EVALUATION OF STORED-GRAIN ECOSYSTEMS VENTILATED WITH NEAR-AMBIENT AIR

by

DONALD BROCK SANDERSON

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ABSTRACT

A near-ambient, grain-drying facility was erected to monitor physical and biological changes in tough to damp stored-wheat-ecosystems during ventilation. Variables measured include: moisture content, temperature, CO_2-O_2 composition of intergranular air, seed germination, microflora, grain grade, bulk shrinkage and fat acidity. The performance of a near-ambient drying and deterioration model was evaluated using the experimental findings. The simulation model was sufficiently accurate for use as a design tool. This model can be used to develop recommended drying airflow rates for farmers to successfully dry tough to damp wheat using near-ambient grain drying.

The effects of ambient-air conditions and ventilation rates on measured and predicted temperature and moisture changes were studied. The speeds of measured and simulated drying fronts were not linearly proportional to airflow rates. A doubling of airflow resulted in a more than doubling of measured drying front speeds but resulted in a less than doubling of simulated drying front speeds for the simulation of the 1984-1985 drying tests. The drying front speeds appeared to be unaffected by periods of high humidity suggesting that ventilation during periods of high humidity continues to force the drying front through the bin.

In the non-ventilated bins the presence of elevated CO_2 concentrations was a better indicator of incipient spoilage than elevated intergranular air temperatures.

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Finally, thanks mom. This one's for you.

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NOMENCLATURE

A	airflow, L/s
a	constant, dependant on particle shape
B	dry matter loss + 10, %
C	f(heat added to air and grain), dimensionless
Ca	specific heat of air, J/(kg•°C)
Cg	specific heat of grain, J/(kg•°C)
Cw	specific heat of water, J/(kg•°C)
D	diffusion coefficient, m^2/h
d	dimensionless depth unit
G	mass flow rate of air, $kg/(m^2 \cdot h)$
h	heat of desorption, J/kg
K	drying coefficient, h^{-1}
M	moisture content (wet basis), decimal fraction
Me	equilibrium moisture content (wet basis), decimal fraction
Mo	moisture content, (wet basis) at start of the time interval, decimal fraction
MR	dimensionless moisture content ratio
N	number of observations
Ps	saturation vapour pressure, Pa
Q	airflow per unit volume of grain, $(L/s)/m^3$
R	relative humidity of air, decimal fraction
s.d.	standard deviation

T	temperature, °C
Ta	air temperature, °C
Te	equilibrium grain temperature, °C
Tf	average grain temperature in the temperature front, °C
Tg	grain temperature, °C
TR	dimensionless temperature ratio
To	original grain temperature, °C
Twb	wet bulb temperature of air, °C
V	velocity of air, m/s
v	grain viability, %
W	absolute humidity of air, decimal fraction
Xo	f(heat added to air and grain), dimensionless
Y	depth, m
α	various constants used and given a common name, dimensionless
θ	time, h
θ'	dimensionless time unit
θv	storage time for grain viability to fall to v, days
ρd	density of dry matter in the grain, kg/m^3
ρg	bulk density of grain, kg/m^3

Chapter I

INTRODUCTION

Grain stored in bulks or bags in a granary is a man-made ecosystem of limited energy. Any physical or biological agent that lowers the energy content of this ecosystem diminishes its value as a source of human food or animal feed (Sinha 1973). An ecosystem is a dynamic unit; many changes within it often lead to grain spoilage. Changes occur unevenly and primarily depend upon: type of grain, preharvest and initial storage condition, type and quantity of microflora, arthropods, birds and rodents invading it during storage, climate and location of storage premises, type of bin and volume of grain stored in it, and length of the storage period (Sinha 1979).

A major concern in preserving stored grain is to limit the growth of postharvest microflora. The interrelationships between postharvest microflora and the major physical and monetary components of the grain is given in Fig. 1.1. Microfloral growth can be inhibited by lowering the grain moisture, temperature, or both, to levels not suited for their growth. Grain moisture may be lowered by high temperature driers or near-ambient (low temperature) driers. Grain temperature may be lowered by aeration or near-ambient driers. Due to the increasing cost of fossil fuels many farmers are turning to near-ambient drying and aeration to dry and cool the harvested grain.

Near-ambient grain drying occurs when a ventilation fan is used to force atmospheric air through a grain bulk mainly to remove moisture.

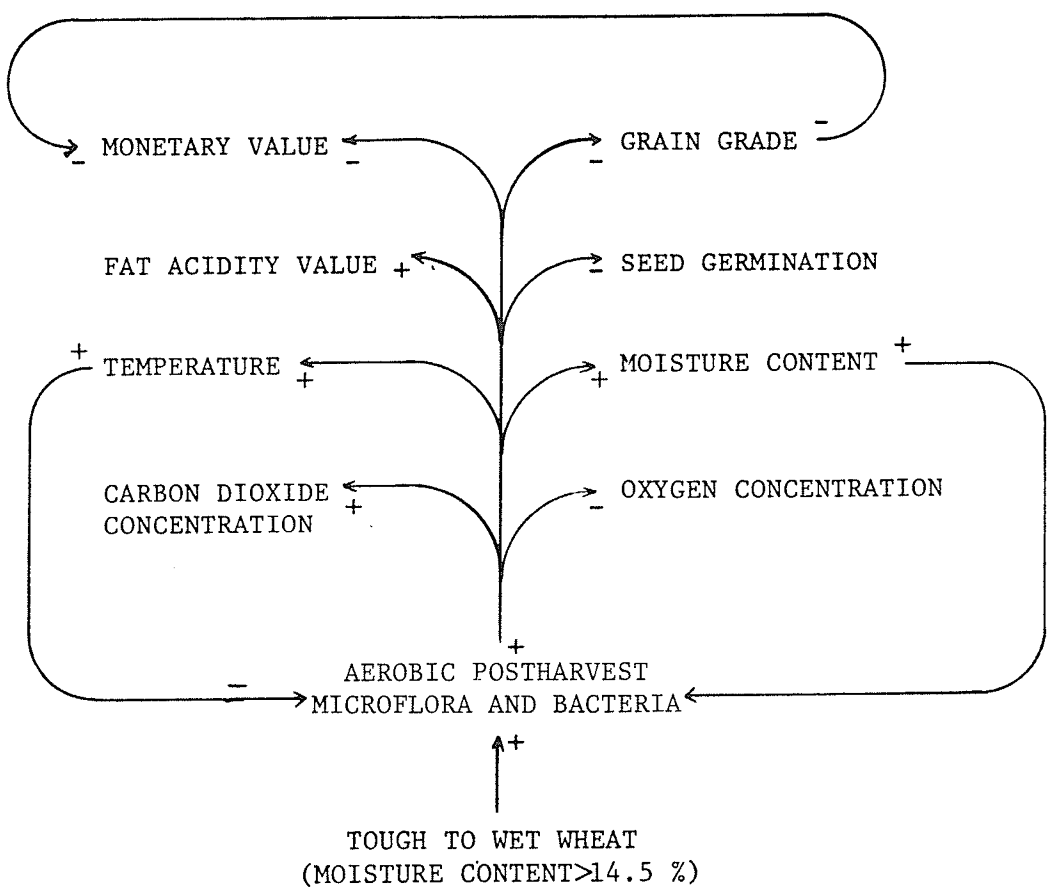


Fig. 1.1: A schema showing the interrelationships between microflora and the major physical and monetary components of grain. The "+" and "-" signs indicate relative effect of one variable on another (+ causes an increase and - causes a decrease).

This type of drying is called near-ambient because there is only a slight increase above atmospheric air temperature (1 to 5°C) as it passes through the fan and ducting. Aeration occurs when a ventilation fan is used to force atmospheric air through a grain bulk mainly to control its temperature. Airflow rates for aeration are considerably lower (1 to 2 $L \cdot s^{-1}m^{-3}$) than for drying (generally above 4 $L \cdot s^{-1}m^{-3}$).

In near-ambient drying the rate of drying is related to airflow rates and thus to fan size. The larger the fan, the higher the airflow rate and the faster the drying. Larger fans, however, also increase the capital and operating costs for drying. Fraser and Muir (1980) reported that with near-ambient drying the highest cost component is generally the drying equipment: up to 66% of the total cost of drying wheat. The remaining cost components being the electricity used and the overdrying penalty incurred while drying. Therefore, optimizing near-ambient drying involves minimizing the required airflow, and thus minimizing required fan size and costs.

The length of time available for drying depends on the grain spoilage rate. Drying must be completed before unacceptable spoilage can occur. To minimize airflow rates the length of time the grain can be dried must be maximized. Optimization of drier design by a series of drier tests would prove costly and time consuming with results obtained being grain and weather dependent. Hence, a more practical method of obtaining design airflows for near-ambient driers is needed. This is where mathematical modelling is useful.

The minimum airflows required to successfully dry grain could be determined by a mathematical model that could simulate near-ambient drying. Such a model requires the initial temperature and moisture content of the grain mass, various physical and biological properties of the grain, and a representative sample of weather conditions for the location studied (say worst year out of 30). Researchers have developed several near-ambient drying models (Bloome and Shove 1971, Thompson 1972, Bakker-Arkema et al. 1971) and deterioration models (Saul 1970, Muir and Ingram 1975, White et al. 1982a) for corn, wheat and barley. These models have had limited validation from in-field drying experiments. Most near-ambient drying models need more testing and possibly modification to improve accuracy, whereas deterioration models are still in the development stage and thus need extensive testing and modification.

Field testing, if done using farm-scale bins, would be expensive. An alternative to this is to use smaller bins to reduce the required grain mass and cost. A smaller size would allow for more airflows, grain moisture contents, and control strategies to be tested and compared under the same conditions for a smaller outlay of capital.

The objective of this thesis is to evaluate the ventilation and drying of stored-wheat ecosystems using a set of multidisciplinary criteria. Criteria used include rates of heat and mass transfer, microfloral growth, seed viability, free fatty acids and carbon dioxide production. Performance of near-ambient drying and deterioration models are evaluated using experimental findings from the test facility.

Chapter II

LITERATURE REVIEW

2.1 PHYSICAL CHANGES IN STORED-WHEAT ECOSYSTEMS

Because of the crucial role played by moisture and temperature in grain bulks as related to storability (Wallace et al. 1983, Abramson et al. 1984, Sinha and Wallace 1964) and market value (Bloome 1983) considerable interest has been shown in the monitoring of these variables.

As a grain bulk is ventilated with heated or unheated air, mass and energy transfer between the ventilation air and the grain bulk occurs. Continual monitoring of temperature and moisture within the bulk should be made to evaluate the risk of spoilage.

When monitoring ventilation of a grain mass the formation of three zones (A, B and C) is generally noted (Fig. 2.1a) (Sutherland et al. 1971). These three zones are separated by two fronts (temperature and moisture) which move through the grain bed in the direction of airflow. The condition of the ventilation air (with constant inlet properties) as it passes through these zones is shown in Fig. 2.1b. With varying inlet air properties (as is the case while ventilating with near-ambient air) the formation of multiple zones and fronts that may interact with each other is possible. The interaction of such zones and fronts complicate the visualization process shown in Fig. 2.1.

In zone A (Fig. 2.1b), the grain has reached equilibrium with the incoming air, the intergranular air and grain temperatures are equal. The

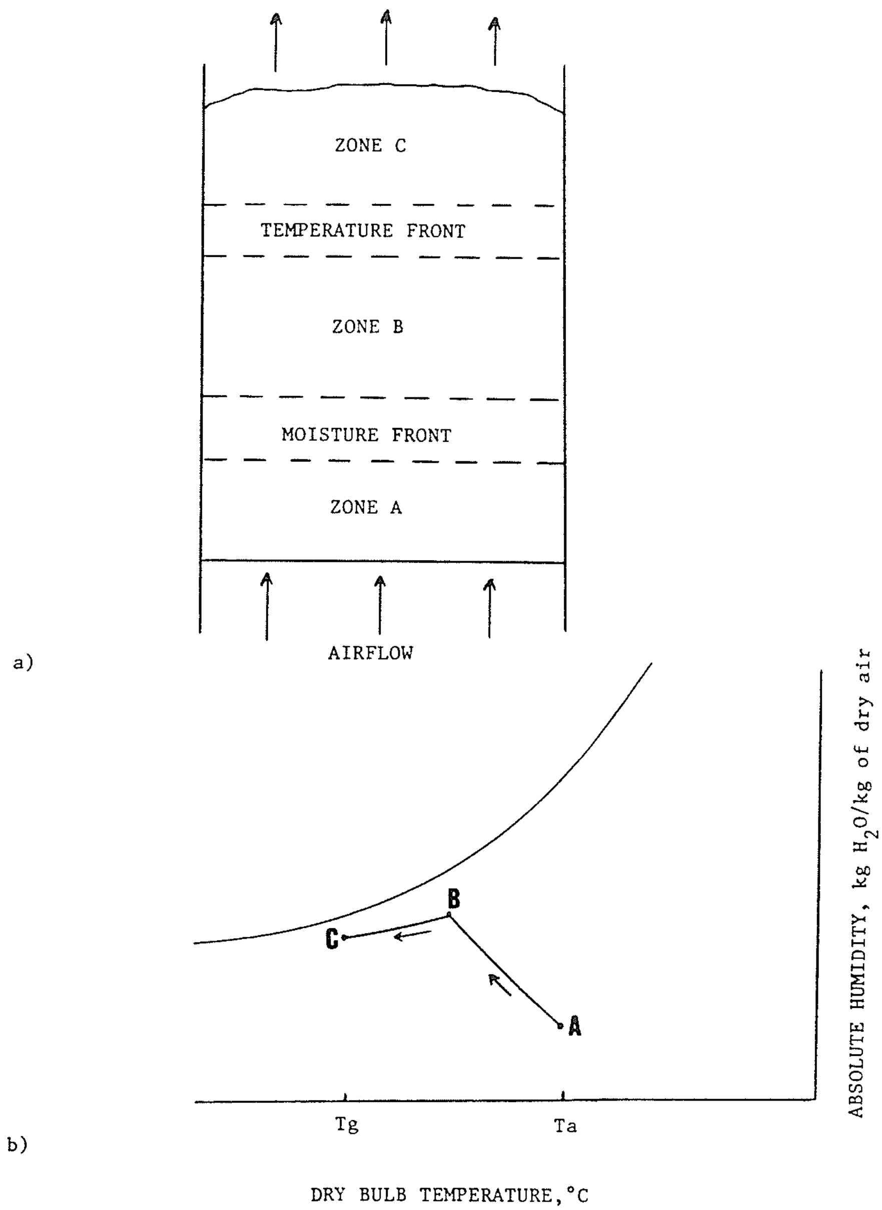


Fig. 2.1: Idealized deep bed drying process (a) formation of 3 zones and (b) skeleton psychrometric chart showing changes in the condition of the ventilation air as it passes through the grain bed (warming and drying the grain).

grain moisture content has reached equilibrium with the humidity of the incoming air.

In zone C (location C in Fig. 2.1b), the grain temperature and moisture content have not changed from their initial values, namely those prior to the step change in the conditions of the incoming air. The temperature of the intergranular air is equal to the grain temperature. The relative humidity of the air leaving the grain mass is in equilibrium with the grain in zone C.

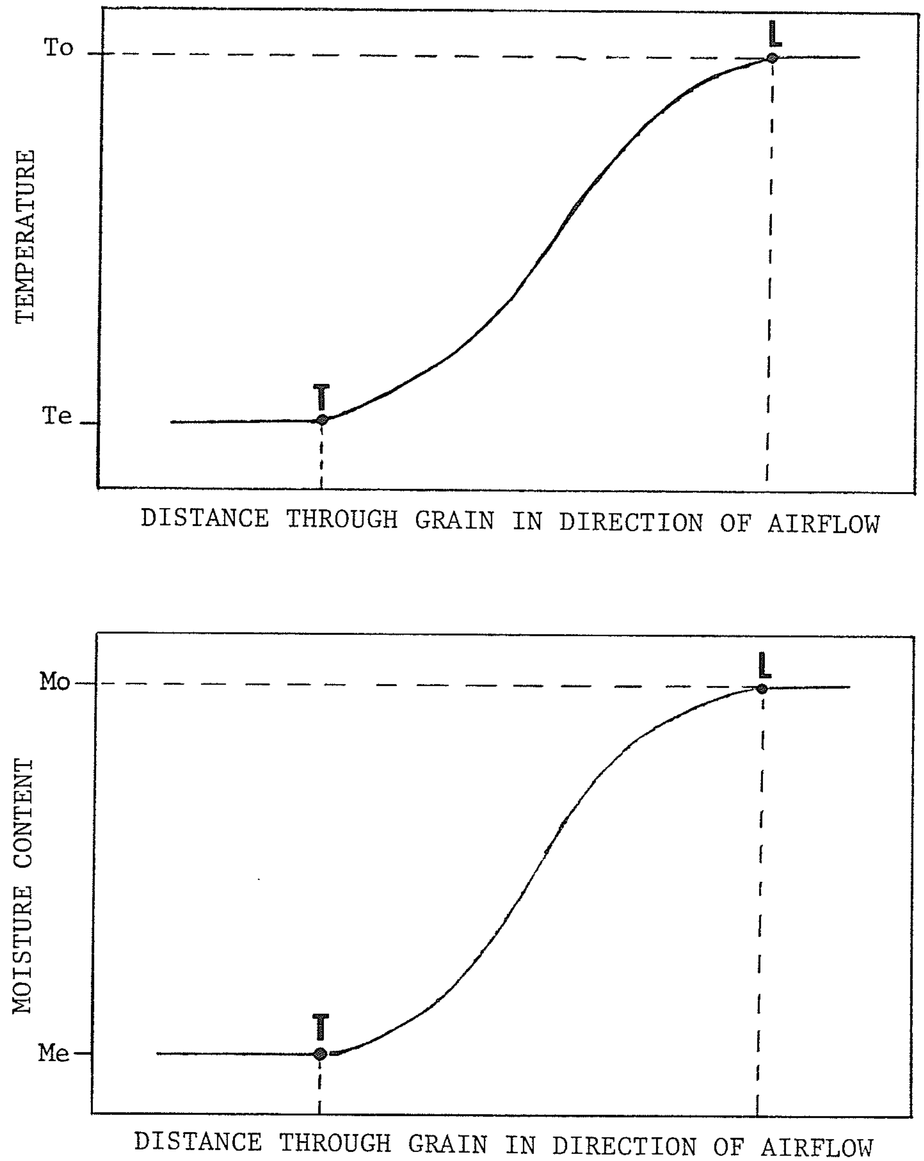
Zone B (location B in Fig. 2.1b), bounded by a temperature and a moisture front, is the transition zone. In the faster moving temperature front the major effect is a change in temperature, although an associated small change in moisture content also occurs. In the slower moving moisture front the major effect is a change in moisture, although an associated change in temperature also occurs (Sutherland et al. 1971).

When the purpose of forced ventilation is to cool the grain mass or to reduce temperature gradients within the mass, or both, (ie. aeration) the movement of the temperature front is important. Ventilation can be stopped when this front has emerged out of the top of the grain bulk even though zone B has not traversed the bulk. When forced ventilation is used to dry the grain the movement of the moisture front is most important. Here ventilation is not stopped until the moisture front has passed through the top of the grain mass. Since zone B has a lower boundary layer defined as this moisture front, it is forced out of the grain mass leaving the grain in equilibrium with the incoming ventilation air (zone A Fig. 2.1).

Shapes, widths and velocities of the temperature and moisture fronts along with the width of zone B as related to ventilation rates have been studied (Sutherland et al. 1971, Barre et al. 1971, Sharma and Muir 1974, Sutherland 1975, Ingram 1976, Ingram 1979, Rouvet et al. 1979, Bowden et al. 1983 and Sutherland et al. 1983). Before the shape and movements of these fronts and zones can be monitored they must be defined. No fixed definitions for the temperature and moisture fronts or zones have been reported in the literature. Therefore, it is difficult to relate observations of various researchers. The presence and characteristics of the three zones described by Sutherland et al. (1971) are in agreement with observations of others (Sharma and Muir 1974, Ingram 1979, Bowden et al. 1983). Such agreement, however, is not found when defining the temperature and moisture fronts.

Sutherland et al. (1971) did a detailed simulation predicting the width and velocities of the two fronts but failed to define the boundaries of the fronts used. These points were presumably chosen by visual inspection of the temperature and moisture profiles. Their work was mainly related to predicting the performance of low-airflow systems. They found that depending on the circumstances the fronts either widen (cooling with high humidity air) or remain narrow (drying with high temperature air). They tested their simulations with some experimental results and good agreement between simulated and experimental findings were noted.

Barre et al. (1971) appear to be the first ones to define temperature and drying fronts in terms of equations. They used temperature and moisture content ratios (TR and MR, respectively) defining the leading and trailing edges as when the ratios equal 0.95 and 0.05 respectively (Fig. 2.2) where:



T=trailing edge L=leading edge
Te=temperature of incoming ventilation air
To=original temperature of grain mass
Me=moisture content of grain in equilibrium with ventilation air
Mo=original grain moisture content

Fig. 2.2: Definition of temperature front (a) and drying front (b) as given by Barre et al. (1971).

$$TR = \frac{Ta - Te}{To - Te} \quad (2.1)$$

and

$$MR = \frac{M - Me}{Mo - Me} \quad (2.2)$$

(symbols are defined in the nomenclature). Barre et al. (1971) also devised a model that predicted the width of the drying front to be six dimensionless units wide. Converting this to dimensional units the width of drying front is:

$$\frac{6 \cdot h \cdot K \cdot \rho d \cdot (Mo - Me) \cdot y}{G \cdot Ca \cdot (To - Te)} \quad (2.3)$$

Sutherland (1975) incorporated Barre's method into his characteristics model to make allowance for the dispersion of a drying front as it traverses a grain bed. With this improvement to the model Sutherland simulated batch grain drier (hot-air driers) performances and found satisfactory agreement with two batch driers.

The above drying zone equation was also used by Ingram (1976,1979) in which he compared widths of drying fronts in tests with those predicted using Barre's formula. The widths of the drying fronts found in the tests agreed with calculated values if the temperature and moisture content differences used to define dimensionless depth are taken to be those between the grain in equilibrium with the drying air (zone A) and the grain which is still unaffected by the front (zone C). Barre's formula agrees with experimental results found by Ingram (1976,1979),suggesting that the width of the drying front is determined mainly by the airflow rate. The effect of temperature is only through its influence on the rate of drying (Ingram 1976,1979).

Some general observations noted by Ingram (1976,1979) with regard to shapes and speeds of drying fronts as affected by inlet air conditions are as follows:

1. Raising the inlet air temperature causes the drying front to move more quickly and the final grain condition (plateau state) is altered by the changes. There is no significant change in the width of the drying front for the temperature ranges tested. This conclusion does not agree with that of Sutherland (1975) who maintains that the formation of a narrow drying front is favoured by a high inlet air temperature.
2. The effect of doubling the airflow rate is an almost doubling of the width of the drying front. This is in agreement with Sutherland (1975).
3. Once established, the width of the drying front is constant.

In a later paper Sutherland et al. (1983) worked towards determining the effects of interaction between successive temperature and moisture fronts during ventilation of deep grain beds. The interaction of the fronts being caused by varying inlet air conditions with respect to airflow rates and temperatures. Graphs presented in the paper allow the rapid determination of temperature and moisture front speeds for various ventilation conditions. An analysis assuming equilibrium between the grain and ventilation air is used to study the interaction of such temperature and moisture fronts which can occur during the ventilation of bulk grain.

Formulas for predicting the width of a drying front other than the one by Barre et al. (1971) were not found in the literature. It appears that research on monitoring the movement and width of a drying front either uses the equations of Barre et al. (1971) (Sutherland et al. 1971, Sutherland 1975, Ingram 1976, Sutherland et al. 1983) or does it visually using moisture profiles (Bloome and Shove 1971, Sharma and Muir 1974, Rouvet et al. 1979, Bowden et al. 1983 and Schultz et al. 1984). No equations could be found to calculate the widths of temperature fronts as most work on monitoring temperature fronts was done visually using temperature profiles in the grain mass. No set definitions for the leading and trailing edges of a temperature front other than the one of Barre et al. (1971) were found in the literature.

Bowden et al. (1983) did a graphical analysis of the ability of various grain drying models to predict the movement of temperature and moisture fronts in a grain bin. They compared experimental with theoretical results and noted that the widths of experimental temperature and moisture content fronts are not maintained as they proceed upwards. This conflicts with Ingram (1979) where he states that once established the width of a drying front remains constant. Plots of experimental drying results shown by Rouvet et al. (1979) demonstrate widening drying fronts that support the work of Bowden et al. (1983).

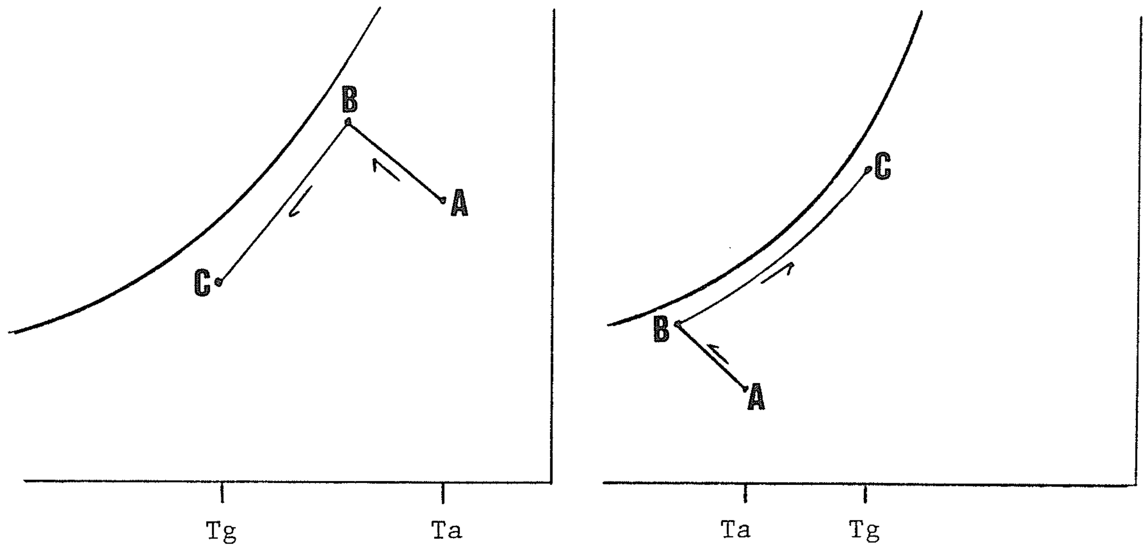
During forced ventilation there are conditions when the ventilation air causes other than heating and drying of the grain as shown in Fig. 2.1b . There are three other possibilities:

1. heating and wetting of the grain
2. cooling and drying of the grain and
3. cooling and wetting of the grain.

These three processes are shown on skeleton psychrometric charts (Fig. 2.3). There are thus four types of fronts that could arise in a ventilated grain bulk (heating, cooling, drying and wetting). All four of which must be watched for while determining the storability of the grain bulk.

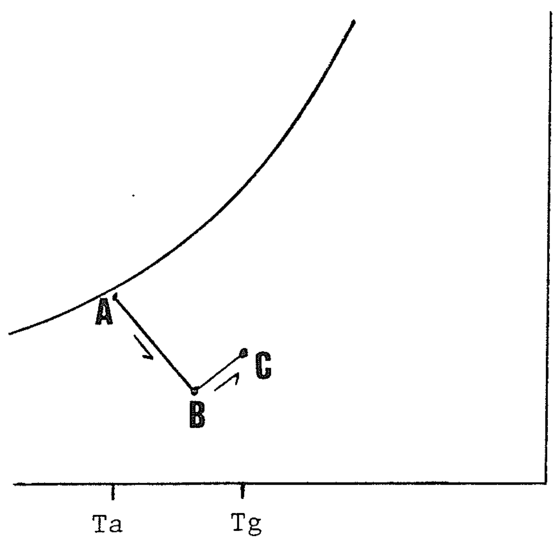
The case of wetting is one of special interest for, in theory, if a wetting front is formed in a bin and has not traversed the grain mass before ventilation is stopped the damp front could cause a storage problem. The question arises as to whether this wetting front remains narrow as it travels through the grain bulk or disperses before it emerges out the top of the bulk. Sutherland et al. (1983) state that wetting fronts may widen and disperse before exiting the grain bed. A possible reason is that, with wetting, moisture transfer to the grain is restricted by moisture adsorption and hysteresis of water movement within the seed. Both of these phenomena hinder wetting and subsequently widen the wetting front. Also, since moisture gradients during wetting are generally small (2 to 3%) dispersal of a front would not require too much widening of the front (far less than to disperse a 4 to 5% drying front). A number of simulated and experimental wetting fronts supporting this are presented in Sutherland et al. (1983).

Shrinkage of grain kernels caused by moisture loss is another important change that occurs in a ventilated grain bulk. This reduces bed depth and total volume of the grain bulk. Smith (1984) reports a 13% reduction in bed depth during low temperature drying tests bringing barley from 26 to 16% moisture content. Similar results suggesting the importance of shrinkage with other grains were reported by Mittal and Otten (1982), Colliver et al. (1983), Bowden et al. (1983).



a) Cooling and drying of the air (warming and wetting of grain)

b) Warming and wetting of the air (cooling and drying of grain)



c) Warming and drying of the air (cooling and wetting of grain)

Ta=air temperature Tg=grain temperature

Fig. 2.3: Skeleton psychrometric charts of air conditions in bulk grain during forced ventilation under three conditions.

The decrease in grain depth caused by moisture loss increases airflow rates in a near-ambient grain drier (Colliver et al. 1983, Mittal and Otten 1980). This increase in airflow is caused by two factors:

1. A decrease in bed depth results in a decrease in total resistance to airflow resulting in increased airflow rates (Anonymous 1984).
2. The decrease in bulk volume increases the airflow rate per unit volume of grain ($L \cdot s^{-1} m^{-3}$).

Models predicting shrinkage have been developed for barley (Bowden et al. 1983 and Smith 1984) and corn (Mittal and Otten 1982). These models relate changes in bulk volume and density to changes in moisture content. From these changes the decrease in bed depth can be predicted. These models appear to have had some testing but to be used confidently more testing should be done.

2.2 MODELLING OF THE PHYSICAL DRYING PROCESS

2.2.1 Overview

A successful near-ambient drying model for grain should be capable of predicting conditions of temperature and moisture content throughout a grain mass. This should be done with sufficient accuracy such that when the model predicts that grain is at a safe storage condition (with respect to temperature and moisture content), it is in fact so. The model must also not be too conservative such that design airflows obtained from the model are far in excess of what is needed to dry the grain. It is difficult to accurately predict all factors involved in the drying process, but with sufficient testing and modification, models should approach the actual process.

The grain drying process has been studied by researchers since 1947 (Hukill 1947). Over this period four different approaches have been taken to simulate the drying process. These four methods are:

1. logarithmic
2. thin layer
3. partial differential equations and
4. near-equilibrium.

2.2.2 Logarithmic models

Hukill (1947) pioneered the development of a model to simulate grain drying. Hukill's model assumed that grain drying took place layer by layer until the entire depth of grain was dried. A logarithmic model was derived using basic heat and mass transfer laws with several simplifying assumptions. Some of these assumptions were:

1. The sensible heat to raise the temperature of the grain and to remove moisture from the grain is negligible when compared with the latent heat of vaporization of the water removed.
2. The increase in the sensible heat of the air due to the increase in moisture content of the air is negligible.
3. Grain density is assumed constant.

With the above assumptions and some experimental thin layer drying data Hukill developed the basic logarithmic equation for grain drying:

$$MR = \frac{M - Me}{Mo - Me} = \frac{2^d}{2^d + 2^{\theta' - 1}} \qquad (2.4)$$

Where the dimensionless time and depth units (d and θ' respectively) are given by:

$$\theta' = K \cdot \theta \qquad d = \frac{K \cdot Cw \cdot \rho g \cdot (Mo - Me)}{G \cdot Ca \cdot (Ta - Twb)} \qquad (2.5)$$

This early model was modified and applied to batch and cross-flow deep-bed drying by Barre et al. (1971). The model was improved by the incorporation of an equation for the drying constant K that takes into account some variations in inlet air conditions:

$$K = \alpha \cdot Ps^{\alpha} \cdot V^{\alpha} \qquad (2.6)$$

This modification helped to increase the accuracy of the model slightly but not to the extent that it could predict grain conditions as well as those in other models. The equation for drying constant K was further modified by Sabbah et al. (1979) to allow for better predictions using time-varying inlet air conditions but the authors found the model inadequate. It did not sufficiently predict moisture profiles, and in particular any wetting that occurred during low-temperature drying. They did show, however, that the logarithmic drying model could be used to predict the average moisture content of a deep bed of grain dried with near-ambient or solar-heated air.

Young and Dickens (1975) also modified Hukill's early model. They used it to evaluate drying costs and to determine the effects that various drying parameters have on these costs. Young and Dickens noted similar drawbacks of the model as mentioned earlier. They concluded that the logarithmic model, in general, is a simple method of determining the relative effects of changing input parameters on the drying times and thus the drying costs.

It appears that the model is not accurate and is not suitable as a design tool for the optimization of airflow in low-temperature grain drying. The model does, however, have its application in comparative analysis of different drying conditions. The major advantage of the model is its simplicity such that drying times can be predicted using only a pocket calculator.

2.2.3 Thin layer models

The definition of thin layer drying used by most researchers is the process of drying a layer of grain one kernel deep. The theory of thin layer drying was developed to model temperature and moisture contents in high temperature grain driers (Thompson et al. 1968). The division of a bed into thin layers did not result in too many layers for a computer program to economically handle as drying times were short (less than 24 h) and beds were shallow (less than 1 m). Layer depth becomes a consideration when the grain bed is deep and drying times are long as is the case with near-ambient drying of grain.

The theory behind thin layer drying models is discussed with reference to Fig. 2.4. If a layer of grain is sufficiently thin, the properties of the grain can be regarded as constant within the layer (Fig. 2.4). Also if the time interval and layer thickness are sufficiently small the properties of the air may be regarded constant (over the time interval). That is, the condition of the inlet air is not affected by changing ambient air conditions until the end of the time interval. After which there can be a step change in its properties. The same consideration is made for the exiting air that has passed through the layer of grain (Fig. 2.4). Grain properties are also assumed to remain con-

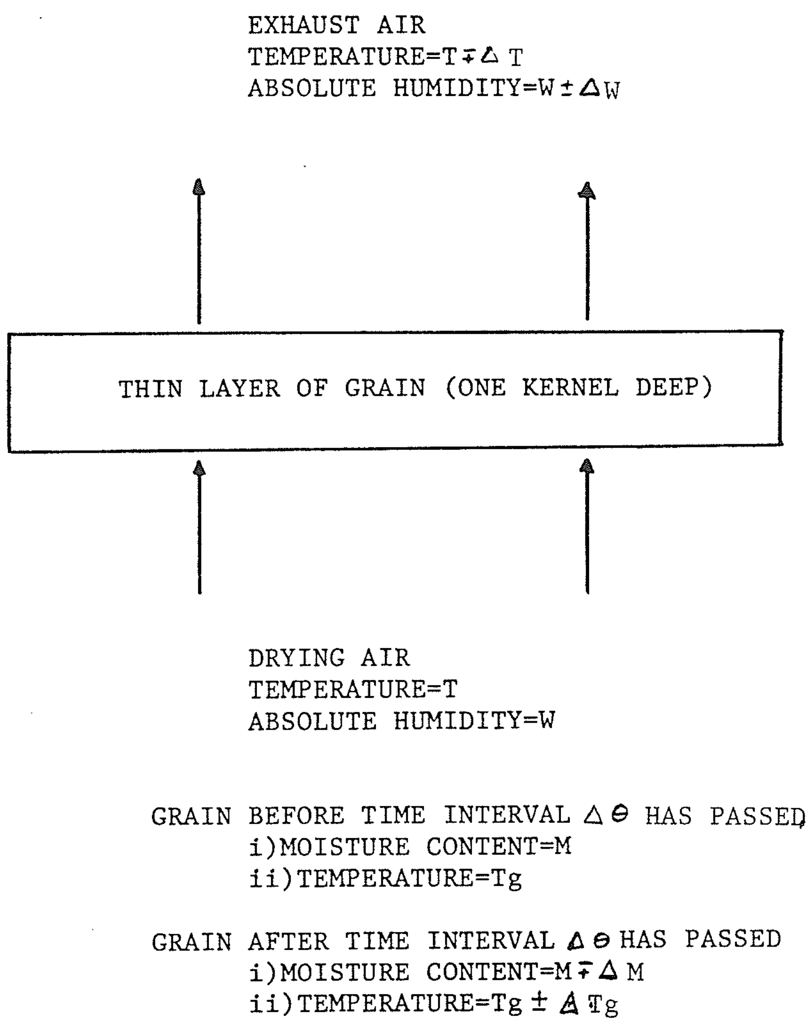


Fig. 2.4: A schema of the basic simulation approach for thin layer drying.

stant over a time increment with changes caused by the drying air not affecting grain properties until the end of the time interval. At the end of the time interval the temperature and moisture changes within the layer, caused by changes in enthalpy and absolute humidity of the air as it passed through the layer over the time interval, are calculated and step changes in the grain properties are implemented.

The changes that must be modelled are changes in the absolute humidity and temperature of the drying air as well as in moisture content and temperature of the grain. These four changes can be described by four equations:

1. a drying rate equation
2. a mass balance equation
3. a rate of heat transfer equation and
4. a heat balance equation.

Due to the complexity of the four equations when solved analytically, researchers (Thompson et al. 1968, Flood et al. 1972, and Misra and Brooker 1980) developed equations in a semi-empirical manner to describe the entire drying process.

Experiments were performed to help develop a diffusion equation which combines equations (1) and (2) above into a simplified equation of the form:

$$\frac{\partial M}{\partial \theta} = \frac{1}{D} \cdot \frac{\partial M}{\partial Y} \qquad \text{(Henderson and Pabis 1961)} \qquad (2.7)$$

The general solution of which takes the form

$$MR = \frac{M - Me}{Mo - Me} = a \cdot e^{-K\theta} \qquad (2.8)$$

where a (constant for a given grain) and K (function of grain temperature and moisture content) are determined experimentally. Due to the hysteresis of moisture absorption and desorption a seperate equation must be used for grain rewetting. One reported by Flood et al. (1972) is

$$MR = \exp[\alpha \cdot (Ps)^{\alpha R} \cdot (R)^3\ Tg] \quad (2.9)$$

and was developed much the same way as the one given for drying.

Similar techniques were used to develop an equation that would simplify the heat transfer and heat balance equations.

Most of the constants in the above equations were developed using constant inlet air conditions at various levels. Using these data some researchers (Flood et al. 1972 and Thompson 1972) have expressed them as functions of inlet air conditions. This modification would theoretically enable the models to accommodate varying inlet air conditions. These researchers noted that incorporation of many psychrometric variables into the models drastically increases the computer times needed to solve the equations. This becomes a problem with thin layer models due to the small time and depth increments needed to satisfy the thin layer assumptions, and the same time coping with long drying times and deep grain beds of near-ambient drying of grain. A trade off is generally made between computer economy and adaptability of the model to varying inlet air conditions. The values of those constants that depend on the inlet air conditions are often averaged so that they can be applied over a wide range of input conditions giving computer economy at the expense of model accuracy.

The major drawback of the thin layer model is its excessive computer demands. Digital computers, however, are increasing in speed and computing times for thin layer models may soon become reasonable enough for them to be used as design tools for near-ambient drying. Thin layer modelling is, by design, more applicable to heated air driers that have relatively constant inlet air conditions, short drying periods and shallow grain depths than to near-ambient driers.

2.2.4 Partial differential equation models

Partial differential equation (P.D.E.) models are generally based on single kernel depth drying similar to the thin layer models. The two types of models are also similar in the way the layers are summed up to create a deep bed of grain. The two models differ in the level of complexity of the equations used to describe the drying process. With thin layer models most researchers (Thompson et al. 1968, Flood et al. 1972, Misra and Brooker 1980) use simplified equations describing heat and mass transfer in the layer, while in the full P.D.E. models four partial differential equations are used to model heat and mass transfer. O'Callaghan et al. (1971), combined the two models by using four simplified equations for the heat and mass transfer that are a combination of thin layer and P.D.E. model equations. The combination model did not noticeably improve on the P.D.E. model's computer time. Thus it will not be discussed further but the option for combining models has been shown and such an option could aid in the developement of future models.

The P.D.E. models are a highly theoretical approach to describing deep bed drying based on the laws of simultaneous heat and mass transfer (Morey et al. 1978). These laws lead to a series of coupled partial differential equations that describe four basic processes. Equations describing the heat and mass transfer vary (Young 1969, Hamdy and Barre 1970, Ingram 1976, Fortes et al. 1981 and Sharp, 1982). The general idea behind these equations are described by Sharp (1982) as follows:

1. Moisture balance for air
   Change in mass of moisture in air across element = (mass of air flowing through) x (change in absolute humidity across element)
2. Heat balance (energy balance of air)
   Change in enthalpy of air across element = (mass of air) x (specific heat of air) x (temperature change of air) + (latent heat of evaporation of moisture in air)
3. Heat balance equation (energy balance of grain)
   Change in enthalpy of grain in element = (mass of grain in element) x (specific heat of grain) x (change in temperature of grain) - (latent heat of evaporation of moisture in the grain)
4. Drying rate equation (a suitable thin layer diffusion equation)
   Rate of moisture loss expressed as a function of the temperature of air and grain, absolute humidity of the air and equilibrium relative humidity of the grain.

Other work in this area was done at Michigan State University starting in the early sixties. A series of theoretical analyses at this institute led to the developement of a deep-bed drying theory similar to those mentioned. A number of papers have been published on this drying model and some of these are summarized in Brooker et al. (1974). These models offer a different set of equations but the theory used to develop them are similar.

All P.D.E. models, regardless of their derivation of the differential equations, require a thin layer drying rate equation to predict moisture transfer in the grain. Ingram (1976a) stated that there are three general methods used to predict this moisture transfer:

1. Early models assumed that the drying rate in a thin layer is described by the same empirical equations as those developed to fit data from thin layer drying experiments (Young 1969).
2. It was later realized that diffusion of moisture within the drying kernel limits significantly the rate of moisture transfer to the air. Hamdy and Barre (1970) and Bakker-Arkema et al. (1971) solved the diffusion equation by finite difference methods.
3. Ingram (1976a,b) used a series solution based on analytical solutions for constant surface conditions. It has the advantage that, when kernel moisture gradients are low, many of the terms become negligible and may be omitted, with a corresponding increase in computing speed.

Depending on the choice of drying rate and equilibrium relative humidity-equilibrium moisture content relationship of the grain and developed energy balance equations, seperate predictions of grain temperature and moisture content as well as air temperature and absolute humidity are possible. Computer requirements for a P.D.E. model are considerably more than for a thin layer model. This may be more than offset by a substantial increase in simulation accuracy and by the fact that grain and ventilation air conditions are not assumed to be in equilibrium throughout the simulation.

As with a thin layer model, simplifying assumptions can be made to decrease computer time. One such assumption used by Bakker-Arkema et al. (1976) is to assume equilibrium between air and grain temperature which means that the speed of the temperature front is considerably faster than the moisture front. The model takes into account the difference between actual grain moisture content and the moisture content in equilibrium with the air and was tested (Bakker-Arkema et al. 1976) with good results.

The major drawback of the P.D.E. model is the extensive amount of computer time required for simulations. Its advantages are that it can:

1. provide accurate predictions,
2. readily use dynamic conditions of inlet air, and
3. predict multiple fronts in a grain bed because the model's analytical development is more capable of handling inlet air changes as compared with thin layer models.

The P.D.E. model's usefulness at present is limited by available computer time but this is changing. Digital computers are increasing in speed and computing times for P.D.E. models may soon become reasonable enough for them to be used as a design tool.

2.2.5 Near-equilibrium models

The near-equilibrium grain drying model is a simplified form of the P.D.E. model with the following assumptions:

1. Equilibrium with respect to moisture and temperature is obtained between the air and the grain for the drying time interval in an incremental layer depth of grain.
2. Heat and mass transfer between the air and the grain are assumed to follow a constant enthalpy line.

Using these two assumptions the set of four partial differential equations used for the P.D.E. model were reduced to three broadly similar simplified equations (Bloome and Shove 1971, Sutherland et al. 1971, Ingram 1979, Bowden et al. 1983). The three equations in word form are:

1. a mass balance equation between air and grain,
2. an energy balance equation between air and grain and
3. an equilibrium grain moisture content equation relating grain moisture content to the ventilation-air properties.

To utilize these equations in a model, suitable time and depth increments must be chosen. The increments must be large enough such that the equilibrium assumption remains valid and small enough to obtain desired accuracy. Time increments used range from 1 h (Metzger and Muir 1983, Morey et al. 1979) to 24 h (Morey et al. 1979) and depth increments ranging from (bed depth)/60 (approximately 40 mm) (Smith 1984) to (bed depth)/10 (approximately 350 mm) (Metzger and Muir 1983). In general a compromise is made between the two with time and depth increments chosen by trial and error as to which increments yield the best predictions with reasonable computing times. Actual sizes of these increments vary widely from researcher to researcher. Thus it appears that the best increment for a particular model should be chosen on the basis of one's own model and not on someone else's model. These time and depth increments are considerably larger than those in the thin layer and P.D.E. models indicating possible savings in computer time.

The earliest model using near-equilibrium theory, developed by Thompson et al. (1968), was used to simulate heated-air driers with constant inlet air conditions. The model was not capable of accounting for rewetting that may occur in low-temperature grain drying. This problem of the model was solved in a later revision (Thompson 1972) in which a moisture adsorption equation was incorporated into the model. This revised model was used to predict heat and moisture transfer in a grain bulk ventilated with near-ambient air. The model overpredicted grain rewetting as no account for hysteresis associated with water movement in grain was incorporated. Others who have adopted Thompson's improved model (Morey et al. 1977, Metzger and Muir 1983) also found the moisture absorption equation to overpredict rewetting. They also noted that Thompson's model was ineffective in predicting moisture transfer at airflow rates above 9 $L \cdot s^{-1} m^{-3}$.

Bloome and Shove (1971) developed a model similar to Thompson's. Their model suffered similar pitfalls as those encountered by Thompson (1972). The model lost accuracy at the higher airflow rates and did not sufficiently predict rewetting. The problems of these two models are reviewed by Morey et al. (1978) who suggested that equilibrium conditions were not reached near the bottom of the bin. Thus thin layer drying and rewetting equations are used to account for the moisture movement in the lower portion of the bin. This method was used by Morey et al. (1979) and Mittal and Otten (1980,1982).

Thompson's model was modified considerably by Morey et al. (1979) by the addition of a thin-layer drying-rate equation for moisture prediction at the bottom of the bin and an alternate equation for the equilibrium moisture contents during rewetting. The model accounts for hysteresis of moisture movement but still overpredicts rewetting and again lost accuracy at the higher airflow rates but not to the extent that Thompson's model did. Mittal and Otten (1980) made additional improvements to the model of Morey et al. (1979). Various thin layer drying and rewetting equations as well as equilibrium desorption equations were tried using shorter time increments (8h instead of 24h). The improved model was validated by others (Otten and Johnson 1979, Otten and Brown 1980 as reported by Sharp 1982, and Mittal and Otten 1982) and was shown to predict moisture profiles with sufficient accuracy to be used as a design tool.

With modifications, using thin layer equations for the lower portion of the bin, near-equilibrium models can accurately predict grain moisture profiles (Mittal and Otten 1980,1982). The improved speed of computation over the P.D.E. models makes the models suitable for operational research. The models not using the thin layer equations (Metzger and Muir 1983) may have application if the airflow rates are low but may lose accuracy with airflow rates over 9 $L \cdot s^{-1} m^{-3}$.

2.3 BIOLOGICAL CHANGES IN STORED-WHEAT ECOSYSTEMS

2.3.1 Grain value

The ultimate goal of postharvest processing is to maintain the desired product qualities and economic value. The monetary value of harvested grain is dependent on many things, three major ones are:

1. the grade the grain recieves from the appropriate grading body (Canadian Grain Commission, 1984).
2. the grain moisture content (grain is sold on a wet mass basis in Canada with financial losses incurred if over or under the level set by the appropriate grading body (14.5 % for wheat)).
3. The grain germination if it is to be used as a seed or in an application which requires high germination (eg. malting).

The grain moisture content is a physical characteristic and is discussed elsewhere while the other two points are biological changes and are discussed below. Canada Western Hard Red Spring Wheat (CWRS) was used in my tests. Any statements about grade will relate to hard red spring wheat. Grading factors vary between grains and cultivars thus what applies to wheat may not apply to other grains. Drops in grade due the presence of fines, foriegn material, fire burnt kernels, stains or other such factors that are not directly related to the storage quality of the grain will not be discussed.

For each grain sample the major inputs to the grade designation are grain test weight (bulk density) and a visual inspection. Grain inspectors look for sprouted, heated, rotted, dark immature, mildewed or smutty kernels and smell the grain to detect any objectional odours (Canadian Grain Commission 1984) The above terminology used by the Canadian

Grain Commission is not too clear so a short section of definitions (supplied by the Canadian Grain Commission) is given in appendix A.

The presence of storage or field fungi is generally involved in all of the above factors that could possibly cause a drop in grade and subsequent value. To understand the causes of some of the problems involved with grain storage a short section on grain microflora is given.

