degradation. Supplemental heating should therefore reduce drying times, improve hay quality and enable the farmer to make better use of his time. If the capital cost of such an alteration is overweighed by the savings incurred when drying, the investment is justified.

For these reasons, research has been undertaken to design, build and test an inexpensive, simple solar collector that could be retro-fitted to existing forced ventilation hay drying systems found in the Province of Quebec.

1.2 Objectives

The following objectives have been defined with regards to this investigation.

1. To document existing research that has been undertaken related to barn solar hay drying systems.
2. To conduct a comparative study of the three main methods of forage dehydration, namely: field curing; forced convection drying with ambient air; and forced convection with solar heated air.
3. To design and build a prototype barn solar hay dryer on the Macdonald College Farm in Ste. Anne de Bellevue, Quebec.

4. To monitor the performance of this prototype over the course of one summer's operation.

5. To examine the potential economic benefits of the proposed system.

6. To propose recommendations for the further development of this system as related to the experiences acquired during this investigation.

1.3 Scope

The focus of the research has primarily been an evaluation of the system from an energy perspective. The barn solar hay dryer should generate heat which would reduce the energy requirements in forced convection drying. The system may have benefits related to the quality of the forage obtained or to the subsequent improvement on milk yields, but these aspects have not been looked into in great detail.

Basically, the investigation has concentrated upon the performance of the solar collection system. Care should be taken when transposing results obtained in this study to potential performances in different situations due to the variety of parameters involved. Some of these include the orienation and shape of the barn, the materials used, the climatological inputs and heat transfer characteristics of a given solar collector design. As this type of application is new in this country, the experiments are expected to cast some light as to whether the system could be a practical alternative to conventional forage drying methods in Quebec.

CHAPTER 2: LITERATURE REVIEW

2.1. Drying Theory

2.1.1 General Drying Theory

The thermal drying of many agricultural crops is generally believed to be an adiabatic process where the sensible heat of the drying air used to vaporize the water from the product is entirely returned to the air stream in the form of latent heat in the water vapour. The value of the total heat content of the air is constant during this transfer of thermal energy (A.S.H.R.A.E., 1972). The drying process can be subdivided into different stages (or periods) of the dehydration of a given material. The "constant rate" drying period is referred to as the stage where the free water is evaporated from the surface of the product. Molecular moisture movement inside the material tends to replenish this deficit rapidly enough to maintain the temperature of the saturated surface constant, lower than the surrounding air. The equilibrium which exists between the heat and mass transfer rates of the air-liquid interface is directly influenced by the temperature of the air, the wet bulb depression, the heat and mass transfer coefficients, and the exposed surface area of the material.

Henderson and Perry (1955) described the drying rate of this equilibrium as:

$$\frac{\partial M}{\partial \theta} = \frac{h\ A\ \Delta\ T}{\lambda} = f\ A\ \Delta\ P \qquad \text{...... (2.1)}$$

where $\frac{\partial M}{\partial \theta}$ = drying rate (kg/s)

h = heat transfer coefficient of air film ($W/m^2 C$)

A = water surface area (m^2)

ΔT = temperature difference between air and water at surface (^oC)

λ = latent heat of vaporization (J/kg)

f = mass transfer coefficient ($kg/s.m^2 \cdot Pa$)

ΔP = water vapour pressure difference between the surface temperature and the air (kg/m^2)

The constant rate period progresses until the "critical moisture content" is reached at which time the flow of free water to the surface becomes just less than the rate of surface moisture removal by evaporation. The dehydration process continues and dry patches appear on the surface resulting in a temperature rise at the outer layer of the material. This is the beginning of the "falling rate" period characterized by (i) unsaturated surface drying and then (ii) internal dehydration. The drying front recedes into the product and the dried cells constitute a resistance to moisture movement. The rate of drying slows down, influenced by diffusion of liquid and vapour, capillarity and vapour pressure gradients due to shrinkage (A.S.H.R.A.E, 1978).

Certain materials, such as forages, are said to be hygroscopic. This means that at a given temperature, the liquid contained on the inside of the material exerts a vapour pressure less than that of free water. The internal moisture is "bound" due to physical and chemical absorption on the solid surfaces of small capillaries or by solution in cell or fiber walls. Hygroscopic materials will eventually attain a particular moisture content known as the equilibrium moisture content if they are maintained in air at a fixed temperature and humidity. The desirable management of drying operations includes the allowing of the hygroscopic material to reach this equilibrium humidity without overdrying. Re-absorption may otherwise take place, rendering the excess dehydration process useless. For most hygroscopic materials, the "critical moisture content" level is greater than the moisture content at which it is initially dried, therefore the falling rate period is the only drying stage which is considered.

2.1.2 Layer Drying Theory Approach

The microscopic factors affecting drying can be integrated into a macroscopic analysis in order to better understand the overall mechanism. Thin layer drying theory assumes that the drying air is in direct contact with the product over its entire surface. Grain drying can be analysed in this fashion as much experimental research has been done on thin layers of grains subjected to warmed airflows. Hall (1980) outlined the basis of the theory currently accepted to describe the dehydration process of agricultural materials. The following approach is a summary of these fundamentals. From basic heat transfer relationships, current drying theory can be elaborated. The cooling phenomenon is described by the Newtonian equation:

$$\frac{\partial T}{\partial \theta} = -k \; (T - T_e) \qquad \ldots\ldots (2.2)$$

where $\frac{\partial T}{\partial \theta}$ = cooling rate of a solid surrounded by a medium at a fixed temperature ($^oC/h$)

k = cooling constant (h^{-1})

$(T - T_e)$ = temperature difference between the solid and the ambient medium (^oC)

By separating the temperature variables and integrating, the following exponential equation can be obtained:

$$\frac{(T - T_e)}{(T_o - T_e)} = \exp\,(-k\theta) \qquad \ldots\ldots (2.3)$$

where: T_o = original temperature of solid (^oC)

T = temperature at time θ (^oC)

T_e = ambient medium temperature (^oC)

exp = natural (Naperian) base of logarithms

A similar analogy can be made for the drying process by substituting temperature with moisture content, dry basis (d.b.) of a material in order to obtain the moisture ratio:

$$\frac{M - M_e}{M_o - M_e} = \exp(-k\theta) \qquad \text{...... (2.4)}$$

where: M = moisture content, dry base at time θ (kg water/kg dry matter)

M_e = equilibrium moisture content (kg water/kg dry matter)

M_o = original moisture content (kg water/kg dry matter)

k = drying constant

The value of the exponent in the equation will depend on the material and relative humidity of the air. The moisture ratio is thus described as an exponentially decaying function which stabilizes as the product reaches equilibrium moisture content.

The drying rate is a function of the vapour pressure driving force and the mass transfer resistance to drying such that:

$$\frac{\partial \bar{M}}{\partial \theta} = \frac{P_s - P_a}{1/fA} \qquad \text{...... (2.5)}$$

where: $\bar{M}$ = mean moisture content (kg water/kg dry material)

f = mass transfer coefficient (kg water/s m^2)

A = effective (exposed) area (m^2)

$(P_s - P_a)$ = difference between the vapour pressure of the solid and the air vapour pressure (Pa)

The remaining variables have been described earlier.

Equations 2.4 and 2.5 constitute the basis of thin layer drying theory.

Deep layer drying theory arose from practical applications where the material being dried was not spread out in a thin uniform layer but rather in a series of layers each of which was subjected to air of different temperature and relative humidity. Deep layer theory assumes the steady movement of a drying front throughout the material stack, the progression of which will be influenced by the physical characteristics of the air (velocity, temperature and humidity). The drying rate during the drying front migration is described as:

$$\frac{\partial M}{\partial \theta} = GA \frac{(H_s - H_i)}{\psi} \qquad \ldots\ldots (2.6)$$

where:
- A = cross sectional area of the dryer (m^2)
- G = mass rate of airflow (kg of dry air/$m^2 \cdot s$)
- $(H_s - H_i)$ = difference in the humidity of saturated drying air and that of the incoming drying air (kg water/kg dry air)
- ψ = weight of the material being dried (kg)

The remaining variables have been denoted previously.

Moisture content can be determined in terms of the ratio of the weight of the water contained to the weight of the product. Moisture content measured on a wet basis (w.b.) is the weight of water divided by the total weight of the product. The moisture content measured on a dry basis (d.b.) is the weight of water divided by the weight of the dry matter of the product. Moisture content is usually expressed in percent.

2.1.3 Forage Drying Theory

Hopkins (1955) related the thin layer drying equation (2.5) to experimental test results and developed the following empirical relationship describing the drying rate of hay:

$$\frac{\partial M}{\partial \theta} = k' \frac{\text{kg dry air/h}}{\text{kg dry matter}} (P - Pa) \qquad \text{...... (2.7)}$$

where: k' is a drying constant = 1.45 for alfalfa

for variations of airflow from 3.09 to 7.36 kg/h

temperatures of 37.8°C to 48.9°C and

initial moisture contents of 29.7 to 48.1% (w.b.)

The remaining variables have been denoted previously.

By combining the deep layer theory to these results, the equation becomes:

$$\frac{\partial M}{\partial \theta} = -(a - bG_2)\ M - M_e \qquad \text{...... (2.8)}$$

which can be substituted to:

$$\frac{M - M_e}{M_o - M_e} = \exp \quad -(a - bG_2)\ \theta \qquad \text{...... (2.9)}$$

where: G_2 = mass velocity of the air (kg of dry air/h/kg dry matter)

a and b = constants such that $k' = (a + bG_2)$

Remaining variables have been denoted previously. The values of "a" and "b" were evaluated at 3.12×10^{-3} and 1.125×10^{-2} respectively. It should be noted that the value of the vapour pressure of the hay will change as the drying continues.

Other researchers have developed empirical relationships to describe the forage dehydration process. O'Callaghan et al. (1971) conducted experiments and simulated agricultural dryer performances using the following drying rate equations:

$$\frac{\partial M}{\partial \theta} = -k_1\ (M - m_1) \text{ when } M > M_c \qquad \text{..... (2.10)}$$

and $$\frac{\partial M}{\partial \theta} = -k_2 \, (M - m_2) \text{ when } M \leq M_c \qquad \text{..... (2.11)}$$

such that:

$$k_1 = 4.97 \times 10^{-5} \exp (7.214 \times 10^{-2} \, T_a)$$

$$k_2 = 9.26 \times 10^{-6} \exp (7.675 \times 10^{-2} \, T_a)$$

$$m_1 = 120.579 \, (H_a/T_a^2 + 0.2364)$$

$$m_2 = 73.282 \, (H_a/T_a^2 + 0.1688)$$

where: k_1 and k_2 = drying rate constants (h^{-1})

M = moisture content of hay, dry base (kg water/kg matter)

m_1 and m_2 = constants related to drying air (kg water/kg dry matter)

M_c = critical moisture content of hay at which drying parameters are considered to change (kg water/kg matter)

H_a = mass of water associated with unit mass air, before drying (kg)

T_a = initial temperature of drying air (°C)

The simulation produced drying rate predictions which compared within 10% of experimental results. The initial rate of drying closely matched the readings obtained from other researchers (Clark and Lamond, 1968), while intermediate and final drying rates agreed fairly well with observations obtained experimentally.

Menzies and O'Callaghan (1971) observed three falling rate periods of drying for low temperature dehydration of grass. The approach was similar to that of O'Callaghan et al. (1971) and the drying equations were of the same form as equations 2.10 and 2.11; only the constants were different. The values of the drying constants "k" and "m" were determined as follows:

$$k = K_b \exp(K_c\ T_a) \qquad \text{..... (2.12)}$$

$$m = K_d\ (H_a/T_a^2) + K_e \qquad \text{..... (2.13)}$$

where the constants for the two equations are listed below.

First falling rate period: $K_{b;c;d;e}$ = 0.031; 0.024; 6763; 1.818

Second falling rate period: $K_{b;c;d;e}$ = 0.0078; 0.037; 7114; 0971

Third falling rate period: $K_{b;c;d;e}$ = 0.0027; 0.046; 5517; 0.597

Ohm *et al*. (1971) investigated a simulation of the heat and mass transfer occurringin a hay tower type forage drying system. The governing parameters including moisture content, air velocity, and bulk density, vary with the physical configuration of the stack (such as height of the hay). A model of the bulk density as a function of stack height was proposed. An equation of the drying rate of the stack was developed such that:

$$\frac{\partial \psi}{\partial \theta} = S\ \rho_b\ \Delta\ M\ \left(\frac{\partial r}{\partial \theta}\right) = S\ V_o\ \Delta\ C \qquad \text{..... (2.14)}$$

where: ψ = weight of water to be removed in layer Δh (kg)

S = area of a cross section (horizontal) of the stack (m^2)

ρ_b = dry bulk density of dry hay (kg/m^3)

ΔM = difference between initial and equilibrium moisture content (kg/kg)

r = radius of the hay tower (m)

θ = time (s)

V_o = superficial velocity of air at $r = r_o$ (m/s)

ΔC = drying capacity of the air (kg/m^3)

It was concluded that due to the non-uniform drying profile obtained using a conventional cylindrical duct, a conical duct should be recommended for hay tower operations.

Imre *et al*. (1984) also studied the heat and mass transfer characteristics of lucerne (alfalfa). The heat transfer coefficient was investigated from the empirical relation to evaluate the Nusselt number for flow at a Reynolds number less than 200 such that:

$$Nu = 6.26 \times 10^{-4} Re^{0.84} Pr^{0.333} \quad ..... (2.15)$$

where:
- Nu = Nusselt number
- Re = Reynolds number
- Pr = Prandtl number

Davis and Barlow (1947 a) using Hukill's methodology (1947) generated a series of curves that can be used to predict the volume of hay that can be dried with given airflow characteristics. The curves are based on the following equation:

$$\frac{dm}{\partial \theta} = \frac{\dot{m}\ \Delta T\ \ cp\ \ \theta H}{\Delta\ M\ L} \quad ..... (2.16)$$

where:
- dm = mass of dry matter in a layer of hay of one "depth unit" (kg)
- $\dot{m}$ = mass flow rate of air (kg/min)
- ΔT = difference between the wet and dry bulb temperatures of the air entering the hay (°C)
- cp = specific heat of the air (kJ/kg.°C)
- θH = proportion of time required by fully exposed hay to reach half of its equilibrium moisture content (%)
- ΔM = difference between the initial and equilibrium moisture content (%)
- L = latent heat of evaporation (2442 kJ/kg)

The definition of a depth unit is: "containing enough hay that, if all the theoretically available heat could be used, it would dry to equilibrium in the time taken to dry fully exposed hay halfway to equilibrium." (Hall,1980). The curves generated by Davis et al. (1950) can be found in the Appendix.

Rossi and Roa (1980) used this data to formulate an empirical equation used to generate the equilibrium moisture content of alfalfa in relation to the physical properties of the drying air such that:

$$M_e = (p_1 H + p_2 H^2 + p_3 H^3) \exp\left[(q_0 + q_1 H + q_2 H^2 + q_3 H^3 + q_4 H^4)(T q_5)\right] \quad \ldots\ldots (2.17)$$

where: M_e = equilibrium moisture content; wet basis (%)

p and q = constants

H = relative humidity of the drying air (%)

T = temperature of the drying air (°C)

$p_1;p_2;p_3$ = 3.04690; −2.68992; −0.315416

$q_0;q_1;q_2$ = −0.062072; 0.164688; 0.164688

$q_3;q_4;q_5$ = −0.188309; 0.100261; 148.993

Clark and Lamond (1971) investigated the drying process of rye grass varying the temperatures of the drying air and density of the stacked unbaled forage. From this research a series of drying curves were generated for the various treatments. Although the general shape of the curves was similar, no basic relationship connecting the various parameters was proposed. Studies on the rate of dehydration of alfalfa subjected to eight different drying pretreatments were undertaken by Pedersen and Buchele (1960). Mechanical pretreatments such as crimping and crushing of the crop in the field have been proven to hasten water evaporation from the stem of the plant (Bilanski and Haylk, 1966; Klinner, 1976). Stem and windrow orientation also influence the drying rate of field cured forages (Duggal, 1969; Lu, 1972).

The hay stem is made up of an impervious outer cuticle which retards moisture transfer. This layer can be cracked or crushed by mechanical means or even dissolved in hot water but this treatment has no practical value (Bagnall et al., 1970). Specific research involving the study of the alfalfa stem tensile properties and leaf separation effects related to moisture content have lead to better understanding of the drying mechanism in field curing (Norris and Bilanski, 1969; Raghavan and Bilanski, 1974).

Mechanical treatments on forages, however, generally cause field leaf losses. The use of a flail mover, rotary tiller or chopper results in relatively high plant dismemberment. Roll type crushers on the other hand increase the drying rate with less harvest losses (Barrington and Bruhn, 1970).

2.2 Applications of Forage Dehydration

2.2.1 Forced Ventilation Hay Drying

The benefits of drying hay with forced ventilation as opposed to field curing have been recognized for at least forty years. The development of artificial drying systems stemmed from a real need to improve the quality and quantity of hay being harvested. Duffee (1942) established some of the first quantitative moisture content measurements at which hay could be safely stored without undue spoilage, discolouration or the risk of spontaneous combustion. The quality of alfalfa is affected by the ultra violet portion of solar radiation. The vitamin A content of hay can be measured by the amount of carotene in the forage. Kane <u>et al</u>. (1937) studied how carotene diminished when exposed to sunlight. The outside ambient temperature and sun exposure time result in overall losses of vitamin A of 6.5% per month during storage. These losses can be as high as 21% per month with ambient temperatures of 20°C. Most of the forage protein and vitamins are contained in the leaves. The per unit dry matter content of field cured baled hay is much less than the dry matter content of the living plant. This is due to the leaf losses incurred through the mechanical handling of the dry hay in the field (Choinard, 1980). Zink (1935 and 1936) analysed the critical moisture content at which alfalfa leaves shatter and observed that leaf field losses ranged from 10 to 65% for moisture contents of 28 to 32% (wet basis).

Artificial drying of forage can reduce the field losses as the crop can be baled at a higher moisture content. Some of the first tests of forced ventilation drying were conducted by Miller and Shier (1943) at the University of Ohio, U.S.A. Tests were carried out on four farms, and moisture contents were brought down from 30% to 11.5% with the use of a multi-vane forward-curved blower rated at 1133 m^3/min at 2.54 cm of water of static pressure. The tests were particularly pertinent that year as an extremely wet summer hampered conventional hay curing and harvesting throughout the State.

Terry (1948) reported that the use of artificial hay curing not only decreased the drying time but also reduced the damage done to the forage by mold and bacterial action. Respiration losses were also decreased when fan drying was practiced. This microbiological process accounts for a loss of dry matter of the forage, production of heat in the stack and loss of moisture content in the hay. The respiration process attains an equilibrium point when the hay is dried to 20% moisture content (dry basis). Respiration has been estimated to account for approximately 8% of the dry matter losses in barn drying applications (Klinner and Shepperson, 1975).

The heat generated by the respiration, combined with the high relative humidity present, encourage the production of mold. This increases the loss of carbon dioxide present in the stack, promoting enzymes in the hay to break down the forage starches and sugars. The feed value of the hay is thus reduced. Rapid hay drying will not only permit the extraction of moisture for forage conservation, but it will reduce the bacterial populations which can severely deteriorate hay quality. (Dexter, Sheldon and Huffman, 1947).

2.2.2 Airflow Resistance through Hay

When hay respiration is combined with a minimum air flow to remove the moisture, effective drying can be obtained. Airflow resistance within the hay is another important factor that affects the efficiency of drying of baled hay. Research carried out in the 1940's established air flow resistance curves for different forages at various moisture contents. One relation that describes this air flow resistance was developed by Hendrix (1947 a) and later confirmed by Davis and Baker (1951). The equation for variation in air velocity through baled hay can be written in the following form:

$$V = KP^n \qquad \text{..... (2.19)}$$

where: V = velocity of the air moving through the stack (m/s);

P = static pressure (cm/water)

K = constant representing the volume of air blown through hay in order to develop a static pressure of 2.5 cm. water gauge.

n = the slope of the static pressure air flow curve plotted on logarithmic scale paper.

Davis and Baker (1951) also point out that some of the factors affecting the air flow resistance which are: moisture content, hay composition, depth of storage, method of handling storage, and bale density. The length of cut of the hay did not appear to significantly affect the static pressure. The value of "K" in equation (2.19) decreases to a critical minimum value during the drying process, then increases to a point slightly less than the value before the drying was started. The value of the coefficient 'n' does not appear to be affected by density, distribution or loading method. Work undertaken by Van Duyne and Kjelgaard (1964) summarized the research efforts in this area. The pressure drop (P) developed through the hay is expressed in the equation:

$$P = K\,L\,B^{m}\,V^{n} \qquad \ldots\ldots (2.20)$$

where: K = constant dependant on the material and air physical properties

L = the length through which air has to travel (m)

B = dry matter density (kg/m^3)

V = air velocity (m/s)

n = velocity exponent

m = density exponent

The bale density exponents obtained by different researchers vary from 1.40 to 1.60 while the velocity exponents range from 2.31 to 3.26 (Van Duyne and Kjelgaard, 1964). Tests were conducted on clover hay and alfalfa and different values of 'K', 'm', and 'n' were obtained for each forage.

The authors conclude that bale slice orientation and dry matter content were instrumental in air flow resistance. The air flow resistance was reduced when the bale slice orientation was set parallel to the stems as opposed to perpendicular to them. The value of 'K' is decreased by a factor of 0.69 to 1.16×10^{-5} in the former case. Moisture content did not seem to affect the alfalfa airflow resistance between 11 and 60 percent (wet basis) yet this was a factor for increasing static pressure in clover hay above 45 percent moisture content.

2.2.3 The Use of Heated Air for Forage Dehydration

The quality of the hay is also a critical factor with respect to the quantity of forage consumed. Field cured forage is characterized by low digestibility associated with the hay's poor quality and nutrient losses (Watson and Nash,1960). High digestibility of a feed has been related to higher intake due to the shorter residence time in the gut of the animal (Campling,1966). Tests undertaken by Clancy et al (1976) compared different conservation methods with respect to nitrogen balance, digestibility and intake of alfalfa. One treatment for the preservation of forage used heated air at 50°C. Of the six treatments tested this method yielded the highest values for digestible crude protein, dry matter and acid detergent protein. This method of conservation had low quantities of lactic acid neutral detergent fiber and acid detergent fiber. Average values of ash and apparent digestible energy were also observed. As far as the intake was concerned, hay dried with heated air had high voluntary intake rates and meal sizes. The forage intake was not apparently related to the moisture content of the various conservation methods.

In addition to the improved quality and digestibility of artificially dried forage cited earlier, heated air has a number of advantages over the use of unheated air. Reduced drying time using air temperatures of 27°C to 37°C has a marked effect on probability of mold formation on hay. At these temperatures the drying time should be kept below 48 hours to avoid formation of visible molds on the forage (Terry,1947). Supplemental heat obtained by coal furnaces or propane burners have been installed in hay drying systems in those areas of the United States where ambient air is generally too humid during the hay drying season (Strait,1944; Bruhn,1947).

Another advantage of supplemental heat systems is that of the continuous drying of the hay at night. This reduces the total time required to dry a batch of hay and consequently, forage deterioration. If the air heating equipment is portable it can be used to dry other agricultural crops on the farm. The disadvantages of such a system are fire hazard, high initial and operating costs and increased supervision required (Davis and Barlow, 1947 b).

As the air is heated, its moisture carrying capacity is increased. At the same time, heating the hay facilitates moisture movement through the leaves and stems and into the air stream. The air thus gathers humidity and the vapour pressure at the surface of the stack is augmented. This results in increased evaporation (Montford,1947). The drying rate can be further affected by the method used for harvesting the forage. Chopped hay will have a higher rate of moisture loss than coarser cut hay due to cutting of the stems and leaves and improved air flow through the material (Boyd, 1959).

Heated air systems however have not been very popular due to the increased cost of fuels being used. As hay has always been considered to be a relatively inexpensive feed, farmers are reluctant to pay for 45 to 90 litres of fuel (1750 to 3500 MJ) per tonne of hay dried (Manby and Shepperson,1975).

It should be noted though, that fuel is not the only source of heat for drying in forced ventilation systems. The hay which is brought into the barn undergoes the metabolic process of respiration that liberates more than 60 percent of the heat absorbed by water evaporation. This is true for air entering the hay at 75 percent or higher moisture content and in the presence of micro-organisms. The heat absorbed drops to 25 percent for low relative humidities and when micro-organism populations have not developed. (Dawson and Musgrave,1946). The heat generated by respiration is due to enzymic action which steadily increases until a critical temperature is reached in the hay. This temperature varies with the moisture content of the hay. Once it is reached, the respiration heating subsides.

The heat generating process is also related to the moisture content in the hay, the stage of drying and the time of day. At night time this heat may account for as much as 91% of the moisture removed per unit time. The heat may represent only 40% of the water loss during the day. It has been shown that the heat of respiration and bacterial activity contributes to a major portion of the total water removed (Hendrix, 1947 b).

Wood and Parker (1971) reported that the respiration rate remains steady at surrounding temperatures of 25°C until any molding causes it to rapidly increase and then fall off. Respiration rates are a function of the forage moisture content (wet basis). For hay at moisture content above 27% in air temperatures from 25°C to 45°C, the respiration rates could be estimated by the equation:

$$R = k\,(0.056\,M - 1.53) \qquad \text{..... (2.18)}$$

where: R = rate of respiration (mg CO_2/g dry matter/h)

k = constant (h^{-1})

M = moisture content, wet basis (%)

The constant 'k' is evaluated at 1.0 for air temperatures above 25°C. For air temperatures ranging between 5° to 25°C, 'k' is a function of the temperature (T) such that:

$$k = 0.177\,\exp(0.069\,T) \qquad \text{..... (2.19)}$$

Nelson (1966) conducted experiments to evaluate the effect of spontaneous heating on nutrient retention in baled alfalfa. The deterioration of the basic nutrients of the forage begins a few hours after baling. The increased density of the bale has an adverse effect on the retention of carotene. This is assumed to be due to the slower drying rates. Organic matter, crude protein, ash, crude fiber, ether, nitrogen-free extracts, and carbohydrates did not appear to be affected by the density of the bales. These factors were affected, however, by increased moisture content at the time of baling.

The equilibrium moisture content of alfalfa is a function of the relative humidity of the surrounding air. Hay which is barn dried to 15% moisture (dry basis) or less will reabsorb moisture from air that has a relative humidity of 80% or more. Hay of moisture content 20% or less will reabsorb moisture if the relative humidity of the surrounding air is 90 percent or more. (Dexter, Sheldon and Wsaldron, 1947). The accepted maximum equilibrium moisture content for good conservation and safe storage of forage is 20%, dry basis (A.S.A.E.,1964; Fortier 1976; C.P.V.Q.,1980).

2.2.4 Some Applications of Solar Drying in Agriculture

A large number of research projects in the uses of solar energy in agriculture have been carried out in the past thirty years. Some of the processes involved have been: air and water heating for use in livestock buildings; solar assisted crop drying and to a much lesser extent the use of photovoltaics for electrical energy. Solar drying by direct and indirect exposure has been the most popular, by far (Lawand, 1981).

In the past ten years much emphasis has been put on developing efficient inexpensive solar collectors for the use of drying cereal grains and forage crops. (Chau and Baird, 1978; Shove, 1977; Johnson and Otten, 1980; Otten and Brown, 1982). Grain drying initially has had a higher priority due to the large amounts of fuel consumed each year in this process and the superior value of this crop. Buelow (1958) was one of the first to work in this area. Several types of collectors were investigated in the course of the research including flat-plate glass covered collectors and opaque galvanized air heaters. The basic collector efficiency theory was devised (Buelow and Boyd, 1957). A simple methodology for estimating daily solar radiation on inclined surfaces was also developed (Buelow,1962). Air temperatures of 49°C were obtained for drying grain in a simple tray collector in the United Kingdom (Bailey and Williamson, 1965). Tests were done on a low cost polyethelyene covered inflatable collector. A plastic absorber mesh increased the collector efficiency by an average of 8%. This conforms with the results obtained by Lawand et al. (1981), testing a similar absorbing screen on a solar wall air preheater.

Problems associated with solar grain drying were: the relatively slow drying rates; cost competitiveness with respect to fossil fuel drying due to the limited use of the equipment; and the necessity of a back-up system in case of inclement weather (Foster,1977; Kline, 1977; Feddes et al., 1980).

2.2.5 Barn Solar Hay Drying

The use of solar energy for in-situ hay drying has had less publicity than grain drying yet quite a number of references have been found dealing with this subject. Of the references consulted, the earliest of these is the use of an opaque flat plate collector system incorporated in the galvanized steel roofing of farm buildings (Sobel and Buelow, 1963). The collector could raise the air temperature as much as 14°C. Provisions were made to duct the heated air to other buildings when the dryer was not being used.

Due to the high cost of electricity in Europe, researchers in several countries have developed solar assisted barn hay drying systems. France seems to be the country where most of the experimentation has been undertaken.

Several comprehensive studies of different solar barn hay dryers built in France have recently been published (Savatier, 1982; Salcedo, 1982; A.S.D.E.R., 1983; Chazee and Madek, 1983 a and b). There are four main configurations to these systems that have been developed in France namely: (a) bare plate collector mounted in the roof of the barn; (b) glazed solar collector mounted in the roof; (c) polyethylene "greenhouse" collector leading up to the hay barn; and (d) black polyethylene inflated tube leading up to the barn. The majority of these installations are located in the Alpine region called Savoie where frequent inclement weather and an extended winter period make indoor hay drying an appropriate technology. Regulations pertaining to the manufacture of the famed Gruyere cheese in this region forbid the feeding of silage to the cattle and consequently hay is the only winter feed given to the animals (Chazee and Madek, 1983 b). Many farmers use fuel heaters to generate low grade heat combined to their forced ventilation hay dryers. Since 1976, an estimated twenty solar-assisted, in-situ forage drying systems have been constructed, some in collaboration with agricultural research centres and others as self-built prototypes erected by the farmers themselves. Temperature increments in the dozen systems that have been investigated range from 5°C to 15°C for different designs. A comparative evaluation of the four main configurations has been adapted from Chazee and Madek, (1983 b) and is presented in Table I.

A few comments can be made with regards to each configuration. The bare plate collector type dryers are relatively simple yet solid in construction. The system is comprised of an air space which is constructed between the roof cladding and an inner insulation layer. Solar radiation heats the roofing material (which is normally galvanized metal or fibro-cement panels) and this permits the air space to heat up subsequently. The air is drawn through the collector and is then blown through the hay. This type of system performs well in direct and diffuse solar radiation and typical temperature increments of 8°C were recorded with airflow rates of 550 m^3/min (Leclerc, 1979).

TABLE I : COMPARATIVE ANALYSIS OF 4 TYPES OF BARN SOLAR HAY DRYING SYSTEMS

Characteristic	Black Inflated Tube	Greenhouse	Roof Collectors	
			Bare Plate	Glazed
- Thermal performance	3	2.5	3	3.5
- Risk of condensation at top of hay stack due to elevated temperatures	1	2.5	4	2
- Performance in wind	1	3	2	4
- Performance in rain	1	2	2	3
- Variability of performance	1	2.5	3.5	2
- Performance in diffuse solar radiation	4	1	3	1
- Time requirements	1	1	3	3
- Preliminary construction time	4	3	1	1
- Annual installation time	1	2	4	4
- Ease of installation	2	3	2	1
- Durability	1	2	4	4
- Maintenance	1	2	4	2
- Flexibility of operation	1	3	4	4
- Passability of automation	1	4	4	4
- Capital investment	4	3	2	1
- Amortization	2	4	3	1
- Maintenance costs	1	2	4	3
- Special problems	snakes	snow		hail
- Possibility of adding a heater	1	4	2	2
- Adaptability to site	1	2	4	3
	1	2	4	4
- Multiple usage	1	4	2	2
TOTALS	34	54.4	64.5	54.5

NOTE: The higher the number, the better the rating (1 to 4).

SOURCE: Chazee and Madek, (1983 b) Rechauffage solaire et ventilation en grange du foin en vrac dans l'Avant Pays Savoyard.

Glazed flat plate roof solar collectors operate at higher ventilation rates however air temperature increases will be comparable to the bare plate design due to the increased performance of the solar collector. The capital investment of the glazing (usually clear corrugated fibreglass-reinforced plastic sheets) is quite high. The basic difference between this type and the bare plate collector type is that the glazed surface is constructed above the roof cladding in order to provide the air space. The incoming air is heated directly due to the greenhouse effect of reflected long wave radiation inside the collector. This system will perform the best of the four types of collectors with temperatures ranging from 12° to 15°C using a 20.8 kW fan to draw the air (A.S.D.E.R., 1983).

Greenhouse type solar collectors are relatively inexpensive and have the advantage of being multi-purpose, capable of being used at different periods of the year as a greenhouse and/or hot air generator for hay drying. This reduces the amortization time, thus enhancing the investment. Air temperatures encountered range from 3°C and 4.5°C for airflows of 830 m^3/min (Savatier, 1982; Chazee and Madek, 1983).

Feuilloley (1979, 1980, and 1981) designed a system that utilizes a black polyethelyene tube collector. The tube is 340 metres long and 1.9 metres in diameter and is placed in a 3000 square meter field adjacent to the hay barn. The average air temperature increase is 8°C.(with peak values of 25°C.) at an average airflow rate of 630 m^3/min.

The advantages of this system are its relatively high capital cost recovery of one year (possibly due to France's expensive fossil fuel costs) and the portability and easy storage of the tube once deflated.

The disadvantages however are the bulkiness of the unit during operation, high annual labour requirements for installation, and the necessity of having a large open area adjacent to the barn.

The black polyethylene inflated tube design appears to be the least practical solution of the four types cited. In addition to the problems mentionned by Feuilloley (1980), other disadvantages include: frequent punctures made in the plastic by branches and roots; attraction of snakes underneath the hot and humid polyethylene; punctures in the plastic by moles, mice and other rodents; general unsightliness of the system; poor performance and material stress in moderate winds or inclement weather (Chazee and Madek, 1983 b; Petitjean, 1980).

In Italy, Facchini et al., (1979) used roll-bond aluminum solar collectors to heat ventilation air by passing heated water through finned heat exchangers in the roof plenum. Another design used simple prefabricated transparent flat plate air heaters capable of increasing the temperature of the air by 10°C to 15°C. The collector efficiency is claimed to be 60 to 70% and air flow velocities are in the order of 5 metres per second. The disadvantage of such installations is the high capital cost and the fact that these collectors are not user-built.

Due to the high incidence of inclement weather during the summer months in Scotland, researchers have also developed an indoor solar hay dryer. (Ferguson and Bailey 1981). This "solar barn" has a bare plate roof collector combined with a polyvinyl fluoride glazed wall collector. Simultaneous testing of forced ventilation with solar heated air and ambient air was carried out as the barn was divided into two parallel drying systems. The tests proved that a 30 percent energy saving could be expected from the use of solar energy due to the reduced drying time.

A Swiss design (Nydeggar,1981) uses a 190 square metre roof collector. Eternit R. plate, a commercially available corrugated asbestos cement sheet, is used as the absorber plate. This material has been extensively tested in Europe and several in-barn hay drying systems are equipped with these plates in covered or bare plate collectors (Veglia,1982). Corrugated glass fiber-reinforced polyester was used as the glazing in the Swiss experiments. This collector normally operated with air flow velocities of 5 m/s and air temperature increases were low (averaging about 2°C). stagnation temperatures however, reached 70°C, but this did not deteriorate the glazing surface. The average saturation deficit of the system was 58 percent. Different glazing materials were tested independently and the glazing that was chosen, (fiberglass reinforced plastic), performed the best in terms of transparency and resistance. During one season's tests the total absorbed energy of the system came to 24,000 kWh which is equivalent to 3,000 litres of fuel burnt in a conventional air heater. The one possible disadvantage of such a system is that it represents a relatively expensive, complex and somewhat impractical construction to be retrofitted on existing older buildings.

Another type of design in Switzerland (Mermier, 1978) uses 26 m^2 of roof-mounted liquid filled collectors that heat the incoming barn air through a heat exchanger. Air temperature increases are from 5°C to 10°C for airflow rates of 400 m^3/min. Although the cost of this installation is quite high, the farmer also uses the solar collectors to store hot water for all his domestic uses and to serve as heat storage for the dryer in times of low solar radiation levels.

A solar-assisted green forage drying plant was developed in West Germany using 1500 square metres of glass collectors (Grammer and Barthel, 1979). The system is made of seven module-type collectors capable of heating the incoming air to 70°C and rated at a maximum efficiency of 70 percent. Although the system is not adapted for barn applications per se, the use of such modular air heaters could be envisaged for this purpose. The unit is said to be capable of processing 13 tonnes of wet fodder per hour. Such systems will have to be modified and tested on a smaller scale on existing barns before they can be proven effective for on-site barn hay drying.

A roof top solar collector was developed in Czechoslovakia (Sladky, 1980) which can be used to dry grain and chopped hay in the barn. The collector efficiency is rated at 50 percent and the air temperature increment is 5°C to 8°C. Maximum temperatures of 45°C have been recorded during testing. The cost of the 800 square metre collector is quoted as being from 16 to 25 U.S. dollars per square metre for a pay back period varying between one and five years (depending on the amount of time the system is used per year).

