MODELLING SAFE STORAGE TIME OF HIGH (17 AND 19%) MOISTURE CONTENT WHEAT

BY
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A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfillment of the Requirements
for the Degree of

MASTER OF SCIENCE

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THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES

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ABSTRACT

Harvesting high moisture grain and drying it on the farm has become a common practice in the Canadian prairies. Economic use of the drying facilities requires knowledge of the safe storage times of wheat at different storage conditions.

In this work, emphasis was given to the determination of the deterioration rates of 19% moisture content (m.c., wet basis) wheat stored at constant temperatures of 35 to 10°C in steps of 5°C, and stored with a step decrease in the storage temperatures. The step decrease in the storage temperatures was 10°C for 35 and 30°C and 5°C for 25 and 20°C. The deterioration rate of 17% m.c. wheat was also determined at 35, 30, and 25°C to compare the deterioration rates of three cultivars of hard red spring wheat.

The cultivar 'Barrie' was used for deterioration tests, because it is becoming the most popular cultivar in the Prairies. Safe storage time was defined as the storage time for the germination of the grain to drop to 90%. Safe storage times of 19% m.c. wheat stored at constant temperatures ranged from 2.5 d at 35 and 30°C to 37 d at 10°C. The measured values were fitted to a prediction equation and compared with published studies. Safe storage times of grain stored with a step decrease in the storage temperatures were satisfactorily predicted except when the temperature was reduced from 30 to 20°C. The safe storage times of 'Barrie' were lower than either 'Katepwa' or 'Domain'.

Microflora were identified and free fatty acid values were determined when mould growth was visible for the first time. Mould growth became visible after the germination had dropped well below 90%. *Aspergillus* and *Penicillium* species were identified as causing the

grain deterioration. Free fatty acid values were high in high moisture content grain stored at high temperatures and increased with time due to the growth of microorganisms which hydrolysed the lipids in the grain.

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LIST OF SYMBOLS

T – safe storage time (d)

M – moisture content (%, wet basis)

θ – storage temperature (°C)

CO_2 – rate of carbon dioxide production ((mg/d)/ kg d.m.)

t – storage time (d)

R – cumulative O_2 consumption (mg/ kg d.m.)

t_h – storage time (h)

a_1, a_2, a_3, a_4, a_5, a_6, a_7, a_8 are the constants

G – germination (%)

I – initial germination (%)

b, c, and e are the constants

1. INTRODUCTION

1.1 Harvesting and storing wheat in Canada

Wheat is the major agricultural crop in Canada. Wheat harvest starts on the Canadian prairies in August or September. Usually the crop is cut when the moisture content of the grain is about 35 – 20% and dried in the field to a safe moisture content (less than14.5%, wet basis) if the weather is warm and dry. Weather patterns sometime result in harvesting high moisture grain or even preventing the farmers from harvesting the crop before winter. This grain may be ultimately used as animal feed. For example, in 1997, 90% of the wheat crop was harvested by the end of September and was of high quality due to the dry weather during harvest. In 1996, even though the harvest began at the same time only about 50% was harvested due to the wet autumn weather (Anonymous 1997).

Harvested crops are stored on-farm or in commercial grain handling facilities, like primary and terminal elevators, until it is exported or delivered to the domestic market. Storage time on the farm varies from less than a month to a few years depending on the market trends and use on the farm. In commercial grain handling systems, grain procured from the producers is temporarily stored and then exported or delivered to domestic consumers. In Canada, grain is mainly stored on-farm (Sode et al. 1995). The total storage capacity of commercial storages in Canada, including 1058 primary elevators, 14 terminal elevators, 28 process elevators, and 15 transfer elevators is about 11.7 Mt, while the production of grains (cereals and oilseeds) in 1997 was 64.2 Mt (Canada Grains Council 1998). Therefore, more than 80% of the grain produced has to be stored on the farm.

Maintaining quality and quantity are the main criteria for safe storage. Quantity losses due to rodents and birds are usually negligible in the present storage systems in Canada. Every year about 80% of the wheat produced in the Prairies is exported to international markets. To compete with other major exporters of wheat in the world market (countries like the United States, Australia, and Argentina), and to maintain Canada's reputation of selling high quality grain, it is extremely important to maintain the quality of the harvested crop until it reaches the foreign consumer.

Freshly harvested wheat (from 1980 to 1987) in Manitoba had temperatures ranging from 36 to 5°C and moisture contents ranging from 20.5 to 10% (Kawamoto et al. 1991). Dry wheat stored at low temperatures is free of the activity of the major wheat deteriorating agents, because most insects will not develop on wheat with moisture contents less than 10% or temperatures less than 15°C, and microorganisms will not grow on wheat below 13.5% moisture content or 0°C (Tipples 1995). Wheat, has a high potential for quality loss by insect infestation at high temperatures and by microfloral infection at high moisture contents (Kawamoto et al. 1991). The high temperature of stored wheat can be reduced by aeration, which does not involve the high airflow rates needed to dry high moisture wheat. But, high moisture wheat should be dried to a safe moisture content to avoid deterioration by microorganisms thus preventing quality and grade loss.

High moisture grain can be dried using near-ambient air or heated air. Harvesting high moisture grain and drying using heated air on the farms was introduced in the Prairies in the 1970's (Dodds and Warder 1970). The knowledge of the deteriorating rates of wheat at different storage conditions would be of great help to farmers and grain managers for

economically using drying facilities and completing drying or cooling the grain before unacceptable deterioration occurs.

A wheat deterioration model was developed in 1979 (Fraser 1979). This model was used in the development and validation of computer simulated studies on drying of wheat using near-ambient air (Fraser and Muir 1981; Metzger and Muir 1983; Sanderson et al. 1989; Sinicio and Muir 1996). The studies revealed that the model predicts the trend but is not precise enough to be adopted in the future. A deviation of 30% in predicting wheat deterioration by the model is reported by Sinicio and Muir (1996).

The most recent development in the management of grain storage systems is the introduction of expert systems. They frequently include mathematical models of agriculture systems that can help farmers and grain managers make better management decisions. One such system developed for Canadian farmers and grain managers is the "Grain Storage Information System" (GSIS, Mann et al. 1997). This system also uses Fraser's wheat deterioration model (Fraser 1979) to calculate the safe storage time of wheat. The GSIS expert system then compares the calculated storage time with the intended storage period and gives a set of recommendations to prevent wheat deterioration. Hence, for consistent use and application of this system, a more accurate wheat deterioration model is required.

To meet the need for more accurate models, Schroth et al. (1998) developed a modified mathematical model of the deterioration rate of 17% moisture content wheat stored at 35 to 20°C. My research work was conducted to extend the model to a higher moisture content.

1.2 Objectives

The objectives of this research were:

1. To determine the deterioration rate of 19 and 17% moisture content wheat stored at constant temperatures.

2. To determine the deterioration rate of 19% moisture content wheat stored with a step decrease in storage temperatures.

3. To compare the deterioration rates of three cultivars of wheat.

2. LITERATURE REVIEW

2.1 Wheat quality and deterioration

2.1.1 Grain grading system Bailey (1992) states "Quality measurement is necessary so that buyer and seller may agree on value without samples of each lot of grain in hand and so that the processor may obtain the desired quality. They are also necessary to determine the possible quality losses during storage." The Canadian Grain Commission has standard measurement systems to determine numerical grades. The most important factors considered in the Canadian grading system are bulk density, varietal purity, vitreousness, soundness, dockage, moisture content, and protein content.

2.1.2 Pre-storage conditions affecting wheat quality Although most deleterious quality changes occur under adverse storage conditions, wheat quality is affected by pre-storage conditions e.g., time of harvest, condition of grain during harvest, and drying methods.

The effect of harvesting time on protein content was determined by Dodds and Warder (1966). Wheat of the same cultivar was grown for 7 yr. The crops were cut at kernel moisture contents ranging from 45 to 14.5% m.c. and allowed to dry in the field until a moisture content of 14.5% was attained. Protein content increases as the crop matures and moisture content decreases from 45 to 35% m.c. Cutting the crop at moisture contents less than 35% has no significant effect on protein content.

Quality parameters (1000 kernel mass, protein content, phosphorus content, and germination) were determined as a function of harvesting and drying methods (Dodds and

Warder 1970). The crop grown in the same year was cut at moisture contents ranging from 47 to 12% and dried by three methods (natural drying after windrowing in the field, near-ambient air drying with air at 20°C, and heated air drying with air at 43°C). The 1000 kernel mass is not significantly affected by drying methods when harvested below 38% m.c. The protein content of field dried samples is lower than that of air dried samples. The phosphorus content and germination percentage are higher in field dried samples than in air dried samples. But there is no significant difference in the phosphorus content and germination percentage between near-ambient air and heated air dried samples. Green et al. (1975) studied the relationship between the moisture content of crops and translocation of phosphorus into the grain kernels after windrowing. Translocation of phosphorus approaches zero at 35% kernel moisture content and lower. These studies indicate that above 35% kernel moisture contents the translocation of minerals and nutrients into the kernels may take place from other vegetative portions of the crop.

Another study of a similar kind was conducted in the Peace River region of northwestern Alberta, where wet weather conditions are common during harvesting (Christensen and Legge 1984). Wheat was harvested from 45 to 15% m.c. and dried by two treatments (naturally in the windrow, and using heated air at 40°C). Time of harvest and drying methods have little effect on 1000 kernel mass and protein content. Windrowing at or below 35% m.c. or direct combining and heated air drying at 20% m.c. or less produces No.1 grades. Windrowing grain above 40% m.c. or direct combining and heated air drying above 20% m.c. produce shrunken kernels, which lead to downgrading of grain.

The effect of wet harvest on the condition of harvested crops was studied by Mills

and Wallace (1979). During wet harvests the growth of fungal spores is spontaneous and prolonged wetting produces blackened seeds, whereas during dry harvests microflora are not visible although fungal spores may be present. One of the predominant storage fungi, *Penicillium*, which causes quality loss, is higher in grain stored after a wet harvest than after a dry season. Also, *Penicillum* is higher in broken kernels than in whole kernels of freshly harvested wheat (Prasad et al. 1978).

All these studies suggest windrowing at about 35% m.c. and field drying during dry seasons and direct combining near 20% m.c and drying using heated air at about 40°C during wet seasons produce better grades and quality wheat. Also, harvesting the crop before a wet fall and cleaning before storage will reduce the rate of deterioration during storage.

2.1.3 Wheat deterioration in storage Wheat is usually stored with the intention of using it for human food or animal feed. The nutritive and energy content of wheat kernels may be used to a small extent by the grain but major portions may be consumed by the deteriorative organisms (Tipples 1995). The quality of stored grain is damaged more by microflora than any other single deteriorating agent.

The fungi on cereal grains may be classified as either field fungi or storage fungi. *Alternaria*, *Cladosporium*, and *Fusarium* are some common pre-harvest fungi or field fungi. *Cladosporium* usually does not cause any damage to the grain in the field or in storage, however, *Altermaria* and *Fusarium* can produce mycotoxins. *Aspergillus* and *Penicillium* species are the dominant storage fungi. Under poor storage conditions field fungi are replaced by the growth of storage fungi. Storage fungi can be prevented by maintaining the

relative humidity of the intergranular air, i.e., the moisture content of the grain, and the temperature of the grain below the minimum levels required for their growth and development (Table I). Mould growth can also be prevented by maintaining the oxygen concentration below 1%. The effects and consequences of the growth of fungi on grains are listed in Table II.