2.3.2 Preharvest field fungi

The three major field fungi found on harvested grain in order of frequency are Alternaria, Helminthosporium and Fusarium (Christensen 1972, Wallace 1973). The levels of infection of these depend on weather conditions prior to the threshing and binning of the crop, high temperature and relative humidity being favourable for their growth (Christensen 1972, Wallace 1973). All three moulds may cause black point or smudge (see appendix A) which could cause subsequent drops in grade depending on level of the infection. Black point caused by Alternaria does not generally result in a drop in germinability, but that caused by Helminthosporium does (Christensen 1972). Hanson and Christensen (1953) (as reported by Christensen 1972) report the results of extensive tests with different varieties of wheat grown in different locations over a period of 8 years. They found Alternaria to be the most prevalent fungus on kernels with black point (and also on sound, bright kernels), followed by Helminthosporium, then Fusarium. When only Alternaria was present, percent germination of the seed was not affected but infection by either Fusarium or Helminthosporium resulted in reduced germinability of the seed. A possible reason for this is that Alternaria does not usually invade the embryo whereas Helminthosporium and Fusarium may invade and kill the developing or mature embryo (Christensen 1972). This damage to the embryo may also occur without any noticeable discolouration of the pericarps or the embryo. The seeds appear sound, but actually are diseased or even dead (Christensen 1972) thus showing possible problems of the visual grading system.

2.3.3 Postharvest storage fungi

The postharvest storage fungi are comprised chiefly of several groups of species of the genus *Aspergillus* and about an equal number of the less well defined species of *Penicillium* (Christensen 1972, Wallace 1973). The group species of *Aspergillus* that are involved with wheat are fungi of the *A. glaucus* group, *A. candidus* Link ex Fries, *A. versicolor* group, *A. ochraceus* group and *A. flavus* Link ex Fries (listed in order of increasing moisture requirement rather than in order of importance). Storage fungi characteristically develop on and within tough and damp seeds when they are stored after threshing (Sinha and Wallace 1965), there is no significant invasion by storage fungi before harvest (Christensen 1972). The high frequency of occurrence of *Penicillium* in hot spots in grain bulks examined by Wallace and Sinha (1962), as well as in an artificially produced hot spot, indicates that in Western Canada it is the most common fungus during the early stages of heating grain. Before *Penicillium* becomes prevalent, however, species of the genus *Aspergillus* (*A. restrictus* or *A. glaucus* or both) are generally involved in raising the grain temperature and moisture content to a range suitable for the growth of *Penicillium* and subsequently other species of the genus *Aspergillus* (*A. candidus*. *A. ochraceus*, *A. versicolor* and *A. flavus*).

The rate at which storage fungi will develop on any given lot of seed will depend mainly on the history and condition of the grain: the degree to which it already has been invaded by these fungi (if transferred from another storage structure), the amount of cracked and broken seeds, the amount, nature, and distribution of any debris, whether the embryos are alive or dead as well as the presence, numbers, and activties of insects and mites. All of the above factors are interrelated and interacting and therefore must be considered together. Keeping all conditions listed above constant the two variables that will determine how well different fungi thrive in the grain mass are temperature and water activity.

The minimum water activities within the grain mass that are beneficial to the growth of various storage fungi and the equilibrium moisture contents of wheat associated with these are given in Table 2.1. The specification of precise limits of moisture for the growth of a given

TABLE 2.1

Moisture requirements for mould growth on stored grains.

Approximate minimum relative humidities and associated equilibrium grain moisture contents (at optimum fungus growth temperature) for the growth of common storage fungi on wheat (Christensen 1972).

Fungus	Minimum relative humidity, %	Minimum wheat moisture content, %
Aspergillus restrictus	70	13.0 to 14.5
Aspergillus glaucus	73	14.0 to 15.0
Aspergillus candidus	80	15.0 to 15.5
Aspergillus ochraceus	80	15.0 to 15.5
Aspergillus flavus	85	18.0 to 18.5
Penicillium (depending on species	80 to 90	15.5 to 19.0

TABLE 2.2

Temperature requirements for mould growth on stored grains.

Approximate minimum, optimum and maximum temperatures for growth of common storage fungi on grains (Christensen 1972).

Fungus	Temperature for growth		
	Minimum	Optimum	Maximum
Aspergillus restrictus	5 to 10	30 to 35	40 to 45
A. glaucus	0 to 5	30 to 35	40 to 45
A. candidus	10 to 15	45 to 50	50 to 55
A. flavus	10 to 15	40 to 45	45 to 50
Penicillium	-5 to 0	20 to 25	35 to 40

fungus oversimplifies their moisture requirements. This is because the moisture content of wheat in equilibrium with a given relative humidity (which limits availability of moisture to fungus) vary to some extent with the treatment of the grain since harvest. This is especially important if the grain has been mechanically dried or moistened because of the hysteresis of water movement in grain (Christensen 1972). Approximate minimum, optimum and maximum temperatures for growth of common storage fungi (as supplied by Christensen 1972) are summarized in Table 2.2. The numbers refer to growth of the fungi on wheat with moisture contents near the optimum for each of the several species.

The major effects of storage fungi upon seeds, in the usual, but not inevitable, order of their appearance are: decrease in germinability, discolouration, production of mycotoxins, heating, development of mustiness and caking, total decay (Christensen 1972). Some fungal species are not involved in some of the above and some have more effect than others. For more detailed information on the effects of each of the fungi the reader is directed to Christensen (1972). How each of the above effects are related to grain value as determined by the grading system is difficult to quantify.

2.3.4 Detection and monitoring of grain spoilage

There has been considerable work on the detection and monitoring of deterioration of unventilated stored cereal grains and oilseeds (Wallace and Sinha 1962, Sinha and Wallace 1977, Sinha 1979, Sinha et al. 1981, Wallace et al. 1976, Abramson et al. 1984). Work on the detection and monitoring of deterioration in aerated and slowly drying grain bulks is not as plentiful. Since most of the work available uses nonventilated grain bulks it will be included in the review.

The measurement of temperature in bulk grain is one of the most commonly used methods to detect deterioration. Rapid growth of storage fungi in grain can cause significant heating (Sinha and Wallace 1965, Christensen 1972). But due to the low thermal diffusivity of bulk grain a temperature sensor would have to be within 0.50 m of the affected grain to detect a hot spot (Muir and Sinha 1983). Muir and Sinha (1983) found temperature to be only a fair indicator of deterioration or insect infestation after studying 12 storage units (175 to 3300 t) located near Minneapolis, Minnesota containing corn harvested in fall of 1981. Other variables measured in this study were germination, electrical resistance and carbon dioxide production. Of all the variables, carbon dioxide production was found to be the best indicator of deterioration caused by insects, fungi or both. Carbon dioxide concentrations were also found useful as a spoilage indicator by others (Sinha and Wallace 1977, Muir et al. 1980, Sinha et al. 1981, Abramson et al. 1984).

The advantage of using elevated carbon dioxide concentrations as an indicator of incipient spoilage is that high carbon dioxide levels can be detected a considerable distance from the point of spoilage (Muir et al. 1980). A potential problem of using it as an indicator of spoilage in a ventilated grain bulk would be dilution caused by the incoming air. Rates of carbon dioxide production in a slowly deteriorating grain bulk are not large enough to prevent dilution to levels near atmospheric by the incoming air. A possible solution to this is to incorporate brief periods of no ventilation to allow for the possible increase in carbon dioxide concentration but this method has not been discussed in the literature. Other variables such as germination and microfloral growth have been commonly used to monitor quality changes in a ventilated grain bulk.

Sinha and Wallace (1977) monitored moisture content, temperature, germination, fat acidity, presence of insects and mites, and microflora in non-ventilated bulks of farm stored rapeseed and barley. They found increases in fat acidity values to be a reliable index of quality of stored cereals. Sinha et al. (1981) monitored the same variables for the quality assesment of stored rapeseed in ventilated and non-ventilated grain bins. This work also suggested the usefulness of fat acidity values as a measure of grain quality.

In a slowly drying grain bulk the use of the above variables for monitoring deterioration is not found in the literature. Researchers have traditionly been using temperature, germination and microfloral growth as indicators of quality loss with most of the emphasis on the monitoring of germination (Thompson et al. 1971, Bartsch et al. 1976, Gustafson et al. 1978, Bowden et al. 1983, Metzger and Muir 1983, Smith 1984a). A problem with using germination as a spoilage indicator of freshly harvested grain is dormancy of the seeds. Dormancy is a condition in a viable seed which prevents it from germinating when supplied with the factors normally considered adequate for germination (Christensen 1972) and is common in freshly harvested wheat. Thus, if it is to be used as an indicator of quality, dormancy may have to be broken using laboratory techniques before accurate germination values can be determined (Mac Kay 1972).

Along with germination various researchers have used the appearance of visible mould (to the unaided eye) on the grain kernels as an indicator of quality changes (Thompson et al. 1971). This crude technique is an attempt to quantify mould growth without using a microscope. It is also similar to the Grain Commission's method of grading except that the grain grader is experienced at visual grading while a researcher or farmer may not be and may miss early signs of spoilage such as kernel discolouration. Because of the variability of moulds (types and their effects on the seed as well as their visibility to the unaided, inexperienced eye) and germination (dormancy, spoilage may occur before drops in germination are detected) the above techniques for quality monitoring does not give reproducible results and therefore could be deemed inadequate. A possible solution is the incorporation of several quality indicators such as fat acidity values, carbon dioxide production and microfloral activity as determined through microscopic examination.

2.3.5 Biological deterioration models

A good biological model is an important tool that should be used in all near-ambient grain drying simulations. The critical factor with near-ambient grain drying is the maintaining of grain quality (Pierce and Thompson 1980). It therefore seems reasonable that to model the drying process, possible changes in quality of the grain must also be modelled.

Spoilage of grain during storage seldom results from the action of a single variable (Sinha 1977). Therefore, when attempting to model biological changes in a grain storage structure (or any other ecosystem) one must be aware of, and contend with, the following facts (Sinha 1977):

1. No tool is available to measure and interrelate all changes and interactions among all variables within an ecosystem.
2. Conceptually, man, unlike a digital computer, is incapable of considering and intergrating more than two or three variables at a time.
3. Biological variables are rarely error free.
4. Most episodes in a community or ecosystem are results of action or interaction of not one or two variables, but several variables usually associated with different disciplines.
5. Most available mathematical models, in general, are inadequate for ecosystem analysis. When used with biological data, they are not effective tools to bring out the full story of even relatively simple ecosystems.
6. Ideally, a model should have in equal proportions precision, generality, and realism. But all three are seldom achieved with our present tools and insight.

This last point summarizes what is required of a successful model for simulating biological quality changes. Whether or not a biological deterioration model can be developed to satisfy this statement remains to be seen.

Quality losses in a grain mass are caused by several agents such as rodents, insects, mites and mould. Some of these are partly or totally controlled by the type and condition of the store. Damage caused by rodents, mites and insects fall into this category and are of little concern to drying operations and are not generally included in a deterioration model for grain drying. Losses caused by mould and possibly insects and mites, however, are of importance to drying operations. Prediction of losses caused by these agents is therefore desirable in a deterioration model.

Present grain deterioration models appear to be statistical correlations among a few conventionaly measured variables in an attempt to predict the presence and subsequent damage caused by moulds. There appears to be no attempt to actually simulate the growth and reproduction of the mould and relate this to quality losses of the grain.

Most grain deterioration models available in the literature seem to fit into two general categories:

1. models relating carbon dioxide production to dry matter decomposition and
2. models that predict maximum storage times for grain before either germination or dry matter loss falls by some amount.

Models relating carbon dioxide production to dry matter decomposition are based on the general respiration formula:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + ENERGY \qquad (2.10)$$

From this equation if one assumes aerobic respiration with complete oxidation of carbohydrates to carbon dioxide and water one can relate a 1% loss in dry matter to the evolution of 14.7 g of carbon dioxide per kilogram of dry matter. However, any interpretation from Eq. 2.10 requires recognition that it is not an exact representation of the deterioration process. The approximate validity of the equation is supported by Saul and Lind (1958) and White et al. (1982).

Saul and Lind (1958) conducted laboratory experiments to determine the longest period of time allowable for safe drying of shelled corn with low-temperature air. Later, Steele et al. (1969) used the work of Saul and Lind (1958) to use carbon dioxide production as an index of deterioration in shelled corn stored under various conditions. From this a series of equations were presented for calculating allowable storage times during storage or slow drying. Saul (1970) reported additional tests relating carbon dioxide production to dry matter loss and showed the deterioration rate of moist shelled corn at low temperatures to be approximately one-half of that reported earlier by Saul and Lind (1958).

White et al. (1982) did extensive laboratory work relating carbon dioxide production to biological activity associated with the spoilage of stored-wheat. Analysis of the data collected (at constant conditions of temperature and moisture) resulted in a regression equation relating the rate of carbon dioxide production to temperature, moisture content and days in storage. Carbon dioxide production was also related to increases in fat acidity values, microfloral growth and decreases in seed germination with a number of regression equations. Carbon dioxide production was noted to exceed the rates of oxygen consumption when quantities of seed were monitored for gaseous composition over time in sealed flasks. The respiratory quotients calculated for the various moisture-temperature treatments were found to lie between one and two. With few exceptions, increasing temperatures were accompanied by higher respiratory quotients at each moisture content. This phenomenon is explained by Foster (1949) (as reported by White et al. 1982) as follows: "When carbon dioxide production is greater than expected, it is possible that carbohydrates are being transformed into fats and the oxygen released is directly used in respiration thereby decreasing the amount taken from the atmosphere. Nonetheless, when the respiratory quotient is greater than 1.0, it is probable that some anaerobic fermentation is occurring and increasing the carbon dioxide output. It is possible that anaerobic microenvironments are present even within a mass of partially-aerated stored grain as numerous species of the genera Aspergillus and Penicillium are capable of fermentation, resulting in respiratory quotients greater than 1.0".

In other words, chemical reactions resulting in the complete combustion of 1.0 kg of dry carbohydrates liberates 1470 g of carbon dioxide, whereas anaerobic fermentation results in the liberation of 493 g of carbon dioxide. Since carbohydrates are the predominant component of cereals, calculations are based on the assumption that metabolism of lipids and proteins does not play a large role and that anaerobic fermentation in negligible. If fermentation occurs, an underestimate in the calculation of mass loss is unavoidable (White et al. 1982). This could alter the allowable safe storage time calculations depending on how mass loss by anaerobic activity affects grain quality. White et al. lists some allowable safe storage times for wheat.

Thompson et al. (1971) used equations for calculating safe storage times incorporating moisture, temperature, and mechanical damage multipliers as given by Steele et al. (1969) to simulate the performance of chilled high-moisture grain storage systems. No mention of using the improved storage data (Saul 1970) was made so it is assumed that the work was done using the old and possibly incorrect deterioration data. Thompson realized that conditions in any storage system are continuously changing and attempted to compensate for this. The accumulated dry matter decomposition at any time since the start of the storage period was represented by the expression

$$\text{percent dry matter loss} = \frac{\Delta\theta \cdot 0.5\ \%}{N \cdot (24\ \text{h/day})} \qquad (2.11)$$

where $\Delta\Theta$ was the time interval per simulation in hours and N was the safe storage period (days) from the work of Steele et al. (1969).

Bloome and Shove (1971) also used the possibly inaccurate equations of Steele et al. (1969) to simulate low-temperature corn drying. They were aware of the modifications in allowable storage times found by Saul (1970) but did not use them as their simulation was carried out prior to publication of these corrections. Deterioration rates are, therefore, greater than would result if Saul's corrections were included. Bloome and Shove developed probability curves for corn and used them to predict the probability of spoilage with given input conditions of airflow, harvest moisture, harvest date and amount of heat added by fan and heaters. The probability curves were of the form:

$$\text{probability} = \frac{1}{C \cdot (A - Xo)^B + 1} \qquad (2.12)$$

The corrected storage life equations for corn (Saul 1970) were eventually incorporated into a deterioration model by Thompson (1972) where he used them to simulate temporary storage of high-moisture shelled corn using continuous aeration. Models similar to the one used by Thompson (1972) were also used by Morey et al. (1979a,b), Van Ee and Kline (1979) and Brooker and Duggal (1982).

A different approach to deterioration modeling was taken by others (Fraser 1979, Bailey and Smith 1982 as reported by Bowden et al. 1983, Sharp 1984) who related allowable safe storage times to the appearance of visible mould. Kreyger (1972) presented safe storage periods of several cereal grains for a range of constant storage conditions. There is little or no indication of how, or where, Kreyger's data was collected for the determination of the safe storage periods of seeds. The applicability of Kreyger's safe storage periods is therefore questionable but still used nonetheless. Multiple regression analyses of these data were done by others (Fraser 1979, Bailey and Smith 1982 as reported by Bowden et al. 1983, Sharp 1984) to relate storage time and either drops in germination or dry matter losses. For example Fraser (1979) and Fraser and Muir (1981) used the following regression equation developed for the allowable storage time of wheat having a moisture content of 12 to 19%

$$\log\theta = 6.234 - 0.2118M - 0.0527Tg \qquad (2.13)$$

Bowden et al. (1983) developed a more complex storage life equation using Kreyger's data and used this in their simulation.

Roberts (1972) presented an extensive review of research into the viability of seeds as affected by storage conditions. Using this, the following equation was developed (Ellis and Roberts 1980 as reported by Sharp 1982) to model the effect of time, temperature and moisture content on the storage life of seeds:

$$\theta_v = (\alpha - v) \cdot 10[\exp(\alpha - \alpha \log M - \alpha Tg - \alpha Tg^2)] \qquad (2.14)$$

where Θv is the safe storage time in days for the viability to fall by 5 %.

These equations are based on static conditions of temperature and moisture and to apply them to a drying process some alterations are required. Flood et al. (1972), Muir and Ingram (1975), Fraser and Muir (1981) all allowed for the fluctuating grain conditions by accounting for the fraction of the actual storage time under a set of conditions divided by the expected storage life for those conditions (a storability index). A running total of these fractions is kept with spoilage defined to have occurred when the summation equals unity.

Both types of deterioration models (cummulative carbon dioxide production and time before appearance of mould) were combined by Sharp (1984) to model spoilage in a low-temperature grain drying study. Sharp used the model based on Kreyger's work for spoilage prediction when the ventilation fans were on and used the cummulative carbon dioxide production type of model to predict heats of respiration when the fans were off. This heat of respiration was then used to calculate temperature rises in the bulk such that more accurate spoilage predictions could be obtained using the Kreyger type of model. How much (if at all) this improved the prediction is uncertain as no validation experiments were performed to test the improved model.

A potential problem of the models mentioned and others like them is that the assessment of deterioration is based on the results of tests done on the grain at constant storage conditions. How this relationship is modified by the fluctuating conditions in a ventilated bin is not certain.

2.3.6 Model interaction

Researchers are realizing the importance of the interaction between the biological and physical processes occurring in low-temperature grain drying. The two processes must be integrated into a single model to obtain a satisfactory picture of the overall drying process. The physical drying model is used to supply input information of grain temperature and moisture content to the deterioration model (Flood et al. 1972, Thompson 1972, Muir and Ingram 1975, Fraser and Muir 1982, Metzger and Muir 1983). The deterioration model in return supplies to the drying model with the level of decay of the grain mass. If this level of decay reaches a certain level the entire simulation is stopped and it is reported that the simulated airflow is insufficient to safely dry the grain. It is therefore apparent that the two models are not independent but should act together to develop a complete picture of the changes occurring in a slowly drying grain bulk.

Chapter III

1983-1984 MATERIALS AND METHODS

3.1 TEST BINS

The nine storage bins were wax-coated cardboard cylinders 3.66 m tall (Fig. 3.1). Eight cylinders had 0.61-m diameters and one had a 1.22-m diameter. The 1.22-m diameter and six of the 0.61-m diameter bins were equipped with fully perforated floors and set on plenum chambers which were supplied with outside air by a centrifugal fan (see appendix B). The remaining two bins were also set on plenum chambers but their bin floors were sealed with plastic sheets to eliminate air entrance from the plenum chambers. These two bins represented the no ventilation conditions and were used as biological controls for the experiment. The bins were all located in an unheated metal shed and individual bins were placed at least 1 m away from any obstruction to facilate sampling.

The metal shed, in which the bins were located, had an unheated portion 14-m wide, 21-m long and 4.6-m high. The shed was equipped with three large doors and a number of ceiling vents which provided adequate ventilation. Temperatures within the shed, for the two test years, were on average 1 to 2°C warmer (range of 17°C warmer to 9°C colder) than ambient. Temperatures being higher or lower in the shed depending on the time of day and the amount of solar radiation present.

To reduce radial heat transfer the bins were insulated with 130-mm thick fiberglass except for the top 2.33 m of the 1.22-m diameter bin

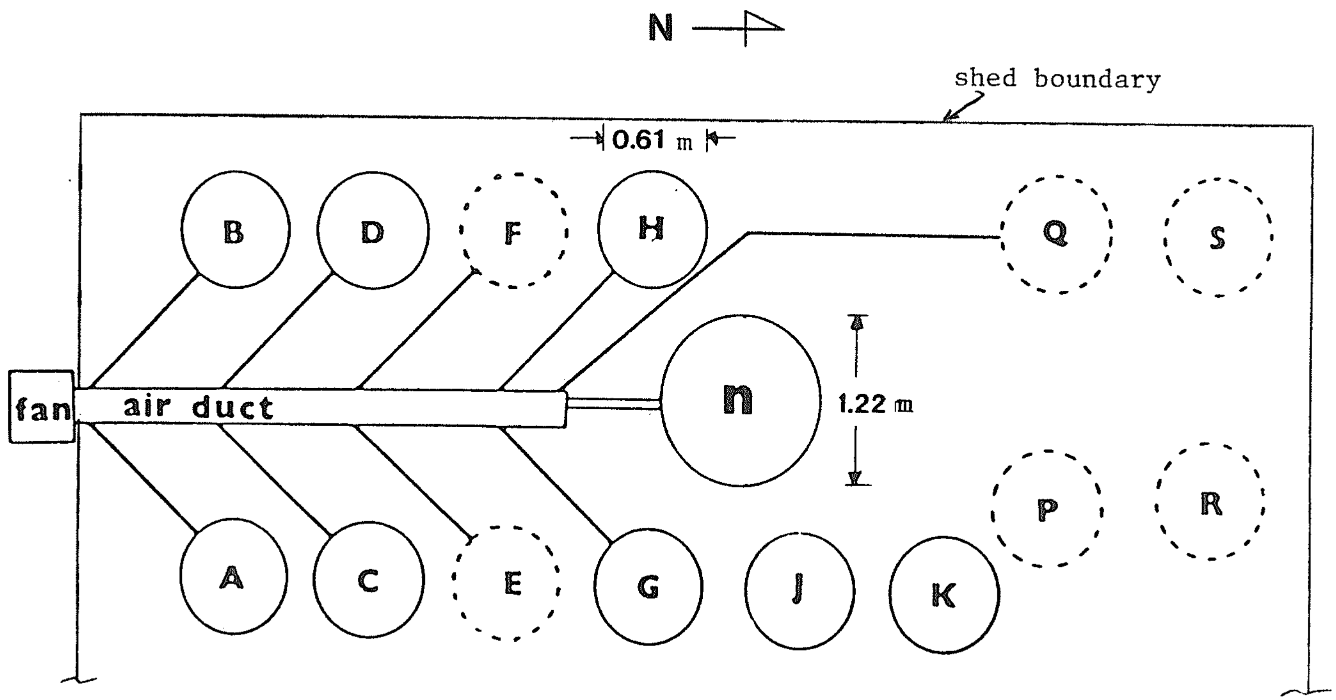


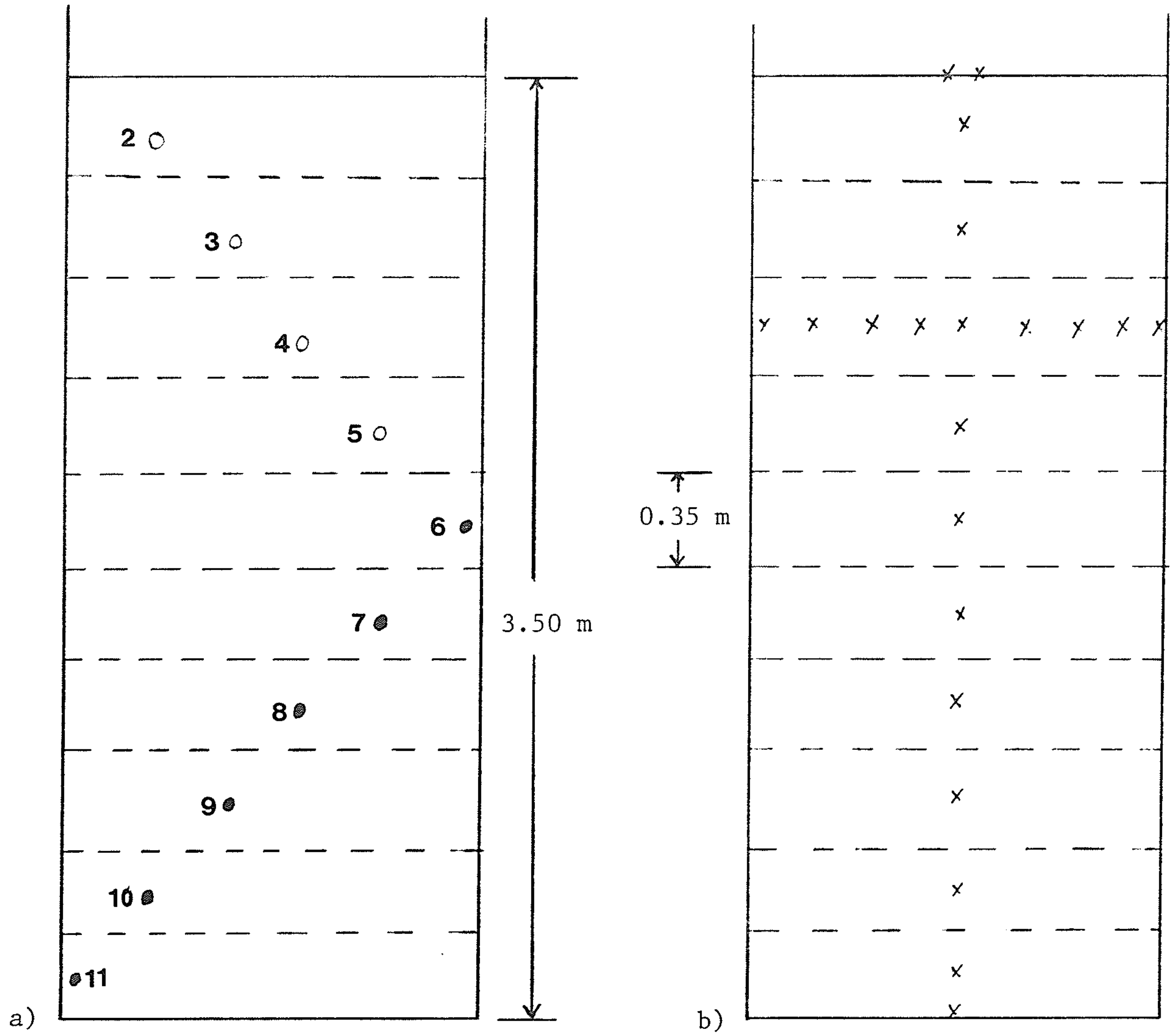
Fig. 3.1: A schema of the experimental area with ventilation system and bin layout. Dashed lines represent bins present but not included in the thesis.

which had 70-mm thick fiberglass insulation. The larger bin had less insulation because of a shortage of available insulation and it was believed that with the larger diameter the insulation would not be as important. Due to labour and scheduling problems during August 1983 the insulating process was not completed before beginning the experiment on 31 August 1983. The insulation completion dates are listed in appendix C.

All bins were divided into 10 imaginary layers 0.35 m deep with sampling ports in the bin walls at the center of each layer (Fig. 3.2). The sampling ports are aligned in a spiral manner to obtain more representative sampling of various layers and to prevent the removal of grain from only one vertical plane causing a drop in grain level in that plane (Fig. 3.2). As the grain dries it shrinks and moves downward passing the sampling ports. Consequently, grain sampled above the drying front during drying in the successive sampling periods was different. Temperature and concentrations of carbon dioxide and oxygen were also measured at these same fixed heights.

3.2 STORED GRAIN

Canadian Western Hard Red Spring Wheat (*Triticum aestivum* L. c.v. Neepawa) harvested on 15 August 1983 was stored at a moisture content of 10.5% in a 15.8-m^3 bulk feed tank. During 28 to 31 August 1983 the moisture content of the wheat was increased to approximately 19% in four step increments. Distilled water was added using an auger, two 15.8-m^3 bulk feed tanks and a propionic acid applicator (consisting of a hopper, a 1.30-m long auger, two sprayer nozzles and a water pump). The grain was slowly unloaded into the hopper of the applicator where the device's



● =SAMPLING PORT
○ =SAMPLING PORT (OTHER SIDE OF BIN)
x =THERMOCOUPLE LOCATION
2–11 =SAMPLING PORT NUMBERS

Fig. 3.2: A schema of vertical cross-section of bins showing: (a)sample port locations on bins (note spiral orientation) and (b)thermocouple locations in bins.

two sprayer nozzles injected distilled water at a constant rate (monitored by a rotameter located on the applicator) into the grain as the grain passed through the applicator. Once through the applicator the moistened grain dropped into the hopper of an 11.0-m long auger and was transported into the second bulk feed tank. The 11.0-m long auger acted as a means of mixing the damp grain as well as a means of transport. Matching the grain and distilled water flow rates to obtain a desired moisture content was done by a trial and error process. The amount of moisture adsorbed by the grain seemed to be limited by the ability of the grain to absorb the water sprayed on it. In our situation the maximum increase in moisture of the grain was 2 to 3 percentage points above which water ran off the grain and down the auger.

Once transferred, the moistened grain was allowed to equilibriate for 15 to 20 h to allow the surface moisture to diffuse into the kernels. Sokhansanj et al. (1983) stated that the tempering time necessary for wheat dipped in water (surface wetting of the kernel) then let to equilibriate at 21°C was 7 to 32 h for grain to reach 95 and 100% of final moisture respectively. They described final moisture as grain with no moisture gradient within the kernel. In their tests wheat was raised from 12 to 22 % moisture content in one step. In our tests the moisture intervals were only 2 to 3 % and tempering temperatures were above 21°C (work was done during a hot spell when ambient mid-day temperatures ranged from 20 to 25°C with partial cloud cover).

Immediately after the last moisture application was completed (31 August 1983) the wetted grain was placed into the test bins with the exception of the two non-ventilated control bins (bins J and K) which were filled the following day. The bins were filled to a depth of 3.5 m which yielded volumes of 1.02 m^3 per bin for the 0.61-m diameter bins and 4.09 m^3 for the 1.22-m diameter bin. The grain was not allowed to temper after the fourth pass because warm temperatures and high moisture contents were conducive to spoilage. The tempering period was forgone so that the grain could be cooled in the ventilated test bins.

3.3 STORAGE CONDITIONS

Four ventilation rates were used in the 1983-1984 tests were:

1. 12.2 $L \cdot s^{-1}m^{-3}$ (bins A and B)
2. 23.2 $L \cdot s^{-1}m^{-3}$ (bins C, D and N)
3. 0.85 $L \cdot s^{-1}m^{-3}$ (bins G and H)
4. no airflow (bins J and K).

Selection of the above airflow rates were based on predicted drying airflow rates required to dry wheat at 19 % moisture content harvested on 1 September in Winnipeg, Manitoba (Fraser and Muir 1981). The published required airflow rate is approximately 24 $L \cdot s^{-1}m^{-3}$ with 12 $L \cdot s^{-1}m^{-3}$ being half of the required predicted airflow rate. An airflow rate of 0.85 $L \cdot s^{-1}m^{-3}$ is slightly less than the usually recommended aeration rate of 1 $L \cdot s^{-1}m^{-3}$ and is not considered sufficient for grain drying. With these airflow rates different drying rates could be monitored and a minimum airflow rate for keeping grain in acceptable condition was to be determined.

The 0.61-m diameter bins were chosen because of their smaller size. This allowed several storage conditions to be tested for a smaller outlay of capital than would be possible if farm-size bins were used. Air distribution within a ventilated bin with a fully perforated floor is assumed to be uniform. Hence, the use of a smaller diameter bin with a fully perforated floor should not present a problem. Two concerns of using 0.61-m diameter bins were :

1. Whether the wall-grain interface affects airflow distribution across the bin due to the increased porosity at the wall.
2. Whether radial heat loss within the bins is excessive.

To check these concerns a 1.22-m diameter bin was included in the experiment. This larger bin was ventilated at 23.3 $L \cdot s^{-1} m^{-3}$ as were two 0.61-m diameter bins.

The airflow to the bins was supplied by a 2.24-kW centrifugal fan (Chicago Blower type SQAD backward curved with a 310 mm square outlet) located outside of the metal shed (Fig. 3.1). The air was transported from the fan to the various bins by way of a painted wooden header and several ABS plastic subsidiary ducts that connect to the plenum chambers (Fig. 3.1). The wooden header had internal dimensions of 310 mm by 310 mm and was 5.5 m long. It was insulated with 51-mm thick polystyrene foam insulation. The internal diameters of the ABS subsidiary ducts connecting the wooden header to the plenums of the 0.61-m and 1.22-m diameter bins were 51 mm and 102 mm respectively. These ducts were not insulated and were 1.0-mm long. Airflow rates were measured using a thermal anemometer (Airflow Developement's model TA 3000) which could measure air velocities in the range of 0 to 15 m/s. Airflow was measured by a thermal anemometer probe manually inserted into the inlet airstream in the ABS pipes. Airflow adjustments were made using ball valves located in the ABS pipes. The thermal anemometer was calibrated against orifice plates in the laboratory to relate anemometer reading to an airflow rate (see appendix D for calibration procedure). The calibration proceedure related anemometer reading to airflow rate with an r-square of 0.997.

Bins equipped with perforated floors were ventilated continuously from the time of filling on 31 August 1983 to 22 December 1983, and from 2 April 1984 to 21 June 1984. There was no forced ventilation in the intervening winter period.

During the first 2 wk of ventilation the airflow rates were checked at least once a day and then the frequency of measurement dropped to approximately 3 to 4 times per week until the end of October. From November to fan shut down in December airflow rates were checked approximately once a week. The purpose of more frequent checks and adjustments during the initial stages of the experiment was to account for changing grain moisture contents and total grain depth. How these factors affect airflow rates is described in the literature review in Section 2.1. Once the grain has dried or when the drying rate has slowed due to low ambient-air temperatures airflows need not be adjusted as often.

3.4 MEASUREMENT METHODS

3.4.1 Temperature

Temperatures in the grain bulks were monitored using a Hewlett-Packard 3497 data logger and copper-constantan themocouples (1.02-mm diameter) located as shown in Fig. 3.2. Thermocouples were located along the centerlines of the bins at the 10 sample heights as well as at the top and bottom of each bin. The centerline thermocouples were used to measure vertical temperature gradients caused by the varying inlet air temperatures and the drying process. In one bin of each paired storage condition thermocouples were placed in a radial pattern 2.625 m above the bin floor. These thermocouples were used to measure radial temperature gradients in the grain columns. To determine the temperature changes through the fan and ducting for a particular bin the difference between outdoor (ambient) temperature and the temperature at the bottom of the bin was used. The thermocouple in the bottom of the bin was located on top of the perforated bin floor.

The thermocouples were supported in the 0.61-m diameter bins by fishing line with a tensile strength of 110 N strung across the diameter of the bin at each measurement level. For the 1.22-m diameter bin 220 N tensile strength line was used in place of 110 N line due to the longer span. This choice of support lines was chosen for two reasons:

1. The fishing line is of a small diameter thus causing minimal effect on airflow patterns.
2. Heat transfer along the support lines (by conduction) is negligible.

A major problem which was overlooked is the load the grain places on these supports as it moves past them due to the bulk shrinkage of the grain as it dries. In most cases the loads were large enough to break the supports causing the thermocouples to be displaced. This problem of weak supports was solved for the 1984-1985 tests by using galvanized wire (2.34-mm diameter) in the 0.61-m diameter bins and 3.18-mm diameter cable in the 1.22-m diamter bin with good results.

In total 206 thermocouples were placed in the bins. Of these 80 were monitored automatically and values stored on magnetic tape. The remaining thermocouples were connected through manual switch boxes to one channel of the data logger with the temperatures being stored on a seperate magnetic tape.

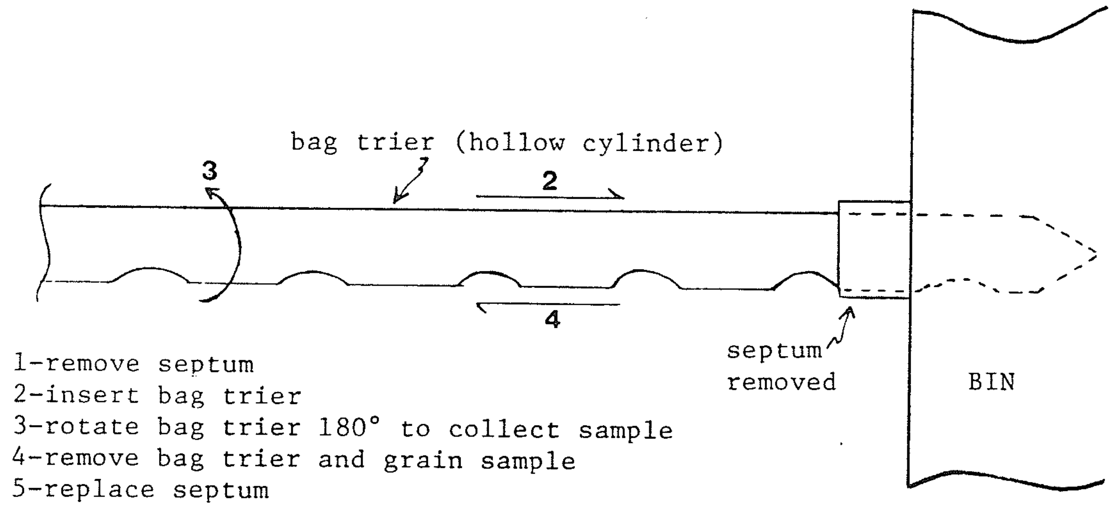
Outdoor air conditions were monitored automatically for dry bulb temperature and relative humidity using thermocouples and a Vaisala Humicap humidity meter (model # HM14). The humidity meter uses a sensor which is based on capacitance change in a thin-film polymer capacitor for measuring relative humidity of the air. The inside of the metal shed was also monitored for dry bulb temperatures automatically using thermocouples.

The thermocouples monitored automatically were read hourly until 22 November 1983 when the time interval was increased to 8 h. Because the low temperatures had already slowed microfloral activity, frequent temperature measurement was deemed unnecessary. Beginning 2 April 1984, the time interval was returned to an hourly basis to record the spring warm-up. Temperatures were recorded manually when grain or intergranular air samples were taken. No intergranular air temperatures were recorded and forced ventilation was discontinued during the period from 22 December 1983 to 21 February 1984 as grain was chilled below 0°C, biological activity was presumed to be negligible.

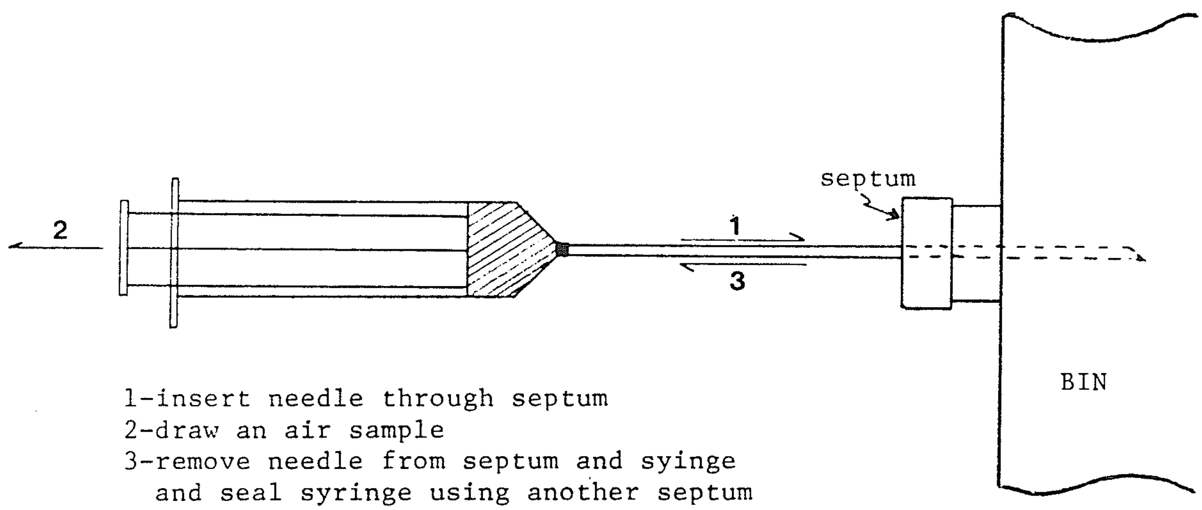
3.4.2 Moisture content

Moisture contents of the grain were determined on a wet-mass basis by oven-drying duplicate samples at 130°C for 19 h (Anonymous 1983). Samples for moisture determination were taken as follows: four times between 1 September 1983 to 14 September 1983, weekly until 21 November 1983, every 4 wk until 19 March 1984, and then weekly until the end of the study on 21 June 1984.

Grain samples were withdrawn from each sample port (total of 10 per bin) using a 610-mm long, 10.2-mm diameter bag trier in a manner shown



a)



b)

Fig. 3.3: Methods used for obtaining (a) grain and (b) intergranular air samples.

in Fig. 3.3a. The sample size taken from each sampling point was approximately 50 g and was stored in sterilized sample bags at 0 to 5°C until processed. The grain samples were used to determine moisture content, fat acidity, germination and microflora.

3.4.3 Intergranular air

Intergranular air was sampled for carbon dioxide concentrations in all bins and for oxygen concentrations in the low-airflow and control bins (G,H,J and K). Oxygen concentrations were not measured in the other bins, because it was assumed that the continuous ventilation maintained oxygen levels similar to those of the outdoor air as was the measured levels of carbon dioxide in these bins. Intergranular air samples were withdrawn through the same ports used to remove grain samples except that only the top port (port number 2) was sampled in the high airflow bins (A,B,C,D and N). Any carbon dioxide produced in these test bins would be carried upward by the ventilation air. Sampling for carbon dioxide measurement were scheduled weekly from 1 September 1983 to 21 November 1983 (with occasional additional sampling during September), usually biweekly from 21 November 1983 to 16 April 1984 and weekly from 16 April 1984 to 21 June 1984. Intergranular air samples were first analyzed for oxygen concentrations on 23 September 1983. Henceforth, the sampling schedule for oxygen was the same as for carbon dioxide. Intergranular air samples were taken prior to grain sampling so that the introduction of fresh air into the grain (by way of the grain probe) could be avoilded.

Intergranular air samples were drawn using syringes and an 11-gauge, 300-mm long needle (Fig 3.3b). For each air sample the syringe and needle were first purged by drawing a 40 mL gas sample from the sample port. This volume was then expelled to the surroundings and a second 40 mL gas sample was drawn from the sample port; the second sample was analyzed for oxygen and carbon dioxide concentrations. The maximum time a sample remained in a syringe prior to analysis was 5 h. Samples were analyzed using a Perkin-Elmer Sigma 3B gas chromatograph and results expressed in percentage concentration by volume. Analysis procedure used is outlined by White et al. (1982).

3.4.4 Fat acidity value

Free fatty acids or fat acidity values (FAV) were measured on duplicate samples using the American Association of Cereal Chemists' rapid method 02-02 (Anonymous 1962). The fat acidity levels were expressed as mg KOH required to neutralize the free fatty acids in 100 g of moisture-free seeds. The grain used for determining fat acidity values was from the oven dried samples that were used for moisture determination. Generally only every other oven dried moisture sample (for a total of 5 per bin) were analyzed for fat acidity for any sampling date.

3.4.5 Seed germination and microflora

The rate of seed germination was measured by the filter paper method (Wallace and Sinha 1962). Frequency of occurrence of seed-borne microflora were determined by the filter paper method; 25 seeds were placed on sterile filter paper saturated with 4.5 mL of sterile water in a petri dish (Wallace and Sinha 1962), and 25 seeds placed on sterile filter paper saturated with 4.5 mL of sterile 7.5% NaCl solution in a petri dish (Mills et al. 1978). The latter technique was used to determine the frequency of occurrence of fungi of the Aspergillus glaucus group and A. candidus link ex. Fr. species. The plates were then stacked, sealed in plastic bags and incubated at 22±1°C for 7 days. The microflora were examined under a stereo microscope.

3.4.6 Grade

Grain samples for grading were taken at the start and end of the experiment for all storage conditions. About 300-g samples were sent to the Grain Inspection Division of the Canadian Grain Commission, Winnipeg, where they were officially graded and their condition noted.

3.4.7 Data presentation

A schematic flow chart summarizing the variables measured during the experiments is shown in Fig. 3.4. Due to the large amounts of variables monitored and storage conditioins tested data from bins tested at similar storage conditions were combined together to represent single storage conditions. For example: data from bins A and B, ventilated at 12.2 $L\cdot s^{-1}m^{-3}$, were combined together to represent a single storage condition. The maximum value for a variable (say moisture content) in this instance represents the maximum moisture content found in either of bins A or B. A mean bin moisture content represents the average moisture content obtained from both bins A and B over their entire bed depths. This is a mean of two bins with 10 sample ports in each bin and with two samples analyzed for each sample port for a total of 40 samples. The minimum moisture content represents the minimum value found in either of bins A or B. Where a profile showing values at various depths is given, the value presented is an average obtained from the two paired bins at

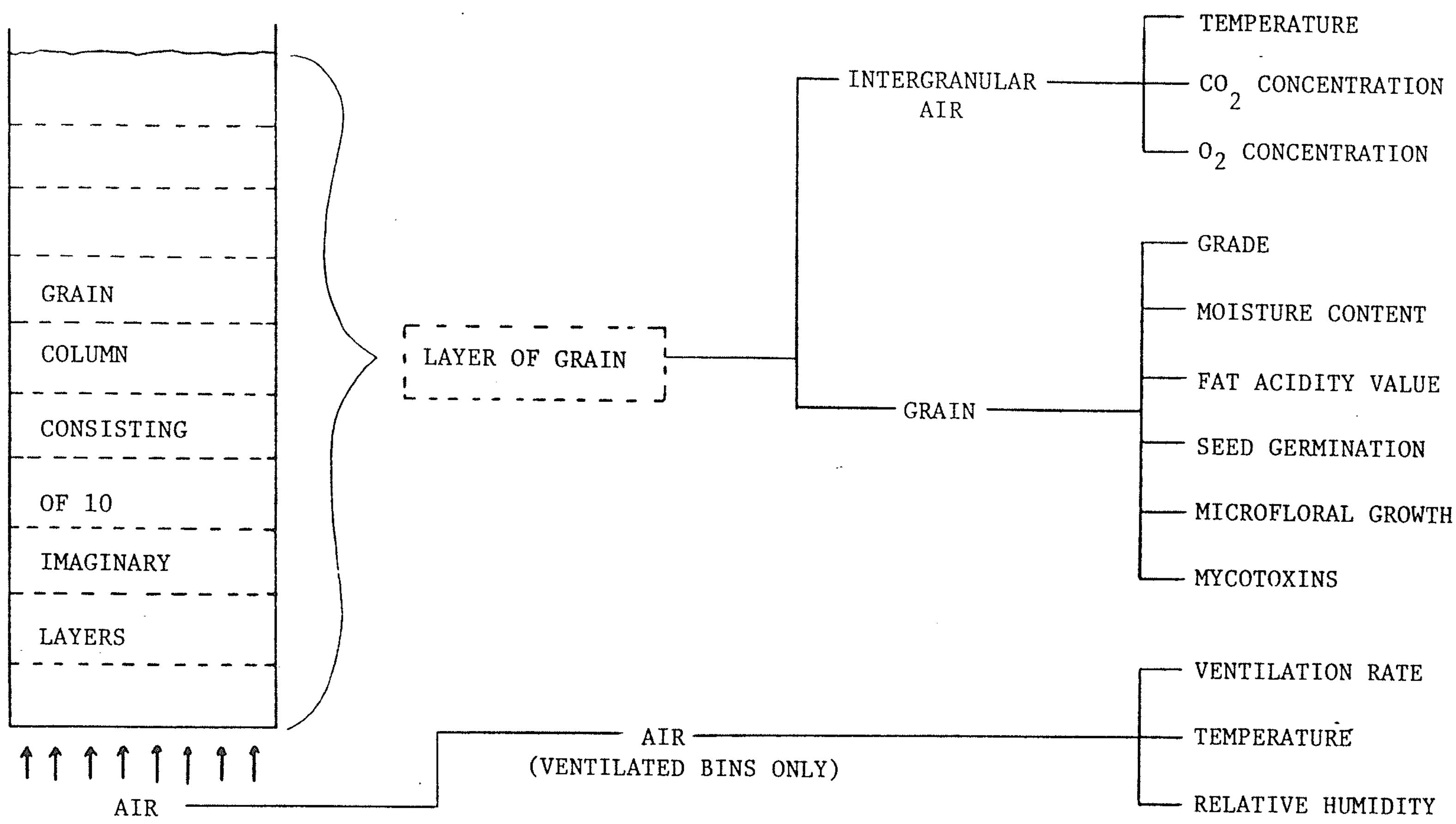


Fig. 3.4: Schematic flow chart summarizing variable analyses.

that location. This is a mean of two sample ports with 2 samples analyzed for each sample port for a total of four samples.