Research of in-situ solar assisted hay drying systems in the United States has focused on the drying of large round hay bales (1.8 metres in diameter by 1.5 metres in length). Baker and Shove (1978) and later Morrison and Shove (1980) established that 20 percent of the electrical energy could be saved with the use of a solar energy for heating the drying air. An additional 29 percent energy saving was obtained when the fans were operated intermittently instead of continuously during night-time operation. An 880 square metre roof top collector of corrugated fiberglass was combined with a transparent wall collector. This design is not adapted to a retrofit situation on existing barns. The installation uses nine centrifugal fans which contributes to the high capital cost of this system.

Bledsoe and Henry (1980) tested bare plate roof collectors and free-standing plastic film collectors for in-barn hay drying. The free standing collectors were capable of increasing the air temperature by 8°C. (twice as much as the bare plate collector whose efficiency was rated at 42 percent). The roof collector however was 2.6 times less expensive ($16.2 U.S. per square metre of collector). It was found that if the large round bales were pierced through the core and a cap was placed covering the opening, the airflow distribution in the bales would be more uniform and the drying rates would be higher. The multiple use of the system was promoted when the heated air was also used to dry grain (Bledsoe et al., 1981).

From the number of barn solar hay drying systems already installed, it is obvious that this technology has been well researched and is being established in Europe. The lower costs of electrical and fossil energy in North America have perhaps deterred the research emphasis in this area. Although solar heating of livestock buildings and solar grain drying are beginning to be used here, more research in in-barn solar forage drying is needed in order to develop efficient and appropriate systems which farmers can apply to existing or new hay barns. The current research will attempt to develop and evaluate a solar-assisted in-situ hay dryer suited to the Canadian context.

CHAPTER 3: MATERIALS AND METHODS

3.1 Preamble

3.1.1 Introduction to Activities Undertaken

From the literature review, it is obvious that the use of solar energy for drying forage inside a barn appears to be a suitable alternative. A lot of research has been undertaken concerning ambient air forced ventilation hay drying. Low temperature forced convection hay drying has not been extensively investigated in Canada. In order to understand more about the hay drying parameters related to air temperatures ranging between 3 and 10°C above ambient, it was necessary to conduct some specific experiments on this subject.

Small scale experimentation at the Brace Research Institute Field Station compared conventional forage drying techniques with that of using solar heated air to dry the hay inside the barn. These experiments were controlled so that the various parameters could be studied in the process. This portion of the research has been denoted as Phase I for identification purposes.

Concurrent investigations involved the testing and evaluation of a full scale prototype Barn Solar Hay Dryer at the Macdonald College experimental farm. This experimentation is identified as Phase II of the project. It should be noted that both the Phase I and Phase II experiments are closely interrelated and were designed to complement the global understanding of artificial forage drying technology. The description of these two research activities will be dealt with separately so as to avoid confusion.

3.1.2 Rationale of the Research Undertaken

Preliminary investigations involved a comparative study of three different forage drying techniques. This study will henceforth be referred to as Phase I of the research.

The main objectives of the experimental work of Phase I was to evaluate the use of forced solar heated air as opposed to forced ambient air or direct field curing for the drying of baled hay.

Tests were designed to compare these three methods of drying forage. The hay was dried in bins (or cribs) that simulated bales of hay dried at the centre of a larger stack. Solar generated heat was provided to dry one of the two lots. Unheated ambient air was used for the second bin and a control batch was field cured. The tests were designed to try to establish the duration of drying required for each of the two bins of forage.

At the end of the dehydration tests, samples were taken from each batch of hay in order to evaluate the quality of the forage. Moisture and dry matter content were measured. The amounts of essential forage constituents was also analysed to determine its overall quality and value.

As the quantitative and qualitative advantages were tested for the small hay samples in Phase I, the ensuing objective was to incorporate a solar-assisted drying system into an operating hay barn. The design included some basic criteria to maximize its acceptance and utility. These criteria are listed below:

(A) The design of a solar assisted hay drying system should have the potential of being retro-fitted onto existing hay barns equipped with or without forced ventilation drying systems.

(B) The overall design should be simple enough to be user built (during the winter months perhaps when the hay stack itself can be used to reach the underside of the roof). The tools of construction of the solar system should be compatible with those found on the typical Canadian farm.

(C) The system should be inexpensive yet durable enough to be used for 5 to 10 years.

(D) The materials will be subjected to extreme temperatures encountered during periods of stagnation or severe winter cold and will have to be able to withstand these extreme temperature fluctuations.

(E) The system must be relatively protected from the habitual or occasional accidents on the farm. A collector should be protected for example, from the event of a hay bale falling onto it, or some other knock, should it be mounted on an exterior wall.

(F) The solar collector should resist deterioration due to ultra-violet radiation, precipitation, or rot.

(G) The design should permit easy repair or replacement of its various components in the event of an accident or breakdown.

The testing of a full scale barn solar hay dryer prototype will be referred to as Phase II of the research.

The Phase II design encompassed all these considerations and offered a certain amount of flexibility of operation. This is in view of the fact that many hay barns are not built to standard specifications, and standardization with respect to one design would be of limited use.

3.2 Materials and Methods of Phase I

3.2.1 Materials and Instrumentation Selection

The comparative drying tests (Phase I) were carried out at the Brace Research Institute Experimental Field Station in Ste. Anne de Bellevue, Quebec, Canada, during the summer months of 1983. Two identical drying bins (or cribs) were constructed, in order to accommodate six bales of hay each, stacked three bales deep. This height of hay is similar to the quantity recommended by House (1982), stating that no more than 1.2 metres of hay should be added to a hay dryer at one time. One of the cribs was fed with ambient air in order to simulate standard forced convection hay drying. The other crib was connected to a solar collector so that the heated air would simulate barn solar hay dryer conditions. The layout of Phase I is found in Figure 1. The bins were connected to separate forced ventilation systems. The two fans for the ambient air crib were located in two existing ventilation plenums (open to outside air) in the western-most building of the Field Station complex. The solar-heated crib drew its air from the Solar Wall Collector, by means of a variable speed fan located in the main building at the Brace Field Station. The air was ducted into the drying cribs through a 10 cm (4") non-perforated plastic corrugated drainage tube. The aforementioned air moving systems required only minimal modifications to

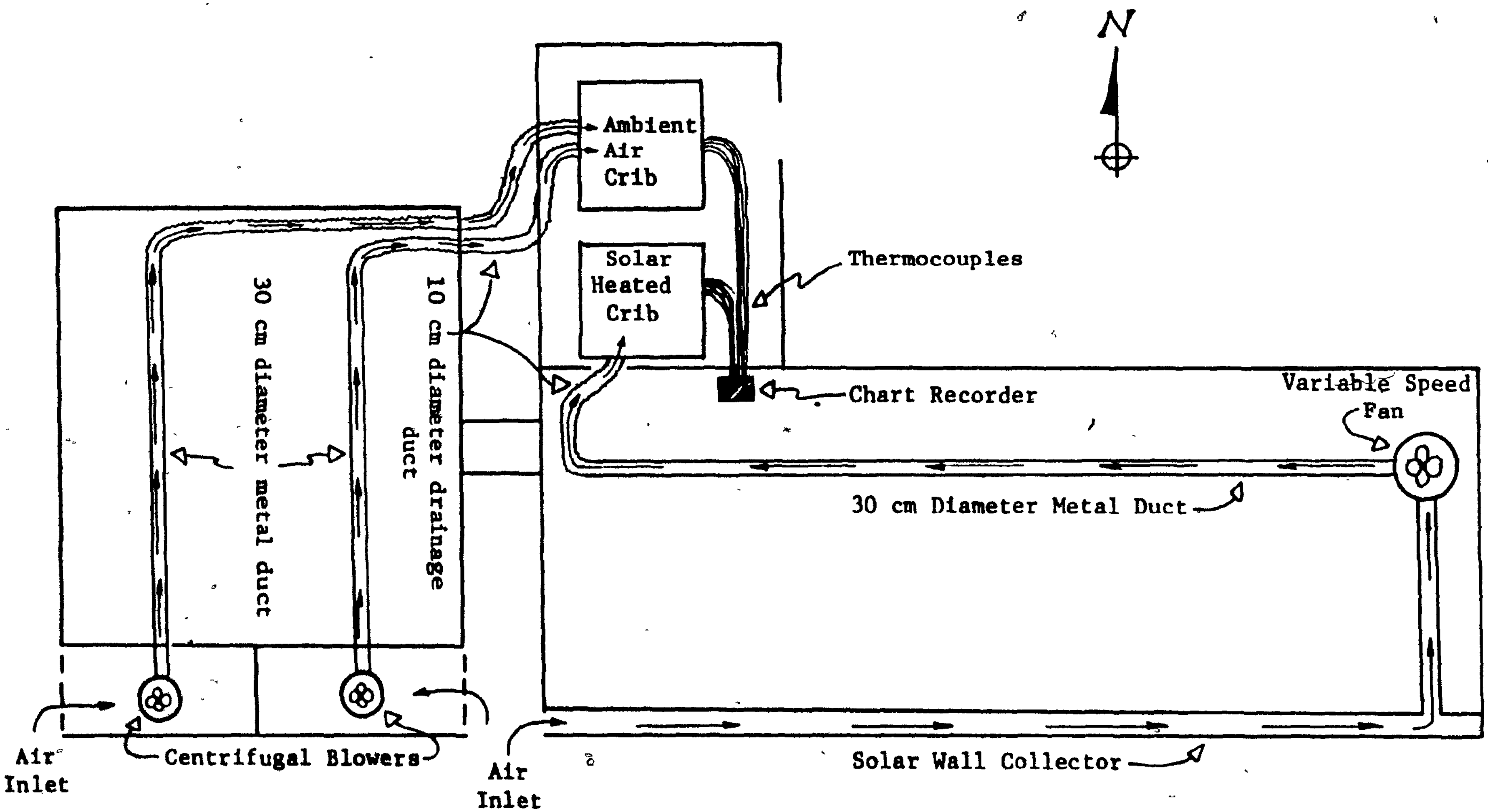


Figure 1: Schematic of Experimental Lay-Out for Comparative Drying Tests (Phase I)

the existing ventilation equipment and provided adequate airflow rates for the experiments.

The drying cribs were constructed of 15 mm (3/8") plywood and braced on the inside with lengths of 38 mm x 38 mm (2" X 2") members. Lenghts of 25 mm x 25 mm x 3 mm (1" x 1" x 1/8") angle iron was used for outer reinforcement. The members were held in place with screws, and caulking was used to seal all joints. Both drying cribs included access doors on one side, to facilitate bale handling. The sides of the bins were equipped with an adjustment mechanism to effect retightening of the bin contents if considerable bale shrinkage were to take place. The inside of the bin was lined with polyethylene plastic sheeting to minimize air leakage could be minimized. An air plenum of roughly 0.3 m^3 was incorporated below the level of the hay, in order to obtain equal air pressure distribution underneath the bales (Figure 2). The floor area of the bins was designed in such a way as to exactly fit the bale size used at the Macdonald College Farm.

In the Phase I experiments, the existing blower-type fans at the Brace Field Station were used for the air flow system and were connected to the drying bins using non-perforated plastic drainage tubes. The fans used for the ambient air crib were two Delhi ~~410~~ centrifugal blowers rated at about 952 m^3/h (560 cfm) at 0.3 cm (1/8") static pressure. The air was ducted through a length of 30 cm (12") galvanized steel circular duct, at which point the airflow was measured, then into the plastic drainage tubes connected to the drying bins. The air flow into the ambient air bin was maintained at a fixed rate, as the fans ran at a contant speed. The solar heated air drying crib was provided with air drawn by a variable speed blower, rated at a maximum capacity of 6800 m^3/h (4000 cfm) and a maximum pressure drop of

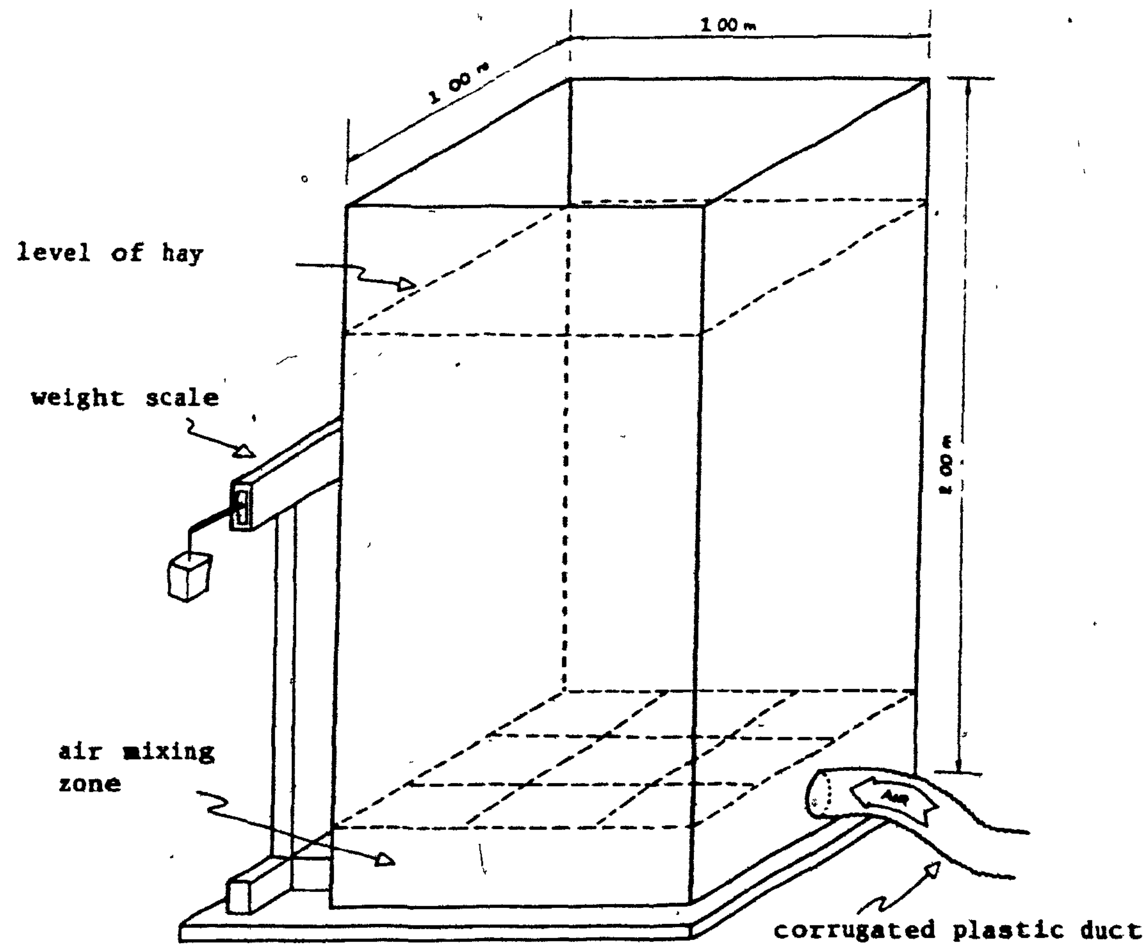


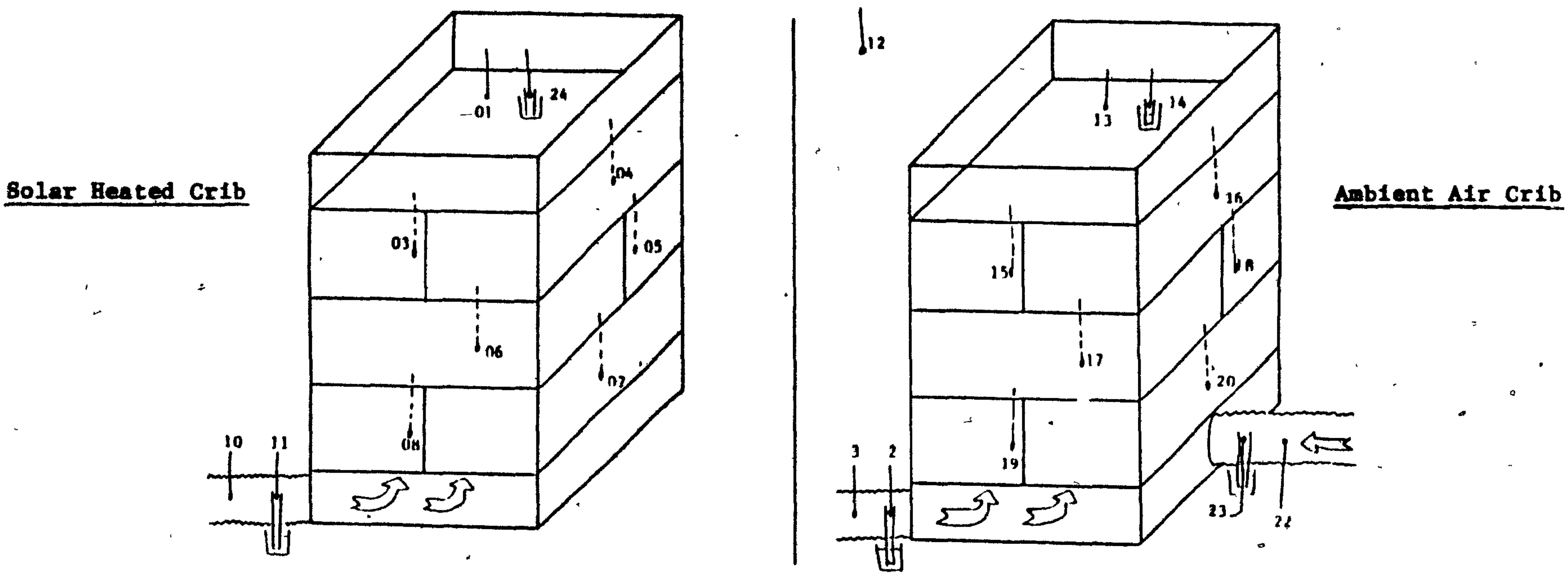
Figure 2: Schematic of Drying Crib for Comparative Drying Tests (Phase I)
Both "Solar" and "Ambient" Cribs were Constructed Identically.

19 mm (3/4") W.G. The airflow rate into the ambient air drying crib was measured using a hot wire anemometer. This flow rate was matched to that of the heated air bin by the use of the variable speed fan.

Four independent tests were carried out. The first test extended from 28 July to 2 August 1983, and was primarily used to calibrate the equipment, The second test dates were from 5 to 12 August 1983. The focus then was on the temperatures within the bales of hay and the progression of the drying zone in each drying crib. The third test was conducted from 15 August to 1 September 1983, and concentrated on drying rates, as well as temperature levels in the test cribs. The final set of experiments was run from 6 to 15 September 1983. These tests were aimed at verifying drying rates as related to the entry and exit air of the respective drying cribs.

3.2.2 Instrumentation

Anaconda-Continental T-type thermocouples (16 gauge) were used to monitor the temperatures of the bin entry and exit air, as well as at different points throughout the hay stack. Tests 1, 2 and 3 monitored of temperatures in the hay, so as to note the progression of the drying zone. Test 4 focused on the relative humidity of the air before and after it passed through the forage. The location of the thermocouples in both types of tests is illustrated in Figures 3 and 4. Wet bulb temperatures of the air were measured, using thinner (24 gauge) thermocouple wire continuously wetted by means of cotton wicks placed in water filled containers. A Texas Instruments 24 channel chart recorder was used to register the temperatures on a continuous basis throughout the experiment.



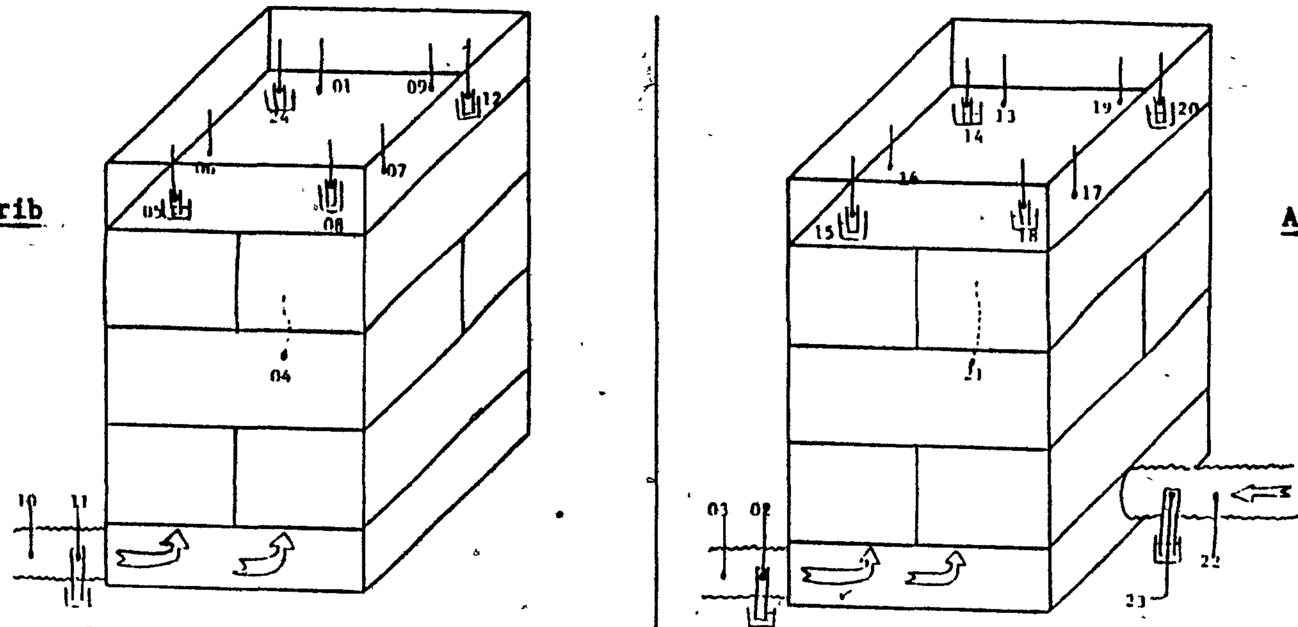
Legend:

Thermocouples		Thermocouples	
01	Exit air (d.b.)	13	Exit air (d.b.)
02	Entry air (w.b.)	14	Exit air (w.b.)
03	Entry air (w.b.)	15	Hay Temperature Centre of Upper Bales
04	Hay Temperature Centre of Upper Bales	16	Hay Temperature Centre of Upper Bales
05	Hay Temperature Centre of Upper Bales	17	Hay Temperature Centre of Middle Bales
06	Hay Temperature Centre of Middle Bales	18	Hay Temperature Centre of Middle Bales
07	Hay Temperature Centre of Middle Bales	19	Hay Temperature Centre of Lower Bales
08	Hay Temperature Centre of Lower Bales	20	Hay Temperature Centre of Lower Bales
10	Entry air (d.b.)	22	Entry air (d.b.)
11	Entry air (w.b.)	23	Entry air (w.b.)
12	Ambient Air Temperature (d.b.)	24	Exit air (w.b.)

Figure 3: Schematic Illustrating Location of Thermocouples in Comparative Drying Test 1 and 2 (2 to 8 August and 18 to 31 August 1983)

Solar Heated Crib

Ambient Air Crib



Thermocouples

Legend:

01	Exit air (d.b.)
02	Entry air (w.b.)
03	Entry air (d.b.)
04	Hay Temperature Middle of Hay Bales
05	Exit air (w.b.)
06	Exit air (d.b.)
07	Exit air (d.b.)
08	Exit air (w.b.)
09	Exit air (d.b.)
10	Entry air (d.b.)
11	Entry air (w.b.)
12	Exit air (w.b.)
13	Exit air (d.b.)
14	Exit air (w.b.)
15	Exit air (w.b.)
16	Exit air (d.b.)
17	Exit air (d.b.)
18	Exit air (w.b.)
19	Exit air (w.b.)
20	Exit air (w.b.)
21	Hay Temperature Middle of Hay Bales
22	Entry air (d.b.)
23	Entry air (d.b.)
24	Exit air (w.b.)

Figure 4: Schematic Illustrating Location of Thermocouples in Comparative Drying Test 3 (05 to 15 September 1983)

The weight loss of the hay bales in each bin was measured by means of mechanical scales. The resolution of these was verified, using a 200 kg mass in conjunction with a digital Toledo balance and was established to be between 0.25 and 0.5 kg. The rate of water loss from each bin was obtained by noting the weight difference with respect to time elapsed.

A TSI model 1000 hot wire anemometer was used to determine the air speed and consequently the air flow generated by each fan.

3.2.3 Construction Details and Test Procedure

The experimental procedure involved hourly, daily and periodical measurements. Hourly readings of the following items were taken:

- temperatures throughout the system
- relative humidity and the difference in temperature of the air entering the ambient and solar heated drying cribs
- moisture loss from the hay crib
- meteorological conditions

Verification and adjustment of the air flow into both drying bins was conducted daily. Periodical testing included:

- airflow speed distribution through the top of the drying cribs
- initial and final moisture contents of the hay
- quality analyses of the forage once the test was completed

The temperature of the incoming solar heated air was regulated on an hourly basis through the use of fresh air dampers in the Solar Wall Collector. This was adjusted to parallel the temperatures measured in the Phase II experiments at the Macdonald College farm. Regular monitoring of the heated air temperatures at the full scale prototype resulted in good correlation with the temperatures obtained for the solar heated air used in the Phase I tests.

The airflow rate into the drying bins was measured by taking a traverse readings through the circular galvanized ducts located at a distance equivalent to 12 duct diameters from the fans. The air speeds were taken at 11 locations through the 30 cm diameter duct and averaged, in order to obtain a mean value used for calculating the airflow rate. As there were no leaks in the ducts leading to the drying cribs, this air flow corresponded to the air being blown through the baled hay.

The initial and final moisture contents of the hay in each bin were obtained from core samples totaling about 800 g, taken from among the six bales of each crib. These samples were weighed, dried in lots of 200 grams in a conventional drying test (24 hours at 70 °C) and re-weighed, in order to obtain the dry basis moisture content. This measurement is represented by the following equation:

$$MC_{db} = \frac{W - D}{D} \times 100 \qquad \text{...... (3.1)}$$

where:

MC_{db} = dry base moisture content (%)

W = weight of material before drying (kg)

D = weight of material after being thoroughly dried (kg)

Periodical airflow tests were conducted at the top of the bin so as to verify that the air was escaping evenly from the cribs. Readings were taken in a grid pattern at spacings of 20 cm with the hot wire anemometer placed just above the level of the hay.

3.2.4 Quality Analysis

Each of the three methods of forage harvesting was analysed with respect to dry matter, crude protein and acid detergent fibre content. In addition, organoleptic examinations (visual, smell and touch) were also used to evaluate the quality of the forage. Comparisons were made on the forage once it had been dried. The methodology for the chemical analysis was undertaken according to the standard procedure established by the Association of Official Analytical Chemists (1980). These procedures have been included in the Appendix for reference purposes. Three replicates were collected for the determination of the crude protein and acid detergent fibre.

3.3 Materials and Methods of Phase II

3.3.1 Design Criteria of the Barn Solar Hay Dryer

When utilizing solar radiation to preheat the drying air, one alternative is to utilize the envelope of the barn as a simple collector for this energy source. The logical areas to examine are the roof surfaces, the south, east and west facing walls. The rationale has always been that farmers would use those surfaces receiving optimum radiation levels, provided simple, robust, easily constructed solar collection systems could be installed.

The criteria mentioned earlier were the primary considerations for the design of the Phase II system. The dehydration process envisaged is low temperature drying. The amount of temperature increase of the heated air should be in the range of 3°C to 6°C., as the airflow rates are very high.

In order to predict which surface of the hay barn would obtain the most incident solar radiation, a computer programme was devised to analyse what average daily incident radiation would fall on the roof and walls of this particular building. The method for predicting the average hourly radiation incident on non-horizontal surfaces was developed by Hay (1977). The outline of the theory behind the model has been included in the Appendix for reference. The location of the prototype solar assisted hay drying barn is the Macdonald College farm in Ste.Anne-de-Bellevue, Quebec. (Latitude 45.5 degrees N). The dimensions of the gambrel-roofed building are 11.0m X 27.4m X 10.7m high. The barn has a wooden inner support structure and is covered with weathered galvanized metal sheets. Plate A illustrates the general appearance of the south wall of the building. The barn was built prior to 1940 and no architectural plans are available. The initial work to be done was to measure the barn dimensions in order to make suitable plans to be used for further calculations. A cross section of the barn appears in Figure 5. Plate B illustrates the complex internal wood framework of the barn. Once the basic dimensions were obtained, the calculations of the average hourly solar radiation incident on each surface could be predicted. Computer modelling was undertaken in order to estimate the incident hourly solar radiation available for different barn surfaces during the forage drying season. A summary of maximum possible energy collected from each surface for the 4 months in question is included in Table II.

The system was designed to encompass two solar collectors; a preheating plenum in the roof and a solar wall air preheater. The various components of the system are illustrated in Figure 6.

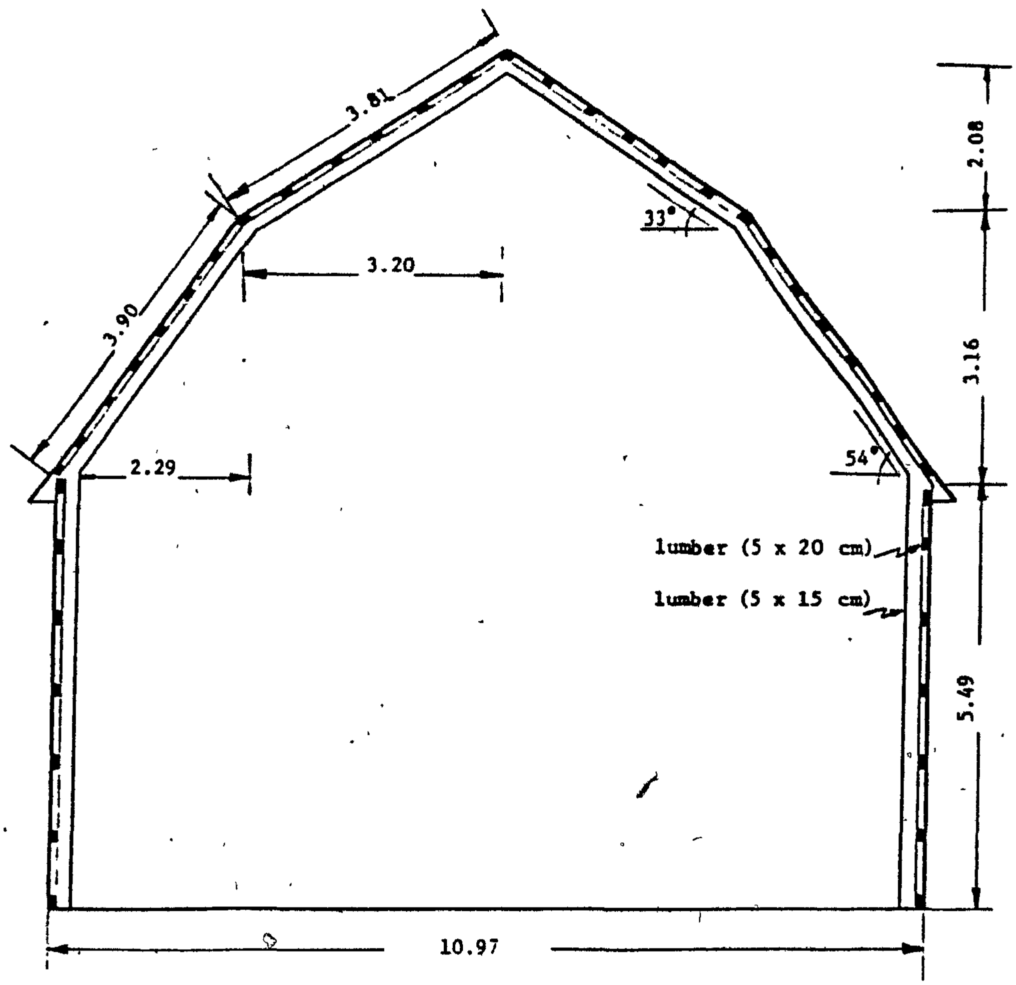


Figure 5: Schematic of Basic Dimensions of Barn Cross Section. (in metres).

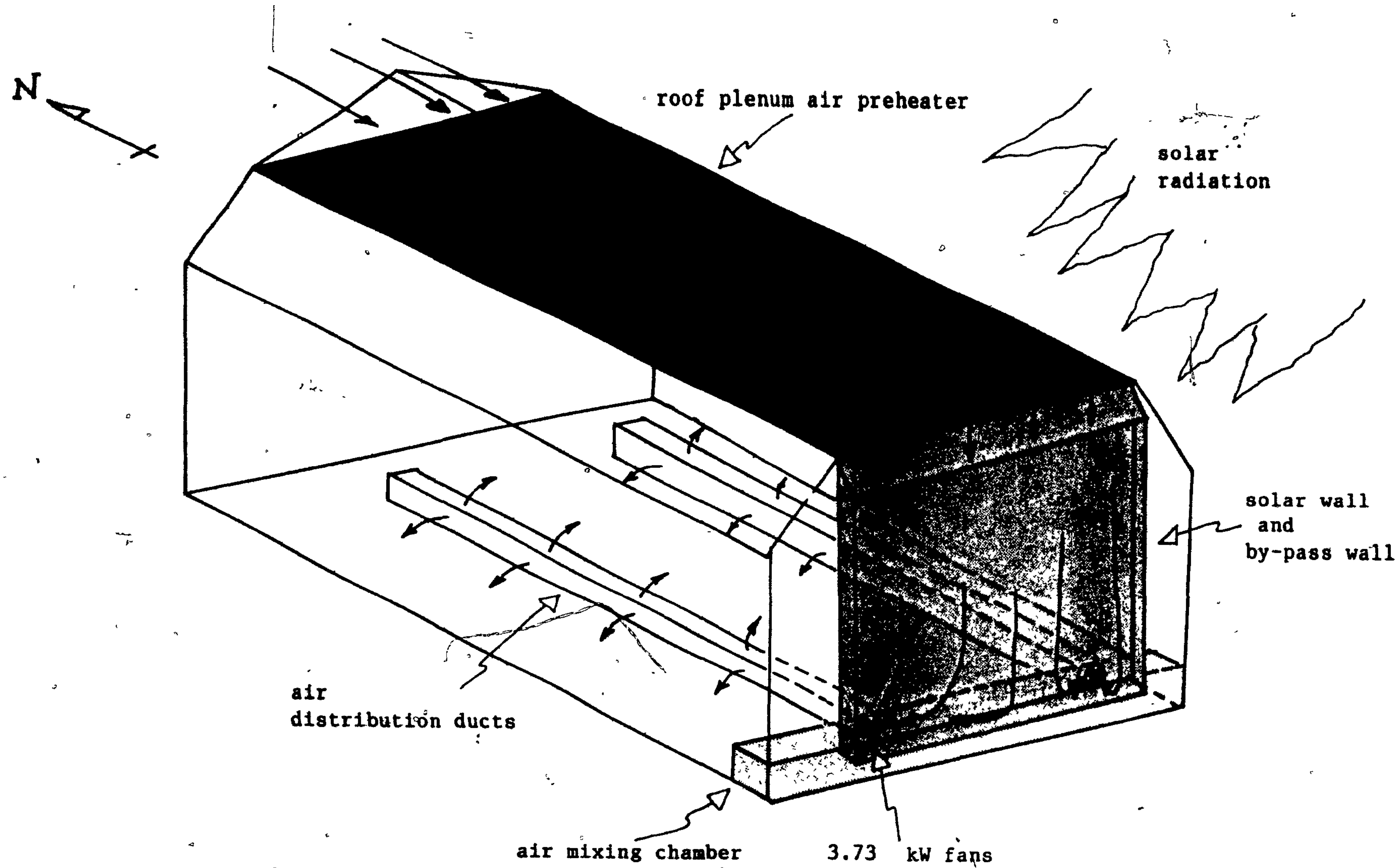


FIGURE 6: Principle of Operation and Major Components of Barn Solar Hay Drying System

Plate A. South Wall of Macdonald College Hay Barn prior to construction.

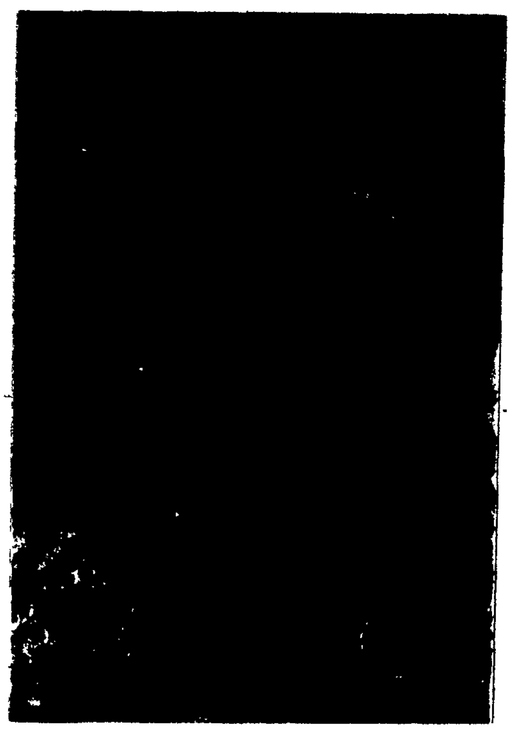


Plate B. View of inner wooden framework of Hay Barn prior to construction.