Table I. Minimum relative humidity, moisture content, and temperature conditions for the growth of common storage fungi in wheat.

Species	Relative humidity (%)	Moisture content (%)	Temperature (°C)
Aspergillus candidus Link	80	15.0	10 –15
Aspergillus glaucus group	73	14.0	0 – 5
Aspergillus flavus Link	85	18.0	10 – 15
Aspergillus ochraceus Wilhelm	80	15.0	---
Aspergillus restrictus Smith	70	13.5	5 – 10
Penicillium	80 – 90	16.5 – 19.0	–5 – 0

Source: Christensen (1974)

Table II. Effects and consequences of microorganisms on stored grain.

Type of damage	Consequence
Dull appearance	Downgrading
Musty odours	Downgrading
Visible moulds	Downgrading
Reduced germination	Rejection for seed purposes
Increased free fatty acids	Rejection for processing
Binburning	Damage to product and premises
Mycotoxins	Feed refusal, illness, death

Source: Mills (1986)

Quality of wheat refers to different things to different types of consumers

(Mills 1992). Wheat deterioration studies have been focused on the effects of storage conditions on the physical (presence of visible mould, respiration rates and dry matter loss, and presence of off-odours), chemical (free fatty acid value (FAV), reducing and non-reducing sugars), and biological (kinds of microflora and seed viability) characteristics of the stored grain. Some studies have measured the production of chitin, ergosterol, and mycotoxin content by the growth of microflora in the stored grain (Abramson et al. 1999).

According to Bailey (1940), moulds will not proliferate freely in wheat until the moisture content is in excess of 17%. Mould growth is not visible in 18% m.c. samples stored at 15.5°C for 16 wk (Swanson 1934). But Christensen and Drescher (1954) reported visible moulds on samples stored for 1 yr with moisture contents ranging from 14.5 to 13.5%. The presence of visible mould has been adopted as an indicator of how long grain can be stored safely (Kreyger 1972). Safe storage periods based on visible mould can be at times unreliable, as significant losses can occur before mould becomes visible if conditions are not favourable for the development of fungal spores. For example, wheat at high moisture contents (31 to 18%) stored at 35°C for 19 d showed reduced viability in the absence of visible mould (Hummel et al. 1954). Seeds that have visible mould are musty but musty seeds do not necessarily have visible mould (Wallace et al. 1983). Mould growth is not visible for 35 d on samples having greater than 18.4% m.c. stored at 10°C, while mould growth is visible within 11 d on samples stored at 30°C with moisture contents greater than 17.4% (White et al. 1982). Visible mould is observed on 19 and 18% m.c. samples after 7 d stored at 25 and 20°C. Mould growth is more at 25°C than at 20°C (Hamer et al. 1991). High moisture contents and low temperatures favour the growth of *Penicillium* species. Low

moisture contents and high temperatures favour the growth of *Aspergillus* species (Wallace et al. 1983; Abramson et al. 1984, 1990). *Aspergillus* species decrease as *Penicillium* infection increases (White et al. 1982).

The respiration rate of grain and microorganisms may be a good indicator of grain condition and active spoilage during storage (Muir et al. 1985). There is considerable variation in the carbon dioxide produced by different grades of grain above 15% m.c. and by different grades at the same moisture level, but the variation does not appear to be related with the grade (Bailey 1940). Hummel et al. (1954) measured the respiratory rates of mould free and mouldy grains. The respiration rates of mould free grains were constant during storage indicating the growth of moulds in high moisture grains is responsible for the increased carbon dioxide production. Respiration rates of 1 to 6 (mg CO_2 /d)/ 100 g of dry grain in mould free samples and 2 to 56 (mg CO_2 /d)/ 100 g of dry grain in mouldy grains were measured in 15 to 18% m.c. grains. The respiration rates of 20.2 to 30.8% m.c. samples stored at 35°C increased from 55 – 265 to 1404 – 1608 (mg CO_2/d)/100 g of dry grain due to mould growth in 19 d. Respiration rates increase linearly with temperature and moisture content (Hamer et al. 1991; Lacey et al. 1994). The cumulative amount of carbon dioxide produced can be used to estimate the dry matter (d.m.) loss based on the simplified respiration equation:

$$C_6 H_{12} O_6 + 6 O_2 \rightarrow 6 CO_2 + 6 H_2 O + \text{heat} \quad \text{.....(1)}$$

According to this equation a loss of 1% d.m./ kg of wheat produces 14.7 g of carbon dioxide. The deterioration rate of 24.2 to 14.4% m.c. wheat stored at 40 to 10°C was determined by measuring the carbon dioxide produced and relating it to the dry matter loss of the grain.

Mould growth is visible when the dry matter loss is 0.1% while only 0.04% dry matter loss is acceptable for grains stored for seed purposes (White et al. 1982). Lacey et al. (1994) however, determined an acceptable limit of 0.13% dry matter loss for visible mould growth and 0.083% dry matter loss for grains stored for seed purposes.

Free fatty acids are produced by the break down of lipids by hydrolysis caused by enzymatic secretions from the associated microorganisms in the grain. Free fatty acid values of 16.3 and 14.4 mg KOH/ 100 g of dry grain was measured in 30.8 and 10.5% m.c. grain respectively that were stored at 35°C for 19 d without the growth of fungi (Hummel et al. 1954). At high moisture contents, FAV is not a good indicator of spoilage. For example, FAV levels were low at high moisture content grains stored at high temperatures and the growth of bacteria at high moisture content grains may influence the FAV values (White et al. 1982). Free fatty acid content correlates positively with moisture content and *Penicillium*, and negatively with temperatures (Wallace et al. 1983). Wheat with FAV contents of 5.9 to 9.7 mg KOH/ 100 g of dry grain was considered as sound seeds by Sinha et al. (1985). They measured FAV levels that were slightly above (7 to 16) the levels in sound grains in wheat stored and ventilated with airflow rates of 0.8 and 12.2 L/m^3. In the control bin with no ventilation the FAV increased to a high of 32 and then abruptly decreased to 25 mg KOH/ 100 g of dry grain due to the growth of microorganisms. Schroth (1996) determined a FAV value of 20 mg KOH/ 100 g of dry grain in deteriorated grain while Baker et al. (1957) determined the same level of FAV content in sound grain. Hence measurement of FAV levels alone cannot be used to determine the grain condition during storage.

The reducing sugar content of the wheat will increase and the non-reducing sugar content of the grain will decrease due the growth of fungi which digest the grain. The reducing sugar content in 10.5 to 18% m.c. grain increased from an initial value of 34 to 84 mg of maltose /10 g of dry grain stored at 35°C for 19 d whereas the non-reducing sugar content of the same grain decreased from 201 to 134 mg of sucrose/ 10 g of dry grain due to mould growth (Hummel et al. 1954).

The germination percentage of wheat stored at high moisture contents and temperatures decreases with storage time. Wheat stored in the farm bins with an average moisture content of 12.4% and temperature of – 4.8°C for 1 yr had 95% germination while wheat stored with an average moisture content of 16.2% and a temperature of 25°C for 1 to 2 yr had 41% germination (Wallace and Sinha 1962). Germination has no correlation with moisture content, a negative correlation with temperature and storage fungi, and a positive correlation with field fungi (Wallace and Sinha 1962). Initial germination percentage was maintained in the samples (24 to 14.4% m.c.) stored at 10°C, whereas at 40°C the germination was maintained only in low moisture content samples (White et al. 1982). The changes in the germination percentage of wheat stored and ventilated with different airflow rates with air at near-ambient conditions were studied (Sinha et al. 1985). Two sets of bins were ventilated with airflow rates of 12.2 and 0.8 (L /s)/m^3, respectively. Two more bins were treated as control without any ventilation. The temperature ranged from 29 to 9°C in the ventilated bins and from 32 to 11°C in the control bins. The mean moisture content decreased from an initial value of 19 to 11.3% in the bins with a high airflow rate, and to 17% in the low airflow bins. The moisture content in the control bins fluctuated between

21 and 18% with time. Average germination percentages of 100 to 88% in the high- airflow bins and 71 to 53% in low-airflow bins were recorded for a storage period of 202 d while germination dropped to the range of 75 to 10% within the first 48 d in the control bins. The effect of moisture content on the germination percentage was determined on 15.1 to 13.7% and 18.6 to 16.7% m.c. wheat stored for 60 wk in the temperature range of 26 to –6°C (Abramson et al. 1984, 1990). Germination of 18.6 to 16.7% m.c. wheat dropped sharply within 12 wk and was 0% at the end of the storage period whereas it was greater than 88% in 15.1 to 13.7% m.c. wheat throughout the storage time.

The moisture content at which mycotoxins can be produced in the grain was studied by Abramson et al. (1984, 1990). The results indicated that a moisture content of 19% may be the critical minimum limit for mycotoxin formation in stored wheat. This may be due to the difference in the deterioration rates of grains above and below 19% m.c. (Fraser 1979).

The microbiological methods (number of seeds infected or number of fungal colonies present) are used to determine the species of live fungi and their relative abundance in stored grain. Measurements of chitin (Golubchuck et al. 1960; Wu and Stahman 1975; Donald and Mirocha 1977; Nandi 1978) and ergosterol (Seitz et al. 1977; Marfleet et al. 1991) content which are constituents of all fungi and not a constituent of grains, can be used to determine living, dormant, and dead mycelium of the microflora present in the samples. Ergosterol content does not distinguish between field fungi and storage fungi and chitin content may give misleading results from samples containing insects (Seitz et al. 1977). Also these methods were evaluated only on limited experiments in the laboratory.

Quality measurements need to be simple enough to be adopted by a farmer and fast

enough to determine the condition of large bulks of grain handled in grain elevators. Determination of microflora species, FAV, mycotoxins, chitin, and ergosterol content requires training and expensive equipments. Also, no definite correlations exist between these quality parameters and grain conditions. Respiration rate of grain is a quick indicator of grain condition (Muir et al. 1985) but varies with the variety and kernel size of the grain (Bailey 1940). Maintenance of seed viability is an important quality to be considered for seed and malting uses. Germination can be affected even if mould growth is not visible. Hence, determination of grain condition by measuring germination capacity of the grain may be a good method of measuring grain quality during storage.

2.1.4 Mathematical model for wheat deterioration The first mathematical model of wheat deterioration was developed by Fraser (1979). While determining the airflow requirements for solar grain drying (Fraser and Muir 1981), the data collected on wheat deterioration by Kreyger (1972) were used to develop a two part model dependent on moisture content and temperature. Safe storage time was defined as the time for germination to drop to 95-90% or when mould growth became visible.

$$\text{Log } T = 6.234 - 0.2118\ M - 0.0527\ \theta \quad (12\% < M < 19\%) \quad (2)$$

$$\text{Log } T = 4.129 - 0.0997\ M - 0.0576\ \theta \quad (19\% < M < 24\%) \quad (3)$$

where: T = safe storage time (d);

M = moisture content (%);

θ = storage temperature (°C).

