THE UNIVERSITY OF MANITOBA

AERATION OF STORED WHEAT IN THE CANADIAN PRAIRIES

by

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A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

DEPARTMENT OF AGRICULTURAL ENGINEERING

WINNIPEG, MANITOBA

November, 1980

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ABSTRACT

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Airflow rates and fan control methods for aeration of stored wheat to maintain quality during storage were evaluated. A computer simulation model which predicts grain conditions in two-dimensions of a cylindrical granary, with no aeration, and with aeration, was developed. The model was verified by comparing predicted and experimental data obtained during the 1979-80 storage year, and was used to investigate various design parameters of aeration systems.

Historical weather data for 15 or more harvest years from four Canadian Prairie locations ranging from Fort St. John, British Columbia, to Winnipeg, Manitoba were used. The effects of climate, initial moisture content, harvest date, and initial grain temperature on the condition of stored wheat were determined. The condition during storage of 15% initial moisture content wheat was predicted with no aeration, with aeration rates from 0.5 to 3.0 $(L/s)/m^3$, and with four different fan control methods.

All aeration airflow rates and fan control methods reduced the rate of grain deterioration. An airflow rate of 1.0 (L/s)/m^3 was optimum for continuous aeration. The optimum fan control methods were humidistat control with settings between 50 and 70%, 6 h time-clock operation at night, and differential thermostat control with settings between -10 and -15°C. The choice of fan control method is independent of climatic variation within the range of climates studied.

ACKNOWLEDGEMENTS

Many individuals and organizations have assisted during the course of my studies in Winnipeg. First of all, I would like to thank Dr. Bill Muir. His support, encouragement, and many suggestions have been extremely helpful. It is my hope that this thesis reflects his high standards. I also wish to thank Mr. Pat Terry for his assistance in instrumenting the aeration bin, in collecting the experimental data, and in the fan performance project.

I am grateful to my employer, the British Columbia Ministry of Agriculture and Food, in particular to Mr. Tom Windt, the Head of the Engineering Branch, for his efforts in pursuing a leave-of-absence for me for this study period. The financial assistance provided by the Department of Agricultural Engineering at the University of Manitoba is very much appreciated. Additional financial support from the Manitoba Department of Agriculture, Agriculture Canada, and the Natural Sciences and Engineering Research Council of Canada is acknowledged as well.

Thanks are due to Dr. Ron Britton, Professor Lorne Buchanan, and Mr. Orly Friesen for serving on my committee.

Finally, I wish to thank my wife Bridget and daughter Andrea for their patient support during this past year.

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Chapter I

INTRODUCTION

The trend to more storage of grain at the farm, and to larger volume granaries appears well established in Canada. Uncertainty in production and marketing can often result in lengthy storage periods. Although the Canadian Grain Commission specifies "dry" moisture contents for market, these may not necessarily be "safe" moisture contents for storage. Moisture migration, or high initial grain temperatures in large storages can result in serious deterioration, even at these "dry" moisture contents. Variable weather and field conditions during harvest may produce "tough" or "damp" grain which has an even greater tendency toward deterioration than "dry" grain.

The use of aeration has been suggested as a means of maintaining grain quality in storage. Present airflow and management recommendations are based largely on data for corn from the United States. Precise data for Canadian crops based on Canadian climatic data are unavailable.

The objectives of this study were to determine effective airflow rates and fan control methods for intermittently operated aeration systems used for on-farm storage in Canadian Prairie regions. The method of investigation was a computer simulation model. This model is capable of predicting wheat temperatures, moisture contents and deterioration, with and without ventilation, in two-dimensions of a circular steel granary, based on initial grain conditions, airflow rate, weather conditions, and a variety of fan control parameters. Although exact predictions by such a method are impossible, the model sufficiently represents the real processes that useful information can be derived. This reduces the need for more expensive and time consuming field studies. This study provides results for wheat aeration in the Canadian Prairies from which guidelines for system designs can be developed.

In this thesis, the term "aeration" refers to grain ventilation during storage for the primary purpose of quality maintenance. It should not be confused with unheated or natural air grain drying.

Chapter II

REVIEW OF LITERATURE

2.1 Benefits of Grain Aeration

The objective of aerating stored grain is to maintain grain quality. This is done by cooling the grain with ambient air to limit biological activity, and by maintaining a relatively uniform temperature throughout the grain mass with sufficient intermittent ventilation to prevent moisture migration (Brooker et al. 1974, Burrell 1974). As well, aeration can be used to remove grain storage odours and to distribute fumigants throughout the grain mass (Brooker et al. 1974).

Although grain aeration is not new, it was not until the early 1950's that it came into general use (Burrell 1974). Much interest in aeration during this time resulted from a need to maintain quality in the large commercial storages (Kelly 1941, Johnson 1957, Holman 1960). It was suggested as an alternative to the management practice of turning to distribute heated grain. Although turning succeeds in producing a more uniform temperature throughout the storage, its ability to cool grain is limited to reducing peak temperatures to near the average of the bulk (Watters 1963). More recent trends to large on-farm grain storages in Canada (Muir 1980) as well as the use of unheated air grain drying has carried interest in aeration systems to the farm level.

Grain moisture content changes during "dry" grain aeration are usually small and incidental to the primary objective of temperature control and quality maintenance. Measured reductions in moisture content vary from less than 0.25 to 1.0 percentage points (Foster 1967, Converse 1977, Holman 1960, Johnson 1957). Foster (1967) recorded similar increases in moisture content during grain warming. Cloud and Morey (1979) suggest that reductions in grain moisture content of about 0.25 percentage points may occur for each 6°C reduction in temperature.

2.2 Grain Cooling

2.2.1 Biological considerations

The allowable safe storage period for grains is determined largely by grain temperature and moisture content. Cool dry grain is less prone to damage resulting from insects, mites and fungi, and to reductions in germination than warm damp grain.

Grainivorous insects do not develop below 15°C (Sinha 1973) to 17°C (Burrell 1974) and at moisture contents below 10% wet mass basis (Sinha 1973). Mites do not develop below 5°C, and most storage fungi do not develop below 0°C. Grain moisture contents below 13% for most cereals arrest the growth of most fungi and mites. Different critical moisture contents exist for other crops with different equilibrium relative humidity relationships.

Germination is reduced at combinations of high moisture contents and both high and low temperatures. At temperatures above 0°C, germination is reduced over time as moisture content and temperature are increased (Burrell 1974). At temperatures below 0°C germination can also be reduced. Agena (1961, cited by Burrell 1974) found germination reductions for wheat, barley and rye at moisture contents of 20 to 30% and temperatures below -6°C. Manchur (1972) found reductions in germination for barley at moisture contents greater than 18.7% at temperatures below -12°C.

These results suggest that the objective of cooling grain should be to reduce temperatures to below 5°C and preferably below 0°C. If, however, the grain is wet and germinative energy is to be retained, temperatures should be limited to above -6 to -12°C.

2.2.2 Initial grain temperature

The initial temperature of freshly harvested grain is a function of by the ambient air temperature at harvest. Prasad et al. (1978) measured average temperature increases for stored wheat of 8°C above the ambient air temperature. Measured grain temperatures were as high as 32 to 42°C on sunny fall days in Manitoba.

In unventilated storages the rate of cooling increases with decreasing bin diameter. The centre of a bin of wheat stored in Winnipeg, at an initial temperature of 35°C takes 323 days to cool to 20°C in an 8 m diameter bin, while it takes only 112 days in a 4 m bin. At an initial temperature of 25°C it takes 225 days in an 8 m bin and 90 days in a 4 m bin for the wheat to cool to 20°C (Yaciuk et al. 1975).

Since initial grain temperatures within the optimum temperature ranges for grain storage pests are likely, grain can deteriorate rapidly if it cools slowly, or biological activity is not limited in some other way. Aeration can be an important means of cooling freshly harvested grain if the grain is harvested during warm weather, and if it is stored in large volume granaries.

2.3 Maintaining Uniform Temperature

Non-uniform temperatures within a storage bin are thought to cause moisture migration from warmer to colder areas of the bin. This may cause localized increases in moisture content resulting in conditions suitable for spoilage. Brooker et al. (1974) described two cycles for moisture migration which depend on ambient air temperatures, which are largely determined by the season. The moisture migration to the top and centre of the grain occurs during the fall and winter when the grain temperature is higher than the ambient air temperature. Migration to the floor and centre occurs during the spring and summer when the grain temperature is cooler than the ambient air temperature.

The wide seasonal temperature variations common in Canadian Prairie climates and the large temperature differentials possible within large granaries (Yaciuk et al. 1975) suggest that moisture migration is potentially a serious problem. Some authors suggest the use of intermittent aeration throughout the year to maintain relatively uniform bin temperatures, especially in large bins greater than 100 m^3 (Friesen and Harms 1980). Summer aeration increases grain temperature thus increasing the rate of deterioration. The benefits of summer aeration to minimize moisture migration have not been established. Deterioration resulting from moisture migration may be less than that resulting from summer aeration.

2.4 Aeration System Performance

2.4.1 Airflow rate

The time required to cool the grain to the ambient air temperature is dependent on the airflow rate. It requires 600 to 700 volumes of air to cool a single volume of grain, assuming even airflow distribution within the grain mass. Therefore at an airflow rate of 1 $(L/s)/m^3$ it takes about 160 to 200 hours of fan operation to change the temperature throughout the bin. If the airflow rate is doubled, it takes only half as long (Burrell 1974, Cloud and Morey 1979).

Higher airflow rates or increased cooling times are required with poor airflow distribution within the grain bulk. Burrell (1974) suggested that the longest air path from the duct to the grain surface should be no more than 1.5 times the shortest air path. Under these conditions airflow rates or times should be increased by 50% for adequate cooling.

The required airflow rate to maintain grain quality is dependent upon the grain moisture content, and the temperature and relative humidity of the air. In this respect aeration may not always be distinguishable in appearance from unheated air grain drying.

Airflow rates recommended for aerating "dry" grain vary from 0.3 to 6.7 $(L/s)/m^3$. Johnson (1957) and Holman (1960) feel that airflow rates of 0.3 to 0.7 $(L/s)/m^3$ are sufficient for continuous aeration in large commercial storages. Shove (1962) suggested 0.7 to 6.7 $(L/s)/m^3$ for on-farm systems, tending to recommend the higher rates for intermittent operation or for higher moisture contents. Cloud and Morey (1979) suggested a minimum of 1.3 $(L/s)/m^3$ for on-farm aeration of dry grain, and Friesen and Harms (1980) recommended 1.0 to 2.0 $(L/s)/m^3$.

Fraser and Muir (1980) related airflow rate to moisture content and harvest date for unheated and solar-heated air drying in Canada. Although their objective was to dry the grain, at high moisture contents minimizing the rate of spoilage is the factor which determines airflow rate. For example, for Winnipeg, wheat harvested at 20% moisture content on 15 August requires an airflow rate of 30 $(L/s)/m^3$. This airflow rate can be approximately halved for each month's delay in harvest and for each 2% decrease in crop moisture content at harvest.

2.4.2 System management periods and fan control methods

To meet the objectives of aeration, fan operation is required in response to ambient temperature variations, which are usually seasonally dependent. Thus, Cloud and Morey (1979) divided aeration system management into four periods:

1. Fall cool-down period.

   After harvest the stored grain is cooled as quickly as possible to between -7°C and 2°C.

2. Winter holding period.

   Intermittent fan operation during the winter when the outside temperature is near the grain temperature to maintain relatively uniform grain temperature.

3. Spring warm-up period.

Intermittent fan operation to warm grain to between 10 and 15°C by the middle of June unless the grain is to be moved by July, in which case no aeration is required. They feel condensation on the cold grain will not be a problem if it is moved before July.

4. Summer holding period.

Intermittent fan operation during the summer when the outside temperature is near the grain temperature (10 to 15°C) to maintain relatively uniform grain temperature.

The spring warm-up and summer holding period ventilations are done to minimize the possibility of the occurrence of the summer moisture migration cycle. The use of spring and summer aeration assumes that less loss will result from grain deterioration at the warmer grain temperatures than from summer moisture migration. If summer moisture migration does occur, the moisture will accumulate in the coldest grain. If, however, this grain remains cold throughout the summer, little or no deterioration may occur, even with increased moisture contents.

Various fan control methods have been suggested for aeration systems. Shove (1962) evaluated thermostat and humidistat controllers and found that they offered no advantage with respect to the resulting grain quality and cost over continuous operation.

Cloud and Morey (1979) recommended continuous operation with some manual control during the fall cool-down period to achieve the objectives outlined above.

Holman (1960) tried to relate aeration to grain and air temperatures. He suggested that the input air temperature be at least 6°C cooler than the grain temperature for fan operation.

Burges and Burrell (1964) in Great Britain suggested humidistat control with fan operation to maximum relative humidities of 75 to 80%.

Since the temperature to which the grain can be cooled is determined by the ambient wet bulb temperature, not the dry bulb temperature, Griffiths (1967) suggested the use of a wet bulb controller. Evaporative cooling due to the wet bulb temperature depression can result in grain below the dry bulb temperature. Conversely, he found that if moisture adsorption occurred during the aeration of very dry grain, the grain always stayed warmer than the cooling air, due to the release of the heat of sorption.

The variety of recommendations for aeration fan controllers may be because ventilation is required in response to climatic variations. As climate varies from region to region, so may the optimum method of fan control.

2.5 Mathematical Models

The condition of grain in ventilated and unventilated storages is highly dependent upon weather conditions, initial grain conditions, airflow rate and other important factors. Because there is neither the time nor money to experimentally investigate all parameter combinations of interest, many investigators have resorted to developing mathematical models of the heat and moisture transfer in grain bins. The models lend themselves to computer solution, using historical weather data on tape. In this way a large number of variable combinations can be examined using weather data from several years, and trends in system performance can be quickly derived.

The accuracy of predictions made using mathematical models depends on the adequacy of the relationships used to describe the physical and biological parameters in the grain. Predictions made using mathematical models are "practically useless" unless the model has been validated by comparing predicted output with experimentally determined data (Brooker et al. 1974).

2.6 Forced Convection Models

2.6.1 Types of models

Models which mathematically predict heat and moisture transfer during forced convection of air through grain can be broadly categorized as one of two types; empirical or analytical. Empirical models use experimental results from shallow beds of grain to predict results in deep beds. Analytical models use a more fundamental approach, deriving relationships from theoretical partial differential equations of heat and moisture transfer.

2.6.2 Empirical models

Bloome and Shove (1971) developed a procedure to predict grain conditions under low airflow rate ventilation by approximating equilibrium temperature and moisture conditions between the air and grain. Thompson (1972) simplified this procedure and included equations for the heat of respiration and dry matter decomposition of the grain. The essential assumption used in this approach is that the air and grain reach temperature and moisture equilibrium. The heat and mass balance equations are solved by an iterative method presented by Thompson and Peart (1968) which converges to the unknown values at the equilibrium point.

The equilibrium assumption is in fact not unconditionally true especially at higher airflow rates. To prevent unrealistic predictions of overdrying or excessive re-wetting, empirical thin-layer drying equations have been included in several subsequent models. Flood et al. (1972) used a modified version of Thompson's model with a thin layer drying equation by Sabbah (1971, cited by Brooker et al. 1974). Morey et al. (1976) also used a version of Thompson's model with Sabbah's equation. Although thin layer equations improve the accuracy of equilibrium models at higher airflow rates, they are also more likely to overestimate drying at low airflow rates due to the more dramatic changes in conditions of the air as it passes through the grain. Therefore, under low airflow conditions the original equilibrium approach is better (Peart 1977, cited by Fraser 1979). The models by Morey et al. (1976) and Pierce and Thompson (1980) incorporate both approaches, selecting the higher of the grain moisture contents predicted by each equation, thus ensuring that the drying rate is not overestimated.

Scott and Barlott (1979) have sufficient confidence in Thompson's model to have incorporated it as part of a grain harvest simulation program. This is available to Alberta Agriculture staff to assist in evaluation and optimization of grain harvest systems for farmers in Alberta.

2.6.3 Analytical models

Analytical models are more fundamental in nature than the empirical models. They are based on partial differential equations describing the laws of heat and mass transfer and therefore may have more general application to other hygroscopic materials. Accurate thin-layer drying equations and equilibrium moisture content relationships are required however, and in this respect the analytical models are no different than the simpler empirical models. Good descriptions of the equations used and the assumptions made have been compiled by Brooker et al. (1974) and Spencer (1969).

Bakker-Arkema et al. (1967) developed an analytical model which simulates the drying and cooling of "wet" biological materials. Because the model only simulates "free" moisture transfer, no thin-layer drying and equilibrium moisture content relationships were required and the model is relatively simple.

Spencer (1969) took a similar approach but included drying rate equations. Successful verification was made with heated air. In his revision (1972) he cautioned against the use of this method at airflow rates less than 2.1 $(L/s)/m^3$ because of a tendency to overestimate drying rates.

Johnson (1979) planned to use the fixed-bed grain drying simulation model of Bakker-Arkema et al. (1974, 1977, cited by Johnson 1979) to model unheated and solar-heat assisted corn drying in Southern Ontario. The model failed to make accurate predictions for these conditions. Johnson learned from Bakker-Arkema that an inherent instability exists in the program for low airflow and low temperature systems.

Low airflow rate "equilibrium" analytical models have been developed by Sutherland et al. (1971) and Ingram (1979). Although both report good agreement with experimental results, neither has been used to simulate in-field deep beds using weather data.

At this time analytical methods appear to be most successful in simulation of non-equilibrium heated air systems. Predictions based on empirical models such as Thompson's and Morey's have resulted in good agreement with experimental data under "equilibrium" conditions.

2.7 Conduction Models

Less research emphasis has been given to predicting temperatures and moisture contents in unventilated granaries. Where effort has been made it was in the area of grain temperature prediction only.

Converse et al. (1969) used an analytical method to describe one-dimensional heat transfer by conduction in the radial direction in wheat stored in cylindrical grain bins. Numerical methods using finite differences were used by Muir (1970) and Yaciuk et al. (1975) to predict temperatures in the radial direction only. Using historical weather data, their predictions agreed satisfactorily with experimental data.

Muir et al. (1980) refined this method to one which would predict temperature gradients in two-dimensions.

Simply stated these models transform the differential equation for unsteady-state temperature distribution (Fourier equation) into finite-difference equations for solution by computer; however, a number of simplifying assumptions are made. No internal heat or moisture generation, as would be expected from respiration of the grain, mold growth, and insect activity are included in the model. Heat transfer by free convection was assumed negligible as well. Grain deterioration prediction models have not been included in these conduction models. An accurate assessment of grain deterioration would require predictions of moisture migration.

2.8 Grain Deterioration Models

An accurate mathematical representation of the biological processes contributing to grain quality deterioration has yet to be derived. Quality deterioration in storage is a function of a large number of variables in addition to the most commonly considered ones of grain temperature and moisture content. Other factors which are difficult, and perhaps impossible to define using mathematical relationships are: mechanical damage to the grain, grain deterioration prior to harvest either in the stand or in the windrow, and the initial level of infestation by fungi, insects and mites.

Steele et al. (1969, cited by Muir 1974) found in their studies with corn that a decrease in market grade corresponded with about 0.5%

loss in dry matter. The mathematical relationship they derived predicting the time for this to occur includes grain temperature, moisture content, and mechanical damage factors. This time is known as the allowable safe storage time. No consideration was included for insect and mite infestations, and mycotoxin production.

Fraser and Muir (1980) developed a similar model for wheat based on data presented by Kreyger (1972) and data from their own laboratory. The allowable safe storage time in their case was defined as the time required for germination to drop to between 90 and 95%, or the time before mold growth became visible. This time was assumed to be a function of grain moisture content and temperature only.

Because of the large number of factors which influence the rate of deterioration, models of this type should be considered approximate; however, nothing more accurate is available. Although their use may not predict absolute safe storage times, relative comparison of the effects of various storage methods on the predicted values can yield useful data from which recommendations for aeration system management can be based.

Chapter III

MATHEMATICAL MODEL

3.1 Modelling Intermittent Aeration

Ventilation systems for grain aeration are usually operated in response to seasonal variations, resulting in intermittent fan operation. There are often extended periods when ventilation is not required; therefore, an accurate mathematical model of aeration must describe grain conditions with and without ventilation. Models presently available are designed to simulate either forced convection or conduction. A model capable of simulating both simultaneously could be developed using analytical methods, deriving relationships for heat and moisture transfer which would apply both with and without airflow. Alternatively, existing modelling methods which describe grain conditions with and without ventilation could be combined into one model. It is this combined model approach which I have employed in developing the mathematical model used in this project.

A simulation model capable of predicting grain conditions in the vertical and radial dimension of cylindrical grain bins was developed for the following reasons:

1. Forced convection through grain results in vertical temperature gradients. These gradients will likely be greater with the low airflow rates required for aeration.

2. Muir et al. (1980) suggested increased accuracy in predictions made with their two-dimensional conduction model, over a one-dimensional model, with diameter-to-height ratios of 1.2 and greater.

The flow chart of the main program is shown in Appendix A. A complete listing in Fortran notation of the main and subroutine programs of the combined model is found in Appendix B. Validation of the model by comparing predicted values with experimental data is described in Chapter IV.

3.2 Conduction Model

The conduction component of the combined model was based on the two-dimensional model developed by Muir et al. (1980) for an unventilated bin. This model was based on heat balance equations for heat flow in both the vertical and radial directions of a cylindrical grain bin. Temperatures throughout the bin were assumed to be symmetrical about the vertical axis and heat generation within the grain was assumed to be negligible. Convective heat transfer was ignored as well.

Equations capable of predicting the temperatures of a sector of a cylindrical bin were developed using a finite-difference method. The cylindrical bin was divided into a finite number of spatial elements in the vertical and radial directions (Fig. 3.1). Equations for the temperature of each element were derived from basic laws of physics. Expressed in finite difference form these are:

1. The rate of conductive heat flow is (Fourier equation):

$$q = -kA \frac{\Delta T}{\Delta x} \tag{1}$$

where: q = rate of heat flow, W

k = thermal conductivity, W/(m•K)

A = cross-sectional area measured normal to the direction of heat flow, m^2

$\frac{\Delta T}{\Delta x}$ = temperature gradient in the direction of heat flow, K/m

2. The rate of change in heat energy contained in a spatial element is:

$$q = Vc\rho \frac{\Delta T}{\Delta t} \tag{2}$$

where: V = volume of element, m^3

c = specific heat, J/(kg•K)

ρ = density, kg/m^3

$\frac{\Delta T}{\Delta t}$ = change in element temperature during time interval Δt, K/s

The volume of three different geometric shapes must be considered in developing the equations. As well, some elements such as the exterior wall or the floor element may consist of two or more materials. Mean values for specific heat and density must be used. Derivations of these equations are presented in detail by Yaciuk (1973).

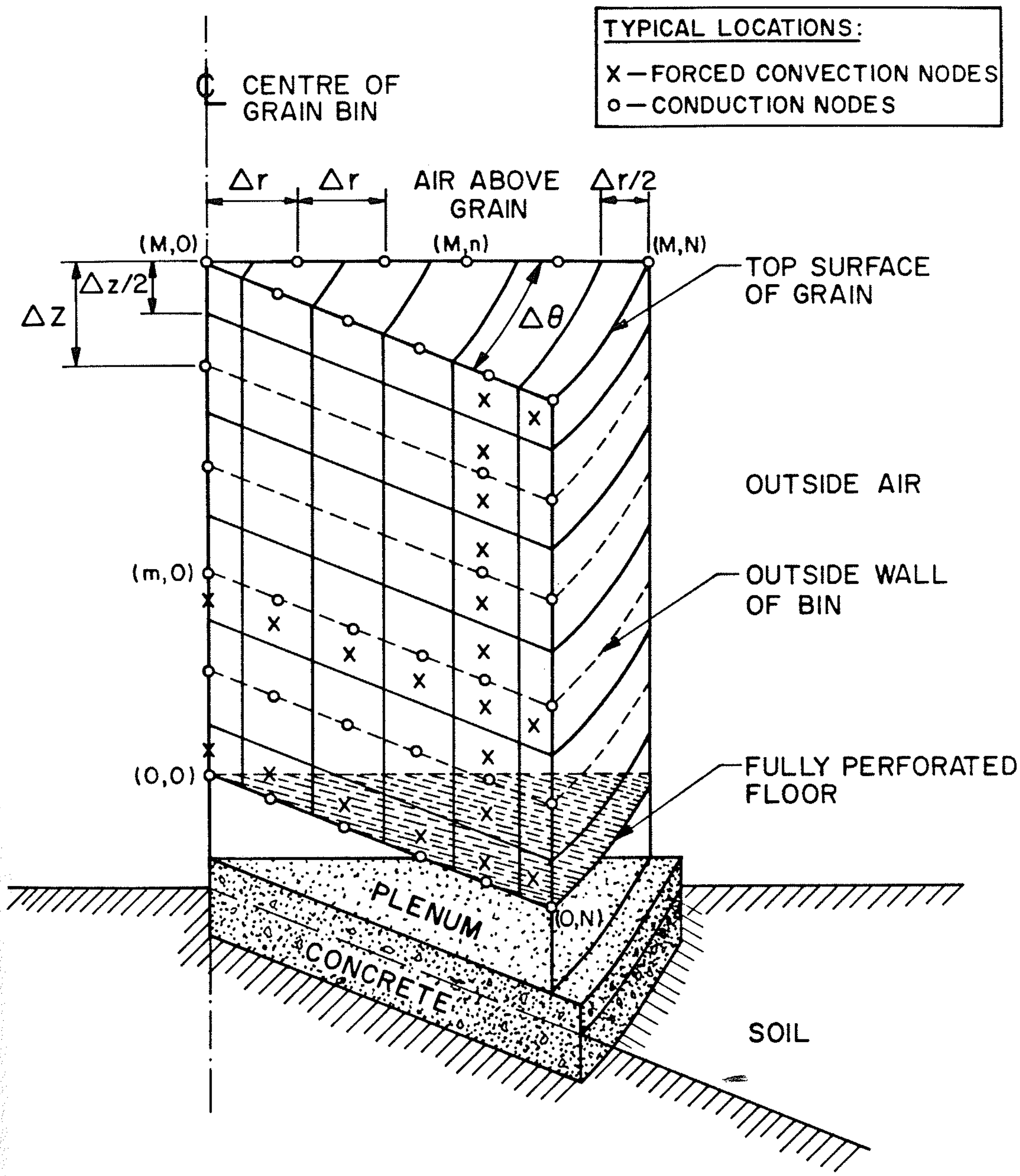

Fig. 3.1: Sector of a cylindrical grain bin divided into M + 1 vertical elements and N + 1 radial elements for conduction simulation, and 2M vertical layers and N + 1 columns for forced convection simulation.

For any interior spatial element m,n, the rate of conductive heat flow into the element is:

$$q = k[(n\Delta r + \frac{\Delta r}{2})\Delta\theta\Delta z]\left[\frac{T_{m,n+1} - T_{m,n}}{\Delta r}\right] + \tag{3}$$

$$k[(n\Delta r - \frac{\Delta r}{2})\Delta\theta\Delta z]\left[\frac{T_{m,n-1} - T_{m,n}}{\Delta r}\right] +$$

$$k[n(\Delta r)^2\Delta\theta]\left[\frac{T_{m+1,n} - T_{m,n}}{\Delta z}\right]\Delta t +$$

$$k[n(\Delta r)^2\Delta\theta]\left[\frac{T_{m-1,n} - T_{m,n}}{\Delta z}\right]\Delta t$$

where: n = number of spatial element in radial direction (Fig. 3.1)

m = number of spatial element in vertical direction (Fig. 3.1)

r = radial distance, m

z = vertical distance, m

θ = included angle of bin sector, rad

$T_{m,n}$ = temperature of element m,n at time t, K

The rate of heat stored in any interior spatial element, m,n, can be written:

$$q = n\Delta\theta\Delta z(\Delta r)^2 \; c_{m,n} \; \rho_{m,n} \; (T'_{m,n} - T_{m,n}) \tag{4}$$

where:

$c_{m,n}$ = mean specific heat of element m,n; J/(kg·K)

$\rho_{m,n}$ = mean density of element m,n; kg/m^3

$T'_{m,n}$ = temperature of element m,n at time t + Δt, K

Where thermal properties in the bin are constant, as with the interior elements, we can define dimensionless moduli:

$$U = \frac{c\rho(\Delta r)^2}{k\Delta t} \tag{5}$$

and:

$$E = \frac{(\Delta r)^2}{(\Delta z)^2} \tag{6}$$

The predicted temperature at the end of time interval Δt can be found by combining equations 3 to 6:

$$T'_{m,n} = \left[\frac{2n + 1}{2nU}\right]T_{m,n+1} + \left[\frac{2n - 1}{2nU}\right]T_{m,n-1} + \frac{E}{U}\left[T_{m+1,n} + T_{m-1,n}\right] + \left[1 - \frac{2(E + 1)}{U}\right]T_{m,n} \tag{7}$$

Equations can similarly be derived for elements at the top surface, wall surface, bottom surface, centre column, bottom centre, top centre, bottom wall and top wall. These are presented as Fortran statements in subroutine TOODEE (Appendix B). They are similar to those presented by Muir et al. (1980) except that heat transfer at the bottom surface is to an aeration plenum, not to a concrete and soil foundation. Calculations for the top, bottom and wall surfaces require that the thermal conductivity be related to the convective heat transfer coefficient using the dimensionless Biot number B defined as:

$$B = \frac{\bar{h}_c \Delta r}{k} \tag{8}$$

where: $\bar{h}_c$ = convective heat transfer coefficient

The convective heat transfer at the wall surface is calculated using the method presented by Yaciuk et al. (1975).

A value for radiant heat transfer to the bin wall surface is calculated according to the method presented by Muir et al. (1980) except in the calculation of the solar radiation components.

The equation derived by Muir et al. (1980) for the average total radiation striking all sides of a cylindrical bin at Winnipeg was used. The coefficients were modified to calculate hourly values:

$$H_{vs} = 0.1152\ H_o + 664.9\ \frac{H_s}{H_o} - 1131 \tag{9}$$

where:

H_{vs} = hourly radiation on a vertical surface, $J/(m^2 \cdot h)$

H_s = total radiation on a horizontal surface, $J/(m^2 \cdot h)$

H_o = extraterrestrial radiation for the given location, $J/(m^2 \cdot h)$

Total solar radiation on a horizontal surface, Hs, was estimated using a model developed for the Canadian Prairies by Won (1977). This model uses readily available hourly meteorological variables to estimate global radiation. This permits use of this program at locations where hourly global radiation data may not be available. The hourly meteorological variables required are cloud opacity, barometric pressure, and dew point and dry bulb temperatures. Extraterrestrial radiation, Ho, is calculated using the relationship presented by Won (1977). The equations which calculate radiant heat at the bin wall are shown in Fortran notation in subroutine RADN.

3.3 Forced Convection Model

The equilibrium drying model developed by Thompson (1972) provided the basis for the forced convection component of the combined model. It was used because of its ease of comprehension, efficient use of computer facilities, reported validity, and availability. Analytical models might have provided more accurate results, but difficulties encountered by previous investigators (Spencer 1969, Johnson 1979) with their use at low airflow rates would have had to be overcome.

The model is limited to use at the equilibrium or near equilibrium moisture and temperature storage conditions common at low airflow rates and near ambient temperatures. The basic assumptions of this model are:

1. Equilibrium is obtained between the air and the grain for the simulation time interval and space increment.

2. Heat and mass transfer between the air and the grain is adiabatic; i.e. there is no heat or moisture transfer to or from the surroundings of the grain storage.

3. No hysteresis exists between the absorption and desorption isotherms relating grain equilibrium moisture content to equilibrium relative humidity of the air.

4. No heat or moisture is generated in the grain bulk. Heat and moisture generation might be expected from respiration of the grain, and insect and fungi activity, but is probably negligible at low moisture contents or until the rate of deterioration increases.

Equilibrium conditions between the air and the grain are found by solving three equations with three unknowns. A heat balance equation, a mass balance equation, and an equilibrium moisture content equation are solved to obtain the air temperature, absolute humidity of the air, and the grain moisture content, at the end of the simulation time interval. An iterative technique developed by Thompson and Peart (1968) is used to solve for the unknowns.

To simulate drying in a deep bed, the grain was assumed to be divided into a series of layers stacked one upon another, with the ventilating air blowing up through the stack. The method outlined above was used to predict average changes in exhaust air and grain during the simulation time interval for each grain layer. The exhaust air from each layer is used as the input air for the next.

The equations first presented by Thompson (1972) in English engineering units were presented by Fraser (1979) in SI units. The Strohman and Yoerger (1967) equilibrium moisture content expression for wheat was used. These can be found in Fortran notation in subroutine DSIM. Thompson and Peart's (1968) method for finding the zero of an unknown function is found in subroutines ZERO and TYPE1.

To permit compatibility with two-dimensional conduction model, this forced convection model was modified to simulate conditions in vertical columns. The number of columns is dependent on the number of conduction nodes used. Conditions in each column were assumed to be independent of those in adjacent columns. To reduce computer time, however, if moisture contents and temperatures of each layer were within specified tolerances of each other, they were averaged, and the grain bin treated as one column. The procedure to utilize the forced convection method in two-dimensions is contained in Fortran notation in subroutine DRYSIM.

3.4 Wheat Deterioration Model

The model developed by Fraser and Muir (1980) to predict the allowable safe storage time for wheat was used to assess grain deterioration with and without ventilation. The equations are presented in Fortran notation in subroutine SAFWH and are shown graphically in Figure 3.2. The allowable safe storage time was defined as the time required for germination to drop to between 90 and 95%, or the time before mold growth became visible. Although there are no data to relate this to the time defined by Steele et al. (1969) for corn to reach 0.5% dry matter loss, an estimate of dry matter loss is made in the model for the layer in each column with the maximum allowable storage time elapsed. The equation by Thompson (1972) for dry matter decomposition is used and assumes that the allowable storage time represents 0.5% dry matter loss.

Grain deterioration during each time interval is estimated by calculating the allowable storage time using the deterioration model.

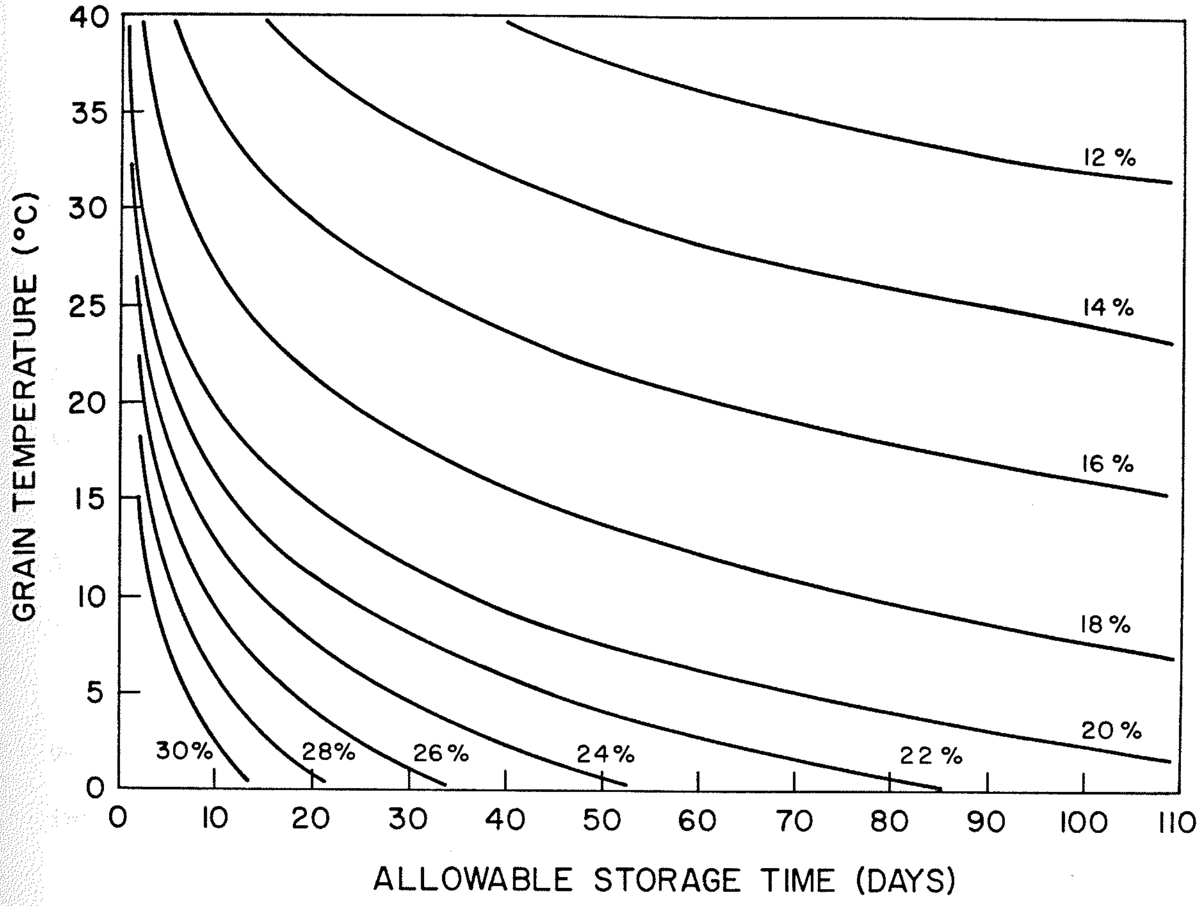

Fig. 3.2: Allowable storage time for wheat at various temperatures and moisture contents (Fraser and Muir 1980, based on data from Kreyger 1972).

The proportion of allowable storage time elapsed during the time interval is calculated by dividing the time interval by this allowable storage time. This value is added to the proportion of allowable storage time which has already elapsed to obtain an estimate of the total deterioration since harvest. The proportion of allowable storage time elapsed value is expressed as a decimal fraction. A value of 1.0 indicates that the allowable safe storage time as defined by the model, has elapsed.