TABLE II : ESTIMATED AVERAGE VALUES OF MAXIMUM POSSIBLE SOLAR RADIATION COLLECTED ON VARIOUS SURFACES OF THE MACDONALD COLLEGE HAY BARN FOR DIFFERENT MONTHS OF THE SUMMER.

Slope (from horizontal) and orientation of Surface	Area of Surface (m^2)	Maximum Possible Collection of Solar Radiation (heat equivalent kWh/day)			
		June	July	August	September
33° East	104.5	398	420	431	460
33° West	104.5	392	407	414	445
54° East	115	377	402	426	496
54° West	115	343	387	378	472
90° East	150.5	337	378	406	285
90° West	150.5	331	349	388	270
90° South	100	181	197	254	247

3.3.2 Principles of Operation of the Barn Solar Hay Dryer

Before describing the construction details and experimental procedure used in assessing the barn solar hay dryer prototype, a brief outline of the mode of operation of the system is warranted.

The barn solar hay drying system is comprised of six major components. These are: roof plenum air preheater, solar wall air preheater, inner bypass wall, fan suction mixing plenum, two 3.73 kW axial fans, and floor air distribution ducts.

Ambient air enters the system through openings cut into the apex of the north wall of the barn. The air then passes through the roof plenum air preheater. A portion of the solar radiation is absorbed on the galvanized roof of the barn, heating the metal surface which in turn heats the incoming air. Once the air has travelled the full length of the roof plenum, it is subdivided into two air streams: one which flows through the solar wall collector and the other which flows through the inner bypass wall. Solar radiation incident on the south facing vertical collector further heats the drying air. The two air streams in the vertical section are combined in the fan suction mixing chamber which acts to stabilize the temperature and dampen the fan noise. Up to this point, the system is operated under negative pressure. Two 3.73 kW axial fans suck air through the roof plenum preheater, down the solar wall air preheater and into the fan suction mixing plenum. The fans then blow the heated air through the two floor ducts around which is piled the hay. The humid barn air is evacuated through two large triangular openings cut into the south barn wall (Plate M).

3.3.3 Material Selection Criteria and Construction Details

The construction, experimentation and evaluation of a full scale in-situ solar hay drying barn (Phase II) was undertaken at the Macdonald College Farm. Following a two month design phase, the construction of the barn solar hay dryer was carried out from 25 April to 25 June 1983. Experiments on forage and grain drying were undertaken from July through to November 1983. There were two men working full time (40 hours per week) during that period and up to 6 people working on the site for the last four weeks of construction. The assembly time was extended as most of the workers had a minimum amount of experience in this field. It should also be noted that the barn at the Macdonald College farm is a relatively old building (circa

1940) with a complex interior framing, including 8 metre metal floor to ceiling braces, that restricted the work space. For this reason, a number of minor modifications were made to this structure and the sealing of the building took more time. In addition, there was no existing hay drying system in the barn, prior to the experiments. The estimated labour requirements for the entire prototype construction appear in Table III. Construction details of the different components of the hay drying system will be described separately.

Roof Plenum Air Preheater:

The roof plenum air preheater is a bare plate (no glazing) collector which transfers radient energy absorbed by the galvanized roof sheeting to the air stream which is used to dry the hay. The main feature of the preheater is that it makes full use of the roof as a simple solar air heater. The roof surface need not necessarily be painted providing it is well weathered and does not reflect too much of the incident solar radiation. If it is painted flat black or with some dark matt finish, it will absorb more solar energy than without this coating. The roof of the Macdonald College Farm is made of galvanized metal sheets which were deemed sufficiently weathered not to require painting. Holes in the roof were patched with plastic cement to prevent rainwater and/or cool air from entering the preheater.

A method had to be devised for isolating the dry air located underneath the galvanized roof from the humid barn air. The floor of the plenum had to be easy to install, relatively inexpensive and well sealed to prevent humid air from short-circuiting into the drying air stream.

Designers of solar barn hay drying systems in France have gone to great efforts and expense to insulate the air stream being heated by a roof solar collector (Savatier, 1982). In the current design, it was decided that insulation could be omitted as the temperature differential between the temperature leaving the hay stack and the air in the preheater would be quite low. Black polyethylene plastic sheeting (0.15 mm) was stretched across the width of the roof span to create a channel for the air to flow through the preheater and to act as a barrier, also to prevent mixing between the dry and humid air masses in the barn. Polyethylene sheeting is readily available in various lengths and in widths up to 10 metres. This material is relatively inexpensive and easy to handle. The greenhouse industry has developed installation techniques which offer good structural resistance to various types of loading (wind, etc).

One of the techniques adapted to this project was the use of wooden nailing strips and a folding technique to secure the polyethylene sheet lengthwise in the barn. As the design of the roof plenum air preheater was a retrofit to an existing barn, the interior framing members, which included many rafters and furring strips (Plate B), made the sealing of the roof plenum difficult. The plastic sheet had to be cut and fitted to contour existing obstructions in order to prevent warm humid barn air from infiltrating into the drying air stream. The low cost of the polyethylene sheeting allows it to be replaced after approximately 2 to 3 seasons and still be an economical investment.

The main portion of the work done on the roof plenum air preheater was the installation of the 300 m^2 polyethylene sheet. As the barn was practically empty of hay when this construction was undertaken, moveable scaffolding was

TABLE III: ESTIMATED TIME REQUIREMENTS FOR SOLAR HAY DRYING BARN CONSTRUCTION

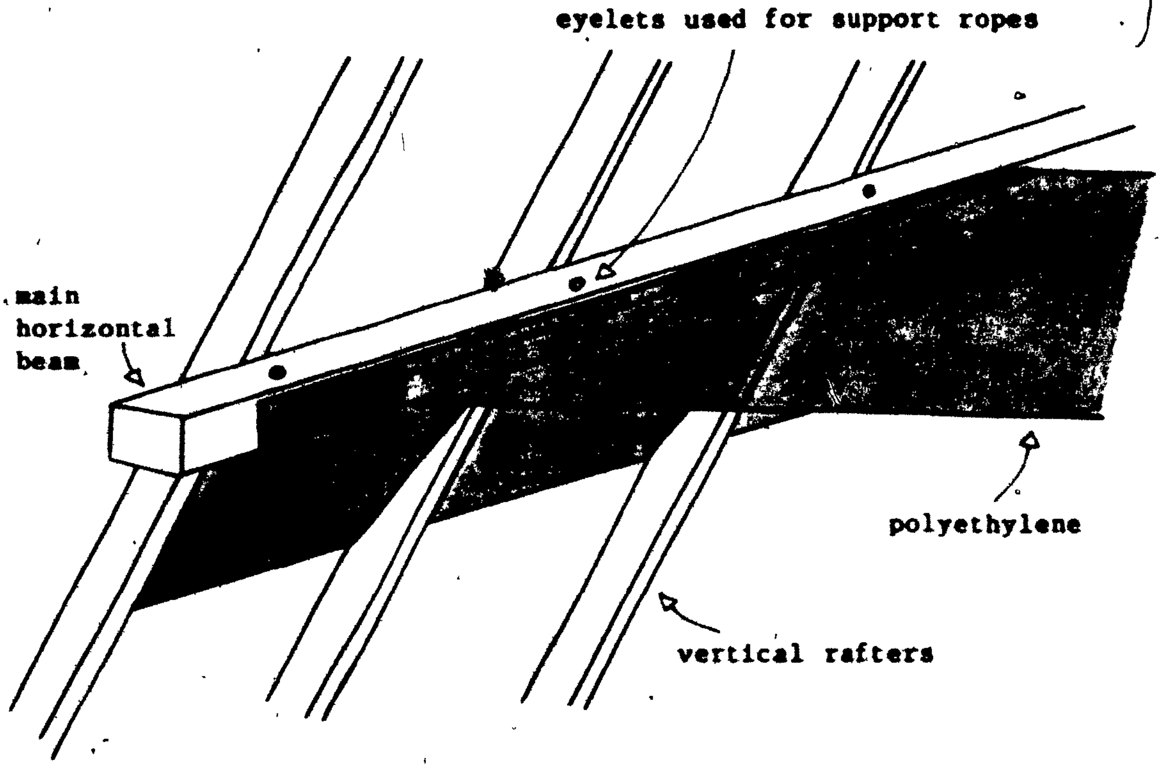
JOB DESCRIPTION	Man Days Required
Levelling of ground inside barn	5
Removal of metal braces in barn	2
Removal of excess hay from work area	5
Construction of floor plenum	20
Sealing of roof of barn	3
Installation of fans (including housing)	5
Preparation of south wall (acid & paint)	3
Construction of Solar Wall Air Preheater (SWAP) frame	15
Installation of metal and glazing in SWAP	15
Sealing and painting in SWAP	5
Making access holes in barn walls	1
Installing screen and frames on these ports	3
Installing the plastic sheeting in roof plenum	15
Constructing inner bypass wall and junction	15
Constructing modular floor ducts	20
Miscellaneous sealing in system	6
Miscellaneous activity (scaffolding,purchases,transporation)	10
Installing instrumentation	10
Total	158

used to reach the apex of the gambrel roof. The use of this equipment proved very satisfactory as the two scaffolding platforms could be moved simultaneously as the plastic was unrolled and fixed in place. The plastic was fastened by folding the sides and overlaying a wooden nailing strip over of this fold. Lengths of polypropylene rope stretched across the roof span, above and below the plastic sheet. These were used to support the weight of the polyethylene in the "off" mode and retain the sheet which tended to bow upward in the operational mode. The polyethylene construction details are found in Figure 7. It should be noted that if a farmer were to install the plastic sheet, he should schedule the work to be done when the hay is piled high in the barn. This would greatly reduce the hazard of working at a dangerous height and simplifying the installation.

The Solar Wall Air Preheater:

The materials used in previous experiments with solar wall air preheaters (or SWAP) have been selected for their relative low cost, structural strength and effectiveness. These materials meet the design criteria described in an earlier section. The SWAP incorporates the basic elements of any solar collector such as: transparent glazing; absorber plate; sealants and frame.

The glazing chosen was corrugated translucent fiberglass reinforced plastic 1.526 kg/m^2 (5 oz. psf) sheets. These are available in 86 cm x 244 cm panels and offer both structural strength and design flexibility. The panels are treated with a protective coating commercially referred to as Excelite R. which prevents ultra-violet deterioration. Corrugated fiberglass is a sturdy material which can withstand the occasional impact that may occur in farm applications. Its installation is simple and the



Detail of Polyethylene Folding Technique

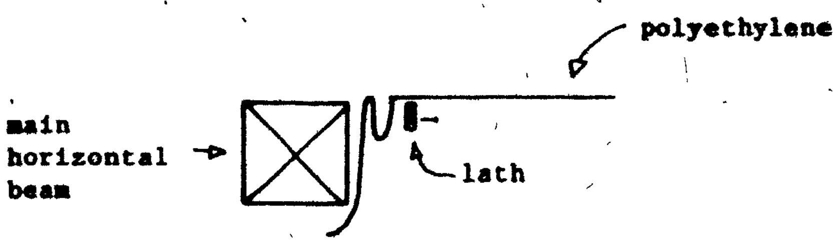


Figure 7: Detail of Roof Plenum Air Preheater Construction

panels can be easily cut to fit any size of collector. Lengths of 19 mm x 19 mm x 1.5 mm (3/4" x 3/4" x 1/16") angle iron were nailed horizontally into the vertical wooden members and the glazing panels were fastened to these using hexagonal screws with neoprene washers.

The absorber plate of the SWAP is the external galvanized metal wall of the barn which is painted with a dark matt finish for optimal performance. The galvanized metal must be pre-treated before painting. An acid etch is recommended, using muriatic acid, to enable the paint to adhere to the metal surface. Black paint was chosen in this application (Plates C, D and E).

An additional absorber surface was included in the form of a black fiberglass mesh. This material is commonly used as screening for windows and offers increased surface area for energy collection and additional heat transfer surface for the passing air stream. The mesh actually oscillates slightly which increases the heat transfer from the heated fiberglass to the air. This mesh was installed parallel to the wall, mid-way between the glazing and the absorber plate. The mesh allows approximately 55% transmissivity of incident solar radiation onto the absorber plate (Brace Research Institute, 1981).

Silicone caulking was used as a sealant between the glazing panels and around the frame. It is very elastic, will not crack with time and adheres well to most construction materials.

The frame of the SWAP was made of construction grade lumber. Spruce was used for the frame which was nailed directly onto the barn wall. The wooden members were toe-nailed into the barn's inner furring strips using 89 mm (3-

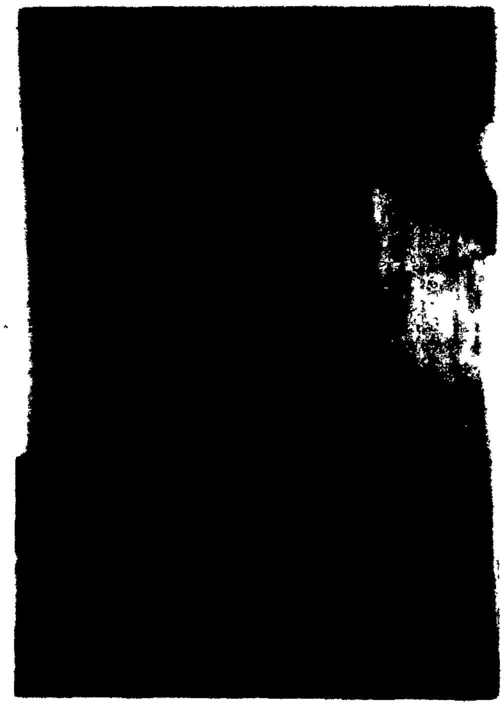


Plate C. Installation of scaffolding for the construction of the Solar Wall Air Preheater (south wall).

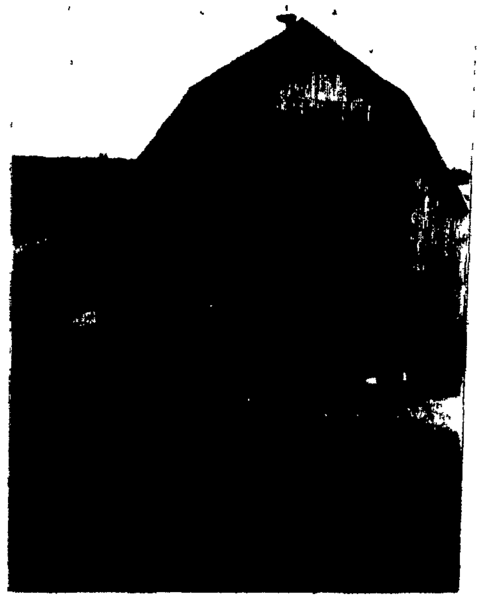


Plate D. Painting of the exterior south wall to be used as the absorber plate of the Solar Wall Collector.

Plate E. South wall of Hay Barn painted flat black.

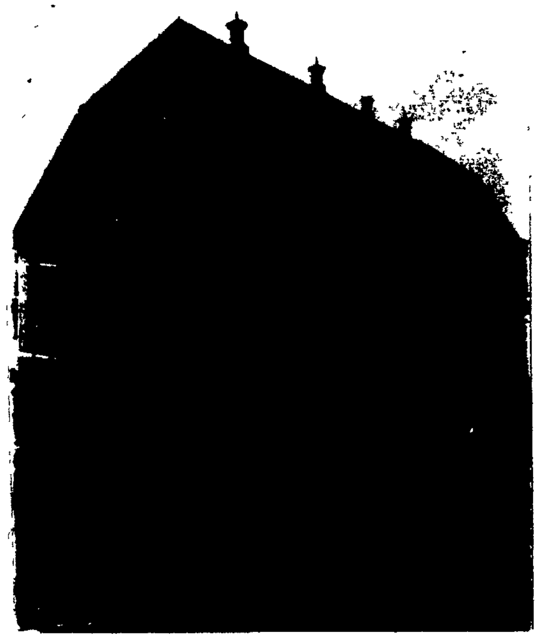


Plate F. Installation of wooden members in the construction of the twelve air channels.

1/2") spiral nails. The interior and exterior surfaces of the frame were painted flat black for maximum radiation absorption. Based on an airflow speed of less than 5 m/s in the solar wall, a space of 178 mm (7") was constructed between the absorber plate and the glazing. This space was provided by two pieces of 38 mm x 89 mm (2" x 4") spruce nailed on end. The frame provided twelve vertical channels through which the air would pass (Plate F). Openings were cut in the galvanized siding at the top and bottom of the vertical channels to permit the air from the roof plenum air preheater to enter into and exit from the SWAP collector (Plate H). A door was constructed above the SWAP to provide access to the roof plenum for air measurement and repair purposes. The junction between the roof plenum air preheater and the vertical section was sloped to reduce the abrupt directional change of the air path and lessen airflow resistance (Figure 8). Pieces of galvanized flashing were nailed at a steep angle at the top of the SWAP to prevent pigeons and other birds from perching on the collector. A detailed drawing of the solar wall air preheater (SWAP) construction is found in Figures 9 and 10.

The Solar Wall Air Preheater (SWAP) was constructed following the design established at Brace Research Institute. Scaffolding was used to reach the different levels in the construction of the SWAP.

The Inner Bypass Wall:

An inner bypass wall was built in order to accommodate the considerable airflows needed to dry hay inside a barn. The airflow resistance on the suction side of the fan had to be kept to a minimum for adequate fan discharge. The total airflow through the hay drying system was rated by the two manufacturer's fans to be above 1370 m^3/minute (48400 cfm) at zero

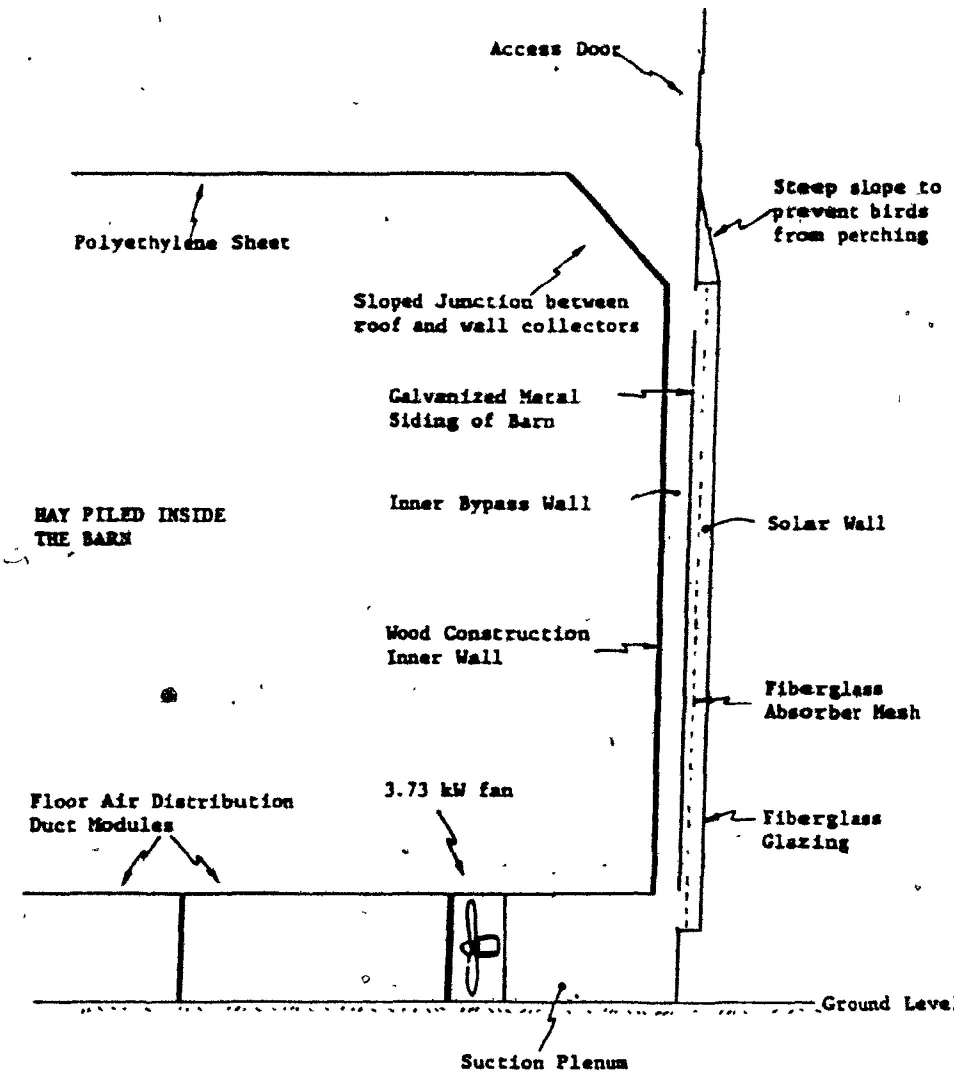


Figure 8: Section View through South Wall of the Barn, showing Solar Wall and Other System Components (not to scale).

Plate G. Installation of the fiberglass absorber mesh in the solar wall.

Plate H. Cutting the openings in the bottom of the channels of solar wall

Plate I. Installation of the angle iron lengths which support the glazing.

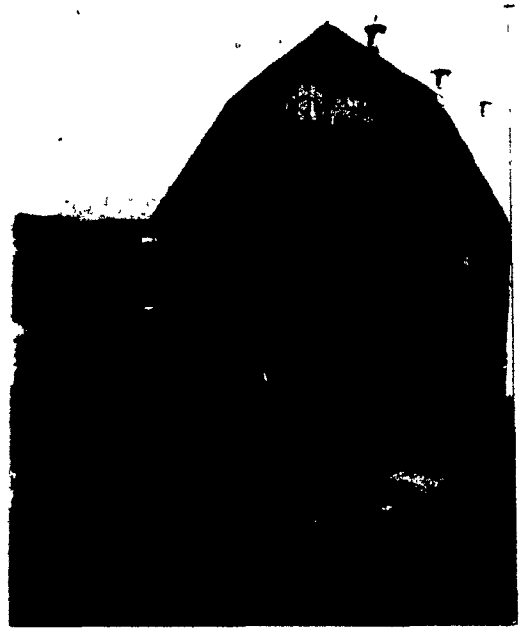


Plate J. Completion of the vertical channels.

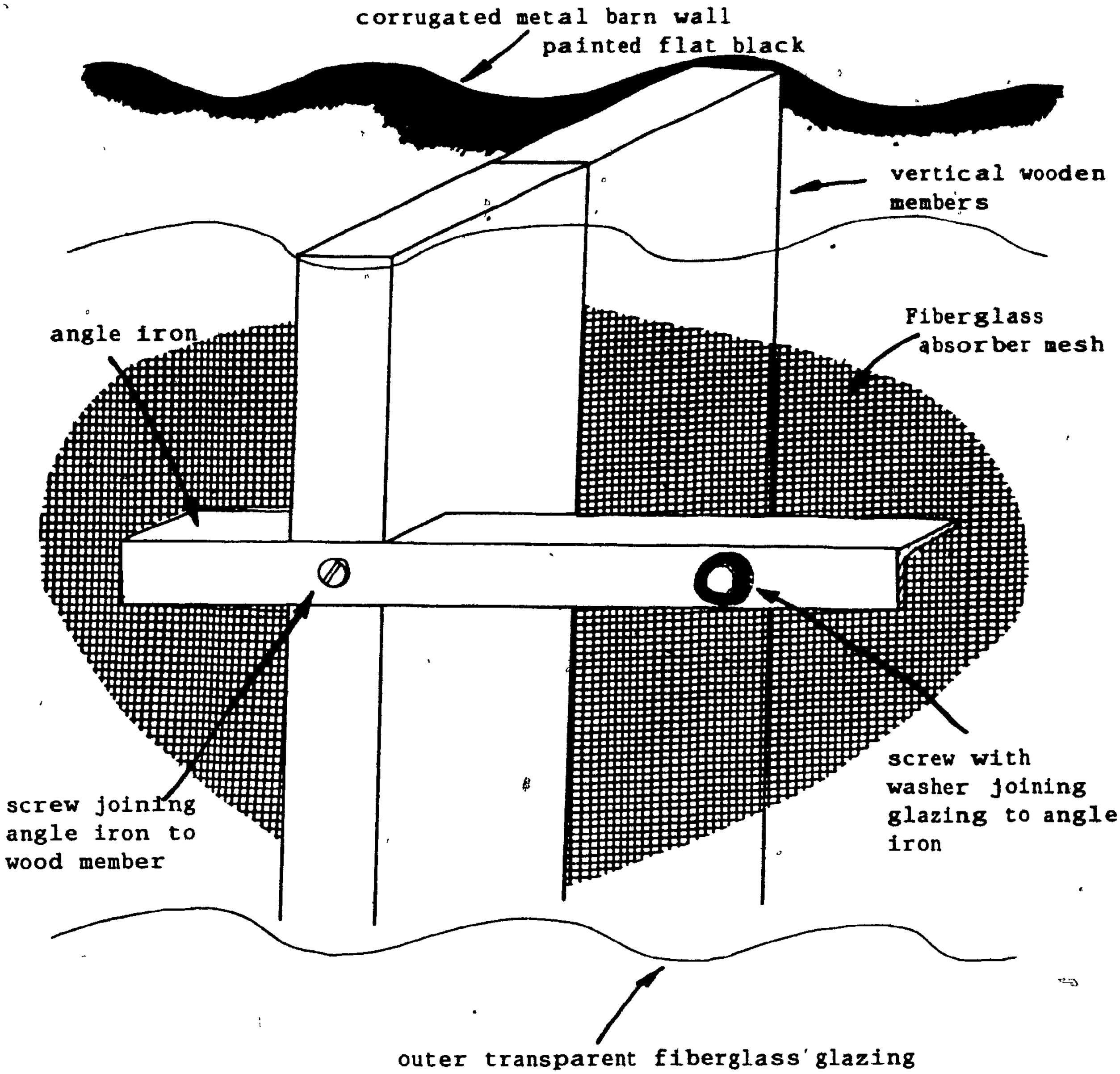


Figure 9: **Detail of Solar Wall Air Preheater Construction (not to scale)**

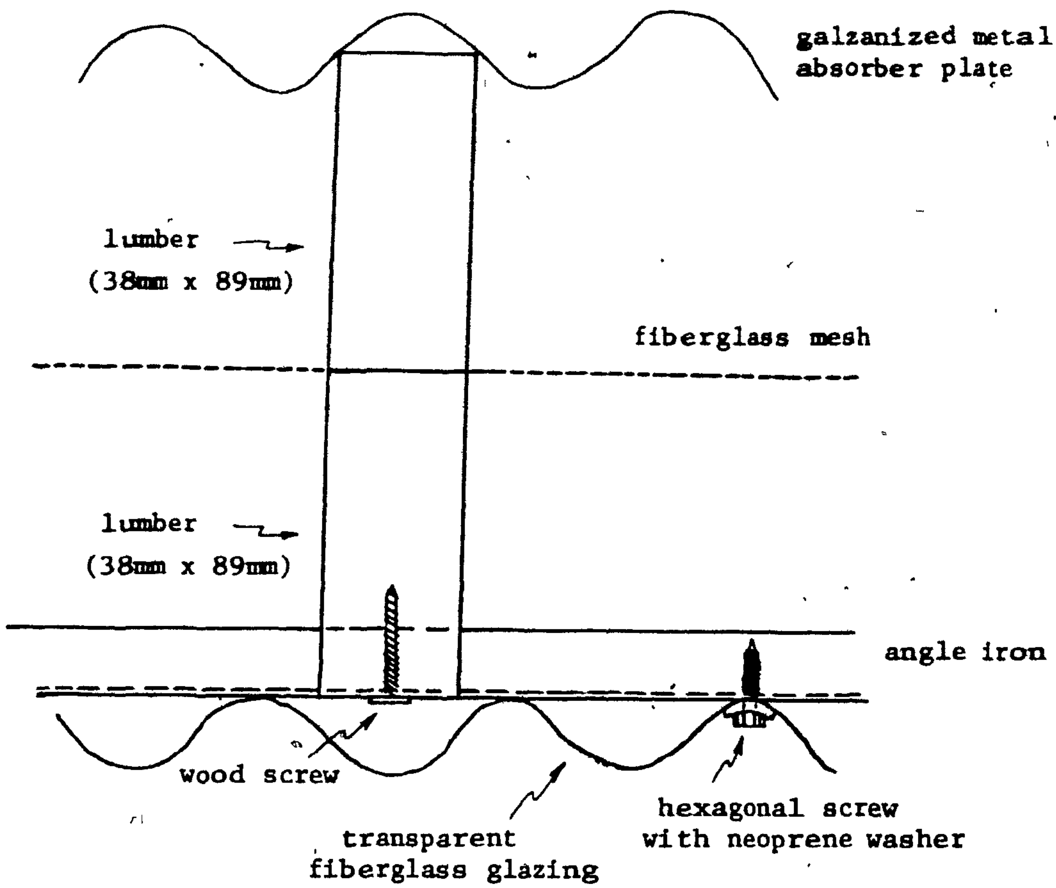


Figure 10 : Section view through Solar Wall Air Preheater.
(not to scale).

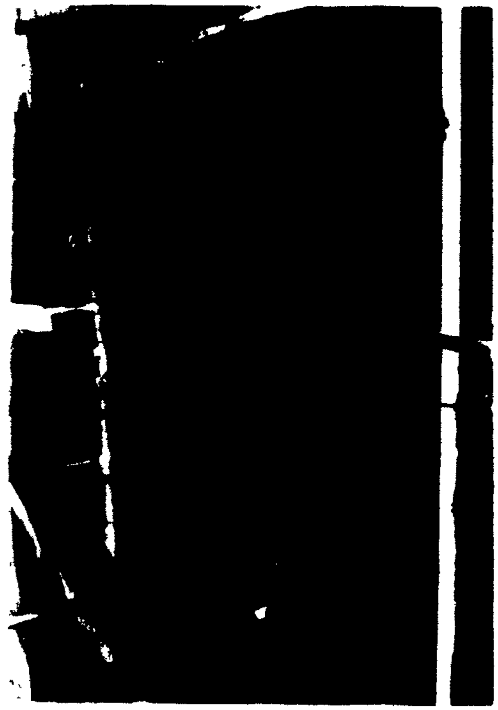


Plate K. Detail of the solar wall in construction.

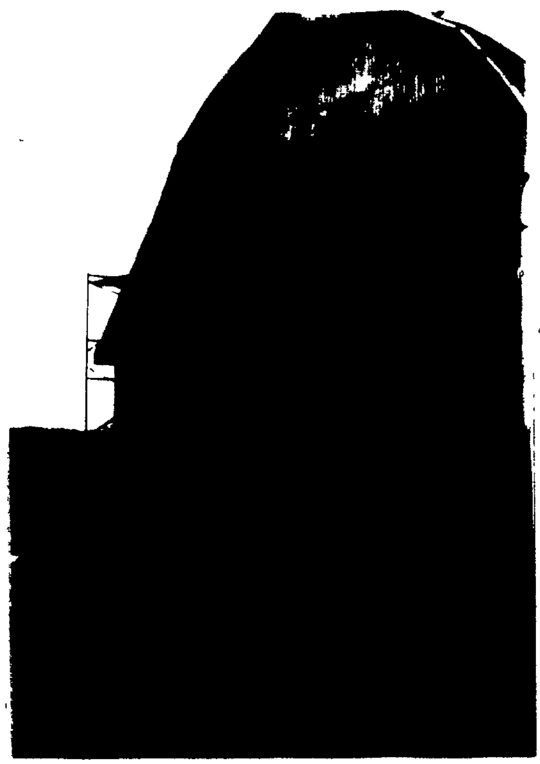


Plate L. Solar wall with one half of glazing installed.

static pressure. The amount of air passing through the SWAP had to be reduced by shunting a portion of the air through an inner bypass wall. The critical air speed in the solar wall is 5 m/s. Higher velocities put undue stress on the fiberglass glazing and significantly decrease the heat transfer characteristics in the collector. Approximately one third of the total airflow of the hay drying system passes through the SWAP. The remaining two thirds of the flow is passed through an air space 30 cm deep on the inside of the galvanized barn wall (inner bypass). This air passage was built overtop of the existing inner wooden framing of the barn (see Figure 11). Lengths of 38 mm x 38 mm (2" x 2") spruce were used to enlarge the passage and support the 6.4 mm (1/4") aspenite sheets which provided the inner covering of the wall. A series of holes (25 mm in diameter) were drilled in the horizontal beams which otherwise blocked the airflow in the bypass passage. Caulking was applied along all joints to prevent air leakage. The inner bypass wall area is 58 m^2.

Fan Suction Mixing Plenum:

The air from the SWAP and inner bypass wall empties into a mixing suction plenum, which allows the incoming air temperatures to stabilize. This plenum has a 1.2 m^2 cross sectional area and is 7.2 m long for a total volume of 8.6 m^3. This plenum extends the entire width of the barn and is made of 38 mm x 89 mm (2" x 4") framing members covered with 16 mm (5/8") plywood. All joints are sealed with caulking. The solar wall and the inner bypass wall open into the floor plenum so as to keep the pressure drop to a minimum. Two 1.2 m x 1.2 m openings were installed to connect both fans. These two openings were covered with a 12 gauge steel mesh to prevent leaves and other debris from entering the fans as well as for safety. Two small 2.25 m^3 compartments were built at the east and west extremities of the

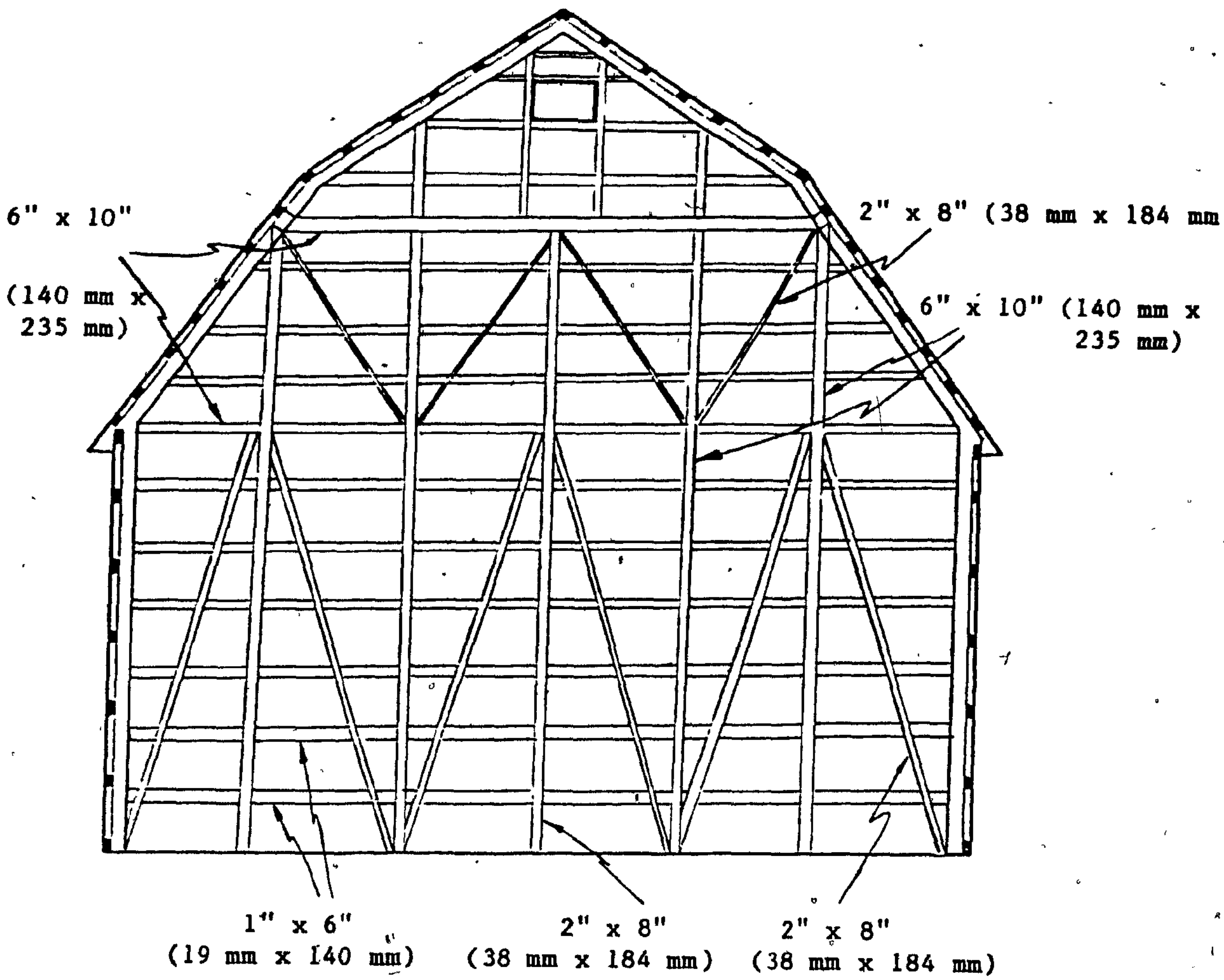


Figure 11: Sketch of Lumber Framework on Inside of Barn South Wall. Units for lumber are specified in British nominal units.

plenum in order to store equipment, house the instrumentation (digital recorder, etc.) and serve as access ports (Figure 3.12). Access to the mixing chamber through the east and west doors was also provided for observations, manual instrumentation, monitoring, maintenance and repairs. The fan suction mixing plenum also reduces the internal air pressure resistance on the suction side of the system and dampens the fan noise.