Sanderson et al. (1989) evaluated the deterioration model, developed by Fraser

(1979), during near-ambient drying of wheat. The variables measured to assess the quality changes were microfloral infection, seed germination, and fat acidity value. Their conclusion was that the model predicts the trend but does not accurately predict grain quality loss. A similar conclusion was determined by Sinicio and Muir (1996) when he used the above model during computer simulation of the aeration of wheat. To apply the deterioration model developed at constant storage conditions to dynamic conditions occurring during drying, a deterioration index was introduced. The deterioration index (D.I.) was calculated by dividing the actual time interval at approximately constant storage conditions by the allowable storage time predicted by Eq. 2 or 3. A D.I. of 1 indicates the predicted allowable storage time has elapsed.

The amount of carbon dioxide produced or oxygen consumed by the grain and microorganisms was used to develop prediction equations for determining the grain condition. The amount of carbon dioxide produced by the stored grain is given by the following equation (White et al. 1982).

$$\text{Log}_{10}\, CO_2 = -4.054 + 0.0406\,\theta - 0.0165\,t + 0.0001\,t^2 + 0.02389\,M \quad \text{.....(4)}$$

where: CO_2 = rate of carbon dioxide production ((mg/ d)/ kg of d.m.);

t = storage time (d).

Cumulative values of 655 to 1470 mg of CO_2/kg of dry wheat may be the limits for grains stored for seed purposes and without visible mould. Lacey et al. (1994) related the amount of oxygen consumed to the moisture content, temperature, and storage time.

$$R = \frac{a_1 + a_2 t_h}{(1 + e^{(a_3(a_4 - \theta))})(1 + e^{(-(a_5 + a_6 t_h + a_7\theta)(M - a_8))})} \quad \text{.....(5)}$$

where: R = cumulative O_2 consumption (mg/ kg d.m.);

t_h = storage time (h);

a_1, a_2, a_3, a_4, a_5, a_6, a_7, and a_8 are the constants.

Assuming a respiratory quotient of one, they determined cumulative values of oxygen consumed to be 1392 and 1911 mg of CO_2/kg of dry wheat for 90% germination drop and for visible mould, respectively.

Several spoilage indices to model grain quality of different grains based on dry matter loss, carbon dioxide production, or visible mould growth, were reviewed by Brook (1987). He concluded that they provide reasonable estimates of allowable storage time for cereal grains and they can be used in simulations of drying with near-ambient air. He found that a spoilage index based on mould growth is safer than an index based on dry matter loss. The mould index tends to underestimate allowable storage time and thus provides a safety margin. This conclusion directed further deterioration models to be developed based on mould growth or germination capacity of grain.

The deterioration rate of 17% moisture content wheat stored at 35 to 15°C, and 35 to 20°C was determined by Schroth (1996) and Schroth et al. (1998), respectively. The rate of germination at constant temperatures in both studies followed an asymmetric sigmoidal pattern and was fitted to the relation given by:

$$G = \frac{I}{\left[1 + \left(\frac{t}{c}\right)^{b}\right]^{e}} \quad \text{.....(6)}$$

where: G = germination (%);

I = initial germination (%);

b, c, and e are constants.

The allowable storage time of 17% moisture content wheat stored at 35 to 15°C (Schroth 1996) is given by:

$$\text{Log } T = 2.5 - 0.045\,\theta \quad \text{.....(7)}$$

The above equation is based on the time for the germination of the wheat to drop to 90%. This model is an improved version of the previous model of Fraser (1979). Further work at other moisture contents was recommended by Schroth (1996).

3. MATERIALS AND METHODS

3.1 Experimental design

3.1.1 Wheat cultivar and experimental conditions Wheat (*Triticum aestivum* L., cultivar 'Barrie') was selected for the experimental study. At present, Barrie is the most popular cultivar of Canadian red spring wheat (CWRS) grown in the Prairies. A Canadian Wheat Board survey shows it covered 29.4% of the seeded acres in 1997 although it became commercially available only 1 yr earlier in 1996 (Anonymous 1999). In addition to its popularity, this variety was selected to meet one of the objectives of comparing the deterioration rates with the other cultivars 'Katepwa' (Schroth 1996) and 'Domain' (Schroth et al. 1998).

The average moisture contents of wheat during harvest across the Prairies are not available. Therefore, the moisture contents were selected based on other available information. Freshly harvested wheat in Manitoba has moisture contents ranging from 20.5 to 10 % (Kawamoto et al. 1991). A survey of Manitoba farmers shows that more than 50% of the farmers harvest wheat above the "Straight-grade" (14.5%) moisture content and 18% of them harvest in the range of 20 to 17% m.c. (Brodeur 1998). Hence, for the determination of deterioration rate of wheat, 19 and 17% m.c. were selected.

The temperature range for the deterioration study was based on the possible temperatures the grain will be exposed to during harvest and storage. In the Canadian prairies, during normal harvesting periods the average 24-h daily temperature is less than 20°C (Muir and Jayas 1997) and on sunny days the temperatures of heads of wheat are 8°C

above the ambient temperatures (Prasad et al. 1978). The temperature of wheat recorded during harvest in Manitoba is in the range of 36 to 5 °C (Kawamoto et al. 1991) and the grain kernels maintain the harvested temperature into the storage bins. For example, wheat harvested on a sunny day recorded an average temperature of 36 °C in the storage bin in southern Manitoba (Prasad et al. 1978). On cloudy days and at night, the grain temperature and the ambient temperature are the same. The temperature of stored grain changes due to seasonal variation in outside temperatures. For example, during summer when the wall temperature is 31 °C the centre temperature in the bin is 5 °C, whereas during winter when the wall temperature is –18 °C the temperature at the centre of the bin is 16 °C (Muir and Jayas 1997). The common storage fungi in wheat do not grow below 10 °C (Section 2.1.3) except *Penicillium*. Hence, a temperature range of 35 to 10 °C for 19% m.c. was selected for the determination of wheat deterioration.

3.1.2 Experimental apparatus and setup All the experiments were conducted under controlled environmental conditions. A CRELAB (Climatic Research Equipment, WHL3 - 610M, Winnipeg, MB.) environmental chamber had eight Styrofoam boxes (Fig. 1), each of them heated with hair dryers (1500 W). Each Styrofoam box could hold a maximum of three replicates (Fig. 2). Temperatures were measured and controlled by a BASIC program through a Datascan 7010 data acquisition system (Firmware v2.0 Measurement Systems Ltd., Newbury, Berkshire, UK) connected to a Tandy computer. To prevent the grain from drying out due to the hot air blown by the heating source, the relative humidities in the boxes were increased by placing open containers of water in the boxes.

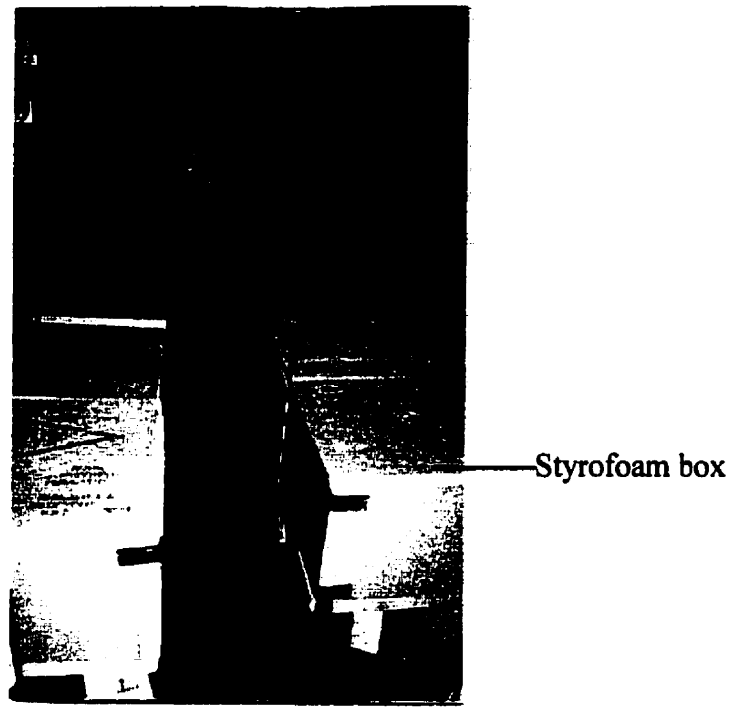

Fig. 1. Environmental chamber.

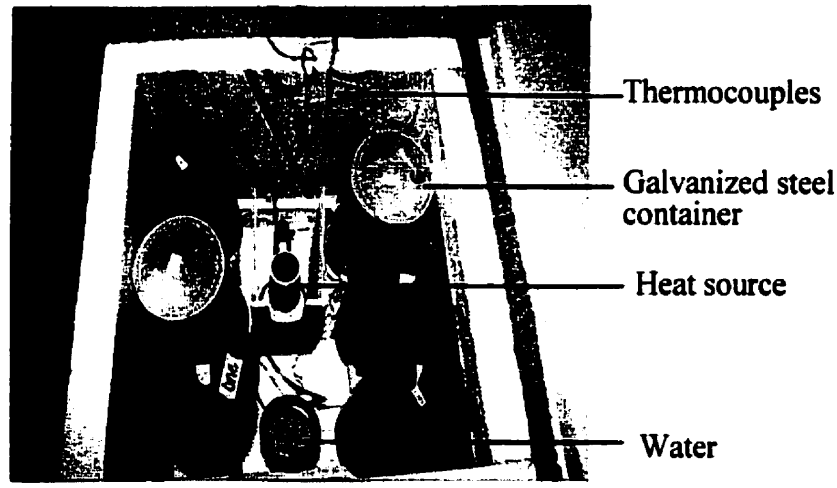

Fig. 2. Styrofoam box with galvanized steel containers.

A total of 46 thermocouples (36 for measuring the sample temperatures, 8 for measuring the ambient temperatures in each box, and 2 for measuring the chamber temperature) were used to measure and control the temperatures. The temperature of each box was calculated as the mean of the sample temperatures and the ambient temperature of the box. The chamber temperature was set 5 °C less than the lowest temperatures in the boxes. The heaters in the boxes maintained sample temperatures within ± 1 °C of the set target temperature. The average temperature of each box was calculated every 10 s. The program was set to control only two heaters at a time to reduce the load on the power circuit. The heaters in the boxes having temperatures furthest from their set points were powered on first.

The grain was conditioned to the 19 and 17% moisture contents by adding calculated amounts of distilled water and then allowing for moisture equilibration at room temperature for 6 h. The conditioned grains were stored in mesh bags in galvanized steel containers (diameter was 12.7 cm and height was 23 cm). The containers had ventilation holes in their bottoms to maintain an aerobic environment for the samples and were covered with plastic lids on their tops. A sample of 450 g in a mesh bag was placed in the middle of the container with guard bags containing 400 g of grain at the same moisture contents above and below it (Schroth et al. 1998).

Experiments were conducted at constant temperature conditions for 19 and 17% m.c. grain and at decreasing temperature conditions for 19% m.c. grain. The moisture contents of the test grains were maintained within ± 0.5% of the target values. Three replicates for each condition were studied. For constant temperature conditions, deterioration rates were determined at six temperatures from 35 to 10 °C in steps of 5 °C for 19% m.c. and at three

temperatures from 35 to 25°C in steps of 5°C for 17% m.c. Deterioration rates during stepped decreases in storage temperatures were determined for 19% m.c. grain. Storage temperatures were reduced by 10°C from initial temperatures of 35 and 30°C and by 5°C from initial temperatures of 25 and 20°C.