The equations which define the wheat deterioration model and calculate the proportion of allowable storage time elapsed are contained in Fortran notation in subroutine DECOMP.

3.5 Combined Model

3.5.1 Additional data

Equations for the specific heat of wheat were taken from Muir and Viravanichai (1972). These can be found in Fortran notation in subroutine SPHT.

The temperature rise for airflow across an axial-flow fan is a function of the total efficiency of the fan, the static pressure, and the airflow rate. This was calculated using the theoretical equation verified by Metzger et al. (1980) (Appendix D). Airflow resistance data for wheat was obtained from ASAE Data D272 (American Society of Agricultural Engineers 1980). A regression equation (r^2=0.997) was derived from this data in SI (metric) units. Airflow resistance was assumed to be 50% higher than the ASAE data. These equations are contained in Fortran notation in subroutine FANSUB.

Numerical calculation of psychrometric properties of absolute humidity, saturation vapour pressure, and relative humidity were made using relationships presented by Wilhelm (1976). These are presented in Fortran notation in subroutines AHUM and RHAIR.

3.5.2 Simulation procedure

The combined computer model simulates grain storage conditions for a maximum of 1 year from the harvest date for each year of historical weather data available to a maximum of 20 years. The Fortran variable array sizes must be increased if simulation of additional harvest years is required.

Fan operation times are determined by input data values. If the appropriate conditions are met the fan is turned on or off. If the fan is on, grain conditions are simulated according to the two-dimensional forced convection model subroutine DRYSIM. If the fan is off grain conditions are simulated according to the two-dimensional conduction model subroutine TOODEE. Because the nodes for each of these modes are not in the same location (Fig. 3.1), a change from one mode to another requires calculation of initial conditions for the other mode. This is done by simply averaging temperatures at the nodes using subroutine CHANGE.

The present model (Appendix B) is capable of simulating to a maximum of 10 horizontal layers and 10 vertical radial columns in the grain bin. The number of convection layers must be an integer multiple of the number of conduction layers. Thompson (1972), Morey et al. (1976) and Fraser (1979) used 10 layers to simulate unheated air drying with the forced convection model. Muir et al. (1980) used 5 layers and 5 columns to simulate grain temperatures using the two-dimensional finite difference conduction model. All simulations made during this study used these values for the conduction and forced convection components.

The simulation time intervals may differ in each mode as well. These must be chosen with consideration given to the layer and column dimensions to obtain stable and accurate predictions. Thompson (1972), Morey et al. (1976) and Fraser (1979) used a time interval of 1 h with the forced convection model. Muir et al. (1980) used a time interval of 6 h with the two-dimensional conduction model. In the combined model, the conduction time interval must be chosen to be an integer multiple of the convection model. These time intervals are used in all simulations made during this study.

The skeleton flow chart (Fig. 3.3) shows a simplified version of the simulation procedure. After reading the input parameters, simulation begins for each harvest year using historical weather data on tape. Normally simulation begins on a fall harvest date and continues for a maximum of 1 year. Based on input parameters deciding fan operation, the grain conditions are determined using the conduction or forced convection subroutines and the appropriate time interval. Grain deterioration during each interval is estimated and the additional proportion of allowable storage time elapsed is added to that already elapsed.

An intermediate "status report" is printed at key dates during each simulation year (Fig. 3.4) by calling subroutine PRINT. This report provides grain temperatures, moisture contents, and proportion of

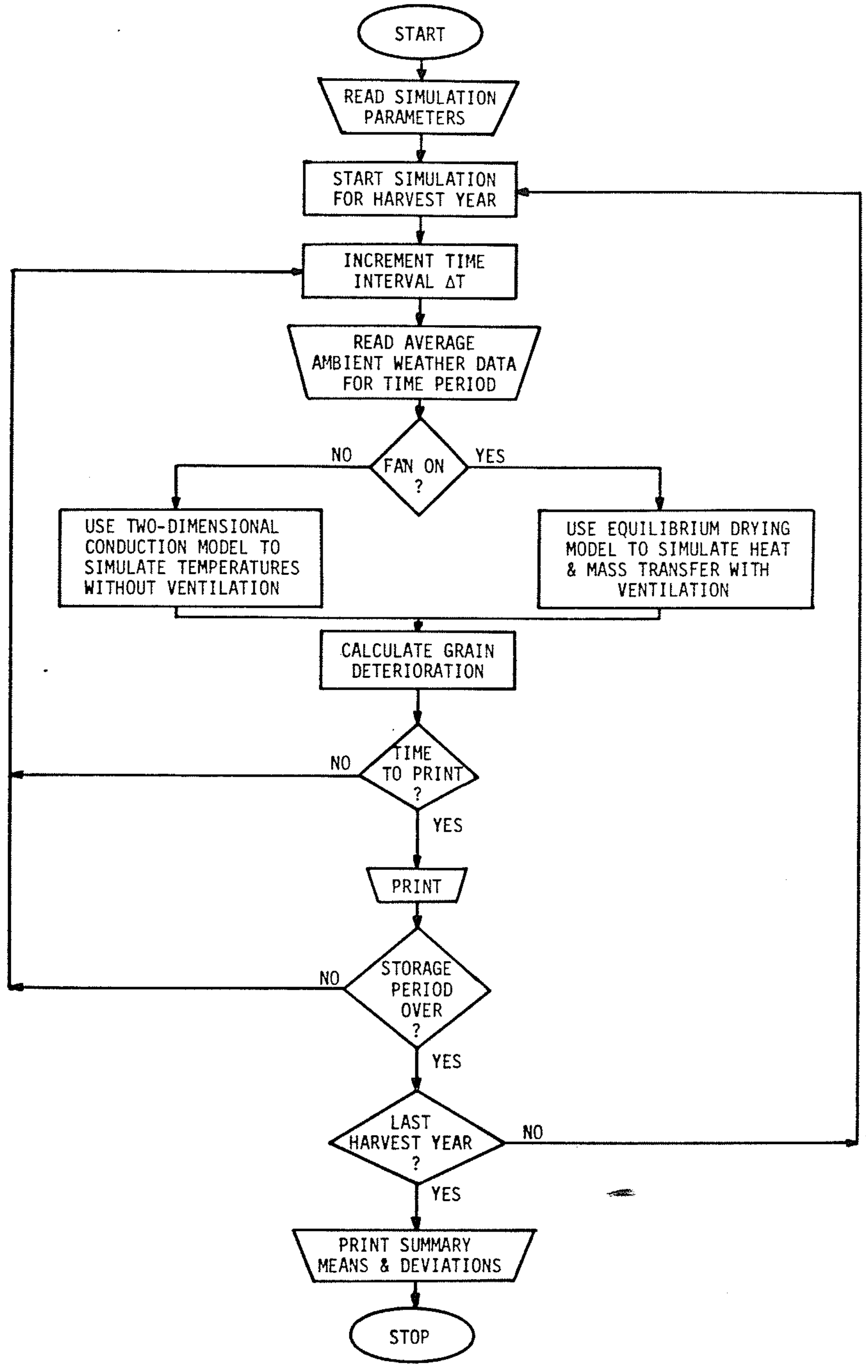

Fig. 3.3: Skeleton flow chart of the combined computer simulation model.

allowable storage time elapsed values for each forced convection volume element. For example, in Fig. 3.4, 10 vertical convection layers and 5 horizontal conduction increments resulting in 6 convection columns (see Fig. 3.1) have been used. Layer 1 is at the floor level and 10 is at the top. Column 1 is at the bin centre and 6 is at the wall. Average bin temperatures, moisture contents and allowable storage time elapsed are calculated. The average difference in moisture contents between the top and bottom layers is determined; a positive value indicates that moisture content is lower at the bottom than at the top.

The percent dry matter decomposition at the "worst" layer of each column is calculated assuming that 0.5% decomposition occurs when the deterioration model predicts that the allowable storage time for the grain has completely elapsed.

The overdrying cost is calculated using the following equation which assumes that the grain is completely mixed before marketing:

$$C_o = C_g \left[\frac{M_d - M_a}{(100 - M_a)} \right] T \qquad (10)$$

where:

C_o = overdrying cost, \$

C_g = input grain value, \$/t

M_d = "dry" moisture content (e.g., 14.5% for wheat), % wet mass basis

M_a = average grain moisture content, % wet mass basis

T = total mass of stored grain at "dry" moisture content, t

INTERMITTENT VENTILATION - STATUS REPORT RUN # 1405
WINNIPEG - MANITOBA

DATE= 63/ 4/ 1 3 HOURS. SIMULATION YEAR: 2
IT IS NOW 211.50 DAYS SINCE THE BIN WAS FILLED

GRAIN CONDITIONS AT THE SPRING REPORT DATE ARE:

GRAIN TEMPERATURES:
AVERAGE: -2.02 C

TOP	1	2	3	4	5	6
10	-5.74	-5.92	-6.39	-6.64	-4.53	-4.93
9	-7.08	-7.25	-7.71	-7.94	-5.65	-5.17
8	-7.04	-7.19	-7.61	-7.80	-5.52	-5.11
7	-5.62	-5.75	-6.09	-6.23	-4.15	-4.75
6	-3.56	-3.66	-3.92	-4.01	-2.24	-4.26
5	-0.85	-0.92	-1.10	-1.16	0.20	-3.63
4	1.27	1.23	1.11	1.08	2.05	-3.15
3	2.80	2.78	2.71	2.69	3.32	-2.83
2	3.92	3.91	3.88	3.87	4.25	-2.64
1	4.63	4.62	4.61	4.61	4.84	-2.58

GRAIN MOISTURE CONTENTS:
AVERAGE: 14.23 % TOP/BOTTOM DIFFERENCE: -0.22 %

TOP	1	2	3	4	5	6
10	14.38	14.37	14.36	14.32	14.25	14.28
9	14.39	14.39	14.40	14.36	14.33	14.32
8	14.36	14.36	14.38	14.36	14.37	14.35
7	14.33	14.33	14.34	14.36	14.39	14.34
6	14.28	14.27	14.29	14.34	14.39	14.30
5	14.21	14.22	14.24	14.29	14.36	14.20
4	14.09	14.10	14.12	14.16	14.23	14.00
3	13.87	13.88	13.90	13.93	13.98	13.69
2	13.81	13.81	13.83	13.85	13.87	13.59
1	14.57	14.57	14.58	14.58	14.58	14.39

PORTION OF ALLOWABLE STORAGE TIME ELAPSED:
AVERAGE: 0.285

TOP	1	2	3	4	5	6
10	0.327	0.327	0.325	0.320	0.311	0.335
9	0.333	0.332	0.328	0.320	0.304	0.327
8	0.338	0.337	0.331	0.319	0.300	0.320
7	0.333	0.331	0.326	0.314	0.294	0.313
6	0.323	0.322	0.317	0.306	0.287	0.302
5	0.308	0.307	0.304	0.295	0.278	0.289
4	0.288	0.288	0.285	0.279	0.265	0.271
3	0.258	0.258	0.256	0.252	0.243	0.242
2	0.217	0.217	0.216	0.215	0.210	0.207
1	0.211	0.211	0.211	0.210	0.208	0.206

PERCENT DM DECOMPOSITION IN THE WORST LAYER OF EACH COLUMN:

1	2	3	4	5	6
0.132	0.131	0.129	0.124	0.120	0.130

OVERDRYING COST: $ 63.08 OR $ 0.63/T

AMOUNT AND VALUE OF SPOILED GRAIN:
VOLUME: 0.0 M**3 MASS: 0.0 T VALUE OF GRAIN SPOILED: $ 0.0

FAN AND HEATER OPERATION LOG:

MONTH	1	2	3	4	5	6	7	8	9	10	11	12	TOTAL
FAN OPERATION:													
HOURS	7.00	92.00	101.00	0.0	0.0	0.0	0.0	0.0	630.00	695.00	6.00	53.00	1584.00
COST	0.04	0.52	0.57	0.0	0.0	0.0	0.0	0.0	3.55	3.91	0.03	0.30	8.92

TOTAL ELECTRICAL ENERGY USE TO DATE BY THE FAN + HEATER: 891.86 MJ OR 8.92 MJ/T OR $ 0.09/T

SYSTEM OPERATING COSTS TO DATE: $ 0.72/T

Fig. 3.4: Example page of computer output for the system status report.

The amount of "spoiled" grain is calculated by summing the volume elements for which allowable storage time has elapsed and by multiplying this volume by the specific density of the grain. The value of this spoiled grain is found by multiplying this "spoiled" mass by the input value of the grain.

A fan and heater operation log for each simulation year is kept. This records and prints the time and cost of fan and supplemental heater operation, based on input electricity costs, for each month of the year (eg. January is month 1 and December month 12). No values for heater operation are shown in Fig. 3.4 because a supplemental heater was not used in this simulation.

A value for "system operating cost" from harvest date to the report date is calculated as follows:

$$C_s = C_{ot} + S_p + E_c \tag{11}$$

where:

C_s = system operating cost, \$/t

C_{ot} = overdrying cost, \$/t

S_p = spoiled grain value, \$/t

E_c = electrical energy cost, \$/t

After grain conditions during all harvest years have been simulated subroutine PRINT is called again to produce summary reports. The "key" variables for each harvest year, and averages, with standard deviations, maxima, and minima are calculated and printed (Fig. 3.5).

INTERMITTENT VENTILATION - SUMMARY REPORT
SWIFT CURRENT - SASK

RUN # 4701

****

AT THE SPRING DATE:

HARVEST YEAR	DAYS	MOISTURE CONTENT (% WB)	TOP/BOT DIFF (% WB)	GRAIN TEMP (DEG C)	ENERGY USE (MJ/T)	OD COST ($/T)	SPOILED MASS (T)	ALLOWABLE STORAGE TIME ELAPSED	OPERATING COST ($/T)
61	211.5	14.63	-0.60	-5.21	4.5	0.0	0.0	0.257	0.05
62	211.5	14.59	-0.61	-1.39	4.6	0.0	0.0	0.327	0.05
63	212.5	14.40	0.38	-3.81	4.4	0.24	0.0	0.425	0.29
64	211.5	14.76	-0.80	-8.29	4.3	0.0	0.0	0.275	0.04
65	211.5	14.72	-0.56	-0.40	4.6	0.0	0.0	0.258	0.05
66	211.5	14.57	-0.87	-8.68	4.6	0.0	0.0	0.323	0.05
67	212.5	14.60	-0.04	-0.05	4.6	0.0	0.0	0.349	0.05
68	211.5	14.77	-1.15	-6.11	4.6	0.0	0.0	0.293	0.05
69	211.5	14.73	-1.36	-6.56	5.1	0.0	0.0	0.296	0.05
70	211.5	14.69	-0.63	-5.08	4.6	0.0	0.0	0.259	0.05
71	212.5	14.65	-0.35	-1.12	4.6	0.0	0.0	0.278	0.05
72	211.5	14.64	-0.06	2.02	5.2	0.0	0.0	0.272	0.05
73	211.5	14.59	-0.39	-5.42	4.6	0.0	0.0	0.282	0.05
74	211.5	14.45	0.29	-10.43	4.9	0.13	0.0	0.300	0.18
75	212.5	14.65	-0.20	1.22	5.2	0.0	0.0	0.311	0.05
AVERAGE:	211.8	14.63	-0.46	-3.95	4.7	0.02	0.0	0.300	0.07
+/-	0.5	0.11	0.49	3.82	0.3	0.07	0.0	0.044	0.07
MAXIMUM:	212.5	14.77	0.38	2.02	5.2	0.24	0.0	0.425	0.29
IN YEAR:	63	68	63	72	75	63	61	63	63
MINIMUM:	211.5	14.40	-1.36	-10.43	4.3	0.0	0.0	0.257	0.04
IN YEAR:	61	63	69	74	64	61	61	61	64

****

Fig. 3.5: Example page of computer output for the summary report.

The computer times and costs used in each simulation varied greatly depending upon the amount of fan operation. The following were used with the Amdahl 470/V7 computer at the University of Manitoba. With no ventilation, computer time averaged about 10 seconds per simulation year at a cost of about 2.5 computer units per year. The highest time use was about 1 minute and 30 seconds per simulation year at a cost of about 24 computer units per year. In the simulations performed during the course of this study, fan operation as modelled by the forced convection component increased computer demands by a factor of nearly 10 when compared with simulations involving no ventilation. The high demand of the combined simulation model on computer use required that most simulations be run during "non-prime" times, usually between midnight and 0800 h.

Chapter IV

MODEL VALIDATION

4.1 Method

Validation of the mathematical model by comparing predicted output with experimentally determined data is required to assure reasonable accuracy. The critical parameters requiring validation are the predictions of grain temperatures, moisture contents, and deterioration. Experimentally obtained values were obtained for wheat stored in an aeration bin. These were compared with values predicted by the computer model.

4.2 Facilities and Equipment

A 4.3 m diameter grain bin, Model 145 by Westeel-Rosco, with a fully perforated ventilation floor located at the University of Manitoba Research Farm, Glenlea, was used for grain storage (Fig. 4.1). A 0.56 kW, 300 mm nominal diameter, Caldwell Model AF12.75 fan was used to provide forced air ventilation to the plenum and grain. A grid of 18 copper-constantin thermocouples on the south-west radius was installed for temperature measurement (Fig. 4.2). A Honeywell 24-point "Electronic 16-Multipoint Strip Chart Recorder" (accuracy ±0.5°C) was used to record grain temperatures.

Fan airflow rates were measured using a Pitot tube traverse across the plane of an inlet duct; ASTM Method D3154-72 (American Society for Testing and Materials 1979) (Fig. 4.3). Static and velocity pressures

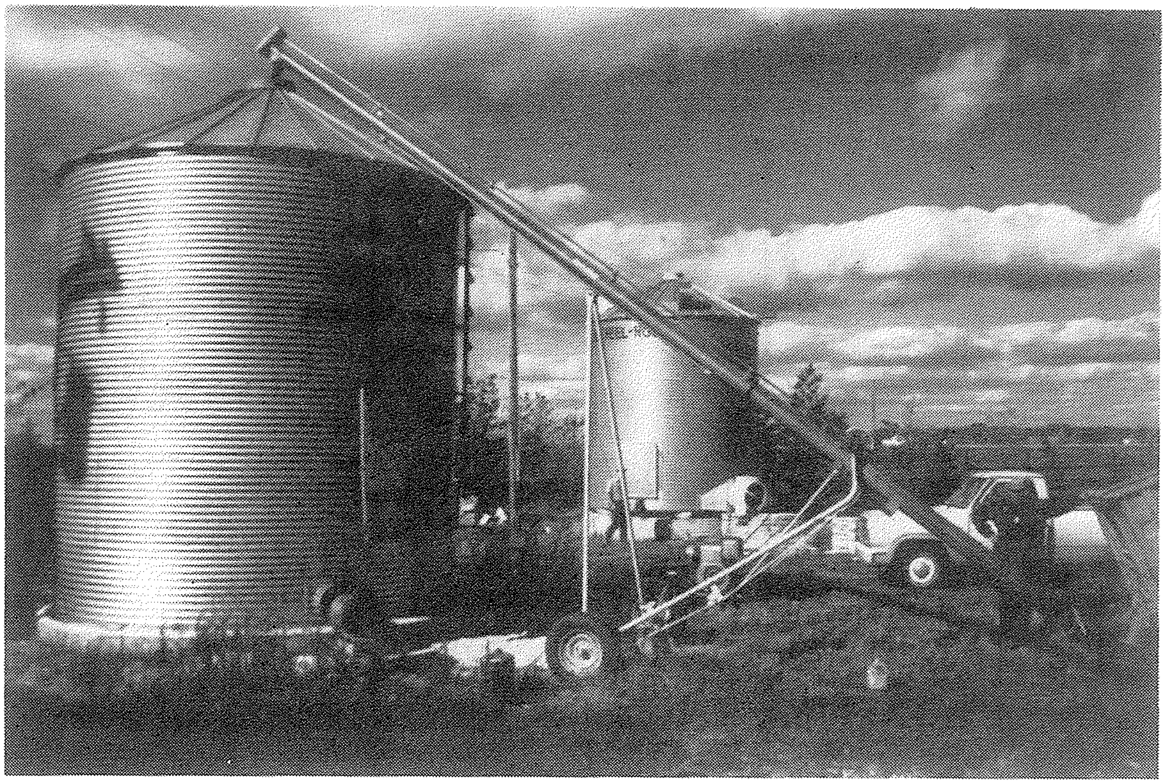

Fig. 4.1: Glenlea aeration bin, October 1979.

were measured using a Pitot tube with inclined manometer (Model Mark 5, Airflow Developments Ltd., High Wycombe, England). Error due to a hand held Pitot traverse made in a field airflow test can be as high as ±10% or more (Air Movement and Control Association 1979).

Grain samples for moisture content and deterioration assessment were made using a 0.2 L capacity torpedo probe (Burrough Equipment Company, Evanston, IL). Samples were obtained while standing on the top surface of the grain and by pushing the probe to each of the six sampling locations (Fig. 4.2).

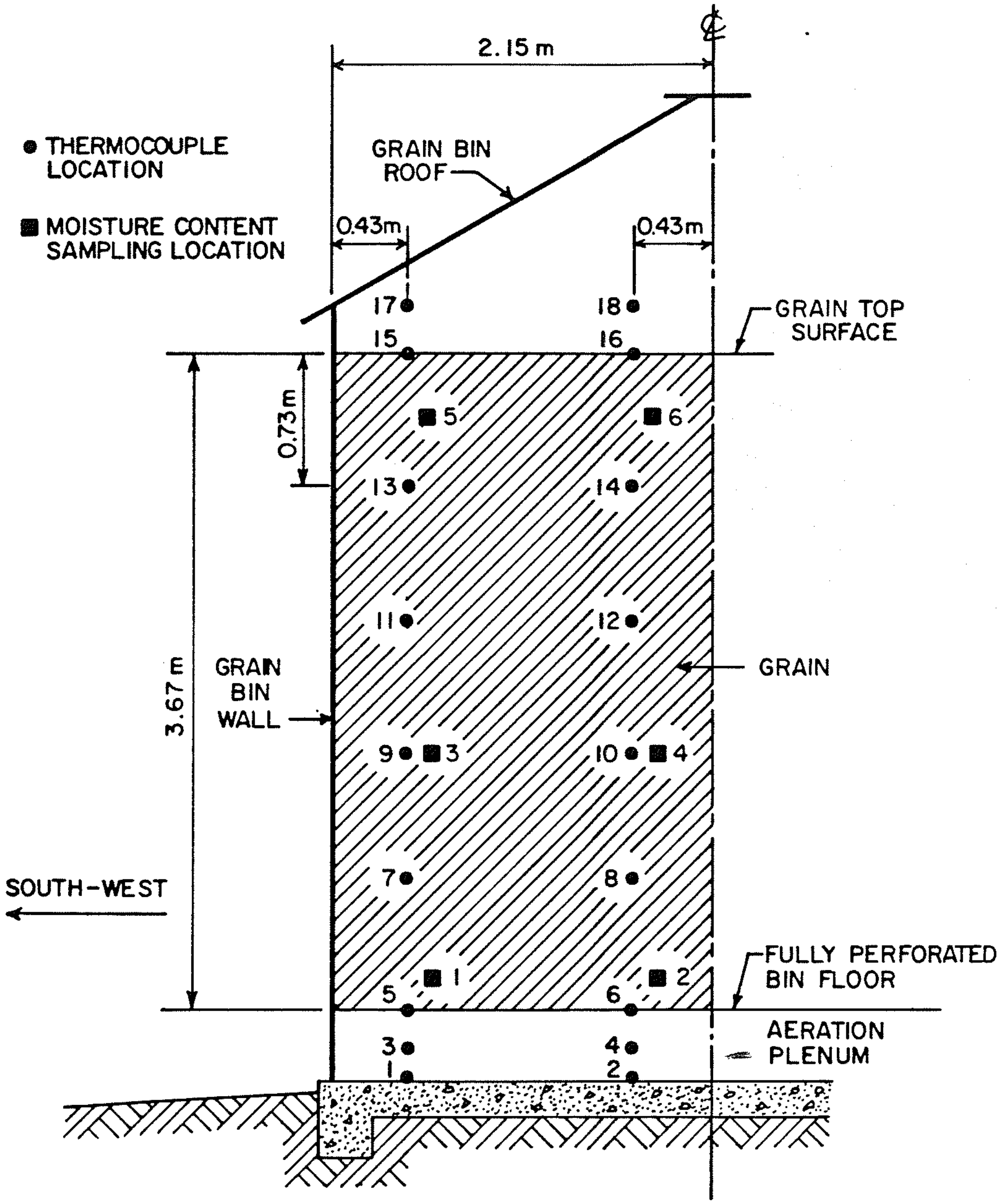

Fig. 4.2: Cross-section of experimental aeration bin showing the thermocouple and grain sampling locations.

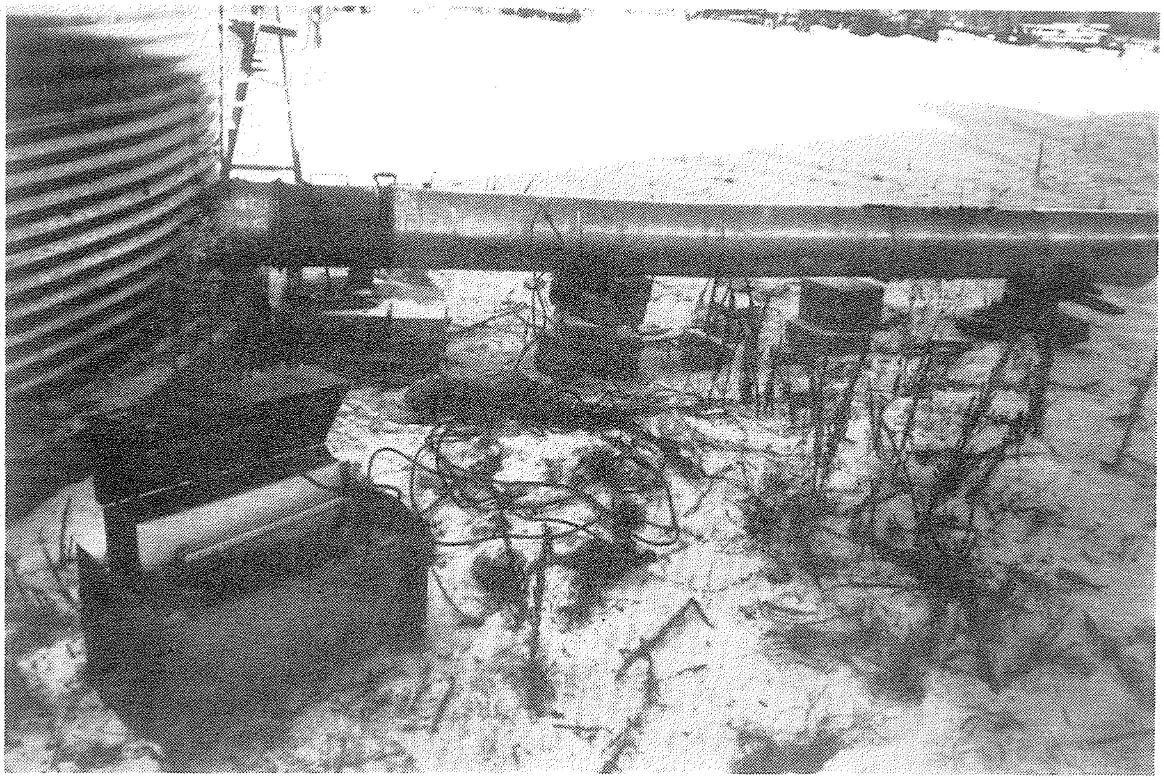

Fig. 4.3: Pitot traverse duct and inclined manometer during a field airflow rate test.

Moisture content determinations of the wheat samples were made according to the oven drying method; ASAE Standard S352 (American Society of Agricultural Engineers 1980). The accuracy of this method is ± 0.2 percentage points.

Air temperature and relative humidity were monitored at the Glenlea site with a thermohygrograph; however, 1979 hourly weather data for the computer verification were obtained for Winnipeg International Airport from the Canadian Climate Centre, Environment Canada, Downsview, Ontario. The Winnipeg Airport weather station is located about 25 km north of the aeration bin at the Glenlea site. The data on tape were used because several climatic variables required by the computer model were not measured at the site (e.g. barometric pressure, cloud opacity, and wind speed).

4.3 Grain Deterioration

Grain deterioration was evaluated with a simple germination test and fungi count. The germination test involved incubating 25 seeds plated on moist filter paper in 10 cm petri dishes at 2.5°C for 3 days to break dormancy, then counting germination after an additional 7 days at 22°C. The fungi count involved counting infestations of field and storage fungi on the plated seeds after the same time period.

This assessment of grain deterioration was made by H.A.H. Wallace, Mycologist, Research Station, Agriculture Canada, Winnipeg.

4.4 Comparison of Measured and Predicted Results

4.4.1 Storage and ventilation periods

The grain bin was filled on 1 to 2 October 1979 with 40 t of variety-Glenlea wheat harvested at the University of Manitoba Research Farm, Glenlea. This wheat graded No. 1 Utility, and had an average dockage level of 6%. Initial grain moisture contents averaged 16.3% and initial temperatures averaged 15.9°C, ranging from 9.8 to 21.2°C. The 1979 wheat harvest in Southern Manitoba was unusually late due largely to spring flooding and the resulting late seeding.

Grain temperatures were recorded at 6 h intervals with the multipoint strip chart recorder. Grain samples were taken periodically during storage for moisture content and deterioration assessment.

The aeration fan was turned on at 1240 h on 3 October 1979. The airflow rate was measured using the Pitot traverse method and found to be 9.0 $(L/s)/m^3$. Since this is a much higher airflow rate than required for aeration, the fan was turned off at 1150 h on 5 October. As grain temperatures and moisture contents were such that spoilage was not likely, the fan remained off until ambient weather conditions permitted further cooling of the grain.

During this time a baffle to restrict airflow was fabricated. It is a 19 mm thick plywood plug, approximately 300 mm in diameter drilled with 12 - 24 mm diameter holes (Fig. 4.4). Four holes were taped closed. This arrangement reduced the measured fan airflow rate to 1.9 $(L/s)/m^3$ when installed. The average temperature rise measured across the baffled fan during the ventilation period was 4.9 ± 1.4°C.

The baffled fan was turned on at 1120 h on 8 November 1979 when average daily air temperatures were less than -10°C. The fan remained on until 0950 h on 21 November 1979. The grain was stored without ventilation until early February 1980 when it was removed for use as livestock feed.

Using the 1979 weather data on tape and the system parameters for the experimental Glenlea aeration bin, two sets of predictions were made of grain temperatures, moisture contents, and deterioration. One set of predictions began on the bin fill date of 2 October 1979 and included the 2 day period of 9.0 $(L/s)/m^3$ ventilation. The second set began at 1200 h on 5 October 1979 and did not include this period of high airflow rate. Tape weather data were available for 1979 only, limiting

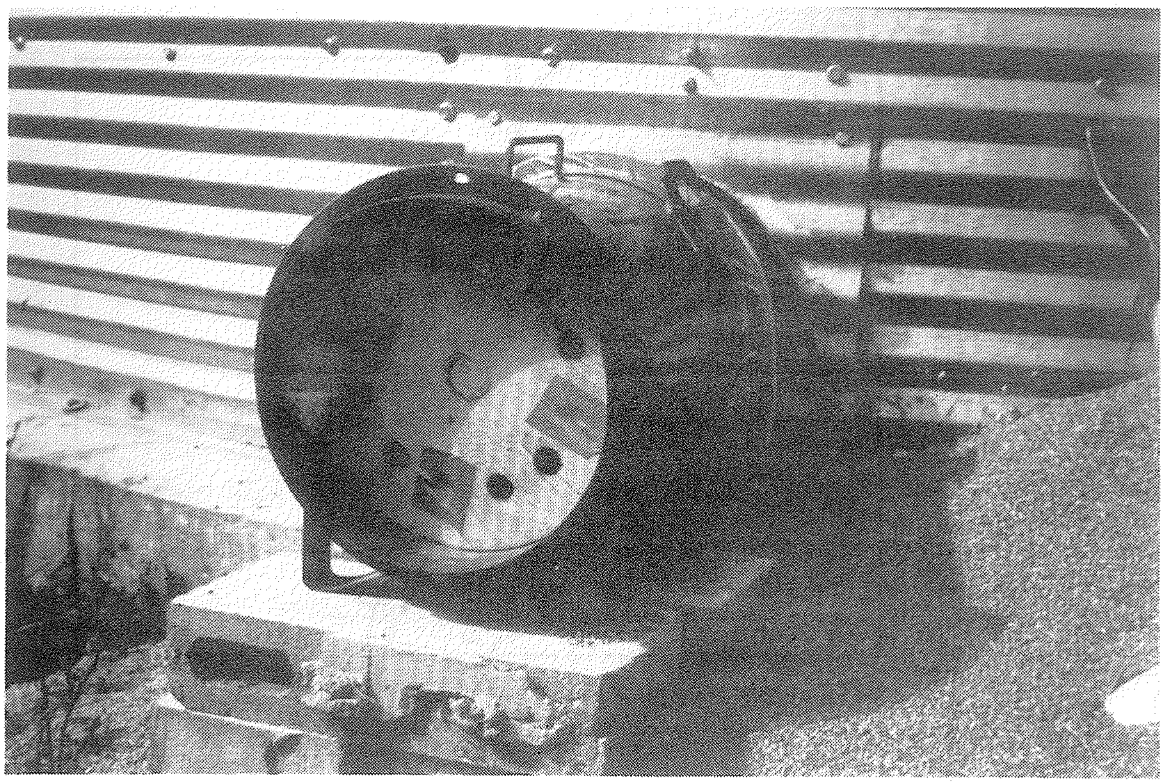

Fig. 4.4: Caldwell Model AF12.75 aeration fan with airflow reduction baffle installed.

comparisons of measured and predicted data from 2 October to 31 December 1979.

4.4.2 Grain temperatures

Predicted and measured grain temperatures at two thermocouple locations were compared (Figs. 4.5 and 4.6). Thermocouple 11 was located 0.43 m from the bin wall, and thermocouple 12, 0.43 m from the bin centre-line. Both were 2.2 m above the bin floor (Fig. 3.3).

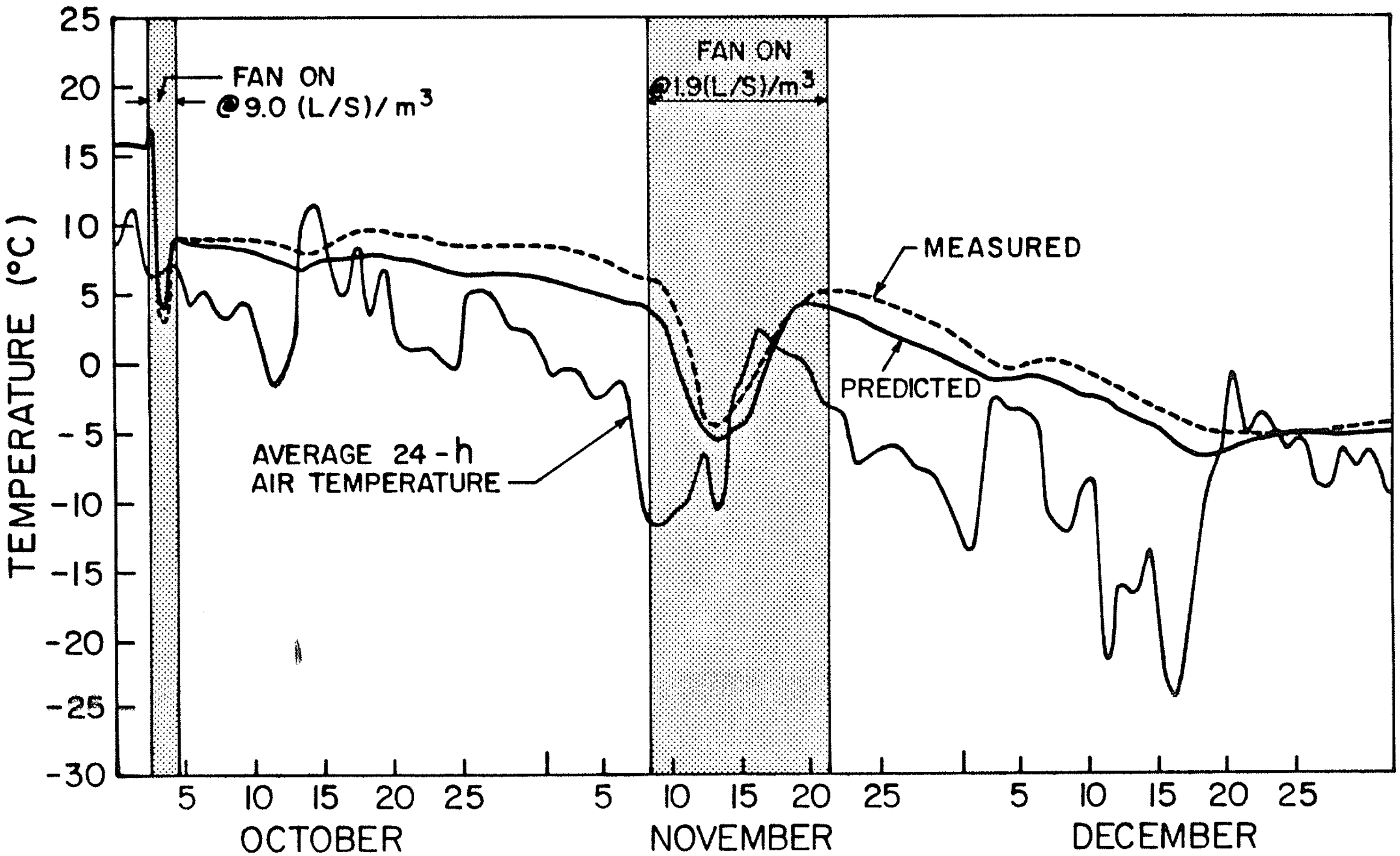

Fig. 4.5: Measured and predicted grain temperature values at thermocouple location 11.