The above procedure was also followed for other variables such as intergranular air temperatures, fat acidity values, seed germination and CO_2-O_2 concentrations.

Chapter IV

MODIFICATIONS FOR 1984-1985 MATERIALS AND METHODS

4.1 TEST BINS

Of the storage containers from the 1983-1984 study only two (bins J and K) could not be re-used on account of damage caused by extensive grain spoilage. The remaining bins were sprayed with a solution of 1.0 % sodium hypochlorite and water solution (5 parts water to 1 part bleach) to kill any possible microorganisms left on the surface of the bins after emptying.

Changes to the amount of insulation on the 1984-1985 bins were that the top 1.17 m of bins C and D were equipped with only 70-mm thick insulation (further details on insulation are given in Appendix C).

The tops of all ventilated bins were equipped with plywood covers to prevent moisture leakage from the storage-shed roof onto the grain surface. Air relief holes were drilled near the top of the bins (above the grain surface) to vent off the ventilation air. Tops of the non-ventilated bins were covered with plastic sheets; these covers are discussed later in Sec. 4.3.

4.2 STORED GRAIN

On 17 August 1984 6.2 m^3 of No. 2 Canada Western Hard Red Spring wheat (*Triticum aestivum* L. cv. Neepawa) with 1 % dockage was harvested at a moisture content of 15.6% and placed in a 15.8 m^3 bulk feed tank. Some of this grain was transferred to two of the 0.61-m diameter bins (G and H) on 18 August 1984. Airflow to bins G and H was turned on at 5:00 p.m. on 19 August 1984. On 18 August 1984 the remaining grain was harvested in two loads producing an average moisture content of approximately 16 %. The grain was graded No. 2 Canada Western Hard Red Spring wheat as was the earlier load.

From 18 to 20 August 1984 the moisture content of the wheat was increased to approximately 18 % in three step increments in much the same manner as in 1983 with the exception that collected rain water was used in place of distilled water. The moistened wheat was placed into the remaining test bins and forced ventilation started on 20 August 1984.

4.3 STORAGE CONDITIONS

The four ventilation rates used in the 1984-1985 tests were:

1. Wheat with 18.2 % moisture content and airflow of 6.9 $L \cdot s^{-1}m^{-3}$ (bins A and B).
2. Wheat with 18.2 % moisture content and airflow of 3.4 $L \cdot s^{-1}m^{-3}$ (bins C, D and N).
3. Wheat with 15.6 % moisture content and airflow of 0.85 $L \cdot s^{-1}m^{-3}$ (bins G and H).
4. Wheat with 18.2 % moisture content with no airflow (bins J and K).

Bins equipped with perforated floors were ventilated continuously from the time of filling to 30 October 1984. Airflow to bins G and H was resumed on 6 May 1985 while the other bins remained unventilated. There was no forced ventilation in any bins between 30 October 1984 and 6 May 1985.

The tops of the non-ventilated bins (J and K) were covered using plastic sheets on 27 September 1984. Up to this date (including the 1983-1984 test) the tops of all bins (including the ventilated bins of 1984-1985) were open to the air inside the metal shed. The tops of non-ventilated bins were covered to avoid entry of any water that would leak through the storage shed roof.

To keep the tops of these bins from becoming air-tight environments a 6-mm diameter plastic tube was inserted into the headspace of these two bins. This tube supplied air from the air supply duct to the tops of the bins at a very low flow rate (less than 0.02 $L \cdot s^{-1}$). To vent off this ventilation air four 6-mm diameter plastic tubes were inserted through the bin wall into the headspace. No pressure buildup in the headspace was noticed during fan operation.

4.4 MEASUREMENT METHODS

4.4.1 Temperature

The thermocouples were supported in the 0.61-m diameter bin with galvanized wire (2.34-mm diameter) strung across the diameter of the bins. Additional strength was added to the support wires by stringing high tensile strength wire (0.46-mm diameter piano wire) vertically and wrapped around this wire. In the 1.22-m diameter bin 3.19-mm diameter cable were used as supports. Both support methods held the thermocouples in place during the drying process.

The total number of thermocouples placed in the various bins for the 1984-1985 experiment was 210. Of these 98 were monitored automatically with the remaining 112 being connected to manual switch boxes.

The thermocouples monitored automatically were read every 2 h from 18 August 1984 to 15 December 1984 and from 9 April 1985 to 15 July 1985. No temperatures were monitored automatically during 15 December 1984 to 9 April 1985 but temperatures were taken manually at least twice a month.

Intergranular and ambient air temperatures were manually taken at varying frequencies to supplement automatic temperature readings.

4.4.2 Moisture content

Samples for moisture determination (1984-1985 experiment) were taken as follows: five times between 20 August 1984 to 9 September 1984, weekly until 29 September 1984, twice in October 1984 then once a month from 1 November 1984 to 15 July 1985 with the occasional extra sampling of specific bins.

Sampling procedures were the same as those described in Sec. 3.4.2 for the 1983-1984 experiment.

4.4.3 Intergranular air

Intergranular air was sampled for carbon dioxide concentrations in all bins and for oxygen concentrations in bins J,K and P. Sampling schedules for carbon dioxide were twice a week from 22 August 1984 to 25 October 1984, weekly from 25 October 1984 to 5 December 1984, biweekly from 5 December 1984 to 1 May 1985 and weekly from 1 May 1985 to 15 July 1985. Intergranular air samples were first analyzed for oxygen on 11

October 1984. Henceforth, the sampling schedule for oxygen was weekly from 14 October 1984 to 31 October 1984, every four weeks from 31 October 1984 to 10 April 1985 and weekly from 21 April 1985 to 15 July 1985.

4.4.4 Fat acidity value, seed germination and microflora

Grain samples were analyzed for free fatty acids, seed germination and microflora in the same manner described in Sec. 3.4.4 and 3.4.5.

4.4.5 Grade

Grain samples for grading were taken at the start and end of the experiment as well as on 23 December 1984 for all storage conditions.

Chapter V

SIMULATION MATERIALS AND METHODS

5.1 FORCED CONVECTION MODEL

The mathematical model used to simulate heat and mass transfer within the ventilated bins was one adapted by Metzger and Muir (1983). This model is based on a near-equilibrium model developed by Thompson (1972). It was chosen even though it has been shown to lose accuracy at airflow rates above 9 $L\cdot s^{-1}m^{-3}$ (Morey et al. 1977, Metzger and Muir 1983) because of its availability. The program was run on the Amdahl 470/V7 mainframe computer located at the University of Manitoba.

The model has three basic assumptions (Metzger and Muir 1983):

1. The ventilation air leaves a spatial element in equilibrium with the average condition of the grain in the element.
2. Heat and mass transfer between the air and grain are adiabatic (there is no heat or moisture transfer to or from the surroundings of the grain storage).
3. No heat or moisture is generated in the grain bulks. Heat and moisture may be expected from respiration of the grain, and insect and fungal activity but these are probably negligible until the rate of deterioration increases to an unacceptable level.

The original model (Metzger 1981) was modified by Kitson (1986) such that hysteresis of moisture absorption may be accounted for. The model predicts no moisture transfer if the relative humidity of the ventilation air is equal or up to 5 % higher than the equilibrium relative humidity of the grain. This has the effect of offsetting the rewetting equilibrium relative humidity equation for the grain by 5 %. Once the ventilation air was above this threshold differential, grain rewetting is predicted to occur. In this revised model rewetted grain comes into equilibrium with a relative humidity 5 % lower than the relative humidity of the ventilation air. The grain drying equations were left unchanged.

5.2 WHEAT DETERIORATION MODEL

The model developed by Fraser and Muir (1981) and used by Metzger and Muir (1983) to predict the allowable safe storage time for wheat was used to predict grain deterioration with and without forced ventilation. The model predicts maximum storage times before germination drops by 5 % or visible mould appears (Fraser 1979). The allowable storage time for wheat having a moisture content greater than 12 % but less than 19 % was defined by the relationship:

$$\log\theta = 6.234 - 0.2118M - 0.0527Tg \qquad (5.1)$$

and for wheat having a moisture content of 19 to 24 %:

$$\log\theta = 4.129 - 0.0997M - 0.0567Tg \qquad (5.2)$$

These equations are based on static conditions of temperature and moisture. To apply them to dynamic conditions of a slowly drying grain bulk Fraser incorporated a storability index. For each time interval the temperature and moisture content of each spatial element are used to calculate the allowable storage time for that element. The proportion of allowable storage time elapsed during the time interval is calculated by dividing the length of time interval by the calculated 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 binning. The proportion of allowable storage time elapsed is expressed as a decimal fraction and is called the storability index. A value of 1.0 indicates that the predicted allowable storage time (based on 5 % germination drop) has elapsed (Metzger and Muir 1983).

5.3 SIMULATION PROCEDURE

A skeleton flow chart (Fig. 5.1) shows a simplified version of the simulation procedure. The model requires the following variables:

1. initial grain temperatures and moisture contents,
2. ventilation rate,
3. ventilation start date,
4. temperature changes through fan and ducting, and
5. dry-bulb-temperature and relative humidity of ambient air for the simulation period on an hourly basis.

The temperature changes through fan and ducting used in the simulation of the 1983-1984 drying period were the temperatures measured hourly. For the 1984-1985 drying period a temperature rise of 4.0°C was used for all drying airflow rates and 1.8°C for the aeration runs. These temperatures were the mean values measured during the 1983-1984 experiment. They were used instead of measured ones for the 1984-1985 experiment be-

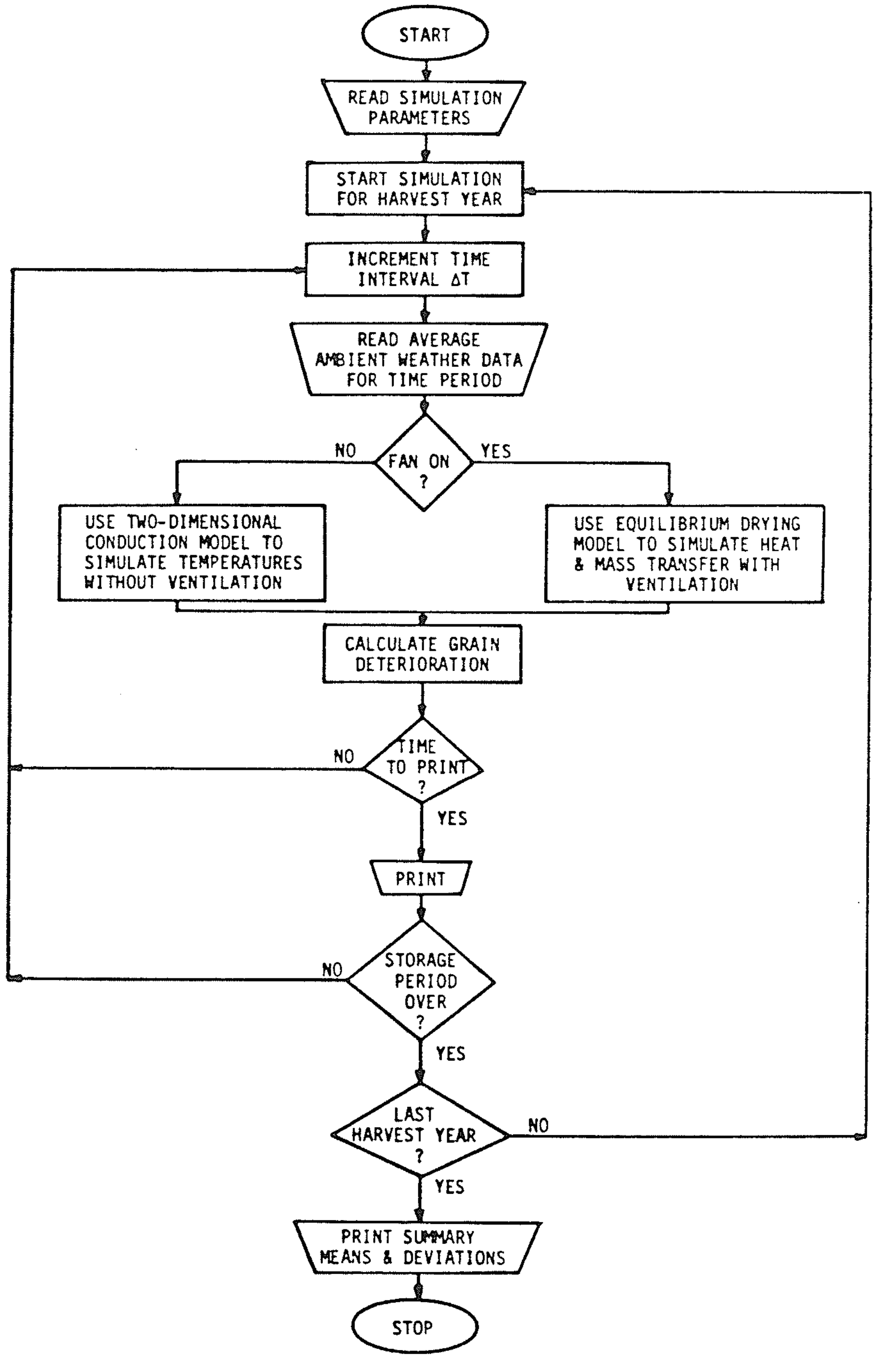


Fig. 5.1: Skeleton flow chart of the computer simulation model (Metzger 1981).

cause of problems that developed in the acquisition of temperatures during the 1984-1985 experiment. The hourly ambient-air dry-bulb-temperature and relative humidity (recorded at the Winnipeg International Airport on magnetic tape) were obtained from Environment Canada. This airport is located approximately 15 km north-west of the experimental site so the use of values obtained at the airport should not introduce noticeable errors into the simulation.

Based on the input parameters, grain conditions are determined using the forced convection subroutine (the two-dimensional conduction routine available in the model was not used). The columns used in the simulation were assumed to be one dimensional and divided into 10 equal layers yielding spatial increments of 0.35 m. The time increment used for the simulation was 1 h.

Deterioration modeling for the control bins in the 1983-1984 experiment was done using the deterioration model with measured intergranular air temperatures and moisture contents as input parameters. That is, the convection and conduction part of the model was not used. For the 1984-1985 experiment a ventilation rate of 0.1 $L \cdot s^{-1} m^{-3}$ was used in the model to predict spoilage in the control bins as hourly-measured temperatures within these bins were not reliable. A low airflow rate was used to simulate intergranular air temperatures near ambient levels. Temperatures measured manually within the control bins indicated that mean bin temperatures were close to ambient temperatures thus justifying this procedure.

To compare results obtained from the simulations with measured results, shrinkage due to moisture loss and particle reorientation should be taken into account. The simulation program does not account for grain shrinkage. Shrinkage is taken into account by a plotting program which is used to compare predicted and measured results. A shrinkage of 11 % (mean value for the 2 test years) was assumed to occur as grain dried from 18 or 19 % to below 14 %. Different shrinkage values were not used for the two moisture contents because of the wide variations experienced during the drying tests (Sec. 6.4). An average value over the 2 years was used to limit experimental error in the measured shrinkage values. Shrinkage in each layer due to moisture loss and particle reorientation was calculated and the location of the simulated layers and related locations for the temperature and moisture content predictions are adjusted (see appendix F for program used).

The complete simulation model, written in Fortran notation, and its application were presented by Metzger (1981). The additional subroutine added to the program to account for hysteresis is given in Appendix E.

Chapter VI

RESULTS

6.1 TEMPERATURE CHANGE THROUGH FAN AND DUCTING

When analyzing temperature and moisture contents within ventilated bins the temperature change through the fan and ducting must be considered. The mean-monthly temperature changes measured during the 1983-1984 tests ranged from -1.8°C to 9.1°C with an average of 3.5°C (Table 6.1). Due to problems which developed with a data acquisition unit after the first 4 wk of the 1984-1985 experiment mean-monthly temperature changes through the fan and ducting are not available.

Diurnal changes in ambient air temperatures and amounts of solar radiation affect temperatures within the shed and thus temperature changes through the fan and ducting. The temperature changes for the various bins vary due to duct layout and the different ventilation rates. Bins ventilated at higher airflow rates tended to have higher temperature changes through the fan and ducting. The length of ducting through which the air must travel may increase or decrease the ventilation-air temperature depending on the direction of the temperature gradient between ambient air and air inside the shed. Temperatures within the shed, for the two test years, were, on average, 1 to 2°C warmer (range of 17°C warmer to 9°C colder) than ambient. The temperatures within the shed may be higher or lower than ambient depending on the time of day and the amount of solar radiation present.

TABLE 6.1

Temperature changes through fan and ducting.

Each value is the mean for the month indicated based on hourly measured temperature data.

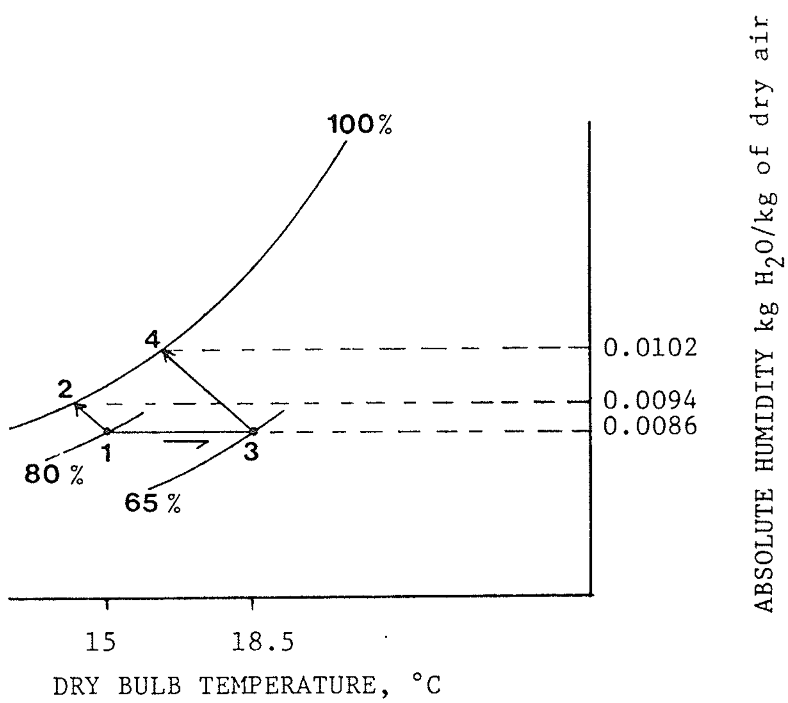
Bins	Airflow rate ((L/s)/m³)	Year	Month	Temperature change (°C) N	mean	s.d.*
C & D	23.2	1983	Sept.	690	4.0	1.4
			Oct.	730	4.5	1.3
			Nov.	524	4.4	0.7
			Dec.	64	5.9	1.0
		1984	April	292	3.4	2.1
			May	741	3.9	1.4
			June	633	3.3	4.1
N	23.2	1983	Sept.	693	4.3	1.4
			Oct.	730	4.9	1.2
			Nov.	524	4.8	0.7
			Dec.	64	6.1	0.9
		1984	April	292	4.2	2.1
			May	741	4.6	1.3
			June	633	2.7	4.3
A & B	12.2	1983	Sept.	693	3.7	1.9
			Oct.	730	4.2	1.6
			Nov.	524	4.1	1.0
			Dec.	64	6.1	1.3
		1984	April	292	2.5	2.6
			May	741	3.0	1.9
			June	633	2.0	4.1
G & H	0.85	1983	Sept.	693	1.2	5.1
			Oct.	730	2.8	3.7
			Nov.	524	3.7	2.7
			Dec.	64	9.1	4.0
		1984	April	292	-1.5	5.4
			May	741	-1.8	5.3
			June	633	-1.0	4.6

* N = the number of observations; s.d. = standard deviation.

A temperature rise increases the drying capacity of the ventilation air by increasing the sensible heat of the air and lowering its relative humidity. For example, a 3.5°C temperature rise for air at 15°C and 80 % relative humidity reduces the relative humidity to 65 %. Then, if adiabatic saturation of the ventilation air is assumed, this would lead to an increase in drying capacity of 100 % (Fig. 6.1). This increase does not mean that the drying front speed is increased by 100 % but means that the moisture holding capacity of the air is increased by 100 %. This increased moisture holding capacity results in lower final grain moisture contents and a slight increase in drying front speeds.

6.2 INTERGRANULAR AIR TEMPERATURES

Mean bin temperatures for each storage condition declined sharply at the onset of winter and rose sharply at the onset of spring (Fig. 6.2 to 6.5). In ventilated bins the mean intergranular air temperatures corresponded closely with outdoor air temperatures. Mean intergranular-air temperatures in the control bins (J and K) of the 1983-1984 experiment increased above ambient (approximately 15°C) to 32°C within 48 h of filling the bins (Fig. 6.3b). Temperatures remained at this level until day 35 (4 October 1983), after which temperatures declined with the onset of winter. In spring, when ambient air temperatures increased to around 10 to 15°C, temperatures within the control bins rose above ambient. Temperatures within these bins (J and K) continued to rise and reached 33°C by the end of the study (21 June 1984). Mean intergranular-air temperatures for the control bins of the 1984-1985 experiment decreased to 20°C by day 10 and remained at this level until day 35 (14 September 1984), after which temperatures declined with the onset of winter (Fig. 6.5b). In the following spring mean temperatures within these bins increased with the outdoor temperatures. Mean temperatures



drying capacity of air at condition 1=(0.0094-0.0086) kg/kg
=0.0008 kg H_2O/kg of dry air

drying capacity of air at condition 3=(0.0102-0.0086) kg/kg
=0.0016 kg H_2O/kg of dry air

percentage increase in drying capacity from point 1 to point 3 is

$$\frac{0.0016-0.0008}{0.0008} * 100 = 100\% \text{ increase}$$

Fig. 6.1: Schematic psychrometric-charts showing effect of a temperature rise on the drying potential of air.

then followed fluctuating ambient air conditions until the end of the study (15 July 1985).

Unlike the ventilated bins for the 1983-1984 test, ventilation was not continued in the spring of 1985 for all bins which were ventilated the previous fall. Only the aeration bins (G and H) were ventilated in the spring.

Intergranular air temperatures after the first 4 wk of the 1984-1985 experiment are based on manual measurements taken at various intervals (less than five times per week). More frequent temperature data after 20 September 1984 is not available due to a faulty data acquisition unit. Temperatures for the first 4 wk of the study were not affected and are included in the thesis. As a result of less frequent temperature data, fluctuating temperatures within the ventilated bins, caused by diurnal fluctuations in ambient air temperatures, could not be followed after the data acquisition malfunctioned. This is of concern while the bins are ventilated. Once ventilation is stopped temperatures within the bins fluctuate very slowly (due to the low thermal conductivity of wheat) and manually measured temperatures are adequate to follow and temperature changes.

Plots showing temperatures at various depths within the grain mass during the first few days of ventilation show the initial cooling of the bins after binning (Fig. 6.6). From these and similar plots, cooling times for ventilated bins were obtained (Table 6.2). The initial cooling time is defined as the total hours of forced ventilation required to lower the temperature in the top layer of the bin (3.33 m above the bin floor) from its initial temperature to where it levels off at a value dictated by ambient air conditions during ventilation (Fig. 6.6). Cool-

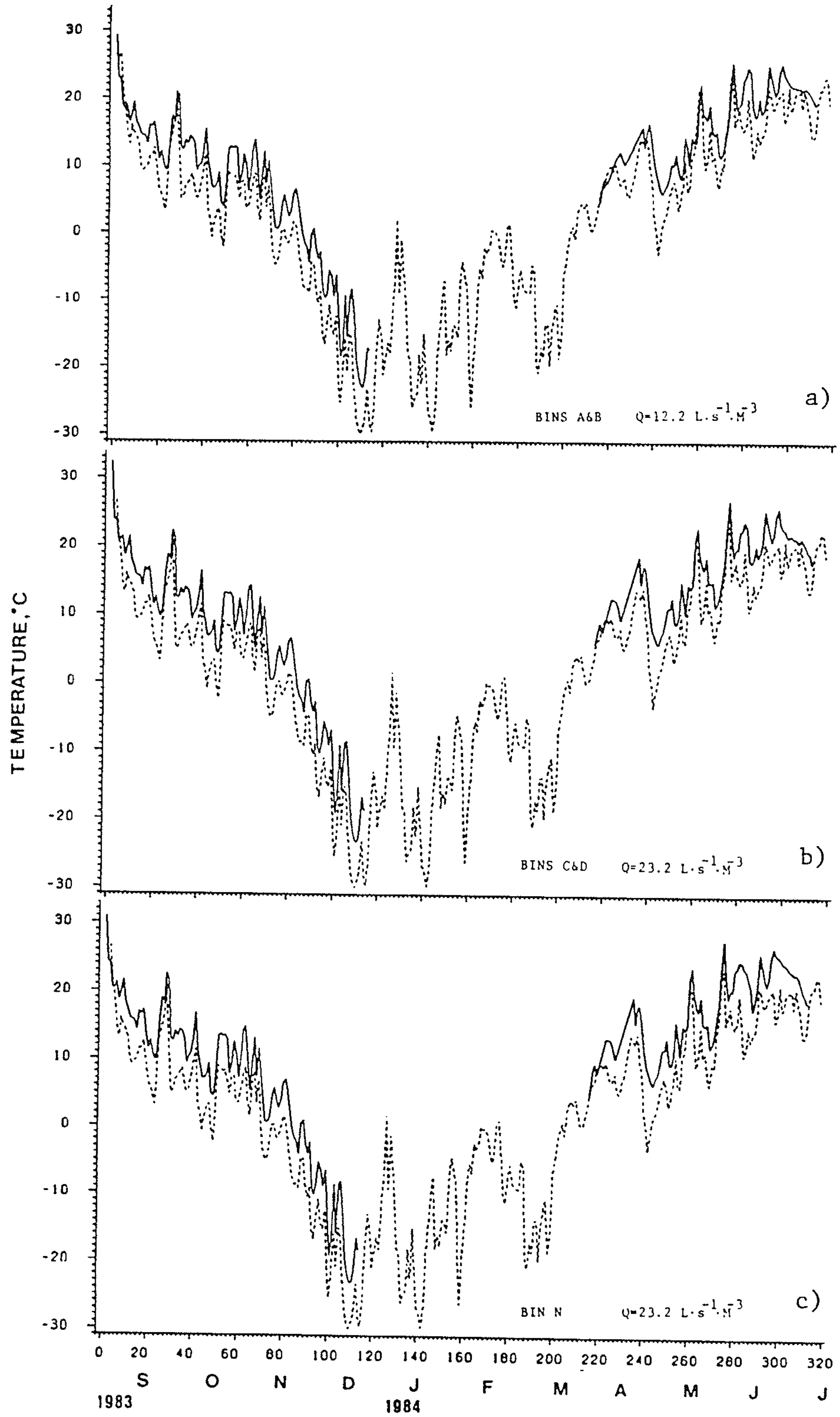


Fig. 6.2: Outdoor (ambient) (-----) and mean intergranular air (——) temperatures during storage of wheat (initial moisture content 19 %) stored at two ventilation rates from 31 Aug. 1983 to 21 June 1984. Ventilation is continuous from 31 Aug. 1983 to 22 Dec. 1983 and from 2 April 1984 to 21 June 1984.

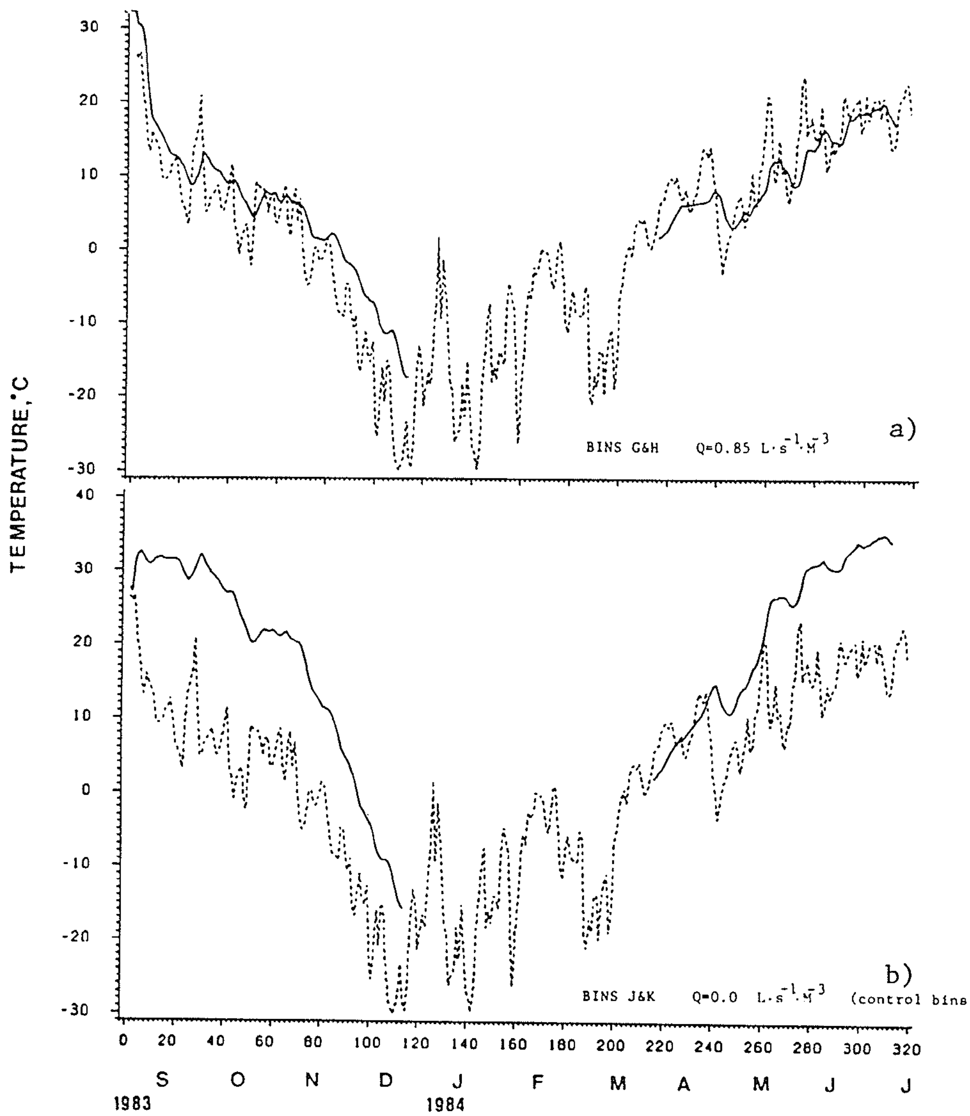


Fig. 6.3: Outdoor (ambient) (-----) and mean intergranular air (———) temperatures during storage of wheat (initial moisture content 19 %) stored at two ventilation rates from 31 Aug. 1983 to 21 June 1984. Ventilation is continuous from 31 Aug. 1983 to 22 Dec. 1983 and from 2 April 1984 to 21 June 1984.

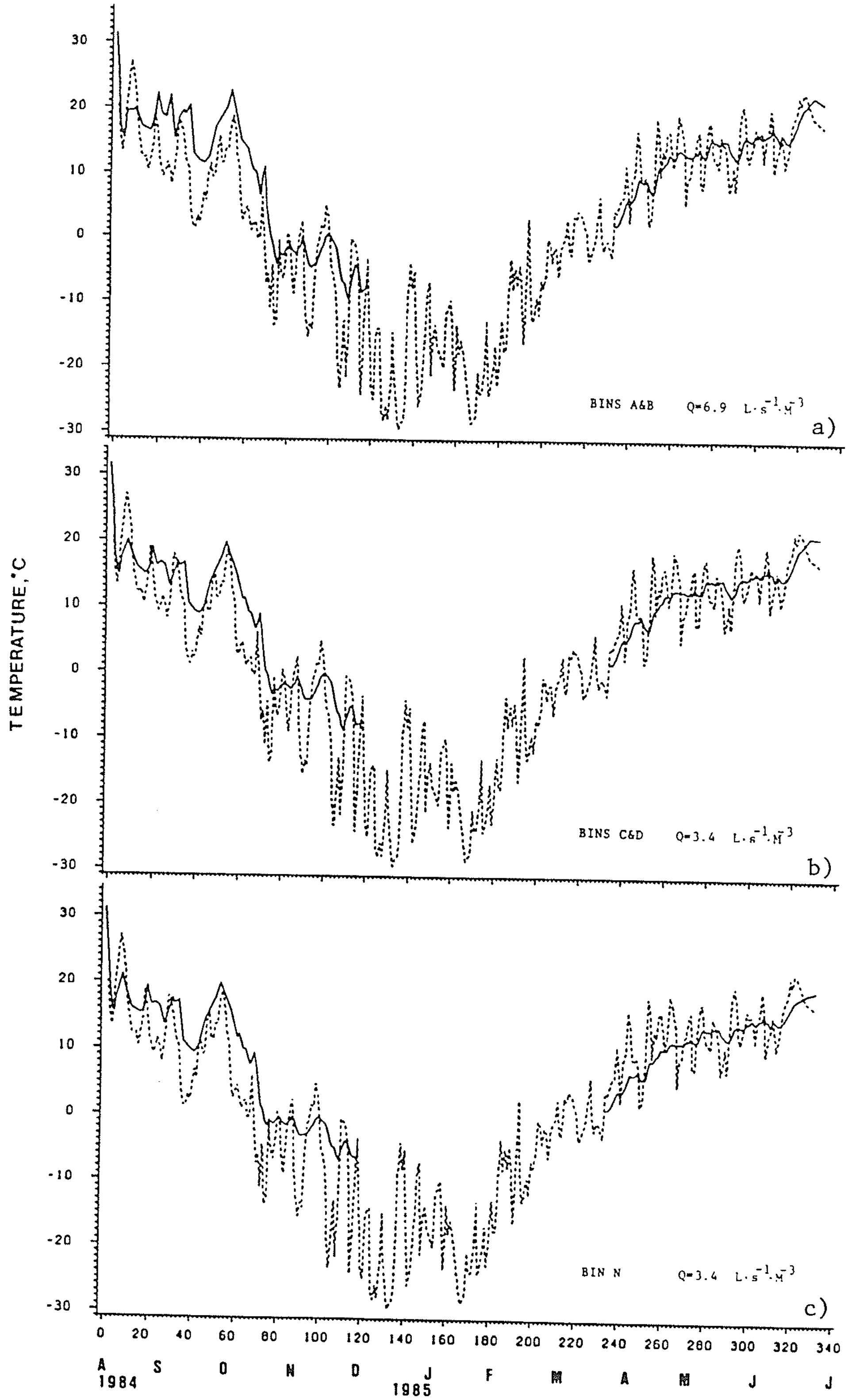


Fig. 6.4: Outdoor (ambient) (-----) and mean intergranular air (———) temperatures during storage of wheat (initial moisture content 18 %) stored at two ventialation rates from 20 Aug. 1984 to 15 July 1985. Ventilation is continuous from 20 Aug. 1984 to 30 Oct. 1984 with no forced ventilation after 30 Oct. 1984.

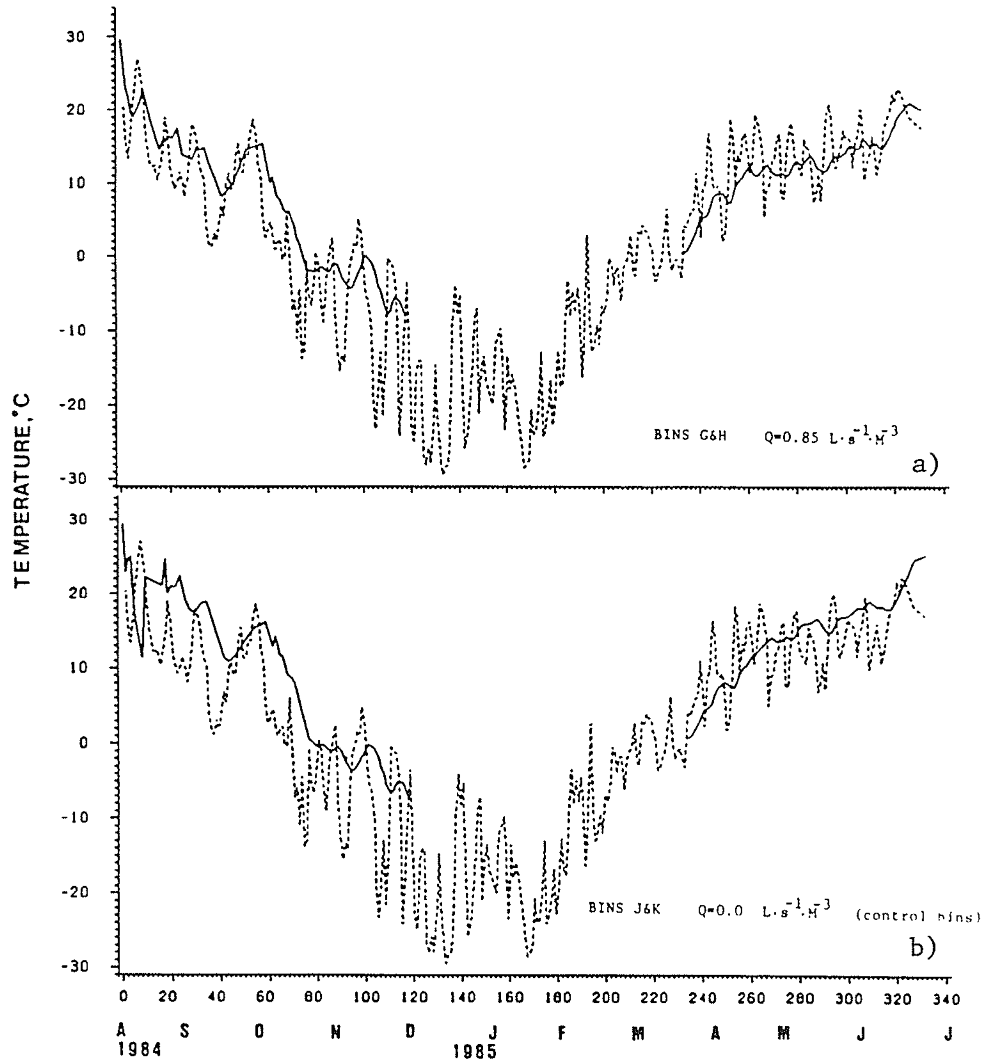


Fig. 6.5: Outdoor (ambient) (- - - -) and mean intergranular air (———) temperatures during storage of wheat (initial moisture content 15.6 % (bins G and H) and 18 % (bins J and K)) stored at two ventilation rates 20 Aug. 1984 to 15 July 1985. Ventilation to bins G and H is continuous from 20 Aug. 1984 to 30 Oct. 1984 and from 6 May 1985 to 15 July 1985.

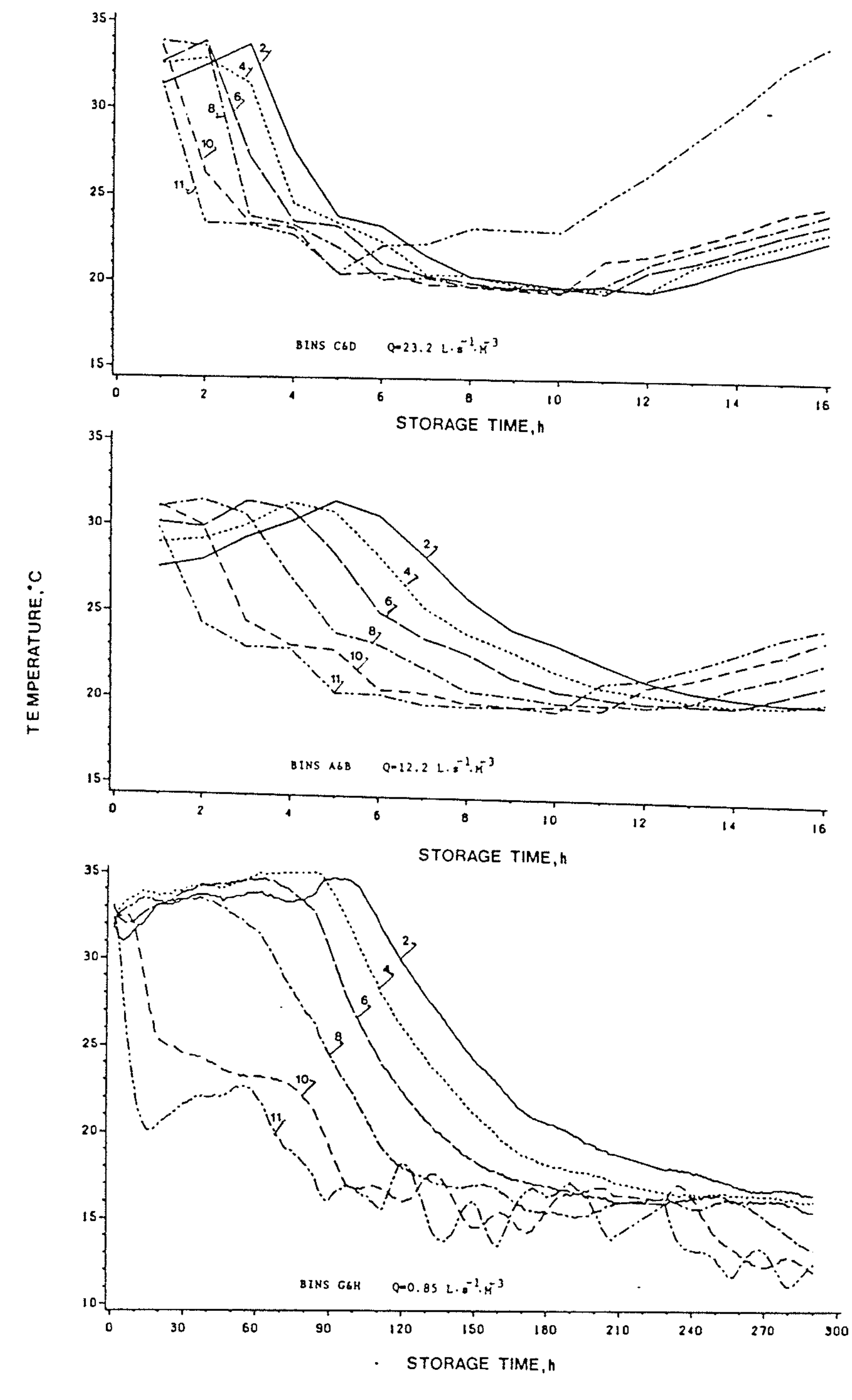


Fig. 6.6: Intergranular air temperatures at various heights above bin floor during the start of ventilation at 3 airflow rates for the 1983-1984 drying test. Heights above bin floor are: 11-0.17 m, 10-0.53 m, 8-1.23 m, 6-1.93 m, 4-2.63 m and 2-3.33 m.

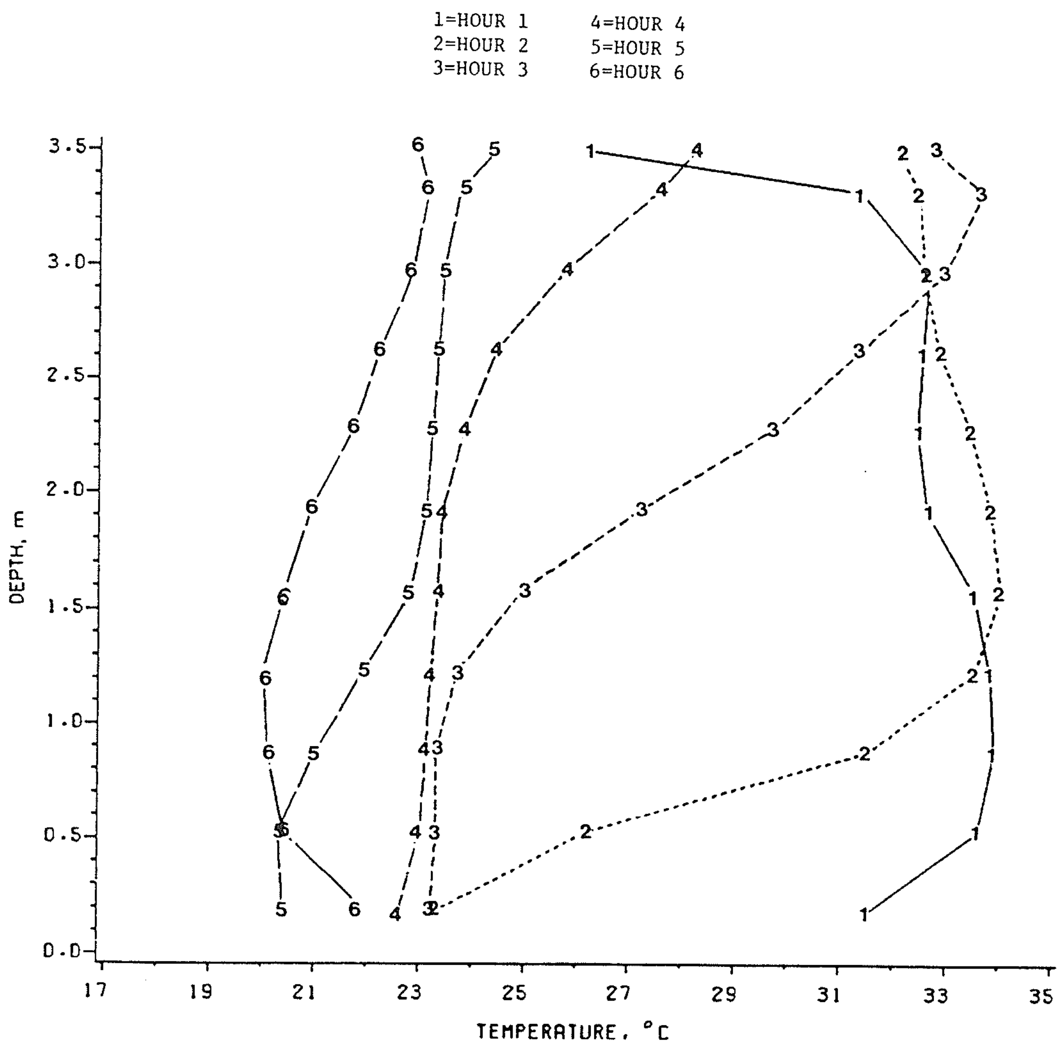


Fig. 6.7: Intergranular air temperatures in a bin of damp wheat ventilated at 23.2 (L/s)/m3. Ventilation start date was 31 Aug. 1983 at 22:00 h. The hour variable corresponds to time from start of ventilation (h).

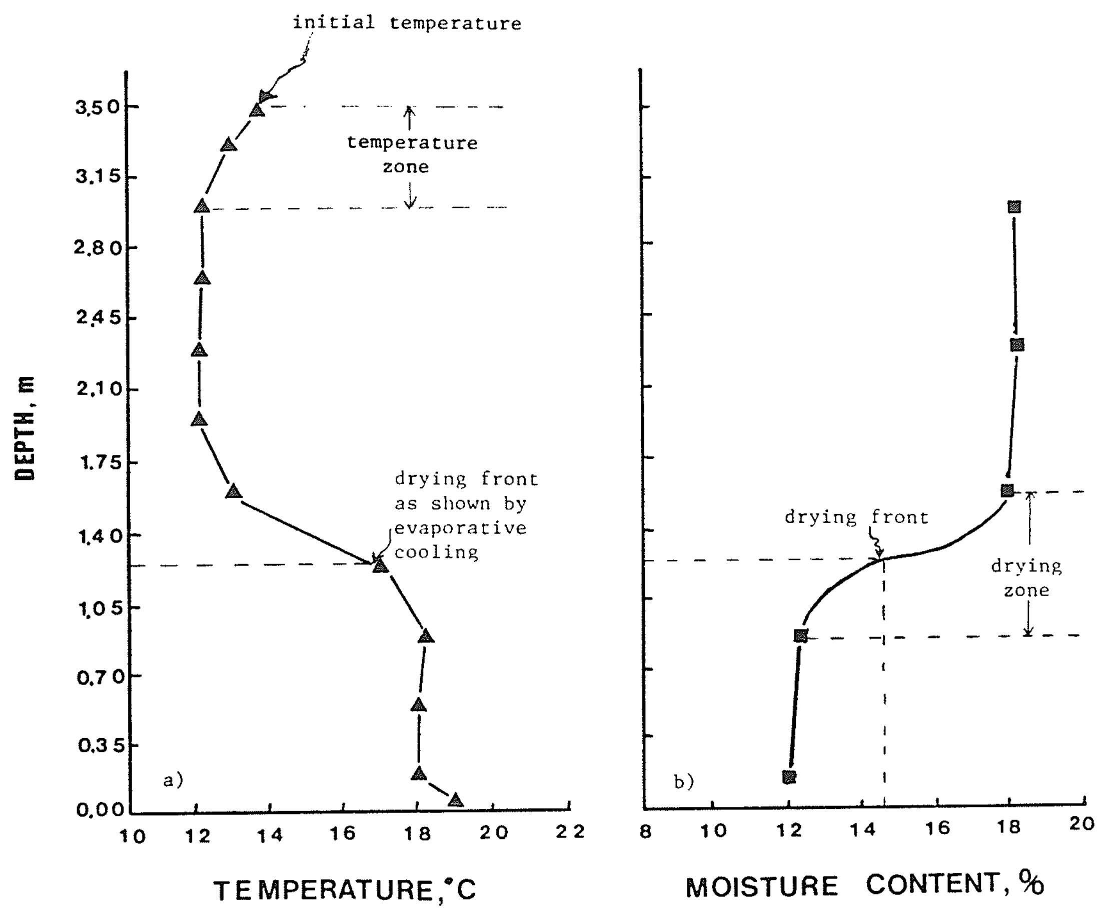


Fig. 6.8: Intergranular air temperatures (a) and moisture contents (b) during storage at a ventilation rate of 12.2 (L/s)/m^3. Profiles are for a sampling date of 06 Sept. 1983.

