THE UNIVERSITY OF MANITOBA

SOLAR GRAIN DRYING IN CANADA: A SIMULATION STUDY

by

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BRUCE MALCOLM FRASER

A dissertation submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements of the degree of

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ABSTRACT

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An inexpensive, efficient method of on-farm grain drying is low-temperature in-bin drying. Such a dryer is easily adapted to solar drying by the addition of a solar collector to warm the drying air. The purpose of this study was to investigate the feasibility of this method of solar drying in Canada.

Computer simulation models were used to determine the effects of variables and to study the economics of various drying systems. The computer drying model assumed that during drying the air and grain reached temperature and moisture equilibrium during each time interval. The grain deterioration models predicted grain quality during the drying period, based on laboratory results.

Minimum airflow rates were predicted by these models for 422 combinations of parameters. The minimum airflow rate was the lowest airflow which would dry the grain before it spoiled. The parameters investigated were geographical location, initial moisture content of the grain, harvest date, weather conditions, grain type and amount of heat added. Weather data for the two most adverse years of weather were used for each location.

The geographical locations considered were Edmonton, Swift Current, Winnipeg and London. The predicted airflow rates were lowest at the driest and coolest locations, Edmonton and Swift Current, where airflows as low as 0.10 $m^3/(min \cdot t)$ (cubic metres per minute per tonne) could be utilized. The minimum airflow rates predicted for the warmest, most humid locations ranged up to 16 $m^3/(min \cdot t)$. The minimum airflow rates were approximately doubled for each 2% increase in initial moisture content of the grain, and each month's delay in harvesting reduced the minimum airflow rate by approximately 50%. Addition of solar heat also reduced the airflow rate by as much as 50%.

The performances of low-temperature dryers over periods of 10 or more years were simulated for 97 combinations of parameters. Solar collectors with average temperature rises of 1 to 2°C were also added to the simulation models. The addition of the collectors reduced the energy consumption by an average of 8% in the Swift Current area and 35% at London, Ontario.

Cost analyses as applied to a 5.7 m diameter bin dryer indicated that the addition of solar heat to the unheated air drying system, reduced the total drying cost in only a few instances.

The cost analysis was set up so that further price increases could be accommodated. The analysis showed that as electricity costs increase more rapidly than other costs, solar grain drying will become more economical than unheated air drying.

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A	Solar collector area per unit mass of grain, m^2/t
a	Coefficient for a particular grain in ERH equation
AC_r	Revised annual equipment cost, \$/bin
AFC_r	Revised allowable first cost of the collector, $\$/m^2$
AFR	Airflow rate per unit mass of grain, $m^3/(min \cdot t)$
A_o	Original horizontal collector area of 50% efficiency, m^2
A_r	Revised collector area for a different orientation or efficiency required to deliver the same amount of energy, m^2
b	Coefficient for a particular grain in ERH equation
C	Specific heat of corn or wheat, $J/(kg \cdot K)$
c	Coefficient for a particular grain in ERH equation
C_{A_r}	Revised annual collector cost, $\$/(m^2 \cdot a)$
C_o	Collector depreciation cost, \$/t
d	Coefficient for a particular grain in ERH equation
Dep	Drying equipment depreciation cost, \$/t
Dep_A	Drying equipment depreciation cost for ambient air drying, \$/t
Dep_S	Drying equipment depreciation cost for solar drying, \$/t
DM	Dry matter decomposition, %
D_r	Revised bin diameter, m
e	Base of natural logarithm
E	Electricity cost, \$/t

E_A	Electricity cost for ambient air drying, $/t
Eff	Average solar collector efficiency, related to total radiation on a horizontal surface, decimal fraction
E_r	Revised electrical rate, $/MJ
ERH	Equilibrium relative humidity of the air, decimal fraction
E_S	Electricity cost for solar drying, $/t
exp	Exponential e
F	Sum of products to be minimized in determining ERH
F_r	Revised annual cost factor, fraction of first cost, decimal
G_o	Grain temperature at the beginning of the time interval, °C
G_r	Revised grain value, $/t
H	Daily solar radiation on a horizontal surface, MJ/m^2
H_f	Absolute humidity of the air at the end of the time interval, kilograms of water per kilogram of dry air
H_o	Absolute humidity of the air at the beginning of the time interval, kilograms of water per kilogram of dry air
i	Sample number
M_D	Mechanical damage multiplier
M_f	Moisture content of the grain at the end of the time interval, % dry mass basis
M_i	Moisture content of sample i, % dry mass basis
M_M	Moisture content multiplier
M_o	Moisture content of the grain at the beginning of the time interval, % dry mass basis
M_T	Temperature multiplier
M_w	Moisture content, % wet mass basis

n	Number of samples or data points
OD	Overdrying cost, \$/t
OD_A	Overdrying cost for ambient air drying, \$/t
OD_S	Overdrying cost for solar drying, \$/t
P_i	Vapor pressure of the air in equilibrium with sample i, kPa
P_s	Saturation vapor pressure of the air, kPa
P_{s_i}	Saturation vapor pressure of the air at the temperature of sample i, kPa
R	Dry matter-to-air ratio, kilograms of dry matter per kilogram of air
R'	Grain-to-air ratio, kilograms of grain per kilogram of air
RH_{air}	Relative humidity of the air
S_e	Standard error of estimate
SC	Solar collector coefficient, °C
T	Grain temperature, °C
TDC_r	Revised total drying cost, \$/t
T_f	Air temperature at the end of the time interval, °C
T_o	Air temperature at the beginning of the time interval, °C
Δt	Temperature rise produced by a solar collector, °C
θ	Estimated allowable storage time, h or d
θ_{eq}	Equivalent storage time, h
θ_R	Reference storage time for corn, 230 h
$\Delta\theta$	Simulation or drying time interval being considered, h

I. INTRODUCTION

Grain crops grown in Canada are sometimes harvested in a tough or damp condition. The reasons may be to speed up the harvest, to reduce field losses or because the grain will not dry in the field.

It is not necessary to dry this grain immediately. It may be fed to livestock, mixed with dry grain, sold or utilized in other ways. The grain quality is best preserved by drying, however. Also, dry grain requires less energy for transportation, because it contains less water. Although off-farm drying may be desirable, it is often precluded by marketing constraints and limited drying capacities. Whatever action is taken, it is normally based on economics and the availability of the various options. On-farm drying is therefore necessary in some circumstances.

Escalating energy costs have emphasized the need of developing grain drying methods which are energy efficient. The use of solar energy may be one way of meeting this goal.

Farmers who annually dry large quantities of grain normally use a high-temperature high-speed grain dryer. Drying is achieved in this type of dryer by forcing heated air at a relatively high velocity through the grain. Combination drying is one method of energy saving in such a dryer (Morey and Cloud, 1977). This combines rapid high-temperature drying for high moisture content grain with low-temperature drying for the final drying stages. Solar heating may be used in this second stage.

Farmers who dry grain infrequently or in small amounts cannot usually justify the high capital cost of a high-temperature dryer. An alternative is the in-bin dryer which is cheaper to purchase and uses less energy (Friesen, 1974). It consists of a grain bin with a perforated floor, a fan and possibly a heater. For batch-in-bin drying, air temperatures of 30°C or more, airflow rates of 10 $m^3/(min \cdot t)$ (cubic metres per minute per tonne) or more and limited grain depths are used (Friesen, 1974). The grain is dried within one or two days.

When the drying time can be extended, energy savings are realized by using a smaller fan and heater. This is low-temperature drying. Heated or unheated air may be used, but the addition of heat lowers the relative humidity of the air. This ensures that drying will occur during periods of high relative humidity. Usual drying times range from a few weeks to several months. The extended drying times and small heat requirements make it possible to collect solar energy with reasonably small and inexpensive collectors. Thus energy can be saved and heating costs may be reduced. Two questions remain.

Is sufficient solar energy available when required, and is the use of solar energy economical?

The objective of this study was thus to determine the cost-effectiveness of utilizing solar energy in a low-temperature drying system in Canada. Such a system appeared to be most suitable for on-farm solar grain drying.

The method of investigation was a computer simulation model. This model predicts the drying of grain based on the initial moisture content, harvest date, airflow rate and weather conditions. Such a technique cannot exactly duplicate the processes occuring in nature. It can, however, produce useful results for a fraction of the cost and time required for field studies. The results of this study provide guidelines for the future of grain drying in Canada.

II. LOW-TEMPERATURE GRAIN DRYING WITH SOLAR ENERGY

2.1 Solar Collectors

Solar collectors for grain drying are generally simple and low-cost. They consist of a surface to intercept the sun's rays and to absorb some of the energy, plus an adjacent passage to move the air. The air collects the heat energy as it passes the absorbing surface before being blown through the grain. The absorbing surface may be metal, wood, paper or plastic and may be flat, corrugated or V-shaped. Best performance results from a slightly rough surface with a dull, black finish (Foster and Peart, 1976).

Solar collectors are normally constructed according to the bare plate, covered plate or suspended plate design. The bare plate collector (Fig. 2.1) is usually the least expensive to build but is also least efficient (Schoneau and Besant, 1976). For grain drying, metal sheets may be fastened to the southern wall of a bin, leaving a few centimetres of space for the air passage.

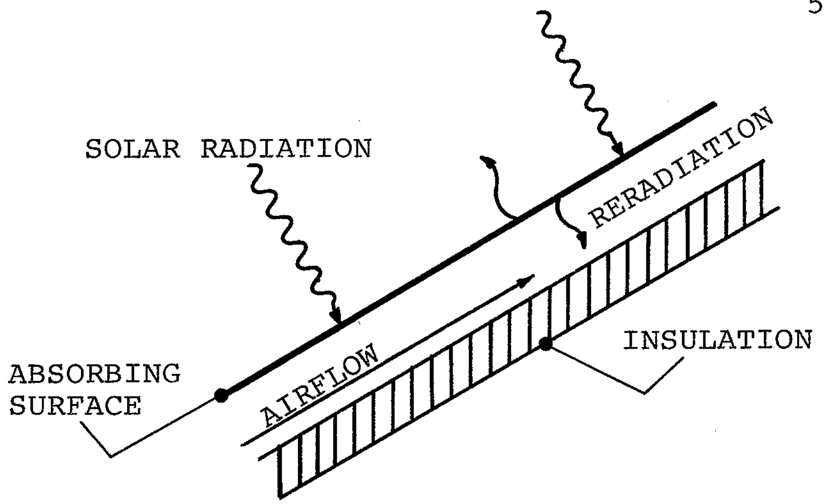

Fig. 2.1 Bare plate solar energy collector (Shove, 1977; Foster and Peart, 1976).

The covered plate collector has a transparent cover to reduce heat loss (Fig. 2.2). This collector is usually more efficient than the bare plate collector and may be low priced if a plastic cover is used. It has the lowest cost per unit of heat collected (Schoneau and Besant, 1976). For grain drying, a transparent cover can be fastened over a bin wall with the wall painted black. During storage when no air is moved to cool the collector, the black wall may cause increased grain temperatures. This is undesirable because warm grain has a greater potential for deterioration. To avoid this problem an adjacent structure may be used to mount the collector.

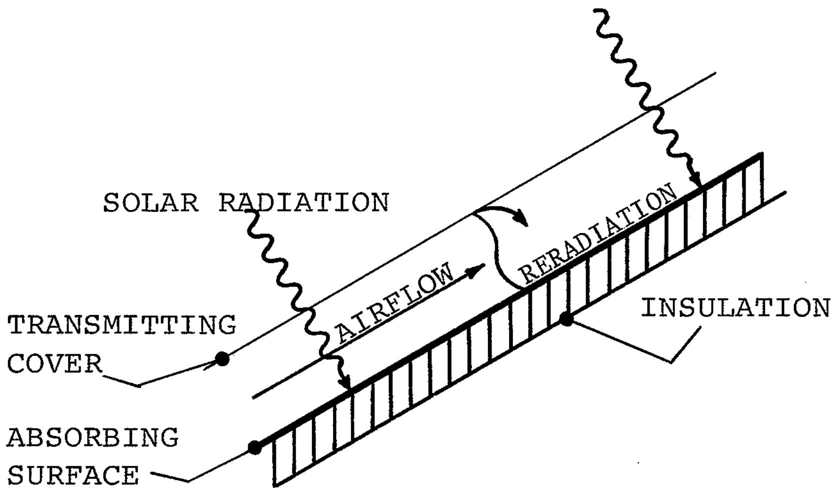

Fig. 2.2 Covered plate solar energy collector (Shove, 1977; Foster and Peart, 1976).

The suspended plate collector has a suspended absorbing surface to provide two air passages (Fig. 2.3). This increased heat transfer area results in highest efficiency but also highest cost compared to the other types (Schoneau and Besant, 1976). For grain drying it may be mounted at any convenient location.

The slope of a solar collector determines the amount of heat collected. Maximum heat is collected with the

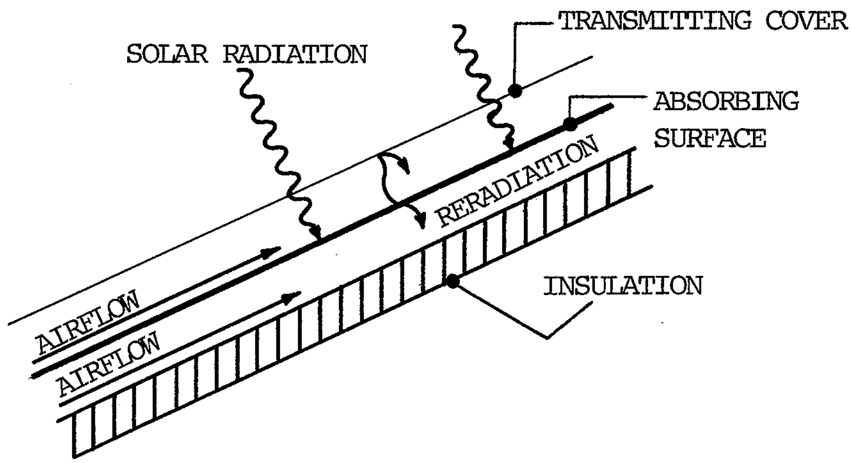

Fig. 2.3 Suspended plate solar energy collector (Shove, 1977; Foster and Peart, 1976).

collector at the optimum slope, perpendicular to the sun's rays. During the fall when most grain is dried the optimum slope is between 40 and 70 degrees from horizontal depending on the location and date (Fig. 2.5). To collect an equal amount of heat, a collector at the optimum slope is smaller than one at any other slope (Fig. 2.4). Similarily, a vertical collector is smaller than a horizontal collector. During the fall a south-facing wall would therefore be better than a horizontal surface for mounting a collector.

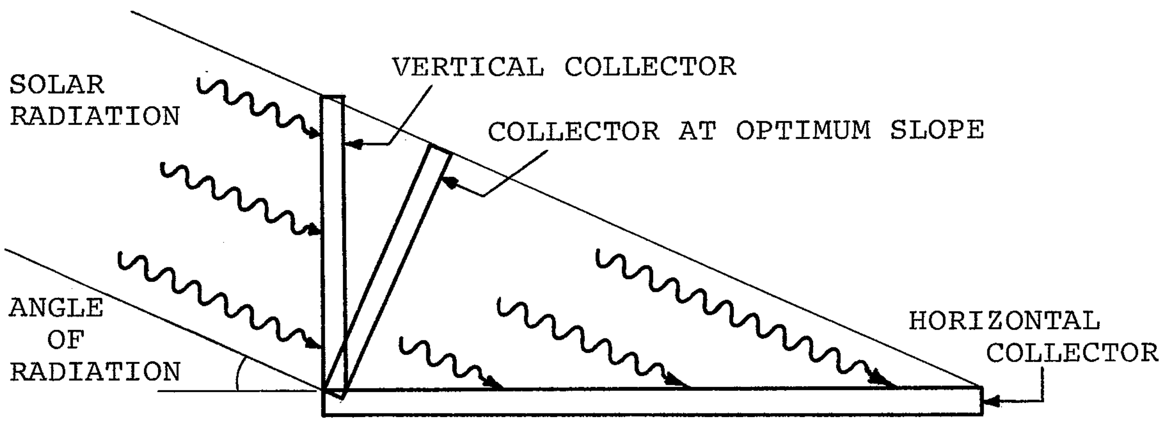

Fig. 2.4 Relative collector areas required to intercept an equal amount of solar radiation during the fall drying period. Exaggerated for illustration.

A variation on the basic solar collector is the use of an intensifier to concentrate and reflect the sun's rays onto a collector (Saienga et al. 1977). The collector is smaller than normal and the intensifier is cheaper per unit area than a collector.

Another variation is a portable collector designed for multiple use (DesChenes et al. 1976). Spreading the cost

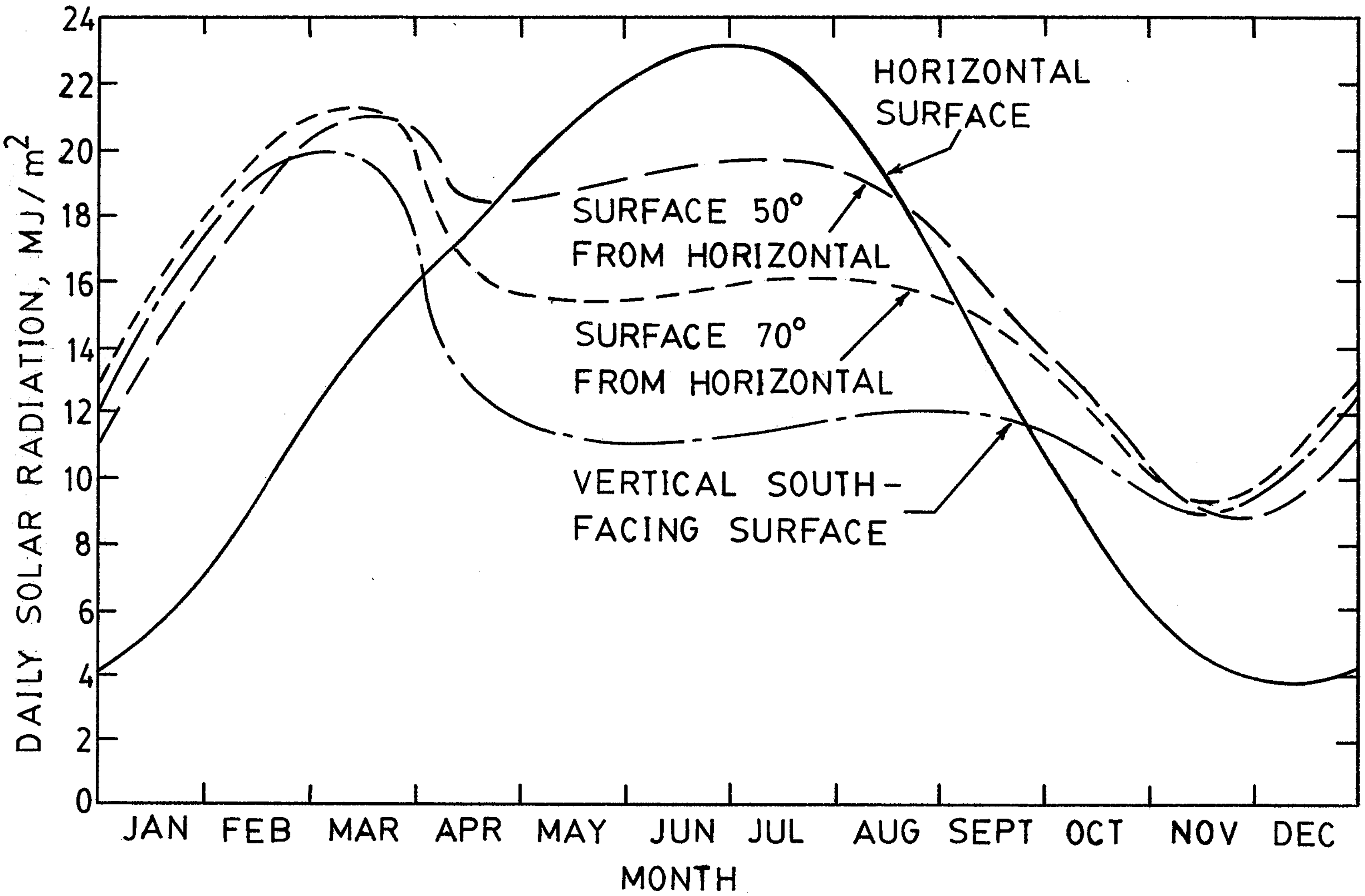

Fig. 2.5 Amounts of radiation received on various surfaces at Winnipeg. Data for radiation on a horizontal surface are averages for 1957 to 1975 (Environment Canada).
Other data were calculated from these data as shown in Appendix A.

over several applications improves the economics and allows a more efficient and durable design. Possible conflicts in use may limit the number of applications.

2.2 Heat Storage

Many solar applications require heat to be stored for use when no radiation is available. In low-temperature grain drying the grain itself acts as a storage medium. During the daytime the bottom layers of grain tend to become overdried. At night the overdried grain picks up moisture from the high humidity air. This reduces over-drying and lowers the air relative humidity. This air continues to dry the grain above (Foster and Peart, 1976).

Other methods of heat storage for grain drying, suggested by Eckhoff et al. (1976), are -

1. Seasonal storage.

   The storage unit is heated during the summer, using the collectors. During the fall the hot air from the collectors is used directly for drying. When there is no radiation, heat from storage is used. This increases the rate of drying over non-storage methods but a large storage is expensive.

2. Collector storage.

   The hot air from the collectors is used to heat the storage unit during the day. At night the stored heat is used to warm the drying air. This provides a more constant heat source than non-storage methods of drying.

3. Ambient storage.

The collectors heat the drying air directly, as in conventional systems. The storage unit is heated by the ambient air.

4. Natural storage.

Ambient air is used both to dry the grain during the day and to heat the storage unit. No collectors are used.

In all of these cases, the storage medium may consist of phase-change materials, rocks, soil or other materials. According to Eckhoff et al. (1976) the three media holding the most promise are sodium sulphate decahydrate, rock and water-saturated-soil.

2.3 Reported Results of Solar Grain Drying

2.3.1 Field Studies

Lipper and Davis (1959) found that solar energy was most suitable for use with low-temperature dryers where slow drying was adequate and where the cost of fuels was high or their availability limited. They suggested that supplemental heating would be necessary to avoid spoilage of high moisture grain during drying. Buelow (1958) suggested that a solar drying system would be most profitable for farmers with small volumes of grain to dry.

In recent years, solar drying of corn has been compared with unheated air and electrically heated air drying in low-temperature drying systems (Bauman et al. 1975; Converse et al. 1976; DesChenes et al. 1976; Foster and Peart, 1976; Hammond and Winsett, 1976; Heid, 1978; Kranzler et al. 1975; Meyer et al. 1975; Morey et al. 1975; Morrison and Shove, 1975; Peterson and Hellickson, 1976; Saienga et al. 1977; Shove, 1977; Smit and Shove, 1976; Williams et al. 1976). In all cases the grain was dried without significant spoilage. Drying rates with solar energy were faster than unheated air drying but slower than heated air drying with a temperature rise of 4 to 5.5°C. Similarly the final moisture contents were lower with solar heating than with unheated air and higher with heated air drying. Although energy was conserved by using solar energy, the economics were not favorable for solar drying.

An economic study of eight solar drying systems showed that solar corn drying may be economical under some conditions. If an additional dryer is needed, if a conventional dryer needs replacing or if fossil fuels are not available, a solar system should be considered (Heid, 1978).

Only one report of solar drying in Canada has been published to date. At Melfort, Saskatchewan, an experimental bin dried wheat from 16.5 to 14.5% moisture content in 47 h of operation (Brad et al. 1977).

2.3.2 Simulation Studies

Mathematical simulation models have been used to evaluate the potential for solar corn drying at different locations and for different crop conditions. Using a prediction of the corn deterioration, these models could evaluate whether or not the corn would spoil before drying.

Results of Pierce and Thompson (1976) showed that selecting a sufficiently high airflow rate was the most important requirement to assure that the grain did not spoil before it was dried. Yearly variations in weather made as much as a threefold difference in this minimum airflow rate. The addition of supplemental heat reduced the drying time and increased the probability that drying would be completed in the fall. Moving from a cool and dry climate to a warm and humid climate resulted in higher airflow rates being required. Solar energy was more effective in reducing the airflow requirements in the warm and humid areas. Grain with an early harvest date and high initial moisture content required the highest airflow rate. Supplemental energy requirements were lowest for solar supplemented systems and highest for systems using continuous supplemental heat. Total drying costs were highest with the solar systems due to the cost of the collector.

Overdrying was more of a problem when supplemental heat was added.

Results of Morey et al. (1977) showed that the effect of solar heat could be obtained by an increased airflow rate of 10% using unheated air. Solar drying was found to be uneconomical in most cases. However, conditions were economically most favorable for solar drying of corn with initial moisture contents of 20 to 22%. It was concluded that strictly low-temperature drying methods were not feasible at moisture contents above 22 to 24%. Constant-source supplemental heat was found to have essentially the same effect as solar heat. When the average temperature rise was the same, the minimum airflow requirements and hours of fan operation were the same for both types of heat.

Peart (1977) simulated the growing as well as drying of corn. He concluded that it was important to design for the earliest possible harvest date. This would ensure that the grain would not spoil some years due to early maturity and harvest.

Simulation results for Missouri and Michigan (Bakker-Arkema et al. 1977) showed that solar drying and unheated air drying were equally feasible. For the same airflow and initial moisture content the quality of the corn dried in both systems was similar. Energy requirements were reduced when solar energy was used but energy savings were not sufficient to justify solar collectors.

III. DEVELOPMENT OF THE SIMULATION MODEL

3.1 Background

The basic processes involved in grain drying are the transfer of sensible heat from the air to the grain, the transfer of moisture and latent heat from the grain to the air and the removal of this air. The potential causing the heat transfer is the difference between the temperatures of the air and the grain. The potential causing the moisture transfer is the difference between the vapor pressure of the water in the grain kernels and in the air surrounding the kernels. The drying rate is therefore proportional to this difference in vapor pressures.

In heated air drying of a deep bed of grain, heating and drying occur continuously. The input air temperature and relative humidity remain constant. The air and grain conditions vary through the bed, however. The relative humidity of the air increases and the temperature decreases as it passes through the bed. Similarly, the moisture content of the grain is greater where the air leaves the bed than where it enters. To predict or model the drying of a deep bed of grain, therefore, it is necessary to consider the bed as a series of layers. The change in air and grain conditions can be calculated for each of the layers in turn, for a certain time interval. The air exhausting from one layer is the air entering the next. The calculations for each layer are based on equations expressing the drying rate of a thin layer of grain. These thin layer drying equations must be determined experimentally (Thompson, et al. 1968).

In low-temperature drying, the air conditions entering the grain bed are determined by the weather. Thus they are likely to vary considerably from hour to hour. As well as heating and drying, processes of cooling and drying, heating and wetting, and cooling and wetting may occur. These must be accounted for in the model.

Low airflow rates are generally used in low-temperature drying, which means a high grain-to-air ratio. This ratio is the mass of grain per layer per unit mass of air for a given time interval. High grain-to-air ratios cause large changes in the condition of the air as it passes through. There are minimal changes in the moisture content of the grain. Most drying simulation models use low grain-to-air ratios. They calculate the final air conditions from the amount of moisture removed from the grain. Use of these conventional drying models for low-temperature drying overestimates the drying rate.

During low-temperature drying with low airflow rates, the air and the grain approach temperature and moisture equilibrium (Thompson, 1972). This equilibrium approach to modeling low-temperature drying systems was first suggested by Bloome and Shove (1971). They developed procedures to follow for each combination of heating or cooling and drying or wetting. Thompson (1972) further developed this approach by using an iterative procedure to converge to the equilibrium point.

Flood et al. (1972) developed a low-temperature drying model based on thin-layer drying equations determined from laboratory tests. It assumes that the air conditions remain constant through the layer. Under higher airflow rates the air and the grain are less likely to reach equilibrium in the layer thickness used in the simulation. This type of drying equation model is then more appropriate. Similarly, when there are greater differences between the grain moisture content and the equilibrium moisture content of the air, this model is appropriate. At lower airflows, however, the air conditions change considerably as the air passes through the layer. In this case the thin layer models are more likely to overestimate the drying rate, and the equilibrium model is better (Peart, 1977).

Other models have been developed which incorporate both thin layer drying equations and equilibrium equations. Whichever set of equations gives the higher grain moisture content at the end of the time interval is used. This ensures that the drying rate is not overestimated by either method. These are known as combination models (Peart, 1977; Morey, et al. 1976).

3.2 The Thompson Equilibrium Model

3.2.1 Reasons for Choosing the Model

The equilibrium drying model developed by Thompson (1972) was used in this project. The reasons for using this model were its ease of comprehension, efficiency with respect to use of computer resources, reported validity and availability. This model requires only the basic properties of a grain which are readily available. Other models using thin layer drying equations would probably produce more accurate results under high airflow conditions, but the drying equations have to be experimentally determined. Drying equations have not yet been determined for the low temperatures common in Canada.

3.2.2. Assumptions

The equilibrium model was designed to simulate drying under conditions of low airflow rates and near ambient temperatures. The basic assumptions of the model were:

1. Equilibrium is obtained between the air and the grain for the drying time interval, $\Delta\theta$, i.e. at the end of the time interval the air and grain are in equilibrium.
2. Heat and mass transfer between the air and the grain is adiabatic, i.e. there is no heat transfer to or from the surroundings as a result of the heating and drying processes.

3. No hysteresis exists between the absorption and desorption isotherms relating equilibrium moisture content to equilibrium relative humidity of the air.
4. No heat or moisture is generated in the grain bulk and no heat transfer occurs through the bin walls.

3.2.3 Simulation Procedure

To find the equilibrium conditions between the air and grain, a heat and a mass balance must be solved. The equilibrium relative humidity of the grain must then be equated to the relative humidity of the air. The following equations in SI units were first presented by Thompson (1972) in English engineering units.

1. Heat balance between the air and the grain:

   The sum of the initial heat content of the air, the initial heat content of the water vapor in the air, the initial heat content of the grain and the initial heat content of the moisture removed from the grain, is equal to the sum of the final heat content of the air, the final heat content of the water vapor in the air and the final heat content of the grain. Substituting from the list of symbols this statement becomes:

$$T_o + H_o(2501.5 + 1.82T_o) + CR'G_o + (H_f - H_o)4.18G_o =$$
$$T_f + H_f(2501.5 + 1.82T_f) + CR'T_f \quad . \; . \; . \; . \; . \; . \; . \; . \; . (3.1)$$

   Solving this equation for the final air temperature:

$$T_f = [CR'G_o + (H_f - H_o) 4.184G_o - 2501.5\ H_f + T_o +$$

$$H_o(2501.5 + 1.82T_o)]/(1 + 1.82\ H_f + CR') \quad . . . \quad (3.2)$$

The grain-to-air ratio, R', is in the equation because the model uses only relative quantities of grain and air. Specific heat values for corn were found from the equation of Kazarian and Hall (1965) converted to SI units.

$$C = 1.4644 + 0.03561\ M_w \quad . . . . \quad (3.3)$$

Specific heat values for wheat were taken from Muir and Viravanichai (1972).

2. Mass balance between the air and the grain:
   Gain or loss in absolute humidity of the air must equal the loss or gain in moisture content of the grain:

$$H_f - H_o = (M_o - M_f)\ R/100 \quad . . . . \quad (3.4)$$

   Solving for the final moisture content of the grain:

$$M_f = M_o - 100(H_f - H_o)/R \quad . . . . \quad (3.5)$$

3. Equivalence between the equilibrium relative humidity of the grain, ERH, and the relative humidity of the air, RH_{air}. The equilibrium relative humidity of corn, converted to SI units:

$$ERH = 1 - \exp[-3.82 \times 10^{-5}(1.8T_f + 82)\ M_f^2] \quad . . . \quad (3.6)$$

   For wheat the expression of Strohman and Yoerger (1967) was used:

$$ERH = \exp(ae^{bM_f} \ln P_s + ce^{dM_f}) \quad . . . . \quad (3.7)$$

where a = 2.40, b = -0.205, c = -10.17, d = -0.186. These coefficients were found by minimizing the sum:

$$F = \sum_{i=1}^{n} [\frac{P_i}{P_{s_i}} - \exp(ae^{bM_i} \ln P_{s_i} + ce^{dM_i})]^2 . \quad . \quad . \quad . \quad (3.8)$$

Data from Ayerst (1965), Becker and Sallans (1956), Bushuk and Hlynka (1960), Gane (1941), and Hubbard et al. (1957) were used. The relative humidity of the air, given the final air temperature, T_f, and humidity ratio, H_f, was calculated from psychrometric relationships. A subprogram was written from the equations given by Wilhelm (1976) in SI units.

Solution of the above equations was by iterative procedures:

1. Estimate the final humidity ratio, H_f.
2. Calculate the final air temperature, T_f, from equation 3.2.
3. Calculate the final moisture content, M_f, from equation 3.5.
4. Calculate the equilibrium relative humidity of the grain using the final air temperature, T_f, and moisture content, M_f.
5. Calculate the relative humidity of the air using the final air temperature, T_f, and the estimated final humidity ratio, H_f.
6. Estimate a new H_f and repeat above steps until the calculated equilibrium relative humidity of the grain is sufficiently close to the calculated value of the air relative humidity.

A method for finding the zero of an unknown function presented by Thompson and Peart (1968) was used.

The advantage of this method was that the same set of equations was used for every combination of heating or cooling and drying or wetting. Also, a high degree of accuracy could be obtained in calculating the equilibrium point.

To simulate drying of grain in a deep bed, a finite difference method was used. The bed was assumed to be divided into a series of layers, stacked one upon another, with the air blowing up through the stack. The procedure described above was applied repeatedly to each layer in turn. Average changes in exhaust air and grain during the specified time interval were predicted. The exhaust air from each layer served as input air to the layer above.

3.3 The Grain Deterioration Model

3.3.1 Importance of the Model

In low-temperature drying, the top layer of grain often remains at a high moisture content for an extended period of time. This results in deterioration of the grain because of high grain respiration rates and growth and respiration of mold and fungi. The grain must be dried quickly enough that the top layer is dried before excessive deterioration has occurred. A method of predicting this deterioration must therefore be included in the drying model.

3.3.2 Corn

Steele et al. (1969) found that a tolerable amount of deterioration for corn would result if the dry matter loss was limited to 0.5%. Dry matter loss occurs as aerobic respiration oxidizes the carbohydrates to carbon dioxide and water. Thus the rate and amount of deterioration can be determined by measuring the evolution of carbon dioxide. The rate of deterioration was found to be related to the temperature, moisture content and mechanical damage of the corn. The time taken to reach 0.5% dry matter loss was therefore also dependent on these factors. This amount of time was called the allowable safe storage time. It was determined by the equation of Steele et al. (1969):

$$\theta = \theta_R \times M_T \times M_M \times M_D \quad \ldots\ldots\ldots\ldots\ldots (3.9)$$

where: θ = estimated maximum storage time for a loss of 0.5% dry matter, hours.

θ_R = time for corn under reference storage conditions to lose 0.5% dry matter = 230 h. Reference storage conditions are 25% moisture content, 15.6°C, and 30% mechanical damage.

M_T = temperature multiplier = 1.0 at 15.6°C.

M_M = moisture multiplier = 1.0 at 25% moisture content.

M_D = mechanical damage multiplier = 1.0 at 30% damage.

During low-temperature drying the grain conditions vary considerably. A prediction of the total deterioration was made as follows. For each time interval, $\Delta\theta$, the allowable safe storage time, θ, was calculated for the conditions of moisture content and temperature determined for that time interval. At the end of that interval the allowable time had decreased by $\Delta\theta$. The percent of the allowable storage time which had been exhausted was $(\Delta\theta/\theta) \times 100\%$. These percentages were accumulated until the grain was dry. If the sum of the percentages reached 100% before the grain had dried, the grain was considered to be spoiled.

The percent dry matter decomposition, DM, was determined from the percent of allowable storage time exhausted, by the equation of Thompson (1972):

$$DM = 0.0884[\exp(0.006\ \theta_{eq}) - 1] + 0.00102\ \theta_{eq} \quad . . (3.10)$$

where: θ_{eq} = equivalent storage time = $\Sigma(\Delta\theta/\theta) \times 230$ h

0.5% DM = 100% allowable storage time elapsed.

3.3.3 Wheat

The allowable safe storage time for wheat was defined as the time required for the grain to drop to 90 to 95% germination, or the time before mold growth became visible. In many cases the mold growth criteria was close to the germination criteria. This definition was based on data presented by Kreyger (1972) for the estimated maximum storage life of wheat with respect to germination and with respect to absence of visible mold growth. Germination data of Sholberg (1977) were also used. The following equations were developed by multiple regression to relate the allowable storage time to temperature and moisture content:

$$\log \theta = 6.234 - 0.2118\ M_W - 0.0527\ T \quad (12\% < M_W < 19\%) \qquad (3.11)$$

$$\log \theta = 4.129 - 0.0997\ M_W - 0.0576\ T \quad (19\% \leq M_W < 24\%) \qquad (3.12)$$

where θ is in days.

3.3.4 Interpretation of the Prediction Equations

The above prediction equations can be used to design a drying system which would complete the drying of wheat or corn at the same time as the allowable safe storage time of the grain was exhausted. Deterioration rates of dry grain are generally low. Therefore after drying under design conditions, further storage would likely produce little change. Wet spots or infestations cannot be tolerated, however, and the temperature must be kept below 15°C.

When drying under better than design conditions, all of the grain would have useful storage life left at the completion of drying. When drying under worse than design conditions, the allowable safe storage time would be exceeded. The spoilage would generally be limited to the top layers. However, under some conditions, higher deterioration rates than predicted may occur. This is because the equations give average predictions based on empirical tests (Morey and Peart, 1971). Other factors such as wet harvesting weather are also likely to affect the outcome. The grain in such a case may begin deteriorating before it is harvested.

3.4 Validation

To ensure that a model gives realistic results, experimental data must be used for comparison. As it was beyond the scope of this project to set up the necessary drying tests, other validation results must be examined.

Morey et al. (1976) compared measured moisture contents with computed results from a modified equilibrium model and found good agreement, with S_e = 1.26% moisture content or less. They concluded that the model adequately predicted moisture changes under low airflow rates and near ambient temperatures.

Foster (quoted by Peart, 1977) concluded that for airflow rates of 2.8 to 5.0m^3/(min·t) the equilibrium model overestimated the drying rate. The model also underestimated the thickness of the drying zone. He decided that the model performed adequately for assessing the relative feasibility of bin drying in various locations. He also noted that the grain deterioration model gave realistic predictions of grain quality.

Pfost et al. (1977) suggested that until models can be shown to be statistically valid, a good factor of safety should be used in designs. They concluded that equilibrium models performed best with time increments of 24 h.

3.5 Solar Collector Coefficient

Methods of calculating the amount of heating provided by various solar collectors have been given by Duffie and Beckman (1974) and others. The objective of this project was not to examine any one collector in particular but to examine solar drying in terms of the radiation received. Therefore a generalized collector coefficient as defined by Pierce and Thompson (1976) was used. This related the amount of heating to the amount of solar radiation received. The solar collector coefficient was defined as the average 24 h temperature rise that a solar collector will produce when the daily solar radiation is approximately 40 MJ/m^2 (1 000 langleys). For example if a collector having a coefficient of 10°C is exposed to daily solar radiation of 10 MJ/m^2, the average temperature rise of the air passing through the collector is 10 x 10/40 = 2.5°C.

This definition makes the solar collector coefficient independent of the amount of grain and the efficiency of the collector. If airflow is in terms of a unit mass of grain, e.g. $m^3/(min \cdot t)$, the collector size is directly proportional to the mass of grain, for a given collector efficiency.

The following calculations show the relationship between the solar coefficient, SC, the collector size and efficiency, and the airflow rate. If an air density of 1.2 kg/m^3 is assumed, the 24 h average temperature rise produced by a given collector is:

$$\Delta t = \frac{H\ MJ/m^2 \times A\ m^2/t \times Eff \times 60\ s/min}{AFR\ m^3/(min \cdot t) \times 1.2\ kg/m^3 \times 1\ 000\ J/(kg \cdot {}^\circ C)}$$

$$\text{or } \Delta t = \frac{H \cdot A \cdot Eff}{AFR \cdot 20} \quad \ldots\ldots\ldots\ldots \quad (3.13)$$

The solar collector coefficient for this collector, from the definition, is:

$$SC = \frac{\Delta t \times 40}{H} = \frac{A \cdot Eff \cdot 40}{AFR \cdot 20} = \frac{A \cdot Eff \cdot 2}{AFR}$$

$$\text{thus } A = \frac{SC \cdot AFR}{Eff \cdot 2} \quad \ldots\ldots\ldots\ldots \quad (3.14)$$

When the proper collector coefficient is found, the designer can select the proper collector size from the airflow rate, the efficiency of the collector and the amount of grain to be dried. This will give the required horizontal area. If the collector is to be mounted at some other angle a different area may be used to provide the same heat input, as explained in Sec. 2.1.

3.6 Program Descriptions

3.6.1 Common Features

Two different programs were used in this study. These programs are equivalent in the basic modeling aspects and in the assumptions used. Both programs simulate grain drying using historical weather data on magnetic tape. Wheat or corn drying may be simulated using ambient air alone, ambient air with solar heat, or ambient air with constant source supplemental heat. Simulated drying of a bin of grain continues until the wettest layer of grain is dry or until other conditions are met. Output includes the date, hours of fan operation, grain moisture contents, grain temperatures, grain deterioration, average weather conditions and total radiation received for each week of drying.

The programs are based on the following assumptions:

1. The bin is filled at one time, i.e. no layer filling.
2. The entire bin floor is perforated for air passage.
3. The airflow is uniform throughout the bin.
4. The moisture content and temperature of the grain is uniform throughout the bin at the start of drying.

3.6.2 Program I: SYSTEMDRY

The program SYSTEMDRY simulates drying in a system in which the fan may be shut off for some periods of time. The fan may be run continuously, turned off over winter, or controlled by a time clock, thermostat or humidistat. The simulation continues until the grain is dry, until a given date is reached or until the wettest layer of grain is spoiled. Output includes the information noted above plus the energy used, and costs of overdrying, spoilage and electricity. The subroutines used in this program are listed in Table 3.1. The flowchart and the program in Fortran statements are included in Appendix B.