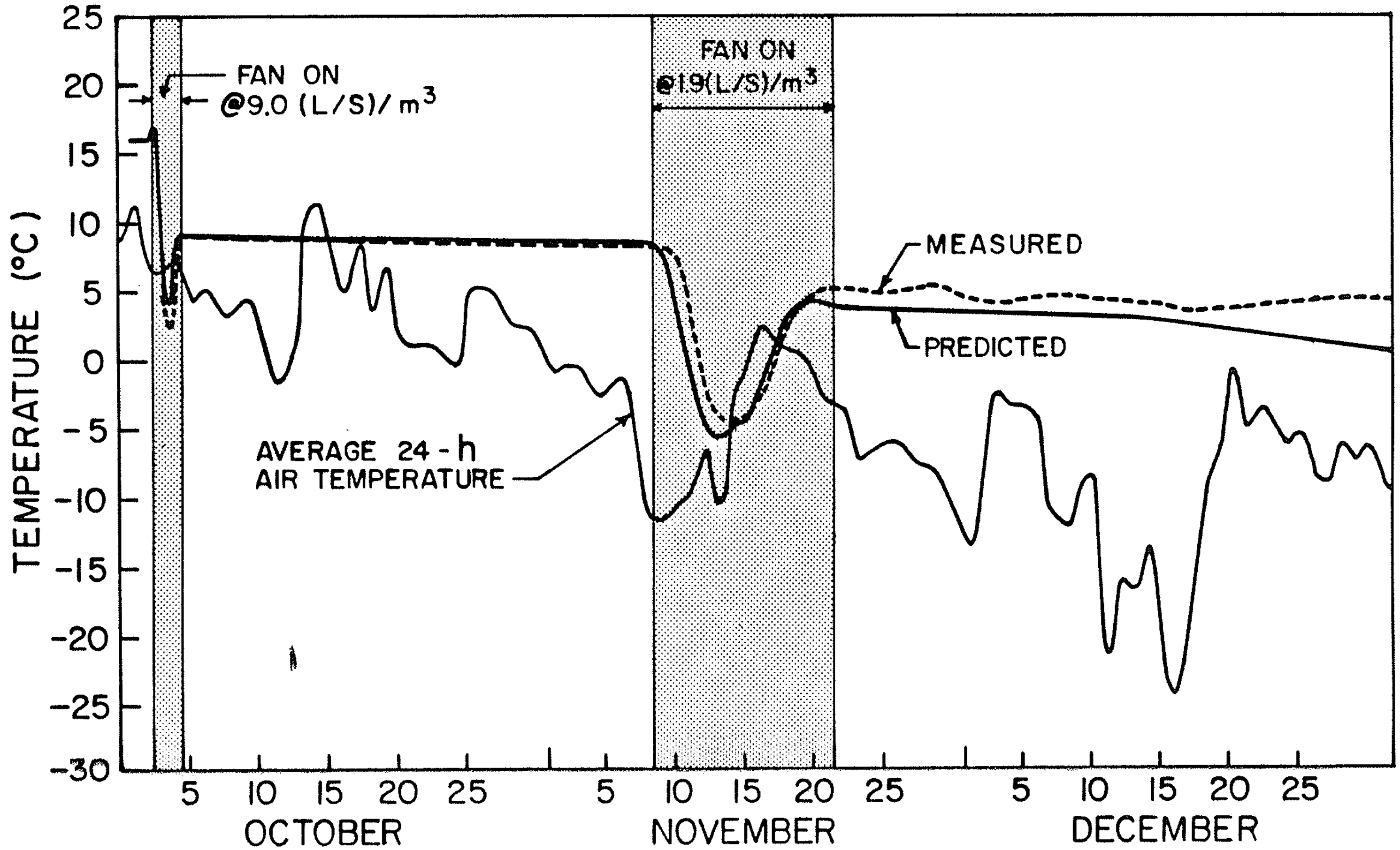

Fig. 4.6: Measured and predicted grain temperature values at thermocouple location 12.

The predicted temperatures at these two locations followed the measured temperatures closely. The maximum differences were 2.5°C for thermocouple 11 on about 3 November, and 3.5°C for thermocouple 12 on 31 December.

4.4.3 Grain moisture contents

Predicted and measured average grain moisture contents at the three sampling depths were compared, as well as the average of moisture contents throughout the bin. Measured and predicted moisture contents from locations 1 and 2 were averaged to obtain floor level values (Fig. 4.7), locations 3 and 4 for centre values (Fig. 4.8), and locations 5 and 6 for top values (Fig. 4.9). All six were averaged to obtain an average moisture content for the grain (Fig. 4.10).

Two sets of predictions were made. One began on 2 October and included the 2 day period of 9.0 $(L/s)/m^3$ ventilation. The second began on 5 October after the high airflow rate ventilation, using grain conditions on that date for initial conditions.

Floor level moisture content predictions, which included the 9.0 $(L/s)/m^3$ ventilation period, appear to have overestimated moisture losses (Fig. 4.7). During the initial 2 day period, measured moisture contents dropped 0.5 percentage points, while the model predicted reductions of about 2.2 percentage points. If the high ventilation period is ignored, the measured and predicted values follow more closely. During the 13 day period of 1.9 $(L/s)/m^3$ ventilation, measured moisture content reductions of 0.6 percentage points occurred. The

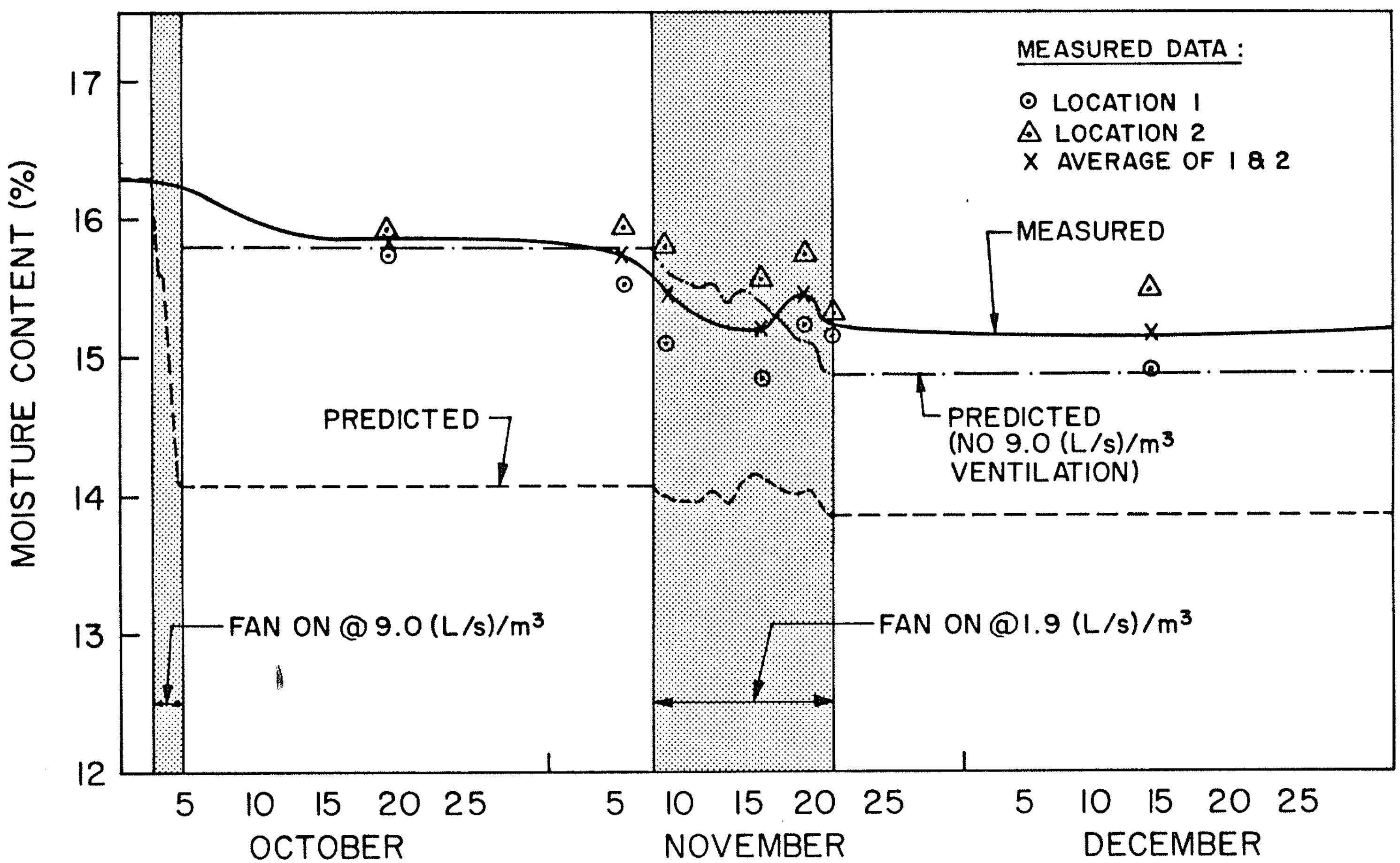

Fig. 4.7: Measured and predicted floor level moisture content values (Mean of sampling locations 1 & 2).

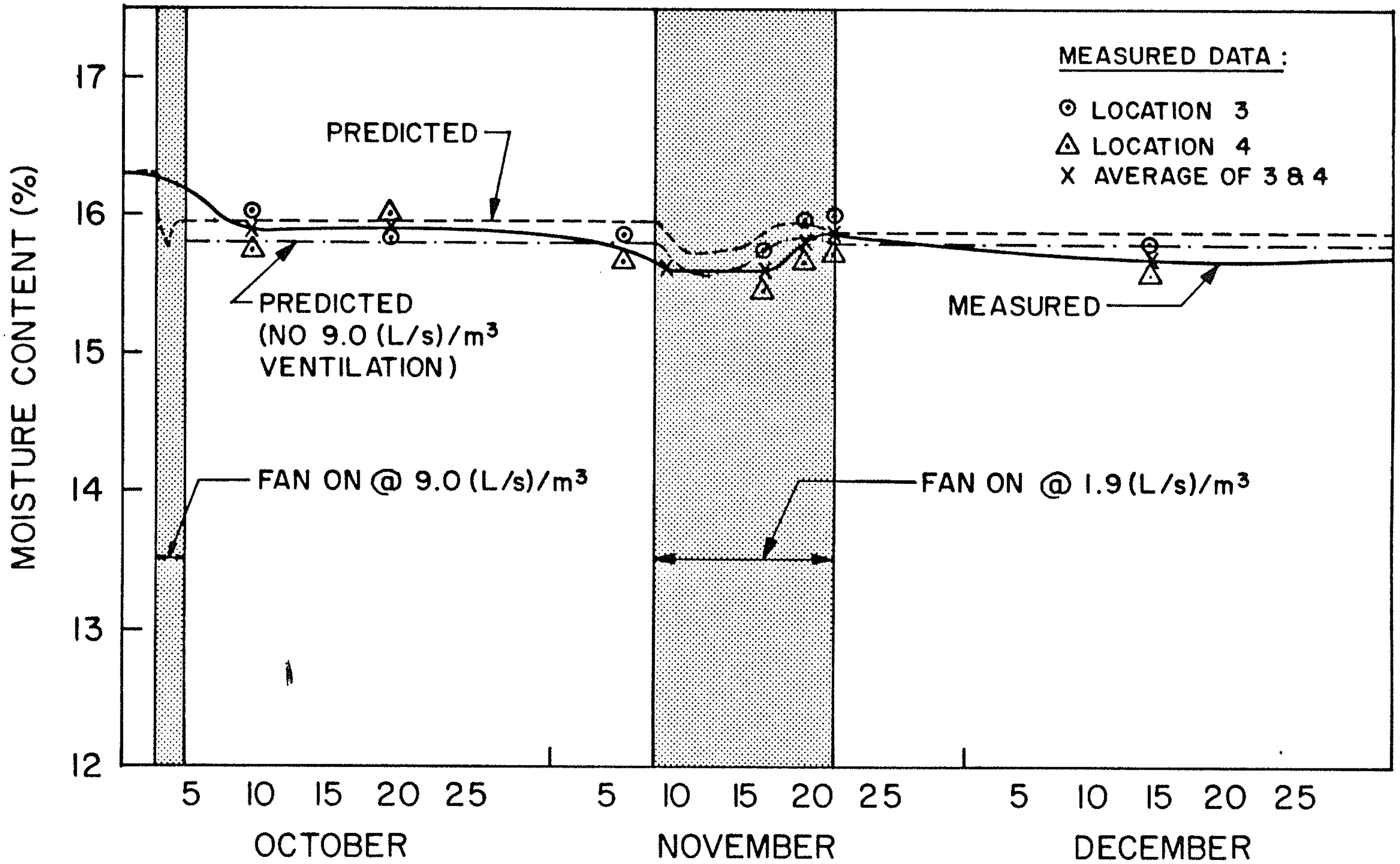

Fig. 4.8: Measured and predicted centre level moisture content values (Mean of sampling locations 3 & 4).

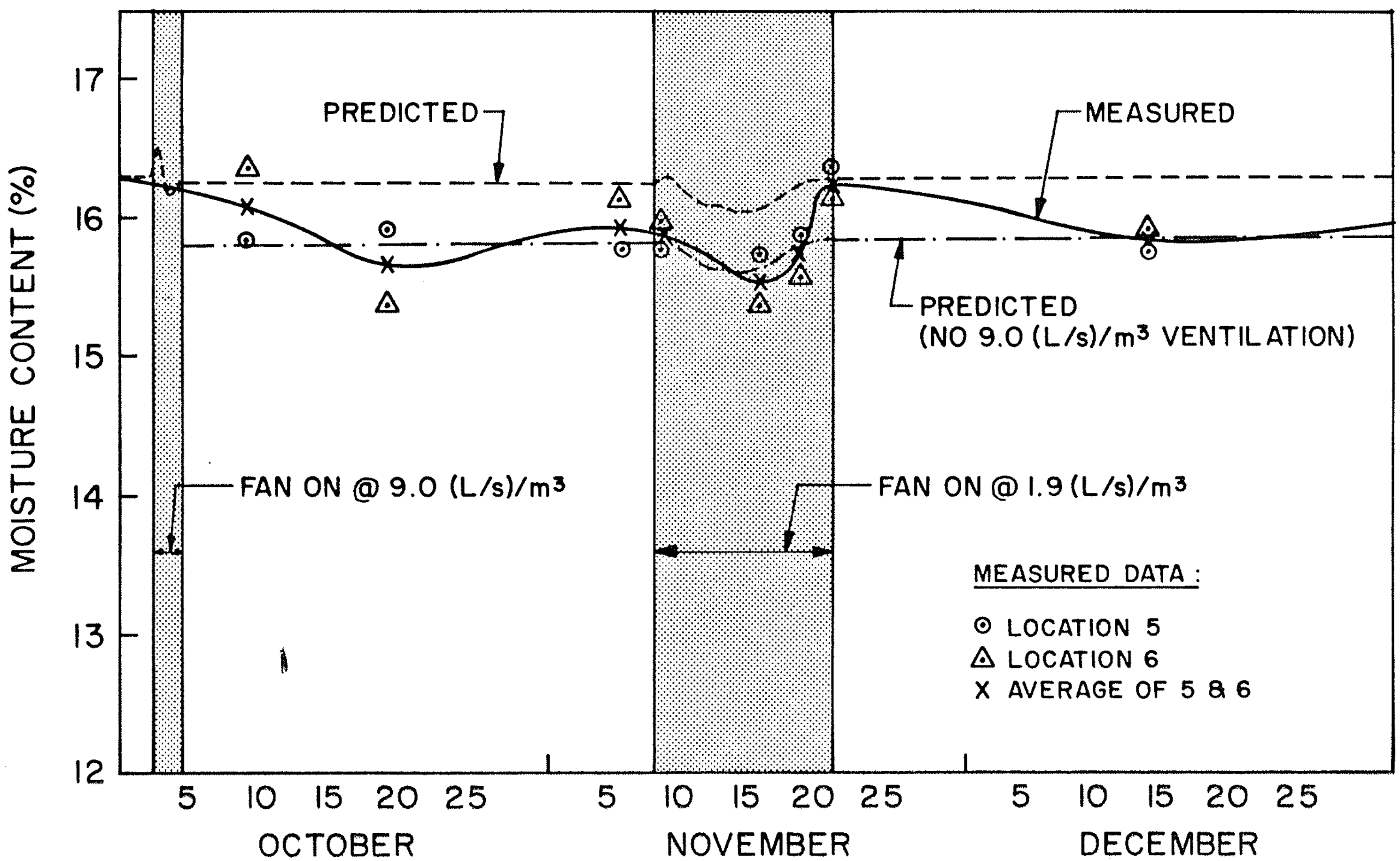

Fig. 4.9: Measured and predicted top level moisture content values (Mean of sampling locations 5 & 6).

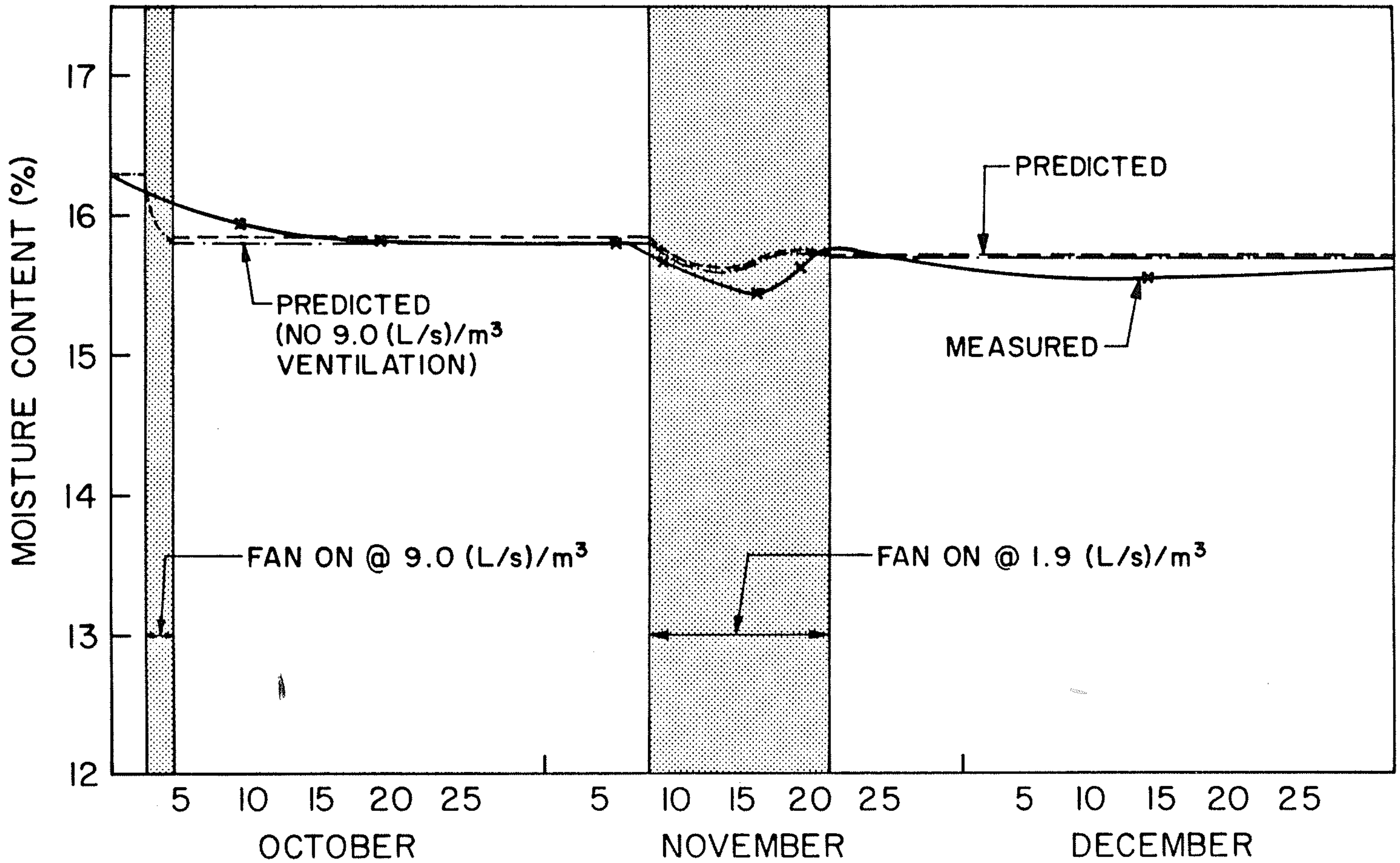

Fig. 4.10: Measured and predicted values of the average bin moisture content (Mean of all six sampling locations).

model predicted reductions of 0.9 percentage points for this period. This is close to the experimental error of about ± 0.2% for moisture measurements.

Centre and top level moisture content predictions follow measured data more closely regardless of whether the high airflow rate period is included (Fig. 4.8 and 4.9). Predictions through and after the 1.9 $(L/s)/m^3$ period agree within 0.4 percentage points with the measured data.

The average grain bulk moisture content predictions followed the measured values closely, even with inclusion of the high airflow rate period. Maximum deviations of 0.3 percentage points occurred (Fig. 4.10).

4.4.4 Grain deterioration

Germination tests and fungi counts indicated that grain quality was not reduced significantly during the fall storage period. Germination averaged 98% ranging from 96 to 99%. Fungi counts identified a predominance of those field fungi normally associated with freshly harvested grains.

The predicted average proportion of allowable storage time elapsed increased to over 0.2 after grain storage for three months (Fig. 4.11). Due largely to the decreases in grain temperature, both ventilation periods decreased the rate of increase of the proportion of allowable storage time elapsed.

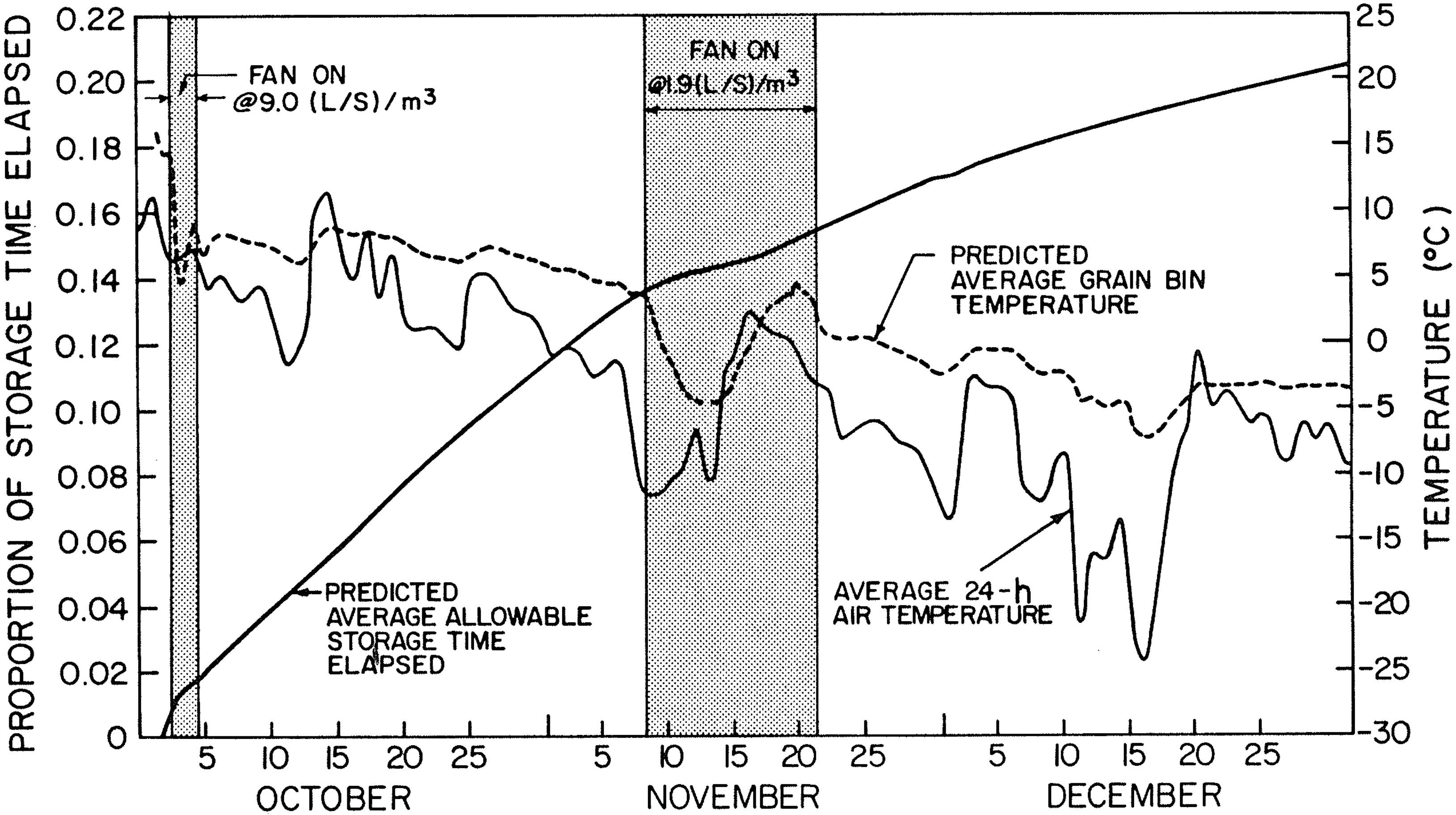

Fig. 4.11: Grain temperature and deterioration in the experimental aeration bin.

4.5 Discussion and Conclusions

4.5.1 Grain temperatures

Grain temperature predictions for the two thermocouple locations examined followed measured values closely (Figs. 4.5 and 4.6). Accuracy of the strip chart recorder is ± 0.5°C. Additional deviations could be due to inaccuracy in the measurement of temperature rise across the fan, air temperature changes within the plenum, poor data for the thermal properties of wheat, and variations in weather conditions between the bin location at Glenlea and the Winnipeg weather station 25 km to the north.

4.5.2 Grain moisture contents

Predicted grain moisture contents for the top, centre, and floor levels, and for the bin average, compared closely with measured values, if the high 9.0 $(L/s)/m^3$ ventilation period was not included in the simulation (Figs. 4.7 and 4.11). The initial two day period of 9.0 $(L/s)/m^3$ ventilation resulted in predictions of significantly greater moisture loss at floor level (1.6 percentage points), and slightly greater moisture gains at centre and top levels (0.1 to 0.5 percentage points) than measured.

These results indicate that equilibrium is not a good assumption at airflow rates as high as 9.0 $(L/s)/m^3$ using these simulation parameters; however, at 1.9 $(L/s)/m^3$ moisture content predictions were within experimental error for the three month period used in this comparison. Simulation parameters which affect the validity of the equilibrium assumption include the convection layer depth, the simulation time interval, and the air velocity through the grain. For the validation simulations, each of the 10 convection layers was 0.367 m in depth, the simulation time interval was 1 h, and the air velocity was 8.24 mm/s at 9.0 $(L/s)/m^3$ airflow rate, and 1.74 mm/s at 1.9 $(L/s)/m^3$ airflow rate. Improved accuracy at the high airflow rates may be possible by increasing the simulation time interval, or by increasing the convection layer depth by decreasing the number of layers. The air velocity is a function of the bin dimensions. It may be, however, that equilibrium is not a good assumption at the higher airflow rates, and other modifications to the model will be required to improve accuracy.

4.5.3 Grain deterioration

Given the late harvest date and the resulting relatively low grain temperatures and moisture contents, difficulties in maintenance of quality during the fall and winter storage periods were not anticipated. The results of both the fungi and germination quality assessments, and the computer prediction of the proportion of allowable storage time elapsed, support this conclusion. Unfortunately, since grain quality deterioration did not reach a critical level, the deterioration model cannot be verified with certainty. To do this, validation of the deterioration model under conditions when deterioration is more likely is required.

Chapter V

SIMULATION RESULTS AND DISCUSSION

5.1 Canadian Prairie Climates

5.1.1 Climatic regions

There are four general climatic regions which encompass most of the grain producing areas of the Canadian Prairies (Putnam and Putnam 1970). These are: the semi-arid or dry-belt, the sub-humid prairie, the sub-boreal, and the humid prairie of Southeastern Manitoba (Fig. 5.1). Differences in climatic variables within these regions do not make these subdivisions exact. The Edmonton area for instance, has a higher summer rainfall than the Peace River area (Putnam and Putnam 1970).

Historical hourly weather data on tape, for use as input data for the computer simulation model were obtained. The climatic data was chosen considering the data presently available at the University of Manitoba and the climatic regions of the Canadian Prairies. The following four locations were used:

1. Winnipeg, Manitoba - Humid Prairie. (1961-1978).

2. Swift Current, Saskatchewan - Semi-arid Prairie. (1961-1976).

3. Edmonton, Alberta - Sub-humid to Sub-boreal Prairie. (1961-1976).

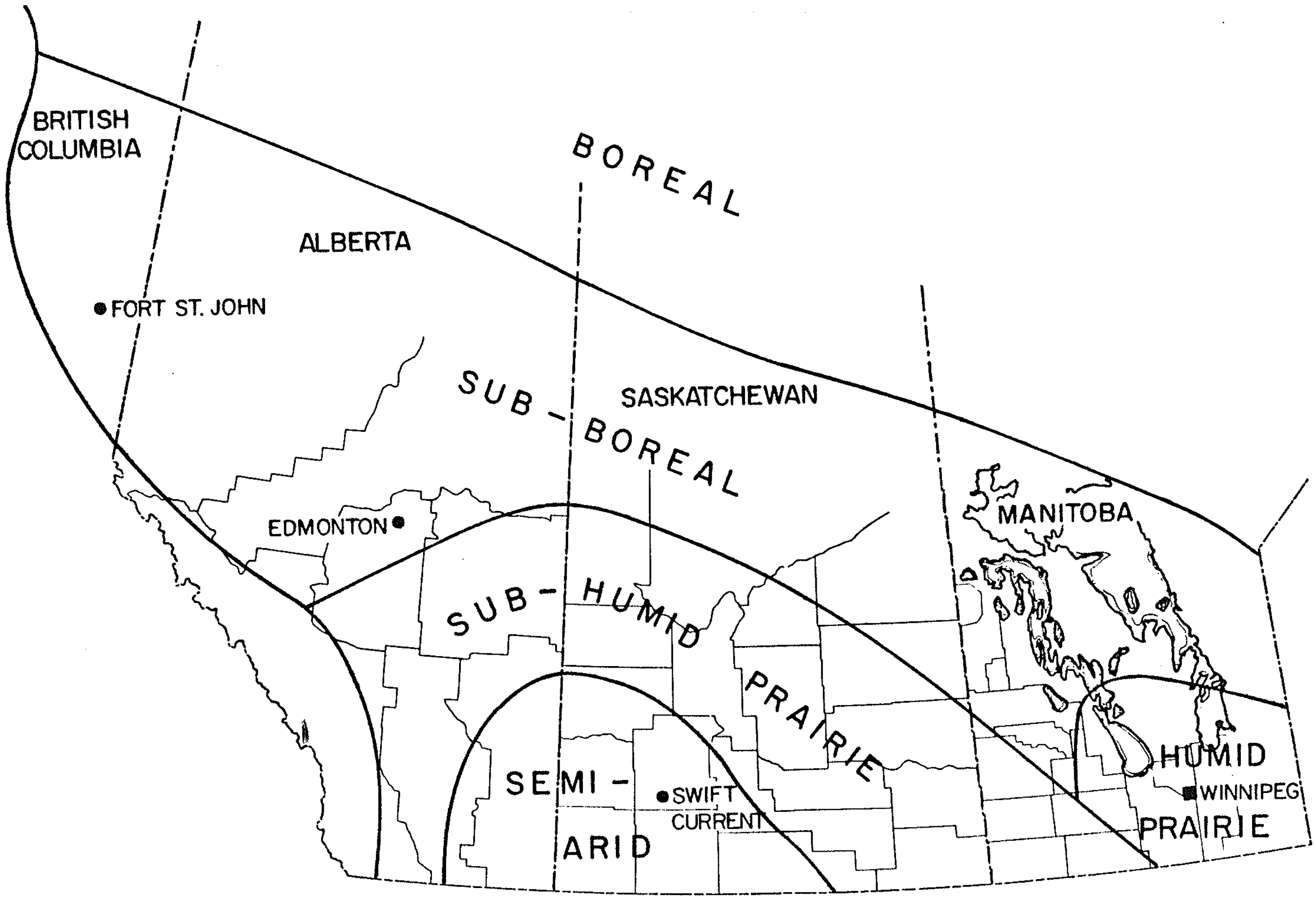

Fig. 5.1: Climatic subdivisions of the Canadian Prairies (based on Putnam and Putnam 1970).

4. Fort St. John, British Columbia - Sub-boreal Prairie, Peace River Region. (1961-1978).

5.1.2 Initial grain temperatures

Prasad et al. (1978) established that the initial temperature of grain in storage can be related to the average air temperature during harvest. They found that the temperature of wheat was 8°C above the ambient air temperature on sunny days.

To establish initial grain temperatures for the computer simulations, average 24 h air temperatures were calculated from the hourly tape weather data for the normal harvest period at the four climatic areas (Fig. 5.2). Initial grain temperature in storage was established by adding 8°C to the temperature on the harvest date. The initial grain temperature could in fact be much higher due to higher daytime temperatures and yearly variations of the 3 week mean.

5.2 Storage Bin and Aeration System

Based on trends in the size of on-farm granaries in Canada, a storage of 133 m^3 capacity (100 t of wheat at 14.5% moisture content) and 5.97 m diameter was chosen (Muir 1980). A fully perforated floor is assumed with air blown upward through the floor and grain from a direct-drive, axial-flow fan.

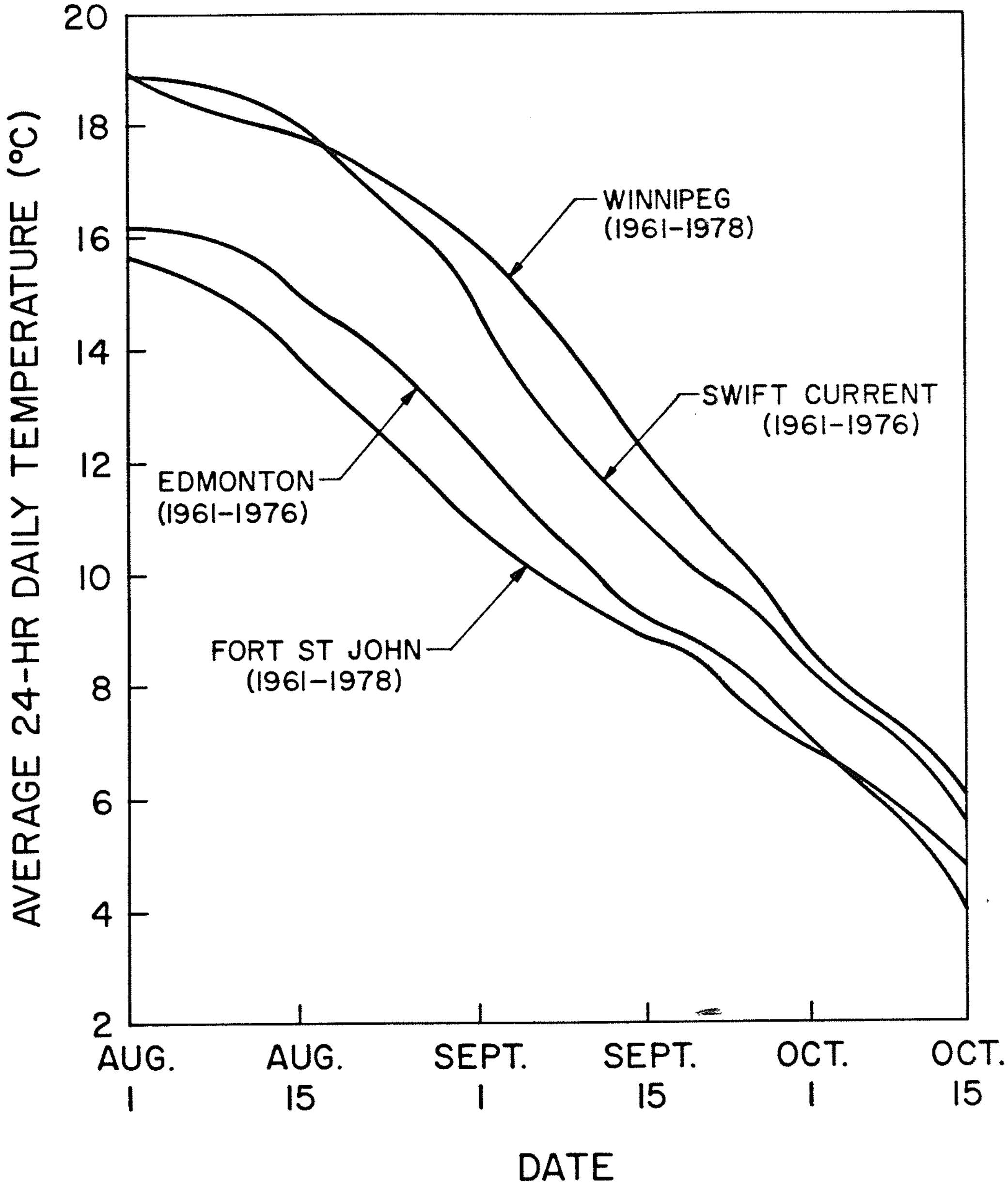

Fig. 5.2: Average 24 h daily temperature (3 week running mean) at four Canadian Prairie locations during the normal harvest period.

5.3 Grain Deterioration in Unventilated Storage

To establish the worst storage conditions, predictions of grain condition were made for wheat stored for 1 year with no ventilation. The effects of harvest date, initial moisture content, and initial temperature at the four climatic locations were examined.

Spoilage occurred within 1 year for wheat stored at an initial moisture content of 15% at most harvest dates (Fig. 5.3). This first occurrence of spoilage was always predicted at the bin centre, approximately 1.5 m from the top grain surface. The later the harvest date, the longer the safe storage period. This is due largely to the reduced grain temperatures at harvest. Fort St. John was the only location which resulted in predictions of safe storage for over 1 year.