3.2 Grain quality assessment

3.2.1 Grain history Wheat harvested in the autumn of 1997 and stored on a farm for 10 mo was used in this study. The grain was clean, dry (12.7% m.c.), and had no apparent mechanical damage. Preliminary grain quality tests showed an average germination of 98% and a free fatty acid value of 10.8 mg KOH/ 100 g of dry grain. The field fungus, *Alternaria*, was identified on 12% of the seeds and storage fungi were not identified on any incubated seeds. The grain was stored in plastic bags at −5°C until used for the experiments.

3.2.2 Moisture content Moisture contents of samples were determined by drying 10 g of unground grain at 130 ± 2°C for 19 h (ASAE 1997) and were expressed in percent of wet mass.

3.2.3 Germination percentage Seed germination capacity was assessed by plating 25 seeds on Whatman no. 3 filter paper in a 9-cm diameter petri-dish saturated with 5.5 mL of distilled water (Wallace and Sinha 1962). The plates were covered with a plastic bag to prevent dessication of filter papers and incubated at 10°C for the first 4 d to begin germination. The bag was removed on the fourth day and the samples were then incubated

at 25°C. On the seventh day the germinated seeds were counted.

3.2.4 Microflora identification Microflora that cause grain deterioration were identified by placing 25 seeds on Whatman no.3 filter paper in a 9-cm diameter petri-dish saturated with 5.5 mL of 7.5% aqueous sodium chloride solution (Mills et al. 1978). The plates were covered with a plastic bag to prevent dessication of filter papers and incubated at 25°C for the first 4 d. On the fourth day the plastic bag was removed and on the seventh day the organisms growing on the seeds were identified using a dissecting microscope.

3.2.5 Free fatty acid value The free fatty acid values were determined using 5 g of dried samples (Schroth 1996). The samples were dried at 130°C for 19 h and were ground in a Tecator Cyclone Sample mill. The ground samples were folded in a Whatman no. 5 filter paper and placed inside the fat extractors (Goldfisch Fat extractor, LabConco Corporation, Kansas City, MO; 115 V, 5.2 A) with beakers containing 30 mL of petroleum ether as the solvent. The solvent was boiled continuously and the condensed vapours were passed through the sample for 6 h. Then the solvent was separated and 25 mL of TAP solution (50% toluene and 50% ethanol with phenolphthalein indicator) was added to the extracted free fatty acid from the sample. This solution was titrated with a KOH solution (normality: 1.1979 mg / mL of solution) until it turned light pink. The FAV value was expressed as mg of KOH / 100 g of dry grain.

4. RESULTS

4.1 Deterioration of wheat at 19% moisture content

4.1.1 Deterioration at constant storage temperatures The germination capacity of wheat was used as an indicator of grain deterioration during storage. The germination percentages of wheat stored at constant temperatures are plotted in Figs. 3 and 4. The measured germination percentages of the three replicates and their mean values with standard deviations are presented in Table A.1 (Appendix A). The experimental data followed an asymmetrical sigmoidal pattern and fitted well to an equation of the form presented by Schroth et al. (1998):

$$G = \frac{I}{\left[1+\left(\frac{t}{c}\right)^{b}\right]^{e}} \quad \text{.....(8)}$$

where: G = germination (%);

I = initial germination (98%);

t = storage time (d);

b, c, e are constants for each moisture content.

Measured germinations down to 60% at each temperature condition were used to calculate the coefficients for Eq. 8 (Table III). The software Sigmaplot (1997) was used to calculate the coefficients and to fit curves to the measured values (Figs. 3 and 4).

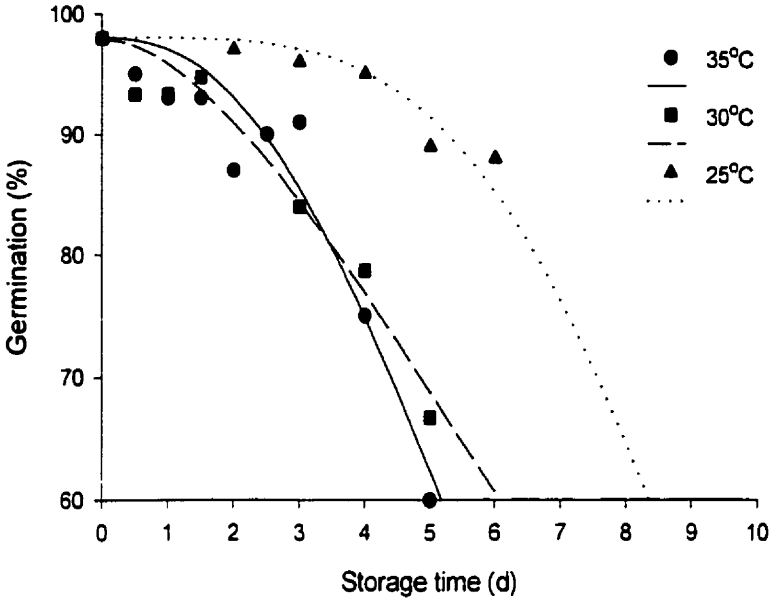

Fig. 3. Germination of 19% m.c. wheat stored at 35, 30, and 25°C*.

*Symbols represent the means of replicates and lines represent the fitted equations.

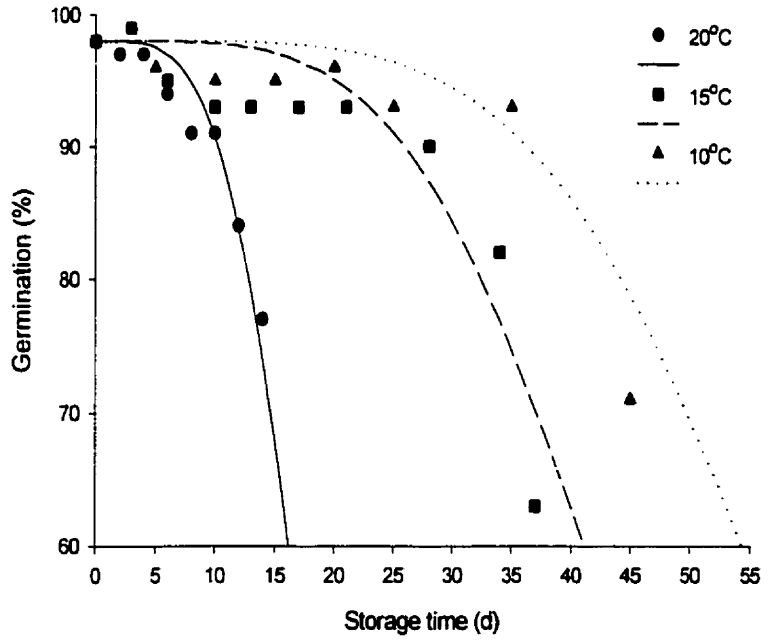

Fig. 4. Germination of 19% m.c. wheat stored at 20, 15, and 10°C*.

*Symbols represent the means of replicates and lines represent the fitted equations.

Table III. Coefficients of the germination equation (Eq. 8) for 19% m.c. wheat.

Temperature (°C)	Coefficients			R^2
	b	c	e	
35	2.39	14.40	5.88	0.91
30	1.72	27.89	6.98	0.96
25	3.82	22.22	20.08	0.99
20	3.86	37.59	12.88	0.97
15	3.99	57.82	2.14	0.92
10	4.42	94.46	5.89	0.97

The germination drop was rapid in the beginning at all temperatures. This drop continued throughout the storage time at the higher temperatures (35 to 25°C), whereas it was more gradual at the lower temperatures. For example, the germination dropped to 90% within 2.5 d at 35 and 30°C whereas it ranged from 5 to 37 d at 25 to 10°C. There was no significant difference in the deterioration rates at 35 and 30°C.

4.1.2 Deterioration of wheat stored with a step decrease in storage temperatures The time interval for which the grain was stored at the initial temperature in each set of experiments was based on the results from the constant temperature conditions. For initial temperatures of 35 and 30°C the storage temperatures were reduced to 25 and 20°C after 36 h. For 25 and 20°C, the storage temperatures were reduced to 20 and 15°C after 3 and 7 d, respectively.

The measured germination percentages (Table A.2) at the four conditions were between the predicted values at the constant higher and lower temperatures (Fig. 5). The Eq. 8 was used to fit germination curves to the measured values, and the time for germination

to drop to 90% at each condition was determined. The coefficients of the fitted curves are presented in Table A.3.

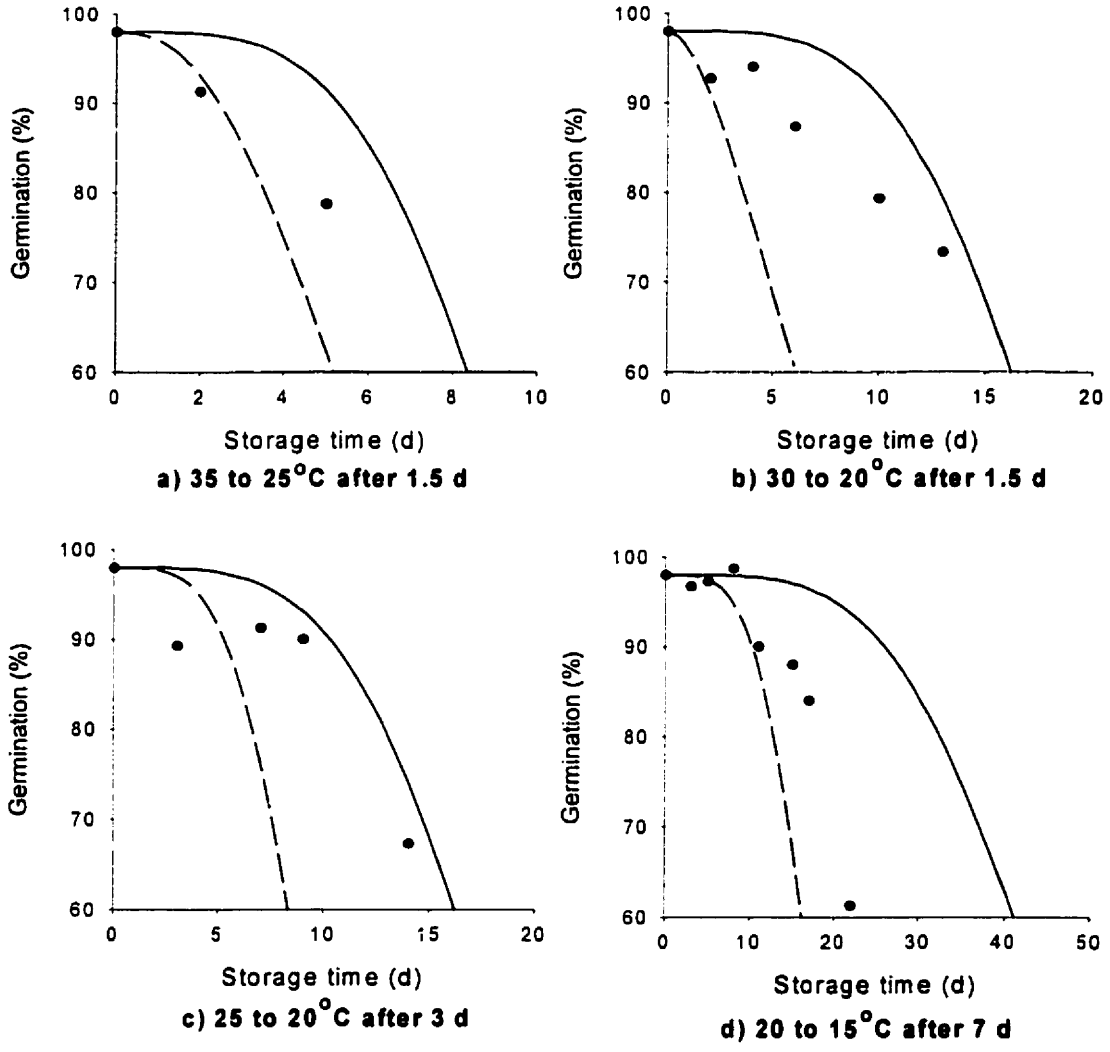

Fig. 5. Germination of 19% m.c. wheat stored with a step decrease in storage temperatures*.