TABLE 6.2

Cooling times for the ventilated bins.

Initial grain temperatures for both years were approximately 30 °C with final temperatures being dependent on ambient conditions.

Test year and ventilation start date	Bins	Airflow rate ((L/s)/m³)	Superficial air velocity (m/s)	Time required for initial cooling (h)	Speed of initial cooling zone* (m/h)
1983-1984	C & D	23.2	0.0812	8.5	0.40
31 Aug. 1983	A & B	12.2	0.0428	14.5	0.23
	G & H	0.85	0.0030	260	0.013
1984-1985	A & B	6.9	0.0242	30	0.11
20 Aug. 1984	C & D	3.4	0.0119	43	0.077
	L & M	3.4	0.0119	47	0.071
	G & H	0.85	0.0030	150	0.020

* The maximum measured differences for the initial cooling zone speeds between paired bins was 4.8 %.

ing times for the 1.22-m diameter bin (N) for 1983-1984 are not reported because of failure of the temperature recording equipment.

Temperature profiles within a ventilated grain bin show the shape and movement of temperature zones (Fig. 6.7). Temperature profiles for bins ventilated at the other ventilation rates are presented in appendix G (Fig. G.1 to G.6). I have defined the temperature zone as that zone where the temperature changes from an initial value to a new value caused by the ventilation air (Fig. 6.8).

Temperature zones develop because the grain and incoming ventilation air are at different temperatures or if there is moisture exchange between the air and the grain. Thus, temperature profiles within the ventilated bins may be modified by a drop in temperature in the drying zone (defined in Sec. 2.1) due to evaporative cooling caused by the moisture exchange (Fig. 6.8 and 6.9).

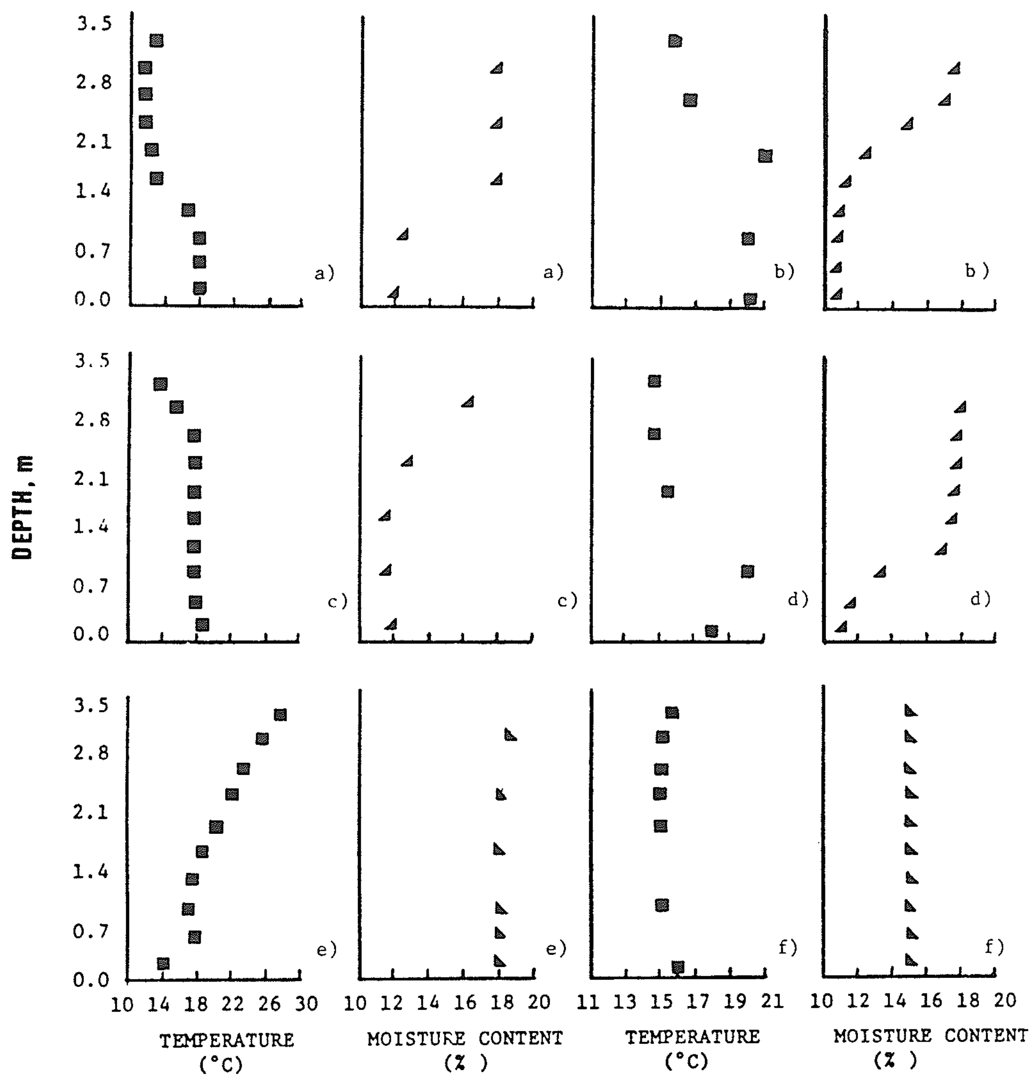


Fig. 6.9: Intergranular air temperatures (■) and moistures contents (◣) during storage at five ventilation rates. The ventilation rates are: (a)12.2 (L/s)/m^3, (b)6.9 (L/s)/m^3, (c)23.2 (L/s)/m^3, (d)3.4 (L/s)/m^3, (e)0.85 (L/s)/$m^3$and (f)0.85 (L/s)/m^3. The sampling dates are 06 Sept. 1983 for storage conditions a,c and e and 09 Sept. 1984 for b,d and f.

The zone of changing temperature due only to sensible heat exchange tends to be wide and not very distinct (Fig. 6.7). Widths were greater than 1.75 m and in most instances spanned the entire bed depth (3.5 m). Diurnal fluctuations of ambient air cause multiple warming and cooling zones to develop within the bin. Due to the large zone-widths, however, these multiple zones disperse before they traverse the bin. Hence, the movement of multiple temperature zones in the bins were not noticed in any of the ventilated bins for either year.

Temperatures in the control bins are affected by heat transfer to the surroundings (by conduction, convection and radiation through and from the bin wall material, free convection from the grain bed surface and free convection within the grain mass) as well as by heat produced by respiration of the grain and associated microflora. Temperature profiles for the 1983-1984 control bins during the first 9 days of storage are shown in Fig. 6.10. A similar temperature pattern was noticed for the 1984-1985 control bins during the first 4 days of storage but temperatures within the bin decreased to below 22°C by day 7 which was not the case in the 1983-1984 experiment where temperatures remained near the original level of around 30°C (Fig. G.7 in appendix G).

6.3 MEASURED MOISTURE CONTENT

Mean bin moisture contents (averaged over all ten layers and between paired storage conditions) of the grain in the drying bins (A,B,C,D and N) were lowered to below 14.5 % before 1 November in both years (Fig. 6.11 and 6.13). Maximum moisture contents of the grain in bins C, D and N in 1984-1985 (airflow of 3.4 $L \cdot s^{-1} m^{-3}$) were not lowered to below 14.5 % by 30 October 1984 at which date ventilation to all bins was

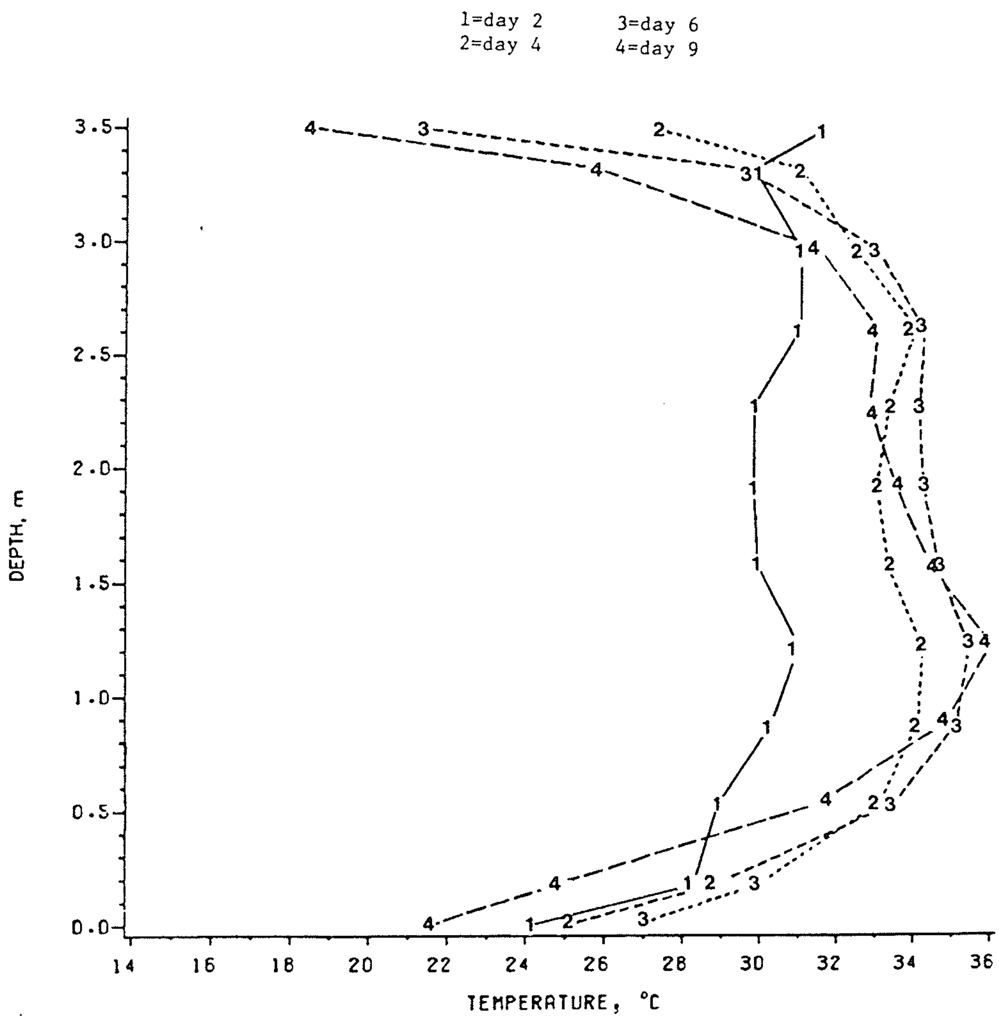


Fig. 6.10: Intergranular air temperatures in a bin of damp wheat with no forced ventilation and a binning date of 31 Aug. 1983. The day variable corresponds to time from binning date (all readings taken at 12:00 h).

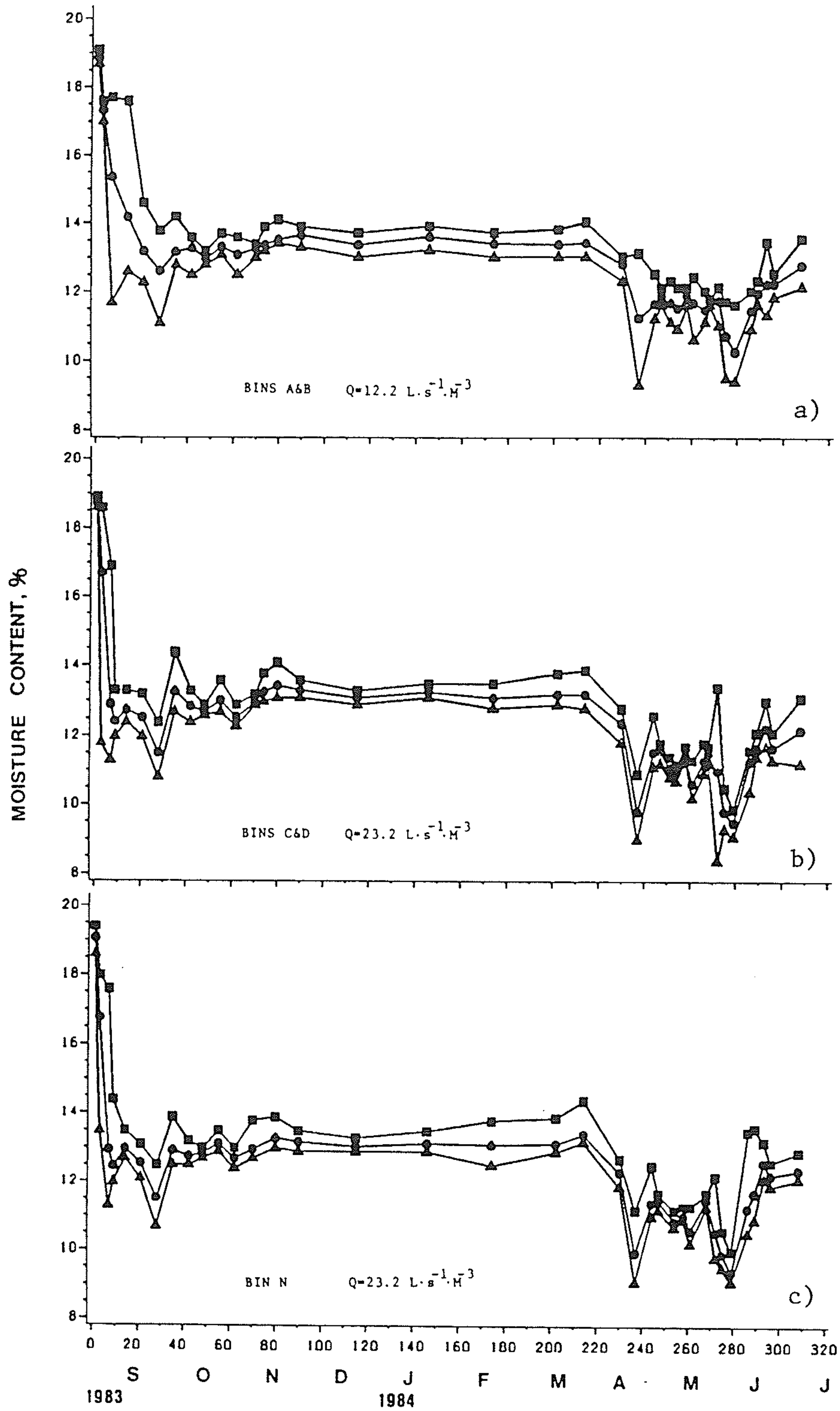


Fig. 6.11: Maximum (■—■), mean (●—●) and minimum (▲—▲) moisture contents of wheat during storage at two ventilation rates from 31 Aug. 1983 to 21 June 1984. Ventilation is continuous from 31 Aug. 1983 to 22 Dec. 1983 and from 02 April to 21 June 1984.

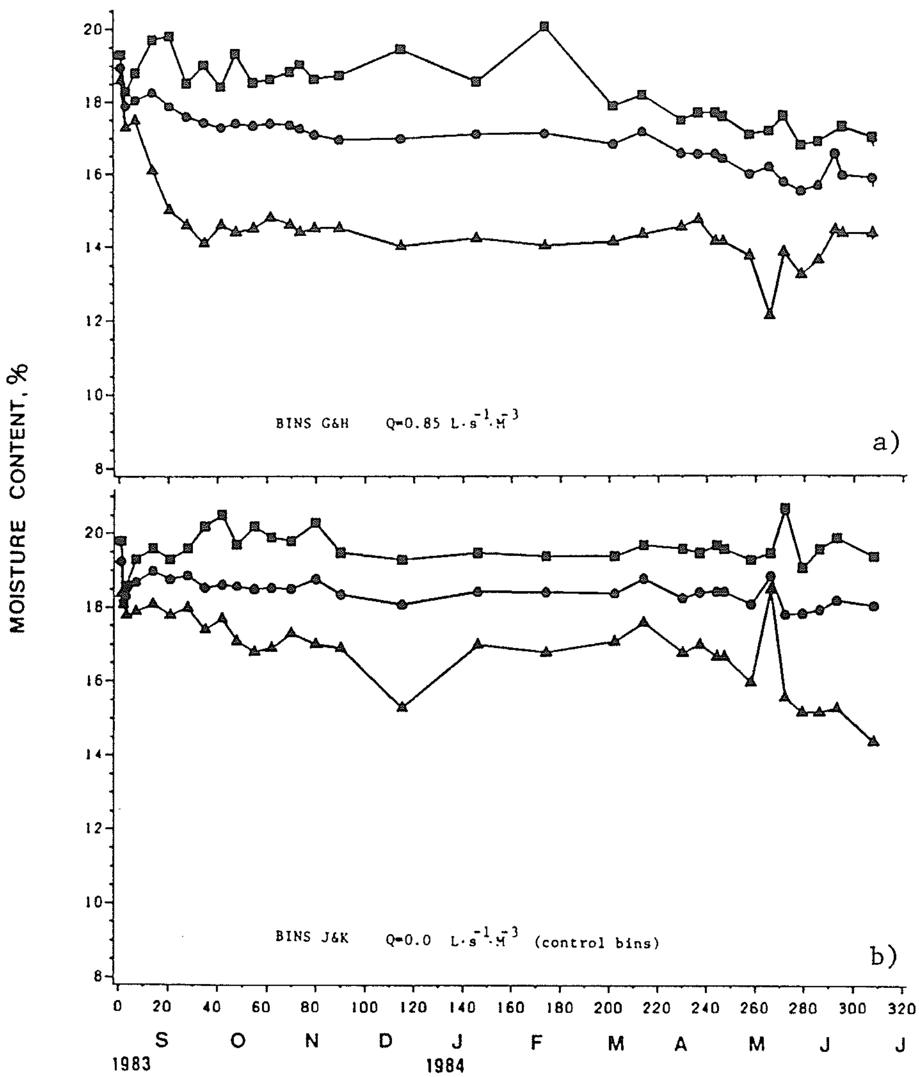


Fig. 6.12: Maximum (■—■), mean (●—●) and minimum (▲—▲) moisture contents of wheat during storage with a) aeration 0.85 (L/s)/m^3 and b) no forced ventilation from 31 Aug. 1983 to 21 June 1984. Ventilation to the aeration bins is continuous from 31 Aug. 1983 to 22 Dec. 1983 and from 2 April 1984 to 21 June 1984.

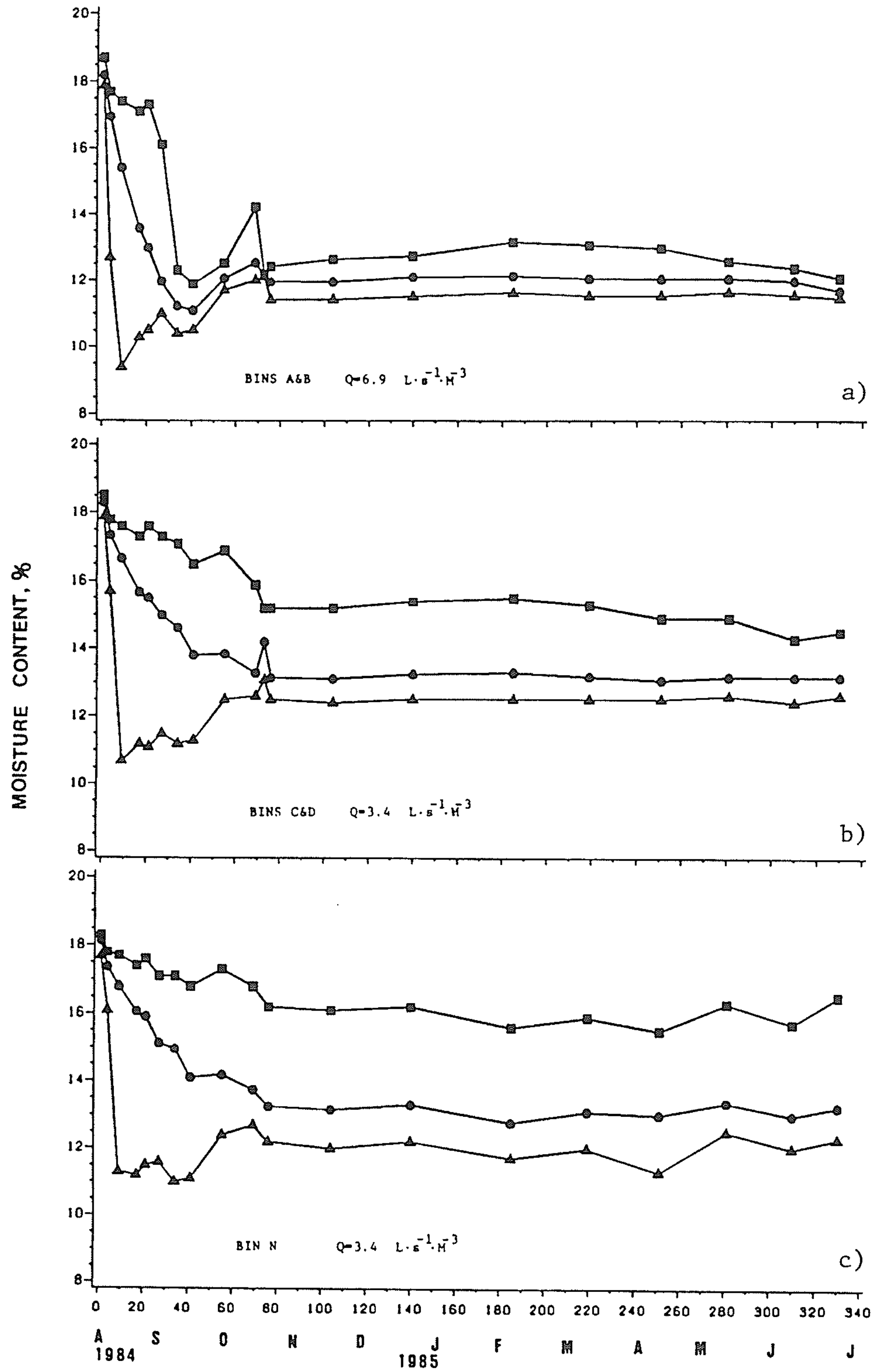


Fig. 6.13: Maximum (■—■), mean (●—●) and minimum (▲—▲) moisture contents of wheat during storage at two ventilation rates from 20 Aug. 1984 to 15 July 1985. Ventilation was continuous from 20 Aug. 1984 to 30 Oct. 1984 with no forced ventilation after 30 Oct. 1984.

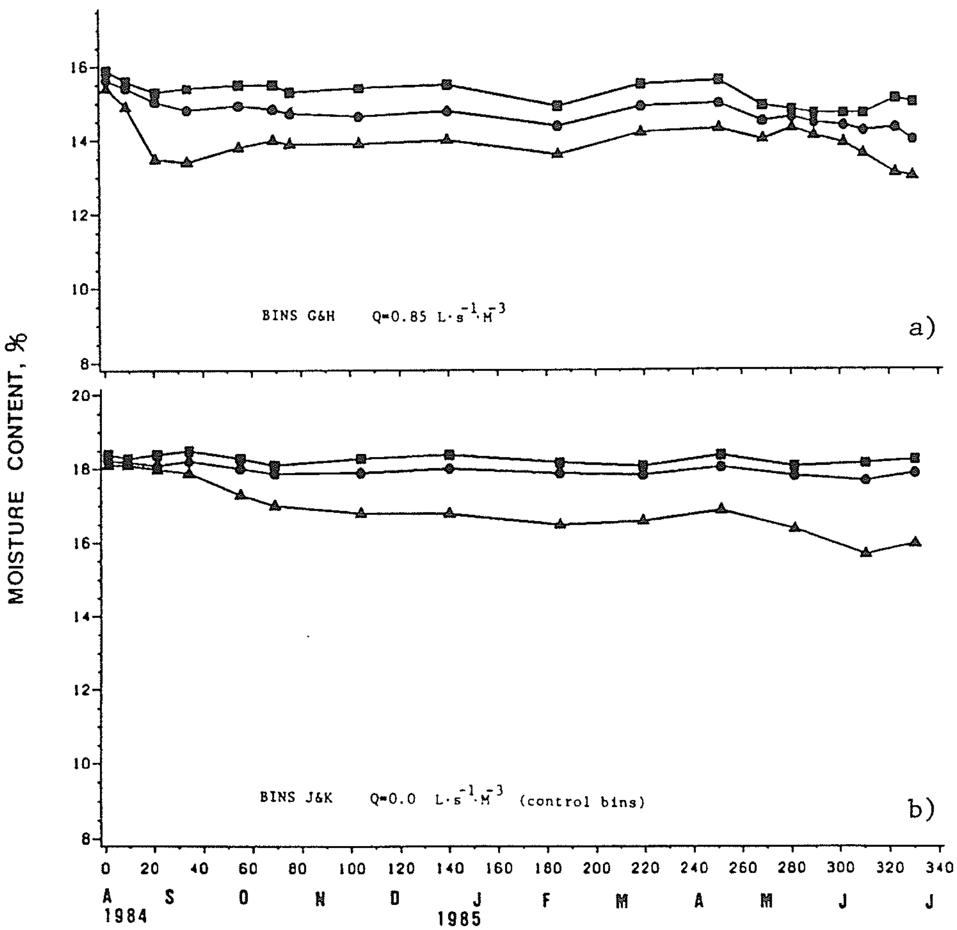


Fig. 6.14: Maximum (■—■), mean (●—●) and minimum (▲—▲) moisture contents of wheat during storage with a) aeration (0.85 $(L/s)/m^3$) and b) no forced ventilation from 20 Aug. 1984 to 15 July 1985. Ventilaion for the aeration bins is continuous from 20 Aug. 1984 to 30 Oct. 1984 and from 6 May 1985 to 15 July 1985.

stopped. Ventilation was stopped on this date to observe whether the higher moisture contents in these bins would create a storage problem. Ventilation to the drying bins (A,B,C,D and N) was not resumed and some of the grain in bins C, D and N was above 14.5 % for the entire test duration. The mean moisture content of the two aeration bins (G and H with airflow of 0.85 $L \cdot s^{-1}m^{-3}$) was not successfully reduced to 14.5 % in the 1983-1984 experiment (Fig. 6.12). For the same bins the following year initial grain moisture content were only 15.6 %. Because of this the aeration reduced the mean moisture contents in bins G and H to below 14.5 % before the end of the study (15 July 1985) (Fig. 6.14). The maximum grain moisture content within bins G and H, however, remained above 14.5 % even though ventilation was resumed on 6 May 1985 unlike ventilation to any of the other bins. In the control bins for both years the mean and maximum moisture content within the bins did not fluctuate appreciably, both remaining between 18 and 21 % in 1983-1984 and between 18 and 19 % in 1984-1985 (Fig. 6.12 and 6.14 respectively). The minimum moisture content found in the control bins fluctuated between 15 and 18.5 % in 1983-1984 and between 16 and 18 % in 1984-1985. In both years the minimum moisture contents were always in the top 1.0 m of the control bins.

Fluctuating conditions of moisture content occurring after the grain bulks have dried to below 14 % are due to moisture readsorption. During times of high humidity, ventilation air adds moisture to the grain. In this experiment the grain was never rewetted to above 14.5 % thus not posing a storage problem. This may be due to a combination of weather conditions experienced during ventilation and temperature increases of the ventilating air as it passed through the fan and ducting.

Moisture profiles within a ventilated grain bin shows the movement of the drying zone (Fig. 6.15). Moisture profiles for bins ventilated at different ventilation rates are presented in appendix G (Fig. G.8 to G.14). I have defined the drying zone as that depth of grain where the moisture content changes from the initial value to a value which is in equilibrium with the ventilation air (Fig. 6.8). The drying front is defined to be located in the drying zone where the grain moisture content is equal to 14.5 %. Using this definition average drying front speeds for the various ventilation rates were calculated and are presented in Tables 6.3 and 6.4.

Typical rewetting profiles for the 12.2 $L \cdot s^{-1} m^{-3}$ airflow bins (A and B) in the 1983-1984 experiment are given in Fig. 6.16. Rewetting profiles for the other bins are similar and thus are not shown.

6.4 SHRINKAGE

In the 1983-1984 drying experiment the initial grain moisture content was approximately 19 % and the mean bed depth decrease was 11 % (range 9.4 to 12.0 %) for the drying bins (A,B,C,D and N). In the 1984-1985 drying experiment the initial grain moisture content was approximately 18 % and the mean bed depth decrease was 12 % (range 8.5 to 13.7 %) for the drying bins (Table 6.5). These decreases in bed depths are due to grain shrinkage (due to moisture loss), settling and sample removal.

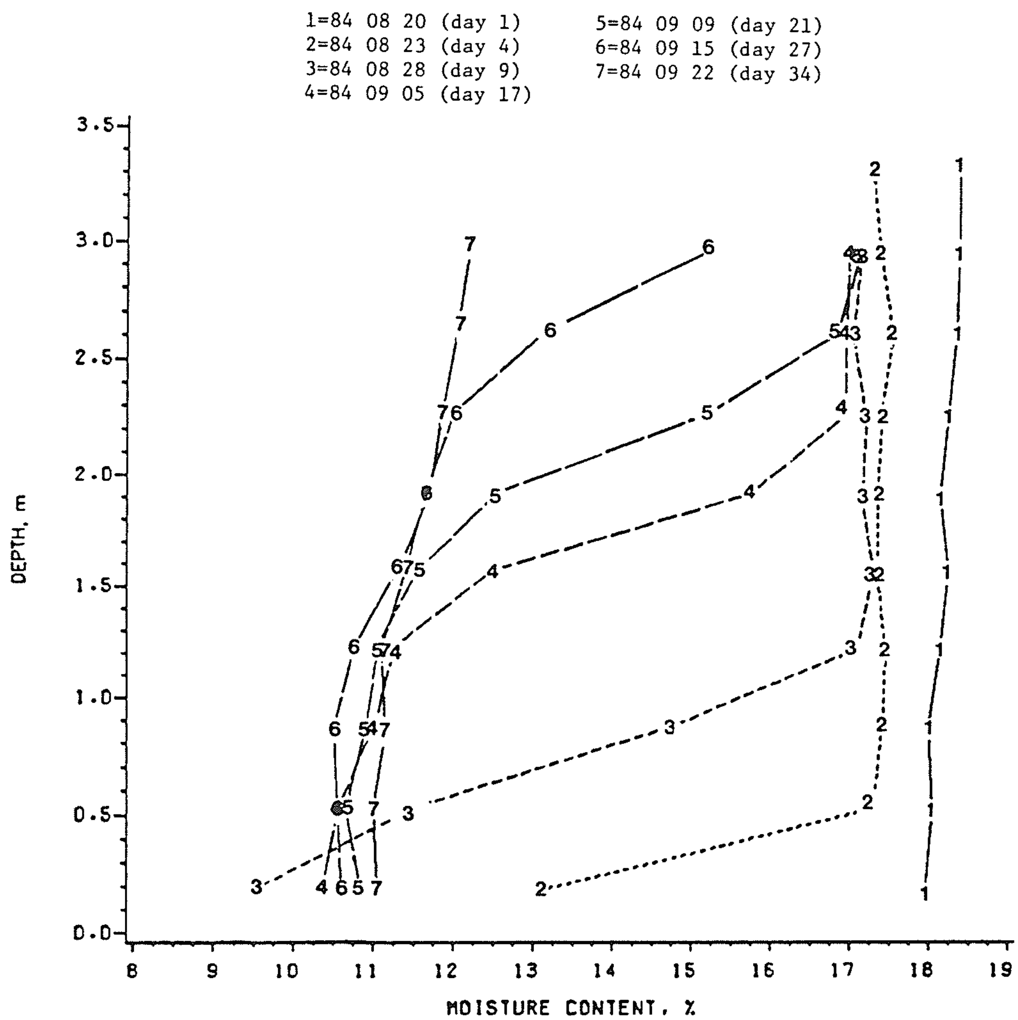


Fig. 6.15: Moisture contents of wheat for 7 sampling dates during storage at a ventilation rate of 6.9 (L/s)/m^3 and a binning date of 20 Aug. 1984 (each value is the mean of bins A and B).

TABLE 6.3

Experimental and simulated drying front speeds, 1983-1984 test.

Results are for wheat dried from 19 % to below 14.5 % moisture content. Drying front speeds (m/day) are calculated from ventilation start date to date shown.

Source	Airflow rate ((L/s)/m³)	date (month day) and days of ventilation 09 02 3	09 06 7	09 08 9	09 13 14	09 20 21
measured						
bins C & D (M1)	23.2	0.46	0.53			
bin N (M2)	23.2	0.51	0.51			
bins A & B (M3)	12.2		0.24	--	0.20	0.17
simulated						
S1	23.2	0.45	0.43	0.41		
S2	12.2	0.28	0.23	0.22	0.20	0.17
ratios						
M1/M2		0.90	1.04	--		
M1/M3		--	2.21	--		
M1/S1		1.02	1.23	--		
S1/S2		1.61	1.87	1.86		
M2/M3		--	2.13	--		
M2/M1		1.11	0.96	--		
M2/S1		1.13	1.19			
M3/M1		--	0.45	--	--	--
M3/M2		--	0.47	--	--	--
M3/S2		--	1.04	--	1.00	1.00
S2/S1		0.62	0.53	0.54	--	--
23.2/12.2		1.90				
12.2/23.2		0.53				

6.5 OXYGEN AND CARBON DIOXIDE COMPOSITION OF INTERGRANULAR AIR

In the control bins intergranular oxygen (O_2) concentrations decreased and carbon dioxide (CO_2) concentrations increased during the first 80 and last 60 days of storage (fall and spring respectively) for both years (Fig. 6.17 and 6.18). Although O_2 data was not measured during the first few weeks of storage for both years it was assumed to be lower than normal as CO_2 values were extremely high indicating accelerated microbial activity.

TABLE 6.4

Experimental and simulated drying front speeds, 1984-1985 test.

Results are for wheat dried from 18.2 % to below 14.5 % moisture content. Drying front speeds (m/day) are calculated from ventilation start date to date shown.

Source	Airflow rate ((L/s)/m³)	date (month day) and days of ventilation 08 28 9	09 05 17	09 09 21	09 15 27	09 22 34	09 29 40	10 27 68
measured								
bins A & B (M1)	6.9	0.12	0.13	0.12	0.12			
bins C & D (M2)	3.4	0.056	0.056	0.056	0.054	0.051	0.052	0.047
bin N (M3)	3.4	0.052	0.048	0.049	0.047	0.046	0.045	0.041
simulated								
S1	6.9	0.10	0.11	0.11	0.10			
S2	3.4	0.064	0.063	0.059	0.056	0.053	0.052	0.047
ratios								
M1/M2		2.14	2.32	2.14	2.22			
M1/M3		2.31	2.71	2.45	2.55			
M1/S1		1.20	1.18	1.09	1.20			
S1/S2		1.56	1.75	1.86	1.79			
M2/M1		0.47	0.43	0.47	0.45	--	--	--
M2/M3		1.08	1.17	1.14	1.15	1.11	1.16	1.15
S2/S1		0.64	0.57	0.54	0.56	--	--	--
M3/M1		0.43	0.37	0.41	0.39	--	--	--
M3/M2		0.93	0.86	0.87	0.87	0.90	0.87	0.87
M3/S2		0.81	0.76	0.83	0.84	0.87	0.87	0.87
6.9/3.4		2.03						
3.4/6.9		0.49						

Carbon dioxide concentrations in the control bins during the 1983-1984 experiment increased to 22.4 % (680 times the ambient air level of 0.033 %) within 14 days of binning and remained above 19 % until day 80 (November 1983) then dropped sharply to 0.17 % during the next 42 days coincident with the onset of winter. At the onset of spring, CO_2 concentrations again increased peaking on day 260 (May 1984) at 22% (Fig. 6.17). Carbon dioxide concentrations in the control bins (J and

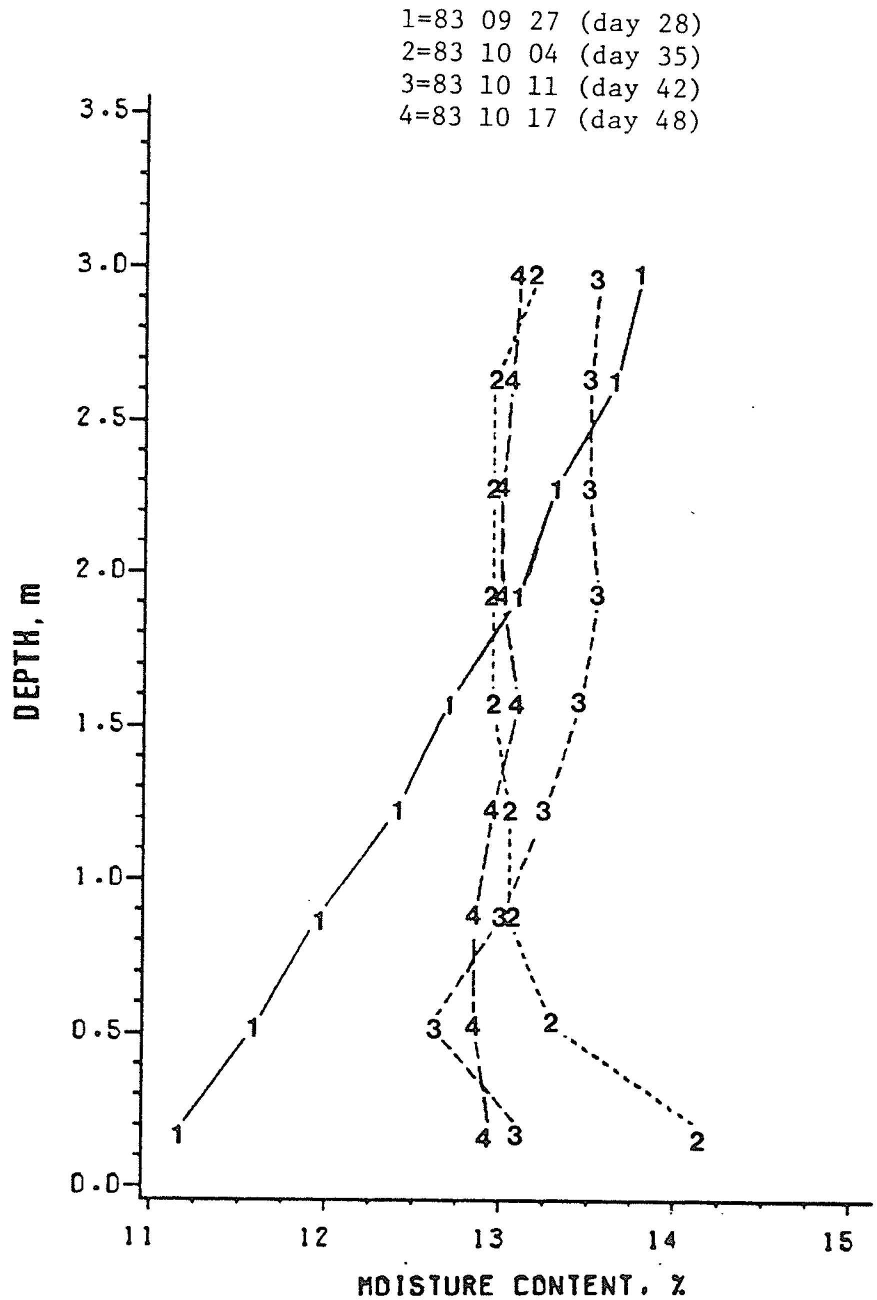


Fig. 6.16: Moisture contents of wheat for various sampling dates during storage at a ventilation rate of 12.2 (L/s)/m^3. Plot shows moisture readsorption by the grain during periods of high humidity.

TABLE 6.5

Bulk shrinkage values for the two test years.

Bin	Airflow rate ((L/s)/m³)	Initial mean moisture content (%)	Final mean moisture content (%)	Shrinkage* (percent of total bed depth) (%) mean	s.d.
		1983-1984 experiment			
C & D	23.2	19.0	12.2	11	0.76
N	23.2	19.0	12.4	12	----
A & B	12.2	19.0	12.8	10	0.76
G & H	0.85	19.0	16.0	4	0.24
J & K	0.00	19.0	18.2	1	0.00
		1984-1985 experiment			
A & B	6.9	18.2	11.8	14	0.52
C & D	3.4	18.2	13.2	11	1.39
N	3.4	18.2	13.3	9	----
G & H	0.85	15.6	14.2	4	0.21
J & K	0.00	18.2	18.0	3	0.51

* N = 2, mean and standard deviation (s.d.). For bin N there is only one observation and therefore it has no standard deviation.

K) during the 1984-1985 experiment increased to 11.6 % within 17 days of binning after which concentrations dropped to 0.2 % during the next 80 days coincident with the onset of winter. In the spring CO_2 concentrations again increased peaking on day 330 (15 July 1985) at 12 % (Fig. 6.18).

Carbon dioxide concentrations in the ventilated bins were not as dramatic as in the control bins for either year. In the ventilated 0.61-m diameter bins CO_2 concentrations increased within 14 days to 0.43 % in the 23.2 and 12.2 $L \cdot s^{-1} m^{-3}$ airflow bins (C,D,A and B) and to 0.76 % in the aeration bins (G and H) during the 1983-1984 experiment (Fig. 6.17). Maximum CO_2 concentrations in these bins decreased to below 0.08 % by

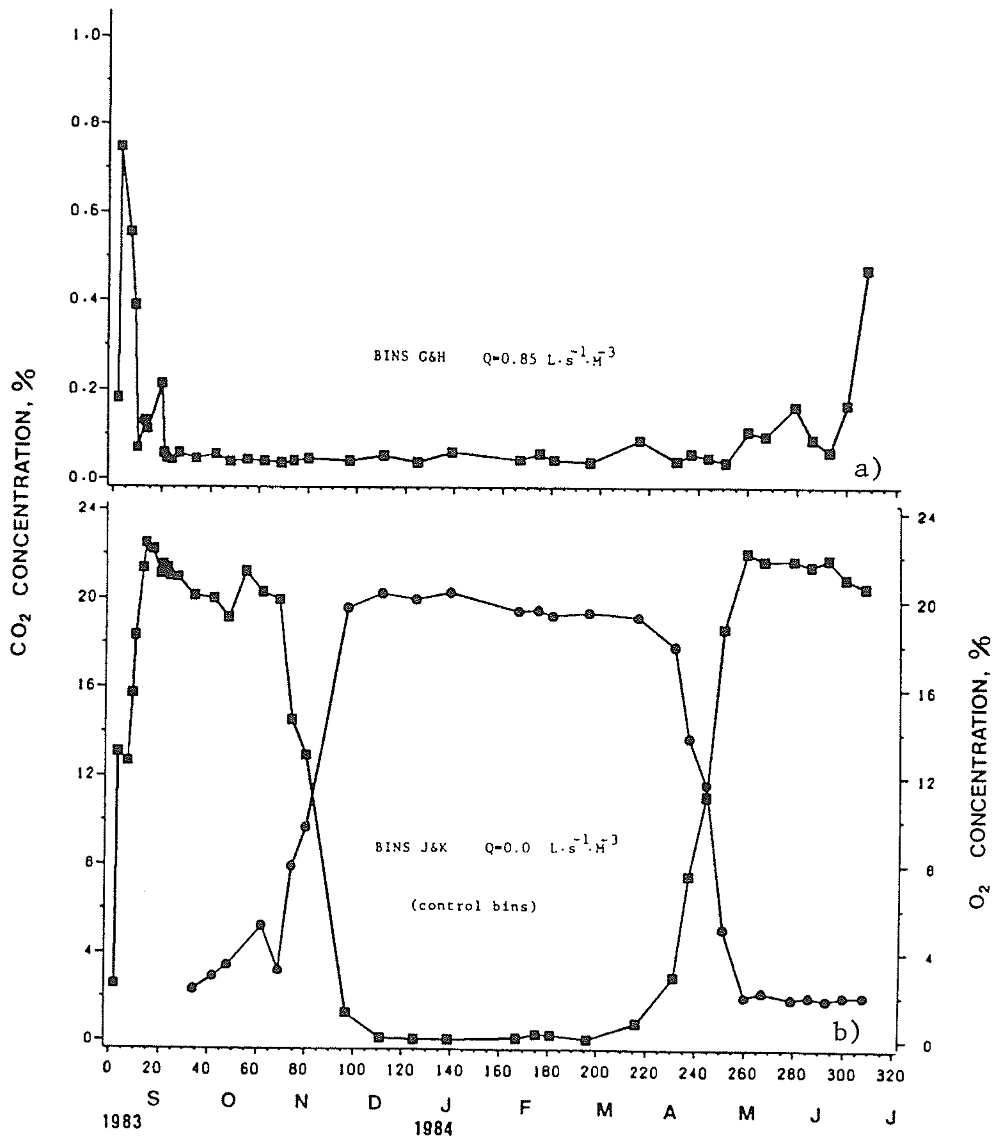


Fig. 6.17: Maximum CO_2 (■——■) and minimum O_2 (●——●) concentrations during storage of wheat (initial moisture content 19 %) stored at two ventilation rates from 31 Aug. 1983 to 21 June 1984.

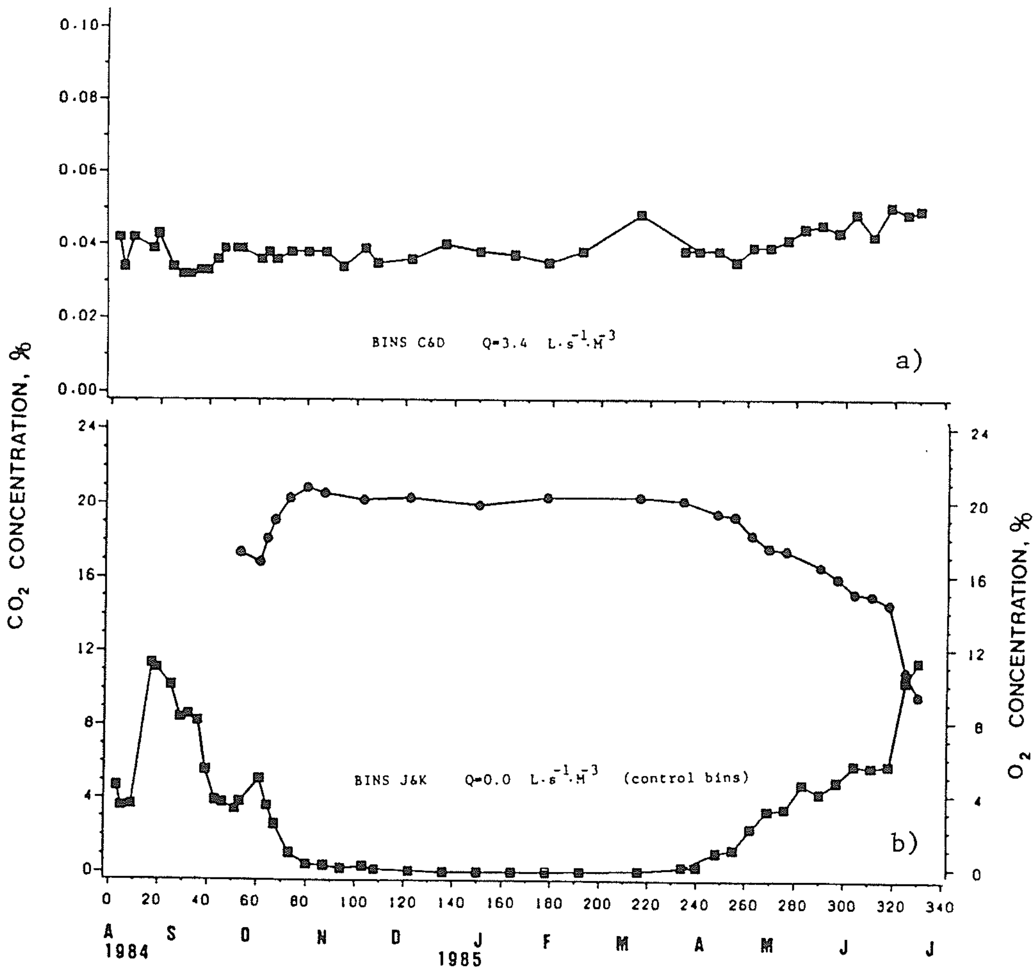


Fig. 6.18: Maximum CO_2 (■——■) and minimum O_2 (●——●) concentrations during storage of wheat (initial moisture content 18 %) stored at two ventilation rates from 20 Aug. 1984 to 15 July 1985.

day 20 and remained below this level for the remainder of the storage period. Carbon dioxide concentrations in the 1.22-m diameter bin (N), with an airflow rate of 23.2 $L \cdot s^{-1} m^{-3}$, increased to 0.65 % within 14 days and then decresed to 0.14 % over the next 70 days. Maximum CO_2 concentrations in this bin then decreased to below 0.08 % and remained below this level for the remainder of the storage period. Carbon dioxide concentrations for all ventilated bins during the 1984-1985 experiment remained less than 0.06 % throughout the entire test period (Fig. 6.18).

Oxygen concentrations in the control bins show an inverse relation to CO_2 concentrations (Fig. 6.17 and 6.18). Oxygen concentrations were not measured in the ventilated bins as forced ventilation continuously flushed the bulk grain; O_2 concentrations in these bins were therefore presumed to be near the atmospheric level as were measured CO_2 concentrations.