3.6.3 Program II: MINAIR

The program MINAIR finds the minimum airflow rate required to dry a bin of grain without spoilage. The fan and heater operate continuously until the grain is dry unless the airflow rate is too low. The minimum airflow rate is determined by an iterative procedure. The drying process is simulated a number of times in succession under identical conditions except airflow rate. The airflow rate is chosen by a search program which attempts to match 0.5% dry matter loss with the end of drying. The main program controls the positioning of the magnetic tapes and determines the number of simulations. The subroutines used in this program are listed in Table 3.1. The flowchart and the program in Fortran statements are included in Appendix B.

3.6.4 Subroutine READRN

The subroutine READRN is used to read the radiation data from the tape and replace any missing values. Estimates for missing values are normally made by averaging the data from previous and following days. The flowchart for this subroutine is included in Appendix B.

TABLE 3.1

SUBROUTINES USED IN THE PROGRAMS SYSTEMDRY AND MINAIR

Subroutine Name	Purpose of Subroutine
AHUM	To calculate the absolute humidity or saturation vapor pressure of the air for a given temperature.
DRYSIM	To calculate the moisture content and temperature at the end of one time interval for each of the 10 layers of grain in turn i.e. to simulate drying for one time interval. -- also see Sec. 3.2.3
FANSUB	To calculate the required fan power for the given bin of grain and airflow rate.
GRNDRY	To control the input, output, and simulation of one year of drying. -- also see Sec. 3.6.5
HRNORM	To check whether the values to be used for time are allowable.
MAX	To find the largest value of an array.
MIN	To find the smallest value of an array.
READRN	To read the solar radiation data from magnetic tape and estimate values for missing data. -- also see Sec. 3.6.4
READWR	To read the weather data from magnetic tape.

TABLE 3.1 (continued)

Subroutine Name	Purpose of Subroutine
RHAIR	To calculate the relative humidity of the air for a given temperature and absolute humidity.
SAFES	To calculate the allowable storage time for corn for a given temperature and moisture content. -- also see Sec. 3.3
SAFWH	To calculate the allowable storage time for wheat for a given temperature and moisture content. -- also see Sec. 3.3
SPHT	To calculate the specific heat of wheat for a given temperature and moisture content. -- also see Sec. 3.2.3
ZERO	To sequentially select better X values for an unknown function of X, such that the function equals some desired value.

3.6.5 Subroutine GRNDRY

The subroutine GRNDRY is the main subroutine of MINAIR. It controls the drying simulation of a bin of grain from the start of drying until it is dry or until excessive spoilage results. This is a simplified version of SYSTEMDRY. The flowchart for this subroutine is included in Appendix B.

3.7 Description of Simulation Tests

The important parameters in solar grain drying are geographical location, grain type, harvest date, initial grain moisture content, weather conditions, amount of heat added, final grain moisture content, airflow rate and time of fan operation. The geographical locations were chosen for this study on the basis of climatic zones, major grain growing regions and the availability of radiation data for 10 or more years. The grain type, wheat or corn, was chosen for each location then a series of harvest dates and initial moisture contents for each grain were chosen (Table 3.2). The effect of yearly variability of weather was investigated by using the 10 or more years of data for each location.

TABLE 3.2

LIST OF THE PARAMETERS USED IN SIMULATIONS

Parameter	Values of Parameter			
Location	Edmonton	Swift Current	Winnipeg	London
Climatic Zone	Sub-boreal	Dry belt	Humid	Temperate East Coast
Years Used	1967 - 76	1960 - 74	1961 - 70	1962 - 73
Grain Type	Wheat	Wheat	Wheat, Corn	Corn
Harvest Date				
Wheat	Aug. 15, Sept. 1, Sept. 15, Oct. 1, Oct.15			
Corn	Sept. 15, Oct. 1, Oct. 15, Nov.1, Nov. 15			
Initial Moisture Content(%)				
Wheat	16, 18, 20, 22, 24			
Corn	20, 22, 24, 26, 28			

Three amounts of solar heating were used, 0, 5 and 10°C solar collector coefficient as defined in Sec. 3.5. When the wettest layer of grain reached 14.5% moisture content for wheat, or 15.5% for corn, the simulation was stopped. These are the maximum values specified by the Canadian Grain Commission for the dry or straight grade.

In all simulations a 1.1°C temperature rise was added to the air to account for heat added by the fan motor. In actual practice the amount of this heat depends upon air-flow rate, motor efficiency and grain depth. The grain depth and fan power required to produce a total temperature rise of 1.1°C were calculated for a range of airflows for wheat and corn (Fig. 3.1). It was assumed that the combined fan and motor efficiency was 50% and that all of the electrical energy was converted to heat in the air.

Simulation of solar drying requires that hourly weather data be correlated with hourly radiation data for most accurate results. This means the use of a 1 h time interval. Bakker-Arkema et al. (1976) found that the error due to averaging the data over a 24 h period was small enough to recommend this practice. Use of a 24 h time interval greatly reduces the computer time.

The first part of this study was the determination of the minimum airflow rate for each combination of parameters. The minimum airflow rate was defined as the lowest airflow

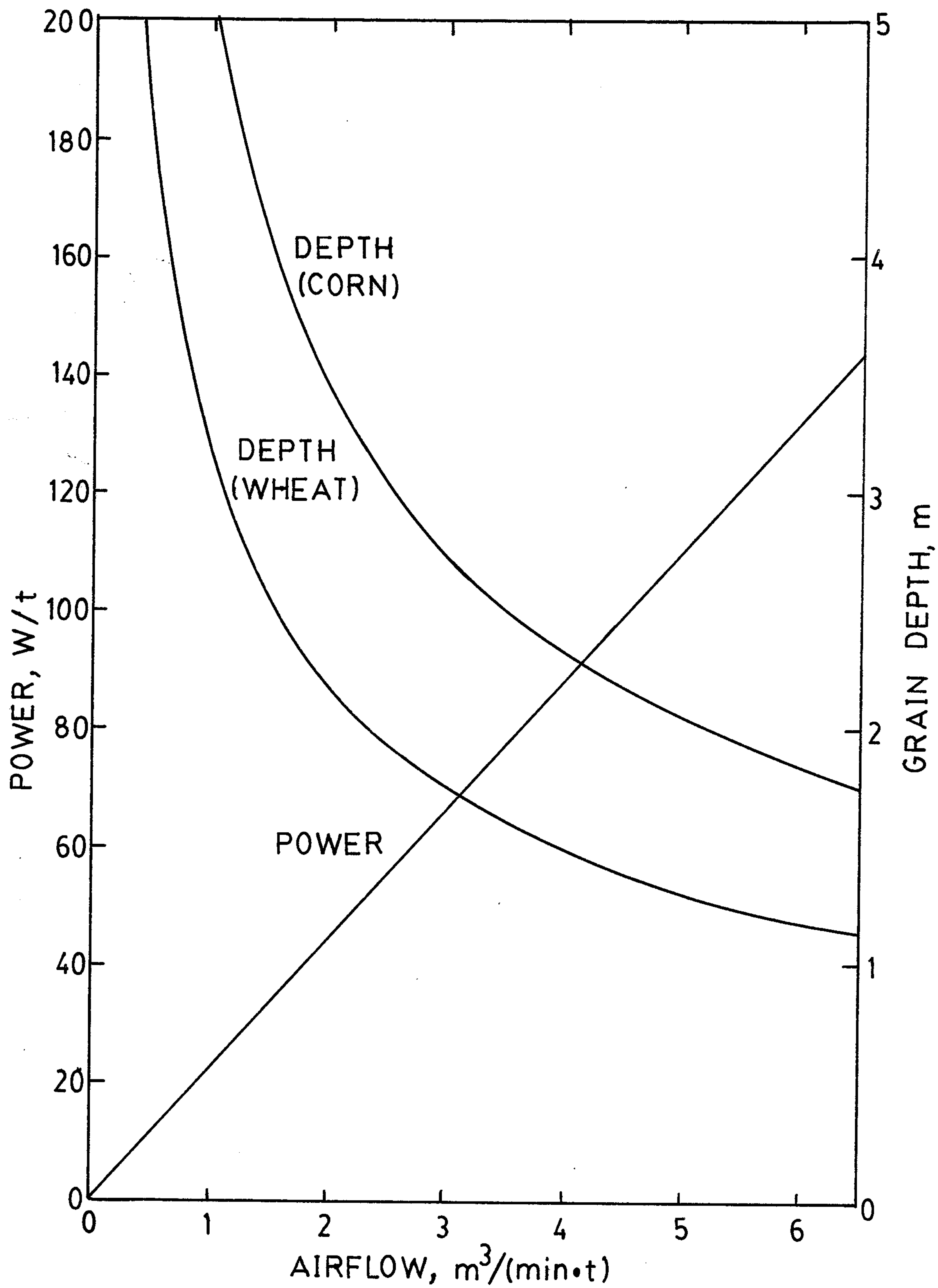

Fig. 3.1 Grain depth and fan power required to produce a total temperature rise of 1.1°C, as a function of airflow rate. Static pressure was assumed to be 50% higher than ASAE standard D272 (Baxter, 1978).

rate which would dry the grain before the allowable storage time was exhausted. Low airflow rates are desirable because fan power requirements increase as approximately the cube of the airflow rate. The computer program MINAIR was used to determine these airflows. Continuous fan operation was assumed and a 24 h time interval was used.

For each combination of parameters, two airflow rates were determined. For the first, weather data were used from the year having the most adverse weather conditions, called the worst year. This was the highest airflow rate. For the second airflow rate, weather data were used from the year having the second most adverse weather conditions. If there was any doubt as to which years of data to use, several were used to ensure that the highest airflow rates had been found.

The second part of the study was the simulation of drying for all years of weather data. The airflow rate used in each case was the minimum which would dry the grain every year without spoilage, i.e. the worst year airflow rate. The computer program SYSTEMDRY was used for these simulations. Continuous fan operation was simulated for the fall drying period until the grain was dry or until the beginning of winter. After the winter period, continuous operation was resumed. The winter period started when the average weekly air temperature fell below 0°C, provided this was before the earliest fall stop date. The winter period ended when the average weekly air temperature rose above 0°C, provided this was after March 31. Continuous fan operation was not desirable during the winter because drying did not occur during that period (Fig. 3.2). Fan operation of 4 h/wk was simulated during the winter to cool the grain. Continuous fan operation during the fall was necessary to keep the deterioration rate low. Drying continued even at night because the moisture content remained high. Preliminary results for London indicated that continuous fan operation followed by humidistat control may be advantageous in some cases. Investigations using humidistat control were beyond the scope of this study, however.

In all cases the simulation of drying was continued until the wettest layer of grain was dry. Results were also given for the point at which the average moisture content of the grain had become dry. The electrical energy use, overdrying costs and solar energy collected were used to estimate the economics of the various methods of low-temperature drying.

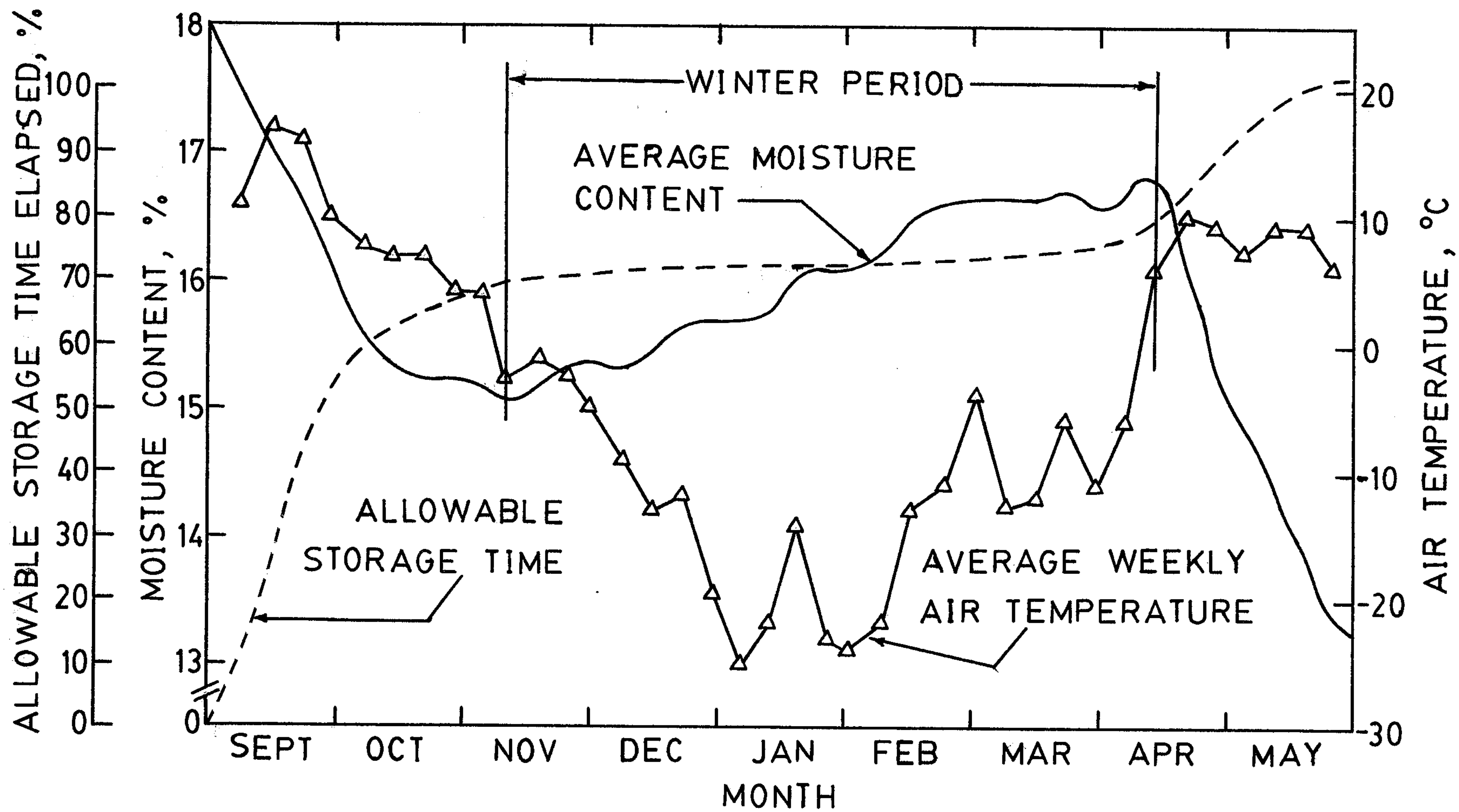

Fig. 3.2 Typical simulation results showing average moisture content, percent of allowable storage time elapsed and average weekly air temperature. Wheat harvested September 1, 1968 with an initial moisture content of 18.0% was dried at Winnipeg. A continuous airflow rate of 0.64 $m^3/(min \cdot t)$ was used with unheated air.

IV. RESULTS AND DISCUSSION

4.1 Minimum Airflow Rates

Minimum airflow rates were found for the worst and second worst years of weather data for each combination of parameters (Tables 4.1 to 4.5). The worst year was the one with the most adverse weather conditions. This airflow rate may successfully dry the grain 10 years out of 10, but on a long term basis there are likely to be a few years in which the grain will spoil. This is because there will be some years with weather conditions more adverse than any of those years simulated. The airflow rate for the second worst year should successfully dry the grain in as many as 9 years out of 10.

The effects of other parameters on the minimum airflow rates can also be seen. A comparison reveals little difference between the airflow rates at Edmonton and Swift Current. Results for Winnipeg indicate that up to twice the airflow rate was needed compared to Edmonton or Swift Current. The results for London and Winnipeg for corn indicate that airflow rates at London were as much as five times those at Winnipeg (Tables 4.1 to 4.5 and Fig. 4.1 and 4.2). In general, airflow requirements increased as the climate changed from cool and dry in western Canada to warm and humid in eastern Canada.

TABLE 4.1

PREDICTIED MINIMUM AIRFLOW REQUIREMENTS [$m^3/(min \cdot t)$] FOR DRYING WHEAT AT EDMONTON*

Harvest Date	Year	S.C.**	Initial Moisture Content,% 16	18	20	22	24
			Airflow, $m^3/(min \cdot t)$				
Aug. 15	2nd Worst	0		0.40	1.6	2.8	
		5		0.35	1.2	2.3	
	Worst	0		0.50	1.8	3.3	
		5		0.40	1.5	3.0	
Sept.1	2nd Worst	0		0.35	1.0	2.3	
		5		0.25	0.9	1.8	
	Worst	0		0.35	1.3	2.3	
		5		0.30	0.9	2.1	
Sept. 15	2nd Worst	0	0.20	0.30	0.60	1.4	3.2
		5	0.15	0.25	0.50	1.2	2.8
		10	0.10	0.20	0.50	1.1	2.6
	Worst	0	0.20	0.35	0.60	1.5	3.3
		5	0.15	0.25	0.60	1.3	2.9
		10	0.15	0.20	0.50	1.2	2.7
Oct. 1	2nd Worst	0		0.30	0.50	0.80	
		5		0.25	0.40	0.70	
	Worst	0		0.35	0.50	0.90	
		5		0.25	0.45	0.80	
Oct. 15	2nd Worst	0		0.30	0.45	0.70	
		5		0.25	0.40	0.60	
	Worst	0		0.35	0.45	0.70	
		5		0.25	0.40	0.70	

*These values were based upon simulated drying results for the years 1967 to 1976, using $\Delta\theta$ = 24 h and continuous fan operation until dry. A 1.1°C temperature rise due to drawing the air over the fan motor was assumed. These values should be increased by 50% for design purposes, to ensure that the indicated airflow rate is passing through the grain (see Pierce and Thompson, 1976; Pfost et al., 1977).

**Solar collector coefficient represents a solar collector capable of providing a 24 h average temperature rise of the indicated magnitude (°C) when the daily solar radiation is approximately 40 MJ/m^2 (see Sec. 3.5); 0 = no collector.

TABLE 4.2

PREDICTED MINIMUM AIRFLOW REQUIREMENTS [$m^3/(min \cdot t)$]
FOR DRYING WHEAT AT SWIFT CURRENT*

Harvest Date	Year	S.C.	Initial Moisture Content, % 16	18	20	22	24
			Airflow, $m^3/(min \cdot t)$				
Aug. 15	2nd Worst	0		0.40	1.1	2.1	
		5		0.30	1.1	1.9	
	Worst	0		0.40	1.2	2.8	
		5		0.35	1.3	2.9	
Sept. 1	2nd Worst	0		0.40	0.9	1.7	
		5		0.30	0.9	1.7	
	Worst	0		0.45	1.0	2.0	
		5		0.30	0.9	1.8	
Sept. 15	2nd Worst	0	0.20	0.30	0.70	1.4	2.7
		5	0.15	0.25	0.60	1.2	2.5
		10	0.10	0.20	0.60	1.2	2.5
	Worst	0	0.25	0.35	0.90	1.5	2.8
		5	0.20	0.25	0.80	1.4	2.6
		10	0.15	0.20	0.80	1.4	2.6
Oct. 1	2nd Worst	0		0.30	0.60	1.0	
		5		0.25	0.50	0.9	
	Worst	0		0.35	0.60	1.2	
		5		0.25	0.50	1.0	
Oct. 15	2nd Worst	0		0.30	0.50	0.80	
		5		0.25	0.40	0.70	
	Worst	0		0.35	0.50	0.90	
		5		0.25	0.40	0.90	

* These values were based upon simulated drying results for the years 1960 to 1974. See footnotes Table 4.1

TABLE 4.3

PREDICTED MINIMUM AIRFLOW REQUIREMENTS [m^3/(min·t)] FOR DRYING WHEAT AT WINNIPEG*

Harvest Date	Year	S.C.	Initial Moisture Content,% 16	18	20	22	24
			Airflow, m^3/(min·t)				
Aug. 15	2nd Worst	0		1.3	2.4	4.1	
		5		0.6	2.0	3.4	
	Worst	0		1.3	3.6	5.0	
		5		0.70	2.1	4.0	
Sept. 1	2nd Worst	0		0.70	2.2	3.6	
		5		0.50	1.4	2.6	
	Worst	0		0.80	2.2	4.8	
		5		0.50	1.5	3.7	
Sept. 15	2nd Worst	0	0.30	0.50	1.2	2.3	5.0
		5	0.20	0.30	1.0	1.8	3.8
		10	0.15	0.30	0.8	1.7	3.8
	Worst	0	0.45	0.50	1.5	3.8	7.9
		5	0.25	0.40	1.3	2.3	6.6
		10	0.20	0.30	1.0	2.3	5.6
Oct. 1	2nd Worst	0		0.50	0.80	1.6	
		5		0.30	0.70	1.6	
	Worst	0		0.50	0.90	1.9	
		5		0.30	0.80	1.6	
Oct. 15	2nd Worst	0		0.40	0.60	1.0	
		5		0.30	0.50	0.8	
	Worst	0		0.50	0.90	1.4	
		5		0.30	0.60	1.2	

*These values were based upon simulated drying results for the years 1961 to 1970. See footnotes Table 4.1.

TABLE 4.4

PREDICTED MINIMUM AIRFLOW REQUIREMENTS [$m^3/(min \cdot t)$] FOR DRYING CORN AT WINNIPEG*

Harvest Date	Year	S.C.	Initial Moisture Content,% 20	22	24	26	28
			Airflow, $m^3/(min \cdot t)$				
Sept. 15	2nd Worst	0	0.85		2.3		6.4
		5	0.50		1.9		6.0
	Worst	0	0.85		2.5		10.0
		5	0.55		2.3		8.7
Oct. 1	2nd Worst	0	0.70		1.8		3.9
		5	0.45		1.7		3.7
	Worst	0	0.70		1.9		4.2
		5	0.60		1.8		3.8
Oct. 15	2nd Worst	0	0.65	0.80	1.0	1.5	2.4
		5	0.45	0.60	0.9	1.3	2.2
		10	0.40	0.50	0.8	1.2	2.0
	Worst	0	0.70	1.1	1.7	2.1	4.5
		5	0.50	0.70	1.4	2.4	5.3
		10	0.40	0.60	1.3	2.5	5.1
Nov. 1	2nd Worst	0	0.70		1.0		1.7
		5	0.50		0.9		1.5
	Worst	0	0.70		1.0		1.7
		5	0.50		0.9		1.6
Nov. 15	2nd Worst	0	0.70		1.1		1.8
		5	0.50		0.9		1.6
	Worst	0	0.70		1.1		1.9
		5	0.60		0.9		1.6

*These values were based upon simulated drying results for the years 1961 to 1970. See footnotes Table 4.1.

TABLE 4.5

PREDICTED MINIMUM AIRFLOW REQUIREMENTS [m^3/(min·t)]
FOR DRYING CORN AT LONDON*

Harvest Date	Year	S.C.	Initial Moisture Content,% 20	22	24	26	28
			Airflow, m^3/(min·t)				
Sept. 15	2nd Worst	0	1.8	3.0	5.9	9.7	15.0
		5	1.0	2.4	4.9	8.3	11.0
	Worst	0	2.3	4.4	6.2	11.0	16.0
		5	1.3	2.4	5.1	8.5	12.0
Oct. 1	2nd Worst	0	1.0	2.2	4.2	7.5	9.5
		5	0.8	1.7	3.0	5.0	7.1
	Worst	0	1.3	2.6	5.7	11.0	14.0
		5	0.9	1.8	3.4	5.3	7.7
Oct. 15	2nd Worst	0	0.9	1.5	3.4	6.0	12.0
		5	0.6	1.2	2.6	4.4	7.3
		10	0.4	1.0	2.3	3.9	6.3
	Worst	0	1.0	2.1	6.3	11.0	13.0
		5	0.6	1.7	3.3	6.2	9.7
		10	0.5	1.8	3.4	5.3	8.2
Nov. 1	2nd Worst	0	0.7	1.1	1.8	3.5	5.8
		5	0.5	0.7	1.3	2.8	5.1
	Worst	0	0.8	1.1	2.0	3.6	6.9
		5	0.5	0.8	1.5	2.9	5.2
Nov. 15	2nd Worst	0	0.7	0.9	1.3	1.9	3.4
		5	0.5	0.7	1.0	1.6	3.0
	Worst	0	0.7	0.9	1.4	2.3	3.9
		5	0.5	0.7	1.1	2.0	3.1

*These values were based upon simulated drying results for the years 1962 to 1973. See footnotes Table 4.1.

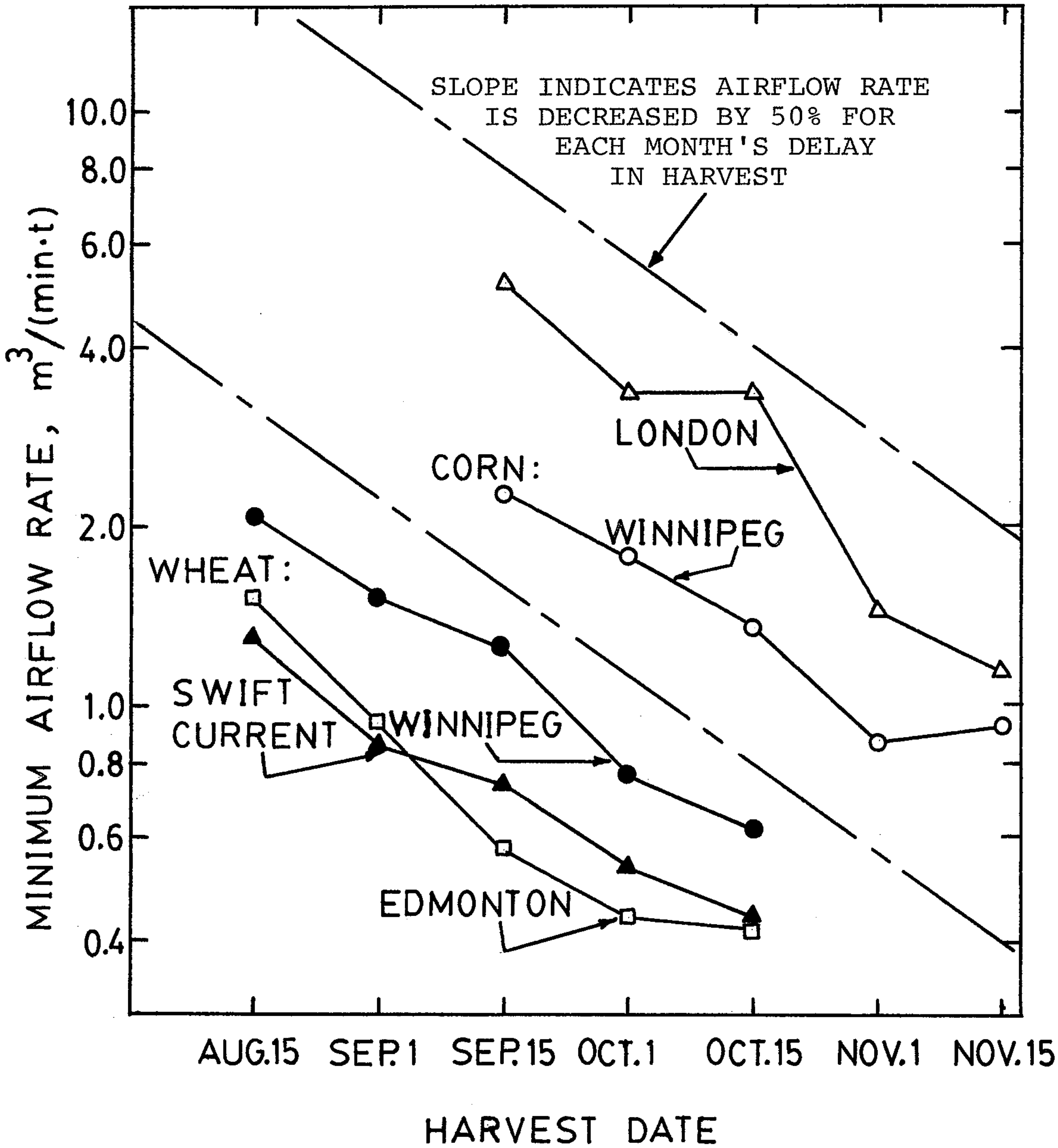

Fig. 4.1 Predicted minimum airflow requirements for various harvest dates and locations. Wheat with an initial moisture content of 20%, or corn with an initial moisture content of 24% was dried with solar heated air in the year of most adverse weather conditions. The solar collector coefficient was 5°C.

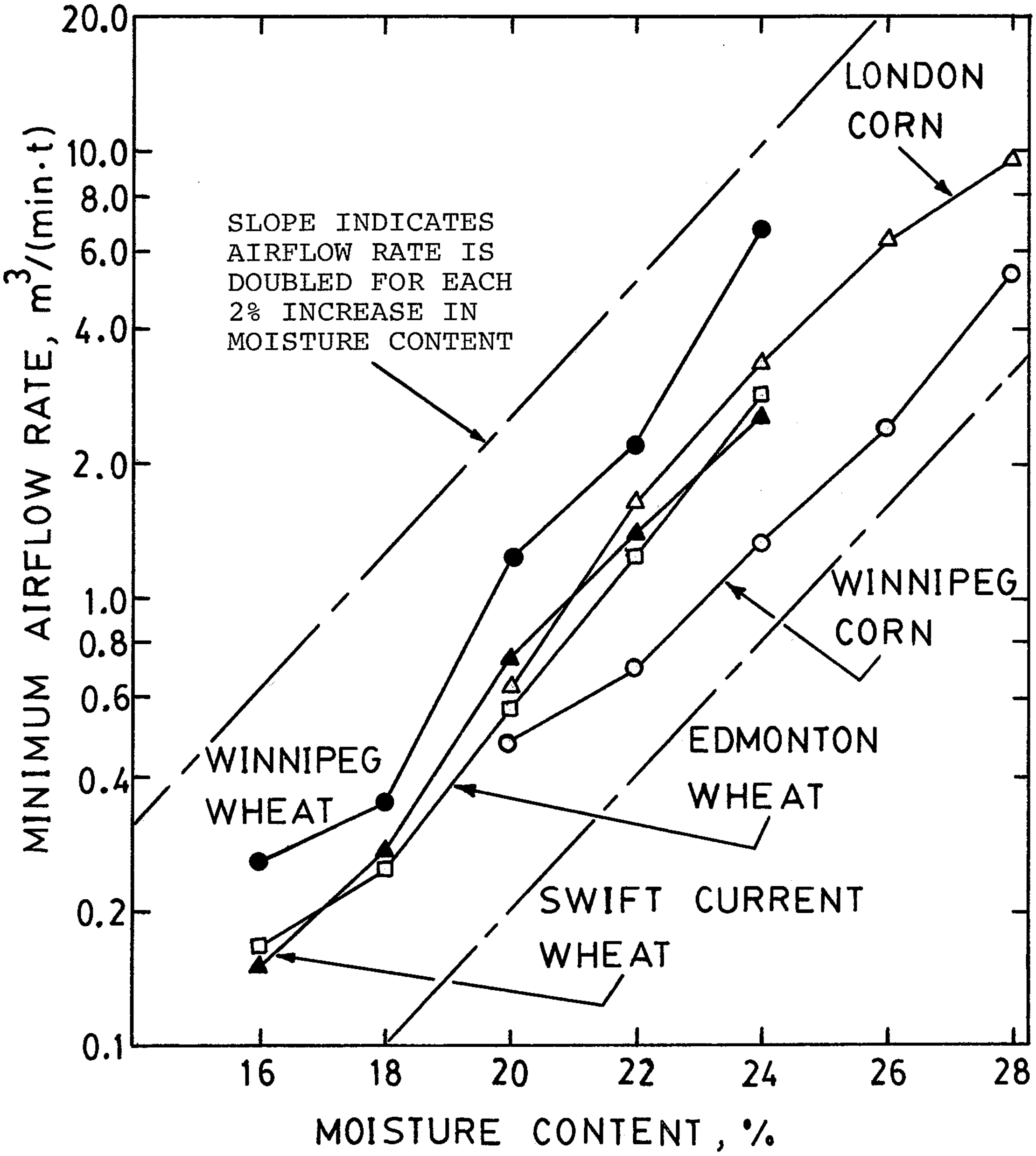

Fig. 4.2 Predicted minimum airflow requirements for various initial moisture contents and locations. Wheat harvested on Sept. 15 or corn harvested on Oct. 15 was dried with solar heated air in the year of most adverse weather conditions. The solar collector coefficient was 5°C.

With respect to harvest date, the required airflow rate was decreased by 50% for each month's delay in harvest (Fig. 4.1). The greatest deviations from this trend occurred at late harvest dates. This can be explained by the fact that the relative humidity of the air increased toward winter. Thus each unit of air removed less moisture than could have been removed earlier in the season. Consequently the grain harvested later in the fall required a larger airflow rate than would have been required if the relative humidity had remained constant. Also, much of the drying occurred during the warm weather of the following spring which required a higher airflow rate.

With respect to moisture content, the required airflow rate was doubled for each 2% increase in moisture content (Fig. 4.2). The greatest deviations from this trend occurred at low moisture contents. This is because the air left the bin in equlibrium with the wettest grain. Thus each unit of air removed less moisture than it could have removed from higher moisture content grain. Furthermore, much of the drying took place the following spring. Consequently the weather conditions in the spring were more important than fall conditions in determining the required airflow rates.

Although the results are consistent up to the highest airflow rates, the equilibrium model cannot be expected to give reliable results at these higher airflow rates.

With respect to heat addition, the effect of using additional solar heat by increasing the collector coefficient from 0 to 5°C was greater than that from 5 to 10°C. The effect of heat addition was largely determined by climate, however. London, having a high relative humidity, benefited much more from additional heat to lower this humidity than Swift Current which has a low relative humidity.

In some cases, the addition of solar heat caused an increase in the airflow rate rather than a decrease. This was likely due to the weather conditions encountered during the year. The addition of heat warmed the grain without increasing the drying rate. The grain therefore deteriorated more rapidly and required a higher airflow rate to dry before spoilage.

These minimum airflow rates are similar to those determined by Pierce and Thompson (1976). For unheated air drying of corn they found that the minimum airflow rate varied from 0.57 $m^3/(min \cdot t)$ at Bismarck, North Dakota, to 2.90 $m^3/(min \cdot t)$ at Indianapolis, Ind., for the second worst year. For the worst year in 10, the minimum airflow rates varied from 0.75 to 4.42 $m^3/(min \cdot t)$ for the same locations. For solar drying with a collector coefficient of 5.5°C, the airflows varied from 0.54 $m^3/(min \cdot t)$ at Bismarck to 2.78 $m^3/(min \cdot t)$ at Columbia, Missouri, for the second worst year. For the worst year, the airflows varied from 0.94 $m^3/(min \cdot t)$

at Bismarck to 4.18 m^3/(min·t) at Des Moines, Iowa. All of these results were for 24% moisture content corn harvested Oct. 15. Minimum airflow rates for unheated air drying of corn in Iowa were also given for various moisture contents. For the second worst year, with an Oct. 15 harvest date, 20% moisture content corn required 0.6 m^3/(min·t), 22% required 1.4 m^3/(min·t), 24% required 2.4 m^3/(min·t) and 26% required 5.5 m^3/(min·t).

Brooker et al. (1978) gave recommended minimum airflow rates for low-temperature dryers as follows. For 20 - 22% moisture content corn, 1.1 m^3/(min·t), for 22 - 24%, 2.2 m^3/(min·t) and for 24 - 26%, 3.3m^3/(min·t). These were recommended for locations where average daily temperatures are 10°C or less early in the fall. The similarity of the above values to those determined in the present study indicate that the results found in this study are reliable.

An alternative to adding supplemental heat to increase the drying rate would be to use a larger fan to dry the grain. This would increase the airflow rate and increase the heat produced by the fan motor. It would also increase the power requirements considerably (Fig. 4.3). As a result, energy consumption would be increased which would increase the operating cost (Fig. 4.4). The economics of this alternative are not known. The increased energy consumption makes it an undesirable option from the energy conservation viewpoint.

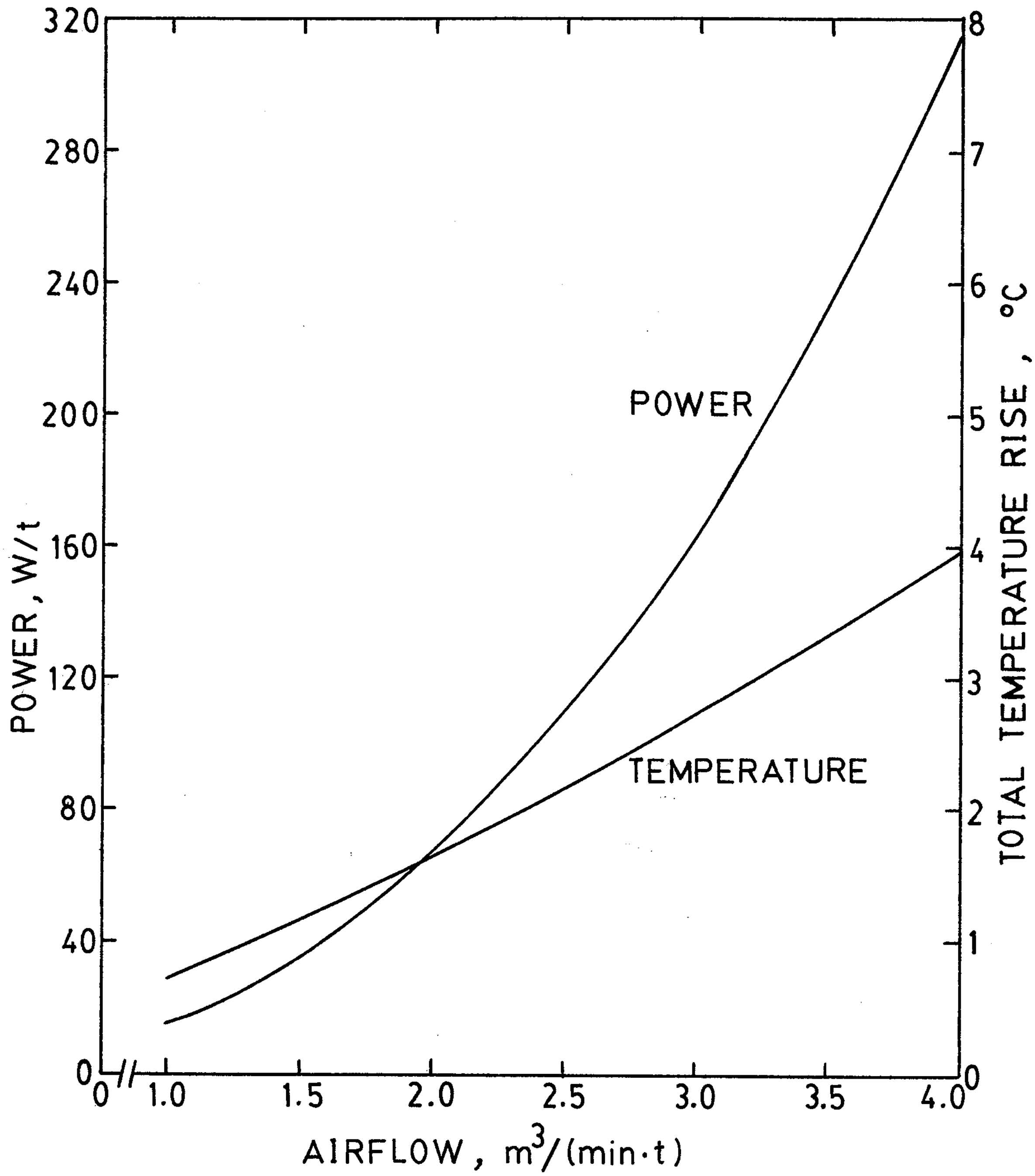

Fig. 4.3 Fan power required and total temperature rise produced for various airflow rates through a fixed depth of wheat, 2.6 m. Static pressure was assumed to be 50% higher than ASAE standard D272 (Baxter, 1978).

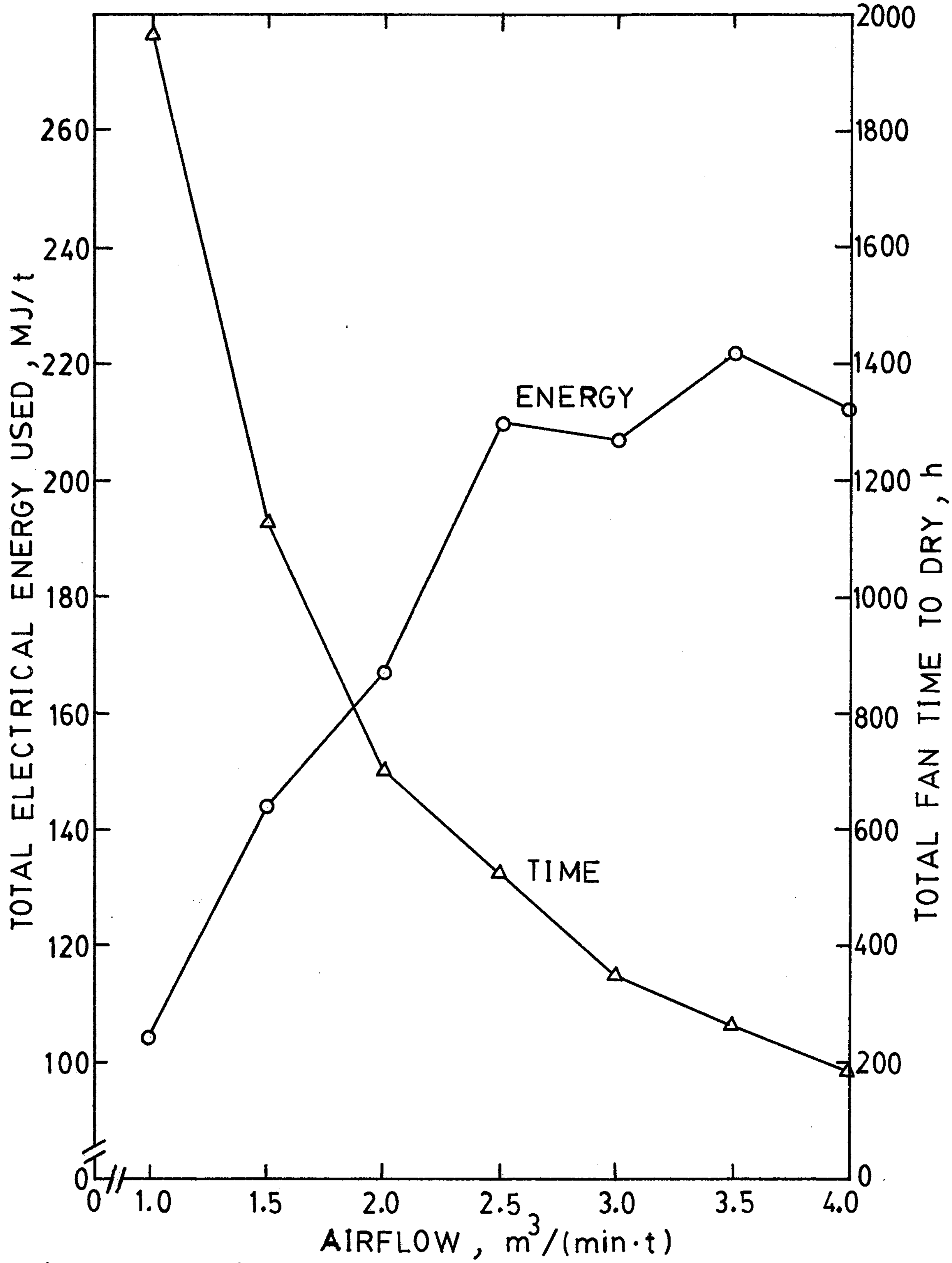

Fig. 4.4 Predicted average electrical energy use and fan time required to dry a fixed amount of wheat, 2.6 m depth, for various airflow rates. The wheat, harvested Sept. 15 at 20% moisture content, was dried at Winnipeg with unheated air. Results are average for a 10 year period.