Fans and Floor Ducts:

Two fans were required to supply the required airflow for the barn. The selection was based on the maximum airflow delivered at the minimal cost. It was believed more appropriate to choose the type of fans that were available to the farmer and those most likely to be found in existing hay drying systems. A list of Quebec and Eastern Ontario suppliers is included in the Appendix.

The fans selected were two Lajoie 3.73 kW hay dryer axial type fans equipped with eight blades with a diameter of 0.92 metres (36"). Each fan was rated at 460 m^3/min at 2.5 cm static pressure. The manufacturer's specifications appear in the Appendix.

The two floor duct tunnels were made as modular wooden frames placed end to end, these could be stored vertically when the barn was empty of hay. Sixteen modular floor duct units were built for the two airflow distribution tunnels. Each unit measured 305 cm in length and had a cross sectional area of 1.2 m^2. These frames were constructed of 38 mm x 89 mm (2" x

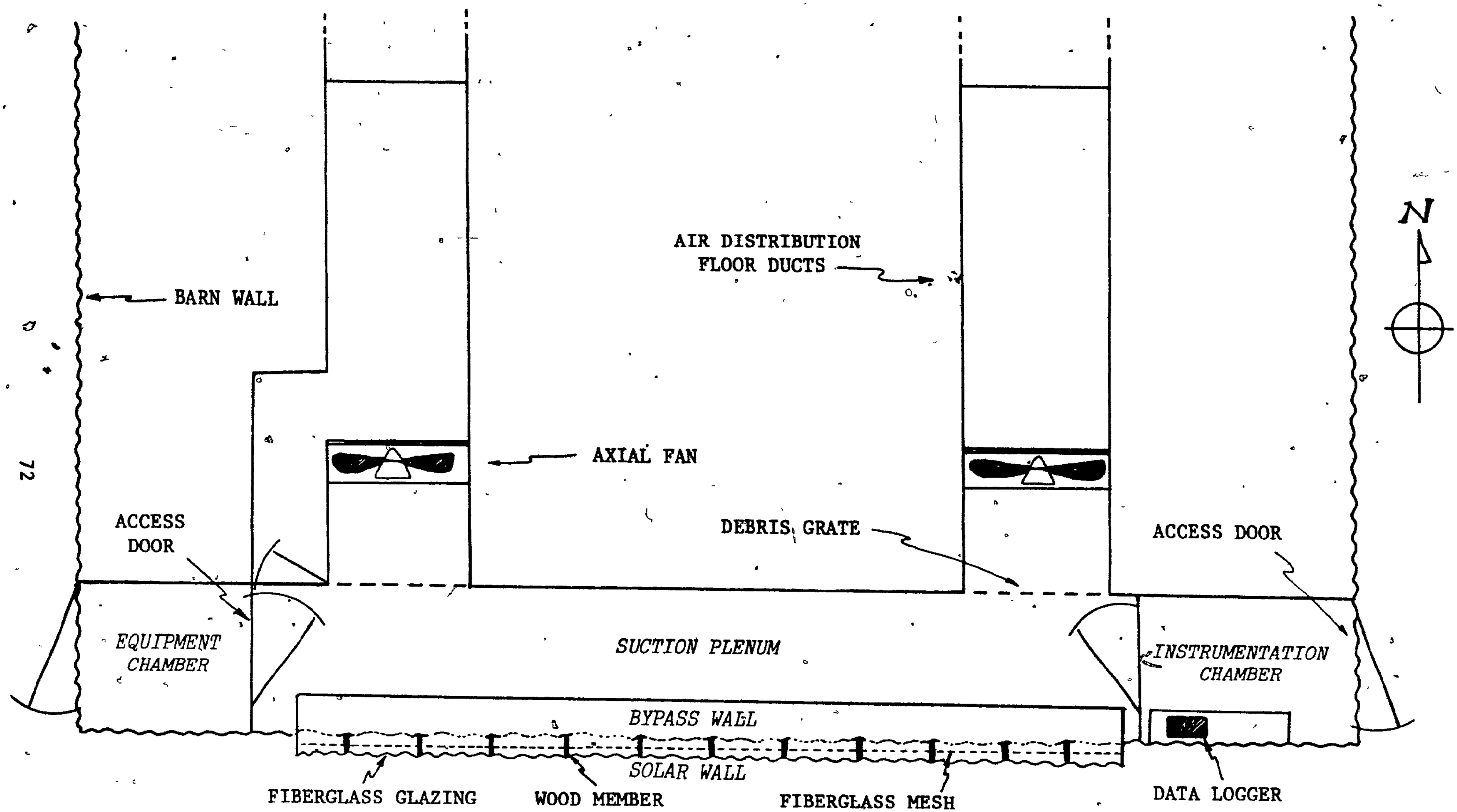


Figure 12 : Floor plan of south section of Barn Solar Hay Dryer (not to scale).

4") with 19 mm x 38 mm (1" x 2") strips nailed on the top and sides to prevent hay bales from falling into the duct. Gusset plates and braces support the corners. A sheet of polyethylene (0.15 mm) was set on top of each duct to direct the air to the back of the barn furthest away from the fan where the hay was being dried. As a section of hay was dried this plastic sheath was retracted and a board installed in the duct to block the air from short circuiting through the already dried hay section. This rudimentary damper control system permitted the drying in different areas of the barn providing that the hay was always loaded from the far end (i.e. away from the fans).

3.3.4 Dryer Operation

The operation of a Barn Solar Hay Dryer system is similar to that of a conventional forced convection hay dryer. As the solar collection system requires no special controls, the only basic difference is on the discharge side of the fan where care must be taken to direct the heated air to the area where the moist hay is placed. Once the hay is properly loaded into the barn, the fans can be switched on and should remain in operation until the uppermost lot of hay (the furthest away from the fans) is sufficiently dry.

Pre-Loading Procedure:

Hay which has wilted several hours in the field can be baled and loaded into the barn at a moisture content as high as 45%, dry base. The hay dryer should be made ready before the hay enters the barn. These preparations include verification of the following points:

- the fans are secure and operational;
- there are no major air leaks in the system on the suction side of the fan;

- the airflow distribution system on the discharge side of the fan has been carefully designed and installed;
- a simple static pressure measuring device has been installed in the airflow distribution tunnels in order to detect air leakage through the hay stack and determine the end of the drying cycle. A simple water filled U-tube is commonly used for this purpose.

Loading Procedure:

The hay may then be loaded on top of the airflow distribution ducts. The air should only be allowed to penetrate the zone which is going to be dried. The distribution duct may contain dampers or control doors to direct the air in a given section of the barn.

Due to construction delays, the Phase II experiments were started after a number of bales had already been field dried and were stored in the north section of the barn. Details of the dates, composition, number of bales and initial moisture contents of the different lots of hay can be found in Table IV. The loading schedule of the Macdonald College hay barn for the 1983 season is illustrated in Figures 13 and 14. These schematics indicate the exact location within the barn for each load of hay to be dried.

The bales were brought into the barn using a bale elevator. Two galvanized metal roofing panels located below the roof plenum plastic sheet were removed and the bales were emptied into the barn through this opening. The bales were placed by hand throughout the drying operation. The first lots of bales were set around the floor ducts and subsequent loads were placed in

TABLE IV : LOADING SCHEDULE FOR BARN SOLAR HAY DRYER 1983 SEASON

DATE	NUMBER OF BALES LOADED IN BARN	HAY TYPE	INITIAL MOISTURE CONTENT (% w.b.)
16 June	800	alfalfa	-
20 June	1165	80% alfalfa	-
24 June	700	80% alfalfa	-
29 June	775	80% alfalfa	-
Subtotal:	3440		
All bales loaded to this point were field cured and stored in barn			
30 June - 1 July	325	mixed Timothy grass	25.9
6 July	325	mixed Timothy grass	29.5
7 July	820	mixed Timothy grass	31.2
19 - 20 July	760	50% alfalfa	29.5
22 - 25 July	680	alfalfa	32.0
27 July - 16 Aug.	1500	alfalfa	30.1
Subtotal:	4410	MEAN =	29.5

Total number of bales loaded in barn = 7850 bales

N.B. Each bale measured 18" x 18" x 40" (0.46 m x 0.46 m x 0.91 m) = 0.212 m^3

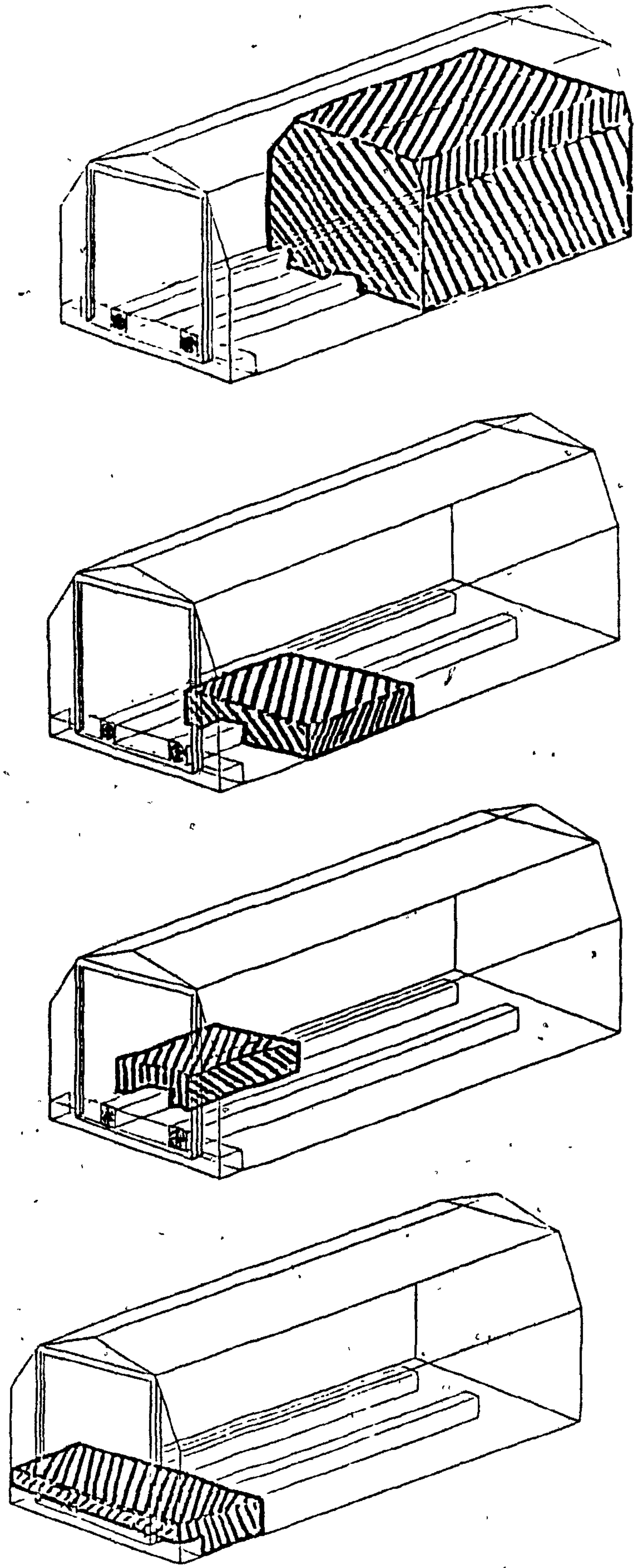


Figure 13 : Schematic of hay barn loading during 1983 season, 30 June to 7 July 1983.

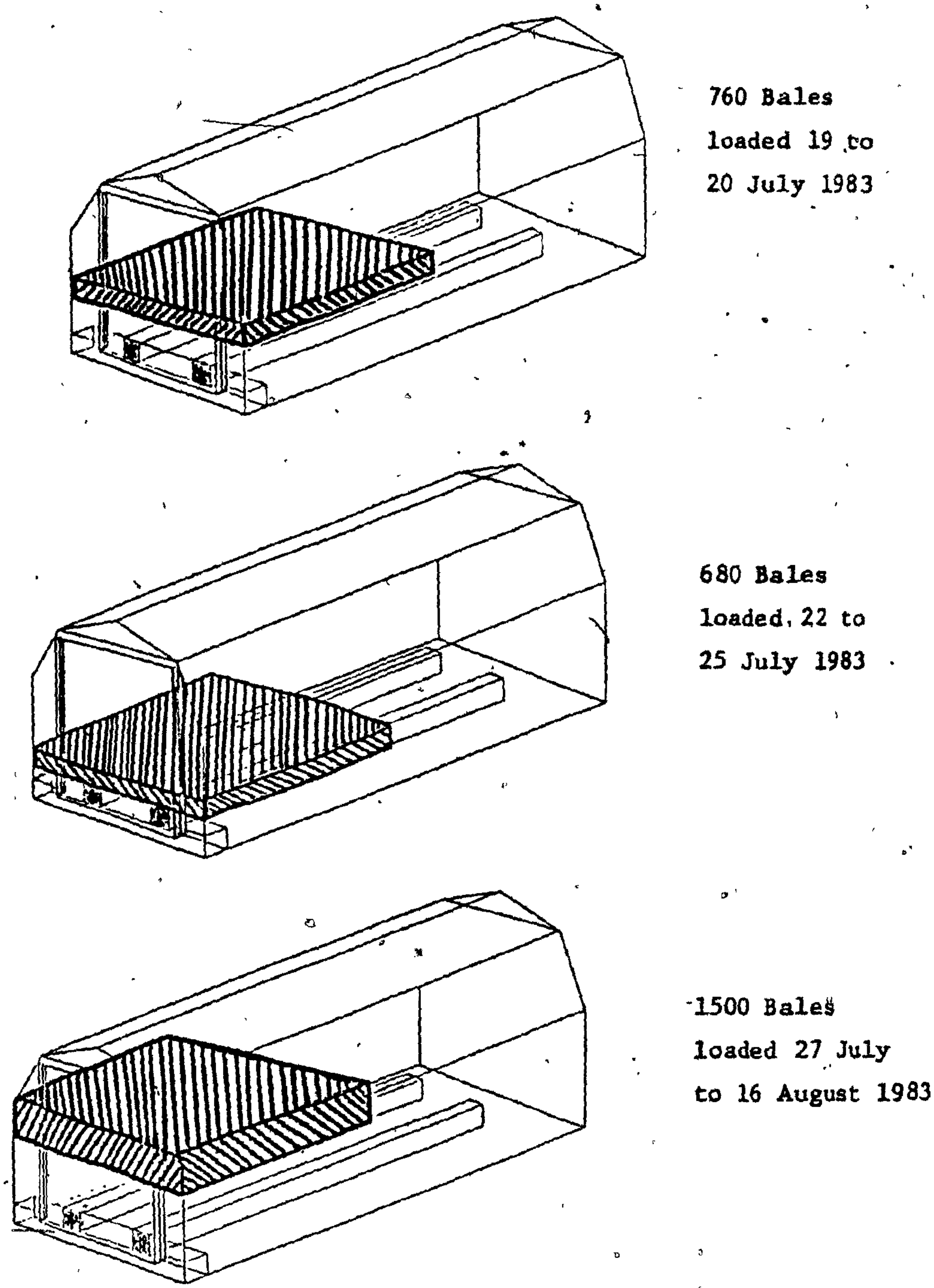


Figure 14 : Schematic of hay barn loading during 1983 season 19 July to 16 August 1983

layers over the floor area of the barn.

The bales were tightly packed and interlocked in alternating perpendicular rows (Figure 15). The bales were set so that the airflow from the ducts would blow parallel to the cut stalks of the forage. This is the recommended loading procedure and allows for good airflow distribution through the stack. As the back portion of the barn was loaded with dry hay, an airflow barrier was erected to separate the dry hay from the fresh, moist hay. A polyethylene sheet was draped the entire width of the barn, which prevented the air from the fan discharge to escape through the dry hay, which is the path of least resistance.

Drying Procedure:

Once approximately 1.2 metres of moist hay was piled on top of the ducts, the fans were started. The starting switch was located far enough away from the dry hay area to avoid any fire hazard originating from a stray electrical spark. A static pressure on the fan discharge of about 1.2 cm of water was measured in a U-tube manometers. If the static pressure is much less than this, then there are probably some air leaks through the hay stack which should be blocked with loose hay before more hay is added. The fans should be operated throughout the drying period. In the experiments carried out in Phase II, the fans remained in operation during the entire summer in order to obtain the most amount of performance data from the solar collection system.

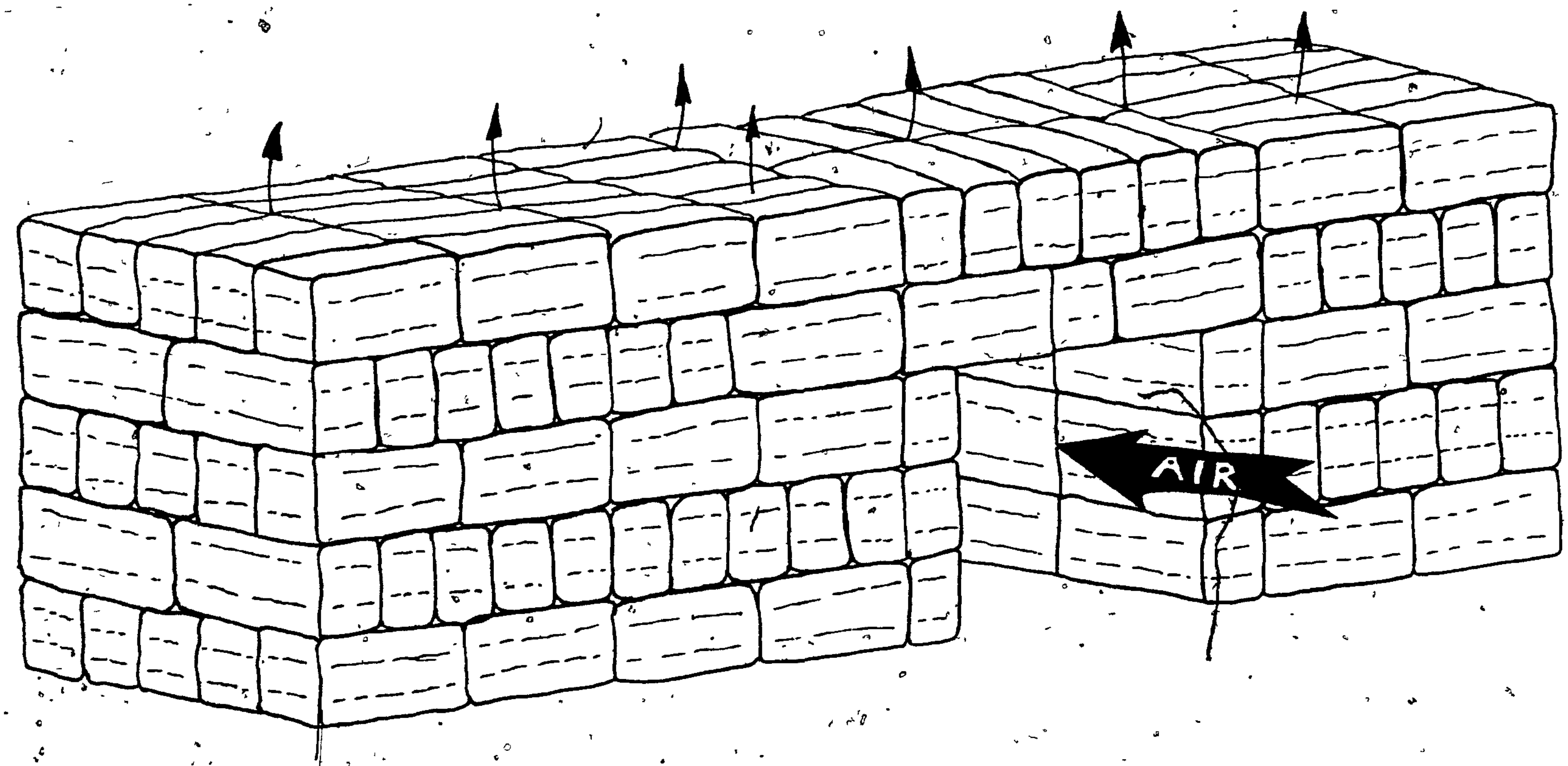


Figure 15: Sketch showing Bale Packing Arrangement used in the Hay Barn.

As the loading of hay in a typical case would occur on a somewhat continuous basis for the three or four cuts of hay, the fans may be operating non-stop throughout the summer months. The fans may be stopped between cuts if the last bales loaded into the barn have sufficiently dried. Spot checks of the hay moisture content would have indicated if it is safe to stop the fans. One easy verification can be done by stopping the fans overnight and starting them again the following morning. If the first air exiting the stack in the morning is warm, respiration has probably not stabilized and the hay should be dried further.

Forage Moisture Content Measurement:

The bales dried in the Macdonald College hay barn were brought into the building at moisture content levels varying between 25% and 42% dry basis. More than four thousand bales were dried with the barn solar hay dryer. The incoming hay from different loadings was sampled and the initial moisture content for every load was determined. One test sample was made up from hay taken from the core of between 15 and 20 bales in order to obtain a representative sample. The samples were oven-dried following the standard forage moisture measurement procedure (24 hours at 70°C). A progressive drying test in the Phase II experiments was carried out for the last load of hay from the first cut (from 7 to 14 July 1983). This test gives an indication of some of the possible drying rates of hay in the full scale application.

Although no in-depth quality evaluation was carried out for the Phase II tests, it should be noted that there has been a marked improvement of the hay quality on the farm since the installation of an artificial dryer. The barn dried hay is greener, less brittle, has a sweeter smell to it and contains more leaves than the hay which was dried in the field. The only way to evaluate the difference between ambient and solar heated fan drying on a full scale operation would be to conduct side-by-side simultaneous full scale drying trials.

Proposed System Maintenance:

The maintenance of the system should include the following items:

- annual verification that the fans are in good working order;
- verification that no leaks have developed in the solar collectors on the suction side of the fans;
- verification of the glazing and absorber surfaces for deterioration from solar radiation or other abrasions;
- occasional cleaning of the glazing and/or absorber surfaces from dust and other deposits;
- verification that the roof plenum air preheater plastic has not deteriorated or ripped along its edges;
- repainting of the absorber surfaces (wherever possible) if these surfaces become excessively worn.

The overall system maintenance should be carried out in the spring prior to the loading of the barn. Alternatively, repairs in the plastic of the roof plenum preheater should be carried out in the autumn while the hay stack could serve as a scaffolding to reach the apex of the barn.

Energy Saving Mechanisms:

The energy costs of operating a barn solar hay dryer can be reduced by good dryer management. This entails stopping the fans if the latest load of hay being dried has reached the equilibrium moisture content. Avoid overloading the dryer as spoilage of the hay may occur due to insufficient and uneven drying. It has been noted that several energy saving devices have been incorporated in forced convection hay drying systems. One of these involves the intermittent operation of the fans during the nocturnal period. An automatic timer can be used to operate the fans for 15 minutes every hour between 20:00 hours and 06:00 hours. This allows the removal of the respiration heat from the hay stack thus eliminating the risk of spontaneous combustion and fire. This mechanism also lessens the amount of moisture content reabsorption during the night-time hours. The timer may also be used during the daytime to shut down the fans if the relative humidity is excessively high.

Another automatic system uses thermocouples to detect whether there is a difference in relative humidity between the entering air and the air exiting the top of the stack. If no gradient exists, then the fans are turned off automatically. This avoids the problem of overdrying the forage, thus deteriorating its quality and wasting electrical energy.

3.3.5 Instrumentation of the Barn Solar Hay Dryer

Much of the instrumentation which was used in the comparative drying tests (Phase I) was re-used at the site of the full scale hay drying barn. The following equipment was used to monitor the experiments in Phase II:

- Anaconda Continental T-type thermocouple wire (16 and 24 guage)
- Digistrip III model DR3-1A data logger

- Haenni model Solar-118 insolometer
- Hollis Geosystems Corp., Model MR5 solarimeters (constant = 13.95 $W/m^2/mV$)
- Kipp and Zonen CM2 solarimeter (Constant = 94.22 W/m^2 / mV)
- T.S.I. Inc. Model 150-2 hot wire anemometer
- Lambrecht cup-counter anemometer
- Dwyer inclined water guage
- Bacharach model 12-7013 sling psychrometer
- Fisher Scientific Model 15000B thermometer

The thermocouples, solarimeters and cup anemometer were connected to the datalogger located in the instrument compartment of the floor plenum. These installations are illustrated in Figures 16 to 19.

The Digistrip recorded the millivolt signals, translated them into engineering units (i.e. watts, °C, etc) and averaged them every 10 seconds printing a combined average value every 30 minutes in a tabular form. The Hollis Geosystems MR5 solarimeters were mounted on the east and west slopes at the apex of the barn roof. The Kipp and Zonen solarimeter was mounted on the south facing wall. The hot wire anemometer was used to measure the air velocity in the floor duct and vertical wall collectors. The measured airflow rate was then compared to the characteristic fan curve supplied by the fan manufacturer. The static pressure in the floor duct was recorded manually using the Dwyer inclined water guage. The relative humidity measurements of the ambient air and the humid barn air were measured using the sling psychrometer thermocouples (24 gauge) with cloth wicks and water containers were used to record relative humidity in different points in the solar collectors.

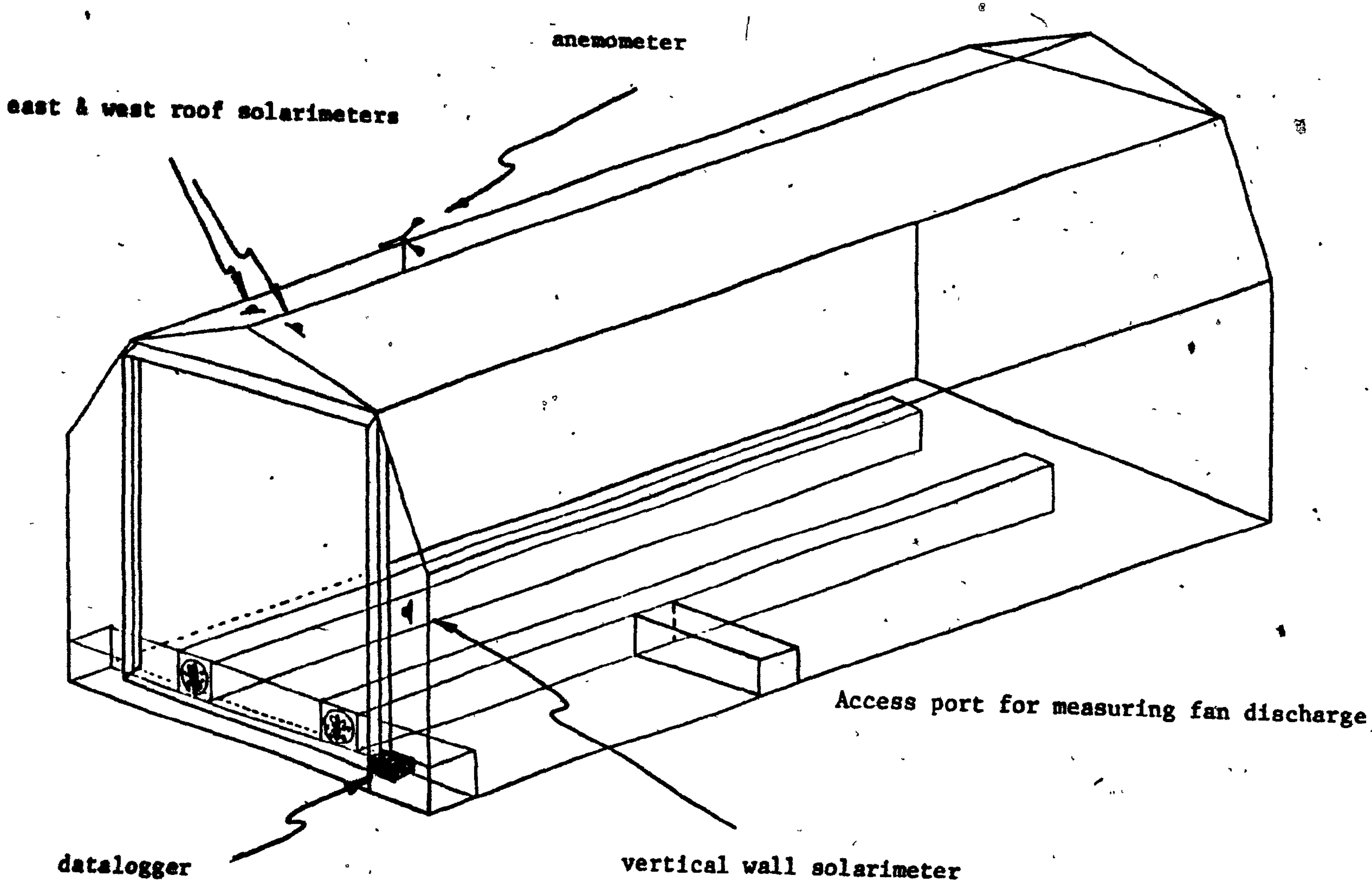
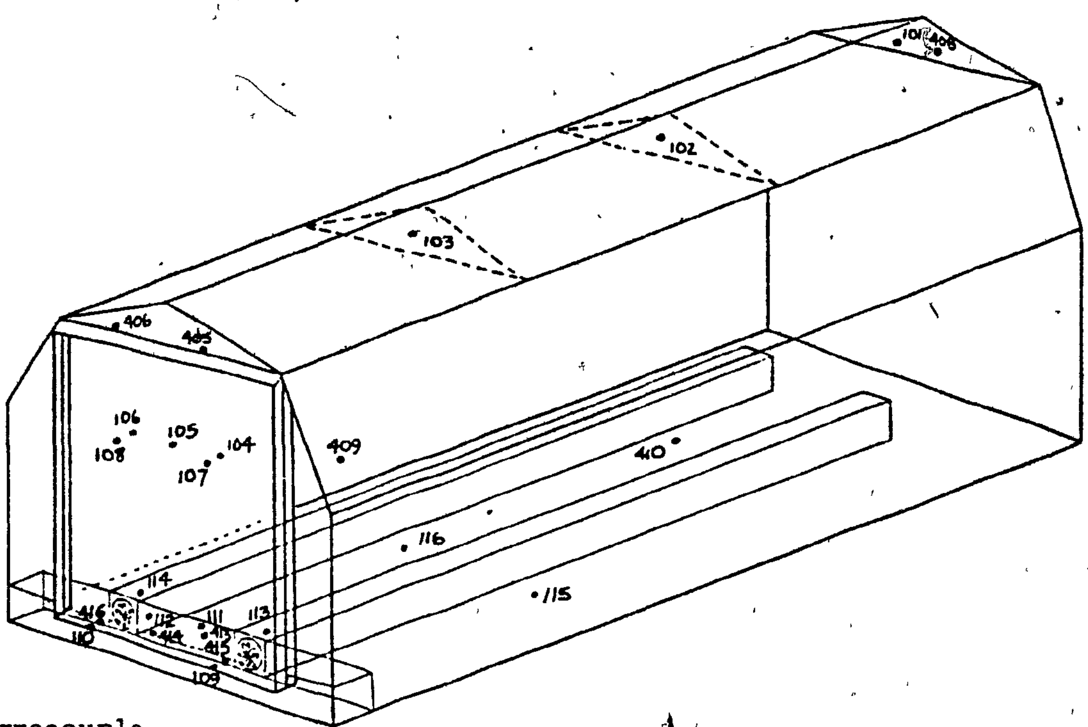


Figure 16: Location of Wind and Solar Instrumentation used in Phase II Experiments.



Thermocouple

101 Ambient air
102 Roof Preheater (1/3 length of barn)
103 Roof Preheater (2/3 length of barn)
104 East Bypass Wall (1/3 distance from top)
105 Middle Bypass Wall (1/3 distance from top)
106 West Bypass Wall (1/3 distance from top)
107 East Solar Wall (1/3 distance from top)
108 West Solar Wall (1/3 distance from top)
109 Bottom of Solar Wall (East)
110 Bottom of Solar Wall (West)
111 Mixing Duct (East)
112 Mixing Duct (West)
113 After the East Fan
114 After the West Fan
115 Temperature inside the Hay Stack
116 Temperature inside the Hay Stack
405 Roof Plenum/Solar Wall Junction (East)
406 Roof Plenum/Solar Wall Junction (West)
408 Ambient air (wet bulb)
409 Temperature inside the Hay Stack
410 Temperature inside the Hay Stack
413 Mixing Duct (wet bulb)
414 Mixing Duct (wet bulb)
415 Bottom of Bypass Wall
416 Bottom of Bypass Wall

All thermocouples measure dry bulb temperatures (°C) unless indicated otherwise.

Figure 17: Location of Thermocouples used in Phase II Experiments

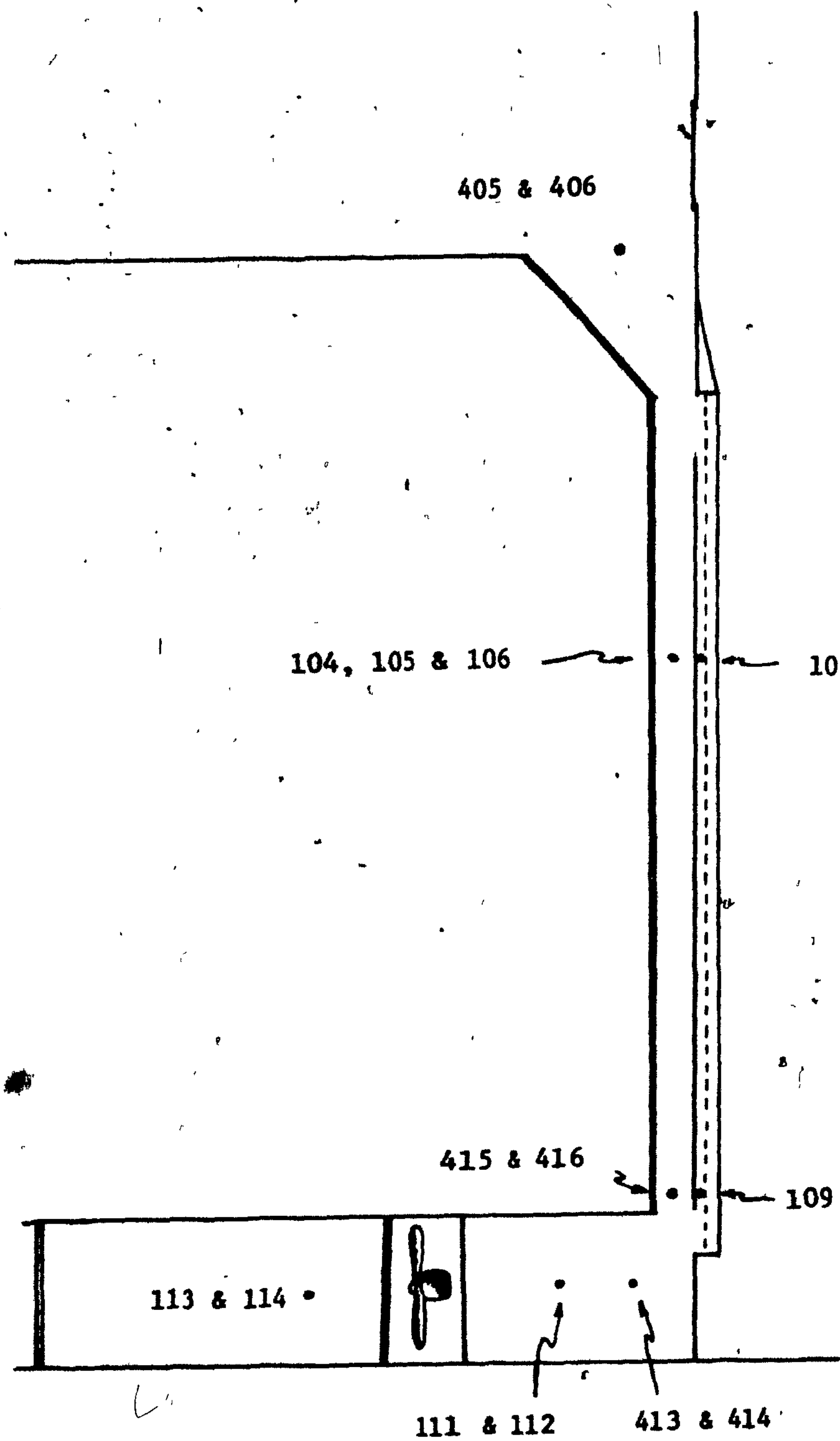


Figure 18 : Section View of Solar Wall, By-Pass Wall and Suction Plenum showing Thermocouple Locations

Numbers indicate the thermocouple channels

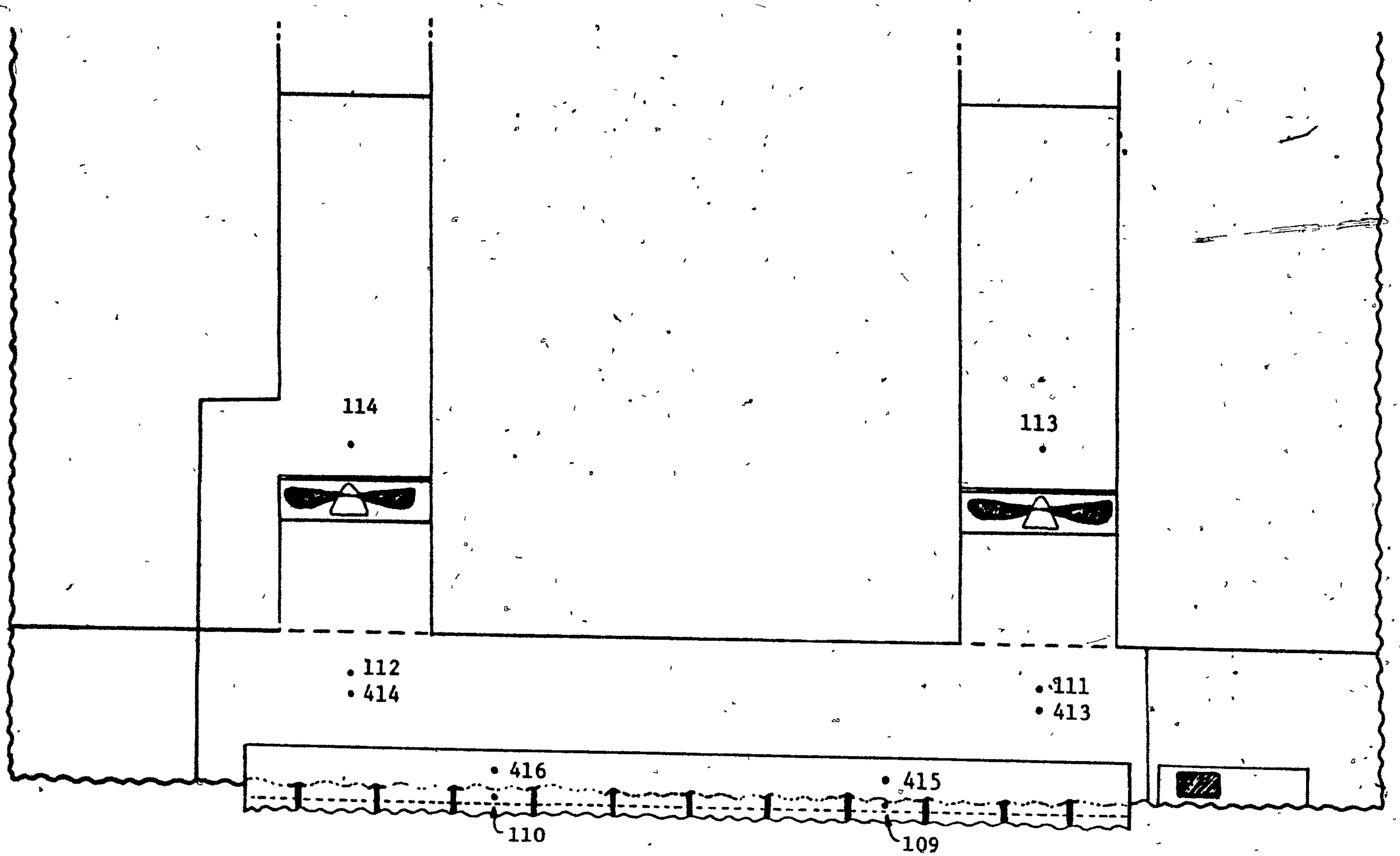


Figure 19 : Plan View of Solar Wall, By-Pass Wall and Suction Plenum showing Thermocouple Locations
The numbers indicate the thermocouple channels.