The effect of initial moisture content on the average number of days to first occurrence of spoilage was evaluated for wheat harvested on 1 September (Fig. 5.4). Initial grain temperatures were again established by harvest temperatures. As moisture content increased, deterioration was predicted to occur within fewer days. The Canadian Grain Commission has established a 14.5% moisture content as "dry" for wheat. At this moisture content, spoilage occurs at an average of 100 days in Winnipeg, 130 days in Swift Current, 355 days in Edmonton, and over 1 year in Fort St. John. Since the deterioration model has not been adequately verified, it is difficult to know how realistic these predictions are. A drop in germination (as used in the deterioration model) may not result in a drop in grade; however, given the relatively high initial grain temperatures at Winnipeg and Swift Current, the size

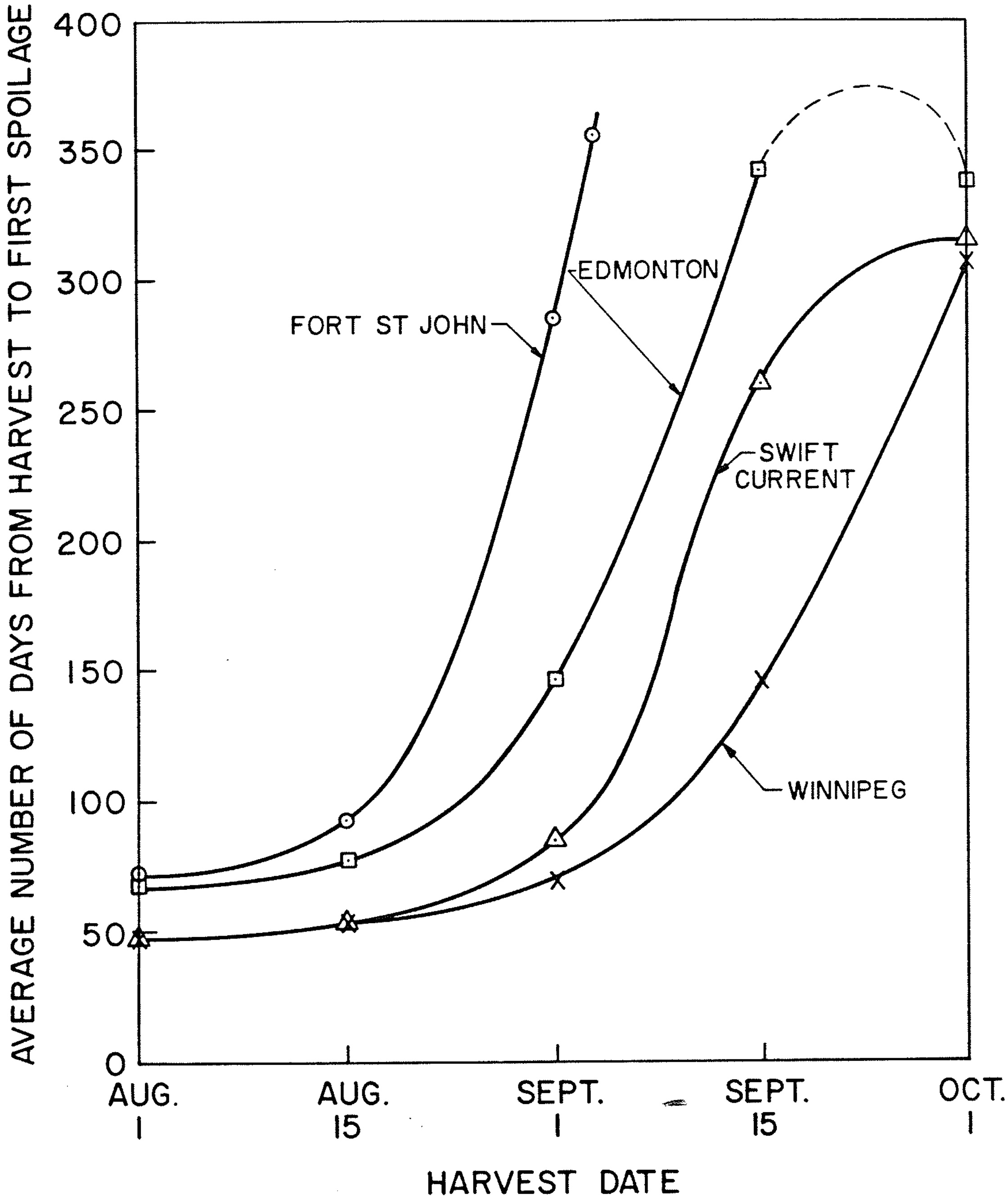

Fig. 5.3: Predicted average number of days from harvest to the first occurrence of spoilage at four prairie locations for various harvest dates.

100 t wheat	15% initial moisture
No ventilation	5.97 m diameter storage bin

of the grain bin, and the low thermal conductivity of wheat, these results may not be unrealistic. In addition, the effect of moisture migration was not included. This may further increase the rate at which deterioration would occur in the grain.

To assess the effect of initial grain temperature on these results, the initial temperature in all simulations was set to 23.6°C; the initial grain temperature in Winnipeg on 1 September. The resulting predictions show that in an unventilated grain bin, the initial grain temperature is more significant than ambient weather conditions during storage (Fig. 5.5). Climate had no significant effect on the predicted number of days to the first occurrence of spoilage.

The previous comparisons were made on the basis of the first occurrence of spoilage. This usually occurred at the bin centre, about 1.5 m from the top suface. Another point of view is to compare deterioration throughout the whole bin based on the average proportion of allowable storage time elapsed for all grain volume elements. The average proportion of allowable storage time elapsed was predicted with no ventilation during the fall (1 September to 1 November), winter (1 November to 1 April), and summer (1 April to 31 August) periods (Fig. 5.6). Initial grain temperature had a significant effect again on the rate of deterioration, although the effect of climate on grain deterioration near the wall resulted in significant differences between the geographical locations.

When the simulations were run again with an initial grain temperature of 23.6°C the effect of climate was still significant.

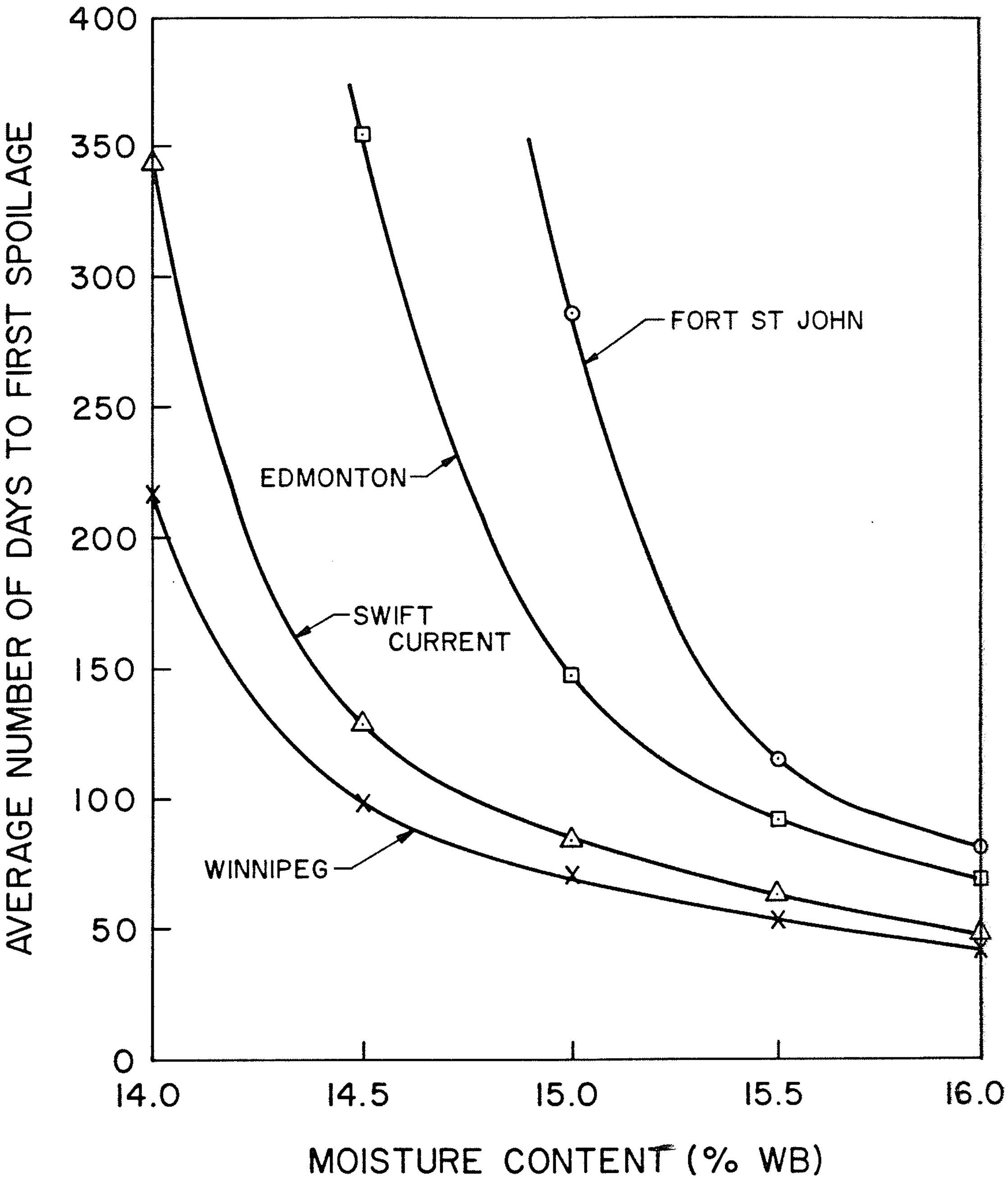

Fig. 5.4: Predicted average number of days from harvest to the first occurrence of spoilage at four prairie locations for various initial moisture contents. Initial grain temperatures based on air temperature on harvest date.

100 t wheat	1 September harvest
No ventilation	5.97 m diameter storage bin

Initial grain temperatures and years of weather data used:

Winnipeg: 23.6°C	1961-77
Swift Current: 22.4°C	1961-75
Edmonton: 19.7°C	1961-75
Fort St. John: 18.5°C	1961-77

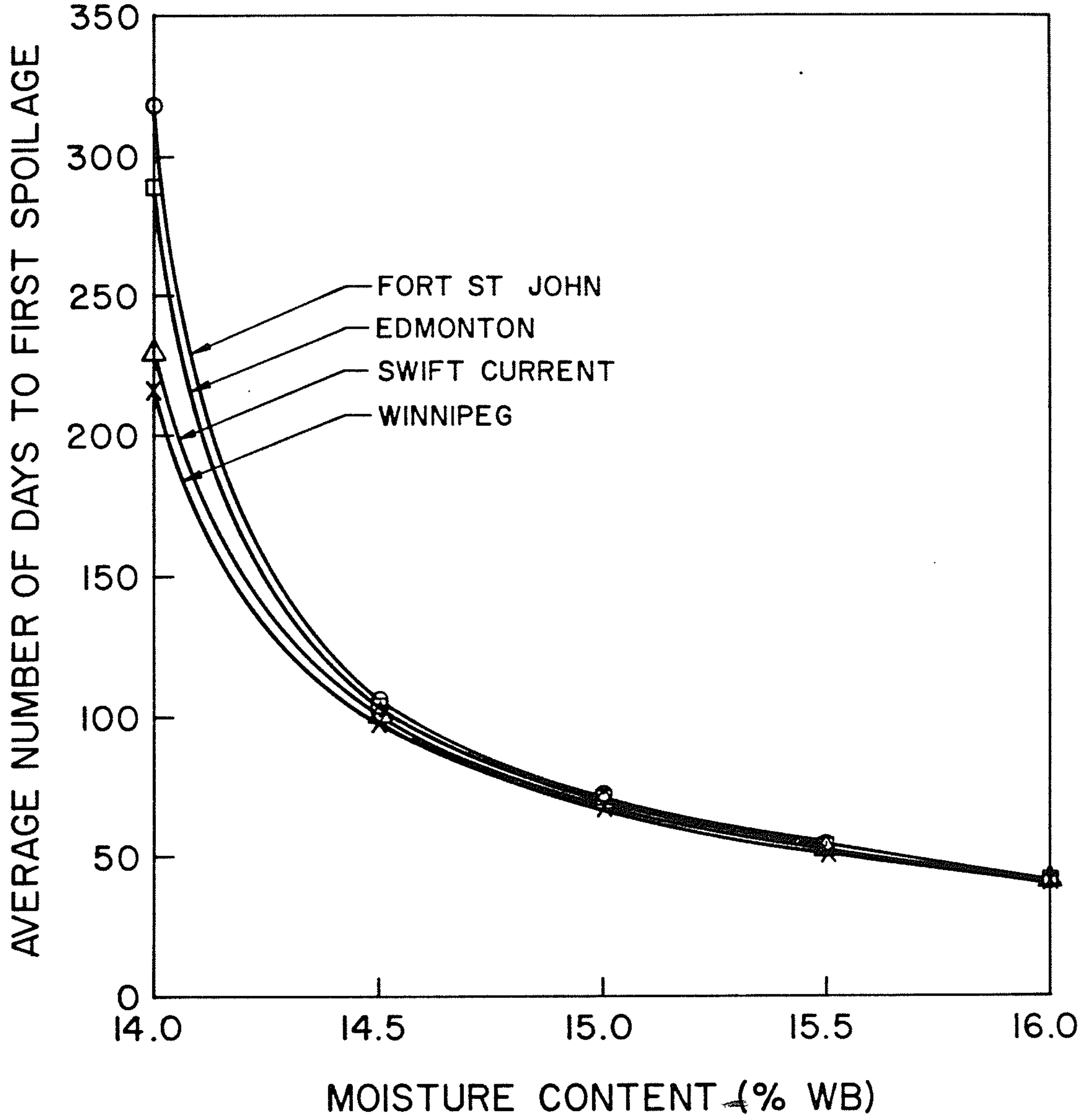

Fig. 5.5: Predicted average number of days from harvest to the first occurrence of spoilage at four prairie locations for various initial moisture contents. Initial grain temperature is the same at all locations.

100 t wheat — 1 September harvest
No ventilation — 5.97 m diameter storage bin
Initial grain temperature: 23.6°C

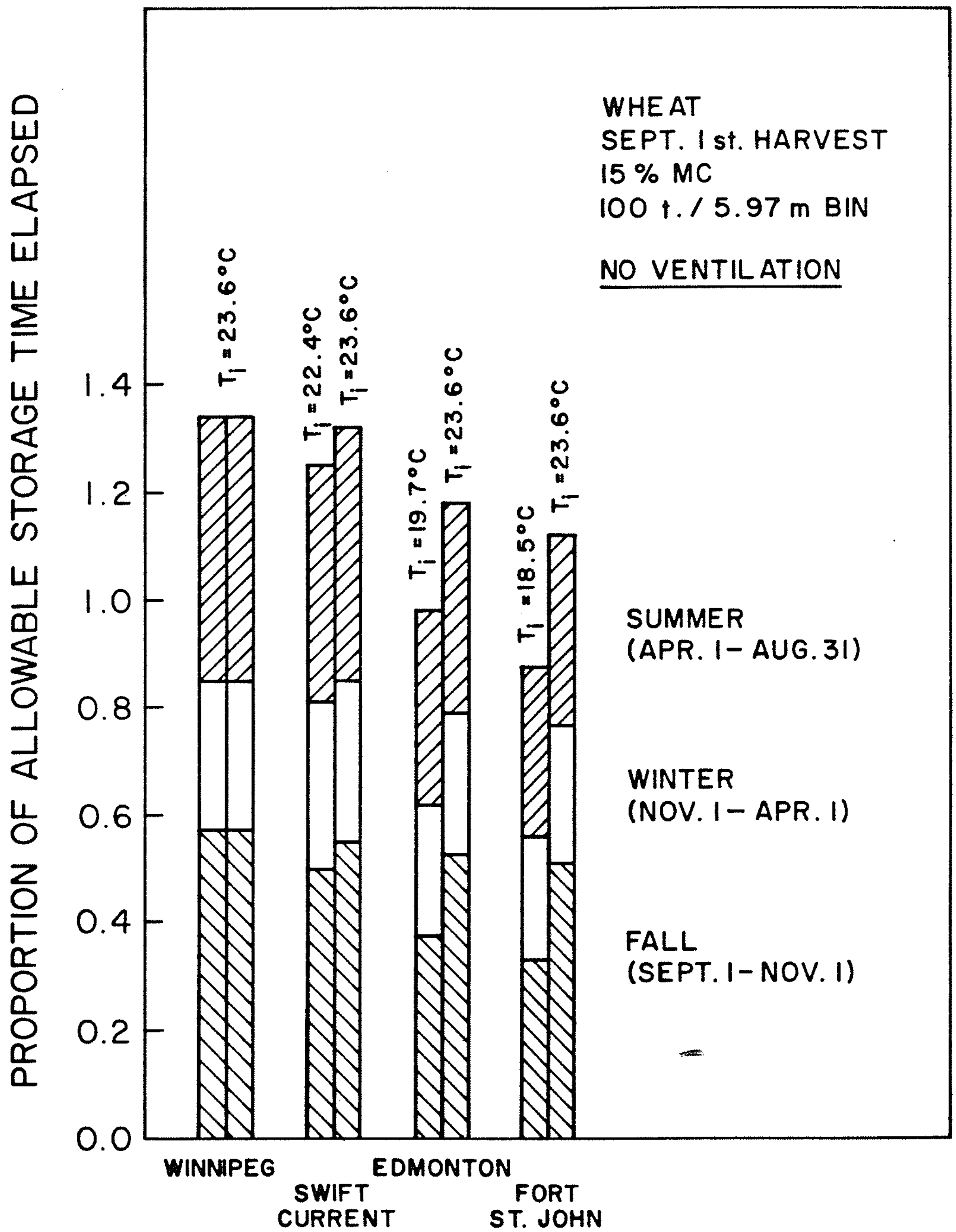

Fig. 5.6: Average proportion of allowable storage time elapsed during one year with no aeration at four prairie locations.

Average allowable storage time elapsed is significantly less at Edmonton and Fort St. John than at Winnipeg and Swift Current.

5.4 Initial Conditions and Aeration Periods

Based on a subjective evaluation of the previous investigations, wheat harvested on 1 September at 15% moisture content was used in all of the following simulations. At most locations, an earlier harvest date would most likely result in "dry" grain; however, on 1 September, a harvest of 15% moisture content grain is not unrealistic. This grain would have a good potential for deterioration unless measures are taken to minimize this. Initial grain temperatures on this date are 23.6°C for Winnipeg, 22.4°C for Swift Current, 19.7°C for Edmonton, and 18.5°C for Fort St. John.

Three aeration periods were evaluated, based on the four periods presented in section 2.4.2 (page 8), suggested by Cloud and Morey (1979). The dates and objectives for each period are:

1. Fall cool-down period.

   After harvest, the stored grain is to be cooled as quickly as possible to between -10°C and 0°C.

2. Winter holding period.

   Intermittent fan operation during the winter when the outside temperature is near the grain temperature, to maintain uniform grain temperatures.

3. Spring warm-up and summer holding period.

Intermittent fan operation to warm grain to 10 to 15°C by the middle of June, and to maintain uniform grain temperatures.

5.5 Airflow Rate for Fall Aeration at Winnipeg

The effect of continuous ventilation on the resulting grain moisture content, temperature and rate of deterioration was evaluated for airflow rates from 0 to 3 $(L/s)/m^3$ during the fall cool-down period at Winnipeg (Fig. 5.7). The points plotted represent mean values for the 17 years of weather data analysed. The vertical bars indicate standard deviations of the mean. Airflow rates of 0.5 to 3.0 $(L/s)/m^3$ resulted in moisture content reductions of 0.5 to 0.7 percentage points. The higher standard deviations at higher airflow rates reflect the rate of response to yearly climatic variations. These can be a disadvantage to the operator as inconsistent results should be expected from year to year if continuous ventilation at the higher airflow rates is practised. Average grain temperatures drop sharply with as little as 0.5 $(L/s)/m^3$ and level off at 4.5 to 5.0°C at higher rates. Average proportion of allowable storage time elapsed drops quickly from 0.58 with no ventilation to 0.24 with 0.5 $(L/s)/m^3$ and levels off at about 0.20 at higher airflow rates. Energy use increases rapidly with increasing airflow rate; however, in all cases energy use is low. For example, at electricity costs of \$0.01/MJ, and wheat priced at \$200/t, the 3.0 $(L/s)/m^3$ airflow rate costs about \$0.28/t for continuous ventilation over 60 days, or less than 0.2% of the grain value.

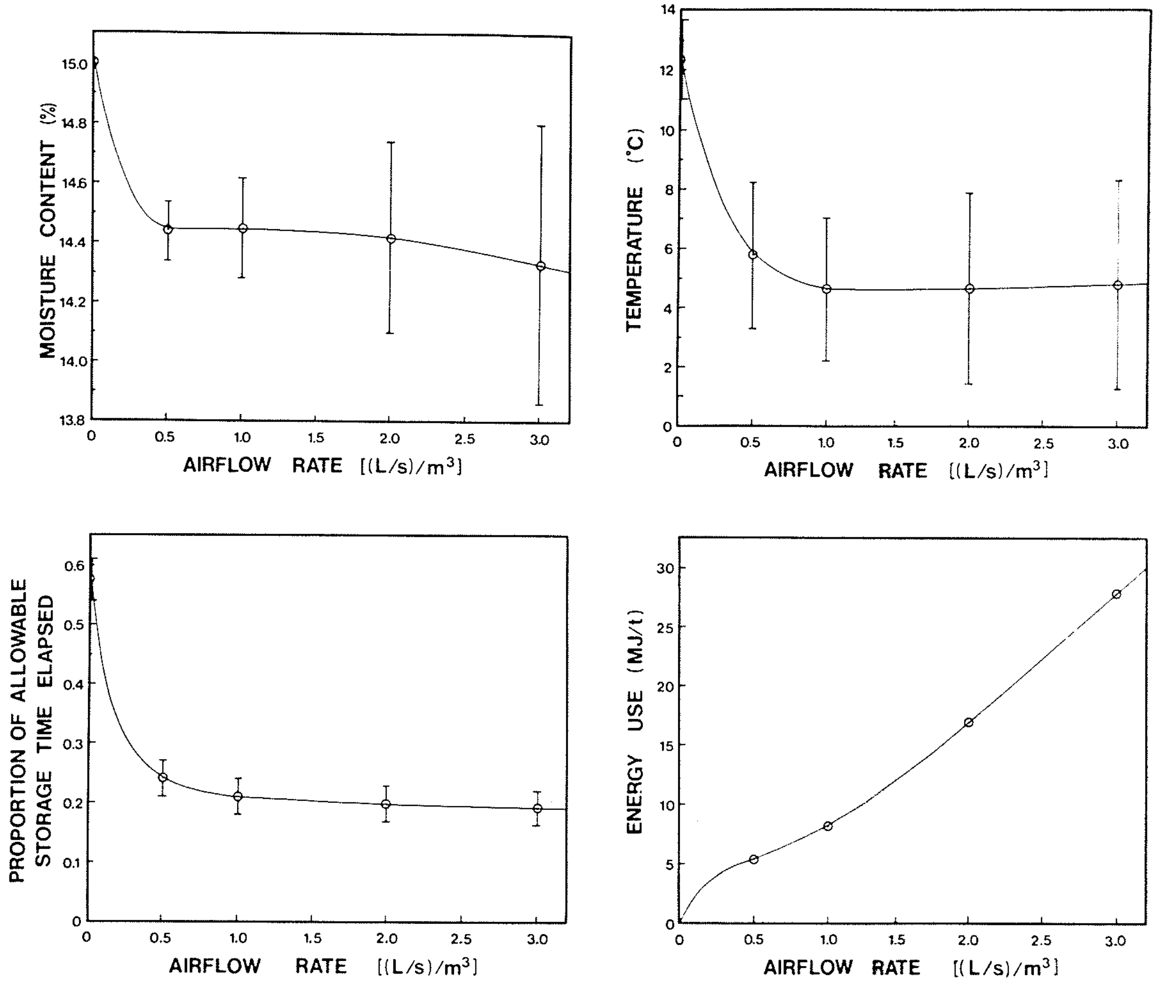

Fig. 5.7: Grain condition and energy consumption for a range of aeration airflow rates, after the fall cool-down period at Winnipeg.

100 t wheat	1 September harvest
15% initial moisture	23.6°C initial temperature
1961-77 weather data	5.97 m diameter storage bin
fully perforated floor	

The range of airflow rates investigated in this study all appear suitable for continuous aeration of 15% wheat at Winnipeg, and are consistent with past recommendations (Friesen and Harms 1980, Cloud and Morey 1979, Holman 1960, Johnson 1957, Shove 1962).

Based on this airflow rate analysis, 1.0 $(L/s)/m^3$ was selected for investigating the various fan control methods. Grain temperature reductions and average allowable storage times are not reduced significantly by airflow rates greater than 1.0 $(L/s)/m^3$. At higher airflow rates, moisture content can be reduced excessively below the economical minimum of 14.5%. The increase in energy use at airflow rates greater than 1.0 $(L/s)/m^3$ does not appear to be justified for continuous operation. If higher airflow rates are used with intermittent operation in the fall cool-down period, energy use may be comparable because of the shorter fan operating times required to cool the grain. This, however, would require more intensive management by the operator, or a suitable fan controller to eliminate the possibility of overdrying the grain and unnecessary energy use. The higher capital cost of larger fans can be more significant than the energy costs, and may make this undesirable.

A 100 t mass of wheat (133 m^3 volume) stored in a 5.97 m diameter bin results in a grain depth of 4.67 m. To provide an airflow rate of 1.0 $(L/s)/m^3$, a 0.16 kW fan operating at a total efficiency of 0.2 is required (Metzger et al. 1980). This results in a temperature rise across the fan of 0.9°C. These values were used in all aeration simulations requiring an airflow rate of 1.0 $(L/s)/m^3$.

5.6 Control of Fan Operating Times During the Fall Cool-down Period at Winnipeg

The uncertainty over which is the best type of fan control method is due in part to differing opinions about the effect that each method may have on the grain condition. This is further complicated by variations in climate and by the complexity of the heat and moisture transfer relationships which exist during grain ventilation under constantly changing air conditions. The following methods were evaluated for Winnipeg during the fall cool-down period. They were chosen on the basis of simplicity of installation and use, and availability.

5.6.1 Humidistat control

Humidistat control permits fan operation only at ambient air relative humidities less than the maximum set on the humidistat. Humidistat control was evaluated for relative humidity settings from 0% or no ventilation, to 100% or continuous ventilation (Fig. 5.8).

As the humidistat setting was increased from 0 to 100% the average grain moisture content after 60 days of storage during the fall cool-down period was reduced. Increases in average moisture contents due to re-wetting at higher relative humidities were expected with humidistat settings greater than 70%. The fact that predicted grain moisture content continued to decrease with increased humidistat settings can be partly explained by the addition of fan heat to the air. For example, the addition of energy sufficient to raise the temperature of saturated air at 10°C by 0.9°C, reduces the relative humidity of that air to about 93%. This air would have a slightly reduced potential for re-wetting the grain than would the saturated air. To test this hypothesis, 70%

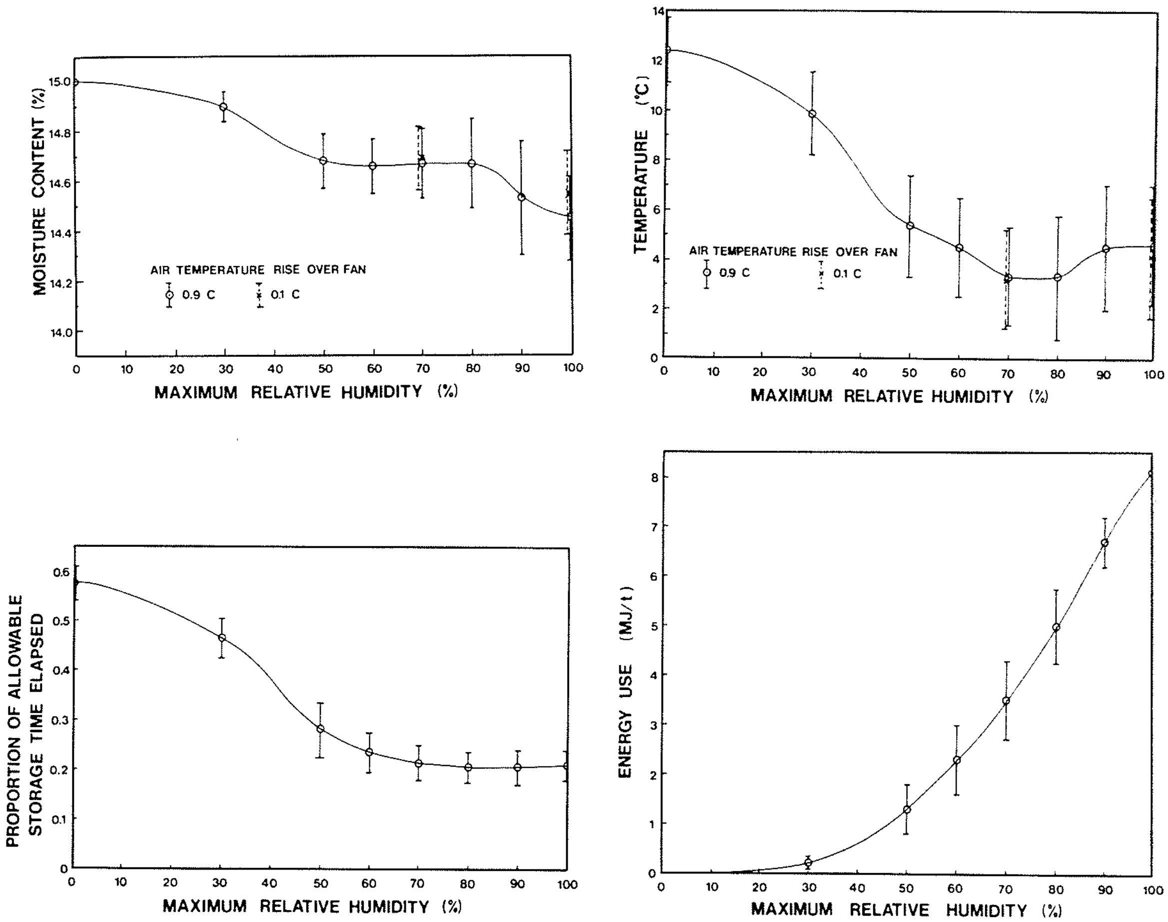

Fig. 5.8: Grain condition and energy consumption with humidistat controlled aeration after the fall cool-down period at Winnipeg.

100 t wheat	1.0 $(L/s)/m^3$ airflow rate
15% initial moisture	fully perforated bin floor
1 September harvest	5.97 m diameter bin
1961-77 weather data	23.6°C initial temperature

and 100% relative humidity simulations were carried out using a temperature rise across the fan of only 0.1°C (Fig. 5.8). Average moisture contents were slightly higher than the 0.9°C simulations by 0.2 percentage points at a humidistat setting of 70%, and 1.0 percentage point at a humidistat setting of 100% relative humidity. Due to yearly climatic variations, at 0.1°C temperature rise there was no statistical difference between the mean grain moisture contents at the 70 and 100% humidistat settings, at the 1% level of significance. The fact that the average moisture content was still not greater at 100% relative humidity than at 70% relative humidity may be further explained by the relatively low temperatures associated with high humidities during the fall. Lower temperatures during the fall offer a reduced potential for re-wetting and if this air warms as it is passed through the grain, its relative humidity would be reduced to offer little or no potential for re-wetting, and may even contribute to moisture removal.

Average grain temperature decreased to about 3.6°C as humidistat setting was increased to 70 to 80%. As humidistat setting was further increased, the average temperature increased slightly to about 4.3°C at continuous operation; however, due to yearly climatic variations, at humidistat settings of 60% or greater, no statistical difference exists between the mean temperatures at the 1% level of significance.

The average proportion of allowable storage time elapsed decreased to about 0.21 as humidistat setting increased to 60% and greater. In this range, no statistical difference exists in storage time values at the 1% level of significance.

5.6.2 Thermostat control

Thermostatic control permits fan operation only at ambient air temperatures less than the maximum set on the thermostat. Thermostat operation was evaluated for maximum temperature settings in the range from 0 to 25°C (Fig. 5.9).

Minimum average grain moisture contents occurred in the 10 to 20°C thermostat setting range. As thermostat settings were increased to 25°C or greater (i.e., continuous fan operation), the resulting average moisture contents were higher. This may be due to the greater re-wetting potential of warm air compared with cold air. Warm air blown into the bin during the day could deposit considerable moisture in the layers of grain cooled by night-time air.

The higher thermostat settings resulted in more continuous ventilation. There were no statistical differences in mean grain temperatures for thermostat settings of 0°C and greater, at the 1% level of significance. Average proportion of allowable storage time elapsed decreased with increases in thermostat setting. The cooling air reached the warm grain sooner with the higher thermostat settings resulting in reduced storage time elapsed. There were no statistical differences in mean allowable storage times elapsed at thermostat settings of 15°C and greater, at the 1% level of significance.

Energy use at thermostat settings of 15°C and over was greater than 79% of the energy use during continuous operation. Overdrying at 15°C was 0.4 percentage points. As thermostat setting was increased, overdrying was reduced and energy consumption increased. The thermostat

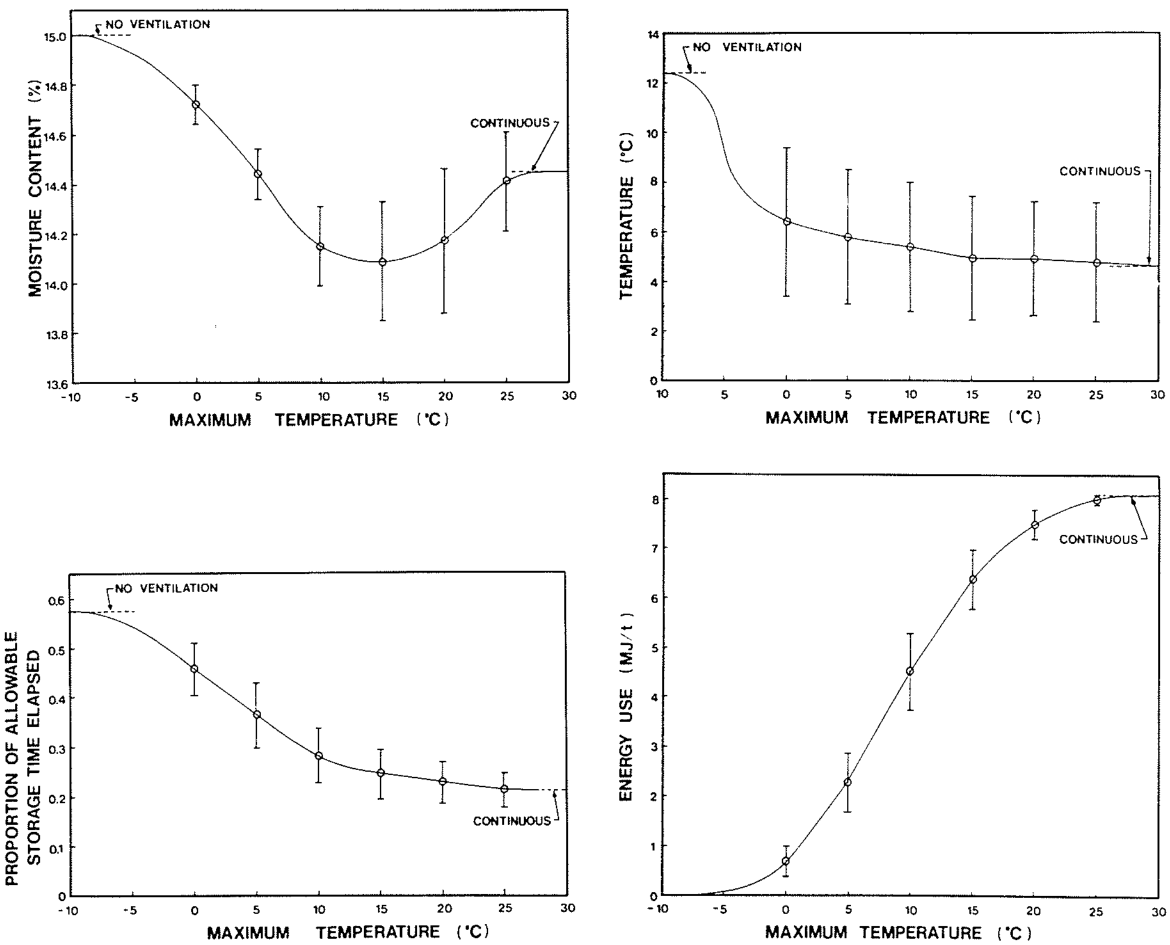

Fig. 5.9: Grain condition and energy consumption with thermostat controlled aeration after the fall cool-down period at Winnipeg.

100 t wheat	1.0 $(L/s)/m^3$ airflow rate
15% initial moisture	fully perforated bin floor
1 September harvest	5.97 m diameter bin
1961-77 weather data	23.6°C initial temperature

did not provide an effective means of reducing the rate of grain deterioration, nor did it minimize energy use and overdrying.

5.6.3 Time-clock control

A time-clock controls fan operation by time of day only. Since night-time air temperatures are usually lower than day-time, and grain temperature control or reduction is a prime objective of aeration, two control strategies using 6 h and 12 h night-time fan operation periods were simulated. These were compared with continuous operation (Table 5.1). Due to the method the simulation model uses to control fan operating times, the fan operation time periods are slightly greater than 6 and 12 hours, and the energy use values are not direct multiples of each other, as would be expected.