As shown in Fig. 4.4, energy usage may tend to level off at some point. This is because the higher airflow causes earlier completion of drying. When drying is completed in the fall of a particular year, instead of the next spring, energy consumption is considerably reduced.

In the design of a particular drying system, it should be noted that a farmer cannot simultaneously control both harvest date and moisture content from year to year. Thus to ensure that a sufficiently large fan is specified, the worst expected combination should be chosen to design the system. This is not likely to be economical, however. Therefore, the potential capacity of the system must be balanced against the cost.

4.2 System Performance

4.2.1 Effects of Variables on Drying Performance

In a low-temperature dryer, electrical energy usage varied from year to year (Fig. 4.5). This variation was caused by variations in the weather. Adding solar heat reduced the electrical energy usage each year (Fig. 4.5). Some years, for example 1966, had more reduction than others. This is because drying was completed in the fall of that year, when solar heat was used, but was not completed until spring, when no heat was added. In some years, such as 1968, considerable amounts of grain were harvested damp and late. The results indicate that unheated air drying

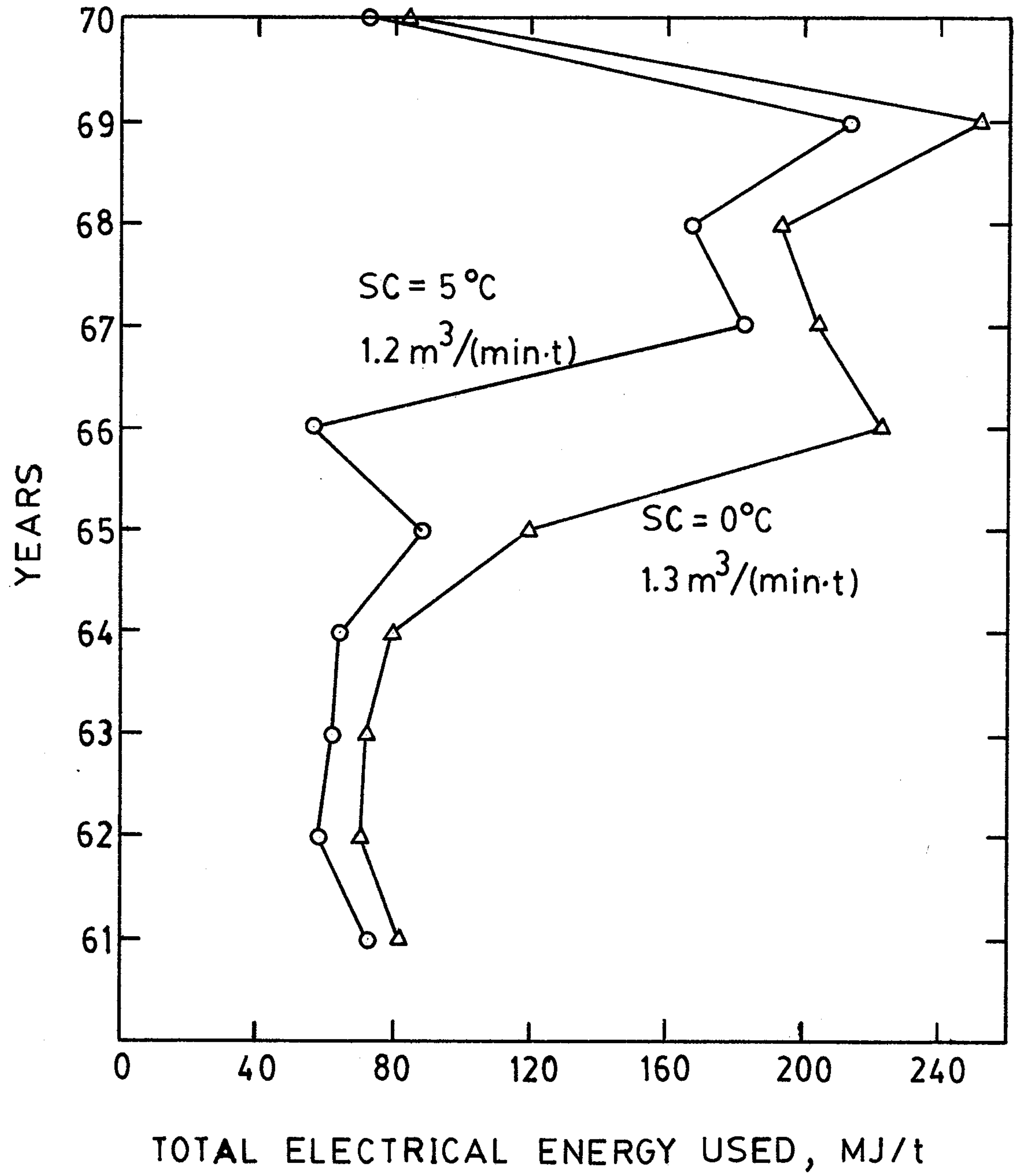

Fig. 4.5 Year-to-year variations in the predicted electrical energy usage required to dry 20% moisture content wheat with unheated and solar heated air. The wheat was harvested Sept. 15 and dried at Winnipeg. A 1.1°C temperature rise was assumed to be added to the air by fan heating.

in such a year was possible. The addition of heat, by solar or other means, would have added a factor of safety, however. This would be particularly important if the drying system was not designed for the most adverse weather conditions.

Plotting these yearly energy requirements from lowest to highest (Fig. 4.6) effectively turns the plot of years into a probability axis (Pierce and Thompson, 1976). Approximately 60% of the time the energy usage was below the average when unheated air was used. Approximately 80% of the time it was below the average when 10°C solar heat was added. This indicates that the addition of solar energy increased the probability that the energy usage would be below the average in any year.

A comparison of energy usage at the various locations indicates the relative energy requirements (Fig. 4.7). For all cases considered, the fan in an unheated air dryer at Swift Current used an average of 100 MJ/(t·a). At Edmonton 120 MJ/(t·a) were used, at Winnipeg 150 MJ/(t·a) were used for wheat, and 240 MJ/(t·a) for corn. At London 370 MJ/(t·a) were used.

Adding 10°C of solar heat at Winnipeg had greater benefit than adding the same amount at Edmonton (Fig. 4.6 and 4.8). The effect at Swift Current was even less for

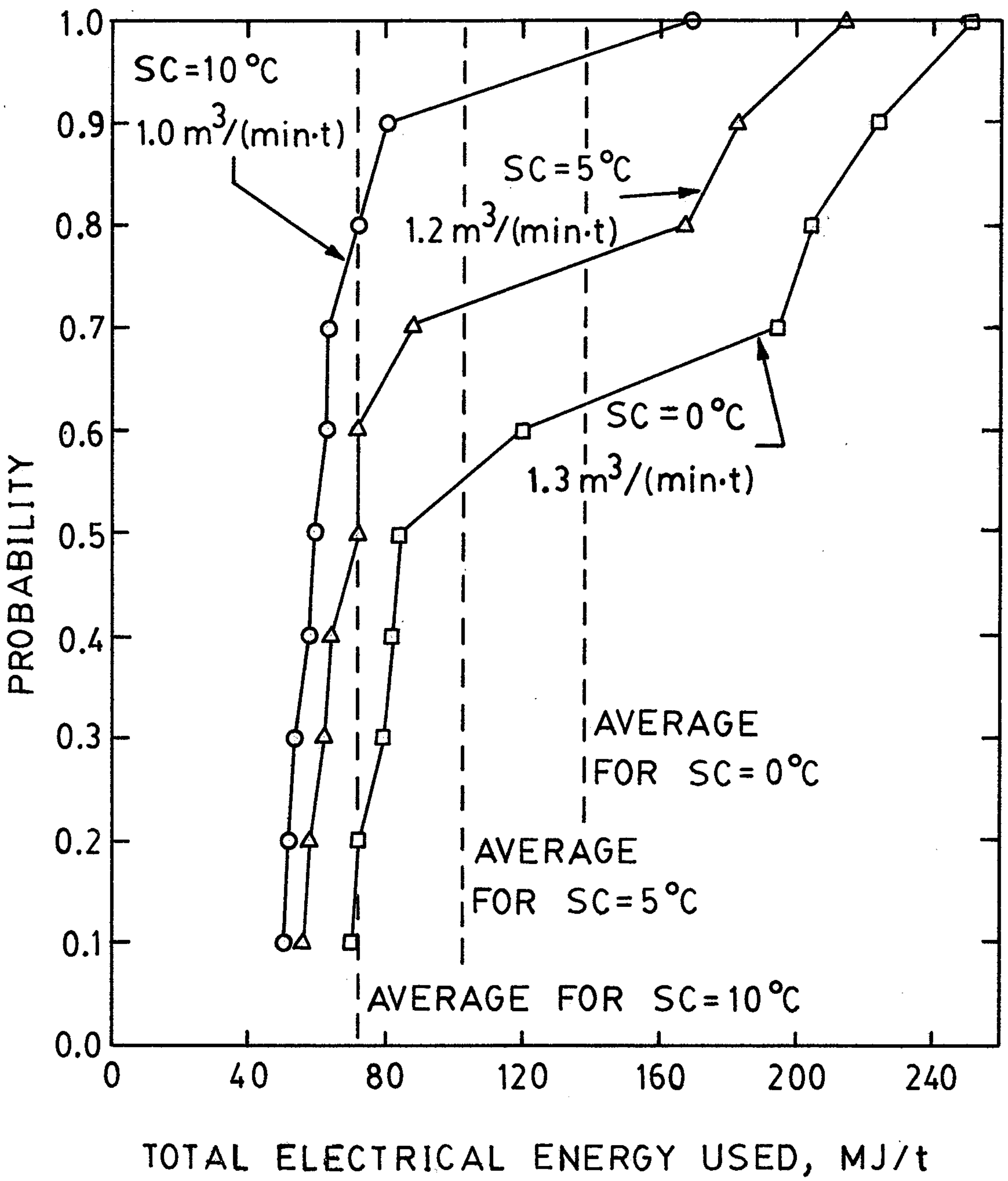

Fig. 4.6 Predicted electrical energy usage required to dry 20% moisture content wheat with unheated and solar heated air. The wheat was harvested Sept. 15 and dried at Winnipeg. A 1.1°C temperature rise was assumed to be added to the air by fan heating.

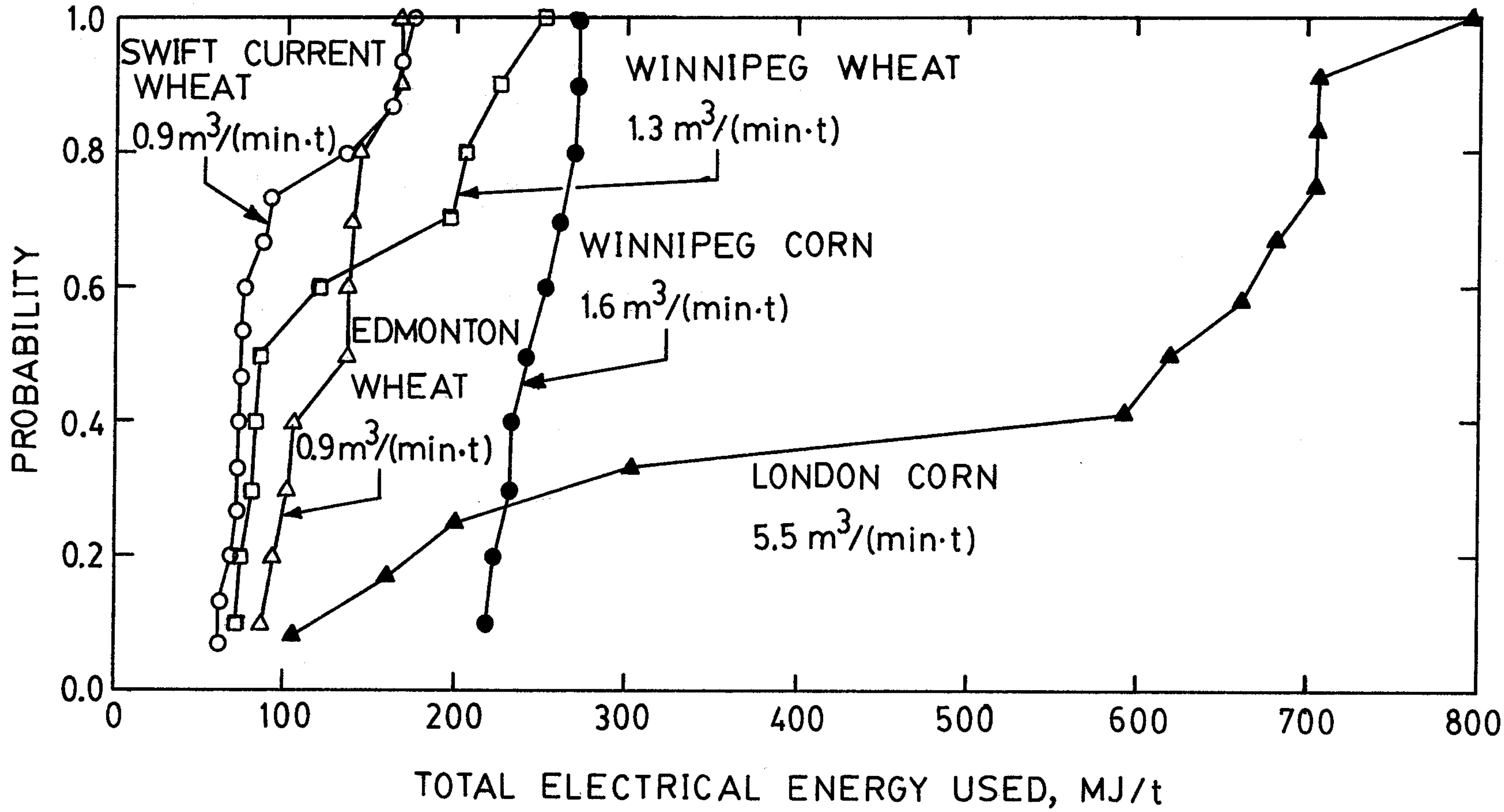

Fig. 4.7 Predicted electrical energy usage required to dry 20% moisture content wheat or 24% moisture content corn at various locations. The wheat was harvested Sept. 15 and the corn Oct. 15 and dried with unheated air. A 1.1°C temperature rise was assumed to be added to the air by fan heating.

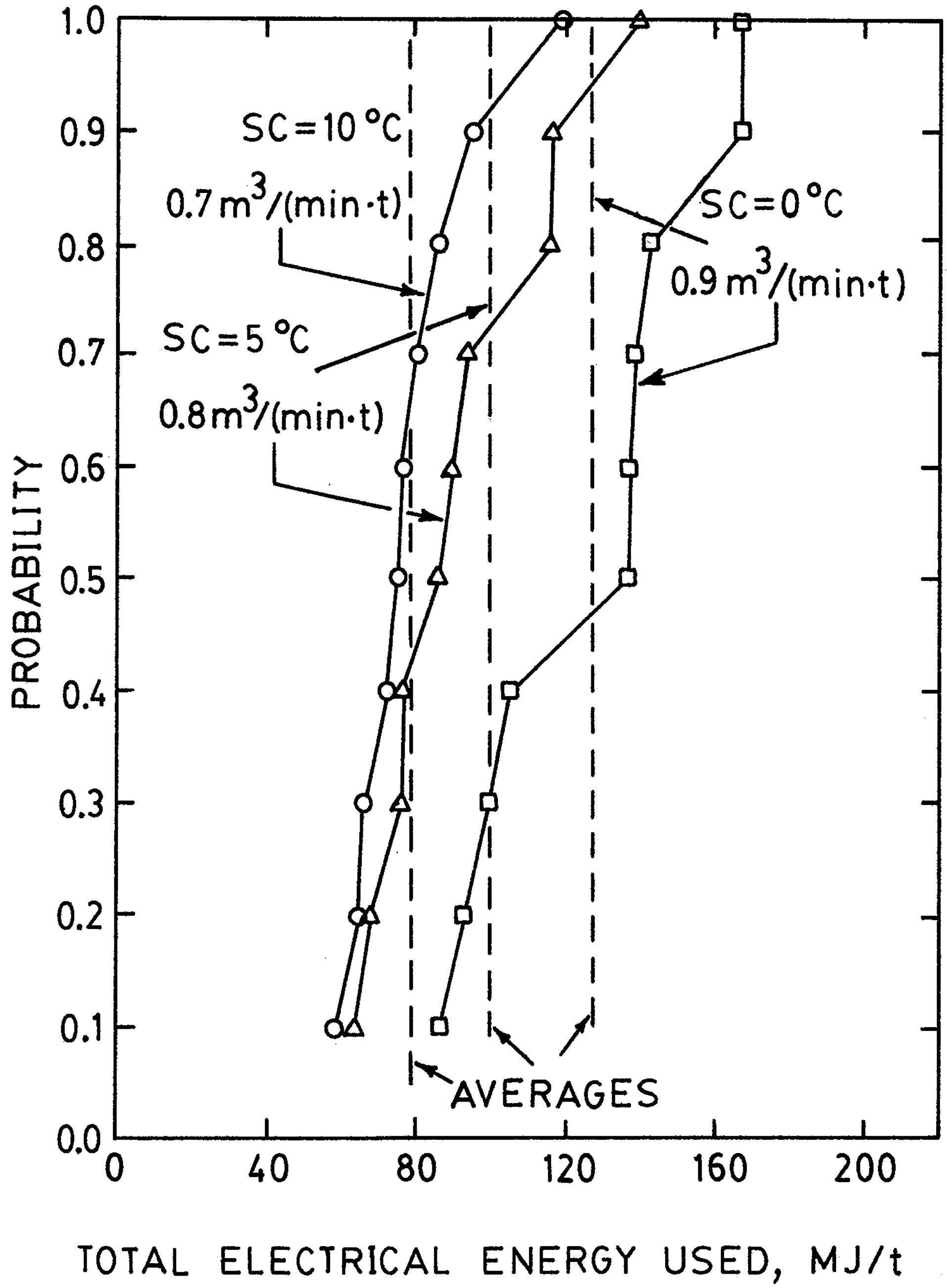

Fig. 4.8 Predicted electrical energy usage required to dry 20% moisture content wheat with unheated and solar heated air. The wheat was harvested Sept. 15 and dried at Edmonton. A 1.1°C temperature rise was assumed to be added to the air by fan heating.

any level of heat (Fig. 4.9). Adding solar heat at London had a greater effect than at Winnipeg (Fig. 4.10 and 4.11). For all cases considered, adding 5°C of solar heat resulted in an 8% reduction in the energy usage at Swift Current, a 23% reduction at Edmontion, a 29% reduction at Winnipeg for wheat and 17% for corn, and a 35% reduction at London.

These results (Fig. 4.6 to 4.11) show the effect of climate. The driest and coolest regions required the least amount of energy, and the warmer and more humid regions required the most. The regions which used the most energy generally benefited the most from the addition of solar heat.

Earlier harvest dates required smaller amounts of energy to dry the grain (Fig. 4.12). This is because the grain generally dried sooner for earlier harvest dates. When it did not dry sooner the energy requirements were increased, as the results for Sept. 15 show.

Energy requirements were the greatest for grain with highest initial moisture content (Fig. 4.13). Increased airflow rates, not longer drying times, caused this increase in energy usage. This confirms the importance of using minimum airflow rates to achieve the least total energy consumption.

The electrical energy requirements for drying grain in a low-temperature dryer depend upon the above variables.

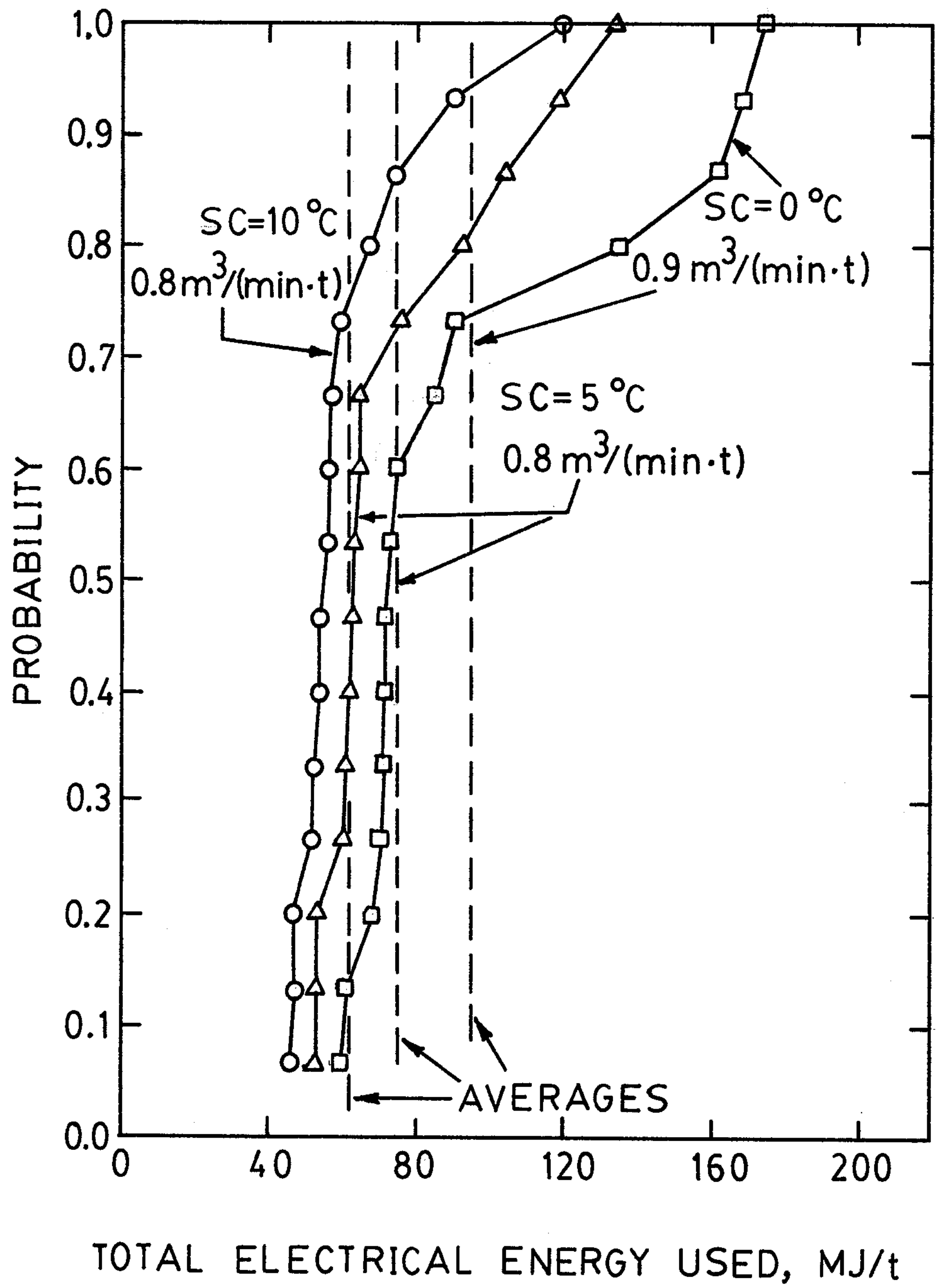

Fig. 4.9 Predicted electrical energy usage required to dry 20% moisture content wheat with unheated and solar heated air. The wheat was harvested Sept. 15 and dried at Swift Current. A 1.1°C temperature rise was assumed to be added to the air by fan heating.

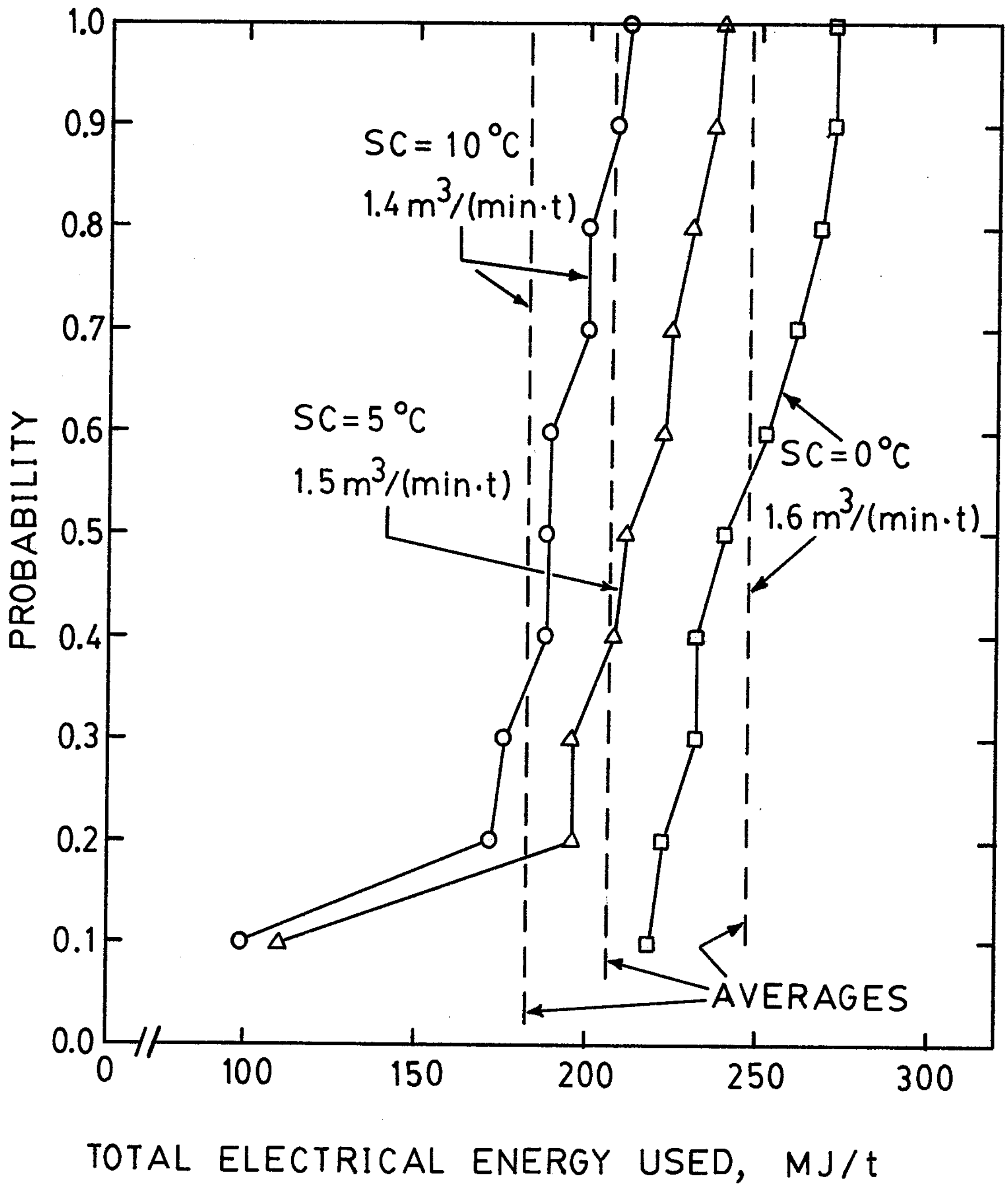

Fig. 4.10 Predicted electrical energy usage required to dry 24% moisture content corn with unheated and solar heated air. The corn was harvested Oct. 15 and dried at Winnipeg. A 1.1°C temperature rise was assumed to be added to the air by fan heating.

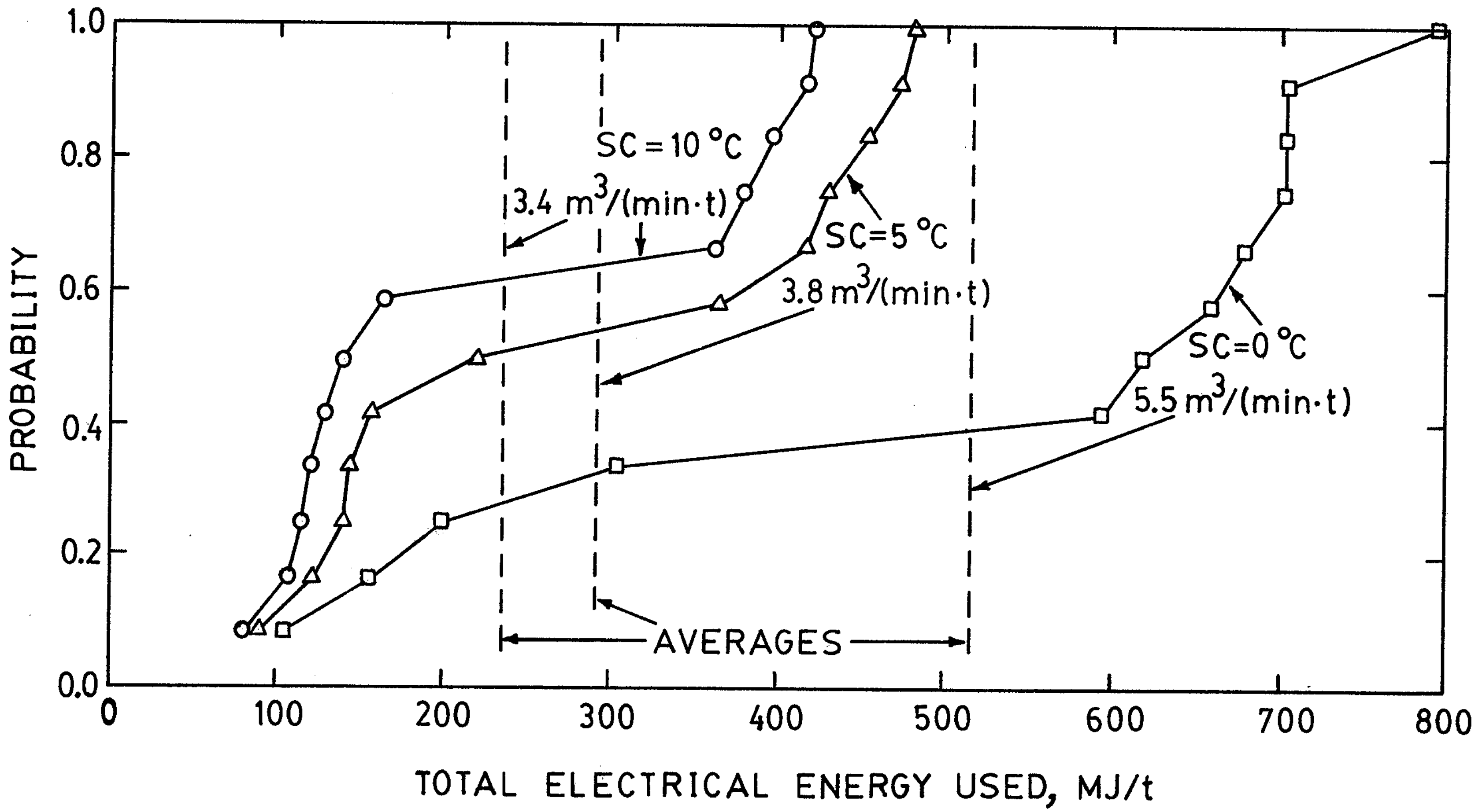

Fig. 4.11 Predicted electrical energy usage required to dry 24% moisture content corn with unheated and solar heated air. The corn was harvested Oct. 15 and dried at London. A 1.1°C temperature rise was assumed to be added to the air by fan heating.

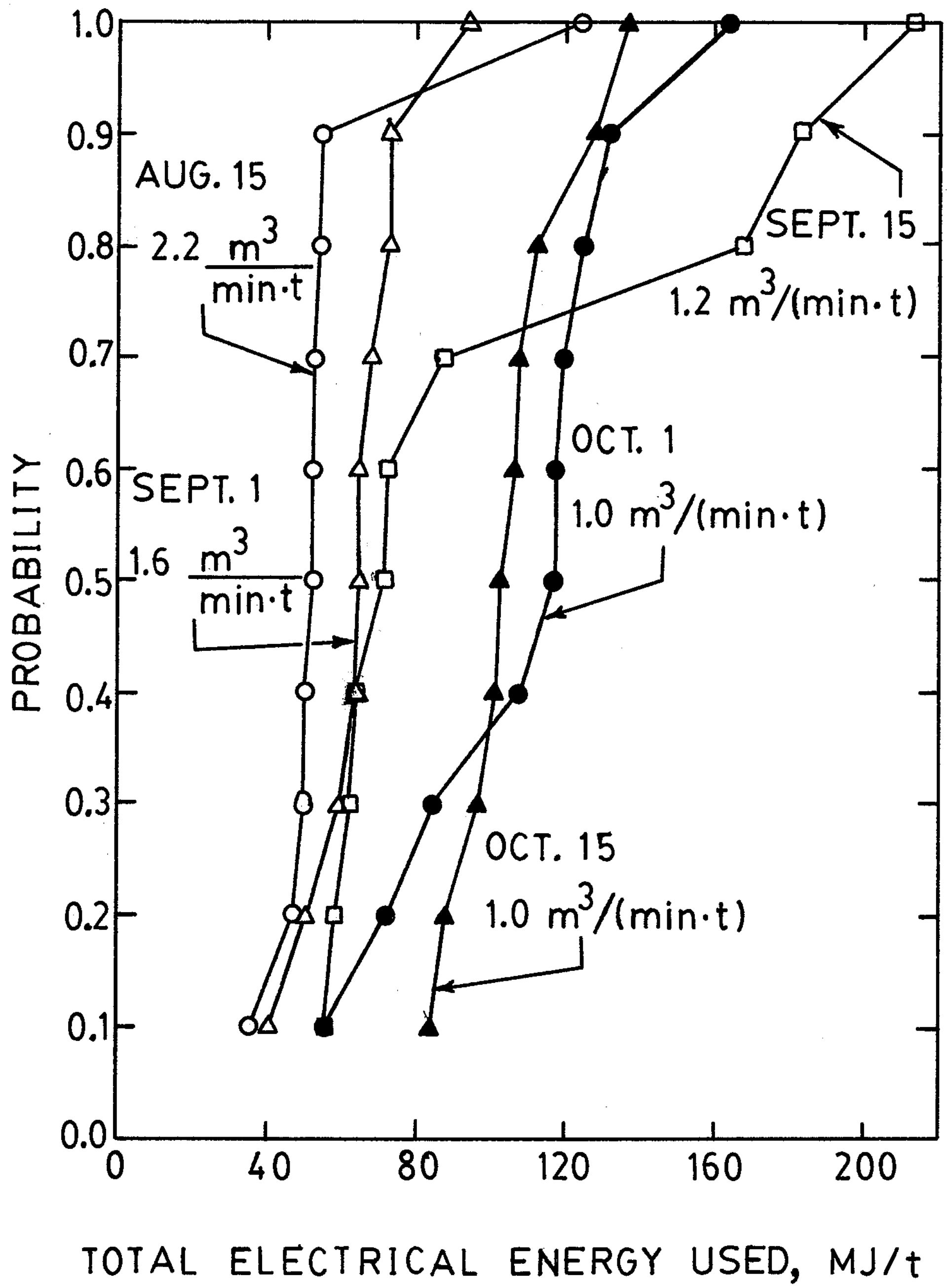

Fig. 4.12 Predicted electrical energy usage required to dry 20% moisture content wheat harvested on five separate dates. The wheat was dried at Winnipeg with solar heated air. The collector coefficient was 5°C. A 1.1°C temperature rise was assumed to be added to the air by fan heating.

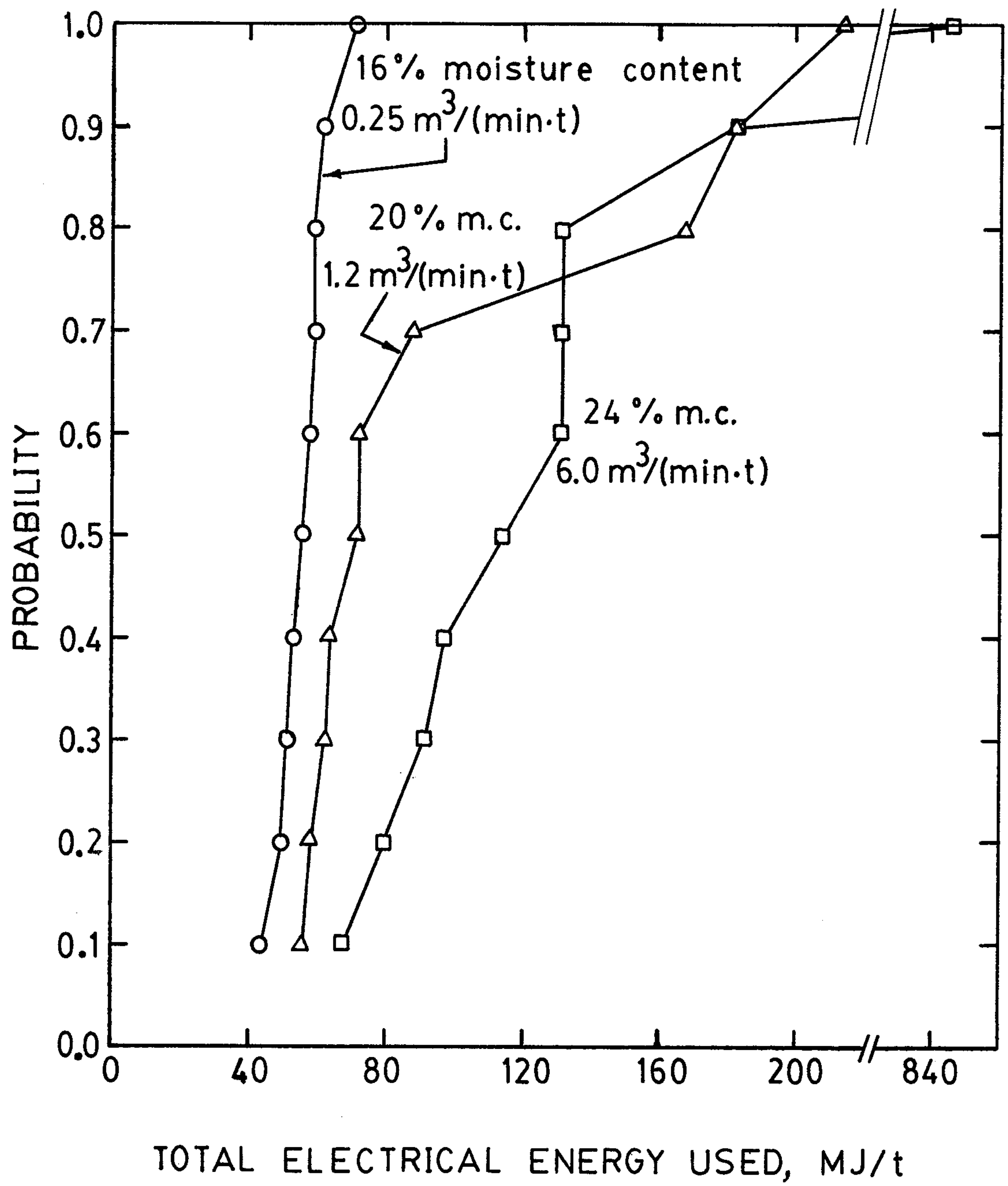

Fig. 4.13 Predicted electrical energy usage required to dry wheat having three different moisture contents, using solar heated air. The wheat was harvested Sept. 15 and dried at Winnipeg. The solar collector coefficient was 5°C. A 1.1°C temperature rise was assumed to be added to the air by fan heating.

For a particular system, the energy required to dry a given amount of grain depends upon weather conditions, harvest date, initial moisture content and amount of heat added. The earlier the harvest date, the less the energy usage. The higher the moisture content, the greater the energy usage. The more solar heat added, the less the electrical energy usage.

4.2.2 Economics of Solar Grain Drying

Drying results for low-temperature dryers varied considerably from year to year (Table 4.6 and Sec. 4.2.1). These results were averaged over all of the years considered to determine the average economic performance which may be expected in the future.

The airflow rate used in each case was the minimum which would dry the grain successfully in every year. The collector area required for each solar dryer was calculated by equation 3.14. A horizontal collector with average efficiency of 50% was assumed. For cost analysis, a bin size of 5.7 m diameter was assumed. The grain depth and fan size for each case were taken from Fig. 3.1.

The required fan power was also expressed in power per unit area of floor (Tables 4.7A to 4.11A). The total power requirement for any given bin can thus be calculated from the total floor area. For systems of differing sizes the relative costs indicated here may be used, but actual costs must be calculated. Changing the bin size would

TABLE 4.6

PREDICTED DRYING RESULTS FOR WHEAT

FOR A 10 YEAR PERIOD AT WINNIPEG[1]

	Unheated Air Drying				Solar Drying[2]			
Drying Year	Dry Date	Final moisture content %	Allowable time elapsed %	Fan time h	Dry Date	Final moisture content %	Allowable time elapsed %	Fan time h
61	10 18	14.1	63	792	10 17	13.7	66	756
62	10 14	13.6	66	684	10 11	12.5	69	612
63	10 14	12.8	76	696	10 12	12.0	80	648
64	10 17	13.1	53	768	10 13	13.5	55	672
65	11 02	13.7	55	1152	10 23	13.8	54	912
66	05 21	12.9	63	2168	10 10	13.9	53	588
67	05 05	12.1	84	1984	05 02	11.4	85	1912
68	05 02	13.2	100	1876	04 27	12.4	99	1756
69	05 25	13.7	89	2440	05 17	13.6	84	2248
70	10 20	13.9	64	828	10 16	13.2	69	744
Average		13.3	71	1339		13.0	71	1085

1. Simulation runs were made with an airflow rate of 1.3 $m^3/(min \cdot t)$ for unheated air and 1.2 $m^3/(min \cdot t)$ for solar drying. The wheat, harvested Sept. 15, had an initial moisture content of 20%. In all cases, a 1.1°C temperature rise was assumed to be added to the air by fan heating.

