ON-FARM BLAST FREEZING OF SASKATOON BERRIES

BY

NEIL STEPHENSON

A Thesis

Submitted to the Faculty of Graduate Studies

in Partial Fulfillment of the Requirements

for the Degree of

MASTER OF SCIENCE

Department of Biosystems Engineering

University of Manitoba

Winnipeg, Manitoba

THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES

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ABSTRACT

Saskatoon berries are grown primarily in the Prairie Provinces in Canada, and the Plains of the United States. Saskatoon yields range from 3250 to 8750 $kg \cdot ha^{-1}$, with a harvest length between 1 and 4 wk. To extend the time period of availability of saskatoons and to increase market flexibility, freezing of saskatoons has been considered a valuable technology .

Experiments were performed with individual saskatoon berries under controlled conditions to determine freezing characteristics. The air velocity, the temperature of the freezing air, and their interaction were statistically significant ($P>0.0001$) on the time for saskatoon berry to drop in temperature from 0 to –10°C.

A 2.2 kW (3 hp) prototype freezer was designed and constructed on a saskatoon farm, and tested in the 1999 and 2000 harvest years. At the beginning of a harvest day, the temperature of the prototype freezer was below –20°C, the initial temperature of berries entering the chamber was approximately 5°C, and the berries reached a temperature of –10°C within 1h. At the end of a harvest day, the chamber temperature had risen to –12°C, the initial temperature of the berries was between 15 and 20°C, and the time for the berries to reach –10°C was greater than 4 h. The extended freezing time indicated that the prototype freezer was overloaded by the quantity of saskatoons in the chamber and the higher initial temperature of the berries. As a result of freezing; changes in colour were considered negligible; the loss of anthocyanin content was 23 % and 30 % in the 1999 and 2000 harvest years, respectively; the loss of benzaldehyde content was 28 % in the 1999 harvest year; there was no recognizable pattern in changes to total acidity (malic acid); and the loss of soluble solids (sugars) was 22.2 % and 4.4 % in the 1999 and 2000 harvest years, respectively. The cost to purchase and operate the $25 000 prototype freezer and a $15 000 storage freezer for a 2 ha producer, both amortized over 10 yr, was estimated at $0.87/kg.

In conclusion, on-farm blast freezing of saskatoons is a viable option for value-added processing at the farm gate.

ACKNOWLEDGMENTS

For giving me the opportunity to complete my Masters degree under his supervision, Dr. Cenkowski deserves my recognition and respect. Thanks to Dr. Muir and Dr. Izydorczyk for being on my committee and for their guidance during my research

Thanks to the Biosystems Engineering technicians, Dale Bourns, Matt Mcdonald, and Jack Putnam for their ideas, expertise, and all around helpfulness.

My appreciation to John, Kim, and the Ritz family of Prairie Lane Saskatoons, for allowing me to conduct experiments and permitting me to stay with them during the saskatoon harvest.

I would like to thank Seema Hegdekar for her help in setting up the quality analysis tests and Erin Searcy for her help in conducing experiments. My gratefulness to the Department of Food Science, their graduate students, and their technicians for access to the freezers, lab space, equipment, and for always willing to lend a helping hand.

This project was funded by the Manitoba Rural Adaption Council (MRAC). They deserve recognition as their support made this research possible.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

Saskatoon berries, also known as June berries, are grown primarily in the Prairie Provinces of Canada, and the Plains of the United States. Saskatoon berries grow on bushes, are spherical in shape, have a diameter of approximately 12 mm, and have a purple colour when ripe. In the Prairie Provinces of Canada, saskatoon berries are harvested in July.

Estimates of saskatoon berry production in Alberta, Saskatchewan, and Manitoba is approximately 500 to 800 ha (St-Pierre et al. 1997). With ideal growing conditions, saskatoon yields range between 3250 and 8750 $kg \cdot ha^{-1}$. The length of the saskatoon harvest ranges from 1 wk to 4 wk. With a short harvest season, many producers may not be able to harvest and sell their entire crop.

Freezing of saskatoons on the farm will increase market flexibility for producers, processors, and consumers by extending the length of time saskatoons are available. Markets for frozen saskatoons include both unprocessed berries and processed products such as pies, sauces, and yogurts.

The rate at which a food product is frozen affects the quality. The expansion of water as it freezes causes an increase of pressure within cells, causing the cell walls to break (Mogens 1984). The purpose of freezing saskatoons at a fast rate is to preserve the quality of the berries.

2. OBJECTIVES

The objective of this research was to design and evaluate the performance of an air-blast freezing system. The air-blast freezing system was evaluated by:

i. determining freezing characteristics of individual saskatoons, and comparing with an existing freezing formula,

ii. analysing time-temperature data of saskatoons frozen in the prototype freezer,

iii. performing quality analyses on fresh and frozen saskatoons to determine the effect of freezing,

iv. conducting experiments to observe the movement of sugars in saskatoons as a result of freezing, and

v. analysing freezing economics.

3. LITERATURE REVIEW

3.1 Background information on saskatoon berries

3.1.1 History of saskatoon production: Wild saskatoon berries (Amelanchier alnifolia Nutt.) were a staple food for natives and early settlers (Green and Mazza 1986, Mazza and Hodgins 1985, St-Pierre et al. 1997) Commercial saskatoon orchards began in the 1970's, with Smoky being the main cultivar planted. Figure 3.1 shows a clump of saskatoon berries in a commercial orchard. Several other cultivars include Pembina, Northline, Thiessen, Martin, and Honeywood (St-Pierre et al. 1997). Interest in commercialization of saskatoons increased in the 1980's and 1990's, with estimates of production area expanding to approximately 500 to 800 ha of in Alberta, Manitoba, and Saskatchewan (St-Pierre et al. 1997). Saskatoon production is predicted to eventually reach 4000 ha in the prairie provinces (St-Pierre et al. 1997).

Fig. 3.1 A clump of saskatoon berries at the end of a branch (St-Pierre et al. 1997).

3.1.2 Composition of saskatoons: Major chemical components of saskatoons include water, sugar, protein, fat, and fibre. Typical values of these components are a moisture content of 75 to 80 % (wet basis), 11 to 19 % sugar, 1.9 to 9.7 % protein, 0.8 to 4.2 % fat, and 3.8 to 19% fibre (St-Pierre et al. 1997).

Several factors that affect saskatoon quality include orchard management, cultivar, and growing conditions (St-Pierre et al. 1997). Quality of saskatoons is determined by physical, chemical, and sensory characteristics. Physical characteristics include size, texture, viscosity, colour, and firmness. Moisture content, anthocyanins, benzaldehyde, acidity , and sugars are included in chemical analyses (St-Pierre et al. 1997). Evaluation of sensory characteristics include smell, touch, and taste.

Differences in quality of saskatoons is easier to represent and compare when quantified. Tests performed by Green and Mazza (1986) and Mazza and Hodgins (1985) that were used to quantify saskatoon quality include colour, anthocyanins, benzaldehyde, total acidity acid, and soluble solids.

Analysis of colour is performed with a Hunterlab Colorimeter, which gives a numerical value to lightness or darkness, redness or greenness, and blueness or yellowness (Green and Mazza 1986). Anthocyanins are responsible for the red and blue colours of saskatoons. The main anthocyanin found in saskatoons is cyanidin-3-galactoside (Green and Mazza 1986). Benzaldehyde is a chemical that is responsible for the aroma of saskatoons and produces an almond flavour in cooked saskatoons (Mazza and Hodgins 1985).

Total acidity is used as a measure of organic acids. Soluble solids represent the sugar content of saskatoons (St-Pierre et al. 1997). The primary sugars found in saskatoons are glucose and fructose. A soluble solids-acidity ratio is used to help determine ripeness of saskatoons (Green and Mazza 1986).

3.2 Freezing equipment

3.2.1 Air-blast room and tunnel freezers: Figure 3.2 illustrates an air-blast tunnel freezer, in which the product is positioned and moved manually. Air-blast room and tunnel freezers can accommodate any size and shape of products that can be frozen (Cleland and Valentas 1997, Fellows 1988, Heldman and Singh 1981). The simplicity of this design makes this system advantageous over other systems. Moisture that is picked up from the food product collects as ice on the evaporator coils. Therefore, evaporator coils need to be defrosted periodically, interrupting the operation of the freezing system. Other disadvantages include the non-uniform air flow inside the air-blast room or tunnel, and the energy required by the fans distributing the air inside the room or tunnel.

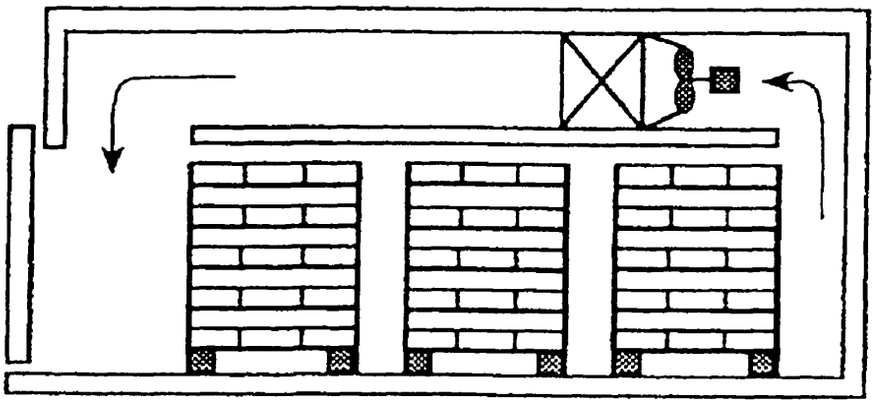

Fig. 3.2 Schematic diagram of an air-blast tunnel freezer with horizontal air flow created by fans. Product is placed on racks and manually positioned inside the tunnel (Cleland and Valentas 1997).

3.2.2 Spiral belt freezers: For processing larger volumes of product, an automatic conveying system is desired, such as a spiral belt freezer (Fig 3.3). The flexibility in design allows for control of residence times and the ability to stack the belts to minimize the required floor space. Even placement and uniform product shape is essential for even air distribution and freezing rate (Cleland and Valentas 1997, Fellows 1988, Heldman and Singh 1981). The disadvantage of the spiral belt freezer over a room or tunnel air-blast freezer is the higher capital cost.

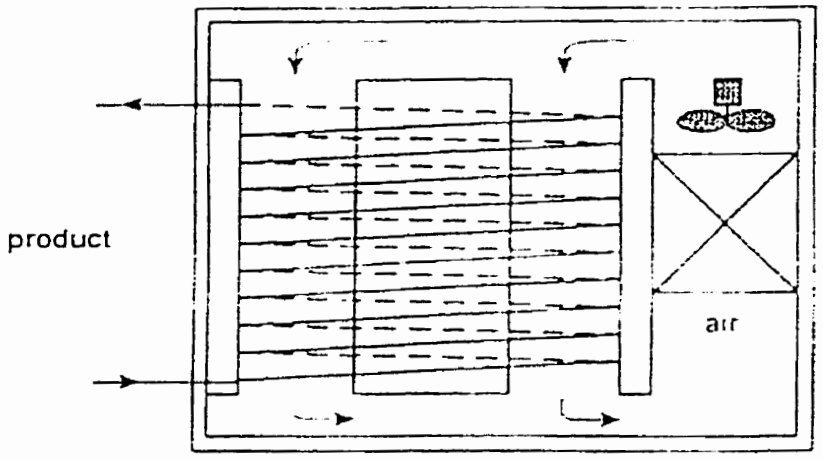

Fig. 3.3 Schematic diagram of a continuous spiral belt freezer with vertical air flow created by fans. The speed of the belt controls the resonance time of the product in the freezer (Cleland and Valentas 1997).

3.2.3 Fluidized bed freezers: Fluidized bed freezers are used to freeze individual products that are uniform in size and shape (Cleland and Valentas 1997, Fellows 1988). The product in a fluidized bed freezer is lifted by air passing through a perforated plate (Fig. 3.4). Convective heat transfer of the fluidized bed is higher than other air-blast systems. The air velocity and energy required to produce a fluidized bed is dependent on the product size (Cleland and Valentas 1997). To avoid excessive energy costs, fluidized bed freezers are most commonly used for small fruits and vegetables. The high capital cost and high energy costs of the fluidized bed freezer are disadvantages of this design (Cleland and Valentas 1997).

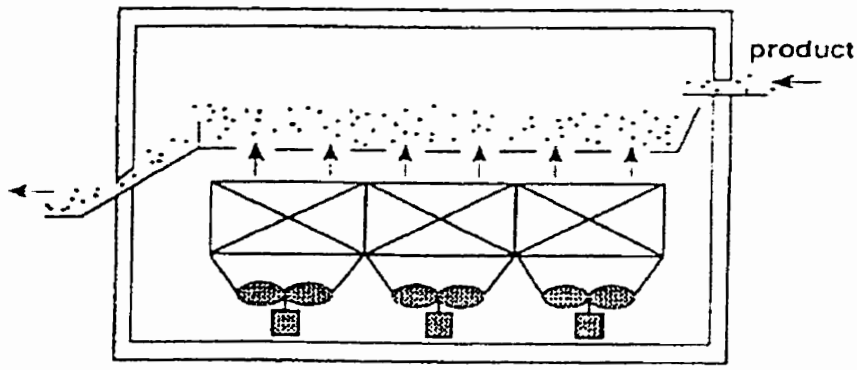

Fig. 3.4 Schematic diagram of a continuous fluidized bed freezer , with vertical air flow created by fans. Product is lifted and moved forward by the air flow (Cleland and Valentas 1997).

3.2.4 Plate freezers: Plate freezers function by direct contact between parallel flat plates and food products (Fig 3.5). A coolant is circulated through the flat plate. The product is loaded between the plates, and a hydraulic system closes the plates to produce the desired contact. Maximum contact is important for freezing rate, while spacers can be used to prevent compression of the food. The plate freezer has a higher capital cost than an air blast freezer (Cleland and Valentas 1997, Fellows 1998).

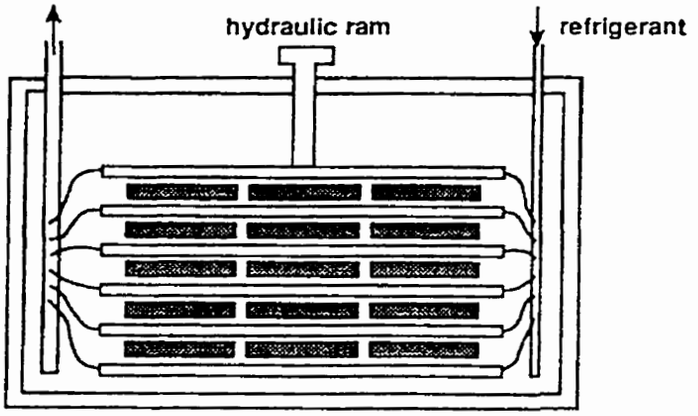

Fig. 3.5 Schematic diagram of a horizontal plate freezer with contact between the plates and product. The light rectangles are the plates and the dark rectangles are the product (Cleland and Valentas 1997).

3.2.5 Cryogenic freezers: Cryogenic freezers most commonly use liquid nitrogen and liquid or solid carbon dioxide (Cleland and Valentas 1997, Fellows 1988). Cryogens have low boiling points, –196°C for liquid nitrogen, and –79°C for liquid carbon dioxide. The low boiling point creates a large temperature difference, increasing the freezing rate. Figure 3.6 illustrates a continuous cryogenic freezer where the product is being conveyed through a tunnel. Advantages of cryogenic freezers include compact size and low cost of the equipment, while the main disadvantages are the cost and availability of cryogens. (Cleland and Valentas 1997). Cryogens may be used in combination with air-blast freezers to increase design flexibility and freezing rates (Fellows 1988).

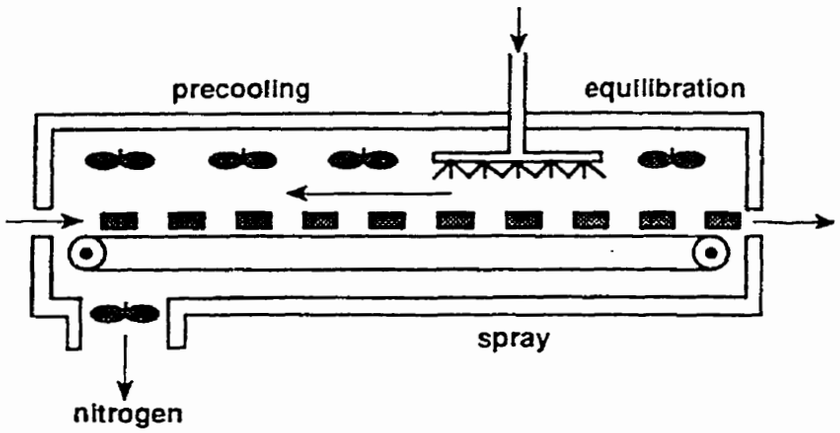

Fig. 3.6 Schematic diagram of a liquid cryogenic tunnel freezer (Cleland and Valentas 1997).

3.3 Fundamentals of freezing

3.3.1 Three stages of freezing: The freezing process can be divided into three basic stages (Fig. 3.7). The first stage involves sensible heat removal from the initial temperature to the freezing temperature. The removal of latent heat at the freezing temperature is the second stage. The third stage of freezing is the lowering of the temperature from the freezing point to the final temperature, with sensible heat removal (Heldman 1992, Reid 1997).

3.3.2 Freezing point depression: Water is a component of most food products, therefore, a freezing point near 0°C is expected (Heldman and Singh 1981, Miles et al. 1997). The magnitude of temperature depression is a function of product composition (Heldman 1992). The depression point can be determined from the following relationship (Heldman and Singh 1981, Heldman 1992):

$$\frac{\lambda'}{R_g}\left[\frac{1}{T_{Ao}} - \frac{1}{T_A}\right] = \ln X_A \qquad (3.1)$$

where:

λ' = latent heat of fusion of water (kJ·kmol^{-1}),

R_g = 8.314 kJ·kmol^{-1}·K^{-1},

T_{Ao} = freezing point of water (K),

T_A = freezing point of the food product (K), and

X_A = mole fraction of water.

The mole fraction of water is the important factor in the initial freezing point, as the rest of the components in Eq. 3.1 are constant.

The mole fraction of water is calculated as follows (Heldman 1992):

$$X_A = \frac{m_A / M_A}{m_A / M_A + m_S / M_S} \qquad (3.2)$$

where:

m_A = product moisture, wet basis (%),

M_A = molecular mass of water (g·mol^{-1}),

m_S = solids content (%), and

M_S = molecular mass of product solids (g·mol^{-1}).

Equation 3.2 is solved first, then substituted back into Eq. 3.1, to find the freezing point depression.

In Fig 3.7 a characteristic freezing curve of water and an aqueous solution is shown. Both curves show the three distinct stages in the freezing process. In the second stage, the water is crystallized from the initial freezing point to the eutectic point. As the temperature decreases below the eutectic point, both water and the solute will crystalize at a constant temperature. (Boyle et al. 1977, Heldman and Singh 1981, Heldman 1992). Eutectic points are a property of individual solutes. Foods may have more than one eutectic point, which may be hidden due to the presence of many solutes.

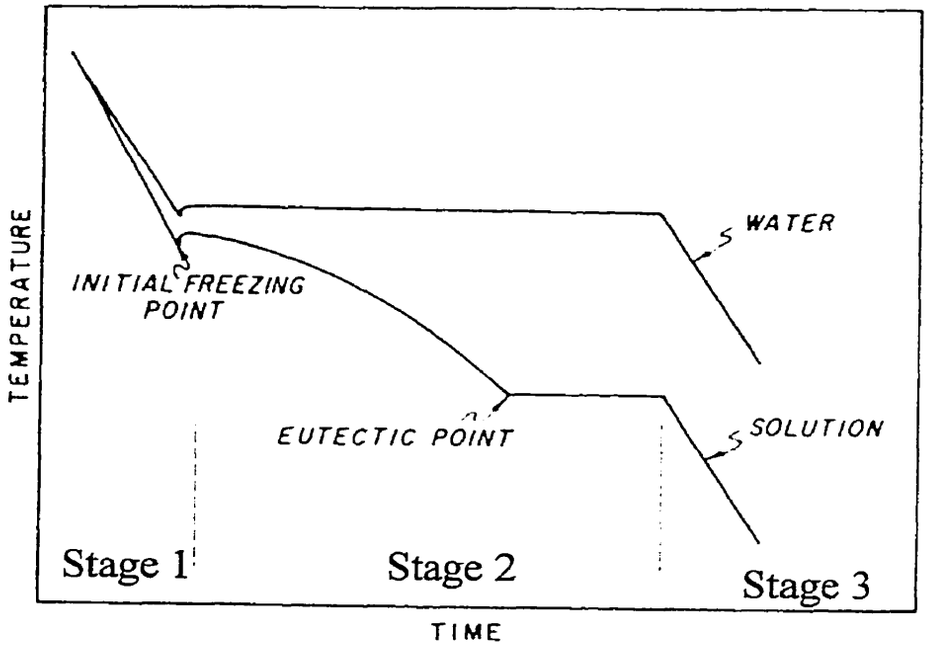

Fig. 3.7 Comparison of freezing characteristics, during the three stages of freezing, for water and an aqueous solution containing one solute (Heldman and Singh 1981).

3.3.3 Ice crystal formation: Ice crystal formation occurs in two steps: i) nucleation or crystal formation and ii) crystal growth (Heldman and Singh 1981, Leniger and Beverloo 1975). At the start of the second stage of freezing, small ice crystals will be generated. The presence of particles, which have a similar structure to ice, act as the nuclei to start the crystal formation (Heldman and Singh 1981, Shagian and Goff 1995). Figure 3.8 illustrates the effect of subcooling on crystal growth and nuclei formation. Subcooling occurs in stage two of freezing when the temperature is below the freezing point. Temperatures up to point A on Fig. 3.8 will have a slow rate of both nucleation and crystal growth. This results in the product freezing at a slow rate, generating large crystals. Temperatures below point A have a faster rate of nuclei formation and crystal growth, resulting in the product freezing faster. The increase in the number of nuclei formed reduces the possibility of larger crystals being formed (Heldman and Singh 1981, Leniger and Beverloo 1975).

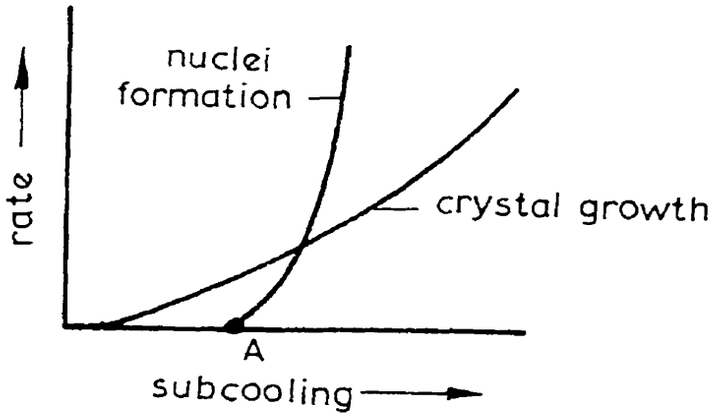

Fig. 3.8 Influence of subcooling on the nuclei formation and crystal growth (Leniger and Beverloo 1975).

After the appearance of the initial nuclei, ice crystals will begin to grow. This growth depends on several factors including; rate of heat removal, rate of reactions of water molecules at the crystal surface, and the rate of diffusion of molecules from the unfrozen solution to the crystal surface (Heldman and Singh 1981). Faster rates of freezing will see smaller ice crystals being formed. (Heldman and Singh 1981, Leniger and Beverloo 1975). Expansion of ice crystals as water freezes causes an increase of pressure within the cells, causing cell walls to break (Jul 1984, Luh et al. 1986).

3.3.4 Freezing time prediction (Plank's equation): The rate of freezing of products can be expressed in several ways including time-temperature method and velocity of the freezing front (Heldman and Singh 1981). The time-temperature method is expressed as the temperature change per unit time. This method has limited meaning because the freezing process is always changing. The velocity of the freezing front can be calculated from the definition for the time to transverse a given range of temperatures (Heldman and Singh 1981). Factors affecting the freezing rate include the temperature of the cooling medium, shape, and physical properties of the product.

There are several different methods and modifications for the prediction of freezing rates including Plank's equation, Neumann problem, Tao solutions, Tien solutions, and Mott procedure (Heldman and Singh 1981). The simplicity of Plank's equation makes it possible to detail the limitations and modifications of this method.

Plank's equation is formed from equations based on convective heat transfer, conductive heat transfer, and the velocity of the freezing front. The most general form of Plank's equation is (Heldman and Singh 1981):

$$t_f = \frac{\rho L}{T_F - T_\infty}\left[\frac{Pa}{h_c} + \frac{Ra^2}{k}\right] \qquad (3.3)$$

where:

t_f = freezing time (s),
ρ = density ($kg \cdot m^{-3}$),
L = latent heat of fusion of water ($kJ \cdot kg^{-1}$),
T_F = freezing point (K),
T_∞ = the temperature of the freezing air (K),
P, R = constants depending on the shape of the product,
a = thickness of the product (m),
h_c = convective heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$), and
k = conductive heat transfer coefficient of the product ($W \cdot m^{-1} \cdot K^{-1}$).

The limitations of the original form of Plank's equation include neglecting a change in latent heat during freezing, assuming that thermal conductivity is constant, and ignoring the sensible heat required to lower the temperature from the initial point to the freezing point and from the freezing point to the final storage temperature (Heldman and Singh 1981). In other words, Eq. 3.3 only predicts the time in stage two of the freezing process (Fig.3.7).

Plank's equation has been modified to allow for the determination of the duration of the entire cooling and freezing process. Values for P and R are modified

taking into account the Fourier number, Biot number, Plank's number, and the Stefan number. These dimensionless numbers take into consideration the thermal diffusivity, the specific heat above and below freezing, the initial temperature, and the enthalpy change during freezing.

The general Fourier number is a ratio of the heat conduction rate to the rate of thermal energy storage in a solid (Incropera and DeWitt 1990):

$$N_{Fo} = \frac{\alpha t}{a^2} \tag{3.4}$$

where:

N_{Fo} = Fourier number (dimensionless),
α = thermal diffusivity ($m^2 \cdot s^{-1}$),
t = freezing time (s), and
a = thickness of the product (m).

The Biot number represents the ratio of the internal thermal resistance of a solid to the boundary layer or external thermal resistance (Incropera and DeWitt 1990). A high Biot number means that the external resistance to heat transfer is negligible. A low Biot number has a low internal resistance, meaning the thermal conductivity is high (Singh 1992).

$$N_{Bi} = \frac{h_c a}{k} \tag{3.5}$$

where:

N_{Bi} = Biot number (dimensionless).

The influence of sensible heat above the initial freezing point is represented by Plank's number (Heldman and Singh 1981).

$$N_{Pk} = \frac{c_{pU}(T_i - T_F)}{\Delta H} \tag{3.6}$$

where:

N_{Pk} = Plank's number (dimensionless),
c_{pU} = specific heat above freezing ($kJ \cdot kg^{-1} \cdot K^{-1}$),
T_i = initial temperature (K),
T_F = freezing temperature (K), and
ΔH = enthalpy change during freezing ($kJ \cdot kg^{-1}$).

The sensible heat removal in the third stage of freezing is incorporated into the freezing time calculation with the Stefan Number.

$$N_{Ste} = \frac{c_{pl}(T_F - T_\infty)}{\Delta H} \tag{3.7}$$

where:

N_{Ste} = Stefan number (dimensionless), and
c_{pl} = specific heat below freezing ($kJ \cdot kg^{-1} \cdot K^{-1}$).