Although the 12 h schedule with fan operation from 1800 to 0600 h resulted in a slightly lower average proportion of allowable storage time elapsed than the 6 h schedule from 0000 to 0600 h, there is no significant difference between these values at the 1% level of significance. The 6 h schedule resulted in half the energy consumption of the 12 h schedule.

5.6.4 Differential thermostat control

The differential thermostat measures the temperature difference between two sensors, one of which is located in the grain approximately 0.5 m below the top surface. The other measures the ambient air dry bulb temperature. Fan operation is permitted only when the temperature of

TABLE 5.1

Grain condition and energy consumption with time-clock controlled aeration after the fall cool-down period at Winnipeg.

100 t wheat	1.0 (L/s)/m^3 airflow rate
15% initial moisture	fully perforated bin floor
1 September harvest	5.97 m diameter bin
1961-77 weather data	23.6°C initial temperature

	Fan Operation		
	6 hours/day (0000-0600 h)	12 hours/day (1800-0600 h)	24 hours/day (continuous)
Moisture Content (%)	14.6 ± 0.1	14.5 ± 0.1	14.5 ± 0.1
Grain Temperature (°C)	4.5 ± 2.1	4.2 ± 2.6	4.6 ± 2.4
Proportion of Allowable Storage Time Elapsed	0.254 ± 0.032	0.227 ± 0.031	0.210 ± 0.032
Energy Use (MJ/t)	2.2	4.2	8.1

the ambient air is less than the temperature of the top grain layer plus the thermostat setting. For example, a -5°C differential thermostat setting would result in fan operation only when the ambient air temperature is at least 5°C below the average temperature of the top layer of grain.

The differential thermostat is more complicated to physically install in an aeration system than the other controllers discussed here. It does, however, simulate the optimum level of manual control, since it is the only method modelled which relates ambient air conditions to grain conditions. A conscientious individual operator would attempt to manage an aeration system by carefully monitoring grain temperatures and weather changes and controlling fan operation in a manner similar to the differential thermostat. Cloud and Morey (1979) suggested that the fan be operated when average air temperatures are greater than 6°C below the temperature of the top layer of grain. This would correspond to a differential thermostat setting of -6°C.

Predicted average grain moisture contents were reduced by over 1.0 percentage points in the differential thermostat range of about 4 to -6°C (Fig. 5.10). Assuming $200/t for the value of wheat at 14.5% moisture content, the average overdrying cost at a thermostat setting of 0°C was $1.53/t, or more than 20 times the energy cost. Fan operating time and energy costs were reduced significantly as the thermostat setting reached -10°C and less; however, the average proportion of allowable storage time elapsed began to increase in this range. The relatively steep slope of the moisture content and proportion of

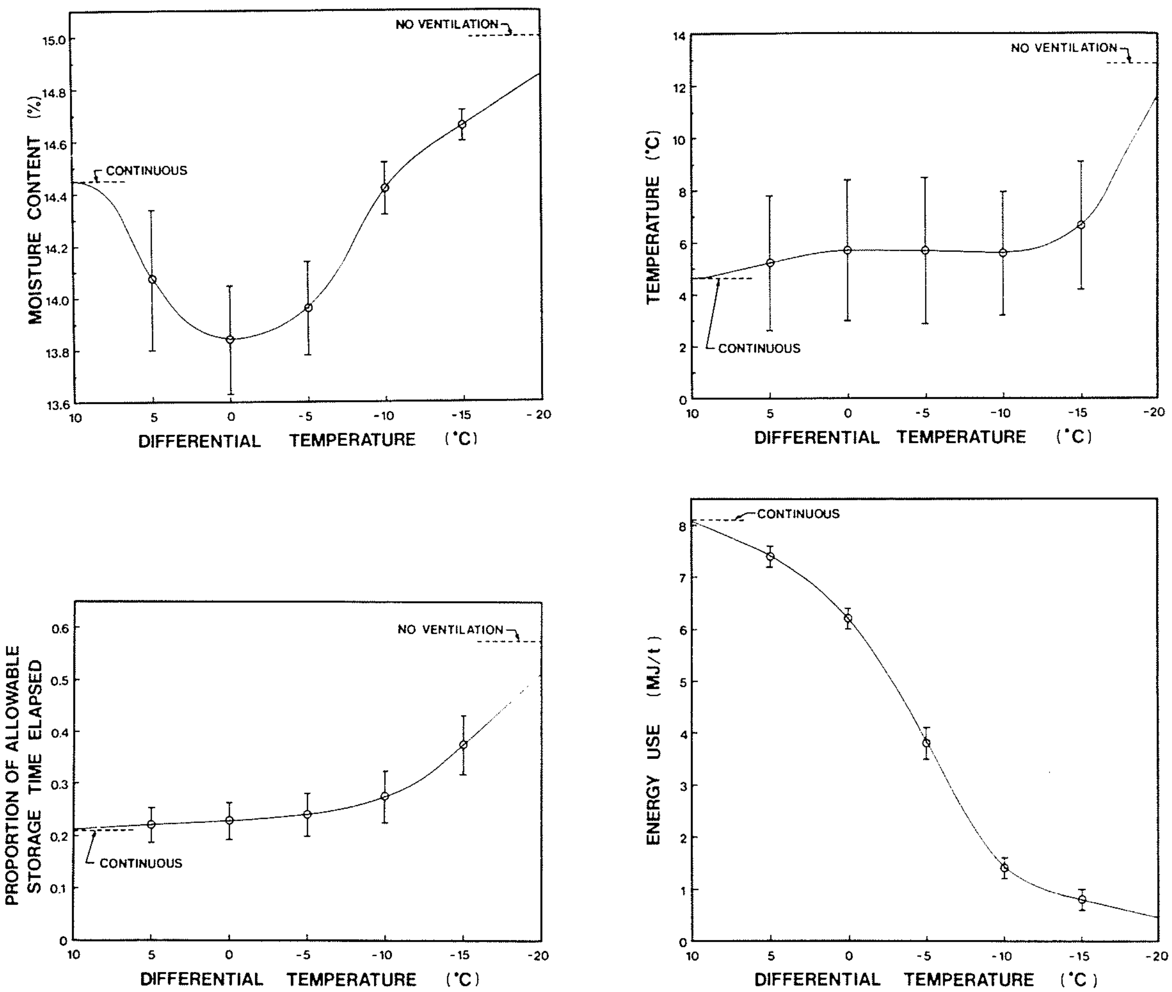

Fig. 5.10: Grain condition and energy consumption with differential thermostat controlled aeration after the fall cool-down period at Winnipeg.

100 t wheat	1.0 $(L/s)/m^3$ airflow rate
15% initial moisture	fully perforated bin floor
1 September harvest	5.97 m diameter bin
1961-77 weather data	23.6°C initial temperature

allowable storage time elapsed relationships at a setting of -10°C, indicates that the resulting grain condition is sensitive to small changes in differential thermostat setting. There was no difference in final mean grain temperature at the 1% level of significance, for differential thermostat settings between 5 and -15°C.

5.7 Control Method Comparison

All aeration methods significantly reduced grain deterioration compared with no ventilation. If fan control methods are evaluated on the basis of minimizing the average porportion of allowable storage time elapsed and minimizing overdrying the following comparisons become evident:

Continuous operation provided effective quality control without excessive overdrying; however, energy use was maximum at 8.1 MJ/t.

Humidistat operation provided effective quality control in the 50% and over relative humidity range with no overdrying up to the 90% setting. Energy use decreased with decreasing relative humidity setting such that at a setting of 60%, energy use was 2.3 MJ/t, or a reduction of 72% from energy use with continuous operation.

Thermostat operation provided effective quality control at maximum temperatures of 15°C and greater. Overdrying with moisture reductions greater than 0.8 percentage points occur in the 10 to 20°C range. At thermostat settings of 15°C and greater energy consumption ($>$ 6.4 MJ/t) was more than 2.8 times greater than for the humidistat control setting of 60%.

Both time-clock operations provided effective quality control with no overdrying. Average energy use was 2.2 MJ/t with the 6 h schedule, and 4.2 MJ/t with the 12 h method.

Differential thermostat operation provided good quality control at 0 to -10°C but considerable overdrying occurred in the +5 to -5°C range. Energy use decreased from 6.2 MJ/t at 0°C to 1.4 MJ/t at -10°C.

Lowest energy use methods which still provided effective grain quality control were the humidistat at 60%, the differential thermostat set at -10°C, and the 6 h time-clock operating the fan between 0000 and 0600 h daily. Thermostat control did not provide an effective means of fan control and was not used in further simulations.

5.8 Aeration During the Fall Cool-down Period: Comparison of Prairie Climates

5.8.1 Humidistat control

Predictions of grain condition with humidistat controlled aeration at the three other prairie climatic areas yielded similar results to those obtained for Winnipeg (Fig. 5.11). Differences reflect variations in climate during the 60 day fall cool-down period.

Average moisture content, grain temperature, proportion of stoage time elapsed, and energy use trends are all similar in shape. The minor variations are insignificant if yearly variations are considered. Based on these results, maximum relative humidity settings between 50 to 70% provide maximum reduction in proportion of allowable storage time elapsed, energy use ranging from 16 to 57% of continuous operation, and

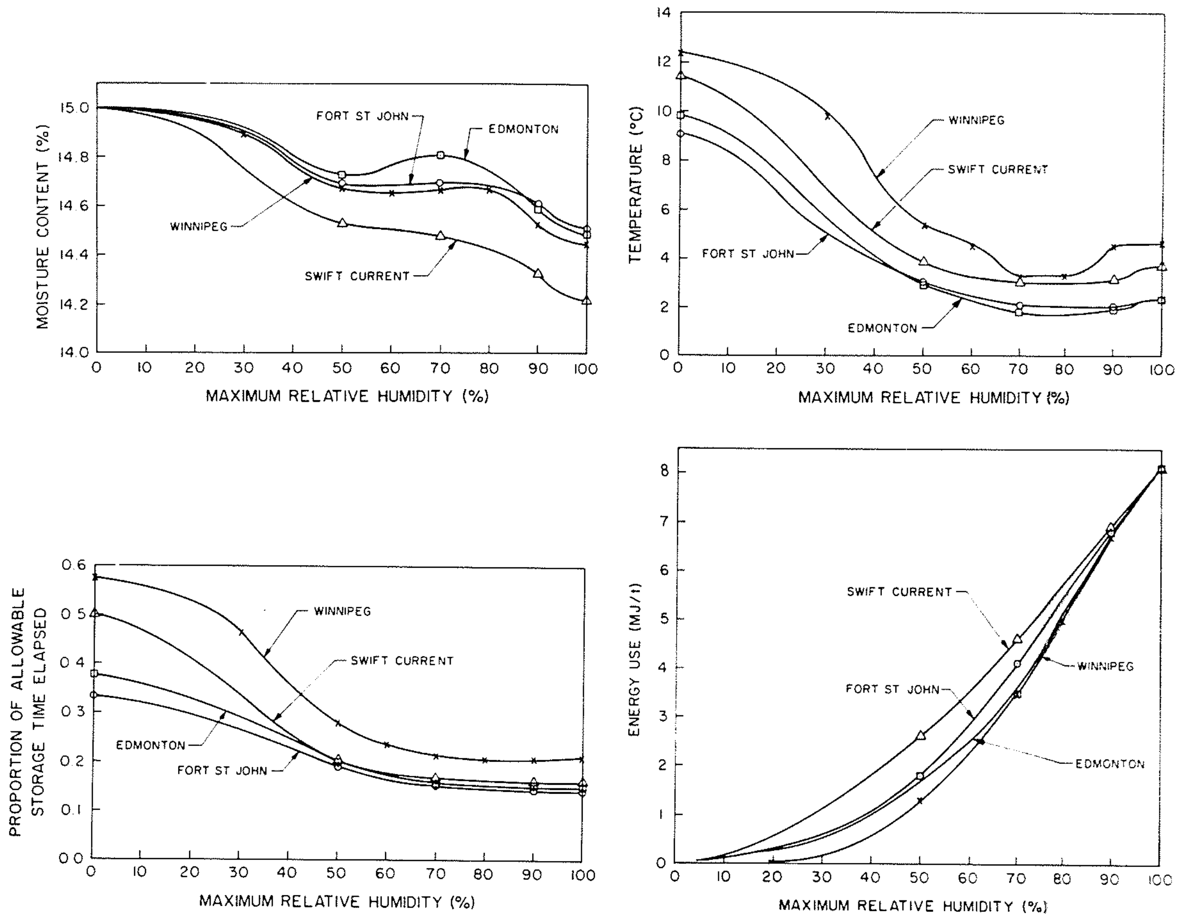

Fig. 5.11: Grain condition and energy consumption with humidistat controlled aeration after the fall cool-down period at four prairie locations.

100 t wheat	1.0 (L/s)/m^3 airflow rate
15% initial moisture	fully perforated bin floor
1 September harvest	5.97 m diameter bin

Initial grain temperatures and years of weather data used:

Winnipeg: 23.6°C	1961-77
Swift Current: 22.4°C	1961-75
Edmonton: 19.7°C	1961-75
Fort St. John: 18.5°C	1961-77

average reductions from initial moisture content of 0.2 to 0.5 percentage points. Humidistat settings greater than 70% would result in further moisture content reductions and increased energy use with little reduction in proportion of allowable storage time elapsed. These humidistat settings should be used if greater moisture content reductions are required.

5.8.2 Time-clock control

The 6 h and 12 h per day time-clock control ventilation schedules were simulated for the three other Prairie climates (Tables 5.2, 5.3 and 5.4). As with Winnipeg, maximum benefit was achieved by the 6 h schedule. Swift Current was the only location where a significant reduction in average proportion of allowable storage time elapsed was achieved by using the 12 h over the 6 h schedule; however, energy use was increased significantly by the 12 h schedule of fan operation. As with the Winnipeg simulation, time periods are simulated as slightly longer than 6 and 12 hours. Therefore, the energy use values shown are not direct multiples of each other.

5.8.3 Differential thermostat control

Predictions of grain conditions using differential thermostat control at Swift Current, Edmonton, and Fort St. John yielded similar trends to those obtained for Winnipeg (Fig. 5.12). Overdrying is a problem with all differential temperature settings near 0°C; however, it is less of a problem at Fort St. John, and is more pronounced at Swift Current. Maximum benefit in reducing the proportion of allowable sto-

TABLE 5.2

Grain condition and energy consumption with time-clock controlled aeration after the fall cool-down period at Swift Current.

100 t wheat	1.0 $(L/s)/m^3$ airflow rate
15% initial moisture	fully perforated bin floor
1 September harvest	5.97 m diameter bin
1961-75 weather data	22.4°C initial temperature

	Fan Operation		
	6 hours/day (0000-0600 h)	12 hours/day (1800-0600 h)	24 hours/day (continuous)
Moisture Content (%)	14.5 ± 0.1	14.5 ± 0.1	14.2 ± 0.2
Grain Temperature (°C)	3.7 ± 2.3	3.8 ± 3.6	3.6 ± 3.0
Proportion of Allowable Storage Time Elapsed	0.226 ± 0.039	0.182 ± 0.031	0.161 ± 0.028
Energy Use (MJ/t)	2.4	4.3	8.1

TABLE 5.3

Grain condition and energy consumption with time-clock controlled aeration after the fall cool-down period at Edmonton.

100 t wheat	1.0 (L/s)/m^3 airflow rate
15% initial moisture	fully perforated bin floor
1 September harvest	5.97 m diameter bin
1961-75 weather data	19.7°C initial temperature

	Fan Operation		
	6 hours/day (0000-0600 h)	12 hours/day (1800-0600 h)	24 hours/day (continuous)
Moisture Content (%)	14.6 ± 0.1	14.5 ± 0.1	14.5 ± 0.2
Grain Temperature (°C)	2.6 ± 2.2	2.3 ± 2.6	2.3 ± 2.7
Proportion of Allowable Storage Time Elapsed	0.182 ± 0.031	0.163 ± 0.024	0.150 ± 0.024
Energy Use (MJ/t)	2.4	4.3	8.1

TABLE 5.4

Grain condition and energy consumption with time-clock controlled aeration after the fall cool-down period at Fort St. John.

100 t wheat	1.0 $(L/s)/m^3$ airflow rate
15% initial moisture	fully perforated bin floor
1 September harvest	5.97 m diameter bin
1961-77 weather data	18.5°C initial temperature

	Fan Operation		
	6 hours/day (0000-0600 h)	12 hours/day (1800-0600 h)	24 hours/day (continuous)
Moisture Content (%)	14.7 ± 0.1	14.6 ± 0.1	14.5 ± 0.1
Grain Temperature (°C)	2.2 ± 2.1	2.1 ± 2.8	2.4 ± 2.8
Proportion of Allowable Storage Time Elapsed	0.166 ± 0.018	0.154 ± 0.019	0.142 ± 0.018
Energy Use (MJ/t)	2.4	4.3	8.1

rage time elapsed, with minimum energy use and moisture content reduction, is achieved at differential temperatures of -10 to -15°C. Increases in differential temperature settings resulted in higher energy use and greater moisture content reductions, both of which may be undesirable. Energy use at -10 to -15°C differential temperature settings range from 10 to 26% of continuous operation. This range is the lowest of all fan control methods which still provided adequate quality control.

Differential temperature settings near -10°C appear most suitable for Winnipeg and Swift Current, and near -15°C for Edmonton and Fort St. John, based on minimizing overdrying and the proportion of allowable storage time elapsed.

5.9 Intermittent Aeration During the Following Winter and Summer Periods

Fan operation of 96 h every 8 weeks was chosen for intermittent ventilation at an airflow rate of 1.0 $(L/s)/m^3$. Operation was limited to air temperatures between -10 and +10°C. The resulting average grain bin temperatures on 1 April were -4.5°C at Swift Current, -4.9°C at Fort St. John, -5.5°C at Edmonton and -6.8°C at Winnipeg.

The effect of initial grain temperature on the average proportion of allowable storage time elapsed was evaluated using continuous fall, and intermittent winter and summer ventilation (Fig. 5.13). With ventilation, climatic variations are more significant and initial grain temperature has less of an effect. In all cases, the model predicted the largest deterioration in grain quality during the five month summer period. The slightly lower proportion of allowable storage time elapsed

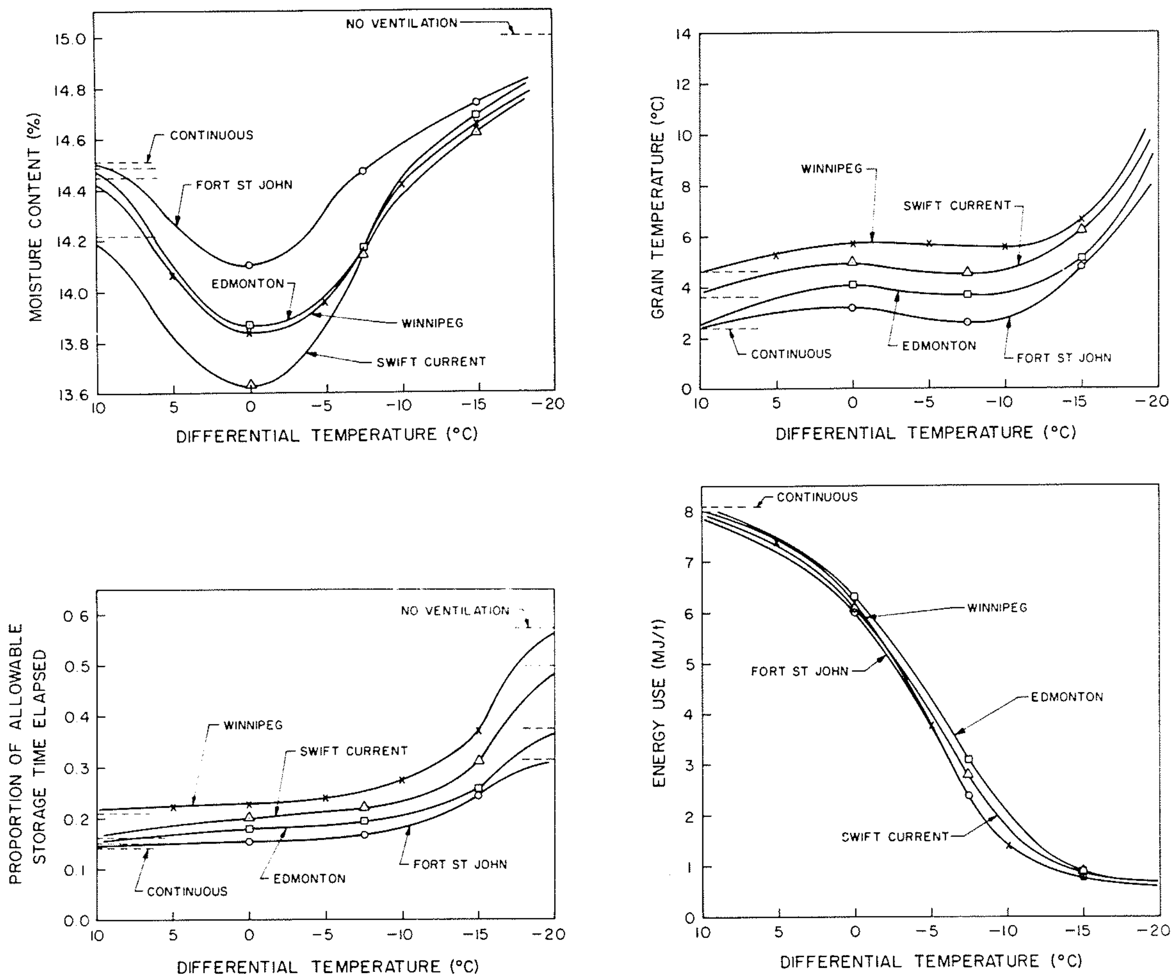

Fig. 5.12: Grain condition and energy consumption with differential thermostat controlled aeration after the fall cool-down period at four prairie locations.

100 t wheat	1.0 $(L/s)/m^3$ airflow rate
15% initial moisture	fully perforated bin floor
1 September harvest	5.97 m diameter bin

Initial grain temperatures and years of weather data used:

Winnipeg: 23.6°C	1961-77
Swift Current: 22.4°C	1961-75
Edmonton: 19.7°C	1961-75
Fort St. John: 18.5°C	1961-77

with an initial grain temperature of 23.6°C at Edmonton and Fort St.John is due to the increased moisture reduction that initially occurred with this higher temperature grain at these locations.

Summer ventilation is recommended as prevention against the summer moisture migration cycle. Unfortunately, the model cannot simulate this; however, deterioration was simulated with no ventilation during the summer. The low grain temperatures achieved by intermittent winter ventilation resulted in reductions in proportion of allowable storage time elapsed, compared with intermittent summer ventilation (Fig. 5.14). If moisture migration during the summer does occur and if it causes serious grain deterioration, then summer ventilation may be effective; however, if summer moisture migration is not a problem, summer ventilation only increases the deterioration of the stored grain.

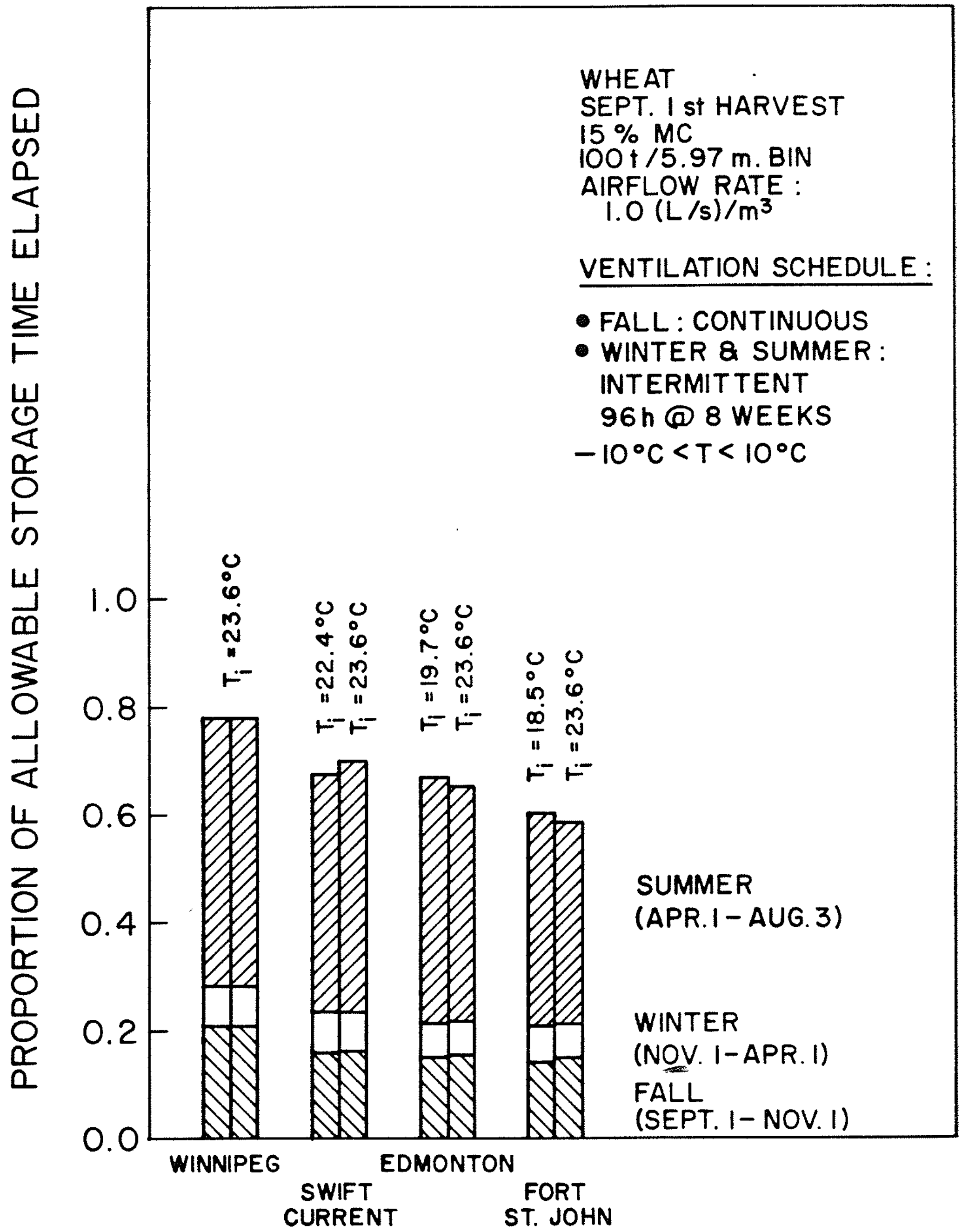

Fig. 5.13: Grain deterioration through the year following harvest with ventilation, comparing the effect of initial grain temperature, at four prairie locations.

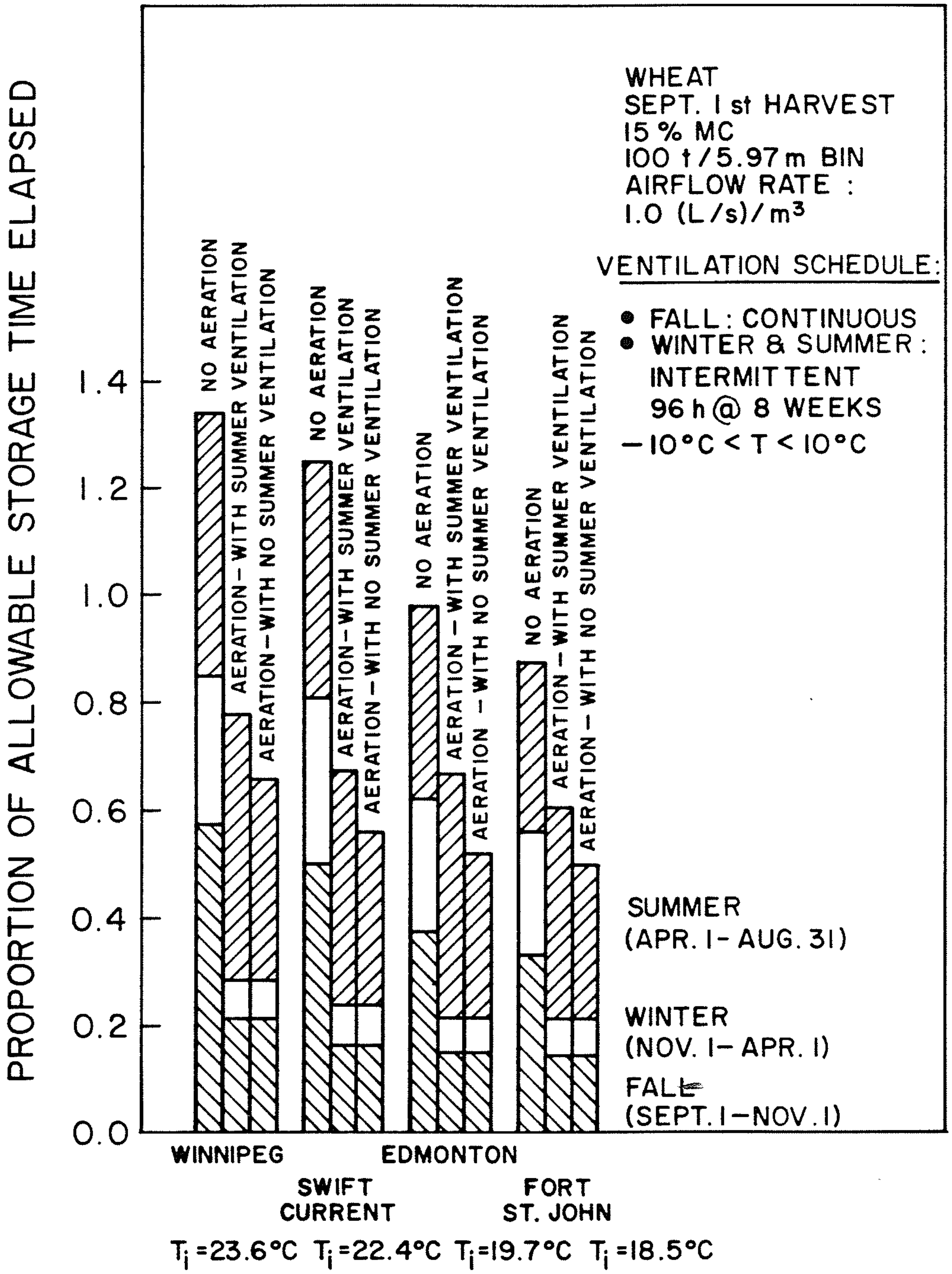

Fig. 5.14: Grain deterioration through the year following harvest, comparing no aeration, and aeration with and without intermittent summer ventilation, at four prairie locations.

Chapter VI

CONCLUSIONS

The following conclusions are evident from the results of this study:

1. The computer model provided reasonably accurate predictions of temperatures and moisture contents during periods of no ventilation and periods of ventilation at airflow rates near those used in aeration. Further experimental work is required to thoroughly verify the grain deterioration model.

2. Simulation of the 2 day period of high airflow rate ventilation [9.0 $(L/s)/m^3$] showed inaccuracies in moisture content predictions when compared with measured data. Further refinement of the model is required to increase the accuracy of predictions at airflow rates as high and higher than this.

3. All continuous aeration airflow rates between 0.5 and 3.0 $(L/s)/m^3$ greatly decreased the rate of grain deterioration during the fall cool-down period at Winnipeg. An airflow rate of 1.0 $(L/s)/m^3$ was judged preferable in terms of minimizing overdrying, grain temperature, and energy use for wheat harvested at 15% moisture content on 1 September and operated continuously for 60 days. As well, the low airflow rates resulted in less variability from year to year in the final moisture content.

4. Ventilation with any of the fan control methods resulted in decreased grain deterioration compared with no ventilation.

5. The choice of fan control method is independent of climatic variation within the range of climates studied. It may be, however, that fan control method selection is affected by various harvest dates and initial moisture contents, which were not studied here.

6. Humidistat control with settings of 50 to 70% resulted in effective control of grain quality deterioration, energy use ranging from 16 to 57% of continuous operation, and moisture content reductions of 0.2 to 0.5 percentage points.

7. Humidistat settings of greater than 70% maximum relative humidity resulted in greater moisture content reductions than at the lower settings, and in increased energy use.

8. Thermostat control did not provide an effective means of reducing the rate of grain quality deterioration, nor reducing energy use and minimizing overdrying.

9. A 6 h time-clock control between 0000 h and 0600 h provided effective grain quality control, reduced energy use, and minimized moisture content reductions for all climates. Swift Current was the only location at which the 12 h schedule of fan operation between 1800 h and 0600 h further significantly reduced the average proportion of allowable storage time elapsed.

10. Differential thermostat settings of -10 to -15°C provided effective control of grain quality deterioration with energy use ranging from 10 to 26% of continuous operation, and moisture content reductions of 0.3 to 0.6 percentage points.

11. Intermittent summer ventilation resulted in predictions of increased grain quality deterioration when compared with no summer ventilation. From this, one might be tempted to conclude that summer ventilation is not required. Because, however, the effects of summer moisture migration were not included in the unventilated simulation, the validity of intermittent summer ventilation cannot be argued with these data. If summer moisture migration is not a major cause of deterioration, summer ventilation may be a liability.

12. Regardless of aeration fan control method, wheat stores at lower rates of deterioration in the sub-boreal and sub-humid prairie climates, than in semi-arid and humid prairie climates.

13. Initial grain temperature affects the rate of deterioration more significantly in unventilated than in ventilated storages. Weather conditions after harvest date affect the rate of deterioration less in unventilated than in ventilated storages.

Chapter VII

RECOMMENDATIONS FOR FURTHER STUDY

1. The verification of the computer model indicated inaccuracy in predictions made using the forced convection component, at airflow rates as high as 9 $(L/s)/m^3$ and likely higher. This model should be modified to account for the less than equilibrium conditions that may occur at these rates. I suggest that a thin-layer drying equation be incorporated and a "combination" approach, such as that used by Morey et al. (1979) be used to ensure that the drying rate is not overestimated. The effect on the accuracy of the predictions of changing the layer depth and the simulation time interval should be examined as well.

2. To more accurately represent conditions during and after harvest, the model should be modified to relate the harvest date for each year (and thus the initial grain temperature) to the spring seeding date and length of growing season, or to historical records of harvest date.

3. The computer model should be modified, or a new approach taken in developing a completely new model to simulate moisture migration under unventillated conditions. This model should be verified with accurate experimental data to establish the

effects of moisture migration cycles. The benefits, if any, of summer ventilation could then be evaluated.

4. The deterioration model should be verified and adjusted if required to more accurately represent the effects of biological and physical variables on grain quality.

