UNIVERSITY OF ALBERTA

OPTIMIZATION OF FORCED-AIR COOLING FOR FRESH FRUIT AND VEGETABLES GROWN IN ALBERTA

BY

IKECHUKWU ERIKA EDEOGU ©

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled *Optimization of Forced-air Cooling for Fresh Fruit and Vegetables Grown in Alberta* submitted by *Ikechukwu Erika Edeogu* in partial fulfillment of the requirements for the degree of *Master of Science* in *Agricultural Engineering*.

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ABSTRACT

Three methods of precooling fresh fruits and vegetables were tested. The methods tested were vertically-directed forced-air cooling (VFC), horizontally-directed forced-air cooling (HFC) and room cooling. Cooling was conducted in a cold room with temperatures varying between 0°C and 2°C. Temperature and weight loss of carrots, lettuce and strawberries were measured and shelf-life assessed.

A statistical analysis based on half-cooling time showed that VFC and HFC differed significantly from room cooling. However, there was no significant difference between VFC and HFC although results of weight loss and shelf-life evaluation suggested that VFC resulted in better cooling.

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h	= unit surface conductance, $Wm^{-2}K^{-1}$
r	= distance from center of a cylinder or sphere, m
k	= thermal conductivity, $Wm^{-1}K^{-1}$
Q	= heat removed or supplied, kJ
θ	= time, h
Z, $X_{1/2}$	= half-cooling time, h
S	= seven-eighth-cooling time, h
A	= surface area, m^2
t, T	= temperature of any point in product, °C
t_a, T_a	= ambient temperature, °C
t_i, T_i	= initial temperature, °C
$T_{1/2}$	= temperature of product at half-cooling time, °C
$(t-t_a)/(t_i-t_a)$	= unaccomplished temperature ratio
X_a	= time taken by product to reach ambient temperature, h
X_i	= time at initial temperature = 0, h
C	= specific heat, $kJkg^{-1}K^{-1}$
c_p	= specific heat at constant pressure, $kJkg^{-1}K^{-1}$
w	= specific weight, kgm^{-3}
V	= volume, m^3
α	= thermal diffusivity, m^2s^{-1}
ρ	= mass density, kgm^{-3}
Cc	= cooling coefficient, $°C/°C^{-1}h^{-1}$
Cc'	= cooling coefficient from linear function, $°C/°C^{-1}h^{-1}$
j	= lag time or lag factor

1. INTRODUCTION

Freshness and quality of fresh fruits and vegetables must be maintained after harvest for a significant length of time. For many decades now, prolonging shelf-life of fresh produce has been pursued by scientists and fruit and vegetable growers as a result of consumer expectations for fresh foodstuff of high quality.

Recently, the ever-increasing demand by consumers for fresh food has called for increased production by fruit and vegetable farmers. Boyette and Rohrbach (1993), referring to the commercial production of high-value specialty fruit such as strawberries, stated that:

> "A growing demand and expanded markets for these commodities from grocery stores and restaurants in addition to a diversifying agricultural base (Agricultural Statistics Division, NCDA, 1990) has prompted many growers to consider expanding their production to accommodate these opportunities."

In effect, the many technologies used for production, harvesting and postharvest preservation need to be highly efficient. Farmers must be quite well equipped to handle the demands of a larger market.

While ensuring increased productivity, farmers must also be guaranteed of accompanying profitability from their investments. This implies that practices such as postharvest preservation have to take into account cost-effectiveness of the technology applied.

1.1 PRIMARY OBJECTIVE

The primary focus of this project was the development of a mobile cooler for postharvest preservation of horticultural produce. Again, according to Boyette and Rohrbach (1993), to expand the size of high-value, specialty fruit farming ventures into commercially viable ones, requires considerable investment in postharvest cooling and handling facilities. Furthermore, to effectuate such an investment would require the growers to have large volumes of fruit and ample financial resources, which only few can afford.

Thus, in a bid to improve postharvest preservation practices of market garden operations, numerous factors were taken into consideration keeping in mind the small-scale size of most of these ventures. These included the type of precooling method (a postharvest technique) to be adopted, portability of the precooling system to field operations and suitability of the packing containers to the precooling system as well as to a wide variety of produce. Economic considerations included capital, labour costs, equipment costs and handling time. Labour costs tend to be quite high in the Edmonton area.

Based on the factors considered, forced-air cooling was chosen as the precooling technique best-suited for the development of a mobile cooler for market gardening. The reasons behind selection of this method are presented in the literature review.

1.2 SECONDARY OBJECTIVE

Although forced-air cooling was selected on the basis of its compatibility with the nature of market gardening, available literature does not show it as an optimally utilized precooling technique. Research is still ongoing on means of enhancing cooling by this method.

Consequently, this particular study was designed to investigate and compare cooling by (1) forcing air vertically through packing boxes and (2) forcing air horizontally through the boxes. Room cooling was used as a control. The percentage vented area of the packing boxes was increased relative to commercially-available boxes. Increasing the percentage of vents in each box was crucial to facilitate better air-to-product contact. Three types of produce (carrots, lettuce and strawberries) were used to test the different cooling techniques. The results obtained from a comparison of (1) and (2) above, would lessen the number of variables to be considered for the design of a mobile cooler.

2. LITERATURE REVIEW

Fruits and vegetables, like other living tissue, continue to metabolize and maintain their physiological systems after harvest. However, respirable substrates and moisture lost from tissues cannot be replenished when these produce are cut off from their source of water, photosynthates and minerals. The harvested fruit or vegetable has to depend on its own food reserves and water content for respiratory and transpiratory processes to occur. Consequently, deterioration takes place (Wills *et al.*, 1981). According to Kays (1991) the loss of substrate from stored plant products results in a decrease in energy reserves within the tissue, which in turn decreases the length of time the product can effectively maintain its existing condition.

The rate at which deterioration occurs is influenced by many factors. Depending on the type of produce, these factors may include the moisture content, the presence of decay organisms, length of the growing season, the respiration rate or amount of ethylene released. They also include genetic factors which control growth, development, postharvest behaviour, and physiological and morphological variations (Janick, 1986; Salunkhe *et al.*, 1991).

Some of these factors are further affected by other factors. For instance, respiratory rate can be strongly influenced by certain commodity and environmentally-related factors (Kays, 1991). Temperature is one such example.

As temperature of the product increases, respiratory rates generally increase (Kays, 1991), especially in the early period after harvest (Salunkhe *et al.*, 1991). High temperatures induce high respiratory rates which further induce high deterioration rates. Schofer *et al.* (1992) stated that high product temperatures are usually observed in freshly-harvested produce because of high field heat. Field heat refers to the product's internal heat caused by external influences of the environment.

Thus, one of the objectives of postharvest handling of fruit and vegetables is to reduce the amount of field heat these products contain, prior to shipping, storage or processing (ASHRAE, 1990). This is achieved by cooling or, rather, precooling. Sargent *et al.* (1988) defined precooling as "the rapid removal of field heat to temperatures approaching proper storage and the first line of defense in slowing the biological processes which reduce product quality".

2.1 PRECOOLING METHODS

Precooling of fresh fruits and vegetables may be achieved by one of many different methods. Each of these methods is often a variation of an underlying method which defines cooling based on principles of heat transfer and the behaviour of matter in gaseous, liquid or solid state. The primary methods of precooling are room cooling, forced-air cooling, hydrocooling, icing and vacuum cooling.

2.1.1 Room Cooling

In room cooling, produce in bulk units or smaller containerized units are simply placed in a refrigerated room and cooled. The cooling unit of these rooms consists typically of evaporator coils and fans which generate air currents. Air circulates over the evaporator coils, around the packing containers (i.e. bulk bins, boxes or cartons) and flows through the containers, via vents in their sides, cooling the produce (Kays, 1991; Sargent *et al.*, 1988; Wills *et al.*, 1981). For adequate cooling to be achieved by room cooling, Wills *et al.* (1981) prescribed air velocities around the containers, of at least 1m/s. Kays (1991) specified a range of air velocity between 1.02m/s and 2.03m/s.

According to Bazan *et al.* (1989) the heat energy flow in room cooling from the center of the bulk of produce to the container surfaces is largely by conduction and convective buoyancy. Boyette and Schultheis (1993) supported this claim. Waelti (1989) considered heat flow from a broader perspective, and seemed to ascribe this flow of energy to conduction from the center of boxes stacked on a pallet outward. However, he did not indicate if these boxes had vents in their sides. Fraser (1991) also attributed heat transfer of room-cooled produce to conduction. Kays (1991) made a third assertion that heat flow is principally by forced convection, due to movement of air around the produce, the other means of heat transfer being by conduction, radiation, and a relatively small amount of evaporation.

Advantages

The main advantages of room cooling are, firstly, the produce is in most cases cooled and stored in the same room and as such handling of produce is minimized (Kays, 1991; Wills *et al.*, 1981). However, it is for this reason (i.e. produce cooled and stored in the same room) that ASHRAE (1990) does not consider room cooling a precooling method claiming that precooling generally occurs in a separate facility and within a few hours or minutes. Secondly, according to Wills *et al.* (1981) the peak heat loads of refrigeration are less in room cooling than those of the other cooling methods.

Disadvantages

Room cooling is commonly known to be a slow cooling process. Geeson (1988) explained this behaviour, stating that most of the air circulates around the packing containers rather than through them, despite the stacking arrangement used. The air adopts this flow pattern because, according to Fraser (1991) air naturally takes the path of least resistance.

Furthermore, loss of water from the product being cooled occurs by transpiration using this method (Sargent *et al.* 1988). Yet another problem is sweating. Sweating occurs because air moves from warm fruit near the center of the container to cooler fruit on the outside (O'Brien and Gentry, 1967).

2.1.2 Forced-Air Cooling

The main purpose behind forced-air cooling is to ensure that cooler air comes in contact with the warm produce (Fraser, 1992). This method is characterised by definite stacking patterns and baffled stacks so that air is forced to flow through each vented container (ASHRAE, 1990) because of a pressure gradient formed (Lauro, 1989). The air should be as cold as the fruit or vegetable being cooled would allow (Janick, 1986) as unsuitable air temperatures can cause chilling or freezing injury.

Wills *et al.* (1981) stated that, compared to room cooling, the rate of cooling by forced air flow is much higher because heat transfer now occurs over a larger surface area i.e., over the total exposed surface of each commodity in each container. Heat transfer in forced-air cooling is by convection and evaporation (Fraser, 1991; Baird *et al.* 1988). According to Tang and Johnson (1989), convective heat transfer in fruit and vegetable cooling, rather than being wholly natural or forced, may be a combination of both resulting from relatively weak forced air flow mixing with very warm produce.

Advantages

Forced-air cooling is reported to cool produce up to four times as fast as room cooling (Sargent *et al.* 1988). Furthermore, according to Hackert *et al.* (1987) forced-air cooling was selected for the design of a portable cooler, at the Department of Agricultural Engineering, University of Minnesota, because of its portability and its potentially wider range of application. Forced-air cooling also requires low capital investment, does not wet the product being cooled (MacKinnon and Bilanski, 1992) and permits more orderly packing of produce (Fraser, 1992). According to O'Brien and Gentry (1967), sweating does not occur by this method because air movement is from colder fruit to warmer fruit.

Disadvantages

As with room cooling, moisture loss occurs in produce cooled by forced-air cooling. Conventional forced-air cooling systems cool fruits and vegetables by passing air of low relative humidity over the fresh produce. These systems cause moisture loss from the produce, which subsequently causes weight loss, shrivelling, softening, loss of colour and shortened shelf-life (Helsen and Willmott, 1991).

MacKinnon and Bilanski (1992) explained that, as air flows over fresh produce heat and moisture are transferred from the warm body to the cold air. Moisture is transferred as a result of a vapour pressure deficit created in the cooling facility. The high moisture content of the produce combined with the effects of temperature, result in a higher vapour pressure in the produce than in the surrounding air. Hence, because too much moisture may be removed, forced-air cooling is not generally recommended as a precooling method (MacKinnon *et al.*, 1991).

Other disadvantages of this method include non-uniform cooling, the need for container venting and proper stacking (MacKinnon and Bilanski, 1992) and the lower rate of cooling when compared with hydrocooling or vacuum cooling (Boyette and Rohrbach, 1989).

2.1.3 Hydrocooling

As the name implies, hydrocooling is a method of cooling in which flowing cold water comes in contact with the produce to be cooled (Kays, 1991). According to ASHRAE (1990) when a film of cold water flows briskly and uniformly over the surface of a warm substance, the surface temperature of the substance becomes equal to that of the water.

Similar to forced-air cooling, heat transfer between the product and the water in hydrocooling, is by convection. ASHRAE (1990) stated that the rate at which heat is removed from the product is related to the surface heat transfer coefficient, the total area and the temperature difference between the product and its surroundings. Thus, according to Wills *et al.* (1981), for rapid cooling to occur, the water needs to be maintained at approximately 0°C and should make contact with most of the product surface.

Advantages

Hydrocooling is reported to cool produce faster than forced-air cooling because water has a higher heat capacity than air (Sargent *et al.*, 1988; Wills *et al.*, 1981). In effect the optimum surface heat transfer coefficient is generally higher for water than it is for air, even when the air is at a lower temperature (ASHRAE, 1990).

Other advantages of hydrocoolers are that moisture loss does not occur (Janick, 1986) and the product may be cleaned during cooling (Wills *et al.*, 1981).

Disadvantages

Two commonly cited disadvantages of hydrocooling are the possibility of water contamination and the high capital investment required (MacKinnon *et al.*, 1991). Contamination occurs when decay organisms accumulate in the water being recycled, subsequently inoculating all the produce being cooled (Sargent *et al.*, 1988).

A third disadvantage of hydrocooling is its limited application to fruits or vegetables which can tolerate wetting (Kays, 1991). For example, strawberries cannot be hydrocooled since wetting makes them more susceptible to decay (Émond *et al.*, 1994).

2.1.4 Icing

Icing, also termed contact icing (Sargent *et al.*, 1988; Janick, 1986; Wills *et al.*, 1981), top icing (Geeson, 1988) or package icing (ASHRAE, 1990; Lauro, 1989) depending on its application, is a simpler form of hydrocooling (Lauro, 1989). Janick (1986) described it as a precooling method whereby cooling is achieved by placing crushed ice in or on the package containing the produce.

Ice has a higher heat capacity than water since it requires substantial heat to change phase from solid to liquid state (Sargent *et al.*, 1988). However, cooling by this method is not necessarily more effective than cooling by hydrocooling (Janick, 1986). Increased cooling effectiveness, according to Kays (1991) may be achieved by increasing the ice-to-product contact area e.g., by using small pieces of ice or liquid ice (slush ice) (Sargent *et al.*, 1988).

Advantages

Janick (1986) mentioned two advantages of icing as, firstly, there is no moisture loss from the produce during cooling and secondly, produce may be shipped immediately after treatment since cooling occurs while the produce is in transit.

Disadvantages

Similar to hydrocooling systems, icing is only applicable to fruits and vegetables which can tolerate wetting and requires water-tolerant containers (Geeson, 1988). It is also possible to cause freezing injury to produce by icing (Ghate *et al.*, 1988). Finally, the weight of the ice tends to increase shipping weights substantially (Kays, 1991).

2.1.5 Vacuum Cooling

This is the most rapid method of precooling horticultural produce (Sargent *et al.*, 1988) in which heat transfer is achieved by evaporation (Salunkhe *et al.*, 1991). According to Sargent *et al.* (1988) vacuum cooling is based on the principle that the boiling point of water lowers as atmospheric pressure is reduced. Consequently, the pressure in the cooling chamber is lowered to saturation point corresponding to the lowest required temperature of the water. Cooling is achieved by boiling water, mostly off the surface of the product to be cooled (ASHRAE, 1990).

That is to say, the product being cooled serves as a heat source. Its field heat provides the latent heat of vapourization required for boiling to occur at the surface. As the product gives up its heat to be used for boiling, its temperature falls and cooling is achieved.

Advantages

The primary advantage of vacuum cooling is that cooling is achieved very quickly. Salunkhe *et al.* (1991) reported cooling times of 3 to 4 minutes for head lettuce cooled from about 27°C to 0°C. Secondly, it can be used for packaged vegetables (Geeson, 1988).

Disadvantages

Vacuum cooling is an expensive method of cooling (MacKinnon *et al.*, 1991; Ghate *et al.*, 1988; Janick, 1986). It also results in weight loss by moisture loss, about 1% for every 6°C drop in temperature (Lauro, 1989; Geeson, 1988). Thirdly, it is better suited to produce of high surface-to-volume ratio such as leafy vegetables (ASHRAE, 1990; Wills *et al.*, 1981).

2.2 THEORY OF COOLING

In this section, the heat transfer characteristics of produce cooled by the various precooling methods, other than vacuum cooling, shall be discussed.

Ryall and Pentzer (1974) described the occurrence of heat loss from fruits during cooling. They stated that heat flows principally by conduction from the interior of the fruit outward i.e., to the fruit surface. Where air voids exist, around the seeds, in the core area, and in the spaces between cells, heat transfer is by convection. However, this accounts for a very small percentage of the total heat flow. Heat from the surface of the fruit is then removed by convection via the cooling medium (water or air).

As mentioned earlier, the rate at which heat is removed from produce is crucial for maintenance of freshness and quality. ASHRAE (1990) stated that the rate of internal cooling is limited by the size and shape and thermal properties of the commodity being cooled. Parameters used by Ryall and Pentzer (1974) to characterize size and shape included the surface-to-volume and mass ratios. Thermal properties included the specific heat, thermal conductivity and surface resistance to heat transfer.

Furthermore, the rate of heat transfer between the commodity being cooled and the cooling medium is influenced by the surface heat transfer coefficient, the total surface area and the temperature difference between the product surface and the cooling medium (ASHRAE, 1990). According to ASHRAE (1993), the surface heat transfer coefficient is affected by factors related to the boundary layer formed outside the fruit or vegetable. The dynamics of the surrounding fluids and the conditions at the surface of the commodity, such as surface roughness or packaging, have effects on the boundary layer thereby influencing the flow regime around the commodity and, as a result, affect the surface heat transfer coefficient.

2.2.1 Cooling Laws

Heat flow during fruit or vegetable cooling follows one of two laws of cooling. These are Newton's law of cooling and Fourier's law of cooling (Mohsenin, 1980). The application of either law derives from the satisfaction of a set of conditions, as presented in Table 2.1 below.

