STOCHASTIC MODELLING OF IN-BIN DRYING OF WHEAT WITH NEAR-AMBIENT AIR

BY

Kenneth D. Dougan

A thesis
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ABSTRACT

There are few operational guidelines available for grain managers to predict drying behaviour of a bulk of wheat ventilated with near-ambient air on a year-to-year basis. A sample of historical weather data (1953-80) for Winnipeg, Canada, was used to simulate the drying behaviour. To study the variability of the time for the drying front to pass completely through the top of the bulk, simulations for each weather year were stopped when the drying front reached the 3rd, 4th and 5th layers and then, for each case, drying was completed using all 28 years of historical weather data. Only recommended design airflow rates for near-ambient drying were studied. Temperature rises of the ventilation air as it passes over the fan and motor comparable to actual fan data were simulated. An estimate of the time for the top-layer to dry can be made within a 10 d range can be made when the drying front has progressed to the midpoint of the bulk. An increasingly accurate estimate of the time for the drying-front to pass completely through the top of the bulk can be made for increasing bed depth, moisture content, or delaying harvest to September 15. An accurate estimate of the time for the bulk to reach an average moisture content of 14.5% (wet basis) could only be made if the temperature rise of the ventilation air was greater than 3.7^{0}C. For a given drying system there is a maximum rate of drying and when the drying rate is reduced during periods of "poor" drying, the time lost cannot be recovered during periods of "good" drying. Near-ambient grain drying systems may

be poorly designed because "design" airflow rates are based on a constant temperature rise of the ventilation air as it passes through the fan and over the fan motor.

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1 INTRODUCTION

1.1 Problem statement

Grain storage managers in Western Canada are faced with the challenge of maintaining good grain quality in times of increasing financial restraint. Good grain quality can be maintained if freshly harvested grain is dried and kept cool. Drying and cooling are normally done by forcing air through the grain bulk using a ventilation fan and motor. The air picks up moisture from the grain as it passes through the bulk. Moisture can also be added to dried grain during periods of high humidity.

Lack of financial resources may limit the ability of the manager to purchase proper storage equipment. Many grain storage managers operate ventilation fans without a control device, such as a computer. A computer can provide greater control over the drying and rewetting of grain. Even with a simple continuous-ventilation strategy, operational management guidelines for the purposes of managing grain quality and minimizing operation costs are often insufficient or unavailable. In addition, the chosen grain drying system often operates beyond design limits. That is, a farmer may operate a particular ventilation fan with an over-filled or under-filled bin.

A software package, GRAIN89, which can be used for design of grain drying systems is available to grain storage managers through the Manitoba Department of Agriculture (Huminicki et al, 1986). The GRAIN89 requires considerable time (in the order of minutes) to analyze a particular design. Systems which may require fans and motors placed in series cannot be simulated. GRAIN89 presents an expected range of final drying times but no information is presented on drying system performance while drying is in progress.

The variability or unpredictability of drying performance is greatest when the bulk is first stored. For an increasing amount of initial drying, that is, the longer the bulk has been dried, then an increasingly accurate estimate can be made of time required to completely dry the bulk. Grain storage management may be improved by providing managers such estimates in the form of operational guidelines. By monitoring drying performance and using estimates of final drying time, the grain storage manager would know in advance when to turn off the drying equipment, whether drying would be completed before the end of the fall drying period, and whether there is a risk of grain spoilage. To develop estimates of final drying times for grain drying systems, many grain drying simulations were carried out for several initial storage conditions and a wide range of weather conditions.

1.2 Objectives and scope

The goals of this research were:

(1) to develop a method of generating synthetic weather data which would be used in simulating grain drying,

(2) to determine the sensitivity of near-ambient drying systems to variations in weather, and

(3) to determine the feasibility of using estimations of

final drying times required to completely dry a bulk of wheat as an aid in the management of grain drying.

The scope of this study was to develop distributions for the times required to completely dry a bulk of wheat ventilated continuously with the recommended airflow rates required to achieve a 100% probability of drying by November 15 (Friesen and Huminicki, 1987). Interrupted ventilation, and non-design scenarios, such as storage systems with airflow rates above and below the recommended levels, were not studied. Other management strategies, such as adding supplemental heat to ventilation air, humidistat control of ventilation equipment, or timer control, were not studied. The validity of the grain drying model has been examined by other researchers (Bowden et al., 1983; Sanderson et al., 1989) and will be only briefly reviewed. Operational economics, including capital and grain quality costs, were not studied. Fan and motor operational costs, however, may be inferred from the results of the study. The methods used for this study were incorporated into a computer program so they might be used or modified by future researchers who wish to develop operational guidelines for a larger range of drying systems.

This research is part of a long-term plan to develop an expert system for the day-to-day management of grain storage systems. The expert system, when completed, will provide the user with

(1) operational guidelines on monitoring the grain bulk for

drying progress and spoilage,

(2) an up-to-date quality assessment of the bulk,

(3) "look-ahead" knowledge such as risk of spoilage and the likelihood of drying by November 15, and

(4) alternative actions which can be taken if the drying performance does not meet the grain manager's needs.

Unlike GRAIN89, the expert system will continuously evaluate the particular storage situation for the storage manager.

2 LITERATURE REVIEW

2.1 Introduction

Discussed below will be the changes in grain quality which can occur with time if grain is stored in an unventilated grain bin. The minor influence of ambient weather conditions on temperatures and moisture contents of an unventilated grain bulk will also be discussed, which will demonstrate the need for near-ambient grain drying equipment as a means of controlling grain quality. The discussion below will also show that results from research into the design of near-ambient drying systems have limited use in the day-to-day operation of drying systems.

A near-ambient grain drying model was used for this study and the validity of the computer model will be reviewed. To simulate grain drying under many weather conditions, synthetic weather data was required. Weather models have been developed by other researchers but are valid only under certain conditions. The statistical tests used to determine whether Winnipeg weather could be used in such models will be reviewed.

2.2 Grain quality changes during storage

The purpose of this section is to describe the changes which can occur in a grain bulk when the environment is not properly controlled by man. There is a natural tendency for the grain to be degraded by microorganisms and insects if the grain storage environment is not controlled.

A storage bin filled with wheat can be considered an ecosystem (Sinha, 1973). An ecosystem contains living plant and animal organisms which interact with each other and the environment to distribute energy through definite flow patterns (i.e. food web). The energy source in the stored-grain ecosystem is the stored grain. Abiotic variables include temperature and moisture content of the grain, intergranular air composition, insecticides and fumigants, and weather conditions. Biotic variables include microorganisms, such as fungi and bacteria; insects and mites; birds and rodents; and the living kernels of grain. If the conditions are right for increased fungal development, then the grain may spoil rapidly. Storage times for wheat depend on its temperature and moisture content (Table 2.1).

By controlling the temperature and moisture content of the grain, biotic variables may be controlled. Canada's most common insect pests develop within certain temperature ranges (15 to 40°C) beyond which they cannot survive (Sinha, 1973). If stored grain is ventilated with cold air, then insect pest development can be reduced or populations eliminated, depending on the time of exposure (Table 2.2, from Friesen and Huminicki, 1987). The grain mite, <u>Acarus siro</u>, requires a high relative humidity and a temperature range of 5 to 32°C with the optimum being 20 to 28°C (Sinha, 1973). Temperatures of -18°C held for 1 week will kill all developmental stages of the grain mite except the hypopus stage (Mills, 1990). Therefore, cold temperatures can be used to prevent or eliminate most insect or mite infestations.

Although cold temperatures cannot eliminate fungal infections, fungal development can be slowed or stopped (Wallace,

TABLE 2.1 - Storage period (days) of wheat for various moisture contents and temperatures after which seed germination decreases below 85%. (Wallace et al., 1983)

Moisture content (% wet basis)	Temperature (°C)				
	3	10	15	21	29
12.7-12.9	180+	180+	180+	180+	60+
14.4-15.2	180+	180+	180+	132+	42+
15.9-16.6	180+	180+	126+	36-48	15-20
17.3-18.5	180+	120+	40-50	12-18	4-8
21.3-22.2	40-60	10-20	6-9	4-6	1-2

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Grain temperature (°C)	Duration (weeks)
-5	6
-10	4
-15	2

1973). Mesophiles, which includes most species of fungi, require temperatures from 5 to 45^{0}C for development. Some species of Penicillium are psychrophiles, that is, fungi which will develop in cold temperatures (-8 to 30^{0}C). Thermophiles, including some species of Penicillium and Aspergillus can develop in relatively hot environments. Most fungi require moist conditions (82-100% relative humidity) for development, but some species of Aspergillus can also develop in grain at moisture contents in equilibrium with relative humidities of less than 80%.

The grain storage manager cannot rely on cold and dry weather to naturally cool and dry stored grain. An unventilated grain mass stored in a grain bin is relatively unaffected by fluctuations in ambient weather conditions because of the low thermal diffusivity of grain (Muir, 1973). Diurnal fluctuations affect only grain temperatures within 15 cm of the outer surface of the bulk (Muir, 1970). The temperature at the center of an unventilated grain mass does vary with seasonal temperatures but does not reach the ambient extremes. In addition, a considerable delay occurs, in the order of months depending on the bulk dimensions, as the temperature at the center of the grain mass responds to the ambient air temperatures. For example, in a 5.5-m diameter cylindrical bin in Kansas, wheat 2.44 m from the bin wall varied from 10 to 18^{0}C while the average ambient outside air temperature varied from 0 to 30^{0}C (Converse et al., 1969). The time difference between the maximum grain temperature and maximum seasonal temperature was 150 d.

The moisture content of grain at the top surface of an unventilated bulk will change slightly with relative humidity fluctuations but not enough to dry the bulk. Sinha et al. (1985) reported that after 202 days the moisture content in the top 0.7 m of a 3.5 m deep bin of wheat, stored August 31 at 19% moisture content wet basis (w.b.), dropped by 1%. After 286 days of storage (June 11), the moisture content in the top 0.35 m, the 10th layer, had dropped to approximately 15.5%, and the moisture content in the 0.35 m below the top layer, or the 9th layer, had dropped to approximately 16.5% moisture content. The remaining 8 layers had moisture contents similar to the initial storage amounts.

Even if an unventilated bulk has been stored at a low initial moisture content, then moisture migration can occur which can increase the risk of spoilage in a local region of the bulk. In Canada, the "dry" market moisture content of wheat, set by the Canadian Grain Commission, is 14.5% wet basis (w.b.). In the fall and winter, pockets of moisture contents above the bin-average can form in the center, near the top surface, of the bulk (Muir, 1973). One theory suggests moisture migration is a result of differences in partial pressures of water vapour within the bulk, and natural convection currents created by temperature differentials within the bulk (Muir, 1973). For a grain bulk initially with uniform moisture content distribution throughout, the partial pressure of the water vapour in the air decreases as the temperature decreases. This creates partial pressure gradients parallel with the temperature gradients. Therefore, moisture will migrate from warm grain to cool grain to equalize partial pressures. Also, during the cool fall and winter, denser, cool air near the outer periphery of the bulk will tend to move downward and force the warmer air in the center of the bulk upward, as seen in Figure 2.1. As the warm, moist air approaches the cool grain near the top surface, moisture is sorbed from the air by the cool grain. Muir (1973) cites work of other researches which tends to support this theory. Another theory supported by experimental results (Reed, 1992) suggests moisture migration is dominantly a result of moisture diffusion along partial pressure gradients. Results indicate that moisture accumulates evenly at the top surface of the bulk and not at the top near the center.

Typically, when the grain bulk begins to spoil, a hot-spot develops in the location of the higher moisture content. Increased moisture content may lead to mould growth, resulting in a temperature increase. This increase in temperature may promote reproduction of insects and mites which in turn can further increase the temperature and moisture content.

To avoid moisture migration, the bulk can be periodically aerated to remove temperature gradients. The airflow rates used for aeration (1-3 $(L/s)/m^3$) are lower than those for near-ambient drying (>10 $(L/s)/m^3$). Aeration can also be used to cool freshly harvested grain to reduce the risk of spoilage. Little moisture is removed during aeration.

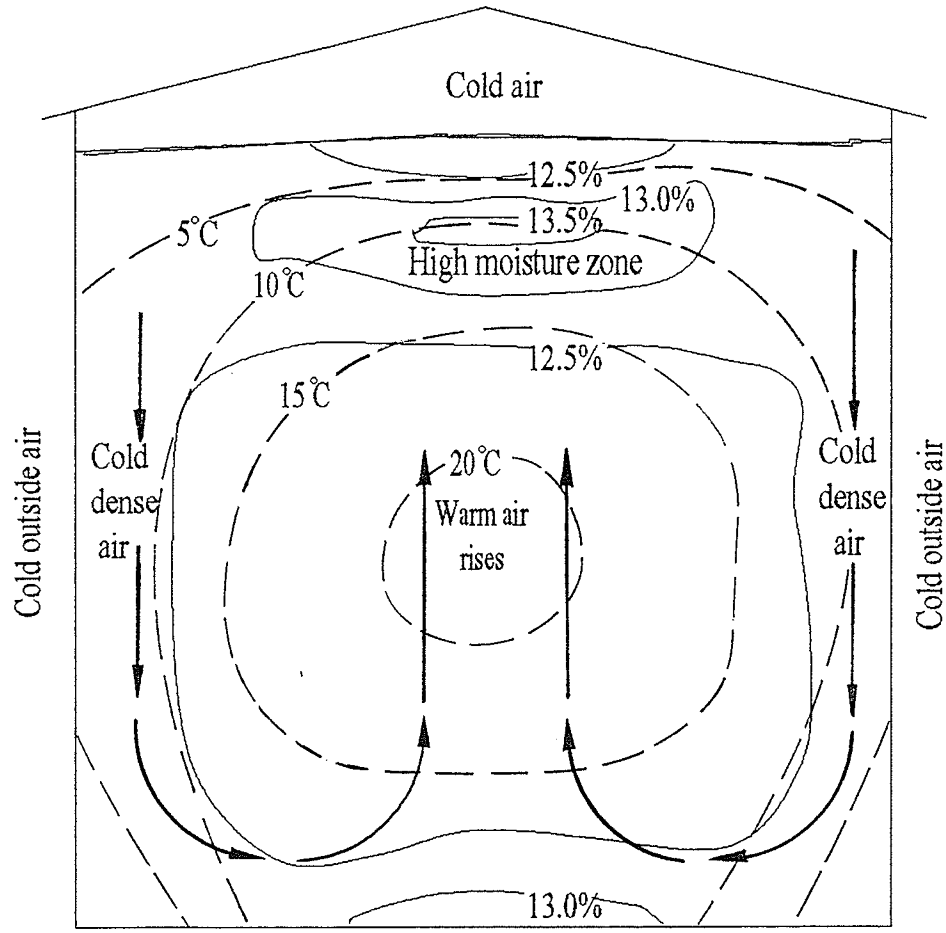

FIGURE 2.1 - Moisture migration in stored grain is caused by differences in vapour partial pressure and natural convection currents (——►). Partial pressure gradients are parallel with temperature gradients (— — —). The result is a region of above average moisture content (———). (Muir, 1973)

The discussion in this section shows the importance of controlling grain temperature and moisture content in maintaining grain quality. Air must be forced through the bulk because penetration of ambient air is limited to the periphery of the bulk and the thermal diffusivity of grain is low.

2.3 Management strategies for maintaining stored grain quality

2.3.1 Near-ambient grain drying

Grain harvested in Western Canada can have a higher moisture content than the required "dry" market moisture content of 14.5%. As well, undesirable grain temperatures, above the ambient air temperature, are often present (Prasad et al., 1978). As discussed earlier, temperature and relative humidity fluctuations of the ambient air have little effect on the overall bulk temperature and moisture content. Therefore, to maintain the quality of stored grain, action is often required to reduce either grain moisture content, grain temperature, or both.

One common technique of drying the stored grain is to force near-ambient air upward through the grain mass using a fan and motor. "Near-ambient" refers to the slight increase in ventilation air temperature and slight decrease in air relative humidity as energy is added to the air as it passes over the ventilation fan and motor. As near-ambient air is forced up through the bottom of a grain bulk, upward-moving drying and temperature fronts pass through the bulk (Figure 2.2). Above the drying front the grain is near the initial storage moisture

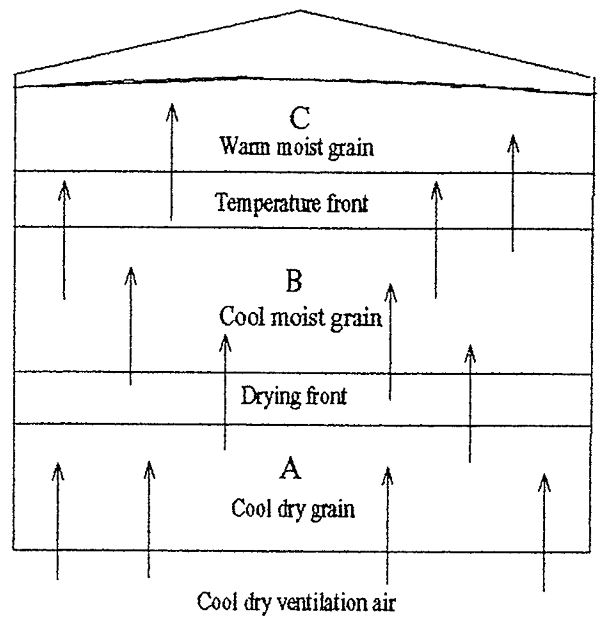

FIGURE 2.2 - Ventilation of a grain bulk creates a temperature front and a drying front.

content and is susceptible to deterioration. Below the drying front the grain temperature and moisture content are in equilibrium with the inlet ventilation air. As weather conditions change during ventilation, additional drying and temperature fronts may develop in the bulk.

The development of the temperature and drying fronts can be explained by psychometrics. If the grain is warm and moist compared with the ventilation air, then, during adiabatic drying at the drying front, evaporative cooling of the air takes place (Phase A-B in Figure 2.3). Phase B-C shows the air remaining in constant moisture equilibrium but coming into temperature equilibrium as it passes through the temperature front.

In Western Canada, near-ambient drying is not effective after November 15 because of the decreasing mean drying potential of the ambient air (Figure 2.4). Drying potential is a function of dry bulb temperature and relative humidity and is defined as the theoretical moisture carrying capacity of the ambient air if it were to be saturated with moisture. If spoilage is not a risk and drying will not be completed by November 15, then the remaining drying can be completed in the spring.

The strategy in continuous near-ambient ventilation is to move the drying front through the top of the bulk before spoilage occurs. In Canada, the top of the bulk is more susceptible to unacceptable levels of spoilage than grain in lower portions of the bulk during ventilation (Figure 2.5).

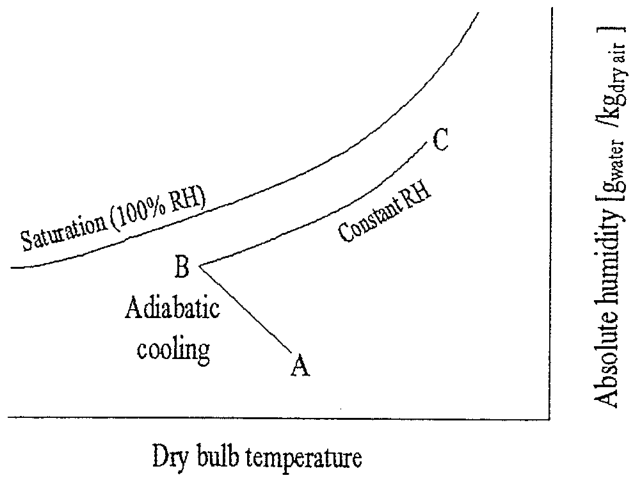

FIGURE 2.3 - The change in temperature and water concentration of cool dry air as it passes through warm moist grain is shown on the psychrometric chart.

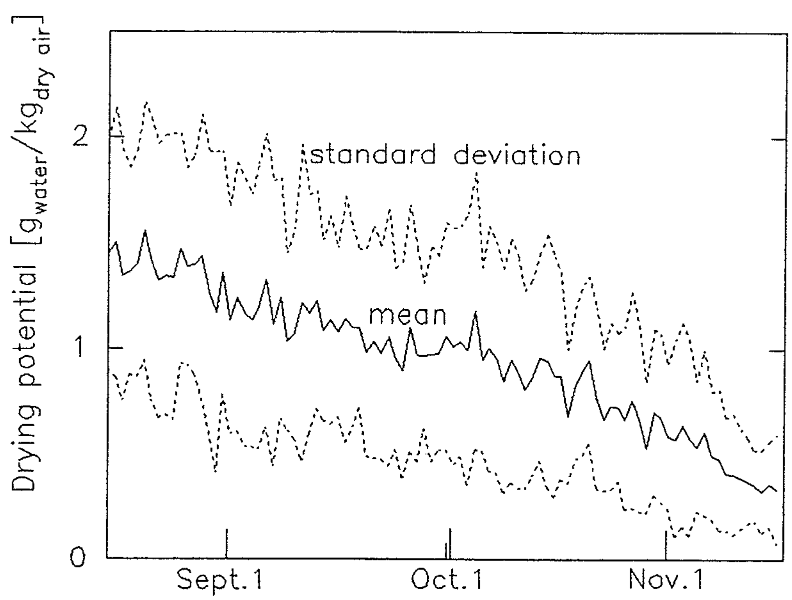

FIGURE 2.4 - The mean drying potential (——) and standard deviation (''') of the ambient air, based on 28 years of historical weather data for Winnipeg, decreases during the fall months. The drying potential is defined as the amount of additional moisture the ambient air could hold if saturated with moisture.

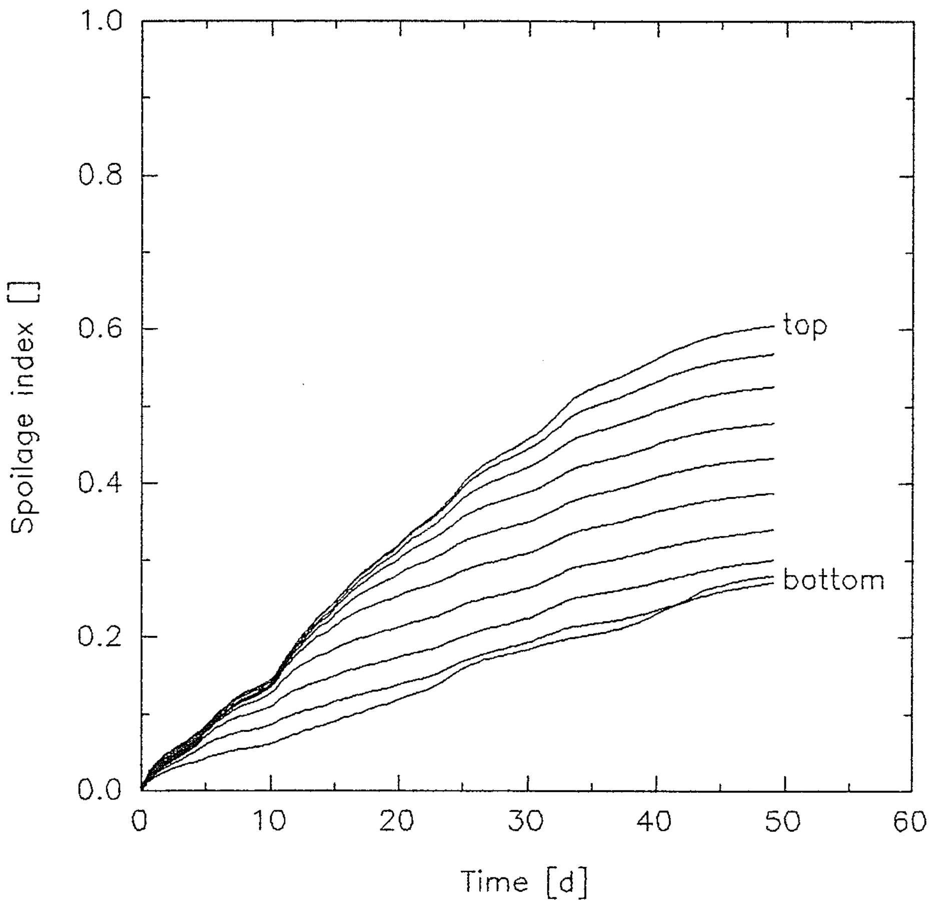

FIGURE 2.5 - Simulated spoilage indices for 10 imaginary layers of grain stored August 15, 1977 in Winnipeg at 18% moisture content in a 3.65 m deep bed ventilated with an airflow rate of 10 $(L/s)/m^3$ in which the probability of drying the top-layer by November 15 is 100%.

2.3.2 Monitoring drying progress and grain quality

As mentioned earlier, the two main causes of grain quality loss are mould growth and insect infestation. Because development of these two agents are dependent on moisture content and temperature of the grain, then these physical properties must be monitored and controlled by the grain storage manager so quality losses can be minimized.

Temperature sensors can be used to monitor the progress of the drying front during ventilation (Sanderson et al., 1988) or the development of any hotspots in the bulk during periods of no ventilation. As mentioned earlier, the ventilation air undergoes evaporative cooling as it passes through the drying front. If temperature readings are taken at regular time intervals, then the grain storage manager should be able to locate the drying front without having to sample the grain. Otherwise, grain samples will be required to detect the moisture front. The moisture content of the grain samples collected by using a torpedo probe (Mills, 1990) can be determined by using an electronic moisture meter, or by an oven-drying method.

In an unventilated bulk, detection of a hotspot depends on the proximity of the temperature sensor to the actual location of the hotspot. Since the thermal diffusivity of grain is low, a temperature sensor not in close proximity to the hotspot may fail to detect a local temperature rise.

Several methods are available to determine quality loss from mould. Mould growth can be detected by the grain storage manager using visual and olfactory inspection of wheat sampled from the bulk; however, quality loss may have already occurred. Seed germination decreasing below 85% is a reliable indicator of spoilage (Wallace et al., 1983). Growth of storage fungi, increase in fat acidity value (FAV), increase in "musty" odour and discolouration, and changes in grade are not as effective in detecting spoilage except in high moisture wheat because spoilage might occur before these changes are observed. When long-chain fat molecules, normally found in kernels, are broken down by mould exoenzyme activity (Wallace, 1973) or kernel respiration, the resulting product is free fatty acids. The FAV is used by researchers to determine the deterioration of quality in the grain. In unventilated bins, elevated carbon dioxide levels may provide the storage manager with a more accurate assessment of deterioration than the other indicators mentioned above (White et al., 1982; Muir et al., 1985; Mills, 1990).

Insect infestations can be detected by measuring CO_2 and temperature, or by inserting insect traps into the bulk (Mills, 1990). The trap is a small tube with perforations which allows insects to fall into the trap but does not allow them to escape. The ability to detect an infestation with an insect trap depends on the location of the trap in relation to the area of infestation (usually in a hot-spot). As well, the trap does not provide instantaneous detection. Alternatively, if a grain sample is available, placing the sample on a mesh in a funnel and subjecting the sample to heat will drive any insects from the sample to a container below the funnel (Mills, 1990) allowing for detection in 24 h. Again, the ability to detect an insect infestation depends on the location in the bin from which the sample was taken.

2.4 Near-ambient drying models

2.4.1 Near-equilibrium drying model

As has been discussed above, near-ambient drying is a valuable technique in maintaining good quality of stored grain. Because of the importance of this technique, computer models were developed so researchers could study near-ambient drying rapidly and inexpensively. A computer model is included in GRAIN89 which is used by grain storage managers to design drying systems. A computer model was also used in this study to develop estimations of final drying times.