Plate M. Solar Wall Air Preheater after completion.

The moisture content of the forage was measured with several commercially available moisture testers namely:

- Delmhorst Model F-4 hay moisture detector
- Dickey-John Model FMT crop moisture tester
- Koster Model C crop moisture tester

These instruments were tested and compared to the conventional (24 hour at 70°C) forage moisture content analysis in a standard laboratory oven located in the Department of Agricultural Engineering at Macdonald College.

3.3.6 Test Procedures

The experiments conducted in Phase II (full scale prototype evaluation) were undertaken between 30 June and 25 August 1983 at the Macdonald College Farm. Data collected manually during the test period include:

- static pressure in the floor ducts after the fans (cm water)
- airflow resistance in the system before the fans (cm water)
- air velocity in the SWAP and bypass wall before the fans (m/s)
- reflectivity tests on the roof of the barn (%)
- initial moisture content of hay samples (% d.b.)
- progressive moisture contents of different hay samples (% d.b.)
- relative humidity of outside air and barn air (%)
- weather observations and wind direction

Automatic readings were recorded every 30 minutes using a Digistrip datalogger. These included:

- values of air temperatures throughout the system for the given time interval (°C)

- incident solar radiation intensities on the two slopes (east and west) of the barn roof apex and on the south facing vertical wall (W/m^2)

- accumulated daily solar radiation values on these same surfaces (Wh/m^2)

- values of wind velocity on the apex of the roof (kph)

- temperatures in hay stack to verify if the hay bales were heating up (°C)

All values were averaged over a time interval which in most cases was half an hour. The reflectivity tests, air velocity and airflow resistance tests were conducted on different occasions during the summer. The discharge static pressure, weather data and relative humidities were taken several times daily. The temperature, radiation and wind velocity recordings were taken on a continuous basis.

The principal experimental objective was to test the performance of the roof plenum air preheater and that of the vertical solar wall collector. This evaluation was carried out over the entire test period. Other tests, such as the air velocity/ and roof reflectivity tests, were taken periodically and will be considered individually.

The collection of values of solar radiation, air temperature, airflow and relative humidity enable an evaluation of the heat and mass transfer characteristics of the system. A rubber hose was inserted in the floor duct tunnel and then connected to the Dwyer inclined water guage. The reading of the static pressure was then converted into airflow using the manufacturer's specifications. These values were verified by making traverses across the tunnel ducts using a hot wire anemometer. The wet bulb thermocouples were wetted with cotton wicks placed in water-filled containers and located in the main air stream.

The air velocity was taken in the SWAP by making traverses through the wall at five locations, namely:

- next to the galvanized absorber plate
- midway between the absorber plate and the mesh
- at the fiberglass mesh
- midway between the mesh and the glazing
- next to the glazing

These readings were taken in at least two locations in every vertical channel and at two different heights in the wall (1.5 metres and 3 metres above the ground). The measurements were taken using the hot wire anemometer. Profiles of the airflow were drawn and the airflow determined. The air velocity in the bypass wall was measured in a similar manner.

A series of moisture tests were conducted in order to obtain a general picture of the drying of the hay bales in the barn. As hay bales are non-homogeneous and their number was considerable (totalling 4410 from the beginning of the experiment), the moisture content sampling was used only as an estimation of the water content in a particular lot of hay. Four different moisture testers were used. The experiments also served to evaluate three of the commercially available forage moisture testers as compared to the standard 200 g sample oven drying test of 24 hours at 70° Celsius.

The Delmhorst tester is equipped with a 25 cm probe which is inserted in the bales. The electrical resistance is registered on a meter and scaled to read directly in moisture content. The Dickey-John moisture meter is a plastic cylinder into which a chopped forage sample is placed. A plunger is then depressed and again the electrical resistance is displayed in the form of a digital read-out which can be converted directly into moisture content. In the case of the above two instruments, the procedure takes less than five minutes per sample. The Koster equipment is a convective heating unit which dries the sample in about 20 minutes. The forage is placed on a balance prior to drying and then set onto an electric fan heater. Once dried, the hay is reweighed and a scale on the balance indicates the initial moisture content of the sample. Several comparative tests were undertaken over the summer test period between these different meters.

Airflow:

The airflow rate in the solar air heating system was measured by making a series of traverses through the SWAP, bypass wall and floor distribution ducts. The air velocity was recorded using a hot wire anemometer. Two traverses in the SWAP were taken in each of the twelve airflow channels at the following different depths:

- at 3 cms from the glazing (1/6 depth)
- at 5.9 cms from the glazing (1/3 depth)
- at 8.9 cms from the glazing (middle of channel)
- at 5.9 cms from the absorber plate (2/3 depth)
- at 3 cms from the absorber plate (5/6 depth)

The traverses were taken at 0.75 metres and at 2.25 metres from the bottom of the collector. Traverses of the SWAP were taken twice on 5 August and again on 9 and 10 August 1983.

The air velocity was recorded at 5 locations in the bypass wall at a height of 2 metres above the bottom of the passage:

- 2 cms from the inside wall
- 7.5 cms from the inside wall (1/4 depth)
- midway into the air passage
- 22.5 cms from the inside wall (3/4 depth)
- 2 cms from the galvanized wall

These traverses were taken 6 and 16 August 1983.

The air velocity in each floor duct on the discharge side of each fan was also measured. A sheet of plastic was fastened on the inside of the flow duct tunnel to channel the air to the measurement location, 10 metres from the fan. The tests were undertaken on the 10 and 16 August 1983. The cross-sectional area of the floor duct was subdivided into a grid and measurements taken at 15 cm spacings using the hot wire anemometer. The static pressure of all test days varied only slightly (1.32 cms $\pm$ 0.076 cms). The airflow rate in the barn system was evaluated by multiplying the air velocity and cross-sectional area of the different air passages. A relation between the static pressure measurements and the airflow was thus obtained.

Mass Flow Rate:

The mass flow rate (kg of air per minute) was calculated by multiplying the airflow rate (cu. m. per minute) by the air density (kg per cu. m.) using the air temperature measured after the fan discharge. The air density values at a given temperature vary slightly over the range of relative humidities measured during the experiment. Therefore in the evaluation of the useful heat output from the system, the air density values were adjusted for different temperatures at a non-varying relative humidity.

Specific Heat:

In order to evaluate the useful heat output of the system, the isobaric specific heat of the air must be evaluated using the equation:

$$cp = 0.2399 + 0.4409\ r + \Delta cp \qquad \ldots\ldots (3.2)$$

where: cp = specific heat (cal/g °C)

r = mixing ratio in kg of water per kg of dry air (from psychrometric tables)

Δcp = isobaric specific heat residual of moist air (cal °C/g dry air)

This equation derives from the Goff-Gratch formulation (List, 1958). In this case, it was noted that the fluctuating temperature difference of the air causes the specific heat to vary only slightly (0.1% difference) in the range of relative humidities encountered. For this reason, the specific heat values are adjusted to the temperature fluctuations only. These values are used in the useful heat output calculation.

Temperature:

The temperatures in the solar barn hay dryer were measured using T-type thermocouples. These were calibrated prior to installation using an ice water 0°C reference point. Over the course of the experiments a total of 25 thermocouples were installed at different locations in the system (Figure 17). During the course of the tests, the thermocouples which were accessible (eight in all) were verified against a Fisher-Scientific thermometer having a resolution of ± 0.1°C. Tests conducted on 12 and 15 July 1983 noted an average percentage difference 0.7% between the accessible thermocouples and the thermometer readings.

Reflectivity Tests:

The reflectivity of the surface of the roof plenum air preheater (i.e. the roof of the barn) was verified on 4 and 13 July 1983 and again on 16 February 1984. A Haenni insolometer was used for this measurement. The sensor of the instrument was placed parallel to the upper slope of the barn roof and the reading of the solar radiation intensity (W/m^2) was recorded with the sensor facing the galvanized metal and then again pivoted 180 degrees, facing the sky. This measurement was repeated for different times of the day. The average reflectivity value obtained for the galvanized roof was 23% of the total radiation incident on the roof surface. The data from these tests can be found in Table IX. The reflectivity tests were also done on a flat black tarred surface of a nearby roof to serve as a possible comparison. It is evident that the albedo from a flat, black roof is low compared to the weathered galvanized surface.

Moisture Contents:

The moisture content of the hay was recorded in both the full scale prototype and the comparative drying tests. In the latter this measurement was done at the beginning and at the end of the experiments only, so as not to disturb the drying samples.

The loading of the full scale, barn solar hay dryer is a dynamic process, where hay was added over the course of the summer. Moisture content was sampled from different lots of hay that were loaded into the barn. This was done mainly to verify that the initial moisture contents were not too high. Moisture content monitoring of hay inside the barn was undertaken from 8 to 14 July 1983 at the end of the second cut of hay. During this test, different moisture testers were compared. Subsequent tests from 2 to 8 August 1983 compared the moisture testers to the standard forage drying test of a 200 g. forage sample dried for 24 hours at 70°C. The analysis of the moisture content measurements are found in Table XVIII.

3.3.7 Grain Drying Experiments using the Barn Solar Hay Dryer

An additional set of experiments was undertaken in October 1983 in order to assess if the barn solar hay dryer could be used during an extended period of the year. The supplementary use of the system could ensure a quicker return on investment and could benefit the farmer in various low grade heat applications.

A steel silo 17 metres south of the Macdonald College hay barn is used to store grain corn (Plate N). In previous years, this corn was dried with a rented propane burner on an asphalt pad nearby and then stored in this silo. The purpose of the experiment was to see what air temperatures could be attained by the barn solar dryer to be used to dry the corn in the steel silo.

The system was to be used in its conventional operating mode (roof plenum air preheater and solar wall) except that the two 3.73 kWh fans were blocked off. A smaller (2.24 kW, 45 cm diameter) axial flow fan was fixed to the silo wall. This fan was used to draw the air from the collector to the silo and was rated at 7600 m^3/h (4000 cfm) a 2.54 cm static pressure. Two 60 cm diameter corrugated plastic drainage tubes were used to channel the warmed air from the collectors to the fan (Figure 20 and Plate 0). A triangular steel duct equipped with staggered 5 x 300 mm slots was installed in the silo on top of which was piled 110 tonnes of grain corn. The tests were carried out during the last week of October, which is the conventional grain harvesting period in Quebec.

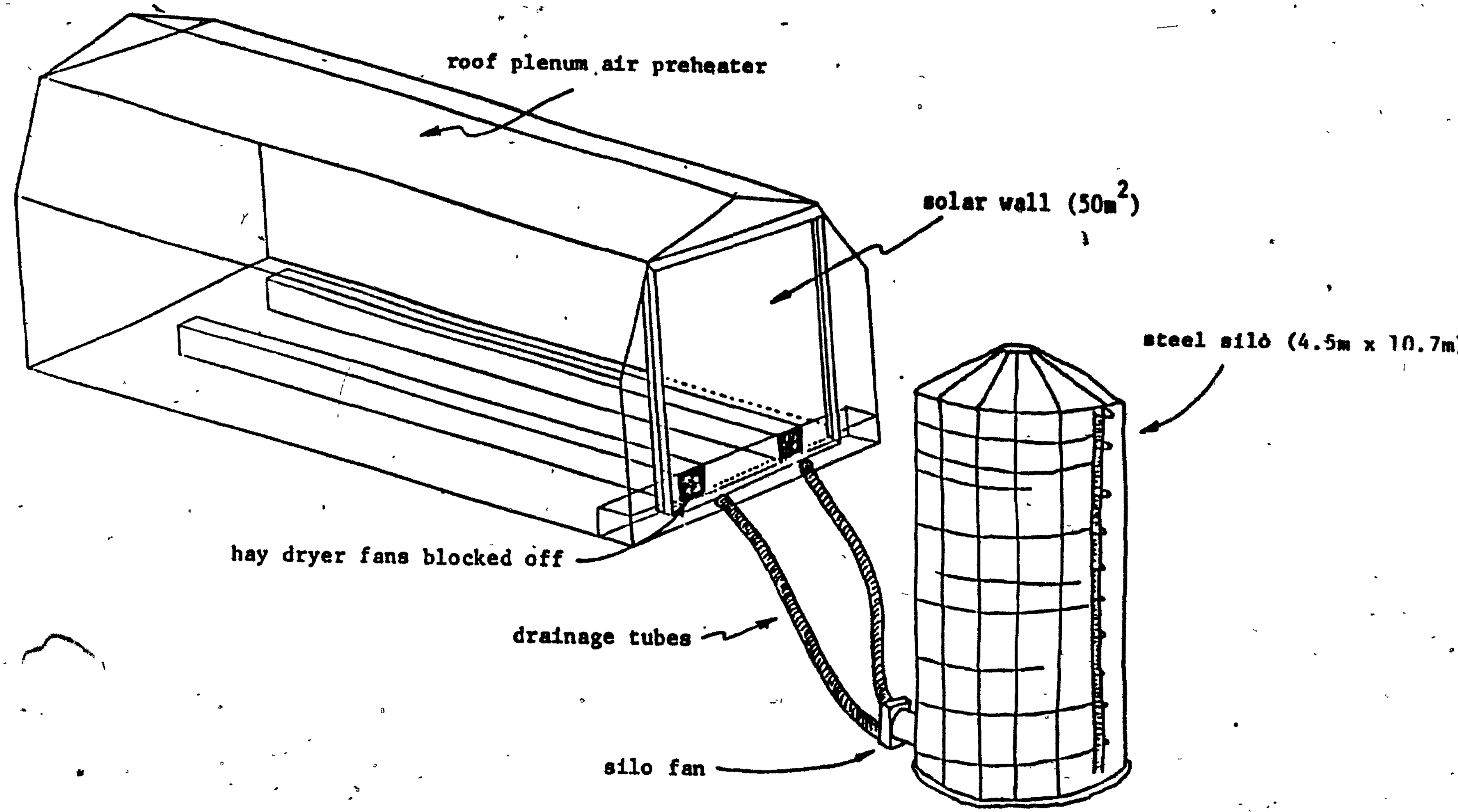


Figure 20: Schematic of Barn Solar Hay Dryer used to dry corn in a neighbouring silo.

Plate N. Ensemble of buildings surrounding Solar Barn Hay Dryer at Macdonald College Farm

Plate O. View of Solar Wall connected to a neighbouring silo.

CHAPTER 4. RESULTS AND DISCUSSION

4.1 Comparative Drying Tests - Phase I

4.1.1 Reduction in Drying Time

It should first be mentioned that a base line had to be established to be considered as the equilibrium moisture content of hay. This was set at 20% moisture content, dry basis. Due to the uncontrolled nature of field curing, no drying rates were established for these samples. Research in the past, however, has revealed that forced convection drying systems permit substantial reduction in the required drying time (i.e. up to 48%) when compared to field curing (Hodgson et al., 1946). In all three tests conducted, the solar-assisted drying cribs dried more rapidly than the ambient air crib. Figures 21, 22 and 23 illustrate the drying rates for the three experiments. During the experiment, the temperatures of the incoming air in the "solar crib" were matched with the Phase II temperture rise.

As moisture loss in the cribs was not recorded during the nocturnal hours, there are apparent gaps in the data collected. Rehydration of the hay was observed to some extent in all three tests. This phenomenon usually occured during the night or when ambient air relative humidities were greater than 80%. This corroborates research conducted on hygroscopic materials conducted by Dexter et al. (1947).

Based on the initial and final moisture content of the forage and the corresponding weight of the hay in the cribs, values of moisture content could be assigned to the respective crib weights during the drying trials. By applying the exponential least square fit to the data, the overall "theoretical" drying curves could be approximated for each trial. The equation used is based on the thin layer drying model (Equation 2.4) and is of the form:

$$M = a \exp(-b\theta) \qquad \text{...... (4.1)}$$

where all variables have been defined previously.

The exponents for each of the three drying trials have been outlined in Table V. It should be noted that the exponents in Test 1 and 3 results are quite similar. This may be due to the fact that both these samples were comprised of mixed grass whereas the forage dried in Test 2 was alfalfa.

TABLE V. COEFFICIENTS DETERMINED FROM LEAST SQUARE REGRESSION OF DRYING RATE DATA

TEST	FORAGE TYPE	CRIB	INTERCEPT	COEFFICIENT b	CORRELATION COEFFICIENT
1	Mixed grass	ambient	27.749	.00245	.9519
		solar	26.749	.00440	.9483
2	Alfalfa	ambient	52.178	.01800	.9801
		solar	42.706	.01745	.9831
3	Mixed grass	ambient	31.000	.00264	.9793
		solar	31.144	.00471	.9945

The reduction in the drying time of the solar heated cribs in Tests 1, 2 and 3 have been summarized in Table VI. There appears to be a distinct difference between the grasses and legumes as to drying time. Person and Sorenson (1968) suggest that this is due to the greater quantity of leaves in alfalfa compared to timothy. It is difficult however to affirm exactly what reductions in the drying time can be expected when solar preheated air is used. Further research is needed in order to draw any quantifiable relationship on this subject.

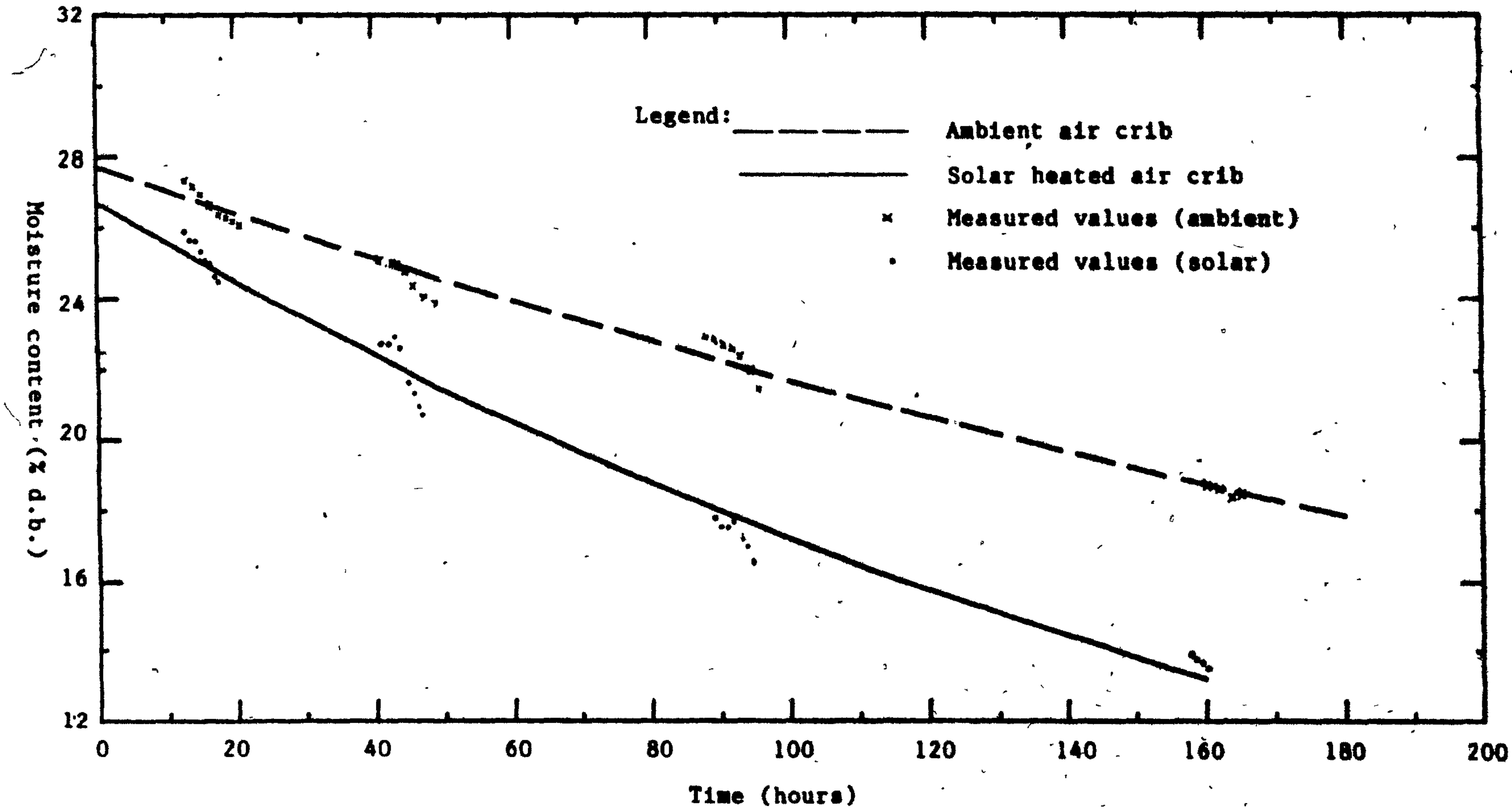


Figure 21: Drying Curve for Phase I Experiments - Test #1 (1 to 8 August 1983)

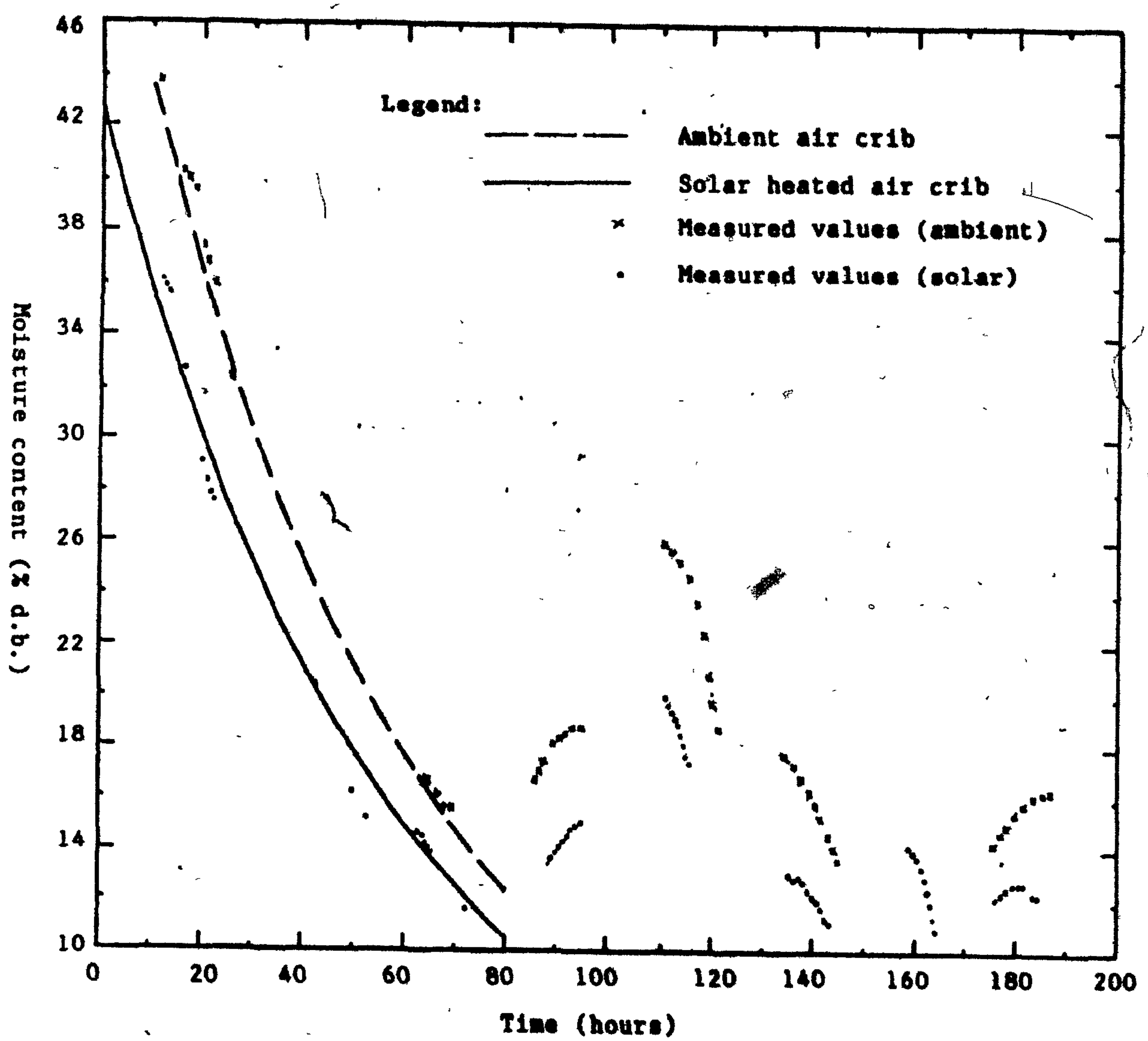


Figure 22 : Drying Curve for Phase I Experiments - Test #2 (18 to 31 August 1983)

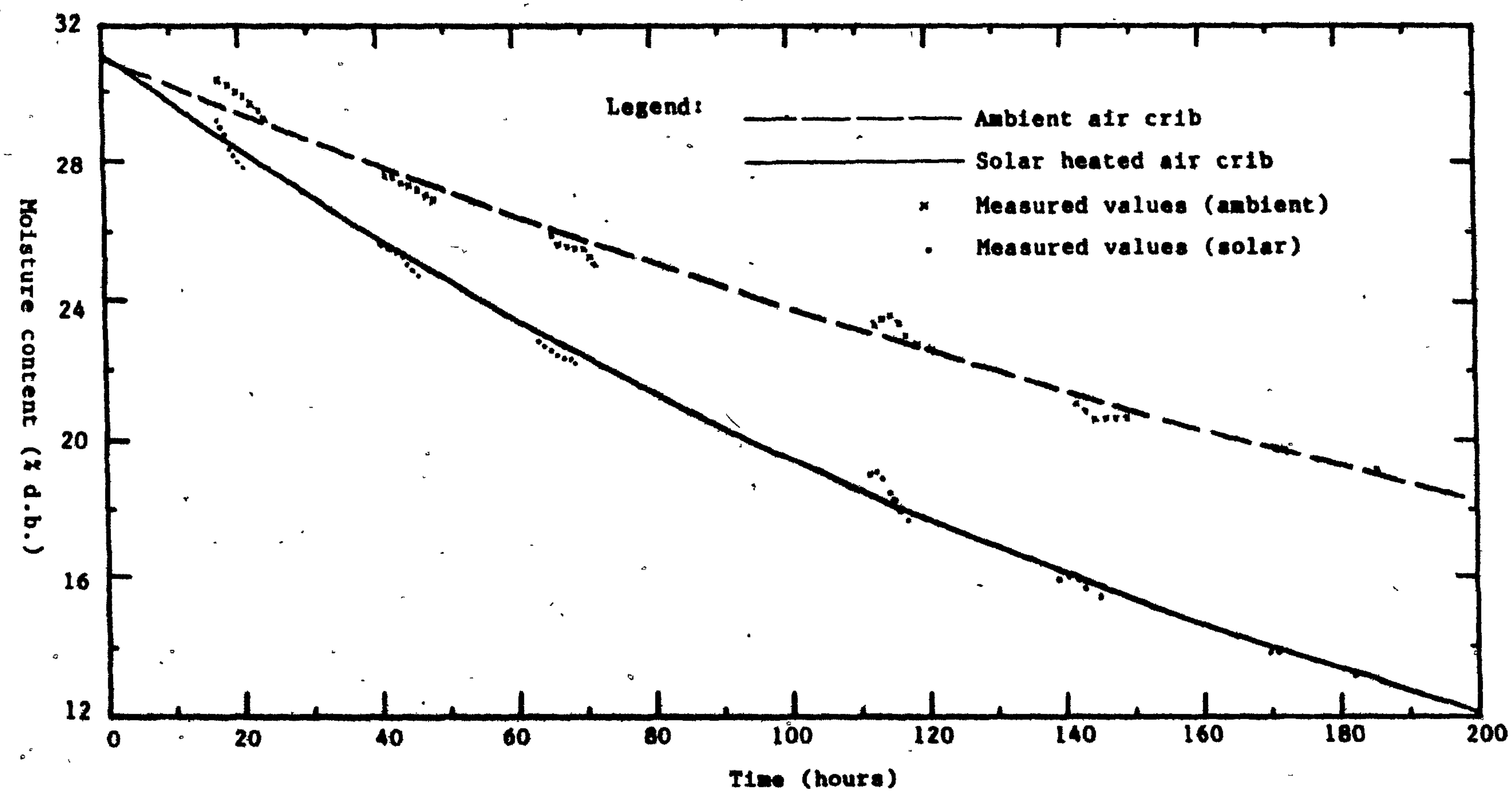


Figure 23: Drying Curve for Phase I Experiments - Test #3 (6 to 14 September 1983)

TABLE VI. SUMMARY OF DRYING TIME REDUCTION USING SOLAR HEATED AIR IN PHASE I EXPERIMENTS

Test Dates	Hay Type	Initial Moisture (% d.b.)	*Time to reach Equilibrium Moisture (hrs) Ambient	Solar	Relative Time Saving Solar vs Ambient
1 Aug. to 8 Aug. 1983	Alfalfa	28.4	133	65	51.1 %
18 Aug. to 31 Aug. 1983	Mixed Grass	40.7	54	44	18.5 %
2 Sept. to	Alfalfa	34.3	165	95	42.4 %
			Average of 3 trials		37.3 %

* Based on drying curves found in Figures 21 to 23.

4.1.2 Quality Comparisons

Quality comparisons for the three forage dehydration methods were conducted for Test 1. Organoleptic analysis revealed that the heated air artificially dried forage was the greenest of the 3 treatments followed by the ambient air artificially dried hay and finally the field cured sample. The two forced convection dried treatments produced hay with a good aroma whereas the field cured sample had much less odour. This latter method also yielded hay which appeared less leafy on the whole. Table VII summarizes the quality analysis for the three experiments.

It should be noted that the dry matter in the field cured lot in Test 1 was significantly less than the forced convection samples. Crude protein and acid detergent fiber (ADF) levels are best for the forced solar heated air crib but these values were not proven significant at the 5% level using Duncan's new multiple range test. Here, better quality refers to more dry matter with less acid fiber (ADF) and more crude protein. It can be noted that there appears to be a similarity in Test 1 and Test 3 with respect to the hay quality.

Due to the limited testing, however, no quantitative conclusions can be drawn concerning any advantages that the use of heated air for forage drying may have. Previous research appears to indicate that heated air may improve hay quality (Clancy et al., 1976; Strait, 1947; Davis et al., 1947) although these experiments have not substanciated this.

TABLE VII. RESULTS OF THE QUALITY ANALYSIS FOR THREE DEHYDRATION METHODS FOR FORAGES

	TEST 1			TEST 2		TEST 3	
	F	A	S	A	S	A	S
Initial moisture (%, d.b.)	28.8	28.8	28.8	40.7	40.7	34.3	34.3
Final moisture (%, d.b.)	14.1	18.6	13.6	11.9	11.4	17.3	11.5
Dry matter (%)	87.7*	90.1	90.0	89.4*	91.1	91.4*	93.0
Crude Protein (% DM)	16.5	17.3	19.2	15.5	14.3*	19.1	20.8
Acid Detergent Fiber (% DM)	45.0	40.0	39.3	39.9*	43.9	33.1	28.3*

Legend: F = Field cured
A = Forced convection with ambient air
S = Forced convection with solar heated air

* These values are significantly lower at the 5% level based on Duncan's new multiple-range test.

4.2 Measurement of Physical Parameters in Phase II

4.2.1 Solar Energy

Meteorological data were collected over the course of the summer test period. Table VIII summarizes this information for the fifteen test days that were analysed from 09 July to 23 August 1983. The solar radiation levels were recorded for the three collector surfaces, namely, the vertical south facing barn wall and the east and west facing slopes of the apex of the barn. In order to verify if the solar radiation intensities measured are reasonable, a comparison with data collected at the Environment Canada Meteorological Station at Jean-de-Brebeuf College in Montreal was undertaken. The Environment Canada values were 12.3% lower than those measured from the average of the roof mounted barn solarimeters (Figure 24). This difference many be attributed to attenuations of the solar radiation associated with urban factors (i.e. pollution) which are normally between 9 and 12% (Hay, 1977). Also, the radiometers used in the experiment are less accurate than those used at the Government observation station. One factor counter-balancing these differences is the fact that the barn solarimeters are mounted on an inclination of 33° from the horizontal. Average differences between radiation levels measured on a 30° slope and the horizontal for July and August in Montreal are between 3.9 and 4.7% (Hawes et al., 1981). Reflectivity from the galvanized roof cladding may also have an effect in increasing the values of the solar radiation intensities recorded during the experiment.

The reflectivity tests conducted during July 1983 on the barn roof indicate that the average reflected solar radiation is 23% of the total incident radiation as compared to 10% for an asphalted surface (Table IX).