Table 2.1 Conditions under which Newton's or Fourier's laws of cooling can be applied (Mohsenin, 1980).

NEWTON'S LAW OF COOLING	FOURIER'S LAW OF COOLING
Thermal conductivity is high compared with unit surface conductance. The Biot number[1] is less than 0.2, approximately.	Unit surface conductance is high compared with thermal conductivity. The Biot number is greater than 0.2, approximately.
Temperature gradient within the object is negligible.	The temperature gradient is not small and varies with time.
The surface temperature at no time is appreciably different from the mean internal temperature.	Mean temperature of the interior of the body is much different than the surface temperature.

[1] Biot number = hr/k. h = unit surface conductance; r = distance from the centre of a cylinder or sphere and; k = thermal conductivity.

Newton's law of cooling

When the resistance to heat flow from the product being cooled is strictly due to its surface resistance (Mohsenin, 1980) and, the surrounding temperature (temperature of the final heat sink) remains constant throughout the cooling process (Lindsay *et al.*, 1975; Guillou, 1960), then Newton's law of cooling can be applied. This law is defined by the following equation (Gariépy *et al.*, 1987):

$$dQ/d\theta = -hA(t-t_a) \qquad (2.1)$$

where, $dQ/d\theta$ is the energy lost by the object per unit time, h is the unit surface conductance also known as the convective heat transfer coefficient, A is the surface area of the object, t is the object temperature, and t_a is the surrounding temperature. If limits of time and temperature are introduced (Mohsenin, 1980), equation (2.1) is transformed into a differential equation whose solution yields:

$$(t-t_a)/(t_i-t_a) = e^{-(hA/CwV)\theta} \tag{2.2}$$

indicating an exponential decay of temperature with time. The constants, C, w and V represent specific heat, specific weight and volume, respectively. The expression $(t-t_a)/(t_i-t_a)$ is the temperature ratio in which, t_i is the initial product temperature. ASHRAE (1990) defined this ratio as the unaccomplished temperature change at any time, θ, in relation to the total temperature change possible for the cooling condition.

Fourier's law of cooling

As indicated in Table 2.1, when a temperature gradient exists within the product being cooled, cooling is transient (Smith and Bennet, 1965) and Fourier's law of cooling can be applied (Mohsenin, 1980). According to ASHRAE (1989) the fundamental equation for unsteady state heat conduction in solids is:

$$\frac{\partial t}{\partial \theta} = \alpha \left(\frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2} + \frac{\partial^2 t}{\partial z^2} \right) \tag{2.3}$$

where, α, the thermal diffusivity, is the ratio $k/\rho c_p$. k, ρ and c_p are the thermal conductivity, density and specific heat at constant pressure, respectively. Equation (2.3) represents heat conduction in rectangular coordinates and can be derived in polar or spherical coordinates for a range of finite and infinite solid geometries (Mohsenin, 1980).

According to Guillou (1960), the conditions for Newton's law are seldom satisfied in commercial cooling of fruits and vegetables. A considerable temperature gradient often exists within the product during cooling, and resistance to heat flow may vary. Moreover, temperature of the cooling medium may fall considerably as cooling progresses. Thus, Newton's law may only be used, in most cases, as a guide to estimate cooling rate (Mohsenin, 1980).

However, for the purpose of this study, Newton's law of cooling was assumed to hold. To apply Fourier's law would require knowledge of unit surface conductance, h, distance from the center of the product, r, and thermal conductivity, k, for the produce cooled. Documented values of these variables, for a number of fresh fruits and vegetables are not available. Additional tests would have to be conducted to determine these values, for which no provision was made.

2.2.2 Cooling Rate

The rate of cooling of a commodity is critical for the efficient removal of field heat and is dependent, essentially, on time, temperature and contact (Sargent *et al.*, 1988). According to Kays (1991) knowledge of the amount of time required to precool a product is crucial for efficient management of a precooling operation. For instance, it allows for more control over the flow of produce for marketing or storage.

However, because cooling rates vary, alternative ways of describing the cooling process (Wills *et al.*, 1989) or comparing cooling data (Ryall and Pentzer, 1974) are used. These are cooling coefficient and cooling time (Kays, 1991; ASHRAE, 1990; Wills *et al.*, 1989; Ryall and Pentzer, 1974).

2.2.2.1 Cooling Coefficient

The cooling coefficient, *Cc*, denotes the change in product temperature per unit increase of cooling time for each degree temperature difference between the product and its surroundings (ASHRAE, 1990; Wills *et al.*, 1989; Gariépy *et al.*, 1987).

This coefficient is equal to the expression *hA/CwV* (Hackert *et al.*, 1987; Mohsenin, 1980) obtained from equation (2.2). Thus, equation (2.2) may be rewritten as:

$$(t-t_a)/(t_i-t_a) = e^{-Cc.\theta} \tag{2.4}$$

This equation suggests that *Cc* may be determined by plotting the temperature ratio against time and is just one of three methods of determining *Cc* mentioned by Mohsenin (1980).

The First Method, uses the slope of the cooling curve if the temperature ratio $(t-t_a)/(t_i-t_a)$ is plotted on the vertical log scale and the time θ on the horizontal arithmetic scale of a semi-log graph. A straight line is obtained which modifies Equation (2.4) to:

$$-Cc = \frac{\ln(t-t_a)/(t_i-t_a)}{\theta} \tag{2.5}$$

If Newtonian cooling is truly followed, the intercept obtained from the linear transformation of the cooling data is unity. Any other value depicts a deviation. Thus, Equation (2.4) may be redefined as,

where, *j* is the intercept on the y-axis of the semi-log graph and is an indicator of the

$$(t-t_a)/(t_i-t_a) = je^{-Cc.\theta} \qquad (2.6)$$

error in assuming Newtonian cooling. Consequently, j is considered a lag factor.

The Second Method, uses the logarithmic mean temperature difference between the material and the surrounding temperature. The following expression for Cc is obtained:

$$Cc = \frac{(t_i-t)/\theta}{\left[\dfrac{(t_i-t_a)-(t-t_a)}{\ln(t_i-t_a)/(t-t_a)}\right]} \qquad (2.7)$$

The numerator in Equation 2.7 signifies the temperature reduction per cooling period, while the denominator is the log mean temperature difference of the product and its surrounding.

The Third Method, takes an average of temperature difference over the elapsed time period. The cooling coefficient is expressed as:

$$Cc = \frac{(t_i-t)/\theta}{(t-t_a)_{ave}} \qquad (2.8)$$

where $(t_i - t)$ is the temperature reduction during time θ and $(t - t_a)_{ave}$ is the average temperature difference for the period θ.

2.2.2.2 Cooling Time

Cooling time, for precooled fresh fruits and vegetables, refers essentially to the half cooling time or the seven-eighths cooling time. The half cooling time (Z) is the time required to reduce the initial temperature difference $(t_i - t_a)$ between the product and the cooling medium by one half. Similarly, the seven-eighths cooling time (S) is the time required to reduce $(t_i - t_a)$ by seven-eighths (Wills *et al.*, 1989; Mohsenin, 1980).

According to Wills *et al.* (1989) theoretically, Z and S are independent of the initial produce temperature and remain constant throughout the cooling period. Furthermore, in commercial cooling operations, S is considered more useful because the produce temperature at seven-eighths cooling time is often close to the required storage or transport temperature.

Thus, to obtain the half cooling time, $(t-t_a)/(t_i-t_a)$ becomes $1/2(t_i-t_a)/(t_i-t_a)$ and θ equals Z. When applied to Equation (2.5) the following expression is obtained (Mohsenin, 1980):

$$\ln \frac{(t_i - t_a)}{1/2(t_i - t_a)} = Cc.Z \qquad (2.9)$$

which implies:

$$Z = ln2/Cc \qquad (2.10)$$

Similarly, S may be expressed as,

$$S = ln8/Cc \qquad (2.11)$$

Moreover, by taking the product of the lag factor, j, and the expression on the right-hand side of Equation (2.10), Mohsenin (1980) claimed that a half cooling time in better agreement with that predicted using experimental data, is obtained.

2.3 FORCED AIR COOLING OF FRESH PRODUCE

The use of forced-air cooling dates back to the early 1960s (MacKinnon and Bilanski, 1992; Parsons *et al.*, 1972; Soule *et al.*, 1966). Since then, numerous commercial precooling operations applying this method of cooling have been developed, and research is still ongoing to optimize cooling efficiency.

2.3.1 Commercial Systems

ASHRAE (1990) listed five commercially-applied techniques of forced-air cooling. These include, (i) circulated air in refrigerated rooms adapted for that purpose, (ii) special portable cooling equipment to cool produce in rail cars or highway vans before transportation, (iii) air forced through the voids of bulk products moving through a cooling tunnel on continuous conveyors, (iv) continuous conveyors in wind tunnels and (v) passing air through containers by differential pressure.

Kays (1991) described three primary applications of forced-air cooling currently in use, namely, cold wall cooling, serpentine cooling and forced-air tunnel cooling.

Cold wall cooling (Fig. 2.1) utilizes a permanently-constructed air plenum and a fan within one or more walls of the cold room. Stacks of single pallets are placed against the wall and cold air from the room is drawn through the containers into the return-air plenum.

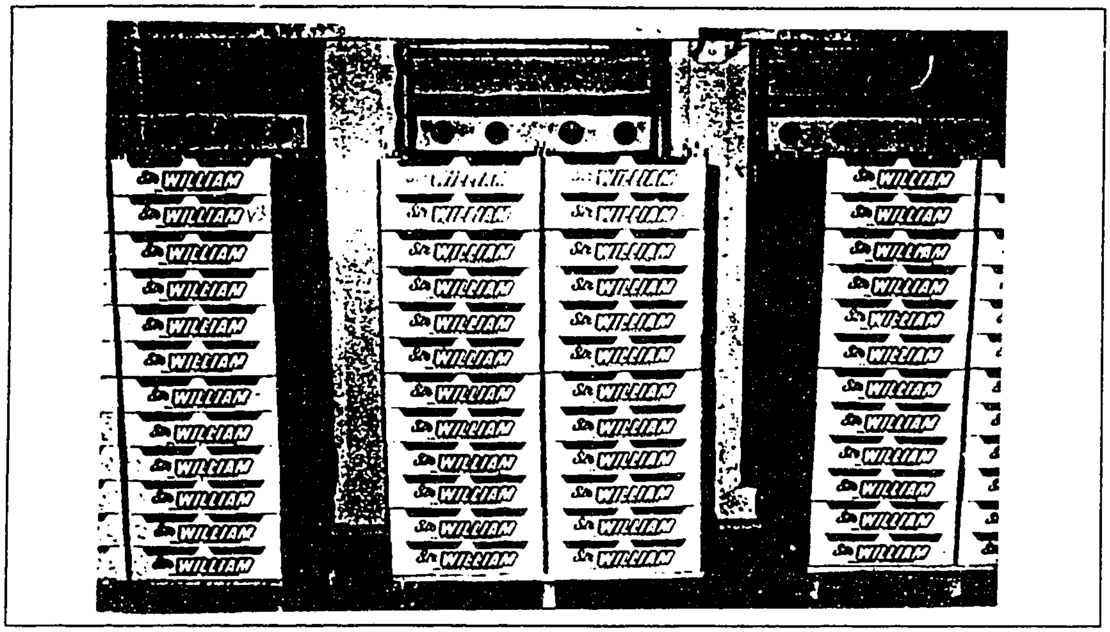

Figure 2.1 Cold Wall Cooling of Stacks of Single Boxes
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Serpentine cooling (Fig. 2.2) is a modification of cold wall cooling which utilizes vents in the bottom rather than side of the container. It is designed particularly for bulk handling of produce in pallet bins, whereby the forklift opening at the base of the pallet forms the air supply and return plenums. By blocking the back of this opening, adjacent to the cold wall, cold air is forced to move vertically upward and downward through the bins. The return-air plenum or forklift opening on every other vertical bin in the stack is blocked on the exterior but open at the cold wall. Air, therefore enters through one forklift opening, moves upward and downward through the bin and exits through the forklift opening at the top or bottom of the next row of bins.

Forced-air tunnel cooling (Fig. 2.3) is a system where pallets or bins of produce are

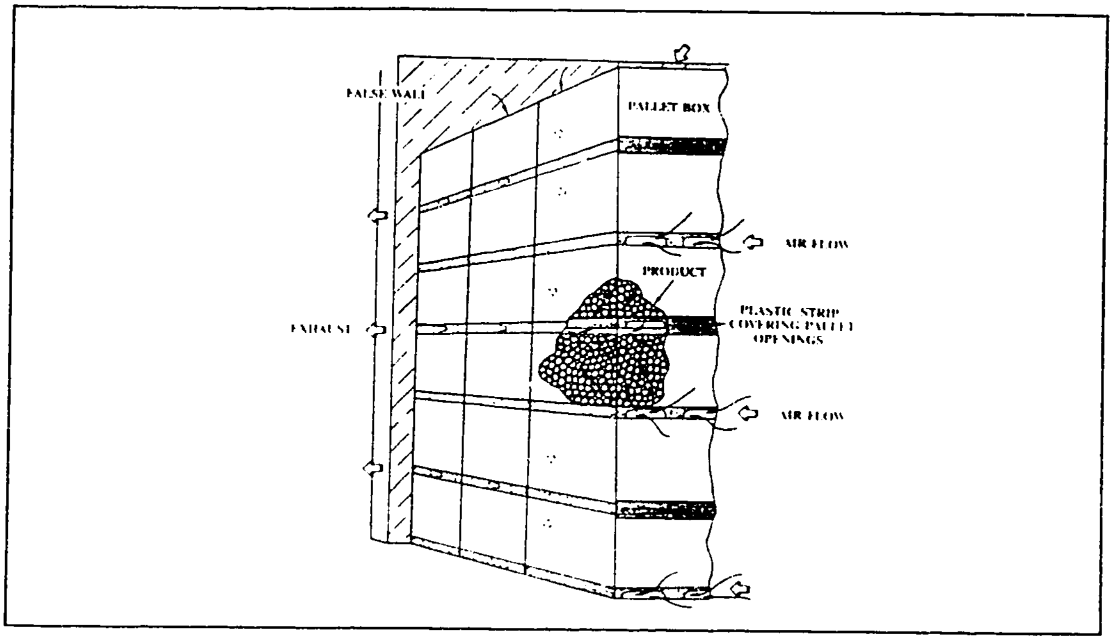

Figure 2.2 Serpentine Cooling for Pallet Boxes of Produce
(Reprinted by permission of Chapman and Hall, NY)

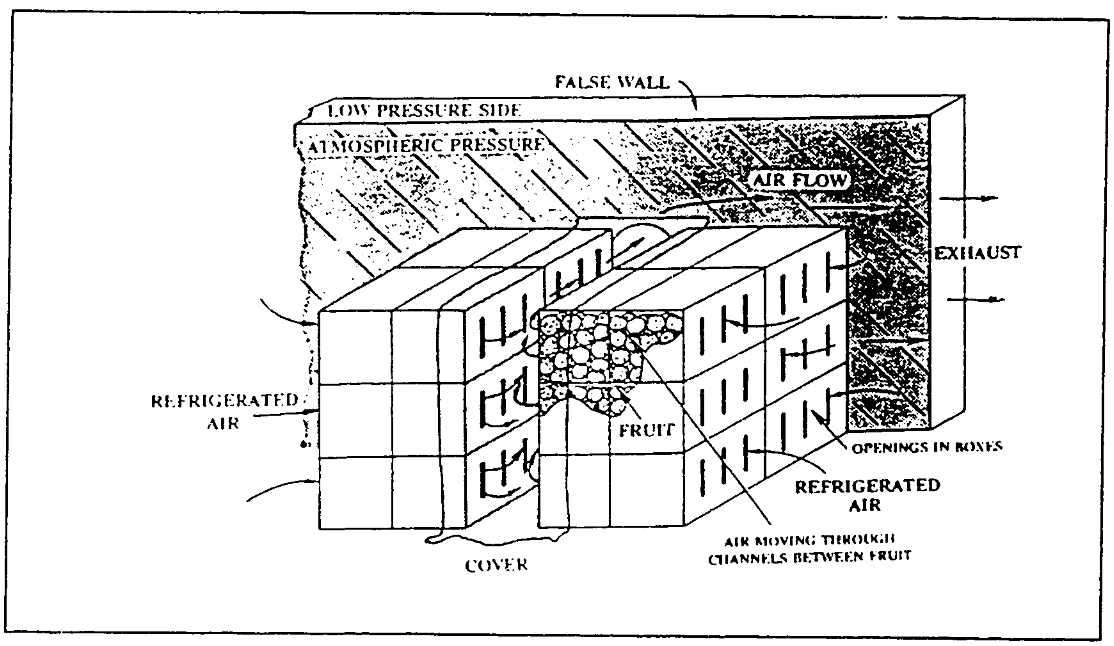

Figure 2.3 Forced-air Tunnel Cooling of Vented Containers
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lined up in two adjacent rows of one pallet width, sitting perpendicular to a single large fan. An alleyway centred on the fan between the rows is created, which is then covered with a heavy fabric cover to form an air-return plenum. The fan draws air from the surrounding room through vents in the container, across the produce, and into the air-return plenum. The length of each row is dependent on the fan capacity.

2.3.1.1 Wet Air Cooling

Wet air cooling systems were developed to reduce the incidence of moisture loss from produce, as mentioned in section 2.1.2. According to Geeson (1988), these systems rely on water at 0°C to cool and humidify the air. Geeson (1988) and Helsen and Willmott (1991) discussed applications of a number of wet air cooling systems used in commercial operations in the United Kingdom and Europe.

2.3.1.2 Mobile/Portable Cooling Systems

Agriculture Canada in 1990 published design specifications for the construction of a mobile precooler for fruits and vegetables. MacKinnon *et al.* (1990) adopted vertically-directed forced-air flow for cooling produce in bulk. United States Department of Agriculture (USDA) have also published design specifications for the construction a portable cooler (Schofer *et al.*, 1993). Literature on the performance of these coolers is not available.

In another study, on the development of a low-cost, portable, forced-air pallet cooling system for small fruit, Boyette and Rohrbach (1993) designed a horizontally-directed forced-air cooling container with a top that may be adjusted to accommodate different stack heights. Their design, a modification of conventional forced-air cooling systems, creates a further problem of additional time required to make the adjustments in order to ensure airflow is only through the produce in the boxes.