There are several drying models available which can be used to simulate the near-ambient drying of wheat stored in a deep bed. Thompson's (1972) near-equilibrium model and Ingram's (1976) thin-layer drying model will be discussed in general terms. The mathematical theory will not be discussed; however, a comparison of each model's predictions with experimental results will be reviewed.

The grain mass in a cylindrical bin can be conceptualized as a set of horizontal layers of grain. The near-equilibrium model typically uses 10 imaginary layers (Huminicki et al., 1986) while the thin-layer model uses 30 (Ryniecki and Nellist, 1991b). Both types of models calculate the moisture content and temperature changes in each layer for a small time increment, usually 1 to 3 h. Based on the initial temperature and moisture content of an imaginary layer, and the rate, temperature and relative humidity of air entering the imaginary layer, the changes in moisture content and temperature of both the air and grain during the time increment are calculated. The new grain conditions in the imaginary layer are used for calculating the changes in the next time increment. The coditions throughout the time interval are assumed constant and then change instantly at the end of the interval. The air exiting the layer is the inlet air to the next layer.

The near-equilibrium model developed by Metzger and Muir (1983), which is based on the work of Thompson (1972), assumes the ventilation air reaches moisture equilibrium with the individual layer of grain. The Modified Henderson equation (Anon., 1987)

$$RH = 1 - \exp\{ -a\cdot(T+b)(100\cdot M)^{c}\}$$

is a commonly used expression for relating the equilibrium relative humidity, RH, to temperature, T, and moisture content, M, of the grain. The constants a, b and c vary for different cereal grains. It is also assumed that the heat and mass transfer between the grain and air is adiabatic.

The model of Thompson (1972) and Metzger and Muir (1983) assume the layers are sufficiently thick for the air to reach equilibrium and in average conditions are sufficiently precise.

That is, the thicker the imaginary layers or the lower the air velocity the more probable the assumption that the air reaches equilibrium with the grain. During periods of high humidity or low temperatures, or drying with low airflows, the rate of mass transfer will be low, which Bloome and Shove (1971) refer to as near-equilibrium conditions. Bloome and Shove state that empirical models have difficulty in simulating near-equilibrium heat and mass transfer, and that simulating such conditions can be successfully completed with a near-equilibrium model.

The near-equilibrium model of Morey et al. (1979) assumes the grain is unlikely to come in moisture equilibrium with the ambient air because the rate of moisture transfer from the kernel is the limiting factor. The time increment, dt, in their model, as with Metzger and Muir's, is in the order of hours to include the diurnal fluctuations. Bowden et al. (1983) describes the change in moisture content as

$$M_f = (M_i - M_e)\ e^{-k\ dt} + M_e$$

where M_e is the equilibrium moisture content of the layer for the ambient air conditions; M_f is the final moisture content of the layer for the interval dt; M_i is the initial moisture content of the layer; and k is the drying constant. The drying constant is given by

$$\ln(k) = a_1 - \frac{a_2}{T+273.15}$$

where T is the grain temperature, ^{0}C; and a_1 and a_2 are constants which vary for different cereals. The effect of relative humidity is not significant for wheat and similar drying coefficients have been reported when corn is dried using different airflow rates (Henderson and Pabis, 1961). The drying constant, k, for barley equals 0.0617 h^{-1} at 20^0C and decreases with temperature (Bowden et al.,1983). At 20^0C the grain moisture content would be $0.94M_i+0.06M_e$ after 1 h, $0.83M_i+0.17M_e$ after 3 h, and $0.22M_i+0.78M_e$ after 24 h. A similar drying rate would be likely for wheat. During periods of grain rewetting Morey et. al. (1979), and Metzger and Muir (1983) assume the air reaches moisture equilibrium with the grain.

In the near-equilibrium model, mass and energy balances are maintained for the layer (Thompson, 1972). Moisture balance is given by

$$(H_f - H_0) = (M_f - M_0) \frac{r\ x}{G\ dt},$$

where H is absolute humidity ratio $[kg_{water}/kg_{dry\ air}]$; M is dry basis moisture content []; r is dry grain bulk density $[kg/m^3]$; x is the layer thickness [m]; G is the mass airflow $[kg/m^2/s]$; and dt is the time increment of the model [s]. Energy balance is given by

$$G_a(c_a + c_v H_0)(T_{a,0} - T_{a,f}) = r(c_g + c_w M_0)(T_{g,f} - T_{g,0})(dx/dt),$$

where c is specific heat $[J/kg/^0C]$; dx is the thickness of the layer [m]; a for ambient air; v for air vapour; o for initial; f for final; g for grain; and w for water in the grain.

Metzger and Muir's (1983) model has been modified to include hysteresis during moisture sorption (Sanderson et al. 1989). For any temperature, grain that is gaining moisture will have a different equilibrium moisture content than grain that is losing moisture, as seen in Figure 2.6. This hysteresis effect has been studied by many researchers but no one theory has been commonly accepted. A literature review on this topic can be found in Parry (1985) and will not be repeated here. An equilibrium relative humidity offset of 5% is applied to the equilibrium calculations to account for hysteresis in the near-equilibrium model.

Fundamental thermodynamic principles are used to calculate the temperature rise as the inlet air passes over the fan and motor. (For more discussion of this theory, see Appendix A.1.) GRAIN89 can use temperature data for a specific manufacturer's fan and does not require the "generic" temperature rise model.

Sanderson et al. (1989) compared their near-equilibrium model predictions with experimental results. They concluded that the near-equilibrium model was sufficiently accurate to predict temperature and moisture content changes in the wheat stored with initial moisture contents of less than 25%. The average difference between simulated and observed moisture contents was less than 1% moisture content (m.c.) for bins stored with wheat initially at 20% m.c. or less. The simulated bin-average moisture content was slightly greater than the observed because of the model's tendency to underpredict the velocity of the drying front.

Bowden et al. (1983) also predicted a slower drying front

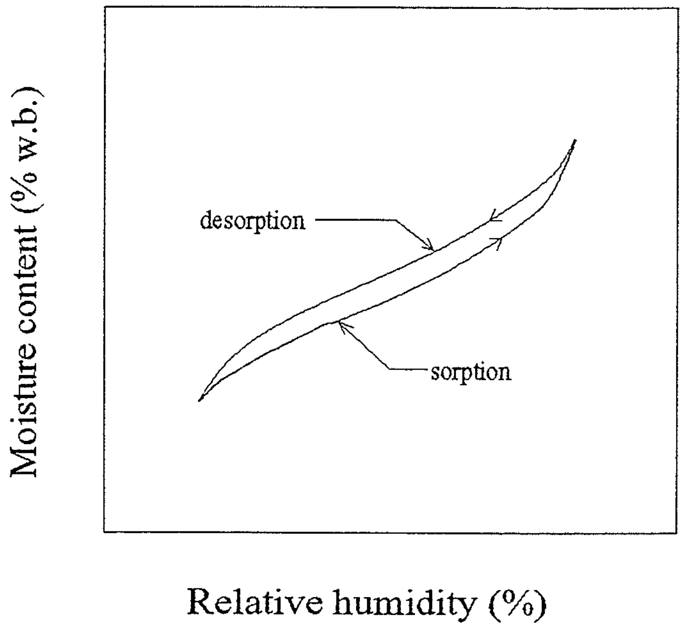

FIGURE 2.6 - The equilibrium moisture content of grain at a particular relative humidity is greater for grain losing moisture than grain gaining moisture (Muir, 1973).

velocity than observed but also reported initial development of the drying front to be more rapid than observed. As well, their model predicted a shallower drying front than observed. Simulated results compared well to observed results for wheat initially stored at less than 22% m.c. unlike predicted results for wheat initially stored at greater than 25% m.c.

The hysteresis offset of 5% in relative humidity for predicting moisture contents during moisture resorption was adequate for rewetting up to 15% but not for rewetting greater than 17% (Sanderson et al., 1989).

2.4.2 Thin-layer drying model

Thin-layer drying equations are based on the theory of diffusion of moisture from a slab approximating the thickness of a kernel (Ingram 1976). Partial differential equations describe the change in temperature and moisture content.

Bowden et al. (1983) compared Ingram's (1976) thin-layer model predictions with experimental results. The predicted width of the drying front, velocity of the drying front, and moisture content and temperature profiles compared well for all initial moisture contents tested (21-28%). The Ingram model requires 5 to 7 times the computing time compared with the near-equilibrium model.

2.4.3 Deterioration model

To model the deterioration of grain in each layer, Fraser and Muir (1981) included the method used by Thompson (1972) to calculate a unitless spoilage index given by

$$ASTE_i = ASTE_{i-1} + dt/t_{safe}$$

where the allowable storage time elapsed (ASTE) for the current time increment, i, of length dt is the sum of the ASTE for the previous time increment, i-1, plus the fraction of the ASTE for the current time increment. The fraction of the allowable storage time elapsed (ASTE) for each time increment is equal to the time increment divided by the allowable safe storage time (Table 2.1 in Section 2.1) for the particular grain conditions during the time increment. For example, if the grain temperature and moisture content are 15^0C and 16%, respectively, then the allowable storage time is 126 d. If the simulation time increment is 3 h, then the fraction of the ASTE used in this particular time increment would be 3/(126*24), or 0.001. For each layer the ASTE fractions are accumulated from all time increments until one layer's total ASTE equals one, at which time the degree of spoilage of the grain is considered to be unacceptable.

The deterioration model in GRAIN89 calculates a spoilage index which is based on percent dry matter decomposition. As with the ASTE model above, the fraction of spoilage for each time increment is accumulated, however, spoilage index can be greater than one. In the input file of GRAIN89, the maximum allowable index indicating spoilage is 0.96. Sanderson et al. (1989) suggest the maximum allowable spoilage index should be 1.5 to accurately reflect the deterioration measured in their experiments. The ASTE can be calculated by dividing the spoilage index by the maximum allowable spoilage index.

During near-ambient drying, ASTE is greatest in layers near the top which are the last to dry (Figure 2.5). Deterioration in the lower layers is not a concern because the grain is quickly cooled and dried during fall ventilation and because hotspots do not occur in the bottom of the bulk.

2.5 Design of grain drying systems

2.5.1 Continuous ventilation with near-ambient air

Brook (1987) stated there is no single best grain drying strategy for all types of weather and the optimum strategy will vary from year-to-year. Combinations of cold or hot temperatures with wet or dry relative humidities vary with time creating a wide range of weather scenarios. Although a particular grain drying strategy may be well suited to a particular class of weather scenarios, there is no way to predict specific weather occurrences. For example, while it is known that during extended cool, wet drying periods, supplemental heat would be beneficial to increasing the rate of drying and reducing the time needed to operate the drying equipment, during most other kinds of weather supplemental heat would cause severe overdrying. Overdrying is an economic penalty the grain storage manager must pay if the average moisture content of the bulk is less than the "dry" market moisture content of 14.5%. Kitson et al. (1991) report that even without supplemental heat overdrying normally occurs during continuous ventilation (Figure 2.7-2.8).

Although the scope of this study includes only continuous

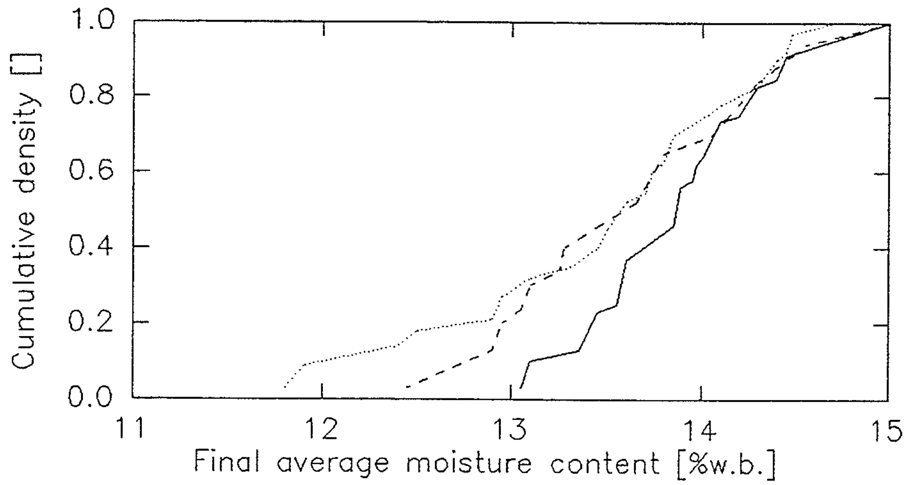

FIGURE 2.7 - Cumulative distributions of bin-average moisture contents when drying of the top of a bulk has been completed based on 33 years of weather data at Winnipeg, Manitoba, for wheat harvested at an initial moisture content of 19% wet mass basis on August 15 (···), September 1 (——) and 15 (- - -) and dried with near-ambient air at required minimum airflows of 15, 13 and 30 (L/s)/m^3 (Kitson et al., 1991).

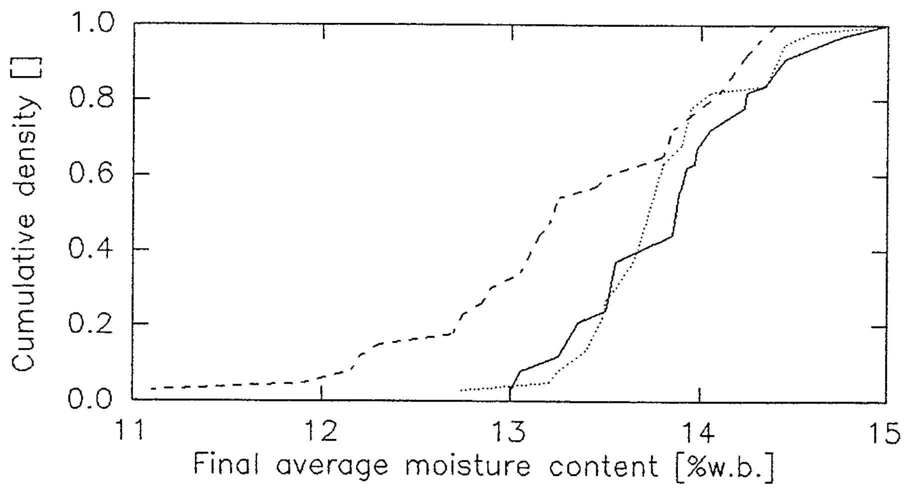

FIGURE 2.8 - Cumulative distributions of bin-average moisture content when drying of the top of a bulk has been completed based on 33 years of weather data at Winnipeg, Manitoba, for wheat harvested on September 1 at an initial moisture content of 16 (···), 19 (——) and 22% (- - -) wet mass basis and dried with near-ambient air at required minimum airflows of 10, 13 and 40 (L/s)/m^3 (Kitson et al., 1991).

ventilation, other methods of grain drying will be reviewed briefly. The purpose of the review is to stress the importance of continuous ventilation as a commonly used strategy and to show that development of an improved strategy to reduce overdrying and energy costs has been difficult and as yet economically unsuccessful. The main reason for the lack of economic success appears to be the additional capital costs. Studies have shown capital costs of drying equipment comprise much of the annual cost of drying grain (Fraser and Muir, 1980b; Manitoba Agriculture, n.d.).

Because the average velocity of the drying front depends mainly on the airflow rate, minimum design airflow rates have been developed for Manitoba which ensure drying before spoilage occurs, as seen in Table 2.3 (Fraser and Muir, 1981; Friesen and Huminicki, 1987). Design guidelines were derived from many computer simulations using the near-equilibrium grain drying model developed by Metzger and Muir (1983), and 33 years of historical weather data. The guidelines allow for the manager to accept a lower probability of drying if desired (eg. a specified airflow rate will dry the bulk in 97 out of 100 years based on simulations using historical weather data). The recommended airflow rates and the simulation model have been incorporated into GRAIN89 which is currently being used for the design of drying systems in Manitoba (Huminicki et al., 1986).

2.5.2 Other drying methods using ventilation fans

The addition of supplemental heat to the near-ambient

TABLE 2.3 - Recommended minimum airflow requirements [(L/s)/m^3] for wheat stored in Manitoba to have 100% probability of drying by November 15 using a fully perforated floor and a level grain surface (Friesen and Huminicki, 1987)

Harvest date	Moisture content (% wet basis)	
	18	20
August 15	10	20
September 1	12	15
September 15	28	32

ventilation air has been investigated by Fraser and Muir (1980a and 1980b) and Morey et al. (1979). In general, addition of supplemental heat does not offer an economic advantage for wheat initially stored below 20 to 22% moisture content. Supplemental heat increases the grain temperature and thus reduces the maximum time for which the top layer can be stored before unacceptable spoiling occurs. Because the temperature of the ventilation air is higher compared with near-ambient drying, the storage time of the grain is reduced. Also, on the ceiling of the bin there is condensation of water which in turn drips back onto the top surface of the grain (Smith, 1984; Morey et al., 1979). Also, the ventilation air will have a higher drying potential and will tend to overdry the grain. Friesen and Huminicki (1987) recommend using supplemental heat only if it appears the grain will not dry in the fall and if it is also to be sold before spring.

Average drying of a bulk is an alternative to forcing the drying front through the top layer of the bulk. Drying is considered complete when the average moisture content of the bulk reaches the "dry" level of 14.5%. The drying front in a continuously ventilated bulk would progress partially through the bulk, then the fan and motor would be turned off, and the grain would be mixed by moving to another bin. There are, however, problems with this approach. Careful monitoring of the bin's average moisture content requires many samples to be taken repeatedly over short time intervals until the dry level is reached (Fraser and Muir, 1980b). An approximate 25% reduction in operating costs could be made for wheat being continuously ventilated, but costs of mixing would have to be added to this estimate. The average-dry method assumes that the bulk can be mixed perfectly. It is unlikely the bulk would be perfectly mixed when turned. A grain stirrer could, however, be employed, but studies with corn have shown a stirrer is not generally economical (Loewer et al. 1984).

Other strategies have been investigated, such as optimized computer control (Ryniecki and Nellist, 1989; Ryniecki and Nellist, 1991a; Ryniecki and Nellist, 1991b). Preliminary computer simulations predict a 33% reduction in mean energy costs and 20% reduction in overdrying costs (Ryniecki et al., 1992). The fan speed and amount of supplemental heat are varied by a computer controller which tends to overdry the grain initially but then fan speed is varied to bring all imaginary layers to the "dry" moisture content of 14.5% (w.b.). At the end of the process, overdrying losses are greatly reduced.

Complete system performance under actual conditions and a final cost analysis, including the equipment costs, have yet to be completed. The availability and cost of the special equipment (i.e. computer, fan speed controller, temperature and relative humidity sensors) will likely determine the feasibility of optimized control.

Less expensive programmable logic controllers (PLCs) have been used successfully in rice storages in Australia (Darby, 1992). The grain storage manager uses operation guidelines to periodically reset the fan control parameters as rice or weather conditions change.

2.5.3 Limitations with design studies

The dependence of drying performance on fall weather conditions introduces variability and uncertainty to the system with which the grain storage manager must contend. Results of simulations of a continuously ventilated bin of wheat using 33 years of weather data (Figure 2.9-2.10) shows a wide range of possible drying times (Kitson et al., 1991).

Evaluation of grain drying systems can be carried out with several methods. Some researchers (Sokhansanj and Lischynski, 1991; Sokhansanj et al., 1991) have compared grain drying strategies using a "typical weather year" while others (Ziauddin and Liang, 1986) have advocated a "systems" approach for evaluation and comparison of strategies (i.e. application of different types of equipment over a wide range of operating conditions) using stochastic modelling. An "average" or "typical" weather year is defined as the year having average ambient conditions on an hourly basis determined from many years of historical weather data (Kitson et al., 1991).

In either the "typical weather year" or "systems" approach, the goal is to develop a general purpose drying method which can be used for grain drying in spite of uncertainties in weather conditions. Design studies do not provide any management recommendations for the manager on how to manage operation of a

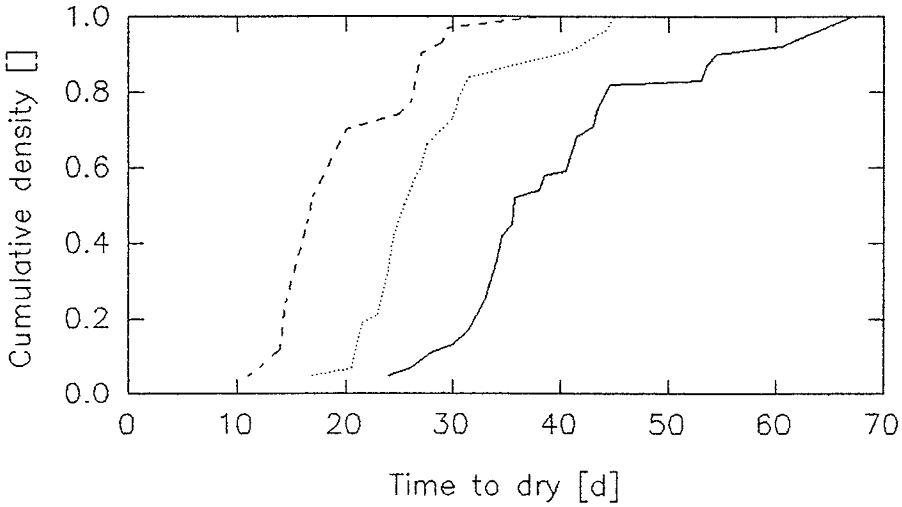

FIGURE 2.9 - Cumulative distributions of time to dry the top of a bulk of wheat based on 33 years of weather data at Winnipeg, Manitoba, for wheat harvested at an initial moisture content of 19% wet mass basis on August 15 (···), September 1 (——) and 15 (- - -) and dried with near-ambient air at required minimum airflows of 15, 13 and 30 (L/s)/m^3 (Kitson et al., 1991).

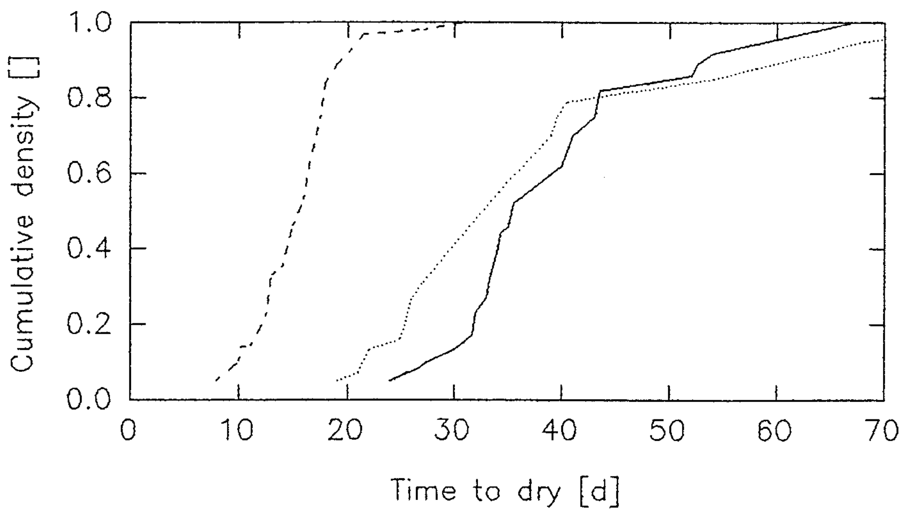

FIGURE 2.10 - Cumulative distributions of time to dry the top of a bulk of wheat based on 33 years of weather data at Winnipeg, Manitoba, for wheat harvested on September 1 at an initial moisture content of 16 (···), 19 (——) and 22% (- - -) wet mass basis and dried with near-ambient air at required minimum airflows of 10, 13 and 40 (L/s)/m^3 (Kitson et al., 1991).

drying system on a year-to-year basis or on a day-to-day basis. Even with continuous near-ambient ventilation there is a need for operational guidelines.

For the grain storage manager to better manage grain drying, he must be able to predict the performance of a grain drying system. Because of uncertainties in weather conditions, the performance must be evaluated while drying is in progress. When the grain storage manager has an accurate assessment of the performance, a decision can be made as to whether the current drying system meets his requirements that spoilage not occur and drying is completed by a certain date.

To develop estimates of drying times when drying is in progress requires many grain drying simulations. Only 28 historical weather years were available for this study. To stochastically generate final drying times a weather model would be needed which generated synthetic weather data.

2.6 Stochastic modelling

2.6.1 Definitions

Because of uncertainty and variability in a time-dependent process, such as weather, a stochastic or probabilistic model can be used to forecast or predict the behaviour of a process (Box and Jenkins, 1976). A regression model describing how y varies with t, coupled with a model describing the random error about the regression model may be used to describe a process (Figure 2.11). The random error is usually presented as a residual series. That is, the regression model is removed from the

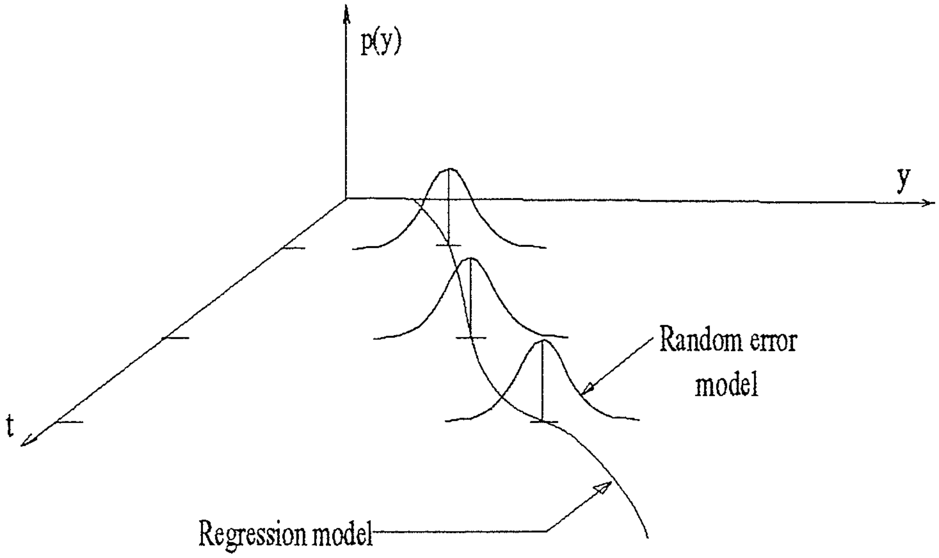

FIGURE 2.11 - A stochastic or probabilistic process can be described by a regression model and random error model. The regression model is the natural mean level of the process which describes the change in some property y as a function of time, t. The random error model describes the variance about the regression model. It is assumed in this figure the probability density function is the same for all t.

observations to isolate the random fluctuations. If the process fluctuates about a natural mean level, then the process is stationary. For example, weather would be a stationary process because the seasonal mean levels are known, but agricultural commodity prices would be non-stationary because there is no known natural mean.