Carbon dioxide and oxygen concentration profiles for the control bins (J and K) indicate accelerated microfloral activity in the central depths and less activity near the top and bottom of the columns (Fig. 6.19). Similar patterns of elevated CO_2 and depressed O_2 concentrations were found in the 1984-1985 control bins (Fig. G.15 in appendix G).

6.6 FAT ACIDITY

The range of FAV (fat acidity values) of newly-harvested moisture-conditioned wheat during binning on 31 August 1983 was from 5.9 to 9.7 mg KOH per 100 mg of dry seed (mean 7.1) and on 20 August 1984 was from 4.8 to 8.2 mg KOH per 100 mg of dry seed (mean 6.4). This indicates that for both years autolyses had not begun by binning date and the seeds in all bins were stored sound. In the drying bins (A,B,C,D and N)

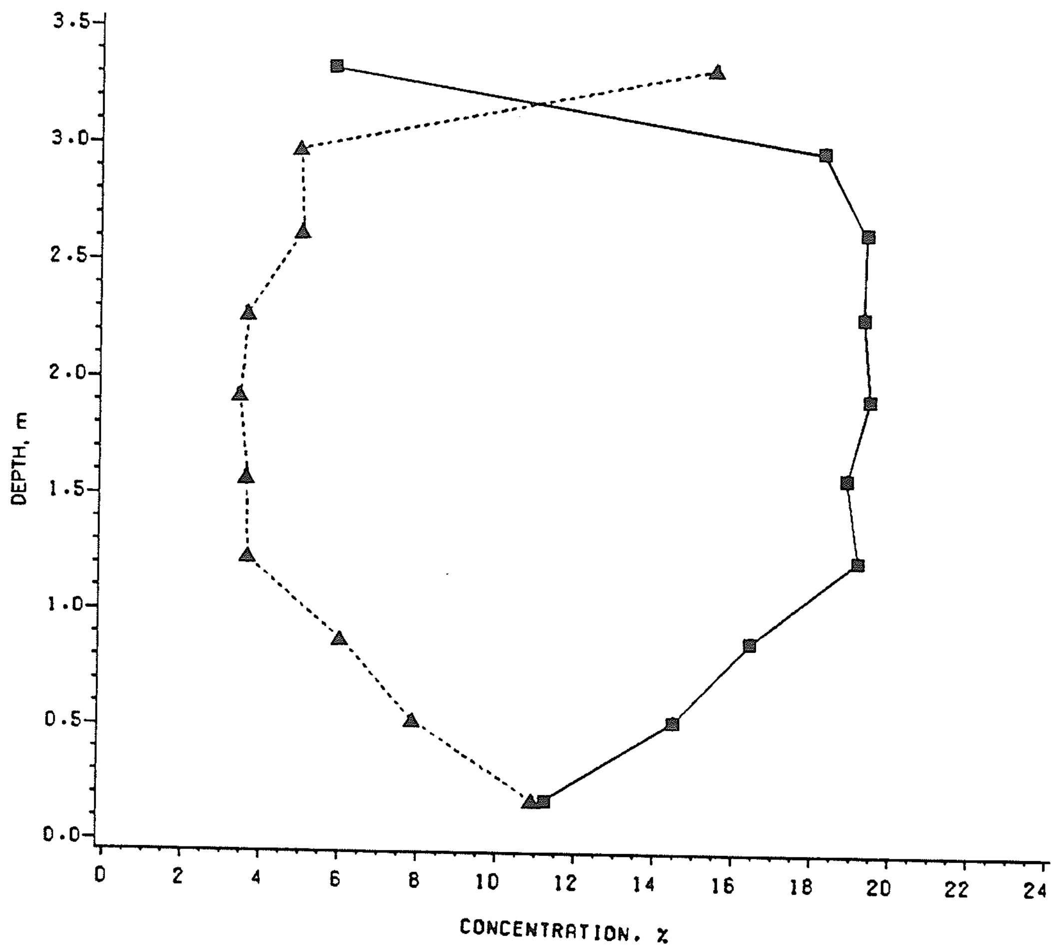


Fig. 6.19: CO_2 (■—■) and O_2 (▲- -▲) concentrations during storage of wheat (initial moisture content 19 %) with no forced ventilation and a binning date of 31 Aug. 1983. Sample date shown is 11 Oct. 1983.

fat acidity values remained close to those of initial values for both years, indicating little biochemical quality loss during storage. For the 1.22-m diameter bin (N) maximum fat acidity values increased from 7.6 mg KOH per 100 mg of dry seed on day 34 (22 Sept. 1984) to 13.5 (mean level of 12.1) on day 55 (13 October 1984) but then decreased to 8.0 by day 69 and remained near this level until the end of the experiment. This "jump" in fat acidity value could have been caused by a pocket of spoiled grain that was dispersed by day 69. How such a pocket of spoiled grain could occur in a ventilated bin is unknown. In the aeration bins (G and H) during 1983-1984 and in the control bins (J and K) for both years noticeable increases took place (Fig. 6.20 and 6.21). In 1984-1985 fat acidity values in the aeration bins remained close to those of the initial values indicating little biochemical quality loss during storage.

For the aeration bins (G and H) of 1983-1984 maximum increases in fat acidity occurred in the top 1.0 m of the bulk grain (Fig. 6.22a). In the control bins (J and K) of 1983-1984 increases were more or less uniform throughout the bins while in 1984-1985 the increases were most pronounced between 1.2 and 2.6 m above the bin floor (Fig. 6.22 b and c).

6.7 SEED GERMINATION AND MICROFLORA

Seed germination and microflora were measured for all bins during the two years. These data have been presented and discussed by Sinha et al. (1985) and Sanderson et al. (1985). Some brief observations pertaining to these variables will be presented here.

Some of the low initial germination values in all groups of bins for both years may have resulted from difficulties encountered in breaking seed dormancy shortly after harvest (Fig. 6.23 and 6.24).

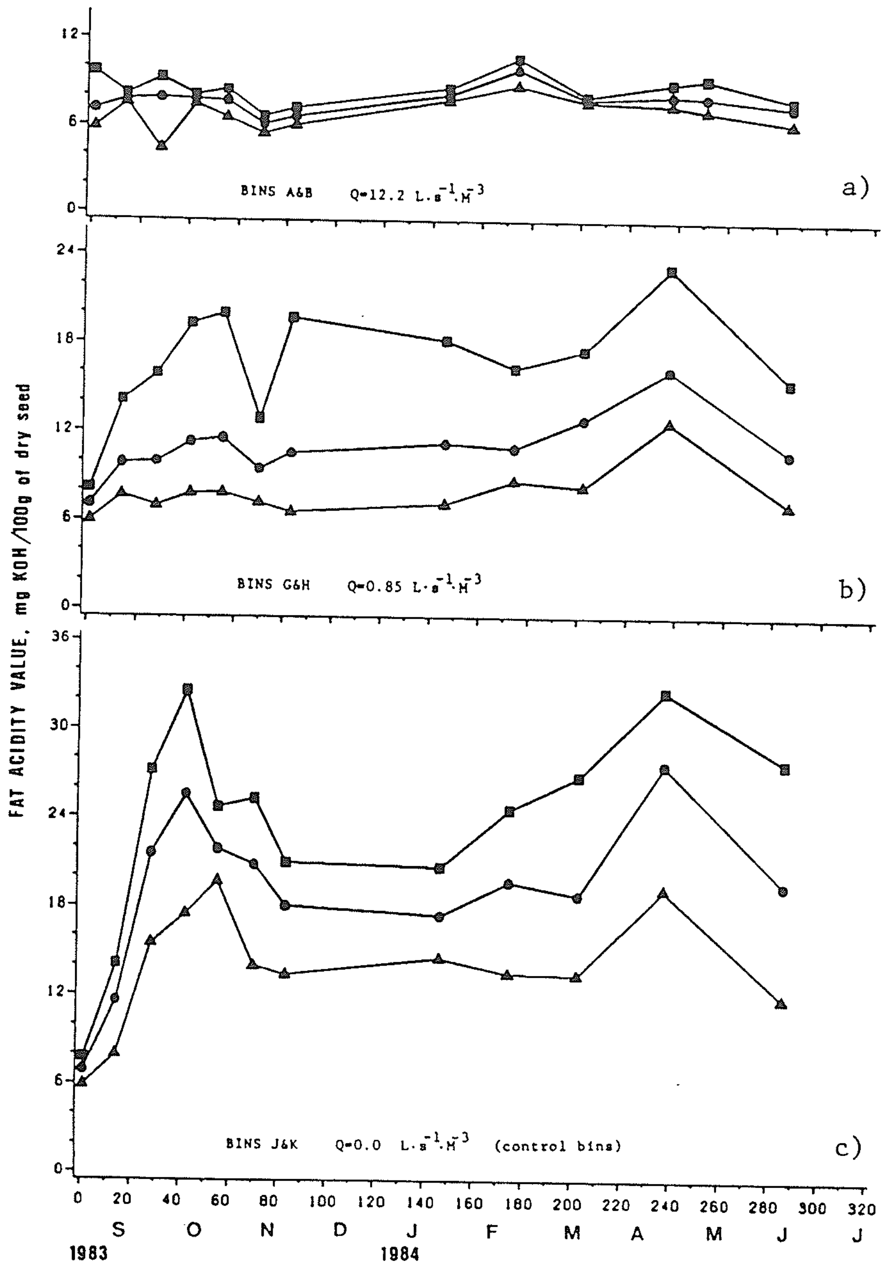


Fig. 6.20: Maximum (■—■), mean (●—●) and minimum (▲—▲) fat acidity values (FAV) of wheat (initial moisture content 19 %) during storage at three ventilation rates from 31 Aug. 1983 to 21 June 1984 (Sinha et al. 1985).

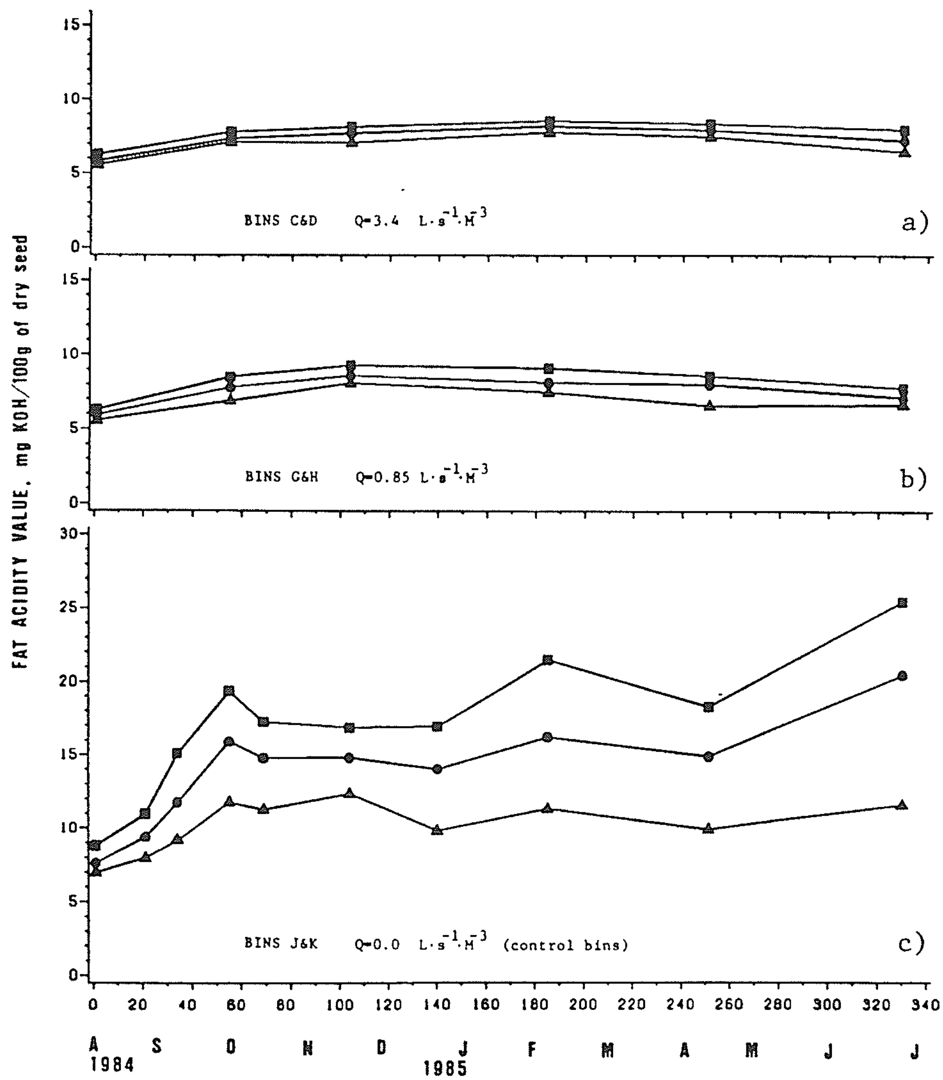


Fig. 6.21: Maximum (■—■), mean (●—●) and minimum (▲—▲) fat acidity values (FAV) of wheat (initial moisture content 18 %) during storage at three ventilation rate from 20 Aug. 1984 to 15 July 1985.

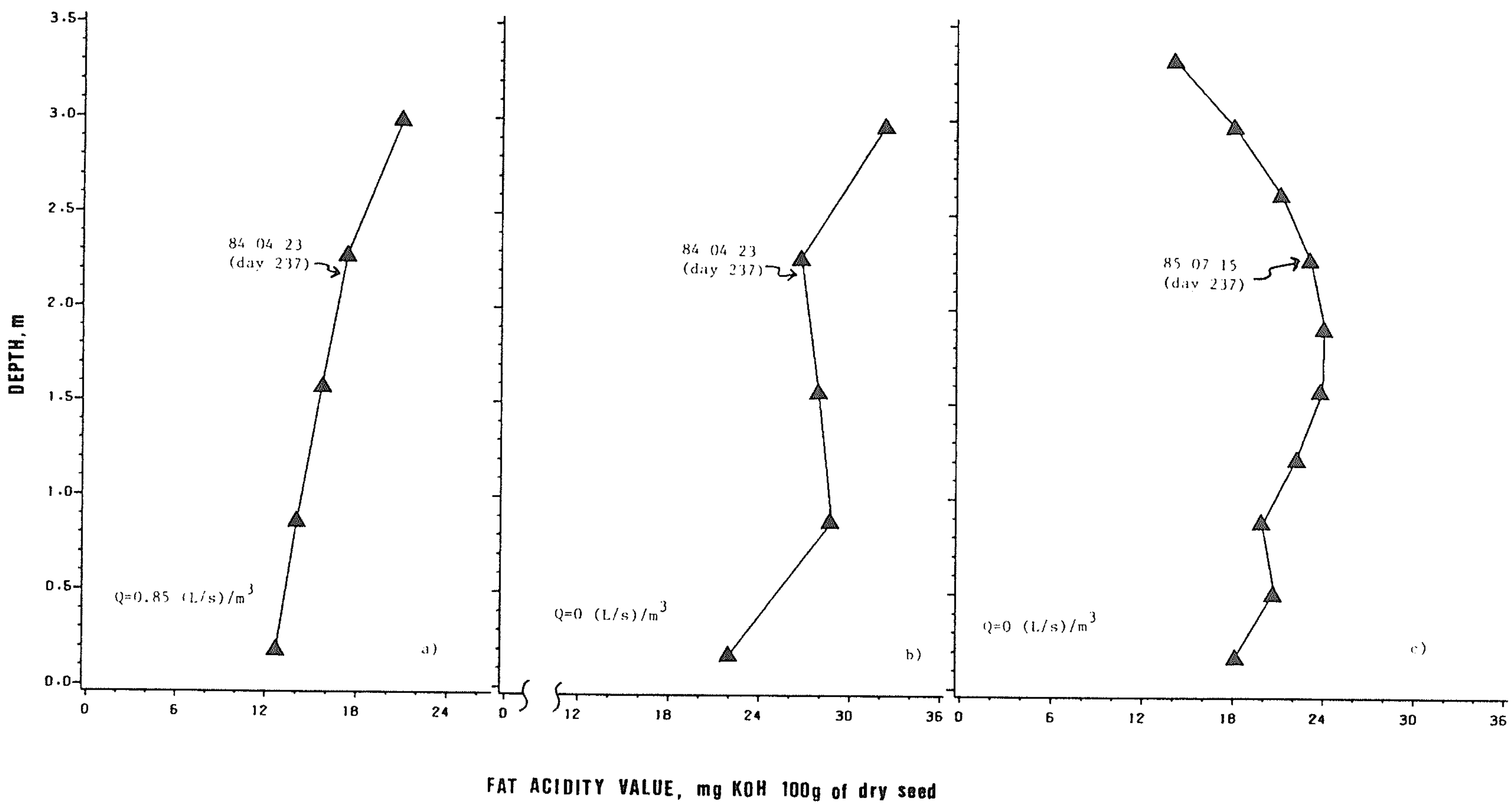


Fig. 6.22: Fat acidity values of wheat for three storage conditions:
(a) wheat (initial moisture content 19 %) ventilated at 0.85 $(L/s)/m^3$,
(b) wheat (initial moisture content 19 %) with no forced ventilation and
(c) wheat (initial moisture content 18 %) with no forced ventilation.

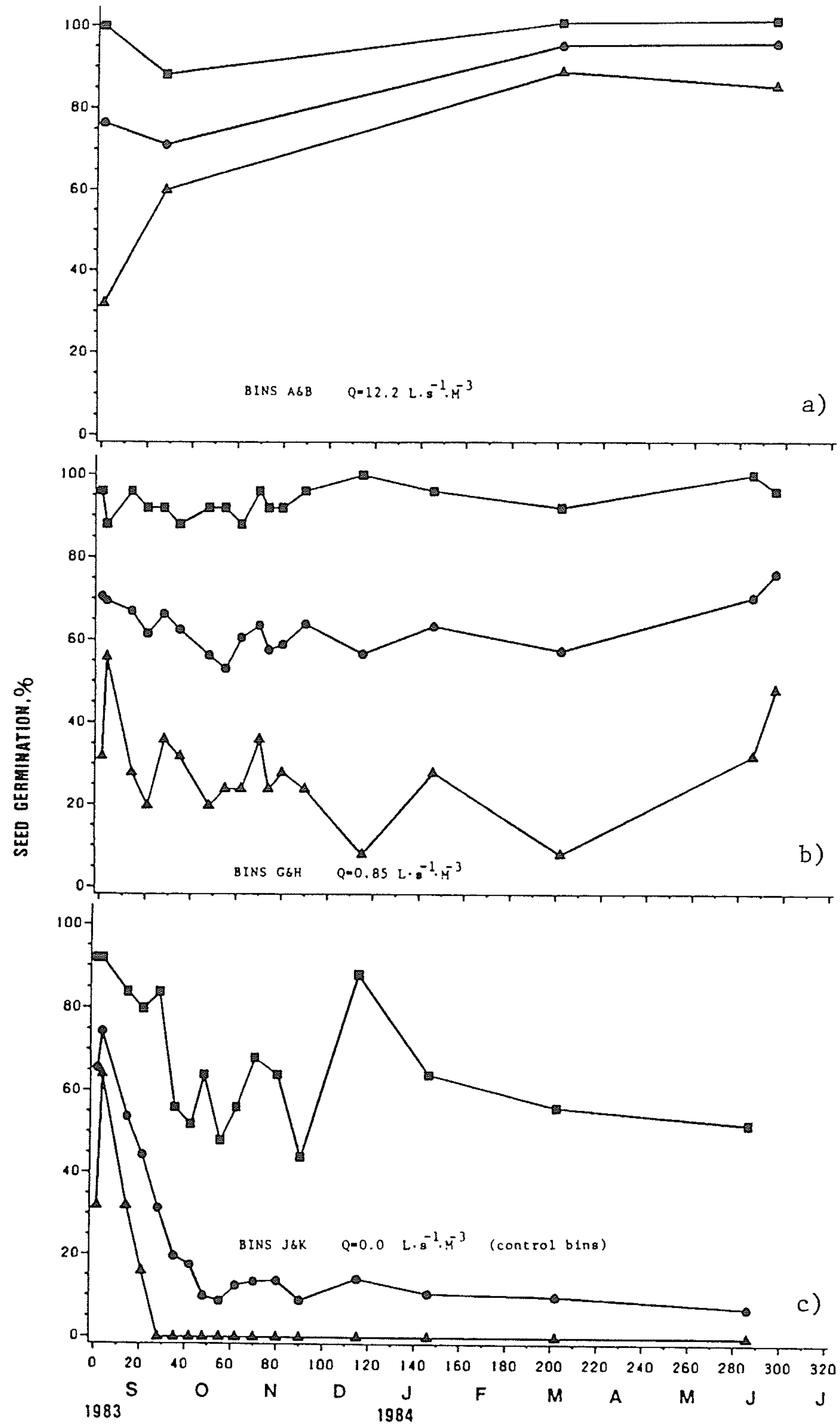


Fig. 6.23: Maximum (■——■), mean (●——●) and minimum (▲——▲) seed germinations of wheat (initial moisture content 19%) during storage at three ventilation rates from 31 Aug. 1983 to 21 June 1984 (Sinha et al. 1985).

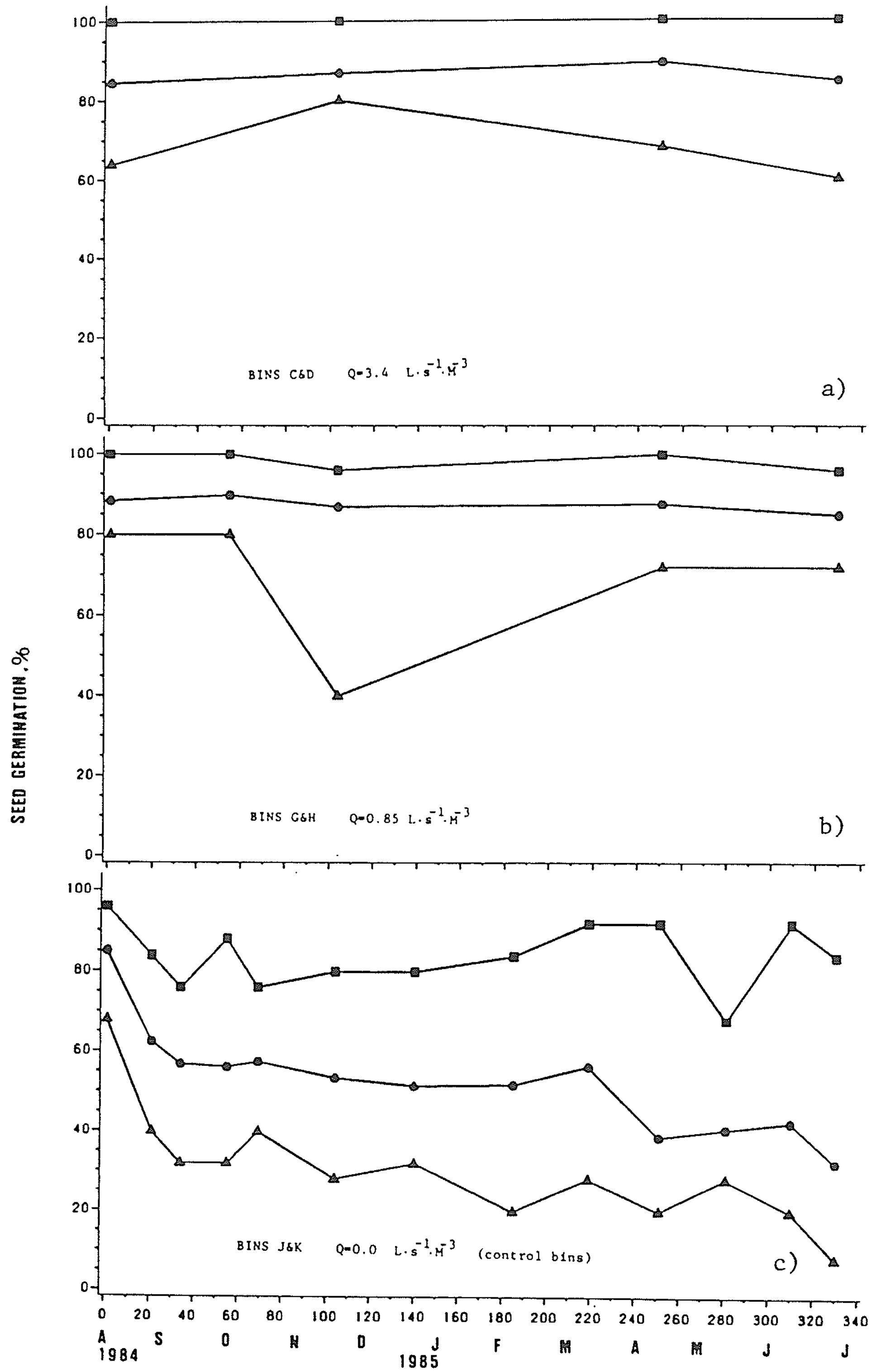


Fig. 6.24: Maximum (■—■), mean (●—●) and minimum (▲—▲) seed germinations of wheat (initial moisture content 18%) during storage at three ventilation rates from 20 Aug. 1984 to 15 July 1985.

In the 12.2 $L \cdot s^{-1}m^{-3}$ airflow bins (A and B 1983-1984 test) seed germination loss was minimal; an average of 92 % of the seeds germinated on day 286 (range 78 to 100 %) (Fig. 6.23a). At an airflow of 23.2 $L \cdot s^{-1}m^{-3}$ similar germination patterns were noted.

In the 1983-1984 aeration bins (G and H), with an airflow of 0.85 $L \cdot s^{-1}m^{-3}$, the mean levels of germination throughout these bins ranged from 53 to 71 %, the maximum from 88 to 100 % and the minimum from 8 to 56 % (Fig. 6.23b). Germination losses in these bins were progressively greater from the bottom layer to the top by the end of storage.

In 1983-1984 mean germination within the control bins was drastically reduced during the first 48 days of storage dropping from 75 % to 10 % staying near this level until the end of the storage period (Fig. 6.23c). Germination being almost completely lost by day 286 (11 June 1984) everywhere except in the top layers where germinations ranged from 36 to 44 %.

For the 1984-1985 drying tests germination loss in the ventilated bins was minimal. An average of 84 % and 86 % of the seeds germinated at the end of the study (15 July 1985) for the 3.4 $L \cdot s^{-1}m^{-3}$ airflow bins (A and B) and the aeration bins (G and H) respectively. Occasional drops in the minimum germinations for the above storage conditions was noticed. These drops are attributed to sample variation as the patterns of reduced germination was not consistent in the bins over several sampling periods (Fig. 6.24 a and b).

In the 1984-1985 control bins mean germination was reduced to below 60 % by day 34 (22 September 1984) and continued to decrease to 30 % by day 330 (15 July 1985) (Fig. 6.24c). Germination being reduced by this date to below 40 % everywhere except in the top layer.

Fewer kinds of microflora occurred in the ventilated bins than in the control bins for both years. Of the preharvest fungi Alternaria and Helminthosporium were most common. Alternaria occurred at mean infection levels of 56 and 37 % for the start of the 1983-1984 and 1984-1985 storage periods respectively. As storage time progressed mean levels of infection decreased indicating the dying of this fungus. Helminthosporium occurred at a mean infection level of less than 10 % for the entire storage period of both years.

Of the postharvest storage fungi only two, fungi of the Aspergillus glaucus group and A. candidus Link ex Fries were common in the aeration bins of 1983-1984. In 1984-1985 A. glaucus and A. candidus were not common in the aeration bins because of low grain moisture content (15.6 %). Aspergillus glaucus group, A. candidus and Penicillium were the postharvest fungi occurring in the control bins for both storage years. Invasion by the A. glaucus group species occurred before those of other postharvest fungi after which invasion of Penicillium and A. candidus occured. In 1983-1984 A. candidus was the predominant postharvest fungus in the control bins while in 1984-1985 it was A. glaucus.

Bacteria were common in all groups of bins during the early stages of storage for both years probably because the grain was conditioned to the desired moisture content on hot days (around 30°C) (Sinha et al. 1985). Because of the method used for moisture conditioning, the moisture content of individual kernel surfaces could have varied considerably from those measured with bulk samples. Consequently, microenvironments favourable for bacterial growth could have been created.

6.8 GRAIN GRADE

The freshly harvested wheat for the 1983-1984 experiment was graded No. 1 C.W. Red Spring and No. 2 C.W. Red Spring (two separate samples). The moisture conditioning process, required to raise the grain moisture content for the drying test, caused the grade to fall to No. 3 C.W. Red Spring on account of mildew. The grain grades for all ventilated bins remained at this level throughout the test period. Grain grades for the control bins, however, dropped by the end of the experiment (21 June 1984) to "rotted on account of strong objectionable odour" indicating severe quality loss.

For the 1984-1985 experiment freshly harvested wheat received a grade of No. 2 C.W. Red Spring on account of immature green kernels. The moisture conditioning process did not alter the grade for this year. The only grade changes noted in all bins throughout the storage period were in the aeration bins (G and H) where the grade for grain at mid-depth (1.75 m from floor) dropped to No. 3 C.W. Red Spring. The grain in the control bins remained at No. 2 C.W. Red Spring throughout the experiment.

6.9 COMPUTER SIMULATION

6.9.1 Simulated temperatures

Selected values of experimental and simulated temperatures throughout the grain beds of the ventilated bins of the 1983-1984 experiment are shown in Fig. 6.25. These plots demonstrate the maximum deviations which occurred between experimental and simulated temperatures. Profiles of experimental and simulated temperatures at other sampling dates generally compare better than what is demonstrated here (see appendix G Fig. G.16 to G.18 for examples).

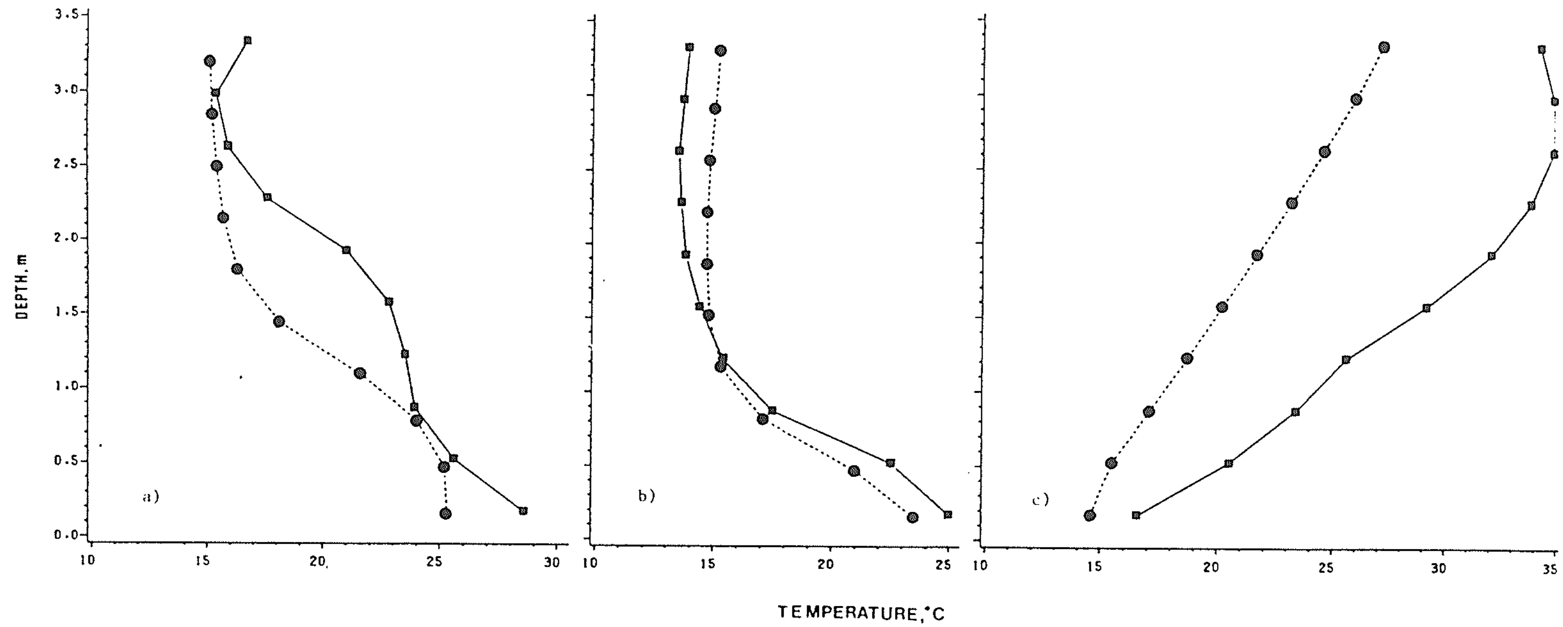


Fig. 6.25: Experimental (■——■) and simulated (●- - ●) intergranular air temperatures during ventilation at an airflow rate of (a) 23.3 (L/s)/m^3 ,(b) 12.2 (L/s)/m^3 and (c) 0.85 (L/s)/m^3. Sampling date shown is 04 Sept. 1983 at 12:00 h.

Maximum observed differences between experimental and simulated temperatures in the drying bins were 5.5^{o}C for the 23.2 $L \cdot s^{-1} m^{-3}$ airflow rate (bins C,D and N) and 3^{o}C for the 12.2 $L \cdot s^{-1} m^{-3}$ airflow rate (bins A and B). These differentials occurred within the drying zone where evaporative cooling is present. Here the accuracy of temperature predictions depend on how well measured and calculated drying front locations compare because a measured drop in temperature of up to 5^{o}C in the drying zone is possible (Fig. 6.8). Simulated temperatures above or below the drying zone were generally within 2^{o}C of the measured experimental values.

Maximum observed differences between experimental and simulated temperatures in the aeration bins (G and H) in the 1983-1984 experiment was 12^{o}C which occurred during the first 11 days of storage (corresponding to the initial cooling period for these bins). Once the initial cooling zone has passed through the bins the maximum observed deviation between measured and simulated intergranular-air temperatures for this airflow rate was 4^{o}C.

Simulated intergranular air temperatures for the 1984-1985 drying season can not be compared to experimental results because of a breakdown of the data acquisition unit (Sec. 6.2).

Simulated intergranular air temperatures for the control bins of either the 1983-1984 or 1984-1985 test years were not produced because the drying model used was not designed to simulate temperatures in a non-ventilated grain bulk which is subject to active spoilage. The active spoilage acts as an internal source of heat and would have to be accounted for.

6.9.2 Simulated moisture contents

The experimental and simulated values of moisture content are shown in Fig. 6.26 to 6.29. The simulated drying fronts moved more slowly through the grain bed than measured ones at airflow rates of 6.9 $L \cdot s^{-1}m^{-3}$ and above (Fig. 6.26 to 6.28 and Table 6.3). This becomes most noticeable at the 23.2 $L \cdot s^{-1}m^{-3}$ airflow rate where the calculated drying front speed for the simulation was 19 % slower than the measured drying front speed on day 7 (Table 6.3) when the calculated drying front lagged behind the experimental one by 0.50 m. At an airflow rate of 3.4 $L \cdot s^{-1}m^{-3}$ calculated drying fronts moved quicker than measured ones (Table 6.3 and Fig. 6.29). The shapes of the calculated drying zones are similar to observed ones.

Experimental and simulated mean moisture contents, averaged for all layers and bins at the same storage condition, for the bins ventilated at 23.2, 12.2 and 3.4 $L \cdot s^{-1}m^{-3}$ remained within 0.5 percentage points of each other during the drying period. Experimental and simulated mean moisture contents for the 6.9 $L \cdot s^{-1}m^{-3}$ airflow rate remained within 0.5 percentage points of each other for the first 26 days of drying (15 September 1984), after which experimental mean moisture contents were 1.0 percentage point below simulated values (Fig. 6.30 and 6.31).

Simulated values of moisture content throughout the grain beds of the aeration and control bins are not presented because of the limited moisture transfer in these bins as shown by measured moisture contents (Fig. 6.12 and 6.14).

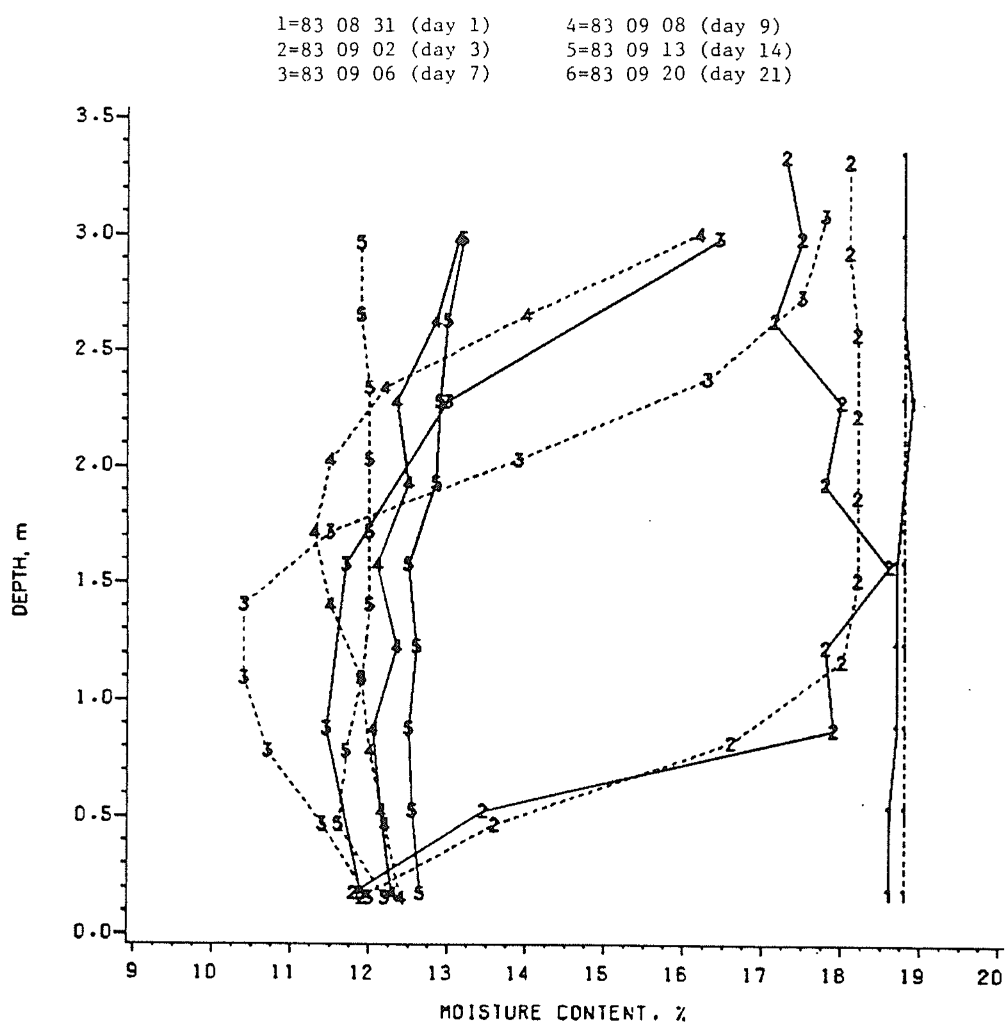


Fig. 6.26: Experimental (———) and simulated (-----) moisture contents of wheat for five sampling dates during storage at a ventilation rate of 23.2 $(L/s)/m^3$ and a ventilation start date of 31 Aug. 1983.

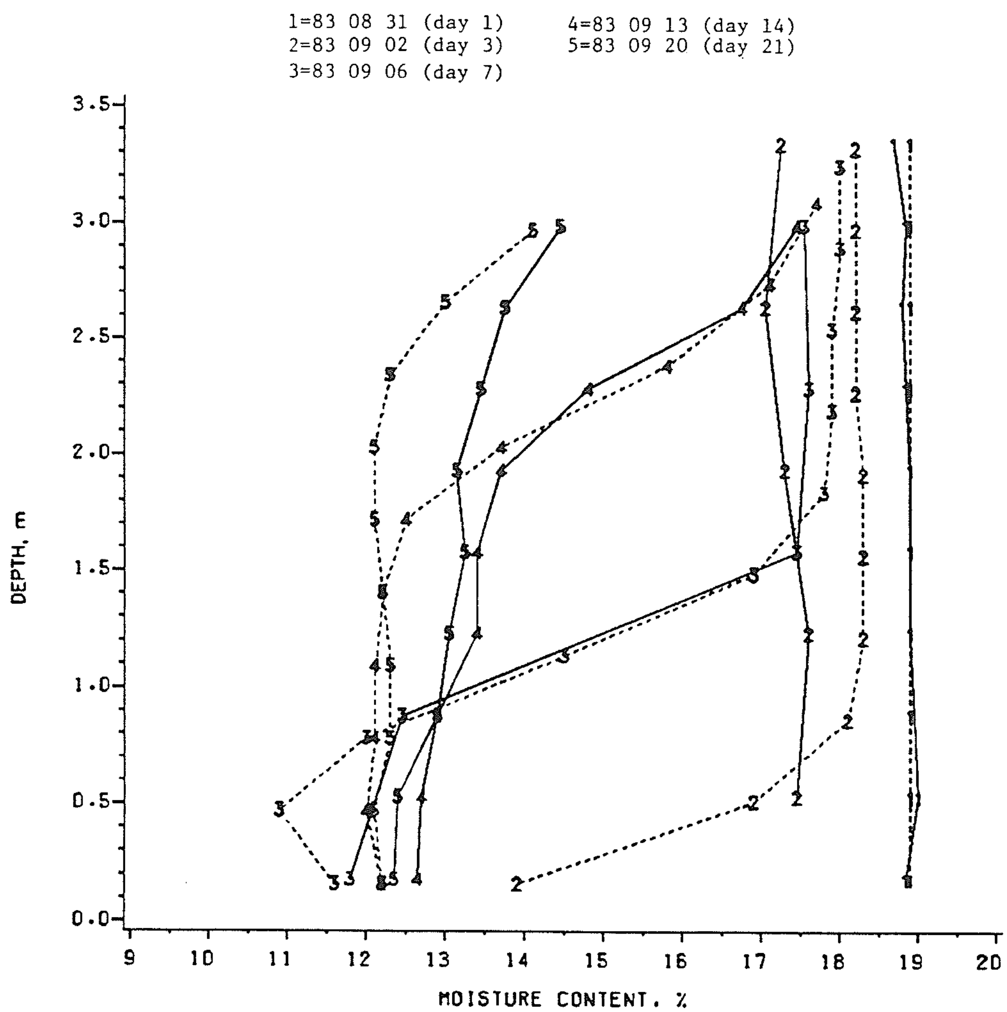


Fig. 6.27: Experimental (———) and simulated (- - - -) moisture contents of wheat for five sampling dates during storage at a ventilation rate of 12.2 (L/s)/m3 and a ventilation start date of 31 Aug. 1983.

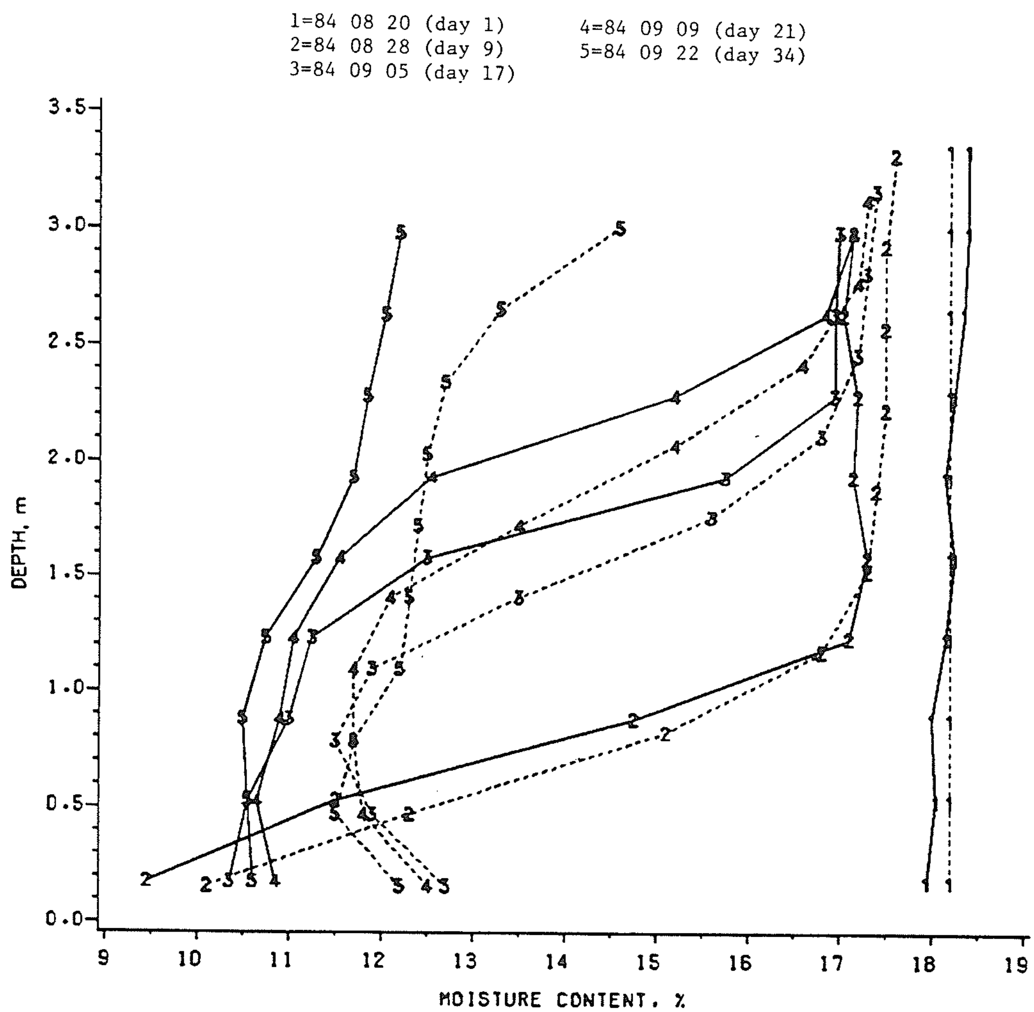


Fig. 6.28: Experimental (———) and simulated (- - - -) moisture contents of wheat for five sampling dates during storage at a ventilation rate of 6.9 (L/s)/m^3 and a ventilation start date of 20 Aug. 1984.

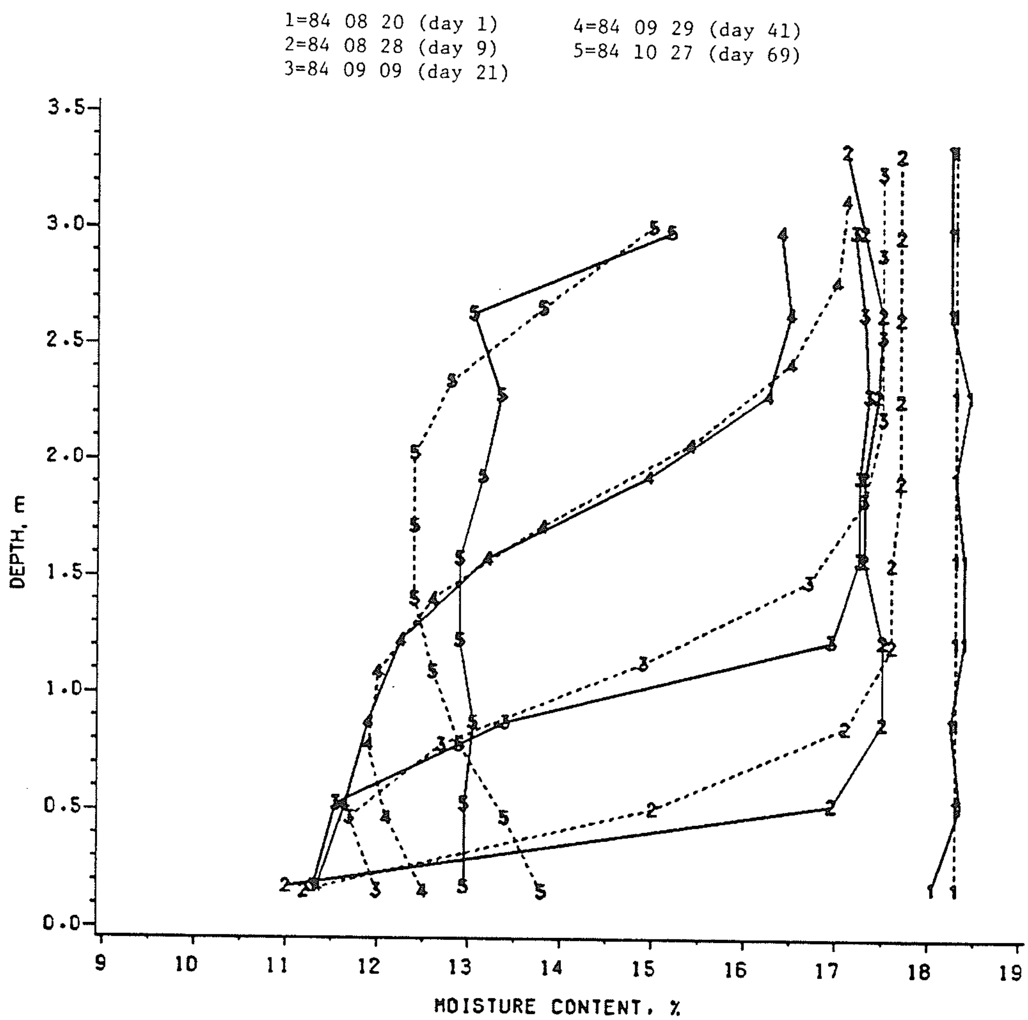


Fig. 6.29: Experimental (———) and simulated (- - - -) moisture contents of wheat for five sampling dates during storage at a ventilation rate of 3.4 (L/s)/m3 and a ventilation start date of 20 Aug. 1984.