* The step decrease in the storage temperatures are indicated below each figure.

● Means of three replicates.

—— Predicted germination at the constant lower temperature.

— – Predicted germination at the constant higher temperature.

4.1.3 Safe storage time of 19% moisture content wheat The safe storage time of wheat was defined with respect to the germinability of seeds. Fraser (1979) and Schroth (1996) defined safe storage time as the time for the germination to drop to 90%. A germination drop to 85% was used by Wallace et al. (1983) to define the safe storage time, but some lots were degraded when the germination dropped to 85%. Hence in this study the time for the germination to drop down to 90% was used as the safe storage time. The safe storage time measured (using Eq. 8) at each constant temperature condition was used to develop an equation for the safe storage time of 19% m.c. wheat:

$$\text{Log } T = 2.057 - 0.049\,\theta \quad \text{..... (9)}$$

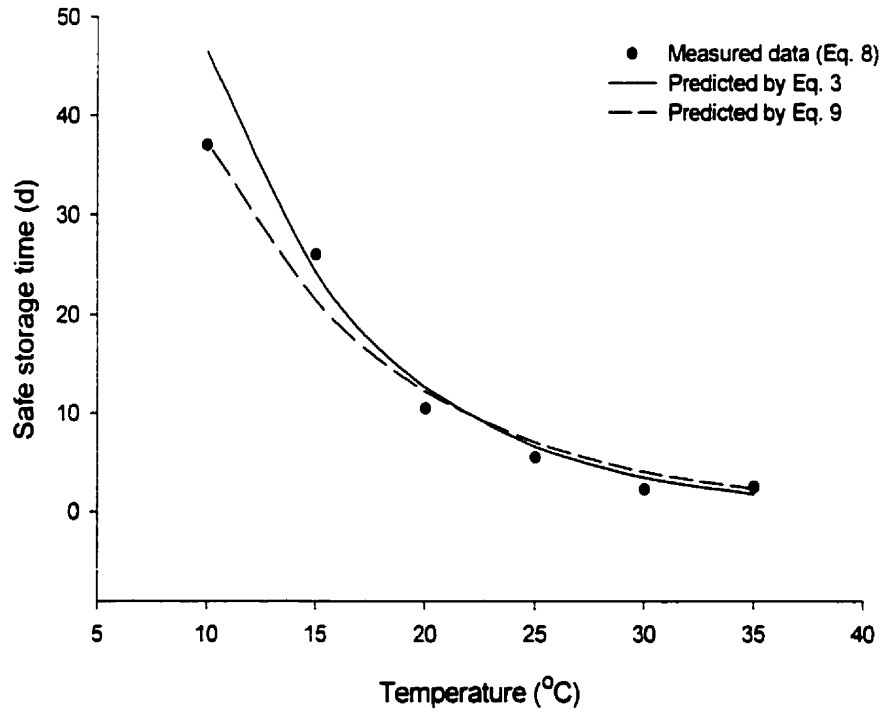

Fig. 6. Safe storage time of 19% m.c. wheat.

The coefficient of determination (R^2) for Eq. 9 was 0.99 and valid for temperatures from 10 to 35°C. The safe storage times predicted by Eq. 9, Eq. 3 (Fraser 1979), and the measured values are compared in Fig. 6. Statistical analysis showed that the safe storage times predicted by Eq. 3 and 9 were not significantly different. Equation 9, with a D.I. of 1, was used to predict the safe storage times of wheat stored with a step decrease in storage temperatures. The predicted values were higher than the measured values. A D.I of 0.8, however, predicted the safe storage time well (Fig. 7). The safe storage time was also predicted by the method used by Schroth et al. (1998) and compared with the measured values (Fig. 7).

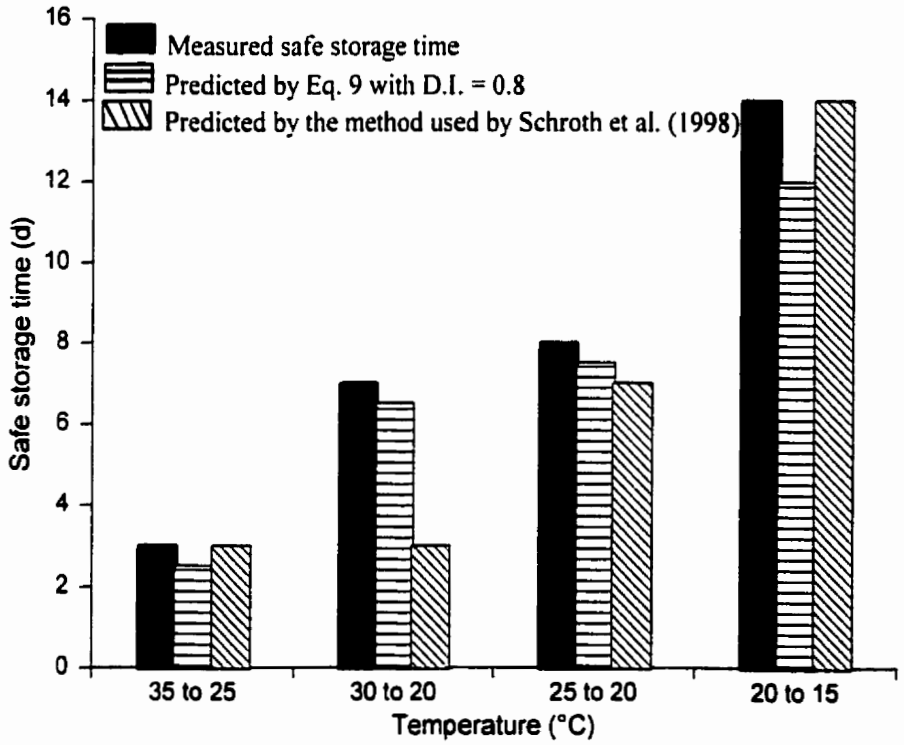

Fig. 7. Safe storage time of 19% m.c. wheat stored with a step decrease in storage temperatures.

4.2 Deterioration of wheat at 17% moisture content

The germination rates of 17% m.c. wheat stored at constant temperatures (Table A.4) are shown in Fig. 8. Germination rates down to 60% in each condition were fitted to Eq. 8 (Table IV).

Table IV. Coefficients of the germination equation (Eq. 8) for 17% m.c. wheat.

Temperature (°C)	Coefficients			R^2
	b	c	e	
35	3.18	5.63	0.20	0.99
30	1.67	165.58	31.88	0.99
25	3.26	112.10	76.07	0.99

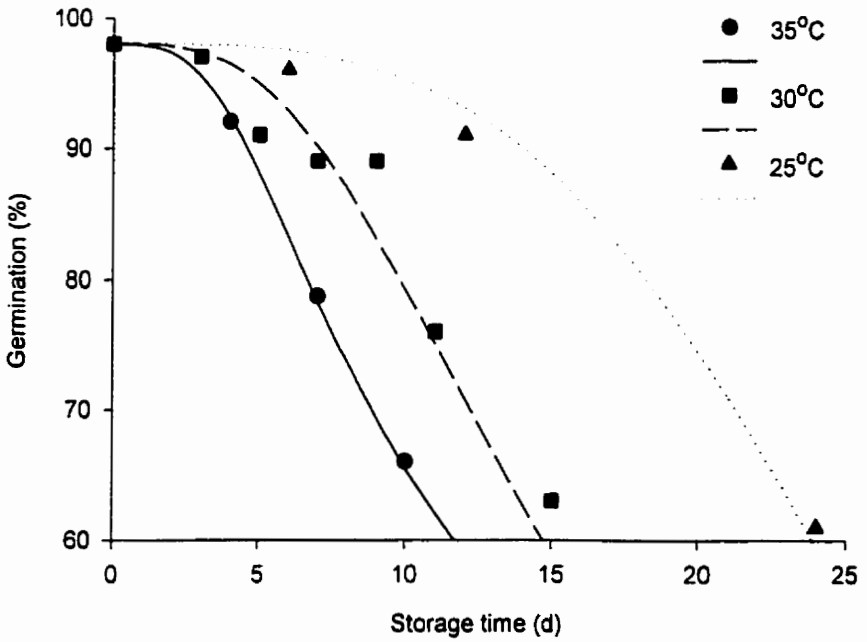

Fig. 8. Germination of 17% m.c. wheat stored at 35, 30, and 25°C*.
*Symbols represent mean values of three replicates and lines represent the fitted equations.

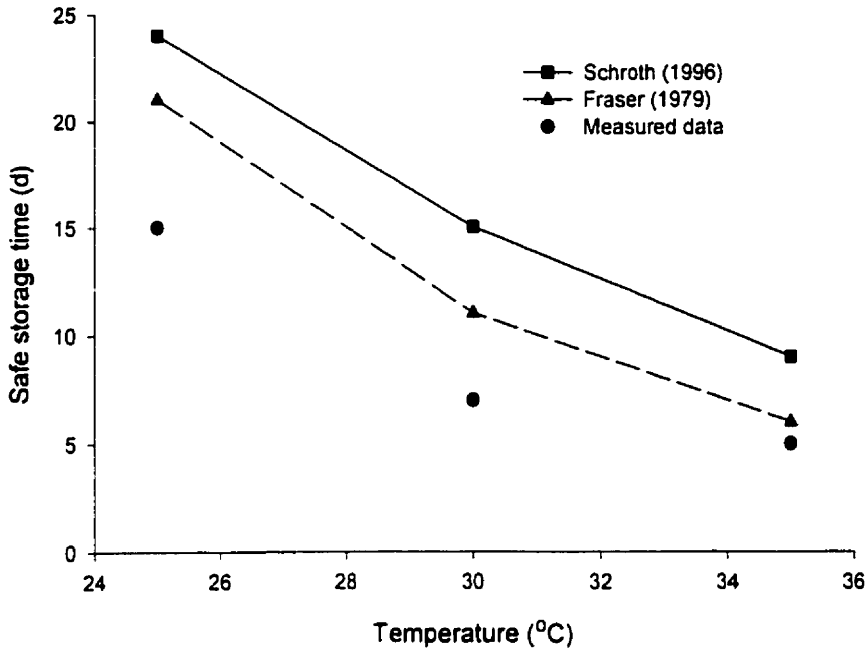

Fig. 9. Comparison of safe storage times* of 17% m.c. wheat.
* The time for the germination to drop to 90%.