Correlation coefficients are used to describe the strength of the relationship between elements of the random process. The estimated lag-k correlation coefficient for all times, t = 1..N, between random elements z_t and z_{t+k}, separated by k time intervals, is defined as:

$$r_k = c_k / c_0 \qquad (2.1)$$

where c_k, the estimated lag-k autocovariance, or spread about the mean between z_t and z_{t+k}, is defined as:

$$c_k = \frac{1}{N} \sum_{t=1}^{N-k} (z_t - \bar{z})(z_{t+k} - \bar{z}) \qquad (2.2)$$

where

$$\bar{z} = \frac{1}{N} \sum_{t=1}^{N} z_t \qquad (2.3)$$

If an element of the random process is a function of previous elements, then the model is autoregressive. That is, the current value of the random element is regressed on previous values of itself. The current value of the process, z_t, can be expressed as an order-p linear function

$$z_t = w_1 z_{t-1} + w_2 z_{t-2} + \dots + w_p z_{t-p} + a_t \qquad (2.4)$$

where w_1, w_2, ..., w_p are weights and a_t is a random shock. The random shock is produced by a white noise function. Elements of white noise are time-independent, and the function typically generates either a normal or uniform distribution.

A first-order autoregressive (Markov) process is

$$z_t = w_1 z_{t-1} + a_t \tag{2.5}$$

where $-1 < w_1 < 1$ for the process to be stationary. The autocorrelation function must satisfy the first-order difference equation

$$r_k = r_1^{k}, \quad k \geq 0. \tag{2.6}$$

A second-order autoregressive process may be expressed as

$$z_t = w_1 z_{t-1} + w_2 z_{t-2} + a_t \tag{2.7}$$

where $w_1 + w_2 < 1$, $w_1 - w_2 < 1$, and $-1 < w_2 < 1$. The function must satisfy the second-order difference equation

$$r_k = w_1 r_{k-1} + w_2 r_{k-2}, \quad k > 0. \tag{2.8}$$

the weights w_1 and w_2 can be determined from

$$w_1 = \frac{r_1(1 - r_2)}{1 - r_1^2} \tag{2.9}$$

$$w_2 = \frac{r_2 - r_1^2}{1 - r_1^2} \; . \tag{2.10}$$

For a stationary process, r_1 and r_2 must lie in the region $-1 < r_1 < 1$, $-1 < r_1 < 1$, $r_1^2 < 0.5(r_2 + 1)$. Derivation of the above models can be found in Box and Jenkins (1976).

2.6.2 Weather modelling

Much research has been done to determine the effect of a previous day's weather on the current day's weather (Gabriel and Neumann, 1962; Matalas, 1967; Stern and Coe, 1984). A linear first-order autocorrelation model, defined in the previous section, compares well with weather data representative of all climatic regions in the United States (Richardson, 1981; Richardson, 1982). If observed weather data fits the first-order model, then a method for generating synthetic weather is available (Richardson, 1981). Weather models have been developed which generate synthetic precipitation, temperature and solar radiation data but not relative humidity data, which is required for grain drying simulations. No weather models are available which generate synthetic weather data for Winnipeg.

To test whether observed weather fits a particular model, the technique of Richardson (1981) can be used. First the seasonal mean (Figure 2.12a) and standard deviation (Figure 2.12b) for wet days (w) and dry days (d) are determined from historical weather data. Richardson defines a wet day as having 0.2 mm or more of precipitation. Then the residual elements are determined by

$$\chi_{p,i} = \begin{cases} (x_{p,i} - \overline{x}_i^w)/\sigma_i^w , & Y_{p,i} \geq 0.2mm \\ \text{or} & \\ (x_{p,i} - \overline{x}_i^d)/\sigma_i^d , & Y_{p,i} < 0.2mm \end{cases} \qquad (2.11)$$

where for the current day, i, and current year, p, x is the value of the weather parameter, Y the precipitation, $\overline{x}_i$ and σ_i are the seasonal mean and standard deviation for day i, and $\chi_{p,i}$ is the residual value. A residual series (Figure 2.12c) has an expected mean and standard deviation of 0 and 1, respectively, while random model elements in the regression model discussed in

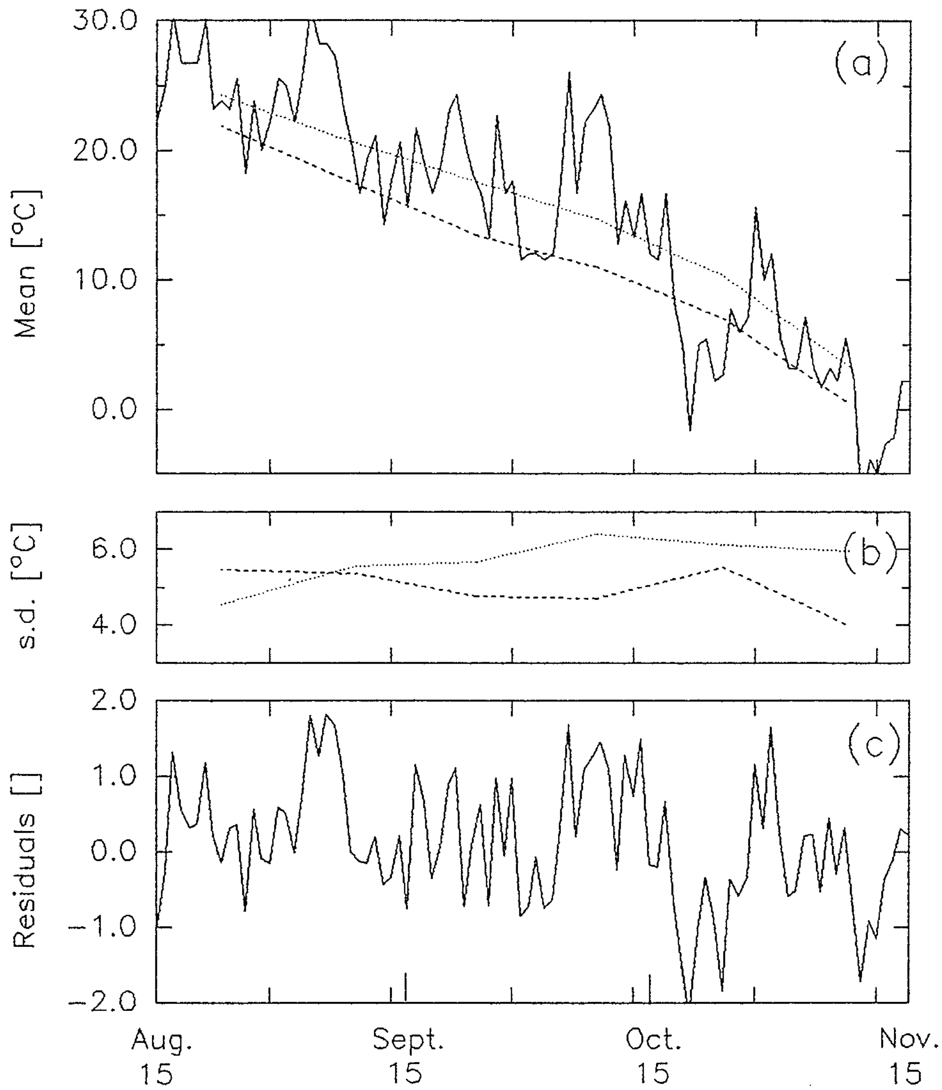

FIGURE 2.12 -Technique for reducing a daily maximum dry bulb temperature to a series of residual elements, conditioned on the basis of wet and dry days. Shown are (a) the maximum daily temperatures for the fall of 1960 superimposed on the seasonal means for wet (- - -) and dry (...) days, (b) the standard deviations, and (c) the residual series.

the previous section (Figure 2.11) have an expected mean of 0 but the standard deviation differs for each weather parameter (Box and Jenkins, 1976). Normalization of weather data must be carried out because the seasonal standard deviations differ for wet and dry days.

3 METHODS AND MATERIALS

3.1 Data requirements and simulation procedures

The response of a bulk of wheat to synthetic and historical weather data (1953-80) for Winnipeg was studied for various scenarios. The response was determined for three harvest dates (August 15, September 1 and September 15), two harvest moisture contents (18 and 20%) and two bed depths (3.65 and 7.30 m). The two bed depths were chosen on the basis of size of commercially available storage bins (Huminicki and Friesen, 1987). Depending on the diameter of the bin, the minimum bin height available is 3 to 4 m. Recommended airflow rates, providing 100% probability of drying by November 15 for continuous ventilation (Friesen and Huminicki, 1987) for these harvest dates and moisture contents, were used. The 100% probability of drying is based on historical weather data for Winnipeg for the years 1953-1985; however, weather conditions may occur which will not ensure drying by November 15. Therefore, the recommended airflow rates provide near 100% probability of drying. The airflow rates assume a 100% perforated floor and level grain surface.

To study the variability in the time for the drying front to pass completely through the top of the bulk using continuous ventilation, simulations for each weather year were stopped when the drying front reached 3, 4 and 5 tenths of the grain depth. Then for each case the simulation was completed using all 28 years of historical weather.

The output data captured from the computer simulations included the following:

- the time the drying front reached each of the 10 imaginary layers in the bulk,
- the percentage of simulations in which the top layer did not dry by November 15,
- the spoilage index of the top layer at the end of each simulation,
- the time for the bin-average moisture content to reach the "dry" level of 14.5% (w.b.)

3.2 Modifications to the near-equilibrium drying model

One modification to the model involved the determination of the temperature rise as the ventilation air passed over the fan and motor. The original model contained a unused routine which calculated the temperature rise based on general thermodynamic principles. Previous researchers had bypassed this routine so temperature rise could be read in from an input file (Huminicki et al., 1986). I revised the program to use the "generic" temperature rise model and not the input file. The numerical models of deterioration, moisture content and temperature were not modified.

The other modifications to the computer program involved the input and output of data. These sections of the program were relatively straight forward and easy to modify. The software was modified to allow for a simulation to be stopped and restarted. When a simulation was stopped on a particular fall date, the temperatures, moisture contents, and deterioration indices for all layers were written to an output file. When the simulation was restarted, these data were read back into the model. A simulation could be stopped and restarted as many times as required.

An attempt was made to modify as little as possible the existing near-equilibrium grain drying model so as not to add errors to the programming. Some simulations were completed to verify that the modified model's output was unchanged compared with the unmodified model's results.

Except for the maximum allowable spoilage index and "dry" moisture content, input parameters for the model (Table 3.1) were unchanged and were the same values as are in the publicly available software package distributed by the Manitoba Department of Agriculture (Huminicki et al., 1986). A spoilage index of 1.5, as suggested by Sanderson et al. (1989), was used. A "dry" moisture content of 10% was chosen to allow the model to simulate drying up to November 15 regardless of grain condition. This was done so data for both top-layer and bin-average drying strategies could be compiled from one simulation.

An operating system command file was used to automate the execution of thousands of simulations. The actual number of runs were the number of weather years squared, times the number of combinations of scenarios (i.e 28*28*3*2*2 = 9408 simulations). The function of the command file was to manipulate data files and execute FORTRAN files when required. The algorithm used for

TABLE 3.1 - Parameters input to the near-equilibrium model that was used to simulate continuous near-ambient ventilation of wheat.

Number of convection layers	10
Time increment during forced convection	3 h
Initial storage temperature	Average of previous 24-hour ambient temperatures plus 5^{0}C (minimum of 20^{0}C)
Spoilage index	1.46
"Dry" moisture content (% wet basis)	Low value (10%)[a]
Fan and motor efficiency	100%
Specific heat of wheat (J/(kg*^{0}C))	1750
Density of wheat (kg/m^3)	770

[a]A moisture content well below the required market "dry" level of 14.5% was chosen to allow simulation of drying up to November 15 regardless of grain condition. Post-processing of one simulation output file could then be used to calculated both the time at which the top layer dried to 15.5% and the time at which the bulk was average-dried to 14.5% moisture content.

```
start:     for all HARVEST_DATES={Aug15,Sept1,Sept15},
           INITIAL_MOISTURE_CONTENTS={18%,20%}, and
           BED_DEPTHS={3.65m,7.30m}

loop1:         for all WEATHER_YEARS={1953..1980}
                   - predict the time required to dry the top
                   layer of a bulk of wheat using continuous
                   ventilation, near-equilibrium drying model
                   - save the time the drying front passes
                   through each layer
               endloop

loop2:         for all WEATHER_YEARS={1953..1980}
                   for each LAYER={3,4,5}
part1:                 - simulate drying up to LAYER using
                       times calculated in "loop1"
                       for all WEATHER_YEARS={1953..1980}
part2:                     - complete drying simulation
                           started in "part1" up to Nov. 15
                           - save the time to drying each
                           layer to 15.5%, the time to
                           average-dry the bulk to 14.5%, and
                           the spoilage index in the top layer
                       endloop
                       - calculate to average spoilage index in
                       the top layer from all simulations in
                       "part2"
                   endloop
               endloop
end:       endloop
```

FIGURE 3.1 - Algorithm used to stochastically generate results for drying bins of wheat stored under various scenarios.

generating results for different grain drying scenarios can be seen in Figure 3.1. The command files themselves are generated by a FORTRAN program. A different grain drying model could be substituted if desired with only a few modifications.

3.3 Location of drying front in simulated bins of wheat

The moisture front was considered to be in a layer when the layer moisture content first fell below 15.5%. The value of 15.5% moisture content was chosen instead of the actual "dry" moisture content of 14.5% because preliminary results showed that in a few years all moisture contents did not "bottomed out" below 14.5%. For example, the moisture content bottomed-out at 13% after 10 d of drying, and then increased to 15% during 20 to 35 d of drying for wheat stored August 15, 1956, at 18% moisture content in a 3.65 m deep bed (Figure 3.2). Inspection of the simulated moisture contents of all layers during the poor drying years indicated that selecting a moisture content close to 14.5% was reasonable because rewetting rarely went above 15.5% for more than a few days (Figures 3.3 - 3.6). The weather during the fall of 1968 was very poor for drying and the bottoming-out moisture content rarely went below 15.0% (Figure 3.7). The drying front reference moisture content was not meant to include this drying year.

The "noise" near the bottoming-out level could interfere with the recording of the times the drying front was within each layer. As well, the deceleration in rate of moisture removal as the bottoming-out moisture content is reached in a particular

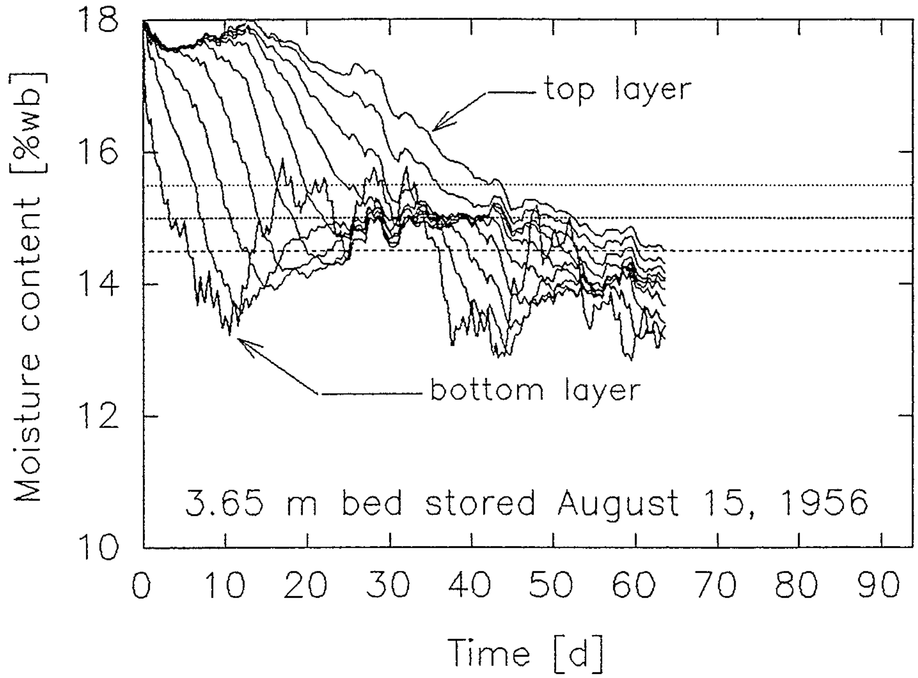

FIGURE 3.2 - Simulated moisture contents for wheat stored August 15, 1956 in a 3.65-m deep bed initially at 18% moisture content and ventilated with 10 (L/s)/m³. Each line represents the moisture content in one of the 10 layers.

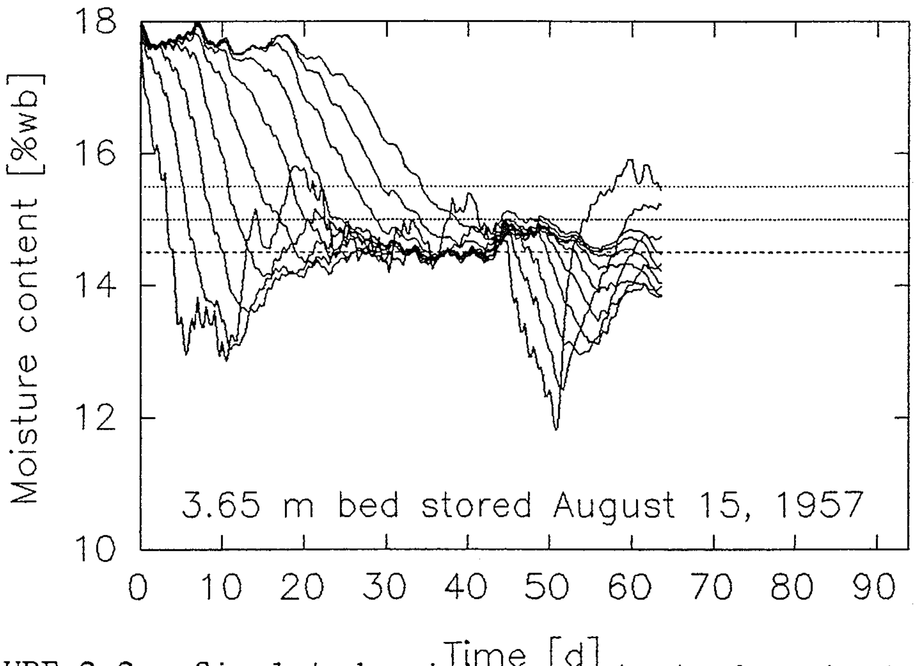

FIGURE 3.3 - Simulated moisture contents for wheat stored August 15, 1957 in a 3.65-m deep bed initially at 18% moisture content and ventilated with 10 (L/s)/m³.

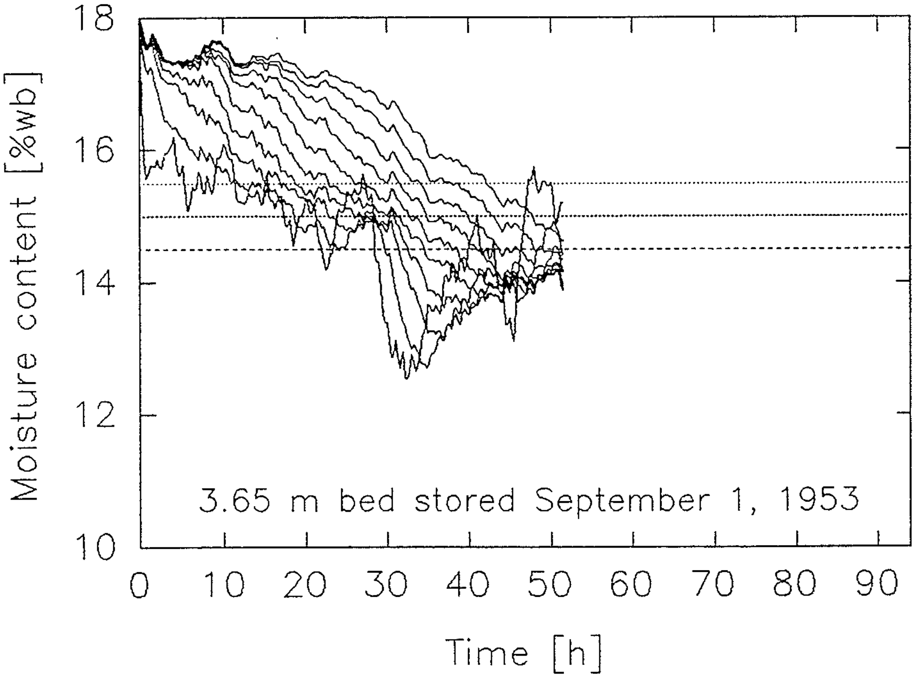

FIGURE 3.4 - Simulated moisture contents for wheat stored September 1, 1953 in a 3.65-m deep bed initially at 18% moisture content and ventilated with 12 (L/s)/m^3.

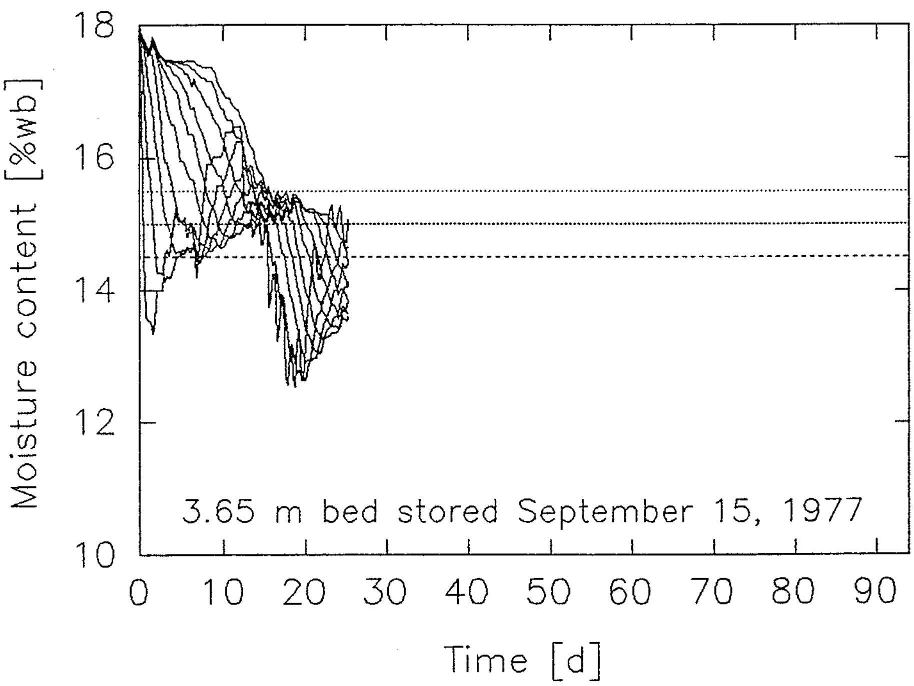

FIGURE 3.5 - Simulated moisture contents for wheat stored September 1, 1977 in a 3.65-m deep bed initially at 18% moisture content and ventilated with 12 (L/s)/m^3.

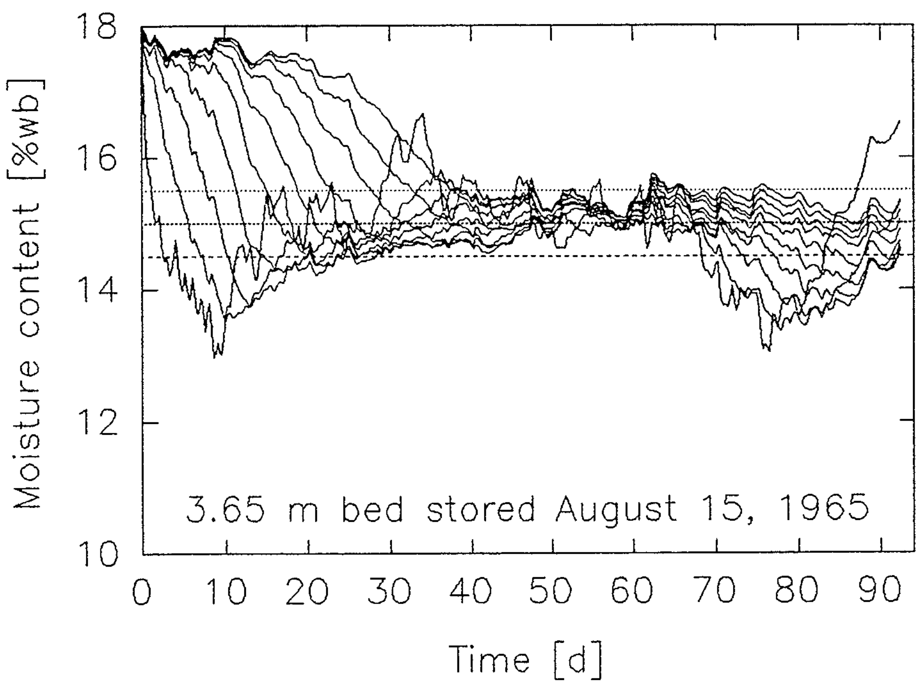

FIGURE 3.6 - Simulated moisture contents for wheat stored August 15, 1965 in a 3.65-m deep bed initially at 18% moisture content and ventilated with 10 (L/s)/m^3.

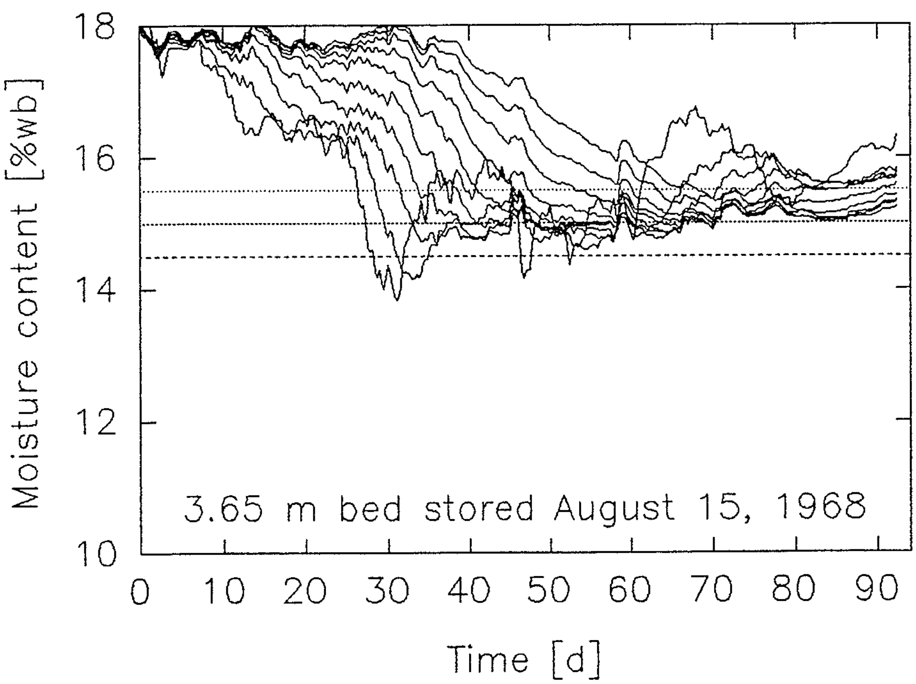

FIGURE 3.7 - Simulated moisture contents for wheat stored August 15, 1968 in a 3.65-m deep bed initially at 18% moisture content and ventilated with 10 (L/s)/m^3.

layer was a concern. Ideally, a moisture content between the initial harvest level and the bottoming-out level should be used as the reference moisture content for determining the location of the drying front. That is, a reference level through which the moisture content quickly drops is preferred.

If a lower airflow rate was simulated, i.e. for less than 100% probability of drying, then the bottoming-out moisture content would be slightly higher because of the reduced energy transfer from the fan and motor to the ventilation air. For example, Figure 3.8a shows a bottoming-out moisture content of 14% after 10 d of drying in a system with an airflow rate having a 100% probability of drying by November 15 but only 15% after 10 d of drying in a drying system with an airflow rate having only a 90% probability of drying the bulk by November 15. This higher bottoming-out moisture content will have to be considered when determining the reference level for defining the drying front in non-design scenarios.