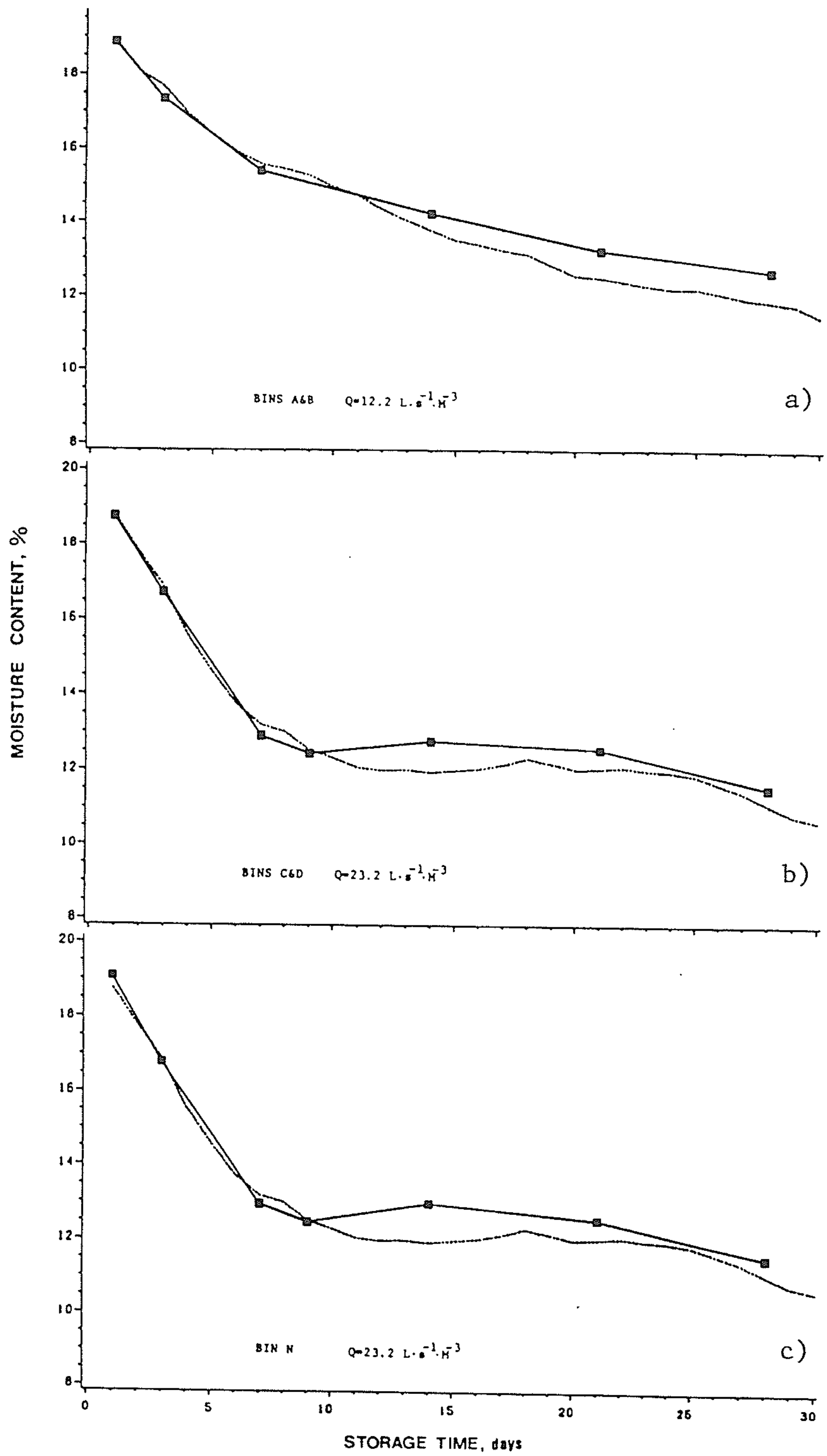


Fig. 6.30: Experimental (■——■) and simulated (-----) mean bin moisture contents of wheat during storage at two ventilation rates and a binning date of 31 Aug. 1983.

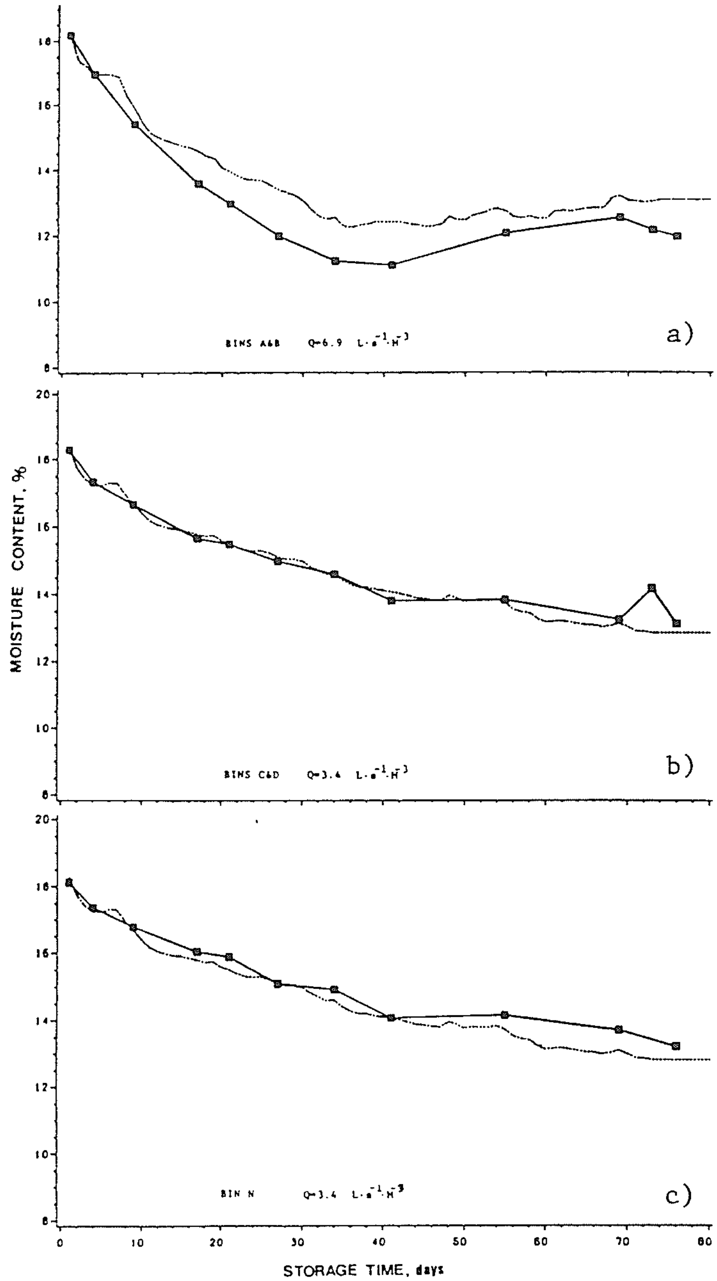


Fig. 6.31: Experimental (■——■) and simulated (-----) mean bin moisture contents of wheat during storage at two ventilation rates and a binning date of 20 Aug. 1984.

6.9.3 Deterioration

By 06 October 1983 simulated moisture contents throughout the 23.2 and 12.2 $L \cdot s^{-1}m^{-3}$ airflow bins were less than 14 %. In the same simulation storability indexes failed to exceed 0.60 by day 37 (06 Oct. 1983) in the 12.2 and 23.3 $L \cdot s^{-1}m^{-3}$ airflow bins indicating that simulated allowable storage times had not elapsed. Thus drying had been predicted to have been completed without simulated grain quality loss. The storability indexes exceed 1.00 (predicted level at which unacceptable deterioration occurs) after 6 and 5 days of storage for the 0.85 (aeration) and 0 $L \cdot s^{-1}m^{-3}$ (control) airflow rates respectively (Fig. 6.32). A value of 2.00 was exceeded after 80 days with 0.85 $L \cdot s^{-1}m^{-3}$ and after only 7 days with 0 $L \cdot s^{-1}m^{-3}$. A storability index of 2.00 is twice the set level for simulated drying without quality loss. It is given here only as an indication of predicted spoilage patterns when the allowable storability index exceeds 1.00.

In the simulations for the 1984-1985 drying tests the storability index failed to exceed 0.62 by day 62 of the simulation (31 Oct. 1984) in the 6.9 $L \cdot s^{-1}m^{-3}$ airflow bin. On 30 October 1984 ventilation to the bins was stopped and simulated moisture contents throughout the 6.9 $L \cdot s^{-1}m^{-3}$ bin were less than 13 % indicating that drying had been predicted to have been completed without quality loss. For the simulations for the 1984-1985 aeration experiment (airflow of 0.85 $L \cdot s^{-1}m^{-3}$ and initial moisture content of 15.6 %) the storability index failed to exceed 0.40 by 31 October 1984. By this date simulated moisture contents throughout the bin were less than 15 %. The simulation was not continued throughout the winter storage period and spring ventilation because it was presumed that the low moisture content would not cause simulated storability index to increase to above 1.00 if ventilation was continued in the spring.

The storability indexes exceed 1.00 after 62 and 7 days of storage for the 3.4 and 0 $L \cdot s^{-1}m^{-3}$ airflow rates respectively (Fig. 6.33). A storability index of 2.00 was exceeded after 13 days of storage for the control bins (Fig. 6.33b) but in the 3.4 $L \cdot s^{-1}m^{-3}$ airflow bin a value of 2.00 was never reached.

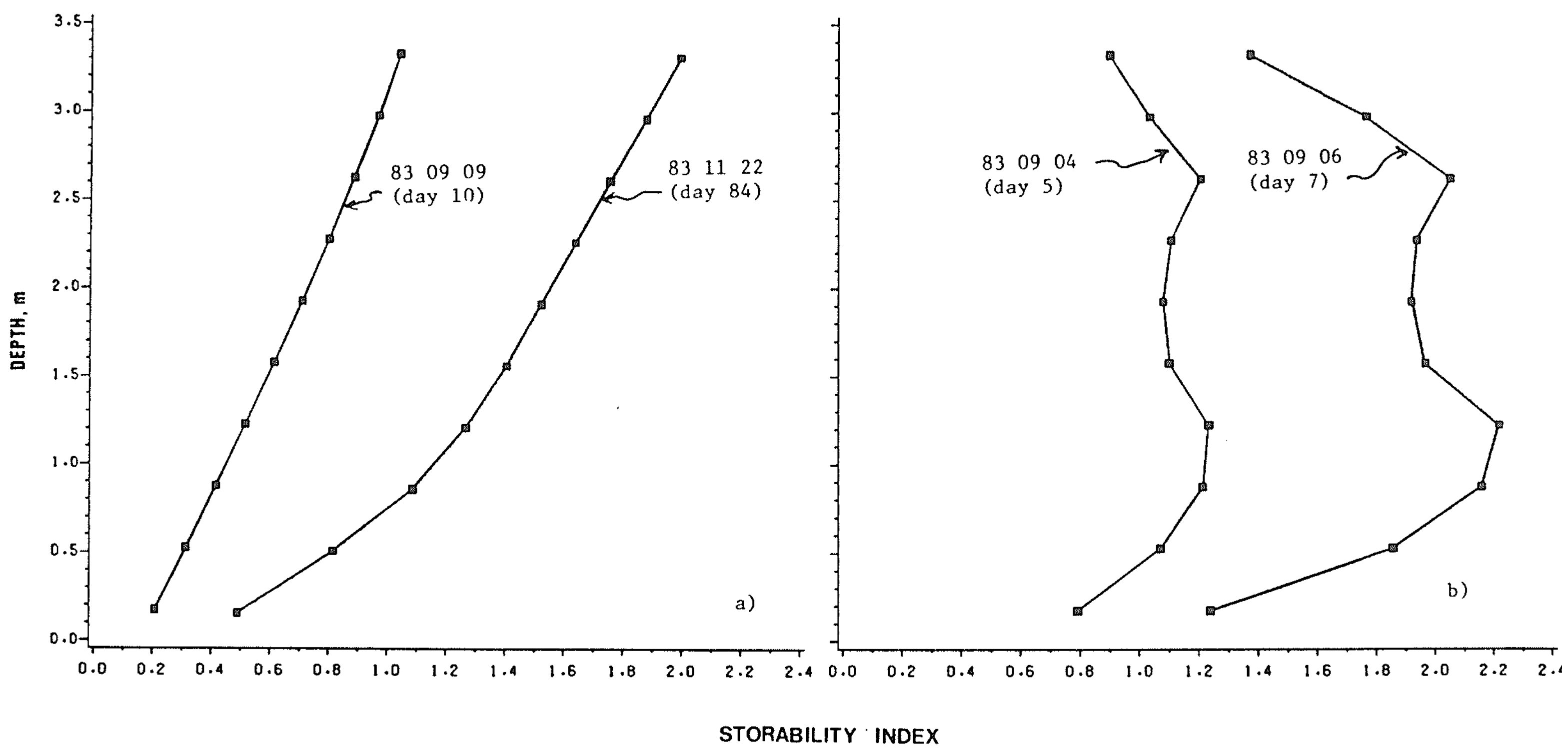


Fig. 6.32: Simulated storability indexes for wheat (initial moisture content 19 %) for several sampling dates during storage at a ventilation rate of: (a) 0.85^{3}(L/s)/m and (b) with no forced ventilation. Experiment and simulation start date was 31 Aug. 1983.

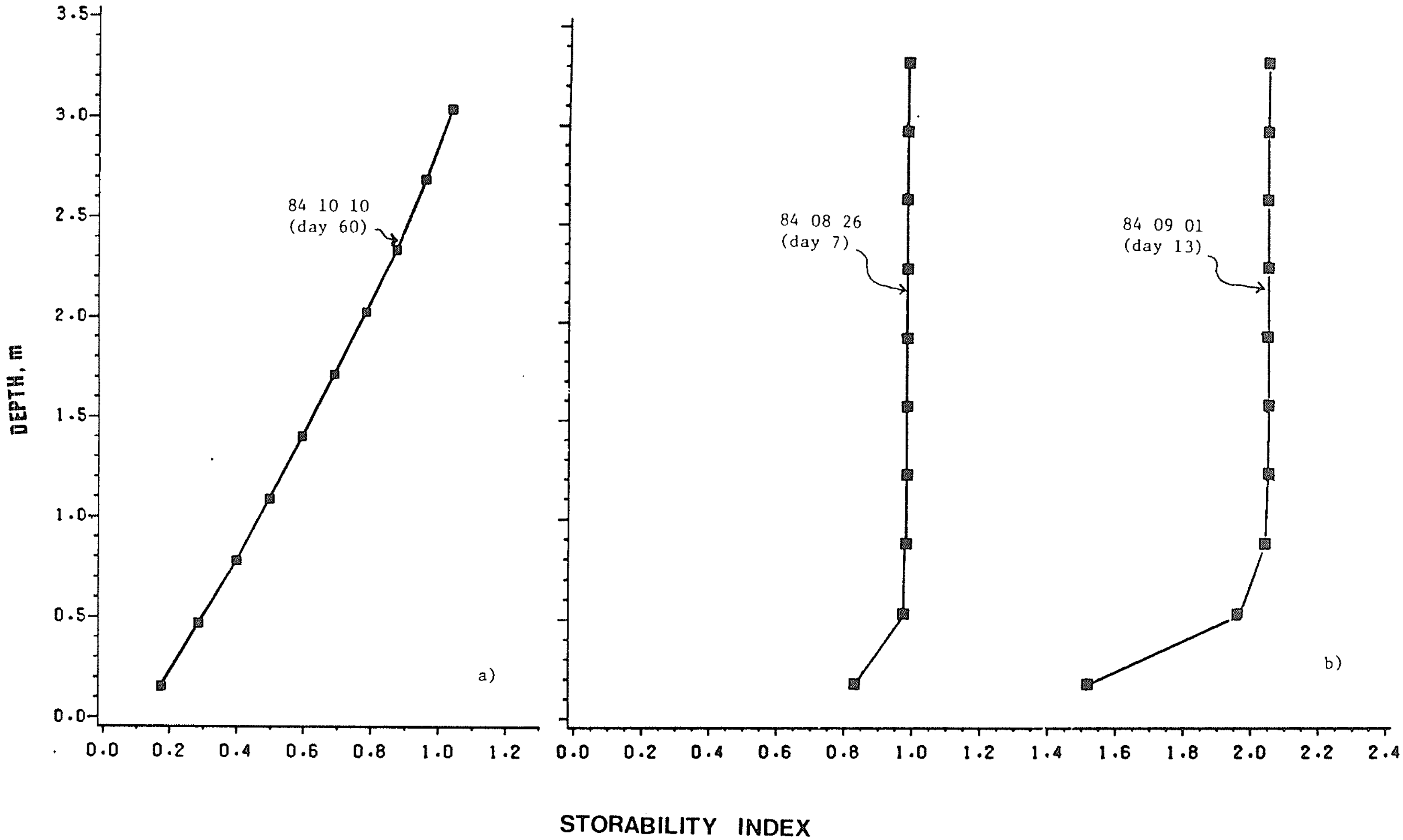


Fig. 6.33: Simulated storability indexes for wheat (initial moisture content 18 %) for several sampling dates during storage at a ventilation rate of: (a) 3.4 $(L/s)/m^3$ and (b) with no forced ventilation. Experiment and simulation start date was 20 Aug. 1984.

Chapter VII

DISCUSSION

7.1 TEMPERATURE

Temperature profiles within the ventilated bins during the initial cool-down periods show the formation of temperature zones (Fig. 6.7 and Fig. G.1 to G.6). Comparing relative widths and speeds of these zones as affected by airflow rates leads to the following observations:

1. No noticeable differences in zone widths could be detected for the different ventilation rates for either year. This does not agree with the work of Sutherland (1975) or Ingram (1976, 1979) who stated that if the superficial air velocity in the grain mass is doubled there is an almost doubling of the width of the temperature zone. A possible explanation for this discrepancy could be due to fluctuating ambient air temperatures which occurred during the ventilation tests. In particular there was generally a drop in ambient air temperature during the initial cool-down caused by the onset of evening. This introduces another cooling zone that alters the shape of the original one making it substantially wider. The work of Sutherland and that of Ingram used conditioned air which would not have fluctuating inlet air temperatures.
2. In all cases the initial cooling zones appeared to widen with continued ventilation but a deeper bed depth would help to con-

firm or disprove this. This is in agreement with Sutherland et al. (1971) as well as Bowden et al. (1983) but not with Ingram (1976, 1979).

3. The speed of a temperature zone is proportional to superficial air velocity and thus airflow rate. That is, a doubling of air velocity results in an almost doubling of the speed of the temperature zone. However, when airflow rates are low (less than 1 $L \cdot s^{-1} m^{-3}$) it appears that heat loss by conduction to the surroundings may shorten cooling times in the 0.61-m diameter bins. This distorts the relative effect of superficial air velocity (or airflow rate) on the speed of a temperature zone.

In 1983-1984, heat loss due to conduction does not appear to be a problem in any of the ventilated bins. In 1984-1985, however, heat loss by conduction appears to have affected temperatures in the aeration bins (G and H). This is evident by the drop in temperature of the intergranular air in the upper portion of the bin before the cooling zone has reached it (Fig. G.5 in appendix G). Why this effect was not evident in the previous year may be due to weather experienced which might have reduced radial temperature differentials and thus heat loss by conduction.

The cooling time for the 1.22-m diameter bin is 7.5 % longer than for the 0.61-m diameter bins at the same ventilation rate (1984-1985 test). This small effect may be due to uneven airflow distribution caused by uneven distribution of fines in the bin. This effect would be more noticeable in the large bin due to the larger cross-sectional area. No noticeable temperature differences between the 0.61 and 1.22-m diameter bins could be detected from a visual comparison of temperature plots for the two bin sizes ventilated at the same airflow rate after the initial cooling period was over. Once ventilation was stopped, however, there was a noticeable difference between the two sizes.

Temperature profiles throughout the drying period can be useful in locating the drying front as well as temperature zones during forced ventilation. This could be done by obtaining temperature profiles for the entire bed depth with the drying front being located by a drop in intergranular air tempeprature caused by evaporative cooling. Caution should be taken when interpreting the temperature profiles so that a cooling zone caused by a sudden drop in ventilation air temperature is not mistaken for the drying front. To minimize risk of falsely identifying a drying zone, temperature profiles should be monitored regularly from the start of ventilation (say every 2 or 3 days). Then from looking at the profiles the movement of the drying front can be followed. Any profile changes caused by changing ambient air conditions can be noticed by referring to previous profiles . This then reduces the risk of falsely identifying a drying front.

In the morning, ambient air temperatures are just beginning to warm up but have not been warm long enough to produce a warming zone in the bin. A larger warming zone tends to mask the zone of evaporative cooling (drying zone) making the zone of evaporative cooling look like part of the warming zone. In the morning intergranular air temperatures just below the drying front are generally as warm or warmer than ambient air temperatures depending on ambient temperatures the previous day which warmed the grain. This helps to make the zone of evaporative cooling more defined.

Periods of high humidity during ventilation for both years did not affect the ability of locating the drying zone (by evaporative cooling). This suggests that the drying zone progresses through the bin even during periods of high humidity. How an extended period of high humidities (say 1 wk) would affect drying, and thus evaporative cooling, is uncertain as extended periods of high humidity did not occur during the drying periods.

In the bins ventilated at 3.4 $L \cdot s^{-1}m^{-3}$ (C,D and N of 1984-1985) evaporative cooling was less distinct than for bins ventilated at higher airflow rates. This may be due to the reduced rate of moisture evaporation in the drying zone because of the lower ventilation rate. Therefore, locating a drying zone by evaporative cooling may become more difficult at airflow rates lower than 3.4 $L \cdot s^{-1}m^{-3}$.

Evaporative cooling in a ventilated grain bin helps to cool the damp grain which is above the drying zone, thus prolonging its storage life. Once the drying front has passed through the bin this cooling effect is no longer present and is usually not needed to preserve the grain as moisture contents have been lowered.

The use of intergranular air temperatures as an indicator of spoilage in ventilated bins proved to be inadequate. The aerated bins (G and H) of the 1983-1984 experiment suffered quality loss as shown by elevated fat acidity values as well as the presence of harmful postharvest fungi (*Aspergillus glaucus* group). Intergranular air temperatures, however, in this bin did not indicate any biological activity.

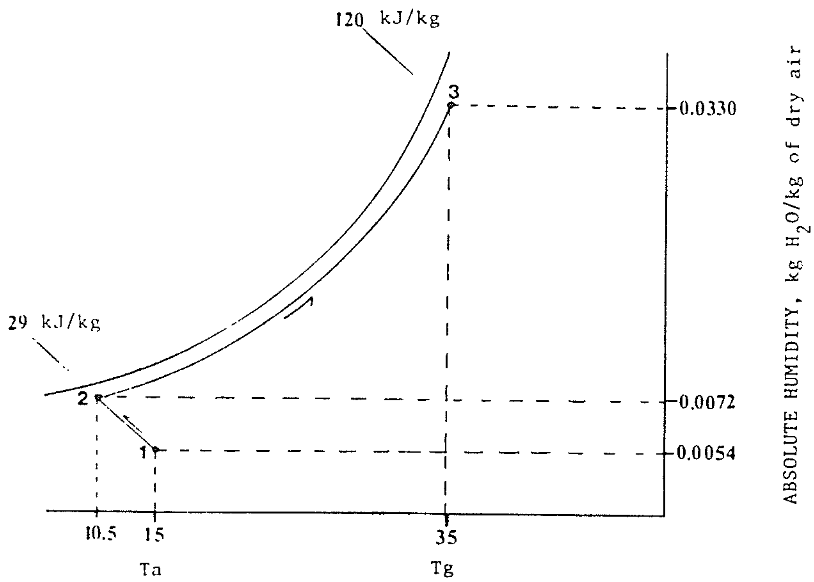
For the control bins (J and K) of the 1983-1984 experiment severe quality losses occurred (as shown by elevated fat acidity levels, rejected grade samples, and the presence of *A. glaucus* group and *A. candi-*

dus Link ex Fries) and in this instance elevated temperatures did indicate advanced biological activity. For the control bins of 1984-1985 intergranular air temperatures remained close to ambient suggesting no biological quality loss even though there was quality loss (as indicated by elevated fat acidity levels and the presence of A. glaucus). Thus temperature, in my tests, is an unreliable indicator of spoilage. One possible reason for its poor performance in the control bins of 1984-1985 could be that lower levels of spoilage activity in this year (as compared to 1983-1984 control bins) could not produce enough heat to maintain elevated temperatures in the small diameter bins.

7.2 MOISTURE CONTENT

For all ventilated bins (both years) a drop in mean bin moisture content of approximately 1 % occurred as the initial cooling front passed through the bins. This drop in moisture content is beneficial as it reduces the moisture content of the grain throughout the bin, prolonging the grains storage life. A drop in mean bin moisture content during initial cooling was also noted by Sutherland et al. (1971) in their ventilation tests with damp wheat. The following example shows how a drop in grain moisture content of 1 % is possible in the cooling zone of a ventilated bin.

A bin of freshly harvested wheat at 19 % moisture content and 35°C is cooled with near-ambient air at 15°C and 50 % relative humidity and an airflow rate of 12 $L \cdot s^{-1} m^{-3}$. Assume the volume of grain in the bin is 1.0 m^3 with a bulk density of 800 $kg \cdot m^{-3}$ and that ambient air conditions remain constant. The cooling process is shown in Fig. 7.1. The drying rate in the cooling zone is 1.35 kg $H_2O \cdot h^{-1}$ and the approximate calcu-



Given:

mass of grain bulk is 800 kg
specific heat of wheat at 19 % is 1.94 kJ/(kg·K)
density of air at 15°C and 50 % rh is 1.212 kg/m^3
airflow rate is 12 L/s or 43.2 m^3/h
mass flow rate of air is then=43.2 m^3/h * 1.212 kg/m^3=52.36 kg/h

step 1: calculation of drying rate in cooling zone (points 2 to 3)

drying rate=(0.0330-0.0072)kg H_2O/(kg dry air)*52.36 kg/h
=1.35 kg H_2O/h

step 2: calculation of time required to cool grain mass

amount of heat to be removed is = Cg* ΔT*(mass of grain)
=1.938 kJ/(kg·K) * (35-10.5)K * 800kg
=39,540 kJ

amount of heat picked up by the air in the cooling zone (points 2 to 3)
=52.36 kg/h * (120-29)kJ/kg
=4,765 kJ/h

cooling time is then (39540 kJ)/(4765 kJ/h)=8.3 h

step 3:calculation of moisture removed in 8.3 h

mass=8.3 h * 1.35 kg H_2O/h =11.2 kg H_2O

this translates to a 1.1 % drop in mean bin moisture content.

Fig. 7.1: Calculation of theoretical moisture transfer that occurs due to a cooling front passing through a warm grain bulk.

lated time to cool the bin is 8.3 h. The amount of moisture removed from the bin in 8.3 h is 11.2 kg which translates to a drop of 1.1 % in moisture content throughout the bin. The magnitude of the moisture loss during initial cooling is dependent on the initial grain temperature and moisture content.

This explanation, however, can not explain the drop of 1 % in mean bin moisture content for the 1983-1984 control bins (J and K) that were not subjected to forced ventilation.

When comparing shapes and speeds of drying zones as affected by air-flow rates the following observations are made:

1. In all cases the observed drying zones start out narrow but widden as they travel up the bin. That is, the leading edge of the drying zone is moving faster than the trailing edge (Fig. 6.15 and G.8 to G.14). This effect was shown in drying tests by Bowden et al. (1983) and theoretically by Rouvet et al. (1979) but conflicts with simulations of Ingram (1979) where he states that once established the width of a drying zone remains constant.
2. As outdoor temperatures decrease (as fall progresses) the speed of the drying front decreases (Table 6.3 and 6.4) indicating a drop in the drying potential of the ambient air. This was also noticed by Ingram (1976,1979). A drop in the drying front speeds is expected as fall progresses due to decreasing air temperatures. Lower temperatures reduce the water holding capacity of the ventilation air and thus slows down the drying rate.
3. The speed of drying fronts was not linearly proportional to air-flow rates in the drying tests for both years where a doubling of

airflow resulted in a more than doubling of the drying rate over the same drying period (up to 2.5 times increase) (Table 6.3 and 6.4).

4. Drying times for the various airflow rates were also not linearly proportional to airflow rates in the drying tests for both years where a reduction of 50 % in airflow resulted in more than doubling of the time required to dry the grain. This reduction is related to points (2) and (3) earlier as drying potential of the air decreases towards the end of fall due to decreased temperatures and that drying rates were found to not be directly proportional to airflow rates when inlet air conditions (temperature and relative humidity) are not held constant.

5. Results obtained suggest no appreciable differences in drying zone widths for the airflow rates tested. Barre et al. (1971), Ingram (1976,1979) and Sutherland (1975) suggested that the width of a drying zone is determined mainly by the airflow rate. They state that the effect of doubling the airflow rate results in an almost doubling of the drying front width. The results presented by Sutherland (1975) are based on ventilating low moisture content grain (less than 15 %) and therefore his results may not be compared with drying 18 and 19 % moisture content wheat. The conclusions of Barre et al. (1971) and Ingram (1976,1979) are based on simulations and were not verified by granary tests. In a granary test the location of the leading and trailing edges of the drying front would be difficult to locate using their definitions (Eq. 2.3 from Sec. 2.1). Therefore their results would be difficult to validate.

6. A 3 and 12 % difference in average drying front speeds between the 0.61-m and the 1.22-m diameter bins at similar airflow rates was found in the 1983-1984 and 1984-1985 drying tests respectively. In both instances drying in the 1.22-m diameter bin (N) was slower.

   This result is surprising as a concern of using small diameter bins was that airflow distribution across the bin diameter may not be uniform (Bailey 1983). The highest airflow being at the wall grain interface where porosity would be the greatest. Thus, as bin diameter increases, this effect, if present, should decrease suggesting slower drying in the smaller bin.

During periods of high humidity ventilated grain is subjected to rewetting. In the 1984-1985 drying experiment no appreciable rewetting occurred because ventilation to the bins was turned off on 30 October 1984 and was resumed the following spring for the aeration bins only. Thus, there was little opportunity for high humidity air to rewet the grain. In the previous year's experiment rewetting did occur. From rewetting profiles (Fig. 6.16 and others like them but not given) and Fig. 6.11 it was noticed that the grain absorbed more moisture from the ventilation air at higher ambient air temperatures. That is, more rewetting occurred in late spring and early summer than during late fall and early spring. An increase in temperature of the grain will increase the rate of diffusion of water into the endosperm (Sokhansanj et al. 1983). This coupled with the increased moisture holding capacity of warm air increase the rate of rewetting during warm and humid weather. This is supported by work of Sokhansanj et al. (1983) and Sutherland et al.

(1971) where they found in experimental tests that grain more readily adsorbs moisture at warmer temperatures.

Rewetting profiles of the 1983-1984 experiment (Fig. 6.16) show widening rewetting zones which eventually dispersed before traversing the entire bed depth. These rewetting zones would have continued through the bin had ambient weather conditions remained humid. During the 1983-1984 ventilation period extended periods of high humidity (say 1 wk or more with ambient air relative humidities above 75 %) did not occur and thus rewetting did not pose a storage problem in these tests. Observed rewetting could be beneficial from a commercial standpoint in that it reduces overdrying and increases marketable mass. For example: In 1983-1984 the mean moisture content in bin N (ventilated at 23.2 $L \cdot s^{-1} m^{-3}$) increased from 9.4 % on 04 June 1984 to 12.6 % on 18 June 1984 due to ventilation during periods of high humidity. This translates into an increase of 3.7 % in marketable mass and the maximum moisture content within the bin was only 13.2 %. Sutherland et al. (1971,1983) reported that rewetting zones widen and might disperse before exiting the grain bed. A hypothesis on why wetting zones widen and may eventually disperse was presented by Sutherland et al. (1983). They discussed the interaction of multiple temperature and moisture zones within a ventilated grain mass and their effect on grain condition. Rewetting zones which have entered a grain bulk as a result of ventilation with air at a high relative humidity, travels very slowly with low moisture content points travelling faster than high moisture content points (producing a widening zone). Subsequent ventilation with air at low relative humidity will immediately generate a drying zone, the speed of which depends on the highest grain moisture content in the preceding wetting zone. In due course, the drying zone will catch the trailing edge of the widening wetting zone. Then, as the drying zone proceeds through the wetting zone the maximum grain moisture content decreases progressively and disperses the wetting zone.

The potential problem of high moisture grain caused by rewetting can thus be reduced by ventilating alternately with high and low relative-humidity air (Sutherland et al. 1983). Natural variations in atmospheric relative humidity in the Canadian praries generally produces this effect automatically. None of the conditions studied indicated that it would be beneficial to turn the ventilation fan off during periods of high humidity.

In my drying tests ventilation was continuous regardless of ambient air relative humidity. Drying front speeds decreased only at the onset of winter (Table 6.3 and 6.4) and appeared to not be affected by periods of high relative humidity which occurred during the drying period. When the top of the grain bed is not dry, ventilation during periods of high humidity continued to force the drying front through the grain. The grain below the drying front removes moisture from the air thus giving it some moisture holding capacity before it reaches the drying front. The rewetted grain below the front did not remain wet in any of our tests as the fronts were quickly dispersed by subsequent ventilation during periods of low humidity thus not posing a storage problem.

In plots showing maximum, mean and minimum moisture contents of wheat at the various ventilation rates the maximum values are of greatest importance with respect to the grain's storability. This is because postharvest microfloral growth, which can kill the seed, is most rapid in regions of high moisture content (Christensen 1972). Therefore, as long as the maximum grain moisture content within a bin is above a safe storage level (14.5 % for wheat) there is a risk of postharvest microfloral growth which would cause a drop in grain quality.

Moisture contents in the control bins (J and K) for both years show that maximum and mean moisture contents within the bins did not fluctuate appreciably, both remaining between 18 and 20 % for 1983-1984 and 18 and 19 % for 1984-1985 (Fig. 6.12 and 6.14). The minimum moisture contents fluctuated between 15 and 18.5 % for 1983-1984 and 16 to 18 % for 1984-1985. The minimum moisture contents were always recorded in the top 1.0 m of the control bins. This was caused by moisture loss from the grain to the air just above the grain surface. There was more fluctuations in the 1983-1984 experiment because in the 1984-1985 experiment the tops of the bins were covered with plastic sheeting limiting the amount of fresh air available to remove moisture from the grain surface. In 1983-1984 no such cover was used.

7.3 SHRINKAGE

Variation among the drying bins for the two years and also between similar airflow rates demonstrates the variability of decreases in bed depth due to shrinkage. Bulk shrinkage in our bins is caused mainly by individual kernel shrinkage due to moisture loss and settling caused by the movement of the grain due to kernel shrinkage. The second factor (settling by kernel reorientation) may be the cause of the variation in the measured shrinkage values. Different bins may have had different filling methods creating different original kernel orientation within the bin. This would affect how much of a decrease in bed depth due to settling could occur. The rate of drying may also have an effect on kernel shrinkage or bulk shrinkage due to settling (or both) but present data is not sufficient to make any comments at this point.

From the results obtained I can conclude that shrinkage in a drying grain bulk is substantial. I recorded bulk shrinkages as high as 13.7 % after drying wheat from 18 % down to 13 %. No increases in bed depth due to grain rewetting occurred in these tests.

If results from a computer simulation are to be compared with experimental results shrinkage must be taken into account. But if the results from the simulation are not to be compared with experimental results shrinkage can be ignored.

7.4 BIOLOGICAL QUALITY CHANGES

Grain quality in a slowly drying bin should be assessed by monitoring several variables. Seed germination, microfloral growth, grain grade and fat acidity levels were used to monitor quality changes in this study (Sinha et al. 1985, Sanderson et al. 1985). Fat acidity values were a good measure of seed quality changes. An increase in fat acidity generally corresponded to increases in the frequency of occurrence of postharvest fungi (*A. glaucus* group and *A. candidus* Link ex Fries) which kill and discolour seeds. Similar results were found by Sinha and Wallace (1977), Sinha et al. (1981) and Wallace et al. (1983). Germination was only a fair measure of quality changes in stored wheat because of difficulties encountered in breaking seed dormancy of the freshly harvested wheat.

Grain grade in this study was inadequate as an indicator of quality changes in slowly drying grain bulks. Grain grade as a variable is not sensitive enough to indicate small changes in grain quality. A drop in grain grade lowers the commercial value of the grain. If a drop in grain grade occurs during drying this would suggest that drying was unsuccessful as unacceptable quality losses occurred resulting in a drop in grain value. Substantial quality losses, (as shown by elevated CO_2 concentrations, increased fat acidity levels, decreased germination and the presence of harmful postharvest fungi), occurred in the aeration bins (G and H) of 1983-1984 and the control bins (J and K) of 1984-1985 but the measured grain grade remained unchanged. Grain grade is useful as an indicator of initial and final grain value but has questionable use for monitoring quality changes during drying.

In the 1983-1984 aeration bins (G and H) spoilage increased with distance above the bin floor as shown by elevated fat acidity values (Sinha et al. 1985). Bartsch and Finner (1976) also noted increased spoilage (as indicated by decreased seed germination and increased microfloral growth) as distance above bin floor increased in their ventilated bins. The reason for such a spoilage pattern is that grain moisture content and temperature towards the top of a ventilated grain bulk are the last to be reduced. These warmer temperatures and higher moisture contents are conducive to more rapid deterioration.

In the control bins (J and K) for both years the area of highest spoilage (as shown by elevated fat acidity values) is between 0.5 and 3.0 m above the bin floor. Decreased spoilage at the top and bottom of these bins is probably due to lower temperatures at these locations (Fig. 6.10 and G.7). The lower temperatures are caused by heat loss through the top layer of grain and the bin floor. In addition some natural convection at the top of the bin also partially dried the top layer of grain. The lower temperatures and moisture contents at the top of the bin decrease the spoilage rate in these locations.

The presence of elevated CO_2 concentrations appeared to be the best indicator of incipient spoilage in the control bins for both years. Maximum CO_2 levels in these bins increased to 350 and 120 times the 0.033 % atmospheric level during the first 2 days of storage in the 1983-1984 and 1984-1985 tests respectively (Fig. 6.17 and 6.18). These elevated CO_2 concentrations indicate the presence of accelerated biological activity within the grain mass. Intergranular air temperatures during these periods remained near the initial values experienced during binning in the 1983-1984 experiment (Fig. 6.3) and were decreasing in 1984-1985 (Fig. 6.5). Hence, intergranular air temperatures did not show any clear indication of accelerated biological activity during the first 2 days of storage in the control bins of both years.

Intergranular air temperatures indicated areas of active spoilage in 1983-1984 but failed to indicate any spoilage in 1984-1985. The reason for the failure of intergranular air temperatures to detect spoilage in 1984-1985 may have been partly due to small bin sizes which allowed radial heat loss to the surroundings (not a factor in a farm-size storage bin). In a larger storage bin, under the same initial conditions of grain moisture content and temperature, deterioration would be greater than experienced in the 0.61-m diameter control bins. The larger size would limit the amount of heat lost to the surroundings keeping grain temperatures warmer. These warmer temperatures would in turn accelerate biological activity in the bin resulting in greater spoilage and further increases in grain temperatures.

The usefulness of CO_2 and temperatures as spoilage indicators agree with the work of others (Muir and Sinha 1983, Sinha and Wallace 1977, Muir et al. 1980, Sinha et al. 1981, Abramson et al. 1984).

A problem encountered using CO_2 as a spoilage indicator is that in ventilated bins the ventilation air dilutes any CO_2 produced. Thus the measured levels remain close to atmospheric despite biological activity. Biological quality loss was encountered in the 1983-1984 aeration bins (G and H) but measured CO_2 concentrations were near-atmospheric. Temperature measurements within these bins also failed to indicate quality losses. A possible technique that could be used to detect quality changes in a ventilated bin is to stop ventilation for a brief period (eg. 1 to 2 h) to allow CO_2 to accumulate. Carbon dioxide concentrations could then be measured and if elevated, the measurement would indicate biological activity.

7.5 COMPUTER SIMULATION

7.5.1 Simulated temperatures

The low-temperature grain-drying model predicted intergranular air temperatures reasonably well when ventilation rates are above 3 $L \cdot s^{-1}m^{-3}$. How well the simulated and experimental temperature profiles compared at airflow rates above 3 $L \cdot s^{-1}m^{-3}$ generally depended on how well the location of simulated and measured drying zones compared. This is because evaporative cooling is present in the measured as well as calculated drying zones. If the measured drying zone was located 0.10 m higher than the calculated one this would cause measured and calculated intergranular air temperatures, within the area of the two drying zones, to be out by as much as 5^{0}C because of evaporative cooling. Simulated intergranular air temperatures above or below the drying zone were generally within 2^{0}C of the measured values for airflow rates greater than 3 $L \cdot s^{-1}m^{-1}$

At the aeration airflow rate tested (0.85 $L \cdot s^{-1}m^{-3}$) simulated and measured intergranular air temperatures differed by as much as 12°C (Fig. 6.25c) indicating that simulated heat transfer occurred at a greater rate than was measured. The faster moving simulated cooling zone caused simulated temperatures to be as much as 12°C lower than measured during the initial cooling period. Even after the initial cooling front has traversed the bin, differences between measured and simulated temperatures were as much as 4°C (Fig. G.18). These differentials did not occur in the drying zone and thus were not caused by differences in evaporative cooling.

7.5.2 Simulated moisture contents

When comparing simulated and measured moisture content profiles the following observations are made:

1. A drop in moisture content of approximately 0.5 to 1.0 % throughout the bin as the initial cooling front passes through the bin was simulated for airflow rates tested. This matches measured results from the experimental bins.
2. The model overpredicts drying in the lower portions of the grain bin in the simulations for the 1983-1984 drying tests. The model also overpredicts rewetting in the simulations for the 1984-1985 drying tests. In the simulation of the 1983-1984 drying tests low ambient-air relative humidities and short drying times resulted in little rewetting during the drying period.
3. Simulated drying front speeds decrease as the ventilation air temperature decreases (as fall progresses) (Table 6.3 and 6.4).

This matches changes in the measured speeds of the drying fronts during fall ventilation.

4. The drying model predicted slower drying rates than were measured at 6.9 and 23.2 $L \cdot s^{-1} m^{-3}$ (by as much as 19 %) (Table 6.3 and 6.4). The model also predicted faster drying rates than were measured at an airflow rate of 3.4 $L \cdot s^{-1} m^{-3}$. At an airflow rate of 12.2 $L \cdot s^{-1} m^{-3}$ measured and simulated drying rates were within 5 % of each other.
5. The speed of simulated drying fronts was not found to always be linearly proportional to airflow rates. In the simulation of the 1983-1984 drying a doubling of airflow resulted in a doubling of drying rate. In the simulation of the 1984-1985 drying test, however, a doubling of airflow resulted in less than a doubling of drying rate over the same simulation period (as low as 1.5 times increase) (Table 6.4). This was reverse of what was found with measured drying rates where a doubling of airflow resulted in a more than doubling of the drying rate. This enforces the observation that the drying model underpredicts drying at higher airflow rates (above 12.2 $L \cdot s^{-1} m^{-3}$) and overpredicts drying at the lower airflow rates (below 6 $L \cdot s^{-1} m^{-3}$).
6. Simulated moisture profiles show no appreciable differences in drying zone widths for the airflow rates tested which agrees with experimental observations.
7. For the simulatons, ventilation was continuous regardless of the ventilation-air relative humidity. Simulated drying front speeds decreased only at the onset of winter (Table 6.3 and 6.4) and appeared to not be affected by periods of high relative humidity

which occurred during the simulated drying period. Any simulated rewetting fronts that did form in the bottoms of the bins were dispersed by subsequent ventilation during periods of low humidity as did measured wetting fronts (Fig. 6.26 to 6.29).

The low-temperature grain drying model accurately predicted mean moisture contents within the bins during the drying periods for the drying airflow rates tested (above 3 $L \cdot s^{-1}m^{-3}$). Maximum deviations between experimental and simulated mean moisture contents within the bins was 1.0 % for the 6.9 $L \cdot s^{-1}m^{-3}$ airflow rate and less than 0.5 % for the others. A prediction of mean moisture contents within a bin could be of use to farmers equipped with grain handling facilities adequate for mixing large quantities of grain. The operator would predict the time required for the mean moisture content within the bin to be lowered to 14.5 %, at which point the grain could be mixed and sold at this optimum moisture content. This practice, however, requires increased management skills and labour requirements than would be required for ventilating the grain until the entire bed of grain is below 14.5 %. The benefit of such a practice would be that required drying times would be reduced and overdrying costs decreased.

In summary, few simulation models are perfect and the low-temperature grain-drying model used here is no exception. It is realized that the model predicted slower drying front speeds than were measured for the 6.9 and 23.2 $L \cdot s^{-1}m^{-3}$ airflow rates and faster than measured at an airflow of 3.4 $L \cdot s^{-1}m^{-3}$. It also tends to overpredict the rate of heat transfer at the lower airflow rates (around 0.85 $L \cdot s^{-1}m^{-3}$). Thus, the model can be improved. It is, however, sufficient to use as a design tool to predict airflow rates required to dry grain in a given period of time if the conditions of the ventilation air are known during the drying period.

The model, in its present state, will predict required drying times which are slightly greater than the actual required times at airflows above 6 $L \cdot s^{-1} m^{-3}$. This is acceptable when the model is to be used as a design tool to produce recommended drying airflow rates for farmers to use. The model would predict an airflow rate based on past weather data that would successfully dry grain in the future. Since future weather data is unpredictable a slight overprediction of required airflow rates is acceptable.

A problem may develop at low airflow rates (below 4 $L \cdot s^{-1} m^{-3}$) where the model predicted shorter drying times than were required. This should not be too much of a concern when using the model as a design tool for grain drying as few required drying airflow rates are this low.

7.5.3 Deterioration

The deterioration model did not predict any unacceptable spoilage for the ventilation rates tested above 6 $L \cdot s^{-1} m^{-3}$. It also did not predict spoilage in the aeration bin (0.85 $L \cdot s^{-1} m^{-3}$) of the 1984-1985 storage season which had an initial bin moisture content of 15.6 %. Similar results were found in the experimental tests as no increases in fat acidity or decreases in seed germination were measured for these bins indicating that the seeds remained in good condition throughout the storage period.

For the simulations of the aeration (0.85 $L \cdot s^{-1} m^{-3}$) and control (0 $L \cdot s^{-1} m^{-3}$) bins for the 1983-1984 storage season the storability index exceeded 1.00 after 6 and 5 days of storage respectively. A value of 2.00 was exceeded after 80 days with aeration and after only 7 days with no ventilation. Measured quality variables (fat acidity and seed germination) indicated quality losses at these storage conditions after 14 days of storage. Because more frequent measurements were not taken, the precision of predicted days of safe storage is doubtful. It is shown, however, that increases in the storability index follows a similar trend as increases in fat acidity and decreases in seed germination.

For the simulation of the 3.4 $L \cdot s^{-1}m^{-3}$ ventilation rate (initial bin moisture content 18.2 %) the storability index exceeded 1.00 after 62 days of storage. There was, however, no noticeable increases in measured fat acidity or decreases in seed germination for this storage condition indicating that the grain maintained quality. In the simulation of the control bins (0 $L \cdot s^{-1}m^{-3}$) for the 1984-1985 storage season the storability index exceeded 1.00 after 7 days and 2.00 after 13 days. Measured quality variables (fat acidity and seed germination) indicated quality losses with this storage condition after 21 days of storage. Again, more frequent measurements were not taken and therefore it is uncertain if the predicted safe storage time of 7 days is exact.

Storability index profiles (Fig. 6.32 and 6.33) show predicted spoilage increases with height in a ventilated bin. Similar results were found in the experiments as shown by fat acidity profiles (Fig. 6.22a). Simulated spoilage profiles for the control bins of the 1983-1984 storage season show similar spoilage patterns as were demonstrated by measured fat acidity. Simulated profiles for the control bins of the 1984-1985 storage season do not demonstrate the same spoilage pattern as was measured because of the proceedure used for this simulation. For this simulation accurate measured temperatures within the bin were not available, as they were for the 1983-1984 storage season, due to equipment failure (Sec. 6.1). Simulated temperatures produced using a low ventilation rate (0.1 $L \cdot s^{-1} m^{-3}$) were used in place of measured ones. This resulted in temperatures throughout the bin being relatively constant and resulted in the spoilage profile shown (Fig. 6.22c).

The deterioration model is difficult to evaluate because of the variability in the biological variables used to assess seed quality (seed germination and fat acidity in this case). A direct comparison of a storability index of 1.00 (present level set for unacceptable deterioration) to measured drops in seed germination, grain grade, or increases in fat acidity is not possible. Extensive work aimed directly at evaluating and improving this deterioration model is needed. The model should also be modified to account for the condition of the grain prior to harvest as affected by weather, mechanical damage and infection by microflora.

In its present state, I speculate that this deterioration model is too conservative, predicting unacceptable quality losses (storability index=1.00) before actual seed quality drops. The model does, however, predict quality trends as shown by the storability index profiles which compare well to trends shown by fat acidity profiles. The deterioration model is based on measured results in small masses of grain exposed to constant conditions of moisture and temperature with no forced ventilation (Fraser 1979). Results presented here tend to indicate that this model is useable for larger grain masses subjected to forced ventilation which create varying conditions of moisture and temperature.