2. Using a solar collector coefficient of 5°C.

TABLE 4.7A

COMPARISON OF AMBIENT AIR AND SOLAR HEATED AIR DRYING SYSTEMS FOR WHEAT AT EDMONTON[a] -- PARAMETERS USED

Test No.	Harvest Date	Earliest Fall Stop[b]	Moisture Content,[c] %	S. C.[d], °C	Airflow Rate,[e] $m^3/(min \cdot t)$	Collector Area,[e] m^2/t	Fan Power, W/m^2 floor
1	Aug. 15	Nov. 1	20	0	1.8	---	68
2				5	1.6	0.66	64
3	Sept. 1	Nov. 1	20	0	1.0	---	52
4				5	0.9	0.37	49
5	Sept. 15	Nov. 1	16	0	0.25	---	27
6				5	0.15	0.06	21
7				10	0.15	0.12	21
8			20	0	0.9	---	49
9				5	0.8	0.33	47
10				10	0.7	0.58	44
11			24	0	3.4	---	91
12				5	3.1	1.28	87
13				10	3.0	2.48	86
14	Oct. 1	Nov. 1	20	0	0.9	---	49
15				5	0.9	0.37	49
16		Dec. 1	20	0	0.7	---	44
17				5	0.7	0.29	44
18	Oct. 15	Nov. 1	20	0	0.8	---	47
19				5	0.8	0.33	47
20		Dec. 1	20	0	0.7	---	44
21				5	0.7	0.29	44

[a] Based upon simulated drying results averaged over the years 1967 to 1976. A 1.1°C temperature rise was assumed to be added to the air by fan heating.

[b] Continuous fan operation until this date or until the average temperature for 1 week is less than 0°C, whichever is later.

[c] Initial moisture content at the start of drying, % wet mass basis.

[d] Solar collector coefficient, average temperature rise over 24 h when the daily solar radiation is approx. 40 MJ/m^2; 0 = unheated air.

[e] Based on a tonne of dry grain.

TABLE 4.7B

COMPARISON OF AMBIENT AIR AND SOLAR HEATED AIR DRYING SYSTEMS FOR WHEAT AT EDMONTON[a] -- SIMULATED DRYING RESULTS

Test No.	Fan Time to Dry,[b] h	Probability of Fall Finish[c]	Final Avg. M.C., %	Energy Input to Fan, MJ/t	Solar Energy Collected, MJ/t	Avg. Temp. Rise, °C	Solar Input / Energy Saved[d]
1	960(620)	0.9	13.4	140(90)	---		---
2	550(180)	1.0	13.0	70(20)	120(30)	2.0	1.9
3	1500(700)	0.7	13.3	120(60)	---		---
4	1200(500)	0.9	13.0	90(40)	100(40)	1.4	2.9
5	3100(400)	0.0	13.2	60(10)	---		---
6	3800(200)	0.0	12.7	40(5)	80(10)	1.9	4.5
7	3400(200)	0.0	11.8	40(5)	140(10)	3.8	6.7
8	1800(400)	0.2	13.3	130(30)	---		---
9	1500(400)	0.4	13.3	90(30)	100(30)	1.2	2.9
10	1400(300)	0.3	13.1	80(20)	160(40)	2.3	3.3
11	690(480)	0.9	13.1	190(130)	---		---
12	570(440)	0.9	12.8	140(110)	160(80)	1.4	3.4
13	420(130)	1.0	12.5	100(30)	240(30)	2.8	2.8
14	1700(300)	0.0	13.2	120(20)	---		---
15	1400(300)	0.1	13.0	100(20)	110(30)	1.2	6.3
16	2500(300)	0.0	12.7	140(20)	---		---
17	2200(300)	0.0	12.8	120(20)	120(30)	1.1	7.1
18	1600(200)	0.0	12.4	100(10)	---		---
19	1400(100)	0.0	12.0	90(5)	120(20)	1.5	10.
20	2200(200)	0.0	12.5	120(10)	---		---
21	2000(200)	0.0	12.1	110(10)	120(20)	1.2	11.

[a] See footnotes Table 4.7A. Standard deviations are given in parentheses.
[b] Time required to dry the wettest layer to 14.5% m.c.
[c] Probability that the drying is completed in the fall.
[d] Ratio of solar energy collected to electrical energy saved at the fan motor. Apparent errors are due to rounding.

TABLE 4.7C

COMPARISON OF AMBIENT AIR AND SOLAR HEATED AIR DRYING SYSTEMS FOR WHEAT AT EDMONTON* -- PREDICTED DRYING COSTS

Test No.	Electricity Cost, $/t	Over-drying Cost, $/t	Drying Equipment Depreciation, $/t	Collector Depreciation, $/t	Total Drying Cost, $/t	Cost per unit Moisture, $/(t.%m.c.)
1	1.40	1.60	7.20	--	10.20	1.50
2	0.70	2.30	6.70	0.66	10.40	1.50
3	1.20	1.70	5.20	--	8.20	1.20
4	0.85	2.20	4.90	0.37	8.40	1.20
5	0.62	1.90	2.50	--	5.10	1.80
6	0.45	2.70	2.00	0.06	5.20	1.60
7	0.41	4.00	2.00	0.12	6.50	1.50
8	1.30	1.80	4.90	--	8.00	1.20
9	0.93	1.80	4.60	0.33	7.70	1.20
10	0.79	2.10	4.30	0.58	7.80	1.10
11	1.90	2.10	10.10	--	14.10	1.30
12	1.40	2.60	9.60	1.30	14.90	1.30
13	1.00	2.90	9.50	2.50	15.90	1.40
14	1.20	2.00	4.90	--	8.10	1.20
15	1.00	2.30	4.90	0.37	8.60	1.20
16	1.40	2.60	4.30	--	8.30	1.10
17	1.20	2.50	4.30	0.29	8.30	1.10
18	1.00	3.00	4.60	--	8.70	1.10
19	0.91	3.60	4.60	0.33	9.50	1.20
20	1.20	2.90	4.30	--	8.50	1.10
21	1.10	3.50	4.30	0.29	9.20	1.20

* See footnotes Table 4.7A. Apparent errors are due to rounding.

TABLE 4.7D

COMPARISON OF AMBIENT AIR AND SOLAR HEATED AIR DRYING SYSTEMS FOR WHEAT AT EDMONTON[a] -- PREDICTED RELATIVE COSTS

Test No.	Electrical Energy Usage, MJ/kg_w [b]	Solar Energy Cost, ¢/MJ[c]	Cost per Unit of Electrical Energy Saved, ¢/MJ[d]			Allowable Collector Cost, $\$/m^2$ [e]
			Solar	Electrical	Propane	
1	1.7					
2	0.8	0.53	1.0	1.9	0.9	3.60
3	1.5					
4	1.0	0.36	1.0	2.9	1.4	2.40
5	1.8					
6	1.1	0.08	0.4	4.5	2.3	nil
7	0.8	0.09	0.6	6.7	3.3	nil
8	1.5					
9	1.1	0.34	1.0	2.9	1.4	9.50
10	0.9	0.36	1.2	3.3	1.7	6.80
11	1.3					
12	1.0	0.81	2.8	3.4	1.7	1.80
13	0.7	1.04	2.9	2.8	1.4	1.40
14	1.4					
15	1.2	0.35	2.2	6.3	3.1	nil
16	1.5					
17	1.3	0.25	1.8	7.1	3.6	5.50
18	1.1					
19	0.9	0.28	2.8	10.0	5.0	nil
20	1.3					
21	1.1	0.24	2.6	11.0	5.6	nil

[a] See previous footnotes.
[b] Average energy used by the fan to remove each kilogram of water.
[c] Yearly collector costs per unit of solar energy collected, assuming $1.00/($m^2 \cdot a$) for the collector.
[d] Ratio from Table 4.7B x cost per megajoule of various fuels -- solar costs column 3, electrical cost 1.0 ¢/MJ, propane cost 0.5¢/MJ.
[e] Allowable first cost for the collector, based upon savings in electricity, overdrying and depreciation costs (Table 4.7C) of solar over ambient.

TABLE 4.7E

COMPARISON OF AMBIENT AIR AND SOLAR HEATED AIR DRYING SYSTEMS FOR WHEAT AT EDMONTON -- SIMULATION RESULTS FOR AVERAGE DRYING[a]

Test No.	Fan Time to Avg. Dry, h	Energy Input to Fan, MJ/t	Electricity Cost, $/t	Total Drying Cost,[b] $/t	Cost per Unit Moisture, $/(t.%m.c.)	Allowable Collector Cost[c], $/m²
1	670(320)	100(50)	0.95	8.10	1.50	
2	450(90)	60(10)	0.57	8.00	1.40	6.20
3	1200(500)	90(40)	0.93	6.20	1.10	
4	1000(400)	70(30)	0.73	6.00	1.10	6.60
5	1800(600)	40(10)	0.36	2.90	1.90	
6	2000(200)	20(5)	0.24	2.30	1.50	58.00
7	1500(500)	20(5)	0.18	2.30	1.50	32.00
8	1300(400)	90(30)	0.94	5.90	1.10	
9	1200(300)	70(20)	0.74	5.70	1.00	7.70
10	1200(200)	60(10)	0.64	5.50	1.00	8.00
11	560(450)	150(120)	1.50	11.70	1.20	
12	430(140)	110(40)	1.10	12.00	1.30	3.80
13	380(90)	90(20)	0.90	12.80	1.40	2.60
14	1400(300)	100(20)	0.98	5.90	1.10	
15	1200(200)	80(10)	0.84	6.20	1.10	1.90
16	2100(300)	120(20)	1.20	5.50	1.00	
17	1800(300)	100(20)	0.97	5.60	1.00	3.10
18	1400(200)	90(10)	0.91	5.50	1.00	
19	1300(100)	80(10)	0.83	5.80	1.10	1.20
20	2000(200)	110(10)	1.10	5.40	1.00	
21	1800(200)	100(10)	1.00	5.60	1.00	1.60

[a] Drying until the bin average moisture content is 14.5% or less, and the top is 17% or less. See footnotes Table 4.7A.

[b] Includes electricity, drying equipment depreciation and solar collector depreciation.

[c] Allowable first cost for the collector, based upon savings in electricity and depreciation costs of solar over ambient.

TABLE 4.8A

COMPARISON OF AMBIENT AIR AND SOLAR HEATED AIR DRYING SYSTEMS FOR WHEAT AT SWIFT CURRENT* -- PARAMETERS USED

Test No.	Harvest Date	Earliest Fall Stop	Moisture Content, %	S. C., °C	Airflow Rate, $m^3/(min \cdot t)$	Collector Area, m^2/t	Fan Power, W/m^2 floor
1	Aug. 15	Nov. 1	20	0	1.2	--	56
2				5	1.4	0.58	61
3	Sept. 1	Nov. 1	20	0	1.0	--	52
4				5	0.9	0.37	49
5	Sept. 15	Nov. 1	16	0	0.25	--	27
6				5	0.2	0.08	24
7				10	0.2	0.17	24
8			20	0	0.9	--	49
9				5	0.8	0.33	47
10				10	0.8	0.66	47
11			24	0	3.2	--	89
12				5	3.0	1.24	86
13				10	2.8	2.31	83
14	Oct. 1	Nov. 1	20	0	1.0	--	52
15				5	0.9	0.37	49
16		Dec. 1	20	0	0.7	--	44
17				5	0.7	0.29	44
18	Oct. 15	Nov. 1	20	0	1.1	--	54
19				5	1.1	0.45	54
20		Dec. 1	20	0	0.7	--	44
21				5	0.7	0.29	44

* Based upon simulated drying results averaged over the years 1960 to 1974. See footnotes Table 4.7

TABLE 4.8B

COMPARISON OF AMBIENT AIR AND SOLAR HEATED AIR DRYING SYSTEMS FOR WHEAT AT SWIFT CURRENT* -- SIMULATED DRYING RESULTS

Test No.	Fan Time to Dry, h	Probability of Fall Finish	Final Avg. M.C., %	Energy Input to Fan, MJ/t	Solar Energy Collected MJ/t	Avg. Temp. Rise, °C	Solar Input / Energy Saved
1	650(300)	1.0	12.3	60(30)	---		---
2	410(80)	1.0	11.6	50(10)	90(10)	2.3	5.5
3	870(240)	1.0	12.9	70(20)	---		---
4	800(160)	1.0	12.5	60(10)	90(10)	1.7	7.2
5	2800(500)	0.0	13.4	60(10)	---		---
6	2800(300)	0.0	12.6	50(5)	70(10)	1.8	7.3
7	2500(300)	0.0	12.2	40(5)	120(20)	3.4	8.0
8	1300(600)	0.7	13.0	100(40)	---		---
9	1200(400)	0.7	12.6	70(30)	90(30)	1.4	4.6
10	990(310)	0.9	12.1	60(20)	160(50)	2.8	4.8
11	540(380)	0.9	12.7	140(100)	---		---
12	470(350)	0.9	12.2	110(80)	150(80)	1.6	6.0
13	370(80)	1.0	11.7	80(20)	230(30)	3.2	4.1
14	1400(500)	0.3	13.0	110(40)	---		---
15	1200(400)	0.3	13.0	90(30)	100(30)	1.3	3.8
16	2500(400)	0.1	13.0	140(20)	---		---
17	2100(500)	0.2	12.5	120(30)	130(40)	1.2	6.1
18	1400(300)	0.0	12.9	120(30)	---		---
19	1100(300)	0.1	12.7	100(20)	120(30)	1.4	4.5
20	2300(300)	0.0	13.1	130(20)	---		---
21	2000(200)	0.0	12.3	110(10)	130(20)	1.3	9.9

* See footnotes Table 4.7 and 4.8A. Standard deviations are given in parentheses.

TABLE 4.8C

COMPARISON OF AMBIENT AIR AND SOLAR HEATED AIR DRYING

SYSTEMS FOR WHEAT AT SWIFT CURRENT*--PREDICTED DRYING COSTS

Test No.	Electricity Cost, $/t	Over-drying Cost, $/t	Drying Equipment Depreciation, $/t	Collector Depreciation, $/t	Total Drying Cost, $/t	Cost per unit Moisture, $/(t.%m.c.)
1	0.62	3.30	5.80	--	9.70	1.30
2	0.45	4.30	6.30	0.58	11.60	1.40
3	0.69	2.30	5.20	--	8.20	1.20
4	0.57	3.00	4.90	0.37	8.90	1.20
5	0.55	1.70	2.50	--	4.80	1.80
6	0.45	2.80	2.30	0.08	5.50	1.60
7	0.40	3.40	2.30	0.17	6.30	1.70
8	0.95	2.30	4.90	--	8.20	1.20
9	0.75	2.80	4.60	0.33	8.50	1.20
10	0.62	3.50	4.60	0.66	9.40	1.20
11	1.40	2.60	9.80	--	13.80	1.20
12	1.10	3.40	9.50	1.20	15.30	1.30
13	0.81	4.10	9.10	2.30	16.30	1.30
14	1.10	2.20	5.20	--	8.60	1.20
15	0.88	2.20	4.90	0.37	8.40	1.20
16	1.40	2.20	4.30	--	7.90	1.10
17	1.20	2.90	4.30	0.29	8.70	1.20
18	1.20	2.30	5.50	--	9.00	1.30
19	0.97	2.70	5.50	0.45	9.60	1.30
20	1.30	2.10	4.30	--	7.70	1.10
21	1.10	3.20	4.30	0.29	8.90	1.20

* See footnotes Table 4.7 and 4.8A

TABLE 4.8D

COMPARISON OF AMBIENT AIR AND SOLAR HEATED AIR DRYING SYSTEMS

FOR WHEAT AT SWIFT CURRENT* -- PREDICTED RELATIVE COSTS

Test No.	Electrical Energy Usage, MJ/kg_w	Solar Energy Cost, ¢/MJ	Cost per Unit of Electrical Energy Saved, ¢/MJ			Allowable Collector Cost, $\$/m^2$
			Solar	Electrical	Propane	
1	0.6					
2	0.4	0.63	3.5	5.5	2.8	nil
3	0.8					
4	0.6	0.43	3.1	7.2	3.6	nil
5	1.8					
6	1.1	0.11	0.8	7.3	3.7	nil
7	0.9	0.14	1.1	8.0	4.0	nil
8	1.1					
9	0.8	0.35	1.6	4.6	2.3	nil
10	0.6	0.42	2.0	4.8	2.4	nil
11	0.9					
12	0.7	0.81	4.9	6.0	3.0	nil
13	0.5	1.0	4.1	4.1	2.1	nil
14	1.3					
15	1.0	0.37	1.4	3.8	1.9	7.60
16	1.6					
17	1.3	0.22	1.3	6.1	3.1	nil
18	1.4					
19	1.1	0.39	1.8	4.5	2.3	nil
20	1.5					
21	1.2	0.22	2.2	9.9	5.0	nil

* See footnotes Table 4.7 and 4.8A

TABLE 4.8E

COMPARISON OF AMBIENT AIR AND SOLAR HEATED AIR DRYING SYSTEMS FOR WHEAT AT SWIFT CURRENT* -- SIMULATION RESULTS FOR AVERAGE DRYING

Test No.	Fan Time to Avg. Dry, h	Energy Input to Fan, MJ/t	Electricity Cost, $/t	Total Drying Cost, $/t	Cost per Unit Moisture, $/(t.%m.c.)	Allowable Collector Cost, $/m^2
1	520(130)	50(10)	0.49	6.30	1.10	
2	370(70)	40(10)	0.41	7.30	1.30	nil
3	750(190)	60(10)	0.59	5.80	1.10	
4	700(130)	50(10)	0.50	5.80	1.10	5.10
5	1200(700)	20(10)	0.23	2.80	1.80	
6	1100(600)	20(10)	0.17	2.50	1.70	20.60
7	780(360)	10(10)	0.12	2.60	1.70	11.20
8	1000(400)	70(30)	0.73	5.70	1.00	
9	960(260)	60(20)	0.61	5.60	1.00	6.50
10	820(130)	50(10)	0.52	5.80	1.10	3.90
11	480(350)	120(90)	1.20	11.00	1.20	
12	370(80)	90(20)	0.87	11.60	1.20	2.70
13	350(80)	80(20)	0.77	12.20	1.30	2.40
14	1100(400)	90(30)	0.85	6.10	1.10	
15	970(290)	70(20)	0.69	6.00	1.10	6.10
16	2000(400)	110(20)	1.10	5.40	1.00	
17	1500(500)	90(30)	0.85	5.50	1.00	4.50
18	1100(300)	100(20)	0.97	6.50	1.20	
19	910(200)	80(20)	0.79	6.70	1.20	2.00
20	1900(200)	110(10)	1.10	5.40	1.00	
21	1700(200)	90(10)	0.92	5.50	1.00	2.60

* See footnotes Table 4.7 and 4.8A.

TABLE 4.9A

COMPARISON OF AMBIENT AIR AND SOLAR HEATED AIR DRYING SYSTEMS FOR WHEAT AT WINNIPEG* -- PARAMETERS USED

Test No.	Harvest Date	Earliest Fall Stop	Moisture Content, %	S. C., °C	Airflow Rate, $m^3/(min \cdot t)$	Collector Area, m^2/t	Fan Power, W/m^2 floor
1	Aug. 15	Nov. 1	20	0	3.0	--	86
2				5	2.2	0.91	75
3	Sept. 1	Nov. 1	20	0	2.4	--	78
4				5	1.6	0.66	64
5	Sept. 15	Nov. 1	16	0	0.35	--	32
6				5	0.25	0.10	27
7				10	0.22	0.18	25
8			20	0	1.3	--	59
9				5	1.2	0.50	56
10				10	1.0	0.83	52
11			24	0	7.5	--	130
12				5	6.0	2.48	117
13				10	5.5	4.54	113
14	Oct. 1	Nov. 1	20	0	1.1	--	54
15				5	1.0	0.41	52
16		Dec. 1	20	0	0.9	--	49
17				5	0.8	0.33	47
18	Oct. 15	Nov. 1	20	0	1.0	--	52
19				5	1.0	0.41	52
20		Dec. 1	20	0	0.9	--	49
21				5	0.9	0.37	49

* Based upon simulated drying results averaged over the years 1961 to 1970. See footnotes Table 4.7

TABLE 4.9B

COMPARISON OF AMBIENT AIR AND SOLAR HEATED AIR DRYING SYSTEMS FOR WHEAT AT WINNIPEG* -- SIMULATED DRYING RESULTS

Test No.	Fan Time to Dry, h	Probability of Fall Finish	Final Avg. M.C., %	Energy Input to Fan, MJ/t	Solar Energy Collected, MJ/t	Avg. Temp. Rise, °C	Solar Input / Energy Saved
1	380(320)	1.0	13.3	90(80)	---		---
2	330(140)	1.0	12.3	60(20)	110(30)	2.2	3.5
3	880(780)	0.8	13.2	170(150)	---		---
4	520(110)	1.0	13.2	70(10)	100(10)	1.7	1.0
5	3000(600)	0.1	13.3	80(10)	---		---
6	2800(400)	0.0	12.8	60(10)	80(20)	1.6	3.2
7	2700(300)	0.0	12.3	50(10)	130(30)	3.2	3.8
8	1300(700)	0.6	13.3	140(70)	---		---
9	1100(600)	0.7	13.0	100(60)	120(60)	1.4	3.4
10	910(450)	0.9	12.8	70(40)	160(50)	2.6	2.5
11	490(570)	0.9	13.3	290(340)	---		---
12	390(490)	0.9	12.9	190(230)	210(160)	1.5	2.0
13	270(210)	1.0	12.7	120(90)	290(120)	3.1	1.7
14	1600(500)	0.2	13.5	140(40)	---		---
15	1400(400)	0.2	13.1	110(30)	120(40)	1.2	4.3
16	2400(500)	0.1	13.1	170(40)	---		---
17	2200(500)	0.1	12.7	140(30)	150(40)	1.2	5.5
18	1600(200)	0.0	13.2	130(20)	---		---
19	1300(200)	0.0	12.8	110(20)	130(20)	1.4	5.7
20	2200(200)	0.0	13.0	160(10)	---		---
21	2000(200)	0.0	12.7	140(10)	150(20)	1.2	8.3

* See footnotes Table 4.7 and 4.9A. Standard deviations are given in parentheses.

TABLE 4.9C

COMPARISON OF AMBIENT AIR AND SOLAR HEATED AIR DRYING SYSTEMS FOR WHEAT AT WINNIPEG* -- PREDICTED DRYING COSTS

Test No.	Electricity Cost, $/t	Over-drying Cost, $/t	Drying Equipment Depreciation, $/t	Collector Depreciation, $/t	Total Drying Cost, $/t	Cost per unit Moisture, $/(t.%m.c.)
1	0.90	1.80	9.50	--	12.10	1.80
2	0.58	3.20	8.00	0.91	12.70	1.60
3	1.70	1.90	8.40	--	11.90	1.80
4	0.65	2.00	6.70	0.66	10.00	1.50
5	0.82	1.80	3.00	--	5.60	2.10
6	0.56	2.50	2.50	0.10	5.70	1.80
7	0.47	3.20	2.40	0.18	6.20	1.70
8	1.40	1.80	6.00	--	9.20	1.40
9	1.00	2.20	5.80	0.50	9.50	1.40
10	0.72	2.50	5.20	0.83	9.30	1.30
11	2.90	1.80	15.80	--	20.50	1.90
12	1.90	2.30	13.90	2.50	20.60	1.90
13	1.20	2.70	13.30	4.50	21.70	1.90
14	1.40	1.40	5.50	--	8.30	1.30
15	1.10	2.10	5.20	0.41	8.90	1.30
16	1.70	2.10	4.90	--	8.70	1.30
17	1.40	2.70	4.60	0.33	9.00	1.20
18	1.30	1.90	5.20	--	8.40	1.20
19	1.10	2.50	5.20	0.41	9.20	1.30
20	1.60	2.20	4.90	--	8.70	1.30
21	1.40	2.60	4.90	0.37	9.30	1.30

* See footnotes Table 4.7 and 4.9A

TABLE 4.9D

COMPARISON OF AMBIENT AIR AND SOLAR HEATED AIR DRYING SYSTEMS FOR WHEAT AT WINNIPEG*--PREDICTED RELATIVE COSTS

Test No.	Electrical Energy Usage, MJ/kg_w	Solar Energy Cost, ¢/MJ	Cost per Unit of Electrical Energy Saved, ¢/MJ			Allowable Collector Cost, $\$/m^2$
			Solar	Electrical	Propane	
1	1.1					
2	0.6	0.81	2.8	3.5	1.8	2.00
3	2.0					
4	0.8	0.67	0.7	1.0	0.5	19.50
5	2.5					
6	1.5	0.13	0.4	3.2	1.6	1.00
7	1.1	0.14	0.5	3.8	1.9	nil
8	1.6					
9	1.2	0.42	1.4	3.4	1.7	1.60
10	0.8	0.50	1.3	2.5	1.3	4.60
11	2.1					
12	1.3	1.2	2.4	2.0	1.0	4.80
13	0.8	1.6	2.7	1.7	0.9	3.70
14	1.7					
15	1.3	0.35	1.5	4.3	2.2	nil
16	2.0					
17	1.6	0.22	1.2	5.5	2.8	nil
18	1.5					
19	1.2	0.32	1.8	5.7	2.9	nil
20	1.8					
21	1.5	0.25	2.1	8.3	4.2	nil

* See footnotes Table 4.7 and 4.9A

TABLE 4.9E

COMPARISON OF AMBIENT AIR AND SOLAR HEATED AIR DRYING SYSTEMS FOR WHEAT AT WINNIPEG* -- SIMULATION RESULTS FOR AVERAGE DRYING

Test No.	Fan Time to Avg. Dry, h	Energy Input to Fan, MJ/t	Electricity Cost, $/t	Total Drying Cost, $/t	Cost per Unit Moisture, $/(t.%m.c.)	Allowable Collector Cost, $/m^2
1	270(150)	60(40)	0.64	10.10	1.80	
2	290(120)	50(20)	0.51	9.40	1.70	8.80
3	500(320)	100(60)	0.96	9.30	1.70	
4	430(70)	50(10)	0.54	7.90	1.40	15.40
5	1700(800)	50(20)	0.47	3.50	2.30	
6	1400(600)	30(10)	0.28	2.90	1.90	33.50
7	1000(500)	20(10)	0.18	2.70	1.80	25.60
8	930(570)	100(60)	0.96	7.00	1.30	
9	760(430)	70(40)	0.72	7.00	1.30	5.00
10	790(390)	60(30)	0.62	6.70	1.20	6.90
11	390(490)	230(290)	2.30	18.10	1.90	
12	210(50)	100(20)	0.98	17.40	1.80	6.50
13	180(20)	80(10)	0.78	18.60	2.00	4.50
14	1200(400)	110(40)	1.10	6.60	1.20	
15	1100(300)	90(30)	0.86	6.50	1.20	6.00
16	1900(600)	140(50)	1.40	6.30	1.10	
17	1700(500)	110(30)	1.10	6.10	1.10	8.60
18	1300(200)	110(20)	1.10	6.30	1.10	
19	1200(200)	90(20)	0.91	6.60	1.20	1.70
20	2000(200)	140(10)	1.40	6.30	1.20	
21	1600(300)	120(20)	1.20	6.50	1.20	3.00

* See footnotes Table 4.7 and 4.9A.

TABLE 4.10A

COMPARISON OF AMBIENT AIR AND SOLAR HEATED AIR DRYING SYSTEMS FOR CORN AT WINNIPEG* -- PARAMETERS USED

Test No.	Harvest Date	Earliest Fall Stop	Moisture Content, %	S. C., °C	Airflow Rate, $m^3/(min \cdot t)$	Collector Area, m^2/t	Fan Power, W/m^2 floor
1	Sept. 15	Nov. 1	24	0	2.4	--	115
2				5	2.3	0.95	113
3	Oct. 1	Nov. 1	24	0	2.0	--	106
4				5	1.9	0.78	104
5	Oct. 15	Dec. 1	20	0	0.7	--	66
6				5	0.6	0.25	61
7				10	0.55	0.45	59
8			24	0	1.6	--	96
9				5	1.5	0.62	94
10				10	1.4	1.16	91
11			28	0	4.8	--	154
12				5	5.4	2.23	162
13				10	5.2	4.30	160
14	Nov. 1	Dec. 1	24	0	1.7	--	99
15				5	1.7	0.70	99
16	Nov. 15	Dec. 1	24	0	1.7	--	99
17				5	1.5	0.62	94

* Based upon simulated drying results averaged over the years 1961 to 1970. See footnotes Table 4.7

TABLE 4.10B

COMPARISON OF AMBIENT AIR AND SOLAR HEATED AIR DRYING SYSTEMS FOR CORN AT WINNIPEG[a] -- SIMULATED DRYING RESULTS

Test No.	Fan Time to Dry,[b] h	Probability of Fall Finish	Final Avg. M.C., %	Energy Input to fan, MJ/t	Solar Energy Collected, MJ/t	Avg. Temp. Rise, °C	Solar Input / Energy Saved
1	1000(600)	0.7	13.7	190(120)	---		---
2	580(130)	1.0	13.0	110(20)	130(10)	1.4	1.5
3	1200(500)	0.4	13.5	200(80)	---		---
4	1000(400)	0.5	13.2	160(60)	150(60)	1.1	4.1
5	2500(200)	0.0	12.9	140(10)	---		---
6	2400(200)	0.0	11.8	110(10)	150(20)	1.5	6.1
7	2300(200)	0.0	10.9	100(10)	250(30)	2.8	6.6
8	1900(200)	0.0	13.5	250(20)	---		---
9	1700(300)	0.1	12.4	210(40)	200(50)	1.1	5.1
10	1700(300)	0.1	11.9	180(30)	330(80)	2.1	5.3
11	1100(600)	0.4	13.7	430(230)	---		---
12	930(590)	0.5	12.8	400(250)	290(150)	0.9	8.2
13	690(490)	0.7	12.8	280(200)	410(230)	1.8	2.7
14	1600(100)	0.0	13.2	220(20)	---		---
15	1500(100)	0.0	12.3	200(10)	210(30)	1.2	9.9
16	1700(100)	0.0	12.8	230(20)	---		---
17	1600(100)	0.0	11.8	200(10)	220(30)	1.3	6.2

[a] See footnotes Table 4.7 and 4.10A. Standard deviations are given in parentheses.

[b] Time required to dry the wettest layer to 15.5% m.c.

TABLE 4.10C

COMPARISON OF AMBIENT AIR AND SOLAR HEATED AIR DRYING SYSTEMS FOR CORN AT WINNIPEG* -- PREDICTED DRYING COSTS

Test No.	Electricity Cost, $/t	Over-drying Cost, $/t	Drying Equipment Depreciation, $/t	Collector Depreciation, $/t	Total Drying Cost, $/t	Cost per unit Moisture, $/(t.%m.c.)
1	1.90	2.80	5.70	--	10.40	1.00
2	1.10	3.80	5.50	0.95	11.30	1.00
3	2.00	3.00	5.10	--	10.10	1.00
4	1.60	3.40	5.00	0.78	10.70	1.00
5	1.40	3.90	2.90	--	8.10	1.10
6	1.10	5.40	2.60	0.25	9.40	1.10
7	1.00	6.60	2.50	0.45	10.60	1.20
8	2.50	3.00	4.50	--	10.00	0.90
9	2.10	4.60	4.40	0.62	11.70	1.00
10	1.80	5.30	4.20	1.20	12.50	1.00
11	4.30	2.70	8.50	--	15.50	1.10
12	4.00	3.90	9.00	2.20	19.20	1.30
13	2.80	3.90	8.80	4.30	19.90	1.30
14	2.20	3.50	4.70	--	10.30	1.00
15	2.00	4.70	4.70	0.70	12.10	1.00
16	2.30	3.90	4.70	--	10.90	1.00
17	2.00	5.40	4.40	0.62	12.30	1.00

* See footnotes Table 4.7 and 4.10A

TABLE 4.10D

COMPARISON OF AMBIENT AIR AND SOLAR HEATED AIR DRYING SYSTEMS FOR CORN AT WINNIPEG*--PREDICTED RELATIVE COSTS

Test No.	Electrical Energy Usage, MJ/kg_w	Solar Energy Cost, ¢/MJ	Cost per Unit of Electrical Energy Saved, ¢/MJ			Allowable Collector Cost, $\$/m^2$
			Solar	Electrical	Propane	
1	1.4					
2	0.7	0.73	1.1	1.5	0.8	nil
3	1.4					
4	1.1	0.51	2.1	4.1	2.1	1.10
5	1.6					
6	1.1	0.17	1.0	6.1	3.1	nil
7	0.9	0.18	1.2	6.6	3.3	nil
8	1.8					
9	1.4	0.31	1.6	5.1	2.6	nil
10	1.2	0.35	1.9	5.3	2.7	nil
11	2.2					
12	1.9	0.78	6.4	8.2	4.1	nil
13	1.3	1.06	2.9	2.7	1.4	nil
14	1.6					
15	1.3	0.34	3.4	9.9	5.0	nil
16	1.6					
17	1.2	0.29	1.8	6.2	3.1	nil

* See footnotes Table 4.7 and 4.10A

TABLE 4.10E

COMPARISON OF AMBIENT AIR AND SOLAR HEATED AIR DRYING SYSTEMS FOR

FOR CORN AT WINNIPEG -- SIMULATION RESULTS FOR AVERAGE DRYING*

Test No.	Fan Time to Avg. Dry, h	Energy Input to Fan, MJ/t	Electricity Cost, $/t	Total Drying Cost, $/t	Cost per Unit Moisture, $/(t.%m.c.)	Allowable Collector Cost, $/m^2
1	700(460)	130(90)	1.30	7.00	0.80	
2	530(120)	100(20)	0.97	7.50	0.90	2.60
3	970(390)	150(60)	1.50	6.70	0.80	
4	810(310)	120(50)	1.20	7.00	0.80	3.00
5	2200(300)	120(10)	1.20	4.10	0.90	
6	2100(300)	100(10)	1.00	3.90	0.90	8.60
7	2100(200)	90(10)	0.92	3.90	0.90	7.10
8	1700(300)	210(40)	2.10	6.60	0.80	
9	1500(300)	180(30)	1.80	6.80	0.80	3.80
10	1400(300)	160(30)	1.60	6.90	0.80	3.80
11	1100(600)	410(220)	4.10	12.50	1.00	
12	680(470)	290(200)	2.90	14.20	1.10	1.30
13	570(400)	240(170)	2.40	15.50	1.20	1.50
14	1500(100)	210(20)	2.10	6.70	0.80	
15	1400(100)	190(20)	1.90	7.30	0.90	1.20
16	1600(100)	220(20)	2.20	6.90	0.80	
17	1600(100)	190(10)	1.90	6.90	0.80	5.00

* Drying until the bin average moisture content is 15.5% or less, and the top is 18% or less. See footnotes Table 4.7 and 4.10A.

TABLE 4.11A

COMPARISON OF AMBIENT AIR AND SOLAR HEATED AIR DRYING SYSTEMS FOR CORN AT LONDON* -- PARAMETERS USED

Test No.	Harvest Date	Earliest Fall Stop	Moisture Content, %	S. C., °C	Airflow Rate, $m^3/(min \cdot t)$	Collector Area, m^2/t	Fan Power, W/m^2 floor
1	Sept. 15	Nov. 1	24	0	6.2	--	172
2				5	5.5	2.30	164
3	Oct. 1	Nov. 1	24	0	5.0	--	157
4				5	3.8	1.60	140
5	Oct. 15	Dec. 1	20	0	1.0	--	78
6				5	0.8	0.33	70
7				10	0.8	0.66	70
8			24	0	5.5	--	164
9				5	3.8	1.60	140
10				10	3.4	2.80	133
11			28	0	18.0	--	267
12				5	9.5	3.90	206
13				10	8.2	6.80	194
14	Nov. 1	Dec. 1	24	0	2.8	--	123
15				5	2.6	1.10	119
16	Nov. 15	Dec. 1	24	0	2.8	--	123
17				5	2.6	1.10	119

* Based upon simulated drying results averaged over the years 1962 to 1973. See footnotes Table 4.7

TABLE 4.11B

COMPARISON OF AMBIENT AIR AND SOLAR HEATED AIR DRYING SYSTEMS FOR CORN AT LONDON[a] -- SIMULATED DRYING RESULTS

Test No.	Fan Time to Dry,[b] h	Probability of Fall Finish	Final Avg. M.C., %	Energy Input to Fan, MJ/t	Solar Energy Collected, MJ/t	Avg. Temp. Rise, °C	Solar Input / Energy Saved
1	390(190)	1.0	14.8	190(90)	---		---
2	240(40)	1.0	14.2	110(20)	150(20)	1.5	1.7
3	840(690)	0.7	14.3	330(270)	---		---
4	580(440)	0.9	13.7	170(130)	170(80)	1.2	1.1
5	2300(200)	0.0	13.9	180(10)	---		---
6	2200(100)	0.0	13.0	140(10)	150(10)	1.2	3.5
7	1900(200)	0.0	12.8	120(10)	230(40)	2.2	3.7
8	1200(600)	0.3	14.0	520(250)	---		---
9	970(520)	0.6	13.6	290(160)	230(100)	0.9	1.0
10	870(530)	0.6	13.3	240(140)	360(180)	1.9	1.3
11	550(560)	0.8	14.1	780(800)	---		---
12	610(520)	0.8	14.0	460(390)	340(200)	1.0	1.0
13	410(350)	0.9	13.6	270(230)	430(220)	2.0	0.8
14	1400(200)	0.0	14.0	310(30)	---		---
15	1300(100)	0.0	13.0	270(30)	210(30)	0.9	5.3
16	1300(100)	0.0	14.0	290(20)	---		---
17	1200(100)	0.0	13.0	250(20)	210(30)	0.9	5.4

[a] See footnotes Table 4.7 and 4.11A. Standard deviations are given in parentheses.

[b] Time required to dry the wettest layer to 15.5% m.c.

TABLE 4.11C

COMPARISON OF AMBIENT AIR AND SOLAR HEATED AIR DRYING SYSTEMS FOR CORN AT LONDON* -- PREDICTED DRYING COSTS

Test No.	Electricity Cost, $/t	Over-drying Cost, $/t	Drying Equipment Depreciation, $/t	Collector Depreciation, $/t	Total Drying Cost, $/t	Cost per unit Moisture, $/(t.%m.c.)
1	1.90	1.10	9.80	--	12.80	1.40
2	1.10	2.00	9.10	2.30	14.40	1.50
3	3.30	1.90	8.60	--	13.80	1.40
4	1.70	2.70	7.40	1.60	13.40	1.30
5	1.80	2.30	3.50	--	7.60	1.20
6	1.40	3.70	3.10	0.33	8.50	1.20
7	1.20	4.00	3.10	0.66	8.90	1.20
8	5.20	2.20	9.10	--	16.50	1.70
9	2.90	2.80	7.40	1.60	14.60	1.40
10	2.40	3.30	6.90	2.80	15.40	1.40
11	7.80	2.10	18.30	--	28.30	2.00
12	4.60	2.30	12.50	3.90	23.30	1.70
13	2.70	2.90	11.50	6.80	23.80	1.70
14	3.10	2.20	6.20	--	11.50	1.20
15	2.70	3.70	5.90	1.10	13.40	1.20
16	2.90	2.20	6.20	--	11.40	1.10
17	2.50	3.80	5.90	1.10	13.30	1.20

* See footnotes Table 4.7 and 4.11A

TABLE 4.11D

COMPARISON OF AMBIENT AIR AND SOLAR HEATED AIR DRYING SYSTEMS FOR CORN AT LONDON* -- PREDICTED RELATIVE COSTS

Test No.	Electrical Energy Usage, MJ/kg_w	Solar Energy Cost, ¢/MJ	Cost per Unit of Electrical Energy Saved, ¢/MJ			Allowable Collector Cost, $\$/m^2$
			Solar	Electrical	Propane	
1	1.6					
2	0.8	1.6	2.6	1.7	0.9	1.50
3	2.6					
4	1.3	0.91	1.0	1.1	0.6	6.40
5	2.4					
6	1.6	0.22	0.8	3.5	1.8	nil
7	1.3	0.29	1.1	3.7	1.9	nil
8	3.9					
9	2.1	0.69	0.7	1.0	0.5	11.00
10	1.7	0.78	1.0	1.3	0.7	7.00
11	4.1					
12	2.4	1.2	1.2	1.0	0.5	11.40
13	1.3	1.6	1.3	0.8	0.4	8.30
14	2.4					
15	1.9	0.50	2.7	5.3	2.7	nil
16	2.2					
17	1.8	0.52	2.8	5.4	2.7	nil

* See footnotes Table 4.7 and 4.11A

TABLE 4.11E

COMPARISON OF AMBIENT AIR AND SOLAR HEATED AIR DRYING SYSTEMS FOR

FOR CORN AT LONDON* -- SIMULATION RESULTS FOR AVERAGE DRYING

Test No.	Fan Time to Avg. Dry, h	Energy Input to Fan, MJ/t	Electricity Cost, $/t	Total Drying Cost, $/t	Cost per Unit Moisture, $/(t.%m.c)	Allowable Collector Cost, $/m^2
1	300(120)	150(60)	1.50	11.30	1.30	
2	210(30)	90(10)	0.93	12.30	1.40	2.60
3	530(440)	210(180)	2.10	10.70	1.30	
4	370(50)	110(10)	1.10	10.10	1.20	7.10
5	1900(200)	150(10)	1.50	5.00	1.10	
6	1600(200)	100(10)	1.00	4.50	1.00	12.70
7	1400(200)	90(20)	0.89	4.60	1.00	7.50
8	880(540)	380(240)	3.80	13.00	1.50	
9	790(480)	240(140)	2.40	11.30	1.30	10.30
10	510(300)	140(80)	1.40	11.10	1.30	8.30
11	390(440)	550(620)	5.50	23.80	1.90	
12	370(350)	280(260)	2.80	19.20	1.50	10.90
13	250(60)	160(40)	1.60	19.90	1.60	7.90
14	1200(200)	280(40)	2.80	9.00	1.10	
15	1100(200)	230(40)	2.30	9.30	1.10	3.30
16	1200(100)	260(20)	2.60	8.80	1.00	
17	1100(100)	230(20)	2.30	9.30	1.10	2.90

* See footnotes Table 4.7, 4.11A and 4.10E.

change the capital costs, and changing the grain depth or fan size would change the electricity costs. In this analysis, using a fixed amount of grain would have resulted in unreasonably high power requirements at the higher airflow rates. Otherwise an unreasonably small amount of grain would have had to be used. Using the grain depths given in Fig. 3.1 gave a better basis of comparison. It also reflected the fact that more grain can be dried by a system with a lower airflow rate.