3.4 Application of weather data

Historical weather data for 28 years were used to stochastically generate synthetic weather data. For each of the 28 years, drying was completed up to a particular layer (3rd, 4th or 5th). Then completion of drying from this particular layer to the 10th layer was simulated with the weather data for the remaining days from each of the 28 years. Statistical tests discussed in the Literature Review were applied to the historical weather data to test the validity of "splicing" weather data from

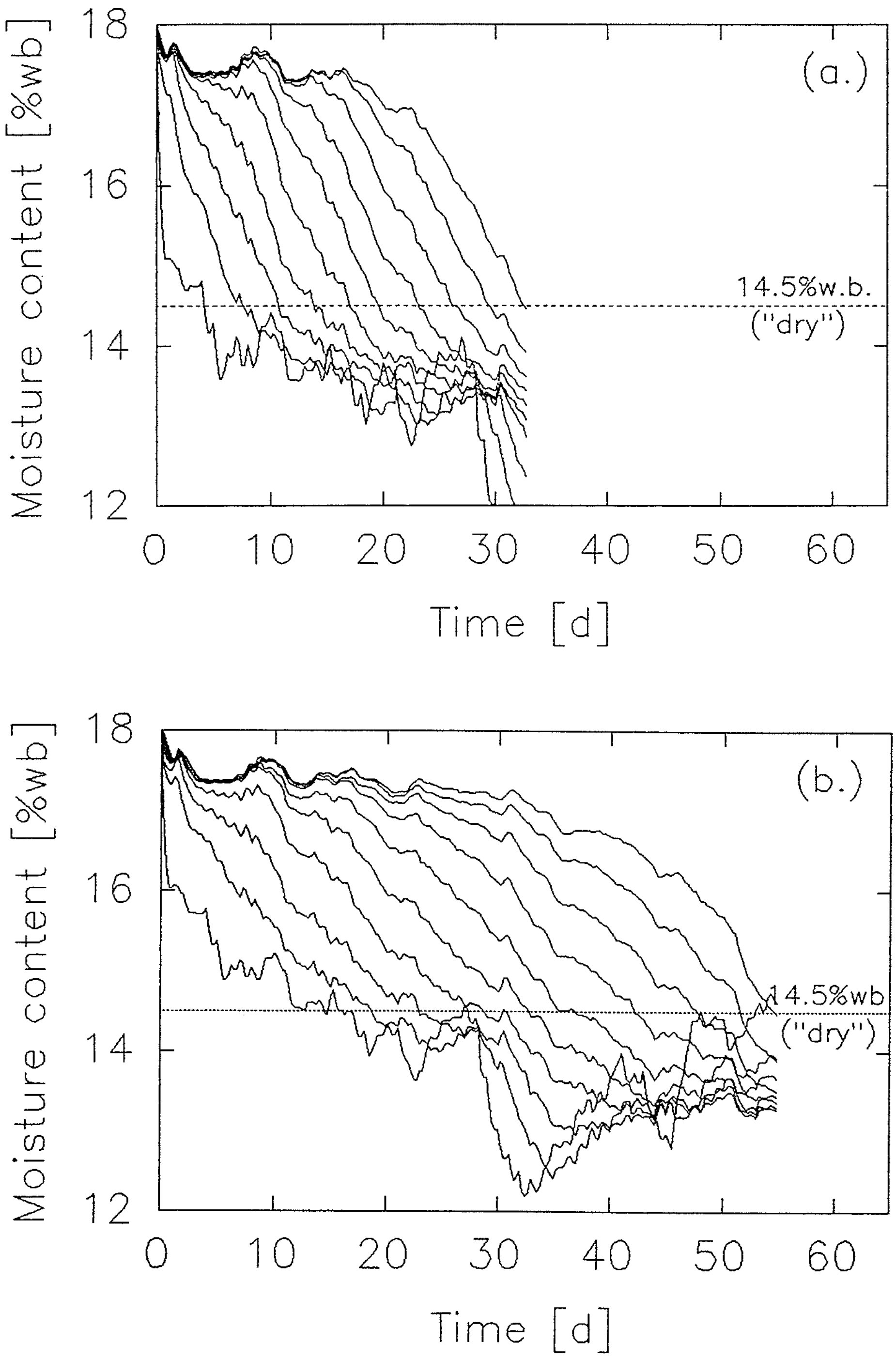

FIGURE 3.8 - A decrease in airflow decreases the amount of energy transferred to the ventilation air. Shown are the changes in moisture content for wheat stored August 15, 1953 at 18% moisture content in a 3.65-m deep bed ventilated with (a) recommended airflow rate of 12 $(L/s)/m^3$ for 100% probability of drying by November 15, and (b) recommended airflow rate of 8 $(L/s)/m^3$ for 90% probability of drying by November 15.

two years in this manner.

Sixteen years of historical weather data (1960-65, 1967, 1968 and 1970-77) were used to determine the serial correlation coefficients for temperature and relative humidity. The amount of clustering was also determined. Only 16 years were used because these were the only years for which precipitation data were available.

4 Results and Discussion

4.1 Weather modelling

A stochastic weather model for temperature and relative humidity was not available (Section 2.5.2), to perform a sufficient number of grain drying simulations. The 28 years of historical weather data would not sufficiently define the variability in grain drying times. Therefore, a method was required which could generate many synthetic weather years. The stochastic weather model described by Richardson (1981) could be used if the observed weather could be described by the first-order autoregressive model. The methods discussed in Section 2.5 were used to determine if observed weather for Winnipeg were similar to with the first-order model.

There was a strong, positive serial correlation for minimum and maximum temperatures (0.485 and 0.538, respectively), and a moderate serial correlation for minimum and maximum relative humidities (0.357 and 0.300, respectively). The observed serial correlations for dry bulb temperature compared well with the serial correlations predicted by the first-order model for 1- and 2-day lags; however, the observed correlation coefficients were larger than expected for lags greater than 2 days (Figure 4.1a,b). (Box and Jenkins (1976) defined the statistical term "lag-k" to be the correlation of day i with day i+k.) The differences between the observed temperature correlations and those predicted by the first-order model were similar to that of Richardson (1981). Richardson, however, observed correlations

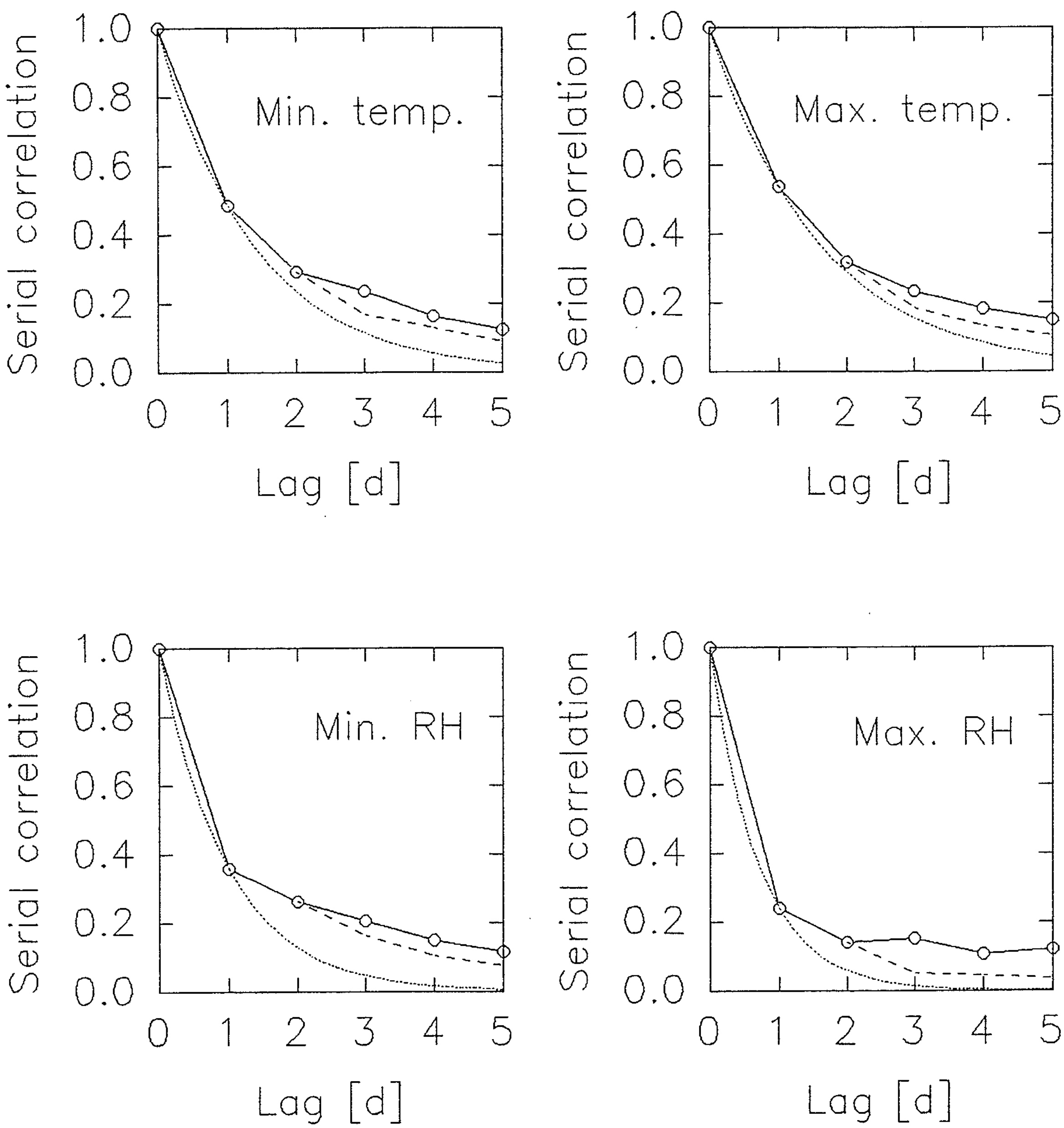

FIGURE 4.1 - Observed serial correlations (o——o) for 16 years of historical weather data for Winnipeg, Canada compared with serial correlations predicted by linear first-order (...) and linear second-order (- - -) autocorrelation models.

lower than the first-order model correlations.

The observed serial correlations for relative humidity did not compare well with the correlations predicted by the first-order model (Figure 4.1c,d). The first-order model implies that the weather for day i is only a function of the previous day i-1 (Box and Jenkins, 1976). The observed serial correlations indicated that weather was a function of more than one previous day. A second-order linear autocorrelation model compared well with the observed serial correlations. Higher-order models were not tested.

Therefore, weather in Winnipeg for a given day in the fall was a function of the weather on the two previous days (i.e. second-order). The model of Richardson (1981) could not be applied because it required the weather for a given day to be a function of the weather on the previous day (i.e. first-order). Instead, a method was needed to generate synthetic weather using the available weather data.

"Splicing" of historical weather data was used to generate 28^2, or 784, synthetic weather years from 28 years of historical weather data. That is, the 28 weather years were used to simulate drying up to a particular layer, and then the 28 years of historical weather data were used to simulate the remainder of the drying for each of the 28 cases. From the point of view of the grain storage manager, each synthetic weather year is a possible weather year, even though the simulation is completed in two steps. Because the simulated grain drying times were on the order of tens of days in length, then weather data for two years could be added to one another to create a new weather year. It is believed that any errors in simulation results introduced because of the data splicing were small because simulations were generally greater than 20 days in length. This method may not be applicable to simulations of only a few days in length as the effect of any discontinuity of weather at the time of the "splice" is unknown.

4.2 Stochastic modelling of grain drying

4.2.1 Format of data presentation

The results of the stochastic modelling are presented in several similar graphs. The horizontal-axis indicates the time required after harvest for the drying front to reach the 3rd or 5th layer (eg. Figure 4.2). The times required for the drying front to reach a particular layer were used to develop a cumulative density function (c.d.f.) in Part (b) of the figures. The vertical-axis in Part (a) of the figures indicates the time from date of harvest required for the drying front to reach the top of the bulk. Each column of '+' contains 28 final drying times in which the initial drying was simulated with the same weather year. If a simulation did not complete drying by November 15, then it is not included in Part (a).

Shown in Part (b) for each of the times for the drying front to reach the specified layer is the fraction of simulations dried by November 15, the fraction of simulations that predicted spoilage before drying was completed, and the average allowable storage time elapsed (ASTE) of the top layer when drying is completed. An ASTE of 1.0 indicates that the degree of spoilage has become unacceptable. Inspection of simulation results for bulks initially dried with the same weather year indicated variation in ASTE for the top layer was approximately 0.1. Therefore, the average ASTE for the top layer is given because the variation was not large.

No spoilage was predicted in any of the simulations because

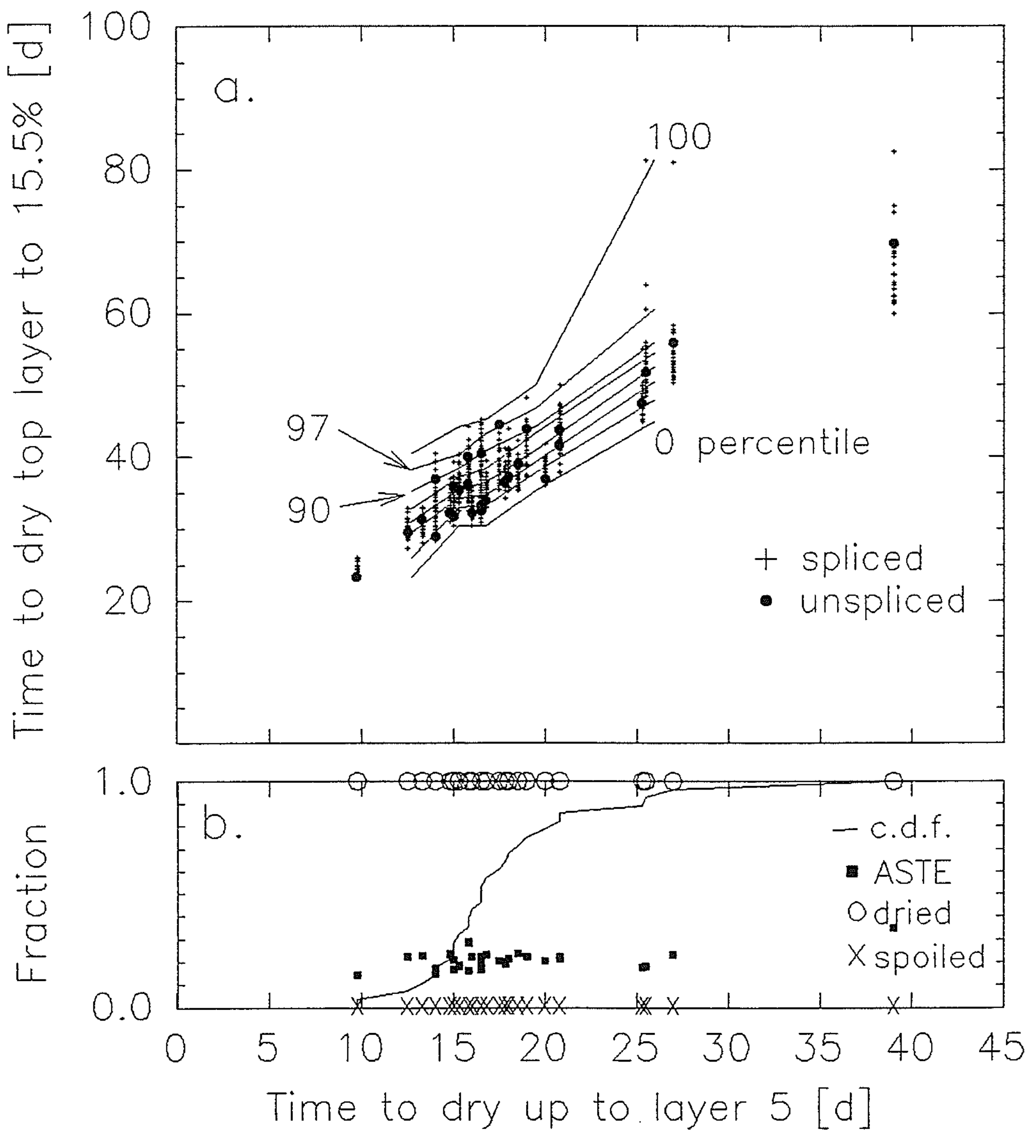

FIGURE 4.2 - (a) Estimated time for the top of a bulk of wheat stored in Winnipeg on August 15 at 18% moisture content in a 3.65-m deep bed and ventilated with 10 (L/s)/m^3 of air to dry to 15.5% moisture content given the time the drying front reached layer 5. The calculated temperature rise of the ventilation air was 0.5^{0}C. Shown are results of simulations where two historical weather years were "spliced" (+) and where all drying was completed with only one weather year (●). (b) Shown is the cumulative density function (c.d.f.) of times for the drying front to reach layer 5 (——), the fraction of simulations dried by November 15 (o) and the fraction of simulations in which unacceptable spoilage was predicted (x). The average allowable storage time elapsed, ASTE, in the top layer is shown for simulations initially dried with the same weather year.

the maximum allowable spoilage index was increased by a factor of 1.5 as recommended by Sanderson et al. (1989). Of all scenarios tested, the largest ASTE calculated was 0.7, therefore, the predicted spoilage index was 0.7*1.5 = 1.05. (ASTE is defined in Section 2.4.3 as the predicted spoilage divided by the maximum allowable spoilage index i.e. the spoilage index is normalized). If the maximum allowable spoilage index had not been increased from 1.0, then spoilage would have been predicted in some simulations.

Percentile lines were added to show the distribution of the final drying times. The percentile lines were incremented by 20 percentiles from 0 to 100 percentile. The percentile lines incremented by 20 were not labelled. Other percentile lines (90 and 97) that are not a multiple of 20 were labelled. Percentile lines were determined by collecting data into bins no greater than 5 d in width. A minimum of 3 columns of data per bin was the criterion for calculating percentile ranges; therefore, percentile ranges were not determined for regions with sparsely distributed data.

In some of the figures (Figure 4.2) the time to dry for the unspliced years (one data point in each column) is indicated by a solid circle. For each set of drying conditions, i.e. for each graph, these drying times for actual, unspliced, years were distributed throughout the full range of variability. The distribution of the 28 historical weather years compared well with the percentile ranges suggesting that the synthetic weather simulations were not unreasonable.

4.2.2 Sensitivity to weather conditions

Results indicated a skewed cumulative density function (c.d.f.) in the time required to dry up to a particular layer. For example, wheat stored on August 15 at 18% moisture content in a 3.65 m deep bed (Figure 4.2b), required 10 to 38 days for the drying front to reach layer 5, with 86% of the simulations between 10 and 21 days. The mean and standard deviation of time for the drying front to reach layer 5 was 17.8 d and 5.8 d, respectively. As well, the time required to dry the top layer was also skewed (i.e. 28 drying times '+' within a column in Figure 4.2a).

The skewness in drying times can be attributed to several factors. The historical weather data used in this study includes the years 1965 and 1968, which were poor drying years. The rate of the drying during periods of poor drying was slower than the mean rate but the rate of drying during good drying periods was limited. Therefore, losses in drying time were not be regained at a later period (Figure 4.3).

The weather during the period of initial drying (i.e. drying of the first 5 layers) has a significant effect on the range of final drying times. The variable moisture contents and temperatures of all layers affect subsequent drying times. For example, if initial drying was simulated with weather year 1973 (at 16 d on the horizontal-axis in Figure 4.2), then all final drying times were in the 0 to 60 percentile range. That is, even

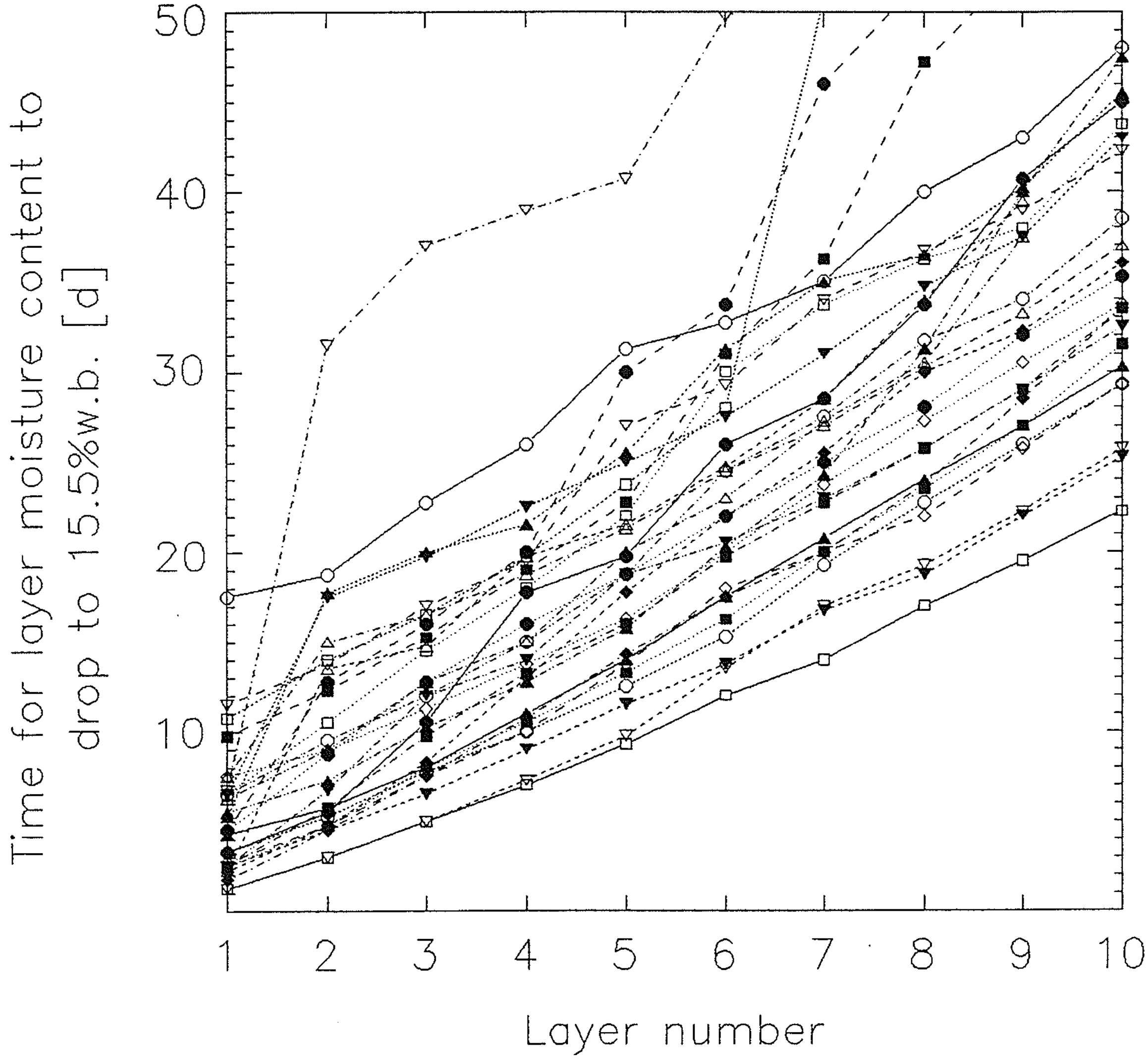

FIGURE 4.3 - Shown are the simulated times the drying front reached each of the 10 imaginary layers in a 3.65 m deep bulk of wheat stored August 15 at 18% moisture content for 28 years of historical weather data (1953-80) for Winnipeg when ventilated with 10 (L/s)/m^3 of near-ambient air. Usually the time lost during periods of poor drying was not recovered during periods of good drying weather.

when drying of layers 6 to 10 were simulated with weather during the poor drying year 1968, the final drying times were below the 60th percentile. (This can be seen more clearly in Figure 4.4 which is an enlargement of a portion of Figure 4.2a).

The categorization of historical weather data as "good", "average" or "poor" drying weather can be done after-the-fact. However, the grain storage manager has no *a priori* knowledge of changes in weather conditions. An attempt by the grain storage manager to categorize a weather year as "good", "average" or "poor" at the beginning of the drying process would likely not produce meaningful results because weather could change dramatically in a few days. Only after a significant portion of the drying has been completed, half the grain bed for example, an attempt might be made to categorize the weather year because the variability in final drying time would be reduced.

Using a "typical" or "average" weather year should be discouraged. The "average" weather year, as used by Kitson et al. (1991), was a set of synthetic weather conditions for each hour averaged for several years. Although a typical year may be used for preliminary comparative studies of different drying systems, a stochastic approach would identify the beneficial and detrimental extremes of drying systems. Performance of drying systems may be quite different during extreme weather conditions than during average weather conditions.

Results presented in this and the following sections are representative of the results generated for this study. Results

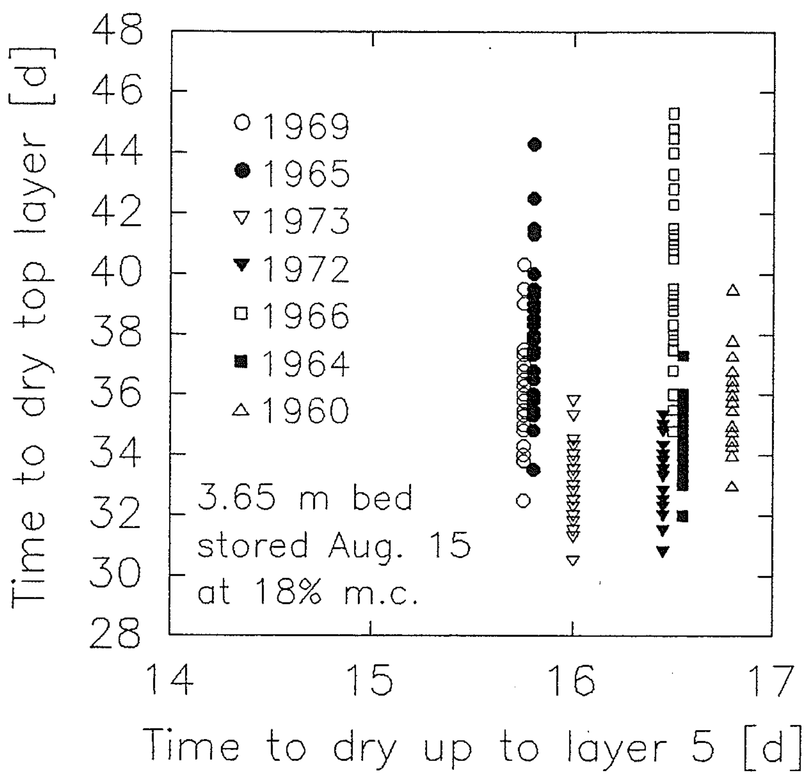

FIGURE 4.4 - Enlargement of a portion of FIGURE 4.2a which shows the range of times for the drying front to reach the top layer of a bulk of wheat stored August 15 at 18% moisture content in a 3.65 m deep bed in Winnipeg.

not included in Section 4 can be found in Appendix A.2.