Chapter VIII

CONCLUSIONS

The following conclusions were drawn based on the results of this investigation carried out under Winnipeg, Manitoba weather conditions:

1. In 1983-1984 wheat dampened to 19 % and binned on 31 August 1983 continuously ventilated with 12.2 $L \cdot s^{-1}m^{-3}$ of air at near-ambient conditions dried to a safe storage level within 28 days. Such drying, followed by winter cooling completely arrested the growth of harmful postharvest storage fungi, prevented production of free fatty acids and maintained the overall grain quality for 310 days.
2. A lower ventilation rate of 0.85 $L \cdot s^{-1}m^{-3}$, although adequate for cooling the grain, was not sufficient to dry the 19 % wheat. Consequently, such operation provided incomplete protection from spoilage as indicated by elavated fat acidity values.
3. In 1984-1985 bulk wheat dampened to 18 % and binned on 20 August 1984 continuously ventilated with 6.9 $L \cdot s^{-1}m^{-3}$ of air at near-ambient conditions dried to a safe storage level within 30 days. Such drying, followed by winter cooling (by conduction) completely arrested the growth of harmful postharvest storage fungi, prevented production of free fatty acids and maintained overall grain quality for 330 days.

4. A lower ventilation rate of 3.4 $L \cdot s^{-1} m^{-3}$ did not successfully dry the entire grain bulk to a safe storage level in the 73 days of ventilation. Ventilation was stopped after 73 days (30 October 1984) and the top layer (0.35-m deep) remained above the safe storage level (14.5 %) with a moisture content ranging from 14.5 to 15 %. There was no appreciable increases in intergranular CO_2 concentrations or in levels of free fatty acids suggesting that the grain had maintained quality for 330 days despite being above a safe storage moisture content.
5. In 1984-1985 bulk wheat harvested at 15.6 % and aerated continuously with an airflow rate of 0.85 $L \cdot s^{-1} m^{-3}$ from the time of filling to 31 October 1984 and from 6 May 1985 to 15 July 1985 successfully dried the grain to below 14.5 %. This drying coupled with winter cooling completely arrested the growth of harmful postharvest storage fungi, prevented production of free fatty acids and maintained overall grain quality for 330 days.
6. Absence of forced ventilation in the control bins for 1983-1984 and 1984-1985 allowed the growth of harmful postharvest storage fungi on the 19 and 18 % wheat respectively. Aspergillus glaucus group and A. candidus Link ex Fries, which discolour and kill wheat during storage (Christensen and Sauer 1982), were the common fungi.
7. In the non-ventilated bins the presence of elevated CO_2 concentrations was shown to be a better indicator of incipient grain spoilage than elevated intergranular air temperatures.
8. Grain grade is useful as an indicator of the commercial value of grain before and after drying. It is not useful for monitoring

quality changes in a slowly drying grain bulk because it is not sensitive enough to show small changes in grain quality.

9. The presence of evaporative cooling in the drying zone of a slowly drying grain bulk facilitates the use of temperature measurement to locate the drying zone during forced ventilation.
10. Continuous ventilation during periods of high humidity caused rewetting zones to form in the bins. These zones were quickly dispersed by subsequent ventilation with low humidity air and thus did not pose a storage problem. Ventilation with high humidity air also continued to move the drying zone through the grain bed. None of the conditions studied indicated that it would be beneficial to turn the ventilation fan off during periods of high humidity.
11. No appreciable differences were noted between the 1.22-m diameter bin and its matched airflow bins with 0.61-m diameter. Thus, according to this study a 1.22-m diameter ventilated bin could be modeled by a 0.61-m diameter bin providing the airflow rates were at or above 3.4 $L \cdot s^{-1} m^{-3}$. The benefit of this is that smaller masses of grain can be used in drying tests thus reducing costs.
12. For airflow rates near 0.85 $L \cdot s^{-1} m^{-3}$ radial heat loss by conduction may become an important factor in controlling mean bin temperatures. Thus for these lower airflow rates a 0.61-m diameter bin may not sufficiently model a larger bin.
13. The speed of drying fronts in these low-temperature grain-drying bins are not linearly proportional to airflow rates. A doubling of airflow resulted in a more than doubling of measured drying rates.

14. Bulk shrinkage in a slowly drying grain bin can be substantial. Bulk shrinkages as high as 13.7 % of original volume were recorded while drying wheat from 18 % down to 13 %.

15. The low-temperature grain drying model used here is sufficiently accurate to use as a design tool to predict airflow rates required to dry grain if the ventilation rates used are above 4 $L \cdot s^{-1}m^{-3}$. Below 4 $L \cdot s^{-1}m^{-3}$ the drying model loses accuracy.

16. A direct comparison of results between measured and simulated spoilage levels is difficult. From the spoilage results obtained in the drying tests and the simulations I can only conclude that the deterioration model is useful to give an indication of quality changes within a ventilated bin. It is not capable of predicting the actual grain quality within the bins but can show spoilage trends.

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Appendix A

DEFINITIONS

Definitions as supplied by the Canadian Grain Commission (1984):

Blackpoint-A dark brown or black discolouration caused by plant disease. Slight discolouration restricted to the germ will be disregarded in assessing blackpoint. When the discolouration affects more than one half of the kernel it is interpreted as smudge.

C.W.-Canada Western.

Damp-For red spring wheat "damp" is grain with moisture content (% w.b.) over 17.0 %.

Dark immature-Is a term used to describe darkened kernels, also referred to as "swath heated". These kernels are somewhat similar in appearance to heated kernels but are sound throughout and do not have a heated taste or odour.

Heated- Refers to kernels having the typical colour, taste, or odour of grain that has heated in storage, including kernels discoloured from artificial drying, but not charred kernels.

Mildew-A condition that develops in unthreshed kernels of grain caused by excessive moisture making the kernels greyish in colour and affecting their quality.

Mould (mildew)-Is a superficial coating or discolouration of downy or powdery fungal growth that develops in damp conditions.

Objectionable odour-All grain that has a distinct objectionable odour other than that associated with heated or fireburnt will be graded Sample Account Odour (kind of odour).

Rotted-Refers to decomposition or decay of kernels caused by bacteria or fungi usually indicated by blackening, discolouration and softening of all or part of the kernel.

Smudge-A dark brown or black discolouration or stain similar to blackpoint affecting more than one half of the kernel or extending into the crease of the kernel, and includes the reddish discolouration associated with some plant diseases.

Smut-A fungus or plant disease caused by smut fungi, characterized by masses of black spores.

Sprouted-Are kernels of grain that show definite signs of germination.

Tough-For red spring wheat "tough" is grain with a moisture conent (% w.b.) between 14.6 % and 17.0 %.

Viability-A viable seed is one which can germinate under favourable conditions, providing any dormancy that may be present is removed.

Appendix B

PLENUM CHAMBER CONSTRUCTION

Plenum chambers for the 0.61-m diameter bins were constructed with 12.7-mm thick plywood. Dimensions for the plenums are shown in Fig. B-1. The fully perforated floor is supported by a sheet metal grid (26 gauge) which transfers the load from the grain mass to the walls of the plenum chamber (Fig. B-2). Construction techniques for the plenum chamber used for the 1.22-m diameter bin are similar with the exception that an internal frame was built within the plenum chamber to help support the additional load. Four 13-mm diameter steel rods were also placed under the perforated floor (above the sheet metal grid, 24 gauge) to help distribute the load on the perforated floor to the plenum chamber walls.

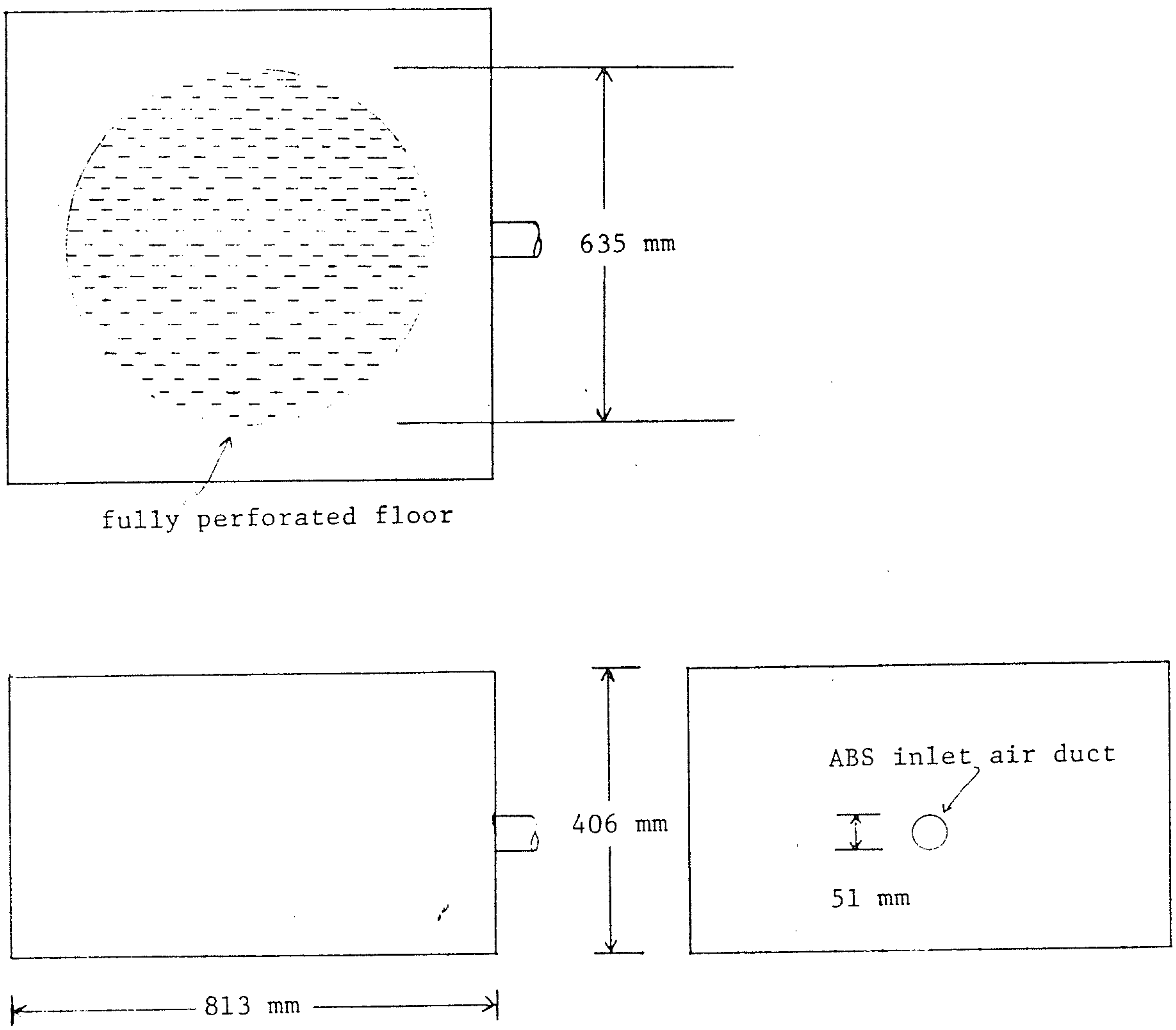


Fig. B-1: Plenum chamber for 0.61-m diameter bins.

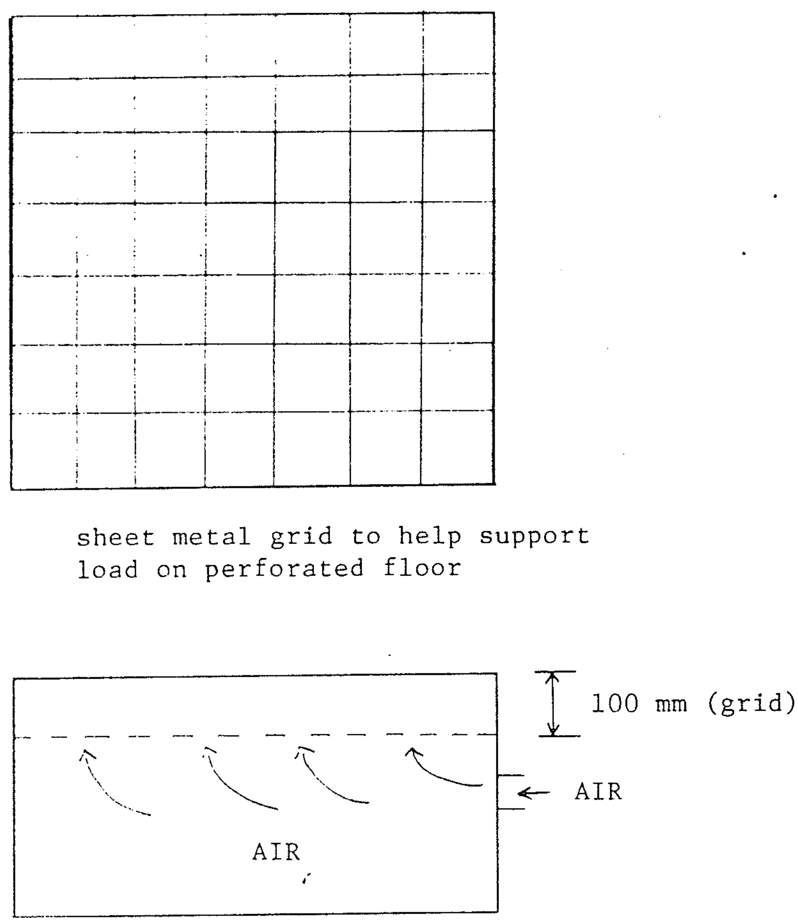


Fig. B-2: Floor supports for plenum chambers.

Appendix C

INSULATION COMPLETION DATES

Insulation completion dates

1)1983-1984 experiment

i)experiment start date of 31 August 1983

ii)To be fully insulated the bins are to be wrapped with 130-mm thick fiberglass with a foil face.

iii)At the start of experiment the following conditions existed:

-bins A to H insulated with 130-mm thick fiberglass for bottom 2.4 m of bin with only 76-mm thick fiberglass on the top 1.1 m of bin.

-bins J and K fully insulated.

-bin N insulated with 76-mm thick fiberglass for entire 3.5 m height of bin (no foil face).

iv)On 13 September 1983 at 16:00 h bins G and H completed.

v)On 20 September 1983 at 16:00 h bins A to F completed and bottom 1.2 m of bin N equipped with 130-mm thick fiberglass (top 2.3 m has only 76-mm thick fiberglass).

2)1984-1985 experiment

i)Experiment start date of 20 August 1984.

ii)To be fully insulated the 0.61-m diameter bins are to be equiped with 130-mm thick fiberglass on bottom 2.4 m of bin with 70-mm thick fiberglass on the top 1.1 m of bin. The 1.22-m diameter bin is to be equiped with 130-mm thick fiberglass on bottom 1.1 m of bin with 70-mm thick fiberglass on the top 2.4 m of bin.

iii)At the start of experiment the following conditions existed:

-Bins A,B,C and G insulated with 130-mm thick fiberglass for bottom 2.4 m of bin with no fiberglass on the top 1.1 m.

-Bins D and H insulated with 130-mm thick fiberglass for bottom 1.1 m of bin with no fiberglass on the top 2.4 m.

-No fiberglass on bin N.

-Bins J and K fully insulated (130-mm thick fiberglass for entire 3.5 m height).

iv)On 09 September 1984 at 16:00 h 70-mm thick fiberglass put on top 1.1 m of bins A,B,C,D,G and H as well as put on the remaining 60-mm thick fiberglass on the bottom 2.4 m of bins D and H. Thus, all 0.61-m diameter bins are completed.

v)On 10 September 1984 bin N completed (fully insulated with 70-mm thick fiberglass for entire height with an extra 60 mm of fiberglass (foil faced) on bottom 1.1 m of bin).

Appendix D

THERMAL ANEMOMETER CALIBRATION AND AIRFLOW DETERMINATION

1)Thermal anemometer calibration

The TA 3000 thermal anemometer was calibrated at least twice a year using a wind tunnel and a micro-manometer. A sketch of the wind tunnel used is shown in Fig. D-1. The theory and procedure used is given below.

i)Theory

Using pressure tap at location 2 (Fig. D-1) the following is true (by Bernouli's equation).

$$\frac{P_1}{\gamma_1} + \frac{V_1^2}{2g} + Z_1 = \frac{P_2}{\gamma_2} + \frac{V_2^2}{2g} + Z_2$$

(assuming no head loss due to friction the following simplifications can be made)

$$Z_1 = Z_2 \qquad V_1 = 0 \qquad g=9.81 \text{ m/s}^2$$

The above equation then reduces to

$$V_2^2 = \frac{P_1 - P_2}{\gamma_1} * 2 * 9.81 \text{ m}^2/\text{s}^2$$

calculate γ_1 using measured atmospheric pressure $\gamma_1 = \frac{P_1 * g}{R * T}$

where: P_1=atmospheric pressure, Pa

P_2=absolute pressure at location 2, Pa

V_1=velocity at location 1, m/s

V_2=velocity at location 2, m/s

g =gravity=9.81 m/s^2 (assumed constant)

γ =specific weight of the air, N/m^3

R =gas constant=287 (J/kg)/K for air

T =air temperature, K

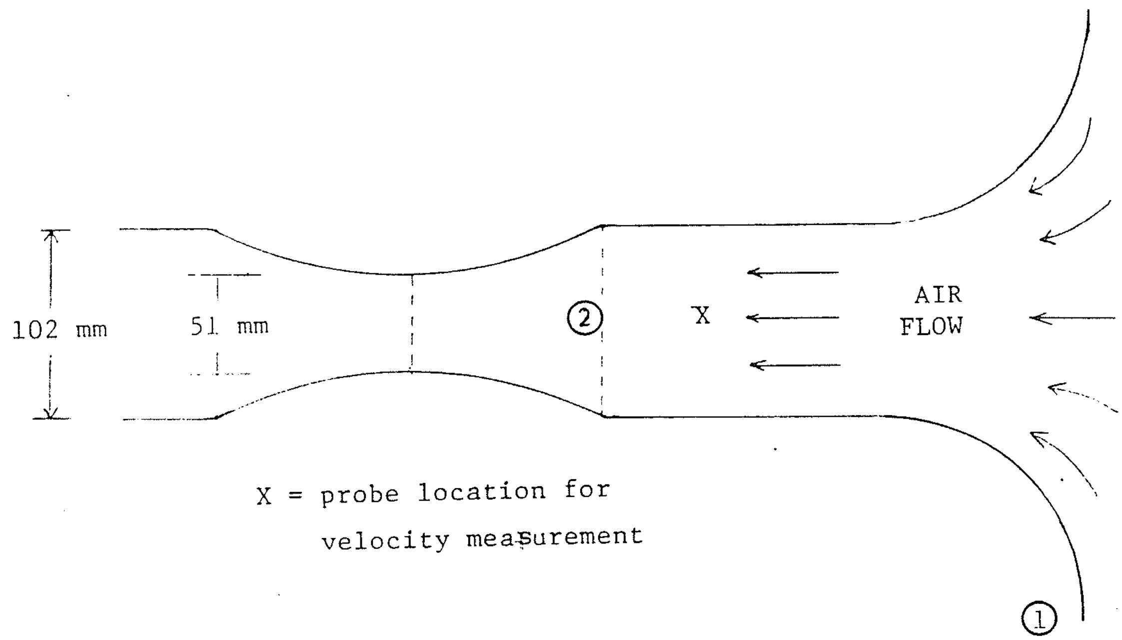


Fig. D-1: Sketch of wind tunnel used to calibrate the TA 3000 thermal anemometer.

ii)Sample calculation

assume: P_1=94,650 Pa

T=298.15 K (25°C)

$$\gamma_1 = \frac{94,650 \text{ N/m}^3 * 9.81 \text{ m/s}^2}{287 \text{ J/(kg K)} * 298.15 \text{ K}} * \frac{\text{J}}{\text{Nm}} = 10.86 \text{ N/m}^3$$

therefore:

$$V_2^{\,2} = \frac{P_1 - P_2}{10.86} * 2 * 9.81 \text{ m}^2/\text{s}^2$$

or

$$V_2 = (1.807 * (P_1 - P_2))^{0.5} \text{ m/s}$$

$(P_1 - P_2)$ is the pressure drop from point 1 to point 2,

if $(P_1 - P_2)$ = 100 Pa then the velocity at point 2 is

$$V_2 = (1.807 * 100)^{0.5} \text{m/s} = 13.4 \text{ m/s}$$

iii)Calibration procedure

1)Remove the two cover screws on the TA 3000 thermal anemometer and remove cover. Prior to calibration the instrument must be zeroed both mechanically (bottom of analog meter) and electrically (black wheel at top of instrument) with the probe cap on. The circuit board inside the instrument (now exposed) has two potentiometers (pots) mounted on the component side.

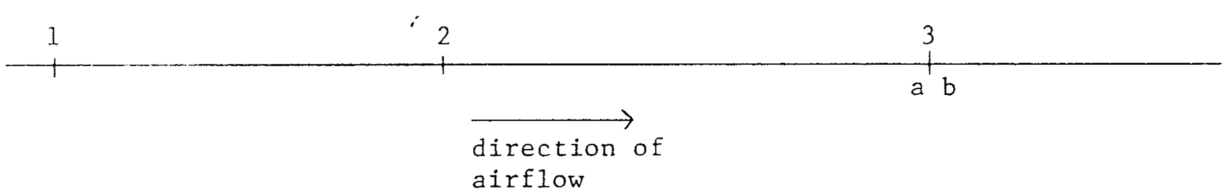
2)Set the wind velocity to 15 m/s in the tunnel, $(P_1 - P_2)$=125 Pa, and adjust lower pot until meter reads correctly.

3)Set the wind velocity to 1 m/s in the tunnel, $(P_1 - P_2)$=0.55 Pa, and adjust upper pot until meter reads correctly.

4)One pot adjustment will effect the adjustment of the previous pot, so repeat steps 2 and 3 until both high and low velocities read correctly. When this is accomplished, the instrument will read correctly over the entire range (0 to 15 m/s).

2)Airflow calibration

Velocity readings from the TA 3000 thermal anemometer are related to volumetric airflow using orifice plates in a laboratory situation. A schematic diagram of the apparatus used is shown in Fig. D-2. The theory and procedure used are give below.



1)Control airflow here using a ball valve located in pipe.

2)Measure airstream velocity here using thermal anemometer.

3)Measure volumetric airflow rate here using orifice plate apparatus.

Fig. D-2: Schematic diagram of airflow calibration device relating thermal anemometer reading to volumetric airflow.

i) Theory

Flow rate through an orifice plate is given by (ISO 1980):

$$q = \frac{1}{\rho_d} * C * E * \epsilon * \frac{\pi d^2}{4} * \sqrt{2 \Delta P * \rho_{up}}$$

where q=volumetric airflow rate, m^3/s

ρd=air density downstream of orifice plate, kg/m^3

ρup=air density upstream of orifice plate, kg/m^3

ΔP=pressure drop across orifice plate, Pa

β =diameter ratio (d/D)

d=orifice throat diameter, m

D=internal pipe diameter, m

Re_d=Reynold's number downstream of orifice plate, dimensionless

V=mean airstream velocity in pipe, m/s

$$C = 0.5959 + 0.0312\beta^{2.1} - 0.1840\beta^{8} + 0.0029\beta^{2.5} * \left[\frac{10^6}{Re_d}\right]^{0.75} + 0.0390\frac{\beta^4}{(1-\beta^4)} - 0.01584\beta^3$$

$$E = (1-\beta^4)^{-0.5}$$

$$\epsilon = 1 - (0.41 + 0.35\beta^4) * \frac{\Delta P}{k \rho up}$$

$$Re_d = \frac{V * D * \rho up}{\mu} \qquad \rho up = \frac{Pup}{R*T}$$

μ=kinematic viscosity, Ns/m^2

R=gas constant=287 (J/kg)/K

T=airstream temperature, K

ii)Calibration procedure

1)Insert anemometer probe into airstream at point 1 and record value.

2)Record pressures at locations a and b.

3)Record pressure drop across orifice plate (a-b).

4)Assume a mean pipe velocity (V) of 0.9 * measured velocity by thermal anemometer and calculate flow rate (q) through orifice plate using above equations. From calculated flow rate determine a mean pipe velocity (V) and repeat calculations using this new mean pipe velocity (mean pipe velocity (V) affects calculations). Repeat process until calculated mean pipe velocity remains constant (or does not change significantly (5%)).

5)Record calculated airflow rate and repeat process with a new airflow rate (by adjusting ball valve).

6)After a number of trials have been completed perform a linear regression on the results to relate thermal anemometer reading to a volumetric airflow rate.

Appendix E

HYSTERESIS SUBROUTINE FOR DRYING PROGRAM

```
C*****************************************************************
      SUBROUTINE DSIM(TO,TD,XM,G,DM,AVEM,AVET,M)
      DOUBLE PRECISION AHUM
      COMMON /AREA1/R,IDELT0,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)
C
C
C
C    HY EFFECT IF FLAG=1
          FLAGRH=1
       IF(FLAGRH.EQ.1)THEN DO
C      THIS IF WILL ALLOW A HYSTERISIS EFFECT
C      IF FLAGRH IS =1
       DIFF=-.05
      RHDIF=ERH-RHS
      IF(N.EQ.0)THEN DO
       IF(RHDIF.LT.0)THEN DO
         FLAG=1
       ELSE DO
```

```
          FLAG=0
        END IF
       END IF
       IF(FLAG.EQ.1)THEN DO
       IF(RHDIF.LT.0)THEN DO
        IF(RHDIF.LT.DIFF)THEN DO
          ERH=ERH-DIFF
        ELSE DO
          ERH=RHS
        END IF
       END IF
       END IF
C
       END IF
C      THIS END IF ENDS THE LOOP THAT ALLOWS HYSTERESIS
       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**************************************************************
```

Appendix F

SHRINKAGE PROGRAM FOR SIMULATION RESULTS

```
  DATA ONE;
  INFILE IN;
  FILE ONE;
  INPUT AIR 10-14 TFAN 23-26;
DO J=1 TO 1000;
  INPUT BLANK 1 DATE YYMMDD8. HR 11-12;
  BIN=0;
  H2=3.325; H3=2.975; H4=2.625; H5=2.275; H6=1.925; H7=1.575;
  H8=1.225; H9=0.875; H10=0.525; H11=0.175;
  INPUT LAYER MC2 T2 SP2;
  INPUT LAYER MC3 T3 SP3;
  INPUT LAYER MC4 T4 SP4;
  INPUT LAYER MC5 T5 SP5;
  INPUT LAYER MC6 T6 SP6;
  INPUT LAYER MC7 T7 SP7;
  INPUT LAYER MC8 T8 SP8;
  INPUT LAYER MC9 T9 SP9;
  INPUT LAYER MC10 T10 SP10;
  INPUT LAYER MC11 T11 SP11;
  IF MC11<14.5 THEN DO;
     H11=.175-.0193; H10=.525-.0193; H9=.875-.0193; H8=1.225-.0193;
     H7=1.575-.0193; H6=1.925-.0193; H5=2.275-.0193; H4=2.625-.0193;
     H3=2.975-.0193; H2=3.325-.0193;
  END;
  IF MC10<14.5 THEN DO;
     H11=.175-.0193; H10=.525-.0578; H9=.875-.0578; H8=1.225-.0578;
     H7=1.575-.0578; H6=1.925-.0578; H5=2.275-.0578; H4=2.625-.0578;
     H3=2.975-.0578;H2=3.325-.0193;
  END;
  IF MC9<14.5 THEN DO;
     H11=.175-.0193; H10=.525-.0578; H9=.875-.0963; H8=1.225-.0963;
     H7=1.575-.0963; H6=1.925-.0963; H5=2.275-.0963; H4=2.625-.0963;
     H3=2.975-.0963; H2=3.325-.0963;
  END;
  IF MC8<14.5 THEN DO;
     H11=.175-.0193; H10=.525-.0578; H9=.875-.0963;
     H8=1.225-.1348; H7=1.575-.1348; H6=1.925-.1348; H5=2.275-.1348;
     H4=2.625-.1348; H3=2.975-.1348; H2=3.325-.1348;
  END;
  IF MC7<14.5 THEN DO;
     H11=.175-.0193; H10=.525-.0578; H9=.875-.0963; H8=1.225-.1348;
     H7=1.575-.1733; H6=1.925-.1733; H5=2.275-.1733; H4=2.625-.1733;
     H3=2.975-.1733; H2=3.325-.1733;
  END;
```

```
IF MC6<14.5 THEN DO;
   H11=.175-.0193; H10=.525-.0578; H9=.875-.0963; H8=1.225-.1348;
   H7=1.575-.1733; H6=1.925-.2118; H5=2.275-.2118; H4=2.625-.2118;
   H3=2.975-.2118; H2=3.325-.2118;
END;
IF MC5<14.5 THEN DO;
   H11=.175-.0193; H10=.525-.0578; H9=.875-.0963; H8=1.225-.1348;
   H7=1.575-.1733; H6=1.925-.2118;
   H5=2.275-.2503; H4=2.625-.2503; H3=2.975-.2503; H2=3.325-.2503;
END;
IF MC4<14.5 THEN DO;
   H11=.175-.0193; H10=.525-.0578; H9=.875-.0963; H8=1.225-.1348;
   H7=1.575-.1733; H6=1.925-.2118; H5=2.275-.2503;
   H4=2.625-.2888; H3=2.975-.2888; H2=3.325-.2888;
END;
IF MC3<14.5 THEN DO;
   H11=.175-.0193; H10=.525-.0578; H9=.875-.0963; H8=1.225-.1348;
   H7=1.575-.1733; H6=1.925-.2118; H5=2.275-.2503; H4=2.625-.2888;
   H3=2.975-.3273; H2=3.325-.3273;
END;
IF MC2<14.5 THEN DO;
   H11=.175-.0193; H10=.525-.0578; H9=.875-.0963; H8=1.225-.1348;
   H7=1.575-.1733; H6=1.925-.2118; H5=2.275-.2503; H4=2.625-.2888;
   H3=2.975-.3273; H2=3.325-.3658;
END;
SAMP=2; MOIST=MC2; TEMP=T2; SPOIL=SP2; HEIGHT=H2;
PUT DATE YYMMDD8. HR 3. BIN 3. SAMP 3. MOIST 5.1
    TEMP 6.1 SPOIL 6.3 HEIGHT 6.3;
SAMP=3; MOIST=MC3; TEMP=T3; SPOIL=SP3; HEIGHT=H3;
PUT DATE YYMMDD8. HR 3. BIN 3. SAMP 3. MOIST 5.1
    TEMP 6.1 SPOIL 6.3 HEIGHT 6.3;
SAMP=4; MOIST=MC4; TEMP=T4; SPOIL=SP4; HEIGHT=H4;
PUT DATE YYMMDD8. HR 3. BIN 3. SAMP 3. MOIST 5.1
    TEMP 6.1 SPOIL 6.3 HEIGHT 6.3;
SAMP=5; MOIST=MC5; TEMP=T5; SPOIL=SP5; HEIGHT=H5;
PUT DATE YYMMDD8. HR 3. BIN 3. SAMP 3. MOIST 5.1
    TEMP 6.1 SPOIL 6.3 HEIGHT 6.3;
SAMP=6; MOIST=MC6; TEMP=T6; SPOIL=SP6; HEIGHT=H6;
PUT DATE YYMMDD8. HR 3. BIN 3. SAMP 3. MOIST 5.1
    TEMP 6.1 SPOIL 6.3 HEIGHT 6.3;
SAMP=7; MOIST=MC7; TEMP=T7; SPOIL=SP7; HEIGHT=H7;
PUT DATE YYMMDD8. HR 3. BIN 3. SAMP 3. MOIST 5.1
    TEMP 6.1 SPOIL 6.3 HEIGHT 6.3;
SAMP=8; MOIST=MC8; TEMP=T8; SPOIL=SP8; HEIGHT=H8;
PUT DATE YYMMDD8. HR 3. BIN 3. SAMP 3. MOIST 5.1
    TEMP 6.1 SPOIL 6.3 HEIGHT 6.3;
SAMP=9; MOIST=MC9; TEMP=T9; SPOIL=SP9; HEIGHT=H9;
PUT DATE YYMMDD8. HR 3. BIN 3. SAMP 3. MOIST 5.1
    TEMP 6.1 SPOIL 6.3 HEIGHT 6.3;
SAMP=10; MOIST=MC10; TEMP=T10; SPOIL=SP10; HEIGHT=H10;
PUT DATE YYMMDD8. HR 3. BIN 3. SAMP 3. MOIST 5.1
    TEMP 6.1 SPOIL 6.3 HEIGHT 6.3;
SAMP=11; MOIST=MC11; TEMP=T11; SPOIL=SP11; HEIGHT=H11;
PUT DATE YYMMDD8. HR 3. BIN 3. SAMP 3. MOIST 5.1
    TEMP 6.1 SPOIL 6.3 HEIGHT 6.3;
END;
```

Appendix G

ADDITIONAL FIGURES

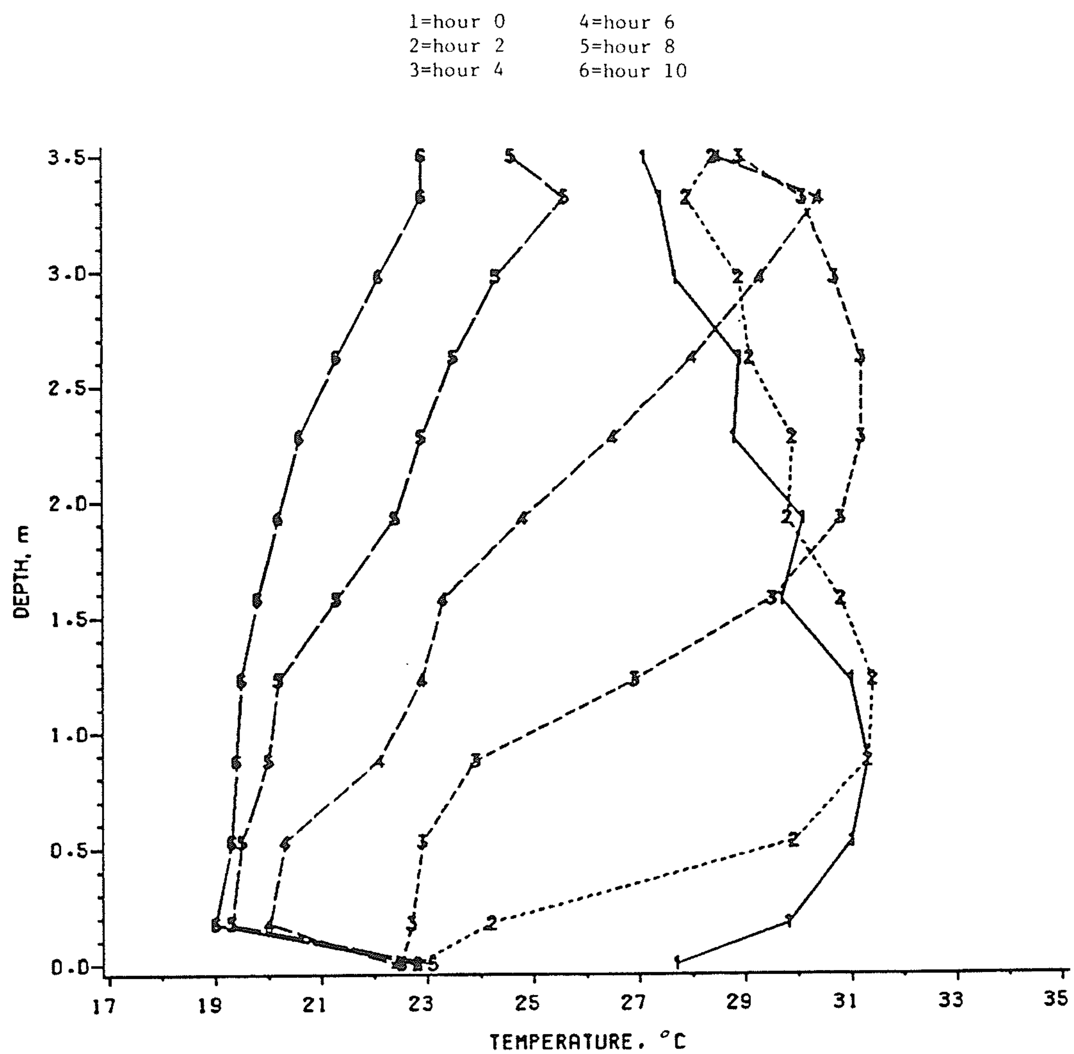


Fig. G.1: Intergranular air temperatures in a bin of damp wheat ventilated at 12.2 $(L/s)/m^3$. Ventilation start date was 31 Aug. 1983 at 22:00 h. The hour variable corresponds to time from start of ventilation (h).

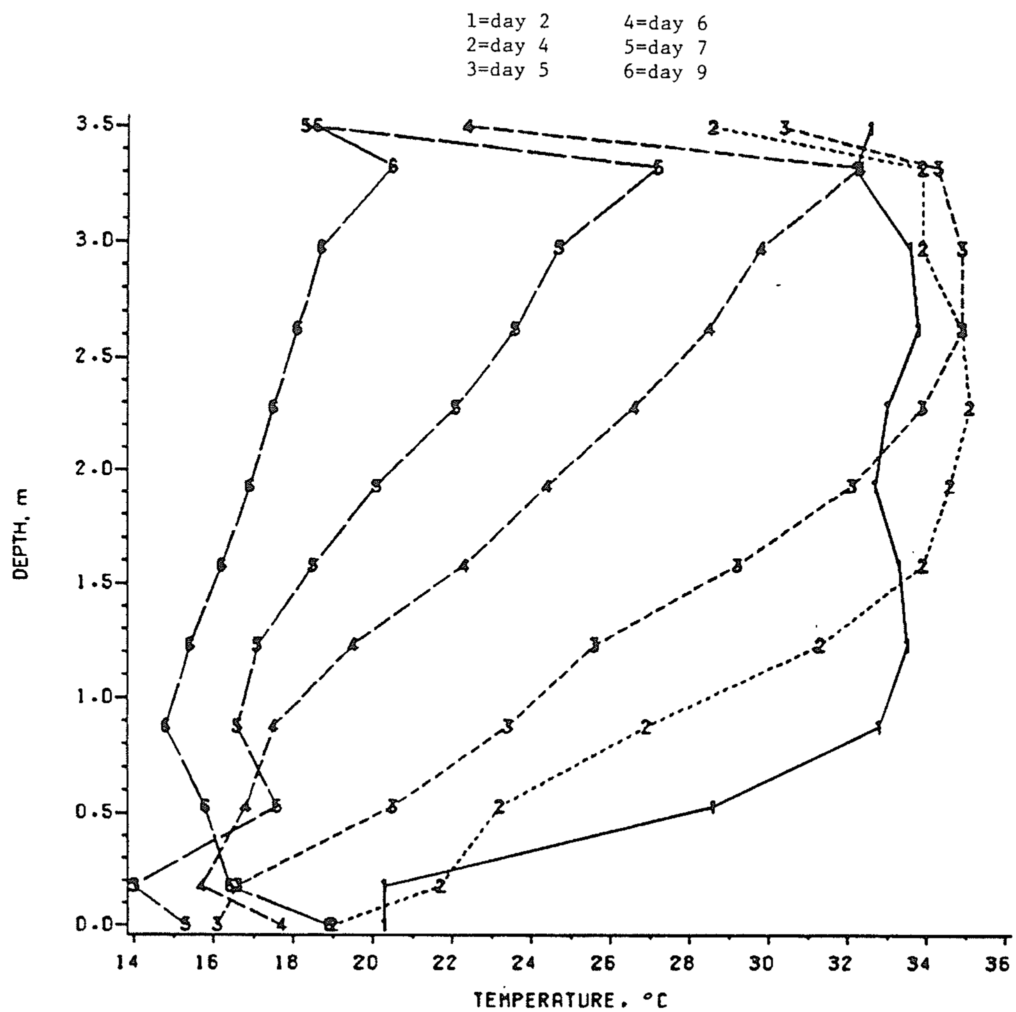


Fig. G.2: Intergranular air temperatures in a bin of damp wheat ventilated at 0.85 (L/s)/m^3. Ventilation start date was 31 Aug. 1983 at 22:00 h. The day variable corresponds to the number of days from the start of ventilation (all readings taken at 12:00 h).

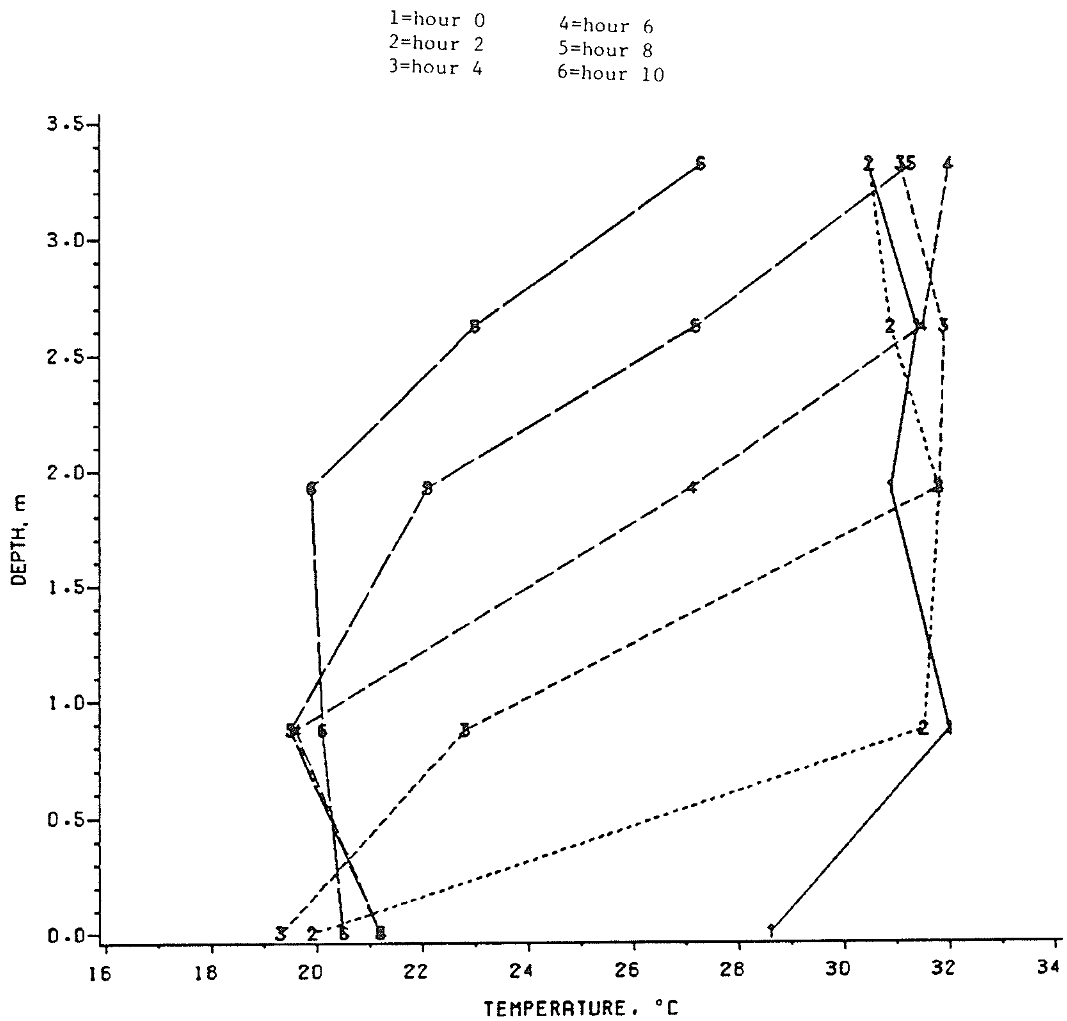


Fig. G.3: Intergranular air temperatures in a bin of damp wheat ventilated at 6.9 (L/s)/m³. Ventilation start date was 20 Aug. 1984 at 15:00 h. The hour variable corresponds to time from 20 Aug. 1984 at 14:00 h (h).

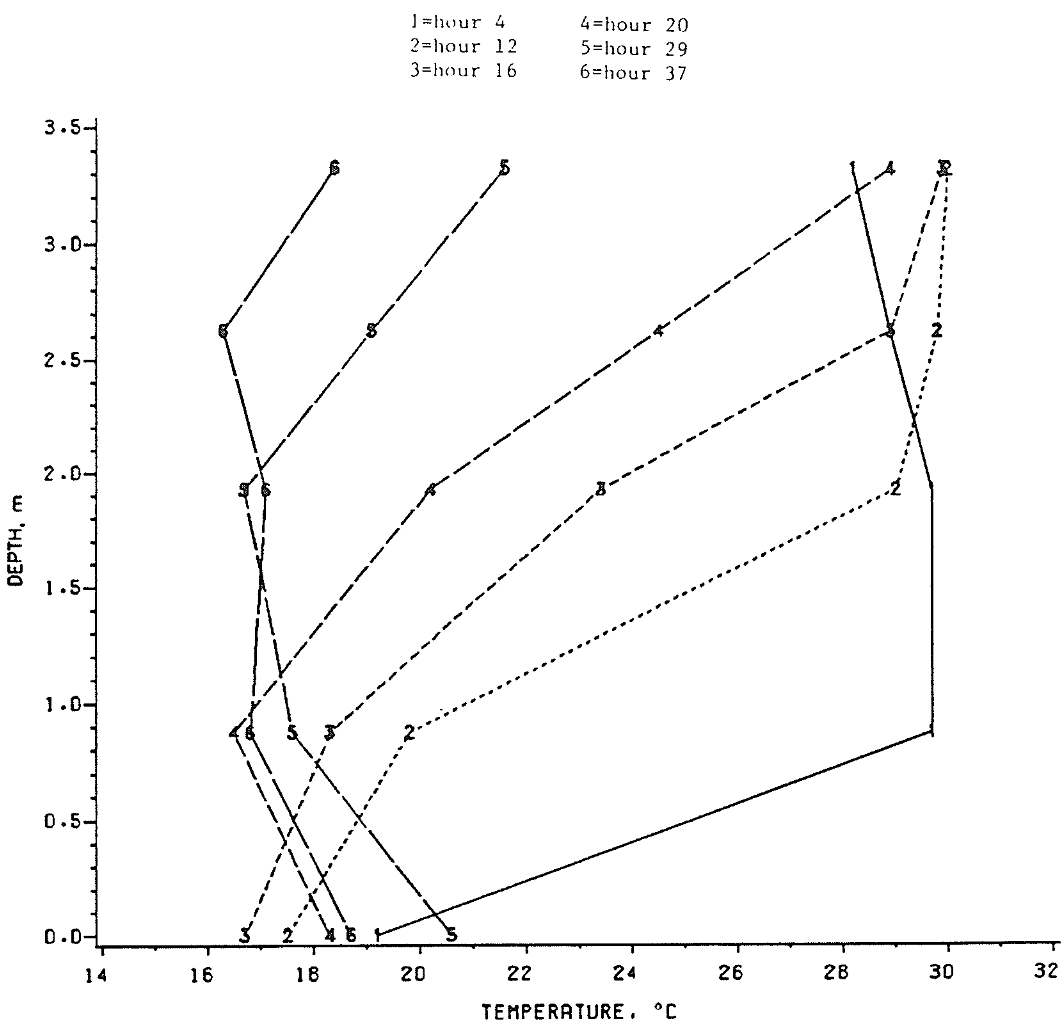


Fig. G.4: Intergranular air temperatures in a bin of damp wheat ventilated at 3.4 (L/s)/m^3. Ventilation start date was 20 Aug. 1984 at 16:00 h. The hour variable corresponds to time from 20 Aug. 1984 at 14:00 h (h).