5. A simple, inexpensive differential thermostat control of grain bin ventilation fans should be designed.

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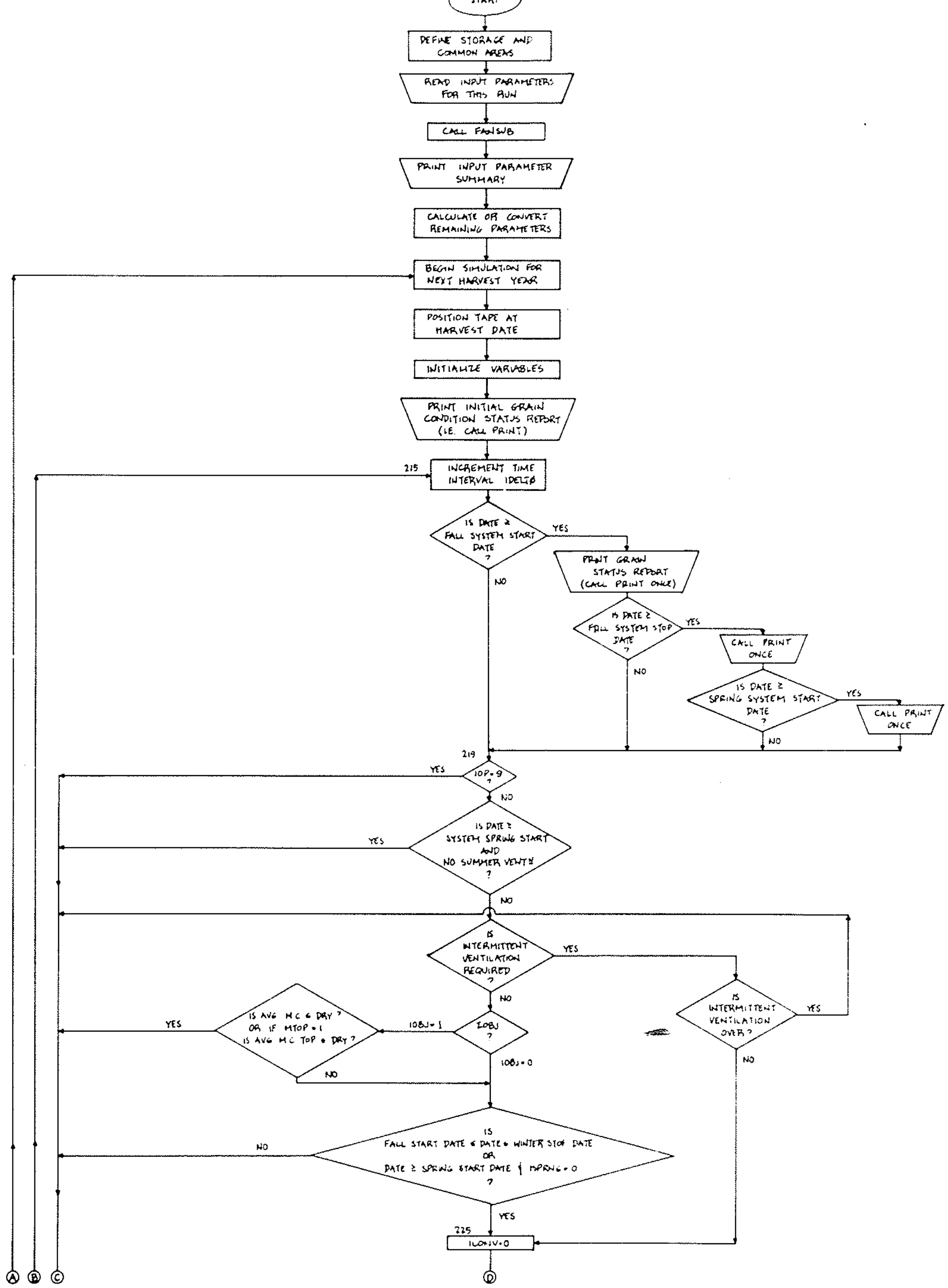
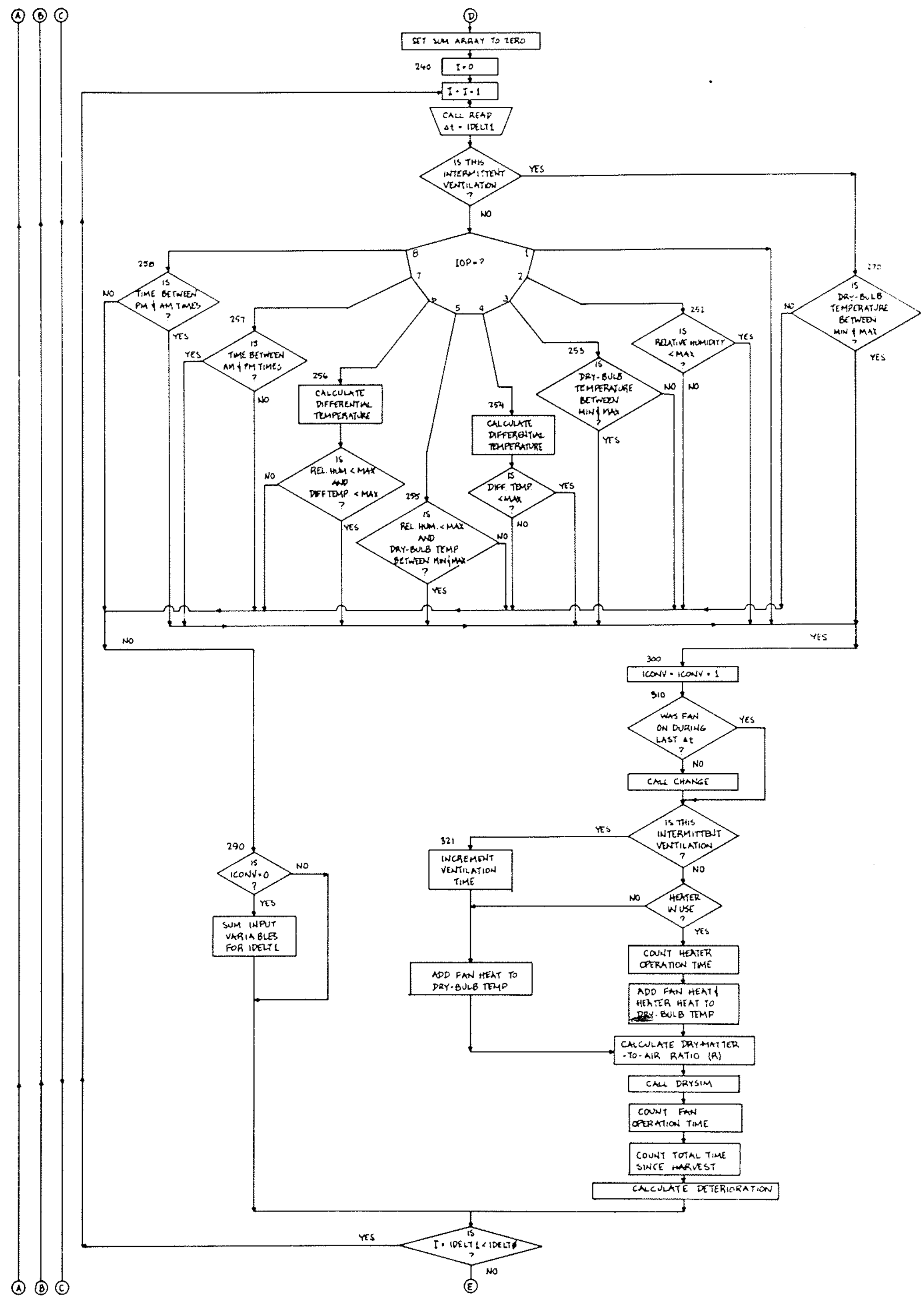
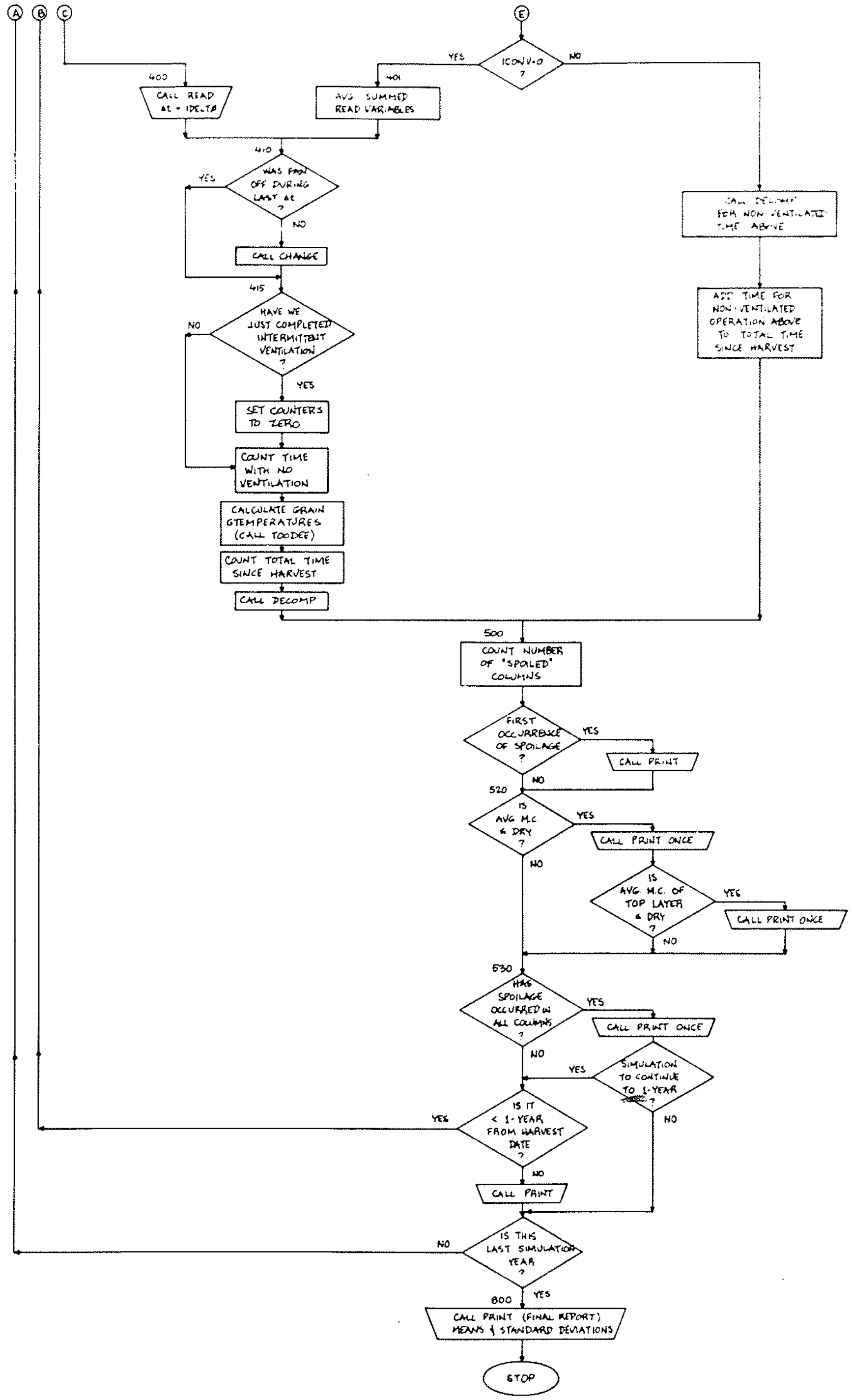
Appendix A

FLOWCHART OF MAIN PROGRAM


START
DEFINE STORAGE AND COMMON AREAS
READ INPUT PARAMETERS FOR THIS RUN
CALL FANSUB
PRINT INPUT PARAMETER SUMMARY
CALCULATE OR CONVERT REMAINING PARAMETERS
BEGIN SIMULATION FOR NEXT HARVEST YEAR
POSITION TAPE AT HARVEST DATE
INITIALIZE VARIABLES
PRINT INITIAL GRAIN CONDITION STATUS REPORT (I.E. CALL PRINT)
215
INCREMENT TIME INTERVAL IDELTØ
IS DATE ≥ FALL SYSTEM START DATE ?
YES
NO
PRINT GRAIN STATUS REPORT (CALL PRINT ONCE)
IS DATE ≥ FALL SYSTEM STOP DATE ?
YES
NO
CALL PRINT ONCE
IS DATE ≥ SPRING SYSTEM START DATE ?
YES
NO
CALL PRINT ONCE
219
IOP = 9 ?
YES
NO
IS DATE ≥ SYSTEM SPRING START AND NO SUMMER VENT ?
YES
NO
IS INTERMITTENT VENTILATION REQUIRED ?
YES
NO
IS INTERMITTENT VENTILATION OVER ?
YES
NO
IOBJ ?
IOBJ = 1
IOBJ = 0
IS AVG MC ≤ DRY ? OR IF MTOP = 1 IS AVG MC TOP ≤ DRY ?
YES
NO
IS FALL START DATE ≤ DATE ≤ WINTER STOP DATE OR DATE ≥ SPRING START DATE & MSPRNG = 0 ?
NO
YES
225
ICONV = 0
A
B
C
D


SET SUM ARRAY TO ZERO
240
I = 0
I = I + 1
CALL READ
Δt = IDELT1
IS THIS INTERMITTENT VENTILATION ?
YES
NO
IOP = ?
258
IS TIME BETWEEN PM & AM TIMES ?
257
IS TIME BETWEEN AM & PM TIMES ?
256
CALCULATE DIFFERENTIAL TEMPERATURE
IS REL. HUM. < MAX AND DIFF TEMP < MAX ?
255
IS REL. HUM. < MAX AND DRY-BULB TEMP BETWEEN MIN & MAX ?
254
CALCULATE DIFFERENTIAL TEMPERATURE
IS DIFF TEMP < MAX ?
253
IS DRY-BULB TEMPERATURE BETWEEN MIN & MAX ?
252
IS RELATIVE HUMIDITY < MAX ?
270
IS DRY-BULB TEMPERATURE BETWEEN MIN & MAX ?
300
ICONV = ICONV + 1
310
WAS FAN ON DURING LAST Δt ?
CALL CHANGE
IS THIS INTERMITTENT VENTILATION ?
321
INCREMENT VENTILATION TIME
HEATER IN USE ?
COUNT HEATER OPERATION TIME
ADD FAN HEAT & HEATER HEAT TO DRY-BULB TEMP
ADD FAN HEAT TO DRY-BULB TEMP
CALCULATE DRY-MATTER-TO-AIR RATIO (R)
CALL DRYSIM
COUNT FAN OPERATION TIME
COUNT TOTAL TIME SINCE HARVEST
CALCULATE DETERIORATION
290
IS ICONV = 0 ?
SUM INPUT VARIABLES FOR IDELT1
IS I · IDELT1 < IDELTΦ ?
A
B
C
D
E



A
B
C
E
ICONV=0 ?
YES
NO
400
CALL READ Δt = IDELTA
401
AVG SUMMED READ VARIABLES
410
WAS FAN OFF DURING LAST Δt ?
CALL CHANGE
415
HAVE WE JUST COMPLETED INTERMITTENT VENTILATION ?
SET COUNTERS TO ZERO
COUNT TIME WITH NO VENTILATION
CALCULATE GRAIN TEMPERATURES (CALL TOODEE)
COUNT TOTAL TIME SINCE HARVEST
CALL DECOMP
ADD TIME FOR NON-VENTILATED OPERATION ABOVE TO TOTAL TIME SINCE HARVEST
500
COUNT NUMBER OF "SPOILED" COLUMNS
FIRST OCCURRENCE OF SPOILAGE ?
CALL PRINT
520
IS AVG M.C. ≤ DRY ?
CALL PRINT ONCE
IS AVG. M.C. OF TOP LAYER ≤ DRY ?
CALL PRINT ONCE
530
HAS SPOILAGE OCCURRED IN ALL COLUMNS ?
CALL PRINT ONCE
SIMULATION TO CONTINUE TO 1-YEAR ?
IS IT < 1-YEAR FROM HARVEST DATE ?
CALL PRINT
IS THIS LAST SIMULATION YEAR ?
800
CALL PRINT (FINAL REPORT) MEANS & STANDARD DEVIATIONS
STOP