The measured safe storage times (Fig. 9) at the three moisture conditions were considerably shorter than the safe storage times predicted by Fraser (1979) and Schroth (1996).

4.3 Microflora

Mould growth was first visible after the germination dropped to well below 90% in all the tests (Table V). Mould growth was not visible at 15 and 10 °C, but the seeds became blackened with time. The percentages of seeds infected with microflora at the storage conditions are presented in Table VI.

In 19% m.c. wheat stored at constant temperatures (Table VI; Table B.1, Appendix

B) *Aspergillus* and *Penicillium* spp. were predominant in all the tests. During the early days of storage, infection levels were high for *A.glaucus* and *A.flavus* at 35°C, for *A.candidus* at 30 and 25°C, and for *A.candidus* and *Penicillium* at 20°C. During the later storage period, infection levels were highest for *A. glaucus* at 35°C, *A.candidus* at 20 and 30°C, and *A.glaucus* and *A.candidus* at 25°C. All species of storage fungi identified, during the time the mould growth became visible increased with storage time, except *A.flavus* at 35°C. Bacteria was present on the incubated seeds at 30 and 25°C on day 9 and 11, respectively.

Table V. Time of the first appearance of visible mould and measured germination percentage.

Moisture content (%)	Temperature (°C)	Visible mould	
		Time (d)	Germination (%)
19	35	4	75
19	30	4	67
19	25	5	89
19	20	12	81
19	35 to 25	5	79
19	30 to 20	13	81
19	25 to 20	11	67*
19	20 to 15	16	84
17	35	7	79
17	30	13	76
17	25	24	61*

* Visible mould might have occurred before this time in these cases because of the length of time interval between sampling dates.

In 19% m.c. wheat stored with a step decrease in storage temperatures (Table B.2) *A.glaucus* was dominant in all cases except for the initial temperature of 20°C where

A.flavus was slightly more dominant. *A.candidus*, *A.flavus*, and *Penicillium* were also present in all the tests.

In 17% m.c. wheat stored at constant temperatures (Table B.3) infection by *A.glaucus* was high at 35 and 30°C. *A.candidus* was high at 25°C. *Penicillium* levels increased with decreased temperatures.

Table VI. Microflora* of stored wheat.

Moisture content (%)	Temperature (°C)	Percent of seeds infected by			
		A.glaucus	*A.candidus*	*A.flavus*	*Penicillium*
19	35_5	21	9	25	1
19	35_{10}	47	36	15	9
19	30_4	9	21	0	9
19	30_9	12	56	0	15
19	25_5	5	10	0	3
19	25_{11}	32	33	0	21
19	20_{12}	12	23	3	20
19	20_{20}	16	37	0	41
19	35 to 25_6	47	21	11	9
19	30 to 20_{13}	63	21	12	7
19	25 to 20_{11}	32	20	8	16
19	20 to 15_{17}	25	4	31	12
17	35_7	56	31	19	5
17	30_{13}	55	15	13	11
17	25_{24}	15	24	4	14

* The microflora were present on the respective storage days as indicated by the subscripts at each condition.

4.4 Free fatty acid value

The free fatty acid values (means of the replicates) measured at the storage conditions are presented in Table VII. Free fatty acid values measured in the samples with visible mould

were higher than the measured FAV (10.8 mg KOH / 100 g of dry grain) initially in the grain and increased with an increase in temperatures. The high values of FAV measured at 19% m.c. wheat stored with a step decrease of 5 °C from the initial storage temperatures of 25 and 20 °C may be due to the weaker KOH solution used during the FAV test. The FAV increased with storage time at 19% m.c. wheat stored at constant temperatures.

Table VII. Free fatty acid values* of stored wheat.

Moisture content (%)	Temperature (°C)	Fatty Acid Value (mg KOH/ 100 g of dry grain)
19	35_5	n.d.
19	35_{10}	64.9
19	30_4	23.1
19	30_9	35.2
19	25_5	15.1
19	25_{11}	23.6
19	20_{12}	11.2
19	20_{20}	27.4
19	35 to 25_6	26.6
19	30 to 20_{13}	15.3
19	25 to 20_{11}	69.4
19	20 to 15_{17}	49.6
17	35_7	28.2
17	30_{13}	21.9
17	25_{24}	17.9

* The FAV was determined on the respective days as indicated by the subscripts at each condition
n.d - not determined.

4.5 Safe storage times of different cultivars of wheat at 17% moisture content

The safe storage times of three cultivars 'Domain', 'Katepwa', and 'Barrie' stored at 17% m.c. and 35 to 25 °C were compared (Fig.10). The safe storage time in the three cases

was defined to be the time for the initial germination to drop down to 90%.

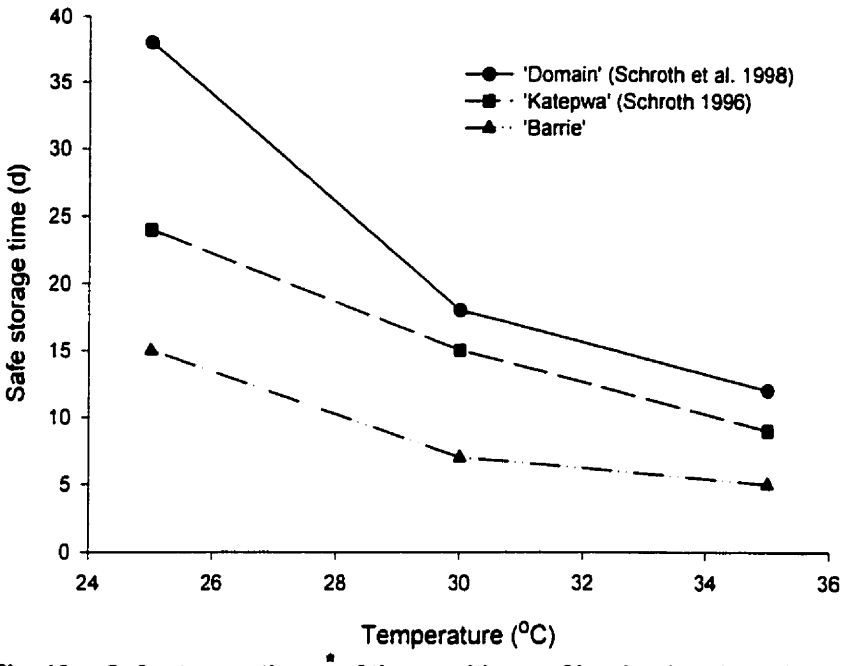

Fig. 10. Safe storage times* of three cultivars of hard red spring wheat at 17% m.c.

*The time for the germination to drop to 90%.

4.6 Safe storage time of high (17 & 19%) moisture content wheat

The measured safe storage times at 17 and 19% m.c. were combined to develop a safe storage model that included the effects of both temperature and moisture content. The Eq. 9 was modified to include the effect of moisture content.

$$\text{Log } T = 4.909 - 0.050\,\theta - 0.149\,M \quad \text{.....(10)}$$

The above equation is valid at 19% and 35 to 10°C; and at 17% and 35 to 25°C. The coefficient of determination of the above equation was 0.97.

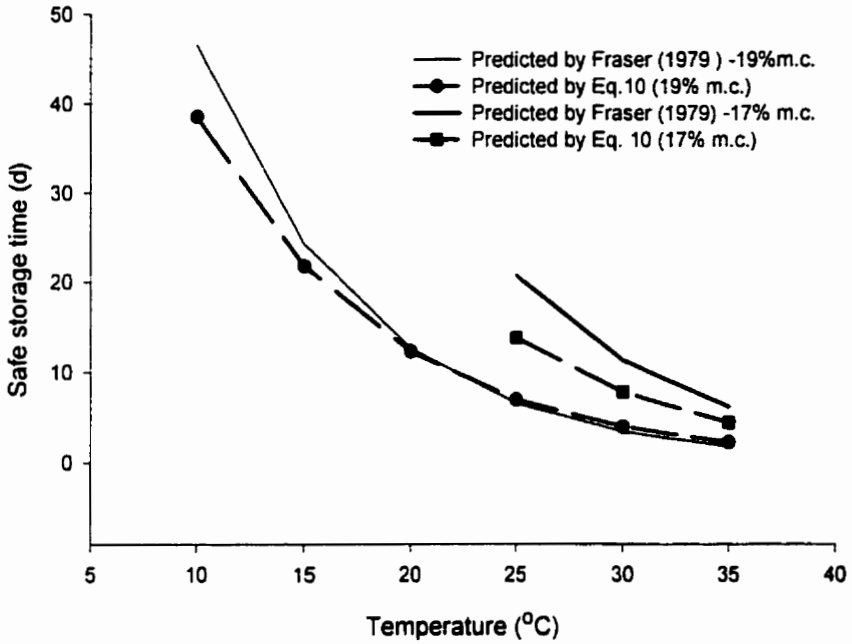

Fig. 11. Comparison of safe storage times of high moisture content wheat (17 & 19%).

The safe storage times predicted by Eq. 10 were compared with the predicted values from Fraser (1979) at both moisture contents (Fig. 11). At 19% m.c., both predictions were close except at 10°C, whereas at 17% m.c., the model (Eq. 10) predicted shorter storage times than Fraser (1979) although it agreed with my measured values at 35 to 25°C (Section 4.2).

5. DISCUSSION

5.1. Deterioration of 19% moisture content wheat

The deterioration of wheat stored at constant high temperatures (35 and 30°C) occurred more rapidly than at other temperatures. The deterioration rate seemed to occur faster at 30°C than at 35°C. This may be due to the differences in microflora species at these two temperatures. At 30°C, infection levels were higher for *A.candidus* and *Penicillium* and lower for *A.glaucus* and *A.flavus* than at 35°C. This kind of result may be compared with the results observed by White et al. (1982), in which the germination of 19% m.c. wheat measured after 7 d of storage time is less at 20°C than at 30°C due to the higher level of infection of *Penicillium* at 20°C. My germination percentages of 19% m.c. wheat stored at constant temperatures of 30, 20, and 10°C after 7 d as calculated by Eq. 8 were compared (Table VIII) with those of White et al. (1982).

Table VIII. Comparison of the germination percentage of 19% m.c. wheat after 7 d of storage at different temperatures.

Temperature (°C)	Germination percentage	
	My results	White et al. (1982)
30	<60	75
20	95	60
10	98	98

Safe storage times of 19% m.c. wheat predicted by Eq.10 were also compared (Fig. 12) with the experimental results from Wallace et al. (1983). The lowest safe storage time of the given

range was selected from Wallace et al. (1983) because they define safe storage time as the time for germination to drop to 85%. My predicted times for a drop to 90% germination were between their safe storage times for 21.3 – 22.2 and 17.3–18.5% m.c. wheat.