Values of P and R can be found using charts based on Plank's and Stefan numbers (Heldman 1992), or solved using equations based on dimensionless

numbers. Equations 3.8 and 3.9 are formulas for P and R for spherical geometries (Cleland and Earle 1979).

$$P = 0.1084 + 0.0924N_{pk} + N_{Ste}(0.231N_{pk} - \frac{0.3114}{N_{Bi}} + 0.6739) \quad (3.8)$$

$$R = 0.0784 + N_{Ste}(0.0386N_{Pk} - 0.1694) \quad (3.9)$$

The use of Eqs. 3.8 and 3.9 to calculate P and R improves the accuracy of the freezing time prediction, by including the three stages of freezing in Plank's equation.

4. MATERIALS AND METHODS

4.1 Single berry freezing apparatus

The main components of the apparatus used for the single berry tests consisted of a galvanized steel tube, a TA600 caged fan (Torin, Japan), a 9T92A86 variac (General Electric, Ft. Wayne, IN), an air straightener, and a 200-W heat coil (Fig 4.1). The temperature was measured using copper-constantan thermocouples connected to a Hewlett Packard 3421A (Hewlett Packard Company, USA) data acquisition system (DAS).

The galvanized steel tube was 150 mm in diameter and 800 mm long. The TA600 caged fan was mounted on one end of the tube, with the fan speed controlled by the variac. An air straightener, 150 mm in diameter and 70 mm in length, was placed on the opposite end of the tube. The meshing on the air straightener consisted of square holes with sides approximately 10 mm in length.

A copper plate was cut and moulded to fit the form of the tube. A 3 mm diameter needle 75 mm in length was soldered to the copper plate. A hole was drilled in the galvanized steel tube to place the needle through. The copper plate was fastened to the tube to keep the needle in a constant position. An elliptical hole 150 mm in length and 75 mm wide was cut in the tube to allow access to the needle. A cap was placed over the elliptical hole during testing.

The galvanized steel tube and cap were covered with a layer of bubble insulation. Another 300 mm length of non-insulated galvanized steel tube, 150 mm

in diameter, was added to the end of the insulated tube. A 110-mm diameter hole was cut in the additional length of tube in order to place the 200-W heating coil inside the apparatus.

A 30 gauge-copper constantan thermocouple was fed through the needle. The 30 gauge thermocouple was used to monitor the temperature of a single berry, and hold the single berry near the centre of the tube. Three 24 gauge copper-constantan thermocouples were placed around the berry to monitor the ambient air. One of the thermocouples was placed in front of the berry, and the other two on either side.

The DAS was used to monitor and record the temperature of the four thermocouples. The DAS was also programmed to control a relay control circuit based on the temperature of the thermocouple placed in front of the single berry. The relay circuit was used to turn the 200 W heat coil on or off as directed by the program. A desired ambient temperature was set in the program controlling the DAS, and the DAS would send a signal to the relay circuit to turn the heat lamp on or off as required to maintain the desired ambient temperature. The temperature of the chamber was colder than the desired control temperature within the freezing tube.

A wooden control box 0.6 m wide by 0.3 m high by 1.5 m long was constructed to place the entire apparatus within it, excluding the DAS. The box had a lid consisting of three removable wooden pieces, each approximately one third the length of the box.

A TA300 hot-wire anemometer (Airflow Developments Ltd., Richmond Hill, ON) was used to measure air velocities inside the freezing tunnel. The variac was set at 5% increments from 5 to 100%, and the air velocity in the galvanized steel tube recorded. The air velocity was measured at the location of a single berry.

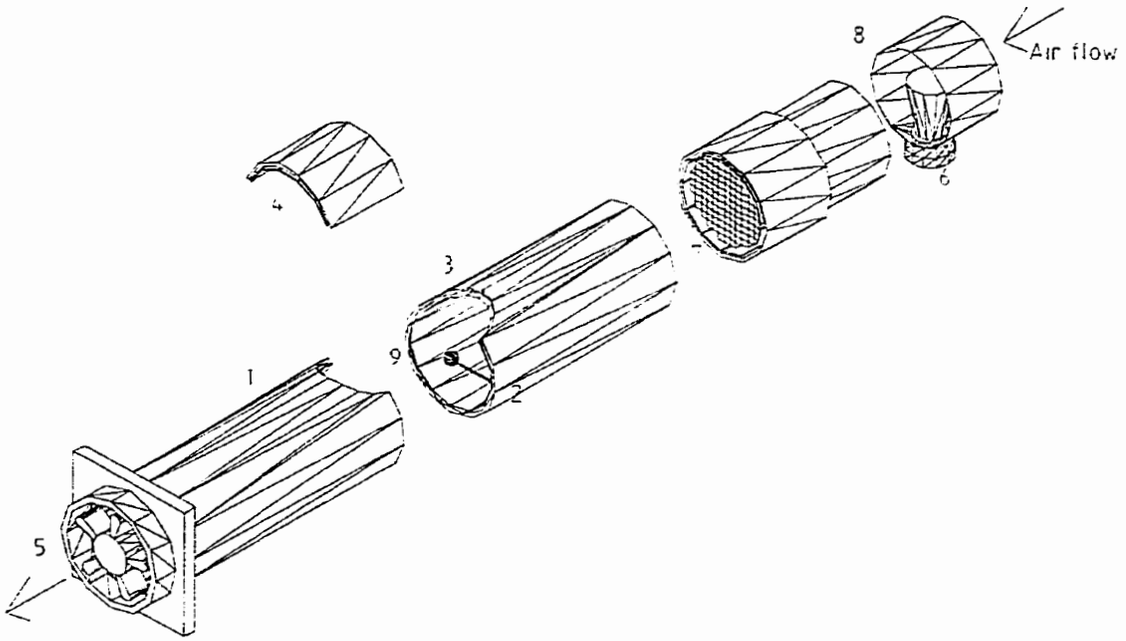

Fig. 4.1 A sectioned view of the single berry freezing apparatus showing the galvanized steel tube (1) covered in insulation, needle (2) , elliptical hole (3), cap (4), fan (5), 200-W heating coil (6), air flow straightener (7), and another section of non-insulated galvanized steel tube (8). A 30 gauge thermocouple was positioned through the needle to monitor the berry temperature (9).

4.2 Prototype freezer

The main criteria considered during the desigh of prototype freezer were cost and power requirements. The freezer was initially limited to $25 000 and single phase power. Both the spiral belt freezer and fluidized bed freezer were eliminated due to their high initial costs. The cryogenic freezer was discarded due to uncertain availability and cost of cryogens. A room air-blast prototype freezer that required single phase power was designed at the University of Manitoba in the Department of Biosystems Engineering.

4.2.1 Details of freezer: A room air-blast system was chosen over other freezing systems due to power availability on the saskatoon farm, initial cost, and operating costs.

The chamber was 2.4 m wide x 2.4 m long x 3.1 m high (Fig. 4.2). The floor, walls, and ceiling consisted of 101.6 mm of polyurethane insulation. Two insulated doors, which were 0.97 m wide by 1.98 m high were situated on opposite sides of the chamber.

A Copelametic air cooled condensing unit (model CJDL-0300) which consisted of a 2.2 kW (3hp) compressor (model 2DF3-030E) was mounted on top of the chamber (Fig. 4.2). The electrical requirement for the condensing unit was 36.7 A at single phase power and 230 V.

Mounted inside the chamber was a Blanchard Ness model SC-6040-E6 evaporator (Fig. 4.3). The model number indicated a capacity of 11 470 $kJ \cdot h^{-1} \cdot °C^{-1}$, (6040 $BTU \cdot h^{-1} \cdot °F^{-1}$), with an electric defrost and 236 fins per metre length of

evaporator (6 fins per inch). A single 0.76 m diameter fan was attached to the evaporator. The heater for the electric defrost required 32 A and the fan motor required 5.1 A, both at single phase power and 230 V. The prototype freezer was charged with R507 refrigerant.

Figure 4.2 is a picture showing the outside view of the chamber, while Fig. 4.3 is a drawing of the inside of the chamber showing the air flow through the fan, evaporator, and a stack of trays.

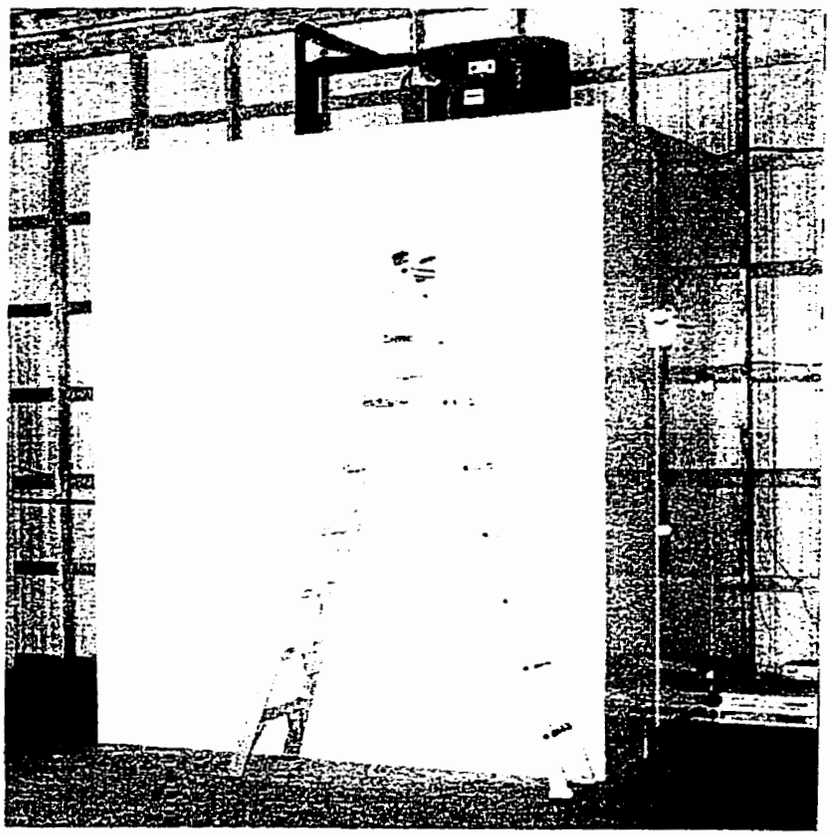

Fig. 4.2 An outside view of the prototype freezing chamber, illustrating the compressor situated on top of the chamber, and one of the doors mounted on the side of the chamber.

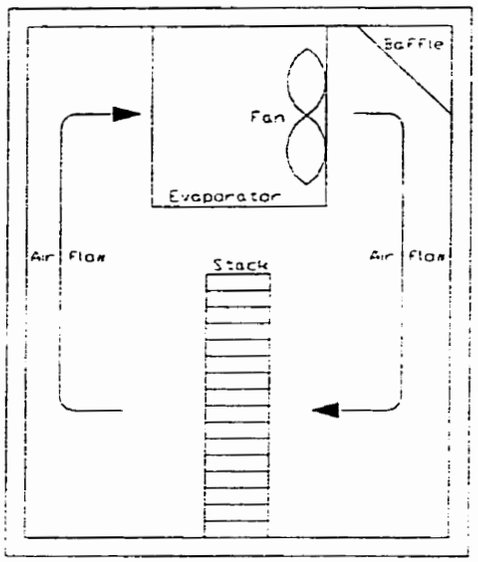

Fig. 4.3 A side-view of the freezer showing the air-flow pattern through the fan, evaporator, and a stack of trays.

4.2.2 Freezing trays used in the prototype freezer: The plastic trays used for the freezing experiments (Fig 4.4) were 470 mm long by 335 mm wide by 95 mm high. Perforations in the tray allowed for air flow, without allowing saskatoon berries to fall through the holes.

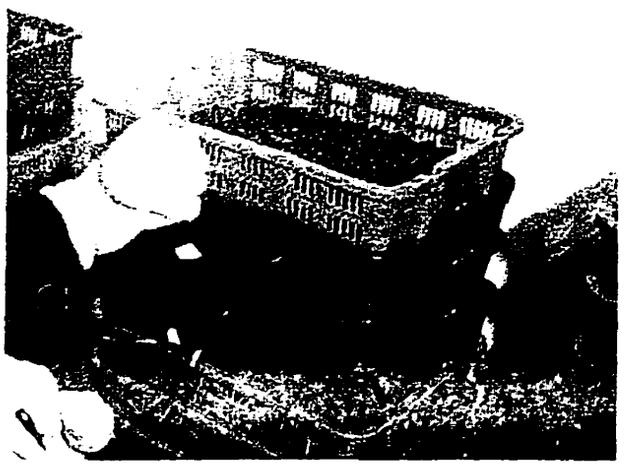

Fig. 4.4 The stackable trays used to freeze saskatoons in the prototype freezer. There are three visible thermocouple wires used to measure the berries temperature.

4.3 Harvesting and cleaning

In the 1999 and 2000 harvest years, saskatoon harvest began as early as 0530 h, and concluded at approximately 1230 h. Smoky was the variety of saskatoons grown on the orchard. Manual labour was used to harvest the berries. The berries were brought from the field to the farm yard, where they were separated from debris including leaves, soil, and rotten berries.

4.4 Single berry freezing experiments

The apparatus (Fig 4.1) was placed in an air-blast freezing chamber located at the University of Manitoba. The apparatus was set in the wooden control box. Five air velocities were used by setting the variac at 40, 50, 60, 70, and 80 %. The corresponding velocities were 2.1, 3.0, 4.2, 5.8, and 6.8 $m \cdot s^{-1}$, respectively. The control temperature of the air passing through the tube was set at –15, –20, or –25°C for each air velocity.

A single berry was weighed and measured before each experiment, with a target mass of 1 g. The system was turned on to allow the heat lamp to warm and stabilize the air at the desired control temperature. The 30 gauge thermocouple was inserted in the berry, trying to place the end of the thermocouple near the centre of the berry. The cap on the tube and the lid on the control box were replaced. The experiment was terminated when the berry was within 2 to 3°C of the control temperature. To remove the berry without damaging the thermocouple, the berry was warmed with a heat gun.

4.5 Freezing methodology for the prototype freezer: After the saskatoons were cleaned, the berries were placed in trays (Fig. 4.4). The trays were then arranged in the prototype freezer. The arrangement depended on the experiment that was being conducted.

Two types of experiments were conducted. The first, labelled Experiment A, consisted of a set arrangement of trays with either a single berry, 1.1 kg of berries,

or 2.3 kg of berries placed in each tray. The arrangement of trays is shown in Fig. 4.5.

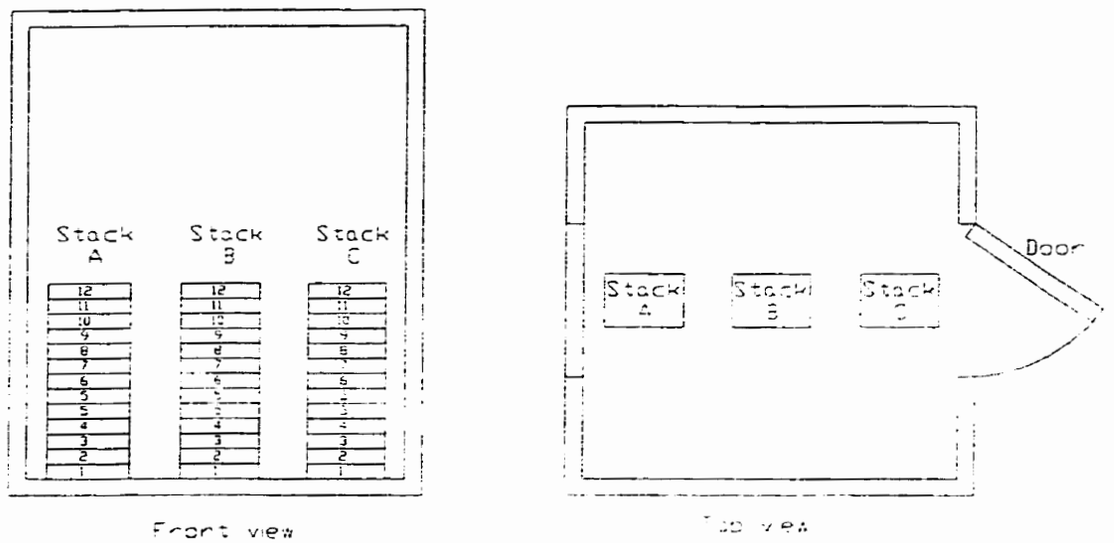

Fig. 4.5 Arrangement of trays for Experiment A with the prototype freezer.

In trays 3, 6, and 9 of all stacks, larger berries were chosen at random and a 30 gauge copper constantan thermocouple was inserted near the centre of the berry. For the single berry in a tray experiment, the berry was positioned near the centre of the tray. For the experiments with 1.1 and 2.3 kg of berries in a tray, the berry with the thermocouple inserted in it was positioned near the centre of the tray, and was buried by surrounding berries at a layer approximately half the thickness of the berries.

Experiment B was performed to observe the operation of the prototype freezer during a full harvest day. Trays with approximately 2.3 kg of saskatoons

were positioned inside the prototype freezer after the berries were cleaned, for a semi-continuos flow of saskatoons. The trays were stacked a maximum of 16 high, and the stacks were positioned to fit a maximum of 4 across the width of the chamber. The location of the 30 gauge copper-constantan thermocouple in different stacks depended on the harvest and freezing rates of the saskatoons. For example, after a thermocouple indicated a temperature below –10°C, that thermocouple was re-located. Thermocouples were only placed in trays 5 and 10 of the stacks. A thermocouple was inserted into the centre of larger berry chosen at random. The berry with the thermocouple inserted in it was positioned near the centre of the tray, and was buried by surrounding berries at a layer approximately half the thickness of the berries.

The first trays were stacked at the same end of the chamber where the fan was located, stacks A, B, C and D (Fig. 4.6). Trays were not stacked near the entry door so as not to inhibit access into the freezer. Stacks were started and finished in alphabetical order before starting the next stack. The rate that trays were brought in depended on the harvesting and cleaning rate. The stack arrangement of trays within the chamber is illustrated in Fig. 4.6.

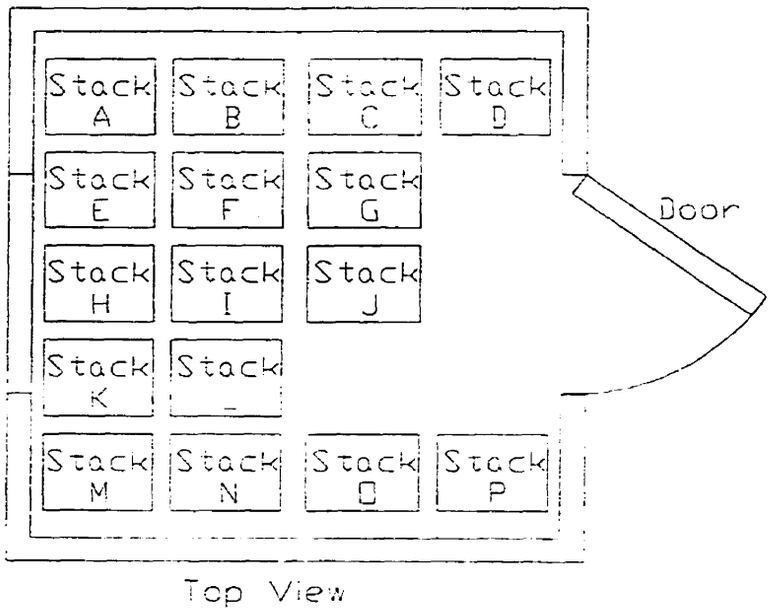

Fig. 4.6 Arrangement of stacks of trays for Experiment B with the prototype freezer.

For Experiments A and B, five copper constantan thermocouples of 24 gauge were positioned inside the chamber to monitor the air temperature. Two of the thermocouples were positioned on the wall behind evaporator, and two on the wall in front the evaporator. These thermocouples were approximately at 1.0 and 2.0 m height and at the centre of the width of the wall. The fifth thermocouple was at the centre of the chamber. The front of the evaporator was considered as the side the fan was located.

Both the 24 gauge and 30 gauge copper constantan thermocouples were connected to an Hewlett Packard HP3421A (Hewlett Packard Company, USA) data acquisition system (DAS) to monitor and record the time-temperature data.

4.6 Transportation and storage of saskatoon berries

4.6.1 Fresh saskatoons: Fresh saskatoon samples were kept cool in either a 2 L or 4 L pail, while being driven for approximately 1.5 h to the University of Manitoba for quality tests.

4.6.2 Frozen berries: After the berries were cleaned, the saskatoons were placed in trays (section 4.2.2), and then the trays were situated inside the prototype freezer. The berries frozen in the prototype freezer were moved to a storage freezer maintained at –20°C.

Frozen saskatoon berries were chosen randomly from the trays from both Experiment A and Experiment B with the prototype freezer. The saskatoons were placed in plastic bags which were then sealed. To perform a quality analysis (section 4.7), approximately 1 kg of berries were taken for each sample. For transportation of frozen samples to the University of Manitoba, saskatoons were kept in a cooler with dry-ice or ice-packs or both, and stored at –15°C. The samples were thawed before the quality analysis.

4.7 Quality analysis of saskatoon berries

The quality of fresh and frozen saskatoons was quantified by colour, anthocyanin content, benzaldehyde content, acidity, and carbohydrate content. The tests were chosen from previous research (Green and Mazza 1986, Mazza and Hodgins 1985) to be representative of the quality change that may occur as a result of freezing.

Quality tests were conducted by performing two simultaneous trials. The preparation of the chemical solutions used in the quality analysis is described in Appendix B.

4.7.1 Colour: The methodology for colour evaluation was adopted from Green and Mazza (1986). A HunterLab Colorimeter model D25L-2 (Hunter Associates Laboratory Inc., Fairfax, VA) was used for the colour evaluation of whole berries and crushed berries. A pink tile, with calibration coefficients of 'L' = 68.8, 'a' = 21.4, and 'b' = 10.9, was used to calibrate the Hunterlab Colorimeter. The colour was tested with sample sizes of 300 g of whole berries or 150 g of crushed berries.

The samples were introduced in a HunterLab container, and placed on the colorimeter. Three values for 'L', 'a', and 'b' were recorded, rotating the container 90° between readings. The Hunter 'L' measures brightness, the 'a' measures redness when positive and greenness when negative, and 'b' measures yellowness when positive and blueness when negative. (Green and Mazza 1986).

4.7.2 Anthocyanins: The method of Fuleki and Francis (1968a), adopted by Green and Mazza (1986) was used to extract anthocyanin from saskatoons. A sample of 100 g of saskatoon berries was blended with an Osterizer Galaxie 8 blender on high speed for 180 s with 100 mL of 95% ethanol / 1.5 M HCl (85:15 v/v). The sample was transferred to a beaker and stored overnight at 4°C.

The next day the sample was filtered using Whatman # 44 filter paper, adding three 100-mL washings and one 75-mL washing, both with the 95% ethanol

/ 1.5 M HCl (85:15 v/v) solution. The volume of the filtrate was brought up to 500 mL with the 95% ethanol / 1.5 M HCl (85:15 v/v) solution.

Total anthocyanin content was determined by the pH differential method described by Fuleki and Francis(1968b) and Green and Mazza (1986). Samples were prepared by diluting the extract with KCl (0.2 N) / HCl (0.2 N) (pH 1.0 buffer). The dilution that resulted in an absorbance reading of 0.6 to 0.8 was used to prepare diluted samples with both a KCl (0.2 N) / HCl (0.2 N) (pH 1.0 buffer) solution and a $NaC_2H_3O_2$ (1N) / HCl (1 N) / distilled water (100:60:90) (pH 4.5 buffer) solution. The diluted samples were allowed to equilibrate in the dark for 2 h. The absorbance at 510 nm of both dilutions (pH 1.0 and pH 4.5) was obtained using a Spectronic 601 spectrophotometer (Milton Roy, USA) and a 1 cm cell. Distilled water was used as the blank.

The total optical density for 100 g of berries (sample size) for the pH 1.0 and pH 4.5 samples was calculated using the following equation:

$$TOD = OD \cdot DV \cdot VF \qquad (4.1)$$

where:

TOD = total optical density (mL/100g),
OD = optical density or absorbance reading of the diluted sample,
DV = volume of the diluted sample (mL), and
VF = volume factor (mL/mL).

The volume factor was needed to correct the difference between the original volume of extract, and the sample volume of extract. The equation for the volume factor was:

$$VF = \frac{OV}{SV} \tag{4.2}$$

where:

VF = volume factor (mL/mL),

OV = original volume of anthocyanin extract (mL), and

SV = volume of anthocyanin extract in diluted sample (mL).

The difference in optical density was calculated by subtracting total optical density at pH 4.5 from the total optical density at pH 1.0:

$$\Delta OD = TOD_{pH1.0} - TOD_{pH4.5} \tag{4.3}$$

where:

ΔOD = difference in optical density (mL/100 g).

The total anthocyanin content (mg/100g) was calculated by dividing the difference in optical density by the extinction coefficient:

$$\text{Total anthocyanin content} = \frac{DOD}{E \cdot L} \tag{4.4}$$

where:

E = the extinction coefficient at 510 nm ($mL \cdot mg^{-1} \cdot cm^{-1}$), and

L = the cell length (cm)

The extinction coefficient, which represents the fraction of light lost to scattering and absorption, reported by Fuleki and Francis (1968 b) was 76.5 $mL \cdot mg^{-1} \cdot cm^{-1}$ at a wavelength of 510 nm. A 1 cm length cell was used in the

spectrophotometer. The total anthocyanin content was expressed as mg of cyanindin-3-galactoside per 100 g of berries (mg/100g). Cyandin-3-galactoside is the major anthocyanin of saskatoon berries (Green and Mazza 1986).

4.7.3 Benzaldehyde: The benzaldehyde analysis was based on methodology described by Mazza and Hodgins (1985). The sample was prepared by blending 50 g of berries with 50 mL of 60% methanol with an Osterizer Galaxie 8 blender on high speed for 180 s. The mixture was transferred to an Erlenmeyer flask, stoppered, and stored overnight at room temperature. The mixture was transferred to a 500 mL evaporating flask, connected to an all-glass rotary vacuum evaporator (Büchi RE11 Rotavapor and Büchi 461 Water Bath, Büchi Laboratories, Flawil, Switzherland) and extracted for 15 min at 48 ± 1°C. The volume of the benzaldehyde containing extract was brought up to 100 mL with 60% methanol. The absorbance of the benzaldehyde was read with a Spectronic 601 spectrophotometer (Milton Roy, USA) at 249 nm, using 60% methanol as a blank.

AOAC (1980) standard method (19.102) was used to establish a standard curve relating absorbance to benzaldehyde concentration of saskatoons. The absorbance of 1 ppm, 2 ppm, 4 ppm, 6 ppm, 8 ppm, and 10 ppm benzaldehyde concentrations were read on the spectrophotometer at 249 nm, using 10 % methanol as a blank. The calibration curve is given in Appendix F.

4.7.4 Total acidity: The method used to prepare the sample for total acidity was adopted from AOAC (1980) standard method (22.008), as described by Green and Mazza (1986). The sample was prepared by blending 150 g of berries with 150 mL

of water with an Osterizer Galaxie 8 blender on high speed for 180 s. Next, 250 mL of distilled water was added to the sample, and the mixture boiled for 1 h. The volume of the slurry was brought up to 1000 mL with distilled water, filtered through two layers of cheese cloth, and suction filtered through Whatman #4 filter paper.