Appendix B

FORTRAN STATEMENT LISTING OF MAIN PROGRAM AND SUBROUTINES

```
C ******************************************************************
C *                                                                *
C *  UNIVERSITY OF MANITOBA - AGRICULTURAL ENGINEERING DEPARTMENT  *
C *                                                                *
C *     COMBINED TWO-DIMENSIONAL CONDUCTION & FORCED CONVECTION    *
C *     (EQUILIBRIUM DRYING) SIMULATION MODEL.                     *
C *     FOR WHEAT STORED IN CIRCULAR STEEL GRANARIES EQUIPPED WITH *
C *     FORCED AIR VENTILATION EQUIPMENT AND A FULLY PERFORATED FLOOR *
C *     IN CANADIAN PRAIRIE CLIMATES.                              *
C *                                                                *
C *     PROGRAMMED BY J.F. METZGER                                 *
C *     LAST UPDATE:  1980 09 15                                   *
C *                                                                *
C *  BASED ON:                                                     *
C *  1. EQUILIBRIUM DRYING MODEL - T.L. THOMPSON                   *
C *     SUBROUTINES "DSIM", "ZERO" & "TYPE1"                       *
C *  2. TWO-DIMENSIONAL CONDUCTION MODEL - W.E. MUIR & B.M. FRASER *
C *     A FINITE DIFFERENCE METHOD. (SUBROUTINE "TOODEE")          *
C *     MODIFIED BY J.F. METZGER                                   *
C *                                                                *
C *  REQUIRES HOURLY WEATHER DATA ON TAPE WITH THE FOLLOWING HOURLY *
C *  INPUT INFORMATION:                                            *
C *     DATE: YEAR, MONTH, DAY, HOUR, (4I2 FORMAT)                 *
C *     DRY BULB TEMPERATURE (DEG C)                               *
C *     DEW POINT TEMPERATURE (DEG C)                              *
C *     RELATIVE HUMIDITY (%)                                      *
C *     WIND SPEED (KM/H)                                          *
C *     CLOUD OPACITY (TENTHS - MAX=1.0)                           *
C *     BAROMETRIC PRESSURE (KPA)                                  *
C *                                                                *
C *  REQUIRES THE FOLLOWING SUBROUTINES:                           *
C *     READ:     READS HOURLY TAPE DATA CONTAINING THE ABOVE INFOR- *
C *               MATION. TAPE FILES FOR SELECTED LOCATIONS AND YEARS *
C *               ARE CUSTOM BUILT TO SUIT THE READ FORMAT.        *
C *     TOODEE:   TWO-DIMENSIONAL FINITE DIFFERENCE HEAT CONDUCTION *
C *               PROGRAM BASED ON THAT DEVELOPED BY MUIR & FRASER. *
C *     DRYSIM:   CALLS SUBROUTINE "DSIM" AND OPERATES IT IN COLUMNS *
C *               WHEN MOISTURE CONTENT AND TEMPERATURE ARE SIGNIFI- *
C *               CANTLY DIFFERENT.                                *
C *     DSIM:     EQUILIBRIUM DRYING (FORCED CONVECTION) SUBROUTINE *
C *               BY T.L.THOMPSON AS MODIFIED BY B.M.FRASER.       *
C *     CHANGE:   TEMPERATURE AVERAGING SUBROUTINE FOR CALCULATING *
C *               TEMPERATURES AT NODES WHEN GOING FROM CONVECTION TO *
C *               CONDUCTION OR FROM CONDUCTION TO CONVECTION.     *
C *     CALC:     CALCULATES AVERAGE THERMAL PROPERTIES FOR CONDUCTION *
C *     RADN:     CALCULATES THE NET RADIATION ON THE BIN WALL USING *
C *               SIMULATION EQUATION DEVELOPED FOR CANADIAN PRAIRIE *
C *               CLIMATES BY T.K.WON.                             *
C *     SPHT:     CALCULATES SPECIFIC HEAT OF WHEAT                *
C *               MUIR & VIRAVANICHAI (1972)                       *
C *     FANSUB:   CALCULATES FAN CAPACITY, GRAIN DEPTH, & TEMPERATURE *
C *               RISE ACROSS THE FAN FOR AXIAL FLOW FANS.         *
C *     DECOMP:   PROPORTION OF ALLOWABLE STORAGE TIME LEFT AT EACH *
C *               ELEMENT IS CALCULATED. DRY MATTER DECOMPOSITION IS *
C *               FOUND FOR THE WORST ELEMENT IN EACH COLUMN.      *
C *     SAFWH:    CALCULATES THE MAXIMUM ALLOWABLE STORAGE TIME FOR *
C *               WHEAT AT TEMPERATURE AND MOISTURE CONTENT INPUT. *
C *               EQUATIONS BY FRASER (1979), BASED ON KREYGER (1972) *
C *     AHUM:     CALCULATES ABSOLUTE HUMIDITY OR SATURATION VAPOUR *
C *               PRESSURE OF THE AIR.                             *
C *     RHAIR:    CALCULATES THE RELATIVE HUMIDITY OF THE AIR FOR THE *
C *               GIVEN CONDITIONS OF TEMPERATURE AND ABSOLUTE HUMIDITY*
C *     MAX:      FINDS AND IDENTIFIES THE MAXIMUM VALUE IN AN ARRAY. *
C *     MIN:      FINDS AND IDENTIFIES THE MINIMUM VALUE IN AN ARRAY. *
```

```
C  *     PRINT:    CONTAINS ALL OUTPUT INFORMATION, SUMMARY CALCULATIONS*
C  *               AND PRINT FORMATS.                                   *
C  *     ZERO:     SEQUENTIALLY SELECTS BETTER X VALUES FOR AN UNKNOWN  *
C  *               FUNCTION F(X) SUCH THAT F(X) EQUALS SOME DESIRED     *
C  *               VALUE OF Y. (BY T.L.THOMPSON)                        *
C  *     TYPE1:    USED WITH "ZERO" TO FIND A BETTER ESTIMATE OF X.     *
C  *                                                                    *
C  *  INPUT/OUTPUT UNIT NUMBERS:                                        *
C  *     UNIT NO:                                                       *
C  *     FT06F001  OUTPUT  INPUT DATA SUMMARY &                         *
C  *                       SUMMARY REPORT AT END OF SIMULATION          *
C  *     FT08F001  OUTPUT  INTERIM GRAIN CONDITION STATUS REPORTS       *
C  *                       OPTION OF PUTTING THIS INFORMATION ON DISK,  *
C  *                       TAPE, TO PRINTER, OR TO DUMMY DATASET        *
C  *     FT09F001   INPUT  DATA VARIABLES                               *
C  *     FT14F001   INPUT  HOURLY TAPE WEATHER DATA                     *
C  *                                                                    *
C  **********************************************************************
C
      DIMENSION T(11,11),XMO(11,11),OM(11,11),G(11,11),C(5),RO(5),AK(5),
     @AKM(5),WIDTH(5),AVM(11),AVT(11),U(10),IDATE(5),OPCOST(20,10),
     @PER(11,11),PERDM(11),LMAX(11),IPRINT(10),AVCOLM(11),AVCOLT(11),
     @FAN(20,13),HEAT(20,13),FANCST(20,13),HTCST(20,13),SUM(6),IDA(6,6),
     @XDAYS(20,10),ATEMP(20,10),AMOIST(20,10),EPTONN(20,10),
     @ODCPT(20,10),SPMASS(20,10),AVGPER(20,10),AMODIF(20,10)
      INTEGER*4 GEO(20)
      INTEGER ONEYR
      COMMON /CAL/C,RO,AK,AKM,WIDTH,U,DELR,DELZ,DIAM
      COMMON/RAD/IDATE,H,TW,TDB,EMA,EMS,CO,QR,TDP,
     @ PBAR,XLAT,XLONG,XLONGS
      COMMON /TDEE/IM,IN,E,WIND,NL,NM,NN,BB,BT,TROOF,TPLEN
      COMMON /AREA1/R,IDELTO,IDELT1,MULT,MODE,VMOIST,VTEMP
      COMMON /PRT/HOURS,DRY,PER,FAN,HEAT,IHEATR,PWRCST,HTPWR,PWR,T,G,XMO
     @,GEO,IRUN,PERDM,KY,NYEARS,IFIRST,TONNE,GRCOST,AVGM,AVGT,ONEYR,IOP,
     @XDAYS,AMOIST,ATEMP,EPTONN,ODCPT,SPMASS,AVGPER,AMODIF,ISPRNG,OPCOST
C
C  **********************************************************************
C  *  INPUT DATA GROUP #1                                               *
C  *  INPUT GEOGRAPHICAL LOCATION & YEARS OF ANALYSIS:                  *
C  *                                                                    *
C  *     LOCATE:  LOCATION INDEX:                                       *
C  *                 1 = WINNIPEG, MANITOBA                             *
C  *                 2 = FORT ST JOHN, B.C.                             *
C  *                 3 = EDMONTON, ALBERTA                              *
C  *                 4 = SWIFT CURRENT, SASK                            *
C  *     GEO:     LOCATION NAME AND PROVINCE                            *
C  *     XLAT:    LATITUDE                                              *
C  *     XLONG:   LONGITUDE                                             *
C  *     XLONGS:  STANDARD LONGITUDE                                    *
C  *     IFIRST:  FIRST SIMULATION YEAR EG 62                           *
C  *     NYEARS:  NUMBER OF HARVEST SEASONS TO BE SIMULATED             *
C  *              (MAX OF 20-YEARS UNLESS ARRAY SIZES ARE INCREASED)    *
C  *     IRUN:    OPTIONAL RUN NUMBER GIVEN BY THE USER                 *
C  *                                                                    *
C  **********************************************************************
C
      READ(9,10)LOCATE,GEO,XLAT,XLONG,XLONGS,IFIRST,NYEARS,IRUN
   10 FORMAT(I1,20A1,3F5.1,2I3,I5)
      WRITE(6,11)IRUN,GEO,XLAT,XLONG,XLONGS,IFIRST,NYEARS
   11 FORMAT('1',/' ',T41,'INTERMITTENT VENTILATION SIMULATION - WHEAT',
     @T120,'RUN #',I6/' ',T55,'INPUT DATA'/
     @'-','GEOGRAPHICAL LOCATION & YEARS OF ANALYSIS:'/
     @'0',T11,20A1,T41,'LATITUDE:',F6.1,T61,'LONGITUDE:',F6.1,T81,
     @'STANDARD LONGITUDE:',F6.1/
```

```
     @' ',T11,'FIRST YEAR: 19',I2,T31,'NO OF YEARS:',I3)
C
C  *********************************************************************
C  *   INPUT DATA GROUP #2                                             *
C  *   INPUT BIN DATA, SIMULATION ELEMENTS, TIME INTERVALS & GRAIN     *
C  *   INITIAL CONDITIONS:                                             *
C  *                                                                   *
C  *      TONNE:    MASS OF STORED GRAIN (TONNES, ON A 14.5% MC BASIS)  *
C  *      DIAM:     BIN DIAMETER (METERS)                               *
C  *      EMA:      EMISSIVITY OF BIN @ 38 DEG C                        *
C  *      EMS:      EMISSIVITY OF BIN (SOLAR)                           *
C  *      TROOF:    TEMPERATURE OF THE BIN ATTIC ABOVE AMBIENT IN THE   *
C  *                CONDUCTION MODE (DEG C)                             *
C  *      TPLEN:    TMPERATURE OF THE PLENUM UNDER THE FLOOR ABOVE      *
C  *                AMBIENT (DEG C)                                     *
C  *      TI:       MINIMUM INITIAL GRAIN TEMPERATURE (DEG C)           *
C  *      XMI:      AVERAGE INITIAL GRAIN MOISTURE CONTENT (% WB)       *
C  *      DRY:      THE "DRY" MOISTURE CONTENT (% WB)                   *
C  *      TGHARV:   INITIAL TEMPERATURE ABOVE THE PREVIOUS 24-HR AVERAGE *
C  *                AMBIENT DRY BULB (DEG C) - SEE D.C. PRASAD'S THESIS *
C  *      ITI:      0  IF THE MAXIMUM OF "TI" OR "AVG 24-H TDB + TGHARV" *
C  *                   IS TO BE USED FOR INITIAL GRAIN TEMPERATURE      *
C  *                1  IF "TI" IS TO BE USED FOR THE INITIAL GRAIN TEMP *
C  *                   REGARDLESS OF WHAT THE 24-H AVG TDB IS           *
C  *      VMOIST:   ALLOWABLE VARIATION IN MOISTURE CONTENT BELOW WHICH *
C  *                COLUMNS ARE AVERAGED & TREATED AS ONE IN CONVECTION *
C  *                MODE (% WB)                                         *
C  *      VTEMP:    ALLOWABLE VARIATION IN TEMPERATURES BELOW WHICH     *
C  *                COLUMNS ARE AVERAGED & TREATED AS ONE IN CONVECTION *
C  *                MODE (DEG C)                                        *
C  *      NL:       NO OF CONVECTION LAYERS        MAXIMUM=10           *
C  *                MUST BE AN INTEGER MULTIPLE OF NM (I.E. 1,2,3, ETC) *
C  *      NM:       NO OF CONDUCTION LAYERS        MAXIMUM=10           *
C  *      NN:       NO OF CONDUCTION COLUMNS       MAXIMUM=10           *
C  *      IDELTO:   DELTA-T FOR THE CONDUCTION MODE (HOURS)             *
C  *                *** MUST BE A MULTIPLE OF IDELTI ***                *
C  *      IDELTI:   DELTA-T FOR THE CONVECTION MODE (HOURS)             *
C  *      NPROP:    INTEGER INDICATING THE NUMBER OF GRAIN AND BIN      *
C  *                PROPERTY CARDS WHICH FOLLOW IN INPUT DATA GROUP #3  *
C  *                                                                   *
C  *********************************************************************
C
      READ(9,12)TONNE,DIAM,EMA,EMS,TROOF,TPLEN,TI,TGHARV,ITI,XMI,DRY,
     @VMOIST,VTEMP,NL,NM,NN,IDELTO,IDELTI,NPROP
   12 FORMAT(8F5.2,I1,1X,2F5.2,2F4.1,6I3)
      WRITE(6,13)TONNE,DIAM,EMA,EMS,TROOF,TPLEN,TI,TGHARV
   13 FORMAT('-','BIN DATA, GRAIN INITIAL CONDITIONS, AND SIMULATION ELE
     @MENTS & TIME INTERVALS:'/
     @'0',T11,'TONNES:',F7.2,T31,'BIN DIA:',F6.2,' M',T51,'EMA:',F5.2,
     @T71,'EMS:',F5.2,T91,'TROOF: +',F5.2,' C',T111,'TPLEN: +',F5.2,' C'
     @/' ',T11,'INITIAL GRAIN TEMPERATURE:',F5.1,' DEG C',T51,
     @'OR INITIAL GRAIN TEMPERATURE ABOVE AVERAGE PREVIOUS 24-H AMBIENT
     @BY:',F6.1,' C')
      IF(ITI.EQ.1)GOTO 15
      WRITE(6,14)ITI
   14 FORMAT(' ',T11,'ITI:',I4,' MAXIMUM OF THE ABOVE TWO INITIAL GRAIN
     @TEMPERATURES IS USED')
      GOTO 17
   15 WRITE(6,16)ITI
   16 FORMAT(' ',T11,'ITI:',I4,' INITIAL GRAIN TEMPERATURE "TI" IS USED
     @REGARDLESS OF THE 24-H AVERAGE TDB')
   17 WRITE(6,18)XMI,DRY,VMOIST,VTEMP,NL,NM,NN,IDELTO,IDELTI
   18 FORMAT(' ',T11,'INITIAL MOISTURE CONTENT:',F5.1,' % WB',T51,
     @'DRY:',F6.1,' % WB'/
```

```
     @' ',T11,'SUBROUTINE DRYSIM: ALLOWABLE VARIATIONS WHEN ALL COLUMNS
     @SIMULATED AS ONE COLUMN. MOISTURE:',F5.1,' % AND TEMP:',F5.1,' C'/
     @' ',T11,'CONVECTION LAYERS:',I3,T41,'CONDUCTION LAYERS:',I3,T71,
     @'COLUMNS:',I3,T91,'IDELT0:',I3,' H',T111,'IDELT1:',I3,' H')
C
C  *******************************************************************
C  *  INPUT DATA GROUP #3                                            *
C  *  INPUT "NPROP" CARDS FOR GRAIN AND BIN PROPERTIES:              *
C  *                                                                 *
C  *     C(I):     SPECIFIC HEAT (J/KG/DEG C)                        *
C  *     RO(I):    DENSITY   (KG/M**3)                               *
C  *     AK(I):    THERMAL CONDUCTIVITY  (W/M/DEG C)                 *
C  *     WIDTH(I):THICKNESS   (METERS)                               *
C  *     NPROP:    1  FOR THE GRAIN                                  *
C  *                  C(1) FOR THE GRAIN IS CALCULATED MORE ACCURATELY *
C  *                  LATER BY SUBROUTINE "SPHT" WHEN REQUIRED       *
C  *               2  FOR THE BIN WALL                               *
C  *               3  FOR THE BIN FLOOR                              *
C  *                                                                 *
C  *******************************************************************
C
      DO 20 I=1,NPROP
         READ(9,21) C(I),RO(I),AK(I),WIDTH(I)
   21    FORMAT(4F12.5)
   20 CONTINUE
C
C  *******************************************************************
C  *  INPUT DATA GROUP #4                                            *
C  *  FAN,  HEATER  &  POWER  INFORMATION:                           *
C  *                                                                 *
C  *     AFR:      SYSTEM AIR FLOW RATE (L/S/M**3)                   *
C  *     EFF:      FAN + MOTOR TOTAL EFFICIENCY                      *
C  *     PWRCST:   ELECTRICAL POWER COST (C/KW-HR)                   *
C  *     GRCOST:   MARKET VALUE OF THE GRAIN ($/TONNE)               *
C  *     IHEATR:   0  IF NO HEATER IS USED                           *
C  *               1  IF SUPPLEMENTAL ELECTRICAL HEATING IS USED     *
C  *                  (HEAT IS NOT ADDED DURING INTERMITTENT WINTER  *
C  *                   VENTILATION)                                  *
C  *     TSUPPL:   AMOUNT OF SUPPLEMENTAL HEAT ADDED TO AIR (DEG C)  *
C  *               (USED ONLY WITH IHEATR=1)                         *
C  *                                                                 *
C  *******************************************************************
C
      READ(9,25)AFR,EFF,PWRCST,GRCOST,IHEATR,TSUPPL
   25 FORMAT(F5.1,F5.2,2F5.1,I2,F5.1)
      CALL FANSUB(DIAM,TONNE,AFR,EFF,XLPS,SP,DEPTH,PWR,DT)
      HTPWR=TSUPPL*1.004*1.2*XLPS/1000.
      WRITE(6,26)AFR,EFF,PWR,DT,DEPTH,XLPS,SP,GRCOST,PWRCST
   26 FORMAT('-','FAN, HEATER & POWER INFORMATION:'/
     @'0',T11,'AFR:',F5.1,' L/S/M**3',T31,'EFFICIENCY:',F5.2,T51,
     @'FAN POWER:',F6.2,' KW',T71,'TEMP RISE:',F5.1,' C',T91,
     @'GRAIN DEPTH:',F6.2,' M'/
     @' ',T11,'FAN AIRFLOW RATE:',F8.1,' L/S',T51,'STATIC PRESSURE:',
     @F7.1,' PASCALS'/
     @' ',T11,'GRAIN VALUE: $',F6.2,'/T',T51,'POWER COST:',F5.1,
     @' C/KW-HR')
      IF(IHEATR.EQ.1)GOTO 27
      WRITE(6,1027)IHEATR
 1027 FORMAT(' ',T11,'IHEATR:',I3,' NO HEATER')
      GOTO 28
   27 WRITE(6,1028)IHEATR,TSUPPL,HTPWR
 1028 FORMAT(' ',T11,'IHEATR:',I3,' HEATER OPERATION EXCEPT FOR INTERMIT
     @TENT AERATION. SUPPLEMENTAL HEAT:',F5.1,' C',6X,'HEATER POWER:',
     @F6.2,' KW')
```

```
C
C ******************************************************************
C *  INPUT DATA GROUP #5                                             *
C *  SYSTEM MANAGEMENT INFORMATION:                                  *
C *                                                                  *
C *     IOP:     FAN OPERATION CONTROL METHOD:                       *
C *              1 MANUAL CONTROL LIMITED BY STOP AND START DATES    *
C *              2 HUMIDISTAT CONTROL WITH RH.LE.RHMAX               *
C *              3 THERMOSTAT CONTROL WITHIN TDBMIN AND TDBMAX       *
C *              4 DIFFERENTIAL THERMOSTAT CONTROL: TDB MINUS TEMP OF *
C *                TOP LAYER MUST BE LESS THAN TDIFFM                *
C *                I.E. TDB MUST BE COOLER THAN THE TOP GRAIN LAYER  *
C *              5 HUMIDISTAT AND THERMOSTAT CONTROL: RH.LE.RHMAX    *
C *                AND TDB WITHIN TDBMIN AND TDBMAX                  *
C *              6 HUMIDISTAT AND DIFFERENTIAL THERMOSTAT CONTROL:   *
C *                RH.LT.RHMAX AND TDB MINUS TEMP OF TOP LAYER MUST  *
C *                BE LESS THAN TDIFFM                               *
C *              7 TIME CLOCK CONTROL OPERATION BETWEEN AM AND PM    *
C *                TIMES (I.E. DAYTIME OPERATION)                    *
C *              8 TIME CLOCK CONTROL OPERATION BETWEEN PM AND AM    *
C *                TIMES (I.E. NIGHTIME OPERATION)                   *
C *              9 NO VENTILATION - CONTINUOUS CONDUCTION ONLY       *
C *     IOBJ:    OBJECTIVE OF STORAGE REGARDING MOISTURE CONTENTS:   *
C *              0 FAN OPERATION REGARDLESS OF GRAIN MOISTURE CONTENT *
C *                (I.E. IF PROGRAM IS SIMULATING AERATION?)         *
C *              1 FAN OPERATION LIMITED BY THE GRAIN MOISTURE CONTENT*
C *                SEE "MTOP"                                        *
C *     MTOP:    0 CONTROL BY AVERAGE MOISTURE CONTENT OF THE GRAIN  *
C *              1 CONTROL BY AVERAGE MOISTURE CONTENT OF THE TOP    *
C *                LAYER                                             *
C *     ONEYR:   0 SIMULATION UNTIL SPOILAGE OCCURS IN ALL COLUMNS,  *
C *                OR FOR 1-YEAR FROM THE BIN FILL DATE              *
C *              1 SIMULATION FOR 1-YEAR FROM THE BIN FILL DATE      *
C *                REGARDLESS OF THE SPOILAGE                        *
C *     JHARVD:  HARVEST DATE (MODAHR)              | IN             *
C *     JSTDT1:  FALL SYSTEM START DATE (MODAHR)    | HARVEST        *
C *     JSPDT1:  WINTER SYSTEM STOP DATE (MODAHR)   | YEAR           *
C *     JSTDT2:  SPRING SYSTEM START DATE (MODAHR) OF FOLLOWING YEAR *
C *     ISPRNG:  0 FOR COMMENCEMENT OF VENTILATION SYSTEM AT THE     *
C *                SPRING START DATE                                 *
C *              1 FOR A STATUS REPORT ONLY AT THE SPRING START DATE *
C *                CONTINUING WITH THE WINTER SCHEDULE FOR INTERMIT- *
C *                TENT VENTILATION                                  *
C *              2 FOR A STATUS REPORT ONLY AT THE SPRING START DATE *
C *                CONTINUING WITH NO VENTILATION THROUGH THE SUMMER *
C *                TO THE END OF THE YEAR                            *
C *     IAM:     AM TIME CLOCK SETTING  (HOUR)  | ** IAM ALWAYS LESS *
C *     IPM:     PM TIME CLOCK SETTING  (HOUR)  |     THAN IPM **    *
C *     RHMAX:   MAXIMUM RELATIVE HUMIDITY (%)                       *
C *     TDBMAX:  MAXIMUM AMBIENT TEMPERATURE (DEG C)                 *
C *              (USED IN INTERMITTENT VENTILATION ALSO)             *
C *     TDBMIN:  MINIMUM AMBIENT TEMPERATURE (DEG C)                 *
C *              (USED IN INTERMITTENT VENTILATION ALSO)             *
C *     TDIFFM:  DIFFERENTIAL THERMOSTAT SETTING (DEG C)             *
C *     INPER:   MAXIMUM PERIOD WITHOUT VENTILATION (DAYS)           *
C *              (UNLESS TDB.LT.TDBMIN)                              *
C *     INAIRT:  INTERMITTENT AERATION TIME INTERVAL (HOURS)         *
C *              (SHOULD BE A MULTIPLE OF IDELTO)                    *
C *     PERMAX:  MAXIMUM ALLOWABLE DRY MATTER DECOMPOSITION (%)      *
C *     PERI:    ALLOWABLE STORAGE TIME ALREADY USED UP ON THE BIN   *
C *              FILL DATE                                           *
C *                                                                  *
C ******************************************************************
C
```

```
   28  READ(9,29)IOP,IOBJ,MTOP,ONEYR,JHARVD,JSTDT1,JSPDT1,JSTDT2,ISPRNG,
      @IAM,IPM,RHMAX,TDBMAX,TDBMIN,TDIFFM,INPER,INAIRT,PERMAX,PERI
   29  FORMAT(4I2,4I7,I2,2I3,4F5.1,2I4,2F4.2)
       WRITE(6,30)
   30  FORMAT('-','SYSTEM MANAGEMENT INFORMATION:')
       GOTO(31,32,33,34,35,36,37,38,39),IOP
   31  WRITE(6,1031)IOP
 1031  FORMAT('0',T11,'IOP:',I4,' CONTINUOUS OPERATION LIMITED BY START A
      @ND STOP DATES')
       GOTO 40
   32  WRITE(6,1032)IOP
 1032  FORMAT('0',T11,'IOP:',I4,' HUMIDISTAT CONTROL WITH RH.LE.RHMAX')
       GOTO 40
   33  WRITE(6,1033)IOP
 1033  FORMAT('0',T11,'IOP:',I4,' THERMOSTAT CONTROL WITHIN TDBMIN AND TD
      @BMAX')
       GOTO 40
   34  WRITE(6,1034)IOP
 1034  FORMAT('0',T11,'IOP:',I4,' DIFFERENTIAL THERMOSTAT CONTROL: TDB MI
      @NUS TEMP OF TOP LAYER MUST BE  .LT.TDIFFM')
       GOTO 40
   35  WRITE(6,1035)IOP
 1035  FORMAT('0',T11,'IOP:',I4,'  HUMISISTAT & THERMOSTAT CONTROL: RH.LE
      @.RHMAX .AND. TDB WITHIN TDBMIN AND TDBMAX')
       GOTO 40
   36  WRITE(6,1036)IOP
 1036  FORMAT('0',T11,'IOP:',I4,' HUMIDISTAT & DIFFERENTIAL THERMOSTAT CO
      @NTROL: RH.LT. RHMAX AND TDB MINUS TEMP OF TOP LAYER .LT.TDIFFM')
       GOTO 40
   37  WRITE(6,1037)IOP
 1037  FORMAT('0',T11,'IOP:',I4,' TIME CLOCK CONTROL: OPERATION BETWEEN A
      @M & PM TIMES.  I.E. DAYTIME VENTILATION')
       GOTO 40
   38  WRITE(6,1038)IOP
 1038  FORMAT('0',T11,'IOP:',I4,' TIME CLOCK CONTROL: OPERATION BETWEEN P
      @M & AM TIMES.  I.E. NIGHTTIME VENTILATION')
       GOTO 40
   39  WRITE(6,1039)IOP
 1039  FORMAT('0',T11,'IOP:',I4,' NO VENTILATION - CONTINUOUS CONDUCTION
      @SIMULATION')
   40  IF(IOBJ.EQ.1)GOTO 41
       WRITE(6,1040)IOBJ
 1040  FORMAT(' ',T11,'IOBJ:',I3,' FAN OPERATION REGARDLESS OF GRAIN MOIS
      @TURE CONTENT')
       GOTO 50
   41  WRITE(6,1041)IOBJ
 1041  FORMAT(' ',T11,'IOBJ:',I3,' FAN OPERATION LIMITED BY GRAIN MOISTUR
      @E CONTENT - SEE VALUE OF "MTOP"')
   50  IF(MTOP.EQ.1)GOTO 51
       WRITE(6,1050)MTOP
 1050  FORMAT(' ',T11,'MTOP:',I3,' CONTROL BY MOISTURE CONTENT OF THE WHO
      @LE GRAIN BULK')
       GOTO 52
   51  WRITE(6,1051)MTOP
 1051  FORMAT(' ',T11,'MTOP:',I3,' CONTROL BY MOISTURE CONTENT OF THE TOP
      @ LAYER OF THE GRAIN BULK')
   52  IF(ONEYR.EQ.1)GOTO 53
       WRITE(6,1052)ONEYR
 1052  FORMAT(' ',T11,'ONEYR:',I2,' SIMULATION UNTIL SPOILAGE OCCURS IN A
      @LL COLUMNS, OR FOR 1-YEAR FROM THE BIN FILL DATE')
       GOTO 54
   53  WRITE(6,1053)ONEYR
 1053  FORMAT(' ',T11,'ONEYR:',I2,' SIMULATION FOR ONE YEAR FROM THE BIN
      @FILL DATE, REGARDLESS OF SPOILAGE')
```

```
   54  WRITE(6,55)JHARVD,JSTDT1,JSPDT1,JSTDT2
   55  FORMAT(' ',T11,'BIN FILL DATE:',I7,T41,'SYSTEM START DATE:',
      @I7,T71,'FALL STOP DATE:',I7,T101,'SPRING START DATE:',I7)
       IF(ISPRNG.GT.0)GOTO 58
       WRITE(6,57)ISPRNG
   57  FORMAT(' ',T11,'ISPRNG:',I2,' FALL VENTILATION SCHEDULE BEGINS AGA
      @IN ON THE SPRING START DATE')
       GOTO 65
   58  IF(ISPRNG.EQ.2)GOTO 60
       WRITE(6,59)ISPRNG
   59  FORMAT(' ',T11,'ISPRNG:',I2,' STATUS REPORT ONLY ISSUED AT SPRING
      @START DATE: INT VENTILATION CONTINUES AS THROUGH THE WINTER')
       GOTO 65
   60  WRITE(6,61)ISPRNG
   61  FORMAT(' ',T11,'ISPRNG:',I2,' STATUS REPORT ISSUED AT SPRING START
      @ DATE. SIMULATION CONTINUES WITH NO VENTILATION TO END OF YEAR')
   65  WRITE(6,66)RHMAX,TDBMAX,TDBMIN,TDIFFM,IAM,IPM,INPER,INAIRT,PERMAX,
      @PERI
   66  FORMAT(' ',T11,'RHMAX:',F5.1,' %',T31,'TDBMAX:',F5.1,' C',T51,
      @'TDBMIN:',F5.1,' C',T71,'TDIFFM:',F5.1,' C',T91,'AM TIME:',I3,
      @' H',T111,'PM TIME:',I3,' H'/
      @' ',T11,'MAX PERIOD WITHOUT VENTILATION:',I4,' DAYS',T61,
      @'INTERMITTENT VENTILATION PERIOD:',I4,' HOURS'/
      @' ',T11,'MAX ALLOWABLE DRY MATTER DECOMPOSITION:',F5.2,' %',T61,
      @'ALLOWABLE STORAGE TIME ALREADY USED UP ON BIN FILL DATE:',F5.2/
      @'1')
C
       INPER=INPER*24
       PWRCST=PWRCST/100.
       DELR=DIAM/(NN*2.)
       DELZ=DEPTH/NM
       E=DELR**2/DELZ**2
       IM=NM+1
       IN=NN+1
       DMI=100.*XMI/(100.-XMI)
       C(1)=1000.*SPHT(TI,DMI)
       CALL CALC
       HC2=1.
       BT=HC2*DELR/AK(1)
       BB=HC2*DELR/AKM(2)
       MULT=IDELT0/IDELT1
       DO 70 KY=1,NYEARS
          DO 70 I=1,12
             HEAT(KY,I)=0.
             FAN(KY,I)=0.
   70  CONTINUE
C
       DO 700 KY=1,NYEARS
C
C      SET INITIAL CONDITIONS FOR EACH HARVEST YEAR:
       IHARVD=JHARVD + (IFIRST+(KY-1))*1000000
       ISTDT1=JSTDT1 + (IFIRST+(KY-1))*1000000
       ISPDT1=JSPDT1 + (IFIRST+(KY-1))*1000000
       ISTDT2=JSTDT2 + (IFIRST+KY)*1000000
   75  READ(14,80,END=710)IDAT
   80  FORMAT(I8)
       IF(IDAT.LT.IHARVD)GOTO 75
       IF(IDAT.EQ.IHARVD)GOTO 90
       DO  86 I=1,24
          BACKSPACE 14
   86  CONTINUE
       GOTO 75
   90  DO 91 I=1,25
          BACKSPACE 14
```

```
   91   CONTINUE
        SUM(1)=0.
 C INITIAL GRAIN TEMPS BASED ON AVERAGE AMBIENT TEMPS SEE PRASAD'S THESIS
        DO 95 I=1,24
           READ(14,92)TDB
   92      FORMAT(8X,F4.1)
           SUM(1)=SUM(1)+TDB
   95   CONTINUE
        THARV=SUM(1)/24. + TGHARV
        IF(THARV.LT.TI .OR. ITI.EQ.1)THARV=TI
 C      INITIAL GRAIN TEMPERATURES TO CONDUCTION NODES:
        DO 100 M=1,IM
           DO 100 N=1,IN
              T(M,N)=THARV
  100   CONTINUE
 C
 C      INITIAL GRAIN TEMPERATURES, MOISTURE CONTENTS AND ALLOWABLE
 C      STORAGE TIMES TO CONVECTION NODES:
        DO 110 L=1,NL
           DO 110 N=1,IN
              G(L,N)=THARV
              XMO(L,N)=XMI
              DM(L,N)=DMI
              PER(L,N)=PERI
  110   CONTINUE
        DO 111 N=1,IN
           PERDM(N)=0.
           AVCOLM(N)=XMI
           AVCOLT(N)=THARV
  111   CONTINUE
        HOURS=0.
        AVTTOP=THARV
        AVMTOP=XMI
        AVGM=XMI
        AVGT=THARV
        DO 120 I=1,10
           IPRINT(I)=0
  120   CONTINUE
        DO 130 J=1,8
           XDAYS(KY,J)=0.
           AMOIST(KY,J)=0.
           AMODIF(KY,J)=0.
           ATEMP(KY,J)=0.
           EPTONN(KY,J)=0.
           ODCPT(KY,J)=0.
           SPMASS(KY,J)=0.
           AVGPER(KY,J)=0.
           OPCOST(KY,J)=0.
  130   CONTINUE
 C
 C      BEGIN SIMULATION FOR EACH HARVEST YEAR:
        READ(14,140)(IDATE(I),I=1,4)
  140 FORMAT(4I2)
        IDATE(5)=IDATE(1)*1000000+IDATE(2)*10000+IDATE(3)*100+IDATE(4)
        BACKSPACE 14
        MODE=0
        CALL PRINT(90,0)
        INTERV=0
        INAIR=0
  215   IDAPL=IDATE(5)+IDELTO
        IF(IDAPL.LT.ISTDT1)GOTO 219
        IF(IPRINT(4).GT.0)GOTO 216
        IPRINT(4)=40
        CALL PRINT(IPRINT(4),0)
```

```
 216   IF(IDAPL.LT.ISPDT1)GOTO 219
       IF(IPRINT(5).GT.0)GOTO 217
       IPRINT(5)=50
       CALL PRINT(IPRINT(5),0)
 217   IF(IDAPL.LT.ISTDT2)GOTO 219
       IF(IPRINT(6).GT.0)GOTO 219
       IPRINT(6)=60
       CALL PRINT(IPRINT(6),0)
 219   IF(IOP.EQ.9)GOTO 400
       IF(IDAPL.GE.ISTDT2 .AND. ISPRNG.EQ.2)GOTO 400
       IF(INTERV.GE.INPER)GOTO 230
       IF(IOBJ.EQ.0)GOTO 222
       IF((AVGM.LE.DRY.AND.MTOP.EQ.0).OR.(AVMTOP.LE.DRY.AND.MTOP.EQ.1))
      @        GOTO 400
 222   IF((IDAPL.GE.ISTDT1 .AND. IDAPL.LT.ISPDT1) .OR.
      @ (IDAPL.GE.ISTDT2 .AND. ISPRNG.EQ.0))GOTO 225
       GOTO 400
 225   ICONV=0
       DO 226 I=1,6
          SUM(I)=0.
 226   CONTINUE
       GOTO 240
 230   IF(INAIR.GE.INAIRT)GOTO 400
       GOTO 225
 240   DO 390 I=1,MULT
          CALL READ(IDATE,TDB,TDP,RH,WIND,CO,PBAR,IDELT1,&710)
          IF(INTERV.GE.INPER)GOTO 270
          GOTO(300,252,253,254,255,256,257,258),IOP
 252      IF(RH.LE.RHMAX)GOTO 300
          GOTO 290
 253      IF(TDB.LT.TDBMAX .AND. TDB.GT.TDBMIN)GOTO 300
          GOTO 290
 254      TDIFF=TDB-AVTTOP
          IF(TDIFF.LE.TDIFFM)GOTO 300
          GOTO 290
 255      IF(RH.LE.RHMAX.AND.(TDB.LT.TDBMAX.AND.TDB.GT.TDBMIN))GOTO 300
          GOTO 290
 256      TDIFF=TDB-AVTTOP
          IF(RH.LE.RHMAX .AND. TDIFF.LT.TDIFFM)GOTO 300
          GOTO 290
 257      IF(IDATE(4).GE.IAM .AND. IDATE(4).LT.IPM)GOTO 300
          GOTO 290
 258      IF(IDATE(4).GE.IAM .AND. IDATE(4).LT.IPM)GOTO 290
          GOTO 300
 270      IF(TDB.GT.TDBMIN .AND. TDB.LT.TDBMAX)GOTO 300
 290      IF(ICONV.GT.0)GOTO 390
          SUM(1)=SUM(1)+TDB
          SUM(2)=SUM(2)+TDP
          SUM(3)=SUM(3)+RH
          SUM(4)=SUM(4)+WIND
          SUM(5)=SUM(5)+CO
          SUM(6)=SUM(6)+PBAR
          DO 295 J=1,5
             IDA(I,J)=IDATE(J)
 295      CONTINUE
          GOTO 390
 300      ICONV=ICONV+1
 310      IF(MODE.EQ.1)GOTO 320
          MODE=1
          CALL CHANGE(T,G,NM,NL,IN,TDB,1)
          DO 315 N=1,IN
             SUMM=0.
             SUMT=0.
             DO 314 L=1,NL
```

```
               SUMM=SUMM+XMO(L,N)
               SUMT=SUMT+G(L,N)
314         CONTINUE
            AVCOLM(N)=SUMM/NL
            AVCOLT(N)=SUMT/NL
315      CONTINUE
320      IF(INTERV.GE.INPER)GOTO 321
         IF(IHEATR.EQ.0)GOTO 322
         HEAT(KY,IDATE(2))=HEAT(KY,IDATE(2))+IDELT1
         TDBIN=TDB+DT+TSUPPL
         GOTO 330
321      INAIR=INAIR+IDELT1
322      TDBIN=TDB+DT
330      R=1000.*(1.-(AVGM/100.))/(AFR*1.33*3600.*IDELT1*NL*1.2/1000.)
         CALL DRYSIM(TDBIN,TDP,G,XMO,DM,AVMTOP,AVTTOP,AVCOLM,AVCOLT,
     @               AVGM,AVGT)
         FAN(KY,IDATE(2))=FAN(KY,IDATE(2))+IDELT1
         HOURS=HOURS+IDELT1
         CALL DECOMP(T,G,XMO,PER,PERDM,LMAX)
390   CONTINUE
      IF(ICONV.EQ.0)GOTO 401
      J=MULT-ICONV
      IF(J.LE.0)GOTO 500
      DO 398 I=1,J
         CALL DECOMP(T,G,XMO,PER,PERDM,LMAX)
         HOURS=HOURS+IDELT1
398   CONTINUE
      GOTO 500
400   CALL READ(IDATE,TDB,TDP,RH,WIND,CO,PBAR,IDELT0,&710)
      GOTO 410
401   TDB=SUM(1)/MULT
      TDP=SUM(2)/MULT
      RH=SUM(3)/MULT
      WIND=SUM(4)/MULT
      CO=SUM(5)/MULT
      PBAR=SUM(6)/MULT
      J=MULT/2 + 1
      DO 402 I=1,5
         IDATE(I)=IDA(J,I)
402   CONTINUE
410   IF(MODE.EQ.0)GOTO 415
      MODE=0
      CALL CHANGE(T,G,NM,NL,IN,TDB,0)
415   IF(INAIR.LT.INAIRT)GOTO 420
      INAIR=0
      INTERV=0
420   INTERV=INTERV+IDELT0
      CALL TODDEE(T,AVGT,AVTTOP,AVGM)
      HOURS=HOURS+IDELT0
      CALL DECOMP(T,G,XMO,PER,PERDM,LMAX)
500   NSPOIL=0
      DO 510 N=1,IN
         IF(PERDM(N).LT.PERMAX)GOTO 510
         NSPOIL=NSPOIL+1
510   CONTINUE
      IF(NSPOIL.LE.IPRINT(1))GOTO 520
      IF(IPRINT(1).GT.0)GOTO 515
      KSPOIL=NSPOIL
      GOTO 516
515   KSPOIL=0
516   IPRINT(1)=NSPOIL
      IF(NSPOIL.GE.IN)GOTO 520
      CALL PRINT(IPRINT(1),KSPOIL)
520   IF(AVGM.GT.DRY)GOTO 530
```

```
      IF(IPRINT(2).GT.0)GOTO 521
      IPRINT(2)=20
      CALL PRINT(IPRINT(2),0)
 521  IF(AVMTOP.GT.DRY)GOTO 530
      IF(IPRINT(3).GT.0)GOTO 530
      IPRINT(3)=30
      CALL PRINT(IPRINT(3),0)
 530  IF(NSPOIL.LT.IN .OR. IPRINT(7).EQ.70)GOTO 550
      IPRINT(7)=70
      CALL PRINT(IPRINT(7),KSPOIL)
      IF(ONEYR.NE.1)GOTO 560
 550  IF(IDATE(5).LT.(IHARVD+1000000))GOTO 215
      CALL PRINT(80,0)
 560  CONTINUE
 700  CONTINUE
      GOTO 800
 710  CALL PRINT(100,0)
 800  CALL PRINT(200,0)
 1000 CONTINUE
      STOP
      END
C***********************************************************************
C
      SUBROUTINE READ(IDATE,TDB,TDP,RH,WIND,CO,PBAR,
     @ IDELT,*)
      DIMENSION IYR(24),MO(24),IDA(24),IHR(24),SUM(6),IDATE(5)
      IF(IDELT.EQ.1)GOTO 110
      DO 100 I=1,6
         SUM(I)=0.
 100  CONTINUE
 110  DO 200 I=1,IDELT
         READ(14,10,END=300)IYR(I),MO(I),IDA(I),IHR(I),TDB,TDP,RH,WIND,
     @                  CO,PBAR
 10      FORMAT(4I2,2F4.1,4X,2F3.0,F2.1,F5.2)
         IF(TDP.LE.TDB .AND. RH.LE.100. .AND. RH.GT.0.)GOTO 210
         TDP=TDB-3.
         RH=80.
 210     IF(IDELT.EQ.1)GOTO 220
         SUM(1)=SUM(1)+TDB
         SUM(2)=SUM(2)+TDP
         SUM(3)=SUM(3)+RH
         SUM(4)=SUM(4)+WIND
         SUM(5)=SUM(5)+CO
         SUM(6)=SUM(6)+PBAR
 200  CONTINUE
      TDB=SUM(1)/IDELT
      TDP=SUM(2)/IDELT
      RH=SUM(3)/IDELT
      WIND=SUM(4)/IDELT
      CO=SUM(5)/IDELT
      PBAR=SUM(6)/IDELT
 220  IN=IDELT/2 +1
      IDATE(1)=IYR(IN)
      IDATE(2)=MO(IN)
      IDATE(3)=IDA(IN)
      IDATE(4)=IHR(IN)
      IDATE(5)=IDATE(1)*1000000+IDATE(2)*10000+IDATE(3)*100+IDATE(4)
      RETURN
 300  CONTINUE
      RETURN1
      END
C***********************************************************************
C
      SUBROUTINE TOODEE(T,AVGT,AVTTOP,AVGM)
```

```
      COMMON /CAL/C.RO.AK.AKM.WIDTH.U.DELR.DELZ.DIAM
      COMMON/RAD/IDATE.H.TW.TDB.EMA.EMS.CO.QR.TDP.
     @ PBAR.XLAT.XLONG.XLONGS
      COMMON /TDEE/IM.IN.E.WIND.NL.NM.NN.BB.BT.TROOF.TPLEN
      COMMON /AREA1/R.IDELTO.IDELT1.MULT.MODE.VMOIST.VTEMP
      DIMENSION T(11.11).XMO(11.11).TP(11.11).C(5).RO(5).AK(5).AKM(5).
     @WIDTH(5).U(10).IDATE(5)
      C(1)=1000.*SPHT(AVGT.(100.*AVGM/(100.-AVGM)))
      CALL CALC
      TT=TDB+TROOF
      TB=TDB+TPLEN
      HC1=.0239*(WIND/3.6*DIAM/1.4E-5)**.805*.025/DIAM
      HC2=1.
      BT=HC2*DELR/AK(1)
      BB=HC2*DELR/AKM(2)
      BW=HC1*DELR/AKM(1)
      TW=0.
      DO 220 I=1.IM
         TW=TW+T(I.IN)
 220  CONTINUE
      TW=TW/IM
      CALL RADN
      QRP=8.*NN*DELR*QR/((4.*NN-1.)*U(2))
C
C TEMPERATURE AT BOTTOM CENTRE:
      TP(1.1)=2.*BB*DELR/(U(3)*DELZ)*TB + 2.*E/U(1)*T(2.1) +
     @        4./U(3)*T(1.2) + (1.-2.*(E+2.)/U(3)-2.*BB*DELR/
     @        (U(3)*DELZ))*T(1.1)
C
C TEMPERATURE AT TOP CENTRE:
      TP(IM.1)=2.*BT*DELR/(U(1)*DELZ)*TT + 2.*E/U(1)*T(NM.1) +
     @         4./U(1)*T(IM.2) + (1.-2.*(E+2.)/U(1)-2.*BT*DELR/
     @         (U(1)*DELZ))*T(IM.1)
C
C TEMPERATURE AT BOTTOM WALL:
      TP(1.IN)=8.*NN*BW/(U(2)*(4.*NN-1.))*TDB +
     @         2.*BB*DELR/(U(3)*DELZ)*TB +
     @         (8.*NN-4.)/(U(2)*(4.*NN-1.))*T(1.NN) +
     @         2.*E/U(2)*T(2.IN) + (1.-(8.*NN*BW+(8.*NN-4.))/
     @         (U(2)*(4.*NN-1.))-2.*BB*DELR/(U(3)*DELZ)-
     @         2.*E/U(2))*T(1.IN) + QRP
C
C TEMPERATURE AT TOP OF THE WALL:
      TP(IM.IN)=8.*NN*BW/(U(2)*(4.*NN-1.))*TDB +
     @         2.*BT*DELR/(U(1)*DELZ)*TT +
     @         (8.*NN-4.)/(U(2)*(4.*NN-1.))*T(IM.NN) +
     @         2.*E/U(2)*T(NM.IN) + (1.-(8.*NN*BW+(8.*NN-4.))/
     @         (U(2)*(4.*NN-1.))-2.*BT*DELR/(U(1)*DELZ)-
     @         2.*E/U(2))*T(IM.IN) + QRP
C
      DO 310 J=2.NN
         N=J-1
         JP=J+1
         JM=J-1
C
C TEMPERATURE OF THE BOTTOM LAYER:
         TP(1.J)=2.*BB*DELR/(U(3)*DELZ)*TB +
     @           (2.*N+1.)/(2.*N*U(3))*T(1.JP) +
     @           (2.*N-1.)/(2.*N*U(3))*T(1.JM) +
     @           (2.*E/U(3))*T(2.J) +
     @           (1.-2.*(E+1.)/U(3)-2.*BB*DELR/(U(3)*DELZ))*T(1.J)
C
C TEMPERATURE OF THE TOP LAYER:
         TP(IM.J)=2.*BT*DELR/(U(1)*DELZ)*TT +
```

```
     @              (2.*N+1.)/(2.*N*U(1))*T(IM,JP) +
     @              (2.*N-1.)/(2.*N*U(1))*T(IM,JM) +
     @              (2.*E/U(1))*T(NM,J) +
     @              (1.-2.*(E+1.)/U(1)-2.*BT*DELR/(U(1)*DELZ))*T(IM,J)
 310  CONTINUE
C
      DO 320 I=2,NM
         M=I-1
         IP=I+1
         IMI=I-1
C
C TEMPERATURES AT THE WALL:
         TP(I,IN)=8.*NN*BW/((4.*NN-1.)*U(2))*TDB +
     @              (8.*NN-4.)/((4.*NN-1.)*U(2))*T(I,NN) +
     @              E/U(2)*(T(IP,IN)+T(IMI,IN)) +
     @              (1.-(8.*NN*BW+8.*NN-4.)/((4.*NN-1.)*U(2))
     @              -2.*E/U(2))*T(I,IN) + QRP
C
C TEMPERATURES OF THE CENTRE COLUMN:
         TP(I,1)=4./U(1)*T(I,2) + E/U(1)*(T(IP,1)+T(IMI,1)) +
     @              (1.-(2.*(E+2.)/U(1)))*T(I,1)
C
         DO 320 J=2,NN
            N=J-1
            JP=J+1
            JM=J-1
C
C TEMPERATURES IN THE MIDDLE OF THE GRAIN BULK:
            TP(I,J)=(2.*N+1.)/(2.*N*U(1))*T(I,JP) +
     @              (2.*N-1.)/(2.*N*U(1))*T(I,JM) +
     @              E/U(1)*(T(IP,J)+T(IMI,J)) +
     @              (1.-(2.*(E+1.)/U(1)))*T(I,J)
 320  CONTINUE
      DO 330 I=1,IM
         DO 330 J=1,IN
            T(I,J)=TP(I,J)
 330  CONTINUE
C CALCULATE AVERAGE GRAIN TEMP FOR BULK
      AVGT=0.
      DO 400 I=1,IM
         DO 400 J=1,IN
            AVGT=AVGT+T(I,J)
 400  CONTINUE
      AVGT=AVGT/(IM*IN)
      AVTTOP=0.
      DO 410 N=1,IN
         DO 410 I=1,2
            M=IM-(I-1)
            AVTTOP=AVTTOP+T(M,N)
 410  CONTINUE
      AVTTOP=AVTTOP/(IN*2.)
      RETURN
      END
C*****************************************************************************
C
      SUBROUTINE DRYSIM(TO,TD,G,XM,DM,AVMTOP,AVTTOP,AVCOLM,AVCOLT,AVGM,
     @AVGT)
      DIMENSION G(11,11),XM(11,11),DM(11,11),AVM(11),AVT(11),AXM(11),
     @ AG(11),ADM(11),AVCOLM(11),AVCOLT(11),SUM(3)
      COMMON /TDEE/IM,IN,E,WIND,NL,NM,NN,BB,BT,TROOF,TPLEN
      COMMON /AREA1/R,IDELTO,IDELTI,MULT,MODE,VMOIST,VTEMP
C TEST FOR COLUMN MOISTURE CONTENT AND TEMPERATURE SIMILARITY:
      DO 100 N=1,IN
         IF(ABS(AVCOLM(N)-AVGM).GT.VMOIST)GOTO 200
```

```
         IF(ABS(AVCOLT(N)-AVGT).GT.VTEMP)GOTO 200
 100  CONTINUE
C CALCULATE TEMPERATURE AND M.C. AVERAGES OF ALL COLUMNS:
      DO 110 L=1,NL
         DO 111 I=1,3
 111        SUM(I)=0.
         DO 112 N=1,IN
            SUM(1)=SUM(1)+XM(L,N)
            SUM(2)=SUM(2)+G(L,N)
            SUM(3)=SUM(3)+DM(L,N)
 112     CONTINUE
         AXM(L)=SUM(1)/IN
         AG(L)=SUM(2)/IN
         ADM(L)=SUM(3)/IN
 110  CONTINUE
      CALL DSIM(TO,TD,AXM,AG,ADM,AVGM,AVGT,NL)
      DO 120 L=1,NL
         DO 120 N=1,IN
            XM(L,N)=AXM(L)
            G(L,N)=AG(L)
            DM(L,N)=ADM(L)
 120  CONTINUE
      DO 130 N=1,IN
         AVCOLM(N)=AVGM
         AVCOLT(N)=AVGT
 130  CONTINUE
      SUMMTP=0.
      SUMTTP=0.
      DO 140 I=1,MULT
         L=NL-(I-1)
         SUMMTP=SUMMTP+AXM(L)
         SUMTTP=SUMTTP+AG(L)
 140  CONTINUE
      AVMTOP=SUMMTP/MULT
      AVTTOP=SUMTTP/MULT
      RETURN
C WHEN COLUMNS ARE SIGNIFICANTLY DIFFERENT THEY'RE TREATED SEPARATELY:
 200  SUMM=0.
      SUMT=0.
      SUMMTP=0.
      SUMTTP=0.
      DO 300 N=1,IN
         DO 210 L=1,NL
            AXM(L)=XM(L,N)
            AG(L)=G(L,N)
            ADM(L)=DM(L,N)
 210     CONTINUE
         CALL DSIM(TO,TD,AXM,AG,ADM,AVEM,AVET,NL)
         DO 220 L=1,NL
            XM(L,N)=AXM(L)
            G(L,N)=AG(L)
            DM(L,N)=ADM(L)
 220     CONTINUE
         DO 230 I=1,MULT
            L=NL-(I-1)
            SUMMTP=SUMMTP+XM(L,N)
            SUMTTP=SUMTTP+G(L,N)
 230     CONTINUE
         SUMM=SUMM+AVEM
         SUMT=SUMT+AVET
         AVCOLM(N)=AVEM
         AVCOLT(N)=AVET
 300  CONTINUE
      AVGM=SUMM/IN
```

```
      AVGT=SUMT/IN
      AVMTOP=SUMMTP/(IN*MULT)
      AVTTOP=SUMTTP/(IN*MULT)
      RETURN
      END
C*********************************************************************
      SUBROUTINE DSIM(TO,TD,XM,G,DM,AVEM,AVET,M)
      DOUBLE PRECISION AHUM
      COMMON /AREA1/R,IDELTO,IDELT1,MULT,MODE,VMOIST,VTEMP
      DIMENSION T(11),H(11),A(4),XM(10),G(10),DM(10)
      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
      DO 240 I=1,M
      IPRT=-1
      IJ=I+1
      C=SPHT(G(I),DM(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)
      ERH=EXP(2.40*EXP(-.205*XMI)*ALOG(PS)-10.17*EXP(-.186*XMI))
C        ERH IS THE EQUILIBRIUM RELATIVE HUMIDITY OF THE GRAIN.
      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)
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)
      AVET=SUMT/M
      AVEM=SUMM/M
C       AVEM IS THE AVERAGE MOISTURE CONTENT OF THE GRAIN COLUMN.
      RETURN
      END
C*********************************************************************
C
      SUBROUTINE CHANGE(T,G,NM,NL,IN,TDB,ICH)
C IF ICH=1 CALCULATES TEMPERATURES AT CONVECTION NODES FROM CONDUCTION
C IF ICH=0 CALCULATES TEMPERATURES AT CONDUCTION NODES FROM CONVECTION
      DIMENSION T(11,11),G(11,11)
      K=NL/NM
      NN=IN-1
```

```
      IF(ICH.EQ.1)GOTO 1
      IF(ICH.EQ.0)GOTO 2
      GOTO 3
C
C CONDUCTION TO CONVECTION:
  1   DO 10 N=1,IN
         L=1
         DO 10 M=1,NM
              DO 10  J=1,K
                 MP=M+1
                 G(L,N)=T(M,N)+(T(MP,N)-T(M,N))/(2.*K)*(2.*J-1.)
                 L=L+1
 10   CONTINUE
      DO 12 L=1,NL
         G(L,IN)=0.75*(G(L,IN)-G(L,NN)) + G(L,NN)
 12   CONTINUE
      RETURN
C
C CONVECTION TO CONDUCTION:
   2  DO 20 N=1,IN
         T(1,N)=TDB
         DO 21 M=2,NM
            JP=M*K
            JM=JP-(K*2-1)
            SUM=0.
            DO 22  J=JM,JP
               SUM=SUM+G(J,N)
  22        CONTINUE
            T(M,N)=SUM/(K*2)
  21     CONTINUE
         JP=NM*K
         JM=JP-(K-1)
         SUM=0.
         DO 23  J=JM,JP
            SUM=SUM+G(J,N)
  23     CONTINUE
         NTOP=NM+1
         T(NTOP,N)=T(NM,N)+2.*(SUM/K-T(NM,N))
  20  CONTINUE
      RETURN
   3  WRITE(6,30)ICH
  30  FORMAT('-','ERROR IN THE VALUE OF ICH =',I3)
      RETURN
      END
C***********************************************************************
C
      SUBROUTINE CALC
      DIMENSION C(5),RO(5),AK(5),AKM(5),WIDTH(5),U(10)
      COMMON /CAL/C,RO,AK,AKM,WIDTH,U,DELR,DELZ,DIAM
      COMMON /AREA1/R,IDELT0,IDELT1,MULT,MODE,VMOIST,VTEMP
      IF(WIDTH(2).GT.DELR/2.) WIDTH(2)=DELR/2.
      IF(WIDTH(3).GT.DELR/3.) WIDTH(3)=DELR/2.
      U(1)=C(1)*RO(1)*DELR**2/(AK(1)*IDELT0*3600.)
      W1=RO(1)*(DELR/4.*(DIAM-DELR/2.)-WIDTH(2)*DIAM/2.)
      IF(W1.LT.0.) W1=0.
      W2=RO(2)*WIDTH(2)*DIAM/2.
      CM=(W1*C(1)+W2*C(2))/(W1+W2)
      ROM=(W1+W2)/(W1/RO(1)+W2/RO(2))
      AKM(1)=DELR/(WIDTH(2)/AK(2)+(DELR-WIDTH(2))/AK(1))
      U(2)=CM*ROM*DELR**2/(AKM(1)*IDELT0*3600.)
      W1=RO(1)*(DELR/4.*(DIAM-DELR/2.)-WIDTH(3)*DIAM/2.)
      IF(W1.LT.0.) W1=0.
      W3=RO(3)*WIDTH(3)*DIAM/2.
      CM=(W1*C(1)+W3*C(3))/(W1+W3)
```

```
      ROM=(W1+W3)/(W1/RO(1)+W3/RO(3))
      AKM(2)=DELR/(WIDTH(3)/AK(3)+(DELR-WIDTH(3))/AK(1))
      U(3)=CM*ROM*DELR**2/(AKM(2)*IDELT0*3600.)
      RETURN
      END
C***********************************************************************
C
      SUBROUTINE RADN
C     RADN CALCULATES THE NET RADIATION ON THE BIN WALL
C     USING T.K.WON'S SIMULATION EQUATION FOR PRAIRIE CLIMATES.
      DIMENSION NDAY(12),A(12),B(12),C(12),DUST(12),E(12),IDATE(5)
      COMMON/RAD/IDATE,H,TW,TDB,EMA,EMS,CO,QR,TDP,PBAR,
     @ XLAT,XLONG,XLONGS
      DATA NDAY/31,28,31,30,31,30,31,31,30,31,30,31/
      DATA A/-.42388,-.64388,-.62338,-.84670,-.99257,-1.01189,
     @ -.98889,-1.03944,-.97999,-.84125,-.67440,-.47288/
      DATA B/-.24152,.02539,.02426,.13116,.24684,.25812,
     @ .23784,.28209,.21494,.03780,-.12326,-.24734/
      DATA C/1.31464,1.29326,1.21914,1.14903,1.09714,1.07446,
     @ 1.08530,1.09079,1.10879,1.16108,1.22667,1.29282/
      DATA DUST/.50,.80,.85,1.15,1.35,1.25,1.25,1.15,.85,.65,.45,.40/
      DATA E/-10.,-14.,-9.,0.,3.,-1.,-6.,-4.,5.,15.,15.,5./
      DATA PI/3.141593/,SC/4872.5/,STEF/5.6697E-08/
      MONTH=IDATE(2)
      IDAY=IDATE(3)
      IHOUR=IDATE(4)
      AA=2.*PI/365.
      ALAT=XLAT*2.*PI/360.
      D=0.
      IF(MONTH.EQ.1)GO TO 20
      J=MONTH-1
      DO 10 I=1,J
10    D=D+NDAY(I)
20    D=D+IDAY
C     D = DAY OF THE YEAR.
      DECL=ARSIN(.3978*SIN(AA*(D-80.)+.0335*(SIN(AA*D)-SIN(80.*AA))))
C     DECLINATION OF THE SUN.
      ST=IHOUR + (E(MONTH)+4.*(XLONGS-XLONG))/60.
C     SOLAR TIME
      WA=(ST-12.)*15.*2.*PI/360.
C     SOLAR HOUR ANGLE (ESTIMATE)
      Z=ARCOS(SIN(DECL)*SIN(ALAT) + COS(DECL)*COS(ALAT)*COS(WA))
      IF(Z.GT.1.5)Z=1.5
C     ZENITH ANGLE
      OAM=1./COS(Z)
C     OPTICAL AIR MASS
      AL=AA*D
      HO=SC*(1.-.0009464*SIN(AL)-.01671*COS(AL)-.0001489*COS(2.*AL)-
     @ 2.917E-5*SIN(3.*AL)-.0003438*COS(4.*AL))**2 * COS(Z)
C     HO IS THE INCIDENT SOLAR RADIATION AT THE TOP OF THE ATMOSPHERE
C     ON A HORIZONTAL SURFACE
      W=EXP(1.2876 + 0.0303*(TDP*1.8+32.))
      TRANS=EXP(-1.*(.000496*(10.*PBAR*OAM)**.75 + .0288*(W*OAM)**.6
     @ + .083*(DUST(MONTH)*OAM)**.9))
      CLOUD=A(MONTH)*CO**2 + B(MONTH)*CO + C(MONTH)
      H=HO*TRANS*CLOUD
C     H IS THE ESTIMATED GLOBAL RADIATION ON A HORIZONTAL SURFACE OF
C     ONE SQUARE METER INTEGRATED OVER ONE HOUR
      QE=0.5*STEF*EMA*(TDB+273.16)**4
C     EARTH-TO-BIN RADIATION.
      QS=0.5*STEF*EMA*1.94481E09
C     SKY-TO-BIN RADIATION.
      QO=STEF*EMA *(TW+273.16)**4
C     BIN-TO-SURROUNDINGS RADIATION.
```

```
      QSN=(-130.5535+0.115189*HO+664.925*H/HO)/3.6*EMS
C     TOTAL SOLAR RADIATION ON THE BIN WALL -- RELATIONSHIP CALCULATED
C     FROM WINNIPEG DATA ; REPRESENTS AVERAGE RADIATION FOR ALL SIDES
C     OF BIN.
      QR=QE+QS-QO+QSN
      RETURN
      END
C**************************************************************************
C
      FUNCTION SPHT(TEMP,DBMC)
      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
      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**************************************************************************
C
      SUBROUTINE FANSUB(DIAM,TONNE,AFR,EFF,XLPS,SP,DEPTH,PWR,DT)
C FOR WHEAT:
      SPWT=0.75
      PF=1.5
      AREA=3.14159*(DIAM/2.)**2
      VOL=TONNE/SPWT
      DEPTH=VOL/AREA
      XLPS=AFR*VOL
      F=XLPS/AREA
C REGRESSION EQUATION FOR ASAE DATA D272 IN SI UNITS (RSQ = 0.9967):
      SPM=2.294975*(F**1.134219)*PF
      SP=SPM*DEPTH
      IF(SP.LT.250.)GOTO 10
      PWR=((SP*XLPS)/(1.0E+6))/EFF
  9   DTCOMP=(((1.+SP/101325.)**0.2857143)-1.)*288.16
      DT=((1.-EFF)*PWR)/(1.004*1.2*XLPS/1000.) + DTCOMP
      RETURN
 10   PWR=XLPS*1000./(4.418-1.614*(SP/1000.))/1.0E+6/EFF
      GOTO 9
      END
C**************************************************************************
C
      SUBROUTINE DECOMP(T,G,XM,PER,PERDM,LMAX)
      DIMENSION T(11,11),G(11,11),XM(11,11),PER(11,11),LMAX(11),P(11),
     @PERDM(11),PCTM(11),IDATE(5)
      COMMON/RAD/IDATE,H,TW,TDB,EMA,EMS,CO,QR,TDP,
     @ PBAR,XLAT,XLONG,XLONGS
      COMMON /TDEE/IM,IN,E,WIND,NL,NM,NN,BB,BT,TROOF,TPLEN
      COMMON /AREA1/R,IDELTO,IDELT1,MULT,MODE,VMOIST,VTEMP
      IF(MODE.EQ.1)GOTO 110
      CALL CHANGE(T,G,NM,NL,IN,TDB,1)
      DT=IDELTO
      GOTO 120
 110  DT=IDELT1
 120  DO 200 N=1,IN
        DO 210 L=1,NL
          PER(L,N)=PER(L,N) + DT/SAFWH(G(L,N),XM(L,N))
```

```
            P(L)=PER(L.N)
 210        CONTINUE
            CALL MAX(NL.P.LMX.PTM)
            LMAX(N)=LMX
            PCTM(N)=PTM*100.
            EQT=PTM*230.
            PERDM(N)=.0884*(EXP(.006*EQT)-1.)+.00102*EQT
 200    CONTINUE
        RETURN
        END
C**********************************************************************
C
        FUNCTION SAFWH(TEMP.XMC)
        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**********************************************************************
C
        DOUBLE PRECISION FUNCTION AHUM(TEMP.N)
        DOUBLE PRECISION A.B.C.D.E.F.G.PW.T.DEXP.DLOG
        DATA A.B.C.D/-.751152D4. .8963121D2. .02399897D0.-.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**********************************************************************
C
        FUNCTION RHAIR(T.HO)
        DOUBLE PRECISION H.PS.AHUM
        H=HO
        PS=AHUM(T.2)
        RHAIR=(101.325D0*H/(H+.62198D0))/PS
        RETURN
        END
C**********************************************************************
C
        SUBROUTINE MAX(N.A.J.BIG)
        DIMENSION A(N)
        BIG=A(1)
        J=1
        IF(N.EQ.1)GOTO 11
        DO 10 I=2.N
        IF(A(I).LE.BIG) GO TO 10
        BIG=A(I)
        J=I
 10     CONTINUE
 11     CONTINUE
        RETURN
        END
C**********************************************************************
C
        SUBROUTINE MIN(N.A.J.SMALL)
        DIMENSION A(N)
        SMALL=A(1)
```

```
      J=1
      IF(N.EQ.1)GOTO 11
      DO 10 I=2,N
      IF(A(I).GE.SMALL)GO TO 10
      SMALL=A(I)
      J=I
10    CONTINUE
11    CONTINUE
      RETURN
      END
C**********************************************************************
C
      SUBROUTINE PRINT(IPRINT,KSPOIL)
      DIMENSION T(11,11),G(11,11),XMO(11,11),PER(11,11),FAN(20,13),
     @HEAT(20,13),FANCST(20,13),HTCST(20,13),IDATE(5),PERDM(11),
     @XDAYS(20,10),ATEMP(20,10),AMOIST(20,10),EPTONN(20,10),NY(9),
     @ODCPT(20,10),SPMASS(20,10),SUM(9),SUMSQ(9),AV(9),SD(9),A1(20),
     @AVGPER(20,10),A(2,9,20,10),OPCOST(20,10),MYEAR(9,20),
     @C(5),RO(5),AK(5),AKM(5),WIDTH(5),U(10),MM(9,4),AMODIF(20,10)
      INTEGER*4 GEO(20)
      COMMON /PRT/HOURS,DRY,PER,FAN,HEAT,IHEATR,PWRCST,HTPWR,PWR,T,G,XMO
     @,GEO,IRUN,PERDM,KY,NYEARS,IFIRST,TONNE,GRCOST,AVGM,AVGT,ONEYR,IOP,
     @XDAYS,AMOIST,ATEMP,EPTONN,ODCPT,SPMASS,AVGPER,AMODIF,ISPRNG,OPCOST
      COMMON/RAD/IDATE,H,TW,TDB,EMA,EMS,CO,QR,TDP,
     @ PBAR,XLAT,XLONG,XLONGS
      COMMON /AREA1/R,IDELTO,IDELTI,MULT,MODE,VMOIST,VTEMP
      COMMON /TDEE/IM,IN,E,WIND,NL,NM,NN,BB,BT,TROOF,TPLEN
      COMMON /CAL/C,RO,AK,AKM,WIDTH,U,DELR,DELZ,DIAM
      DATA PI/3.141593/
      IF(MODE.EQ.0) CALL CHANGE(T,G,NM,NL,IN,TDB,1)
      IF(IPRINT.EQ.200)GOTO 350
C
C INTERIM REPORT CALCULATIONS:
      WRITE(8,1)IRUN,GEO
    1 FORMAT('1',40X,'INTERMITTENT VENTILATION - STATUS REPORT',
     @T120,'RUN #',I6/' ',50X,20A1)
      DAYS=HOURS/24.
      WRITE(8,2)(IDATE(I),I=1,4),KY,DAYS
    2 FORMAT('0',40X,'DATE=',I3,'/',I2,'/',I2,I5,' HOURS.',2X,
     @'SIMULATION YEAR:',I3/
     @' ',40X,'IT IS NOW',F7.2,' DAYS SINCE THE BIN WAS FILLED')
      J=IPRINT/10
      GOTO(10,20,30,40,50,60,70,80,90,100),J
   10 WRITE(8,11) IPRINT
   11 FORMAT('0',06X,'SPOILAGE HAS NOW OCCURRED IN',I4,' COLUMNS')
      GOTO 190
   20 WRITE(8,21) DRY
   21 FORMAT('0',06X,'THE AVERAGE MOISTURE CONTENT OF THE GRAIN BULK IS
     @NOW LESS THAN OR EQUAL TO',F5.1,' %')
      GOTO 190
   30 WRITE(8,31) DRY
   31 FORMAT('0',06X,'THE AVERAGE MOISTURE CONTENT OF THE TOP LAYER IS N
     @OW LESS THAN OR EQUAL TO',F5.1,' %')
      GOTO 190
   40 WRITE(8,41)
   41 FORMAT('0',06X,'GRAIN CONDITIONS AT THE SYSTEM FALL START DATE ARE
     @:')
      GOTO 190
   50 WRITE(8,51)
   51 FORMAT('0',06X,'GRAIN CONDITIONS AT THE SYSTEM WINTER STOP DATE AR
     @E:')
      GOTO 190
   60 IF(ISPRNG.GT.0)GOTO 62
      WRITE(8,61)
```

```
 61   FORMAT('0',06X,'GRAIN CONDITIONS AT THE SPRING DATE ARE:')
      GOTO 190
 62   WRITE(8,63)
 63   FORMAT('0',06X,'GRAIN CONDITIONS AT THE SPRING REPORT DATE ARE:')
      GOTO 190
 70   WRITE(8,71)
 71   FORMAT('0',06X,'SPOILAGE HAS NOW OCCURRED IN ALL OF THE GRAIN COLU
     @MNS')
      IF(ONEYR.EQ.1)GOTO 190
      WRITE(8,72)
 72   FORMAT(' ',6X,'PROGRAM TERMINATES OPERATION FOR THE HARVEST YEAR')
      GOTO 190
 80   WRITE(8,81)
 81   FORMAT('0',06X,'GRAIN HAS NOW BEEN STORED FOR ONE YEAR FROM THE BI
     @N FILL DATE')
      GOTO 190
 90   WRITE(8,91)
 91   FORMAT('0',06X,'THE CONDITION OF THE GRAIN IS AS FOLLOWS')
      GOTO 190
100   WRITE(8,101)
101   FORMAT('0',06X,'END OF THE TAPE WEATHER DATA FILE. THE GRAIN CONDI
     @TIONS ARE:')
190   CONTINUE
      IF(IPRINT.LT.10 .AND. KSPOIL.NE.0)J=1
      IF(IPRINT.LT.10 .AND. KSPOIL.EQ.0)J=10
      SUM(1)=0.
      SUM(2)=0.
      DO 199 N=1,IN
         SUM(1)=SUM(1)+XMO(1,N)
         SUM(2)=SUM(2)+XMO(NL,N)
199   CONTINUE
      AMODIF(KY,J)=SUM(2)/IN - SUM(1)/IN
      WRITE(8,201)AVGT,AVGM,AMODIF(KY,J),(N,N=1,IN),(N,N=1,IN)
201   FORMAT('-',6X,'GRAIN TEMPERATURES:',T72,'GRAIN MOISTURE CONTENTS:'
     @/' ',T23,'AVERAGE:',F7.2,' C',T78,'AVERAGE:',F7.2,' %',4X,
     @'TOP/BOTTOM DIFFERENCE:',F6.2,' %'/
     @'0',6X,6I7,T72,6I7/' TOP',T66,'TOP')
      DO 200 I=1,NL
         L=NL-(I-1)
         WRITE(8,202)L,(G(L,N),N=1,IN),L,(XMO(L,N),N=1,IN)
202      FORMAT(' ',6X,I2,6F7.2,T72,I2,6F7.2)
200   CONTINUE
      SUM(1)=0.
      DO 210 L=1,NL
         DO 210 N=1,IN
            SUM(1)=SUM(1)+PER(L,N)
210   CONTINUE
      AVGPER(KY,J)=SUM(1)/(NL*IN)
      WRITE(8,221)AVGPER(KY,J),(N,N=1,IN),(N,N=1,IN)
221   FORMAT('-',6X,'PORTION OF ALLOWABLE STORAGE TIME ELAPSED:',T72,
     @'PERCENT DM DECOMPOSITION IN THE WORST LAYER OF EACH COLUMN:'/
     @' ',T23,'AVERAGE:',F7.3/
     @'0',6X,6I7,T72,6I7/' TOP')
      WRITE(8,222)NL,(PER(NL,N),N=1,IN),(PERDM(N),N=1,IN)
222   FORMAT(' ',6X,I2,6F7.3,T74,6F7.3)
      DO 220 I=2,NL
         L=NL-(I-1)
         WRITE(8,223)L,(PER(L,N),N=1,IN)
223      FORMAT(' ',6X,I2,6F7.3)
220   CONTINUE
      IF(IOP.EQ.9)GOTO 251
      IF(AVGM.GE.DRY)GOTO 230
      ODCPT(KY,J)=GRCOST*(DRY-AVGM)/(100.-AVGM)
      ODCOST=ODCPT(KY,J)*TONNE
```

```
      GOTO 240
 230  ODCPT(KY,J)=0.
      ODCOST=0.
 240  WRITE(8,250)ODCOST,ODCPT(KY,J)
 250  FORMAT('-',6X,'OVERDRYING COST: $',F7.2,' OR $',F7.2,'/T')
 251  VCL=0.
      DO 260 N=1,IN
         IF(N.EQ.1)ELVOL=PI*DELZ*(DELR**2)/8.
         IF(N.GT.1 .AND. N.LT.IN)ELVOL=(N-1.)*PI*DELZ*(DELR**2)
         IF(N.EQ.IN)ELVOL=(4.*N-5.)*PI*DELZ*(DELR**2)/8.
         K=0
         DO 255 L=1,NL
            IF(PER(L,N).GT.1.)K=K+1
 255     CONTINUE
         VOL=VOL + K*ELVOL
 260  CONTINUE
      SPMASS(KY,J)=VOL*0.75
      SPCOST=SPMASS(KY,J)*GRCOST
      WRITE(8,270)VOL,SPMASS(KY,J),SPCOST
 270  FORMAT('-',6X,'AMOUNT AND VALUE OF SPOILED GRAIN:'/
     @' ',T11,'VOLUME:',F7.2,' M**3',T41,'MASS:',F7.2,' T',T71,
     @'VALUE OF GRAIN SPOILED: $',F9.2)
      IF(IOP.EQ.9)GOTO 341
      FAN(KY,13)=0.
      HEAT(KY,13)=0.
      FANCST(KY,13)=0.
      HTCST(KY,13)=0.
      DO 300 I=1,12
         FAN(KY,13)=FAN(KY,13) + FAN(KY,I)
         FANCST(KY,I)=FAN(KY,I)*PWRCST*PWR
         FANCST(KY,13)=FANCST(KY,13) + FANCST(KY,I)
         IF(IHEATR.EQ.0)GOTO 300
         HEAT(KY,13)=HEAT(KY,13) + HEAT(KY,I)
         HTCST(KY,I)=HEAT(KY,I)*PWRCST*HTPWR
         HTCST(KY,13)=HTCST(KY,13) + HTCST(KY,I)
 300  CONTINUE
      ELECTR=(FANCST(KY,13)+HTCST(KY,13))/PWRCST * 3.6
      EPTONN(KY,J)=ELECTR/TONNE
      ECPT=EPTONN(KY,J)/3.6 * PWRCST
      WRITE(8,310)(I,I=1,12),(FAN(KY,I),I=1,13),(FANCST(KY,I),I=1,13)
 310  FORMAT('-',6X,'FAN AND HEATER OPERATION LOG:'/
     @'0',12X,'    MONTH',I5,11I7,'     TOTAL'/'0',12X,'FAN OPERATION:'/
     @' ',12X,'   HOURS',12F7.2,F9.2/' ',12X,'    COST',12F7.2,F9.2)
      IF(IHEATR.EQ.0)GOTO 330
      WRITE(8,320)(HEAT(KY,I),I=1,13),(HTCST(KY,I),I=1,13)
 320  FORMAT('0',12X,'HEATER OPERATION:'/' ',12X,'   HOURS',12F7.2,F9.2/
     @' ',12X,'    COST',12F7.2,F9.2)
 330  WRITE(8,340)ELECTR,EPTONN(KY,J),ECPT
 340  FORMAT('0',12X,'TOTAL ELECTRICAL ENERGY USE TO DATE BY THE FAN + H
     @EATER:',F8.2,' MJ  OR',F7.2,' MJ/T  OR $',F8.2,'/T')
      OPCOST(KY,J)=ODCPT(KY,J) + SPCOST/TONNE + ECPT
      GOTO 342
 341  OPCOST(KY,J)=SPCOST/TONNE
 342  WRITE(8,345)OPCOST(KY,J)
 345  FORMAT('-',6X,'SYSTEM OPERATING COSTS TO DATE: $',F7.2,'/T')
      XDAYS(KY,J)=DAYS
      ATEMP(KY,J)=AVGT
      AMOIST(KY,J)=AVGM
      RETURN
C
C     SUMMARY REPORT CALCULATIONS:
 350  DO 500 J=1,8
         DO 360 I=1,9
            SUM(I)=0.
```

```
          SUMSQ(I)=0.
          NY(I)=0
360     CONTINUE
        DO 400 KY=1,NYEARS
          A(1,1,KY,J)=XDAYS(KY,J)
          A(1,2,KY,J)=AMOIST(KY,J)
          A(1,3,KY,J)=AMODIF(KY,J)
          A(1,4,KY,J)=ATEMP(KY,J)
          A(1,5,KY,J)=EPTONN(KY,J)
          A(1,6,KY,J)=ODCPT(KY,J)
          A(1,7,KY,J)=SPMASS(KY,J)
          A(1,8,KY,J)=AVGPER(KY,J)
          A(1,9,KY,J)=OPCOST(KY,J)
          DO 370 I=1,9
            IF(A(1,I,KY,J).EQ.0. .AND. (J.EQ.1 .OR. J.EQ.2
     a      .OR. J.EQ.3 .OR. J.EQ.7))GOTO 370
            SUM(I)=SUM(I)+A(1,I,KY,J)
            SUMSQ(I)=SUMSQ(I)+A(1,I,KY,J)**2
            NY(I)=NY(I)+1
            A(2,I,NY(I),J)=A(1,I,KY,J)
            MYEAR(I,NY(I))=KY
370       CONTINUE
400     CONTINUE
        DO 407 I=1,9
          IF(NY(I).LE.1)GOTO 405
          AV(I)=SUM(I)/NY(I)
          X=((SUMSQ(I)-(SUM(I)*SUM(I))/NY(I))/(NY(I)-1.))
          IF(X.LT.0.)GOTO 406
          SD(I)=SQRT(X)
          GOTO 407
405       AV(I)=SUM(I)
406       SD(I)=0.
407     CONTINUE
        DO 410 I=1,9
          DO 408 II=1,2
            MM(I,II)=IFIRST
408       CONTINUE
          DO 409 II=3,4
            MM(I,II)=1
409       CONTINUE
410     CONTINUE
        DO 415 I=1,9
          IF(NY(I).LT.1)GOTO 415
          NYY=NY(I)
          DO 411 N=1,NYY
            A1(N)=A(2,I,N,J)
411       CONTINUE
          CALL MAX(NYY,A1,MX,X)
          CALL MIN(NYY,A1,MN,X)
          MM(I,3)=MYEAR(I,MX)
          MM(I,4)=MYEAR(I,MN)
          MM(I,1)=MM(I,3) + (IFIRST-1)
          MM(I,2)=MM(I,4) + (IFIRST-1)
415     CONTINUE
        WRITE(6,420)IRUN,GEO
420     FORMAT('1'/' ',40X,'INTERMITTENT VENTILATION - SUMMARY REPORT',
     a  T120,'RUN #',I6/' ',50X,20A1/'-',06X,118('*'))
        GOTO(421,422,423,424,425,426,427,428),J
421     WRITE(6,431)
        GOTO 440
422     WRITE(6,432)
        GOTO 440
423     WRITE(6,433)
        GOTO 440
```