2.3.2 Designing Forced-Air Cooling Systems

Essentially, most studies on forced-air cooling of a variety of fruits and vegetables have been directed toward enhancing cooling rates and prolonging shelf-life, by making cooling as efficient as this method would permit. According to Baird *et al.* (1988), engineers must have knowledge of the many variables which affect cooling rate and cooling cost in order to ensure the design of efficient and effective forced-air cooling systems. Among the variables mentioned are product size, shape and thermal properties; type of packing containers used, i.e., bulk bins or cartons; where cartons are used, the percent vent area; depth of product load; initial product temperature and final desired temperature; relative humidity, temperature and flow rate of the cooling air. Another important variable is the stacking pattern (Kays, 1991; ASHRAE, 1990). In the following sections, those variables which are influenced by the choices made by the operator, are discussed.

2.3.2.1 Container Venting

Commercially-available packing containers are reported to be poorly vented with respect to the number and, often, locations of the air vents (Fraser, 1992; Arifin and Chau, 1988). Baird *et al.* (1988) developed an engineering/economic model for designing and evaluating forced-air cooling systems. From their model they determined that the larger the vent area of the packing container, the lower the power required by the fan and compressor, and the more uniform the cooling rate. They also determined that, as the vent area is reduced below 10%, the product cooling time increases over that required for cooling produce in bulk.

In other studies, aimed at increasing vent holes of strawberry containers, Arifin and Chau (1988) and Émond *et al.* (1994), also observed that cooling rate increased when percentage vent openings was increased. Arifin and Chau (1988) noticed that the vent holes in standard cartons were cut at the very top edge of the carton; hence, the air tended to flow through the head-space (i.e., over the baskets of strawberries) bypassing most of the fruit in the process. Their new designs had the vent holes more uniformly distributed, forcing the air to flow through the strawberries.

One limitation Baird *et al.* (1988) encountered, with increasing the percentage vents in standard cartons was strength of the cartons. For this reason, they recommended a percentage venting of about 5%. Boyette and Schultheis (1993) reported a similar experience. In their bid to increase the venting of packing containers, they determined that their desired percentage vent area (5% - 7%) would critically weaken the container, and as such had to settle for a lower percentage vent area of 3.5%.

2.3.2.2 Cooling Air Velocity

The approach air velocity has an important effect on the cooling performance of forced-air cooling systems. The higher the air velocity the higher the heat transfer rate and the lower the change in air temperature as the air moves through the produce (Baird *et al.*, 1988). However, Baird *et al.* (1988) also noted that cooling time is not significantly reduced at velocities greater than 1.5 m/s. Minimum-cost air velocities reported were 0.25 m/s for produce in cartons and 0.76 m/s for produce in bulk.

ASHRAE (1990) pointed out that the average product film coefficient is a function of the interstitial mass velocity, in other words, the airflow rate. Depending on the product being cooled, mass airflow rates recommended range between 0.1 L/s/kg and 4.0 L/s/kg of produce (Fraser, 1991; ASHRAE, 1990; Wills *et al.*, 1989; Arifin and Chau, 1988; Ryall and Pentzer, 1974).

2.3.2.3 Type of Airflow Pattern

According to Tang and Johnson (1989), the angle between forced airflow and natural airflow also significantly influences the heat transfer rate. Three main combinations identified were, aiding flow, counter flow and cross flow. In aiding flow, forced convective flow and natural convective flow travel in the same direction. In counter flow the two oppose each other and in cross flow, forced convective flow travels perpendicularly to natural convective flow. Under cross flow, forced convective flow is horizontal and natural convective flow is vertical.

Forced-air cooling studies have been limited to, either vertically-directed air flow through produce packed in bulk bins (Baird *et al.*, 1975; Lindsay *et al.*, 1975; Chau *et al.*, 1985; MacKinnon *et al.*, 1991; MacKinnon and Bilanski, 1992;) or horizontally-directed air flow through produce in cartons (Parsons *et al.*, 1972; Arifin and Chau, 1988; Boyette and Rohrbach, 1993; Talbot *et al.*, 1993). Little or no investigations have been carried out on vertically-directed forced-air cooling of produce in cartons or carton-sized containers. Chau *et al.* (1985) conducted a test, using vertically-directed forced-air cooling to cool oranges in a carton. However, their cooling system was only designed to simulate horizontally-directed forced-air cooling of oranges in a standard carton with vents in its side.

Arifin and Chau (1988) and Baird *et al.* (1988) gave reasons why most cooling systems involving forced-air cooling of produce in cartons tend towards horizontally-directed airflow compared to vertically-directed airflow. Arifin and Chau (1988) claimed that blowing air vertically would require major rearrangement of precoolers, because the airflow pattern would differ from that commonly used in practice. Baird *et al.* (1988) stated that cartons are usually cooled with horizontally-directed airflow because carton venting is usually on the sides/ends rather than top or bottom. They further stated that pallets upon which the cartons rest, may restrict vertical airflow, and products in the cartons tend to cover any vent holes made in the bottom.

2.3.2.4 Stacking Patterns

When stacking patterns are mentioned, reference is often made to conventional, horizontally-directed forced-air cooling systems. Fraser (1991) explained that cooling speed is enhanced if the vents line-up with each other when the containers are stacked on pallets. In separate studies, Boyette and Schultheis (1993) and Talbot *et al.* (1993) found it essential to align vents of containers used, in order to "facilitate" forced-air cooling. Parsons *et al.* (1972) conducted tests to determine the effects of different stacking patterns on the "effectiveness" of forced-air cooling, and on cooling rate.

3. METHODOLOGY

This study was carried out at the Crop Diversification Centre North (CDCN) formerly known as Alberta Tree Nursery and Horticultural Centre (ATNHC), Edmonton, Alberta. The trials were conducted in August and September 1994. At this time of the year, maximum daily temperatures averaged about 26°C and falls within the fruit and vegetable production season of market gardeners in Alberta.

3.1 CARROT, LETTUCE AND STRAWBERRY PRODUCTION

Carrots, lettuce and strawberries are three commonly produced horticultural crops in Alberta. Carrots are marketed as baby carrots (8 - 10 weeks) by market gardeners. The carrots (*cv. Presto-nantes Hybrid*) used for this study were provided by CDCN. Lettuce (Romaine lettuce - *cv. Paris island*) were grown by Sunnyside Fruit and Vegetables, Vimy, Alberta. They were harvested about nine weeks from planting. The strawberries (day neutrals - *cv. Tristar*) were also provided by CDCN.

3.2 TEMPERATURE SENSING

Ninety-one standard ntc thermistors (ISO-CHIP™ SERIES, Fenwal Electronics, Milford, MA) were used for temperature measurement. The thermistors were immersed in water and calibrated using an electronic temperature controller (model 9001, Polyscience, Niles, IL). The thermistors were connected to a custom built datalogger (University of Alberta, Edmonton, AB) which incorporated constant current sources for the thermistors. The voltage drops across the thermistors were functions of measured temperature.

The voltage drops across the thermistors, corresponding to the temperatures between 0°C and 35°C, were read by the dataiogger. The calibration data were saved as an array (matrix), on the hard drive of an IBM-286 compatible computer. Calibration was attained by using the temperature values (0°C - 35°C) as rows of the matrix, while each thermistor represented a column. Thus, temperature read by each thermistor at any time, *t*, could be determined by interpolating between the two nearest calibration values. Calibration data was read every two minutes.

3.3 DESIGN OF COOLING APPARATUS

Packing containers, ducts and plenums were designed specifically for each of the following methods: (i) Vertically-directed forced-airflow, (ii) Horizontally-directed forced-airflow, and (iii) Room cooling - control.

3.3.1 Packing Container Design

Eighteen packing boxes were fabricated from 19mm plywood sheets. The dimensions of each box were 460mm x 310mm x 190mm as found in some standard commercial packing containers. Six boxes were used for each method.

Under the vertically-directed airflow method (Fig. 3.1), the bottom of the six boxes were replaced with a plastic-coated wire grate of mesh size 25mm x 50mm. The bottom edges of the box sides were lined with foam weather stripping, 19mm

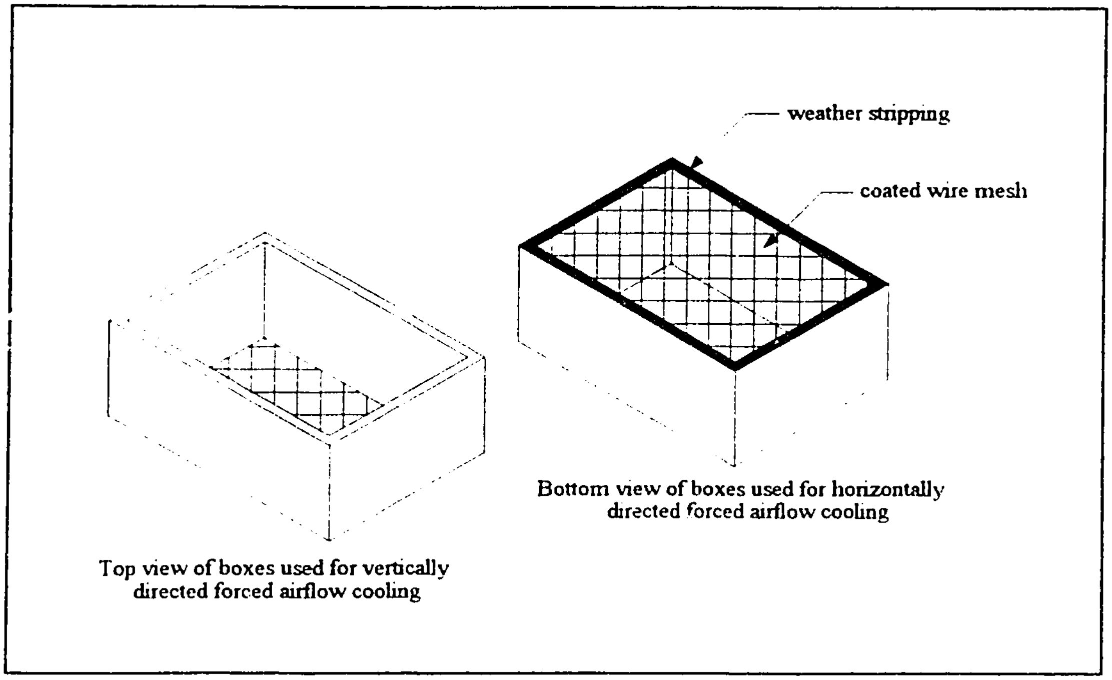

Figure 3.1 Schematic of Boxes used for Vertically-directed Forced-air Cooling

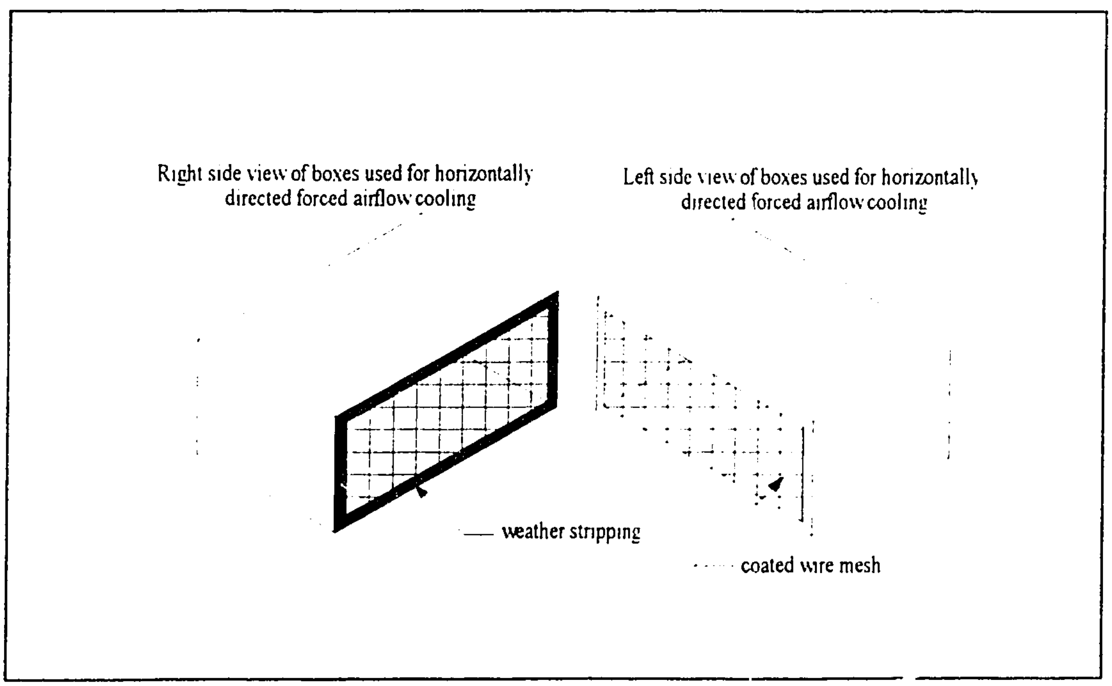

Figure 3.2 Schematic of Boxes used for Horizontally-directed Forced-air Cooling

wide to provide an air seal between the stacked boxes.

In the horizontally-directed airflow method (Fig. 3.2), opposite sides of each box, along their length, were replaced with the coated wire grate. The edges of the right sides of each box were lined with weather stripping.

Vent holes (60mm in diameter) were cut in the sides of the boxes used for room cooling (Fig. 3.3). The percentage vent area for each box was 10%. The top edges of these boxes were also lined with weather stripping to ensure air movement could only occur through the vents as in commercial operations.

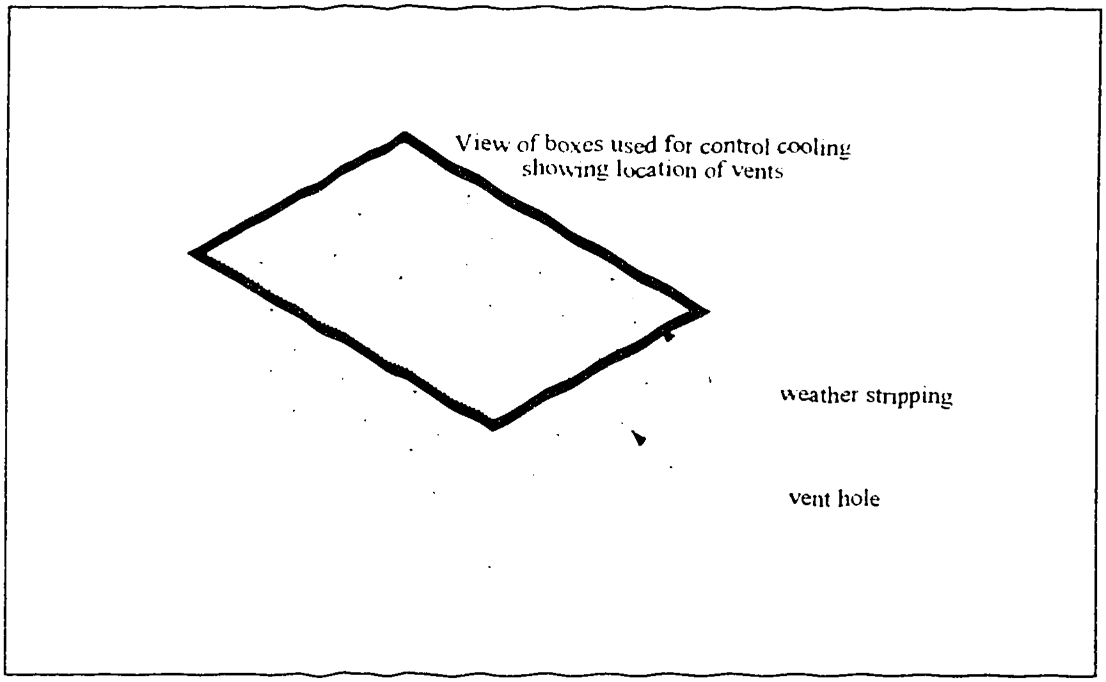

Figure 3.3 Schematic of Boxes used for Control Room Cooling

3.3.2 Strawberry Containers

Strawberry picking containers, also called fruit tills (MRP Plastic, Laval, PQ) were supplied by Sunnyside Fruit and Vegetables. These clear plastic, 159mm x 159mm x 51mm containers were designed with solid, tapered sides, and a bottom with five drain holes.

The strawberry picking containers were modified for vertically-directed airflow cooling, by making sixteen additional vent holes (10mm in diameter) in the bottom of each container. The percentage vents of these containers was approximately 5%.

Similarly, the containers used under the horizontally-directed airflow cooling method were modified by making sixteen additional holes. The holes were distributed around the container sides. The percentage vent area of these containers was approximately 3%.

Standard, unmodified strawberry picking containers were used for room cooling of strawberries.

3.3.3 Duct and Plenum Designs

Three air ducts were fabricated. Two of the ducts (150mm x 150mm x 1000mm) were used under the vertically-directed forced-airflow method. The third (150mm x 300mm x 1000mm) was used for horizontally-directed forced-airflow cooling. All the ducts were made with 19mm plywood. The ends of both ducts were lined with a layer of weather stripping to provide an air seal between the ducts and distribution plenums.

Two plenums were also fabricated from the 19mm plywood to supply air. One of the plenums was designed for the vertically-directed forced-air cooling method and the other for the horizontally-directed cooling method (Fig. 3.4).