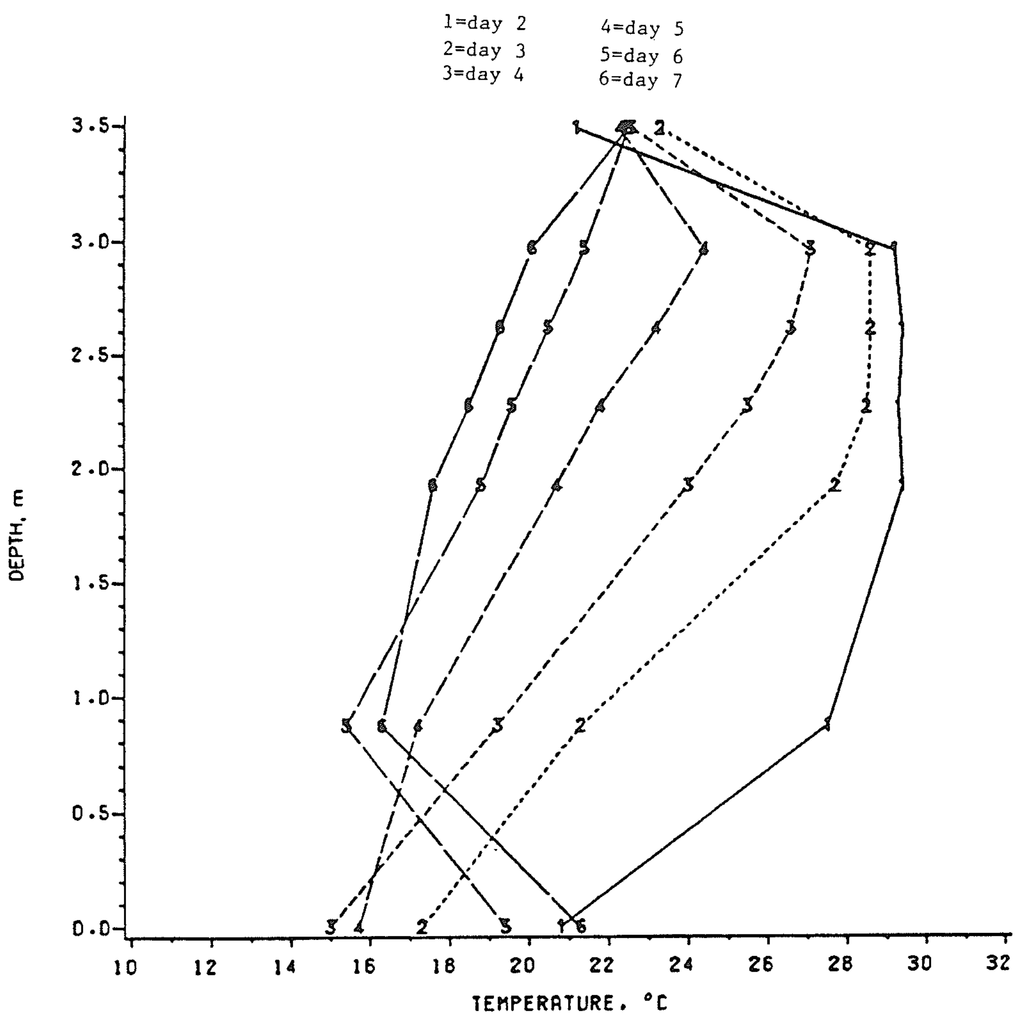


Fig. G.5: Intergranular air temperatures in a bin of tough wheat ventilated at 0.85 (L/s)/m^3. Ventilation start date was 19 Aug. 1984 at 17:00 h. The day variable corresponds to the number of days from 20 Aug. 1984 (all readings taken at 12:00 h).

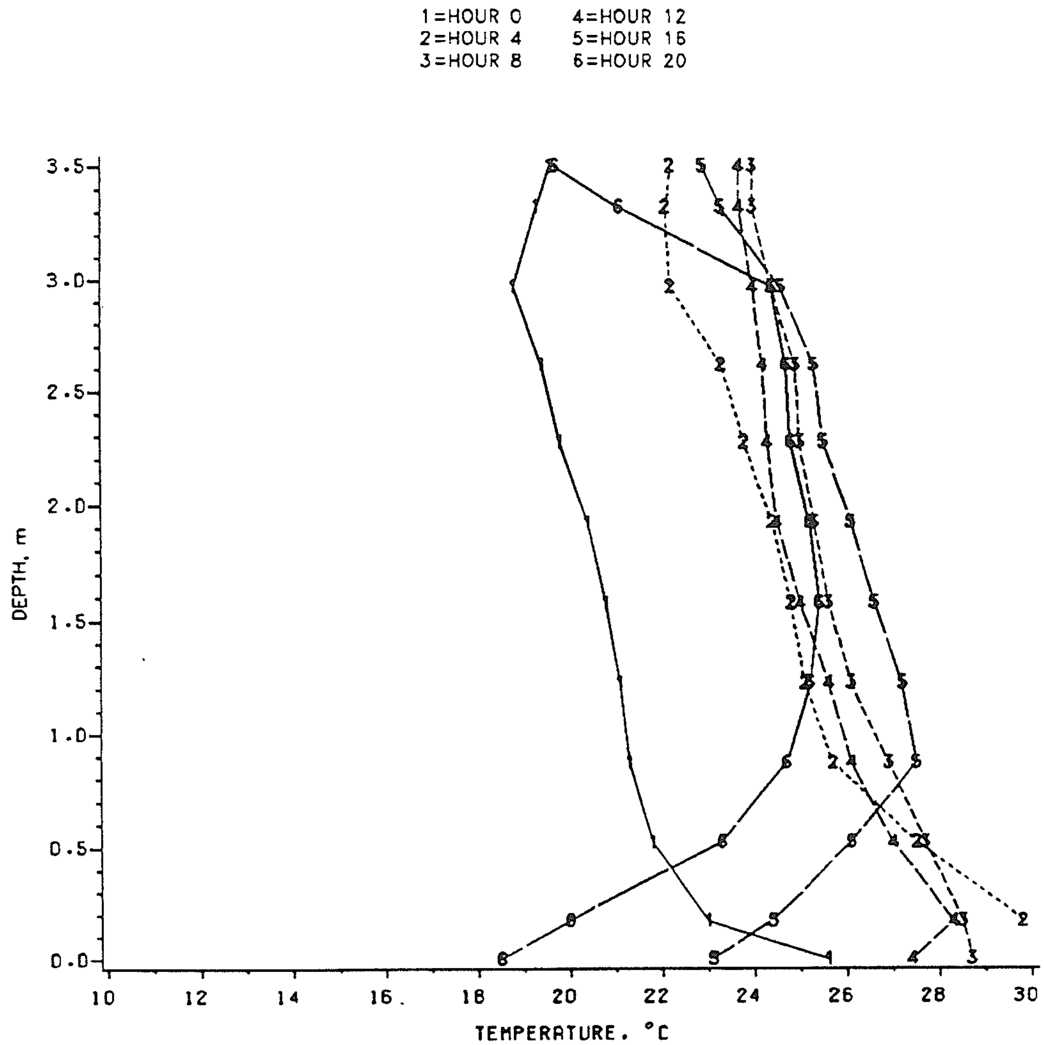


Fig. G.6: Intergranular air temperatures in a bin of wheat (dried to approximately 13 %) ventilated at 12.2 (L/s)/m^3. Profiles are for a 24 h period starting on 27 Sept. 1983 at 12:00 h.

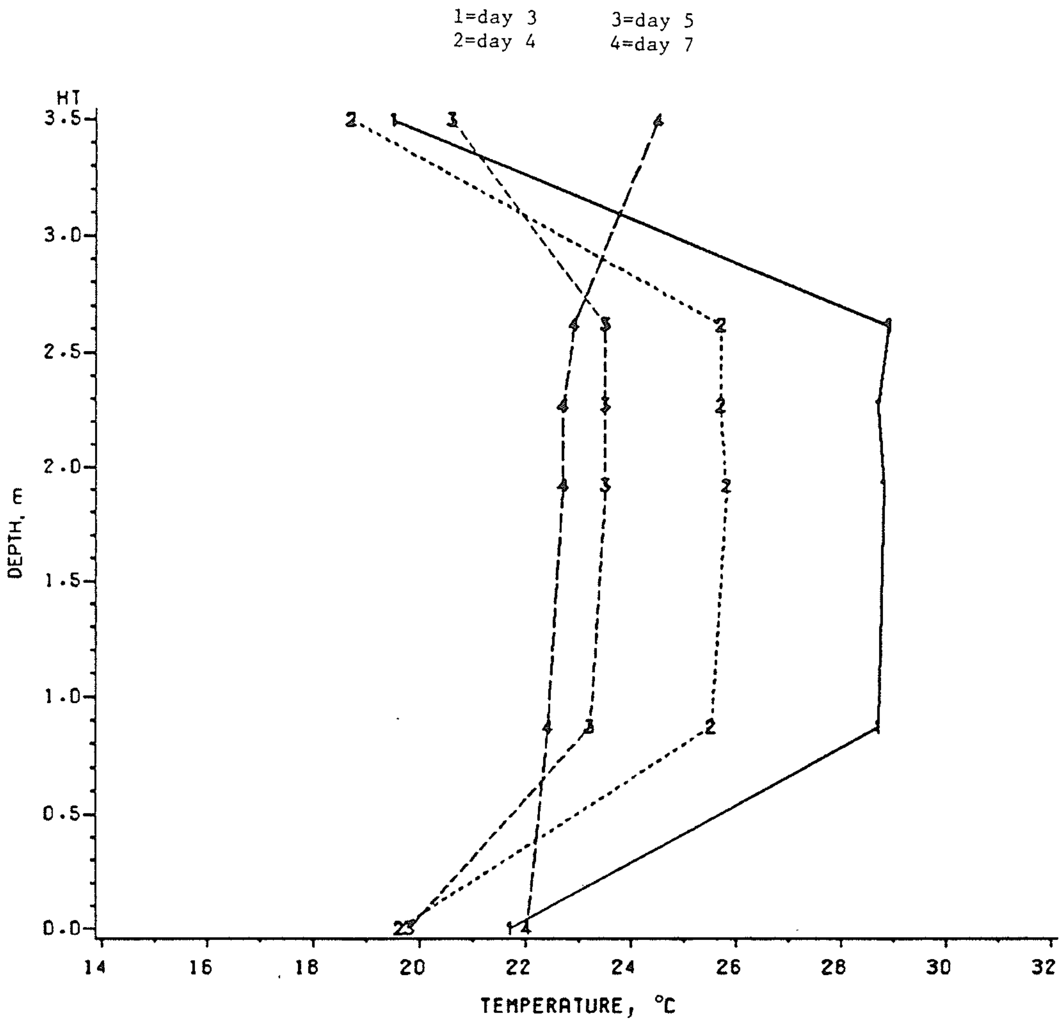


Fig. G.7: Intergranular air temperatures in a bin of damp wheat with no forced ventilation and a binning date of 20 Aug. 1984. The day variable corresponds to time from binning date (all readings taken at 12:00 h).

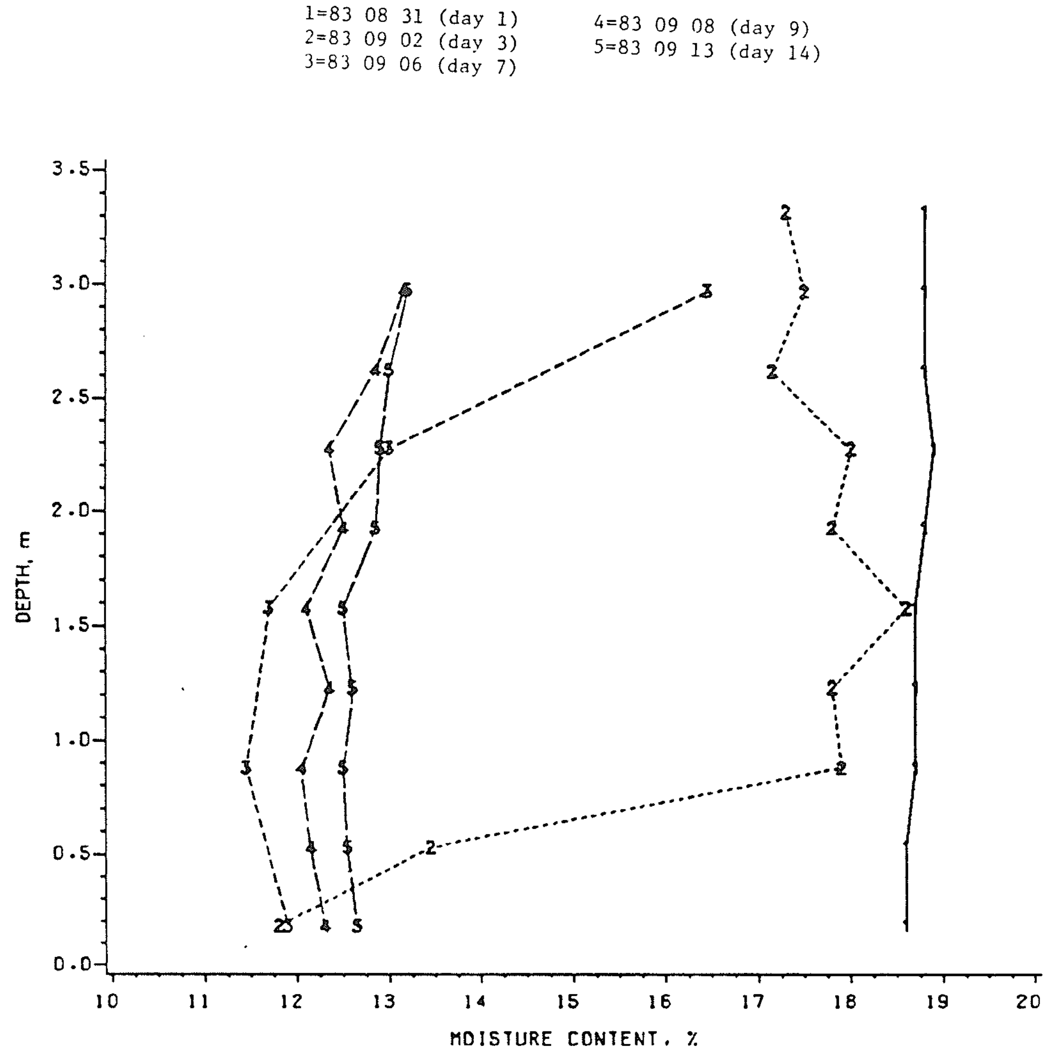


Fig. G.8:: Moisture contents of wheat for 5 dates during storage at a ventilation rate of 23.2 (L/s)/m^3 with a binning date of 31 Aug. 1983 (each value is the mean of bins C and D).

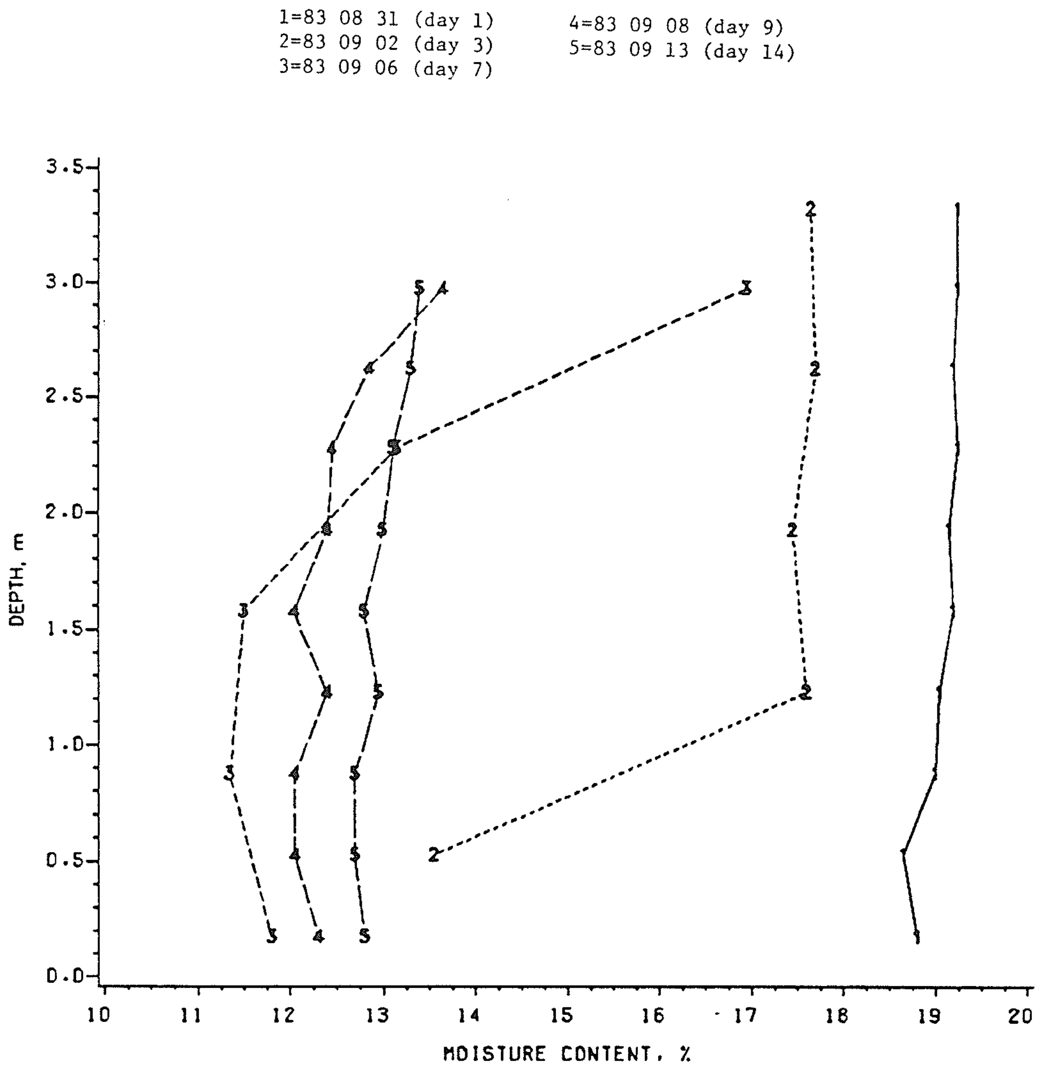


Fig. G.9: Moisture contents of wheat for 5 dates during storage at a ventilation rate of 23.2 (L/s)/m^3 with a binning date of 31 Aug. 1983 (each value is the mean of bins L and M).

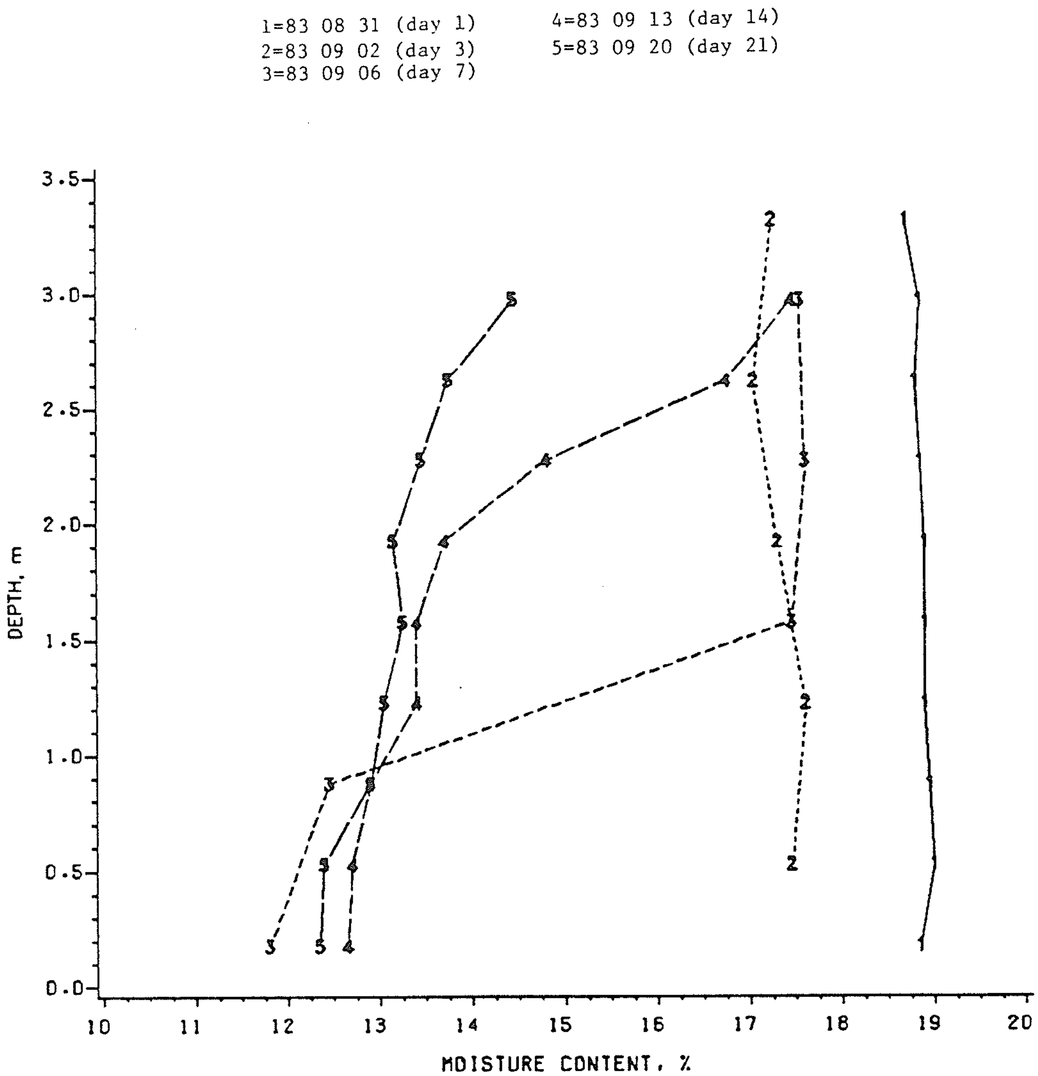


Fig. G.10: Moisture contents of wheat for 5 dates during storage at a ventilation rate of 12.2 (L/s)/m^3 with a binning date of 31 Aug. 1983 (each value is the mean of bins A and B).

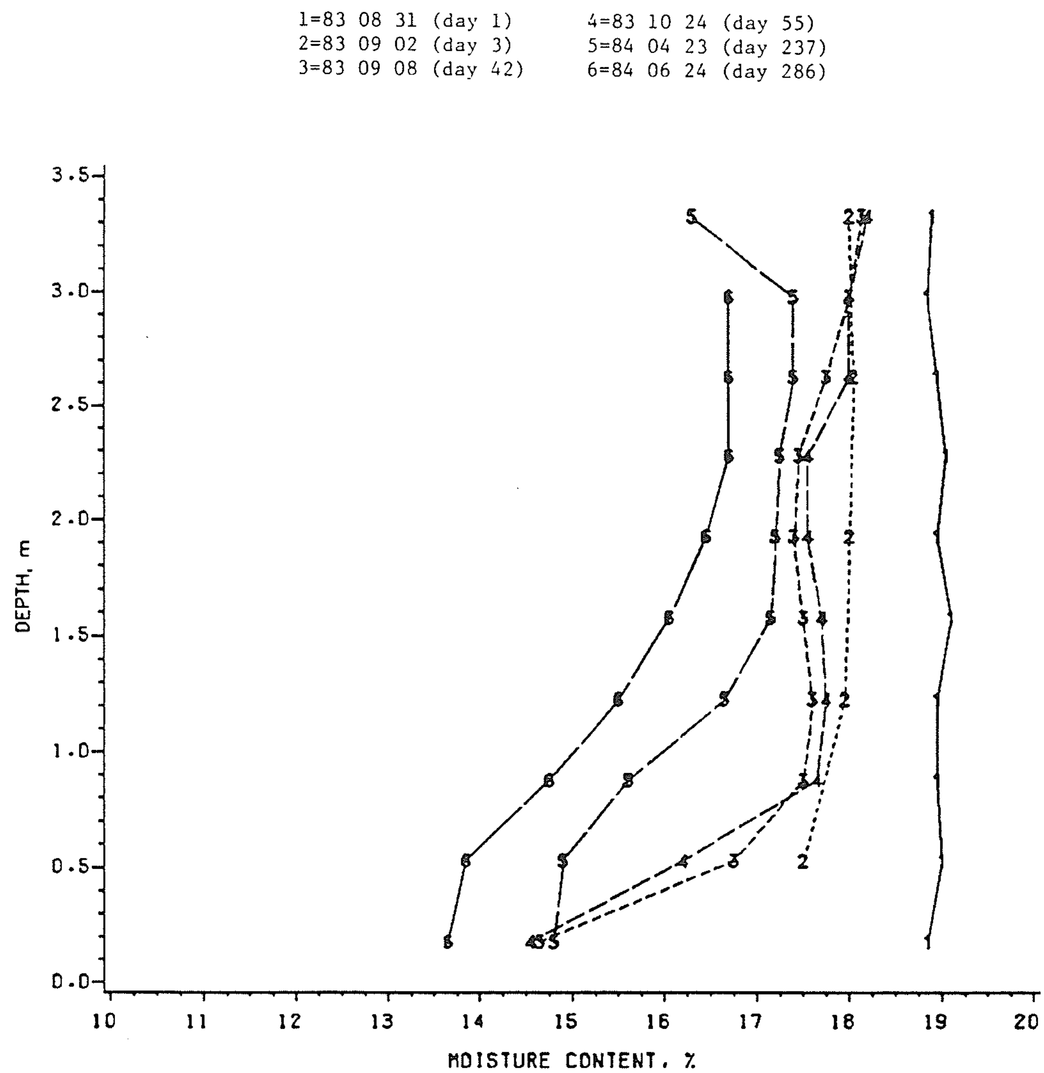


Fig. G.11: Moisture contents of wheat for 6 dates during storage at a ventilation rate of 0.85 (L/s)/m^3 with a binning date of 31 Aug. 1983 (each value is the mean of bins G and H).

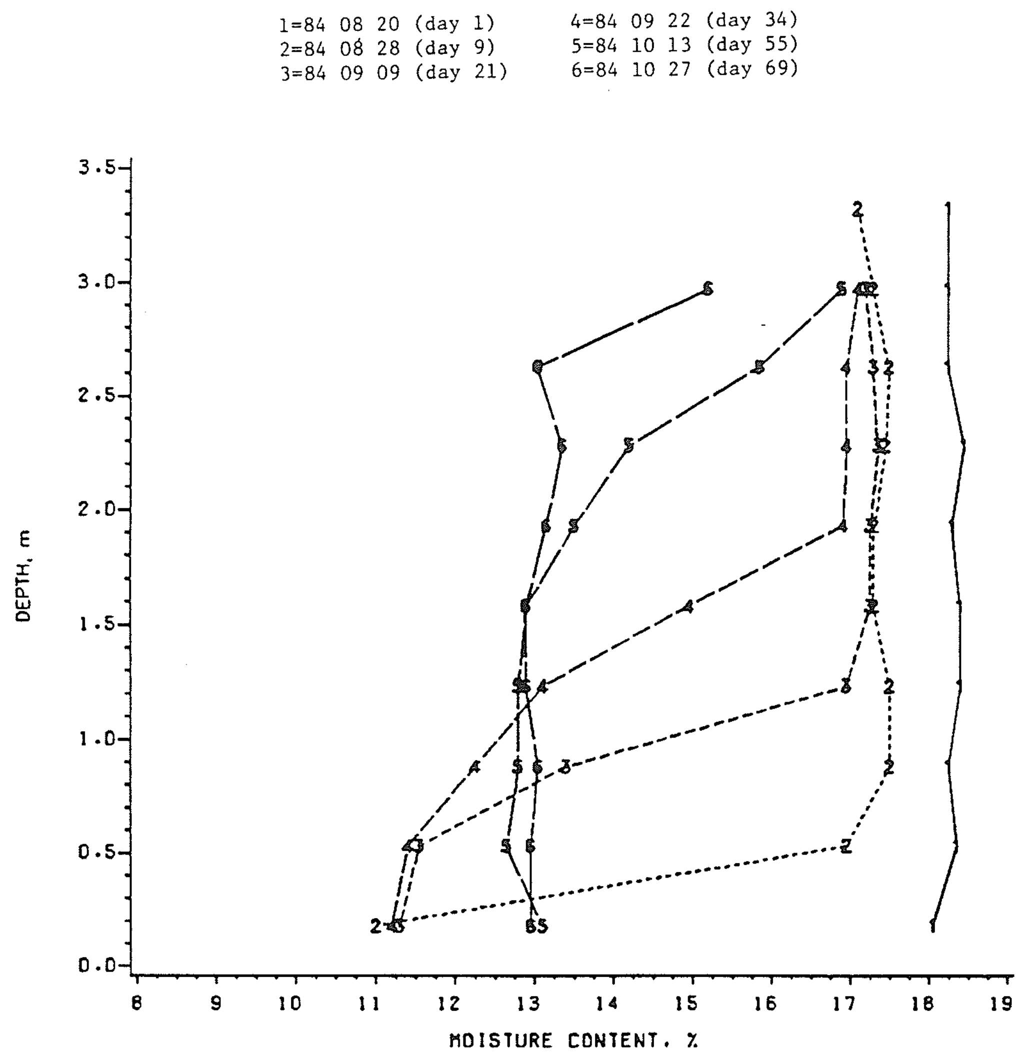


Fig. G.12: Moisture contents of wheat for 6 dates during storage at a ventilation rate of 3.4 $(L/s)/m^3$ with a binning date of 20 Aug. 1984 (each value is the mean of bins C and D).

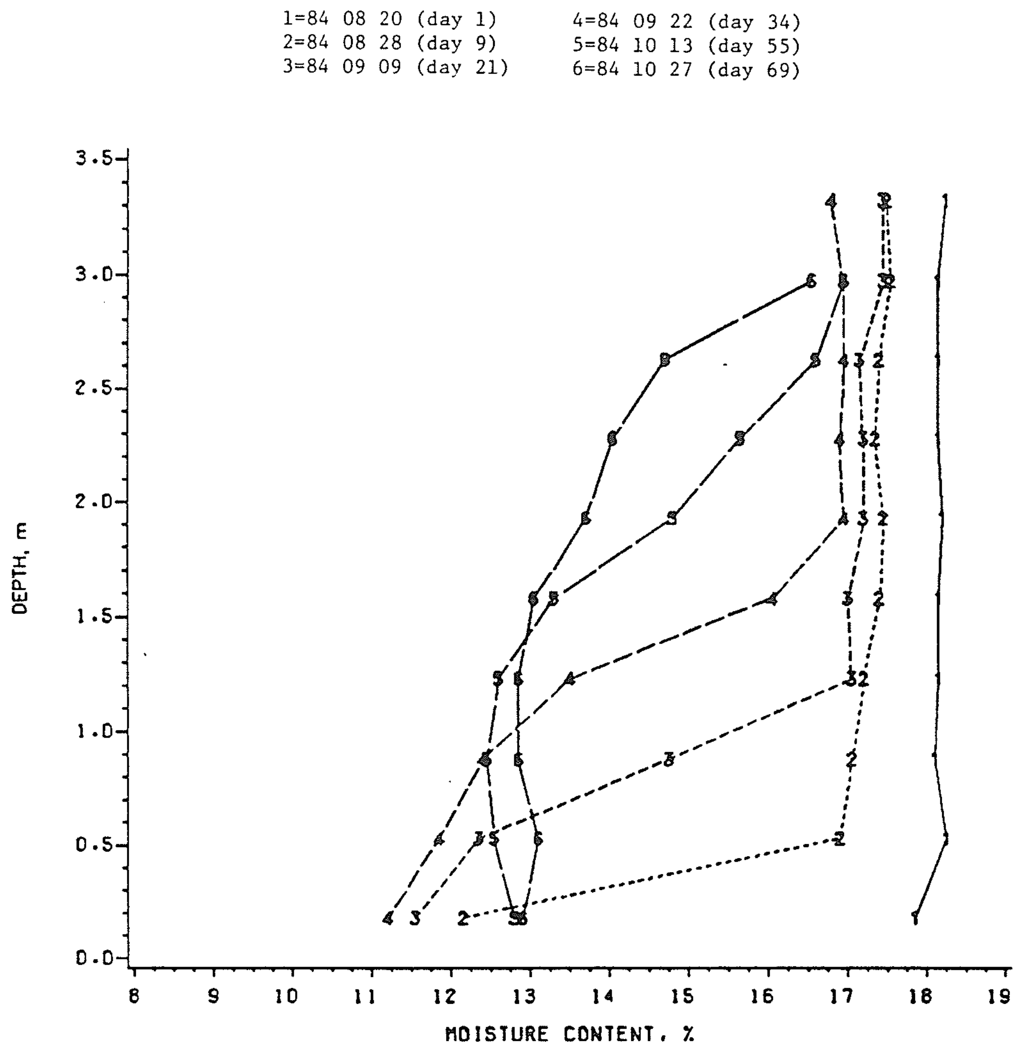


Fig. G.13: Moisture contents of wheat for 6 dates during storage at a ventilation rate of 3.4 $(L/s)/m^3$ with a binning date of 20 Aug. 1984 (each value is the mean of bins L and M).

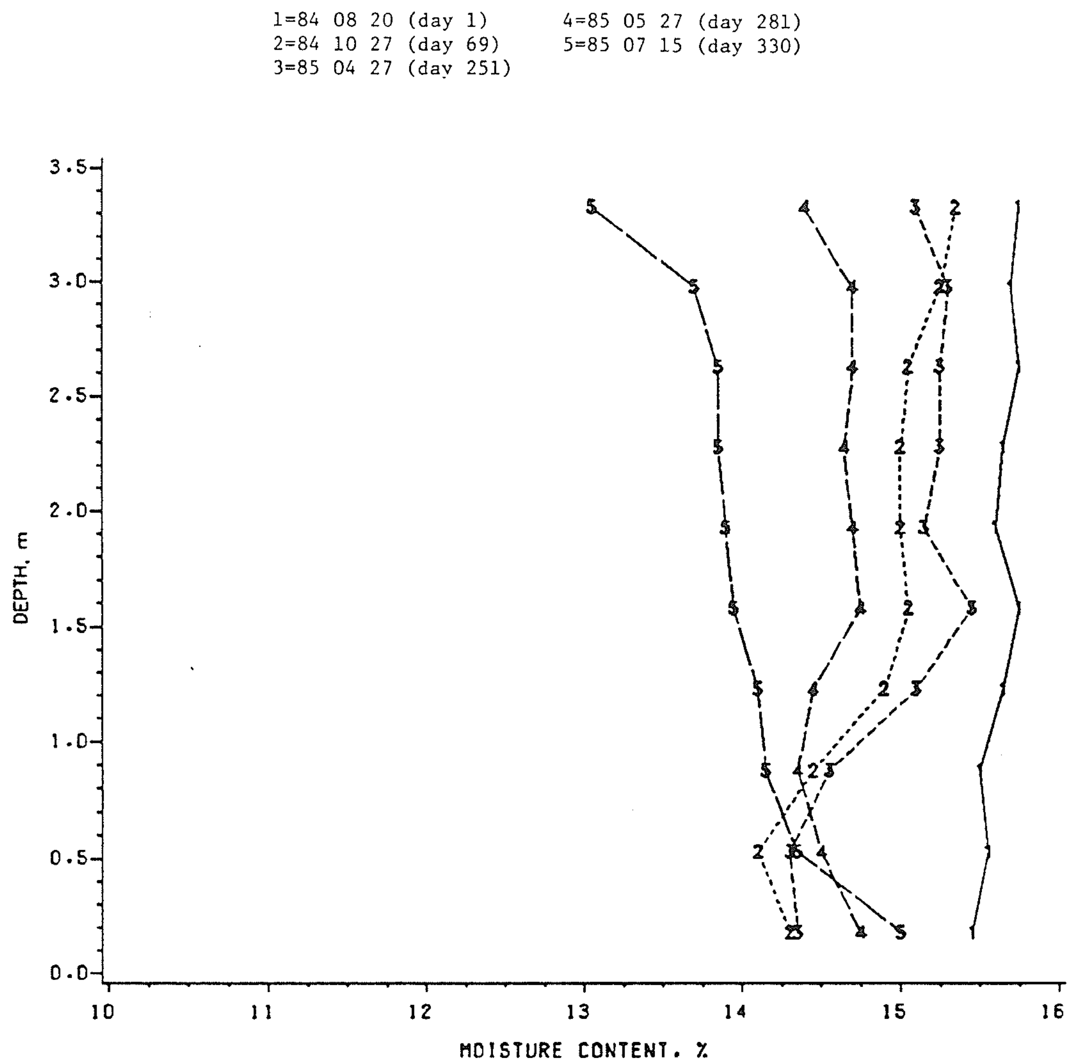


Fig. G.14: Moisture contents of wheat for 5 dates during storage at a ventilation rate of 0.85 $(L/s)/m^3$ with a binning date of 20 Aug. 1984 (each value is the mean of bins G and H).

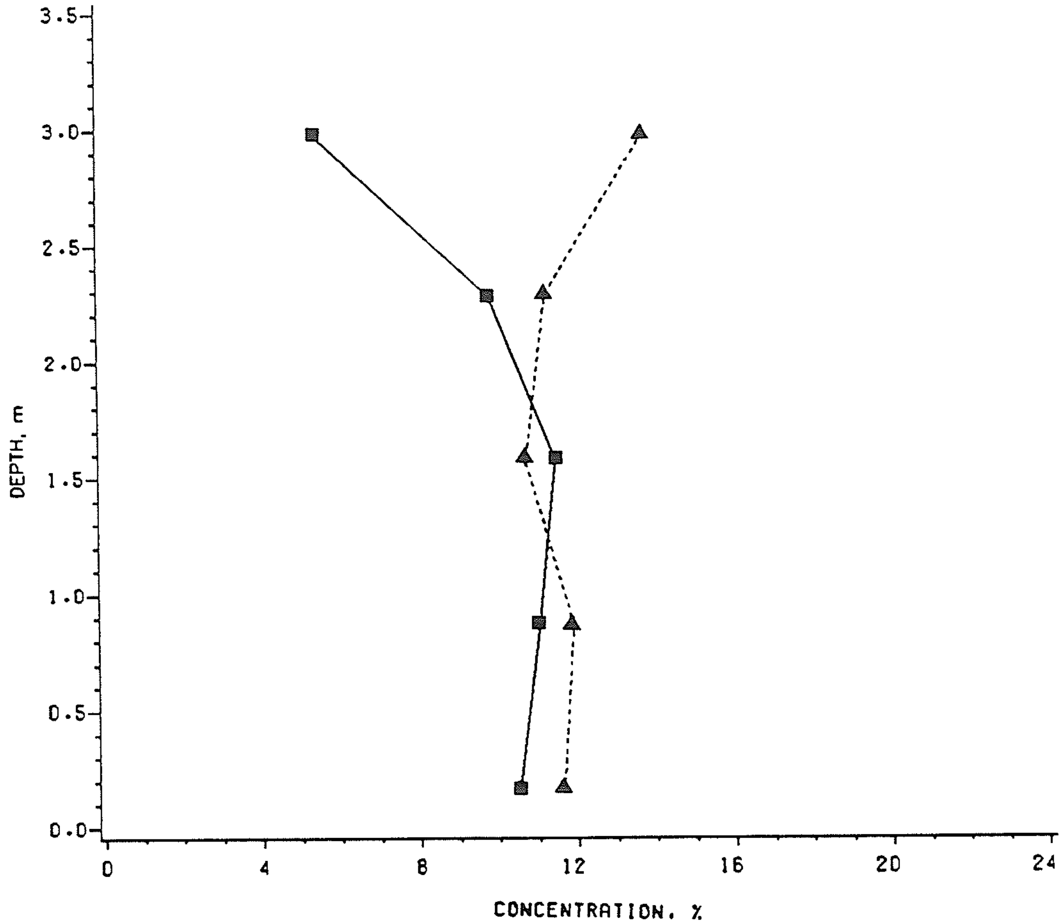


Fig. G.15: CO_2 (■——■) and O_2 (▲--▲) concentrations during storage of wheat (initial moisture content 18 %) with no forced ventilation and a binning date of 20 Aug. 1984. Sample date is 15 July 1985.

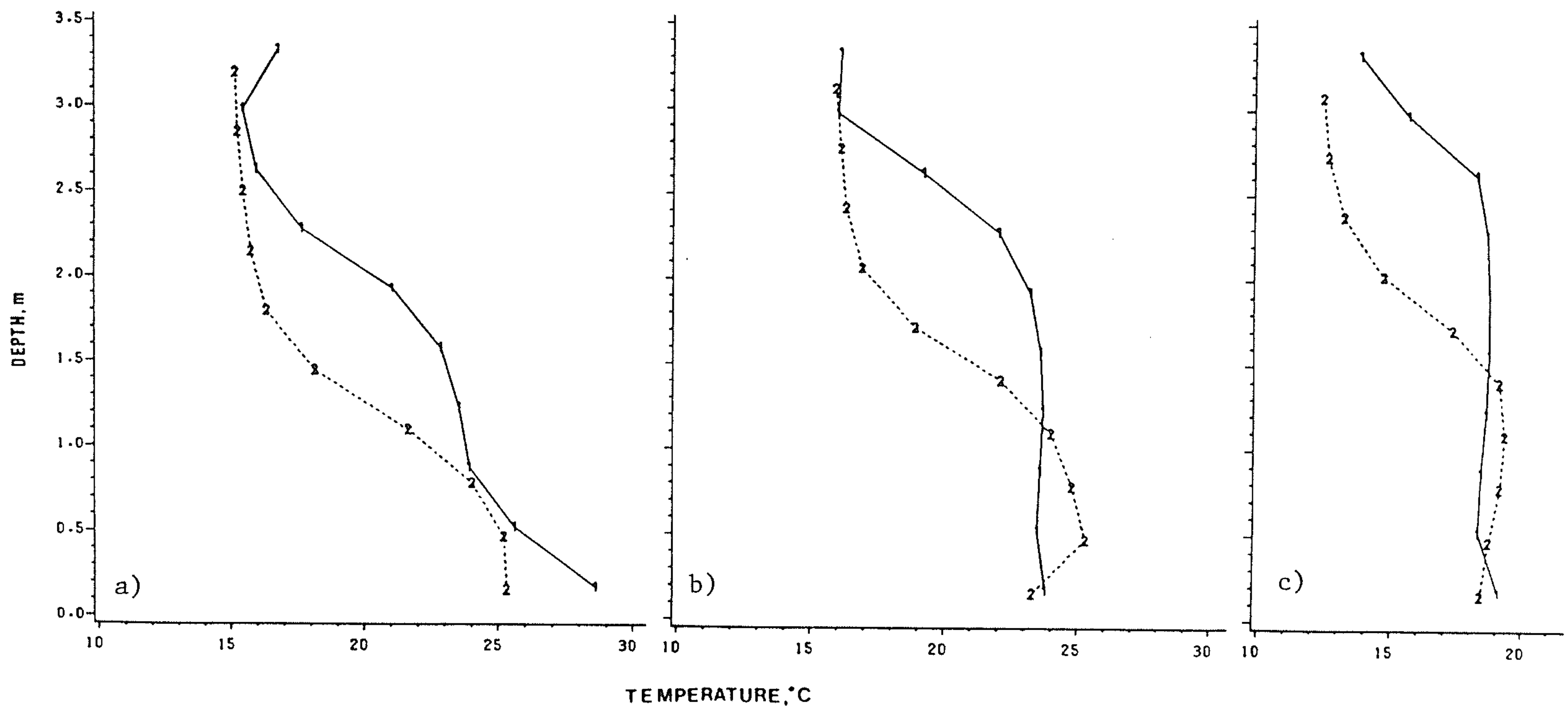


Fig. G.16: Experimental (1——1) and simulated (2- -2) intergranular air temperatures during ventilation at an airflow rate of 23.2 (L/s)/m³. Sample dates shown are (a) 04, (b) 05, and (c) 06 Sept. 1983 (all readings are taken at around 12:00 h).

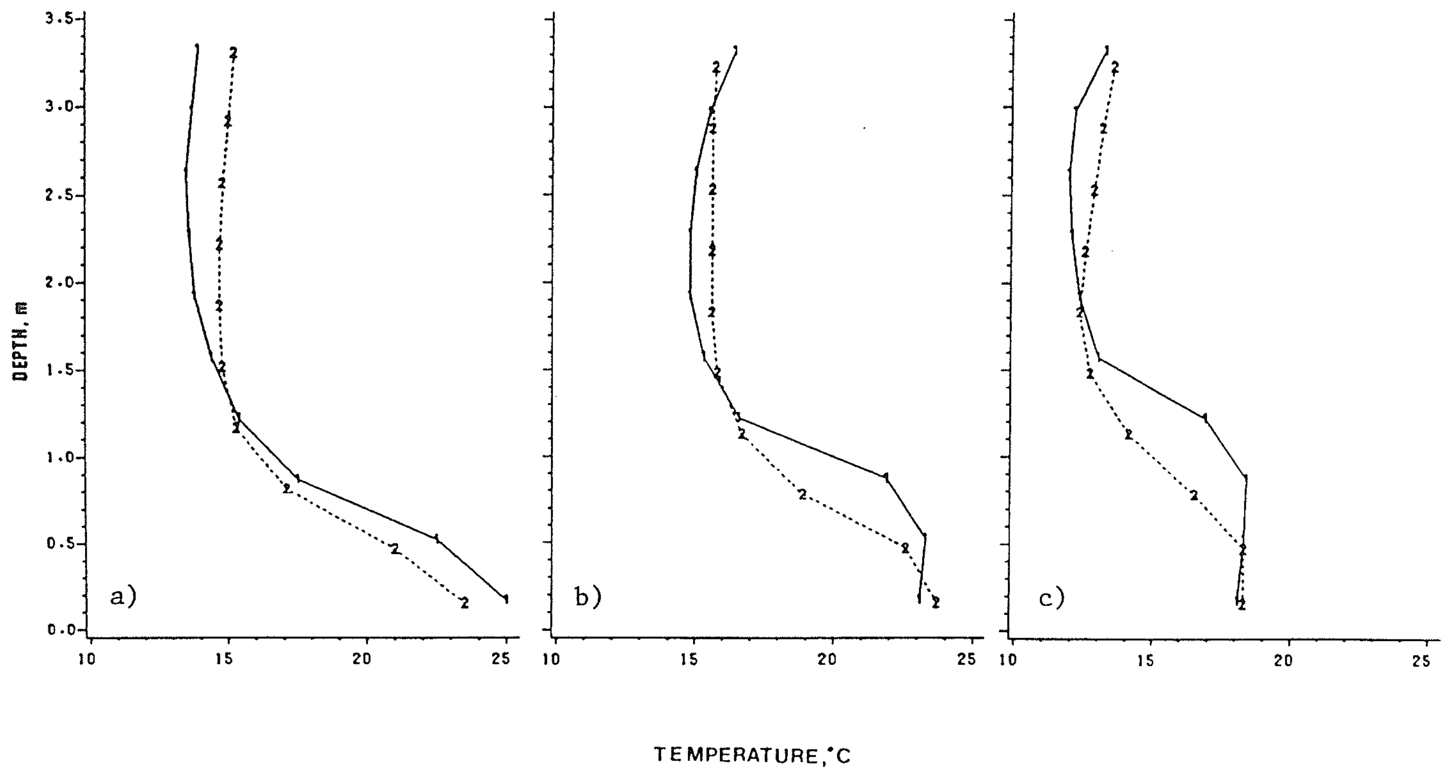


Fig. G.17: Experimental (1——1) and simulated (2 - - 2) intergranular air temperatures during ventilation at an airflow rate of 12.2 (L/s)/m^3. Sample dates shown are (a) 04, (b) 05, and (c) 06 Sept. 1983 (all readings are at around 12:00 h).

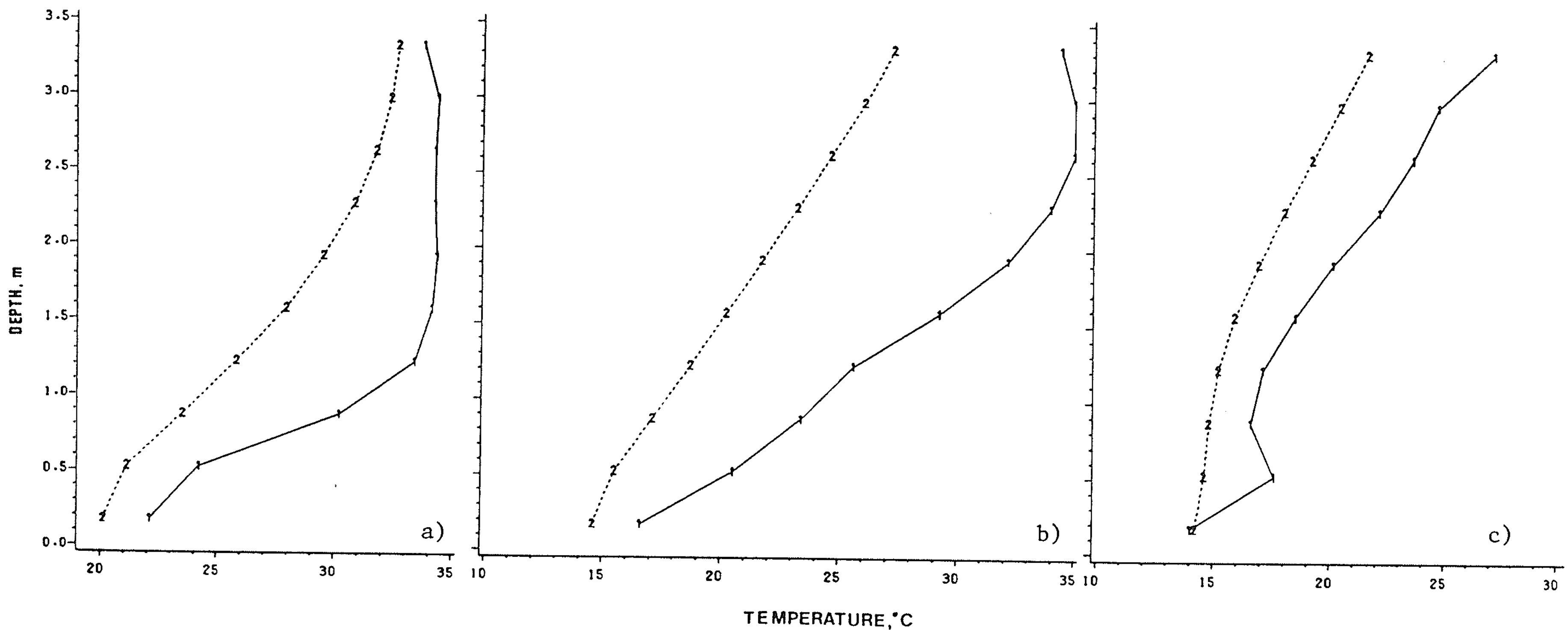


Fig. G.18: Experimental (1——1) and simulated (2 - -2) intergranular air temperatures during ventilation at an airflow rate of 0.85 $(L/s)/m^3$. Sample dates shown are (a) 02, (b) 04, and (c) 06 Sept. 1983 (all readings are at around 12:00 h).