The glass electrode method, AOAC (1980) standard method (22.061), as described by Green and Mazza (1986) was used to determine pH and total acidity. An Accument pH meter model 901 (Fisher Scientific Ltd., Napean, ON) was used for measurements. The pH meter was standardized using two point standardization with pH 7 and pH 10. From the filtered solution, 50 mL was titrated with 0.1N NaOH in a 250 mL beaker, until the solution reached a pH of 8.7. The solution was continuously mixed with a magnetic stirrer. The initial pH, final pH, and volume of 0.1N NaOH titrated were recorded.

Malic and citrcic are the major acid of saskatoons (Mazza and Miniati 1993). Total acidity was expressed as percent malic acid. The percent malic acid for the titrated sample was calculated by using the following formula:

$$\mathrm{MATS} = \mathrm{Volume} \cdot \mathrm{Normality} \cdot \mathrm{MWDA} \qquad (4.5)$$

where:

MATS	= malic acid in the titrated sample (%),
Volume	= volume of NaOH titrated (mL)
Normality	= normality of NaOH (0.1 N), and
MWDA	= milliequivalents of the dominant acid (0.06705).

The % malic acid in 100 g of berries was calculated using the following formula:

$$\% \text{ malic acid} = \text{MATS} \cdot \frac{1000 \text{ mL}}{50 \text{ mL}} \cdot \frac{100 \text{ g}}{150 \text{ g}} \qquad (4.6)$$

In Eq. 4.6, the volume ratio corrects for the titrated volume(50 mL), from the total volume (1000 mL), and the mass ratio corrects the reading to 100 g of berries from the 150 g of berries used to prepare the sample The milliequivalents of the malic acid is 0.06705 (Green and Mazza 1986).

4.7.5 Soluble solids: The refractometer method for determination of soluble solids, expressed as percent sucrose, was based on AOAC (1980) standard method (31.011), as described by Green and Mazza (1986). A sample of 20 g of saskatoons was mixed with 75 mL of distilled water and blended with an Osterizer Galaxie 8 blender on high speed for 180 s. The mixture was suction filtered through Whatman #4 filter paper. The volume of the slurry was brought up to 100 mL with distilled water. The refractometer (Carl Zeiss, Germany) was standardized with distilled water. Two drops of the filtered solution were placed on the refractometer then the Brix (% sucrose w/w) and refractive index were obtained. The Brix value was multiplied by a mass ratio to represent the percent sucrose for a 100 g.

The sucrose and total acidity values were combined to determine the soluble solids - acidity ratio (Brix/acid ratio test). The ratio can be used as a practical measure of saskatoon berry ripeness (Green and Mazza 1986). The ratio is calculated by dividing the percent sucrose by the percent malic acid.

4.8 Sugar movement in saskatoons due to freezing

An experiment was designed to observe the effect of one-dimensional freezing on sugar movement in saskatoon berries. Saskatoons were blended then placed into an plastic cylinder, with a diameter of 26 mm and a length of 145 mm (Fig 4.7). Three copper-constantan thermocouples of 24 gauge were placed at the cross-sectional centre of the cylinder to monitor the temperature (Fig 4.7, top view). The plastic cylinder was positioned in a foam insulation sleeve, which was then covered with fibreglass insulation (Fig. 4.7, front view). The entire device (cylinder with blended saskatoons, insulation, and thermocouples) was placed in the single berry freezing apparatus. The freezing conditions were air at a velocity of 3.0 $m \cdot s^{-1}$ and –28°C. One end of the cylinder was not insulated, exposing it to the moving cold air, in order to produce a freezing front within the blended saskatoons. Three trials were performed at separate times.

The frozen berries were removed from the cylinder, then checked for soluble solids (as described in section 4.7.5) with 20 g samples from both the front (windward) and back of the frozen cylinder (Fig. 4.7, top view).

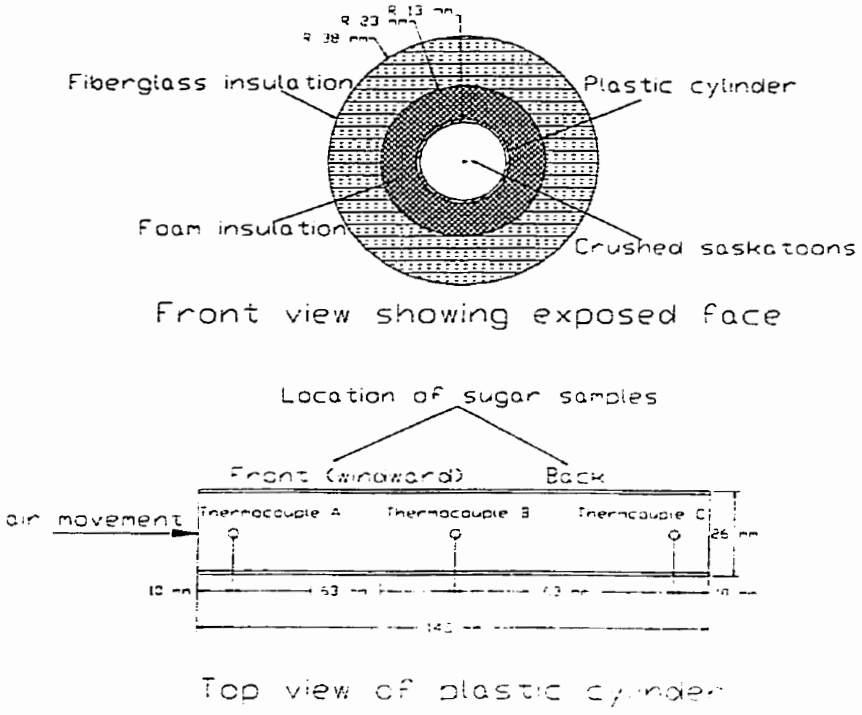

Fig. 4.7 Plastic cylinder used to observe sugar movement in blended saskatoons. The dimensions and locations of thermocouples are illustrated.

5. RESULTS AND DISCUSSION

5.1 Single berry freezing experiments

5.1.1 Single saskatoon berries: Figure 5.1 shows the experimental results of freezing a single saskatoon berry. The freezing conditions were: an air velocity of 5.8 $m \cdot s^{-1}$ and a freezing air temperature of –20±1°C. The three stages of freezing and the freezing point depression are illustrated in the figure. In stage 1 sensible heat is removed, and there is a sharp decline in the berry temperature until the freezing point depression is observed. This stage was approximately 2.0 min in length.

At the end of stage 1 the time-temperature curve levels off below 0°C, indicating the beginning of the second stage of freezing, as well as the freezing point depression. This occurs at approximately –2°C. Latent heat is removed during stage 2 of freezing. Stage 2 was approximately 7.0 min in duration.

After all water in the berry is frozen, stage 3 of freezing begins. In this stage, sensible heat is removed until the temperature of the freezing air is reached. The time it took from the beginning of stage 3 to reach –18°C, 2°C warmer than the –20°C freezing air, was approximately 8 min. The total freezing time of all three stages was approximately 18 min.

Appendix C contains single saskatoon berry freezing graphs at five air velocities and three freezing air temperatures.

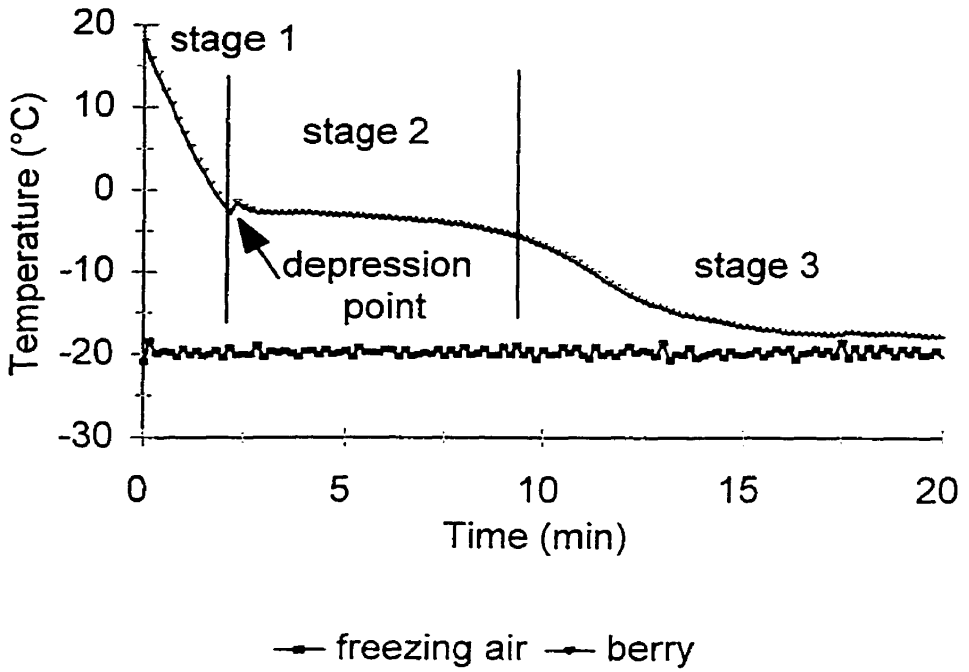

Fig. 5.1 The time-temperature freezing curve for a single saskatoon berry. Freezing conditions: air velocity 5.8 $m \cdot s^{-1}$, freezing air temperature –20°C, berry mass 1.01 g.

Figures 5.2 and 5.3 show the average length of time, for three trials, that it took for a single saskatoon berry to drop in temperature from 0 to –5°C and from 0 to –10°C, respectively. Due to different initial temperatures, a reference point of 0°C was chosen. The –5 and –10°C temperatures were chosen as the second reference point because these temperatures were reached for each freezing condition.

In Figs. 5.2 and 5.3, a trend is shown that as the air velocity is increased, and the temperature of the freezing air is decreased, the freezing time decreases. An exception to this trend is shown in Fig 5.2 at air velocity of 3.0 $m \cdot s^{-1}$ and a freezing

air temperature of –15°C. This could be a result of an experimental error; for example, the thermocouple tip was not placed exactly at the centre of the berry.

In Fig. 5.2 the longest time for a berry to drop in temperature from 0 to –5°C was 11.9 min at 2.1 $m \cdot s^{-1}$ and –15°C freezing air temperature. The shortest time was 3.8 min at 5.8 $m \cdot s^{-1}$ and –25°C freezing air temperature. In Fig 5.3 the longest time was 25.0 min at 2.1 $m \cdot s^{-1}$ and –15°C freezing air temperature, while the shortest time was 5.6 min at 6.8 $m \cdot s^{-1}$ and –25°C freezing air temperature.

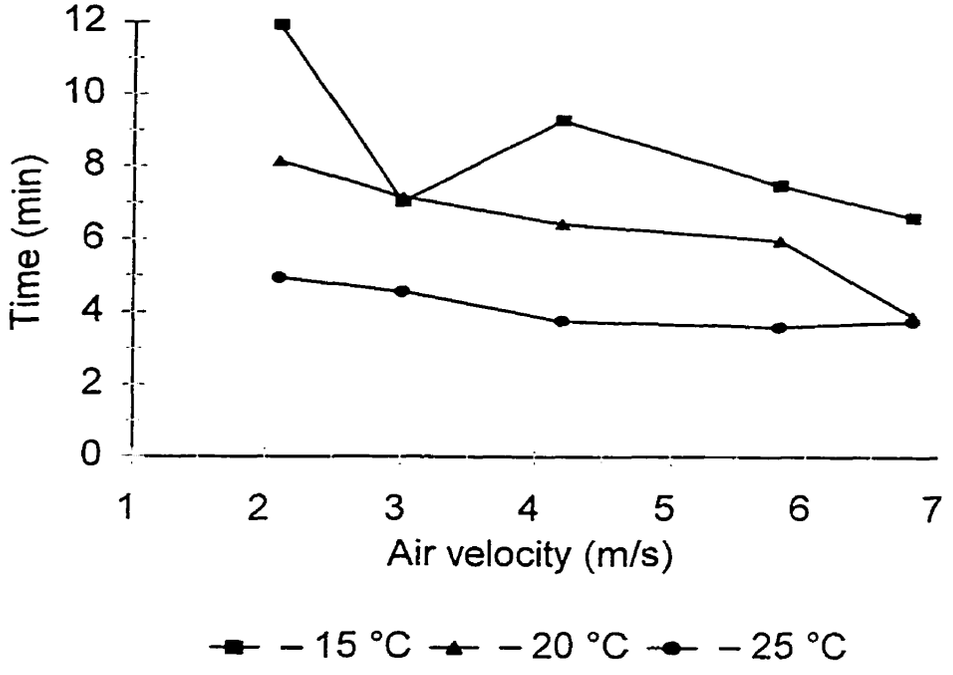

Fig. 5.2 The time it took for a single berry to drop in temperature from 0 to –5°C at freezing air temperatures of –15, –20, and –25°C. The points represent the average of three trials.

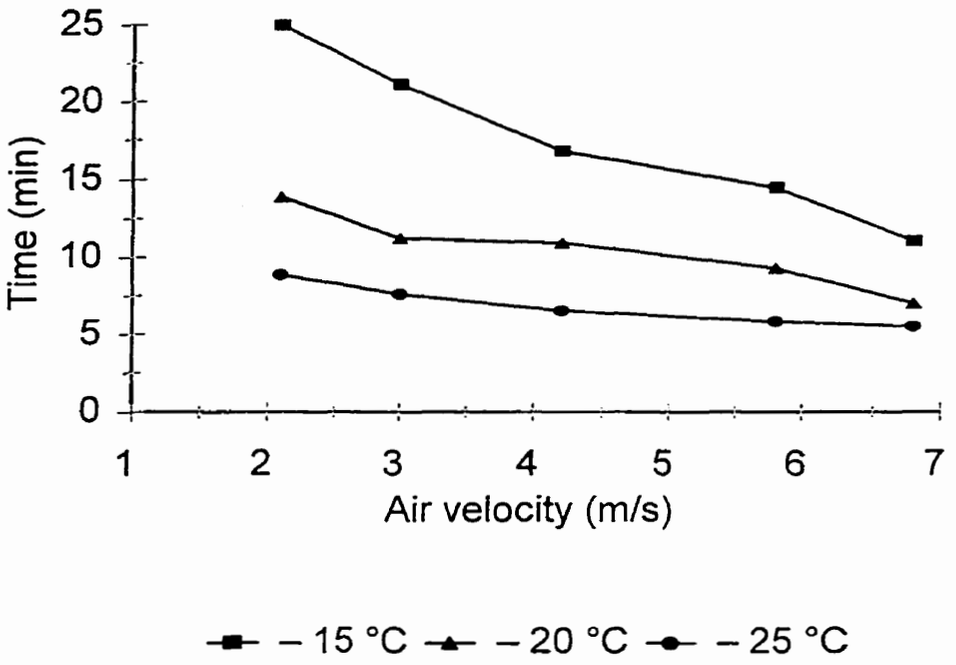

Fig. 5.3 The time it took for a single berry to drop in temperature from 0 to –10°C at freezing air temperatures of –15, –20, and –25°C. The points represent the average of three trials.

These times were analysed as a 5 x 3 factorial design using the statistical software SAS (Release 6.12, 1994, Cary, NC). The software produced an analysis of variance (ANOVA) table. The input and output of the program are given in Appendix D. The velocity and temperature were considered independent variables, while the time for the drop in freezing temperature was considered the dependent variable. Table 5.1 shows the results of the ANOVA for the time it took a single berry to drop in temperature from 0 to –5°C and from 0 to –10°C.

Table 5.1 Probabilities of significance for the time it took for a drop in temperature from 0 to –5°C, and from 0 to –10°C. Five air velocities and three freezing air temperatures were used to freeze single saskatoon berries. The data were analysed as a 5 x 3 factorial experiment.

Factor	Time from 0 to –5°C	Time from 0 to –10°C
Air velocity	0.0001*	0.0001*
Temperature	0.0001*	0.0001*
Air velocity-temperature interaction	0.0759**	0.0001*

* A probability less than 0.05 was considered significant
** A probability greater than 0.05 was not considered significant.

In Table 5.1, the air velocity ($P > 0.0001$) and freezing air temperature ($P > 0.0001$) had a significant effect on the freezing time from 0 to –5°C and from 0 to –10°C. The air velocity-temperature interaction was not significant for the drop in berry temperature from 0 to –5°C ($P > 0.0759$), but was significant for the drop in temperature from 0 to –10°C ($P > 0.0001$). The significant effect of the air velocity, the freezing air temperature, and their interaction can be explained by the equation for convective heat transfer (Incropera and DeWitt 1990):

$$q = h \cdot A \cdot \Delta T \qquad (5.1)$$

where:

- q = convective heat transfer (W),
- h = convective heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)
- A = product surface area (m^2), and
- ΔT = difference in freezing air temperature from product temperature (K).

Convective heat transfer is increased by a greater difference between the surface temperature of the berry and the freezing air, or by increasing the

convective heat transfer coefficient. The Nusselt number, which is a measure of convective heat transfer, provides a explanation in which the heat transfer coefficient can be increased (Incropera and DeWitt 1990):

$$N_u = f(N_{Re}) \tag{5.2}$$

where:

N_u = Nusselt number (dimensionless), and

N_{Re} = Reynolds number (dimensionless).

The Reynolds number, an indicator of laminar, transition, and turbulent flow, is proportional to the air velocity (Incropera and DeWitt 1990). Therefore, a higher air velocity increases the convective heat transfer.

5.1.2 Freezing point depression: To estimate the freezing point depression of a food product, Eq 3.1 was used. The freezing point depression is a function of the mole fraction of water, calculated using Eq. 3.2.

To solve Eq. 3.2, a product moisture (m_A), of 80 %, and a solids content (m_s) of 20 % was assumed. The molecular weight of water (M_A) is 18 g·mol^{-1}. A molecular mass sugar (M_s) of 180 g•mol^{-1} was also assumed to solve the equation. The mole fraction of water (X_A) was calculated to be 0.976 kmol•kg^{-1}.

The latent heat of fusion of water (λ') is 6003 kJ•kmol^{-1} , the universal gas constant (R_g) is 8.314 kJ·kmol^{-1}·K^{-1} (Cengel and Boles 1989), and the freezing point of water (T_{Ao}) is 273.15 K. Substituting these values into Eq 3.1, and solving for the freezing point of the food (T_A) resulted in a value of 270.6 K. Therefore, the freezing

point of saskatoons calculated using Eq. 3.1 was –2.6°C. The freezing point for the single experiment shown in Fig 5.1 was approximately –2.0°C.

5.1.3 Freezing time prediction using Plank's equation: Equation 3.3 illustrated Plank's equation for freezing time prediction. Saskatoons are approximately 80 % moisture, therefore the density of the berries (ρ) was assumed to be that of water, which is 1000 $kg \cdot m^{-3}$. The latent heat of fusion of water (L) is 333 000 $J \cdot kg^{-1}$. The freezing point which was calculated in section 5.1.2 was –2.6°C. A saskatoon berry diameter of 12 mm was used. For spherical geometries, values for P and R are 1/6 and 1/24 respectively (Heldman and Singh 1981).

The conductive heat transfer can be estimated based on saskatoon composition. For fruits and vegetables with a water content greater than 60%, Heldman and Singh (1981) proposed the following equation:

$$k = 0.148 + 0.00493w \tag{5.3}$$

where:

k = conductive heat transfer coefficient of the product ($W \cdot m^{-1} \cdot K^{-1}$), and

w = the water content (%).

Assuming a water content of 80% (St-Pierre et al. 1997), the conductive heat transfer was calculated to be 0.5424 $W \cdot m^{-1} \cdot K^{-1}$. The convective heat transfer coefficient can be calculated based on equations for the Reynolds number and Nusselt number as described by Incropera and Dewitt (1990).

$$N_{Re} = \frac{V \cdot D}{\nu} \tag{5.4}$$

where:

N_{Re} = Reynolds number (dimensionless),

V = velocity of the freezing air ($m \cdot s^{-1}$),

D = diameter of the sphere (0.012m), and

ν = kinematic viscosity ($m^2 \cdot s^{-1}$).

$$N_{Nu} = 2 + (0.4N_{Re}^{1/2} + 0.06N_{Re}^{2/3})N_{Pr}^{0.4}\left(\frac{\mu}{\mu_s}\right) \tag{5.5}$$

where:

N_{Nu} = Nusselt number (dimensionless),

N_{Pr} = Prandtl number (dimensionless),

μ = dynamic viscosity of the freezing air (Pa·s), and

μ_s = dynamic viscosity at the surface of the berry (Pa·s).

The convective heat transfer coefficient was calculated from the Nusselt number as follows:

$$h = N_{Nu}\frac{k}{D}$$

where:

h = convective heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$), and

k = conductive heat transfer coefficient of the freezing air ($W \cdot m^{-1} \cdot K^{-1}$).

The kinematic viscosity, Prandtl number, dynamic viscosity and conductive heat transfer coefficient were found using the temperature of the freezing air. The

dynamic viscosity at the surface of the berry was found using the average of the initial temperature of the berry and the temperature of the freezing air.

Table 5.2 shows the calculated convective heat transfer coefficient and the flow condition of the freezing air during freezing of single saskatoon berries..

Table 5.2 Calculated values of Reynolds number, Nusselt number, and convective heat transfer coefficient for the freezing of individual saskatoons.

Freezing air temperature (°C)	Freezing air velocity ($m \cdot s^{-1}$)	N_{Re}	N_{Nu}	h ($W \cdot m^{-2} \cdot K^{-1}$)	Flow condition †
–15 *	2.1	2074	28.7	54.7	transition
	3.2	3160	35.7	68.1	transition
	4.2	4148	41.2	78.6	turbulent
	5.8	5728	48.9	93.3	turbulent
	6.8	6716	53.3	101.7	turbulent
–20 **	2.1	2152	29.2	54.8	transition
	3.2	3279	36.4	68.2	transition
	4.2	4304	42.0	78.7	turbulent
	5.8	5944	49.9	93.5	turbulent
	6.8	6968	54.3	101.8	turbulent
–25 ***	2.1	2232	29.8	54.8	transition
	3.2	3401	37.1	68.2	transition
	4.2	4464	42.8	78.8	turbulent
	5.8	6165	50.8	93.6	turbulent
	6.8	7228	55.4	102.0	turbulent

† $N_{Re} < 2000$ is considered laminar; $2000 < N_{Re} < 4000$ is considered transition, and $N_{Re} > 4000$ is considered turbulent (Incropera and Dewitt 1990)

* $\nu = 12.15 \cdot 10^{-6}\ m^2 \cdot s^{-1}$, $\mu = 163.6 \cdot 10^{-6}$ Pa·s, $\mu_s = 171.1 \cdot 10^{-6}$ Pa·s, $N_{Pr} = 0.718$, $k = 22.9 \cdot 10^{-3}\ W \cdot m^{-1} \cdot K^{-1}$.

** $\nu = 11.71 \cdot 10^{-6}\ m^2 \cdot s^{-1}$, $\mu = 161.1 \cdot 10^{-6}$ Pa·s, $\mu_s = 170.1 \cdot 10^{-6}$ Pa·s, $N_{Pr} = 0.719$, $k = 22.5 \cdot 10^{-3}\ W \cdot m^{-1} \cdot K^{-1}$.

*** $\nu = 11.29 \cdot 10^{-6}\ m^2 \cdot s^{-1}$, $\mu = 158.5 \cdot 10^{-6}$ Pa·s, $\mu_s = 168.6 \cdot 10^{-6}$ Pa·s, $N_{Pr} = 0.721$, $k = 22.1 \cdot 10^{-3}\ W \cdot m^{-1} \cdot K^{-1}$.

The convective heat transfer coefficient at all of the freezing air temperatures ranged from approximately 54 to 102 $W \cdot m^{-2} \cdot K^{-1}$. For each freezing air temperature, freezing air velocities of 2.1 and 3.2 $m \cdot s^{-1}$ produced a transition air flow, while freezing air velocities of 4.2, 5.8, and 6.8 $m \cdot s^{-1}$ produced turbulent air flow.

Riedel (1951) suggested that at –10°C, approximately 80% of moisture in fruits and vegetables is frozen. Plank's equation only predicts the time required for stage two of freezing, therefore, the experimental time for a single saskatoon to drop in temperature from 0 to –10°C was compared to the predicted freezing time, as shown in Table 5.3.

Table 5.3 Experimental time for the drop in temperature for a single saskatoon from 0 to –10°C, compared to the predicted freezing time determined using Plank's equation using calculated values for the convective heat transfer coefficient.

Freezing air temperature (°C)	Freezing air velocity ($m \cdot s^{-1}$)	Experimental freezing time† (min)	Convective heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)	Predicted Freezing time (min)
–15	2.1	25.0	54.7	21.3
	3.2	21.1	68.1	18.1
	4.2	16.8	78.6	16.3
	5.8	14.4	93.3	14.5
	6.8	11.1	101.7	13.8
–20	2.1	13.9	54.8	15.2
	3.2	11.2	68.2	12.9
	4.2	10.9	78.7	11.6
	5.8	9.3	93.5	10.4
	6.8	7.1	101.8	9.8
–25	2.1	8.9	54.8	11.8
	3.2	7.6	68.2	10.0
	4.2	6.5	78.8	9.0
	5.8	5.8	93.6	8.0
	6.8	5.6	102.0	7.6

† Time is for a drop in temperature from 0 to –10°C

At freezing air temperatures of –15, –20, and –25°C the largest difference between the experimental and predicted freezing time was 3.1 min at a freezing air velocity of 2.1 $m \cdot s^{-1}$, 2.7 min at a freezing air velocity of 6.8 $m \cdot s^{-1}$, and 2.9 min at a freezing air velocity of 2.1 $m \cdot s^{-1}$, respectively. The smallest difference between the experimental and predicted freezing times at freezing air temperatures of –15, –20°C, and –25°C was 0.1 min at a freezing air velocity 5.8 $m \cdot s^{-1}$, 0.7 min at a freezing air velocity 4.2 $m \cdot s^{-1}$, and 2 min at a freezing air velocity 6.8 $m \cdot s^{-1}$, respectively.

For the freezing conditions that single saskatoons were tested under, Plank's equation predicted the freezing time within 0.1 to 3.1 min from the experimental results for the time for a drop in temperature from 0 to –10°C.

5.2 Saskatoon freezing experiments with the Prototype freezer

Figures 5.4, 5.5, and 5.6 show time-temperature characteristics of single berries during freezing in Experiment A with a single berry placed in the centre of an empty tray, with a single saskatoon buried in 1.1 kg of berries in each tray, and with a single saskatoon buried in 2.3 kg of berries in each tray, respectively. The tray arrangement is discussed in section 4.5, and shown in Fig 4.5. The mass of berries in the chamber for 1.1 kg of berries per tray and for 2.3 kg of berries per tray was approximately 40 kg and 83 kg, respectively. For the trial shown in Fig 5.4 the thermocouple at location 9B was faulty, therefore, the measurement is not shown. The chamber temperature was chosen from the thermocouple located in the centre of the freezer. The three stages of freezing were observed, as was discussed in

section 5.1.1. For the trial shown in Fig.5.4, berries located in tray 9 of the stacks (triangle symbols) experienced the fastest freezing time, reaching the chamber temperature in approximately 20 min. The berries in tray 6 (circle symbols) had the slowest freezing time, approaching the chamber temperature in approximately 25 min. The times for the drop in temperatures from 0 to –5°C and 0 to –10°C are shown in Table 5.3.