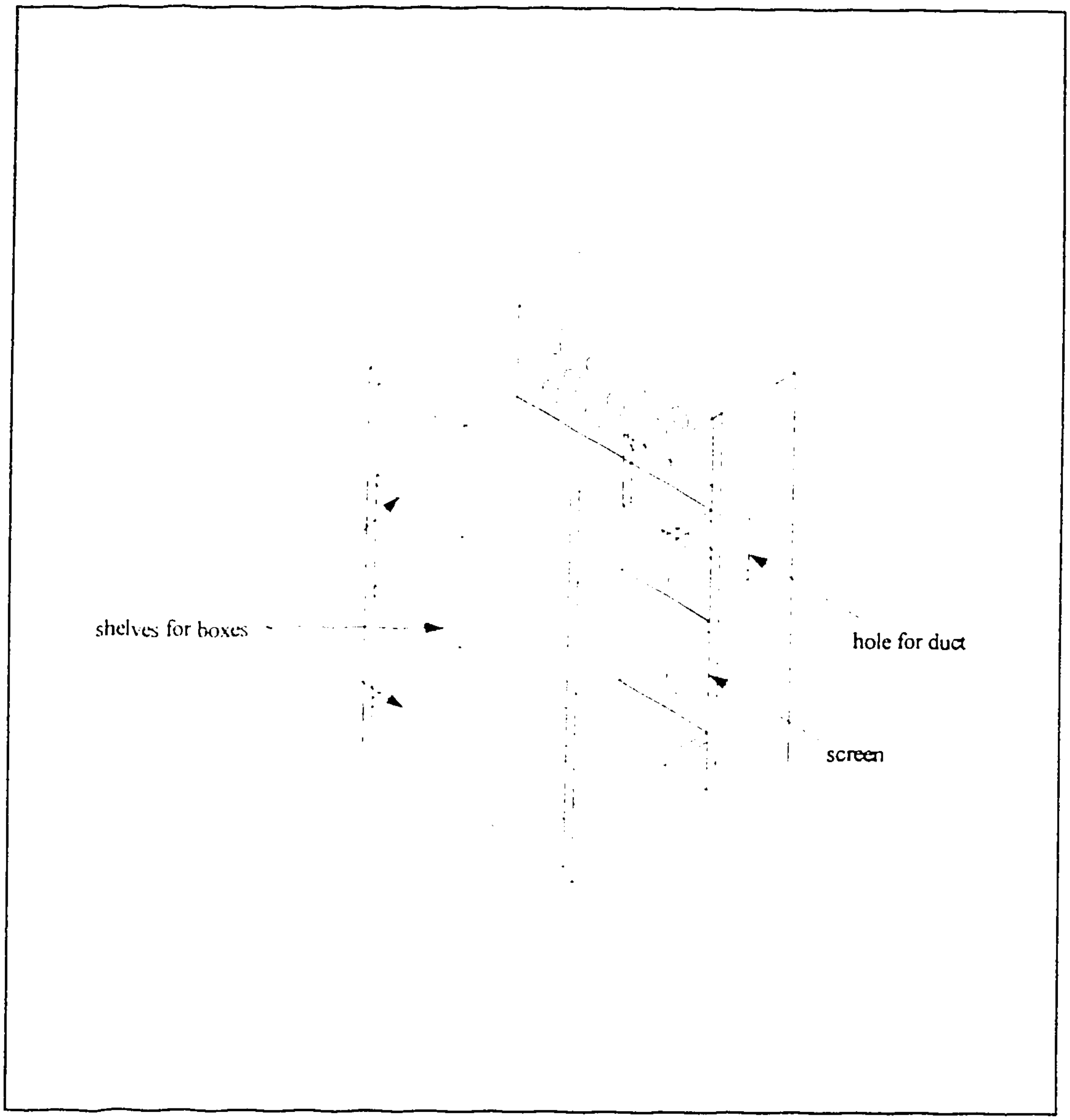

Figure 3.4 Isometric View of Plenum used for Horizontally-Directed Air Cooling

Two square holes, to fit the 150mm x 150mm x 1000mm ducts, were made in the side of the plenum used for the vertically-directed airflow method. A 19mm groove was cut into the plenum, around the holes to fit the ducts. Similarly, two openings each 310mm x 460mm, were cut on top of the plenum. Platforms, 50mm in height and made from the 19mm plywood were built around these openings. The boxes at the bottom of the stacks were placed on these platforms (Fig. 3.5).

A rectangular hole (150mm x 300mm) with a groove around it, was cut in the plenum designed for horizontal air flow (Fig. 3.4). Within the plenum, a screen was built 150mm from the duct hole. Between the screen and the other end of the plenum, three shelves were built. The shelves were spaced 190mm apart. Holes 50mm in diameter were drilled in the portion of the screen at each level. Similarly, holes of the same diameter were drilled in 6mm plywood plates. The plates were 460mm x 190mm in dimension (same dimension as the exposed portion of the screen at each level). By sliding the drilled plates back and forth through slots made in the side of the plenum, the percentage opening in the screen at any level could be adjusted. This was used to control airflow at the three levels.

3.4 EXPERIMENTAL SETUP

A cold store room located at CDCN supplied the refrigerated air required to cool the produce. The temperature of the air when the cooling coils were operating ranged between 0°C and 2°C.

3.4.1 Cooling Apparatus

Vertically-directed forced-airflow cooling: The boxes used under this method were stacked three high, in two separate stacks on the plenum, as shown in Fig. 3.5. The two ducts fabricated for this method were fitted into grooves on the side of the plenum and were held firmly in place by latches. At the other end of the ducts, supplying the airflow, were 42 L/s centrifugal fans (MagneTek, St. Louis, MO). A fan speed control switch (LR-61719, Carlon Thyrocon, Costa Rica) was connected to each fan to control fan speed.

Horizontally-directed forced-airflow cooling: Under this method (Fig. 3.6) the boxes were stacked three high, but in joined stacks on a pallet. The top box of the first stack was latched to the top box of the second stack. This was repeated for the middle and bottom boxes. The boxes in the first stack were also latched to the plenum so that the weather stripping on the plenum (Fig. 3.4) could effectively prevent any air leaks. The air duct, with a 61 L/s centrifugal fan (MagneTek, St. Louis, MO) at one end, was latched in place in the groove on the plenum. The other end of the duct, with the fan, was placed on a support. A fan speed control switch (LR-61719, Carlon Thyrocon, Costa Rica) was connected to the fan.

Room cooling: The boxes designed for this method were stacked three high, in two stacks, on a pallet. The boxes at the top of both stacks were covered with lids during cooling so air circulating in the room could only make contact with the produce by flowing through the vents in the boxes.

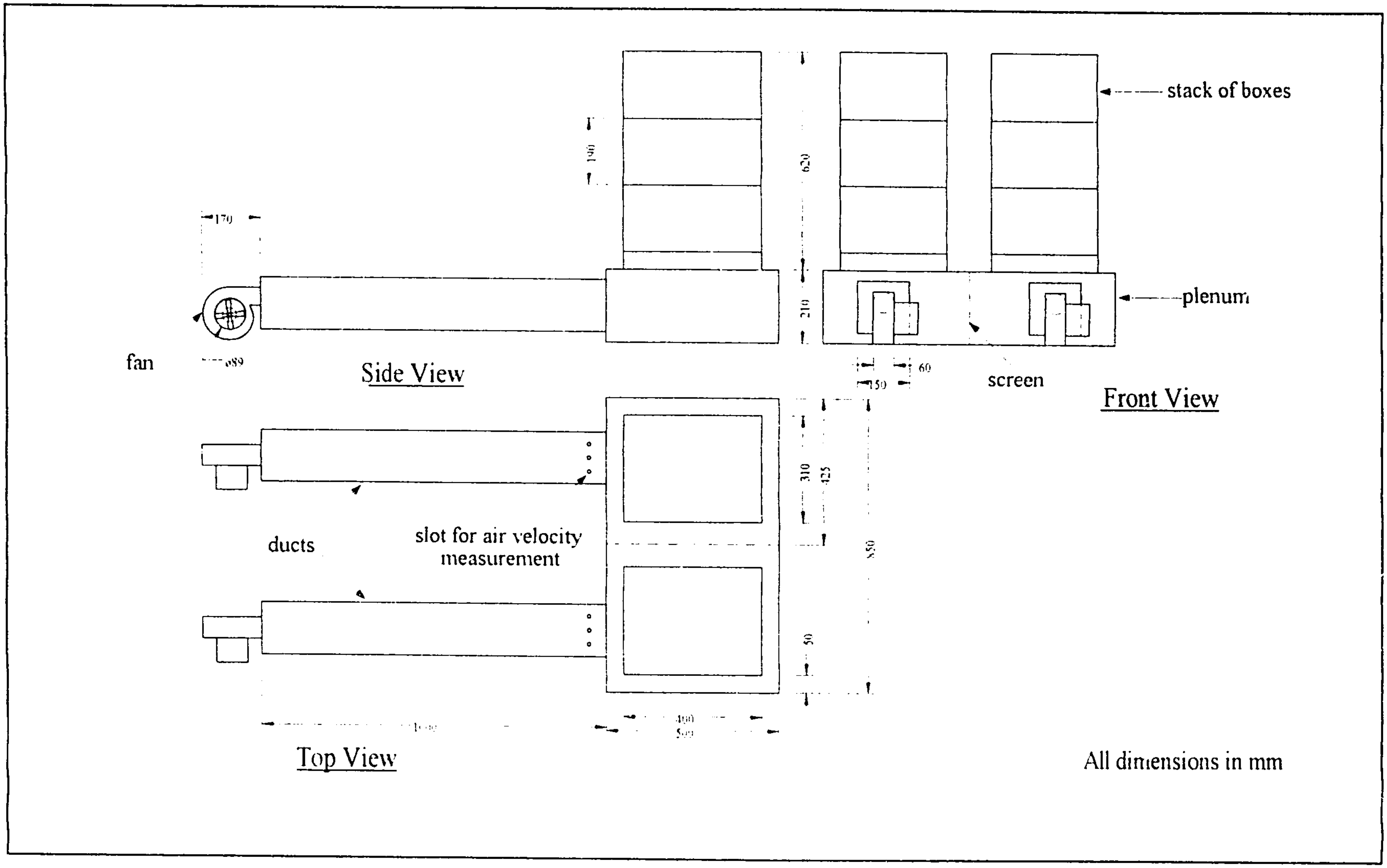

Figure 3.5 Layout of the Vertically-Directed Forced-Air Cooling Apparatus

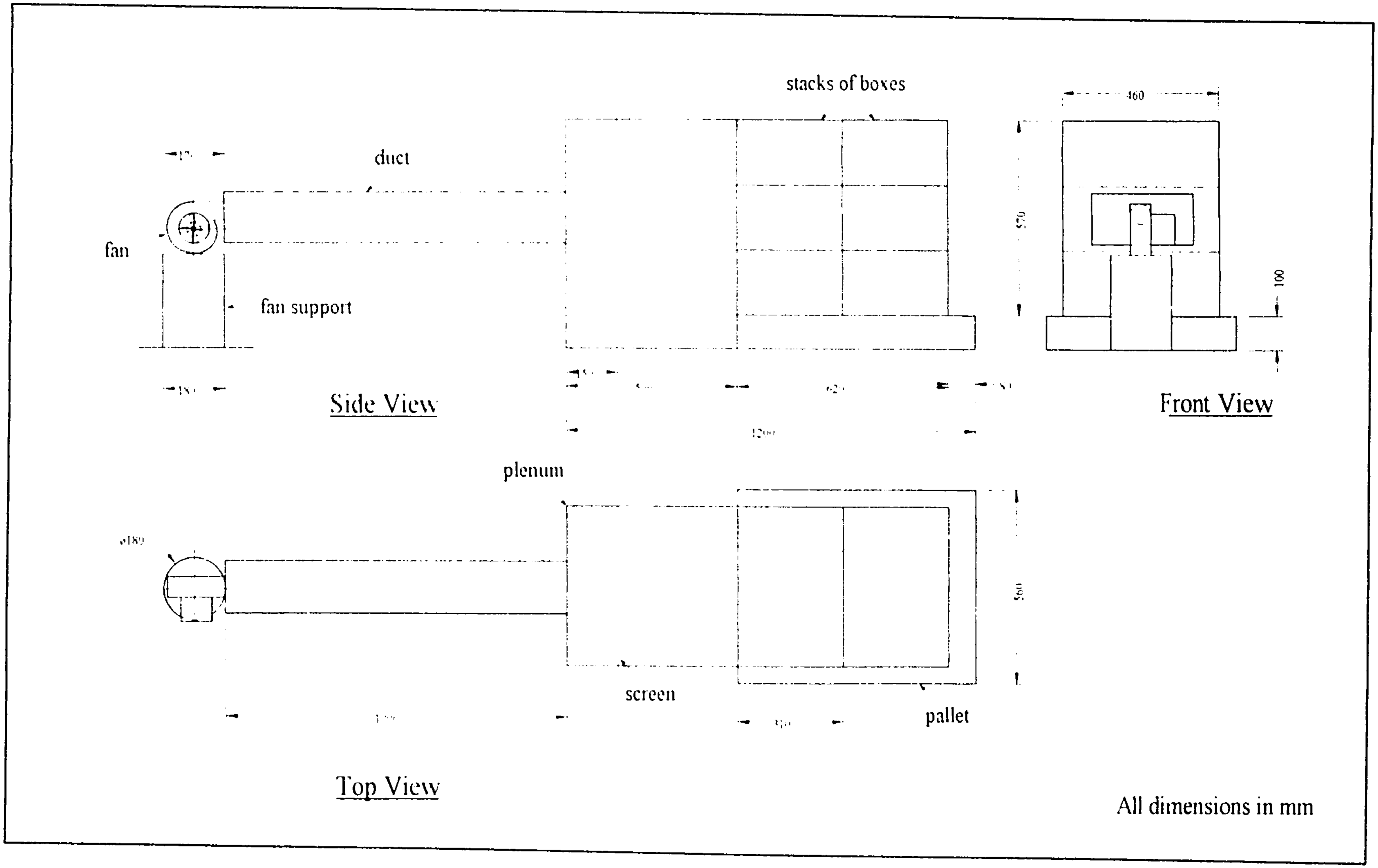

Figure 3.6 Layout of the Horizontally-Directed Forced-Air Cooling Apparatus

3.4.2 Temperature Sensors

Fig. 3.7 is an illustration of the layout of the thermistors, datalogger and the computer. Five thermistors were used to measure temperature change of produce within each box, under the different methods. Each set of five thermistors was connected to a fifteen-pin male connector via 22-gauge speaker wire. Each male connector was fastened to the outer surface of the box. From the fifteen-pin female connector, five pairs of conductors (speaker wire) ran to a thirty-seven-pin male connector. Three fifteen-pin female connectors from each stack of three boxes, were connected to a thirty-seven-pin male connector as shown in Fig. 3.8.

The datalogger was capable of reading a total of a hundred and forty-four channels. The channels are divided into groups of sixteen, with each group connected to a thirty-seven-pin female connector. Thus, temperature responses of fifteen thermistors from each stack of boxes, under each method, were read to a group of channels on the datalogger. An additional thermistor, reading the cooling air temperature, was connected to the sixteenth channel in one of the groups. Furthermore, an in-built clock in the datalogger was used to read time. The datalogger communicated with the computer via an RS-232 serial connection.

3.4.3 Software programming

A turbo C++ software, serial-port interfacing, program (Borland, Scotts Valley, CA) was modified to read data as voltages, convert to temperature values and store the data in files (see Appendix A). Similar to the format used to store the

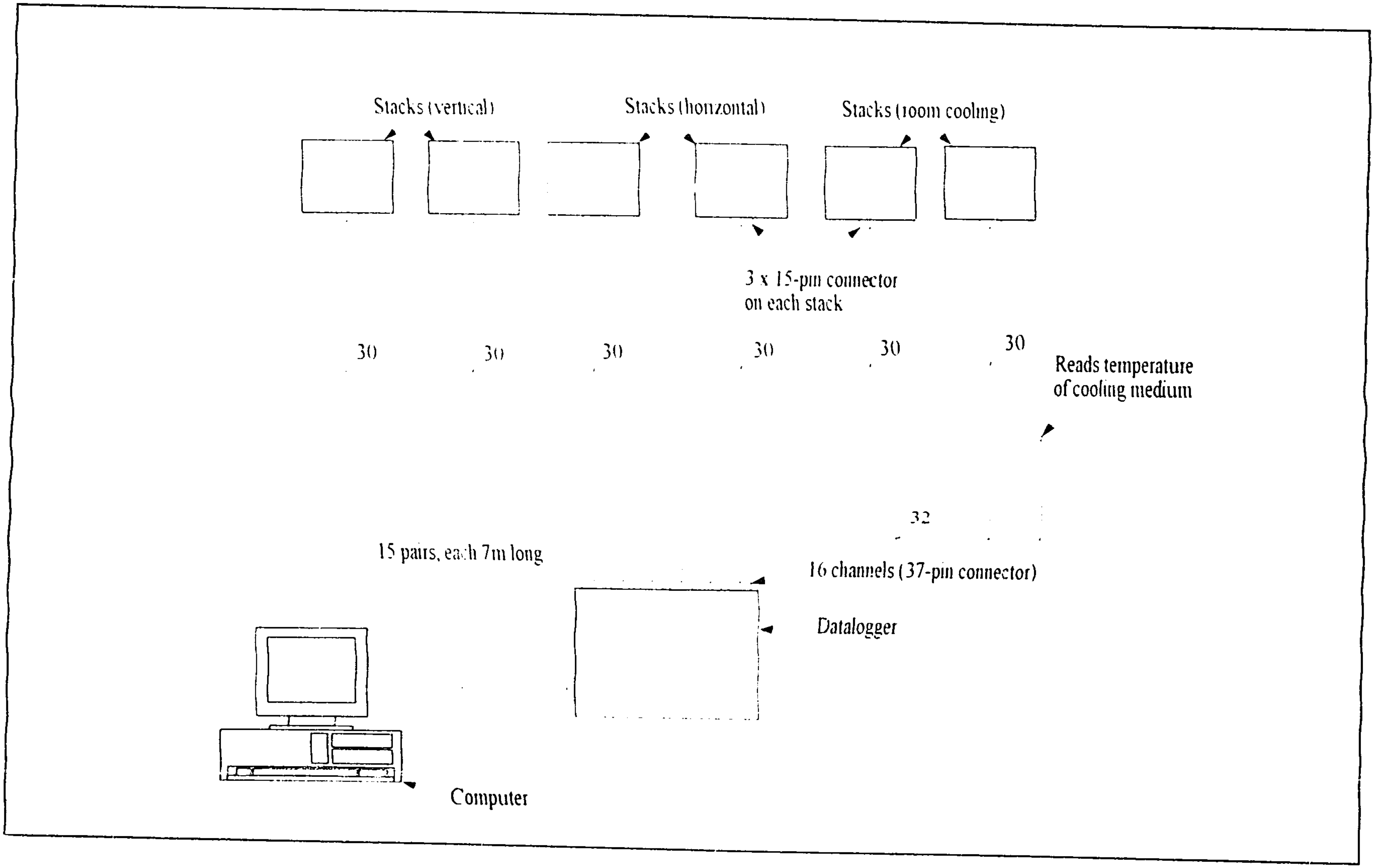

Figure 3.7 Layout of Stacks, Conductors, Datalogger and Computer

calibration data, the program was designed to store cooling data for each run in a matrix (array), having the same number of columns as the calibration data matrix.