To predict the safe storage times of grain stored with a step decrease in the storage

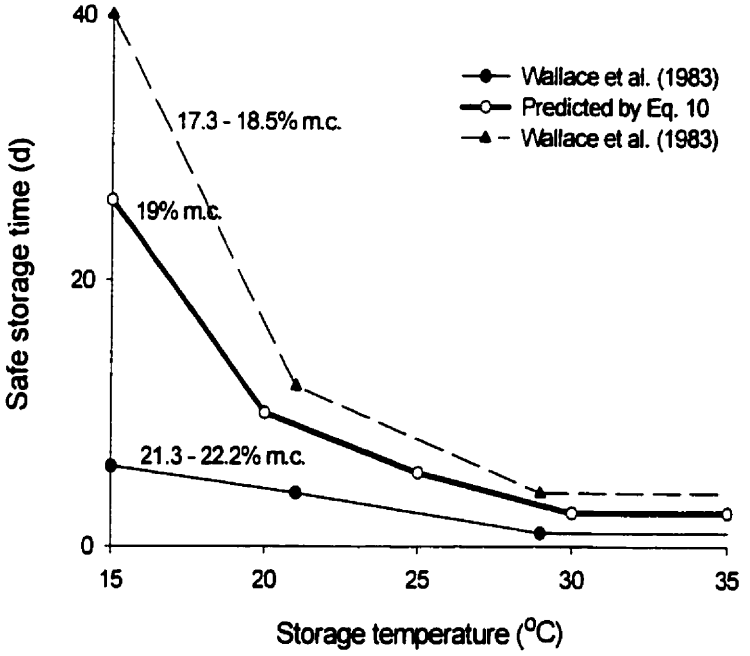

Fig. 12. Safe storage time of 19% m.c. wheat compared with Wallace et al. (1983).

temperatures, the model proposed by Schroth et al. (1998) was used. This model predicted the safe storage times by applying Eq. 8 at successive storage temperatures. The germination curves at the highest and lowest storage temperatures were drawn using Eq. 8. At the time the temperature was reduced, the germination curve at the lowest temperature was shifted and joined with the highest temperature germination curve to predict the safe storage time.

This model predicted the safe storage times well (Fig. 7) except when the temperature was reduced from 30 to 20°C. Schroth et al. (1998) also reported that their developed model predicted safe storage time less than the measured value when the temperature was dropped from 30 to 20°C. Sanderson et al. (1989) measured slower deterioration rates than predicted by Fraser (1979) and suggested a D.I. higher than 1 could be used. But safe storage times predicted by applying Eq. 9 and Fraser's model (Eq. 3) with D.I. of 1 predicted safe storage times higher than the measured values (Fig. 13). A D.I. of only 0.8 predicted the measured values (section 4.1.3). Hence this method may not be applied to predict the safe storage times. Fraser's model was based on Kreyger's data (Kreyger 1972) in which deterioration rates are determined for grains stored in the temperature range 5 to 25°C.

The results from drying experiments showed that, Fraser's model predicted deterioration faster than it actually occurs (Sanderson et al. 1989). This may be due to the low temperatures encountered during the drying experiments, that might have delayed the deterioration rates. For example, in the drying experiments in 1985, the temperature of the grain was above 10°C for about 10 d, between 10 and 0°C for 2 mo, and between 0 and –20°C for 4 mo while the moisture content was between 20 –19%. When the temperature is dropped suddenly from the optimum range for the growth of fungi, development of fungi will be delayed. The growth of microflora is slowed down after the temperature is dropped which is indicated by the percentage of seeds infected by microflora (Sanderson et al. 1989). This may be the reason for the reduced deterioration rates in the drying experiments.

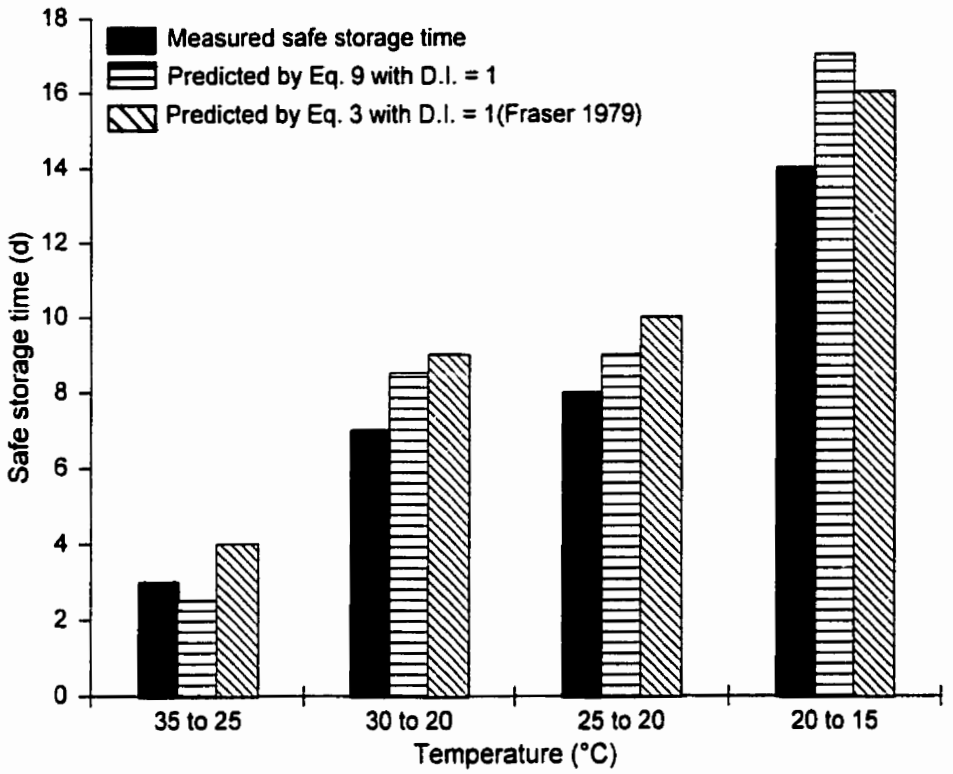

Fig. 13. Comparison of safe storage time of 19% m.c. wheat stored with a step decrease in storage temperatures.

Schroth et al. (1998) also reported that when the temperature is reduced from 30 to 20°C, which is below the optimum temperature for fungal growth, the reduction in the deterioration rate of wheat could not be adequately predicted.

5.2 Deterioration of 17% moisture content wheat

The safe storage times for 17% m.c. wheat, predicted by Eq. 10 were satisfactorily between the safe storage times of 17.3 – 18.5 and 15.9 – 16.6% m.c. grain (Wallace et al. 1983)(Fig. 14) .

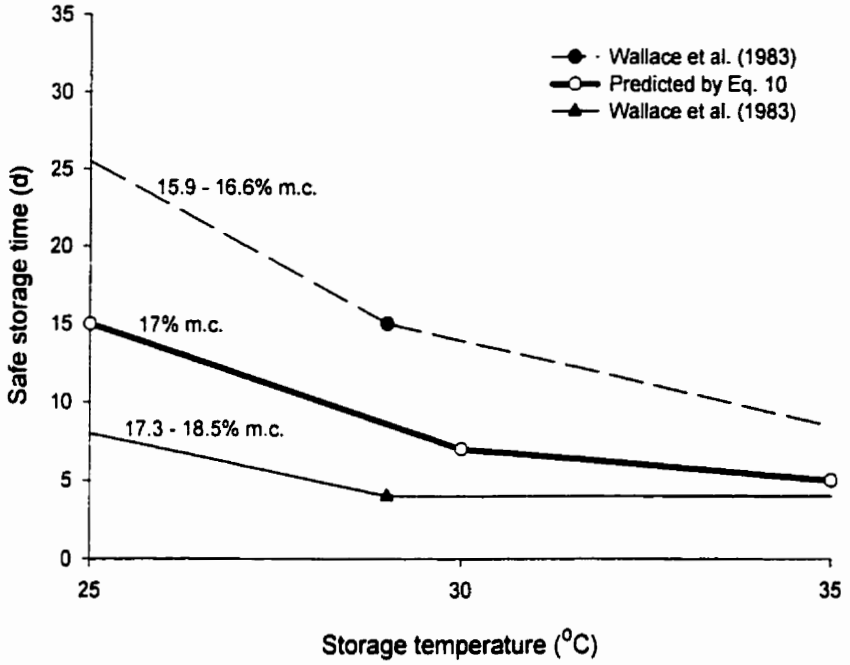

Fig.14. Safe storage time of 17% m.c. wheat compared with Wallace et al. (1983).

The deterioration rates of three cultivars of hard red spring wheat; 'Domain', 'Katepwa', and 'Barrie'; were significantly different from each other (Fig. 10). Safe storage times of 'Domain' were highest of the three cultivars. To determine the deterioration rates of 'Katepwa' (Schroth 1996) and 'Domain' (Schroth et al. 1998) the test grains were mixed throughly by hand each time they were sampled. Fungal growth may have been interrupted by the sampling and mixing procedure. In spite of the same test method and some of the grain dried below 16% m.c. during the tests with 'Katepwa' (Schroth 1996), the safe storage times of 'Katepwa' are less than 'Domain'. In this study the sample grains were stored strictly at 17±0.5% m.c. The test grains were sampled and moisture contents were measured

without disturbing them. Tests in which the sample grains dried below 16.5% were repeated. But my measured safe storage times for 'Barrie' were less than for the other two cultivars. These considerations lead to the conclusion that varietal differences may have some effect on the safe storage time.

5.3 Microflora and free fatty acid values

In my study, mould growth was visible in 19% m.c. grain stored at 25°C on day 5 which was visible on day 7 in a study by Hamer et al. (1991). White et al. (1982) reported visible moulds occur on grains of moisture contents greater than 17.4% stored at 30°C in 11 d while in my study mould was visible on 17% m.c grain at 30°C in 13 d. The absence of mould growth on grains of moisture contents greater than 18.4% stored at 10°C for 35 d (White et al. 1982) and the presence of bacteria on 19% m.c. grain at 30°C (Sinha et al. 1985) agrees with my results. Schroth (1996) reported that mould growth became visible in 17% m.c. grains in 5 d after germination dropped to 90% whereas it was visible when the germination is 92% (Schroth et al. 1998). High infection levels of *Penicillium* at low temperatures and *A.glaucus* at high temperatures were observed. The FAV values increased with an increased temperature and storage time.

6. CONCLUSIONS

1. The deterioration rates of 19 and 17% m.c. wheat stored at constant temperatures can be predicted by an equation of the form:

$$G = \frac{I}{\left[1 + \left(\frac{t}{c}\right)^{b}\right]^{e}}$$

where: G = germination (%);

I = initial germination (98%);

t = storage time (d);

b, c, and e are constants for each moisture content.

The above equation is valid for wheat of 19% m.c. stored at 35 to 10°C and 17% m.c. stored at 35 to 25°C.

2. The safe storage time, defined by a germination drop to 90%, of 19% m.c. wheat stored at constant temperatures increased from 2.5 d at 35°C to 37 d at 10°C. The safe storage time of 17% m.c wheat increased from 5 d at 35°C to 15 d at 25°C.

3. Mould growth became visible only after the germination dropped well below 90% in 19 and 17% m.c. wheat.

4. The deterioration rate of 19% m.c. wheat stored with a step decrease in the storage

temperature can be predicted from the germination curves obtained at constant storage temperatures.

5. The deterioration rates of cultivars 'Domain', 'Katepwa', and 'Barrie' were different. 'Domain' had the longest storage time and 'Barrie' had the shortest storage time.

6. The safe storage times of 19 and 17% m.c. wheat stored at constant temperatures can be predicted by the equation

$$\text{Log } T = 4.909 - 0.05\,\theta - 0.149\,M$$

where: T = safe storage time (d);

θ = storage temperature (°C);

M = moisture content (%, wet basis).

valid at: 19% m.c, at 10 to 35°C and 17% m.c., at 25 to 35°C.