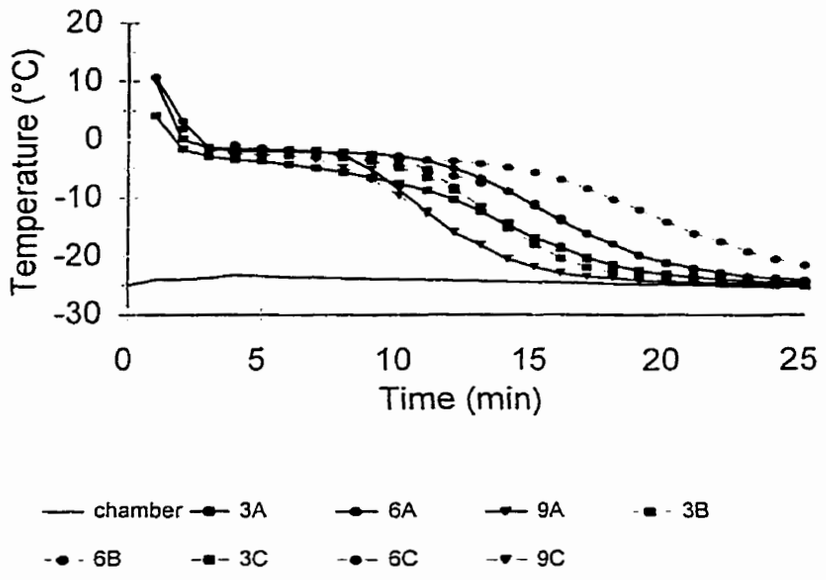

Fig. 5.4 The freezing temperature history for a single saskatoon placed in the centre of an empty tray. The letters A, B, and C correspond to a stack of 12 trays, and the numbers indicate the position of the tray in the stack. See Fig 4.5 for the arrangement.

In Fig. 5.5, the three stages of freezing were still visible, however in Fig. 5.6 it was more difficult to distinguish the three stages of freezing. The initial temperature of the chamber in Figs. 5.4, 5.5, and 5.6 was around –25°C. After placement of the trays with the berries in the prototype freezer, the air temperature

of the chamber rose to –22°C, –18°C, and –15°C for a single saskatoon placed in an empty tray, for 1.1 kg of saskatoons in a tray, and for 2.3 kg of saskatoons in a tray, respectively. For the trials illustrated in Figs. 5.4, 5.5, and 5.6, the initial temperature of the saskatoon berries was between 5 and 12°C for a single saskatoon placed in an empty tray, between 10 and 13°C for 1.1 kg of saskatoons in a tray, and between 10 and 23°C for 2.3 kg of saskatoons in a tray. The time between placement of the trays in the chamber, and inserting the thermocouples into the berries affected the initial temperature. The heat energy brought into the chamber with the saskatoons, as well as opening of the chamber door to the warm temperature in the shed, affected the air temperature of the chamber.

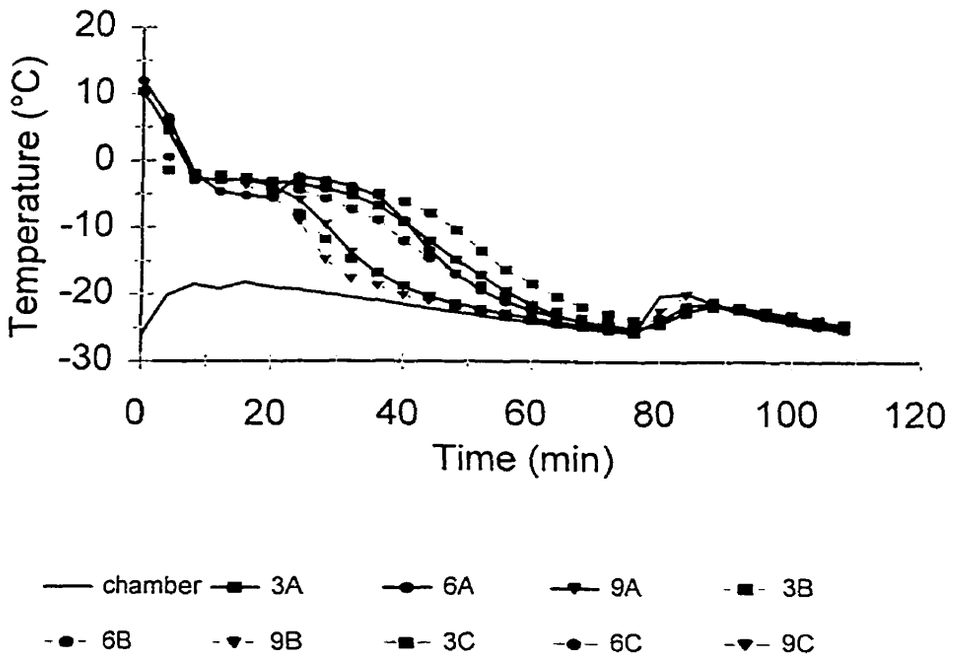

Fig. 5.5 The freezing temperature history for 1.1 kg of saskatoons placed in a tray. The letters A, B, and C correspond to a stack of 12 trays, and the numbers indicate the position of the tray in the stack. See Fig 4.5 for the arrangement.

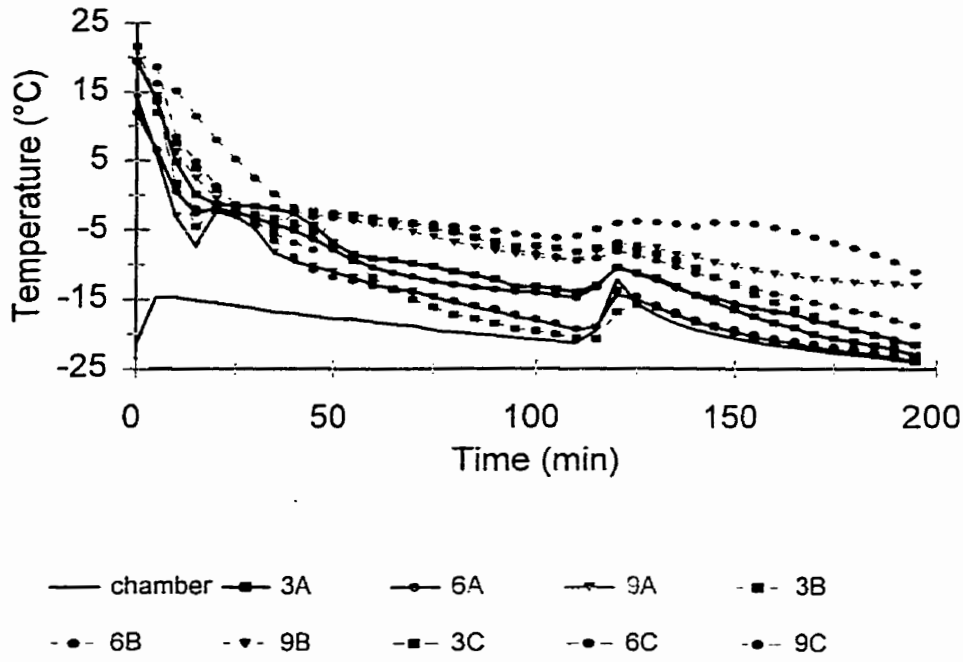

Fig. 5.6 The freezing temperature history for 2.3 kg of saskatoons placed in a tray. The letters A, B, and C correspond to a stack of 12 trays, and the numbers indicate the position of the tray in the stack. See Fig 4.5 for the arrangement.

The mean time and standard deviation for a temperature drop from 0 to –5°C and from 0 to –10°C for the same arrangement of trays is shown in Table 5.4.

Table 5.4 The time for a saskatoon berry to drop in temperature from 0 to –5°C, and from 0 to –10°C for Experiment A with the prototype freezer.

Amount of berries per tray	Position of tray	Time from 0 to –5°C (min)		Time from 0 to –10°C (min)	
		Mean *	S.D. *	Mean *	S.D. *
single berry in an empty tray	3 [5]	5.8	0.4	8.0	0.6
	6 [5]	9.0	2.1	12.6	2.0
	9 [5]	7.2	2.1	10.3	1.6
1.1 kg of berries in a tray	3 [8]	15.8	4.8	27.1	8.6
	6 [8]	21.4	16.7	44.5	18.8
	9 [8]	27.6	9.0	41.0	13.2
2.3 kg of berries in a tray †	3 [6]	19.7	15.2	47.0	38.6
	6 [3]	24.5	10.8	104.3	44.7
	9 [3]	27.3	6.6	72.0	31.5

Three trials were performed for each mass, with three trays in each position (one each in stacks A, B, and C)

* Mean and S.D. (standard deviation) evaluated based on superscript number in the column marked 'position of tray'.

† The DAS crashed during the third trial, therefore, only two trials were available

As the mass in each tray was increased, the mean time and standard deviation for the temperature drop from 0 to –5°C and from 0 to –10°C also increased. The range in times for a temperature drop from 0 to –10°C for a single saskatoon per empty tray, 1.1 kg of saskatoons per tray, and 2.3 kg of saskatoons per tray was 8.0 to 12.6 min, 27.1 to 44.5 min, and 47.0 to 104.3 min, respectively. In Experiment A (section 5.1.1), the time for a single berry to drop in temperature from 0 to –10°C averaged 11.2 min at 3.0 $m \cdot s^{-1}$ and –20°C. This time was in the range of 8.0 to 12.6 min for a single berry in an empty tray for Experiment B.

To freeze the total mass of harvested berries in the chamber, approximately 2.3 kg of berries was placed in each tray for the semi-continuous flow of saskatoons

during a full harvest day (Experiment B). The arrangement of trays is discussed in section 4.5. Figure 5.7 shows the time-temperature data for the harvest day on 17 July 2000, in which approximately 580 kg of saskatoons were frozen. The beginning of saskatoon freezing began at approximately 0730 h with the chamber temperature at approximately –30°C, indicated by 0 h on Fig. 5.7. Thermocouples inserted in saskatoon berries between 0 and 1.5 h were placed in trays 5 and 10 of stacks A, B, C, and D (Fig. 4.6). Thermocouples placed in berries between 5.5 and 6.5 h were placed in trays 5 and 10 of stacks M, N, O and P (Fig. 4.5). The chamber temperature was chosen from the thermocouple located in the centre of the freezer.

The initial temperature of the berries entering the chamber, at the beginning of the harvest day, was approximately 5°C. There was approximately between 1 to 5 min lag time between placement of trays in the chamber, and the initial temperature recorded with the data acquisition system. The temperature within the shed where the prototype freezer was located was approximately 15°C at 0730 h. The berries that entered the chamber at 0 h reached –10°C within 1 h. Berries that entered the chamber at around 1 h took approximately 2 h to reach a temperature of –10°C. In both cases, there was a sharp rise in the temperature of the berry due to the heat load of fresh berries entering the chamber. The freezer had only a 2.2 kW (3 hp) compressor that was unable to handle the quantity of fresh berries entering the chamber.

At the end of the harvest day, the last berries were placed in the chamber at approximately 1330 h with a chamber temperature of approximately –12°C, indicated by 6 h and 6.5 h in Fig. 5.7. These berries dropped to 0°C within 1 h. The

removal of field heat can halt post-harvest deterioration because harvested fruit is still respiring which will affect the quality (St-Pierre et al. 1997). The time for the two berries that dropped below a temperature of –10°C was approximately 4 and 6 h. The other two berries did not reach –10°C within 7 h. The initial temperature of these berries ranged between 15 and 20°C. The temperature within the shed was approximately 25°C.

Berries introduced to the chamber at the beginning of the harvest day (Stacks A, B, C, and D) were representative of the fastest freezing rates as the chamber temperature was below –20°C and the temperature of the berries entering the chamber were approximately 5°C. Berries introduced to the chamber at the end of the harvest day (Stacks M, N, O, and P) were representative of the slowest freezing rates because the chamber temperature had risen to –12°C, the temperature of the berries entering the chamber was between 15 and 20°C, and the 2.2 kW compressor was unable to handle the quantity of berries entering the chamber chamber.

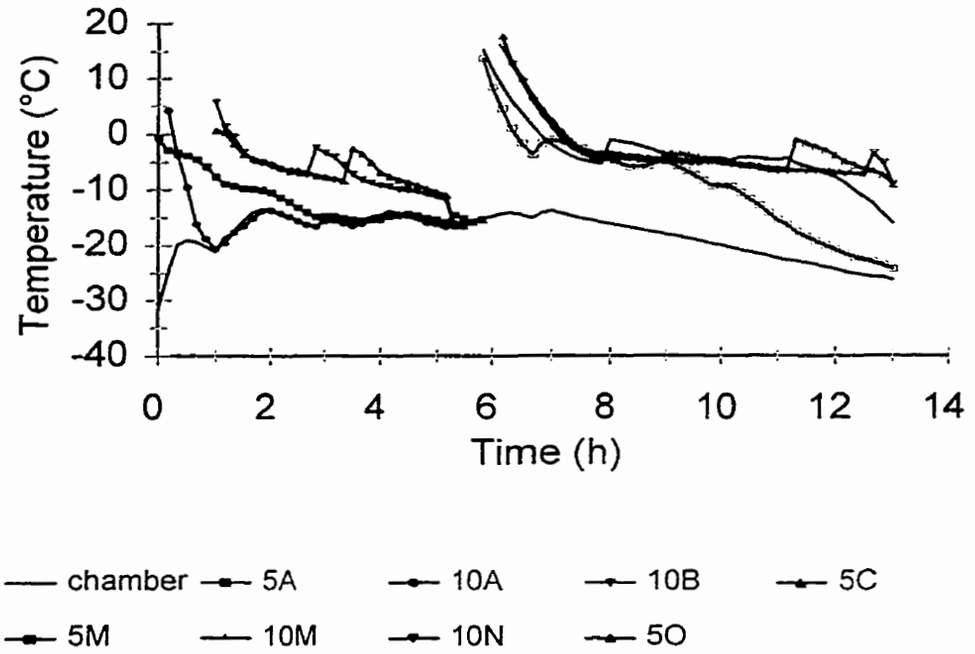

Fig. 5.7 Experiment B with the prototype freezer on 17 July 2000, time 0 was 0730 h. The letters correspond to a stack of 16 trays, and the numbers indicate the position of the tray in the stack. Approximately 2.3 kg of saskatoons were placed in each tray. See Fig. 4.6 for the arrangement.

Time-temperature data for all freezing experiments with the prototype freezer is given in Appendix E.

5.3 Quality analysis

To observe the effect of freezing on the quality of saskatoon berries, two comparisons were made. Comparison 1 was between fresh saskatoons and frozen saskatoons stored less than 1 wk. Comparison 2 was between frozen saskatoons stored for various lengths of time. A relationship between the freezing time and the

quality of saskatoons can not be performed for two reasons. The first is the relatively short harvest season in both the 1999 and 2000 harvest years which limited the number of quality trials conducted. The second is because the effect of respiration, due to field heat, on the saskatoons that were harvested is unknown. The discussion of the results of these comparisons is presented in subsections 5.3.1 to 5.3.3.

5.3.1 Colour: Tables 5.5 to 5.8 contain data on the colour evaluation of saskatoons. From the data on the colour evaluation of fresh whole saskatoons in the 1999 and 2000 harvest years (Table 5.5), the 'L' value ranged between 13.4 and 16.8 , the 'a' value ranged between 0.7 and 4.1, and the 'b' value ranged between –0.9 and 0.3. The range for the 'L', 'a', and 'b' values for the frozen samples of whole saskatoons in the 1999 and 2000 harvest years was 16.6 to 19.5, 2.4 to 6.2, and –2.6 to 0.0, respectively.

From the data on the colour evaluation of fresh crushed saskatoon berries in the 1999 and 2000 harvest years (Table 5.6), the 'L' value ranged between 14.7 to 18.7, the 'a' value ranged between 5.9 to 8.6, and the 'b' value ranged between 0.9 to 1.9. The range for the 'L', 'a', and 'b' values for the frozen samples of whole saskatoons in the 1999 and 2000 harvest years was 15.7 to 20.3, 6.4 to 8.4, and 0.4 to 2.6, respectively.

The colour evaluation of both whole and crushed saskatoons produced the same result, in which the 'L', 'a', and 'b' values from the fresh samples overlapped the respective 'L', 'a' and 'b' values from the frozen samples. Colour change may also be due to environmental conditions at harvest. Due to the overlapping values

and the effect of the environmental conditions, colour changes as a result of freezing were considered negligible for both whole and crushed saskatoons.

Table 5.5 Comparison 1 for colour evaluation of whole saskatoons.

Harvest Year	Date harvested	Condition of saskatoon berries	Date tested	L	a	b
1999						
	13 Jul	premature	13 Jul	14.2	4.3	–0.2
	19 Jul	fresh	19 Jul	14.6	2.6	–0.9
	20 Jul	Frozen; experiment B ǂ	21 Jul	18.2	2.9	–0.2
	22 Jul	Frozen; experiment B ǂ	26 Jul	18.0	3.3	–0.3
	24 Jul	Frozen; experiment B ǂ	28 Jul	16.6	2.4	–0.5
2000						
	12 Jul	fresh	12 Jul	16.8	0.7	0.3
	16 Jul	fresh	18 Jul	13.4	4.1	–0.4
	15 Jul	Frozen; experiment A *	17 Jul	18.0	6.2	–0.1
	17 Jul	Frozen; experiment B †	22 Jul	19.5	4.8	0.0
	17 Jul	Frozen; experiment B ††	20 Jul	18.0	3.9	–2.6

ǂ Samples selected from berries frozen throughout the experiment.
* Samples selected from trials 2 and 3 with 1.1 kg of saskatoons per tray
† Sample selected from berries frozen at the beginning of the harvest day.
†† Samples selected from berries frozen at the end of the harvest day.

Table 5.6 Comparison 1 for colour evaluation of crushed saskatoons.

Harvest year	Date harvested	Condition of saskatoon berries	Date tested	L	a	b
1999						
	13 Jul	premature	13 Jul	14.6	10.7	1.4
	19 Jul	fresh	19 Jul	14.7	8.6	0.9
	20 Jul	Frozen; experiment B ǂ	21 Jul	16.2	7.2	1.6
	22 Jul	Frozen; experiment B ǂ	26 Jul	15.7	7.0	1.7
	24 Jul	Frozen; experiment B ǂ	28 Jul	17.0	6.4	1.7
2000						
	12 Jul	fresh	12 Jul	18.7	5.9	1.9
	16 Jul	fresh	18 Jul	14.7	7.5	1.6
	15 Jul	Frozen; experiment A *	17 Jul	19.9	8.4	2.2
	17 Jul	Frozen; experiment B †	22 Jul	20.3	7.9	2.6
	17 Jul	Frozen; experiment B ††	20 Jul	20.2	7.4	0.4

ǂ Samples selected from berries frozen throughout the experiment.
* Samples selected from trials 2 and 3 with 1.1 kg of saskatoons per tray
† Sample selected from berries frozen at the beginning of the harvest day.
†† Samples selected from berries frozen at the end of the harvest day.

Table 5.7 shows the effect of storage on whole saskatoons. For the 1999 harvested berries, after approximately 9 mo of frozen storage, the "L' value decreased from 16.6 to 12.9, the 'a' value increased from 2.4 to 2.8, and the 'b' value did not change. For the 2000 harvest year samples after 2 wk of frozen storage, the 'L' value decreased for the 15 July sample from 18.0 to 16.3 and for the early 17 July sample from 19.5 to 16.4, but increased for the late 17 July sample from 18.0 to 18.7. The 'a' value decreased and the 'b' value increased as a result of frozen storage of 2 wk for all three harvest dates in the 2000 samples.

The maximum difference in the 'L', 'a', and 'b' values after frozen storage was 2.9 for the 24 July 1999 sample, 5.4 for the 15 July 2000 sample, and 3.4 for the

late 17 July 2000 sample, respectively. 'L' is on a scale from 0 to +100, and both 'a' and 'b' are on scales from –100 to +100. Experimental error may have caused some of the difference in the Hunterlab values, therefore, colour evaluation of whole saskatoons as a result of storage was considered negligible.

Table 5.7 Comparison 2 for colour comparison of whole saskatoons.

Harvest year	Date harvested	Prototype freezing experiment	Date tested	L	a	b
1999						
	24 Jul	B ǂ	28 Jul	16.6	2.4	–0.5
	24 Jul	B ǂ	20 Dec	13.2	3.0	–0.5
	24 Jul	B ǂ	4 May	12.9	2.8	–0.5
2000						
	15 Jul	A ✳	17 Jul	18.0	6.2	–0.1
	15 Jul	A ✳	31 Jul	16.3	0.8	1.2
	15 Jul *	A ✳	14 Aug	n/a	n/a	n/a
	17 Jul	B †	22 Jul	19.5	4.8	0.0
	17 Jul	B †	31 Jul	16.4	0.4	1.2
	17 Jul *	B †	14 Aug	n/a	n/a	n/a
	17 Jul	B ††	20 Jul	18.0	3.9	–2.6
	17 Jul	B ††	31 Jul	18.7	–0.3	0.8

ǂ Samples selected from berries frozen throughout the experiment.
✳ Samples selected from trials 2 and 3 with 1.1 kg of saskatoons per tray
† Sample selected from berries frozen at the beginning of the harvest day.
†† Samples selected from berries frozen at the end of the harvest day.
* Colorimeter bulb was being replaced.

Table 5.8 shows a similar trend to Table 5.7, therefore the colour change of saskatoons crushed after storage was considered negligible.

Table 5.8 Comparison 2 for colour comparison of crushed saskatoons.

Harvest year	Date harvested	Prototype freezing experiment	Date tested	L	a	b
1999						
	24 Jul	B ‡	28 Jul	17.0	6.4	1.7
	24 Jul	B ‡	20 Dec	12.1	8.1	1.8
	24 Jul	B ‡	4 May	10.6	6.1	1.4
2000						
	15 Jul	A *	17 Jul	19.9	8.4	2.2
	15 Jul	A *	31 Jul	19.4	4.7	2.8
	15 Jul *	A *	14 Aug	n/a	n/a	n/a
	17 Jul	B †	22 Jul	20.3	7.9	2.6
	17 Jul	B †	31 Jul	19.8	4.3	3.1
	17 Jul *	B †	14 Aug	n/a	n/a	n/a
	17 Jul	B ††	20 Jul	20.2	7.4	0.4
	17 Jul	B ††	31 Jul	18.9	3.4	2.7

‡ Samples selected from berries frozen throughout the experiment.
* Samples selected from trials 2 and 3 with 1.1 kg of saskatoons per tray
† Sample selected from berries frozen at the beginning of the harvest day.
†† Samples selected from berries frozen at the end of the harvest day.
* Colorimeter bulb was being replaced.

5.3.2 Anthocyanins and benzaldehyde: Table 5.9 contains data for the anthocyanin and benzaldehyde content tests performed on fresh saskatoons and frozen saskatoons tested within 1 wk of being frozen. In 1999, the fresh sample had the highest anthocyanin content at 143.2 mg/100g. After freezing in the 1999 harvest year, the anthocyanin content was between 98.0 and 120.0 mg/100g. In the 2000 harvest year the anthocyanin content of the fresh samples were 121.9 and 107.4 mg/100g. The range of anthocyanin content for the frozen samples, in the 2000 harvest year, in Table 5.9 was 63.9 to 107.5 mg/100g. The fresh samples in

the 1999 harvest year had a higher anthocyanin content than the fresh samples in the 2000 harvest year.

The average loss of anthocyanins from the fresh to the frozen samples tested within 1 wk of being harvested was 32.9 mg/100g in 1999, and 34.5 mg/100g in 2000. The loss of anthocyanin content as a result of freezing was 23.0 % and 30.0 % in the 1999 and 2000 harvest years, respectively.

In 1999, the benzaldehyde concentration of the fresh sample was 28.3 ppm. There was contamination between the benzaldehyde and cooling water with the Büchi rotoevaporator during some trials, resulting some readings being not available (Table 5.9). The range of benzaldehyde concentrations in the 1999 harvest year was from 16.2 to 24.8 ppm. The average loss of benzaldehyde concentration in 1999 was 7.8 ppm, for a decrease of 27.6 %. Assuming the benzaldehyde level in the 2000 harvest year was similar to the 1999 harvest year, the loss due to freezing would be in the range of 84 %.

Table 5.9 Comparison 1 for anthocyanin and benzaldehyde content of saskatoon berries.

Harvest year	Date harvested	Condition of saskatoon berries	Date tested	Anthocyanin (mg/100g)	Benzaldehyde (ppm)
1999					
	13 Jul	premature	13 Jul	111.5	24.6
	19 Jul	fresh	19 Jul	143.2	28.3
	20 Jul	Frozen; experiment B ‡	21 Jul	112.8	24.8
	22 Jul	Frozen; experiment B ‡	26 Jul	98.0	16.2
	24 Jul *	Frozen; experiment B ‡	28 Jul	120.0	n/a
2000					
	12 Jul *	fresh	12 Jul	121.9	n/a
	16 Jul *	fresh	18 Jul	107.4	n/a
	15 Jul *	Frozen; experiment A *	17 Jul	107.5	n/a
	17 Jul	Frozen; experiment B †	22 Jul	69.2	6.2
	17 Jul	Frozen; experiment B ††	20 Jul	63.9	1.5

‡ Samples selected from berries frozen throughout the experiment.
* Samples selected from trials 2 and 3 with 1.1 kg of berries per tray
† Sample selected from berries frozen at the beginning of the harvest day.
†† Samples selected from berries frozen at the end of the harvest day.
* Benzaldehyde sample was contaminated with cooling water

Table 5.10 contains anthocyanin and benzaldehyde data of frozen saskatoons stored for various lengths of time. The anthocyanin content dropped from 120.0 to 99.7 mg/100g in the 1999 harvest year samples after approximately 5 mo (20 Dec 1999) of storage, and to 79.7 mg/100g after approximately 9 mo (4 May 2000) of frozen storage. This is a loss of anthocyanins of 16.9% and 33.6 % after 5 mo and 9 mo of storage, respectively. The anthocyanin content of the 2000 samples increased after 2 wk (31 July 2000) and 4 wk (14 Aug 2000) of frozen storage. These results are greater than the anthocyanin content of fresh saskatoons (Table 5.9), and were attributed to possible experimental error.

The benzaldehyde reading of the frozen sample, from the 1999 harvest year, with less than 1 wk of storage is not available. The benzaldehyde concentration rose with 2 wk and 4 wk of storage in the 2000 harvest year samples. This was an unexpected result, attributed to possible experimental error.

Table 5.10 Comparison 2 for anthocyanin and benzaldehyde content of saskatoon berries.

Harvest year	Date harvested	Prototype freezing experiment	Date tested	Anthocyanin (mg/100g)	Benzaldehyde (ppm)
1999					
	24 Jul *	B ǂ	28 Jul	120.0	n/a
	24 Jul *	B ǂ	20 Dec	99.7	n/a
	24 Jul *	B ǂ	4 May	79.7	n/a
2000					
	15 Jul *	A *	17 Jul	107.5	n/a
	15 Jul	A *	31 Jul	160.6	11.4
	15 Jul	A *	14 Aug	165.1	17.3
	17 Jul	B †	22 Jul	69.2	6.2
	17 Jul	B †	31 Jul	162.9	7.4
	17 Jul	B †	14 Aug	157.4	16.6
	17 Jul	B ††	20 Jul	63.9	15.0
	17 Jul	B ††	31 Jul	140.6	16.7

ǂ Samples selected from berries frozen throughout the experiment.
* Samples selected from trials 2 and 3 with 1.1 kg of saskatoons per tray
† Sample selected from berries frozen at the beginning of the harvest day.
†† Samples selected from berries frozen at the end of the harvest day.
* Benzaldehyde sample was contaminated with cooling water

5.3.3 Total acidity and soluble solids: The data for total acidity was expressed as percent malic acid, and the data for soluble solids was expressed as percent sucrose. Table 5.11 shows the comparison of total acidity and soluble solids

between fresh saskatoons and frozen saskatoons tested within 1 wk of being harvested.