4.2.3 Sensitivity of top-layer drying times to amount of initial drying

The variability in time to dry the top layer to 15.5% moisture content decreased as the drying front approached the top of the bulk (Figures 4.2 and 4.5). That is, the greater the amount of initial drying, the less the "fanout" of final drying times. For wheat stored August 15 in a 3.65 m bed at 18% moisture content, if the drying front had progressed to layer 3, then the time to dry the top layer could be estimated to occur within a 25 d range (i.e. the maximum vertical distance between 0 and 100 percentile lines at any initial drying time in Figure 4.5). If the drying front had progressed to layer 5 in 25 d or less, then the time of final drying could be estimated to occur within a 15 d range (Figure 4.2). If the drying front had progressed to layer 5 in 25 d or longer, then final drying could only be estimated within a 40 d range.

4.2.4 Sensitivity of top-layer drying time to initial drying conditions

Harvesting 15 days later than September 1 reduced the variability in final drying times from 20 d to 10 d because of the different airflow rates used to dry the grain (Figures 4.6 and 4.7). The objectives and recommendations for drying grain differ with harvest date. Early harvests are susceptible to rapid spoilage because of warm grain temperatures, and the grain must therefore be dried quickly. Recommended airflow rates for September 15 assume drying must be completed by November 15 which

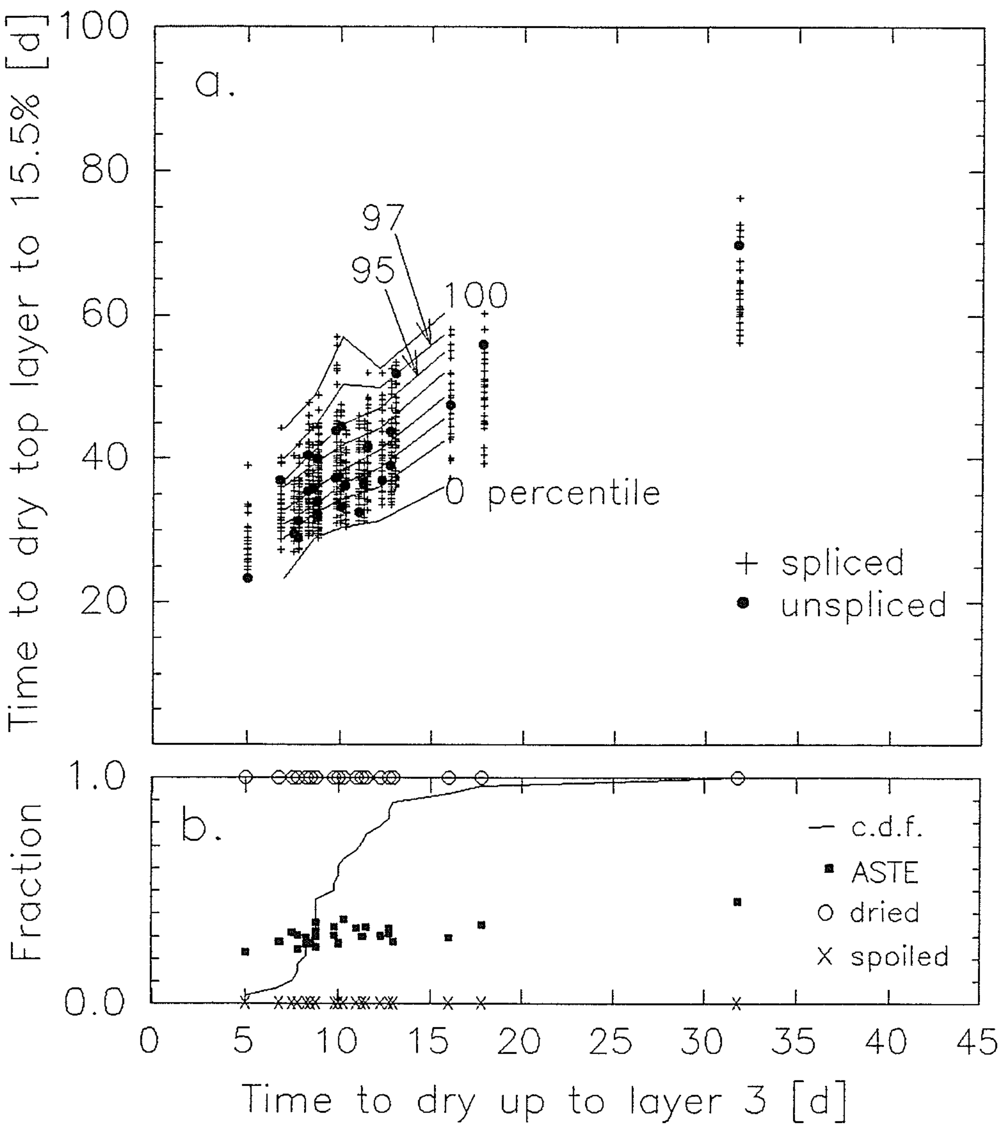

FIGURE 4.5 - Estimated time for the top of a bulk of wheat stored in Winnipeg on August 15 at 18% moisture content in a 3.65-m deep bed ventilated with 10 (L/s)/m^3 of near-ambient air to dry to 15.5% moisture content given the time the drying front reached layer 3. The calculated temperature rise of the ventilation air was 0.5^{0}C.

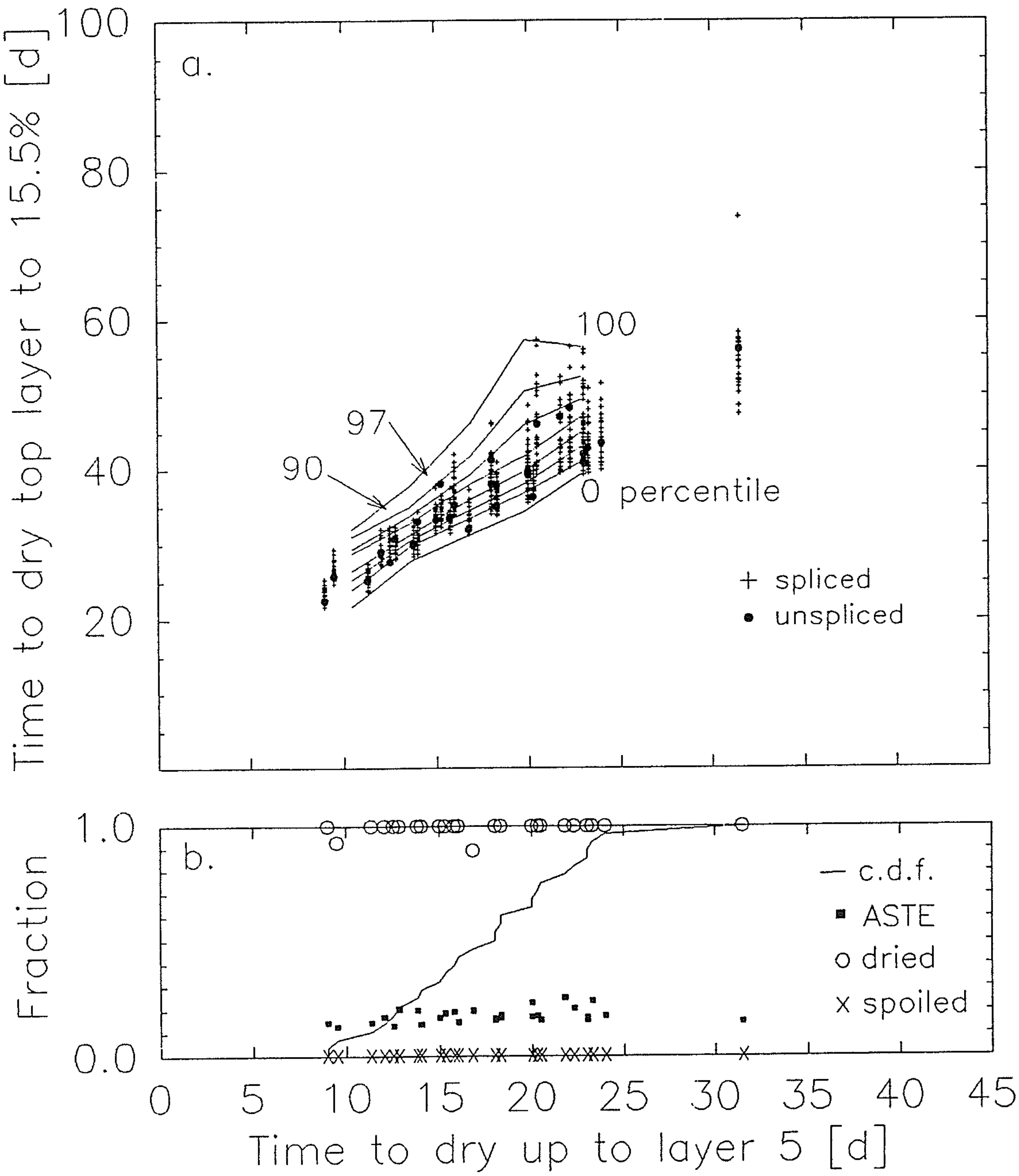

FIGURE 4.6 - Estimated time for the top of a bulk of wheat stored in Winnipeg on September 1 at 18% moisture content in a 3.65-m deep bed ventilated with 12 $(L/s)/m^3$ of near-ambient air to dry to 15.5% moisture content given the time the drying front reached layer 5. The calculated temperature rise of the ventilation air was 0.6^0C.

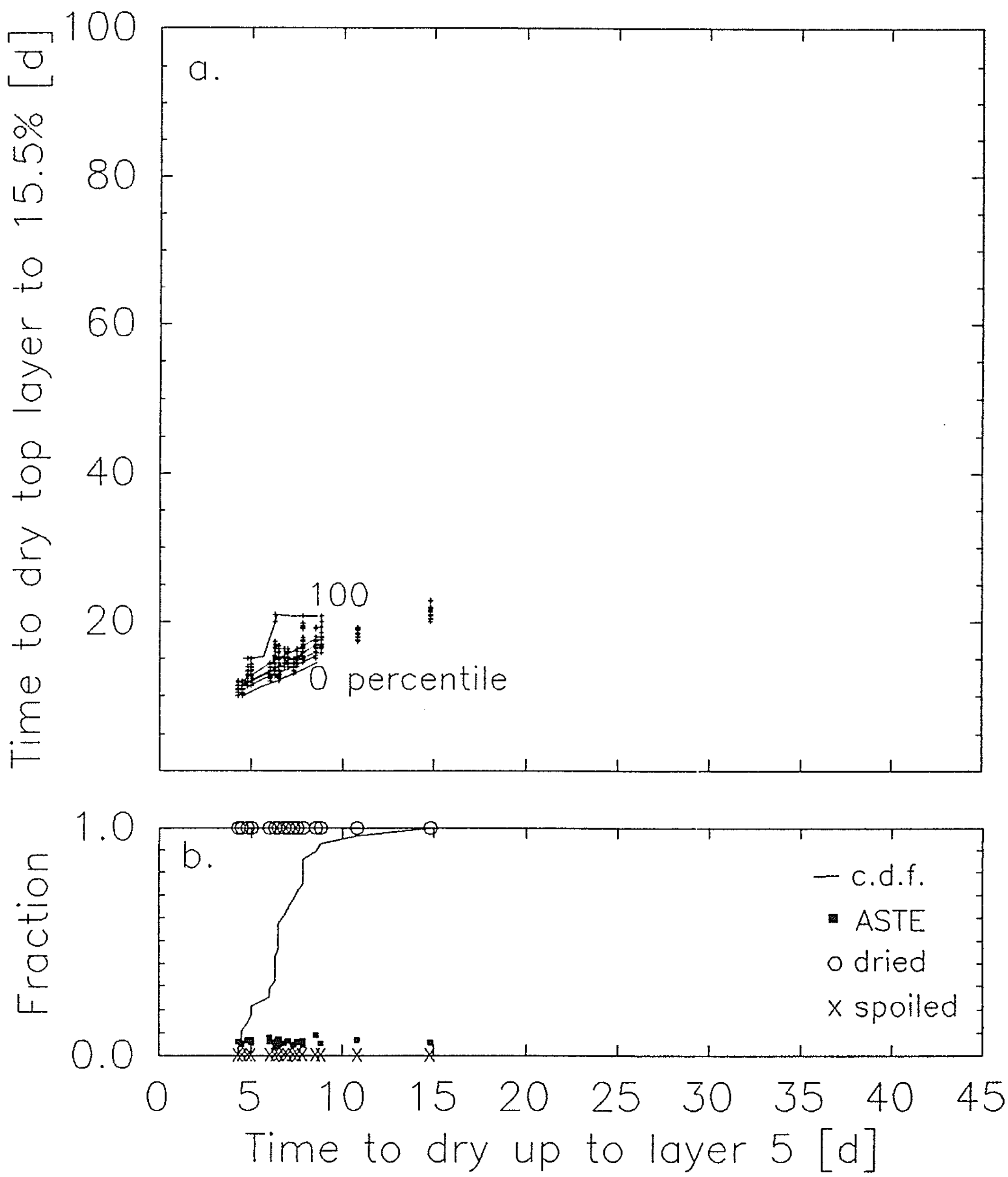

FIGURE 4.7 - Estimated time for the top of a bulk of wheat stored in Winnipeg on September 15 at 18% moisture content in a 3.65-m deep bed ventilated with 28 (L/s)/m^3 of near-ambient air to dry to 15.5% moisture content given the time the drying front reached layer 5. The calculated temperature rise of the ventilation air was 1.7^{0}C.

limits the variability in final drying time despite the low risk of spoilage. The highest airflow rates are used for September 15 harvest dates. Increased airflow rates caused increased temperature rises of the ventilation air (Table 4.1) which also tended to reduce the drying time.

Comparison of scenarios differing only by bed depth indicated reduced variability in final drying time for increasing bed depth (Figures 4.2 and 4.8). The calculated temperature rise of the ventilation air as it passed over the fan and motor increased with increasing depth (Table 4.1). Rewetting was less in the deeper beds than in shallower beds because of the increased temperature and drying potential of the ventilation air.

Increasing the initial storage moisture content reduced the variability in final drying times (Figures 4.2 and 4.9). Wheat with a high moisture content must be dried more rapidly than wheat with a low moisture content to avoid spoilage; this is reflected in the recommended airflow rates (Table 4.1). The calculated temperature rise of the ventilation air increased with increasing airflow rate (Table 4.1). The mean drying rate increases with higher airflows recommended for increased bed depth or increased moisture content.

The predicted temperature rises of the ambient air as it passed over the fan and motor were large for a few scenarios. Although no formal comparison was made, calculated temperature rise for most scenarios was within the range of observed

TABLE 4.1 - Predicted temperature rise (^{0}C) of inlet ventilation air as it passes over the fan and motor. Fundamental thermodynamic principles were used to determine the temperature rise. Also shown in parenthesis are the recommended airflow rates ((L/s)/m^3) of Huminicki and Friesen (1987) for 100% probability of wheat drying by November 15 at Winnipeg, Canada.

Moisture content [% w.b.]	Bed depth [m]	Predicted temp. rise [^{0}C]		
		August 15	September 1	September 15
18	3.65	0.5 (10)	0.6 (12)	1.7 (28)
18	7.30	2.3 (10)	2.9 (12)	7.5 (28)
20	3.65	1.0 (20)	0.8 (15)	2.0 (32)
20	7.30	4.3 (20)	3.7 (15)	8.8 (32)

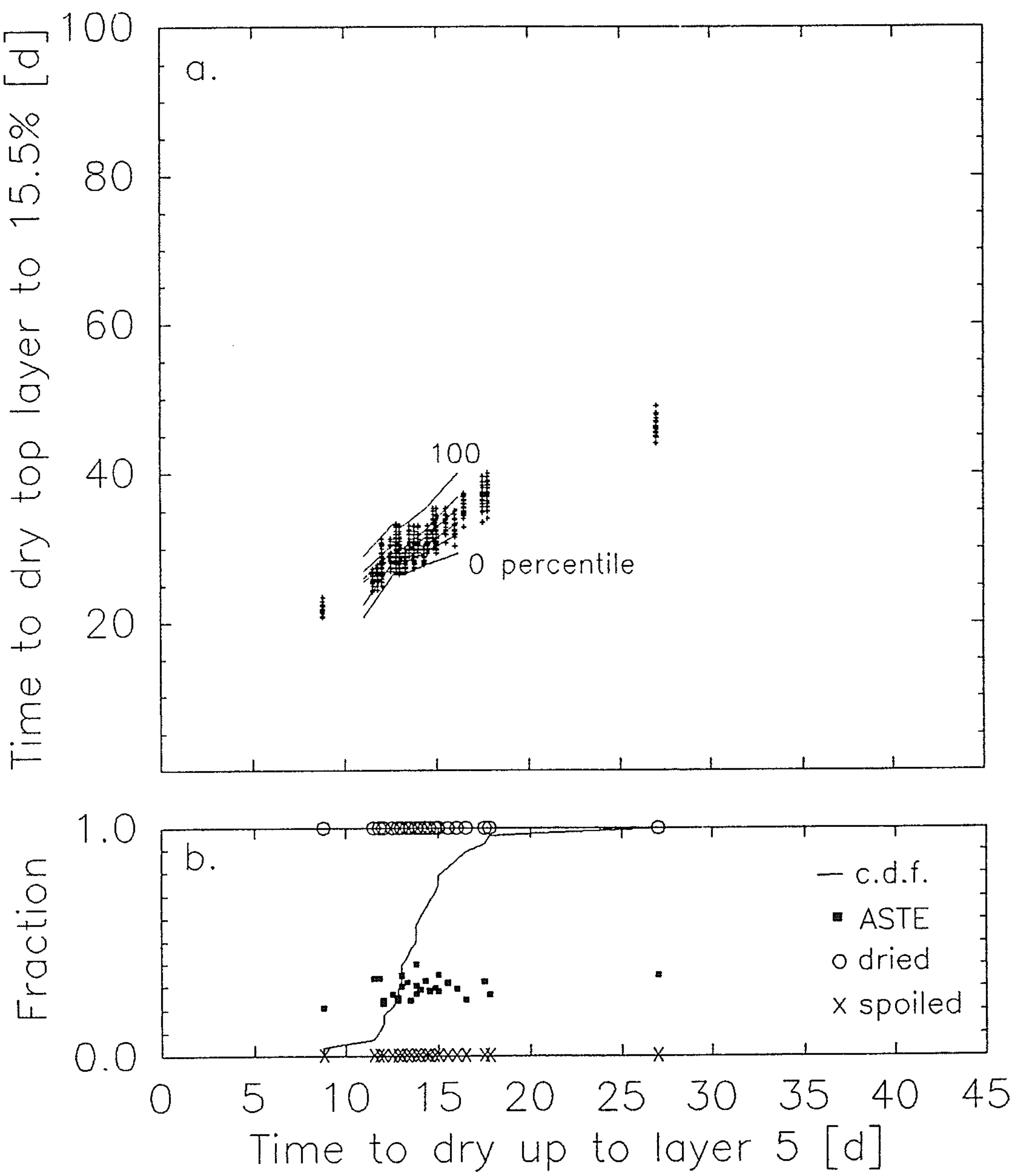

FIGURE 4.8 - Estimated time for the top of a bulk of wheat stored in Winnipeg on August 15 at 18% moisture content in a 7.30-m deep bed ventilated with 10 (L/s)/m^3 of near-ambient air to dry to 15.5% moisture content given the time the drying front reached layer 5. The calculated temperature rise of the ventilation air was 2.3^{0}C.

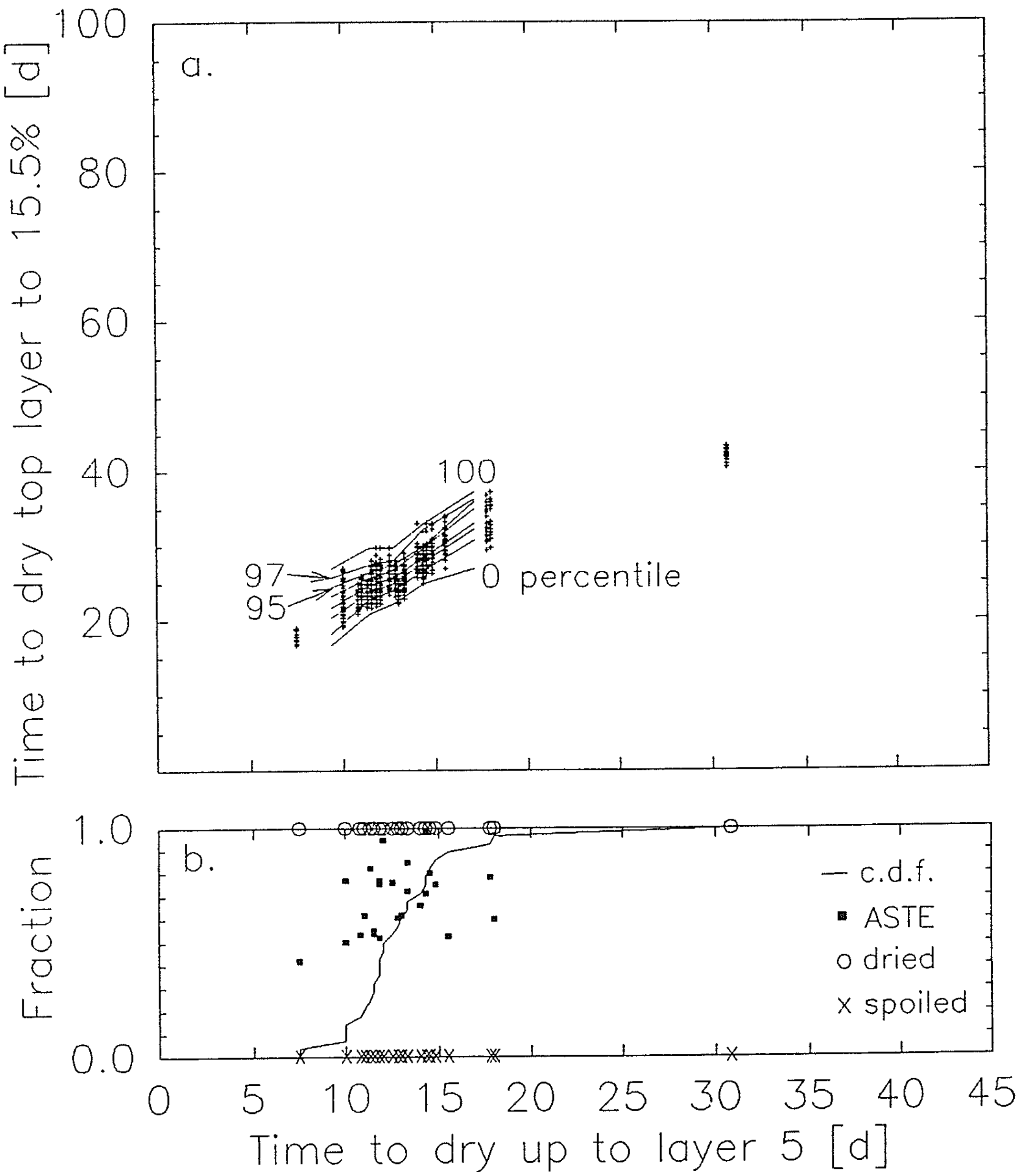

FIGURE 4.9 - Estimated time for the top of a bulk of wheat stored in Winnipeg on August 15 at 20% moisture content in a 3.65-m deep bed ventilated with 20 $(L/s)/m^3$ of near-ambient air to dry to 15.5% moisture content given the time the drying front reached layer 5. The calculated temperature rise of the ventilation air was 1.0^0C.

temperature increases for typical ventilation equipment (Huminicki et al., 1986). The minimum temperature rise for commercially available ventilation equipment was typically greater than 1.0^{0}C. Therefore, the calculated temperature rise for a few scenarios in this study were likely too low. The large temperature rise predicted for a few scenarios could not be compared with observed values for commercial ventilation equipment because the design software of Huminicki et al. (1986) was not allow for simulation of wheat bulks as deep as those used in this study. The design software of Humnicki et al. does not allow for in-line placing of fans in series to overcome large static pressures.

The above results should be interpreted carefully. The results are not meant to encourage high moisture content harvests, or harvesting late in the fall. The recommended airflow rates are based on a constant temperature rise but for this study the recommended airflow rates were used with a varying temperature rise. This tends to leave one with the impression that the drying systems were poorly designed. However, it is expected there will be poorly designed systems in use by grain storage managers. Therefore, the scenarios tested for this study are not unlikely and would correspond to the drying systems designed using Huminicki and Friesen (1987).

In general, the amount of variability in the scenarios is determined by the recommended airflow rates and the total bed depth. Because it is assumed for this study that the grain storage manager is using recommended airflow rates, control of variability can be made through controlling the total bed depth. In other words, if the equipment is available, bins could be filled to the eaves for increased accuracy in predicting final drying times but at the increased cost of fan size and operation costs.

4.2.5 Average-bin drying

The data generated for this study indicated average-bin drying was unpredictable. In most scenarios, variability in time to average-dry a bulk of wheat (Figure 4.10a) was large compared with time to dry the top layer (Figure 4.2a). For the average-dry scenario the time to dry layer 5 to 15.5% moisture content was used rather than the time to average-dry the bottom 5 layers.