Using the fan size and the hours of fan operation (Tables 4.7B to 4.11B), the electrical energy required to dry the grain was calculated. Whenever solar heating was added the energy requirements were reduced. In most cases, more energy was collected as solar radiation than was saved in electricity to run the fan. Earlier harvest dates appeared to give the most energy reduction per unit of solar energy collected (Tables 4.7B to 4.11B). The average air temperature rise provided by the solar energy was also greatest at the earliest harvest dates. Using a solar collector coefficient of 10°C instead of 5°C resulted in nearly doubling the average temperature rise.

The costs for low-temperature drying of grain included electricity, overdrying and depreciation costs. The electricity cost was calculated from the energy input to the fan, assuming an electrical cost of \$0.01/MJ (\$0.036/kWh). In nearly all cases the electricity cost was the smallest of the three.

Overdrying occurred as a result of drying the grain more than was required, i.e. below 14.5% for wheat or 15.5% for corn. Removal of moisture below this level would result in less mass for the same amount of dry matter. Because grain is sold by mass, less money would be received. The overdrying cost was calculated from the average final moisture content of the grain and the grain price, assumed to be \$130/t. For wheat, overdrying cost =

$$[(14.5 - M_f) \times \$130/t] \times [no.\ tonnes/(100 - M_f)].$$

For corn, overdrying cost =

$$[(15.5 - M_f) \times \$130/t] \times [no.\ tonnes/(100 - M_f)],$$

where M_f = final average moisture content, % wet mass basis. In almost all cases solar drying resulted in more overdrying. The increased cost of overdrying more than offset the decrease in energy costs (Tables 4.7C to 4.11C).

The third cost, depreciation, was divided into two parts, depreciation of the drying equipment and depreciation of the solar collector. The drying equipment included the drying floor, substructure, transition unit and fan. It was assumed that the bin structure was already available for use as grain storage and thus would not be included in the drying costs. In some cases the grain depth was less than bin capacity so full use could not be made of the bin for storage.

For a 5.7 m diameter bin, the drying equipment was assumed to cost \$2000. Assuming a 10 year economic life, 10% interest rate and zero salvage value, the cost was \$325/a. Solar drying usually required smaller airflow rates. Therefore, more grain could be dried in the bin, resulting in lower depreciation costs per unit of grain.

The solar collector costs were calculated assuming a rate of \$1.00/($m^2 \cdot a$). Collector costs were lowest for the lowest initial moisture content grain because of the small collector sizes required. The yearly cost of \$1.00/m^2 was taken from an analysis by Schoneau and Besant (1976). They calculated total yearly costs to be \$1.04/m^2, \$0.89/m^2 and \$1.49/m^2 for bare plate, covered plate and suspended plate collectors respectively. These were considered to be optimistic costs, as most other studies used a higher cost. The effect of assuming different costs is discussed below.

The total drying cost, which included electricity, overdrying and depreciation costs, was calculated for each set of conditions (Tables 4.7C to 4.11C). Solar drying was economical in only a few cases at any of the locations. Total costs were lowest for the lowest moisture content grain. On a cost per unit moisture basis, however, the lowest moisture content grain was in many cases more costly. For all locations, the total cost per unit of moisture removed was within \$0.90 to \$2.10/(t·%m.c.).

The energy efficiency of various dryers can be compared on the basis of energy usage per unit of water removed. This analysis showed a range of 0.4 to 4.1 MJ/kg_w, with an average of 1.4 MJ/kg_w (Tables 4.7D to 4.11D). Solar drying required 1.1 MJ/kg_w, on the average, compared to 1.7 MJ/kg_w for ambient air drying. A survey of several high-temperature dryers by Friesen (1978) showed a range of fuel usage of 2.6 to 6.5 MJ/kg_w, with an average of 4.0 MJ/kg_w. Adding the energy used by the fan and other motors would increase these amounts significantly. Low-temperature drying therefore appears to be at least three times as efficient as the high-temperature method.

These values are comparable to values given by Keener (1977). For in-bin drying of corn from 25 to 15% moisture content in Ohio, the drying energy varied from 1.42 to 4.41 MJ/kg_w. Grain depths were 0.6 to 1.5 m. The energy usage of high-temperature continuous flow dryers was given to be about 5.8 MJ/kg_w. Deep bed drying was stated to be less efficient, however. For a 4.6 m deep bed of corn, the total energy cost would be over 9.3 MJ/kg_w because of the high fan power required. This is why the grain depth was made dependent on the airflow rate in this study.

Low-temperature drying costs also compared favorably with those for high-temperature drying. At a rate of \$10/t (27¢/bu) for high-temperature drying, low-temperature wheat drying was less expensive in 47 out of 63 cases. Generally the cases most favorable to low-temperature drying were those in which the airflow rate was below about 1.5 $m^3/(min \cdot t)$. For corn, low-temperature drying costs were less than \$10/t in only 5 cases out of 34. When drying was stopped when the average moisture content was dry, low-temperature drying costs were lower. In 53 out of 63 cases for wheat, and 21 out of 34 cases for corn, low-temperature drying costs were less than \$10/t.

The results of this study may be applied to other forms of supplemental heat, such as that provided by an electrical resistance heater or a propane burner. Morey et al. (1977) found that the effect of solar heat was essentially the same as for other types of heat. The only requirement was that the average temperature rise be the same. Thus the economics of using electricity or propane in place of solar energy could be investigated using the same simulation results.

Cost per unit of heat for electricity or propane is a known and constant value, determined by the supplier or regulating agency. An electrical cost of \$0.01/MJ (\$0.036/kWh) and a propane cost of \$0.005/MJ were assumed. The propane cost included an efficiency factor because not all of the heat was usable. For solar energy the cost per unit of heat was found by dividing the amortized collector cost by the average amount of energy collected per year. This resulted in a different solar cost for each case (Tables 4.7D to 4.11D).

On the basis of these costs, solar energy was the cheapest form of supplemental heat in 63% of the cases. It was second cheapest in 23% of the cases. The cases favoring solar energy were those in which the lowest moisture content grain or a later harvest date were used.

Addition of supplemental heat to low-temperature dryers increases the drying rate. This reduces the hours of fan operation, which saves electrical energy. Usually more energy is added as heat than is saved as electricity. There are two factors which determine the total energy cost when supplemental heat is used, (1) the amount of electrical energy saved per unit of heat added and (2) the relative costs of electricity and supplemental heat. If the cost for heat is low enough, the total energy cost will be reduced when the heat is added. These two factors can be combined into one number, called the final cost of the supplemental heat. The final cost is defined as the cost of supplemental heat per unit of electrical energy saved. If this final cost is less than the cost of electricity, the total energy cost will be reduced.

For example, suppose the electrical energy usage is decreased by 0.5 units for each unit of heat added. The final cost of the heat thus is twice the original cost. If the supplied cost of the heat is 0.5¢/MJ, the final cost is 2 x 0.5 = 1.0¢/MJ. If the cost of electricity is 1.0¢/MJ or more, the total energy cost will be decreased by adding the heat.

The ratio of heat added to energy saved was calculated for each case in which solar energy was added (Tables 4.7B to 4.11B). The final cost for each type of supplemental heat was found by multiplying this ratio by the cost of the heat as given above (Tables 4.7D to 4.11D). Using the above criteria, supplemental heat was economical in only 36% of all cases. In 40% of those cases solar energy was the cheapest form of heat. The cases which favored solar energy were those in which the lowest moisture content grain was used. This was because of the relatively small collector sizes required, which resulted in low cost. Also, more energy was collected over the long drying period. Thus there was less cost per unit of energy collected.

Another way of investigating the economics of solar drying would be to calculate the allowable first cost of the solar collectors. This is the amount of money available for purchase and installation of the collectors. It is based upon the annual savings in electricity, overdrying and depreciation costs of solar over ambient air drying. In this study, the savings were divided by 0.20 to find the allowable first cost. This was based on the assumption that the annual cost of the collectors was 20% of the first cost. The capital recovery factor for a collector of 10 year life at 10% interest is 16.3% of the first cost. This leaves 3.7% for annual maintenance costs.

Schoenau and Besant (1976) gave estimated material costs for bare plate, covered plate and suspended plate collectors as \$5.65, \$2.56 and \$6.60/m^2 respectively. The low cost for the covered plate collector was due to the use of plastics. Other sources gave higher values. If a minimum possible first cost of \$3.00/m^2 is used for comparison, the results show that solar energy would be economical in 25% of the cases (Tables 4.7D to 4.11D). The factors which appear to result in economical solar systems are little or no increase in overdrying, compared to ambient air drying, and lower depreciation costs (Tables 4.7C to 4.11C).

A method of minimizing the overdrying cost would be to stop the drying when the average moisture content of the grain is dry. When this was done, energy costs were reduced due to shorter operating times. The elimination of overdrying costs reduced the total drying cost, also (Tables 4.7E to 4.11E). On the average, the total drying cost was reduced by 31% by stopping drying earlier. It therefore appears that stopping drying early and mixing the grain would save money as well as energy. For any particular case the savings available to pay for the cost of mixing the grain can be found by the difference between the total costs for the two methods.

This procedure was advantageous for solar drying, because the drying penalty was eliminated. Using a minimum possible first cost of $3.00/m^2 for the collectors, solar drying would be economical in 71% of the cases. As in previous comparisons, the best cases for solar drying were those in which low moisture content grain was used.

The primary disadvantage of this method of drying is that careful management is required. Accurate determination of the average moisture content of the grain and thorough mixing of the grain at the end of drying are both essential.

All of the above comparisons have been based upon the assumption of an arbitrary, fixed cost for each input. Costs are rarely fixed, however. It would be useful, therefore, to determine the effect that different costs would have on the final results. In each case the total drying cost depends upon the costs of electricity, equipment, collectors and grain. For any given case a revised total drying cost can be calculated as follows:

$$TDC_r = E\left(\frac{E_r}{\$0.01}\right) + OD\left(\frac{G_r}{\$130}\right) + Dep\left(\frac{AC_r}{\$325}\right)\left(\frac{5.7}{D_r}\right)^2 + (C_o \times C_{A_r})\left(\frac{A_r}{A_o}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4.1)$$

where E, OD, Dep, C_o, and A_o are found from the appropriate table (Tables 4.7 to 4.11). C_{A_r}, the revised annual collector cost, can be found from Table 4.12 or calculated from the initial cost.

As an example, suppose that wheat harvested Sept. 15

with a moisture content of 20% is to be dried at Winnipeg. The electrical rate is \$0.02/MJ, the value of wheat is \$150/t and a 10 m diameter bin is to be used. The amortized drying equipment cost is assumed to be \$600/a. A vertical south-facing collector of 40% efficiency is to be constructed for a cost of \$10/m^2, with an estimated life of 20 years.

From Table 4.12, the annual cost for the collector will be \$1.18/m^2. If an annual repair and maintenance cost of \$0.22/m^2 is added, the cost will be \$1.40/($m^2 \cdot a$). The area of the collector must be multiplied by 1.25 to offset the decreased efficiency. On the other hand, the area can be decreased because of the change in orientation. The amount of change can be approximated in the following manner. As there is a 70 to 90% probability of finishing drying in the fall (Table 4.9B), most of the drying will occur between Sept. 15 and Nov. 1. From Fig. 2.5, approximately 15% more radiation is received on a vertical than a horizontal surface during this time. Thus, a 15% smaller area could be used. In this example, the total effect due to changes in orientation and efficiency would be to mulitply the area by 1.09.

Using equation 4.1 and Table 4.9C, test numbers 8, 9 and 10, the total drying costs for the three cases are:

TABLE 4.12

ANNUAL COLLECTOR COSTS AS A FUNCTION OF INITIAL COLLECTOR COSTS AND ECONOMIC LIFE*

Collector Cost, $\$/m^2$	ANNUAL COLLECTOR COSTS, $\$/m^2$						
	Economic Life, Years						
	1	2	3	5	10	15	20
5.00	5.50	2.88	2.01	1.32	0.81	0.66	0.59
7.50	8.25	4.32	3.02	1.98	1.22	0.99	0.88
10.00	11.00	5.76	4.02	2.64	1.63	1.32	1.18
15.00	16.50	8.64	6.03	3.96	2.44	1.97	1.76
20.00	22.00	11.52	8.04	5.28	3.25	2.63	2.35
30.00	33.00	17.29	12.06	7.91	4.88	3.95	3.53
40.00	44.00	23.05	16.08	10.55	6.51	5.26	4.70

*Assuming a 10% interest rate, zero salvage value, and no allowance for repairs.

(1) $$TDC_r = \$1.40\left(\frac{\$0.02}{\$0.01}\right) + \$1.80\left(\frac{\$150}{\$130}\right) + \$6.00\left(\frac{\$600}{\$325}\right)\left(\frac{5.7}{10}\right)^2 = \$8.50/t$$

(2) $$TDC_r = \$1.00\left(\frac{0.02}{0.01}\right) + \$2.20\left(\frac{150}{130}\right) + \$5.80\left(\frac{600}{325}\right)\left(\frac{5.7}{10}\right)^2 + (\$0.50 \times \$1.40 \times 1.09) = \$8.80/t$$

(3) $$TDC_r = \$0.72\left(\frac{0.02}{0.01}\right) + \$2.50\left(\frac{150}{130}\right) + \$5.20\left(\frac{600}{325}\right)\left(\frac{5.7}{10}\right)^2 + (\$0.83 \times \$1.40 \times 1.09) = \$8.70/t$$

In this example the solar drying remains more expensive, even though the electrical rate was doubled and the other costs increased only slightly. Due to the larger bin size, the equipment cost per unit of grain actually decreased. This is why the total cost decreased.

For the same example, suppose that all costs except electricity increase by 100% over those in the tables. Electricity costs are allowed to increase sufficiently to cause a switch to solar energy. The required electrical rate can be found by equating the total drying costs for ambient air drying and solar drying. Thus for SC = 5°C:

$$\$1.40\left(\frac{E_r}{\$0.01}\right) + (\$1.80 \times 2) + (\$6.00 \times 2) =$$

$$\$1.00\left(\frac{E_r}{\$0.01}\right) + (\$2.20 \times 2) + (\$5.80 \times 2) + (\$0.50 \times 2)$$

E_r = \$0.035/MJ, a 250% increase.

For SC = 10°C:

$$\$1.40\left(\frac{E_r}{\$0.01}\right) + \$15.60 = \$0.72\left(\frac{E_r}{\$0.01}\right) + (\$2.50 \times 2) +$$

$$(\$5.20 \times 2) + (\$0.83 \times 2)$$

E_r = \$0.021/MJ, a 110% increase.

It can be seen by this example that the effect of various price increases is different for each case. The final result is dependent upon the relative increase or decrease of each cost.

If all costs, including electricity, increased by 100%, the total drying costs would also increase by 100%, by equation 4.1. Thus the relative costs for solar and ambient air drying would remain the same throughout. Electrical costs must continue to increase more than other costs to make solar drying economical.

A revised estimate for the allowable first cost of the collector can be calculated as follows:

$$AFC_r = [(E_A - E_S) \times (\frac{E_r}{\$0.01}) + (OD_A - OD_S)(\frac{G_r}{\$130}) + (Dep_A - Dep_S)(\frac{AC_r}{\$325})(\frac{5.7}{D_r})^2] \div (A \times F_r)$$

where E_A, E_S, OD_A, OD_S, Dep_A and Dep_S are taken from the appropriate table (Tables 4.7 to 4.11). F_r, the revised annual cost factor, depends upon the chosen economic life, interest rate, salvage value, maintenance costs, etc.

For example, suppose the value of wheat increased by 20% while the cost of the other inputs increased by 100%. The allowable first cost of the collectors for the previous example would be:

(1) SC = 5°C

$$[(\$1.40 - \$1.00) \times 2 + (\$1.80 - \$2.20) \times 1.2 + (\$6.00 - \$5.80) \times 2] \div (0.50 \times 0.2)$$

$= \underline{\$7.20/m^2}$, assuming an annual cost factor of 0.20. This is a 350% increase.

(2) SC = 10°C

$[(\$1.40 - \$0.72) \times 2 + (\$1.80 - \$2.50) \times 1.2 +$

$(\$6.00 - \$5.20) \times 2] \div (0.83 \times 0.2)$

$= \underline{\$12.80/m^2}$, a 180% increase.

The results of this study are in agreement with the conclusions of Bakker-Arkema et al. (1978). They drew the following conclusions, based on research thus far conducted on in-bin solar corn drying:

1) solar drying and natural air drying are equally feasible on a technical basis when practised under similar drying conditions,
2) solar drying results in major energy savings when compared to high-temperature drying,
3) solar drying results in small energy savings when compared to natural air drying,
4) for a given location the airflow requirements for in-bin solar drying are determined by 1 or 2 out of 10 years of unfavorable weather conditions.

In some cases, particularly for early harvest dates, it may be possible to use the in-bin dryer as a batch dryer. In that case, more grain could be dried with the same system, thereby reducing the unit cost of drying.

Another management approach which may be used for reducing the overdrying problem, is to stir the grain as it is being dried. This is accomplished by a number of vertical augers in the bin which move about the bin while lifting the lower moisture content grain up from the bottom. This allows grain of higher moisture content to come into direct contact with the incoming air, thus reducing the vertical moisture gradient. The stirrers also break up areas where wet grain may be packed or where trash has accumulated (Frus, 1968). The stirring of the grain reduces the resistance of the grain mass to airflow. This results in increased airflow through the grain. As a result of these effects, a greater bed depth or a lower airflow rate can be used (Williams et al. 1978). Overdrying costs are eliminated and costs per unit of grain may be reduced as a result. These savings could be applied against the cost of stirring equipment.

V. CONCLUSIONS

A computer model was used to simulate moisture content changes and grain quality deterioration for low-temperature drying systems. The model was used to determine the minimum airflow rates required for drying with unheated air and solar heated air at selected sites in Canada. The model was also used to simulate drying over a number of years at each of the locations. Wheat and corn drying were simulated for different initial moisture contents and different harvest dates. The results indicated the following:

1. Minimum airflow rates are approximately doubled for each 2% increase in initial moisture content of the grain. They are decreased by 50% for each month's delay in harvest. In cases where most of the drying is carried over into the next spring, however, the airflow rate must be increased over this amount.
2. The addition of solar energy reduces the required airflow rate by as much as 50% for a collector coefficient of 5°C. The amount of reduction depends on the harvest date, initial moisture content and location. Generally the greatest reduction occurs where the highest airflow rates are required.
3. The time of fan operation and the average energy requirements are reduced, when solar energy is added, by 10 to 60% for a collector coefficient of 5°C.

4. Addition of solar heat leads to increased overdrying of grain in the bottom layers before the top layer is dry.
5. Across Canada, the required airflow rates and energy requirements increase from the cool, dry regions of Edmonton and Swift Current to the warm, humid regions of Winnipeg and London.
6. Energy requirements vary considerably from year to year, due to variations in weather. For the year with most adverse weather conditions, the energy requirements may be as much as 10 or more times those in the years having the best weather conditions.
7. The use of higher airflow rates generally results in higher energy consumptions.
8. A solar collector with a coefficient of 5°C provides an average temperature increase of 1 to 2°C at all of the locations.
9. At present electricity and grain prices, solar grain drying is not economically feasible in most circumstances.
10. Overdrying costs are a major factor in determining the economic feasibility of solar grain drying.
11. If overdrying costs are removed, solar drying is economical in approximately 60% of the cases on a total cost basis.
12. Total drying costs are lowest for lowest initial

moisture content grain.

13. Drying until the bin average moisture content is dry, rather than drying until the top layer is dry, results in both less energy usage and less total cost.

14. Considering energy and solar collector costs alone, solar energy is the cheapest form of supplemental heat in about 60% of the cases.

15. Considering energy and solar collector costs alone, conditions are most favorable for solar drying of low initial moisture content grain.

16. High airflow rates are required to successfully dry grain at initial moisture contents above 22 to 24% for wheat, and 24 to 26% for corn. This leads to large power and energy requirements for the fan or significant reductions in grain depth. Low-temperature drying is therefore best suited to drying lower moisture content grain.

17. If the price of electricity continues to increase faster than other prices, solar energy will eventually become economically feasible for grain drying in most cases. If all prices increase at the same rate, however, the economic feasibility of solar grain drying will remain the same as it is at present.

VI. RECOMMENDATIONS FOR FURTHER STUDY

1. A study should be made of various grain growing, harvesting and storage systems, at various locations, to determine the optimum solar drying system for each case.
2. A study should be made of various fan management methods and levels of supplemental heat to determine the most energy efficient methods of drying and cooling grain. These could include continuous fan operation , control by humidistat or thermostat, or combinations of these.
3. Various methods of preserving grain (both dry and tough or damp) should be studied on an energy use basis to determine the most energy efficient methods. These may include airtight storage, addition of chemicals, refrigeration, or other methods, in comparison with aeration and drying.
4. Other methods of solar drying should be studied, with the objective of reducing the effect of overdrying.
5. Alternative energy sources, especially renewable sources, should be investigated for their feasibility in drying grain. For example, methods of utilizing excess plant material could be investigated.
6. The basic properties of grains grown in Canada should be determined for the entire range of temperatures encountered in Canadian climatic regions, for use in

various simulation models. These properties include specific heat, equilibrium relative humidity, bulk density and thermal conductivity.

7. The deterioration rates or a storability index for Canadian grains should be determined as a function of temperature, moisture content, gaseous environment, physical damage, and other factors, to aid in finding methods of preserving the quality of grain under various conditions.
8. The equilibrium drying model and other models should be compared to actual drying results in Canada, and if necessary, modified, so they can be used for a wider range of applications in simulating drying and aeration, i.e. under any set of conditions.
9. For conditions of zero and low airflow rates, conduction heat transfer should be incorporated into the model.

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APPENDIX A

CALCULATION OF RADIATION ON A TILTED SURFACE

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CALCULATION OF RADIATION ON A TILTED SURFACE

To calculate the average daily radiation on a tilted surface for a particular month, the average daily diffuse and total radiation values for a horizontal surface must be known. While total radiation is measured at many locations on a regular basis, diffuse radiation is not. Thus, in most cases, the diffuse radiation component must be estimated. The usual method of estimation is to use the relationship between H/H_o and H_d/H, where H is the total radiation on a horizontal surface for the location and time in question, H_o is the extraterrestrial radiation on a horizontal surface for the same location and time, and H_d is the diffuse radiation for the same location and time. Ruth and Chant (1976) presented a relationship between H/H_o and H_d/H, for Canadian locations, which is approximated by the following set of equations:

$$H_d/H \simeq 0.97 \qquad (H/H_o<0.12) \quad \ldots \quad (A.1)$$

$$H_d/H = 0.97 - 2.5\ (H/H_o - 0.12)^2 \qquad (0.12<H/H_o<0.44) \quad . \quad (A.2)$$

$$H_d/H = 1.486 - 1.763\ H/H_o \qquad (0.44<H/H_o<0.66) \quad . \quad (A.3)$$

$$H_d/H = 9.0\ (|\ H/H_o - 0.82|)^{2.4} + 0.213 \qquad (H/H_o>0.66) \quad \ldots \quad (A.4)$$

Because the relationship was developed from daily data, it was used to calculate daily diffuse radiation values, H_d, from daily horizontal radiation data, H. The value of H_o was calculated for each day by the following equation (Duffie and Beckman, 1974):

$$H_o = 24/\pi \quad I_{sc} \left([1 + 0.033 \cos (2\pi n/365)][\cos\phi\cos\delta\sin \omega_s + \omega_s \sin\phi\sin\delta]\right) \quad \ldots \quad (A.5)$$

where I_{sc} = solar constant, 4871 kJ/(m^2·h),

n = day of the year,

ϕ = latitude, radians,

δ = declination, radians,

ω_s = sunrise hour angle, radians.

The declination can be found by the equation:

$$\delta = \sin^{-1} [0.3978 \sin[2\pi/365 (n - 80) + 0.0335 (\sin (2\pi n/365) - \sin (160\pi / 365))]] \quad \ldots \quad (A.6)$$

The sunrise hour angle can be found by the equation of Duffie and Beckman (1974):

$$\omega_s = \cos^{-1} (-\tan\phi\tan\delta) \quad \ldots \quad (A.7)$$

From the daily diffuse radiation values, calculated by the above equations for the years 1957 to 1975, monthly average values were obtained. The average daily radiation on a surface tilted toward the equator was then found for each month by the following method, taken from Klein, et al. (1976) (originally presented by Liu and Jordan, 1962).

$$\overline{H}_T = \overline{R}\ \overline{H} \quad \ldots \quad (A.8)$$

where $\overline{H}_T$ = monthly average daily radiation on a tilted surface, kJ/m^2,

$\overline{H}$ = monthly average daily radiation on a horizontal surface, kJ/m^2,

$$\bar{R} = (1 - \bar{D}/\bar{H})R_D + \bar{D}/\bar{H}\ (1 + \cos s)/2 + \rho\ (1 - \cos s)/2 \quad \text{(A.9)}$$

where

$\bar{D}$ = monthly average daily diffuse radiation, kJ/m^2

s = slope of the surface (angle between the horizontal and the surface), radians,

ρ = reflectance of the ground for solar radiation,

$$R_D \simeq \frac{\cos(\phi - s)\cos\delta\sin\omega_s' + \omega_s'\sin(\phi - s)\sin\delta}{\cos\phi\cos\delta\sin\omega_s + \omega_s\sin\phi\sin\delta} \quad \text{(A.10)}$$

where $\omega_s' = \min[\cos^{-1}(-\tan\phi\tan\delta), \cos^{-1}(-\tan(\phi - s)\tan\delta)]$ (A.11)

$$\omega_s = \cos^{-1}(-\tan\phi\tan\delta) \quad \text{(A.12)}$$

APPENDIX B

COMPUTER SIMULATION MODELS

APPENDIX B.1 MODEL NOTATION AND FORTRAN VARIABLES

Model Notation	FORTRAN Variables	Model Notation	FORTRAN Variables
A	CA1	M_T	XMT
AFR	AFR	M_w	XM(I), XMC
C	C	P_s	PS
DM	PERDM	R	R
e	EXP	RH_{air}	RHAIR, RHS
ERH	ERH	SC	SC
G_o	G(I)	T	TEMP, G(I)
H	RAD	T_f	T(IJ)
H_f	HF	T_o	T(I)
H_o	H(I)	Δt	SOLHT
M_D	DM	θ	SAFES, Z, SAFWH, WT
M_f	XMI	θeq	EQT
M_M	XMM	Δ_R	TR
M_o	DM(I)	$\Delta\theta$	DELT

APPENDIX B.2 ALPHABETICAL INDEX OF FORTRAN NOTATION USED IN THE SIMULATION MODELS

A	-	integer ratio of time to time interval in Subroutine HRNORM
	-	location of data value in subroutine AHUM
A(I)	-	array which stores the status of search in subroutines DRYSIM, ZERO, TYPE1, and program MINAIR
	-	array of which the minimum value is found in subroutine MIN
	-	array of which the maximum value is found in subroutine MAX
AD(I,J)	-	year, month, day, and hour read from the weather tape for hour I
AF(I)	-	data for air velocity versus pressure
AFR	-	airflow rate through the grain, $m^3/(min \cdot t)$
AHUM	-	subroutine which calculates the absolute humidity or the saturation vapour pressure of the air
AIR(I)	-	airflow rate (AFR) found by MINAIR for simulation I, $m^3/(min \cdot t)$
AIRHR	-	total time of continuous aeration to date, h
ALOGSP	-	log of the static pressure through the grain
ALOGT1	-	log of the allowable storage time for wheat from equation 1
ALOGT2	-	log of the allowable storage time for wheat from equation 2
AM	-	desired month of starting the drying process
AMT(I)	-	month (AM) used by MINAIR for simulation I
AREA	-	bin floor area, m^2
ASP(I,J)	-	data for static pressure versus air velocity for grain J
AVEM	-	average moisture content of the grain in the bin, % wet mass basis

AVET - average temperature of the grain in the bin, °C

AW(I) - year, month, day, and hour of the last record read from the tape

B - ratio of time to time interval in subroutine HRNORM

- location of data value in subroutine AHUM

BIG - largest value in the array A(I)

C - specific heat of the grain, converted to $J/(kg_a \cdot °C)$

- location of data value in subroutine AHUM

CA1 - horizontal collector area, m^2

CC - year read from the tape, for checking

CMM - total airflow rate through the grain, m^3/min

CMNI(I) - initial m.c. (XMO) used by MINAIR for simulation I

COD - cost of overdrying the grain, $

COR - indicator to check if tape is in the correct position

CS(I) - solar coefficient (SC) used by MINAIR for simulation I

D - year, month, and day, or month, day, and hour read from the tape

- location of data value in subroutine AHUM

DATE(I) - date read from the tape at the start of drying

DATS(I) - date read from the solar tape at the last reading

DATW - date read from the weather tape at the last reading

DAY - desired day of starting the drying process

DAYNO - present day of the week

DAYPWK(I) - number of days per week that the fan is to operate during period I

DB - moisture content of the grain, % dry mass basis

DBMC - moisture content of the grain, % dry mass basis

DEL - allowable error in determining X

DELT - equivalent to IDELT (time interval, h)

DHEAT(I) - number of degrees the temperature of the input air is increased by the heater during period I, °C

DHEATC - number of degrees the temperature of the input air is increased continuously until the end of drying, °C

DIA1 - diameter of the grain bin, m

DIAM - equivalent to DIA1, m

DM - mechanical damage multiplier for the storage time of corn

DM(I) - moisture content of the grain in layer I, % dry mass basis

DRY - moisture content of the grain in the driest layer, % wet mass basis

DRYSIM - subroutine which simulates the drying process for the whole bin of grain during one time interval, IDELT

DT - harvest year, month and day, used to align the tape

- present month and day

- time interval used in MINAIR

DT1 - present year, month, and day; used for checking

DT2 - year, month and day of desired stopping point

- present month and day

DYA(I) - day (DAY) used by MINAIR for simulation I

E	-	location of data value in subroutine AHUM
ELCOST	-	price of electricity, ¢/kWh
ENERG1	-	total electrical energy used to date by the fan, MJ
EPT1	-	total electrical energy used by the fan, per tonne of grain, MJ/t
EQT	-	equivalent storage time, h
ERH	-	equilibrium relative humidity of the grain, %
F	-	location of data value in subroutine AHUM
FANCST	-	total cost of electricity to run the fan to date, $
FANH	-	total time of fan operation to date, h
FANHR	-	hours of fan operation so far today
FANHT	-	number of degrees the temperature of the input air is increased by the fan, °C
FANSUB	-	subroutine which calculates the required power to drive the fan for the given conditions, kW
FAT	-	portion of the allowable storage time already passed at the start of drying, decimal fraction
FT	-	temporary location for TIME(I)
G	-	location of data value in subroutine AHUM
G(I)	-	temperature of the grain in layer I, °C
GMASS1	-	mass of grain in the bin, t
GO	-	initial grain temperature, °C
GRNDRY	-	subroutine which simulates drying of grain from start to finish for a given set of conditions
GRNPRC	-	price of grain, $/t

GRNTMP(I) - grain temperature setting for aeration(aeration occurs when the grain temperature is above this), during period I, °C

H - equivalent to HO

H(I) - absolute humidity of the air entering layer I, kilograms of water per kilogram of air

HARV - desired month, day and hour of starting the drying process

HEAT - number of degrees the temperature of the input air is increased by the fan and heater, °C

HF - absolute humidity of the air leaving the layer of grain at the end of the time interval

HO - absolute humidity of the air entering the layer of grain at the beginning of the time interval

- absolute humidity of the air in subroutine RHAIR

HOT - temperature of the grain in the hottest layer, °C

HOUR - desired hour of starting the drying process

HRNORM - subroutine which checks whether the values to be used are allowable

HRPDAY(I) - maximum hours of fan operation per day during period I, h

HRS - time in subroutine HRNORM, h

HSTAT(I) - humidistat setting for the heater during period I, %RH

HTEMP(I) - thermostat setting for the heater during period I, °C

HTHPD(I) - maximum hours of heater operation per day during period I, h

HTRH - total time of heater operation to date, h

HTRHR - hours of heater operation so far today, h

HTTIME(I) - time of day that the heater is turned on, h

I - index of a DO-loop

- indicator of the hour in subroutine READRN

IAB - indicator to ensure the correct calculation

IAV - indicator for correct routing

IC - indicator of A.M. or P.M. on the radiation tape

ID - equivalent to AW(4) = hour of the last reading

- equivalent to IDELT in subroutine READWR

IDEL - time interval in subroutine HRNORM, h

IDELT - time interval used in the program, h

IFR - initial value used in a DO-loop

IG - grain type; 0 = wheat, 1 = barley, 2 = corn

IGR - grain type in subroutine FANSUB

- equivalent to IG in subroutine GRNDRY

IJ - difference between the dates on the two tapes, if any, in subroutine READRN

- indicator of the air and grain conditions at the end of the time interval, in subroutine DRYSIM

IJ(I,J) - array for storing data values

IN - indicator for determining the date

IND - indicator for the period of time (1 = fall, 2 = winter, 3 = spring)

INTWEK - number of time intervals, IDELT, per week

INV - number of time intervals, IDELT, per day

IOP - indicator of the type of operation (for fan and heater control)

IPRT - indicator of the search status

ISAVE	-	temporary location of IDELT
ISP	-	spoilage indicator
IWD(I)	-	title to be printed with the output
J	-	index of a DO-loop
	-	indicator of the day in subroutine READRN
	-	indicator of the curve type in subroutines DRYSIM, ZERO, TYPE1, and program MINAIR
	-	temporary location of IDEL in subroutine HRNORM
	-	indicator of the minimum value of an array in subroutine MIN
	-	indicator of the maximum value of an array in subroutine MAX
J1	-	indicator of search position
J2	-	indicator for tape positioning
JDAY	-	indicator of the day for correct fan operation
JJ	-	indicator for routing
JP	-	alternate location of J in subroutine ZERO
K	-	index of a DO-loop
	-	convergence indicator in subroutines DRYSIM, ZERO, TYPE1, and program MINAIR
KK	-	indicator of the number of aeration intervals, IDELT
	-	indicator of the number of records (hours) read from the weather tape in subroutine GRNDRY and program MINAIR
KR	-	temporary location of IDELT
L	-	index of a DO-loop

	- indicator of the number of records read from the radiation tape in subroutine GRNDRY and program MINAIR
L1	- indicator for routing
LH	- indicator of the layer of grain having the maximum temperature
M	- equivalent to MM
M(I)	- character indicator read from the radiation tape for hour I
MAX	- subroutine which finds and identifies the maximum value in an array
MD(I)	- character indicator read from the radiation tape for day I
MIN	- subroutine which finds and identifies the minimum value in an array
MINAIR	- program which determines the minimum airflow rate required to dry a bin of grain without spoilage under specified conditions
MISS	- character used to check for missing data on the radiation tape
MM	- special indicator which indicates the status of search
N	- indicator for routing in subroutine READRN
	- counter used in subroutines DRYSIM, ZERO, TYPE1, and program MINAIR
	- indicator of the desired calculation in subroutine AHUM
	- indicator of the size of the array in subroutines MAX and MIN
N1	- indicator of the layer of grain having the lowest moisture content
N2	- indicator of the layer of grain having the highest m.c.

N3	- indicator of the layer of grain in the worst condition
N5	- indicator of the number of times READRN has been called
NJ	- indicator one less than NO
NN	- indicator of the number of times the radiation tape has been read since reaching a wrong date
NO	- indicator of the number of time intervals, IDELT, that have passed
	- equivalent to N5 in subroutine READRN
	- indicator of the number of simulations run in MINAIR
NOTE	- indicator for routing
P	- portion of the allowable time already elapsed in the worst layer, %
PCTDM(I)	- dry matter decomposition in layer I, %
PCTM	- equivalent to P as a decimal
PER(I)	- portion of the allowable storage time already elapsed in layer I, %
PERDM	- dry matter decomposition in the worst layer, %
PF	- packing factor used in the static pressure calculations
PS	- saturation vapour pressure of the air, kPa
PTIME	- time elapsed since the start of drying, h
PW	- vapour pressure of the air at T, kPa
PWR	- power required to drive the fan, kW
PWR1	- equivalent to PWR
R	- dry matter to air ratio, kilograms of dry matter per kilogram of air

RAD - total radiation received during the time interval IDELT, cal/cm^2

RAD(I) - solar radiation received during hour I, cal/cm^2

RDNBN1 - total solar energy collected to date, MJ

READRN - subroutine which reads the radiation data from the tape for one day and calculates values to replace any missing data

READWR - subroutine which reads the weather data from the tape and fills in any missing values

REL(I) - relative humidity of the air during hour I,%

RH - average relative humidity of the air during the time interval IDELT, %

RHAIR - subroutine which calculates the relative humidity of the air for the given conditions

RHS - relative humidity of the air leaving the layer of grain at the end of the time interval, IDELT, %RH

RHSTAT(I) - humidistat setting for the fan during period I, %RH

RSDT - earliest date that the fan can resume continuous operation after the winter period, month and day

RSTEMP - minimum average temperature for one week that allows the fan to resume continuous operation in the spring, °C

S - value used to determine a new estimate for X

SAFES - subroutine which calculates the allowable storage time (h) for corn at the given temperature and moisture content

SAFWH - subroutine similar to SAFES for wheat

SC - solar collector coefficient; average 24h temperature rise that the collector will produce when the daily solar radiation is approximately 40 MJ/m^2, °C

SDATE - earliest date that the fan can cease continuous operation for the winter period, month and day

SMALL - smallest value in the array A(I)

SOL(I) - solar radiation received during hour I, langleys (cal/cm^2)

SOLHT - temperature rise of the incoming air due to radiation received during the time interval, IDELT, °C

SP - static pressure drop through the grain, kPa

SPHT - subroutine which calculates the specific heat of wheat at the given temperature and moisture content

SPLGCT - cost of spoilage in the grain, $

SPM - static pressure drop per metre depth of grain, kPa/m

SPWT - specific weight of grain, t/m^3

STEMP - maximum average temperature for one week that allows the fan to cease continuous operation for the winter period, °C

STPDT(I) - desired stopping date for the I^{th} operational period of time, month and day

STPYR - final year of drying to be simulated

SUMM - sum of the moisture contents of all the layers, % wet mass basis

SUMT - sum of the temperatures of all the layers, °C

T - temporary location of HRS in a subroutine HRNORM

- equivalent to TEMP in subroutine SAFES, °F

- temperature of the air in subroutine RHAIR, °C

- equivalent to TEMP in subroutine AHUM, K

T(I) - temperature of the air entering layer I, °C

TAB	-	temperature of the air leaving the layer of grain at the end of the time interval, IDELT, °C
TAEH(I)	-	HEAT used by MINAIR for simulation I
TAIR	-	sum of the ambient air temperatures for the week, °C
TD	-	average dew point temperature of the air entering the bottom layer of grain during the time interval IDELT, °C
	-	average dew point temperature for the week, °C
TDP(I)	-	dew point temperature of the air during hour I, °F
TDPT	-	sum of the dewpoint temperatures for the week, °C
TEMP	-	temperature of the grain in subroutines SAFES, SAFWH, and SPHT, °C
	-	temperature of the air in subroutine AHUM, °C
TEMP(I)	-	thermostat setting for the fan during period I, °C
TEMPA	-	ambient air temperature at the start of drying, °C
TIME	-	time elapsed since the start of drying, h
TIME(I)	-	time of day that the fan is turned on, h
TIMS	-	time at the beginning of the present time interval, h
TINV	-	equivalent to INV
TLRAD	-	total radiation received since the start of drying, MJ/m^2
TO	-	average temperature of the air entering the bottom layer of grain during the time interval, IDELT, °C
	-	average ambient air temperature for the week, °C
	-	equivalent to TP in subroutine READWR
TONNE	-	equivalent to GMASS1, t

TP	-	average ambient air temperature for the time interval, IDELT, °C
TP(I)	-	ambient air temperature during hour I, °F
TR	-	reference storage time for corn, h
TRAD	-	total radiation received during the week, J/cm^2
TYPE1	-	subroutine used with ZERO to find a better estimate for X
V	-	velocity of the air through the grain, m/min
W	-	equivalent to WB in subroutine SAFES
	-	similar to S in subroutine TYPE1
WB	-	moisture content of the grain, % wet mass basis
WET	-	moisture content of the grain in the wettest layer, % wet mass basis
WETAL	-	maximum moisture content (wettest layer) when the average is dry, % wet mass basis
WEEKIN	-	equivalent to INTWEK
WKFNHR	-	total fan operation time so far during the week, h
WT	-	allowable storage time for wheat at the present conditions, h
X	-	the present year
	-	independent variable in the subroutines ZERO and TYPE1 which is to be found such that f(X) = YD (X = HF in DRYSIM; X = AFR in MINAIR)
XL	-	alternate location for A(1)
XM(I)	-	moisture content of the grain in layer I, % wet mass basis
XMC	-	moisture content of the grain, % wet mass basis

XMF	-	desired final grain moisture content, % wet mass basis
XMI	-	moisture content of the grain at the end of the time interval, IDELT, % dry mass basis
XMM	-	moisture multiplier for the storage time of corn
XMO	-	initial grain moisture content, % wet mass basis
XMT	-	temperature multiplier for the storage time of corn
XU	-	alternate location for A(3)
Y	-	function of X (Y = ERH - RHS in DRYSIM; Y = % dry matter decomposition in MINAIR)
Y4	-	similar to S
YD	-	desired value of Y
YER(I)	-	year (YR) used by MINAIR for simulation I
YL	-	alternate location for A(2)
YR	-	desired year of starting the drying process
YU	-	alternate location for A(4)
Z	-	allowable storage time for corn at the present conditions, h
	-	temporary location of A(I) in subroutine ZERO
ZERO	-	subroutine which sequentially selects better X values for an unknown function f(X) (= Y), such that f(X) equals some desired value of Y (YD)