The 1999 harvest year fresh sample had a malic acid level of 0.333 %. The range for the malic acid for the 1999 harvest year, tested within 1 wk of being harvested, was 0.290 to 0.353 %. The malic acid for the 1999 harvest year fresh sample was within the range of the 1999 harvest year frozen samples.

For the 2000 harvest year samples, the malic acid of the fresh samples was 0.270 and 0.331 % (Table 5.11). The range for the malic acid of the frozen samples was 0.277 to 0.326 %. The values of the malic acid for fresh and frozen samples overlapped. There was no recognizable trend for the effect of freezing on the malic acid of saskatoons.

The fresh sample from the 1999 harvest year had a sucrose level of 14.8 % (Table 5.11). The average value for the frozen samples was 11.5 %. This was a drop in the sucrose level of 3.3, for a 22.2 % decrease in the soluble solids content.

In the 2000 harvest year samples, the range for the sucrose for the fresh samples was 9.9 to 12.5 %, for an average value of 11.3 %. The range of the sucrose in the 2000 harvest year frozen samples was 9.5 to 12.4 %, for an average of 10.8 %. The decrease in soluble solids between the average of the fresh samples and the average of frozen samples, in the 2000 harvest year, was 0.5, for a 4.4 % decrease.

Because there was no recognizable trend to the malic acid, the Brix acid ratio followed the sucrose content. The fresh sample had the highest ratio, and the ratio decreased with freezing.

Table 5.11 Comparison 1 of soluble solids and total acidity of saskatoon berries. Soluble solids was expressed as % sucrose, and total acidity was expressed as % malic acid.

Harest year	Date harvested	Condition of saskatoon berries	Date tested	Malic acid (%)	Sucrose (%)	Brix acid ratio
1999						
	13 Jul	premature	13 Jul	0.377	7.5	19.8
	19 Jul	fresh	19 Jul	0.333	14.8	44.5
	20 Jul	Frozen; experiment B ‡	21 Jul	0.353	14.9	42.1
	22 Jul	Frozen; experiment B ‡	26 Jul	0.304	10.0	32.9
	24 Jul	Frozen; experiment B ‡	28 Jul	0.290	9.5	32.6
2000						
	12 Jul	fresh	12 Jul	0.331	12.5	37.8
	16 Jul	fresh	18 Jul	0.270	9.9	36.7
	15 Jul	Frozen; experiment A *	17 Jul	0.326	12.4	38.0
	17 Jul	Frozen; experiment B †	22 Jul	0.311	9.5	30.6
	17 Jul	Frozen; experiment B ††	20 Jul	0.277	10.5	37.9

‡ Samples selected from berries frozen throughout the experiment.
* Samples selected from trials 2 and 3 with 1.1 kg of berries per tray
† Sample selected from berries frozen at the beginning of the harvest day.
†† Samples selected from berries frozen at the end of the harvest day.

Table 5.12 contains the data for the total acidity and soluble solids for frozen saskatoons stored for various lengths of time. The malic acid content of the frozen saskatoons in the 1999 harvest year was initially 0.290%, and increased to 0.337 % after 5 mo of frozen storage, and to 0.374 % after 9 mo of frozen storage. The 15 Jul 2000 sample had an initial malic acid content of 0.326 %, then fell to 0.273 % and 0.297 % after 2 wk and 4 wk of frozen storage, respectively.

The sucrose for the 1999 harvest year sample had an initial level of 9.5 %, and fell to 7.7 % after 5 mo of storage, and to 7.3 % after 9 mo of storage. This was a decrease in soluble solids of 18.9 % and 23.2 % after 5 mo and 9 mo,

respectively. The 2000 harvest year frozen samples also decrease in sucrose as a result of 2 wk and 4 wk of storage.

The Brix acid ratio followed the same trend as sucrose. The highest ratio occurred with the samples tested within 1 wk of harvesting, and decreased with storage.

Table 5.12 Comparison 2 of soluble solids and total a cidity of saskatoon berries. Soluble solids was expressed as % sucrose, and total acidity was expressed as % malic acid.

Harvest year	Date harvested	Prototype freezing experiment	Date tested	Malic acid (%)	Sucrose (%)	Brix acid ratio
1999						
	24 Jul	B ǂ	28 Jul	0.290	9.5	32.6
	24 Jul	B ǂ	20 Dec	0.337	7.7	22.7
	24 Jul	B ǂ	4 May	0.374	7.3	19.5
2000						
	15 Jul	A *	17 Jul	0.326	12.4	38.0
	15 Jul	A *	31 Jul	0.273	3.8	13.9
	15 Jul	A *	14 Aug	0.297	3.3	11.1
	17 Jul	B †	22 Jul	0.371	9.5	30.6
	17 Jul	B †	31 Jul	0.379	5.7	17.9
	17 Jul	B †	14 Aug	0.286	2.9	10.1
	17 Jul	B ††	20 Jul	0.277	10.5	37.9
	17 Jul	B ††	31 Jul	0.237	7.4	31.2

ǂ Samples selected from berries frozen throughout the experiment.
* Samples selected from trials 2 and 3 with 1.1 kg of saskatoons per tray
† Sample selected from berries frozen at the beginning of the harvest day.
†† Samples selected from berries frozen at the end of the harvest day.

5.4 Sugar movement in saskatoons due to freezing

Figure 5.8 shows the temperature history for trial 3 of saskatoons that were blended then frozen in a plastic cylinder (Fig. 4.7). The temperature history for all

three trials is given in Appendix H. The front of the plastic cylinder was not insulated, exposing the blended berries to freezing air at 3.0 $m \cdot s^{-1}$ and –28°C. The movement of the freezing front is indicated by the time needed for thermocouples B and C to reach the same temperature as thermocouple A. For example, thermocouple (C) located at 135 mm from the exposed surface reached –10°C after 2.2 h. The same temperature was reached by the thermocouple (A) located 10 mm from the exposed surface within 0.9 h.

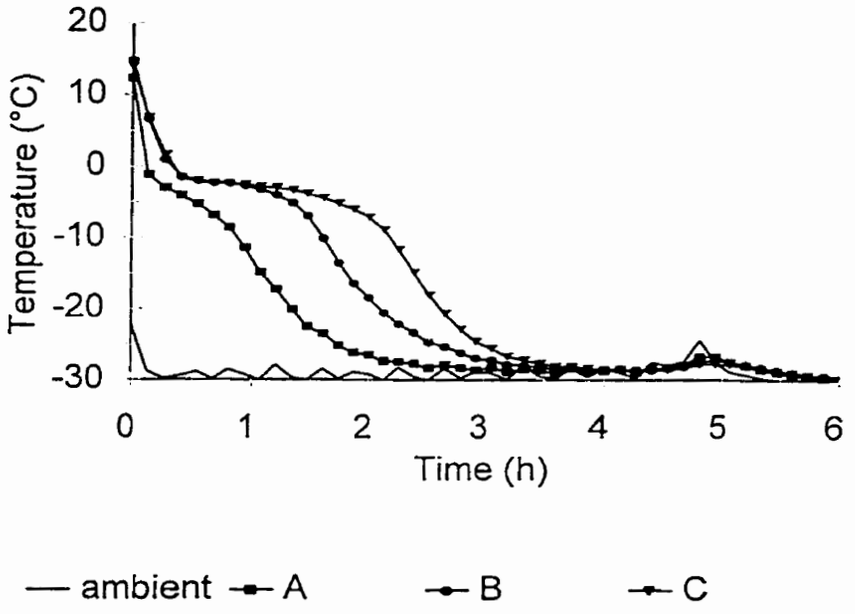

Fig. 5.8 Temperature history of blended saskatoons that were placed in an insulated plastic cylinder. Thermocouple A, B, and C are located 10 (front), 73 (middle) and 135 mm (back) from the freezing surface.

Table 5.13 shows the soluble solids, expressed as percent sucrose, for three separate trials. The sucrose at the exposed surface of the cylinder ranged from 4.7 to 7.4 %, the average sucrose ranged from 6.0 to 8.7 %, and the sucrose at the

back of the cylinder ranged from 7.2 to 9.8 %. The soluble solids (sugars) moved with the freezing front in the cylinder of blended saskatoons.

Table 5.13 The % sucrose at two locations of a 145 mm long plastic cylinder of blended saskatoons freezing lengthwise of the cylinder.

Trial	Front	Back	Average
1	6.3	9.8	8.1
2	7.4	9.9	8.7
3	4.7	7.2	6.0

In Fig 5.9, the average percent sucrose was given a fraction value of 1.0, while the percent sucrose for the front and back were scaled by dividing their values by the percent sucrose of the average for that trial. For example, for trial 1 the sucrose at the front, 6.3 %, was divided by the average sucrose, 8.1 %, yielding a fraction of 0.78. The lines in Fig. 5.9 are representative of the fraction of sugar along the length of the cylinder, as affected by one-dimensional freezing. For the three trials conducted, the average fraction value of sugar at the front of the cylinder (exposed surface) was 0.80 and the average fraction value at the back of the cylinder was 1.18.

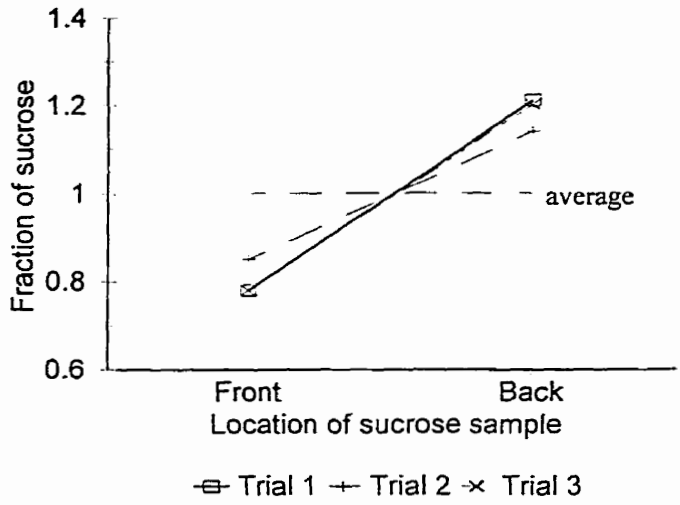

Fig. 5.9 The fraction of sucrose in a cylinder filled with blended saskatoons and exposed to one-dimensional freezing. Freezing conditions were; air velocity of 3.0 $m \cdot s^{-1}$ and freezing air temperature of –28°C.

5.5 Analysis of freezing economics:

The size of individual orchards varies from producer to producer. The orchard the prototype freezer was constructed on was 2 ha. An economic analysis of a freezing system for a 2 ha operation was developed, using information from the prototype freezer that was constructed. These numbers, as well as the size of the freezers, can be scaled to represent individual orchard sizes. A producer interested in the operation of a saskatoon orchard should conduct a complete economic analysis. Other costs for an orchard not included in the analysis of freezing economics include, but are not limited to, irrigation equipment, purchase of land, fertilizer, labour, sheds, mechanical harvester, and cleaning equipment.

On the constructed prototype freezer, the air cooled condenser unit required 36.7 A at 230V, for a power requirement of 8.4 kW. The air cooled condensing unit of the prototype freezer included the condenser, a 2.2 kW compressor, and a fan. The evaporator had a fan to provide air movement and a heater for a defrost cycle, which drew 5.1 A and 32 A respectively, each at 230 V. This corresponded to a power requirement of 1.2 kW for the fan and 7.4 kW for the heater. The total cost for the prototype freezer was approximately $25 000, with an estimated useful life of 10 yr and no salvage value. The prototype freezer is expected to run 24 h a day for 20 d each harvest. This allows for the movement of the saskatoons to the storage freezer the following day. The evaporator had 3 defrost cycles daily, each lasting approximately 0.5 h. Power requirements for the chamber lights and door heaters were considered negligible. The calculated power required for the air cooled condensing unit, fan on the evaporator, the heater on the evaporator, and the total power was:

$$P_{\text{air cooled condensing unit}} = 8.4 \ \text{kW} \cdot 24 \ \frac{\text{h}}{\text{d}} \cdot 20 \ \text{d} = 4032 \ \text{kW} \cdot \text{h} \tag{5.4}$$

$$P_{\text{fan}} = 1.2 \ \text{kW} \cdot 24 \ \frac{\text{h}}{\text{d}} \cdot 20 \ \text{d} = 576 \ \text{kW} \cdot \text{h} \tag{5.5}$$

$$P_{\text{heater}} = 7.4 \ \text{kW} \cdot 3 \cdot 0.5 \ \frac{\text{h}}{\text{d}} \cdot 20 \ \text{d} = 222 \ \text{kW} \cdot \text{h} \tag{5.6}$$

$$P_{\text{prototype freezer}} = 4032 + 576 + 222 = 4830 \ \text{kW} \cdot \text{h} \tag{5.7}$$

The estimated cost of a single phase 1.5 kW (2 hp) storage freezer was $15 000, with an estimated useful life of 10 yr and no salvage value. The total power requirements of the storage freezer was assumed to be 2/3 of the prototype freezer, and assumed to operate for 90 days instead of 20 days. The calculated total power required by the storage freezer was:

$$P_{\text{storage freezer}} = 4830\ \text{kW}\cdot\text{h}\cdot\frac{90\ \text{d}}{20\ \text{d}}\cdot\frac{1.5\ \text{kW}}{2.2\ \text{kW}} = 14820\ \text{kW}\cdot\text{h} \tag{5.8}$$

Saskatoon yields range from 3250 to 8750 kg·ha^{-1}. A yield of 3500 kg·ha^{-1}, was chosen because of risk factors and the short harvest period in the 1999 and 2000 harvest years. The total harvest year production for a 2 ha operation is 7000 kg. Sales of fresh saskstoons sold directly to consumers was estimated at 1000 kg, leaving 6000 kg of saskatoons to be frozen and stored. Table 5.14 shows the freezing economic analysis on a per kg basis.

Table 5.14 Analysis of freezing economics for a 2 ha saskatoon producer.

Prototype freezer	
Depreciation cost*: $25 000 over 10 yr	$2500
Operation cost: 4830 kW h • $0.0625/kW·h†	$300
Storage freezer	
Depreciation cost*: $15 000 over 10 yr	$1500
Operation cost: 14 820 kW h • $0.0625/kW·h†	$925
Total cost on a yearly basis	$5225
Total cost on a per kg basis (assuming 6000 kg per year)	$0.87

Capital cost and operational costs are rounded to the nearest $5

* Depreciation cost = (original cost - salvage value)/useful life (Granof et al.1996)

† Electricity cost based on Manitoba Hydro pamphlet (Manitoba Hydro 1999)

The estimated cost was $0.87 per kg of saskatoon berries. This cost could be reduced if the prototype freezer was emptied at night, allowing it to be shut off overnight, reducing the operating costs. Taking into account that the compressor on the storage freezer does not need to continually run to maintain the storage temperature would also lower the freezing cost. Producers sell fresh saskatoons at approximately $4.40 per kg for U-pick, and $6.60 per kg for already picked berries. U-pick is the harvesting of the berries by the consumer. The extra $2.20 for already picked berries covers the cost of manual labour to harvest the berries. Berries that are frozen are most likely to be processed, therefore the cost of processing, and the possible profit need to be studied.

6. CONCLUSIONS

On-farm blast freezing of saskatoons is a viable option for value-added processing at the farm gate. Conclusions derived from this research were:

1. The effect of air velocity, effect of temperature of the freezing air, and effect of their interaction was statistically significant ($P>0.0001$) on the time for a drop in temperature from 0 to –10°C for individual saskatoon berries.

2. For the freezing of individual saskatoons at freezing air velocities of 2.0 to 6.8 $m \cdot s^{-1}$ and freezing air temperatures of –15, –20, and –25°C, Plank's equation predicted the freezing time within 0.1 to 3.1 min from the experimental results for the time for a drop in temperature from 0 to –10°C.

3. Freezing time of saskatoons in the prototype freezer was affected by the amount of berries in each tray. The average range in time for a saskatoon to drop in temperature from 0 to –10°C for a single saskatoon per tray, for 1.1 kg of saskatoons per tray, and for 2.3 kg of saskatoons per tray were 8.0 to 12.6 min, 27.1 to 44.5 min, and 47.0 to 104.3 min, respectively.

4. At the beginning of a harvest day (Experiment B with the prototype freezer) the temperature of the prototype freezer was below –20°C, the initial temperature of berries entering the chamber was approximately 5°C, and the berries reached a temperature of –10°C within 1 h. At the end of a harvest day, the chamber temperature had risen to – 12°C, the initial temperature of the berries was between 15 and 20°C, and the time for the berries to reach –10°C was between 4 h and 7 h. The extension of the length in the freezing time indicated that the prototype freezer was overloaded by the quantity of saskatoons in the chamber.

5. As a result of freezing; the effects on colour were negligible; the loss of anthocyanin content was 23 % and 30 % in the 1999 and 2000 harvest years, respectively; the loss of benzaldehyde content was 27.6 % in the 1999 harvest year; there was no recognizable effect on total acidity (malic acid); and the loss in soluble solids (sucrose) was 22.2 % and 4.4 % in the 1999 and 2000 harvest years, respectively. A relationship between the freezing time and the quality of saskatoons was not performed because of the short harvest season which limited the number of quality trials conducted, and the effect of respiration on saskatoons is unknown.

6. Sugar movement was observed in blended saskatoons that were placed in a plastic cylinder and exposed to one-dimensional freezing. The average fraction value of sugar at the front of the cylinder (exposed surface) was 0.80 and the average fraction value at the back of the cylinder was 1.18.

7. Capital and operational costs of a $15 000 storage freezer and the $25 000 prototype freezer, both amortized over a period of 10 yr, for a 2 ha producer was estimated at $0.87/kg.

7. RECOMMENDATIONS

1. Periodic opening of the door to bring trays of saskatoons into the chamber of the prototype freezer causes loss of cold air. A wooden pre-chamber constructed on the entry door of the prototype freezer would help in decreasing the loss of cold air in the chamber of the prototype freezer with warm outside air. The pre-chamber would be constructed with wooden stud frame, insulation, and vapour barrier. A similar insulated walkway could be constructed to transport frozen saskatoons from the prototype freezer to the storage freezer.

2. Air temperature of the chamber significantly affects the freezing time of saskatoons. A cryogenic could be used to help keep the prototype freezing chamber at a temperature below –20°C and decrease freezing time of saskatoons in the chamber.

3. Determine how the quality affects processing of saskatoon products to determine allowable quality losses.

4. The use of the prototype freezer could be used for other small fruit grown in the Prairie Provinces. Increasing the length of use and number of products frozen in the prototype freezer would improve freezing economics. A more mechanized system (i.e. a belt conveyor or other handling system) may become viable.

5. Market studies should be performed to determine the value of processed saskatoon products, leading to a complete economic analysis, including startup of an orchard to final processed product. This information would help producers and designers to size freezing equipment for individual orchards.

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APPENDIX A **Relationship between the variac percentage and air velocity for the single element freezing apparatus**

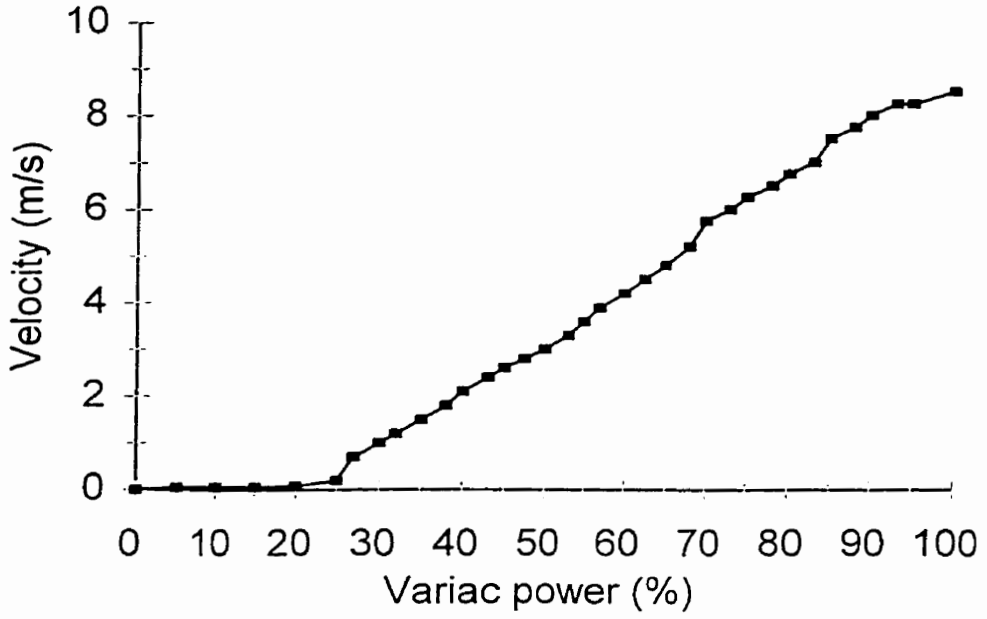

Fig. A.1 Air velocity as a function of the variac percentage

APPENDIX B Preparation of solutions for quality analysis

Chemiicals prepared for determination of anthocyanin content

1) 95% Ethanol / 1.5 M HCl (85:15 v/v):

1.5 M HCl

124.2 mL of concentrated HCl (37%, specific gravity 1.17) was made up to 1.0 L with distilled water.

95% Ethanol

Comes in a container as 95% ethanol

95% Ethanol - 1.5 M HCl (85:15 v/v)

150 mL of HCl was made up to 1.0 L with 95 % ethanol.

2) pH 4.5 buffer: 1N $NaC_2H_3O_2$ / 1N HCl / distilled water (100:60:90)

1 N $NaC_2H_3O_2$ (sodim acetate)

82.06 g of $NaC_2H_3O_2$ was made up to 1.0 L with distilled water.

1N HCl

82.8 ml HCl (37%, specific gravity 1.17) was brought up to volume with distilled water.

pH 4.5 buffer

400 mL of 1 N $NaC_2H_3O_2$ was added to 240 mL of 1 N HCl, and made up to 1.0 L with distilled water.

The pH of the buffer was checked with a 901 Accument pH metre adjusting the pH with 1 N $NaC_2H_3O_2$ or 1 N HCl as required.

3) pH 1.0 buffer: 0.2 N KCl / 0.2 N HCl (25:67)

0.2 N KCl

14.91 g of KCl was made up to 1.0 L with distilled water

0.2 N HCl

16.55 ml HCl (37%, specific gravity 1.17) was made up to 1.0 L with distilled water

0.2 N KCl / 0.2 N HCl (25:67)

250 mL of 0.2 N KCl was made up to 1.0 L with 0.2 N HCl.

The pH of the buffer was checked with a 901 Accument pH metre adjusting the pH by adding 0.2 N KCl or 0.2 N HCl as required.

Chemicals required for determination of benzaldehyde

1) 60 % methanol

600 ml of 100 % methanol was made up to 1.0 L with distilled water.

Chemicals required for total acidity determination

1) 0.1 N NaOH

4 g of sodium hydroxide (NaOH) was made up to 1.0 L with distilled water.

APPENDIX C Time-temperature graphs from single berry freezing

Five different air velocities and three freezing temperatures were used, for a total of 15 different conditions. Three trials were performed at each condition. The three trials are presented on the same graph. The mass of the individual berries was approximately 1 g. The chart within each graph represented the time to reach that temperature from the initial temperature. The analysis performed for single berries was the time from 0 to –5°C and from 0 to –10°C. Figure C.1 shows the measuring procedure used for each saskatoon berry.

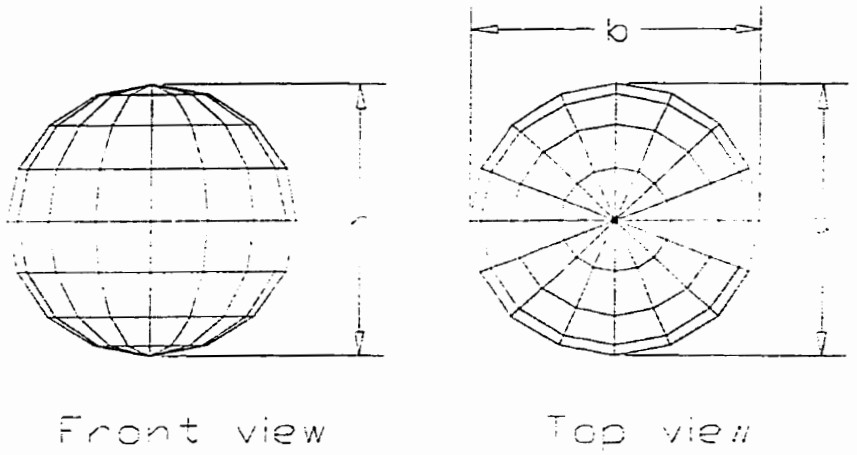

Fig. C.1 Measuring technique used for single saskatoon berries. The height was indicated by 'h', and two diameters of the berry were indicated by 'a' and 'b'.

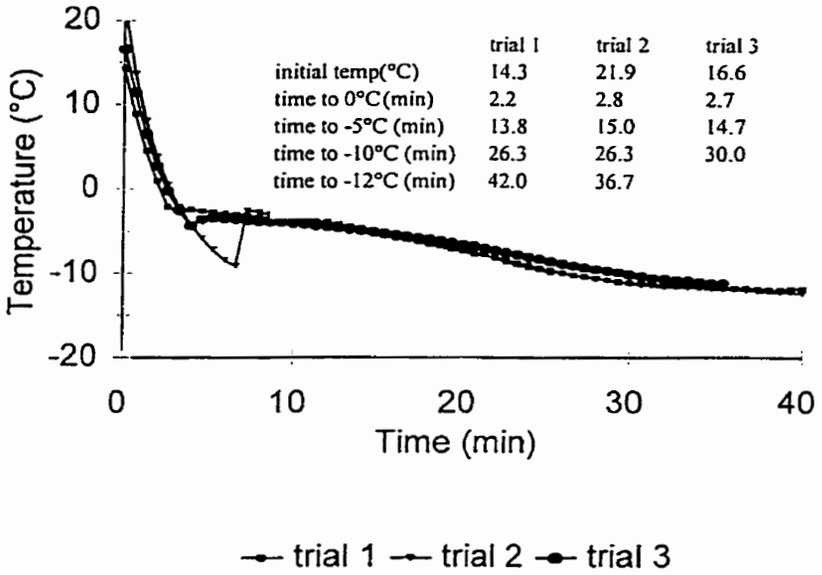

Fig. C.2 Freezing conditions: air velocity = 2.1 $m \cdot s^{-1}$, air temperature = –15°C.
Trial 1: mass = 1.01 g, h = 12.3 mm, a = 12.4 mm, b = 11.8 mm.
Trial 2: mass = 1.00 g, h = 12.9 mm, a = 11.7 mm, b = 11.7 mm.
Trial 3: mass = 1.07 g, h = 12.8 mm, a = 12.5 mm, b = 12.7 mm.