TABLE VIII : SUMMARY OF CLIMATALOGICAL DATA COLLECTED FOR HAY DRYING TESTS – PHASE II

DATE 1983	PERIOD OF MEASUREMENT (hours)	AVERAGE AMBIENT TEMP. (°C) T_{AMB}	DAILY SOLAR RADIATION ON GIVEN BARN SURFACE: East Facing Roof (Whr/m²) I_E	West Facing Roof (Whr/m²) I_W	Vertical South Facing Wall (Whr/m²) I_V	WIND SPEED (Km/hr) WD	WIND DIRECTION Morning	WIND DIRECTION Afternoon	WEATHER OBSERVATIONS Morning	WEATHER OBSERVATIONS Afternoon
09 July	05:42 to 20:15	18.3	8782	8388	4776	25.2	W	W	a	b
10 July	05:30 to 20:19	18.6	8861	7827	2387	18.9	W	W	a	b
12 July	06:30 to 16:59	25.7	6574	5555	2219	6.6	SSE	W	a	a
13 July	08:55 to 16:30	24.9	5674	5044	2558	22.6	W	W	c	b
15 July	08:35 to 16:43	26.7	5538	5430	2720	16.9	W	W	bfh	bfh
19 July	06:57 to 19:15	27.1	5952	5601	2954	20.7	W	W	a	b
22 July	06:00 to 20:30	22.9	8124	7017	3349	18.1	E	NW	b	c
26 July	06:00 to 20:26	24.1	7070	7038	3282	9.3	W	W	a	c
02 Aug.	06:00 to 20:35	23.0	5072	6808	2696	17.8	W	W	e	d
03 Aug.	06:00 to 20:07	26.0	7262	6159	3345	18.0	W	W	f	cf
04 Aug.	06:00 to 20:32	25.9	4326	4574	2229	6.6	E	E	e	e
05 Aug.	06:00 to 20:18	28.2	6225	5607	3288	6.0	E	E	af	af
18 Aug.	06:30 to 20:35	24.3	3714	3835	1928	6.7	E	W	f	f
22 Aug.	06:30 to 19:54	16.7	1790	2081	777	8.9	E	E	g	e
23 Aug.	06:54 to 20:21	20.8	6965	6911	4381	20.3	W	W	a	a
Mean	06:32 to 19:29 13:01 hours	23.6	6129	5858	2859	14.8				

LEGEND:
a = clear - cloudless
b = clear with clouds (up to 30%)
c = 30 to 50% cloudy
d = 50 to 75% cloudy
e = 75% cloudy to totally overcast
f = hazy
g = rain
h = rain during previous night
W = West
SSE = South-South East
E = East

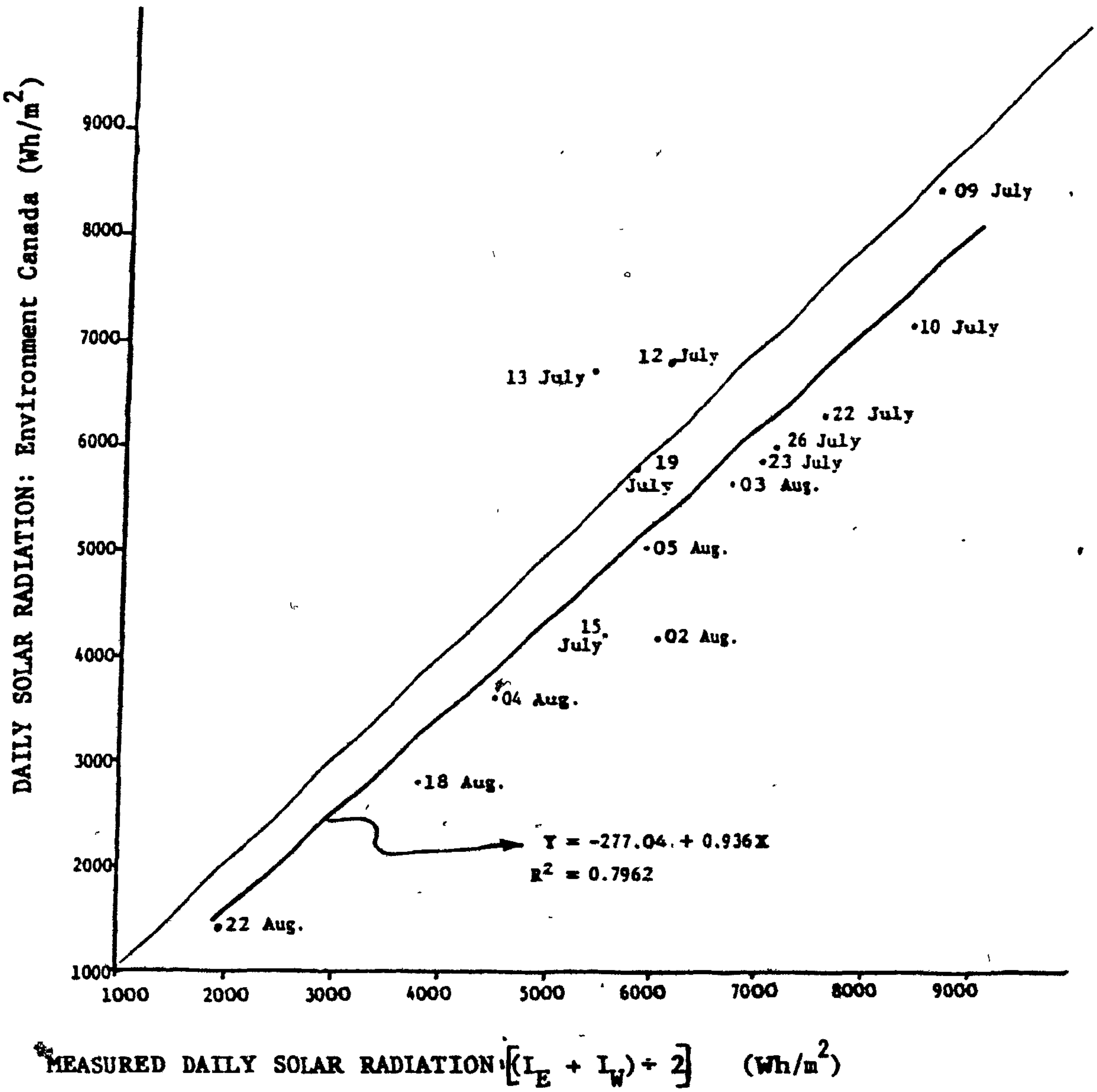


Figure 24 : Correlation between the Measurements taken in the Phase II Experiment and those recorded by Environment Canada

Source: Monthly Radiation Summary, Environment Canada, 1983.

TABLE IX : RESULTS OF SOLAR REFLECTIVITY TESTS ON BARN ROOF.

Date 1983	Time (hours)	Location	Solar Radiation Intensity (W/m^2) Facing roof slope = 33°	Facing sky	Reflectivity (%)
04 July	10:30	east roof	183	805	22.7
"	11:30	east roof	192	816	23.5
"	12:30	east roof	176	847	20.8
"	15:30	east roof	238	855	27.8
13 July	10:15	west roof	181	854	21.2
"	11:15	west roof	183	856	21.4
"	15:15	west roof	230	986	23.3
					MEAN = 23%
			Flat Black Surface slope = 10°		
04 July	11:35	west facing	29	816	3.5
"	12:35	west facing	34	845	4.0
"	15:35	west facing	28	821	3.4
13 July	11:30	west facing	21	862	2.4
"	14:00	west facing	29	858	3.4
					MEAN = 3.3%

Additional tests conducted in February 1984 on a sample piece of weathered galvanized sheeting show that reflectivity may be as high as 30% for the angle of the barn roof apex (Table X). These results would seem to indicate that there would be an advantage to painting the apex section of the roof with flat black paint. This investment would be marginal, yet the increased solar radiation collected should improve the performance of the collector significantly. The radiation levels received during the two month period are within the average values encountered for the region (Environment Canada, 1983). Daily maximum and minimum incident solar radiation levels were 8462 Wh/m^2 (09 July) and 1471 Wh/m^2 (22 August) respectively with an average value of 5335 Wh/m^2 for the test period.

The wind is also a type of solar energy phenomenon measured during the experiment. The site of the barn is an open area which is swept frequently by prevailing winds coming from the west. The daily average wind speed for the period of examination was 14.8 kph with a daily maximum and minimum of 25.2 kph (09 July) and 6.0 kph (05 August) respectively. Wind obviously has a cooling effect on the roof plenum air preheater which is a bare plate solar collector.

4.2.2 Airflow rate

The airflow rate in the system was measured for the range of operating discharge static pressures (between 1.0 and 1.4 cm of water). Airflow rates were calculated from the air velocity and cross sectional area through the channels being measured. The flow rates obtained in the solar wall air preheater (SWAP) ranged from 201 to 210 m^3/min with an average value of 207 m^3/min at a discharge static pressure of 1.3 cm of water. This value is the sum of the airflows in the twelve vertical channels which were measured in

TABLE X : ADDITIONAL REFLECTIVITY TESTS ON ROOFING SAMPLE

Date - 16 February 1984
Time - 09:30 to 10:00 hours
Material - Galvanized Iron Corrugated Roofing
Colour - Natural Weathered , originally silver
Size - 75cm X 85cm, corrugations 1.5 cm

Instruments - Radiometer Hollis Geo Systems MR-5 1642R
- Micro Voltimeter, Keithly 177 DMM

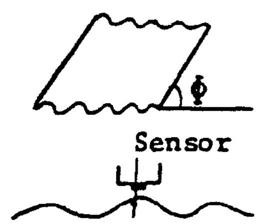
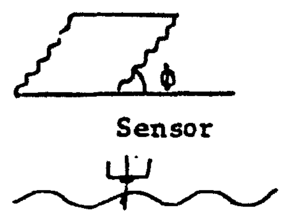
ANGLE OF INCIDENCE Φ	TEST 1		TEST 2	
				
0^o	26.1% 27.0% 26.5%	M=26.5%	27.2% 27.0% 26.8%	M=27.0%
20^o	27.3% 29.6% 28.5%	M=28.5%	24.9% 26.1% 27.7%	M=26.2%
30^o	28.3% 31.9% 29.3%	M=29.8%	24.2% 26.9% 29.4%	M=26.8%
40^o	29.1% 35.1% 30.4%	M=31.5%	26.2% 28.9% 32.3%	M=29.1%
50^o	30.7% 37.2% 31.9%	M=33.3%	27.5% 31.2% 37.0%	M=31.9%
60^o	31.6% 42.1% 32.6%	M=35.4%	27.2% 33.0% 41.0%	M=33.7%

TABLE XI : AIR FLOW MEASUREMENTS TAKEN IN BARN EXPERIMENTS

DATE 1983	TIME (hours)	STATIC PRESSURE (cm of H_2O)	STATIC PRESSURE (inches of H_2O)	AIR FLOW RATE (m^3/min)
09 July	09:15	1.27	0.50	651.3
	16:00	1.47	0.58	636.3
10 July	08:30	1.22	0.48	658.8
	10:00	1.22	0.48	658.8
	17:00	1.28	0.51	650.0
12 July	11:40	1.31	0.52	648.8
	13:15	1.27	0.50	651.3
	15:00	1.27	0.50	651.3
13 July	10:30	1.33	0.53	646.3
	12:00	1.31	0.52	648.8
	14:05	1.31	0.52	646.8
	16:30	1.27	0.50	651.3
15 July	08:30	1.31	0.52	648.8
	11:00	1.28	0.51	650.0
	13:30	1.27	0.50	651.3
19 July	09:30	1.55	0.61	631.3
22 July	12:00	1.13	0.45	660.0
	17:00	1.07	0.42	665.0
26 July	10:00	1.35	0.53	645.0
	15:15	1.08	0.43	662.5
02 August	09:30	1.37	0.54	643.8
	11:30	1.37	0.54	643.8
	13:30	1.41	0.56	641.3
	16:30	1.35	0.53	645.0
03 August	10:10	1.35	0.53	645.0
	12:10	1.35	0.53	645.0
	14:10	1.28	0.51	650.0
	16:10	1.31	0.52	648.8
04 August	10:30	1.35	0.53	645.0
	12:30	1.31	0.52	648.8
	14:30	1.31	0.52	648.8
	16:30	1.31	0.52	648.8
05 August	10:00	1.40	0.55	642.0
	12:00	1.35	0.53	645.0
	14:00	1.31	0.52	648.8
	16:00	1.28	0.51	650.0
13 August	09:30	1.31	0.52	648.8
	11:00	1.31	0.52	648.8
	13:00	1.28	0.51	650.0
	14:30	1.28	0.51	650.0
	17:15	1.28	0.51	650.0
22 August	09:30	1.37	0.54	643.8
	11:30	1.40	0.55	642.0
	13:30	1.37	0.54	643.8
	17:00	1.35	0.53	645.0
23 August	09:30	1.35	0.53	645.0
	11:30	1.35	0.53	645.0
	13:30	1.37	0.54	643.8
	15:30	1.31	0.52	648.8

the SWAP at 1.75 and 3 metres from the ground level. The flow through the inner bypass wall ranged from 435 to 454 m^3/min with an average value of 443 m^3/min at a discharge static pressure of 1.30 cm of water. The total airflow through the system was therefore 650 m^3/min at 1.30 cm of water. The suction pressure in the system ranged from 1.14 to 1.52 cm of water. Airflow measured in the floor duct ranged from 518 to 587 m^3/min with an average value of 560 m^3/min at 1.35 cm of water. Although this value is lower than the suction end tests, the conditions of measurement were more complicated on the discharge side of the fans. Added to this fact was the ever-present air leaks that lower the discharge airflow reading. The total discharge of the fans compares well with the manufacturer's specifications at the given total airflow resistance levels. Table XI summarizes the airflow discharge recorded for the fifteen test days.

4.3 Evaluation of the Barn Solar Hay Dryer

4.3.1 Roof Plenum Air Preheater

The evaluation of the roof plenum air preheater has been undertaken in terms of solar efficiency. The air temperature increase through the collector can be used to calculate the useful heat output (Q_{in}) from this section. The incident radiation on the roof is used to evaluate the heat input to this system. The ratio of useful heat outputs over useful heat inputs is referred to as the solar efficiency. This is represented by the equation:

$$\eta = \frac{\dot{m}\ cp\ (T_o\ T_i)}{I_E\ A_E + I_W\ A_W\ \theta} \qquad \text{...... (4.2)}$$

where: η = solar efficiency of the system (%)

$\dot{m}$ = mass flow rate of air in collector (kg/h)

cp = specific heat of the air at temperature $\bar{T}$ (J/kg°C)

T_i = temperature of air entering the collector (°C)

T_o = temperature of air exiting the collector (°C)

$\bar{T}$ = $(T_o + T_i) /2$ (°C)

I_E, I_W = average solar radiation intensity on the east and west slopes of the barn apex in a given time interval (W/m^2)

A_E, A_W = area of the east and west section of the barn apex (m^2)

θ = time interval between readings (h)

Table XII summarizes the daily performance of the roof plenum air preheater for the fifteen test days analysed. The outlet temperature was measured at the junction between the roof plenum air preheater and the vertical wall collector. The inlet temperature is the ambient temperature. The average daily temperature increase ranged from 0.4°C (22 August) to 3.0°C (12 July) with a mean increase of 1.5°C for the test period. It can be noted that the daily solar efficiency of the collector varied from 6.2% (22 July) to 31.4% (12 July) with an average value of 18.2%. This efficiency is not uncommon of bare plate collectors and can be considered adequate as the design of the collector has yet to be optimized. Based on the simplicity and low cost of the roof plenum air preheater, the performance is satisfactory, as marginal improvements could further boost the heat output for the system.

In order to comprehend how the radient solar heat is transferred to the air stream in the collector, a progressive evaluation has been undertaken for two test days, namely 15 July and 23 August 1983. Tables XIII and XIV summarize the performance of the collector for these two test dates. The maximum temperature rise in the system generally occurs between 11:30 and 13:00 yet this does not always correspond to the maximum solar efficiency which may be high in the early morning or late afternoon due to sharp temperature increases on thermal storage respectively. Although the trend

TABLE XII : DAILY EVALUATION OF ROOF PREHEATER

09 July to 23 August 1983

DATE	PERIOD OF MEASUREMENT (hrs)	AMBIENT TEMP. (°C)	OUTLET TEMP. (°C)	$\overline{\Delta T}$ (°C)	STATIC PRESSURE (cm H_2O)	MASS FLOW (kg/min)	HEAT IN (kWhr)	HEAT OUT (kWhr)	WIND (km/hr)	EFFICIENCY (%)
09 July	05:42 to 20:15	18.3	19.7	1.4	1.4	763.7	1794.3	260.9	25.2	14.5
10 July	05:30 to 20:19	18.6	20.9	2.3	1.2	778.2	1742.9	444.7	18.9	25.5
12 July	06:30 to 16:59	25.7	28.7	3.0	1.3	754.9	1267.5	398.0	6.6	31.4
13 July	08:55 to 16:30	24.9	26.5	1.6	1.3	753.4	1120.0	153.2	22.6	13.7
15 July	08:35 to 16:43	26.6	29.1	2.5	1.3	744.6	1140.0	252.3	16.6	22.1
19 July	06:57 to 19:15	27.1	28.8	1.7	1.6	729.0	1207.3	255.5	20.7	21.2
22 July	06:00 to 20:30	22.9	23.4	0.5	1.1	776.1	1521.6	94.3	18.1	6.2
26 July	06:00 to 19:56	24.3	25.2	0.9	1.3	761.5	1412.1	160.1	9.3	11.3
02 Aug.	06:00 to 20:35	23.0	24.5	1.5	1.4	752.8	1241.5	276.0	17.8	22.2
03 Aug.	06:00 to 20:07	26.0	27.4	1.4	1.4	749.7	1412.9	248.1	18.0	17.6
04 Aug.	06:00 to 20:32	25.9	27.1	1.2	1.3	750.8	929.4	219.3	6.6	23.6
05 Aug.	06:00 to 20:18	27.6	28.5	0.9	1.3	745.0	1235.9	160.6	6.0	13.0
18 Aug.	06:30 to 20:35	24.3	25.1	0.8	1.3	756.8	788.9	142.6	6.7	18.1
22 Aug.	06:30 to 19:54	16.7	17.1	0.4	1.4	770.9	404.5	69.3	8.9	17.1
23 Aug.	06:54 to 20:21	20.8	22.3	1.5	1.4	764.0	1450.0	258.5	20.3	17.8
MEAN 09 July to 23 August 1983	06:32 to 19:34 (13.03 hours)	23.5	25.0	1.5	1.3	757.2	1244.6	226.2	14.8	18.2

of the solar efficiency is generally patterned to the temperature rise in the system, other factors such as incident radiation and wind velocity also influence the collector performance. The air temperature in the system may remain constant over a given time interval due to thermal storage or dead air spaces. If during this time the solar radiation decreases, the effect in the solar efficiency may be a marked increase. If the solar radiation increases as well as the wind velocity, the efficiency may drop. Such was the case between 15:00 and 16:00 on 15 July (Table XIII). The wind influence on the air temperature rise is subject to a time lag factor. In Figure 25, the temperature increment and wind velocity are plotted against time for the data collected on 03 August. It can be noted that the sharp decrease in the outlet air temperature recorded at 10:30 probably corresponds to a wind peak encountered an hour earlier. The time lag appears to diminish towards the afternoon.

During the course of the experimental test period, it was observed that there was an air temperature drop along the passage in the roof plenum preheater. This decrease in temperature took place in the last two thirds of the collector and amounted to between 0.6 and 1.3°C. Rather than gain heat in this section, heat was being lost. It was believed that the roof vents which had not been sealed off were contributing to this loss. Once these vents were sealed, the section in question accounted for a temperature increase of between 0.4 and 1.3°C. It is felt that additional simple improvements to the roof plenum preheater could further increase the collector's performance.

TABLE XIII : PROGRESSIVE EVALUATION OF ROOF PREHEATER Date: 15 July 1983

TIME (hrs)	Ambient Temp. (°C)	Outlet Temp. (°C)	$\overline{\Delta T}$ (°C)	Static Pres. (cm of H_2O)	Mass Flow (kg/min)	Heat in (kWhr)	Heat out (kWhr)	Wind (km/hr)	EFF. (%)	Angle of Incidence (degrees) east	west
08:35	22.0	23.4	1.4	1.3	758.0	23.9	7.2	7.1	30.1	74.9	15.3
09:00	22.6	24.5	1.9	1.3	753.0	42.7	12.2	10.7	28.6		
09:30	24.0	26.2	2.2	1.3	749.4	42.5	9.4	12.1	22.1		
09:50	24.2	26.4	2.2	1.3	751.9	52.3	14.0	11.4	25.3	74.9	15.3
10:20	24.1	26.7	2.6	1.3	749.4	66.1	16.3	15.3	24.7	69.0	16.2
10:50	24.5	27.3	2.8	1.3	747.0	76.1	17.6	15.9	23.1	63.1	19.4
11:20	25.2	28.0	3.2	1.3	745.7	26.3	6.8	14.6	25.9	59.1	22.3
11:30	25.8	28.1	2.3	1.3	747.0	81.0	14.4	16.3	17.8	55.1	25.7
12:00	26.3	28.9	2.6	1.3	744.7	84.1	16.2	14.3	19.3	49.1	31.1
12:30	27.1	30.3	3.2	1.3	741.1	84.6	19.9	12.9	23.5	43.1	36.8
13:00	27.7	30.7	3.0	1.3	741.1	85.3	18.6	17.6	21.8	37.2	42.7
13:30	28.0	31.1	3.1	1.3	739.9	84.7	19.2	19.7	22.7	31.5	48.7
14:00	28.3	30.6	2.3	1.3	741.1	83.0	14.3	21.2	17.2		
14:30	28.9	31.6	2.7	1.3	738.6	80.9	16.7	19.1	20.6		
15:00	29.7	32.4	2.7	1.3	738.6	56.1	16.7	17.8	29.8		
15:30	30.2	32.9	2.7	1.3	737.4	73.4	16.7	20.6	22.8		
16:00	30.2	32.1	1.9	1.3	738.6	67.3	11.8	25.5	17.5		
16:30	30.2	31.8	1.6	1.3	739.9	27.2	4.3	25.9	15.8		
16:43											
MEAN	26.6	29.1	2.5	1.3	744.6	1140.0	252.3	16.6	22.1		

TABLE XIV : PROGRESSIVE EVALUATION OF ROOF PREHEATER Date: 23 August 1983

TIME (hrs)	Ambient Temp. (°C)	Outlet Temp. (°C)	$\overline{\Delta T}$ (°C)	Static Pres. (cm of H_2O)	Mass Flow (kg/min)	Heat in (kWhr)	Heat out (kWhr)	Wind (km/hr)	EFF. (%)	Angle of Incidence (degrees) east	west
05:54	15.0	15.2	0.2	1.4	775.8	15.3	2.6	11.7	17.0		
06:54	16.0	16.9	0.9	1.4	771.8	56.8	11.6	12.5	20.4		
07:54	17.7	18.7	1.0	1.4	765.2	77.5	11.1	14.2	14.4		
08:47	17.6	18.8	1.2	1.4	763.9	71.2	11.3	17.0	15.8		
09:31	18.5	20.3	1.8	1.4	760.0	59.2	11.5	16.6	19.4		
10:01	19.4	21.4	2.0	1.4	756.2	66.3	12.7	15.2	20.8	81.7	25.8
10:31	19.9	22.1	2.2	1.4	753.7	71.7	13.9	17.3	19.4	73.5	26.7
11:01	20.5	22.7	2.2	1.4	752.4	76.3	13.9	19.3	18.2	67.5	29.3
11:31	20.6	22.7	2.1	1.4	753.7	79.6	12.0	21.9	15.0	61.5	33.0
12:01	20.9	23.2	2.3	1.4	751.1	82.0	14.5	23.3	17.6	55.6	37.6
12:31	21.3	23.2	1.9	1.4	749.7	82.0	11.9	23.5	14.6	49.8	42.8
13:01	21.6	23.1	1.5	1.4	749.7	82.6	9.4	26.2	11.4	44.2	42.8
13:31	22.0	23.4	1.4	1.4	749.7	81.4	8.8	26.0	10.8	39.0	54.0
14:01	22.3	23.6	1.3	1.4	749.7	80.0	8.2	27.9	10.4		
14:31	22.6	23.8	1.2	1.3	755.5	75.8	7.6	26.9	10.0		
15:01	23.1	24.4	1.3	1.3	754.2	70.9	8.2	25.8	11.6		
15:31	23.2	24.5	1.3	1.3	754.2	65.5	8.2	25.4	12.6		
16:01	23.8	24.7	0.9	1.3	745.2	38.1	3.8	20.9	10.0		
16:21	23.3	24.6	1.3	1.3	755.5	52.6	8.2	24.4	15.6		
16:51	23.1	24.8	1.5	1.3	755.5	44.6	9.5	24.6	21.3		
17:21	23.1	24.3	1.2	1.3	756.8	73.3	15.2	19.8	20.8		
18:21											
MEAN	20.7	22.2	1.5	1.4	756.6	1402.0	214.1	21.0	15.3		

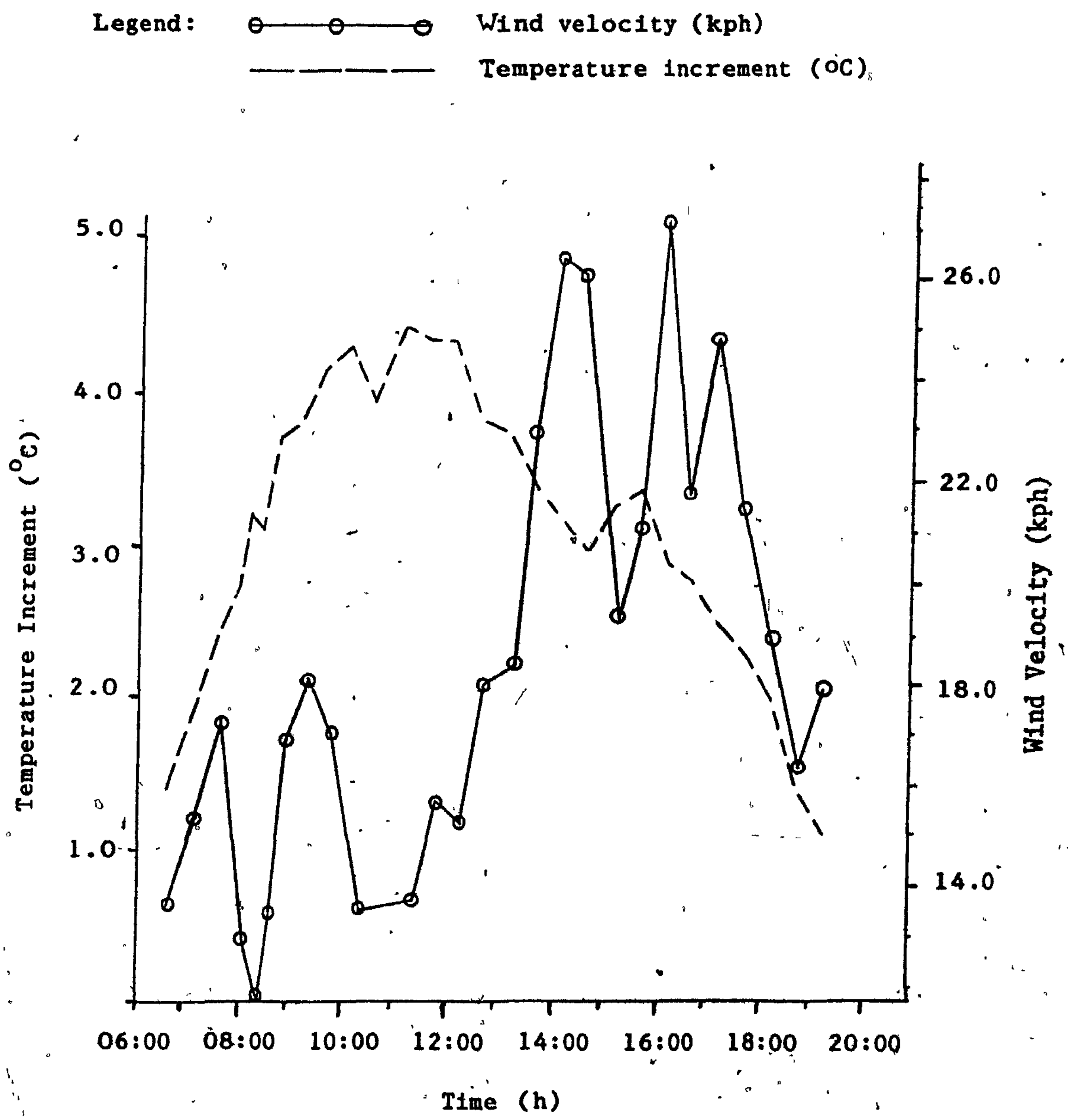


Figure 25: Comparison Between Temperature Increase in the Barn Solar Hay Dryer and Wind Velocity with Respect to Time for 03 August 1983

4.3.2 Evaluation of the Vertical Wall Collector

This evaluation focuses on the Solar Wall Air Preheater (SWAP) as the inner bypass wall is essentially a deviation duct used to reduce the airflow in the SWAP. The performance of the Brace Research Institute design of a solar wall air preheater has been extensively analysed (Andreadakis, 1981; Lawand et al., 1981; Brace Research Institute, 1981; Lamarche, 1981). The average solar efficiency recorded was about 45% for spring testing of the SWAP in these previous investigations. Table XV summarizes the results obtained during the tests conducted on the barn solar hay dryer.

As mentioned earlier, the air flowing through the solar wall represents about one third of the total airflow (206 m^3/min). The critical air velocity in this collector (5 m/s) was never reached and velocities ranged from 2.8 to 3.2 m/s. It is believed that the air flowing through the SWAP could have been increased to 500 m^3/min without undue stress to the collector. This would have improved the overall heat pick-up through the vertical section of the system due to the SWAP's superior solar efficiency when compared to the inner bypass wall.

4.3.3 System Performance of the Barn Solar Hay Dryer

The evaluation of the barn solar hay dryer as a system has been summarized in Table XVI. Average daily air temperature increases range from 1.3 to 3.9°C with an average value of 2.4°C at an airflow rate of 640 m^3/min. It should be noted that an additional 0.6°C is contributed to the air stream 24 hours per day from heat given off by the two 3.73 kW electrical fans. Figure 26 depicts the contributions to the air temperature increment from the various components in the system for 02 August 1983. This test date was chosen because the mean temperature increase in the roof preheater was

TABLE XV : DAILY EVALUATION OF SOLAR WALL AIR PREHEATER

Date	Period of Measurement (hrs)	$\overline{\Delta T}$ (^oC)	Air flow (m^3/min)	Mass flow (kg/min)	Heat in (kWhr)	Heat out (kWhr)	Efficiency (%)
09 July	06:12 to 19:45	2.5	205.7	245.7	234.5	139.1	59.3
10 July	08:56 to 19:19	2.0	209.6	246.6	117.2	84.7	72.3
12 July	08:30 to 16:30	2.8	205.0	233.3	108.9	87.7	80.5
13 July	08:55 to 18:15	2.3	207.3	238.2	125.6	84.9	67.6
15 July	08:35 to 16:43	2.9	207.9	240.9	133.6	86.7	71.7
19 July	08:24 to 18:49	2.4	201.9	231.3	145.0	91.4	65.7
22 July	06:00 to 20:30	2.1	211.5	247.1	164.4	126.1	76.7
26 July	08:15 to 19:56	2.7	208.7	241.8	161.1	128.5	79.8
02 August	08:00 to 20:05	1.9	205.9	239.0	132.4	86.6	69.0
03 August	06:00 to 19:37	2.4	206.6	236.6	164.2	128.4	78.2
04 August	08:30 to 19:30	1.9	207.1	239.9	109.4	84.0	76.8
05 August	07:30 to 18:30	3.0	206.6	234.7	161.4	129.7	80.4
18 August	07:48 to 18:35	1.5	207.7	240.7	94.7	65.0	68.7
22 August	08:39 to 17:54	0.5	205.8	247.5	38.1	19.7	51.7
23 August	08:54 to 19:21	2.2	207.5	240.5	215.0	153.1	71.2
MEAN	09 July to 23 August 07:54 to 18:12 (10.3 hours)	2.2	207.0	240.3	140.4	99.7	71.3

TABLE XVI : DAILY EVALUATION OF ROOF PREHEATER AND SOLAR WALL

Date 1983	Period of Measurement (hrs)	Ambient Temp. (°C)	Outlet Temp. (°C)	ΔT (°C)	Mass Flow (kg/min)	Heat in (kWhr)	Heat out (kWhr)	Efficiency (%)
09 July	06:12 to 19:45	18.5	20.4	1.9	763.7	1885.9	343.5	18.2
10 July	06:00 to 20:19	19.0	21.7	2.7	778.2	1852.2	498.0	26.9
12 July	06:30 to 16:59	26.3	29.2	2.9	753.3	1075.2	411.5	38.3
13 July	08:55 to 20:19	25.2	28.1	2.9	753.4	1262.4	275.3	21.8
15 July	08:35 to 16:43	26.6	30.5	3.9	750.7	1280.8	398.7	31.1
19 July	08:24 to 17:00	27.2	30.0	2.8	729.0	1316.2	304.6	23.1
22 July	06:00 to 20:30	22.9	24.6	1.7	776.1	1727.4	253.2	14.7
26 July	06:00 to 19:56	24.3	26.8	2.5	761.5	1624.0	421.9	26.0
02 August	08:00 to 20:05	23.5	26.0	2.5	752.8	1383.6	382.8	27.7
03 August	06:00 to 19:37	26.0	28.3	2.3	749.7	1563.5	394.5	25.2
04 August	07:30 to 19:37	26.4	28.3	1.9	750.8	1031.4	294.3	28.5
05 August	06:30 to 19:48	27.5	30.2	2.7	745.4	1406.3	437.2	43.4
18 August	07:48 to 18:35	24.8	26.9	2.1	756.8	889.8	286.0	32.1
22 August	08:39 to 17:54	17.0	18.3	1.3	770.9	433.4	177.3	40.9
MEAN 09 July to 22 August	07:33 to 19:04 (11:05 hrs)	24.0	26.4	2.4	756.6	1338.0	346.3	25.9

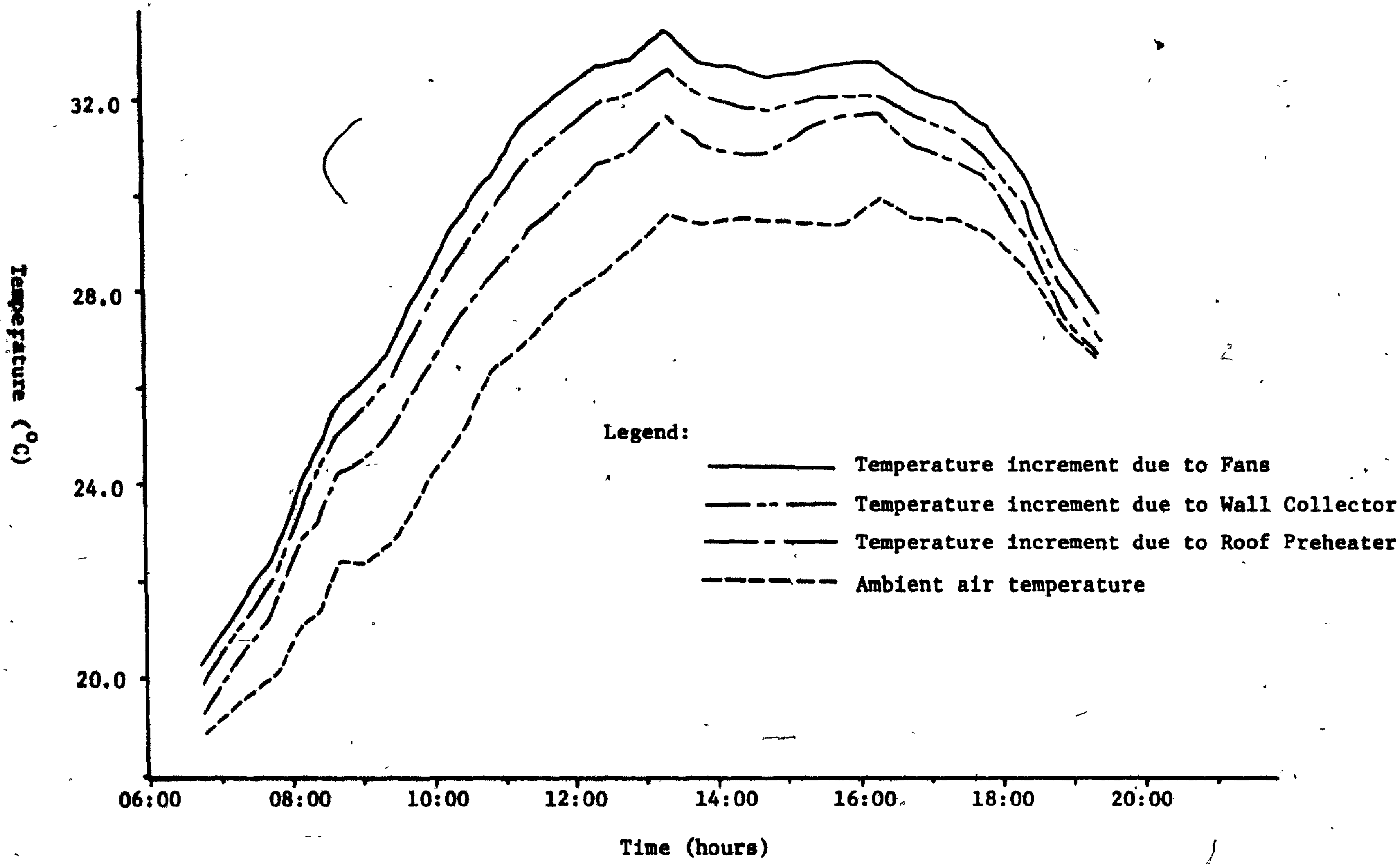


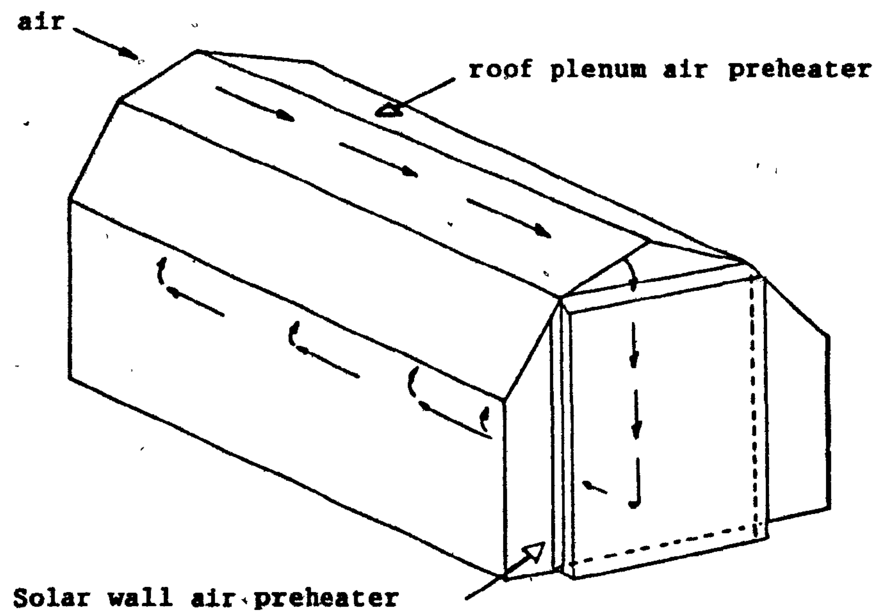
Figure 26 : Air Temperature Increment due to the Different Elements of the Barn Solar Hay Dryer with respect to Time of day for 23 August, 1983. Note: Curves actually represent the cumulative temperature totals. Temperature increments are gaps between curves.