APPENDIX B.3 FLOWCHART OF SYSTEMDRY PROGRAM

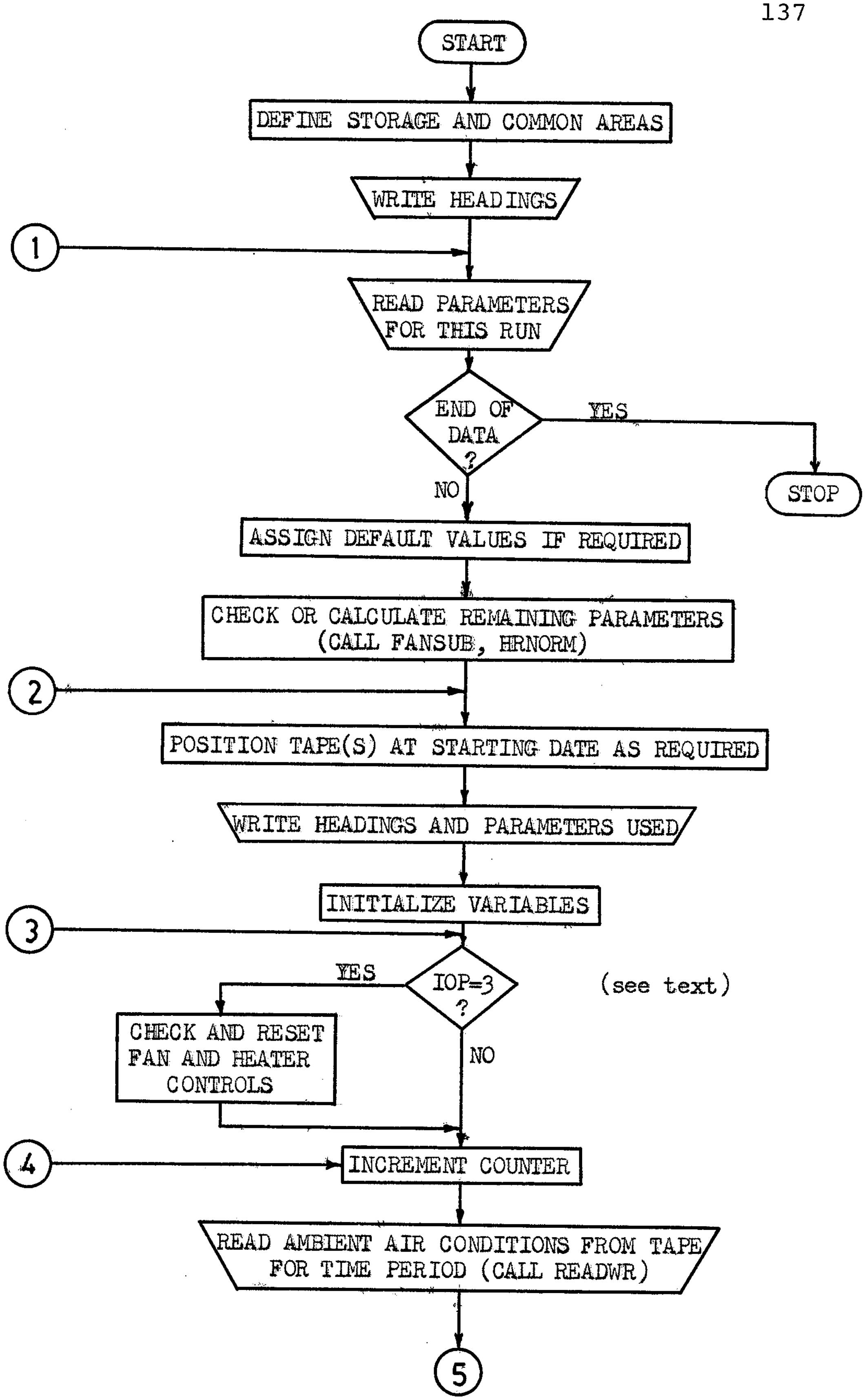
Variable IOP indicates the operation of fan and heater:

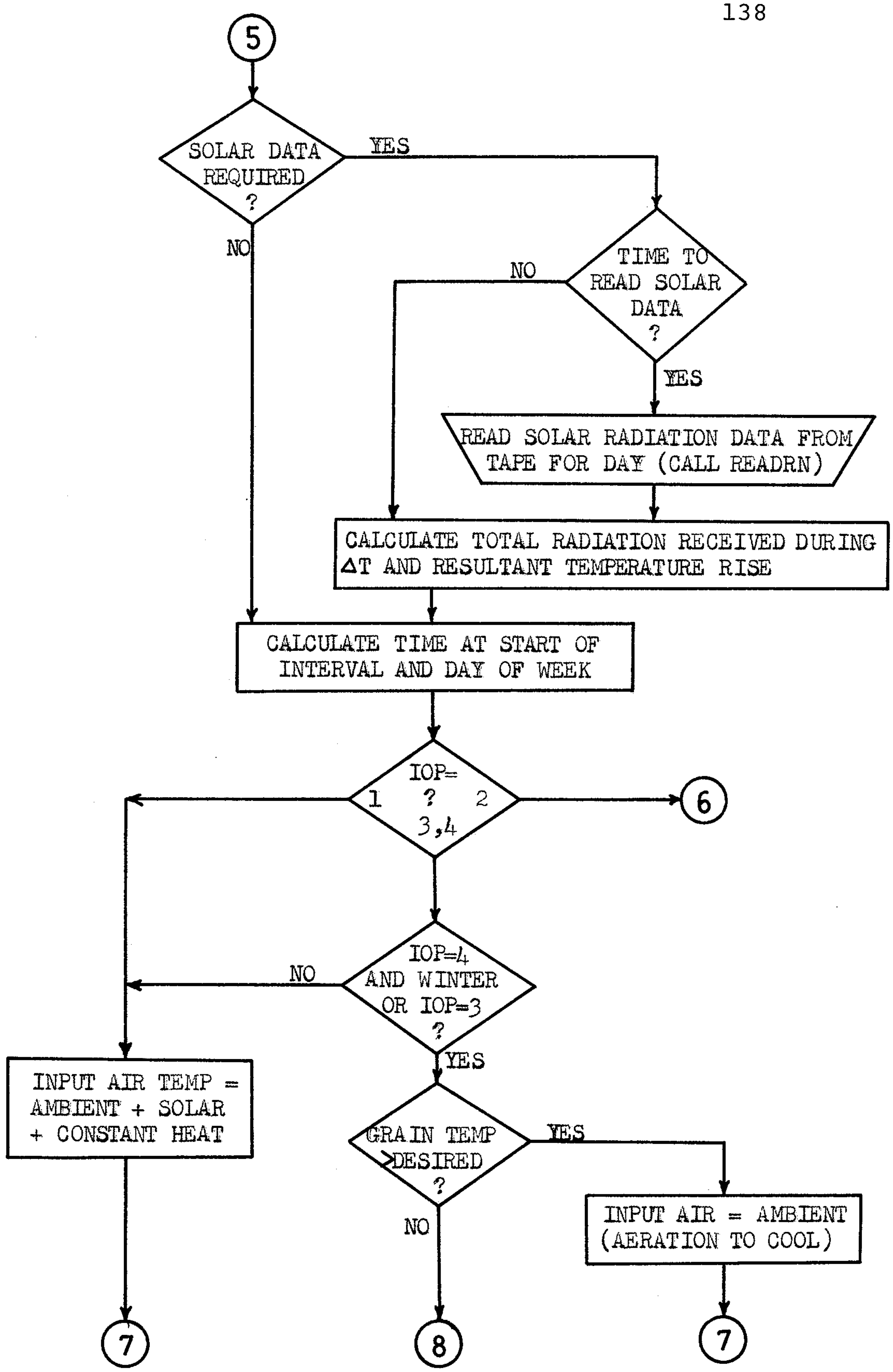
1 = continuous fan and heater operation

2 = continuous fan operation with heater controlled by time clock, thermostat, humidistat or a combination of these.

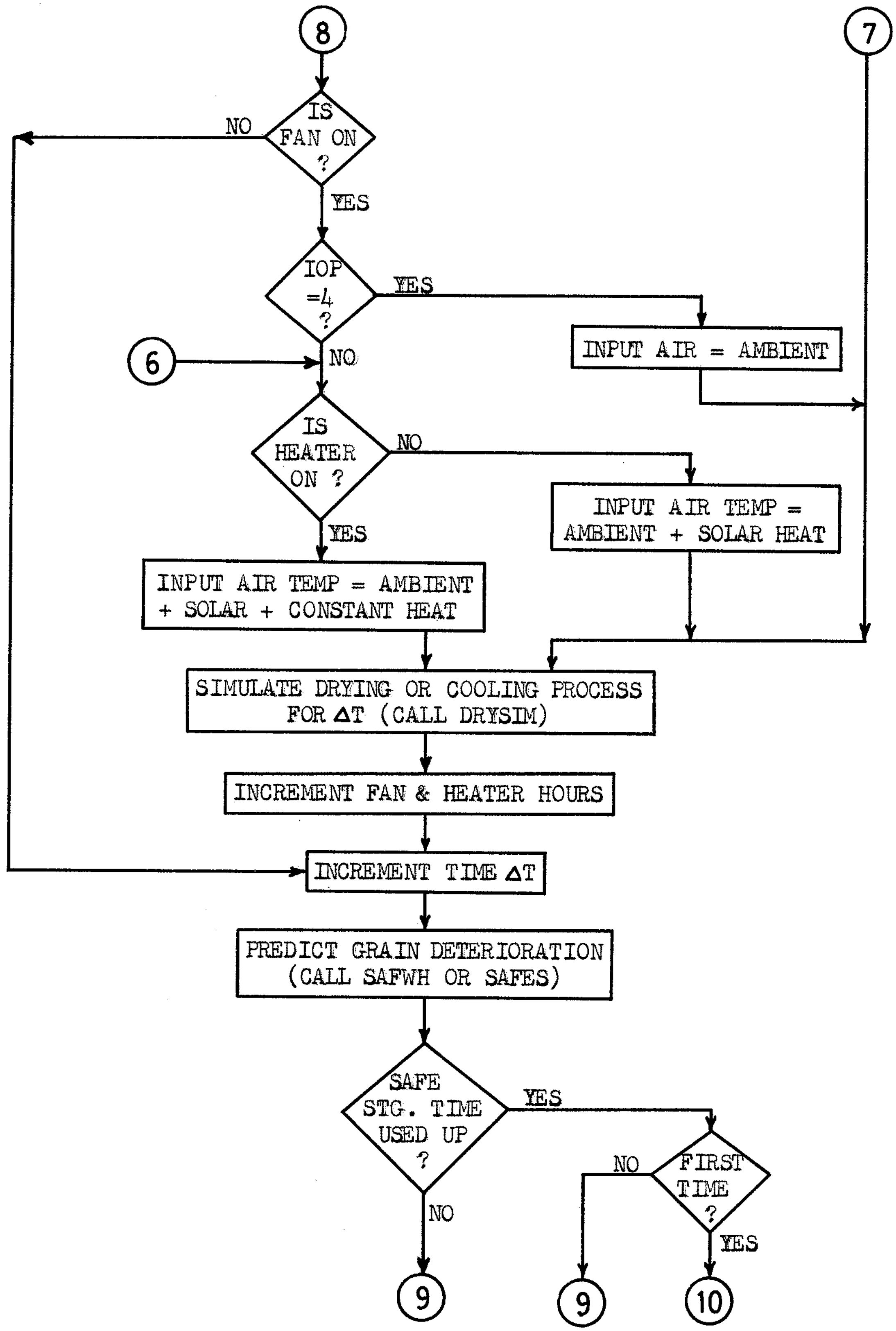
3 = fan and heater both controlled by time clock, thermostat, humidistat, or a combination.

4 = fan and heater off during winter, as specified by temperature and date.

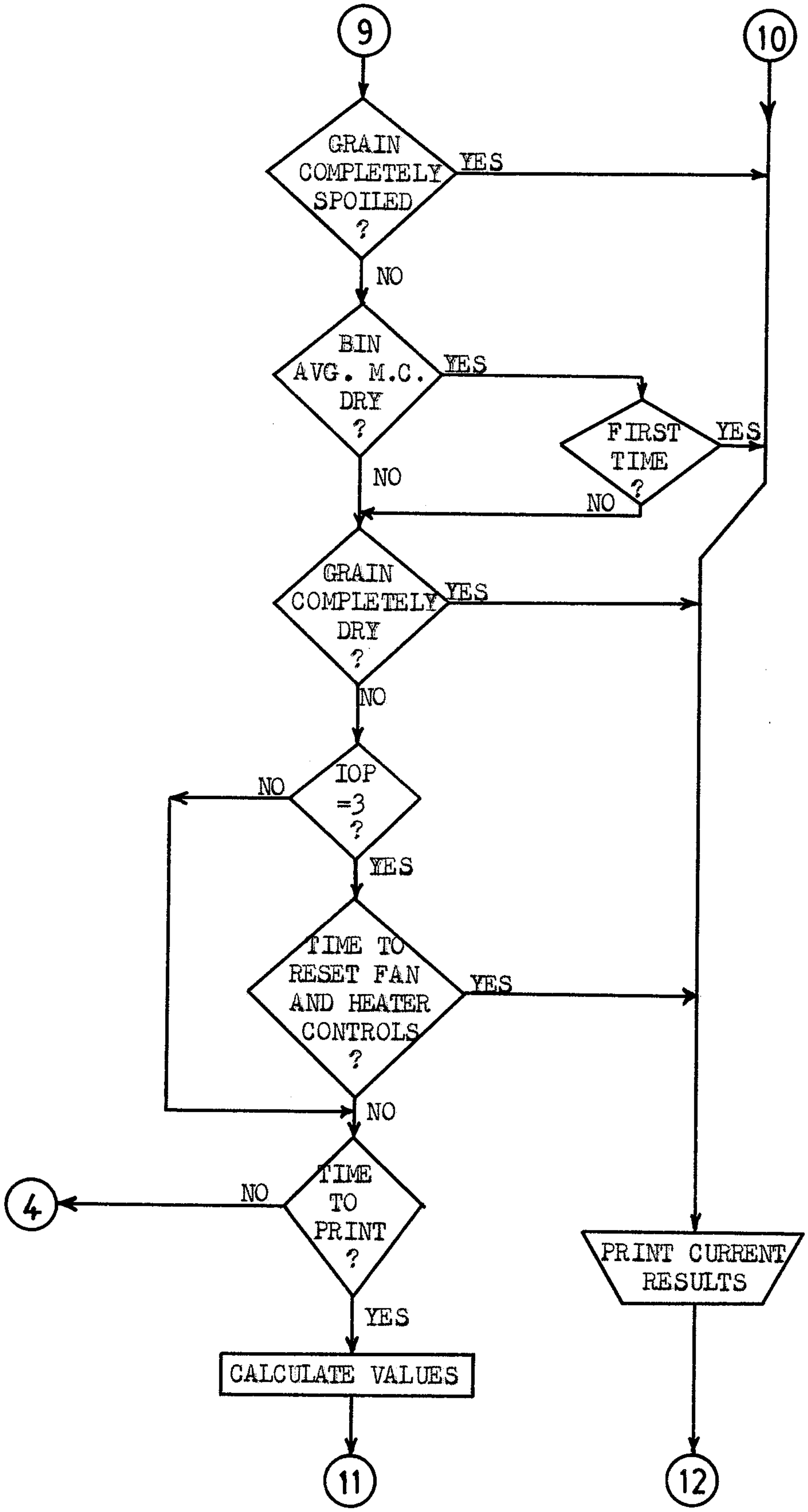

START
DEFINE STORAGE AND COMMON AREAS
WRITE HEADINGS
1
READ PARAMETERS FOR THIS RUN
END OF DATA ?
YES
STOP
NO
ASSIGN DEFAULT VALUES IF REQUIRED
CHECK OR CALCULATE REMAINING PARAMETERS (CALL FANSUB, HRNORM)
2
POSITION TAPE(S) AT STARTING DATE AS REQUIRED
WRITE HEADINGS AND PARAMETERS USED
INITIALIZE VARIABLES
3
IOP=3 ?
YES
CHECK AND RESET FAN AND HEATER CONTROLS
NO
(see text)
4
INCREMENT COUNTER
READ AMBIENT AIR CONDITIONS FROM TAPE FOR TIME PERIOD (CALL READWR)
5

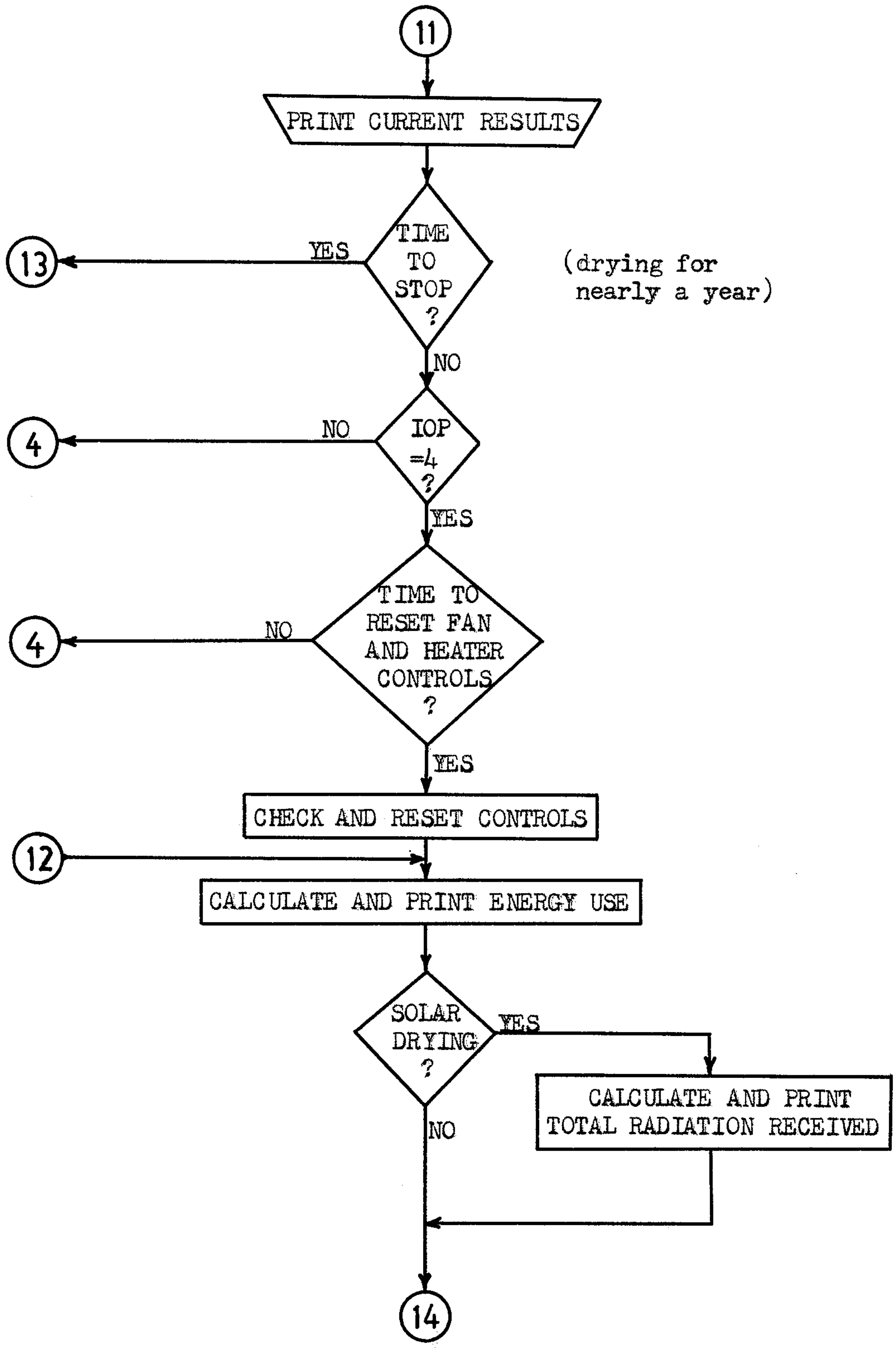


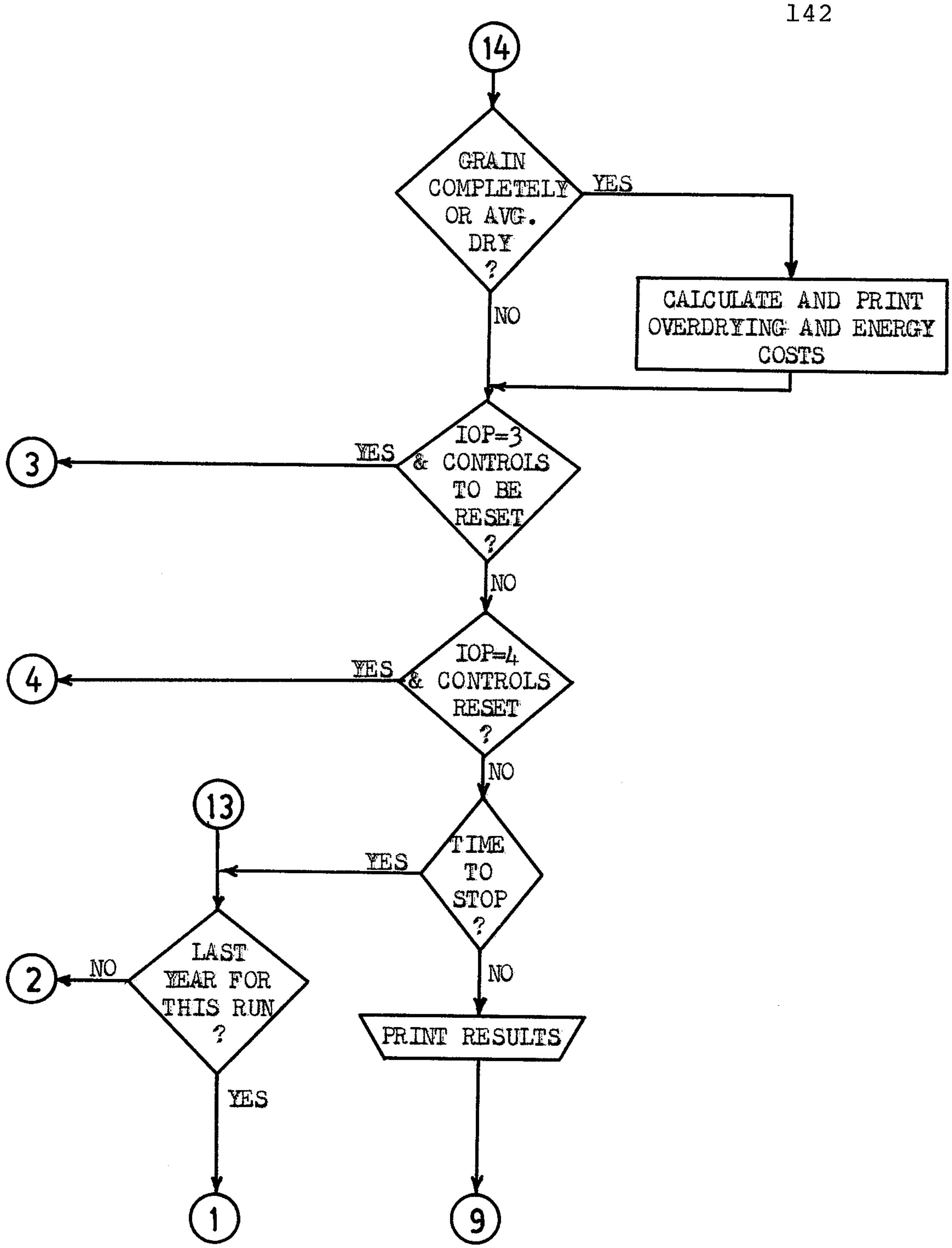
5
SOLAR DATA REQUIRED ?
YES
NO
TIME TO READ SOLAR DATA ?
NO
YES
READ SOLAR RADIATION DATA FROM TAPE FOR DAY (CALL READRN)
CALCULATE TOTAL RADIATION RECEIVED DURING ΔT AND RESULTANT TEMPERATURE RISE
CALCULATE TIME AT START OF INTERVAL AND DAY OF WEEK
IOP= ?
1
2
3,4
6
IOP=4 AND WINTER OR IOP=3 ?
NO
YES
INPUT AIR TEMP = AMBIENT + SOLAR + CONSTANT HEAT
GRAIN TEMP >DESIRED ?
YES
NO
INPUT AIR = AMBIENT (AERATION TO COOL)
7
8
7



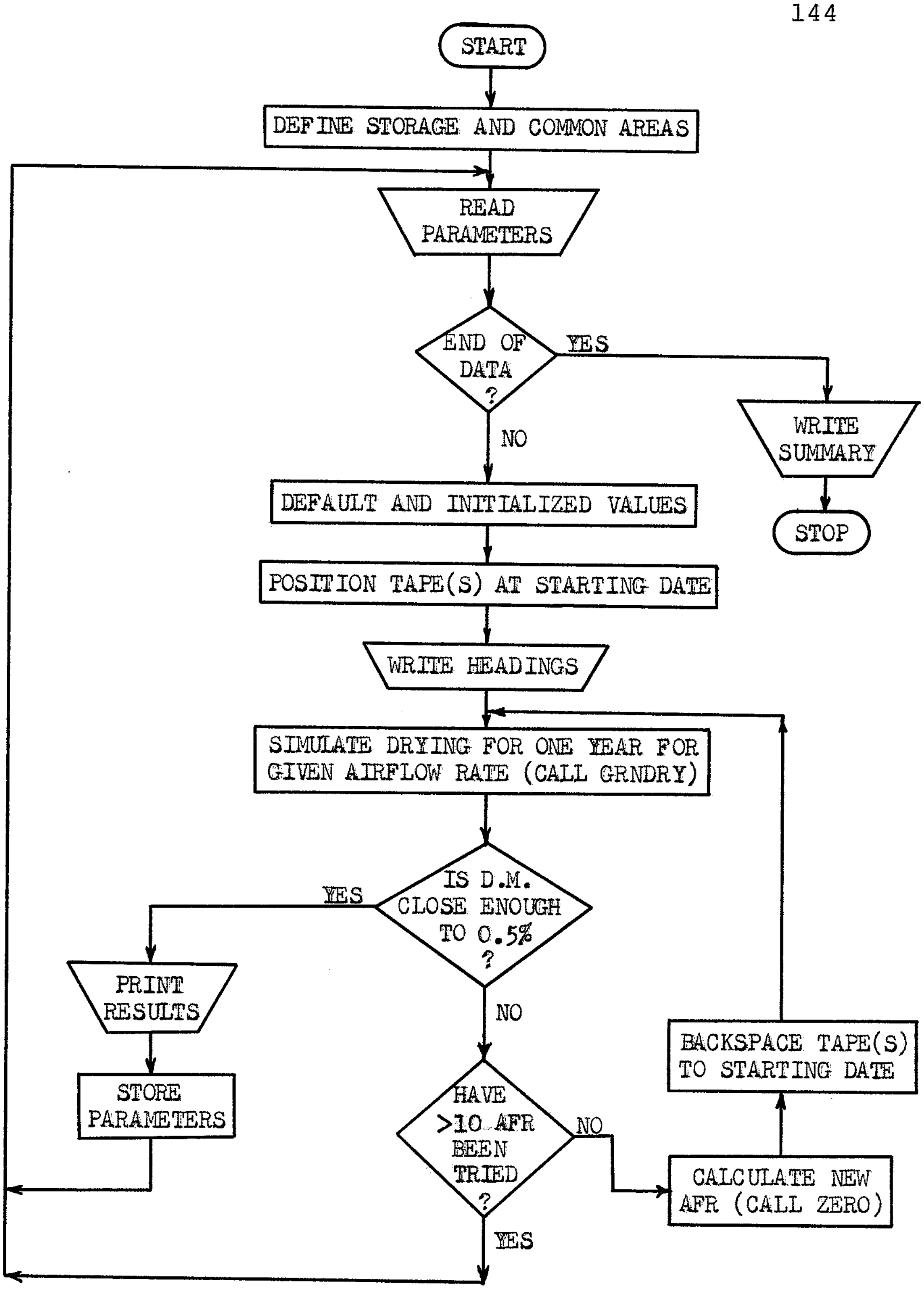
8
7
IS FAN ON ?
NO
YES
IOP =4 ?
YES
INPUT AIR = AMBIENT
6
NO
IS HEATER ON ?
NO
INPUT AIR TEMP = AMBIENT + SOLAR HEAT
YES
INPUT AIR TEMP = AMBIENT + SOLAR + CONSTANT HEAT
SIMULATE DRYING OR COOLING PROCESS FOR ΔT (CALL DRYSIM)
INCREMENT FAN & HEATER HOURS
INCREMENT TIME ΔT
PREDICT GRAIN DETERIORATION (CALL SAFWH OR SAFES)
SAFE STG. TIME USED UP ?
YES
FIRST TIME ?
NO
YES
NO
9
9
10


9
10
GRAIN COMPLETELY SPOILED ?
YES
NO
BIN AVG. M.C. DRY ?
YES
FIRST TIME ?
YES
NO
NO
GRAIN COMPLETELY DRY ?
YES
NO
IOP =3 ?
NO
YES
TIME TO RESET FAN AND HEATER CONTROLS ?
YES
NO
TIME TO PRINT ?
NO
4
YES
CALCULATE VALUES
PRINT CURRENT RESULTS
11
12

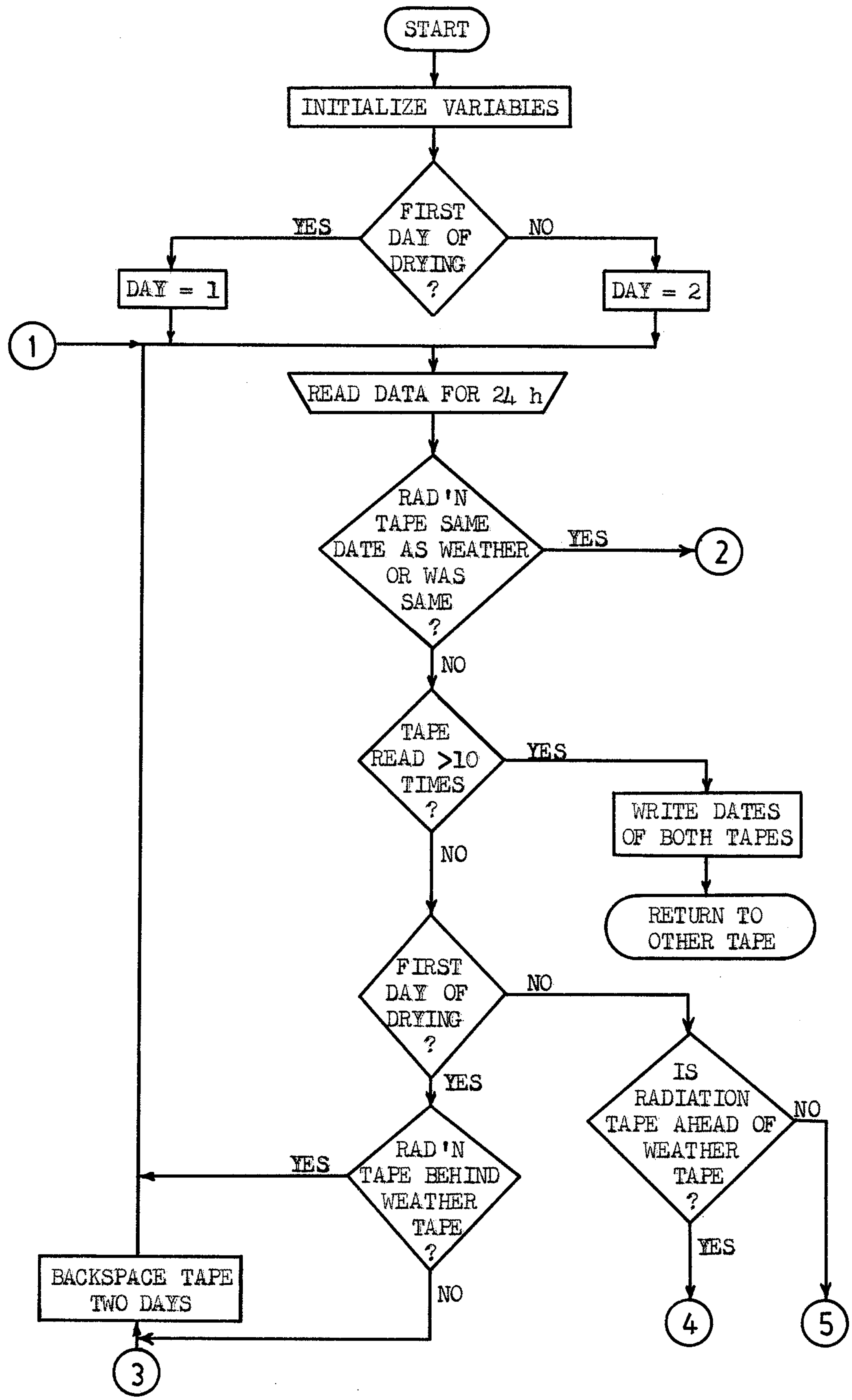

11
PRINT CURRENT RESULTS
TIME TO STOP ?
YES
13
(drying for nearly a year)
NO
IOP =4 ?
NO
4
YES
TIME TO RESET FAN AND HEATER CONTROLS ?
NO
4
YES
CHECK AND RESET CONTROLS
12
CALCULATE AND PRINT ENERGY USE
SOLAR DRYING ?
YES
CALCULATE AND PRINT TOTAL RADIATION RECEIVED
NO
14

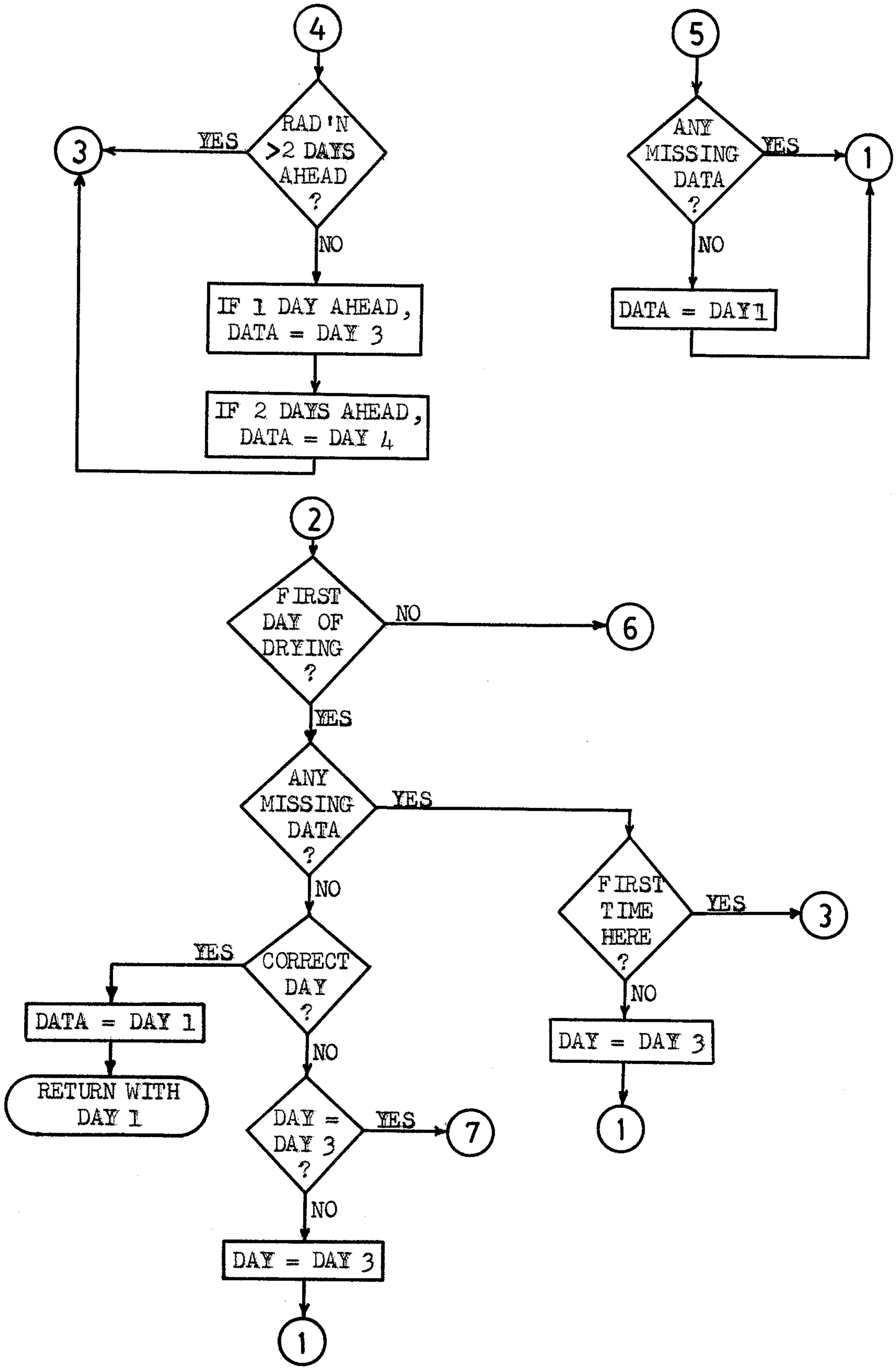

14
GRAIN COMPLETELY OR AVG. DRY ?
YES
CALCULATE AND PRINT OVERDRYING AND ENERGY COSTS
NO
IOP=3 & CONTROLS TO BE RESET ?
YES
3
NO
IOP=4 & CONTROLS RESET ?
YES
4
NO
TIME TO STOP ?
YES
13
LAST YEAR FOR THIS RUN ?
NO
2
YES
1
NO
PRINT RESULTS
9

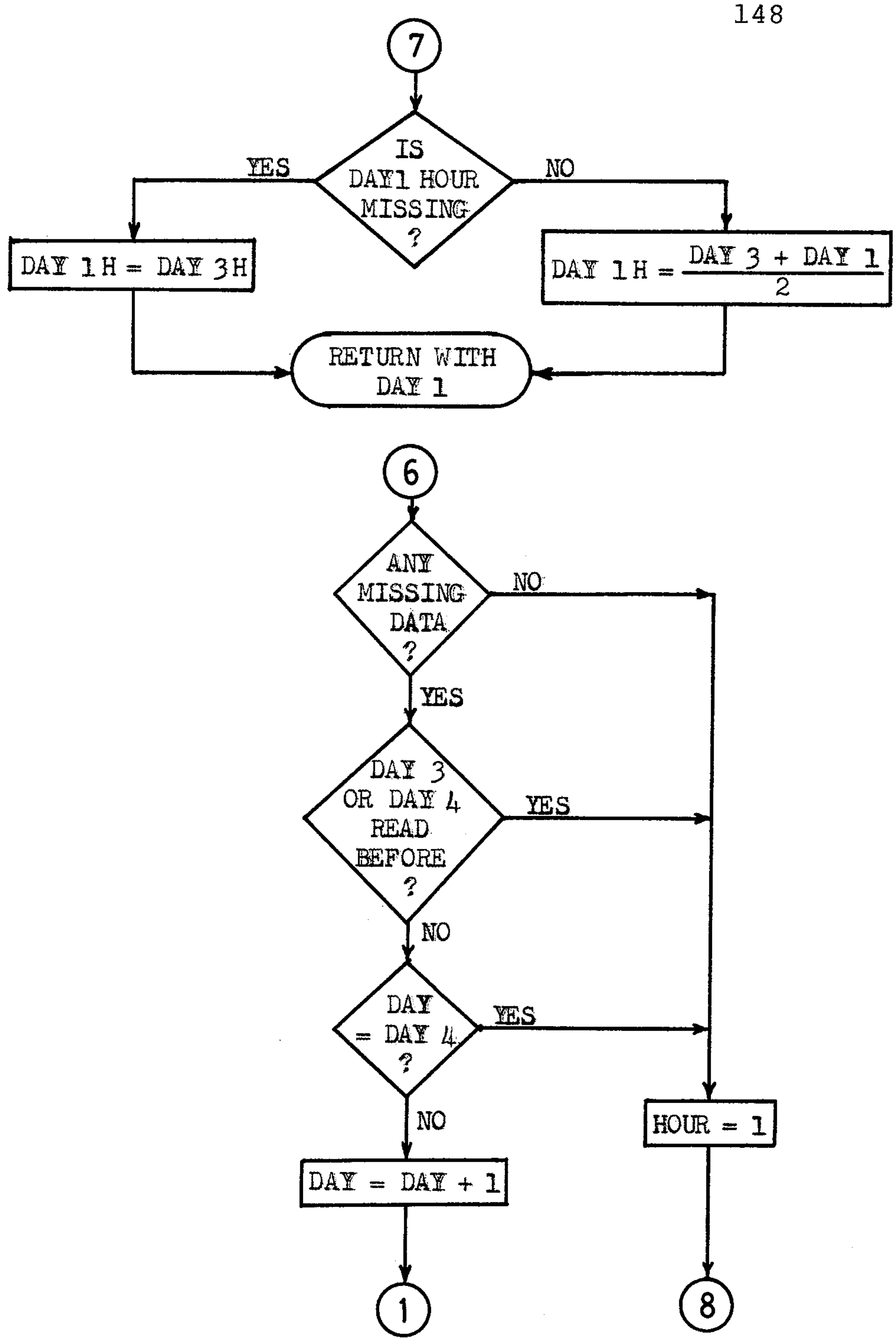
APPENDIX B.4 FLOWCHART OF MINAIR PROGRAM