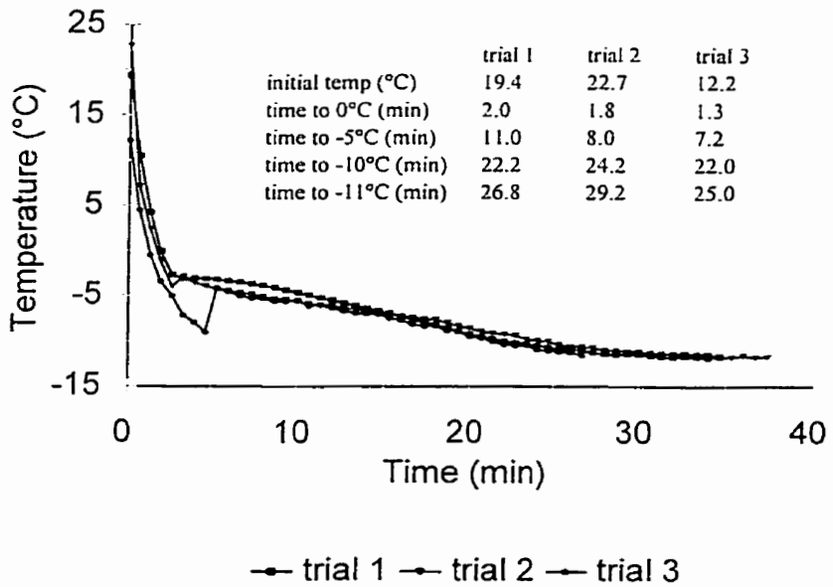

Fig. C.3 Freezing conditions: air velocity 3.0 $m \cdot s^{-1}$, air temperature –15°C.
Trial 1: mass = 0.95 g, h = 12.8 mm, a = 11.9 mm, b = 11.5 mm.
Trial 2: mass = 0.98 g, h = 12.5 mm, a = 11.7 mm, b = 11.6 mm.
Trial 3: mass = 1.00 g, h = 11.9 mm, a = 11.4 mm, b = 11.7 mm.

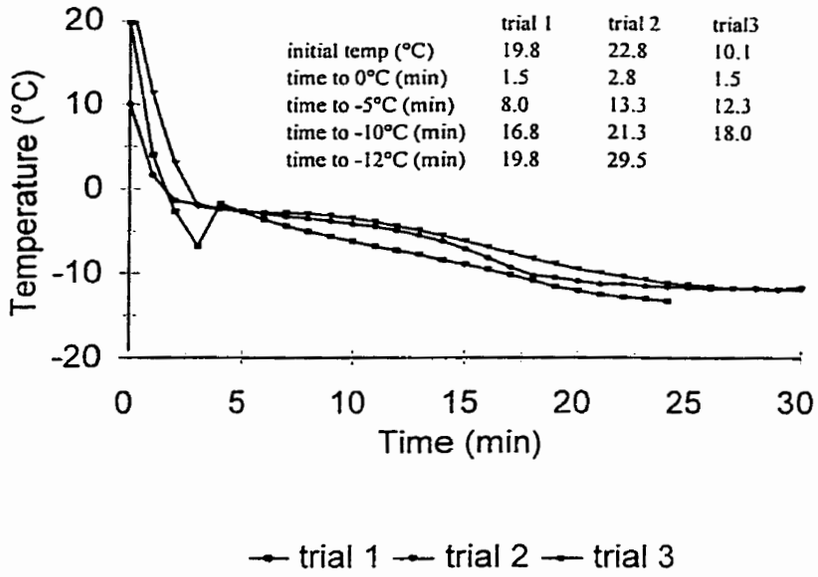

Fig. C.4 Freezing conditions: air velocity 4.2 $m \cdot s^{-1}$, air temperature –15°C.
Trial 1: mass = 1.09 g, h = 11.9 mm, a = 12.2 mm, b = 12.4 mm.
Trial 2: mass = 1.03 g, h = 13.2 mm, a = 12.0 mm, b = 11.8 mm.
Trial 3: mass = 0.96 g, h = 13.0 mm, a = 11.8 mm, b = 11.7 mm.

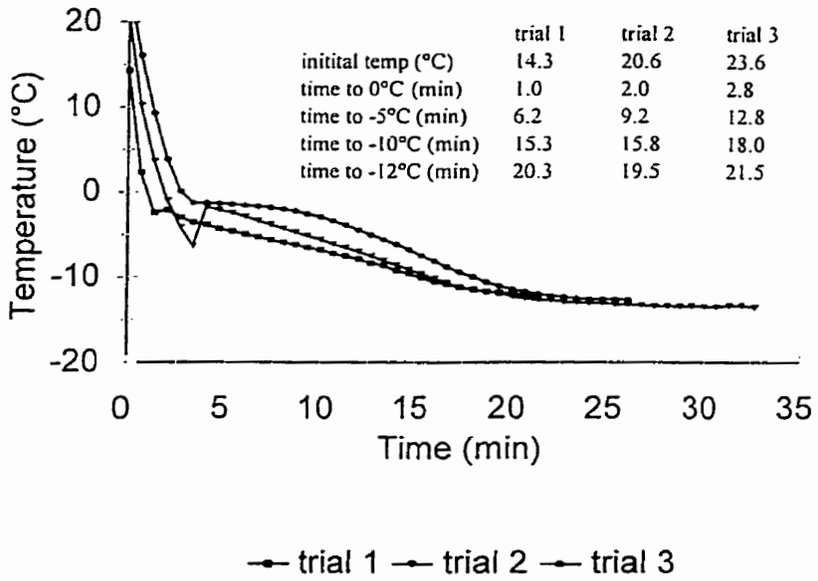

Fig. C.5 Freezing conditions: air velocity 5.8 $m \cdot s^{-1}$, air temperature –15°C.
Trial 1: mass = 0.99 g, h = 13.2 mm, a = 11.6 mm, b = 11.9 mm.
Trial 2: mass = 1.09 g, h = 13.0 mm, a = 12.4 mm, b = 11.7 mm.
Trial 3: mass = 1.04 g, h = 12.4 mm, a = 11.8 mm, b = 12.0 mm.

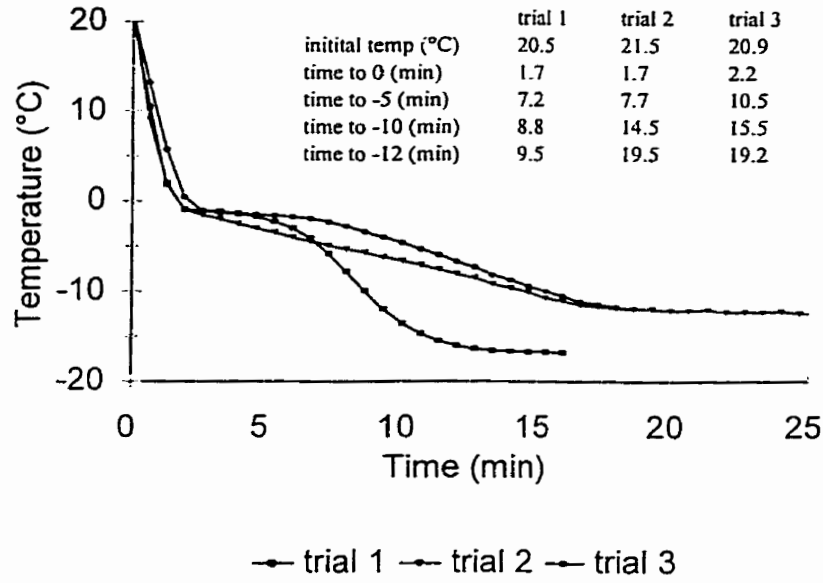

Fig. C.6 Freezing conditions: air velocity 6.8 $m \cdot s^{-1}$, air temperature –15°C.
Trial 1: mass = 1.05 g, h = 11.8 mm, a = 11.9 mm, b = 11.9 mm.
Trial 2: mass = 0.95 g, h = 11.1 mm, a = 12.0 mm, b = 11.9 mm.
Trial 3: mass = 1.06 g, h = 11.5 mm, a = 12.3 mm, b = 12.4 mm.

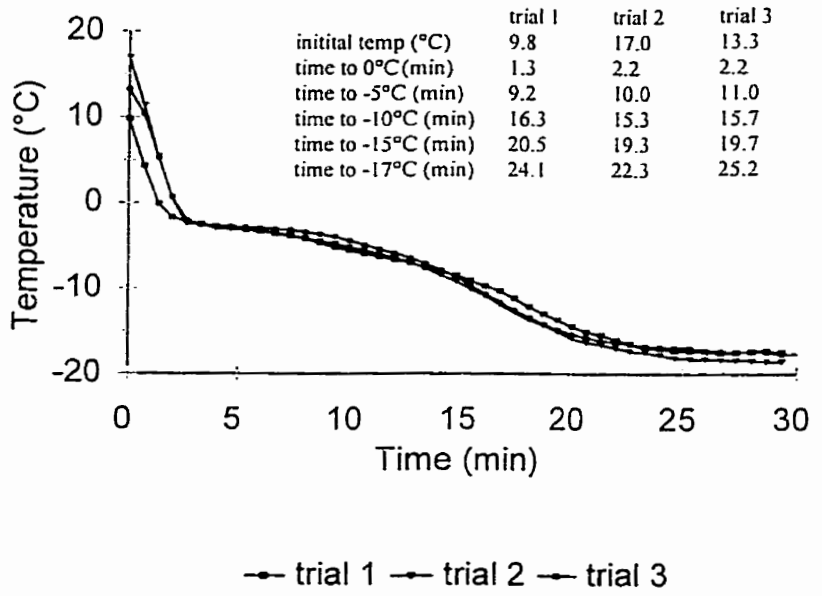

Fig. C.7 Freezing conditions: air velocity 2.1 $m \cdot s^{-1}$, air temperature –20°C.
Trial 1: mass = 1.11 g, h = 13.1 mm, a = 12.1 mm, b = 12.0 mm.
Trial 2: mass = 0.98 g, h = 12.5 mm, a = 11.9 mm, b = 12.3 mm.
Trial 3: mass = 0.98 g, h = 12.3 mm, a = 12.3 mm, b = 11.9 mm.

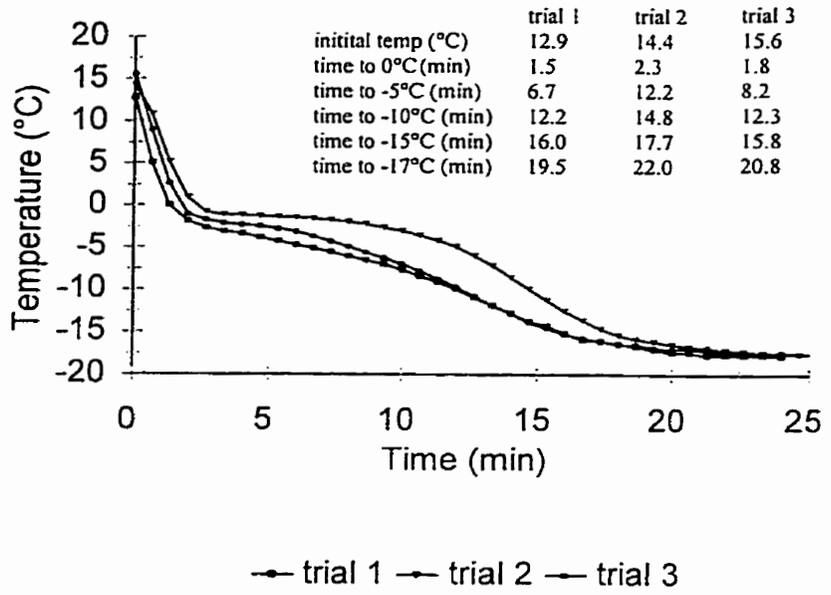

Fig. C.8 Freezing conditions: air velocity 3.0 $m \cdot s^{-1}$, air temperature –20°C.
Trial 1: mass = 1.03 g, h = 13.0 mm, a = 11.6 mm, b = 11.8 mm.
Trial 2: mass = 1.12 g, h = 12.6 mm, a = 12.7 mm, b = 12.8 mm.
Trial 3: mass = 0.99 g, h = 13.0 mm, a = 12.0 mm, b = 11.9 mm.

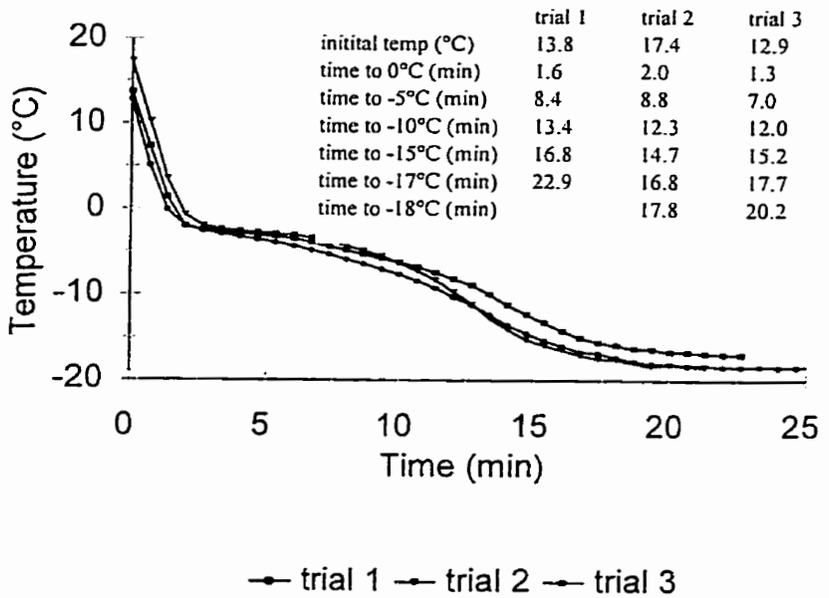

Fig. C.9 Freezing conditions: air velocity 4.2 $m \cdot s^{-1}$, air temperature –20°C.
Trial 1: mass = 1.01 g, h = 11.7 mm, a = 11.7 mm, b = 12.0 mm.
Trial 2: mass = 0.97 g, h = 12.7 mm, a = 11.6 mm, b = 11.6 mm.
Trial 3: mass = 1.09 g, h = 12.0 mm, a = 12.1 mm, b = 12.8 mm.

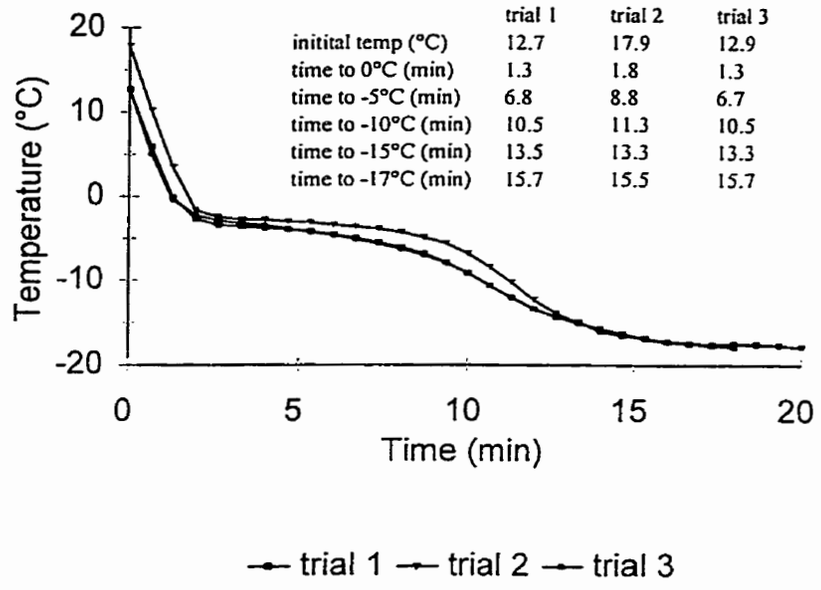

Fig. C.10 Freezing conditions: air velocity 5.8 $m \cdot s^{-1}$, air temperature –20°C.
Trial 1: mass = 1.00 g, h = 12.1 mm, a = 11.9 mm, b = 11.7 mm.
Trial 2: mass = 1.01 g, h = 12.7 mm, a = 12.6 mm, b = 11.6 mm.
Trial 3: mass = 1.06 g, h = 12.5 mm, a = 12.4 mm, b = 12.4 mm.

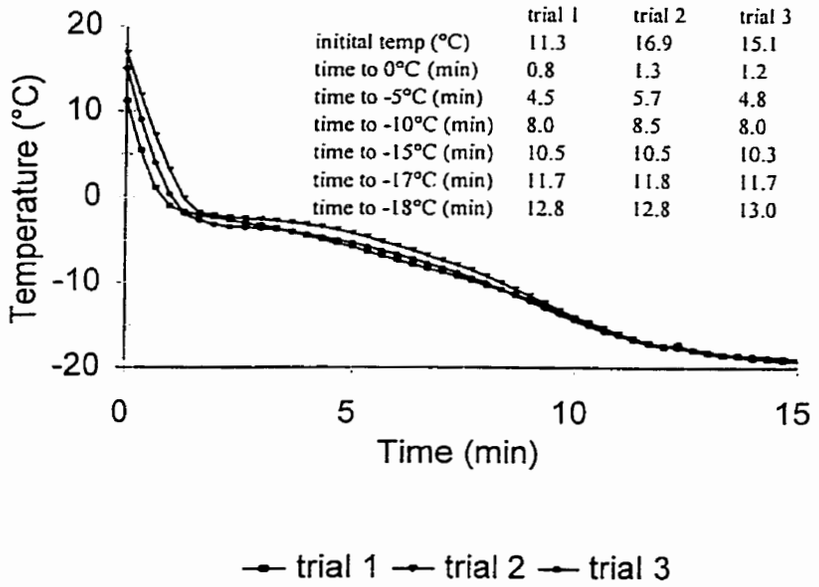

Fig. C.11 Freezing conditions: air velocity 6.8 $m \cdot s^{-1}$, air temperature –20°C.
Trial 1: mass = 1.03 g, h = 11.5 mm, a = 12.1 mm, b = 12.0 mm.
Trial 2: mass = 1.06 g, h = 12.6 mm, a = 11.9 mm, b = 11.7 mm.
Trial 3: mass = 0.97 g, h = 12.0 mm, a = 11.9 mm, b = 12.0 mm.

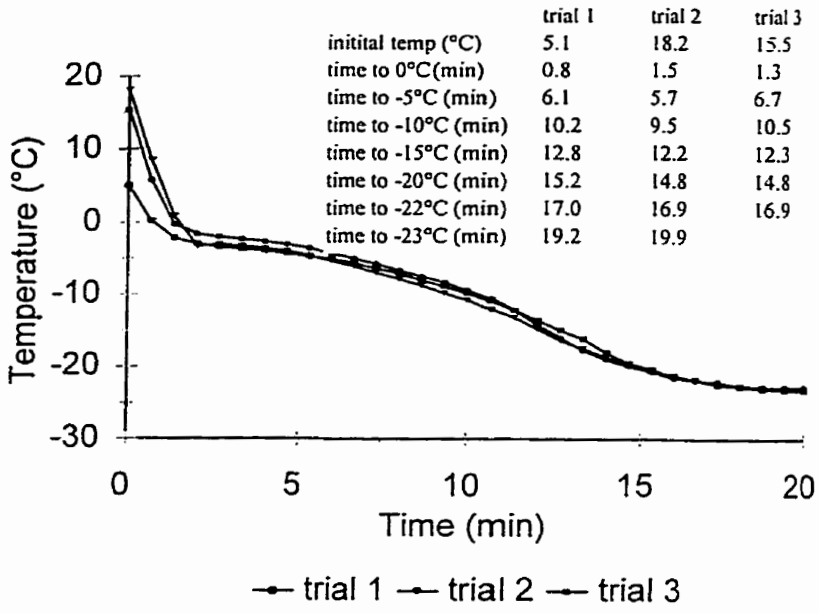

Fig. C.12 Freezing conditions: air velocity 2.1 $m \cdot s^{-1}$, air temperature –25°C.
Trial 1: mass = 0.96 g, h = 11.6 mm, a = 12.0 mm, b = 11.7 mm.
Trial 2: mass = 1.03 g, h = 12.7 mm, a = 12.1 mm, b = 12.0 mm.
Trial 3: mass = 0.99 g, h = 11.8 mm, a = 11.6 mm, b = 11.7 mm.

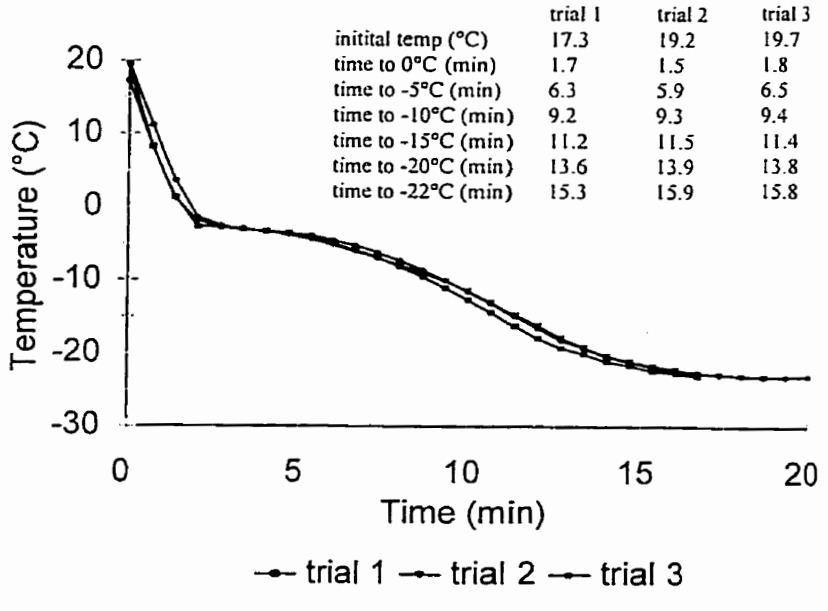

Fig. C.13 Freezing conditions: air velocity 3.0 $m \cdot s^{-1}$, air temperature –25°C.
Trial 1: mass = 1.04 g, h = 12.5 mm, a = 12.1 mm, b = 12.1 mm.
Trial 2: mass = 1.13 g, h = 12.2 mm, a = 12.0 mm, b = 12.4 mm.
Trial 3: mass = 1.03 g, h = 12.5 mm, a = 12.2 mm, b = 12.0 mm.

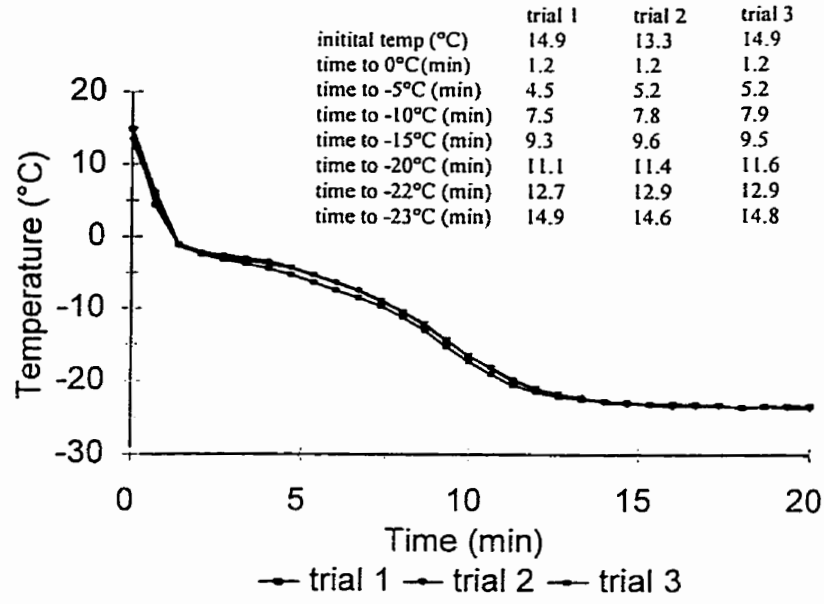

Fig. C.14 Freezing conditions: air velocity 4.2 $m \cdot s^{-1}$, air temperature –25°C.
Trial 1: mass = 0.94 g, h = 11.5 mm, a = 11.9 mm, b = 11.6 mm.
Trial 2: mass = 1.04 g, h = 12.8 mm, a = 12.2 mm, b = 11.9 mm.
Trial 3: mass = 1.07 g, h = 12.2 mm, a = 11.6 mm, b = 11.4 mm.

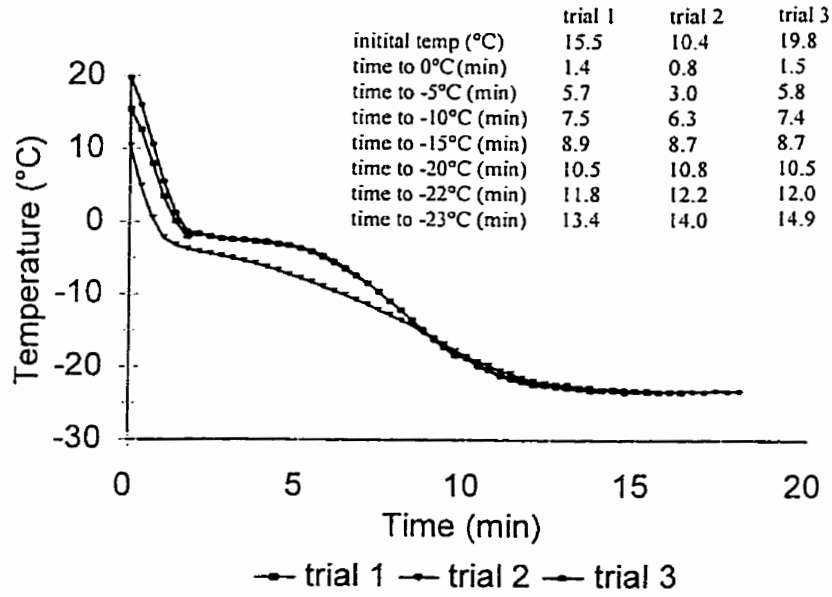

Fig. C.15 Freezing conditions: air velocity 5.8 $m \cdot s^{-1}$, air temperature –25°C.
Trial 1: mass = 1.11 g, h = 13.6 mm, a = 11.9 mm, b = 11.8 mm.
Trial 2: mass = 1.10 g, h = 13.3 mm, a = 11.9 mm, b = 11.9 mm.
Trial 3: mass = 1.01 g, h = 13.5 mm, a = 11.4 mm, b = 12.0 mm.

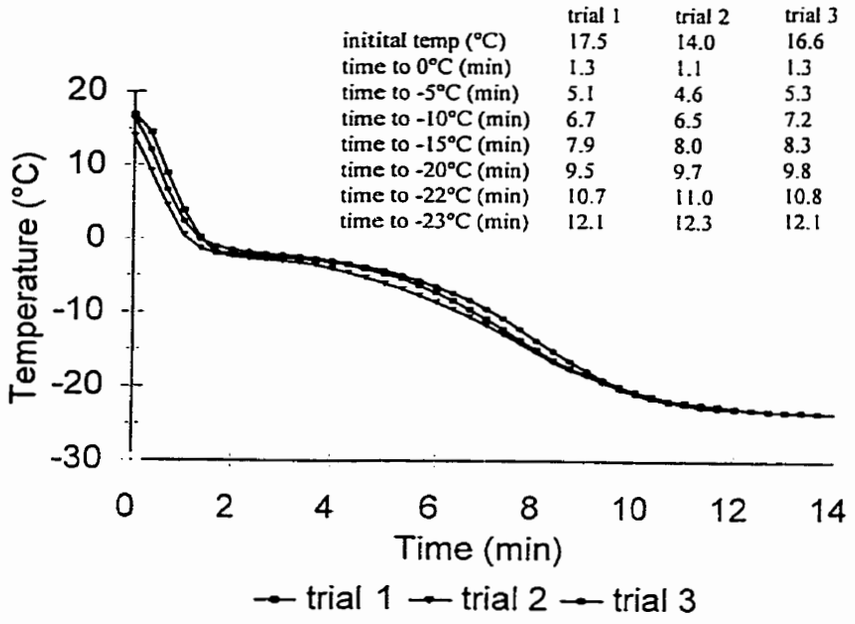

Fig. C.16 Freezing conditions: air velocity 6.8 $m \cdot s^{-1}$, air temperature –25°C.
Trial 1: mass = 1.04 g, h = 12.8 mm, a = 11.6 mm, b = 11.5 mm.
Trial 2: mass = 1.05 g, h = 12.6 mm, a = 11.8 mm, b = 11.8 mm.
Trial 3: mass = 1.08 g, h = 12.4 mm, a = 11.9 mm, b = 12.0 mm.