Fluctuating moisture contents in all layers resulted in a large variability in final drying times. Although the top layer of a bulk might have reached the dry level, periods of high ambient relative humidity caused rewetting of the bottom layers, increased time required to average-dry and reduced the number of simulations which dried before November 15. For wheat in a 3.65 m bed initially at 18% moisture content on August 15 or September 1, many of the weather years used for drying layers 1 to 5 did not affect the time required to average-dry when the remainder of the drying was completed with the poor drying weather of 1965 and 1977 (i.e. the two horizontal rows of '+' in Figure 4.10a). That is, the equilibrium moisture content for the most of the fall drying period for the years 1965 and 1977 was above 14.5% and the

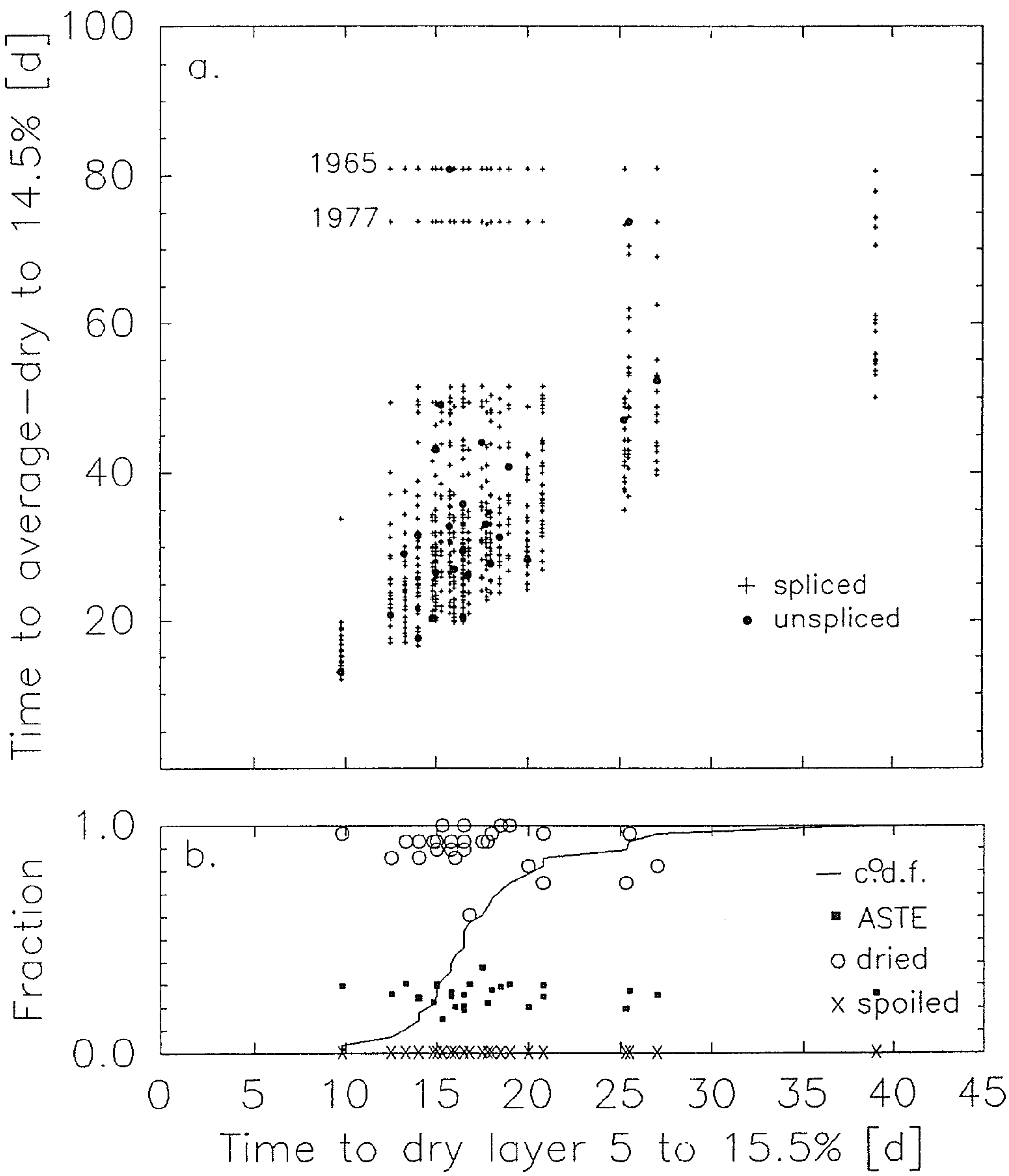

FIGURE 4.10 - Estimated time for the average moisture content of a bulk of wheat stored in Winnipeg on August 15 at 18% moisture content in a 3.65-m deep bed ventilated with 10 $(L/s)/m^3$ of near-ambient air to dry to 14.5% moisture content given the time the drying front reached layer 5. The calculated temperature rise of the ventilation air was 0.5^0C.

time to average-dry depended on the equilibrium moisture content to fall below 14.5% late in the fall. After the drying front had reached layer 5, the bottom layers were rewetted to greater than 14.5% moisture content and remained at that level for most of the fall drying period.

Variability in time to average-dry in scenarios with temperature rises greater than or equal to 3.7^{0}C were similar to top-layer drying scenarios (Figure 4.11 compared with Figure 4.12, both having a temperature rise of 3.7^{0}C). The increased temperature rise of the ventilation air tended to overdry the wheat and reduce the effect of rewetting. Moisture differentials between the top and bottom layers were as great as 9 moisture points for scenarios with temperature rises greater than 3.7^{0}C. The probability of completing drying by November 15 using the average-dry strategy was reduced for scenarios with a relatively low temperature rise of the ventilation air (less than 2^{0}C) because the lower layers were not as overdried as in scenarios with higher temperature rises.

Although moving the grain may provide moderate mixing, moisture content differentials are likely to remain even after bulks have been moved. Aeration can be used to reduce the risk of spoilage but only during fall and winter. No literature was found on the effectiveness of moving grain to another bin for the purpose of removing moisture content differentials.

Given the unpredictability of average-bin drying in a large number of the scenarios, average-bin drying is not an attractive

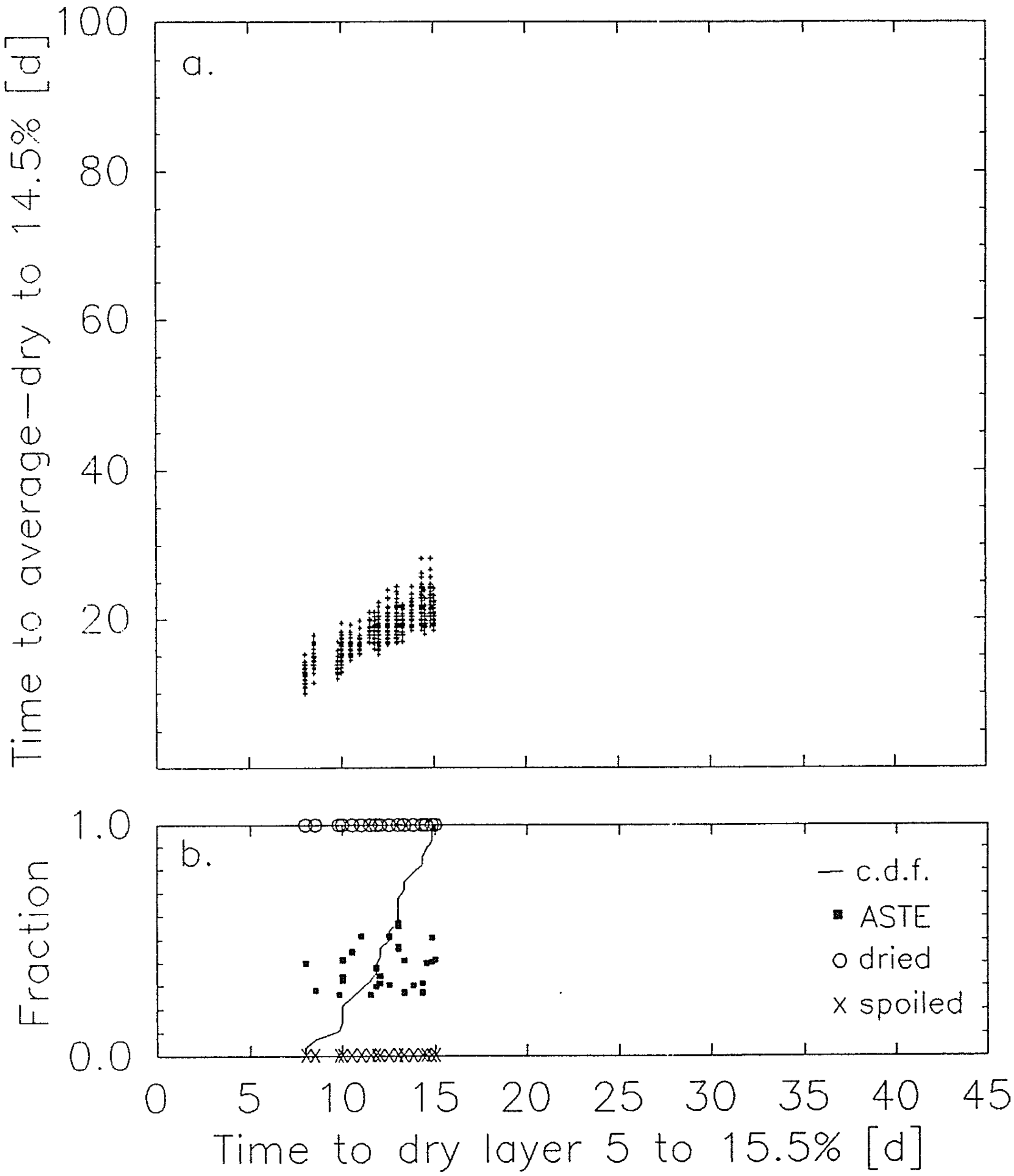

FIGURE 4.11 - Estimated time for the average moisture content of a bulk of wheat stored in Winnipeg on September 1 at 20% moisture content in a 7.30-m deep bed ventilated with 15 $(L/s)/m^3$ of near-ambient air to dry to 14.5% moisture content given the time the drying front reached layer 5. The calculated temperature rise of the ventilation air was 3.7°C.

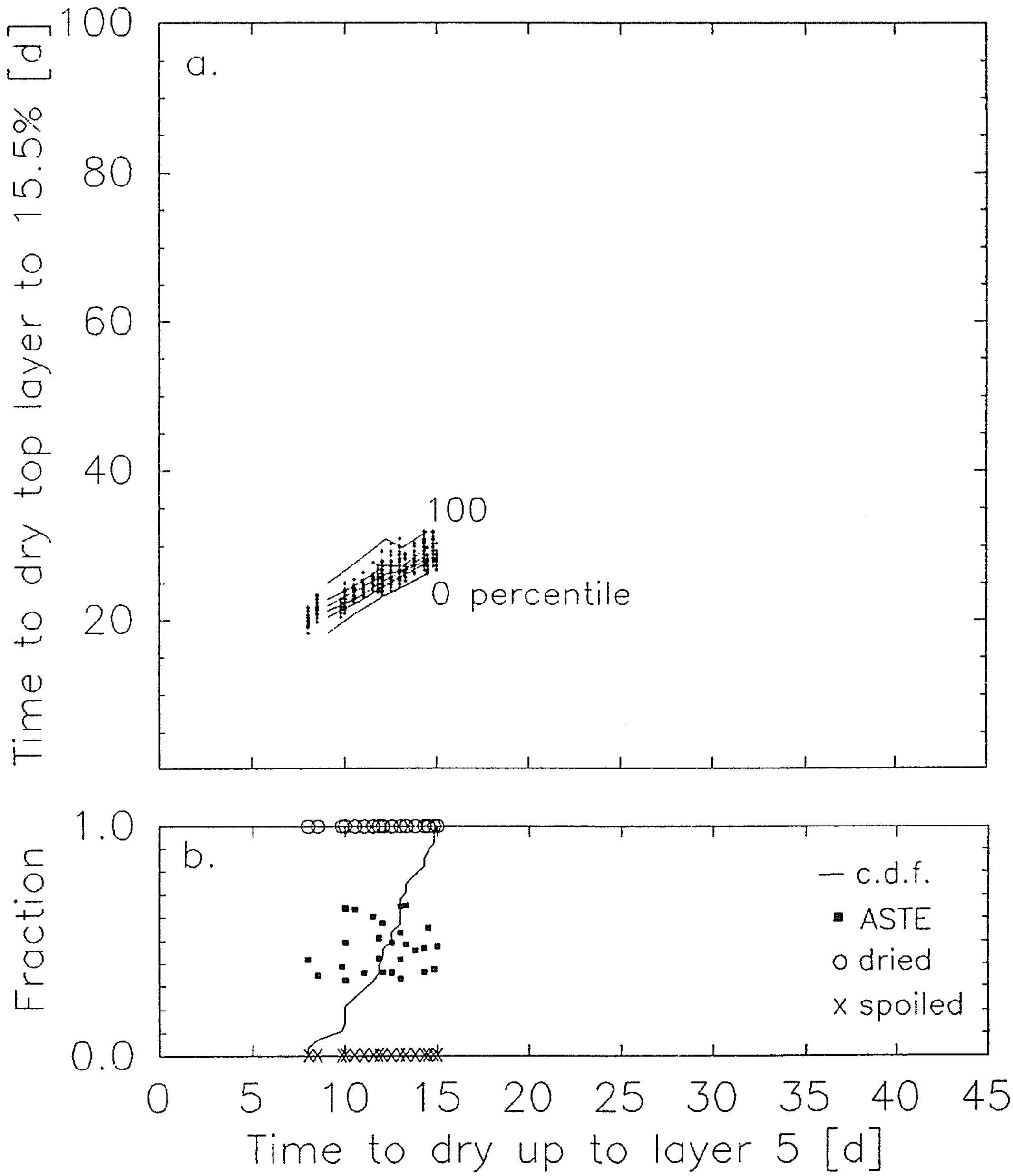

FIGURE 4.12 - Estimated time for the top of a bulk of wheat stored in Winnipeg on September 1 at 20% moisture content in a 7.30-m deep bed ventilated with 15 (L/s)/m^3 of near-ambient air to dry to 15.5% moisture content given the time the drying front reached layer 5. The calculated temperature rise of the ventilation air was 3.7^{0}C.

grain drying method. Samples must be taken from several depths and at relatively short time intervals (?days) if average bin drying is to be successful. The large number of samples required, coupled with the large time range in which samples would be required, make average-bin drying labour and management intensive.

5 Management guidelines for operating drying equipment

5.1 Monitoring the progress of the drying front

By using results presented in the previous section, the grain storage manager would have knowledge about possible future occurrences regarding a particular drying situation. An example will be given below which will show how the results might be used by a grain storage manager to aid in the operation of a drying system.

The way in which the results in the previous section were presented may not be well suited for everyday use by grain storage managers. The results might be presented to the grain storage manager in a simpler form (Table 5.1).

Suppose a grain storage manager has stored 18% moisture content wheat on August 15 in a 3.65 m bed. Also suppose the manager is removing grain samples from the bulk to monitor the progress of the drying front. On the day of storage, the guidelines would tell the manager that the best possible drying time would be 22 d while the worst would be 80 d (Figure 4.2a or column A3 in Table 5.1A). The manager would also know there was no risk of spoilage and the grain would dry by November 15 (Figure 4.2b or column A4 and A5).

The next step for the grain storage manager would be to determine the best time to take samples from the grain bulk. From the c.d.f. of time for the drying front to reach layer 3 (Figures 4.5b), the manager can see 90% of all cases require 5 to 15 d for the drying front to reach layer 3, with the other 10% of

TABLE 5.1 - Guidelines for estimating time when the drying front will pass through the top of a bulk wheat stored at 18% moisture content on August 15 in a 3.65-m deep bed in Winnipeg. The drying front is defined as having a 15.5% moisture content.

[If wheat has just been harvested, then recommended sampling is at 2.6, 2.2 and 1.8 m from the top surface 10 to 14 d after storage to determine the location of the drying front. Sampling in this time range ensures the drying front is at or below the midpoint of the bulk (1.8 m below the top surface), as seen by times in column B2.]

A) Drying front 2.6 m below the top surface

A1 Time for drying front to reach 2.6 m from top surface	A2 % of the time drying front detected at time in "A1"	A3 Estimated time after harvest for top-layer dried to 15.5%				A4 % of time dried by Nov. 15	A5 % of time spoiled before dried	A6 Performance rating
		Percentile 0	90	97	100			
14 to 32 d	10	33	—	—	80	100	0	6 poor
12 to 14	10	30	51	55	57	100	0	5
10 to 12	20	30	47	50	55	100	0	4
9 to 10	20	29	44	51	57	100	0	3 average
8 to 9	20	27	42	46	50	100	0	2
5 to 8	20	22	40	44	47	100	0	1 good

B) Drying front 1.8 m below the top surface

B1 Previous rating	B2 Time for drying front to reach 2.6 m from top surface	B3 % of the time drying front detected at time in "B2"	B4 Estimated time after harvest for top-layer dried to 15.5%				B5 % of time dried by Nov. 15	B6 % of time spoiled before dried	B7 Revised rating
			Percentile 0	90	97	100			
6	25 to 39 d	10	45	—	—	82	100	0	6 poor
≥ 5	20 to 25	10	36	55	60	82	100	0	5
≥ 4	18 to 20	20	32	46	48	53	100	0	4
≥ 3	16 to 18	20	30	41	44	47	100	0	3 ave.
≥ 2	14 to 16	20	27	38	42	45	100	0	2
≥ 1	10 to 14	20	22	37	40	43	100	0	1 good

all cases requiring up to 32 d. A range of 5 to 14 d for 90% of all cases can be determined from the tabular guidelines (columns A1 and A2). The time for the drying front to reach layer 5 for 90% of all cases would be 10 to 25 d after harvest (Figure 4.2b or columns B1 and B2). For 100% of all cases, the time for the drying front to reach layer 5 would be 10 to 39 d after harvest. The best time and locations for the manager to take grain samples to determine the location of the drying front would be 10 to 15 d after harvest in layers 3, 4 and 5. The drying front should be detected in layers 3, 4 or 5 at that time because the drying front would not have progressed past layer 5 after 10 to 14 d (column B2). If the drying front is not detected in layers 3, 4 or 5, then the drying performance is poor (90 to 100 percentile range for times in column A1).

Once the location of the drying front is known, the manager can gauge the drying performance thus far. Suppose the time required for the drying front to reach layer 3 was 12 days. The c.d.f. of time to reach layer 3 (Figure 4.5b) would indicate that the drying progress is slower than average because the c.d.f. would indicate 80% of all cases would have better times. The estimated time to dry the top layer would be 30 to 55 d after harvest. The tabular guidelines would rate drying performance as average-to-poor (column A6) and estimate the final drying time at 30 to 60 d after harvest.

The manager could use the performance information to set the next sampling date. If the drying performance is poorer than average, then the time the drying front would reach layer 5 would also be less than average because the drying time lost during poor drying periods could not be regained during good drying periods. Assuming the drying performance to be in the worst 20% of all cases, the graphical guidelines would indicate that the next sampling time might be 20 to 39 d after harvest (i.e. times corresponding to c.d.f. $\geq$ 0.8 in Figure 4.2b). Sampling 21 to 25 d after harvest might be more reasonable (i.e. 0.8 $\leq$ c.d.f. $\leq$ 0.9, or column B1). Knowledge of the time at which the drying front reached layer 5 would narrow the possible range of final drying times to within 10 d if the manager was to consider 90% of all cases (i.e. the 0 to 90 percentile lines in Figure 4.2a), or within 15 d if considering 97% of all cases. The tabular guidelines would estimate the time of final drying to be 35 to 85 d after harvest (column B4).

5.2 Presentation of operational guidelines

The above example illustrates how the operational guidelines might be presented in a graphical or tabular format. In either the graphical or tabular presentation, the interpretation of the information requires some skill. The interpretation of the results may be better carried out by an expert system. The number of possible drying system designs would likely warrant the use of a computer program because the number of figures or tables could become unmanageable.

5.3 Monitoring the moisture content of the top of the bulk

Suppose the grain storage manager described in the previous section decided not to monitor the progress of the drying front but instead sampled the grain near the top surface of the bulk. The operational guidelines would estimate the final drying time to be 20 to 80 d after harvest, which would be the same information obtained from GRAIN89. Using the same example scenario as above, the grain storage manager would determine the range of final drying times to be greater than 20 d. Monitoring the moisture content at the top of the bulk could begin after 20 d. The manager would also know there would be zero risk of spoilage, the ASTE would be low, and the bulk would dry by November 15.

Initially, it might seem that monitoring the top layer moisture content would be less labour intensive than monitoring the progress of the drying front. Monitoring the progress of the drying front in the example discussed in the previous section would require possibly 5 sampling dates, assuming 2 sample dates are for detecting the date on which the drying front reached layers 3 and 5, and 3 sampling dates in the range of estimated final drying times. Assuming the manager was going to monitor the top layer moisture content by taking samples every 5 days, a minimum of 4 samples would be required 20, 25, 30 and 35 d after harvest if the bulk was to dry by day 35, and a maximum of 13 samples if the final drying time was to be 80 d after harvest. The number of samples required for monitoring the progress of the drying front in the bulk would remain relatively low and stable, while the number of samples required if measuring only the top-layer moisture content could vary greatly.

6 Conclusions

The following conclusions can be made based on the results of this study in which continuous ventilation of wheat using recommended airflow rates for Winnipeg, Canada, were simulated:

(1) Provided that the simulated period of grain drying is more than ten days, drying simulations can be carried out using historical weather data from one weather year for an initial portion of the drying simulation and a second weather year for the remaining portion of the simulation. This technique of "splicing" historical weather data is valid for Winnipeg, Canada, because the weather of a particular day is a function of no more than the weather of the two previous days.

(2) Provided that recommended airflow rates are used, variability in the time for the drying front to reach a particular imaginary layer is sensitive to airflow rates recommended for particular moisture contents, bed depths, and harvest dates. Increasing the airflow rate for increased bed depth, moisture content, or delaying harvest to September 15 reduces the variability in estimating the final drying time. Although the grain storage manager has no control over the harvest date and harvest moisture content, bed depth can be used to reduce the amount of variability in estimating the final drying time but at the cost of increased fan size and energy consumption.

(3) By monitoring the time at which the drying front reaches the midpoint of the bulk, an accurate estimate of the final drying time can be made. Operational guidelines have been developed which can be used to estimate within 10 d or less the time at which the drying front would reach the top of a bulk of wheat.

(4) For most near-ambient drying scenarios, the time for the bulk to reach an average moisture content of 14.5% cannot be accurately estimated. An accurate estimate of when the bulk is average-dried can be made when the temperature increase of the ventilation air is a significantly increased. The larger temperature rise rewetting in the bottom layers of grain during periods of high ambient relative humidity.

(5) Stochastic analysis has shown there is a maximum rate of drying for each drying scenario and that when losses in drying time occur during periods of "poor" drying, the time lost cannot be recovered when periods of "good" drying follow periods of "poor" drying.

(6) The variability in the time to dry the top layer was sensitive to the drying performance in the bottom portion of the bulk. It is suggested that the use of a "typical" or "average" weather year in simulation studies of grain drying systems be discouraged because weather conditions are variable from year-to-year. Therefore, simulated behaviour of grain drying systems

may be better studied using stochastic analysis.

(7) Near-ambient grain drying systems may be poorly designed because current recommendations for airflow rates are based on a constant temperature rise. Temperature rise of the ventilation air increased with airflow rates recommended for increasing bed depth and moisture content, which increased the moisture carrying capacity of the ventilation air.

Future work is needed to evaluate a wider range of grain drying scenarios, particularly non-design scenarios. Operational guidelines using temperature rises of ventilation air from actual fan tests should be developed. Also, design practices should be revised to include actual temperature rises. This study considered temperature rises calculated with a "generic" temperature rise model but were not compatible with the recommended airflow rates of Huminicki and Friesen (1987). The software developed for this study can be used by future researchers to develop these guidelines.

The value of the guidelines to grain storage managers should be investigated. It would be worthwhile knowing current drying practices so guidelines could be provided for those practices. Also, managers should be consulted as to whether the guidelines should be available in tabular or graphical form, and whether in a handbook or a computer program.

References

Anon., 1987. ASAE Standards, R.H. Hahn and E.E. Rosentreter (eds.). Moisture relationships of grains. ASAE Data: ASAE D245.4, p.301-305, St. Joseph, MI.

Bloome, P.D., and G.C. Shove, 1971. Near equilibrium simulation of shelled corn drying. Trans. ASAE (Am. Soc. Agric. Eng.) 14:709-712.

Bowden, P.J., W.J. Lamond and E.A. Smith, 1983. Simulation of near-ambient grain drying. I. Comparison of simulations with experimental results. J. Agric. Eng. Res. 28:279-300.

Box, G.E.P., and G.M. Jenkins, 1976. Time series analysis: forcasting and control. San Francisco: Holden-Day Inc.

Brook, R.C., 1987. A look at control of in-bin grain drying equipment. Paper 87-6037. Am. Soc. Agric. Eng., St. Joseph, MI.

Converse, H.H., A.H. Graves and D.S. Chung, 1969. Transient heat transfer witin wheat stored in a cylindrical bin. Paper 69-855. Am. Soc. Agric. Eng., St. Joseph, Mi.

Darby, J.A., 1992. Personal communication. Ricegrowers' Association Ltd., Yanco Ave., Leeton, Australia, 2705.

Fraser, B.M., and W.E. Muir, 1980a. Energy consumptions predicted for drying grain with ambient and solar-heated air in Canada. J. Agric. Eng. Res. 25:325-331.

Fraser, B.M., and W.E. Muir, 1980b. Cost predictions for drying grain with ambient and solar-heated air in Canada. Can. Agric. Eng. 22:55-59.

Fraser, B.M., and W.E. Muir, 1981. Airflow requirements predicted for drying grain with ambient and solar-heated air in Canada. Trans. ASAE (Am. Soc. Agric. Eng.) 24:208-210.

Friesen, O.H., and D.N. Huminicki, 1987. Grain aeration and unheated air drying. Agdex 732-1. Manitoba Department of Agriculture, Winnipeg, MB.

Gabriel, K.R., and J. Neumann, 1962. A Markov chain model for daily rainfall occurrence at Tel Aviv. Quart. J. Royal Met. Soc. 88:90-95.

Henderson, S.M., and S. Pabis, 1961. Grain drying theory. Part I. Temperature effect on drying coefficient. J. Agric. Eng. Res. 6:169-174.

Huminicki, D.N., C.I. Kitson, O.H. Friesen and W.E. Muir, 1986. Computerized design of ventilated systems for stored grain. Paper NCR-86-604. Am. Soc. Agric. Engrs., St. Joseph, MI.

Ingram, 1976. Deep bed drier simulation with intra-particle moisture diffusion. J. Agric. Eng. Res. 21:263-272.

Kitson, C.I., W.E. Muir and R.N. Sinha, 1991. Probability curves from simulated drying of wheat with near-ambient air in Manitoba. Can. Agric. Eng. 33:67-71.

Loewer, O.J., T.C. Bridges, D.G. Colliver and G.M. White, 1984. Economics of stirring devices in grain drying. Trans. ASAE (Am. Soc. Agric. Eng.) 27:603-608.

Manitoba Agriculture, n.d.(1989?) Direct-cut grain harvesting and drying. Manitoba Department of Agriculture MG-788.

Matalas, N.C., 1967. Mathematical assessment of synthetic hydrology. Water Resources Res. 3:937-945.

Metzger, J.F., and W.E. Muir, 1983. Aeration of stored wheat in the Canadian Praries. Can. Agric. Eng. 25:127-137.

Mills, J.T., 1990. Protection of farm-stored grain and oilseeds form insects, mites and molds. Agriculture Canada publication 1851/E, Ottawa, ON.

Morey, R.V., H.A. Cloud, R.J. Gustafson and D.W. Petersen, 1979. Evaluation of the feasibility of solar energy grain drying. Trans. ASAE (Am. Soc. Agric. Eng.) 22:409-417.

Morey, R.V., H.A. Cloud and H.J. Hansen, 1981. Ambient air wheat drying. Trans. ASAE (Am. Soc. Agric. Eng.) 24:1312-1316.

Muir, W.E., 1970. Temperatures in grain bins. Can. Agric. Eng. 12:21-24.

Muir, W.E., 1973. Temperature and moisture in grain storages. In: Grain storage: part of a system. R.N. Sinha and W.E. Muir (eds.). AVI Publishing, Westport, CT.

Muir, W.E., D. Waterer and R.N. Sinha, 1985. Carbon dioxide as an early indicator of stored cereal and oilseed spoilage. Trans. ASAE (Am. Soc. Agric. Eng.) 28:1673-1675.

Muir, W.E., 1992. Personal communication. University of Manitoba, Department of Agricultural Engineering, Winnipeg, Manitoba, R3T 2N2.

Parry, J.L., 1985. Mathematical modelling and computer simulation of heat and mass transfer in agricultural grain drying: a review. J. Agric. Eng. Res. 32:1-29.

Prasad, D.C., W.E. Muir and H.A.H. Wallace, 1978. Characteristics of freshly-harvested wheat and rapeseed. Trans. ASAE (Am. Soc. Agric. Eng.) 21:782-784.

Reed, C., 1992. Grain cooling, moisture translocation, and theories of convection currents. Extended Abstracts, International Symposium on Stored Grain Ecosystems, June 7-10, 1992, Winnipeg, Manitoba. D.S. Jayas, N.D.G. White, W.E. Muir, and R.N. Sinha (eds.), Department of Agricultural Engineering, Winnipeg, Manitoba, R3T 2N2.

Richardson, C.W., 1981. Stochastic simulation of daily precipitation, temperature, and solar radiation. Water Resources Res. 17:182-190.