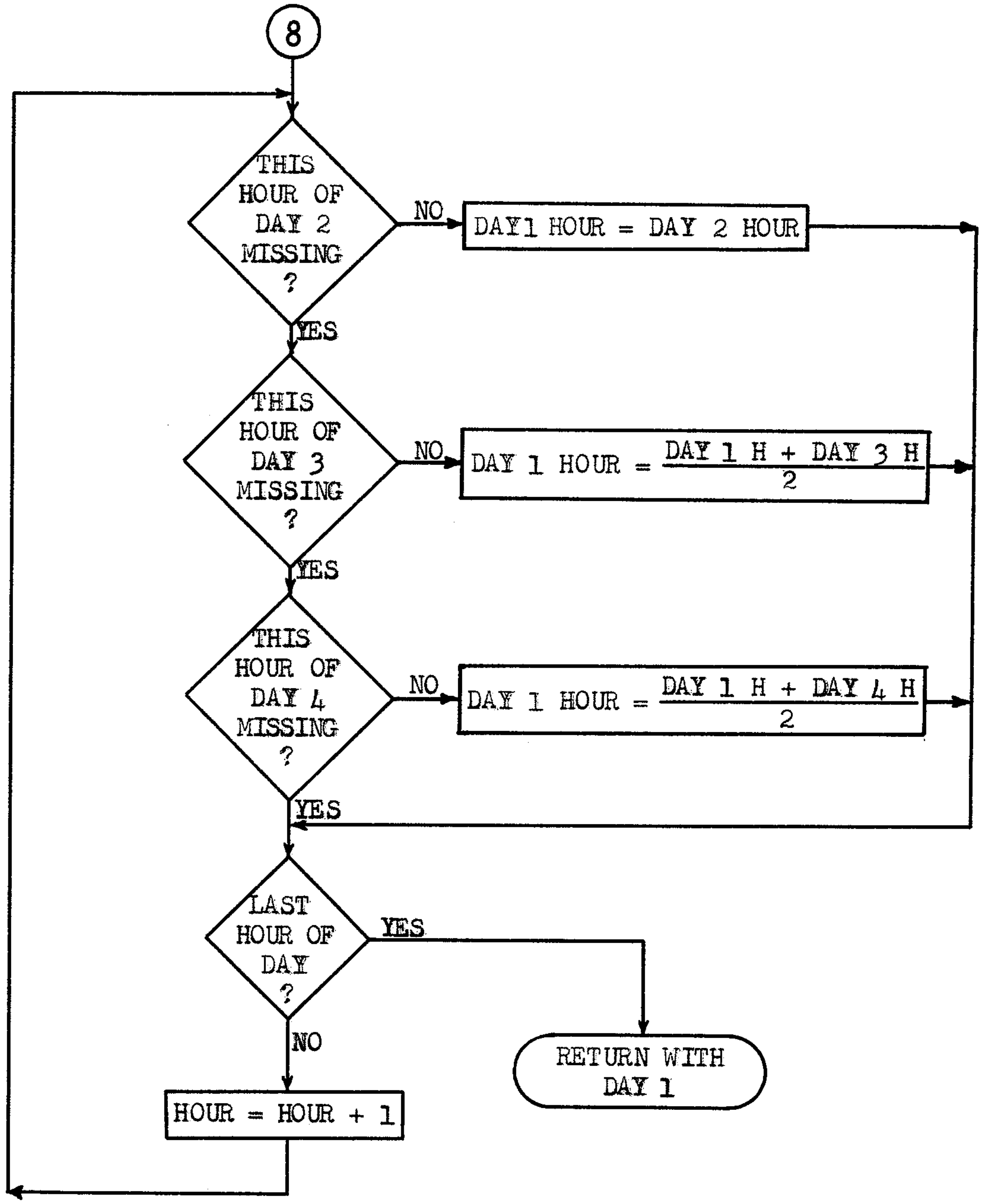

START
DEFINE STORAGE AND COMMON AREAS
READ PARAMETERS
END OF DATA ?
YES
WRITE SUMMARY
STOP
NO
DEFAULT AND INITIALIZED VALUES
POSITION TAPE(S) AT STARTING DATE
WRITE HEADINGS
SIMULATE DRYING FOR ONE YEAR FOR GIVEN AIRFLOW RATE (CALL GRNDRY)
IS D.M. CLOSE ENOUGH TO 0.5% ?
YES
PRINT RESULTS
STORE PARAMETERS
NO
HAVE >10 AFR BEEN TRIED ?
NO
CALCULATE NEW AFR (CALL ZERO)
BACKSPACE TAPE(S) TO STARTING DATE
YES

APPENDIX B.5 FLOWCHART OF READRN SUBPROGRAM

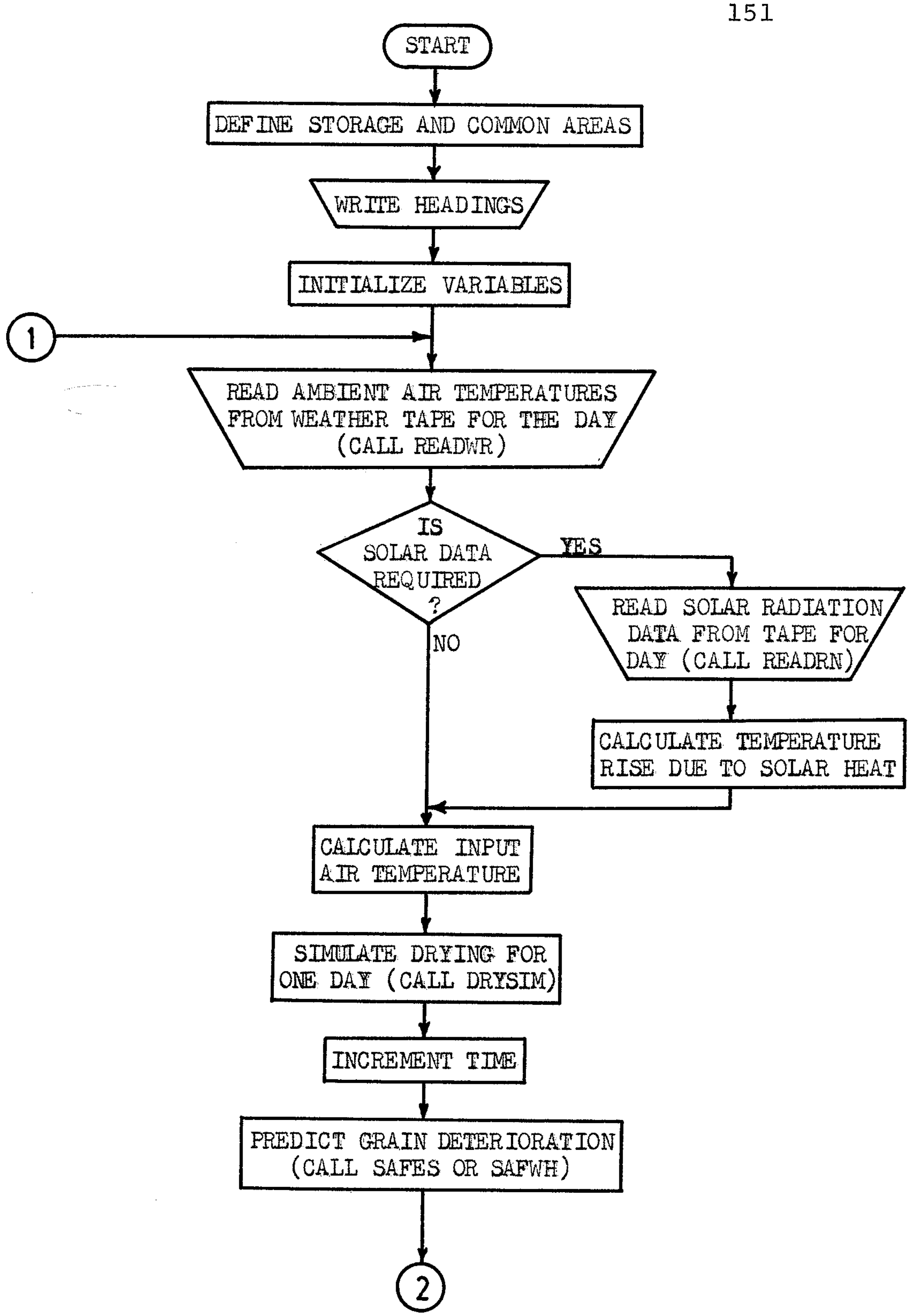

START
INITIALIZE VARIABLES
FIRST DAY OF DRYING ?
YES
NO
DAY = 1
DAY = 2
1
READ DATA FOR 24 h
RAD'N TAPE SAME DATE AS WEATHER OR WAS SAME ?
YES
2
NO
TAPE READ >10 TIMES ?
YES
WRITE DATES OF BOTH TAPES
RETURN TO OTHER TAPE
NO
FIRST DAY OF DRYING ?
NO
IS RADIATION TAPE AHEAD OF WEATHER TAPE ?
NO
YES
4
5
YES
RAD'N TAPE BEHIND WEATHER TAPE ?
YES
NO
BACKSPACE TAPE TWO DAYS
3

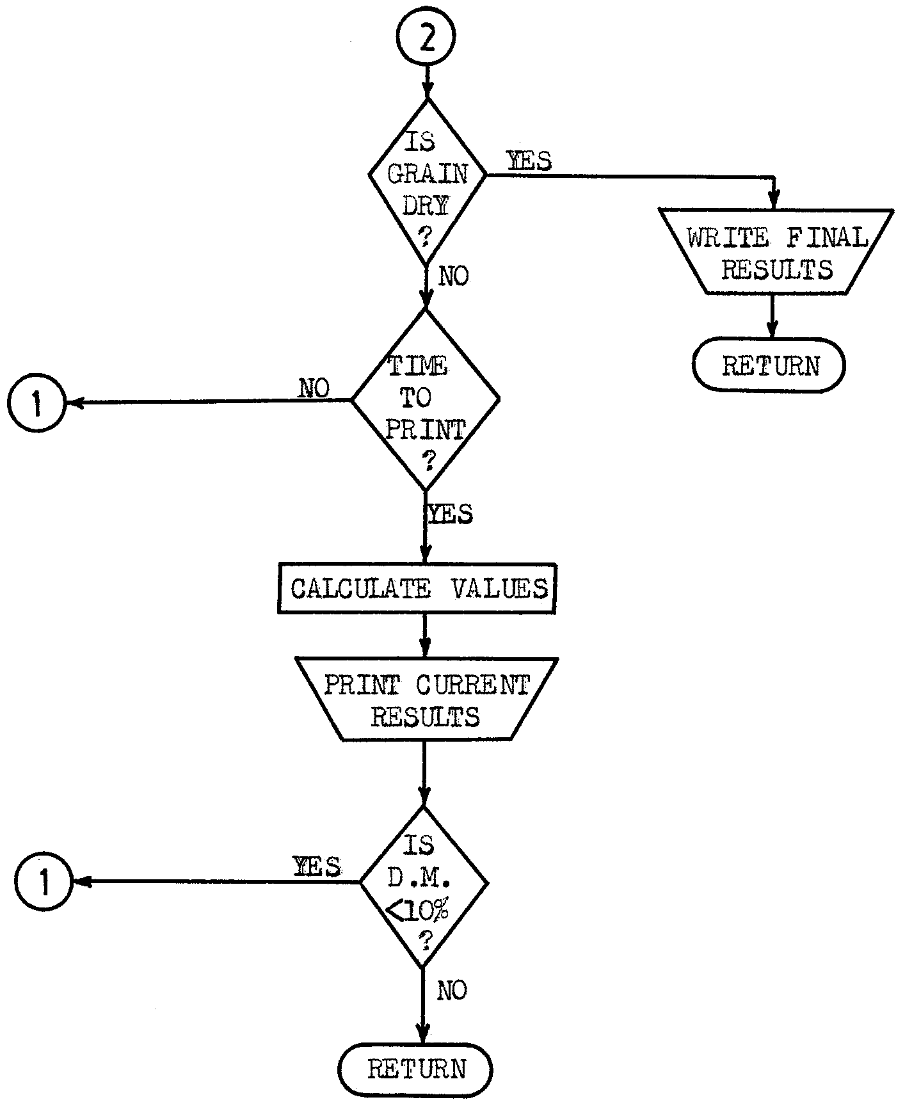

4
RAD'N >2 DAYS AHEAD ?
YES
3
NO
IF 1 DAY AHEAD, DATA = DAY 3
IF 2 DAYS AHEAD, DATA = DAY 4
5
ANY MISSING DATA ?
YES
1
NO
DATA = DAY1
2
FIRST DAY OF DRYING ?
NO
6
YES
ANY MISSING DATA ?
YES
FIRST TIME HERE ?
YES
3
NO
DAY = DAY 3
1
NO
CORRECT DAY ?
YES
DATA = DAY 1
RETURN WITH DAY 1
NO
DAY = DAY 3 ?
YES
7
NO
DAY = DAY 3
1


7
IS DAY1 HOUR MISSING ?
YES
NO
DAY 1H = DAY 3H
DAY 1H = (DAY 3 + DAY 1) / 2
RETURN WITH DAY 1
6
ANY MISSING DATA ?
NO
YES
DAY 3 OR DAY 4 READ BEFORE ?
YES
NO
DAY = DAY 4 ?
YES
NO
HOUR = 1
DAY = DAY + 1
1
8


8
THIS HOUR OF DAY 2 MISSING ?
NO
DAY1 HOUR = DAY 2 HOUR
YES
THIS HOUR OF DAY 3 MISSING ?
NO
DAY 1 HOUR = DAY 1 H + DAY 3 H / 2
YES
THIS HOUR OF DAY 4 MISSING ?
NO
DAY 1 HOUR = DAY 1 H + DAY 4 H / 2
YES
LAST HOUR OF DAY ?
YES
RETURN WITH DAY 1
NO
HOUR = HOUR + 1

APPENDIX B.6 FLOWCHART OF GRNDRY SUBPROGRAM


START
DEFINE STORAGE AND COMMON AREAS
WRITE HEADINGS
INITIALIZE VARIABLES
1
READ AMBIENT AIR TEMPERATURES FROM WEATHER TAPE FOR THE DAY (CALL READWR)
IS SOLAR DATA REQUIRED ?
YES
NO
READ SOLAR RADIATION DATA FROM TAPE FOR DAY (CALL READRN)
CALCULATE TEMPERATURE RISE DUE TO SOLAR HEAT
CALCULATE INPUT AIR TEMPERATURE
SIMULATE DRYING FOR ONE DAY (CALL DRYSIM)
INCREMENT TIME
PREDICT GRAIN DETERIORATION (CALL SAFES OR SAFWH)
2


2
IS GRAIN DRY ?
YES
WRITE FINAL RESULTS
RETURN
NO
TIME TO PRINT ?
NO
1
YES
CALCULATE VALUES
PRINT CURRENT RESULTS
IS D.M. <10% ?
YES
1
NO
RETURN