APPENDIX D Statistical analysis of single berry freezing

The SAS program generates an analysis of variance (ANOVA) table based on a 5 x 3 factorial designed experiment. There were two variables that were controlled. There were 5 air velocity settings, and 3 control temperatures. Three berries were frozen at each condition, for a total of 45 data points.

The variables of the SAS program correspond to control temperatures and velocities as follows:

v2p1	= air velocity of 2.1 m/s,
v3p0	= air velocity of 3.0 m/s,
v4p2	= air velocity of 4.2 m/s
v5p8	= air velocity of 5.8 m/s,
v6p8	= air velocity of 6.8 m/s,
m15	= freezing air temperature of –15°C,
m20	= freezing air temperature of –20°C, and
m25	= freezing air temperature of –25°C.

SAS input file for the time it took saskatoons to drop in temperature from 0 to –5°C

```
options linesize = 78;
data one;
  Input vel $ temp $ @;
        Do berry = 1 to 3;
        Input time @;
        Output;
  End;
Cards;
v2p1 m15 11.6 12.2 12.0
v3p0 m15 9.0 6.2 5.9
v4p2 m15 6.5 10.5 10.8
v5p8 m15 5.2 7.2 10.0
v6p8 m15 5.5 6.0 8.3
v2p1 m20 7.9 7.8 8.8
v3p0 m20 5.2 9.9 6.4
v4p2 m20 6.8 6.8 5.7
v5p8 m20 5.5 7.0 5.4
v6p8 m20 3.7 4.4 3.6
v2p1 m25 5.3 4.2 5.4
v3p0 m25 4.6 4.4 4.7
v4p2 m25 3.3 4.0 4.0
v5p8 m25 4.3 2.2 4.3
v6p8 m25 3.8 3.5 4.0
Proc GLM;
        classes vel temp;
        model time = vel temp vel*temp;
Quit;
```

SAS outupt file for the time it took saskatoons to drop in temperature from 0 to –5°C

The SAS System
17:51 Friday, November 17, 2000

General Linear Models Procedure
Class Level Information

Class	Levels	Values
VEL	5	v2p1 v3p0 v4p2 v5p8 v6p8
TEMP	3	m15 m20 m25

Number of observations in data set = 45

The SAS System
17:51 Friday, November 17, 2000

General Linear Models Procedure

Dependent Variable: TIME

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	14	232.6680000	16.6191429	9.35	0.0001
Error	30	53.3000000	1.7766667		
Corrected Total	44	285.9680000			

R-Square	C.V.	Root MSE	TIME Mean
0.813616	21.13504	1.332917	6.306667

Source	DF	Type I SS	Mean Square	F Value	Pr > F
VEL	4	63.3168889	15.8292222	8.91	0.0001
TEMP	2	140.4093333	70.2046667	39.51	0.0001
VEL*TEMP	8	28.9417778	3.6177222	2.04	0.0759

Source	DF	Type III SS	Mean Square	F Value	Pr > F
VEL	4	63.3168889	15.8292222	8.91	0.0001
TEMP	2	140.4093333	70.2046667	39.51	0.0001
VEL*TEMP	8	28.9417778	3.6177222	2.04	0.0759

SAS input file for the time it took saskatoons to drop in temperature from 0 to −10°C

```
options linesize =78;
data one;
  Input vel $ temp $ @;
        Do berry = 1 to 3;
        Input time @;
        Output;
  End;
Cards;
v2p1 m15 24.1 23.5 27.3
v3p0 m15 20.2 22.4 20.7
v4p2 m15 15.3 18.5 16.5
v5p8 m15 14.3 13.8 15.2
v6p8 m15 7.1 12.8 13.3
v2p1 m20 15.0 13.1 13.5
v3p0 m20 10.7 12.5 10.5
v4p2 m20 11.8 10.3 10.7
v5p8 m20 9.2 9.5 9.2
v6p8 m20 7.2 7.2 6.8
v2p1 m25 9.4 8.0 9.2
v3p0 m25 7.5 7.8 7.6
v4p2 m25 6.3 6.6 6.7
v5p8 m25 6.1 5.5 5.9
v6p8 m25 5.4 5.4 5.9

Proc GLM;
        classes vel temp;
        model time = vel temp vel*temp;
Quit;
```

SAS output file for the time it took saskatoons to drop in temperature from 0 to –10°C

The SAS System
17:52 Friday, November 17, 2000

General Linear Models Procedure
Class Level Information

Class	Levels	Values
VEL	5	v2p1 v3p0 v4p2 v5p8 v6p8
TEMP	3	m15 m20 m25

Number of observations in data set = 45

The SAS System
17:52 Friday, November 17, 2000

General Linear Models Procedure

Dependent Variable: TIME

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	14	1361.771111	97.269365	60.28	0.0001
Error	30	48.406667	1.613556		
Corrected Total	44	1410.177778			

R-Square	C.V.	Root MSE	TIME Mean
0.965673	10.87757	1.270258	11.67778

Source	DF	Type I SS	Mean Square	F Value	Pr > F
VEL	4	343.7511111	85.9377778	53.26	0.0001
TEMP	2	903.8431111	451.9215556	280.08	0.0001
VEL*TEMP	8	114.1768889	14.2721111	8.85	0.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
VEL	4	343.7511111	85.9377778	53.26	0.0001
TEMP	2	903.8431111	451.9215556	280.08	0.0001
VEL*TEMP	8	114.1768889	14.2721111	8.85	0.0001

APPENDIX E Time-temperature graphs from tests performed using the prototype freezer

With Experiment B with the prototype freezer, sometimes a thermocouple was moved after the berry reached a temperature below –10°C. In the legent, a symbol indicates more than one position if the tray and stack are separated by a slash (\). The movement of a thermocouple to the next location is indicated by a break in the line.

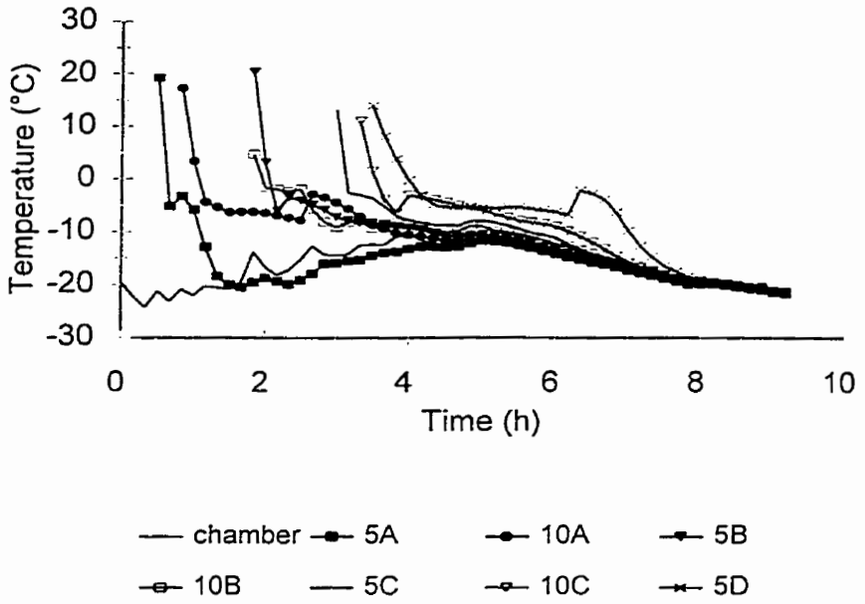

Fig. E.1 Experiment B; 22 July 1999

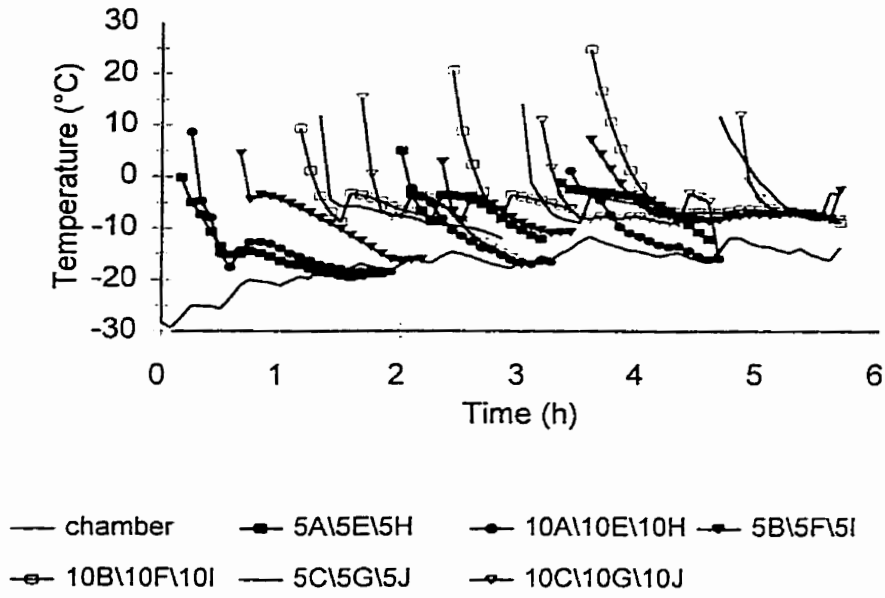

Fig. E.2 Experiment B

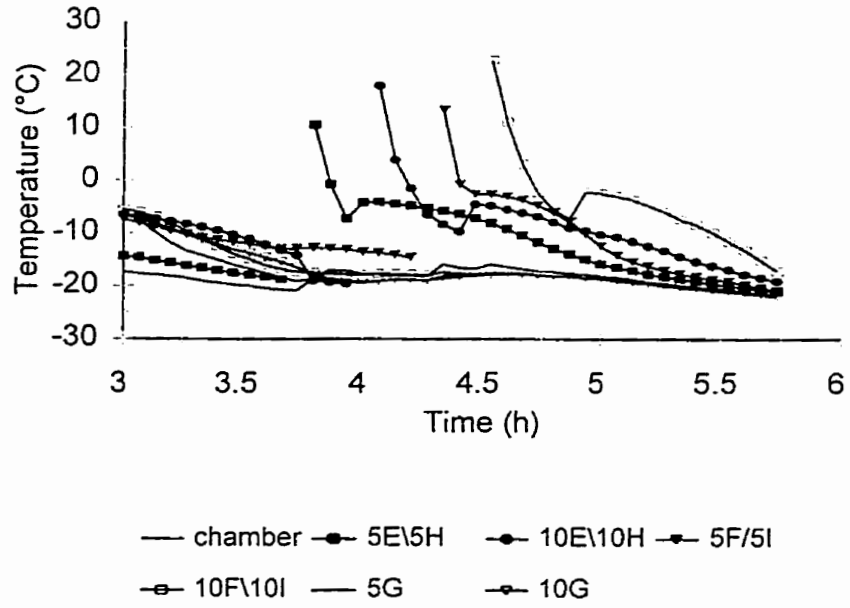

Fig. E.3 Experiment B; 24 July 1999 (only the second half of the day, first half day of data lost due to a computer crash)