Richardson, C.W., 1982. Dependence structure of daily temperature and solar radiation. Trans. ASAE (Am. Soc. Agric. Eng.) 25:735-739.

Ryniecki, A., and M.E. Nellist, 1989. An optimum strategy for near-ambient grain drying. Divisional Note DN 1493, AFRC Institute of Engineering Research, Silsoe, England.

Ryniecki, A., and M.E. Nellist, 1991a. Optimization of control systems for near-ambient grain drying: part 1, the optimization procedure. J. Agric. Eng. Res. 48:1-17.

Ryniecki, A., and M.E. Nellist, 1991b. Optimization of control systems for near-ambient grain drying: part 2, the optimizing simulations. J. Agric. Eng. Res. 48:1-17.

Ryniecki, A., D.S. Jayas and W.E. Muir, 1992. Generalized control-strategy for near-ambient drying of wheat under Canadian-prairie climate. Unpublished report, Department of Agricultural Engineering, University of Manitoba, Winnipeg, MB.

Sanderson, D.B., W.E. Muir and R.N. Sinha, 1988. Intergranular air temperatures of ventilated bulks of wheat. J. Agric. Eng. Res. 40:33-43.

Sanderson, D.B., W.E. Muir, R.N. Sinha, D. Tuma and C.I. Kitson, 1989. Evaluation of a model of drying and deterioration of stored wheat at near-ambient conditions. J. Agric. Eng. Res. 42:219-233.

Sinha, R.N, 1973. Interrelations of physical, chemical, and biological variables in the deterioration of stored products. In: Grain storage: part of a system. R.N. Sinha and W.E. Muir (eds.). AVI Publishing, Westport, CT.

Sinha, R.N., W.E. Muir and D.B. Sanderson, 1985. Quality assessment of stored wheat during drying with near-ambient temperature air. Can. J. Plant Sci. 65:849-866.

Smith, E.A., 1984. Maximum safe depth for barley in near-ambient temperature grain dryers. Agric. Eng. 39:3-9.

Sokhansanj, S., W-G. Lang and D.E. Lischynski, 1991. Low temperature drying of wheat with supplemental heat. Can. Agric. Eng. 33:265-271.

Sokhansanj, S., and D.E. Lischynski, 1991. Combination drying of wheat. Can. Agric. Eng. 33:273-277.

Stern, R.D., and R. Coe, 1984. A model fitting analysis of daily rainfall data. J. Royal Stat. Soc. A, 147:1-34.

Thompson, T.L., 1972. Temporary storage of High-moisture shelled corn using continuous aeration. Trans. ASAE (Am. Soc. Agric. Eng.) 15:333-337.

Van Wylen, G.J., and R.E. Sonntag, 1978. Fundamentals of Classical Thermodynamics. John Wiley and Sons, Toronto, ON.

Wallace, H.A.H., 1973. Fungi and other organisms associated with stored grain. In: Grain storage: part of a system. R.N. Sinha and W.E. Muir (eds.). AVI Publishing, Westport, CT.

Wallace, H.A.H., P.L. Sholberg, R.N. Sinha and W.E. Muir, 1983. Biological, physical and chemical changes in stored wheat. Mycopathologia 82:65-76.

Wallis, W.A., and H.V. Roberts, 1966. Statistics: A new approach, Collier-Macmillan, London, UK.

White, N.D.G., R.N. Sinha, and W.E. Muir, 1982. Intergranular carbon dioxide as an indicator of biological activity associated with the spoilage of stored wheat. Can. Agric. Eng. 24:35-42.

Ziauddin, A.M., and T. Liang, 1986. A weather risk model for grain drying system design and management in a developing region. Trans. ASAE (Am. Soc. Agric. Eng.) 29(5):1434-1440.

APPENDIX A.1 Calculation of temperature rise of inlet ventilation air as it passes over the fan and motor.

This section outlines the steps taken in Metzger and Muir's (1983) near-equilibrium grain drying model to calculate the temperature rise of the ventilation air as it passes over the fan and motor.

Assuming the following is given for a cylindrical grain storage bin:

AFR	airflow rate [(L/s)/m^3],
V	volume of the grain mass [m^3],
eff	fan and motor efficiency [],
P_{amb}	ambient air pressure [Pa],
T_{amb}	ambient dry bulb temperature [K],
d	depth of the grain bed [m],
A	area of the bin floor [m^2]

then the total airflow

$$AF = AFR * V \qquad [L/s]$$

and the air velocity

$$F = AF / A . \qquad [(L/s)/m^2]$$

can be calculated.

From the air velocity, F, the pressure drop per unit depth can be calculated using the equation

$$dP_d = 2.6*(F^{1.17}) \qquad [Pa/m]$$

which is based on published data (Anon., 1987) describing the resistance of airflow per unit depth for wheat at 11% moisture content. The equation is valid for relatively dry wheat (11% w.b.). For higher moisture content wheat (greater than 85% equilibrium relative humidity) only 80% of the indicated pressure drop should be used. This is not included in the temperature rise model.

The pressure drop for the bed can be calculated by

$$P = dP_d * d \qquad [Pa]$$

which can be used to calculate the fan power required to overcome the static pressure

$$W' = P\ v'/eff \qquad [N*m/s]$$

where v' is total fan airflow [m^3/s]. The total airflow can be calculated from the airflow rate, AFR, and the volume of the grain mass, V.

The change in ambient air temperature due to change in pressure can be calculated from fundamental thermodynamic principles and the loss of energy from the fan and motor. Assuming the air to be an ideal gas undergoing an isentropic, adiabatic process (Van Wylen and Sonntag, 1978), then the change in temperature is defined as

$$(P_1/P_{amb})^{k-1/k} = T_1/T_{amb}$$

where k=1.4, which is the specific heat ratio for air. The contribution in temperature rise from the fan and motor can be calculated from

$$T_{equip} = W'(1-eff) \,/\, (density * c_{p,air} * V') \qquad [K]$$

where the density for air is 1.2 [kg/m^3], and specific heat for air is $1.004*10^{-3}$ [J/(kg*K)].

APPENDIX A.2 Summary of Results

This section contains results from scenarios simulated for this study which are not included in Section 4. Not included are the results for drying where the transition in weather took place at layer 3 and 4. That is, only results in which initial drying was up to layer 5 are included in this section.

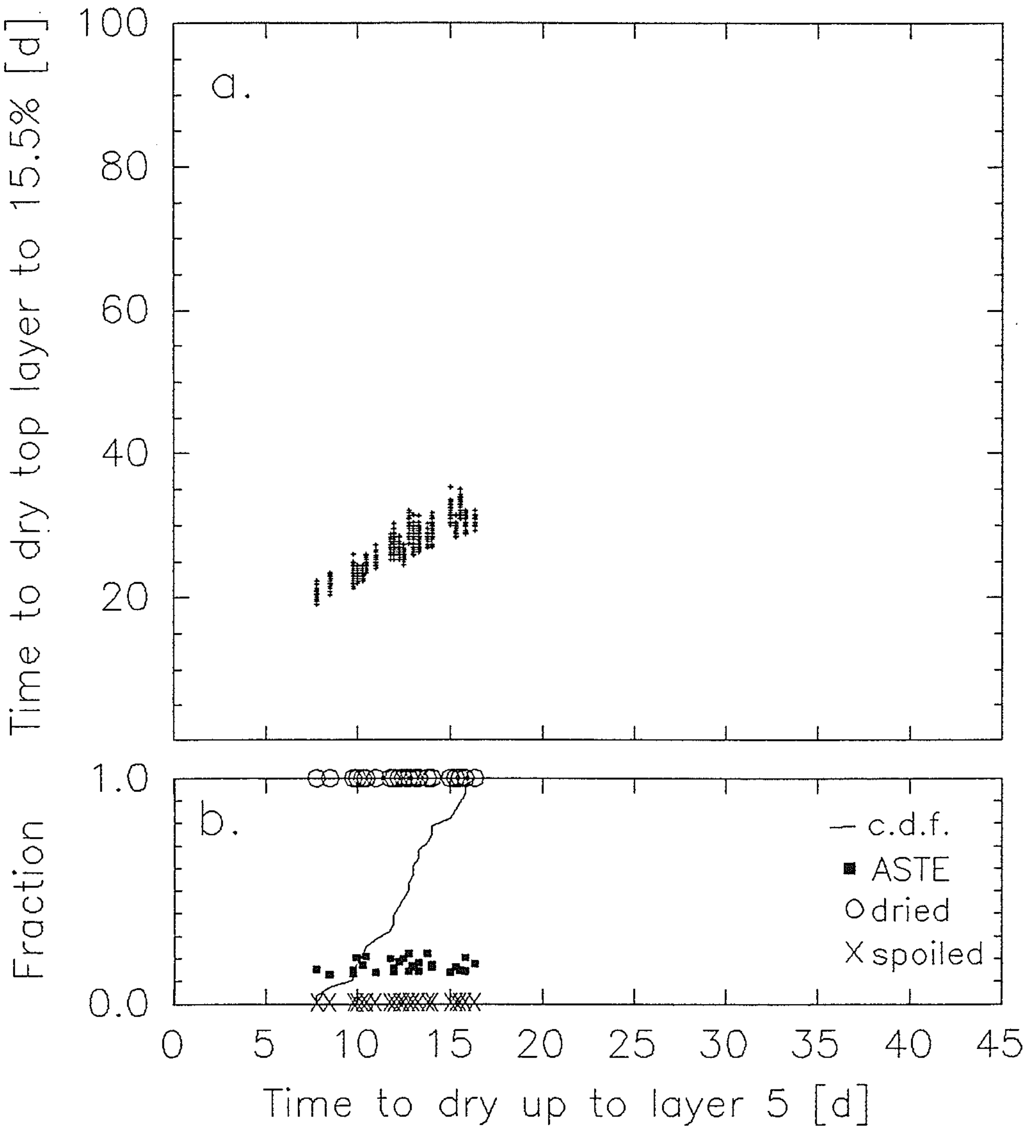

FIGURE A2.1 - Estimated time for the top of a bulk of wheat stored in Winnipeg on September 1 at 18% moisture content in a 7.30-m deep bed ventilated with 12 $(L/s)/m^3$ of near-ambient air to dry to 15.5% moisture content given the time the drying front reached layer 5. The calculated temperature rise of the ventilation air was 2.9^0C.

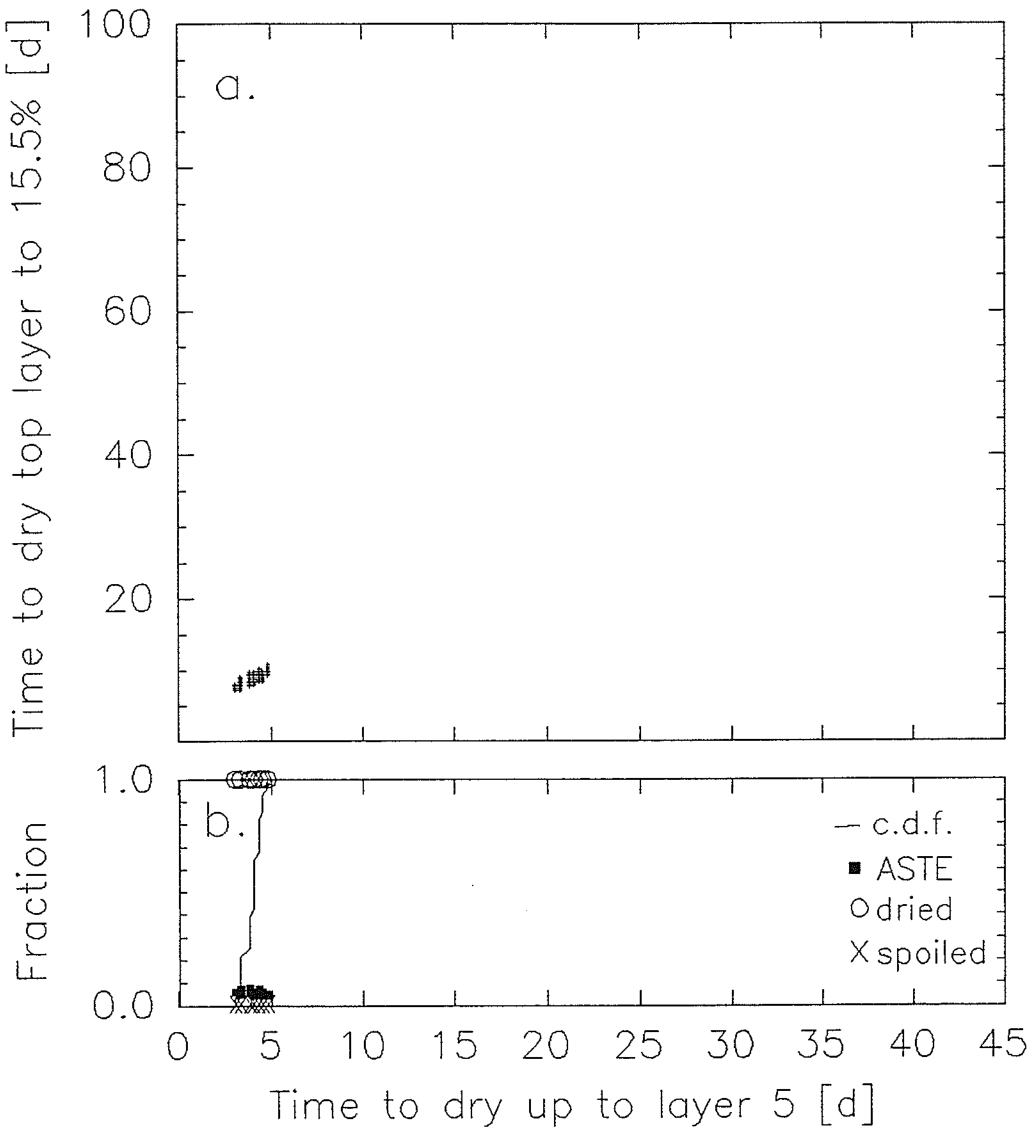

FIGURE A2.2 - Estimated time for the top of a bulk of wheat stored in Winnipeg on September 15 at 18% moisture content in a 7.30-m deep bed ventilated with 28 $(L/s)/m^3$ of near-ambient air to dry to 15.5% moisture content given the time the drying front reached layer 5. The calculated temperature rise of the ventilation air was 7.5^{0}C.

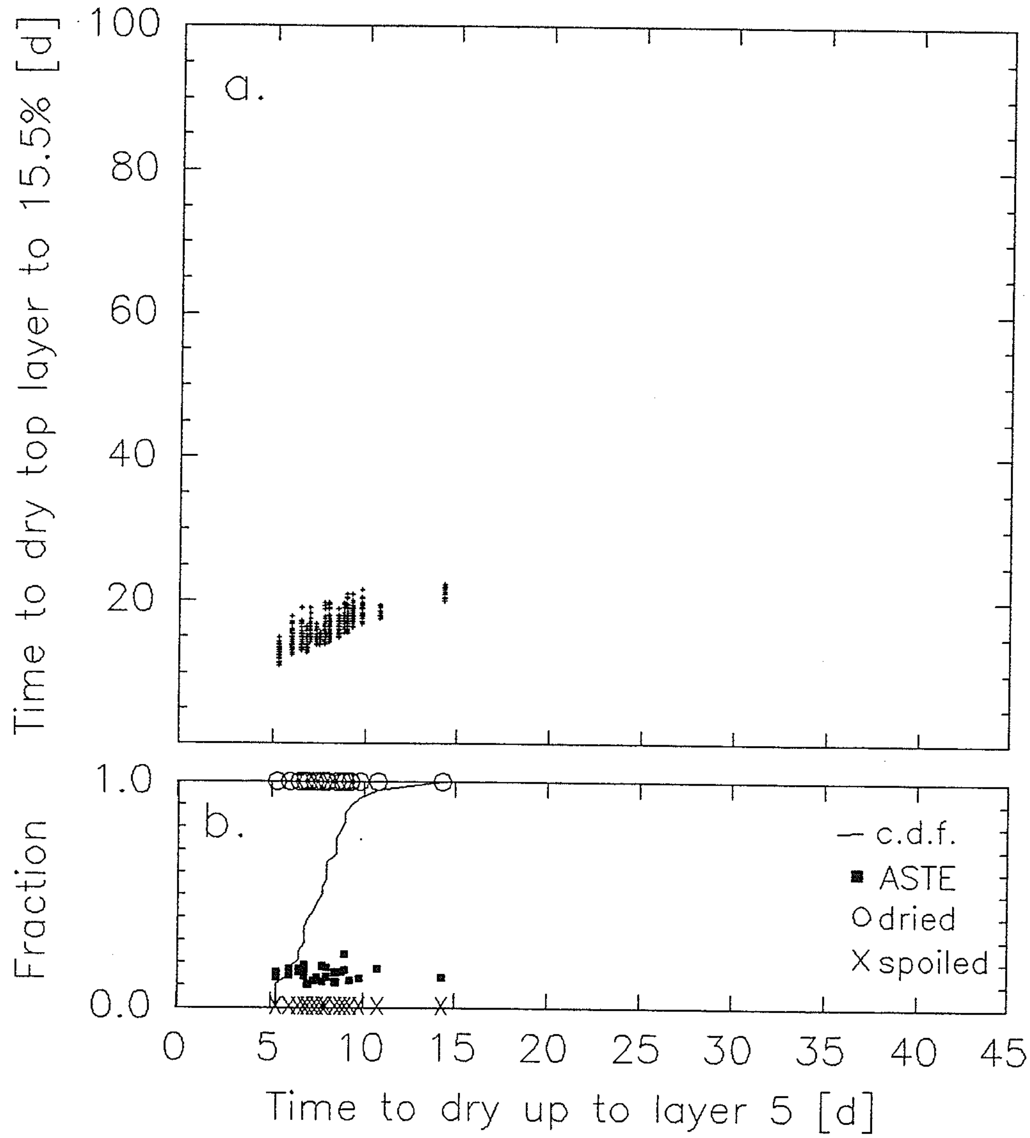

FIGURE A2.4 - Estimated time for the top of a bulk of wheat stored in Winnipeg on September 1 at 18% moisture content in a 7.30-m deep bed ventilated with 12 $(L/s)/m^3$ of near-ambient air to dry to 15.5% moisture content given the time the drying front reached layer 5. The calculated temperature rise of the ventilation air was 2.9^0C.

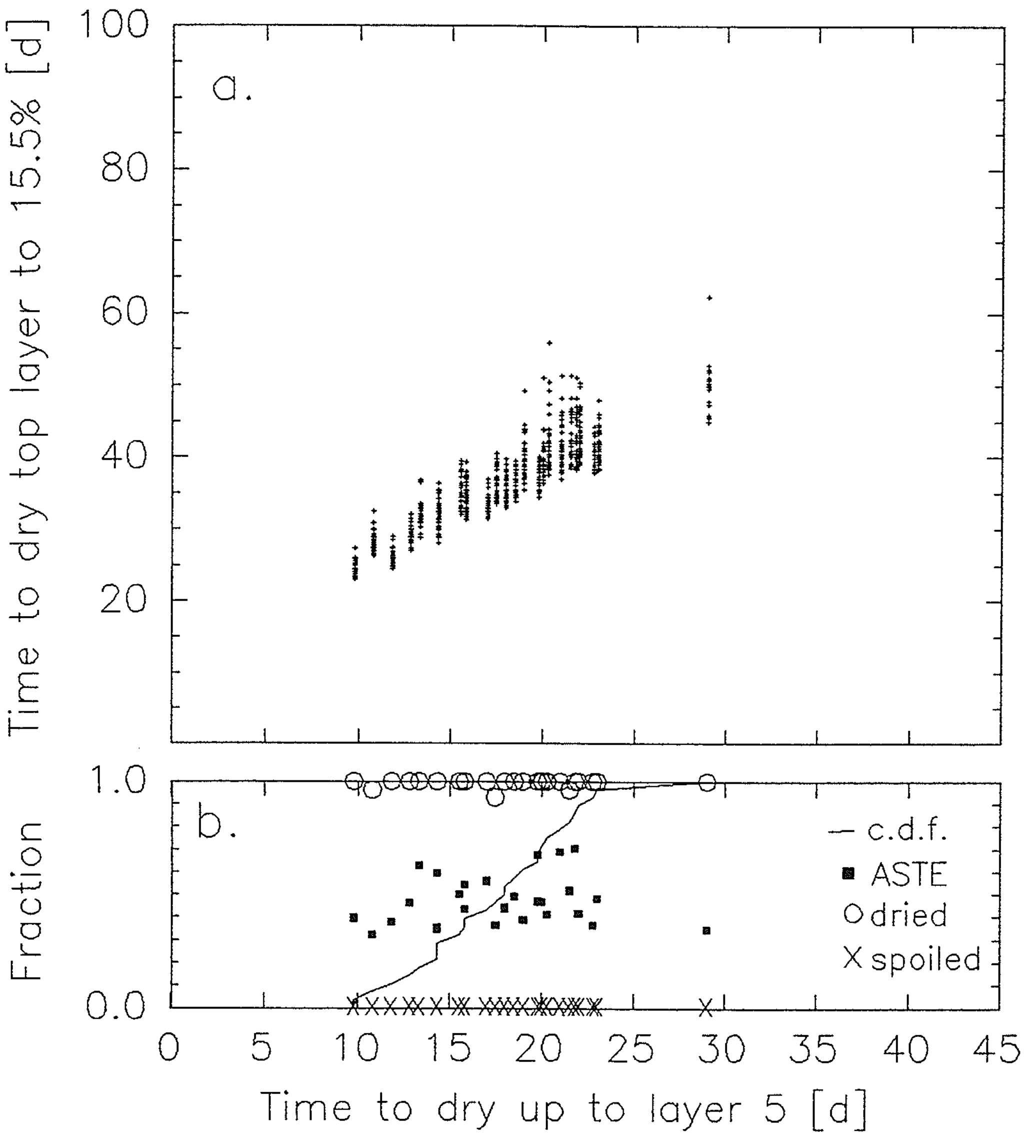

FIGURE A2.3 - Estimated time for the top of a bulk of wheat stored in Winnipeg on September 1 at 20% moisture content in a 3.65-m deep bed ventilated with 15 $(L/s)/m^3$ of near-ambient air to dry to 15.5% moisture content given the time the drying front reached layer 5. The calculated temperature rise of the ventilation air was 0.8^0C.

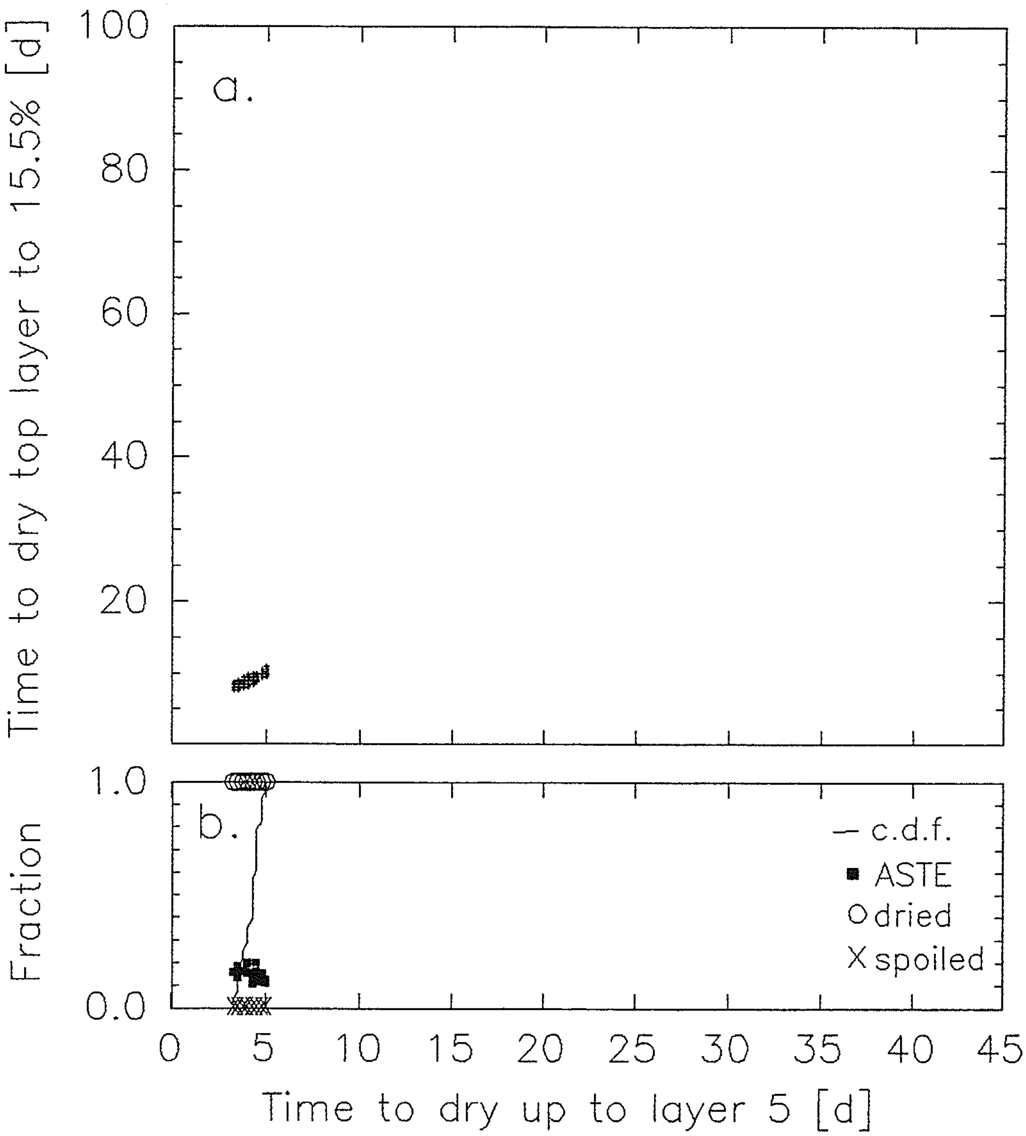

FIGURE A2.5 - Estimated time for the top of a bulk of wheat stored in Winnipeg on September 15 at 20% moisture content in a 7.30-m deep bed ventilated with 32 (L/s)/m^3 of near-ambient air to dry to 15.5% moisture content given the time the drying front reached layer 5. The calculated temperature rise of the ventilation air was 8.8^{0}C.