APPENDIX B.7 MATHEMATICAL MODEL OF SYSTEMDRY IN FORTRAN STATEMENTS

```
C  NATURAL AIR DRYING MODEL BY TOM THOMPSON, MODIFIED BY BRUCE FRASER
C  FOR WHEAT, BARLEY, OR CORN FOR NATURAL, SOLAR, OR HEATED AIR DRYING.
C  REQUIRES WEATHER INFO ON TAPE.    LAST UPDATE 78 02 08
C
      COMMON /AREA1/XM(10),G(10),DM(10),IG,R
      DIMENSION AW(4),DATE(4),PER(10),IWD(20),DHEAT(3),HTHPD(3),
     +HTTIME(3),HTEMP(3),HSTAT(3),STPDT(3),HRPDAY(3),DAYPWK(3),TIME(3),
     +TEMP(3),RHSTAT(3),GRNTMP(3),SOL(24),PCTDM(10)
C
      WRITE(6,110)
      WRITE(6,111)
110   FORMAT('-','SIMULATED DRYING RESULTS FOR SPECIFIED FAN AND HEATER
     +OPERATION WITH THE INDICATED PARAMETERS.'/' TOTAL FAN AND HEATER
     +HOURS OF OPERATION TO DATE, GRAIN MOISTURE CONTENTS (WB) AND TEMPE
     +RATURES (GT) ARE GIVEN AT THE END OF'/' EACH WEEK, ALONG WITH AN
     +INDICATION OF GRAIN CONDITION (%ALL.TIME), AVERAGE AMBIENT AIR TEM
     +P (TAIR) AND DEW POINT TEMP (TDPT)')
111   FORMAT(' FOR THE WEEK, AND TOTAL RADIATION RECEIVED DURING THE WEE
     +K (J/SQ.CM).')
C
C  READ AND WRITE TITLE FOR OUTPUT (LOCATION) *************************
      READ(5,120,END=1000)(IWD(I),I=1,20)
120   FORMAT(20A4)
      WRITE(6,130)(IWD(I),I=1,20)
130   FORMAT('0',20A4)
C
140   READ(5,145,END=1000)IG,IOP,IDELT,XMO,XMF,GO,YR,AM,DAY,HOUR,STPYR,
     +AFR,SC,FANHT,DHEATC,DIA1,GMASS1,GRNPRC,ELCOST,FAT
C  ****************************************************************
C  * READ GRAIN TYPE, IG(0=WHEAT,1=BARLEY,2=CORN), OPERATION INDICATOR *
C  * IOP(1=CONTINUOUS FAN OPERATION WITH CONTINUOUS OR NO HEATER,      *
C  * 2=CONTINUOUS FAN OPERATION WITH HEATER OPERATION DEFINED BY SECOND*
C  * CARD, 3=DISCONTINUOUS FAN OPERATION WITH OR WITHOUT HEATER,       *
C  * OPERATION OF BOTH DEFINED BY FOLLOWING 3 CARDS, 4=FAN & HEATER    *
C  * SHUT OFF DURING THE WINTER WHEN AVERAGE AMBIENT TEMP. FOR 1 WEEK  *
C  * IS BELOW A CERTAIN TEMP, AS DEFINED BY FOLLOWING CARD), TIME      *
C  * INTERVAL, IDELT(ALLOWABLE VALUES ARE 1,2,3,4,6,8,12, OR 24 HOURS--*
C  * SHORTER INTERVAL TAKES MORE COMPUTER TIME. SHORT FAN AND/OR HEATER*
C  * OPERATING TIMES PER DAY REQUIRE EQUALLY SHORT TIME INTERVALS, BUT *
C  * PROGRAM WILL AUTOMATICALLY USE THE SHORTEST TIME INTERVAL        *
C  * SPECIFIED BY HTHPD OR HRPDAY, IF LESS THAN IDELT), INITIAL GRAIN  *
C  * MOISTURE CONTENT, XMO(% WET WEIGHT BASIS), FINAL DESIRED M.C., XMF*
C  * (WETTEST LAYER, %WB), INITIAL GRAIN TEMP., GO(DEG. CELSIUS. IF    *
C  * LESS THAN 10 DEG., IT IS ADDED TO THE AMBIENT AIR TEMP. TO BECOME *
C  * INITIAL TEMP.), YEAR, MONTH, DAY, & HOUR OF STARTING DRYING (HOUR *
C  * MUST BE 0.(MIDNIGHT) OR A MULTIPLE OF IDELT), FINAL YEAR TO BE    *
C  * SIMULATED, STPYR(PROGRAM SIMULATES DRYING IN SUCCESSIVE YEARS FROM*
C  * FIRST YEAR GIVEN TO THIS YEAR, STARTING AT THE SAME DATE EACH     *
C  * YEAR), AIRFLOW RATE, AFR(CU.M/MIN-T), SOLAR COEFFICIENT, SC(AVG.  *
C  * TEMP RISE THROUGH THE COLLECTOR WHEN RECEIVING 1000 LANGLEYS OF   *
C  * RADIATION PER DAY. USE SC=0 FOR NATURAL AIR DRYING (NON-SOLAR)),  *
C  * AMOUNT OF HEAT ADDED TO THE AMBIENT AIR BY THE FAN MOTOR, FANHT   *
C  * (DEG. CELSIUS TEMP INCREASE), AMOUNT OF HEAT ADDED BY THE HEATER, *
C  * DHEATC(DEG. CELSIUS--FOR CONTINUOUS HEATER OPERATION ONLY),       *
C  * DIAMETER OF BIN, DIA1(METRES), MASS OF GRAIN IN BIN, GMASS1       *
C  * (TONNES), GRAIN PRICE, GRNPRC(DOLLARS PER TONNE), COST OF         *
C  * ELECTRICITY, ELCOST(CENTS PER KILOWATT-HOUR), AND FRACTION OF     *
C  * ALLOWABLE STORAGE TIME ALREADY USED UP AT THE START OF DRYING,    *
C  * FAT(0 OR BLANK IS USUAL ASSUMPTION, 0.5=50% USED UP).             *
C  ****************************************************************
145   FORMAT(3I2,2F5.1,10F4.1,4F5.1,F4.1)
C
```

```
      IF(IDELT.EQ.0)IDELT=12
      IF(IOP.GT.4 .OR. IOP.LT.1)IOP=1
      IF(DIA1.EQ. 0.)DIA1=5.0
      IF(GMASS1.EQ. 0.)GMASS1=50.
      CALL FANSUB(DIA1,GMASS1,IG,AFR,PWR1)
      GO TO(200,150,160,180),IOP
C
150   READ(5,170,END=1000)DHEAT(1),HTHPD(1),HTTIME(1),HTEMP(1),HSTAT(1)
C   ******************************************************************
C   * READ AMOUNT OF HEAT ADDED TO THE AIR BY THE HEATER, DHEAT(DEGREES *
C   * CELSIUS TEMPERATURE INCREASE), MAXIMUM NUMBER OF HOURS PER DAY    *
C   * THAT THE HEATER IS TO OPERATE, HTHPD(MUST BE A MULTIPLE OF IDELT--*
C   * USE 24 TO ALLOW TOTAL CONTROL BY THERMOSTAT AND/OR HUMIDISTAT),   *
C   * TIME OF DAY THAT THE HEATER IS TO BE TURNED ON, HTTIME(24 HOUR    *
C   * CLOCK --MUST BE A MULTIPLE OF IDELT-- USE 50 TO ALLOW CONTROL BY  *
C   * OTHER CONTROLS), TEMPERATURE SETTING ON THE THERMOSTAT, HTEMP     *
C   * (HEATER OPERATES WHEN THE AVERAGE TEMP FOR THE TIME INTERVAL IS   *
C   * BELOW THIS SETTING-- USE 100 IF THIS CONTROL IS NOT DESIRED), AND *
C   * SETTING ON THE HUMIDISTAT, HSTAT(% RELATIVE HUMIDITY-- HEATER     *
C   * OPERATES WHEN THE AVERAGE RH IS ABOVE THIS SETTING. USE 0 IF THIS *
C   * CONTROL IS NOT DESIRED).                                          *
C   ******************************************************************
      IF(DHEAT(1) .EQ. 0. .OR. HTHPD(1) .EQ. 0.) IOP=1
      CALL HRNORM(IDELT,HTHPD(1))
      HTTIME(1)=AINT(HTTIME(1)/IDELT)*IDELT+1.
      IF(HTTIME(1).EQ.24.)HTTIME(1)=0.
      IF(HTTIME(1).EQ.25.)HTTIME(1)=1.
      IF(HSTAT(1).LT.1.)HSTAT(1)=HSTAT(1)*100.
      GO TO 200
C
160   DO 165 I=1,3
165   READ(5,170,END=1000)STPDT(I),HRPDAY(I),DAYPWK(I),TIME(I),TEMP(I),
     +RHSTAT(I),GRNTMP(I),DHEAT(I),HTHPD(I),HTTIME(I),HTEMP(I),HSTAT(I)
C   ******************************************************************
C   * 3 CARDS ARE REQUIRED-- 1 FOR FAN & HEATER OPERATION DURING THE    *
C   * FALL, 1 FOR THEIR CONTROL SETTINGS DURING THE WINTER, AND THE     *
C   * THIRD FOR THE SPRING OPERATION PERIOD.                            *
C   * READ STOP DATE FOR THESE SETTINGS, STPDT(MONTH & DAY, EG. 1030--  *
C   * DATE WHEN CONTROLS CAN BE RESET FOR WINTER OR SPRING OPERATION),  *
C   * MAXIMUM NUMBER OF HOURS PER DAY THAT THE FAN IS TO OPERATE, HRPDAY*
C   * (TIME CLOCK  CONTROL -- SAME AS HTHPD ON HEATER, BUT ZERO DEFAULTS*
C   * TO 24 HOURS), NUMBER OF DAYS PER WEEK THAT THE FAN IS TO BE       *
C   * OPERATED FOR SPECIFIED HOURS PER DAY, DAYPWK (1 TO 7 DAYS), TIME  *
C   * OF DAY THAT THE FAN IS TO BE TURNED ON. TIME(SAME TIME CLOCK      *
C   * CONTROL AS HTTIME FOR HEATER),  TEMPERATURE SETTING ON THE THERMO-*
C   * STAT FOR THE FAN, TEMP(EQUIVALENT TO HTEMP), HUMIDITY SETTING FOR *
C   * THE FAN, RHSTAT(% RELATIVE HUMIDITY-- FAN OPERATES WHEN THE       *
C   * AVERAGE RH IS BELOW THIS SETTING-- USE 100 IF THIS CONTROL NOT    *
C   * DESIRED). TEMPERATURE SETTING FOR GRAIN AERATION, GRNTMP(IN CASE  *
C   * OF HEATING IN THE GRAIN, THE FAN OPERATES WHEN THE GRAIN TEMP IS  *
C   * ABOVE THIS LEVEL, AND CONTINUES UNTIL IT FALLS BELOW IT AGAIN--   *
C   * DESIGNED FOR WINTER OPERATION-- OVERRIDES ALL OTHER CONTROLS. USE *
C   * 100 IF THIS CONTROL NOT DESIRED), AND OTHER PARAMETERS FOR HEATER *
C   * OPERATION, DHEAT, HTHPD, HTTIME, HTEMP, AND HSTAT.                *
C   ******************************************************************
      IF(STPDT(1).EQ.0.)STPDT(1)=1201.
      IF(STPDT(2).EQ.0.)STPDT(2)=401.
      IF(STPDT(3).EQ.0.)STPDT(3)=801.
C  DEFAULT VALUES
      GO TO 200
170   FORMAT(12F4.0)
C
```

```
180   READ(5,170,END=1000)STEMP,SDATE,RSTEMP,RSDT,HRPDAY(2),
     +DAYPWK(2),TIME(2),TEMP(2),RHSTAT(2),GRNTMP(2)
C   *****************************************************************
C   * READ STOP TEMPERATURE, STEMP, & STOP DATE, SDATE (WHEN AVERAGE    *
C   * AMBIENT TEMPERATURE FOR ONE WEEK HAS BEEN BELOW THIS LEVEL, AND   *
C   * IF THE DATE IS AFTER SDATE, CONTINUOUS FAN AND HEATER OPERATION   *
C   * IS SUSPENDED), RESTART TEMPERATURE & RESTART DATE, RSTEMP, RSDT   *
C   * (WHEN THE AVERAGE TEMP HAS BEEN ABOVE THIS LEVEL FOR A WEEK, AND  *
C   * IF THE DATE IS AFTER RSDT, CONTINUOUS FAN & HEATER OPERATION IS   *
C   * RESUMED. RSDT IS THE MONTH AND DAY), AND OTHER PARAMETERS FOR FAN *
C   * OPERATION DURING DURING THE WINTER SHUT-DOWN TIME, HRPDAY (ZERO   *
C   * DEFAULTS TO 2 HOURS PER DAY), DAYPWK, TIME, TEMP, RHSTAT, GRNTMP, *
C   *****************************************************************
      IF(SDATE.EQ.0.)SDATE=1101.
      IF(RSDT.EQ.0.)RSDT=401.
      IF(HRPDAY(2).EQ.0.)HRPDAY(2)=2.
      IF(DAYPWK(2).EQ.0.)DAYPWK(2)=7.
      IF(RHSTAT(2).EQ.0.)RHSTAT(2)=100.
      IF(RHSTAT(2).LT.1.)RHSTAT(2)=RHSTAT(2)*100.
C
200   IF(GRNPRC.EQ. 0.)GRNPRC=110.
      IF(ELCOST.EQ.0.)ELCOST=2.
      IF(AW(1).GT.YR)REWIND14
      IF(SC.GT. 0. .AND. AW(1).GT.YR)REWIND13
      IF(IG .GT. 2)IG=0
      IF(XMF.EQ.0. .AND. IG.EQ.0)XMF=14.5
      IF(XMF.EQ.0. .AND. IG.EQ.1)XMF=14.8
      IF(XMF.EQ.0. .AND. IG.EQ.2)XMF=15.5
C  DEFAULT VALUES
      CALL HRNORM(IDELT,0.)
      ISAVE=IDELT
      HOUR=AINT(HOUR/IDELT)*IDELT
      IF(HOUR.EQ.24.)HOUR=0.
      HARV=AM*10000.+DAY*100.+HOUR
C
210   DT=YR*10000.+AM*100.+DAY
      IF(SC.EQ.0.)GO TO 240
220   READ(13,230,END=750)D
230   FORMAT(9X,F6.0)
      IF(D.LT.DT)GO TO 220
      BACKSPACE13
240   READ(14,250,END=750)CC
250   FORMAT(5X,F2.0)
      IF(CC.LT.YR)GO TO 240
260   READ(14,270,END=750)D
270   FORMAT(7X,F6.0)
      IF(D.LT.HARV)GO TO 260
C  FINDS SPECIFIED STARTING DATE ON TAPE(S)
      READ(14,280,END=750)(DATE(I),I=1,4),TEMPA
280   FORMAT(5X,4F2.0,30X,F3.0)
      BACKSPACE14
      IF(GO.LT.10.)GO=(TEMPA-32.)/1.8+GO
      IF(SC.EQ.0.)WRITE(6,290)
290   FORMAT('-','NATURAL AIR DRYING')
      IF(SC.GT.0.)WRITE(6,300)
300   FORMAT('-','SOLAR HEATED AIR DRYING')
      IF(IG.EQ.0) WRITE(6,310)
      IF(IG.EQ.1) WRITE(6,320)
      IF(IG.EQ.2) WRITE (6,330)
310   FORMAT('+',24X,'--WHEAT')
320   FORMAT('+',24X,'--BARLEY')
330   FORMAT('+',24X,'--CORN')
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      IF(IOP.EQ.1)WRITE(6,335)
335   FORMAT('+',33X,'  CONTINUCUS FAN (& HEATER) OPERATION')
      IF(XMO .LT. 1.)XMO=XMO*100.
      IF(XMF .LT. 1.)XMF=XMF*100.
      IDELT=ISAVE
      DELT=IDELT
      WRITE(6,340)XMC,XMF,GO,(DATE(I),I=1,4),AFR,SC,FANHT,DHEATC,FAT,
     +DELT
340   FCRMAT('0    WBO    WBF    GO     START DATE     AFR    SC    FANH
     +T  HEATR  FAT   DELT'/' ',3F7.1,3X,4F3.0,F7.2,4F7.1,F7.0)
      IF(IOP.EQ.2)WRITE(6,345)DHEAT(1),HTHPD(1),HTTIME(1),HTEMP(1),
     +HSTAT(1)
345   FORMAT('OCONTINUCUS FAN WITH FCLLCWING HEATER CONTROLS--'/' HEAT
     + HRS/DAY  TIME START  THERM   HUMID'/' ',F5.0,F8.0,2F10.0,F8.0)
      IF(IOP.EQ.4)WRITE(6,350)STEMP,SDATE,RSTEMP,RSDT,HRPDAY(2),
     +DAYPWK(2),TIME(2),TEMP(2),RHSTAT(2),GENTMP(2)
350   FCRMAT('OCONTINUCUS FAN (& HEATER) OPERATION UNTIL AVG WEEKLY TEMP
     + IS BELOW',F5.0,' DEG.CELSIUS, IF DATE IS AFTER',F6.0/' AND RESUME
     +D WHEN TEMP IS ABOVE',F5.0,'DEG.CELSIUS, IF DATE IS AFTER',F6.0,
     +'  DURING WINTER, FAN CONTROLS ARE AS FOLLOWS--'/'        HRS/DAY
     +  DAYS/WK  TIME START    THERM   HUMID  GENTEMP'/' ',4F11.0,2F8.0)
360   FORMAT('ODATE & TIME    FANH    HTRH    WB(MIN)    WBAVE    WB(MAX)
     +   GT(1)    GTAVE   GT(10)   %ALL.TIME    %DM(MAX)   TAIR    TDPT
     +RAD''N'/'+___________  ____   ____   _______   _____   _______
     +    _____  _____  ______  _________  ________  ____   ____
     + _____')
C  WRITES HEADINGS FOR OUTPUT
      PTIME=0.
      R=870./(AFR*60.*DELT*12.)
      IF(FAT.GE.1.)FAT=FAT/100.
      IND=1
      ISP=0
      IAV=0
      JDAY=0
      KK=0
      FANH=0.
      HTRH=0.
      FANHR=0.
      HTRHR=0.
      DAYNO=0.
      WKFNHR=0.
      TRAD=0.
      TLRAD=0.
      SCLHT=0.
      N5=0
      NC=0
      TAIR=0.0
      TDPT=0.0
C  INITIALIZATION CF VARIABLES
      DO 370 I=1,10
      PER(I)=FAT
C        PER(I)= PERCENT OF ALLOWABLE STORAGE TIME FOR LAYER I
      XM(I)=XMO
C        MOISTURE CONTENT OF EACH LAYER IS SET TO INITIAL GRAIN M.C.
      DM(I)=(XMO*100.)/(100.-XMO)
C        M.C. OF EACH LAYER IS SET TO INITIAL GRAIN M.C. ON DRY WT. BASIS
370   G(I)=GO
C        TEMP. OF EACH LAYER IS SET TO INITIAL GRAIN TEMP.
C
380   IF(IOP.NE.3)GO TC 395
      KR=IDELT
      IDELT=ISAVE
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      IF(KR.NE.IDELT)WRITE(6,385)KR,IDELT
385   FORMAT('0TIME INTERVAL CHANGED FROM',I3,' HOURS TO',I3,' HOURS')
      IF(HRPDAY(IND).EQ.0.)HRPDAY(IND)=24.
      IF(DAYPWK(IND).EQ.0.)DAYPWK(IND)=7.
      IF(RHSTAT(IND).EQ.0.)RHSTAT(IND)=100.
      CALL HRNORM(IDELT,HRPDAY(IND))
      CALL HRNORM(IDELT,HTHPD(IND))
      TIME(IND)=AINT(TIME(IND)/IDELT)*IDELT+1.
      IF(TIME(IND).EQ.24.)TIME(IND)=0.
      IF(TIME(IND).EQ.25.)TIME(IND)=1.
      HTTIME(IND)=AINT(HTTIME(IND)/IDELT)*IDELT+1.
      IF(HTTIME(IND).EQ.24.)HTTIME(IND)=0.
      IF(HTTIME(IND).EQ.25.)HTTIME(IND)=1.
      DELT=IDELT
      NC=NO*KR/DELT
      IF(RHSTAT(IND).LT. 1.)RHSTAT(IND)=RHSTAT(IND)*100.
      IF(HSTAT(IND).LT.1.)HSTAT(IND)=HSTAT(IND)*100.
      R=870./(AFR*60.*DELT*12.)
      WRITE(6,390)STPDT(IND),HRPDAY(IND),DAYPWK(IND),TIME(IND),
     +TEMP(IND),RHSTAT(IND),GRNTMP(IND),DHEAT(IND),HTHPD(IND),
     +HTTIME(IND),HTEMP(IND),HSTAT(IND)
390   FORMAT('0FOLLOWING CONTROLS ON FAN & HEATER ARE OPERATIONAL UNTIL'
     +,F6.0/' FAN-- HRS/DAY   DAYS/WK  TIME START    THERM   HUMID  GRNT
     +EMP'/' ',F11.0,F10.0,2F11.0,2F8.0/' HEATER-- HEAT   HRS/DAY  TIME
     +START    THERM   HUMID'/' ',F13.1,F8.0,2F11.0,F8.0)
395   WRITE(6,360)
C  ..........          ..........          ..........          ..........
400   NC=NO+1
      INV=24/IDELT
      TINV=INV
      NJ=NC-1
      RAD=0.
403   CALL READWR(IDELT,DATW,TP,TD,RH,AW,&750)
C  READ AIR TEMPERATURES FOR TIME INTERVAL
      IF(SC.EQ.0.)GO TO 408
      IF(NJ/TINV.EQ.NJ/INV)CALL READRN(N5,DATW,&403,SOL,&750)
C  READ RADIATION DATA ONCE PER DAY
      ID=AW(4)
      IF(ID.EQ.0)ID=24
      IFR=ID-IDELT+1
      DO 405 I=IFR,ID
405   RAD=RAD+SOL(I)
      SOLHT=SC*TINV*RAD*0.001
      TRAD=TRAD+RAD*4.184
408   TAIR=TAIR+TP
      TDPT=TDPT+TD
      TIMS=AW(4)-DELT+1.
      IF(AW(4).EQ.0.)TIMS=24.-DELT+1.
      IF(TIMS .NE. (HOUR+1.) .OR. JDAY .NE. 1)GO TO 409
      DAYNO=DAYNO+1.
      JDAY=0
409   GO TO(450,440,410,410),IOP
410   IF(IOP .EQ. 4 .AND. IND .NE. 2)GO TO 450
      CALL MAX(10,G,LH,HOT)
      IF(KK.GT.0 .AND. HOT.LE.GRNTMP(IND))GO TO 425
      IF(HOT .LE. GRNTMP(IND))GO TO 430
      KK=KK+1
      IF(KK.GT.1)GO TO 420
      WRITE(6,415)LH,HOT
415   FORMAT(' GRAIN IN LAYER',I3,' IS',F4.0,' DEG.CELSIUS-- AERATION WI
     +TH UNHEATED AIR IS BEGUN')
      TC=TP+FANHT
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      AIRHR=DELT
      GO TO 460
420   TC=TP+FANHT
      AIRHR=AIRHR+DELT
      GO TO 460
425   KK=0
      WRITE(6,428)AIRHR,HOT,LH
428   FORMAT(' AFTER',F5.0,' HOURS OF AERATION WITH UNHEATED AIR, THE MA
     +XIMUM GRAIN TEMPERATURE IS',F4.0,' IN LAYER',I3)
430   IF(TIME(IND).GT.24.)GO TO 435
      IF(TIMS.EQ.TIME(IND))FANHR=0.
      IF(FANHR.GE.HRPDAY(IND))GO TO 480
435   IF(DAYNO.GT.DAYPWK(IND))GO TO 480
      IF(WKFNHR.GE.(HRPDAY(IND)*DAYPWK(IND)))GO TO 480
      IF(TP.GT.TEMP(IND) .OR. RH.GT. RHSTAT(IND))GO TO 480
      IF(IOP.EQ.3)GO TO 440
      TO=TP+FANHT
      GO TO 460
440   IF(HTTIME(IND).GT.24.)GO TO 442
      IF(TIMS.EQ.HTTIME(IND))HTRHR=0.
      IF(HTRHR.GE.HTHPD(IND))GO TO 445
442   IF(TP.GT.HTEMP(IND) .OR. RH.LT.HSTAT(IND))GO TO 445
      IF(DHEAT(IND).EQ.0.)SOLHT=0.
      TO=TP+DHEAT(IND)+SOLHT+FANHT
      HTRH=HTRH+DELT
      HTRHR=HTRHR+DELT
      GO TO 460
445   TC=TP+SOLHT+FANHT
      IF(DHEAT(IND).EQ.0.)TC=TP+FANHT
      GO TO 460
450   TO=TP+SOLHT+FANHT+DHEATC
      IF(DHEATC.GT.0.)HTRH=HTRH+DELT
460   CALL DRYSIM(TO,TD,AVEM,AVET)
C  SIMULATES DRYING FOR ONE TIME INTERVAL
      FANHR=FANHR+DELT
      FANH=FANH+DELT
      WKFNHR=WKFNHR+DELT
      JDAY=1
      CALL MIN(10,XM,N1,DRY)
C       TO DETERMINE AND IDENTIFY THE DRIEST LAYER
      CALL MAX(10,XM,N2,WET)
C       TO DETERMINE AND IDENTIFY THE WETTEST LAYER
480   PTIME=PTIME+DELT
      IF(IG.EQ.2)GO TO 520
      DO 510 I=1,10
      WT=SAFWH(G(I),XM(I))
510   PER(I)=PER(I)+DELT/WT
      CALL MAX(10,PER,N3,PCTM)
      GO TO 540
520   DO 530 I=1,10
      Z=SAFES(G(I),XM(I))
530   PER(I)=PER(I)+DELT/Z
      CALL MAX(10,PER,N3,PCTM)
540   EQT=PCTM*230.
      PERDM=.0883*(EXP(.006*EQT)-1.)+.00102*EQT
C  PREDICTS GRAIN QUALITY
      P=PCTM*100.
      IF(PERDM.LT. 0.5)GO TO 544
      IF(ISP .EQ. 1 .AND. PERDM .LT. 1.0)GO TO 544
      IF(ISP .EQ. 0)GO TO 543
      NOTE=6
      GO TO 600
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C  HAS GRAIN PASSEC ALLOWABLE STORAGE TIME?
543   ISP=1
      NOTE=1
      GC TO 600
544   IF(AVEM.GE.XMF .CR. WET.GE.(XMF+2.5))GO TO 545
      IF(IAV.EQ.1)GO TO 545
      IAV=1
      NOTE=7
      GC TC 600
C  IS THE BIN AVERAGE MOISTURE CONTENT DRY?
545   IF(WET.GT.XMF)GO TO 550
      NOTE=2
      GO TC 600
C  IS THE WETTEST LAYER DRY ?
550   IF(ICP.NE.3)GC TO 555
      DT1=AW(1)*10000.+AW(2)*100.+AW(3)
      X=YR
      IF(IND.GE.2)X=YR+1.
      DT2=X*10000.+STPCT(IND)
      IF(DT1.LT.DT2)GO TO 555
      NOTE=3
      TO=TP
      GC TO 600
C  TIME TO RESET CONTRCLS?
555   INTWEK=24/IDELT*7
      WEEKIN =24./DELT*7.
      IF(NO/WEEKIN  .NE. NC/INTWEK )GO TO 400
C  TIME TO PRINT? (ONCE PER WEEK)
C
      CAYNO=0.
      WKFNHR=0.
      JDAY=1
      TO=TAIR/WEEKIN
      TD=TDPT/WEEKIN
      TAIR=0.0
      TDPT=0.0
      WRITE(6,610)(AW(I),I=1,4),FANH,HTRH,DRY,N1,AVEM,WET,N2,G(1),AVET,
     +G(10),P,N3,PERDM,TO,TC,TRAD
      TLRAD=TLRAD+TRAD/100.
      TRAD=0.
      IF(PTIME.GT. 8550.)GC TO 700
      IF(ICP.NE.4)GO TC 400
C
      GO TO(560,580,400),IND
560   IF(TO.GE.STEMP)GC TO 400
      DT=AW(2)*100.+AW(3)
      IF(DT.LT.SDATE)GC TO 400
      IND=2
      WRITE(6,570)
570   FORMAT('0CONTINUOUS FAN & HEATER OPERATION SUSPENDED FOR THE WINTE
     +R')
      KR=IDELT
      CALL HRNORM(IDELT,HRPDAY(2))
      DELT=IDELT
      NC=NC*KR/DELT
      FT=TIME(2)
      TIME(2)=AINT(TIME(2)/IDELT)*IDELT+1.
      IF(TIME(2).EQ.24.)TIME(2)=0.
      IF(TIME(2).EQ.25.)TIME(2)=1.
      IF(FT.NE.TIME(2))WRITE(6,575)FT,TIME(2)
575   FORMAT('0FAN TIME START CHANGED FROM',F4.0,' TO',F4.0)
      R=870./(AFR*60.*DELT*12.)
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      NOTE=4
      GO TO 620
580   IF(AW(1).EQ.YR)GO TO 400
      DT2=AW(2)*100.+AW(3)
      IF(TO.LE.RSTEMP .OR. DT2.LT.RSDT)GO TO 400
      IND=3
      WRITE(6,590)
590   FORMAT('0CONTINUOUS FAN & HEATER OPERATION RESUMED')
      KR=IDELT
      IDELT=ISAVE
      DELT=IDELT
      IF(KR.NE.IDELT)WRITE(6,595)KR,IDELT
595   FORMAT('0TIME INTERVAL CHANGED FROM',I3,' HOURS TO',I3,' HOURS')
      R=870./(AFR*60.*DELT*12.)
      NOTE=4
      GO TO 620
C  ..........            ..........            ..........            ..........
600   WRITE(6,610)(AW(I),I=1,4),FANH,HTRH,DRY,N1,AVEM,WET,N2,G(1),AVET,
     +G(10),P,N3,PERDM,TO,TC,TRAD
610   FORMAT('0',4F3.0,2F7.0,F7.2,'(',I2,')',2F8.2,'(',I2,')',2F8.2,
     +F9.2,F8.2,'(',I2,')',F10.4,2F8.2,F8.0)
      IF(NOTE .GT. 1 .AND. NOTE .LT. 5)IND=IND+1
      IF(IND.GT.3 .AND. NOTE.EQ.3)NOTE=5
620   ENRG1=PWR1*FANH*3.6
      EPT1=ENRG1/GMASS1
      CA1=413.*SC*AFR*2.*GMASS1*.0001
      WRITE(6,630)DIA1,GMASS1,ENRG1,EPT1
630   FORMAT('0ENERGY USED TO DATE BY THE FAN FOR A ',F5.1,' M. DIAMETER
     + BIN WITH ',F5.0,' TONNES OF GRAIN, IS ',F8.0,' MEGAJOULES, OR',
     +F7.0,' MJ/TONNE')
      IF(SC.EQ.0.)GO TO 645
      TLRAD=TLRAD+TRAD/100.
      RDNBN1=CA1*TLRAD/2.
      TRAD=0.
      WRITE(6,640)TLRAD,RDNBN1,CA1
640   FORMAT('0TOTAL RADIATION RECEIVED ON A HORIZONTAL SURFACE SINCE TH
     +E START OF DRYING =',F7.0,' MJ/SQ.M., OR'/' ',F7.0,' MEGAJOULES
     +COLLECTED BY THIS SYSTEM ASSUMING 50% COLLECTOR EFFICIENCY'/' ',
     +'(THIS SYSTEM HAS A COLLECTOR AREA OF ',F6.2,' SQ. METRES)')
645   IF(NOTE.EQ. 2 .OR. NOTE.EQ. 7)GO TO 800
C
646   GO TO (650,670,380,400,658,720,740),NOTE
650   WRITE(6,655)
655   FORMAT('0********** ALLOWABLE STORAGE TIME EXCEEDED **********')
658   DO 660 I=1,10
660   PCTDM(I)=0.0883*(EXP(.006*PER(I)*230.)-1.)+.00102*PER(I)*230.
      WRITE(6,665)(XM(I),I=1,10),(PCTDM(I),I=1,10),PTIME
665   FORMAT('0MOISTURE CONTENT AND %D.M. DECOMPOSITION OF EACH LAYER'/'
     + M.C.',10F10.2/' %D.M.',10F10.4/'0TOTAL HOURS ELAPSED SINCE START
     +OF DRYING=',F6.0)
      IF(NOTE.EQ.5)GO TO 700
      IF(PERDM.LT. 1.0 .AND. WET.GT.XMF)GO TO 544
      GO TO 700
670   IF(PERDM .GE. 0.5)GO TO 730
      WRITE(6,680)
680   FORMAT('0********** GRAIN DRIED SUCCESSFULLY **********')
      WRITE(6,690)(XM(I),I=1,10),PTIME
690   FORMAT('0MOISTURE CONTENT OF EACH LAYER'/' ',10F10.2/'0TOTAL HOURS
     + ELAPSED SINCE START OF DRYING=',F6.0)
700   WRITE(6,710)
710   FORMAT('0-----------------------------------------------------------
     *-----------------------------------------------------------------')
```

```
      YR=YR+1.
      IF(YR.LE.STPYR)GO TO 210
      GO TO 140
720   WRITE(6,725)
725   FORMAT('0********** TOP GRAIN COMPLETELY SPOILED **********')
      GO TO 658
730   WRITE(6,735)
735   FORMAT('0********** GRAIN DRIED WITH SPOILAGE **********')
      SPLGCT=0.
      DO 737 I=1,10
      PCTDM(I)=0.0883*(EXP(.006*PER(I)*230.)-1.)+.00102*PER(I)*230.
      IF(PCTDM(I).GT. 0.5)SPLGCT=SPLGCT+(PCTDM(I)/0.5)**4*0.005*GMASS1
     */10.*GRNPRC
737   CONTINUE
      WRITE(6,738)(XM(I),I=1,10),(PCTDM(I),I=1,10),SPLGCT
738   FORMAT('0MOISTURE CONTENT AND %D.M. DECOMPOSITION OF EACH LAYER'/'
     + M.C.',10F10.2/' %D.M.',10F10.4/'0PENALTY FOR SPOILAGE IS $',F7.2)
      GO TO 700
740   WETAL=XMF+2.5
      WRITE(6,745)XMF,WETAL
745   FORMAT('0***** AVERAGE MOISTURE CONTENT OF THE GRAIN IS LESS THAN'
     +,F5.1,' %M.C. AND WETTEST LAYER IS LESS THAN',F5.1,' %M.C. *****')
      GO TO 658
750   WRITE(6,760)
760   FORMAT(' END OF TAPE')
      GO TO 140
800   COD=0.
      DO 805 I=1,10
805   COD=COD+(XMF-XM(I))/(100.-XM(I))*GMASS1/10.*GRNPRC
      FANCST=PWR1*FANH*ELCCST/100.
      WRITE(6,810)FANCST,COD
810   FORMAT('0COST OF RUNNING THE FAN TO DATE IS $',F7.2,', WHILE OVERD
     +RYING THE GRAIN HAS COST $',F7.2)
      GO TO 646
1000  STOP
      END
C  **********           **********           **********           **********
      SUBROUTINE MIN(N,A,J,SMALL)
C  SUBROUTINE FINDS AND IDENTIFIES THE SMALLEST VALUE IN THE ARRAY A
      DIMENSION A(10)
      SMALL=A(1)
      J=1
      DO 10 I=2,N
      IF(A(I).GE.SMALL)GO TO 10
      SMALL=A(I)
      J=I
10    CONTINUE
      RETURN
      END
C  **********           **********           **********           **********
      SUBROUTINE MAX(N,A,J,BIG)
C  SUBROUTINE FINDS AND IDENTIFIES THE LARGEST VALUE IN THE ARRAY A
      DIMENSION A(10)
      BIG=A(1)
      J=1
      DO 10 I=2,N
      IF(A(I).LE.BIG) GO TO 10
      BIG=A(I)
      J=I
10    CONTINUE
      RETURN
      END
```

```
C    **********          **********          **********          **********
      SUBROUTINE DRYSIM(TO,TD,AVEM,AVET)
C    SUBROUTINE SIMULATES DRYING FOR ONE TIME INTERVAL
      DOUBLE PRECISION AHUM
      COMMON /AREA1/XM(10),G(10),DM(10),IG,R
      DIMENSION T(11),H(11),A(4)
      DATA A/4*0./
      J=1
      HO=AHUM(TD,1)
      T(1)=TO
C        TO= AMBIENT AIR TEMPERATURE
      H(1)=HO
C        HO= AMBIENT AIR ABSOLUTE HUMIDITY
      SUMM=0.0
      SUMT=0.0
C
      DO 240 I=1,10
      IPRT=-1
      IJ=I+1
      IF(IG.EQ.0)C=SPHT(G(I),DM(I))*R/(1.-XM(I)/100.)
      IF(IG.EQ.1)C=((1.07211+0.04356*XM(I))*R)/(1.-XM(I)/100.)
      IF(IG.EQ.2)C=((1.4644+0.035606*XM(I))*R)/(1.-XM(I)/100.)
C          C IS THE SPECIFIC HEAT OF THE GRAIN
140   N=0
      HF=HO
      IPRT=IPRT+1
200   T(IJ)=(C*G(I)+(HF-H(I))*G(I)*4.184-2501.49*HF+1.005*T(I)+H(I)
     1*(2501.49+1.82*T(I)))/(1.005+HF*1.82+C)
      XMI=DM(I)-100.*(HF-H(I))/R
      IF(XMI.LT..001)XMI=.001
      PS=AHUM(T(IJ),2)
      IF(IG.EQ.0)ERH=EXP(2.40*EXP(-.205*XMI)*ALOG(PS)-10.17*EXP(-.186
     .*XMI))
      IF(IG.EQ.1)ERH=EXP(1.5379*EXP(-.1774*XMI)*ALOG(10.*PS)
     1-9.4132*EXP(-.1565*XMI))
      IF(IG.EQ.2)ERH=1.-EXP(-3.82E-5*(1.8*T(IJ)+82.)*XMI**2)
C         ERH IS THE EQUILIBRIUM RELATIVE HUMIDITY OF THE GRAIN.
C
      TAB=T(IJ)
      RHS=RHAIR(TAB,HF)
      Y=ERH-RHS
      IF(IPRT.LE.0)GO TO 220
      WRITE(6,210)T(IJ),XMI,HF,Y,J,N,MM,A
210   FORMAT(5X,4F10.5,3I4,4F10.5)
C
220   CALL ZERO(J,0.0,HF,Y,A,.025,K,N,MM)
      IF(N.EQ.1) HF=(HF+HO)/2.
      IF(N.GE.20.AND.IPRT.LE.0)GO TO 140
      GO TO (200,230),K
C         K IS A CONVERGENCE INDICATOR
230   DM(I)=XMI
      XM(I)=(100.*DM(I))/(100.+DM(I))
      G(I)=T(IJ)
      H(IJ)=HF
      SUMT=SUMT+G(I)
240   SUMM=SUMM+XM(I)
C
      AVET=SUMT/10.
      AVEM=SUMM/10
C       AVEM IS THE AVERAGE MOISTURE CONTENT OF THE GRAIN BULK.
      RETURN
      END
```

```
C   **********          **********          **********          **********
      SUBROUTINE READRN(NO,DATW,*,SOL,*)
C   SUBROUTINE READS THE DATA FROM THE RADIATION TAPE AND FILLS IN ANY
C   MISSING DATA
      DIMENSION DATS(4),M(96),SOL(24),RAD(96),MD(4)
      DATA MISS/'M'/
      NN=0
      JJ=1
      N=0
      L1=0
      IF(NO .GT. 0)GO TO 10
      I=1
      J=1
      GO TO 20
10    I=25
      J=2
20    READ(13,30,END=300)DATS(J),IC, RAD(I),M(I), RAD(I+1),M(I+1),
     + RAD(I+2),M(I+2), RAD(I+3),M(I+3), RAD(I+4),M(I+4), RAD(I+5),
     +M(I+5), RAD(I+6),M(I+6), RAD(I+7),M(I+7), RAD(I+8),M(I+8),
     + RAD(I+9),M(I+9), RAD(I+10),M(I+10), RAD(I+11),M(I+11)
      IF(IC.NE.1)GO TO 20
25    READ(13,30,END=300)DATS(J),IC, RAD(I+12),M(I+12), RAD(I+13),
     +M(I+13), RAD(I+14),M(I+14), RAD(I+15),M(I+15), RAD(I+16),M(I+16),
     + RAD(I+17),M(I+17), RAD(I+18),M(I+18), RAD(I+19),M(I+19),
     + RAD(I+20),M(I+20), RAD(I+21),M(I+21), RAD(I+22),M(I+22),
     + RAD(I+23),M(I+23),MD(J)
30    FORMAT(9X,F6.0,3X,I1,F3.1,A1,F3.1,A1,F3.1,A1,F3.1,A1,F3.1,A1,F3.1,
     +A1,F3.1,A1,F3.1,A1,F3.1,A1,F3.1,A1,F3.1,A1,F3.1,A1,4X,A1)
      IF(DATS(J) .EQ. DATW .OR. N.GT.0)GO TO 40
      NN=NN+1
      IF(DATS(J).LT.DATW .AND. MD(J).NE. MISS)JJ=2
      IF(DATS(J).GT.DATW)JJ=3
      IF(NO.EQ.0)JJ=4
      IF(NN.GT.10)JJ=5
      GO TO(20,200,130,35,250),JJ
35    IF(DATS(J)-DATW)20,40,65
40    N=N+1
      JJ=0
      IF(NO.EQ.0 .AND. MD(J).EQ.MISS)GO TO 60
      IF(NO.EQ.0)GO TO 80
      IF(MD(J).NE.MISS)GO TO 200
      IF(L1.GT.0)GO TO 200
      IF(I.EQ.73)GO TO 200
50    I=I+24
      J=J+1
      GO TO 20
60    IF(N.GT.1 .AND. I.EQ.49)GO TO 20
      IF(N.GT.1)GO TO 80
65    DO 70 K=1,4
70    BACKSPACE13
      GO TO 20
80    IF(N.EQ.1)GO TO 110
      IF(I.EQ.49)GO TO 90
      I=49
      J=3
      GO TO 20
90    DO 100 K=1,24
      IF(M(K).EQ.MISS)SOL(K)= RAD(K+48)
      IF(M(K).NE.MISS)SOL(K)=( RAD(K)+ RAD(K+48))/2.
100   CONTINUE
      GO TO 240
110   DO 120 K=1,24
```

```
120   SOL(K)= RAD(K)
      GO TO 240
130   IJ=DATS(J)-DATW
      L1=2
      GO TO(140,160),IJ
      GO TO 65
140   DO 150 K=25,48
      RAD(K+24)= RAD(K)
150   M(K+24)=M(K)
      GO TO 65
160   DO 170 K=25,48
      RAD(K+48)=RAD(K)
170   M(K+48)=M(K)
      GO TO 65
200   DO 230 K=1,24
      IF(M(K+24).EQ.MISS)GO TO 210
      SOL(K)= RAD(K+24)
      GO TO 230
210   IF(M(K+48).EQ.MISS)GO TO 220
      SOL(K)=(SOL(K)+RAD(K+48))/2.
      GO TO 230
220   IF(M(K+72).EQ.MISS)GO TO 230
      SOL(K)=(SOL(K)+RAD(K+72))/2.
230   CONTINUE
      IF(JJ.GT.1)GO TO 20
240   NO=NO+1
      RETURN
250   WRITE(6,260)DATS(J),DATW
260   FORMAT(' RADIATION TAPE OUT OF LINE. DATS=',F7.0,' DATW=',F7.0)
      RETURN1
300   RETURN2
      END
C  **********          **********          **********          **********
      SUBROUTINE HRNORM(IDEL,HRS)
C     PURPOSE OF HRNORM IS TO ASSURE THAT ANY IDEL IS AN ALLOWABLE VALUE
C     (1,2,3,4,6,8,12, OR 24 HOURS) AND THAT ANY HRS IS A MULTIPLE OF IDEL
C     (IF HRS IS LESS THAN IDEL, IDEL BECOMES EQUAL TO HRS).
      J=IDEL
      T=HRS
      A=AINT(HRS/IDEL)
      B=HRS/IDEL
      IF(B.EQ.0.)GO TO 10
      IF(B.LE. 1.)A=1.
      IF(B.LE. 1.)IDEL=HRS
      IF((B-A).GE. 0.5)A=A+1.
10    IF(IDEL.EQ.0)IDEL=1
      IF(IDEL.LE.8)IDEL=24/(24/IDEL)
      IF(IDEL.GE.8 .AND. IDEL .LE.9)IDEL=8
      IF(IDEL.GT.9 .AND. IDEL.LT.18)IDEL=12
      IF(IDEL.GE.18)IDEL=24
      HRS=IDEL*A
      IF(IDEL.EQ.J)GO TO 30
      WRITE(6,20)J,IDEL
20    FORMAT('0TIME INTERVAL CHANGED FROM',I3,' HOURS TO',I3,' HOURS')
      IF(HRS.GT.0.)WRITE(6,25)HRS
25    FORMAT('+',50X,'(HRS/DAY=',F4.1,' HOURS)')
30    IF(HRS.EQ.T)RETURN
      WRITE(6,40)T,HRS,IDEL
40    FORMAT(' HOURS PER DAY CHANGED FROM ',F4.1,' HOURS TO ',F4.0,
     +' HOURS (TIME INTERVAL=',I3,' HOURS)')
      RETURN
      END
```

```
      SUBROUTINE READWR(ID,DATW,TO,TD,RH,AW,*)
C  SUBROUTINE READS THE DATA FROM THE WEATHER TAPE
      DIMENSION AD(24,4),AW(4),TDP(24),TP(24),REL(24)
      DELT=ID
10    READ(14,30,END=100)(AD(1,I),I=1,4),TDP(1),TP(1),REL(1)
      IF(AD(1,3).EQ.0. .OR. REL(1).GT.100.)GO TO 10
      COR=(AD(1,4)-1.)/DELT
      IF(COR.NE.AINT(COR))GO TO 10
      IF(TDP(1).LE.TP(1))GO TO 15
      TDP(1)=TP(1)-3.
      REL(1)=80.
15    IF(DELT.EQ.1.)GO TO 40
      DO 20 I=2,ID
      READ(14,30,END=100)(AD(I,J),J=1,4),TDP(I),TP(I),REL(I)
      IF(AD(I,3).EQ.0. .OR. REL(I).GT.100.)GO TO 35
      IF(TDP(I).LE.TP(I))GO TO 20
      TDP(I)=TP(I)-3.
      REL(I)=80.
20    CONTINUE
      GO TO 40
30    FORMAT(5X,4F2.0,18X,F3.0,9X,F3.0,3X,F3.0)
35    DO 38 J=I,ID
      READ(14,30,END=100)(AD(J,K),K=1,4),TDP(J),TP(J),REL(J)
      IF(TDP(J).LE.TP(J))GO TO 38
      TDP(J)=TP(J)-3.
      REL(J)=80.
38    CONTINUE
40    IN=ID/2+1
      IF((ID-IN).EQ.0 .AND. AD(ID,4).EQ.0.)GO TO 50
      DATW=AD(IN,1)*10000.+AD(IN,2)*100.+AD(IN,3)
50    DO 60 I=1,4
60    AW(I)=AD(ID,I)
      TO=TD=0.
      RH=0.
      DO 70 I=1,ID
      TO=TO+TP(I)
      TD=TD+TDP(I)
70    RH=RH+REL(I)
      TO=(TO/DELT-32.)/1.8
      TD=(TD/DELT-32.)/1.8
      RH=RH/DELT
      RETURN
100   RETURN1
      END
C  **********           **********           **********           **********
      DOUBLE PRECISION FUNCTION AHUM(TEMP,N)
C  SUBROUTINE CALCULATES THE SATURATION VAPOUR PRESSURE OR THE
C  ABSOLUTE HUMIDITY OF THE AIR AT THE GIVEN TEMPERATURE
      DOUBLE PRECISION A,B,C,D,E,F,G,PW,T,DEXP,DLOG
      DATA A,B,C,D/-.751152D4, .896312102, .02399897000,-.11654551D-4/
      DATA E,F,G/-.12810336D-7, .20998405D-10,-.12150799D02/
      T=TEMP + 273.16D0
      IF(TEMP.GT.0.) GO TO 1
      PW=DEXP(24.2779D0-6238.64D0/T-0.344438D0*DLOG(T))
      IF(N.EQ.1) AHUM=0.62198D0*PW/(101.325D0-PW)
      IF(N.EQ.2) AHUM=PW
      RETURN
1     PW=DEXP(A/T+B+C*T+D*T**2+E*T**3+F*T**4+G*DLOG(T))
      IF(N.EQ.1) AHUM=0.62198D0*PW/(101.325D0-PW)
      IF(N.EQ.2) AHUM=PW
      RETURN
      END
```

```
C  **********          **********          **********          **********
      FUNCTION RHAIR(T,HO)
C  SUBROUTINE CALCULATES THE RELATIVE HUMIDITY OF THE AIR AT THE
C  SPECIFIED TEMPERATURE AND ABSOLUTE HUMIDITY
      DOUBLE PRECISION H,PS,AHUM
      H=HO
      PS=AHUM(T,2)
      RHAIR=(101.325D0*H/(H+.62198D0))/PS
      RETURN
      END
C  **********          **********          **********          **********
      FUNCTION SPHT(TEMP,DBMC)
C  SUBROUTINE CALCULATES THE SPECIFIC HEAT OF WHEAT FOR THE GIVEN
C  TEMPERATURE AND MOISTURE CONTENT
      IF(TEMP.LE.-21.4)GO TO 5
      IF(TEMP.LE.-10.8)GO TO 10
      IF(TEMP.LE.0.6)GO TO 15
      IF(TEMP.LE.8.9)GO TO 20
C
      SPHT=1.1422+0.03904*DBMC
      RETURN
5     SPHT=1.046+0.03109*DBMC
      RETURN
10    SPHT=1.1673+0.02427*DBMC
      RETURN
15    SPHT=1.2426+0.02962*DBMC
      RETURN
20    SPHT=1.0251+0.04427*DBMC
      RETURN
      END
C  **********          **********          **********          **********
      FUNCTION SAFWH(TEMP,XMC)
C  SUBROUTINE CALCULATES THE ALLOWABLE STORAGE TIME FOR WHEAT AT THE
C  GIVEN TEMPERATURE AND MOISTURE CONTENT
      ALOGT1=6.23447 -0.21175*XMC -0.05267*TEMP
      ALOGT2= 4.12855 -0.09972*XMC -0.05762*TEMP
      SAFWH=AMAX1(10.**ALOGT1,10.**ALOGT2)*24.0
      RETURN
      END
C  **********          **********          **********          **********
      FUNCTION SAFES(TEMP,WB)
C  SUBROUTINE CALCULATES THE ALLOWABLE STORAGE TIME FOR CORN AT THE
C  GIVEN TEMPERATURE AND MOISTURE CONTENT
      T=TEMP*1.8+32.
      W=WB
      IF(W .LE. 1)W=W*100.
      DM=1.0
      TR=230.0
      DB=W/(100.-W)*100.
      XMM=.103*(EXP(455./DB**1.53)-.00845*DB+1.558)
      IF(T-60.)10,20,20
10    XMT=128.76*EXP(-.081*T)
      GOTO70
20    IF(W-19.)30,30,40
30    W=19.
40    IF(W-28.)60,60,50
50    W=28.
60    XMT=32.3*EXP(-3.48*T/60.)+(W-19.)*.01*EXP(.61*(T-60.)/60.)
C
70    SAFES=TR*XMM*XMT*DM
      RETURN
      END
```

```
C   **********          **********          **********          **********
      SUBROUTINE FANSUB(DIAM,TONNE,IG,AFR,PWR)
C   SUBROUTINE CALCULATES THE REQUIRED POWER TO DRIVE THE FAN FOR THE
C   SPECIFIED BIN OF GRAIN AND AIRFLOW RATE
      DIMENSION AF(14),ASP(14,3)
      DATA AF/.01,.02,.04,.06,.10,.20,.40,.60,1.0,2.0,4.0,6.0,10.0,20.0/
      DATA ASP/.00059,.0011,.0021,.0031,.005,.01,.021,.032,.055,.115,
     *.26,.43,.82,2.0,.00032,.0006,.00115,.0017,.0028,.0056,.0115,.0175,
     *.03,.065,.15,.26,.51,1.3,.00021,.00039,.00076,.00112,.0019,.0038,
     *.008,.0125,.021,.045,.10,.17,.34,.98/
      IGR=IG+1
      PF=1.5
      IF(IGR.EQ.1)SPWT=0.75
      IF(IGR.EQ.2)SPWT=0.62
      IF(IGR.EQ.3)SPWT=0.70
      AREA=3.1416*DIAM**2/4.
      CMM=AFR*TONNE
      V=AFR*TONNE/AREA
      DO 50 I=1,13
      J=14-I
      IF((V-AF(J)).GE.0.)GO TO 60
50    CONTINUE
60    ALOGSP=ALOG10(ASP(J,IGR))+(ALOG10(V)-ALOG10(AF(J)))/(ALOG10(AF(J+1
     +))-ALOG10(AF(J)))*(ALOG10(ASP((J+1),IGR))-ALOG10(ASP(J,IGR)))
      SPM=10.**ALOGSP*PF
      SP=SPM*TONNE/(AREA*SPWT)
      IF(SP.LT.0.25)GO TO 70
      PWR=(SP*CMM)/30.
      RETURN
70    CMM=CMM/(4.418-1.614*SP)
      PWR=CMM/30.
      RETURN
      END
C   **********          **********          **********          **********
      SUBROUTINE ZERO(J,YD,X,Y,A,DEL,K,N,M)
C   SUBROUTINE SEQUENTIALLY SELECTS BETTER ESTIMATES OF X SUCH THAT THE
C   UNKNOWN FUNCTION F(X) (=Y) APPROACHES THE DESIRED VALUE YD
      DIMENSIONA(4),IJ(4,3)
      DATA IJ/1,2,3,4,4,3,2,1,3,4,1,2/
      J1=1
      IF(N.LE.0)M=1
    5 JP=J
      J=IJ(J,J1)
      IF(J.LE.2 .AND. JP.LE.2) GO TO 6
      IF(J.GE.3 .AND. JP.GE.3) GO TO 6
      Z=A(1)
      A(1)=A(3)
      A(3)=Z
      Z=A(2)
      A(2)=A(4)
      A(4)=Z
    6 IF(J1.EQ.3) GO TO 51
      IF(J.LE.2)GO TO 10
      X=-X
      A(1)=-A(1)
      A(3)=-A(3)
   10 IF(J.EQ.1 .OR. J.EQ.4)GO TO 20
      YD=-YD
      Y=-Y
      A(2)=-A(2)
      A(4)=-A(4)
   20 J1=1
```

```
      CALL TYPE1(J1,YD,X,Y,A,DEL,K,N,M)
      IF(M.EQ.2 .AND. J.GE.3) X=A(1)/2.5
      IF(M.EQ.3 .AND. J.GE.3) X=A(1)*4.0
      IF(M.EQ.4.AND.J.GE.3)X=A(1)/100.
      IF(J.LE.2)GO TC 30
      X=-X
      A(1)=-A(1)
      A(3)=-A(3)
   30 IF(J.EQ.1 .OR. J.EQ.4)GO TO 50
      YD=-YD
      Y=-Y
      A(2)=-A(2)
      A(4)=-A(4)
   50 IF(K.EQ.2)RETURN
      IF(J1.NE.1)GCTC 5
   51 IF(N.LT.15)RETURN
      K=2
      WRITE(6,52)YD,X,Y,A
   52 FORMAT(' DOES NOT CONVERGE ',7F10.5)
      RETURN
      END
      SUBROUTINETYPE1(J,YD,X,Y,A,DEL,K,N,M)
      DIMENSIONA(4)
      XL=A(1)
      YL=A(2)
      XU=A(3)
      YU=A(4)
      K=1
      IF(ABS(Y-YD)-ABS(DEL))2,2,6
2     K=2
      M=1
      GOTO35
    6 N=N+1
      GOTO(10,20,37,55,21,21),M
10    XL=X
      X=2.5*X
      YL=Y
      M=2
      GOTO35
   20 YU=Y
      XU=X
21    IF(YL-YU)30,40,40
30    J=2
      N=N-1
      M=6
35    A(1)=XL
      A(2)=YL
      A(3)=XU
      A(4)=YU
      RETURN
37    YL=Y
      XL=X
40    IF(YL-YD)45,60,60
   45 X=XL/100.
52    M=3
      XU=XL
      YU=YL
      GOTO70
53    K=2
      M=1
      WRITE(6, 54)
   54 FORMAT(' NOT WITHIN LIMITS')
```

```
      GOTO35
55    YU=Y
      XU=X
60    IF(YD-YU)65,80,80
65    XL=XU
      YL=YU
      X=XU*4.
      M=4
70    IF(N-6)35,35,53
80    IF(M-5)85,90,90
85    W=(YL-YD)/(YL-YU)*(XU-XL)+XL
      X=(XL+W)/2.
      M=5
      GOTO35
90    Y4=YL-(YL-YU)*(X-XL)/(XU-XL)
      IF(Y4-Y)100,130,130
100   J=3
      M=6
      IF(Y.GT.YD.AND.Y.LT.YL)XL=X
      IF(Y.GT.YD.AND.Y.LT.YL)YL=Y
      IF(Y.LT.YD.AND.Y.GT.YL)XU=X
      IF(Y.LT.YD.AND.Y.GT.YL)YU=Y
      X=XL+(YL-YD)*(XU-XL)/(YL-YU)
      GOTO35
130   IF(Y-YD)150,140,140
140   IF(YL-Y)141,142,141
141   S=(X-XL)*(YL-YD)/(YL-Y)+XL
      GO TO 143
142   S=XL
143   W=((Y-YD)/(Y-YU))*(XU-X)+X
      XL=X
      YL=Y
      X=(S+W)/2.
      GOTO35
150   W=((X-XL)*(YL-YD))/(YL-Y)+XL
      S=((YD-YU)*(X-XU))/(Y-YU)+XU
      IF(XL-S)170,170,160
160   S=XL
170   XU=X
      YU=Y
      X=(S+W)/2.
      GOTO35
       END
```

APPENDIX B.8 MATHEMATICAL MODEL OF MINAIR IN FORTRAN STATEMENTS

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C  MINAIR PROGRAM
C  THIS PROGRAM FINDS THE MINIMUM AIRFLOW RATE REQUIRED TO DRY A BIN OF
C  GRAIN WITHOUT SPOILAGE. IT USES TOM THOMPSON'S NATURAL AIR DRYING
C  MODEL, WITH TIME INTERVALS OF 24 HOURS AND CONTINUOUS FAN OPERATION.
C  WEATHER INFORMATION ON MAGNETIC TAPE IS REQUIRED.
C
      DIMENSION A(4),IWD(20),DATE(4),AIR(100),CMNI(100),YER(100),
     +AMT(100),DYA(100),CS(100),TAEH(100)
      DATA A/4*0./
      COMMON IG,XMC,XMF,SC,HEAT,GO,KK
      NO=0
      KK=0
      J2=0
C
20    READ(5,18,END=250)IG,XMO,XMF,GO,YR,AM,DAY,AFR,SC,HEAT
C  *********************************************************************
C  * READ GRAIN TYPE (0=WHEAT,1=BARLEY,2=CORN,3=REWIND), INITIAL GRAIN *
C  * MOISTURE CONTENT (%WB), FINAL DESIRED MOISTURE CONTENT (%WB),     *
C  * INITIAL GRAIN TEMPERATURE (DEG. CELSIUS), YEAR, MONTH, & DAY OF   *
C  * STARTING DRYING, FIRST AIRFLOW RATE (SHOULD BE LOW)-- THE PROGRAM *
C  * FINDS THE MINIMUM AFR (CU.M./MIN-T), SOLAR COEFFICIENT (AVERAGE   *
C  * TEMPERATURE RISE WHEN RECEIVING 1000 LANGLEYS PER DAY), AND THE   *
C  * NUMBER OF DEGREES OF TEMPERATURE RISE ADDED TO THE AMBIENT AIR    *
C  * BY THE FAN AND HEATER (DEGREES CELSIUS).                          *
C  *********************************************************************
18    FORMAT(I1,2F5.1,7F4.1)
      IF(XMO.EQ.0.)XMO=20.
      IF(XMF.EQ.0. .AND. IG.EQ.0)XMF=14.5
      IF(XMF.EQ.0. .AND. IG.EQ.1)XMF=14.8
      IF(XMF.EQ.0. .AND. IG.EQ.2)XMF=15.5
      IF(AFR.EQ.0.)AFR=0.5
C  DEFAULT VALUES
      IF(IG .LE. 2)GO TO 19
      IF(SC .GT. 0.)REWIND13
      REWIND14
      GO TO 20
19    HARV=AM*10000.+DAY*100.
21    DT=YR*10000.+AM*100.+DAY
      IF(SC.EQ.0.)GO TO 32
22    READ(13,23,END=220)D
23    FORMAT(9X,F6.0)
      IF(D.LT.DT)GO TO 22
      IF(D.GT.DT)GO TO 28
      BACKSPACE13
      GO TO 32
28    IF(KK.EQ.0)KK=12
      L=KK/12+3
      DO 29 I=1,L
29    BACKSPACE13
       GO TO 22
32    IF(J2.EQ.2)GO TO 41
25    READ(14,30,END=220) CC
30    FORMAT(5X,F2.0,73X)
      IF (CC.LT.YR)GO TO 25
      IF(CC.GT.YR)GO TO 41
35    READ(14,40,END=220)D
40    FORMAT(7X,F6.0,67X)
      IF(D.LT.HARV)GO TO 35
      IF(D.GT.HARV)GO TO 41
C          FINDS SPECIFIED STARTING DATE ON TAPE(S)
      READ(14,45,END=220)(DATE(I),I=1,4)
45    FORMAT(5X,4F2.0)
```

```
      BACKSPACE14
      GO TO 49
41    IF(KK.EQ.0)KK=24
      KK=KK+2
      DO 42 I=1,KK
42    BACKSPACE14
      GO TO 25
49    IF(SC.EQ.0.)WRITE(6,50)
50    FORMAT('-','NATURAL AIR DRYING')
      IF(SC.GT.0.)WRITE(6,51)
51    FORMAT('-','SOLAR HEATED AIR DRYING')
      IF(IG.EQ.0) WRITE(6,55)
      IF(IG.EQ.1) WRITE(6,60)
      IF(IG.EQ.2) WRITE (6,65)
55    FORMAT('+',24X,'--WHEAT')
60    FORMAT('+',24X,'--BARLEY')
65    FORMAT('+',24X,'--CORN')
      WRITE(6,75)GC,XMC,XMF,(DATE(I),I=1,4),SC,HEAT
75    FORMAT('0     GO        WBO       WBF       START DATE       SC     HEAT'/
     +' ',3F8.2,3X,4F3.0,2F7.1)
      J=1
      N=0
      IAB=0
100   Y=GRNDRY(AFR)
      IF(Y .GT. 0.50)IAB=2
      CALL ZERO(J,0.50,AFR,Y,A,0.03,K,N,M)
      GO TO (110,180),K
110   IF(N .GT. 5 .AND. ABS(Y-0.50) .LE. 0.05)GO TO 180
      IF(N.EQ.1 .AND. Y.LT. 0.5)AFR=AFR/5.
      IF(N .GT. 1 .AND. IAB .LT. 2)AFR=AFR/8.
      IF(AFR.LE. 0.)AFR=5.
      IF(N.LE.10)GO TO 112
      J2=2
      GO TO 20
112   L=KK/12+3
      KK=KK+1
      DO 115 I=1,KK
115   BACKSPACE14
120   READ(14,40,END=220)D
      IF(D .LT. HARV)GO TO 120
      IF(SC .EQ. 0. .AND. D .EQ. HARV)GO TO 100
      IF(D .EQ. HARV)GO TO 130
      DO 125 I=1,5
125   BACKSPACE14
      GO TO 120
130   DO 135 I=1,L
135   BACKSPACE13
140   READ(13,145,END=220)D,IC
145   FORMAT(9X,F6.0,3X,I1)
      IF(D .LT. DT)GO TO 140
      BACKSPACE13
      IF(D .EQ. DT .AND. IC .EQ. 1)GO TO 100
      DO 150 I=1,3
150   BACKSPACE13
      GO TO 140
180   WRITE(6,200)XMC,XMF,YR,AM,DAY,AFR
200   FORMAT('OMINIMUM AIRFLOW RATE REQUIRED TO DRY THE GRAIN FROM',
     +F5.1,' % M.C. TO',F5.1,' % M.C. (MAXIMUM)'/' FOR A HARVEST DATE OF
     + ',3F3.0,', WITHOUT SPOILAGE, IS',F6.2,' CU.M./MIN/TONNE')
      NO=NO+1
      CMNI(NO)=XMO
      YER(NO)=YR
```

```
      AMT(NO)=AM
      DYA(NO)=DAY
      AIR(NO)=AFR
      CS(NC)=SC
      TAEH(NO)=HEAT
      GO TO 20
220   WRITE(6,230)
230   FORMAT(' END OF TAPE')
      REWIND14
      IF(SC .GT. 0.)REWIND13
      GO TO 20
250   WRITE(6,260)(IWD(I),I=1,20)
260   FORMAT('-',20X,'SUMMARY OF RESULTS FOR MINIMUM AIRFLOW RATE'/'0',
     +30X,20A4)
      WRITE(6,265)
265   FORMAT('0',17X,'IN.M.C.    HARV.DATE    MIN.AFR    SCL.COEFF    HEAT'/
     +'+',17X,'_______    _________    _______    _________    _____')
      DO 270 I=1,NC
270   WRITE(6,280)CMNI(I),YER(I),AMT(I),DYA(I),AIR(I),CS(I),TAEH(I)
280   FORMAT('0',17X,F5.1,5X,3F3.0,4X,F5.2,2F10.1)
      STOP
      END
C   **********         **********         **********         **********
      FUNCTION GRNDRY(AFR)
C   SUBROUTINE SIMULATES DRYING FOR THE GIVEN YEAR, GRAIN TYPE, MOISTURE
C   CONTENT, ETC., AND THE AIRFLOW RATE SELECTED BY MINAIR.
      DIMENSION AW(4),PER(10),SCL(24)
      COMMON /AREA1/XM(10),G(10),DM(10),IGR,R
      COMMON IG,XMC,XMF,SC,HEAT,GO,KK
C
      WRITE(6,10)AFR
10    FORMAT('-AIRFLOW RATE=',F5.2,' CU.M./MIN/TONNE')
      WRITE(6,80)
80    FORMAT('0DATE & TIME    HOURS    WB(MIN)    WBAVE    WB(MAX)    GT(1
     +)    GTAVE    GT(10)    %ALL.TIME    %DM(MAX)    TAIR    TDPT    RAD''N'
     +/'+__________    _____    _______    _____    _______    _____    __
     +___    ______    _________    ________    ____    ____    _____')
      TIME=0.
      IGR=IG
      DT=24.0
      R=870./(AFR*60.*DT*12.)
      N5=0
      EQT=0.
      TLRAD=0.
      TRAD=0.
      SCLHT=0.
      KK=0
      NC=0
      TAIR=0.0
      TDPT=0.0
      DO 90 I=1,10
85    PER(I)=0.0
      XM(I)=XMC
C        MOISTURE CONTENT OF EACH LAYER IS SET TO INITIAL GRAIN M.C.
      DM(I)=(XMC*100.)/(100.-XMC)
C        M.C. OF EACH LAYER IS SET TO INITIAL GRAIN M.C. ON DRY WT. BASIS
90    G(I)=GO
C        TEMP. OF EACH LAYER IS SET TO INITIAL GRAIN TEMP.
100   NC=NC+1
      TD=0.
      TD=0.
      RAD=0.
```

```
110   CALL READWR(24,DATW,TP,TD,RH,AW,&450)
      KK=KK+24
      IF(SC .EQ. 0.)GO TO 140
      CALL READRN(NS,DATW,&110,SOL,&450)
      DO 125 I=1,24
125   RAD=RAD+SOL(I)
      SOLHT=SC*RAD*0.001
      TRAD=TRAD+RAD*4.184
140   TO=TP+HEAT+SOLHT
      TAIR=TAIR+TO-HEAT-SOLHT
      TDPT=TDPT+TD
      CALL DRYSIM(TO,TC,AVEM,AVET)
      CALL MIN(10,XM,N1,DRY)
C       TO DETERMINE AND IDENTIFY THE DRIEST LAYER
      CALL MAX(10,XM,N2,WET)
C       TO DETERMINE AND IDENTIFY THE WETTEST LAYER
245   TIME=TIME+DT
      IF(IG.EQ.2)GO TO 270
      DO 250 I=1,10
      WT=SAFWH(G(I),XM(I))
250   PER(I)=PER(I)+DT/WT
      CALL MAX(10,PER,N3,PCTM)
      GO TO 290
270   DO 280 I=1,10
      Z=SAFES(G(I),XM(I))
280   PER(I)=PER(I)+DT/Z
      CALL MAX(10,PER,N3,PCTM)
290   EQT=PCTM*230.
      PERDM=.0883*(EXP(.006*EQT)-1.)+.00102*EQT
      P=PCTM*100.
      IF(WET.LE.XMF)GO TO 350
C  IS THE WETTEST LAYER DRY YET?
      IF(N3/7. .NE. N3/7)GO TO 100
C          PRINT THE VALUES ONCE PER WEEK
      TC=TAIR/7.
      TD=TDPT/7.
      TAIR=0.0
      TDPT=0.0
      WRITE(6,300)(AW(I),I=1,4),TIME,DRY,N1,AVEM,WET,N2,G(1),AVET,G(10),
     +P,N3,PERDM,TC,TD,TRAD
300   FORMAT('0',4F3.0,F7.1,F7.2,'(',I2,')',2F8.2,'(',I2,')',2F8.2,F9.2,
     +F8.2,'(',I2,')',F10.4,2F8.2,F8.0)
      TLRAD=TLRAD+TRAD/100.
      TRAD=0.
      IF(PERDM.LT. 10.)GO TO 100
      WRITE(6,320)
320   FORMAT(' AIRFLOW RATE MUCH TOO LOW')
      GRNDRY=PERDM
      RETURN
350   WRITE(6,300)(AW(I),I=1,4),TIME,DRY,N1,AVEM,WET,N2,G(1),AVET,G(10),
     +P,N3,PERDM,TC,TD,TRAD
      TLRAD=TLRAD+TRAD/100.
      WRITE(6,360)TLRAD
360   FORMAT('0GRAIN DRIED',27X,'TOTAL RADIATION RECEIVED ON A HORIZONTA
     +L SURFACE SINCE START OF DRYING =',F7.0,' MJ/SQ.M')
      GRNDRY=PERDM
      RETURN
450   WRITE(6,460)
460   FORMAT(' END OF TAPE')
      GRNDRY=PERDM +0.5
      RETURN
      END
```