3.5 EXPERIMENTAL PROCEDURE

Experimental runs were conducted with the carrots, lettuce and strawberries between the 10th of August and 6th of September, 1994. A single run, to serve as a check, was also conducted using a thousand golf balls. Golf balls were chosen, as opposed to using another fruit or vegetable, because of their uniform shape, size and mass. Furthermore, no weight loss occurs during cooling. The procedures involved are discussed in the following sections.

3.5.1 Study Design

This study was set up as a completely randomized block design. For each of the three types of produce mentioned above, two replicate runs were conducted. The replicates represent different days on which the experiment was repeated. The entire experiment was thus comprised of six runs. Freshly harvested produce was used on each day. The produce was loaded in packing boxes modified to suit the three cooling methods. Six boxes were used under each cooling method. Each batch of six boxes was divided into two stacks, three boxes high. Thus, the total number of boxes was eighteen. Temperature of the cooling produce was measured over time.

3.5.2 Produce Harvesting

All experimental runs were conducted on different days. Volunteers were recruited to assist in harvesting produce.

Carrots were harvested at CDCN. The carrots were bunched in bunches of eight, washed and loaded in the boxes. One of the replicate runs in which carrots were cooled was incomplete because of insufficient produce. Only one stack of boxes of carrots was thus cooled under the room cooling method.

Lettuce was grown at Vimy, Alberta. The lettuce were loaded directly into the packing boxes and taken back to the crop centre in Edmonton.

Like the carrots, the strawberries were harvested at the horticultural centre. Picking took about ninety minutes. Strawberry picking containers were used for picking. Because there were not enough strawberries to fill each picking container, these containers were partially filled.

The picking containers were sorted according to the different cooling methods and loaded in the appropriate boxes. Six containers could fit in each box, forming one layer. Again, for lack of sufficient strawberries, only one stack of boxes was cooled by room cooling during one of the runs.

To keep moisture loss from the carrots, lettuce and strawberries to a minimum, the boxes were covered with burlap during harvesting.

Used golf balls were purchased from Alberta Custom Golf Centre in Edmonton, Alberta. The balls were divided into three groups. One group was loaded into only one box used under the vertically-directed air cooling method. Similarly, one box each from the other two methods were loaded with the remaining two groups of golf balls.

3.5.3 Pre-cooling Preparation

Generally, the same pre-cooling procedure was conducted for the three types of produce and the golf balls. The boxed produce were weighed outside the cold room and weights were recorded. With the measured weights, airflow rates (approximately 2 $Ls^{-1}kg^{-1}$ -section 2.3.2.2) were determined, and on the basis of the cross-sectional area of the ducts, air velocity was determined.

For the carrots, five bunches were randomly selected from each box and a thermistor was inserted in a randomly picked carrot from each bunch (Fig. 3.9). The five bunches were then randomly distributed within the boxes. Under the horizontally-directed air cooling treatment head spaces were apparent in the boxes. To prevent air from flowing over the produce, the head spaces in each box were filled with plastic wrap thereby ensuring increased air-product contact.

To measure temperature of the strawberries during cooling, five picking containers, of the six in each box, were randomly selected. From each container, a randomly selected strawberry was inserted with a thermistor. Again, head spaces and dead spaces in the boxes under the horizontally-directed air cooling treatment were filled with plastic wrap. Head spaces were present above the strawberries in the containers. Dead spaces existed between the tapered sides of the picking containers and between the containers and sides of the packing boxes.

With lettuce, thermistors were inserted in the stalks of five randomly picked heads in each packing box. The five heads were distributed within the boxes. Similarly, five golf balls from each treatment were randomly selected and thermistors inserted in them. The balls were also distributed in the boxes.

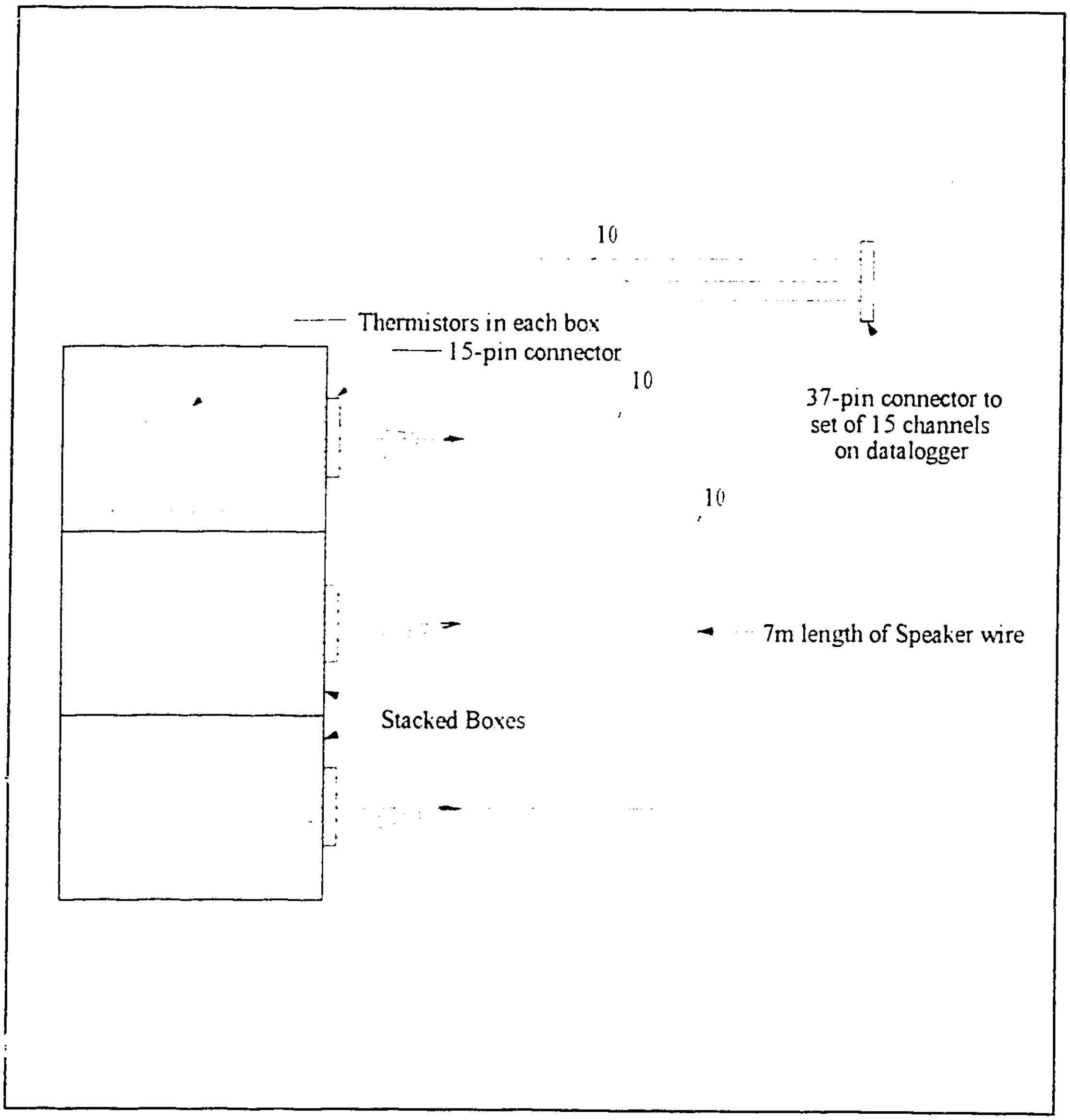

Figure 3.8 Layout of Thermistors, Conductors and Connectors for Stacked Boxes

3.5.4 Airflow Control

The boxes were set up in the cold room under the different treatments. Under the vertically-directed and horizontally-directed forced-air cooling treatments the fans were turned on and the air velocity set with fan speed control switches to correspond with the airflow rate of 2 $Ls^{-1}kg^{-1}$ (section 3.5.3). An air velocity meter, (Velocicalc 8350, TSI, St. Paul, MN) was used to measure air velocity. For the two ducts used under the vertically-directed airflow cooling treatment, nine-point traverses were made across the duct cross-section, approximately 950mm downstream from the fans. For the duct used under horizontally-directed airflow cooling, a twenty-five-point traverse was made (owing to its larger cross-sectional area), at approximately the same distance from the fan as the nine-point traverse. No flow straightening vanes were used.

After setting the airflow rate, the data-storage computer program was loaded and the datalogger switched on to sample data once every minute. Cooling was conducted until temperature of the produce inserted with thermistors under the two forced-air cooling treatments, dropped below 4°C.

3.6 DATA COLLECTION

Temperature: The datalogger read the voltage equivalent of temperature of the ninety box thermistors and the cooling medium thermistor and recorded time. These values were stored in the computer.

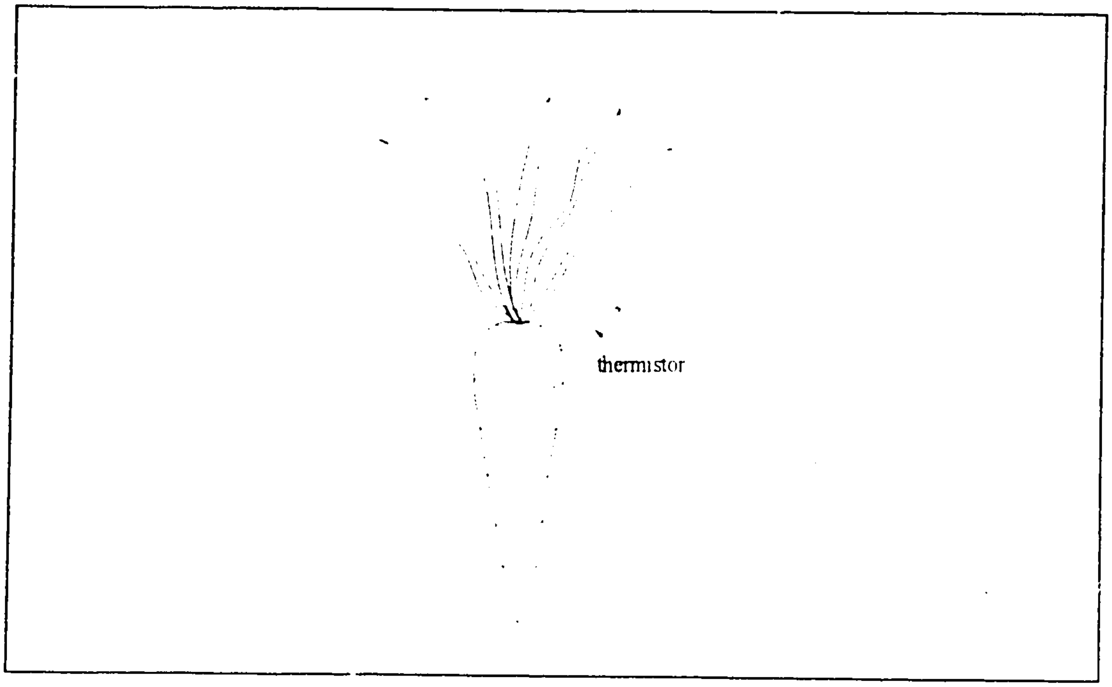

Figure 3.9 Illustration of a Carrot Showing Location of a Thermistor

Relative humidity: During cooling runs for some of the products, Relative humidity (RH) of the room was measured after cooling had begun. Only a few random readings of RH were taken in order to give an indication of the humidity of the room. An electronic hygrometer (MIK 200, Novasina, Switzerland) was used to measure RH, and the values were recorded.

Mass of produce: At the conclusion of the cooling, weights of the boxes of produce were each measured again and recorded. This was essential so weight loss could be determined.

Shelf-life evaluation: After the cooling period, samples of lettuce from each box were stored in a cold room at 10°C. Similarly, a container of strawberries was randomly selected from each box and these were stored in a cold room at 1°C. The stored lettuce were evaluated for shelf-life after four days by a vegetable specialist at CDCN. Shelf-life of the strawberries were evaluated after three, seven and eleven days.

3.7 DATA ANALYSIS

Temperature values of cooled produce were stored in data files as voltages. Hence, a computer program was written, in turbo C++, to convert the voltages to temperature by interpolating between calibration values (see Appendix A). A second program was written to average temperature values of produce within each box. The averaged box produce temperatures were imported into Lotus, a software spreadsheet (Lotus 2.2, Cambridge, MA).

3.7.1 Cooling Coefficient

A graphics software package (FreeLance 4.0, Lotus, Cambridge, MA) was used to plot values of temperature against time. In all cases, an exponential relationship was obtained. Cooling coefficients, *Cc*, were determined by the software package.

Generally, data transformation for cooling experiments is achieved by plotting the unaccomplished temperature change against time on a semi-log graph (Section 2.2.2.2). In other words, the natural log of the unaccomplished temperature change is plotted against time. Hence, a linear relationship is established between temperature and time.

However, using this method of data transformation, resulted in low regression coefficients. Consequently, data transformation was achieved by plotting lnT/T_i against θ where, T is the product temperature at any time, θ, and T_i is the initial product temperature. Regression coefficients which related very closely to those from the plot of the measured temperatures versus time were obtained. Thus, the following linear relationship was obtained:

$$Y = \ln(T/T_i) = Cc'\theta + k \tag{3.1}$$

where k is the intercept on the y-axis and Cc' is the cooling coefficient of the linearized relationship. Values of Cc' were observed to be very close to those of Cc, obtained by plotting raw temperature data values against time.

3.7.2 Half-cooling Time

Based on the linear relationship between temperature and time obtained from equation (3.1), a formula for determining half-cooling time was derived as follows:

Let $\ln(T_i/T_i) = Y_i$; $\ln(T_a/T_i) = Y_a$; and $\ln(T_{1/2}/T_i) = Y_{1/2}$.

T_a is the temperature of the produce equal to the temperature of the surrounding air, and $T_{1/2}$ is the temperature at half cooling time.

Using similar triangles (Fig. 3.10),

$$\frac{Y_i - Y_a}{Y_i - Y_{1/2}} = \frac{X_i - X_a}{X_i - X_{1/2}} \tag{3.2}$$

X_i, X_a and $X_{1/2}$ represent the time taken for the temperature of the produce to be at T_i,

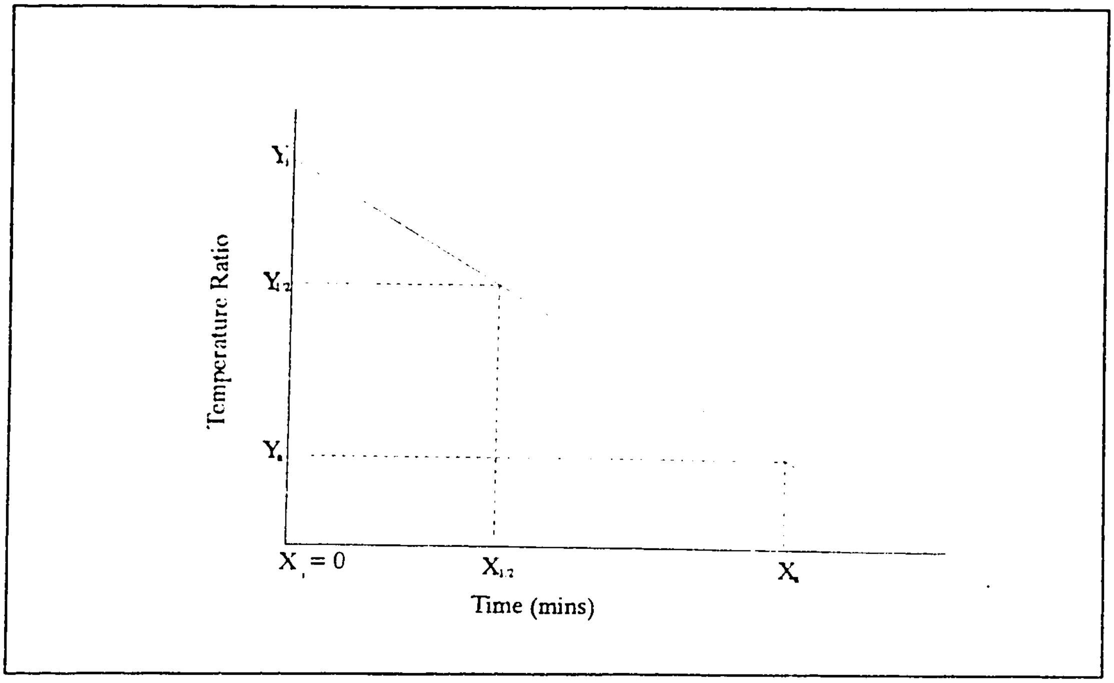

Figure 3.10 Plot of Temperature Ratio, Y, against Time, X.

T_a and $T_{1/2}$ respectively. Since, $X_i = 0$, equation (3.2) becomes,

$$\frac{Y_i - Y_a}{Y_i - Y_{1/2}} = \frac{-X_a}{-X_{1/2}} = \frac{X_a}{X_{1/2}}$$

which implies:

$$X_{1/2} = X_a \frac{(Y_i - Y_{1/2})}{(Y_i - Y_a)} \tag{3.3}$$

Replacing the Y terms yields,

$$X_{1/2} = X_a \frac{(\ln[T_i/T_i] - \ln[T_{1/2}/T_i])}{(\ln[T_i/T_i] - \ln[T_a/T_i])} \tag{3.4}$$

But,

$$T_{1/2} = T_i - \frac{(T_i - T_a)}{2}$$

which implies that:

$$T_{1/2} = \frac{2T_i - T_i + T_a}{2} = \frac{T_i + T_a}{2} \qquad (3.5)$$

Substituting equation (3.5) in equation (3.4)

$$X_{1/2} = X_a \frac{(\ln T_i/T_i - \ln\frac{T_i + T_a}{2}/T_i)}{(\ln T_i/T_i - \ln T_a/T_i)} \qquad (3.6)$$

Now,

$$\ln T_i/T_i = \ln 1 = 0$$

thus:

$$X_{1/2} = X_a \frac{(0 - \ln\frac{T_i - T_a}{2}/T_i)}{(0 - \ln T_a/T_i)}$$

which implies:

$$X_{1/2} = X_a \frac{(\ln T_i - \ln\frac{T_i + T_a}{2})}{(-\ln T_a/T_i)}$$

and finally:

$$X_{1/2} = X_a \frac{(\ln\frac{T_i+T_a}{2} - \ln T_i)}{\ln T_a/T_i} \tag{3.7}$$

A computer program was written in Quickbasic (MS-DOS QBasic 1.0, Microsoft, Redmond, WA) to determine values of X_a and to calculate the half cooling time, $X_{1/2}$ (see cooltime.bas in Appendix B). The same program could be used to determine the seven-eigh[illegible] time.