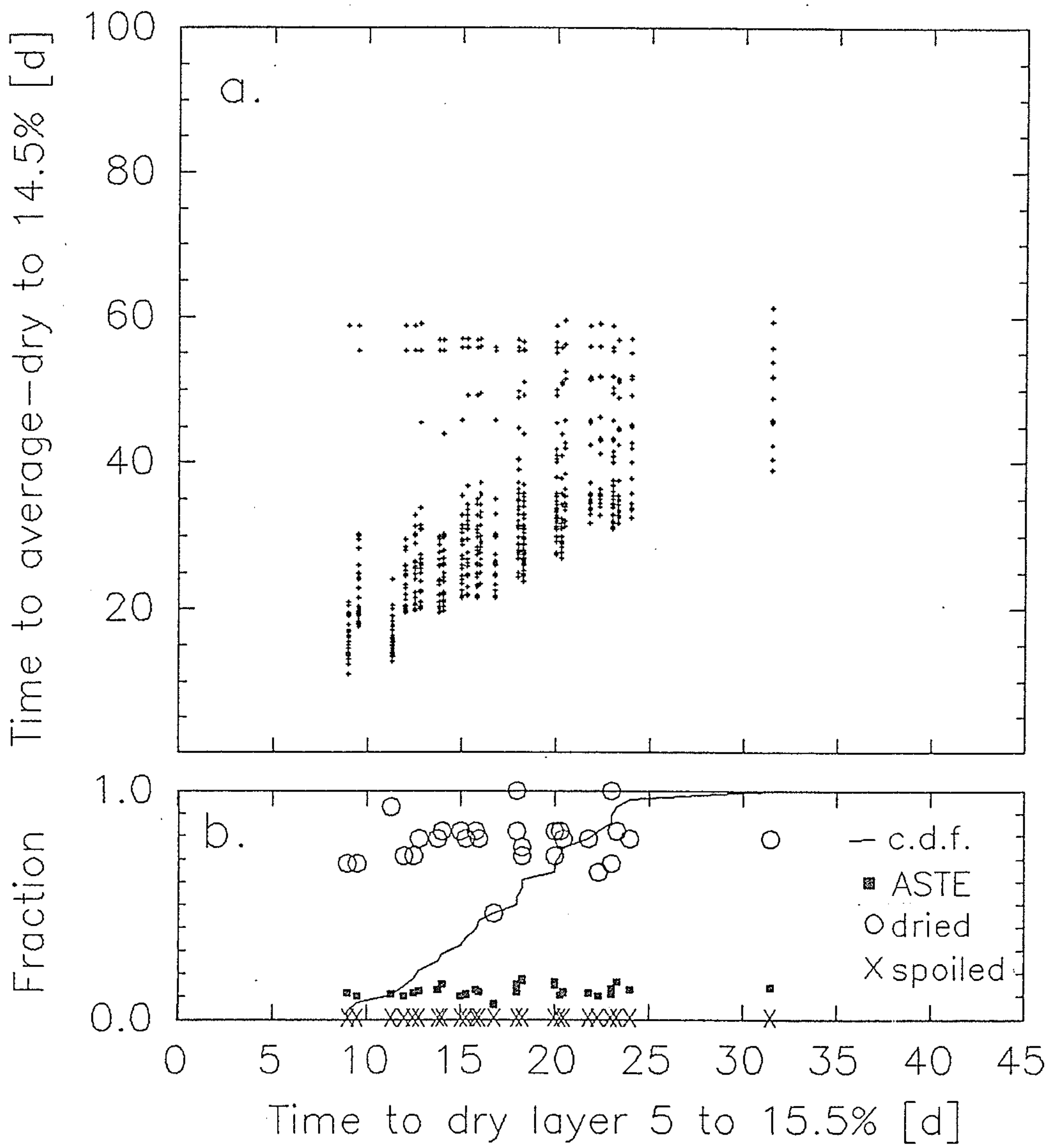

FIGURE A2.6 - Estimated time for the average moisture content of a bulk of wheat stored in Winnipeg on September 1 at 18% moisture content in a 3.65-m deep bed ventilated with 12 $(L/s)/m^3$ of near-ambient air to dry to 14.5% moisture content given the time the drying front reached layer 5. The calculated temperature rise of the ventilation air was 0.6^0C.

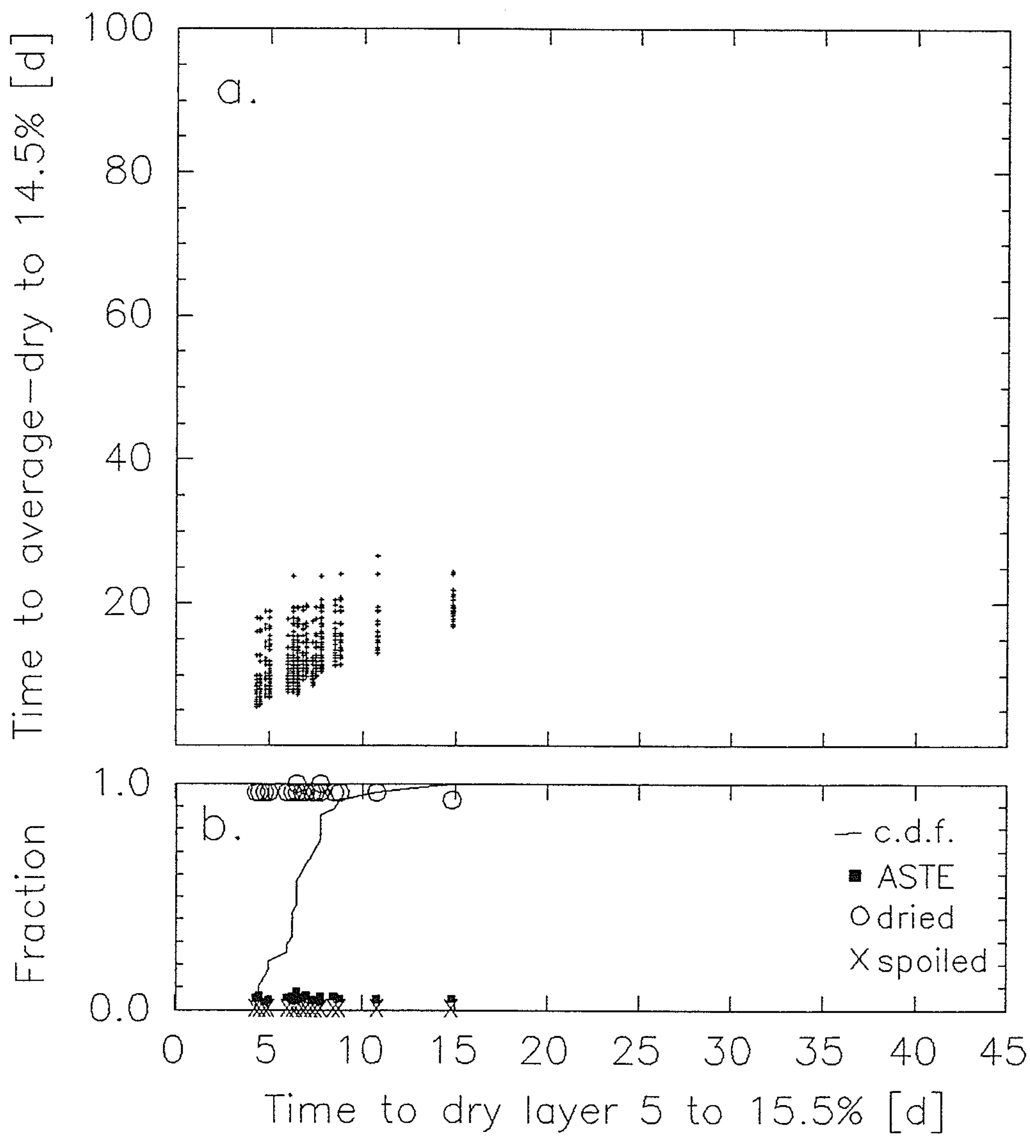

FIGURE A2.7 - Estimated time for the average moisture content of a bulk of wheat stored in Winnipeg on September 15 at 18% moisture content in a 3.65-m deep bed ventilated with 28 $(L/s)/m^3$ of near-ambient air to dry to 14.5% moisture content given the time the drying front reached layer 5. The calculated temperature rise of the ventilation air was 1.7^0C.

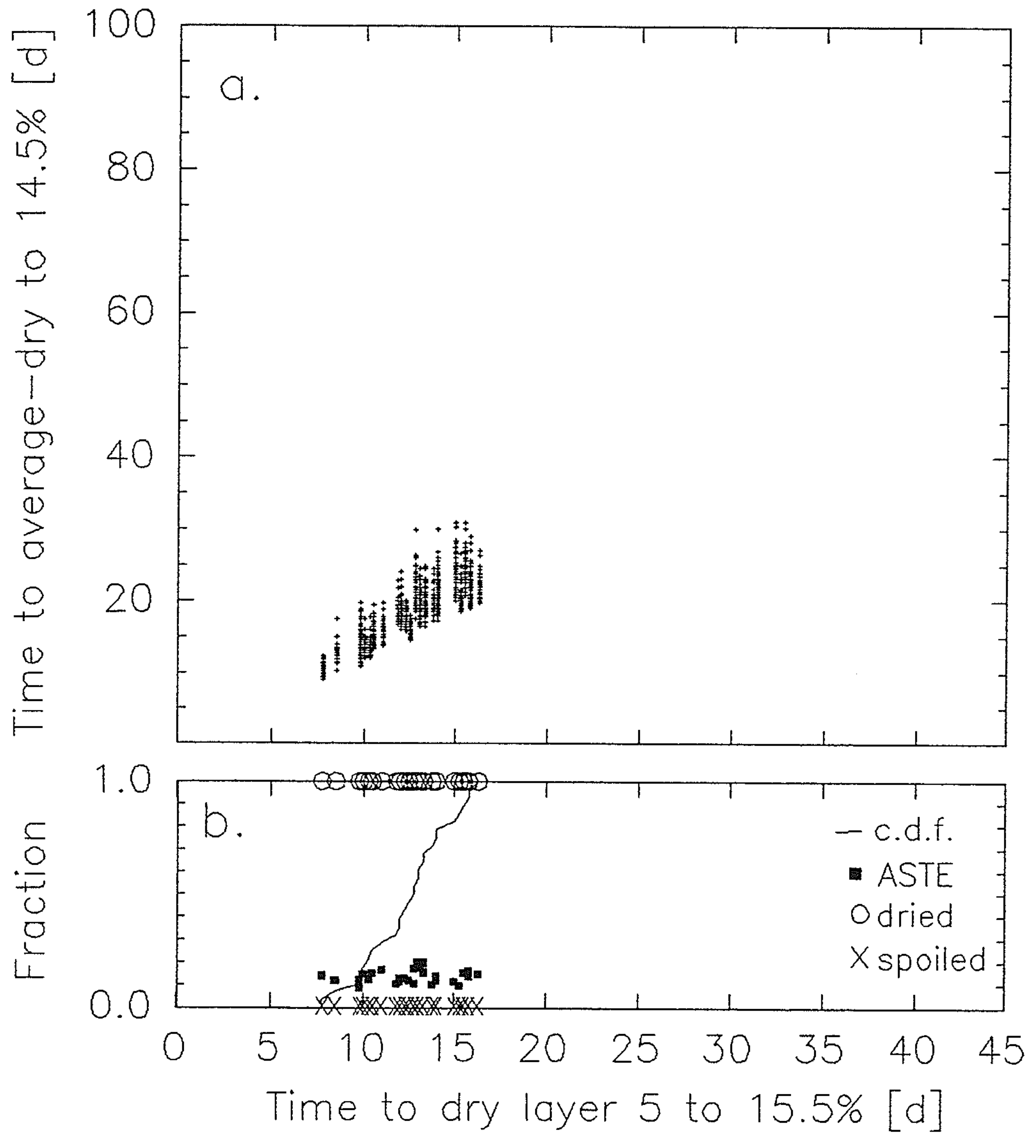

FIGURE A2.8 - Estimated time for the average moisture content of a bulk of wheat stored in Winnipeg on September 1 at 18% moisture content in a 7.30-m deep bed ventilated with 12 $(L/s)/m^3$ of near-ambient air to dry to 14.5% moisture content given the time the drying front reached layer 5. The calculated temperature rise of the ventilation air was 2.9^0C.

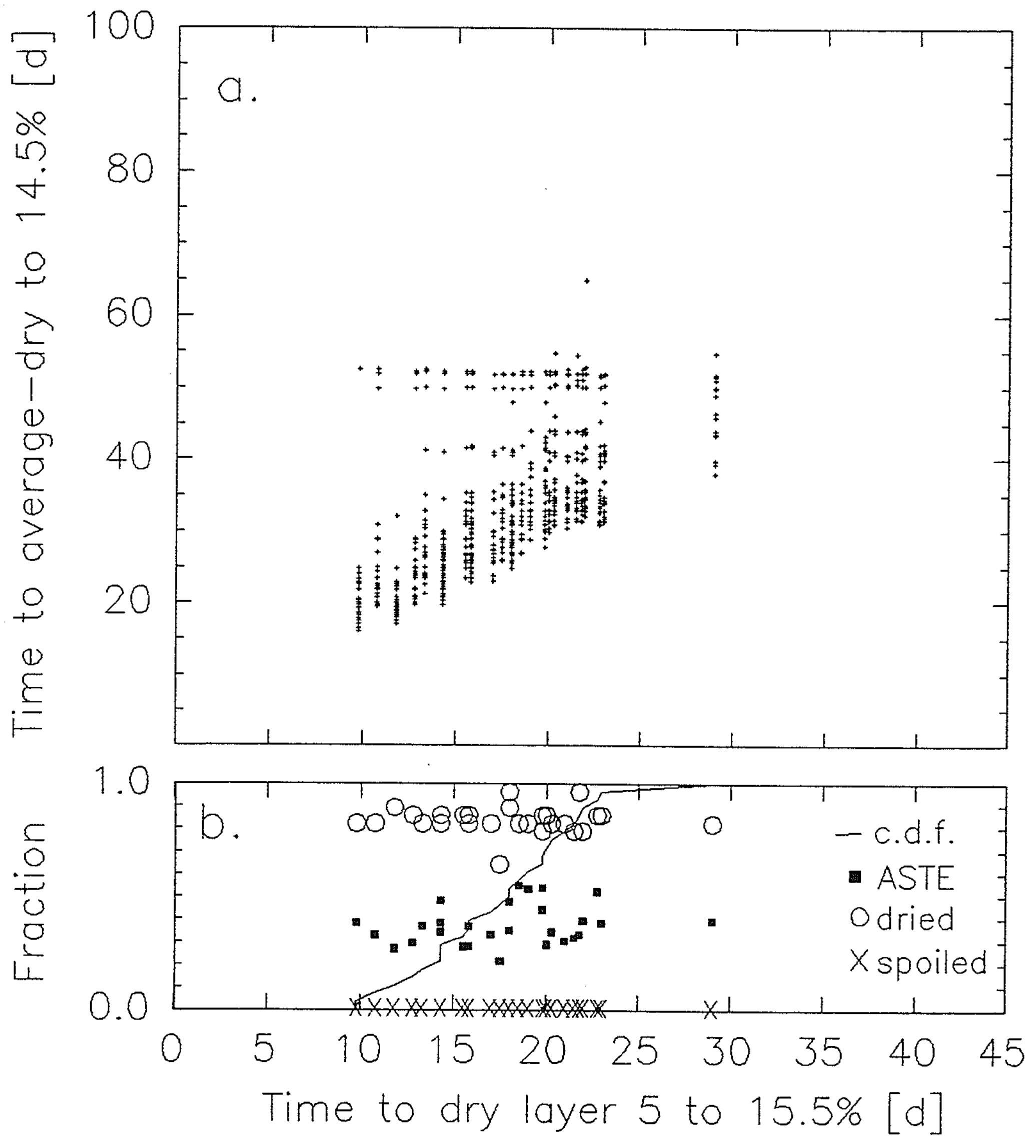

FIGURE A2.9 - Estimated time for the average moisture content of a bulk of wheat stored in Winnipeg on September 1 at 20% moisture content in a 3.65-m deep bed ventilated with 15 $(L/s)/m^3$ of near-ambient air to dry to 14.5% moisture content given the time the drying front reached layer 5. The calculated temperature rise of the ventilation air was 0.8^0C.

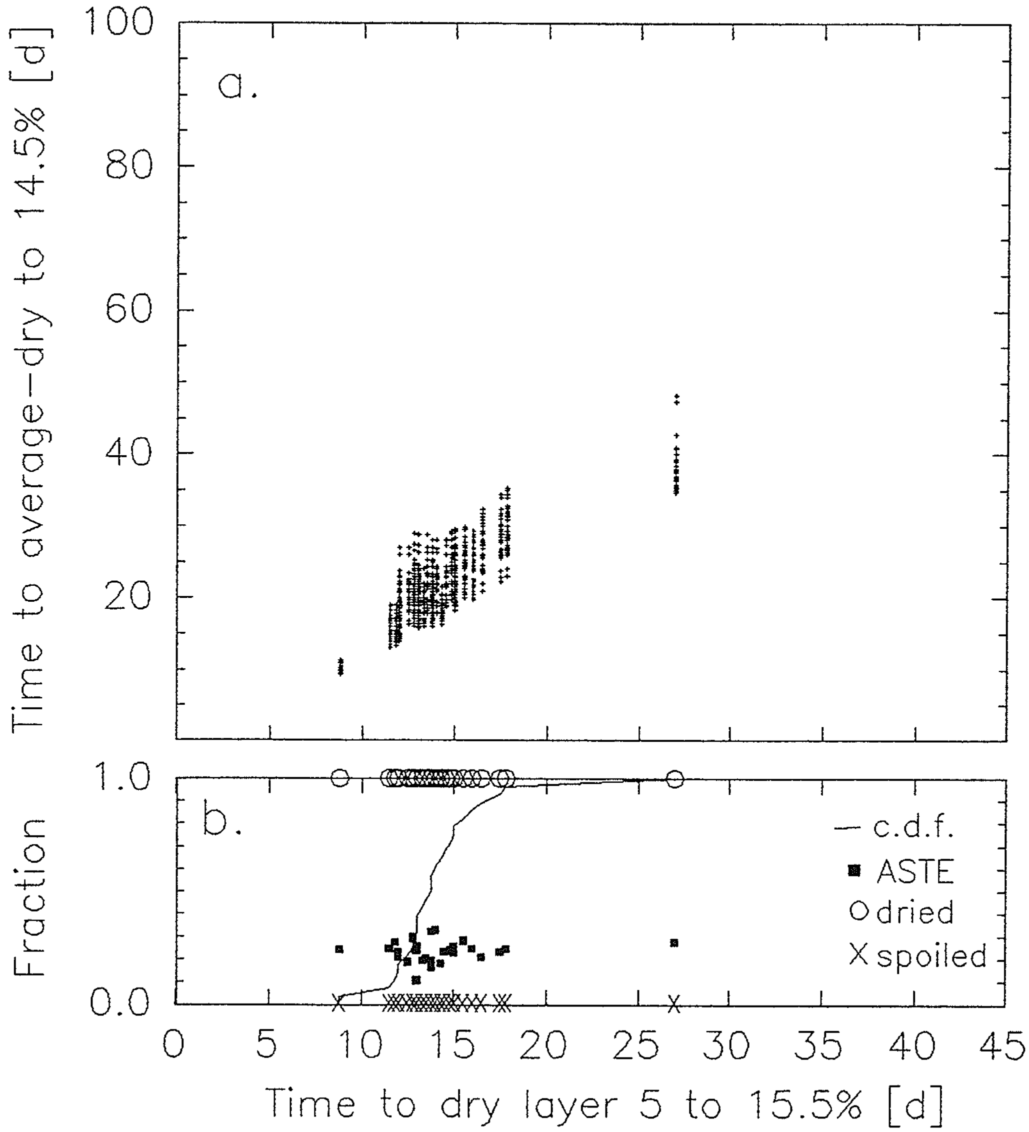

FIGURE A2.10 - Estimated time for the average moisture content of a bulk of wheat stored in Winnipeg on August 15 at 18% moisture content in a 7.30-m deep bed ventilated with 10 (L/s)/m^3 of near-ambient air to dry to 14.5% moisture content given the time the drying front reached layer 5. The calculated temperature rise of the ventilation air was 2.3^{0}C.

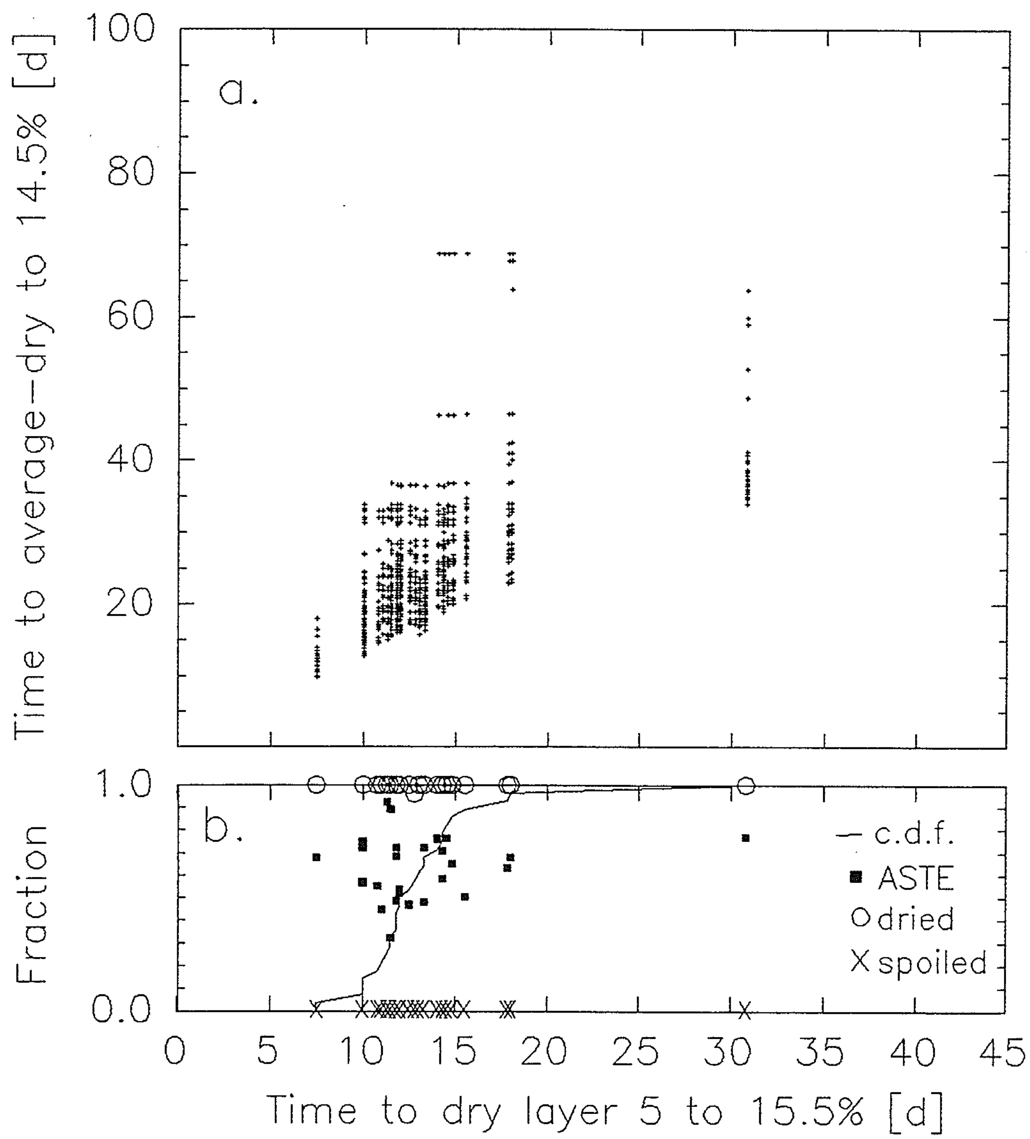

FIGURE A2.11 - Estimated time for the average moisture content of a bulk of wheat stored in Winnipeg on August 15 at 20% moisture content in a 3.65-m deep bed ventilated with 20 (L/s)/m^3 of near-ambient air to dry to 14.5% moisture content given the time the drying front reached layer 5. The calculated temperature rise of the ventilation air was 1.0^{0}C.

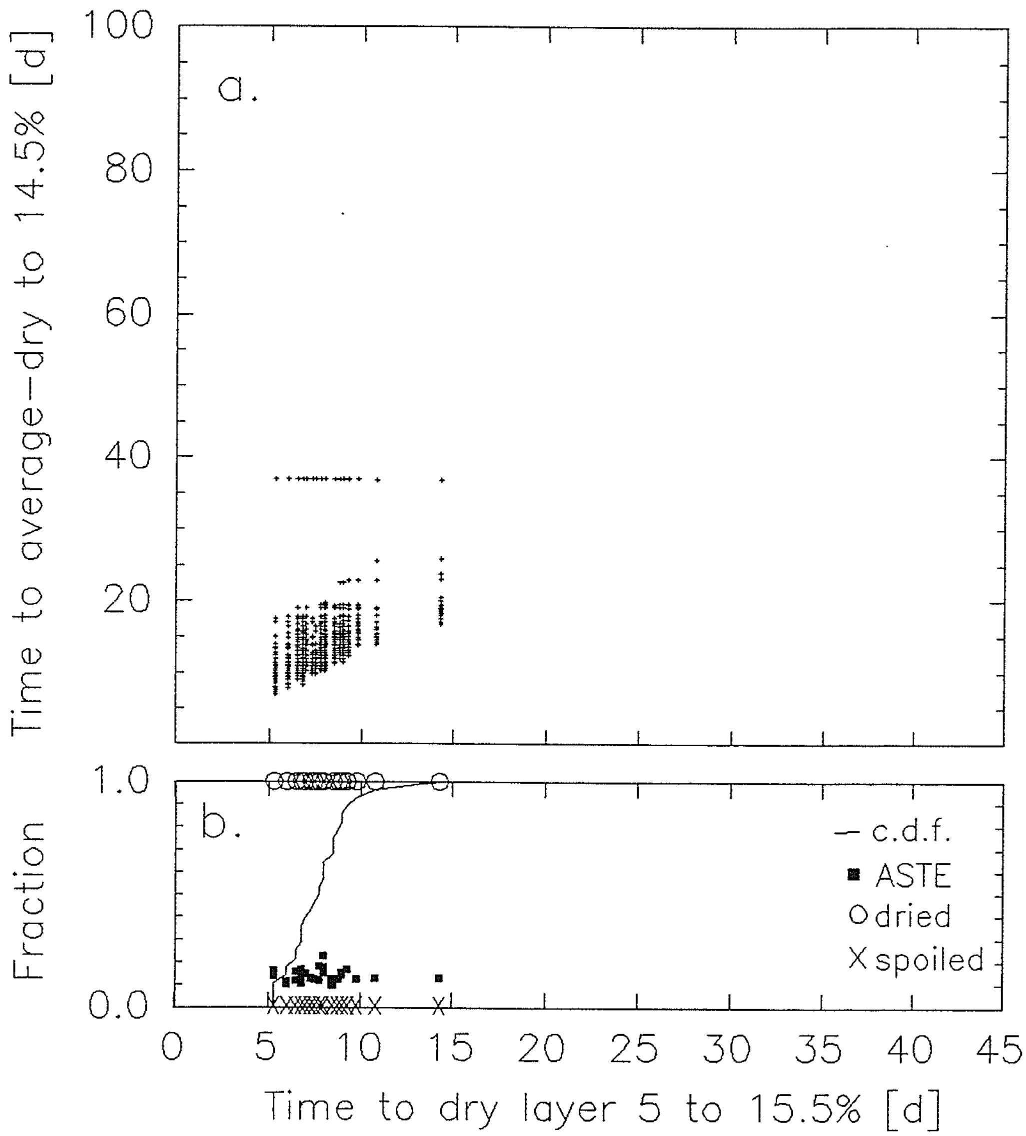

FIGURE A2.12 - Estimated time for the average moisture content of a bulk of wheat stored in Winnipeg on September 15 at 20% moisture content in a 3.65-m deep bed ventilated with 32 $(L/s)/m^3$ of near-ambient air to dry to 14.5% moisture content given the time the drying front reached layer 5. The calculated temperature rise of the ventilation air was 2.0°C.