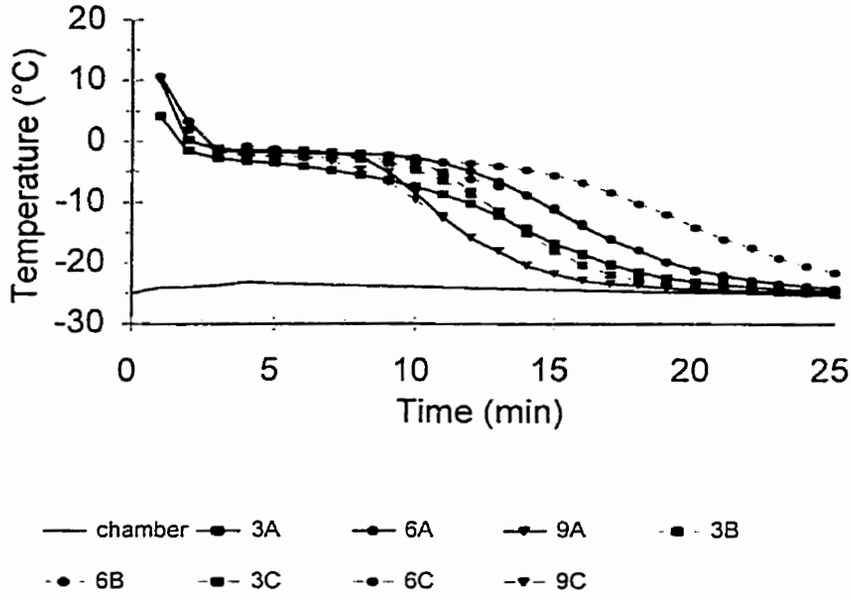

Fig. E.4 Experiment A; single berry in a tray, trial 1

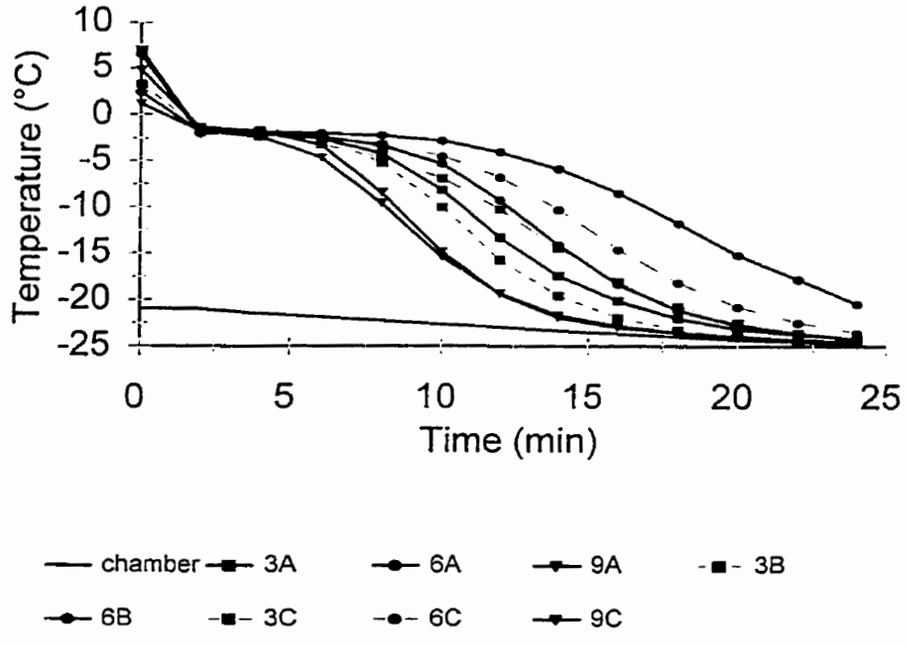

Fig. E.5 Experiment A; single berry in a tray, trial 2

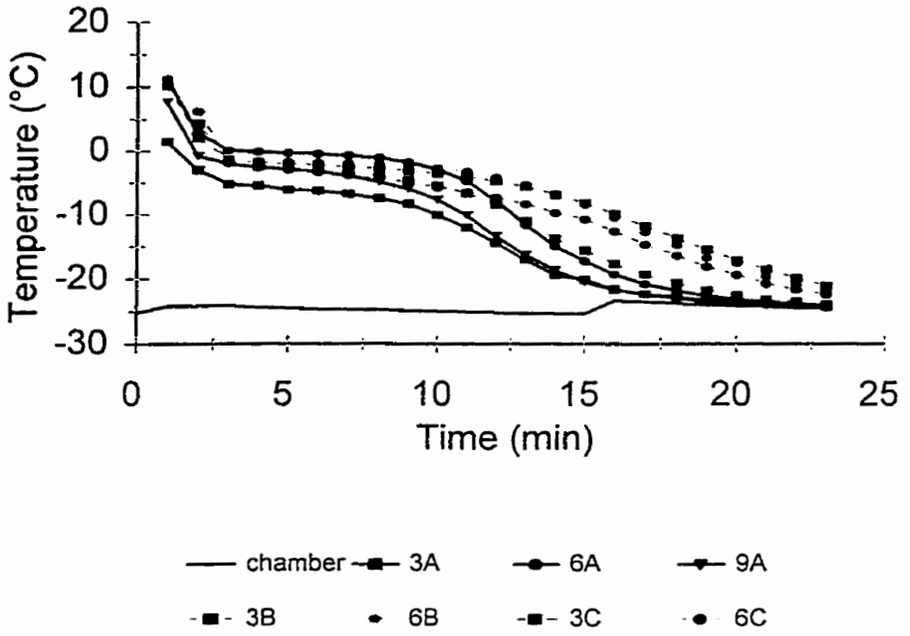

Fig. E.6 Experiment A; single berry in a tray, trial 3

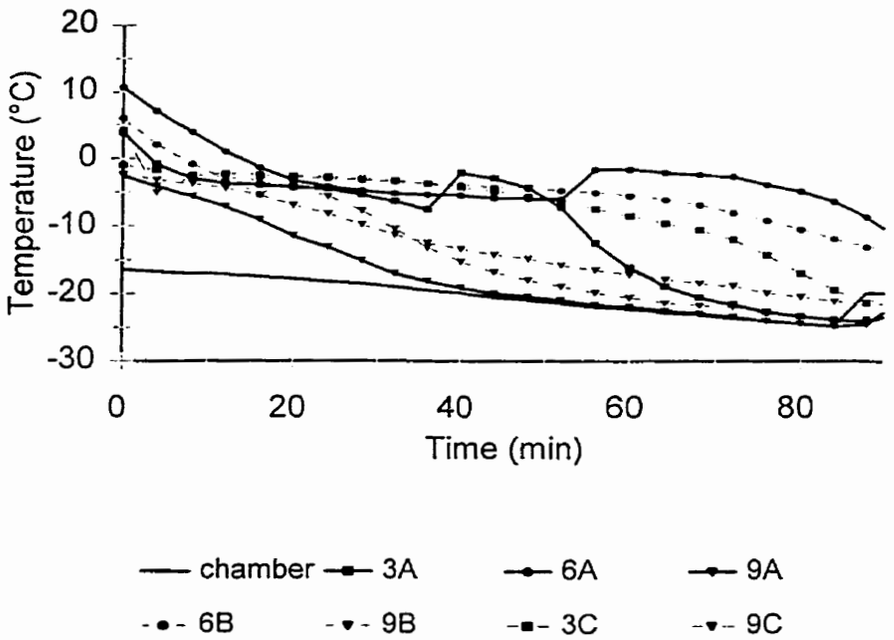

Fig. E.7 Experiment A; 1.1 kg of berries in a tray, trial 1

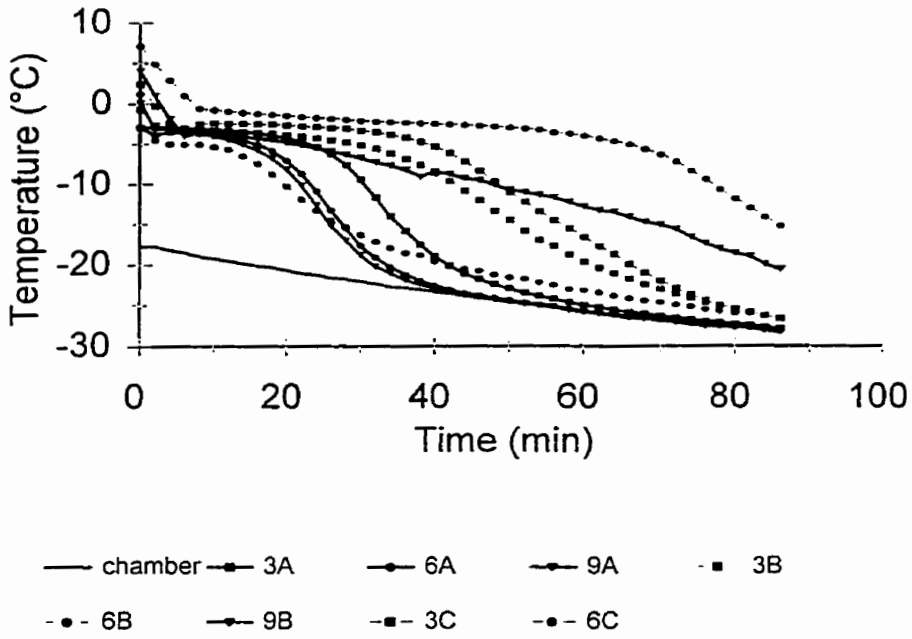

Fig. E.8 Experiment A; 1.1 kg of berries in a tray, trial 2

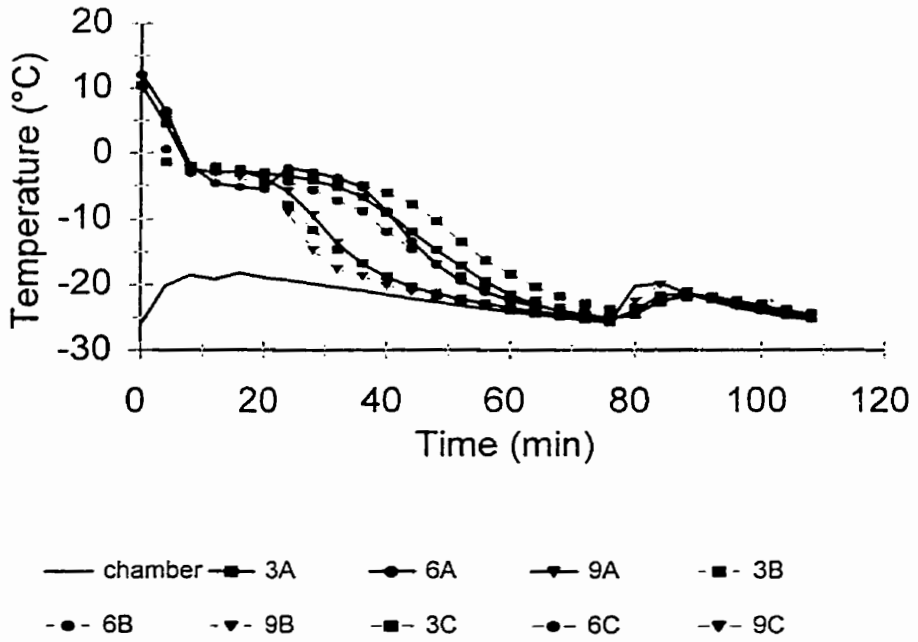

Fig. E.9 Experiment A; 1.1 kg of berries in a tray, trial 3

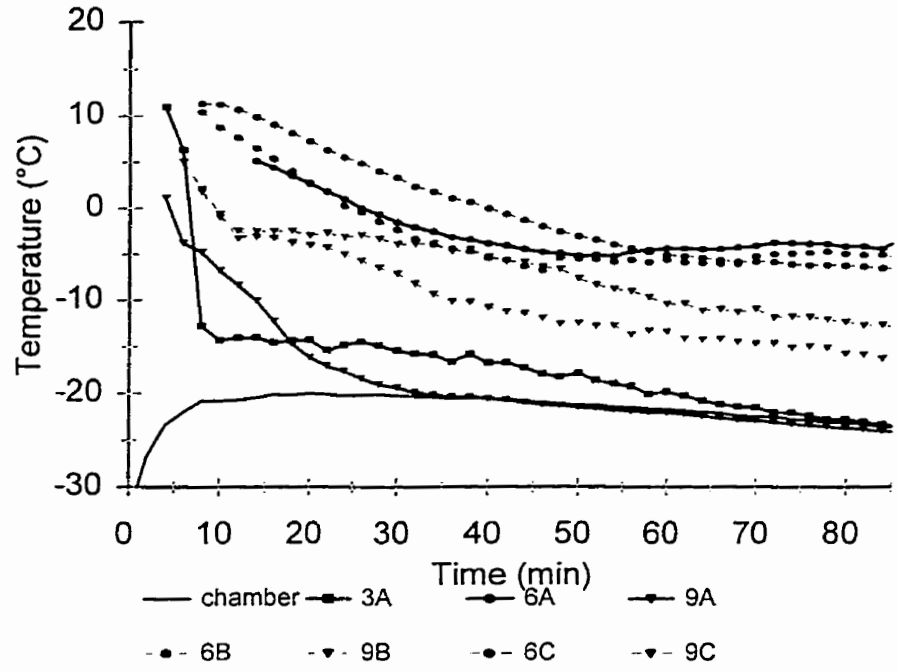

Fig. E.10 Experiment A; 2.3 kg of berries in a tray, trial 1

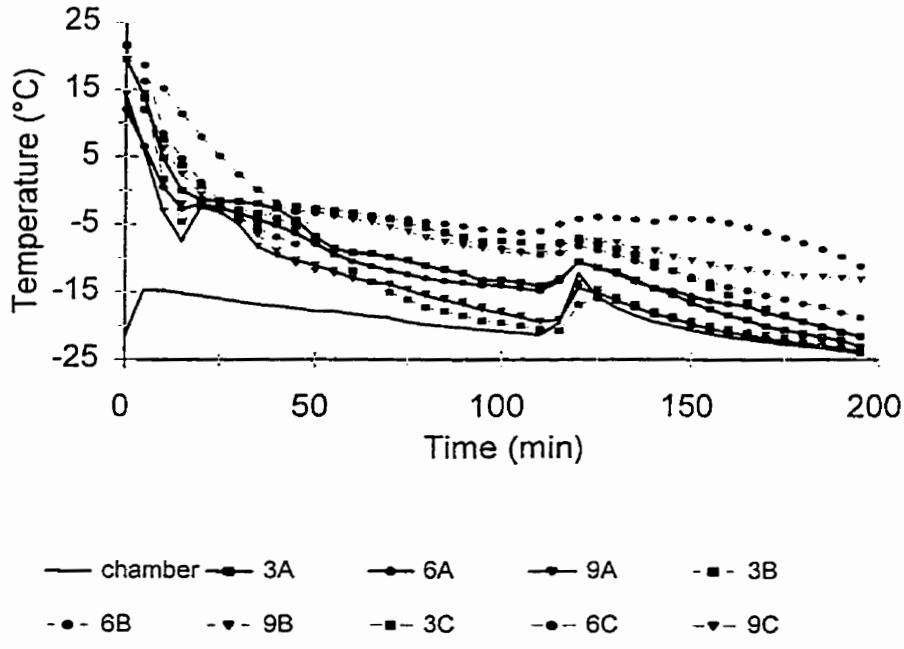

Fig. E.11 Experiment A; 2.3 kg of berries in a tray, trial 2

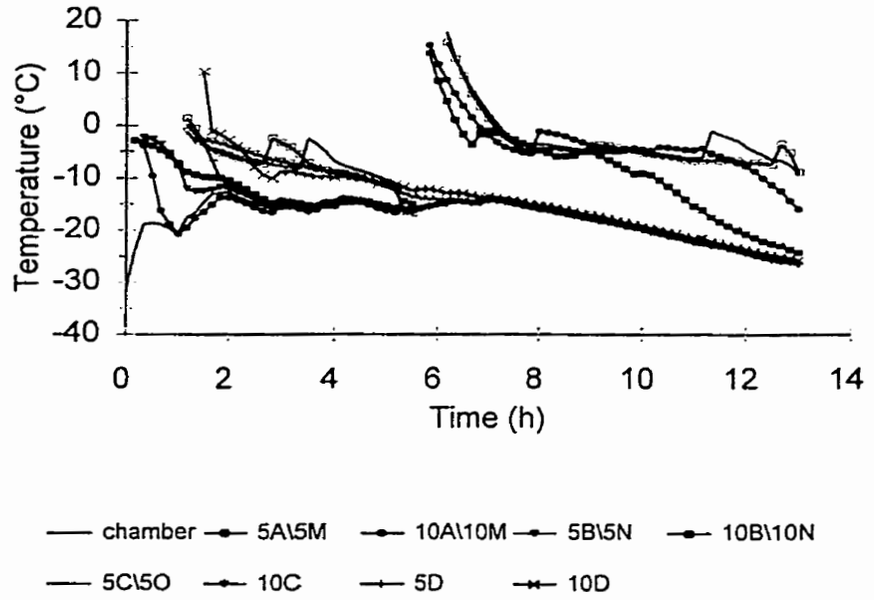

Fig. E.12 Experiment B; 17 July 2000

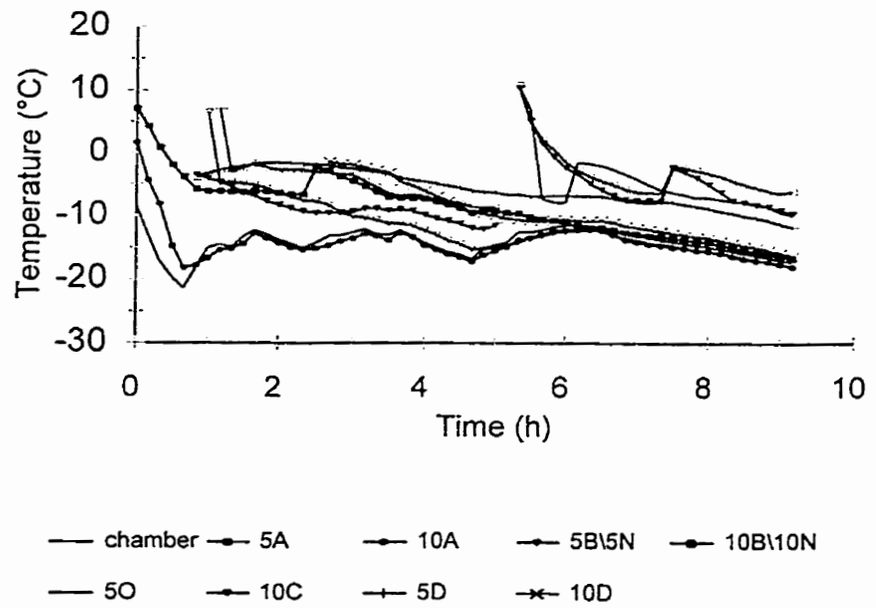

Fig. E.13 Experiment B; 18 July 2000

APPENDIX F Calibration of the benzaldehyde content of saskatoons

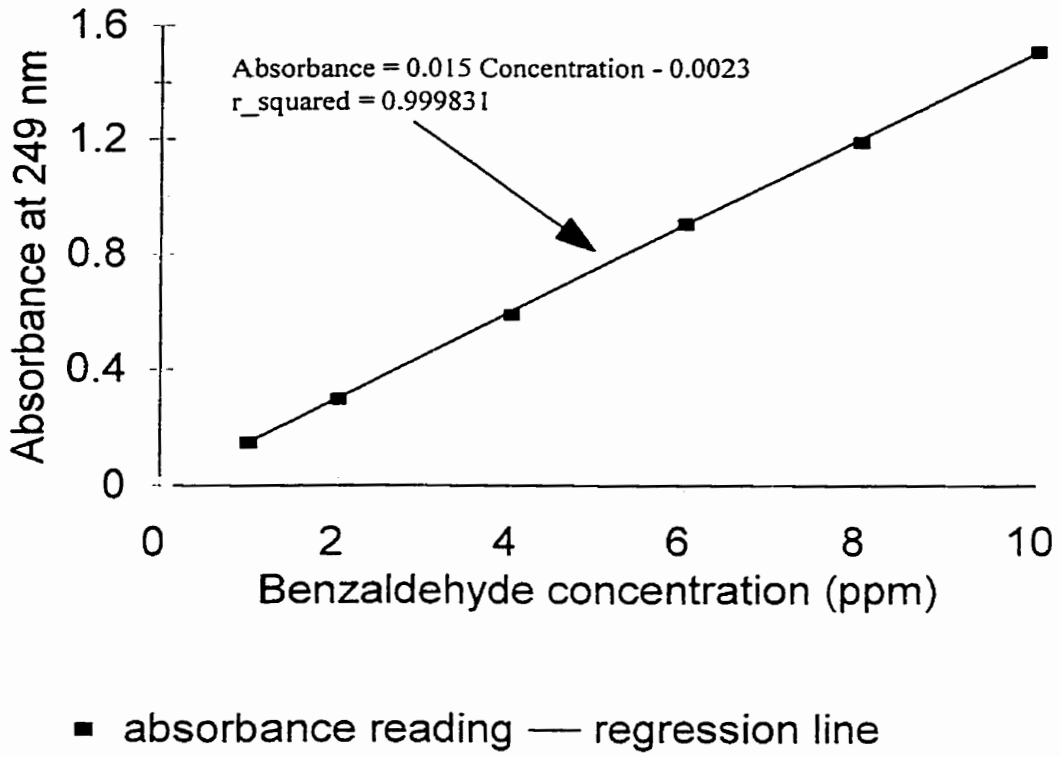

Fig. F.1 Relationship between known concentrations of benzaldehyde and the absorbance read with a Spectronic 601 spectrophotometer (Milton Roy, USA) at 249 nm.

APPENDIX G Data on quality analysis tests

Table G.1 13 July 1999 premature sample and 19 July 1999 fresh sample.

Date Harvested:	13 July and 19 July 1999			
Frozen or Fresh:	Fresh			
Date Tested:	13 July 1999		19 July 1999	
Colour (avgof 2 trials, 3 readings/trial)	Whole	Crushed	Whole	Crushed
L	**14.2**	**14.6**	**14.6**	**14.7**
a	**4.3**	**10.7**	**2.9**	**8.6**
b	**–0.2**	**1.4**	**–0.9**	**0.9**
Anthocyanins (1 reading per trial)	Trial 1	Trial 2	Trial 1	Trial 2
mass	100.40	100.03	100.70	100.20
Absorbance (pH 1.0)	0.703	0.843	0.889	1.060
Absorbance (pH 4.5)	0.080	0.101	0.092	0.104
TOD (pH 1.0)	8788	10538	11113	13250
TOD (pH 4.5)	1000	1263	1150	1300
TOD Difference	7788	9275	9963	11950
Total anthocyanin (mg/100g)	**101.8**	**121.2**	**130.2**	**156.2**
Benzaldehyde (1 reading per trial)	Trial 1	Trial 2	Trial 1	Trial 2
Mass	50.10		50.08	50.20
Absorbance (Y)	0.366		0.404	0.440
X = (Y+0.0023)/0.15	2.455		2.709	2.949
Dilution factor	10.0		10.0	10.0
Benzaldehyde (ppm)	**24.6**	**n/a**	**27.1**	**29.5**
Total acidity (average of 2 reading per trial)	Trial 1	Trial 2	Trial 1	Trial 2
mass	150.50	150.50	149.97	150.20
initial pH	3.82	3.78	3.96	3.94
mL 0.1 NaOH titrated	4.3	4.2	3.7	3.8
final pH			8.74	8.74
% malic acid	**0.383**	**0.371**	**0.331**	**0.335**
Soluble solids (1 reading per trial)	Trial 1	Trial 2	Trial 1	Trial 2
mass	10.00	10.20	9.94	10.34
refractometer reading	0.75	0.75	1.50	1.50
% sucrose	**7.5**	**7.4**	**15.1**	**14.5**
refractive index	**1.3340**	**1.3340**	**1.3350**	**1.3350**

Table G.2 Prototype freezing experiment B; 20 July 1999 and 22 July 1999 samples.

Date Harvested:	20 July 1999 and 22 July 1999			
Frozen or Fresh:	Frozen			
Date Tested:	21 July 1999		26 July 1999	
Colour (avgof 2 trials, 3 readings/trial)	Whole	Crushed	Whole	Crushed
L	**18.2**	**16.2**	**18.0**	**15.7**
a	**2.9**	**7.2**	**3.3**	**7.0**
b	**–0.2**	**1.6**	**–0.3**	**1.7**
Anthocyanins (1 reading per trial)	Trial 1	Trial 2	Trial 1	Trial 2
mass	100.05	100.01	100.02	100.02
Absorbance (pH 1.0)	0.737	0.707	0.779	0.566
Absorbance (pH 4.5)	0.047	0.017	0.119	0.027
TOD (pH 1.0)	9213	8838	9738	7075
TOD (pH 4.5)	588	213	1487	338
TOD Difference	8625	8625	8251	6737
Total anthocyanin (mg/100g)	**112.7**	**112.7**	**107.9**	**88.1**
Benzaldehyde (1 reading per trial)	Trial 1	Trial 2	Trial 1	Trial 2
Mass	50.06	50.16	50.22	50.33
Absorbance (Y)	0.405	0.333	0.283	0.197
X = (Y+0.0023)/0.15	2.715	2.235	1.902	1.329
Dilution factor	10.0	10.0	10.0	10.0
Benzaldehyde (ppm)	**27.2**	**22.4**	**19.0**	**13.3**
Total acidity (average of 2 reading per trial)	Trial 1	Trial 2	Trial 1	Trial 2
mass	150.07	150.09	150.23	149.98
initial pH	3.96	3.96	3.97	3.96
mL 0.1 NaOH titrated	4.0	4.0	3.4	3.5
final pH	8.73		8.73	8.71
% malic acid	**0.353**	**0.353**	**0.299**	**0.309**
Soluble solids (1 reading per trial)	Trial 1	Trial 2	Trial 1	Trial 2
mass	10.13	10.09	10.02	10.03
refractometer reading	1.50	1.50	1.00	1.00
% sucrose	**14.8**	**14.9**	**10.0**	**10.0**
refractive index	**1.3350**	**1.3350**	**1.3345**	**1.3345**

Table G.3 Prototype freezing experiment B; 24 July 1999 sample.

Date Harvested:	24 July 1999					
Frozen or Fresh:	Frozen					
Date Tested:	28 July 1999		20 Dec 1999		4 May 2000	
Colour (avgof 2 trials, 3 readings/trial)	Whole	Crushed	Whole	Crushed	Whole	Crushed
L	**16.6**	**17.0**	**13.2**	**12.1**	**12.9**	**10.6**
a	**2.4**	**6.4**	**3.0**	**8.1**	**2.8**	**6.1**
b	**–0.5**	**1.7**	**–0.5**	**6.1**	**–0.5**	**1.4**
Anthocyanins (1 reading per trial)	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2
mass	100.22	100.45	100.70	100.54	99.20	100.34
Absorbance (pH 1.0)	0.885	0.804	0.715	0.698	0.574	0.573
Absorbance (pH 4.5)	0.117	0.103	0.097	0.096	0.081	0.090
TOD (pH 1.0)	11063	10050	8938	8725	7175	7163
TOD (pH 4.5)	1463	1287	1213	1200	1013	1125
TOD Difference	9600	8763	7725	7525	6162	6038
Total anthocyanin (mg/100g)	**125.5**	**114.5**	**101.0**	**98.4**	**80.5**	**78.9**
Benzaldehyde (1 reading per trial)	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2
Mass	50.57	50.36	50.80	50.46	49.72	50.76
Absorbance (Y)	0.051	0.026			2.537	
X = (Y+0.0023)/0.15	0.355	0.189			16.929	
Dilution factor	10.0	10.0			1.0	
Benzaldehyde (ppm)	**3.6**	**1.9**	**n/a**	**n/a**	**16.9**	**n/a**
Total acidity (average of 2 reading per trial)	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2
mass	150.08	150.70	150.40	149.90	150.00	150.10
initial pH	4.28	4.26	4.19	4.26	4.67	4.86
mL 0.1 NaOH titrated	3.3	3.2	4.0	3.6	3.9	4.6
final pH	8.69	8.76	8.75	8.72	8.66	8.68
% malic acid	**0.295**	**0.285**	**0.357**	**0.318**	**0.342**	**0.407**
Soluble solids (1 reading per trial)	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2
mass	10.87	10.36	20.01	20.41	20.26	20.80
refractometer reading	1.00	1.00	1.60	1.50	1.50	1.50
% sucrose	**9.2**	**9.7**	**8.0**	**7.3**	**7.4**	**7.2**
refractive index	**1.3345**	**1.3345**	**1.3355**	**1.3354**	**1.3352**	**1.3351**

Table G.4 12 July 2000 fresh sample.

Date Harvested:	12 July 2000
Date Tested:	12 July 2000
Frozen or Fresh:	Fresh

Colour (avgof 2 trials, 3 readings/trial)	Whole	Crushed
L	**16.8**	**18.7**
a	**0.7**	**5.9**
b	**0.3**	**1.9**

Anthocyanins (1 reading per trial)	Trial 1	Trial 2
mass	100.96	100.71
Absorbance (pH 1.0)	0.397	0.429
Absorbance (pH 4.5)	0.039	0.041
TOD (pH 1.0)	9925	10725
TOD (pH 4.5)	975	1025
TOD Difference	8950	9700
Total anthocyanin (mg/100g)	**117.0**	**126.8**

Benzaldehyde (1 reading per trial)	Trial 1	Trial 2
Mass	50.52	49.78
Absorbance (Y)	overflow	0.300
X = (Y+0.0023)/0.15	overflow	2.015
Dilution factor	10.0	10.0
Benzaldehyde (ppm)	**overflow**	**20.2**

Total acidity (average of 2 reading per trial)	Trial 1	Trial 2
mass	150.02	150.08
initial pH	3.77	3.91
mL 0.1 NaOH titrated	3.6	3.8
final pH	8.77	8.71
% malic acid	**0.322**	**0.340**

Soluble solids (1 reading per trial)	Trial 1	Trial 2
mass	20.63	20.66
refractometer reading	2.0	3.0
% sucrose	**10.0**	**15.0**
refractive index	**1.3360**	**1.3375**

Table G.5 16 July 2000 fresh sample.

Date Harvested:	16 July	2000
Frozen or Fresh:	Fresh	
Date Tested:	18 July 2000	
Colour (avgof 2 trials, 3 readings/trial)	Whole	Crushed
L	**13.4**	**14.7**
a	**4.1**	**7.5**
b	**–0.4**	**1.6**
Anthocyanins (1 reading per trial)	Trial 1	Trial 2
mass	100.74	100.68
Absorbance (pH 1.0)	0.622	0.890
Absorbance (pH 4.5)	0.089	0.108
TOD (pH 1.0)	7775	11125
TOD (pH 4.5)	1113	1350
TOD Difference	6662	9775
Total anthocyanin (mg/100g)	**87.1**	**127.8**
Benzaldehyde (1 reading per trial)	Trial 1	Trial 2
Mass	50.34	50.11
Absorbance (Y)	1.640	1.108
X = (Y+0.0023)/0.15	10.949	7.402
Dilution factor	1.0	1.0
Benzaldehyde (ppm)	**10.9**	**7.4**
Total acidity (average of 2 reading per trial)	Trial 1	Trial 2
mass	150.40	150.86
initial pH	4.49	4.49
mL 0.1 NaOH titrated	3.3	2.9
final pH	8.70	8.69
% malic acid	**0.288**	**0.252**
Soluble solids (1 reading per trial)	Trial 1	Trial 2
mass	20.02	20.78
refractometer reading	1.56	2.48
% sucrose	**7.8**	**11.9**
refractive index	**1.3353**	**1.3360**

Table G.6 Prototype freezing experiment A (1.1 kg) ;15 July 2000 samples.

Date Harvested:	15 July 2000					
Frozen or Fresh:	Frozen					
Date Tested:	17 July 2000		31 July 2000		14 August 2000	
Colour (avgof 2 trials, 3 readings/trial)	Whole	Crushed	Whole	Crushed	Whole	Crushed
L	**18.0**	**19.9**	**16.3**	**19.4**	**n/a**	**n/a**
a	**6.2**	**8.4**	**0.8**	**4.7**	**n/a**	**n/a**
b	**–0.1**	**2.2**	**1.2**	**2.8**	**n/a**	**n/a**
Anthocyanins (1 reading per trial)	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2
mass	99.87	100.76	100	100	100.30	100.10
Absorbance (pH 1.0)	0.366	0.392	0.810	0.879	0.883	0.854
Absorbance (pH 4.5)	0.052	0.048	0.097	0.118	0.112	0.109
TOD (pH 1.0)	9150	9800	13500	14650	14717	14233
TOD (pH 4.5)	1300	1200	1617	1967	1867	1817
TOD Difference	7850	8600	11883	12683	12850	12416
Total anthocyanin (mg/100g)	**102.6**	**112.4**	**155.3**	**165.8**	**168.0**	**162.3**
Benzaldehyde (1 reading per trial)	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2
Mass			50.26	50.83	50.10	50.40
Absorbance (Y)			0.768	0.935	0.685	0.612
X = (Y+0.0023)/0.115			5.135	6.249	4.582	4.095
Dilution factor			2.0	2.0	4.0	4.0
Benzaldehyde (ppm)	**n/a**	**n/a**	**10.3**	**12.5**	**18.3**	**16.4**
Total acidity (average of 2 reading per trial)	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2
mass	150.54	150.54	150	150	150.40	150.40
initial pH	3.91	3.90	4.39	4.56	4.49	4.54
mL 0.1 NaOH titrated	3.8	3.6	3.0	3.1	3.1	3.6
final pH	8.72	8.67	8.70	8.69	8.64	8.73
% malic acid	**0.334**	**0.319**	**0.268**	**0.277**	**0.272**	**0.321**
Soluble solids (1 reading per trial)	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2
mass	20.63	20.33	20	20	20.30	20.50
refractometer reading	2.48	2.59	0.75	0.75	0.75	0.60
% sucrose	**12.0**	**12.7**	**3.8**	**3.8**	**3.7**	**2.9**
refractive index	**1.3365**	**1.3370**	**1.3340**	**1.3340**	**1.3340**	**1.3330**

Table G.7 Prototype freezing experiment B; early 17 July 2000 samples.

Date Harvested:	17 July 2000					
Frozen or Fresh:	Frozen					
Date Tested:	22 July 2000		31 July 2000		14 August 2000	
Colour (avgof 2 trials, 3 readings/trial)	Whole	Crushed	Whole	Crushed	Whole	Crushed
L	**19.5**	**20.3**	**16.4**	**19.8**	**n/a**	**n/a**
a	**4.8**	**7.9**	**0.4**	**4.3**	**n/a**	**n/a**
b	**0.0**	**2.6**	**1.2**	**3.1**	**n/a**	**n/a**
Anthocyanins (1 reading per trial)	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2
mass	100.29	100.68	100	100	100.20	100.80
Absorbance (pH 1.0)	0.696	0.728	0.643	0.741	0.538	0.598
Absorbance (pH 4.5)	0.061	0.093	0.088	0.100	0.088	0.085
TOD (pH 1.0)	5800	6067	13396	15438	13450	14950
TOD (pH 4.5)	508	775	1833	2083	2200	2125
TOD Difference	5292	5292	11563	13355	11250	12825
Total anthocyanin (mg/100g)	**69.2**	**69.2**	**151.2**	**174.6**	**147.1**	**167.6**
Benzaldehyde (1 reading per trial)	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2
Mass		50.00	50.47	50.90	50.10	50.30
Absorbance (Y)		0.928	0.949	0.959	0.645	0.595
X = (Y+0.0023)/0.15		6.202	6.342	6.409	4.315	3.982
Dilution factor		1.0	1.0	1.3	4.0	4.0
Benzaldehyde (ppm)	**n/a**	**6.2**	**6.3**	**8.5**	**17.3**	**15.9**
Total acidity (average of 2 reading per trial)	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2
mass	150.90	150.70	150.07	150.15	151.20	150.90
initial pH	4.50	4.40	4.46	4.45	4.37	4.32
mL 0.1 NaOH titrated	3.5	3.5	3.6	3.6	3.2	3.3
final pH	8.66	8.80	8.86	8.81	8.66	8.70
% malic acid	**0.309**	**0.313**	**0.317**	**0.322**	**0.280**	**0.293**
Soluble solids (1 reading per trial)	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2
mass	21.50	20.60	20.29	20.48	20.10	20.70
refractometer reading	2.00	2.00	1.30	1.00	0.60	0.70
% sucrose	**9.3**	**9.7**	**6.4**	**4.9**	**3.0**	**3.4**
refractive index	**1.3346**	**1.3360**	**1.3348**	**1.3345**	**1.3330**	**1.3340**

Table G.8 Prototype freezing experiment B; late 17 July 2000 samples.

Date Harvested:	17 July 2000 late			
Frozen or Fresh:	Frozen			
Date Tested:	20 July 2000		31 July 2000	
Colour (avgof 2 trials, 3 readings/trial)	Whole	Crushed	Whole	Crushed
L	**18.0**	**20.2**	**18.7**	**18.9**
a	**3.9**	**7.4**	**–0.3**	**3.4**
b	**–2.6**	**0.4**	**0.8**	**2.7**
Anthocyanins (1 reading per trial)	Trial 1	Trial 2	Trial 1	Trial 2
mass	100.90	100.50	100	100
Absorbance (pH 1.0)	0.762	0.539	0.823	0.672
Absorbance (pH 4.5)	0.076	0.051	0.103	0.101
TOD (pH 1.0)	6350	4492	13717	11200
TOD (pH 4.5)	633	425	1717	1683
TOD Difference	5717	4067	12000	9517
Total anthocyanin (mg/100g)	**74.7**	**53.2**	**156.9**	**124.4**
Benzaldehyde (1 reading per trial)	Trial 1	Trial 2	Trial 1	Trial 2
Mass	50.90	50.20	50.28	50.49
Absorbance (Y)	0.347	0.096	0.562	0.688
X = (Y+0.0023)/0.15	2.329	0.655	3.762	4.602
Dilution factor	10.0	10.0	4.0	4.0
Benzaldehyde (ppm)	**23.3**	**6.6**	**15.0**	**18.4**
Total acidity (average of 2 reading per trial)	Trial 1	Trial 2	Trial 1	Trial 2
mass	151.00	151.00	150.34	150.34
initial pH	4.43	4.36	4.86	4.78
mL 0.1 NaOH titrated	3.1	3.2	2.7	2.6
final pH	8.63	8.77	8.71	8.84
% malic acid	**0.275**	**0.279**	**0.241**	**0.232**
Soluble solids (1 reading per trial)	Trial 1	Trial 2	Trial 1	Trial 2
mass	20.80	20.00	20.29	20.48
refractometer reading	2.00	2.27	1.50	1.50
% sucrose	**9.6**	**11.4**	**7.4**	**7.3**
refractive index	**1.3359**	**1.3370**	**1.3350**	**1.3350**

APPENDIX H **Time-temperature graphs for blended saskatoons frozen in a plastic cylinder and exposed to one-dimensional freezing**

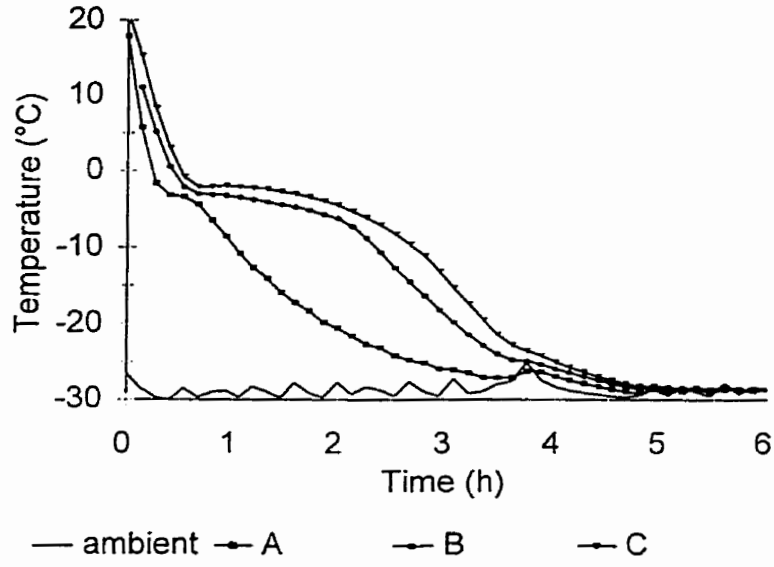

Fig. H.1 Trial 1

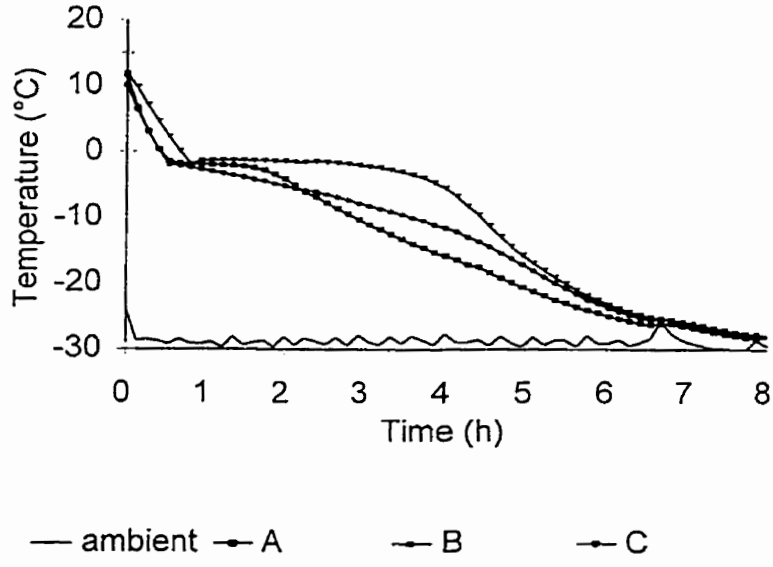

Fig. H.2 Trial 2

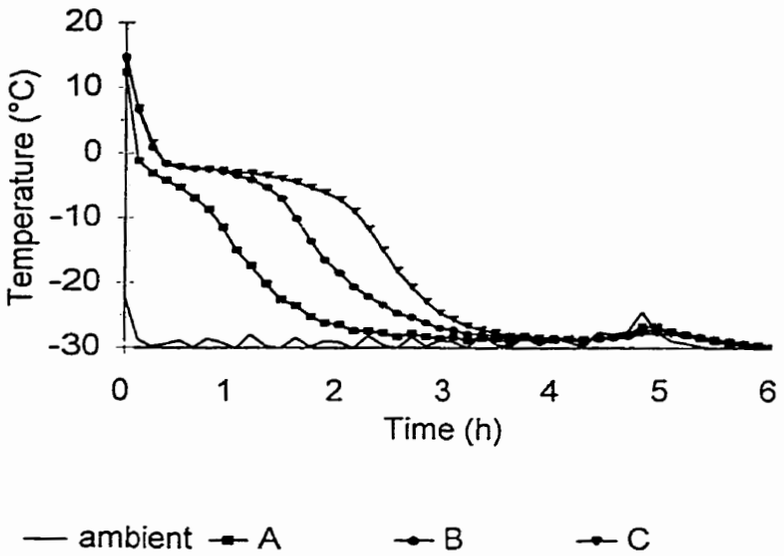

Fig. H.3 Trial 3