Equation (3.7) ca[illegible]ed to determine half cooling time when T_a is less than or equal to zer[illegible]

3.7.3 Statistical Analysis

An analysis of variance (ANOVA) test was conducted using the half-cooling time data. A statistical software package (SAS, Cary, NC) was used to run the tests and determine levels [illegible] significance at the 5% level. The ANOVA model was a nested-split-plot design (Appendix C). The different treatments were compared to see if their half-cooling times differed significantly. A different ANOVA and comparison was used for each type of produce. Where data were incomplete because of incomplete experimental runs as explained in section 3.5.1, a pdiff comparison was conducted as required by the SAS program. Pdiff is a variation of the Fisher's Protected Least Significant Difference (FPLSD) comparison test which does a probability test for comparisons involving unequal data sets. A Duncan's

Multiple Range (DMR) test was used to compare the three cooling methods for the lettuce runs. These lettuce runs were complete runs.

4. RESU' TS

The results presented in this chapter are the cooling coefficient (*Cc*), the half cooling time ($X_{1/2}$), weight loss, and the evaluation of shelf-life.

4.1 COOLING COEFFICIENT

Typical cooling curves representing cooling of carrots, lettuce, strawberries and golf balls are presented in Figs. 4.1 to 4.4. In all cases these results show vertically-directed forced airflow cooling to be a faster method of cooling than horizontally-directed forced-air cooling or room cooling.

The cooling curves for strawberries (Fig. 4.3) indicate that strawberries cooled at a slower rate under the horizontally-directed air cooling method than did the carrots, lettuce or golf balls.

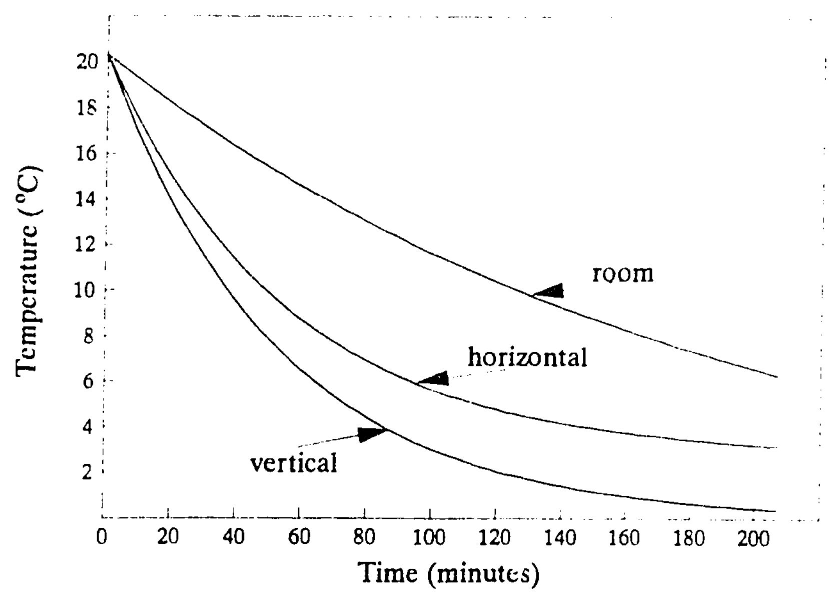

Figure 4.1 Cooling Curves for Carrots Cooled by Different Methods

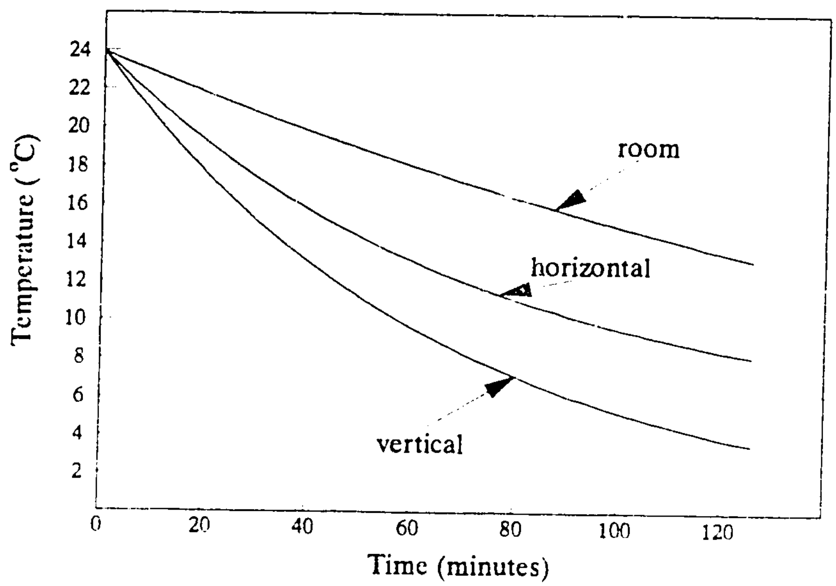

Figure 4.2 Cooling Curves for Lettuce Cooled by Different Methods

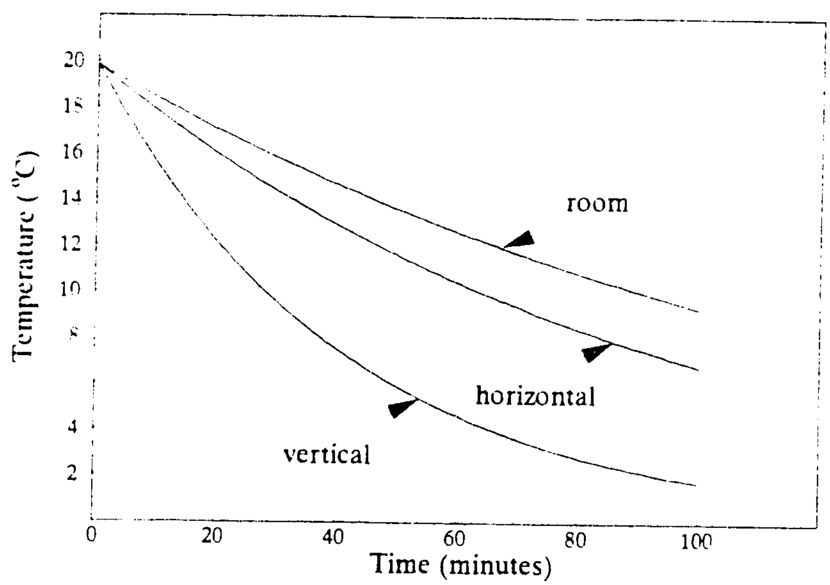

Figure 4.3 Cooling Curves for Strawberries Cooled by Different Methods

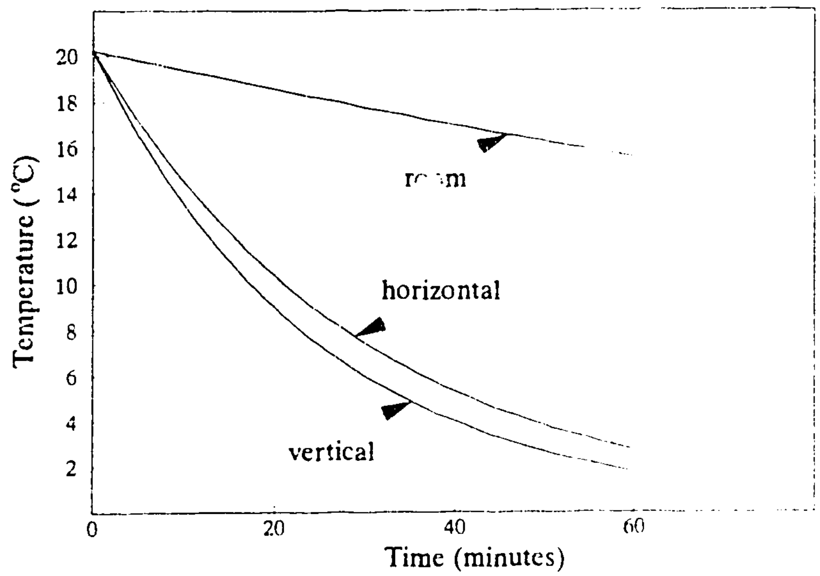

Figure 4.4 Cooling Curves for Golf Balls Cooled by Different Methods

Table 4.1 Regression Coefficients from Plot of Temperature Data Against Time

	Product Cooled			
Method[1]	Carrots	Lettuce	Strawberries	Golf Balls
VFC	0.998	0.999	0.998	0.998
HFC	0.998	0.998	1.00	0.998
CRC	0.999	0.998	1.00	0.994

[1] VFC, HFC and CRC refer to vertically-directed forced-air cooling, horizontally-directed forced air cooling and control room cool respectively.

4.2 HALF-COOLING TIME

Values of half-cooling time obtained using equation (3.7) are shown in Tables 4.2 to 4.5. The boxes are identified according to airflow direction, location in a stack

Table 4.2 Half-Cooling Time, $X_{1/2}$, of Golf Balls Cooled in Packing Boxes
(Ambient Temperature = 2.15°C; Airflow rate = 2 $Ls^{-1}kg^{-1}$)

Box[1]	$X_{1/2}$ (minutes)
VB1	15.0
HM2	16.1
RB2	132.1

[1] The symbols used in this column represent the cooling method, box position and stack. V, implies vertically-directed forced-air cooling; H, horizontally-directed forced-air cooling and; R, room cooling. T, implies box at the top of the stack; M, box in the middle of the stack and; B, box at the bottom of the stack. 1, refers to the first stack and; 2, the second stack. Thus, VT1 refers to carrots in the box at the *top* of the *first* stack, cooled by the vertically-directed forced-airflow method.

Table 4.3 Half-Cooling Time, $X_{1/2}$, of Carrots Cooled in Packing Boxes
(Airflow rate = 2 $Ls^{-1}kg^{-1}$; Relative Humidity = 82%)

Box	Day 1 (1.02)*		Day 2 (1.83)	
	$X_{1/2}$ (minutes)	SD** (minutes)	$X_{1/2}$ (minutes)	SD (minutes)
VT1	37.0		29.0	
VM1	31.6	2.7	28.2	1.9
VB1	34.5		31.8	
VT2	32.0		35.7	
VM2	31.7	1.5	31.8	4.7
VB2	29.3		26.4	
HT1	39.7		30.4	
HM1	33.3	5.5	31.4	1.6
HB1	28.7		28.2	
HT2	46.1		37.5	
HM2	29.6	9.5	31.8	2.9
HB2	29.6		35.7	
RT1	122.8		.	
RM1	116.5	8.0	.	.
RB1	106.9		.	
RT2	97.0		91.8	
RM2	91.2	7.7	111.7	13.8
RB2	81.8		85.3	

* Values in parentheses indicate ambient temperature in °C
** SD = Standard deviation.

and stack number. For example, VT1 refers to produce in the box at the *top* of the *first* stack, cooled under the *vertically* directed forced-air cooling method. The periods in Tables 4.3 and 4.5 represent missing values for the incomplete runs mentioned in Chapter 3.

Table 4.4 Half-Cooling Time, $X_{1/2}$, of Lettuce Cooled in Packing Boxes
(Airflow rate = 2 $Ls^{-1}kg^{-1}$; Relative Humidity = 83%)

Box	Day 1 (0.92) $X_{1/2}$ (minutes)	Day 1 (0.92) SD (minutes)	Day 2 (1.54) $X_{1/2}$ (minutes)	Day 2 (1.54) SD (minutes)
VT1	43.9		37.2	
VM1	45.6	0.9	33.8	6.0
VB1	44.5		45.4	
VT2	35.5		42.4	
VM2	47.3	6.1	37.3	2.6
VB2	38.6		39.0	
HT1	37.0		98.9	
HM1	47.1	5.5	69.3	20.2
HB1	38.2		60.3	
HT2	67.4		116.2	
HM2	64.7	17.9	64.8	33.5
HB2	35.2		53.3	
RT1	146.2		126.7	
RM1	260.9	73.8	118.9	7.7
RB1	284.0		111.3	
RT2	166.3		100.9	
RM2	250.4	49.9	97.3	3.6
RB2	161.7		104.4	

* Values in parentheses indicate ambient temperature in °C
** SD = Standard deviation.

Table 4.5 Half-Cooling Time, $X_{1/2}$, of Strawberries Cooled in Packing Boxes
(Airflow rate = 2 $Ls^{-1}kg^{-1}$; Relative Humidity = 81%)

Box	Day 1 (1.23)		Day 2 (1.00)	
	$X_{1/2}$ (minutes)	SD (minutes)	$X_{1/2}$ (minutes)	SD (minutes)
VT1	34.5		33.4	
VM1	26.1	6.7	22.8	5.8
VB1	21.3		23.9	
VT2	32.0		28.2	
VM2	23.5	7.0	24.4	2.4
VB2	18.2		23.9	
HT1	57.8		46.8	
HM1	59.8	1.7	37.9	9.5
HB1	56.4		27.9	
HT2	85.3		82.7	
HM2	81.3	10.6	38.3	24.0
HB2	65.3		44.7	
RT1	95.2		97.1	
RM1	88.3	6.0	98.4	4.1
RB1	83.3		90.7	
RT2	.		95.0	
RM2	.	.	103.8	9.0
RB2	.		85.8	

* Values in parentheses indicate ambient temperature in °C

** SD = Standard deviation.

4.2.1 Analysis of Results

The results of the statistical analysis presented in this section (Table 4.6) show a comparison of the three methods of cooling used.

The means of half-cooling time showed lower values for the carrots, lettuce and strawberries cooled under VFC, compared with HFC, and CRC (Table 4.6). A comparison of the three methods indicated that VFC and HFC had no significantly different effects on cooling of carrots and lettuce, but were significant for strawberries. However, the effects of both methods on the cooling of carrots. lettuce and strawberries did differ significantly from the effects of the CRC method.

Table 4.6 A Comparison of the Vertically and Horizontally Directed Forced-Air Cooling and Room Cooling Methods

	Mean Values of Half-Cooling Time (mins)*		
Method	Carrots	Lettuce	Strawberries
VFC	31.6[a]	40.9[b]	26.0
HFC	33.5[a]	62.7[b]	57.0
CRC	99.5	161	92.0

* Means with the same letter are not significantly different at the .% confidence interval.

4.3 WEIGHT LOSS

Although the relative humidity of the cold room averaged about 82%, weight loss due to moisture loss occurred from the carrots. lettuce and strawberries, under all three methods. Table 4.7 shows the percentage weight loss of the fresh produce cooled under the different methods. Although these data could not be analyzed because individual boxes were not weighed in all cases, the data does however give an indication of cooling effectiveness.

Loss of weight of the lettuce was approximately twice that of the other produce under all three cooling methods. Weight loss was least under the CRC method. Although slightly less weight loss of the carrots occurred when cooled by HFC compared with VFC, the results show the reverse when lettuce and strawberries were cooled.

Table 4.7 Percentage Weight Loss of Fresh Produce (kg/kg) after Cooling

	Average Weight Loss (%)		
Method	Carrots	Lettuce	Strawberries
VFC	1.61	3.78	1.87
HFC	1.52	4.36	2.22
CRC	1.13	2.64	1.78

4.4 SHELF-LIFE EVALUATION

The results of the evaluation on the shelf-life of the lettuce are presented in Table 4.8 and show that cooling lettuce heads by the VFC method resulted in over 80% acceptability after four days. The number of acceptable heads cooled by control room cooling was also relatively high, compared with those cooled under the HFC method.

Table 4.8 Shelf-life Rating of 12 Lettuce Heads Cooled Under Different Methods and Stored for Four Days at 10°C

	Four Days After Cooling	
Method	Rating*	Comments
VFC	3.7	83% acceptable
HFC	2.7	17% acceptable
CRC	3.6	75% acceptable

* Rating was based on wilting and desiccation. The following ratings were used: 1 = worst; 2 = poor; 3 = fair; 4 = good; 5 = excellent. Heads rated 1 to 3 were considered unacceptable and those rated 4 and 5, acceptable. The ratings in the above Table are averaged values for the different methods.

Results of the shelf-life evaluation of strawberries at three days, seven days and eleven days after cooling are presented in Tables 4.9, 4.10 and 4.11, respectively. The results indicate that about a third of the berries cooled by VFC were marketable by the eleventh day after cooling. Only a sixth of the berries cooled by HFC were marketable at this time. No berries cooled by room cooling were marketable by the eleventh day.

Table 4.9 Shelf-life Rating of Strawberries (Rep. 2) Cooled at 1°C Under Different Methods and Stored for Three Days at 1°C

	Three Days after Cooling	
Method	Rating*	Comments
VFC	5.0	Marketable
HFC	5.0	"
CRC	5.0	"

* Rating was based on marketability. The following ratings were used: 1 = discard; 2 = poor; 3 = fair; 4 = good; 5 = excellent. Strawberries rated 1 to 3 were considered unmarketable and those rated 3.5 to 5 marketable. The ratings shown in the above table are averaged values for the different methods.

Table 4.10 Shelf-life Rating of Strawberries (Rep. 2) Cooled at 1°C Under Different Methods and Stored for Seven Days at 1°C

	Seven Days after Cooling	
Method	Rating	Comments
VFC	4.8	Some of the damaged berries showed no signs of mold growth.
HFC	4.2	Damaged berries showed signs of mold growth
CRC	3.3	Moldly berries had begun to shrivel.