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424       WRITE(6,434)
          GOTO 440
425       WRITE(6,435)
          GOTO 440
426       WRITE(6,436)
          GOTO 440
427       WRITE(6,437)
          GOTO 440
428       WRITE(6,438)
431       FORMAT('0',06X,'FIRST OCCURRENCE OF SPOILAGE -  AVERAGES FOR NO
     @N-ZERO YEARS ONLY:')
432       FORMAT('0',06X,'AVERAGE MOISTURE CONTENT IS "DRY" - AVERAGES FO
     @R NON-ZERO YEARS ONLY:')
433       FORMAT('0',06X,'AVERAGE MOISTURE CONTENT OF THE TOP LAYER IS "D
     @RY" - AVERAGES FOR NON-ZERO YEARS ONLY:')
434       FORMAT('0',06X,'AT THE FALL START DATE:')
435       FORMAT('0',06X,'AT THE WINTER STOP DATE:')
436       FORMAT('0',06X,'AT THE SPRING DATE:')
437       FORMAT('0',06X,'SPOILAGE IN ALL COLUMNS - AVERAGES FOR NON-ZERO
     @ YEARS ONLY:')
438       FORMAT('0',06X,'ONE YEAR FROM THE BIN FILL DATE:')
440       WRITE(6,441)
441       FORMAT('0',06X,118('-')/
     @    '0',4X,'  HARVEST',17X,'MOISTURE      TOP/BOT      GRAIN',7X,
     @    'ENERGY',8X,'DD',7X,'SPOILED      ALLOWABLE    OPERATING'/
     @    ' ',4X,'    YEAR        DAYS       CONTENT        DIFF ',
     @    '        TEMP',8X,'USE',9X,'COST',8X,'MASS     STORAGE TIME',4X,
     @    'COST'/
     @    ' ',4X,27X,'(% WB)       (% WB)      (DEG C)       (MJ/T)',6X,
     @    '($/T)',8X,'(T)        ELAPSED       ($/T)'/'0',6X,118('-'))
          WRITE(6,450)
450       FORMAT('0')
          DO 470 KY=1,NYEARS
             IY=IFIRST+(KY-1)
             WRITE(6,461)IY,(A(1,I,KY,J),I=1,9)
461          FORMAT(' ',4X,I7,F13.1,3F12.2,F14.1,F11.2,F11.1,F13.3,F12.2)
470       CONTINUE
          WRITE(6,482)(AV(I),I=1,9)
482       FORMAT('0',6X,118('-')/
     @    '0',6X,'AVERAGE:',F10.1,3F12.2,F14.1,F11.2,F11.1,F13.3,F12.2)
          WRITE(6,483)(SD(I),I=1,9)
483       FORMAT(' ',6X,'   +/-',F13.1,3F12.2,F14.1,F11.2,F11.1,F13.3,
     @            F12.2)
          WRITE(6,485)(A(1,I,MM(I,3),J),I=1,9)
485       FORMAT('0',6X,'MAXIMUM:',F10.1,3F12.2,F14.1,F11.2,F11.1,F13.3,
     @            F12.2)
          WRITE(6,486)(MM(I,1),I=1,9)
486       FORMAT(' ',6X,'IN YEAR:',I10,3I12,I14,2I11,I13,I12)
          WRITE(6,489)(A(1,I,MM(I,4),J),I=1,9)
489       FORMAT('0',6X,'MINIMUM:',F10.1,3F12.2,F14.1,F11.2,F11.1,F13.3,
     @            F12.2)
          WRITE(6,486)(MM(I,2),I=1,9)
          WRITE(6,490)
490       FORMAT('0',6X,118('*'))
500   CONTINUE
      WRITE(6,600)
600   FORMAT('1')
      RETURN
      END
C**************************************************************************
C
      SUBROUTINE ZERO(J,YD,X,Y,A,DEL,K,N,M)
      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 TO 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)GOTO 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
C*************************************************************************
C
      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
C*********************************************************************
```

Appendix C

ALPHABETICAL LISTING OF FORTRAN VARIABLE AND SUBROUTINE NAMES

A - location of data value in subroutine AHUM

A(I) - array which stores the status of search in subroutine DRYSIM, ZERO, and TYPE1

- array of which the minimum value is found in subroutine MIN, and the maximum value is found in subroutine MAX

- regression constant array in subroutine RADN

A(I,J,K,L) - array for manipulation of grain condition values for calculation of means and standard deviations in subroutine PRINT

A1(I) - dummy array for maximum and minimum calculation in subroutine PRINT

AA - 2(PI/365)

ADM(I) - moisture content of grain in layer I, % wet mass basis

AFR - airflow rate through grain, $(L/s)/m^3$

AG(I) - temperature of grain in layer I, °C

AHUM - subroutine which calculates the absolute humidity or the saturation vapour pressure of the air

AK(I) - thermal conductivity, W/(m.K)

AKM(I) - mean thermal conductivity between conduction nodes used in finite difference method, W/(m.K)

AL - day angle, radians

ALAT - station latitude, radians

AMODIF(I,J)- average difference in moisture content between the top and bottom layers in the bin, at year I and time J, % wet mass basis

AMOIST(I,J)- average grain moisture content in bin, at year I and time J, % wet mass basis

AREA - grain bin floor area, m^2

ATEMP(I,J) - average grain temperature, at year I and time J, °C

AV(I) - average

AVCOLM(I) - average moisture content of column I, % wet mass basis

AVCOLT(I) - average temperature of column or I, °C

AVEM - average moisture content of grain column, % wet mass basis

AVET - average temperature of grain column, °C

AVGM - average moisture content of entire bin, % wet mass basis

AVGPER(I,J)- average allowable storage time elapsed in year I and time J, decimal fraction

AVGT - average temperature of entire bin, °C

AVMTOP - average moisture content of top two convection layer, % wet mass basis

AVTTOP - average temperature of top two convection layers, °C

AXM(I) - moisture content of grain in layer I, % wet mass basis

B - location of data value in subroutine AHUM

B(I) - regression constant array in subroutine RADN

BB - Biot number for bottom surface of the grain and floor

BT - Biot number for top grain surface

BW - Biot number for exterior wall surface

C - location of data value in subroutine AHUM

- specific heat of grain, converted to J/(kg.°C) in subroutine DSIM

C(I) - specific heat, J/(kg.°C)

CALC - subroutine which calculates average thermal properties for conduction

CHANGE - subroutine which calculates temperatures and moisture contents at new nodes when changing from convection to conduction or conduction to convection simulation

CLOUD - cloud modification factor

CM - mean internodal specific heat values, J/(kg.°C)

CO - cloud opacity, tenths

D - location of data value in subroutine AHUM

- day in subroutine RADN

DAYS - number of days at current simulation year

DECL - declination of the sun, radians

DECOMP - subroutine which calculates allowable storage time elapsed in each volume element, and dry matter decomposition for the worst element in each column

DEL - allowable error in determining X

DELR - column width, m

DELZ - conduction layer height, m

DEPTH - total grain depth in bin, m

DIAM - grain bin diameter, m

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

DRY - "dry" grain moisture content, % wet mass basis

DRYSIM - calls subroutine DSIM and operates it in columns when grain moisture contents and temperatures are significantly different

DSIM - subroutine which simulates drying process for grain column during one time interval IDELT1

DT - air temperature rise over direct-drive axial fan in subroutine FANSUB, °C

- time interval in subroutine DECOMP, h

DTCOMP - isentropic air temperature rise over fan, °C

DUST(I) - dust factor in month I

E - location of data value in subroutine AHUM

- $DELR^2/DELZ^2$

E(I) - solar time correction factor in month I (estimate)

ECPT - energy cost per tonne of grain, $/t

EFF - total fan efficiency, decimal

ELECTR - electrical energy used, MJ

ELVOL - grain element volume, m^3

EMA - emissivity of grain bin wall at 38 °C

EMS - emissivity of grain bin wall, solar

EPTONN(I,J)- electrical energy used per tonne of grain, in year I at time J, MJ/t

EQT - equivalent storage time, h

ERH - equilibrium relative humidity of the grain, %

F - location of data value in subroutine AHUM

- airflow rate per bin floor area, $(L/s)/m^2$

FAN(I,J) - fan operation time in year I and month J, h

FANCST(I,J)- fan operating cost, $

FANSUB - subroutine which calculates fan airflow and power requirements, grain depth and temperature rise accross direct-drive axial-flow fan

G - location of data value in subroutine AHUM

G(I) - temperature of grain in layer I, subroutine DSIM, °C

G(I,J) - temperature of grain in element I, J, °C

GEO - location name, alphanumeric

GRCOST - value of grain, $/t

H - equivalent to HO, subroutine RHAIR

- estimated global radiation on a horizontal surface of one square meter integrated over a period of one hour, $(kJ/(m^2.h)$

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

HC1 - convective heat transfer coefficient for bin wall, $W/(m^2.K)$

HC2 - convective heat transfer coefficient for free convection at grain surface, $W/(m^2.K)$

HEAT(I,J) - heater operating in year I and month J, h

HF - absolute humidity of the air leaving the layer of grain at the end of the time interval IDELT1

HO - absolute humidity of the air entering the layer of grain at the beginning of the time interval IDELT1, in subroutine DSIM

- absolute humidity of air in subroutine RHAIR

- incident solar radiation at the top of the atmosphere on a horizontal surface, in subroutine RADN, $kJ/(m^2.h)$

HOURS - total time since bin fill date, h

HTCST(I,J) - cost of heater operation in year I and month J

HTPWR - calculated output power of supplemental heater, kW

I - integer index

IAM - AM time for time-clock fan control, h

ICH - integer indicator for subroutine CHANGE

ICONV - indicates whether or not convection should take place during IDELTO

IDA(I) - day of the month, subroutine READ

IDA(I,J) - array containing date information

IDAPL - date after last time interval plus IDELTO or IDELT1

IDAT - date

IDATE(I) - array containing date information

IDAY - day of the month

IDELT - time interval, h

IDELTO - time interval for conduction model, h

IDELT1 - time interval for convection model, h

IFIRST - first simulation year e.g. 62

IHARVD - harvest date, YRMODAHR

IHEATR - indicates whether or not supplemental heat is used

IHOUR - hour of the day, h

IHR(I) - hour of the day, h

II - integer index

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

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

IM - number of conduction layers (NM)+1

IMI - I-1 in subroutine TOODEE

IN - number of conduction columns (NN)+1

INAIR - number of hours of intermittent ventilation, h

INAIRT - intermittent ventilation time interval; should be a multiple of IDELTO, h

INPER - maximum period without ventilation, day

ISPNG - indicates management of ventilation system after spring start date

INTERV - counter for period of time without ventilation, h

IOBJ - indicates objective of storage regarding moisture content

IOP - fan operation control method

IP - I+1 in subroutine TOODEE

IPRINT - indicates time to print, subroutine PRINT

IPRINT(I,J)- indicates time to print

IPM - PM time for time-clock fan control, h

IPRT - indicator of the search status in subroutine DSIM

IRUN - optional run number given by user

ISPDT1 - winter system stop date, YRMODAHR

ISTDT1 - fall system start date, YRMODAHR

ISTDT2 - spring system start date, YRMODAHR

ITI - indicates which initial grain temperature to be used

IY - harvest year, subroutine PRINT

IYR(I)	- year, subroutine READ
J	- integer index
JHARVD	- same as IHARVD except only MODAHR
J1	- indicator of search position
JM	- J-1
JP	- J+1
	- alternate location of J in subroutine ZERO
JSPDT1	- same as ISPDT1 except only MODAHR
JSTDT1	- same as ISTDT1 except only MODAHR
JSTDT2	- same as ISTDT2 except only MODAHR
K	- integer index
KSPOIL	- indicates whether or not first grain spoilage has occurred
KY	- year integer index
L	- integer index
LOCATE	- integer geographical location index
LMAX(I)	- layer in column I with maximum deterioration
LMX	- same as LMAX(I)
M	- integer index
	- equivalent to MM in subroutine ZERO
MAX	- subroutine which identifies the maximum value in any array
MIN	- subroutine which identifies the minimum value in any array
MM	- special indicator whcih indicates the status of search in subroutine DSIM
MM(I,J)	- array used to store maximum and minimum values
MN	- minimum year number
MO(I)	- month
MODE	- indicates convection or conduction
MONTH	- month

MP - M+1

MTOP - indicator of which moisture content value limits system operation

MULT - integer multiple of simulation time interval, (=IDELTO/IDELT1)

MX - maximum year number

MYEAR(I,J) - non-zero year integer

N - integer index

NDAY(I) - array containing days in month I

NL - number of convection layers, to be an integer multiple of NM

NM - number of conduction layers

NN - number of conduction columns

NTOP - top conduction grain layer

NSPOIL - number of columns in which spoilage has occurred

NPROP - number of grain and bin property cards, usually 3

NY(I) - non-zero year number

NYEARS - number of harvest years for simulation

NYY - same as NY(I)

OAM - optical air mass

ODCOST - overdrying cost, $

ODCPT(I,J) - overdrying cost per tonne in year I at time J, $/t

ONEYR - indicates whether simulation is to continue for year regardless of grain deterioration

OPCOST(I,J)- operating costs to date including overdrying, spoilage and energy in year I at time J, $

P(I) - proportion of allowable storage time already elapsed in layer I, decimal fraction

PBAR - station barometric pressure, kPa

PCTM(I) - maximum allowable proportion of storage time already elapsed in column I, decimal fraction

PER(I,J) - proportion of allowable storage time already elasped in layer I and column J, decimal fraction

PERDM(I) - dry matter decomposition in the worst layer of column I, %

PERI - proportion of allowable storage time already used up on the bin fill date, decimal fraction

PERMAX - maximum allowable dry matter decomposition, %

PF - packing factor used in the airflow resistance through grain static pressure calculation

PI - 3.1459

PRINT - subroutine which contains all output information, calculates summary values and prints output

PS - saturation vapour pressure of the air, kPa

PTM - maximum allowable storage time already elapsed in column

PW - vapour pressure of the air at T, kPa

PWR - power required to drive the fan, kW

PWRCST - input electrical energy cost, cents/kW-h

QE - earth-to-bin radiation, W/m^2

QO - bin-to-surroundings radiation, W/m^2

QR - net radiation, W/m^2

QRP - net radiation on surface area of element, W/m^2

QS - sky-to-bin radiation, W/m^2

QSN - total solar radiation on the bin wall; represents average radiation for all sides of bin, W/m^2

R - dry matter to air mass ratio, kilograms of dry matter per kilogram of air

RADN - subroutine which calculates the net radiation on the grain bin wall

READ - subroutine which reads hourly tape weather data and calculates average values for time interval

RH - relative humidity of the air, %

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

RHMAX - maximum relative humidity for humidistat fan control, %

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

RO(I) - density, kg/m^3

ROM - average density, kg/m^3

S - value used to determine a new estimate for X

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

SC - solar constant, $kJ/(m^2.h)$

SD(I) - standard deviation

SMALL - smallest value in array A(I)

SP - static pressure drop through grain, kPa

SPCOST - cost of spoiled grain, $

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

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

SPMASS(I,J)- spoiled mass in year I at time J, t

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

ST - solar time, h

STEF - Stefan-Boltzmann constant, $W/(m^2.K^4)$

SUM(I) - array containing values of sums

SUMM - sum of moisture contents

SUMMTP - sum of moisture contents of top layers

SUMSQ(I) - array containing values of sum of the squares

SUMT - sum of grain temperatures

SUMTTP - sum of grain temperatures of top layers

T - temperature of air, °C

T(I) - temperature of air entering layer I in subroutine DSIM, °C

T(I,J)	- array containing values of grain temperatures at conduction nodes, °C
TAB	- temperature of the air leaving the layer of grain at the end of the time interval, °C
TB	- temperature of the air in bin plenum, °C
TD	- average dew point temperature of the air entering the bottom layer of grain during the time interval, °C
TDB	- dry bulb air temperature, °C
TDBIN	- actual dry bulb temperature of air entering first layer of grain, °C
TDBMAX	- maximum air temperature for fan operation, °C
TDBMIN	- minimum air temperature for fan operation, °C
TDIFF	- differential temperature; i.e. air temperature minus temperature of top two grain layers, °C
TDIFFM	- differential thermostat setting; i.e. fan operation only when TDIFF is less than TDIFFM, °C
TDP	- dew point air temperature, °C
TGHARV	- value that initial grain temperature will be above average 24-h ambient temperature, °C
THARV	- initial grain temperature at harvest, °C
TI	- input initial grain temperature, °C
TO	- average temperature of the air entering the bottom layer of grain during the time interval, °C
TOODEE	- subroutine which calculates grain temperatures at conduction nodes with no ventilation
TONNE	- mass of stored grain at "dry" moisture content, t
TP(I,J)	- final grain temperatures after time interval IDELTO, °C
TPLEN	- input value of plenum air temperature above ambient, °C
TRANS	- estimate of transmittance of whole-spectrum, direct-beam solar radiation
TROOF	- input value of grain bin attic temperature above ambient, °C
TSUPPL	- input value of supplemental heat added to incoming air by heater, °C

TT	-	temperature of air in bin attic, °C
TW	-	average bin wall temperature, °C
TYPE1	-	subroutine used with ZERO to find a better estimate for X
U(I)	-	dimensionless modulus
VOL	-	total grain bin volume in subroutine FANSUB, m^3
	-	volume of spoiled grain in subroutine PRINT, m^3
VMOIST	-	allowable variation in grain moisture content between columns below which they are averaged and treated as one column, % wet mass basis
VTEMP	-	allowable variation in grain temperature between columns below which they are average and treated as one column, °C
W	-	precipitable water based on dew point temperature in subroutine RADN, mm
W1	-	mass of material in finite difference volume element, kg
W2	-	same as W1
W3	-	same as W1
WA	-	estimate of solar hour angle, radians
WIDTH(I)	-	thickness, m
WIND	-	wind speed, km/h
X	-	independent variable in subroutines ZERO and TYPE1 which is to be found such that f(X)=YD
	-	dummmy variable in subroutine PRINT
XDAYS(I,J)	-	array which stores value of DAYS for year I at time J
XL	-	alternate location for A(1)
XLAT	-	latitude of geographical location, degrees
XLONG	-	longitude of geographical location, degrees
XLONGS	-	standard longitude of geographical location, degrees
XLPS	-	fan airflow rate, L/s
XM(I)	-	grain moisture content in layer I, % wet mass basis
XM(I,J)	-	grain moisture content in layer I and column J,

% wet mass basis

XMO(I,J) - initial moisture content in layer I and column J, % wet mass basis

XMI - initial grain moisture content in MAIN, % wet mass basis

- moisture content of the grain at the end of the time interval, % wet mass basis

XU - alternate location for A(3)

Y - function of X (Y=ERH-RHS)

Y4 - similar to S

YD - desired value of Y

YL - alternate location for A(2)

YU - alternate location for A(4)

Z - zenith angle in subroutine RADN, radians

- 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 D

PERFORMANCE OF SEVERAL AXIAL-FLOW FANS FOR GRAIN BIN VENTILATION

CSAE Paper No. 80-105