(1.4°C) and that of the solar wall (0.9°C) are the closest to the overall average temperature increases over the entire test period. The fan heat produced is fairly constant throughout the day (0.6°C). It should be noted that the roof plenum air preheater contributes to roughly one half of the total air temperature increment during the daylight hours. The overall solar efficiency of the barn solar hay dryer (excluding the effect of the fans) was evaluated at 25.9% for the summer test period. The average daily heat output from the system was evaluated at 346 kWh.

A computer simulation was undertaken to predict the influence of positioning the barn solar hay drying system in a different orientation or of varying the collector configuration all together. Two configurations were studied (Figure 27): Type I is the present case with an apex enclosed roof plenum preheater leading to a SWAP located on an end wall; Type II uses an apex-roof plenum preheater with a SWAP located on a side wall and collector located between the two, on the lower slope of the gambrel roof (referred to as Junction collector). Estimates of daily solar radiation for varying orientations and different months were calculated according to the method established by Hay (1977). The collector areas used were set according to the barn dimensions of the tested prototype. The predicted efficiencies are also averages of values observed during the summer operation of the system. Table XVII outlines some of the different configurations that were evaluated.

It should be noted that the difference in Type I and II expected heat output is largely due to the difference in the size of the respective collectors for each configuration. The adaptation of the barn solar hay dryer concept to structures of different orientations would warrant an individual

Type I - Solar Wall Air Preheater Mounted on End Wall



Type II - Solar Wall Air Preheater Mounted on Side Wall

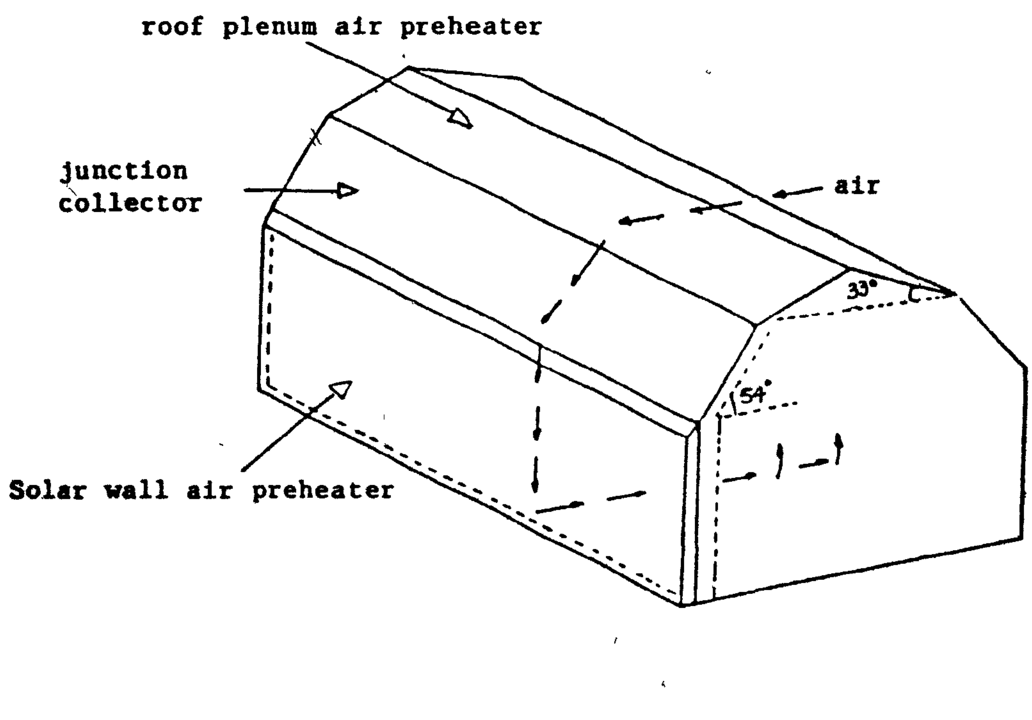


Figure 27 : Schematic of Solar Barn Configurations Used in Simulation Estimates

TABLE XVII : ESTIMATED PERFORMANCE OF BARN SOLAR HAY DRYER SYSTEM WITH VARIOUS ORIENTATIONS AND CONFIGURATIONS

		Solar Radiation Estimates for Different Months (Whr/m²/day)										Mean Total Useful Heat Output (kWh/day)	
Orientation	Collector	June		July		August		September		Mean		Type I	Type II
		Type I	Type II	Type I	Type II	Type I	Type II	Type I	Type II	Type I	Type II		
Due South	Roof	5299	5206	5428	5325	4464	4332	3451	3321	4683	4570	178	171
	Junction	-	4679	-	4939	-	4540	-	4325	-	4597	-	96
	SWAP	3222	3222	3464	3464	3580	3580	3931	3931	3498	3498	101	309
Due East/ West	Roof	5206	5299	5325	5428	4332	4464	3321	3451	4570	4683	174	178
	Junction	-	4484	-	4612	-	3863	-	3038	-	4018	-	84
	SWAP	3701	3701	3835	3835	3331	3331	2688	2688	3405	3405	98	300
Southeast/ Southwest	Roof	5245	5245	5368	5368	4390	4390	3392	3392	4622	4622	176	176
	Junction	-	4734	-	4956	-	4422	-	3691	-	4475	-	94
	SWAP	3669	3669	3895	3895	3730	3730	3610	3610	3706	3706	141	327

	Efficiency (%)	Area (m²)	
		Type I	Type II
Roof	18.2	209	209
Junction	18.2*	-	115
SWAP	71.3	49	150

* This efficiency is an assumed value. Actual efficiency of this collector would probably be higher.

evaluation to select the most advantageous configuration.

The amount of incident solar radiation on the roof preheaters is relatively independent of the orientation of the barn. This does not necessarily mean, however, that the amount of useful heat that can be extracted from a roof air preheater will be identical in each case. The principal reason for this is that the angles of incidence on each surface will differ depending on the orientation. This is true as the reflectivity of the surface is a function of the angle of incidence but not necessarily a straight line function.

Although an evaluation of the drying efficiency of the system was not attempted, drying trials were recorded in order to verify that the forage was dehydrating at a satisfactory rate. Table XVIII summarizes the moisture content measurement of one lot of hay that was dried from 7 July to 14 July 1983. It can be noted that a progressive moisture loss was recorded in the forage. A different drying rate was observed for the bales that were positioned furthest away from the fans and distribution ducts.

TABLE XVIII : ANALYSIS OF MOISTURE TESTS CONDUCTED IN BARN HAY DRYER From 7 to 14 July 1983

Date	Method of Testing *	Number of Samples	Moisture Content % W.b	Mean Moisture Content % W.b.
7 July	STD	4	33.2	33.2
8 July	K	2	25.6	25.2
	DJ	5	25.5	
	D	3	24.3	
10 July	K	2	21.0	18.3
	DJ	3	16.4	
11 July	K	4	16.7	16.7
	DJ		16.7	
12 July	K	2	17.3	15.1
	DJ	8	14.3	
	K**	1	24.0	25.2
	DJ**	6	25.5	
13 July	K	5	11.7	10.9
	DJ	8	10.5	
14 July	K**	5	20.4	19.4
	DJ**	8	19.9	

* Legend for Test Identification

STD - Standard Oven Test (24 hours @ 70°C)

K - Koster Moisture Tester

DJ - Dickey John Moisture Tester

D - Delmhorst Moisture Tester

** These samples were taken next to the barn wall at a point furthest away from the fans.

4.3.4 Assessment of the Materials used in the Solar Barn Hay Dryer

At the time of the preparation of this report, the following observations had been made concerning the materials that were installed in the solar barn hay dryer. It should be noted that these details were observed nine months after the construction of the facility.

- The polyethylene sheeting had developed rips at several locations along the length of the roof air preheater. Wind entering the barn on the north end produced a wave action along the polyethylene sheet which may have contributed to this damage. One possible remedy for this situation would be the addition of ventilation chutes to the inlet ports made in the north wall so that there would be no possibility of the north wind directly accessing the upper plenum chamber. These chutes should face down and should be covered with wire mesh to prevent entry of birds and insects, etc.

- Birds entering the barn through the open side doors were noticed to have flown into the upper plenum through the rips in the polyethylene. This was especially evident during the cooler weather. These birds tend to nest in the apex of the barn and may cause serious operational problems if not eradicated.

- The fiberglass of the solar wall has held up well after one season of use. Spiderwebs and dust, however, have been noted in the vertical channels of the SWAP. These were expected due to the vast populations of spiders and the prevailing dust levels in any barn (and this barn was by no means an exception).

- The floor duct modules used for the air distribution under the hay stacks had to be reinforced in the course of the 1983 summer operations. The design of these duct modules did not allow much control of the channelling of the warmed air. These units were fairly battered after one season and may have to be reconceived.

- The wooden sheets covering the inner bypass wall held up well against the hay that was piled against them. The same can be said of the suction plenum and instrumentation/storage chambers.

4.3.5 Grain Drying Experiments

Due to an exceptionally dry autumn, the corn crop required little or no supplementary drying. Nonetheless, the tests were run to see what temperatures could be reached in the system. The graph in Figure 28 illustrates the average hourly outlet air temperatures from the solar collectors for different test dates. The average daytime system efficiency was evaluated at 35%. The daytime temperature increase in the system ranged between 4°C and 10°C with an average value of 5.3°C at an airflowrate of 115 m^3/min. These temperatures are higher than those encountered in the hay drying experiments. This is probably due to the lower solar altitude angle encountered in October which improves the performance of the vertical solar collector. It should also be noted that the lesser airflow rate will contribute to a higher heat pickup in the system. It can be noticed that there are significant oscillations in the hourly outlet air temperatures recorded for any given day. These variations may be due to a number of factors. The solar radiation received during the test period varied in intensity much more so than in the summer months. As the ambient temperatures were lower, the wind had a direct effect on cooling the air outlet temperatures. The corrugated plastic ducts were not insulated and subsequently much of the heat of the warmed air was lost to the surrounding environment. In a permanent installation, these ducts would best be insulated and buried so that they would not constitute an obstacle to farm traffic and the earth may also serve to contribute to the duct insulation.

Although somewhat rudimentary, these experiments seem to indicate that for a relatively minor investment, the solar wall air preheater section of the solar hay barn could also be used in grain drying applications. If the barn was located close to heated buildings on the farm, the SWAP could also be

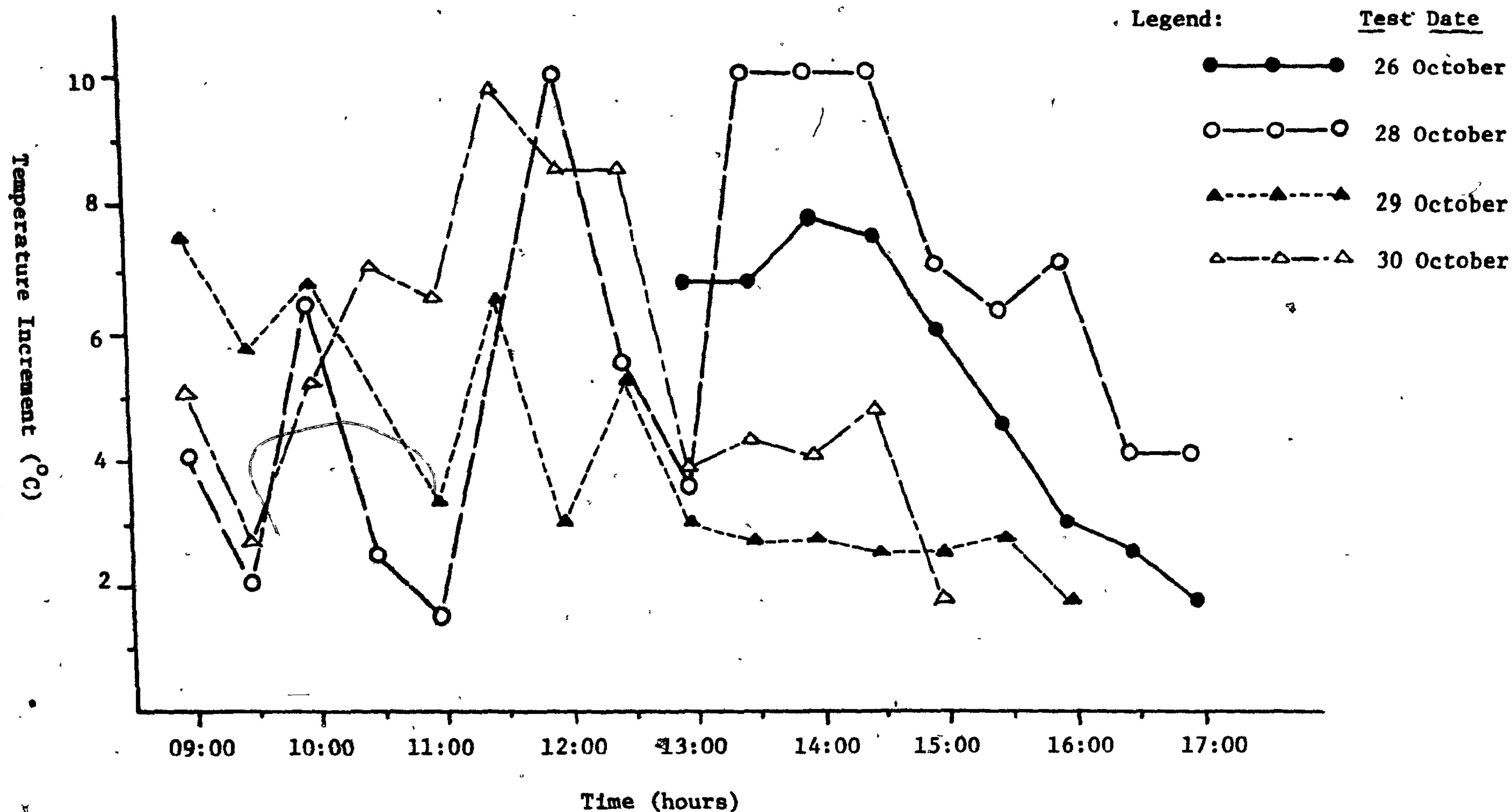


Figure 28 : Average Hourly Air Outlet Temperature Increment obtained in Corn Drying Experiments using Barn Solar Hay Dryer System (26 to 30 October 1983).

used for providing low grade heat during the period November to April.

4.7 Cost Analysis of the Solar Hay Dryer System

This section deals with an estimate of the cost of the materials of the barn solar hay dryer built at the Macdonald College farm. Table XIX outlines a bill of materials of the different components of the system. These estimates were established from the actual supplies used to build the prototype. The labour requirements for the construction of each system component have been included in the section on construction details.

The entire question of labour costs has been included to illustrate these requirements. It should, however, be stressed that many farmers do their own construction work. The design of this solar hay drying system is aimed at the resourcefulness of the Canadian farmer. Construction is simple. Only standard building materials were used. These materials are easily accessible to the farmer. In fact, the prices quoted are retail prices. Farmers often have access to materials, on a wholesale basis, so that some cost savings can be effected.

The opportunity costs to farmers are a matter of individual consideration. Generally the solar air heating systems could be installed during the winter months, when many farmers have extra time. As the construction procedures are relatively simple, farmers can allocate their time according to their availability. It is essential to note that the roof air preheaters (which will work reasonably well during the haying season regardless of orientation) would preferably be built by the farmer at the end of the haying season, when the level of hay is still relatively high, eliminating the need for renting scaffolding.

The different components of the system have been costed individually. From these calculations it can be noted that the roof plenum air preheater is a very inexpensive collector ($1.07 per square metre). For the cost, however, the temperature increment for the given mass flow rates is quite appreciable. This output would probably be increased if the roof were painted flat black. It is questionable as to whether the installation of insulation on the base of the roof plenum would be cost effective, as the difference in temperature between the air in plenum and the air leaving the top of the hay is only a few degrees Celsius.

The materials cost of the solar wall air preheater (SWAP) is relatively high ($30.48 per square metre) compared to the other system components. This is due to the price of fibreglass reinforced plastic corrugated glazing panels which has increased by more than 35% in the past two years. Other less expensive single or double glazed materials, such as Mylar, Tedlar or Qualex etc. should also be investigated. In addition, the width of the hay dryer SWAP was larger than those used to preheat ventilation air and this results in the use of more materials per square metre. It should be noted, however, that this collector is a chief component contributing to the increase in the air temperatures in the system.

The materials cost of the inner bypass wall has been kept relatively low ($5.47 per square metre). This expense should not be added to the SWAP cost as a duct is needed in any case to channel the air from the roof plenum air preheater to the fans, should a forced ventilation system already exist in the barn.

From the Tables in this section, a cost can be established for the two basic types of installations related to barn solar hay drying. Firstly, the cost of the system to "solarize" an existing conventional forced convection hay drying barn. In the case of a building identical to the Macdonald College farm hay barn this would amount to roughly $1750.00 of materials. The labour would be left up to the farmer because the design is simple enough to be built quite easily.

The second case would be to build the entire system into a barn. In the present case this would cost roughly $5200.00 for the materials, including the acquisition of the fans. If electricity is not available in the barn, an additional $500 to $1000 might have to be allocated for the installation of electrical wiring, switches, fuse boxes, etc. The actual installation costs at the Macdonald College barn were $1150.

Table 4.16 summarizes all materials and labour costs for the Solar Hay Drying System, if one were to take a barn and solarize it completely, using outside labour. Depending on individual requirements, needs and capacities, the actual direct costs to the farmer would be a portion of this total cost.

The economic evaluation of the system is one which involves several parameters. One of the savings that can be measured is the reduction in drying time when air is solar preheated as opposed to using ambient air forced convection. Based on the results obtained in Phase I experiments, these time savings may be quantified.

If these savings are averaged for all three tests the resulting time savings is 37.3%. This corroborates with the results obtained by Ferguson and Bailey (1981) and Morrison and Shove (1980). The summary of these calculations is found in Table VI. From these results, an economic evaluation based on energy expended can be undertaken. To do this, certain assumptions must be made:

- assume that the fans in a standard conventional hay drying operation are run for roughly 60 days during the average season;
- assume that these fans are operated on a 24 hours basis;
- assume a system with two 3.73 kW fans such as the Macdonald College application;
- assume an energy cost of 3.5 cents per kilowatt hour.

Based on these assumptions, the cost of drying hay with an ambient air forced convection system would be:

Energy expanded for conventional forced convection hay dryer:

60 days x 24 hours/day x 3.73 kW/fan x 2 fans = 10742 kWhrs

10742 kWhrs x $0.035/kWhr = $376.00 drying cost per season

Assuming that the average energy savings of the system are 30%, the capital recuperation for hay drying would be $125.32 per season. This evaluation however is based on the results obtained from only three comparative drying tests. The value should be used in comparison with other system evaluations. It is evident that further testing will be necessary before an accurate estimate of the time and energy savings of the barn solar hay dryer can be calculated.

Another approach is to assess a value to the heat being produced in the Barn Solar Hay Dryer. Table XVI summarizes the overall performance characteristics of the system over the 2 month testing period. If the average values of mass flow rates and temperature increments are used, a global average daily heat output from the system can be calculated. From the basic heat transfer relation, this calculation yields:

$$Q_{OUT} = \dot{m} \; cp \; (\Delta T) \qquad \ldots\ldots (4.3)$$

$$Q_{OUT} = 756.6 \text{ kg/min} \times \text{min}/60 \text{ s} \times 1.0057 \text{ kJ/kg}^{o}\text{C} \times (2.4^{o}\text{C})$$

$$= 30.4 \text{ kW/hour}$$

Taking an average day length of 11.5 hours, this represents an average daily heat output of 350.0 kWhrs. This represents a daily production of heat which can be estimated at 350.0 kWhrs x $0.035/kWh (for the Quebec region, one of the lowest electrical rates in Canada) = $12.25 per day. If the solar hay drying system is operated approximately 40 days of the year, then this represents a production of heat valued at $490.00 per season. This could be compared to propane or electrical heating units which are the other types of heating mechanisms used to produce instantaneous heat on the farm.

In this case, it is obvious that the use of this heat will depend upon the efficiency of the dryer. Industrial drying plants use multi-staged operations in order to recuperate the energy that would normally be ejected to the atmosphere. The Solar Barn Hay Dryer is a single phase dryer and consequently it is questionable whether all the heat from the solar collectors is indeed being used efficiently. The reduced air temperatures and high relative humidities exiting from the hay stack would indicate that most of the heat coming out of the top of the hay stack has been used, however this does not account for any air leakages out the sides of the stack.

The economic analysis Table XXI attempts to quantify the cost of solarizing an existing hay drying system. There is a marked difference in cost-effectiveness when the labour component of the cost is taken into consideration. The economic benefits of the system have been estimated in relation to the installation at Macdonald College. The value of electrical energy saved is an average of the two potential savings discussed earlier. No attempt has been made to evaluate the possible savings incurred when using the warmed air to dry grain, yet this application appears to have good economic potential. It is difficult however with a prototype of this kind to make any predictions of pay-back periods, as the system has yet to be optimized. Further research is required to explore the true economic benefits of this application. The system may already hold real potential in provinces where the electrical rates are considerably higher than those of Quebec.

The actual energy savings that could be obtained from the Solar Barn Hay Dryer probably lie somewhere between the $125.00 and $490.00 figures. Further testing will have to be undertaken in order to narrow down this range. Increasing energy costs and the multi-purpose nature of the low grade heat producing system will improve the return on investment for such a system. The cost effectiveness is largely a question of usage and local energy costs.

TABLE XIX : SUMMARY OF MATERIALS AND LABOUR EXPENSES INCURRED FOR VARIOUS COMPONENTS OF THE BARN SOLAR HAY DRYER.

System Components	Cost	Cost per M^2
A) Roof Plenum Air Preheater		
Labour	1,050.00	5.02
Materials	222.60	1.07
Sub Total	1,272.60	6.09
B) Inner Bypass Wall		
Labour	950.00	19.35
Materials	268.70	5.47
Sub Total	1,218.70	24.82
C) Solar Wall Air Preheater		
Labour	2,300.00	46.84
Materials	1,496.45	30.48
Sub Total	3,796.45	77.32
D) Floor Ducts		
Labour	1,100.00	
Materials	730.40	
Sub Total	1,830.40	
E) Barn preparation, Fan Suction Plenum, Installation of Fans		
Labour	1,400.00	
Materials	289.80	
Sub Total	1,689.80	
F) Fans, Electrical Wiring		
Labour	600.00	
Materials	2,200.00	
Sub Total	2,800.00	
Total Labour	$7,400.00	
Total Material	5,207.95	
TOTAL	$12,607.95	

Note: The cost of one man day was estimated at $50.00

TABLE XX : BREAK-DOWN OF COST OF MATERIALS USED TO BUILD THE BARN SOLAR HAY DRYER.

Materials Description	Quantity Required	Unit Price	Cost
Solar Wall Air Preheater			
Corrugated Fiberglass Sheeting Translucent (Excelite) 81cm X 2.44m (32" X 8')	24 sheets	28.00	$ 672.00
Fiberglass Mesh (Black)	95 metres	1.15	125.00
Hexagonal Screws with neoprene washers			30.00
Chicken Wire	9m	1.50	13.50
Muriatic Acid	4 litres	1.50	6.00
Black Paint (matt)	20 litres	5.22	104.40
Angle Iron 19mm X 19mm X 6.10m (3/4" X 3/4" X 20')	12 pieces	10.50	126.00
Transparent Silicone Caulking	6 tubes	6.79	40.75
Caulking (Black)	10 tubes	3.69	36.90
Lumber (Spruce) (38mm X 88mm X 3.28m (2" X 4" X 10')	65 pieces	0.85/m	181.90
Lumber Planking 19mm X 184mm X 2.44m (1" X 8" X 8')	12 pieces	2.20/m	64.40
Galvanized Metal Flashing	5 sheets	11.00	55.00
Styrofoam Board 38mm X .91m X 2.44m (2" X 3" X 8')	1 sheet	10.60	10.60
Fasteners (nails,screws,etc.)			30.00
			$1,496.45
	Cost per m^2 of Collector		\$30.48/m^2

Materials Description	Quantity Required	Unit Price	Cost
Fan Suction Plenum			
Lumber (spruce) 3mm X 8mm X 2.44m (2" X 4" X 10')	30 pieces	0.85 /m	$ 62.25
Plywood 16mm X 1.22mm X 2.44m (5/8" X 4' X 8')	12 pieces	16.00	192.00
Lumber (spruce) 38mm X 38mm X 2.44m (2" X 2" X 8')	12 pieces	0.36 /m	10.55
Hinges, Locks, Handles, etc.			15.00
Fasteners (Nails, Screws etc.)			10.00
			$ 289.80
Fans (3.5kw) Lajoie Ltée	2	778.00	$1,556.00

TABLE XX (continued): BREAK-DOWN OF COST OF MATERIALS USED TO BUILD THE BARN SOLAR HAY DRYER.

Materials Description	Quantity Required	Unit Price	Cost
Roof Plenum Air Preheater			
Polyethylene sheeting (6 mil)	9.75m X 30.25m(1roll)	$115.00	$ 115.00
Polypropylene twine	250m (1 box)	35.00	35.00
Wooden furring strips 19mm X 38mm X 3.66m (1" X 2" X 12')	55 m	0.66/m	36.20
Metal eyelets	120	0.22	26.40
Fasteners (nails,staples,etc.)			10.00
			$ 222.60
	Cost per m² of Collector		$1.07/m²
Inner Bypass Wall			
Aspenite: 6mm x 1.22m x 2.44 (¼" X 4' X 8')	19 sheets	5.50	$ 104.50
Lumber 38mm X 88mm X 3.66m (2" X 4" X 12')	10 pieces	0.79/m	28.80
Lumber 38mm X 38mm X 3.66m (2" X 2" X 12')	22 pieces	0.59/m	47.55
Styrofoam Board 38mm X .91m X 2.44m (2" X 3' X 8')	2 sheets	10.60	21.20
Caulking	14 tubes	3.69	51.65
Fasteners (nails etc.)			15.00
			$ 268.70
	Cost per m² of duct area		$5.47/m²

Materials Description	Quantity Required	Unit Price	Cost
Floor Ducts			
Lumber (spruce) 38mm X 38mm X 3.28m (2" X 2" X 10')	32	0.43/m	$ 45.15
Lumber (spruce) 38mm X 88mm X 3.28m (2" X $" X 10')	112	0.85/m	312.35
Wood Furring Strips 19mm X 38mm X 3.28m (1" X 2" X 10')	96	0.66/m	207.90
Polyethylene Sheeting (6 mil) 9.75mX 30.35m	1 Roll	115.00	115.00
Fasteners (Nails, Screws etc.)			50.00
			$ 730.40
TOTAL COST OF MATERIALS	$4,564.00 plus tax X $1.09		$4,975.00

TABLE XXI : ECONOMIC ANALYSIS OF THE SOLAR WALL AND ROOF AIR PREHEATER FOR HAY DRYING.

Note: All numbers are Canadian dollars unless otherwise indicated.

ANNUAL COST INCURRED IF MATERIALS AND LABOUR ARE CONSIDERED	Roof Air Preheater	Inner Bypass	Solar Wall	Totals
Initial Cost	1272.6	1218.7	3796.5	6287.8
Annual Interest (@ 13%)*	165.4	158.4	493.6	817.4
Expected Life (years)*	2.5	12	12	
Depreciation (Initial Cost/Expected Life)	590.4	101.6	316.4	1008.4
Annual Maintenance (%)*	10	5	5	
Annual Maintenance	127.3	60.9	189.8	378.0
Labour for Operation (assume ½ hour/day @ $5/day for 40 days)				100.0
Electricity (3.73 kW/fan × 2 fans × 11 h/day × 40 days × $.035/kWh				114.9
Total Costs per Year (Interest + Deprec. + Maint. + Labour + Elect.)				2418.7
ANNUAL COST INCURRED IF MATERIALS ARE CONSIDERED ALONE				
Initial Cost	222.6	268.7	1496.5	1987.8
Annual Interest (@ 13%)*	28.9	34.9	194.5	258.4
Depreciation*	89.0	22.4	124.7	236.1
Annual Maintenance*	22.3	13.5	75.0	110.8
Labour and Electricity*				214.9
Total Costs per Year				820.2
ESTIMATED ANNUAL SAVINGS				
Estimated Annual Savings in Electrical Costs				300.0
Estimated Annual Savings due to Fewer Losses (assume 3% fewer losses than for ambient air forced convection)				800.0
Total Estimated Savings per Year				1100.0

* estimated or assumed

CHAPTER 5 - CONCLUSIONS AND RECOMMENDATIONS

The principal activities and findings are listed below:

1) Control tests were undertaken to compare the solar forced convection drying of hay with forced convection hay drying. The time savings when using solar energy for low grade heat range from 18.5% to 51.5% when compared to ambient air drying, the average saving being 37.3%.

2) Under controlled tests there do not appear to be any significant differences in the quality of forage when dried with low grade heat as compared with ambient forced air. It must be remembered, however, that the increases in temperature were only of the order of 3°C to 6°C above ambient air temperatures. Undoubtedly further testing with more replicates are necessary, probably using larger samples. These detailed quality tests were undertaken in conjunction with the drying trials.

3) The barn at the Macdonald College Farm has been solarized with a non-glazed air preheater in the roof, as well as a single glazed solar wall air preheater on the south facing wall surface. A design has been developed to permit a simple retrofitted solarization which could be undertaken by the farmer without the need for external contracting services. The barn was operated for the entire hay drying season, during the summer of 1983.

4) The mean airflow rate used in these operations, corresponds to current forced convection drying practice and in this case amounts to approximately 650 m^3 per minute. During the course of the haying season, the average daily increase in temperature over ambient conditions was 2.4°C with almost equal increases in temperature in the roof preheater and the solar wall air preheater. The maximum temperature increases varied from 4 to 6°C at these flow rates.

5) The average solar efficiencies for the total system during the test period was evaluated at 25.9%. The roof plenum air preheater and the solar wall air preheater operated with efficiencies of 18.2% and 71.3% respectively.

6) While the system operated successfully, it would seem that the design of the solar collectors used should be optimized. The roof plenum air preheater provides low grade heat at a very competitive cost. Simple improvements and modifications to the existing design could increase the heat output without affecting the overall cost. The solar wall on the other hand appears to be an expensive element in the system. This is primarily due to the cost of the fiberglass glazing material. The use of a cheaper transparent covering may be warranted even if this means its replacement at shorter intervals.

7) The Barn Solar Hay Dryer concept integrates simplicity and ease of operation. These two issues have had significant appeal and reaction from the farming community thus far has been favourable. In order to offset the capital cost of the solarization of a barn multiple usage has been emphasized. Low grade heat production could have applications for grain drying in the autumn or space heating in the winter and spring.

Operation during these seasons justifies the use of a vertical solar collector which performs better when the solar altitude angle is reduced.

Recommendations for future investigations:

Minor structural recommendations:

1) The outer roof cladding above the roof air preheater should be painted a dark colour to increase solar radiation, absorbtivity hence increasing the air temperature.
2) The openings in the roof, including the roof vents, should be securely sealed to improve the roof preheater efficiency.
3) A separate electric line must be installed for the datalogger and other instrumentation to ensure that there are no power failures or power shutoffs due to auxilliary farm machinery during testing periods.
4) The installation of galvanized sheet metal wind deflectors on north wall inlet would avoid direct ingress of north wind into roof preheater.
5) The ductwork on the discharge of the ventilation fans should be strengthened. The ductwork should be lined with an impervious material which can be opened and closed along the base so as to control the flow of air.
6) The plastic base sheet of the roof plenum air preheater should be replaced with a stronger reinforced plastic membrane which will have a longer life.

Instrumentation and monitoring recommendations:

1) The electric consumption of the ventilating fans should be monitored.

2) Wet bulb thermocouple sensors should be installed above the hay stack at 3 different locations so as to monitor continuously the exit air relative humidity. Additional wet bulb sensors should be installed after the fans as well as in the ambient air inlet.

3) There should be much more complete monitoring of hay moisture content during the drying of particular cuts of hay.

4) There should be better monitoring of airflow in the floor ducts on the fan discharge.

5) Some resolution of the question of hay quality monitoring should be undertaken so as to quantify whether solar dried produce has increased nutritional value, as has been found by some other researchers.

Recommendations for operating procedures:

1) Improved sampling procedures for the hay drying in the barn trials should be developed.

2) In order to make the hay drying analysis more precise, it would be necessary to take hour by hour readings of:

   a) the moisture content of the hay using the indirect testing method which has previously been calibrated against standard drying in an oven.

   b) the relative humidity of outside air, after the fan discharge and above the hay stack.

   c) control temperature measurements within the hay stack.

3) A complete investigation should be undertaken to determine the contribution made by the operation of the fans during night-time periods in a solar drying operation. It is recognized that some wetting will occur, however, during periods of high ambient air relative humidity. It has actually been shown in the Phase I experiment that the hygroscopic hay stacks reabsorbed moisture quite readily. Therefore it is essential that the optimum period of operation at night-time be determined. It may also be necessary to halt the fans during high daytime relative humidities. This should be studied in greater detail.

4) Study the optimization of the airflow rate in the Barn Solar Hay Dryer to determine the ideal flow rate for solar energy collection as well as for drying. For example, if there are low airflow rates then there will be higher inlet air temperatures to the hay stacks. There will also be lower electrical operating costs. It is also possible that the lower relative humidities of the inlet air stream might enhance drying rates.

5) It would be interesting to do an economic analysis comparing:

   a) field curing (only storage inside the barn)

   b) forced convection drying using ambient air

   c) forced convection using solarized systems as described in this report.

   The following factors should be considered:

   - the cost of the systems including fans, ducts, solar components, etc.
   - the cost of labour
   - the quality of the dried material. It is necessary to quantify the best quality of material that can be obtained for the quickest

drying time. Therefore it will be necessary to measure the leaf content, protein, vitamin content and determine the economic benefit of any improvement in quality with respect to feed intake, digestibility and milk yields, etc.

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APPENDICES

APPENDIX A

A.O.A.C. METHODS FOR DETERMINING FORAGE NUTRIENTS

(b) *Nonacidulated samples.*—Place 1 g sample (ground to pass No. 40 sieve in case of Ca metaphosphate) on dry 9 cm paper. Without previous washing with H_2O, proceed as in (a)(*1*) or (*2*). If (*2*) is used, wash residue until vol. soln is ca 350 mL. Cool, dil. to 500 mL, and mix.

2.031 ***Alkalimetric Quinolinium Molybdophosphate Method (16)—Official Final Action***

Treat 1 g sample by appropriate modification of 2.050. Transfer aliquot contg ≤30 mg P_2O_5 and ≤10 mL NH_4 citrate soln, 2.044(a), to 500 mL erlenmeyer. Dil., if necessary, to 50 mL, add 10 mL HNO_3 (1+1), and boil gently 10 min. Cool, dil. to 100 mL, and continue as in 2.031(a), beginning "Add 60 mL quimociac reagent, ..."

2.032 ***Spectrophotometric Molybdovanadophosphate Method (18)—Official Final Action***

(Not applicable to materials yielding colored solns or solns contg ions other than orthophosphate which form colored complexes with molybdovanadate. Not recommended for basic slag.)

Prep. std curve as in 2.023, using photometer, 2.021.

Pipet, into 100-mL vol. flasks, 5 mL aliquots std phosphate solns contg 2 and 3.5 mg P_2O_5/aliquot, 2.022(b), resp., add 2 mL 70% $HClO_4$, and develop color as in 2.023. Adjust instrument to zero *A* for 2 mg std and det. *A* of 3.5 mg std. (*A* of latter must be practically identical with corresponding value on std curve.)

Prep. sample as in 2.050.