Table 4.11 Shelf-life Rating of Strawberries (Rep. 2) Cooled at 1°C Under Different Methods and Stored for Eleven Days at 1°C

Method	Eleven Days after Cooling	
	Rating	Comments
VFC	3.3	33% marketable
HFC	2.6	17% marketable
CRC	1.9	Reject all

5. DISCUSSION

The results presented in the last chapter do not give a clear indication of the differences between vertically-directed forced-air cooling (VFC) and horizontally-directed forced-air cooling (HFC). While both methods differed significantly from room cooling (CRC) as shown by the results of the comparison of half-cooling time (Table 4.5), and by the cooling curves, and the results of weight loss, the differences between HFC and VFC are not as apparent. As a result, it is difficult to identify a single, general pattern of cooling for the three types of produce cooled by these variations of forced-air cooling.

In the following sections the cooling behaviour of the produce and the golf balls are discussed.

5.1 Cooling of Carrots

The results of Table 4.5 show that the effects of VFC and HFC on cooling of the carrots were not significantly different, though a lower half-cooling time was obtained under VFC. In addition, a higher cooling coefficient (Fig. 4.1) was obtained for the carrots cooled by VFC, which is to be expected since half-cooling time and cooling coefficient are related (Section 3.7.2). Finally, weight loss in the carrots was slightly greater under the VFC method compared to the HFC method.

The results of the comparison of the different methods are satisfactory (Table 4.5). In the literature review it was noted that heat transfer in room cooling is chiefly by conduction through the walls of the container. The results show that the nature of heat transfer certainly plays an important role in achieving faster cooling. The carrots were observed to take three times longer to cool by CRC than by VFC or HFC. On the other hand, less moisture was lost under CRC compared with both forced-air cooling methods, because of the limited air movement over the carrots.

Although none of the boxes used for the carrot runs were filled, under the VFC method, air flowed through the bottom of the boxes and good air-product contact was achieved. Similarly, by filling the boxes used in HFC with plastic, possible effects of head space on cooling (Section 3.5.2) were eliminated. Thus, the air was restricted from flowing overtop the carrots and was forced to flow through the voids between bunches of carrots and between the bunches and walls of the boxes. Consequently, good air-product contact was also realised.

The variation in cooling rates of carrots cooled by VFC and HFC, may be attributed to the cumulative effects of slightly different airflow rates, and the arrangement of the produce in the boxes. Under the HFC method, the carrots were laid along the path of flow, unlike the VFC method, where they were laid across the path of flow. Baird *et al.* (1975) stated that product arrangement is an important variable to be considered during forced air cooling. Based on tests which were conducted to investigate the effect of different product arrangements on forced-air cooling of oranges, Chau *et al.* (1985) showed the relevance of proper product arrangement to achieving faster cooling .

The higher weight loss of the carrots cooled by VFC may also have been influenced by the slightly higher airflow and the product arrangement under this method. Generally, transpiration rate is increased by higher airflow (MacKinnon and Bilanski, 1992) more so if there is good air-product contact.

5.1.2 Cooling of Lettuce

The comparison of the VFC and HFC methods, for cooled lettuce (Table 4.5), also showed no significant difference between the methods. The difference in cooling rate, as represented by the difference in half-cooling time (12 minutes) and cooling coefficient (Fig. 4.2), seems to reflect in weight loss of the lettuce and, even in the shelf-life (Tables 4.6 and 4.7 respectively).

Again, the difference in cooling rate of the lettuce under both methods may have been influenced by the product arrangement, which ultimately affected the air-product contact. When the lettuce were cooled by VFC, each head was placed upside down, with its stalk facing up. Hence, as the air travelled vertically, it was forced to flow through each layer of foliage thereby cooling the lettuce more uniformly. Under HFC, the air-product contact was only on the outer layer of foliage, and on one side. This caused cooling to be less uniform.

Also of importance is the fact that the thermistors were inserted in the stalks of the lettuce. Under the HFC method, these stalks were directly exposed to the airflow. As a result, temperature readings of the heads may have been lower than they ought to have been, and may not be truly representative of cooling of the whole lettuce head.

Thirdly, the lettuce heads used in each run varied in size. Small, medium and large lettuce heads were harvested but not sorted when packed. Thus, in some boxes relatively larger, non-uniform head spaces were created, than in other boxes. With the increased head space in the box, it appears that air-product contact was reduced. Values of half-cooling time obtained for lettuce cooled by HFC on the second day (Table 4.3), give an indication of the effect of head spaces on cooling. Smaller lettuce heads were used for the second replicate run compared with the first.

5.1.3 Cooling of Strawberries

The strawberries responded differently to HFC than did the carrots and the lettuce. Cooling was very slow by this method though at a rate high enough for it to differ significantly from room cooling (Table 4.5). Like the carrots the head-space overtop the strawberries was stuffed with plastic wrap and cooling by this method should have related more closely to that by VFC. Furthermore, the effect of produce arrangement on cooling, as observed for the carrots and lettuce, did not apply for the strawberries since the strawberries were first picked into picking containers.

The cooling pattern of the berries cooled under the HFC method, was affected by the location of the additional vents made in the strawberry picking containers. Under the VFC method, the additional vent holes (Section 3.3.2) were all made in the bottom of the strawberry picking containers. This meant that for each container, a total of twenty-one vents were located in the air path. Under HFC, the additional vents were distributed over the four sides of the containers. In effect, the number of vents in the airflow path at the first container surface were eight, implying 62% less venting than containers used under the VFC method.

This cooling pattern exhibited by the strawberries cooled by HFC shows the importance of sufficient container venting to cooling and the necessity to locate the vents properly. Fraser (1992) stated that these are important criteria if rapid air cooling is to be achieved.

5.1.4 Cooling of Golf Balls

Values of half cooling time of the golf balls cooled by directing air vertically and horizontally were close (Table 4.1). Similarly, the cooling curves (Fig. 4.4) show closely related cooling coefficients, for both methods, compared with those of the carrots, lettuce and strawberries. Again, the balls cooled under the VFC method, appeared to have cooled faster. Yet, it is difficult to make any assertions based on these results, since no statistical analysis was conducted.

For golf ball cooling, problems of product arrangement or "venting" did not arise. Furthermore, no mass (moisture) transfer occurred implying that there was no heat transfer by evaporation from the golf balls.

When the balls were loaded in the boxes, head-spaces were created in all three boxes. Unlike the carrot and strawberry runs, head-space of the box used under the HFC method was not filled with plastic wrap, or any other material, so that the effect of head space on cooling could be observed. When compared with cooling under the VFC method, the results seemed to suggest that head-space had little effect on cooling. In effect, the high rate of cooling exhibited under the HFC method may be attributed to high porosity of the golf balls, causing most of the air to travel through the pores rather than over the balls. Furthermore, an airflow pattern similar to that presented in Fig. 5.1 may have developed, whereby a fraction of the in-flowing air was deflected off the top of the container and diverted back through the product. Because the balls with thermistors were randomly distributed within the boxes, the effects of location could not be assessed, relative to the source of air-flow.

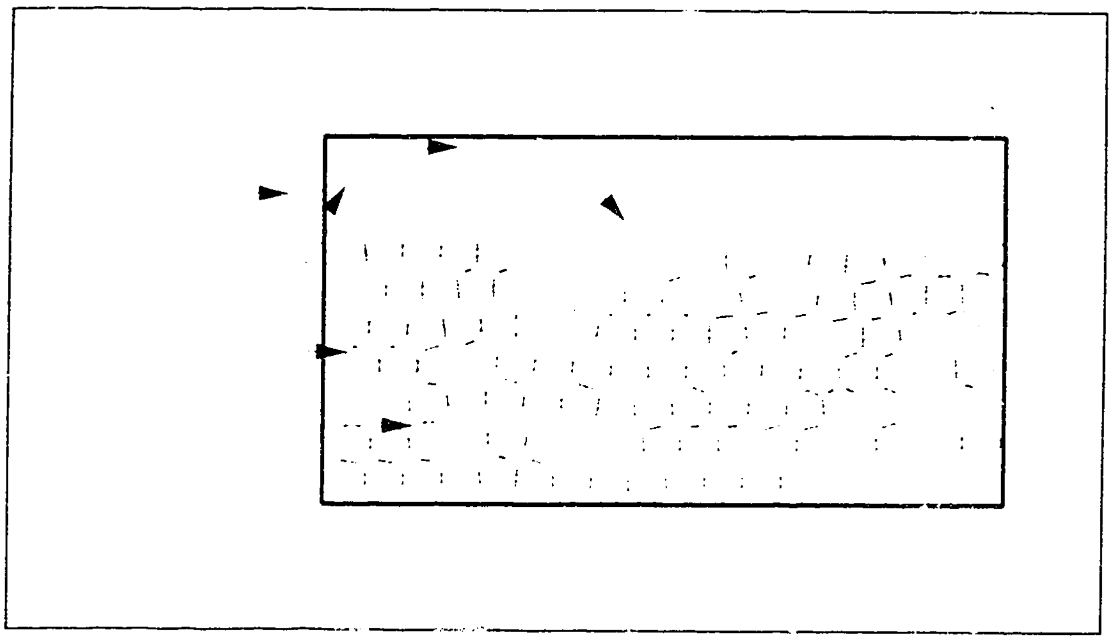

Figure 5.1 Airflow Pattern Through Golf Balls in a Box (Adapted from Émond *et al.*, 1994)

6. SUMMARY AND CONCLUSIONS

Three methods of cooling were tested, vertically-directed forced-air cooling (VFC), horizontally-directed forced-air cooling (HFC) and room cooling (CRC) which served as a control. The specific aim of this study was to compare the VFC and HFC treatments. Carrots, lettuce, strawberries and golf balls were used to run the tests. The golf balls were used as a check. Values of temperature over the period of cooling were measured, as well as weight loss of the three types of produce. A qualitative evaluation of shelf-life of the cooled produce was equally conducted. With the temperature data of the different produce, half-cooling time was determined and used for a statistical analysis comparing the three cooling treatments. Based on the results of this study the following conclusions can be drawn.

1. Inasmuch as VFC gave faster cooling rates than HFC, statistical analysis of the half-cooling times indicated that there was no significant difference between the two methods for lettuce and carrots. It is possible that different airflow rates, stack heights or widths and/or produce orientation within boxes could affect the statistical significance of differences between the two methods. Further experimental work is justified to investigate this.

2. Generally, better cooling was achieved by the VFC method compared with the HFC method, as observed from the data obtained on cooling rate (cooling coefficient and half-cooling time), weight loss and shelf-life evaluation. For example, while 83% of the lettuce heads cooled by VFC were acceptable after four days, 17% of those

cooled by HFC were acceptable. Similarly, only half the strawberries cooled by HFC were acceptable compared to those cooled by VFC eleven days after cooling.

3. As a follow-up to (2), VFC would be best suited for the design and development of a mobile precooler for use in market gardening operations. If HFC is used, as in current commercial practice, careful attention needs to be paid to ensure correct stacking patterns and alignment of vents. Furthermore, for cooling to be efficient by this method the presence of head-spaces or dead-spaces in packing boxes cannot be tolerated which may require selective picking of produce or sorting during packing.

4. Cooling rate of the golf balls under HFC suggests that the effect of head-space on cooling is related to the amount of space created over the produce. An investigative study aimed at identifying a minimum percentage of head-space at which cooling is influenced using this method may be of some benefit.

7. RECOMMENDATIONS

7.1 RE-DESIGN OF PACKING CONTAINERS

The cartons currently used for packing of fresh produce ought to be replaced with standard carton-sized plastic containers. These containers, to resemble milk crates, should have grated bottoms and no side vents, as would be appropriate for vertically-directed forced-air cooling. Furthermore, these containers, again like milk crates, should allow for direct stacking without the operator having to bother with air leak control. With the design of such containers, direct packing and cooling can be carried out in the field for a wide variety of produce.

These containers should also be able to accommodate smaller containers like the strawberry picking containers. Implicitly, the strawberry picking containers would have to be modified and standardized. Modification of the strawberry picking containers would mean, grated bottoms and the ability to stack these containers, leaving no room for air leakage.

A problem often encountered with grated or basket-like containers is bruising. To limit this problem, material similar to that used for cartons, may be designed as cushioning grates to fit the inside of the containers.

Finally, to ensure the market gardeners do not have to invest in the continuous purchase of packing containers, a container recycling process as illustrated in Fig. 6.1. could be adopted.