7. RECOMMENDATIONS FOR FUTURE RESEARCH

1. Compare the deterioration rates of several cultivars of wheat harvested in the same year and same location, and compare the deterioration rates of disturbed and undisturbed grains during storage.

2. Determine the deterioration rates of freshly harvested wheat and wheat of the same cultivar stored dry for selected time intervals. The deterioration rates determined for wheat at a particular time are different from the deterioration rates determined after 4 mo (Schroth 1996).

3. Determine the deterioration rates of wheat stored with decreasing temperatures. The decrease in the storage temperatures should correspond to the temperature profiles from drying experiments (Sanderson et al. 1989).

4. Determine the deterioration rates of wheat at moisture contents greater than 19%. Combining the results from all wheat deterioration studies will be useful in developing a safe storage time chart for a range of moisture contents and temperatures.

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APPENDIX A: Germination data

Table A.1. Germination (%) of 19% m.c. wheat stored at constant temperatures.

35°C

Storage time (d)		0.5	1	1.5	2	2.5	3	4	5	6	7
Replicate	a	94	94	92	94	94	92	76	48	36	18
	b	96	92	94	82	86	90	76	62	38	18
	c	96	94	92	86	90	90	74	68	32	18
Mean		95.3	93.3	92.7	87.3	90.0	90.7	75.3	59.3	35.3	18.0
s.d.*		1.7	1.8	1.8	9.3	6.3	1.6	1.1	11.8	3.3	0.0

30°C

Storage time (d)		0.5	1	1.5	2	3	4	5	6	7	8
Replicate	a	94	100	100	94	80	70	70	32	18	12
	b	96	96	96	84	74	68	68	42	20	12
	c	90	84	88	74	82	62	62	50	18	10
Mean		93.3	93.3	94.7	84.0	78.7	66.7	66.7	41.3	18.7	11.3
s.d.		3.3	7.4	5.6	10.0	5.9	3.7	3.7	9.4	9.4	1.1

25°C

Storage time (d)		2	3	4	5	6	9	10	11
Replicate	a	98	100	98	90	86	60	30	16
	b	100	92	94	94	90	52	22	14
	c	94	96	92	84	88	44	28	16
Mean		97.3	96.0	94.7	89.3	88.0	52.0	26.7	15.3
s.d.		3.3	6.3	3.4	5.8	3.2	8.0	6.6	1.8

20°C

Storage time (d)		2	4	6	9	10	12	14	18	20	22
Replicate	a	96	98	88	92	86	80	72	56	34	24
	b	100	98	94	88	92	84	78	60	26	12
	c	96	100	100	92	94	88	80	60	38	40
Mean		97.3	98.7	94.0	90.7	90.7	81.3	76.7	58.7	32.7	25.3
s.d.		3.5	1.1	6.0	3.5	4.9	3.5	4.9	3.1	8.3	16.4

15°C

Storage time (d)		3	6	10	13	17	21	25	32	39	44
Replicate	a	96	94	94	90	92	92	88	76	56	52
	b	100	98	96	94	94	94	96	88	70	68
	c	100	92	90	94	94	92	84	82	64	56
Mean		98.7	94.7	93.3	92.7	93.3	89.3	82.0	82.0	63.3	58.7
s.d.		3.1	4.1	3.3	3.1	1.6	1.8	8.3	9.5	11.0	13.2

10°C

Storage time (d)		5	10	15	20	25	35	45	55
Replicate	a	94	96	96	96	96	96	78	50
	b	98	94	94	96	92	96	72	60
	c	96	96	96	96	92	86	64	64
Mean		96.0	95.3	95.3	96.0	93.3	92.7	71.3	58.0
s.d.		3.2	1.8	1.8	0.0	3.1	3.1	6.7	8.4

**Standard deviation of the replicates from the mean.

Table A.2. Germination (%) of 19% m.c. wheat stored with a step decrease in the storage temperatures.

35 to 25°C

Storage time (d)		2	5	8	10
Replicate	a	92	78	56	56
	b	90	80	54	46
	c	92	78	50	48
Mean		91.3	78.7	53.3	50.0
s.d.*		1.8	1.8	2.8	7.8

30 to 20°C

Storage time (d)		2	4	9	13	16	22
Replicate	a	90	98	86	82	66	36
	b	98	90	86	78	74	48
	c	90	94	90	84	80	52
Mean		92.7	94.0	87.3	81.3	73.3	45.3
s.d.		7.1	6.3	2.1	4.1	7.4	9.9

25 to 20°C

Storage time (d)		3	7	9	14	21	32
Replicate	a	86	92	82	62	42	28
	b	92	92	96	60	44	36
	c	90	90	92	80	54	44
Mean		89.3	91.3	90.0	67.3	46.7	36.0
s.d.		4.7	1.1	10.9	10.5	5.7	8.0

20 to 15°C

Storage time (d)		3	5	8	11	14	16	18	23	30
Replicate	a	98	98	98	86	90	84	66	40	42
	b	92	96	98	88	90	82	70	54	52
	c	100	98	100	96	84	86	48	44	36
Mean		96.7	97.3	98.7	90.0	88.0	84.0	61.3	46.0	43.3
s.d.		5.9	1.8	1.1	4.7	3.2	2.5	11.6	11.5	10.7

• Standard deviation of the replicates from the mean.

Note: The step decrease in the storage temperatures were after 36 h, 36 h, 3 d, and 7 d at 35, 30, 25, and 20°C, respectively.

Table A.3. Coefficients of the germination equation (Eq. 8) for 19% m.c. wheat stored with a step decrease in storage temperatures.

Temperature (°C)	Coefficients			R^2
	b	c	e	
35 to 25	2.03	7.25	0.67	0.97
30 to 20	2.53	94.02	29.52	0.97
25 to 20	4.53	9.34	0.19	0.98
20 to 15	8.70	13.22	0.13	0.97

Table A.4. Germination (%) of 17% m.c. wheat at constant temperatures.

35°C

Storage time (d)		3	7	10	17	23
Replicate	a	90	74	62	50	44
	b	94	82	66	54	44
	c	92	80	70	46	22
Mean		92.0	78.7	66.0	50.0	36.7
s.d.*		3.2	6.2	4.0	4.9	11.6

30°C

Storage time (d)		3	7	9	11	13	15	17	19	23	27
Replicate	a	98	96	90	90	72	64	70	52	44	34
	b	98	92	90	86	78	54	50	54	52	50
	c	94	86	86	92	78	54	50	54	52	50
Mean		96.7	91.3	88.7	89.3	76.0	57.3	56.7	53.3	49.3	44.7
s.d.		2.1	4.7	2.1	4.1	4.7	7.8	15.6	1.6	6.3	12.5

25°C

Storage time (d)		6	12	24	30
Replicate	a	96	90	58	28
	b	96	92	64	40
Mean		96.0	91.0	61.0	34.0
s.d.		0.0	1.4	4.2	8.5

* Standard deviation of the replicates from the mean.

APPPENDIX B: Microflora data

Table B.1. Microflora* of 19% m.c. wheat stored at constant temperatures.

Temperature (°C)	Replicate	Percent of seeds infected by				
		A.glaucus	*A.candidus*	*A.flavus*	*Penicillium*	*Fusarium*
35_5	a	33	26	8	4	0
	b	30	0	66	0	0
	c	0	0	0	0	0
35_{10}	a	56	38	22	0	0
	b	46	32	12	12	0
	c	40	38	10	14	0
30_4	a	8	24	0	12	0
	b	12	16	0	8	4
	c	8	24	0	8	0
30_9	a	12	68	0	12	0
	b	12	52	0	20	0
	c	12	48	0	24	0
25_5	a	4	12	0	0	4
	b	8	12	0	4	0
	c	4	8	0	4	0
25_{11}	a	28	32	0	20	0
	b	28	40	0	16	0
	c	40	28	0	28	0
20_{12}	a	16	16	4	30	0
	b	8	22	4	14	0
	c	12	32	0	16	0
20_{20}	a	22	28	0	44	0
	b	14	30	0	48	0
	c	12	52	0	30	0

* The microflora were present on the respective storage days as indicated by the subscripts at each temperature.

Table B.2. Microflora* of 19% m.c. wheat stored with a step decrease in the storage temperatures.

Temperature (°C)	Replicate	Percent of seeds infected by			
		A.glaucus	*A.candidus*	*A.flavus*	*Penicillium*
35 to 25_6	a	64	20	24	12
	b	36	16	4	4
	c	40	28	4	12
30 to 20_{13}	a	64	28	12	0
	b	60	16	12	12
	c	64	20	12	8
25 to 20_{11}	a	44	28	4	16
	b	32	20	12	16
	c	20	12	8	16
20 to 15_{17}	a	24	0	40	8
	b	28	4	32	12
	c	24	8	20	16

* The microflora were present on the respective storage days as indicated by the subscripts at each condition.

Table B.3. Microflora* of 17% m.c. wheat stored at constant temperatures.

Temperature (°C)	Replicate	Percent of seeds infected by			
		A.glaucus	*A.candidus*	*A.flavus*	*Penicillium*
35_7	a	52	32	16	8
	b	56	32	28	0
	c	60	28	12	8
30_{13}	a	56	16	20	4
	b	44	8	10	8
	c	64	20	8	20
25_{24}	a	16	28	0	16
	b	28	20	8	12

* The microflora were present on the respective storage days as indicated by the subscripts at each temperature.

APPENDIX C: Free fatty acid values

Table C.1. Free fatty acid values* of 19% m.c. wheat stored at constant temperatures.

Temperature (°C)	Replicate	Fat acidity value (mg KOH/ 100 g of dry grain)	
$35_{5, 10}$	a	$n.d_5$	56.70_{10}
	b	n.d	53.43
	c	n.d	84.64
$30_{4, 9}$	a	21.39_4	36.77_9
	b	22.49	34.81
	c	25.28	34.12
$25_{5, 11}$	a	15.73_5	24.27_{11}
	b	14.82	22.47
	c	14.69	23.98
$20_{12, 20}$	a	11.85_{12}	30.23_{20}
	b	10.62	26.79
	c	11.03	25.33

* The FAV were determined on the respective storage days as indicated by the subscripts at each temperature.
n.d - not determined.

Table C.2. Free fatty acid values of 19% m.c. wheat stored with a step decrease in storage temperatures.

Temperature (°C)	Replicate	Fat acidity value (mg KOH/ 100 g of dry grain)
35 to 25_6	a	27.37
	b	28.19
	c	24.10
30 to 20_{13}	a	15.93
	b	15.93
	c	13.89
25 to 20_{11}	a	63.07
	b	73.53
	c	71.57
20 to 15_{17}	a	n.d
	b	59.48
	c	39.22

* The FAV were determined on the respective storage days as indicated by the subscripts at each condition.
n.d - not determined.

Table C.3. Free fatty acid values of 17% m.c. wheat stored at constant temperatures.

Temperature (°C)	Replicate	Fat acidity value (mg KOH/ 100 g of dry grain)
35_7	a	28.56
	b	26.70
	c	29.41
30_{13}	a	22.87
	b	22.60
	c	20.14
25_{24}	a	17.90
	b	17.90

*The FAV were determined on the respective storage days as indicated by the subscripts at each temperature.