(a) *Samples containing up to 5% P_2O_5.*—Pipet 10 mL sample soln into 125 mL erlenmeyer, and treat by one of following methods (*Caution: See* 51.019, 51.028, and 51.029):

(*1*) Add 5 mL 20% $NaClO_3$ soln and 10 mL HNO_3-$HClO_4$ mixt., 2.049(a). Boil gently until greenish-yellow color disappears (ca 20 min), cool, and add 2 mL HCl. After vigorous reaction subsides, evap. to fumes of $HClO_4$, and fume 2 min.

(*2*) Add 5 mL ternary acid mixt., 2.049(b), swirl, boil gently 15 min, and digest at 150–200° until clear white salt or colorless soln remains. Evap. to white fumes and continue heating 5 min.

Cool, add 15 mL H_2O, and boil 5 min. Transfer to 100 mL vol. flask, dil. to 60 mL, swirl, and cool to room temp. Add 5 mL std phosphate soln contg 2 mg P_2O_5 and 20 mL modified molybdovanadate soln, 2.049(c). Dil. to 100 mL, and continue as in 2.025(a).

(b) *Samples containing more than 5% P_2O_5.*—Dil. soln to such vol. that 5–10 mL aliquot contains 2–5 mg P_2O_5. Digest as in (a)(*1*) or (*2*). Without adding std phosphate soln, continue as in (a).

2.033 ***Gravimetric Quinolinium Molybdophosphate Method (19)—Official Final Action***

(a) *Solns containing no organic phosphorus.*—Prep. sample as in 2.050. Pipet, into 500 mL erlenmeyer, aliquot contg ≤25 mg P_2O_5 and ≤10 mL original NH_4 citrate soln. Dil., if necessary, to ca 50 mL, add 10 mL HNO_3 (1+1), and boil gently 10 min. Cool, dil. to 150 mL, and proceed as in 2.028(a) or (b).

(b) *Solns containing organic phosphorus.*—(*Caution: See* 51.019, 51.026, and 51.028.) Select aliquot as in (a). Add 10 mL 20% $NaClO_3$ and 10 mL HNO_3-$HClO_4$ mixt., 2.049(a). Boil vigorously until greenish-yellow color disappears (usually ca 30 min), cool, and add 2 mL HCl. After vigorous reaction subsides, evap. to white fumes, and continue heating 5 min. Cool, and proceed as in 2.028(a) or (b).

NITROGEN

2.054 Detection of Nitrates—Official Final Action

Mix 5 g sample with 25 mL hot H_2O, and filter. To 1 vol. of this soln add 2 vols H_2SO_4, free from HNO_3 and oxides of N, and let cool. Add few drops concd *$FeSO_4$ soln* in such manner that fluids do not mix. If nitrates are present, junction at first shows purple, afterwards brown, or if only minute amt is present, reddish color. To another portion of soln add 1 mL *1% $NaNO_3$ soln* and test as before to det. whether enough H_2SO_4 was added in first test.

Total Nitrogen

(Provide adequate ventilation in laboratory and do not permit accumulation of exposed Hg.)

2.055 ***Reagents—Official Final Action***

(a) *Sulfuric acid.*—93–98% H_2SO_4, N-free.

(b) *Mercuric oxide or metallic mercury.*—HgO or Hg, reagent grade, N-free.

(c) *Potassium sulfate (or anhydrous sodium sulfate).*—Reagent grade, N-free.

(d) *Salicylic acid.*—Reagent grade, N-free.

(e) *Sulfide or thiosulfate soln.*—Dissolve 40 g com. K_2S in 1 L H_2O. (Soln of 40 g Na_2S or 80 g $Na_2S_2O_3.5H_2O$ in 1 L may be used.)

(f) *Sodium hydroxide.*—Pellets or soln, nitrate-free. For soln, dissolve ca 450 g solid NaOH in H_2O, cool, and dil. to 1 L. (Sp gr of soln should be ≥1.36.)

(g) *Zinc granules.*—Reagent grade.

(h) *Zinc dust.*—Impalpable powder.

(i) *Methyl red indicator.*—Dissolve 1 g Me red in 200 mL alcohol.

(j) *Hydrochloric or sulfuric acid std soln.*—0.5*N*, or 0.1*N* when amt of N is small. Prep. as in 50.011 or 50.028.

(k) *Sodium hydroxide std soln.*—0.1*N* (or other specified concn). Prep. as in 50.032–50.034.

Stdze each std soln with primary std, Chap. 50, and check one against the other. Test reagents before use by blank detn with 2 g sugar, which ensures partial reduction of any nitrates present.

Caution: Use freshly opened H_2SO_4 or add dry P_2O_5 to avoid hydrolysis of nitriles and cyanates. Ratio of salt to acid (wt:vol.) should be ca 1:1 at end of digestion for proper temp. control. Digestion may be incomplete at lower ratio; N may be lost at higher ratio. Each g fat consumes 10 mL H_2SO_4 and each g carbohydrate 4 mL H_2SO_4 during digestion.

2.056 ***Apparatus—Official Final Action***

(a) *For digestion.*—Use Kjeldahl flasks of hard, moderately thick, well-annealed glass with total capacity ca 500–800 mL. Conduct digestion over heating device adjusted to bring 250 mL H_2O at 25° to rolling boil in ca 5 min or other time as specified in method. To test heaters, preheat 10 min if gas or 30 min if elec. Add 3–4 boiling chips to prevent superheating.

(b) *For distillation.*—Use 500–800 mL Kjeldahl or other suitable flask, fitted with rubber stopper thru which passes lower end of efficient scrubber bulb or trap to prevent mech. carryover of NaOH during distn. Connect upper end of bulb tube to condenser tube by rubber tubing. Trap outlet of condenser in such way as to ensure complete absorption of NH_3 distd over into acid in receiver.

Source: Association of Official Analytical Chemists, Official Methods of Analysis, William Horwitz, editor. 13th Edition. Washington D.C., 1980

2.057 *Improved Kjeldahl Method for Nitrate-Free Samples (20)—Official Final Action*

(*Caution:* *See* 51.030 and 51.065.)

Place weighed sample (0.7–2.2 g) in digestion flask. Add 0.7 g HgO or 0.65 g metallic Hg, 15 g powd K_2SO_4 or anhyd. Na_2SO_4, and 25 mL H_2SO_4. If sample >2.2 g is used, increase H_2SO_4 by 10 mL for each g sample. Place flask in inclined position and heat gently until frothing ceases (if necessary, add small amt of paraffin to reduce frothing); boil briskly until soln clears and then ≥30 min longer (2 hr for samples contg org. material).

Cool, add ca 200 mL H_2O, cool <25°, add 25 mL of the sulfide or thiosulfate soln, and mix to ppt Hg. Add few Zn granules to prevent bumping, tilt flask, and add layer of NaOH without agitation. (For each 10 mL H_2SO_4 used, or its equiv. in dild H_2SO_4, add 15 g solid NaOH or enough soln to make contents strongly alk.) (Thiosulfate or sulfide soln may be mixed with the NaOH soln before addn to flask.) Immediately connect flask to distg bulb on condenser, and, with tip of condenser immersed in std acid and 5–7 drops indicator in receiver, rotate flask to mix contents thoroly; then heat until all NH_3 has distd (≥150 mL distillate). Remove receiver, wash tip of condenser, and titr. excess std acid in distillate with std NaOH soln. Correct for blank detn on reagents.

$$\% N = [(\text{mL std acid} \times \text{normality acid}) - (\text{mL std NaOH} \times \text{normality NaOH})] \times 1.4007/\text{g sample}$$

2.058 *Improved Kjeldahl Method for Nitrate-Containing Samples—Official Final Action*

(Not applicable to liqs or to materials with high Cl:NO_3 ratio. *Caution:* *See* 51.030 and 51.065.)

Place weighed sample (0.7–2.2 g) in digestion flask. Add 40 mL H_2SO_4 contg 2 g salicylic acid. Shake until thoroly mixed and let stand, with occasional shaking, ≥30 min; then add (*1*) 5 g $Na_2S_2O_3.5H_2O$ or (*2*) 2 g Zn dust (as impalpable powder, not granulated Zn or filings). Shake and let stand 5 min; then heat over low flame until frothing ceases. Turn off heat, add 0.7 g HgO (or 0.65 g metallic Hg) and 15 g powd K_2SO_4 (or anhyd. Na_2SO_4), and boil briskly until soln clears, then ≥30 min longer (2 hr for samples contg org. material).

Proceed as in second par. of 2.057.

Comprehensive Nitrogen Method (21)
Official Final Action

(Applicable to all fertilizer samples. *Caution:* *See* 51.030 and 51.079.)

2.059 ***Reagents***

(a) *Chromium metal.*—100 mesh, low N (Fisher Scientific Co. No. C-318 or Sargent-Welch Scientific Co. No. SC11432 is satisfactory).

(b) *Alundum.*—Boiling stones, 8–14 mesh (Arthur H. Thomas Co. No. 1590–D18, or equiv.).

(c) *Dilute sulfuric acid.*—Slowly add 625 mL H_2SO_4 to 300 mL H_2O. Dil. to ca 1 L and mix. After cooling, dil. to 1 L with H_2O and mix. Avoid absorption of NH_3 from air during prepn, particularly if stream of air is used for mixing.

(d) *Sodium thiosulfate or potassium sulfide soln.*—160 g $Na_2S_2O_3.5H_2O$/L or 80 g K_2S/L.

For other reagents, *see* 2.055.

2.060 ***Determination***

Place 0.2–2.0 g sample contg ≤60 mg nitrate N in 500–800 mL Kjeldahl flask and add 1.2 g Cr powder. Add 35 mL H_2O or, with liqs, amt to make total vol. 35 ml. Let stand 10 min with occasional gentle swirling to dissolve all nitrate salts. Add 7 mL HCl and let stand ≥30 sec but ≤10 min.

Place flask on preheated burner with heat input set at 7.0–7.5 min boil test, 2.0[illegible](a). After heating 3.5 min, remove from heat and let cool.

Add 22 g K_2SO_4, 1.0 g HgO, and few granules Alundum. Add 40 mL dil. H_2SO_4, (c). (If adequate ventilation is available, 25 mL H_2SO_4 may be added instead of dil. H_2SO_4. If org. matter which consumes large amt of acid exceeds 1.0 g, add addnl 1.0 mL H_2SO_4 for each 0.1 g org. matter in excess of 1.0 g.)

Place flask on burners set at 5 min boil test. (Pre-heated burners reduce foaming with most samples. Reduce heat input if foam fills ≥⅓ of bulb of flask. Use variable heat input until this phase is past.) Heat at 5 min boil test until dense white fumes of H_2SO_4 clear bulb of flask. Digestion is now complete for samples contg ammoniacal, nitrate, and urea N. For other samples, swirl flask gently and continue digestion 60 min more.

Proceed as in 2.057, second par., substituting 2.0[illegible](d) for 2.0[illegible](e).

Modified Comprehensive Nitrogen Method (22)
Official First Action

(Applicable to all fertilizer samples)

2.061 ***Reagents***

See 2.0[illegible](a), (e), (f), (i), (j), (k), 2.0[illegible](a), (b), and in addn:

Copper sulfate pentahydrate (or anhydrous copper sulfate).—Reagent grade, N-free.

2.062 ***Determination***

(*Caution:* *See* 51.019 and 51.030.)

Proceed as in 2.060, par. 1 and 2, using 0.2–1.6 g sample. For samples contg orgs other than urea or urea-form, use ≥0.5 g sample.

Add 15 g K_2SO_4 or 12 g anhyd. Na_2SO_4, 0.4 g anhyd. $CuSO_4$ or 0.6 g $CuSO_4.5H_2O$, and ca 0.8 g Alundum granules. Add 37 mL H_2SO_4 (1+1). (If adequate ventilation is available, 20 mL H_2SO_4 may be added instead of H_2SO_4 (1+1). If org. matter other than urea exceeds 1.0 g, add addnl 1.0 mL H_2SO_4 for each 0.1 g fat or 0.2 g other org. matter in excess of 1.0 g.)

Proceed as in 2.060, par. 4, substituting 75 min for 60 min in last sentence.

Cool flask until it can be handled without gloves, and add ca 250 mL H_2O. Swirl to dissolve contents, and cool <25°. Add ca 0.8 g Alundum granules to minimize bumping, tilt flask, and add layer of NaOH without agitation. (For each 10 ml H_2SO_4 used, or its equiv. in H_2SO_4 (1+1), add 15 g solid NaOH or enough soln to make contents strongly alk.) Proceed as in 2.057, par. 2, beginning "Immediately connect flask to distg bulb . . ."

Raney Powder Method (21)
Official Final Action

(Applicable to all fertilizer samples except "nitric phosphates" contg nonsulfate S. *Caution:* *See* 51.030 and 51.079.)

2.063 ***Reagents***

(a) *Raney catalyst powder No. 2813.*—50% Ni, 50% Al (W. R. Grace & Co., Davison Chemical Division, 10 E Baltimore St, Baltimore, MD 21203) *Caution:* Raney catalyst powders react slowly in H_2O or moist air to form alumina; avoid prolonged contact with air or moisture during storage or use.

(b) *Sulfuric acid-potassium sulfate soln.*—Slowly add 200 mL H_2SO_4 to 625 mL H_2O and mix. Without cooling, add 106.7 g repeat with three 50 mL washings. (Work rapidly to keep mat from becoming dry.) Remove filter from beaker and drain all H_2O from line by raising above trap level. Return mat and residue to beaker by breaking suction and blowing back. Add 200 mL boiling 1.25% NaOH and boil exactly 30 min. Remove beaker, and filter as above. Without breaking suction, wash with 25 mL boiling 1.25% H_2SO_4 and three 50 mL portions boiling H_2O. Drain free of excess H_2O by raising filter. Lower filter into beaker and wash with 25 mL alcohol. Drain line, break suction, and remove mat by blowing back thru filter screen into ashing dish. Proceed as in (c).

(b) *Using California buchner.*—Filter contents of beaker thru buchner (precoated with asbestos if extremely fine materials are being analyzed), rinse beaker with 50–75 mL boiling H_2O, and wash thru buchner. Repeat with three 50 mL portions H_2O, and suck dry. Remove mat and residue by snapping bottom of buchner against top while covering stem with thumb or forefinger and replace in beaker. Add 200 mL boiling 1.25% NaOH and boil exactly 30 min. Remove beaker, and filter as above. Wash with 25 mL boiling 1.25% H_2SO_4, three 50 mL portions H_2O, and 25 mL alcohol. Remove mat and residue; transfer to ashing dish.

(c) *Treatment of residue.*—Dry mat and residue 2 hr at 130±2°. Cool in desiccator and weigh. Ignite 30 min at 600±15°. Cool in desiccator and reweigh.

% Crude fiber in ground sample = C = (Loss in wt on ignition − loss in wt of asbestos blank) × 100/wt sample.

% Crude fiber on desired moisture basis = C × (100 − % moisture desired)/(100 − % moisture in ground sample).

Report results to 0.1%.

Asbestos-Free (AF) Method (20)
Official Final Action

7.066 *Principle*

Principle is same as in 7.061, except sample is exposed to min. vac. needed to regulate filtration, and heating of sample solns prevents gelling or pptn of possible satd solns.

7.067 *Apparatus and Reagents*

See reagents 7.062(a), (b), and (f); app. 7.063(a), (c), (d), and (f), and 14.088; and in addn:

(a) *Filtration apparatus.*—System to permit application of min. vac. necessary for filtration and washing of each sample within 3–5 min. Each unit consists of reservoir manifold connected to (*1*) H_2O aspirator thru 120° stopcock, (*2*) atm. thru second stopcock with metering device, and (*3*) receptacle contg cone-shaped hard rubber gasket which provides vac. seal with crucible. Vac. gage attached to manifold indicates vac. applied to crucible. Crucible can be heated before and during filtration by flow of hot H_2O in surrounding jacket. (For photograph of app., *see* JAOAC 56, 1353(1973). Filtration unit is available as Model 150 from Analytical BioChemistry Laboratories, Inc., PO Box 1097, Columbia, MO 65201.)

(b) *Crucible.*—Fritted glass, 50 mL, coarse porosity. Clean as follows: Brush, and flow hot tap H_2O into crucible to remove as much ash as possible. Submerge crucible in base soln, (c)(*2*), ≥5 min, remove, and rinse with hot tap H_2O. Submerge in HCl (1+1), (c) (*1*), ≥5 min, remove, and rinse thoroly with hot tap H_2O followed by distd H_2O. After 3–4 uses, back wash by inverting crucible on hard rubber gasket in filtration app., and flowing near-boiling H_2O thru crucible under partial vac.

(c) *Cleaning solns.*—(*1*) *Acid soln.*—HCl (1+1). (*2*) *Base soln.*—Dissolve 5 g Na_2H_2EDTA, 50 g Na_3HPO_4 (tech. grade), and 200 g KOH in H_2O, and dil. to 1 L. Storage in sep. wide mouth containers holding 2–3 L soln into which crucibles can be placed is convenient.

7.068 *Determination*

(*Caution: See* 51.011 and 51.073.)

Ext 2 g ground material with ether or pet ether, 14.088. If fat is <1%, extn may be omitted. Transfer to 600 mL reflux beaker, avoiding fiber contamination from paper or brush. Add 0.25–0.5 g bumping granules, followed by 200 mL near-boiling 1.25% H_2SO_4 soln in small stream directly on sample to aid in complete wetting of sample. Place beakers on digestion app. at 5 min intervals and boil exactly 30 min, rotating beakers periodically to keep solids from adhering to sides. Near end of refluxing place California buchner, 7.063(d), previously fitted with No. 9 rubber stopper to provide vac. seal, into filtration app., and adjust vac. to ca 25 mm Hg (735 mm pressure). At end of refluxing, flow near-boiling H_2O thru funnel to warm it; then decant liq. thru funnel, washing solids into funnel with min. of near-boiling H_2O. Filter to dryness, using 25 mm vac., and wash residue with four 40–50 mL portions near-boiling H_2O, filtering after each washing. Do not add wash to funnel under vac.; lift funnel from app. when adding wash.

Wash residue from funnel into reflux beaker with near-boiling 1.25% NaOH soln. Place beakers on reflux app. at 5 min intervals and reflux 30 min. Near end of refluxing, turn on filtration app., place crucible, (b), in app., and adjust vac. to ca 25 mm. Flow near-boiling H_2O thru crucible to warm it. (Keep near-boiling H_2O flowing thru jacket during filtration and washing.) At end of refluxing, decant liq. thru crucible and wash solids into crucible with min. of near-boiling H_2O. Increase vac. as needed to maintain filtration rate. Wash residue once with 25–30 mL near-boiling 1.25% H_2SO_4 soln, and then with two 25–30 mL portions near-boiling H_2O, filtering after each washing. (Filtering and washing takes ca 3–5 min/sample.) Do not add wash to crucible under vac.

Dry crucible with residue 2 hr at 130±2° or overnight at 110°, cool in desiccator, and weigh. Ash 2 hr at 550±10°, cool in desiccator, and weigh. Do not remove crucibles from furnace until temp. is ≤250°, as fritted disk may be damaged if cooled too rapidly.

% Crude fiber = Loss in wt on ignition × 100/wt sample.

Acid-Detergent Fiber and Lignin (21)
Official Final Action

(*Caution: See* 51.088.)

7.069 *Reagents*

(a) *Sulfuric acid.*—72% by wt. Stdze reagent grade H_2SO_4 to sp gr 1.634 at 20° or 24.00*N*: Add 1200 g H_2SO_4 to 440 mL H_2O in 1 L MCA vol. flask with cooling. Stdze to 1634 g/L at 20° by removing soln and adding H_2O or H_2SO_4 as required. (*Caution: See* 51.030.)

(b) *Acid-detergent soln.*—Add 20 g cetyl trimethylammonium bromide (tech. grade) to 1 L 1.00*N* H_2SO_4, previously stdzd. Agitate to aid soln.

(c) *Asbestos.*—Place 100 g asbestos in 3 L flask contg 850 mL H_2O. Add 1.4 L H_2SO_4 (tech. grade), mix, and let cool 2 hr at room temp. Filter on large buchner and wash with H_2O. Resuspend mat in H_2O and pour into bag sewn from rectangle of fiberglass window screening, 14 × 18 mesh (bag should be ≥45 cm wide × 30 cm deep). Wash by immersion and agitation in partly filled sink to remove fine particles. Ash recovered asbestos 16 hr in 800° furnace. Store in dry form until use. Used asbestos may be rewashed, reashed, and reused. Com. prepd acid-washed asbestos is unsatisfactory unless treated with 72% H_2SO_4 and ashed at 800°.

7.070 *Apparatus*

(a) *Refluxing apparatus*.—Any conventional app. suitable for crude fiber detns. Berzelius beakers (600 mL) and condensers made from 500 mL r-b flasks are also satisfactory.

(b) *Fritted glass crucibles*.—Use coarse porosity, 40–50 mL Pyrex crucible. Wash new crucibles and ash at 500°. Remove while still hot and place in 100° forced-draft oven ≥1 hr. Cool 15 min in desiccator over P_2O_5 or $Mg(ClO_4)_2$ and weigh in same order samples are to be weighed. Check balance 0 after each weighing if crucibles are still warm. Hold length of time from oven to balance pan as const as possible and always weigh crucibles in same order.

7.071 *Determination of Acid-Detergent Fiber*

Weigh 1 g air-dried sample ground to pass 1 mm screen, or approx. equiv. amt wet material, into refluxing container. Add 100 mL acid-detergent soln at room temp.

Heat to boiling in 5–10 min; reduce heat to avoid foaming as boiling begins. Reflux 60 min from onset of boiling, adjusting boiling to slow, even level. Remove container, swirl, and filter thru weighed (W_1) fritted glass crucible, using min. suction. Increase vac. only as needed. Shut off vac. Break up filtered mat with rod and fill crucible ⅔ full with hot (90–100°) H_2O. Stir and let soak 15–30 sec. Dry with vac. and repeat H_2O washing, rinsing sides of crucible. Wash twice similarly with acetone.

Repeat acetone washings until no more color is removed, breaking up all lumps so that solv. wets all particles of fiber. Remove residual acetone with vac. Dry 3 hr or overnight in 100° forced-draft oven and weigh (W_2). Calc. % acid-detergent fiber = $100 (W_2 - W_1)/S$, where S = g sample × g oven-dried matter/g air-dried or wet matter, detd on sep. sample.

7.072 *Determination of Lignin*

To crucible contg fiber, 7.071, add 1 g asbestos. Place crucible in 50 mL beaker for support or arrange crucibles in shallow enamel pan. Cover contents of crucible with cooled (15°) 72% H_2SO_4 and stir with glass rod to smooth paste, breaking all lumps. Fill crucible about half-way with acid and stir. Leave glass rod in crucible; refill with 72% H_2SO_4 and stir hourly as acid drains, keeping crucible at 20–23° (cool if necessary). After 3 hr, filter as completely as possible with vac., and wash with hot H_2O until acid-free to pH paper. Rinse sides of crucible and remove stirring rod. Dry crucible in 100° forced-draft oven, cool in desiccator over P_2O_5 or $Mg(ClO_4)_2$, and weigh (W_3). Ignite crucible in 500° furnace 2 hr or until C-free. Place crucible while still hot into 100° forced-draft oven 1 hr. Transfer to desiccator, cool, and weigh (W_4).

Det. asbestos blank by weighing 1 g asbestos into tared crucible. Proceed as above, beginning "Cover contents of crucible . . ." Record any loss in wt on ashing (W_5). Discontinue detn of blank if asbestos blank is <0.0020 g/g asbestos. Calc. % acid-insol. lignin = $(W_3 - W_4 - W_5)/S$.

Total Sugars (22)—Official Final Action

7.073 *Reagents*

(a) *Soxhlet modification of Fehling soln*.—Prep. as in 31.034(a) and (b).

(b) *Invert sugar std soln*.—1.0%. Prep. as in 31.034(c), but do not neutze. Dil. to 0.5% just before use for analysis of most products.

(c) *Lactose std soln*.—1.0%. Dissolve 5.000 g lactose in H_2O and dil. to 500 mL. Prep. daily.

7.074 *Apparatus*

(a) *Lamp*.—Fluorescent desk lamp or 150 watt reflector spot lamp, to illuminate boiling soln.

(b) *Heater*.—Glas-Col mantle, 250 mL, placed over mag. stirrer. Adjust heat so that 50 mL H_2O contg stirring bar will boil in 3 min. Mag. stirring hot plate is also satisfactory.

7.075 *Preparation of Sample and Inversion*

(a) *Feeds containing molasses*.—Weigh appropriate size sample, prepd as in 7.002 but not ground, to provide final soln ca 0.5% invert sugar but ≥5 g, into 250 mL P flask (Corning Glass Works No. 5640, or equiv.). Add 150 mL H_2O, swirl to wet and mix, and heat just to bp. Let stand to cool, dil. to vol., mix, and let stand to settle coarse particles. Transfer 50 mL supernate to 100 mL vol. flask and add 2.5 mL HCl (sp gr 1.18 at 20/4°). Let stand overnight at ≥25°, dil. to vol., and mix. (If aliquot to be used in detn is >25 mL, it is necessary to neutze inverted soln.)

(b) *Feeds containing milk products*.—Weigh appropriate size sample to provide final soln ca 1% lactose into 250 mL vol. flask. Thoroly moisten sample with H_2O, swirl to dissolve lactose, dil. to vol., mix, and let stand to settle coarse particles. Proceed as in 7.077(b).

7.076 *Standardization*

Fill 50 mL buret, with offset tip, with std sugar soln (invert sugar for use with 7.077(a) and lactose with 7.077(b)). Proceed as in 31.080, par. 2, except use same type flask as used in 7.077, do not add H_2O, and start stirring after addn of indicator.

7.077 *Determination*

(a) *Difference method*.—Add reagents and stirring bar to 250 mL extn flask (Corning Glass Works No. 5160, or equiv.) or to erlenmeyer, as in 7.076. Transfer aliquot inverted soln, (a), to flask so that >1 but <5 mL std soln will be required to reach end point, place on preheated mantle or hot plate, heat to bp, boil 2 min, add ca 1 mL indicator, and begin stirring. Complete detn by titrg with std sugar soln to same end point used in stdzn. Color change is not so sharp as in stdzn, but under suitable light it is definite, discernible, and repeatable.

(b) *Alternative method*.—Fill buret with sample soln, (b), or inverted sample soln, (a). As in 7.076, place reagents in flask, place on heater, add sample soln to within 2 mL of final titrn (detd by trial), bring to bp, boil 2 min, and complete titrn as in (a).

7.078 *Calculations*

% Total sugar (as invert or lactose)

$$= [(F - M) \times I \times 100]/[V \times (W/250) \times D],$$

where F = mL std sugar required to reduce mixed Soxhlet reagent in stdzn; M = mL std soln required to complete detn (omit in alternative method); I = concn std soln; V = mL sample soln in aliquot used; W = g sample; and D = diln factor.

Report total sugars, expressed as invert or as lactose.

7.079 Sucrose (23)—Official Final Action

Place 10 g sample in 250 mL vol. flask. If material is acid, neutze by adding 1–3 g $CaCO_3$. Add 125 mL 50% alcohol by vol., mix thoroly, and boil on steam bath or by partially immersing flask in H_2O bath 1 hr at 83–87°, using small funnel in neck of flask to condense vapor. Cool and let mixt. stand several hr, preferably overnight. Dil. to vol. with neut. 95% alcohol, mix thoroly, let settle or centrf. 15 min at 1500 rpm, and decant closely. Pipet 200 mL supernate into beaker and evap. on steam

APPENDIX B

LIST OF SOME OF THE HAY DRYER FAN MANUFACTURERSIN QUEBEC AND ONTARIO

Aston Industries Inc.
Box 222
50 Courchesne
St-Leonard d'Aston, Ste-Nicolet
Quebec JOC 1MO
Tel. (819) 399-2175

Canarm Ltd.
Danor Agricultural Products
Box 367
149 Parkdale Avenue
Brockville, Ontario
K6V 5V6
Tel. (613) 342-5424

Dri-Stor Industries
RR#1
Uxbridge, Ontario
LOC 1KO
Tel. (416) 852-7431

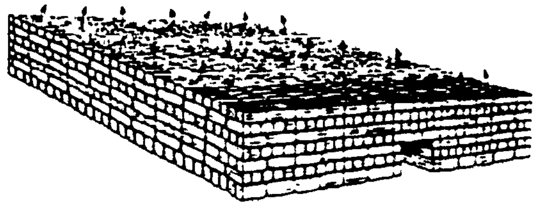
Lajoie Ltée.
Ralco Farm Equipment Co.
Box 69
St-Pie, Québec
JOH 1WO
Tel. (514) 772-2465

Ventillateur Victoria Ltée.
Box 69
400 Bonaventure Blvd.
Victoriaville, Québec
G6P 6S4
Tel. (819) 758-6411

APPENDIX C

HAY DRYING FAN MANUFACTURER'S SPECIFICATIONS

FAN SPECIFICATIONS



FEATURES

- **MOTOR** — Totally enclosed ball bearing continuous duty capacitor-start capacitor-run specially designed for crop drying. Electrical rating 5 HP 230 volts 1 phase 60 cycles 1725 RPM
- **PROPELLER** — Cast aluminum airfoil section blades on cast iron hub. Direct drive 36" size
- **HOUSING** — Rugged welded construction made of heavy gauge rust-resistant steel painted red enamel
- **MOTOR MOUNT** — Motor base supported by robust steel plate welded to orifice panel
- **GUARDS** — Made of sturdy steel wire mesh

GENERAL INFORMATION

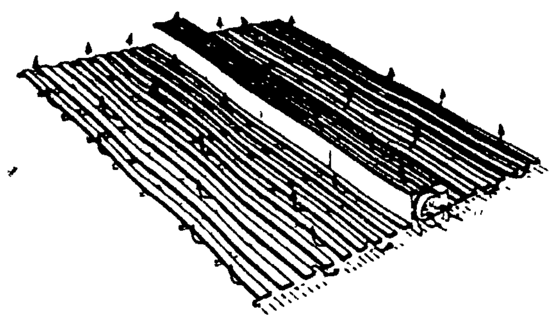
The use of a hay dryer in the barn eliminates loss of quality due to weather damage. Field curing exposes the hay crop to the dangers of leaching by rain and bleaching by the sun. Mow drying produces hay a full two grades better based on testing for percentage of clinging leaves, green colour and percentage of foreign material; also hay is richer in protein with savings up to 25 % in the amount of grain needed as food supplement.

The hay dryer circulates air through the hay and evaporation of moisture keeps the mow cool — this prevents spontaneous combustion and greatly reduces the possibility of a barn fire.

With barn drying, hay can be cut and stored the same day. Partially dried in the field to approximately 40 % moisture content, stems and leaves are still tough enough to resist shattering and handling losses are kept low. Fan should be left in operation day and night until moisture content is down to 20 % for safe storage.

The Ralco Hay Dryer is entirely contained within a rugged steel housing. Outlet opening is protected by wire guards. The propeller has a cast iron hub and cast aluminum blades with airfoil section profile for maximum efficiency. The totally enclosed long-life quality motor was specially designed for crop drying. The motor base is supported by robust plates welded to the orifice panel. Thanks to the solid welded steel construction of the housing and the motor mount, the heavy duty motor and the massive well-balanced propeller, the fan runs very smoothly.

With the propeller mounted directly on the motor shaft and no belts to worry about, operation is trouble-free with minimal maintenance. The Ralco Hay Dryer is shipped completely assembled after it has been thoroughly tested at the factory.



PERFORMANCE DATA

SPECIFICATIONS SUBJECT TO CHANGE WITHOUT NOTICE

Model Number	Fan Size	Motor HP	Volts	Phase	Speed RPM	Airflow Capacity CFM							Shipping Weight
						0" S.P	¼" S.P	½" S.P	¾" S.P	1" S.P	1¼" S.P	1½" S.P	
925-00000	36"	5	230	1	1725	24200	22400	20800	19200	16400	14300	14000	285 LB

APPENDIX D : PROCEDURE FOR ESTIMATING HOURLY SOLAR RADIATION INCIDENT ON A NON-HORIZONTAL SURFACE

The method used for estimating monthly average hourly radiation incident on a non-horizontal surface, given horizontal surface data, was that developed by Hay (5). The method is reviewed below.

- Basic data requirements include direct (or beam) and diffuse components for radiation incident on the horizontal. The radiation incident on a sloping surface can be separated into three components as follows:

$$Sb = \frac{Hb \cdot \cos i}{\sin a} \qquad 1.$$

$$Sd = Hd\left(\left(\frac{Hb}{I \sin a}\right)^{1/m} \cos i \quad \left(1 - \left(\frac{Hb}{I \sin a}\right)^{1/m} \sin i\right)\right)\left(\frac{1 + \cos s}{2}\right) \qquad 2.$$

$$Sr = \frac{Ht \cdot \alpha \ (1 - \cos s)}{2} \qquad 3.$$

where Sb = hourly beam radiation on non-horizontal surface
Sd = hourly diffuse radiation on non-horizontal surface
Sr = hourly reflected radiation on non-horizontal surface
Hb = hourly beam radiation on horizontal surface
Hd = hourly diffuse radiation on horizontal surface
Ht = hourly global radiation on horizontal surface
i = angle of incidence
a = solar altitude
m = air mass
s = slope of surface
I = solar constant = 1353 watt-hour/m^2
α = albedo or reflectivity of horizontal surface

and

$$\begin{aligned} \cos i = & (\sin \delta \sin \phi \cos s) \\ & - (\sin \delta \cos \phi \sin s \cos \gamma) \\ & + (\cos \delta \cos \phi \cos s \cos \omega) \\ & + (\cos \delta \sin \phi \sin s \cos \gamma \cos \omega) \\ & + (\cos \delta \sin s \sin \gamma \sin \omega) \end{aligned} \qquad 4.$$

$$\sin a = \sin \phi \sin \delta + \cos \phi \cos \delta \cos \omega \qquad 5.$$

where δ = solar declination

ϕ = latitude of location

γ = azimuth of surface (0° = South, -90° = East, etc)

ω = hour angle (Noon = 0, 15° for each hour after noon and -15° for each hour before noon)

The air mass is given as:

$$m = 1.0/ (\sin a + 0.15 (3.885 + a)^{-1.253}) \qquad 6.$$

NOTE: If $i > 90^\circ$ then $Sb = 0$

and $$Sd = Hd \left(1 - \left(\frac{Hb}{I.\sin a}\right)^{1/m} \sin a\right)\left(\frac{1+\cos s}{2}\right) \qquad 2A.$$

The diffuse component from equation 2 or 2A is assumed to be anisotropic and the reflected component is assumed to be isotropic.

The average monthly solar radiation is a junction of solar geometry as specified in Table (C-1) and albedos are representative of the type of ground cover (usually varying between 0.2 and 0.7 depending upon snow cover). Albedo values used for Montréal can also be found in Table (C-1).

The following example will clarify the use of equation 1 - 6:

Location - Montréal, Québec

Latitude - 45.5° North

It is required to calculate the average monthly hourly radiation incident on a surface sloped at 90° (wall) and oriented 30° west of south between the hours of 10 and 11 for February.

DATA:
- solar radiation incident on the horizontal between the hours of 10 to 11 (solar time)

  $Hb = 167$ watt-hour/m^2

  $Hd = 171$ watt-hour/m^2
- albedo = 0.63 (from Table (C-1))
- solar declination = -12.95° (from Table (C-1))
- $\gamma = +30^\circ$
- $s = +90^\circ$
- $\omega = 1.5 \times 15 = 22.5^\circ$ (mean hour angle)

From equation 4: $\cos i = 0.5060$

$i = 59.6^{o}$

From equation 5: $\sin a = 0.4712$

$a = 28.1^{o}$

From equation 6: $m = 2.113$

Since $i < 90^{o}$, equations 1 & 2 apply

From equation 1: $Sb = 179$ watt-hours/m^2

From equation 2: $Sd = 110$ watt-hours/m^2

From equation 3: $Sr = 106$ watt-hours/m^2

therefore global radiation incident on sloping surface:

$$St = Sb + Sd + Sr = 395 \text{ watt-hours}/m^2$$

NOTE: Hay's method requires a knowledge of the hourly diffuse components in the global solar radiation data. When diffuse readings are unavailable, they can be estimated by a method shown in Reference (6)

TABLE C-1 SOLAR DECLINATIONS AND ALBEDOS USED IN ESTIMATING INCIDENT SOLAR RADIATION. (6)

note: albedos are for Montreal area only

MONTH	SOLAR DECLINATION DEGREES	ALBEDO
*****	*****************	******
JAN	-20.92	0.62
FEB	-12.95	0.63
MAR	-2.42	0.25
APR	+9.41	0.25
MAY	+18.79	0.25
JUN	+23.09	0.25
JUL	+21.18	0.25
AUG	+13.45	0.25
SEP	+2.22	0.25
OCT	-9.60	0.25
NOV	-18.91	0.25
DEC	-23.05	0.28

SECTION 1 - REFERENCES

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4) Duffie, J.A., Beckman, W.A., SOLAR ENERGY THERMAL PROCESS, Wiley Interscience, New York, 1964.

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7) Osborne, W.C., Turner, C.G., (editors), WOODS PRACTICAL GUIDE TO FAN ENGINEERING, Woods of Colchester Ltd., 1954.