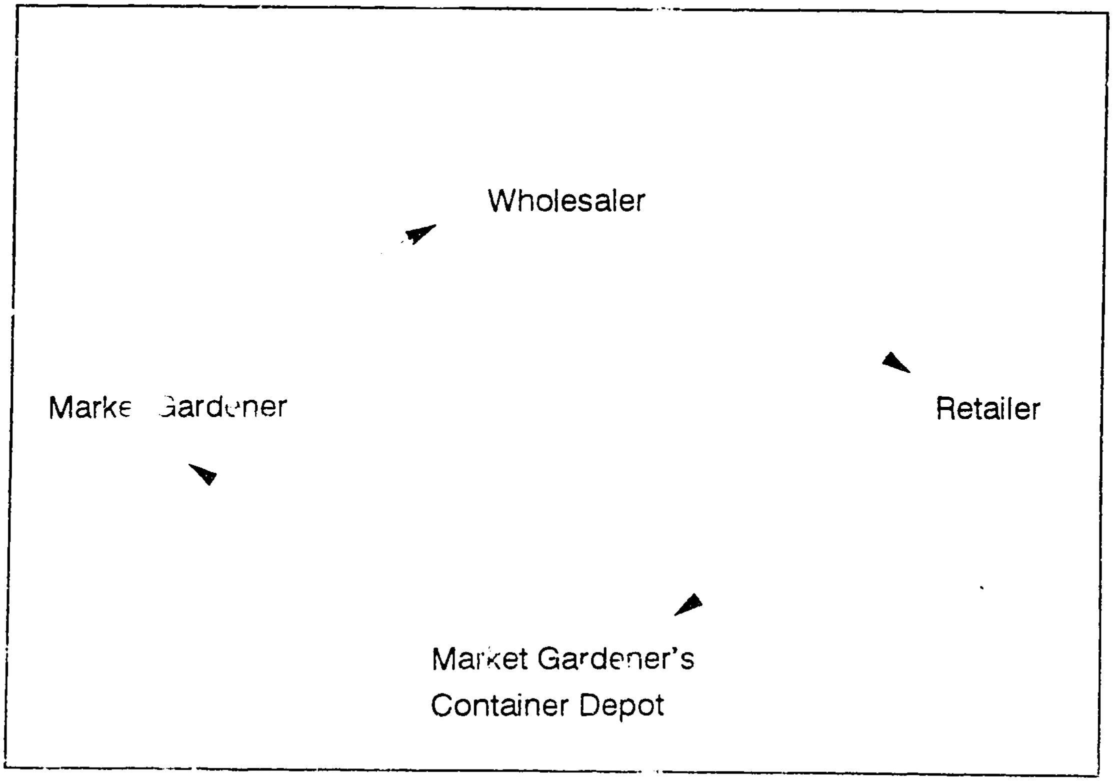

Figure 6.1 Recycling of Packing Containers in the Fruit and Vegetable Industry

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APPENDIX A

COMMUNICATIONS PROGRAM TO COLLECT AND STORE DATA

```
<< DATALOGGER COMMUNICATIONS >>
<< COMPILE THIS PROGRAM WITH TEST STACK OVERFLOW OFF >>


#include <io.h>
#include <stdlib.h>
#include <dos.h>
#include <conio.h>
#include <stdio.h>
#include <math.h>
#include <string.h>
#include "serial.h"

store_data1(); /* prototype*/
new_file1();   /* prototype */

#define VERSION 0x0101

#define FALSE0
#define TRUE(!FALSE)

#define NOERROR0/* No error */
#define BUFOVFL1/* Buffer overflowed */

#define ESC   0x1B/* ASCII Escape character */
#define ASCII0x007F/* Mask ASCII characters */
#define SBUFSIZ0x4000/* Serial buffer size  */


int SError     =NOERROR;
int portbase =0;
void     interrupt(*oldvects[2])();

static   char  ccbuf[SBUFSIZ];
unsigned       intstartbuf = 0;
unsigned       intendbuf = 0;

char     f_name[12];/* new filename*/
char     buf[10], string1[10];/* to creat newfile*/
int therm[36][118], z[5][118];/* temp. calibration array */
unsigned int   i, i_temp, d, j, k, m, s, t, tmp, r, q, l;
FILE *textfile;/* Pointer to file being used*/

   /* Handle communications interrupts and put them in ccbuf */
```

```
void     interrupt  com_int(void)
{
    disable();
    if ((inportb(portbase + IIR) & RX_MASK) == RX_ID)
    {
        if (((endbuf + 1) & SBUFSIZ - 1) == startbuf)
        SError = BUFOVFL;

        ccbuf[endbuf++] = inportb(portbase + RXR);
        endbuf &= SBUFSIZ - 1;
    }

    /* Signal end of hardware interrupt */

        outportb(ICR, EOI);
        enable();
}

    /* Output a character to the serial port */

int  SerialOut(char x)
{
    long        inttimeout = 0x0000FFFFL;

    outportb(portbase + MCR, MC_INT | DTR | RTS);
    timeout = 0x0000FFFFL;

    /* Wait for transmitter to clear */

    while ((inportb(portbase + LSR) & XMTRDY) == 0)
    if (!(--timeout))
    return (-1);

    disable();
    outportb(portbase + TXR, x);
    enable();
    return (0);
}

    /* Output a string to the serial port */

void  SerialString(char *string)
{
    while (*string)
    SerialOut(*string++);
}

    /* This routine return the current value in the buffer */

int  getccb(void)
```

```
{
    int  res;

    if (endbuf == startbuf)
    return (-1);

    res = (int) ccbuf[startbuf++];
    startbuf %= SBUFSIZ;
    return (res);
}

    /* Install our functions to handle communications */
void    setvects(void)
{
    oldvects[0] =  getvect(0x0B);
    oldvects[1] =  getvect(0x0c);
    setvect(0x0B, com_int);
    setvect(0x0c, com_int);
}

    /* Uninstall our vetors before exitingthe progam */
void    resvects(void)
{
    setvect(0x0B, oldvects[0]);
    setvect(0x0C, oldvects[1]);
}

    /* Turn on communication interrupts */

void    i_enable(int pnum)
{
    int  c;

    disable();
    c = inportb(portbase + MCR) | MC_INT;
    outportb(portbase + MCR, c);
    outportb(portbase + IER, RX_INT);
    c = inportb(IMR) & (pnum == COM1 ? IRQ4 : IRQ3);
    outportb(IMR, c);
    enable();
}

    /* Turn Off communication interrupts */

void    i_disable(void)
{
    int  c;

    disable();
    c = inportb(IMR) | ~IRQ3 | ~IRQ4
    outportb(IMR, c);
```

```
        outportb(portbase + IER, 0);
        c = inportb(portbase + MCR) & ~MC_INT;
        outportb(portbase + MCR, c);
        enable();
    }

        /* Tell modem that we're ready to go */

    void     comm_on(void)
    {
        int  c, pnum;

        pnum = ( portbase == COM1BASE ? COM1 : COM2);
        i_enable(pnum);
        c = inportb(portbase + MCR) | DTR | RTS;
        outportb(portbase + MCR, c);
    }

        /* Go off-line */

    void     comm_off(void)
    {
        i_disable();
        outportb(portbase + MCR, 0);
    }

    void     initserial(void)
    {
        endbuf = startbuf = 0;
        setvects();
        comm_on();
    }

    void     closeserial(void)
    {
        comm_off();
        resvects();
    }

        /* Set the port number to use */

    int  SetPort(int Port)

    {
        int  Offset, far  *RS232_Addr;

        switch (Port)
        {
            /* Sort out the base address */

            case COM1 : Offset = 0x0000;/* normal case */
```

```
            break;
            case COM2 : Offset = 0x0002;/* normal case */
            break;
            default: return (-1);/* abnormal case */
        }
        RS232_Addr = MK_FP(0x0040, Offset);/*Find out where the port is. */
        if (*RS232_Addr == NULL) return (-1);/* if null then port not used */
        portbase = *RS232_Addr;/* Otherwise set portbase */

        return (0);/* in normal case return 0 */
    }

        /* This routine sets the speed; will accept funny baud rates */
        /* Setting the speed requires that the DLAB be set on.      */

    int  SetSpeed(int Speed)


    {
        char       c;
        int  divisor;

        if (Speed == 0)/* avoid divide by zero */
        return (-1);
        else
        divisor = (int) (115200L/Speed);

        if (portbase == 0)
        return (-1);

        disable();
        c    inporth(portbase + LCR);
        outportb(portbase  + LCR, (c | 0x80));/* Set DLAB */
        outporth(portbase  + DLL, (divisor & 0x00FF));
        outporth(portbase  + DLH, ((divisor >> 8) & 0x00FF));
        outporth(portbase  + LCR, c);/* Reset DLAB */
        enable();

        return (0);
    }

        /* Set other communication parameters */

    int  SetOthers(int Parity, int Bits, int StopBit)

    {
        int  setting;

        if (portbase == 0) return (-1);
        if (Bits <5 || Bits > 8)  return (-1);
        if (StopBit != 1 && StopBit != 2)  return (-1);
```

```
    if (Parity != NO_PARITY && Parity != ODD_PARITY && Parity != EVEN_PARITY)
    return (-1);
    setting  = Bits - 5;
    setting |= ((StopBit == 1) ? 0x00 : 0x04);
    setting |= Parity;

    disable();
    outportb(portbase + LCR, setting);
    enable();

    return (0);
}

    /* Set up the port */

int  SetSerial(int Port, int Speed, int Parity, int Bits, int StopBit)
{
    if (SetPort(Port))return (-1);
    if (SetSpeed(Speed))return (-1);
    if (SetOthers(Parity, Bits, StopBit))return (-1);

    return (0);
}

    /* Control-Break interrupt handler */

int  c_break(void)

{
    i_disable();
    fprintf(stderr, "\nStill online. \n");

    return(0);
}

main()
{

    /* Communication Parameters */
    int  port = COM1;
    int  speed = 300;
    int  parity = NO_PARITY;
    int  bits = 8;
    int  stopbits = 1;

    int  c, done = FALSE; /*, store = FALSE; */
    int  flag = 0;

if (SetSerial(port, speed, parity, bits, stopbits) != 0) /* abnormal case */
    {
        fprintf(stderr, "Serial Port setup error. \n");
```

```
        return (99);
    }
 initserial();
 ctrlbrk(c_break);

 window(1, 1, 80, 25);
 clrscr();
 fprintf(stdout, "\n     DATA LOGGER TERMINAL\n\n"
        "...You're now in terminal mode...\n "
        "...press [ESC] to quit...\n\n"
        "...ready to receive data from DATA LOGGER...\n\n");

/* The main loop acts as a dump terminal.  We repeatedly check the keyboard buffer, and
communication buffer.*/

 i = -1; k = 0; j = 0; d = 0;/* data buf first byte*/
 do
 {
    if (kbhit())
    {
        /* Look for an Escape key */
        switch (c=getch())
        {
               case ESC: done = TRUE;  /* exit program */
               /* if (i!=0) no data are received */
               {
               printf("\nDo you want to store the data (Y/N)?");
               c=getch();
               printf("  %c \n", c);
               if(c==89 || c==121)/*Y or y is pressed*/
               {
               printf("\n input your filename...\n\n"); /* for DURA application */
               new_file1();
               store_data1();
               }
               printf("\nDo you want to load data again (Y/N)?");
               c=getch();
               printf("  %c \n", c);
               if (c==89 || c==121)
               {
               done=FALSE;
               i=0;
               printf("\n...ready to receive data from DATA LOGGER...\n\n");
               }
               else if(c==78 || c==110)
               done=TRUE;
               break;
               }
        }
        /* You may want to handle other key here... */
        if (!done)
```

```
            c = 254;
            SerialOut(c);
        }
        if ((c = getccb()) != -1)
        {
            buf[i]=c & ASCII;/* buffer to store data */
/*************************************************************************************
******/
            if (i>6)
            {
                    string1[7] = 0; string1[8]=0;
                    strncpy(string1, buf, 7);
                    therm[j][k] = atoi(string1);
                    k = k + 1;
                    if (k==118)
                    {
                    j = j + 1;
                    }
                    i=0;
            }
/*************************************************************************************
*****/
            if (flag==0 && c==13)/* there are two CR del one */
            {
                    flag=1;
                    i=i;
            }
            else
            {
                    flag=0;
                    i=i+1;
            }
        }
        t=0;
        if (k==118)
        {
            j = j - 1;
            printf("j = %d \n\n", j);
            for(m=0; m<=116; m++)
            {
                    therm[j][m] = therm[j][m+1]; /* remove first garbage value */
                    printf("%6d", therm[j][m]); /* print 2-d calib array on screen */
                    if (m==12*(t+1) + t)
                    {
                    printf("\n");
                    t = t + 1;
                    }
            }
            printf("\n\n");
            printf("%6d \n", therm[j][48]);
            printf("\n");
```

```
            k = 0;
            if (d == 0)
            {
                  j = 0;
            }
            else
            {
                  j = j + 1;
            }
            d = d + 1;
        }
  }
  while (!done && !SError);

      /* Check for errors */
      switch (SError)
 {
      case NOERROR: fprintf(stderr, "\nbye. \n");
      closeserial();
      return (0);

      case BUFOVFL: fprintf(stderr, "\nBuffer Overflow. \n");
      closeserial();
      return (99);

      default:    fprintf(stderr, "\nUnknown Error, SError = %d\n", SError);
      closeserial();
      return (99);
}
}

/*******************************************************************************
******

<< FUNCTION No.1: STORE DATA IN NEW FILE >>
<< This function stores data in buf[i] to the new file >>


store_data1()
{

    /* open the file named as string f_name */

    if ((textfile = fopen(f_name, "wb")) == NULL)
    {
         printf("Error opening text file for writing\n");
         exit(1);
    }
    else
    {
         /* Write the collected data to the file named as string f_name */
```

```
        for (t = 0; t <= j; t++)
        {
              for (m = 0; m <= 116; m++)
              {
              putw(therm[t][m], textfile);   /* save menu string in file*/
              }
        }
        /* Close file   */
        fclose(textfile);
        printf("Your data file %s has been successfully stored in disk.\n", f_name);
    }
return 0;
}

/*******************************************************************************************
******/

<< FUNCTION No. 2: CREATE A NEW FILE >>


/* Open a disk file for data acquisition */

new_file1()
{
int  handle;    /* to creat newfile*/

name_in:
    gets(f_name);
    printf("\nThe filename is: %s\n\n", f_name);

    /*  attempt to creat a file that doesn't already exist */
    handle = creatnew(f_name, 0);/* creat and return handle*/

    if (handle == -1)
    {
        printf("%s already exists, please enter another filename... \n\n", f_name);
        goto name_in;
    }
    else
    {
        close(handle);
    }
    return 0;
}
```

DATA CONVERSION PROGRAM: VOLTAGE TO TEMPERATURE

```
< < PROGRAM COOLDAT6.CPP: Converts Cooling Data Collected for Fruits and Vegetables to > >
< < Temperature Values (2 dp) and Stores Values in Files > >


# include "stdio.h"
# include "stdlib.h"
# include "io.h"
# include "dos.h"
# include "string.h"
# include "math.h"
# include "float.h"
temp_deriv();
stor_tmp();
new_file2();
char data_name[15], t_name[15];
FILE *celsius, *calibr, *tmpr;
float tmpval[70][117];
int calib[36][117];
int thrmval[70][117];
int t, j, tc, jc, n, m, r, p, s, lt, rt;
main()
{
    if ((calibr = fopen("TEST1.DAT","rb")) = = NULL) /*Recalls the Calibration Array*/
    {
        printf("cannot open file\n");
        exit(1);
    }
    else
    {
        for (tc = 0; tc< =35; tc+ +)
        {
            s = 0;
            for (jc=0; jc< =116; jc+ +)
            {
            calib[tc][jc] = 0;
            calib[tc][jc] = getw(calibr);
            printf("%5d", calib[tc][jc]); /* print on screen */
            if (jc = = 12*(s+1) + s)
            {
            printf("\n");
            s = s + 1;
            }
            }
            printf("\n");
        }
        fclose(calibr);
    }
```

```
printf("\n\n");
printf("Enter the filename of the data to be converted: ");
gets(data_name);  /* Strawberry, Lettuce or Carrot Filename */
printf("The filename is: %s\n\n", data_name);
if ((celsius = fopen(data_name,"rb")) == NULL)
{
    printf("cannot open file\n");
    exit(1);
}
else
{
    new_file2();
    printf("m = ");
    scanf("%d", &m);
    printf("\n\n");
    for (t=0; t<=m; t++)
    {
        for (j=0; j<=116; j++)
        {
        thrmval[t][j] = 0;
        thrmval[t][j] = getw(celsius);
        }
    }
fclose(celsius);
}
n = 0;
for (p=0; p<=m; p++)
{
    printf("%d \n\n", p);
    s = 0;
    for (r=0; r<=116; r++)
    {
        printf("%5d", thrmval[p][r]);  /*Print on Screen*/
        if (r == 12*(s+1) + s)
        {
            printf("\n");
            s = s + 1;
        }
        tc = 0;
        jc = r;
        lt = p;
        rt = r;
        n = m;
        temp_deriv();
    }
printf("\n");
}
stor_tmp();
return 0;
}
```

```
/*****************************************************************************************
**/

<< FUNCTION NO. 1: Temperature Deriving Function >>


temp_deriv()
{
    lt = p;
    rt = r;
    tmpval[lt][rt] = 0.00;
    tc = 0;
    jc = r;
    n = m;
    if (rt == 48)
    {
        tmpval[lt][rt] = thrmval[lt][rt];
    }
    else
    {
        if (thrmval[lt][rt] > 2000 )
        {
              tmpval[lt][rt] = 99.00;
        }
        else
        {
              do
              {
              tc = tc + 1;
              }
              while (thrmval[lt][rt] < calib[tc][jc]);
              if (thrmval[lt][rt] > calib[tc][jc])
              {
              tmpval[lt][rt] = (float)tc + ((-1)*((float)thrmval[lt][rt] -
(float)calib[tc][jc])/((float)calib[tc-1][jc] - (float)calib[tc][jc]);
              }
              else
              {
              if (thrmval[lt][rt] == calib[tc][jc])
              {
              tmpval[lt][rt] = tc;
              }
              }
        }
    }
if (jc == 116)
{
    printf("\n\n");
    s = 0;
    for (rt=0; rt<=116; rt++)
    {
```

```
        printf("%8.2f", tmpval[lt][rt]);
        if (rt == 8*(s+1) + s)
        {
              printf("\n");
              s = s + 1;
        }
    }
}
return 0;
}

/*****************************************************************************************
******/

<< FUNCTION NO. 2: Open a new file >>


new_file2()
{
    float handle;
    name_in:
              printf("Enter the filename to store converted data: ");
              gets(t_name);
              printf("The filename is: %s\n\n", t_name);
              handle = creatnew(t_name, 0);
              close(handle);
              return 0;
}

/*****************************************************************************************
******/

<< FUNCTION NO. 3: Store converted characters in seperate file b_name>>


stor_tmp()
{
    if ((tmpr = fopen(t_name,"ab")) == NULL)
    {
        printf("Cannot open file \n");
        exit(0);
    }
    else
    {
        fwrite(tmpval, sizeof(tmpval), 1, tmpr);
        fclose(tmpr);
    }
    return 0;
}
```

APPENDIX B

PROGRAM COOLTIME.BAS TO DETERMINE COOLING TIME

```
DECLARE SUB prntsub (nn, ctm(), xaa(), coolt)
DECLARE FUNCTION ctfunc! (k, crit!, Taa!, Tii!, xaa())
DECLARE FUNCTION xafunc! (Taa!, Tii!, cc!, mm!)
DIM ctime(18), xa(18)
'Program: Half cooling time and Seven-eigth cooling time.
CLS
INPUT "    Half cooling time and seven-eigth cooling time of ", hort$
PRINT ""
INPUT "For 1/2 or 7/8 cooling time, enter 1 or 2: ", cooltime
produce = 1
DO
  INPUT "The no. of files n = ", n
  INPUT "Temperature of the surrounding air Ta = ", Ta
  FOR i = 1 TO n
    PRINT ""
    PRINT USING "i = ##"; i
    PRINT ""
    INPUT "Initial temperature of the produce Ti = ", Ti
    INPUT "Enter intercept value on the y axis c : ", c
    INPUT "Enter slope value obtained for reg. m : ", m
    xa(i) = xafunc(Ta, Ti, c, m)
    PRINT ""
    PRINT USING "Ta = #.##"; Ta
    PRINT ""
    PRINT USING "xa = ####.# "; xa(i)
    PRINT " "
    SELECT CASE cooltime
         CASE 1
              crit = LOG((Ti + Ta) / 2)
         CASE 2
              crit = LOG((Ti + 7 * Ta) / 8)
    END SELECT
    ctime(i) = ctfunc(i, crit, Ta, Ti, xa())
    PRINT USING "ctime = ###.# "; ctime(i)
    PRINT ""
  NEXT i
  CALL prntsub(n, ctime(), xa(), cooltime)
  produce = produce + 1
LOOP UNTIL produce > 6
END

FUNCTION ctfunc (k, crit, Taa, Tii, xaa())
ct = (crit - LOG(Tii)) * xaa(k)
ctfunc = ct / LOG(Taa / Tii)
```

```
END FUNCTION

SUB prntsub (nn, ctm(), xaa(), coolt)
OPEN "c:\ik\thesis\cooldata\cooltime\halfglf.dat" FOR OUTPUT AS #2
CLS

SELECT CASE coolt
    CASE 1
        PRINT #2, "      File       xa       x(t/2)"
        PRINT "      File       xa       x(t/2)"

    CASE 2
        PRINT #2, "      File       xa       x(7t/8)"
        PRINT "      File       xa       x(7t/8)"
END SELECT
FOR j = 1 TO nn
  PRINT #2, USING "       ##        ####.#      ###.#"; j; xaa(j); ctm(j)
  PRINT USING "       ##        ####.#      ###.#"; j; xaa(j); ctm(j)
NEXT j
CLOSE #2
END SUB

FUNCTION xafunc (Taa, Tii, cc, mm)
xaa = LOG(Taa / Tii) - cc
xafunc = xaa / (-mm)
END FUNCTION
```

APPENDIX C

STATISTICAL ANALYSIS: COMPARISON OF COOLING METHODS

```
options ps = 60;
/******************************************************/
/* PROGRAM TO OBTAIN ANOVA FOR COOLED PRODUCE USING THE*/
/*   HALF COOLING TIME AND/OR SEVEN-EIGTH COOLING TIME */
/******************************************************/
/* INPUT THE MERGED DATA FROM FILE HBERRYA */
data bval;
    do block = 1 to 2;
      do method = 1 to 3;
        do stack = 1 to 2;
          do position = 1 to 3;
            infile 'a:hberrya.dat';
            input box $ berry12 @@;
            output;
          end;
        end;
      end;
    end;
cards;
proc print;
title 'Half Cooling Time for Strawberries';
title2 'ANOVA for Nested-Split-Plot Design (Stack Nested)';
proc glm;
    class block method stack position;
    model berry12 = block method stack(method*block) position
                position*method;
    random block stack(method*block) /test;
    lsmeans method / e= stack(method*block) stderr pdiff;
/*****************************************************************
/* INPUT THE MERGED DATA FROM FILE HCARROTA *
data cval;
    do block = 1 to 2;
      do method = 1 to 3;
        do stack = 1 to 2;
          do position = 1 to 3;
            infile 'a:hcarrota.dat';
            input box $ carrot12 @@;
            output;
          end;
        end;
      end;
    end;
cards;
proc print;
```

```
title 'Half Cooling Time for Carrots';
title2 'ANOVA for Nested-Split-Plot Design (Stack Nested)';
proc glm;
    class block method stack position;
    model carrot12 = block method stack(method*block) position
                position*method;
    random block stack(method*block) /test;
    lsmeans method / e= stack(method*block) stderr pdiff;


/*****************************************************************/
/* INPUT THE MERGED DATA FROM FILE HLETTUCE */
data lval;
    do block = 1 to 2;
      do method = 1 to 3;
        do stack = 1 to 2;
          do position = 1 to 3;
            infile 'a:hlettuce.dat';
             input box $ lett12 @@;
            output;
          end;
        end;
      end;
    end;
cards;
proc print;
title 'Half Cooling Time for Lettuce';
title2 'ANOVA for Nested-Split-Plot Design (Stack Nested)';
proc glm;
    class block method stack position;
    model lett12 = block method stack(method*block) position
                position*method;
    random block stack(method*block) /test;
    means method / e= stack(method*block) duncan lsd;
run;
```